Microrobotics Summary

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This is my summary of the course Microrobotics HS2021. I cant guarantee the correctness of the document, so read it with causion. I am happy for any feedback if errors are found.

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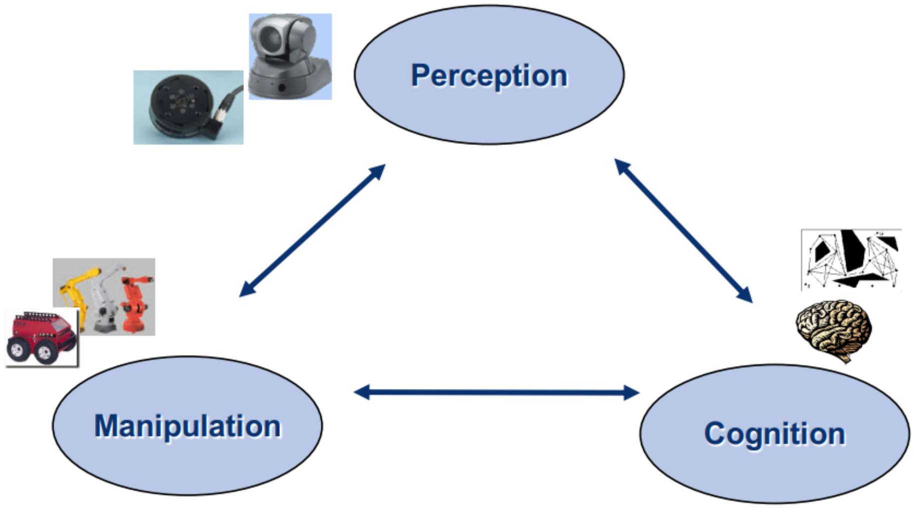
1 Introduction to Microrobotics

Robotics is a interdisciplinary field including mechanical engineering, electrical engineering and computer science. Microrobotics is then a subgroup of robotics, with focus on developing small scale (μm) intellignet robots.

In robotics there are three main components, namly **perception**, **manipulation** and **cognition**.



Robots can be build in any scale, but **microrobotics is focusing on the** mm **to** nm **scale.**

1.1 A Brief History of Microrobotics

The history is not very important, so it will be held very short.

Timeline of the invnetions:

1600's Invention of the Optical Microscope

1665 Robert Hooke's Micrographia(a book)

1675 Antonie van Leeuwenhoek and animalicus(also a book)

- Microassembly and the Watch industry get big

1930-1973 Swimming Microorganisms are researched

- Manipulation of small objects begins

  1922, 1949 Magnetic Trapping
  1930 Electrophoresis
  1970 Optical Trapping

1982 Silicon as Mechanical Material gets big

1980-90 MEMS (Micro-Electro-Mechanical-Systems) are researched

1995 Mechanics of Micromanipulation

1995- Microassembly

1998- Cell Manipulation

2003- Biomedical Robots

1.2 Impact of Microrobotics

Microrobotics are widly used as **Tools for Biology**, as the facilitate *Lab Automation* and help to understand the *Mechanics of Mechanobiology (Force Relationship in Cells)* There are a few examples on the Slides 01 Introduction.

The second big impact of Microrobotics is for **Medical Devices**, as the enable *Targeted Therapy* or *good control for very small operations.*

Figure 1: Mechanical Tasks for Microrobots

One example of a medical microrobot, is the *Camera Pill*. The Camera Pill is a small pill the patient can swallow equiped with cameras and other sensors to get data from the patients digestive system.

1.3 Connection to Robotics Research

As Microrobotics is a subgroup of Robotics, nearly all Robotics Research can be used for Microrobotics but on other scale levels and specific applocation. The following list names the most important connections.

- Planning and Systems Control
- Machine Learning
- Localizaton and Mapping
  - MRI, CT, Ultrasound, Optical, PET
- User Interfaces

Special challanges for Microrobotics are *Sensing*, *Actuation* and most of all **Power**. Getting power to the microrobot is one of the biggest challanges today.

An Example can be found on the slides regarding Eye Surgery wiht Micrrobots.

1.4 Introduction Summary

Primary Applications:

- Biology
- Medicine

Main Challanges:

- Powerdelivery
- Propulsion
- Fabrication

The Potential for Microrobotics is huge, but the field is at its infancy.

2 Scaling

As Microrobotics act on the sub mm scale, the physics differ a lot from the to us known macroscale physics. Namly the following physical concepts have to be revisited:

- Mechanical Forces
- Thermal Effects
- Surface Tension becomes important
- Fluidic Motion

2.1 Scaling Laws in Nature

As things get smaller and smaller concepts like surface to volume ratios $\left(\frac{S}{V}\right)$ or relative strenght of external forces become very important and differ a lot from the form we are used to.

Two Examples:

- Small Animals have a difficulty surviving due to heat loss, as the heat loss is scaling with $\sim L^2$ but the heat generation is scaling $\sim L^3$. For the meter scale this is not a problem, but for the smallest animals this gets problematic.
- Capillary Tubes: weigth scales with $\sim L^3$ but surface tension scales with $\sim L^1$. As a result, a $1\mu m$ diameter capillary could raise water $30m$.

As the size decreaces the importance of the phenomena that scales with the largest length dimensions decreaces as well. In most cases these are phenomena that scale with the volume ($\sim L^3$) of the object.

On the slides of Scaling, there are more interesting facts about scaling in nature.

2.2 Non-dimensional Numbers

As things get non intuitive at small scale, some non-dimensional numbers are introduced to compare systems we know with microsystems. The goal of non-dimensional numbers is to determine the importance of physical effects and compare systems.

Reynolds Number:	$\frac{\text{Inertial Forces}}{\text{Viscous Forces}}$	Fourier Number:	$\frac{\text{Diffusion}}{\text{Storage Rate}}$
Biot Number:	$\frac{\text{Conduction Resistance}}{\text{Convection Resistance}}$	Mach Number:	$\frac{\text{Velocity}}{\text{Speed of Sound}}$
Weber Number:	$\frac{\text{Inertia}}{\text{Surface Tension}}$	Bond Number:	$\frac{\text{Gravity}}{\text{Surface Tension}}$
Froude Number:	$\frac{\text{Inertia}}{\text{Gravity}}$		

2.3 Scaling of Mechanical Effects

2.3.1 Scaling of Forces

At small scales the forces coupled to the volume become less important as seen above. As a result effects like **gravity or inertia become irrelevant** while effects like **friction**, which is coupled to the surface area, **become dominant**.

For Microrobotics newtonian mechanics can be used until we get to the nanometer scale at that point quantum effects begin to influence the behaviour of objects.

As microrobots mostly opperate in aqueous environements fluiddynamic effects like viscosity need to be considered.

The most important mechanical scalling effect, is the rapid decrease of mass, which is related to volume (keeping the density constant). As a result Inertial effects become less important and therefore objects can **quickly change the velocity** and **resonant ferquencies get very high**.
Additionaly gravity gets irrelevant $F_{gr} \sim L^3$.
In contrast the Van der Waals forces get more dominant $F_{vdw} \sim L^2$.
Comparing these two forces, Adhesion gets dominant at small scales $\frac{F_{vdw}}{F_{gr}} \sim L^{-1}$.

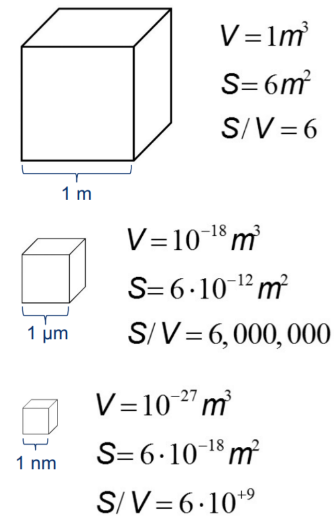


Figure 2: Scaling of a cube

As an example we can look at the frequency of a cantilever. The vibrations has it origin in the following PDE.

$$\frac{EI}{\rho A}\frac{\partial^4 w}{\partial x^4} + \frac{\partial^2 w}{\partial t^2} = 0 \tag{1}$$

With E being the Younds modulus, ρ being the density, A being the surface area and I being the moment of inertia. The first resonant frequency of this equation is

$$\omega_1 = 3.516\sqrt{\frac{EI}{\rho A L^4}} \tag{2}$$

We see if all dimensions are scaled the vibration scales with $\sim L^{-1}$ and if only the length is scaled $\sim L^{-2}$. If we pug in some numbers $a = 10\mu m$, $L = 100\mu m$, we get a frequency of

$$f = \frac{3.516}{2\pi}\sqrt{\frac{EI}{\rho A L^4}} \approx 1.29MHz, \qquad I = \frac{bd^3}{12} \quad \text{(for a rectangular cross section)} \tag{3}$$

We see that at small scales objects can move very fast as the inertial forces are very small.

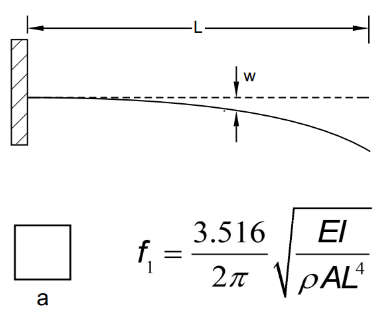


Figure 3: Cantilever

2.4 Scaling of Fluidic Effects

Which form of flow occurse is determined by the Reynolds Number.

$$Re = \frac{\rho D v}{\eta} \tag{4}$$

With ρ being the density, D being the characteristic length, v being the linear velocity and η being the viscosity. **At the microscale laminar flow is dominant**, as the characteristic length and velocity are mostly very small.

Another important fluidic aspect at the microscale is the volumetric flow through a capillary. The flow is described by the **Hagen-Poiseuille Flow**.

$$\boxed{Q = \frac{\pi r^4 \Delta p}{8 \eta l}} \tag{5}$$

With Q as volumetric flow, r as radius, l the length, η viscosity and Δp a pressure drop. As a result the flowrate scales with $\sim L^3$. This scaling can have dramatic effects. For example a aterial occlusion can have dramatic effects on the flowrate.
The pressure change over the capillary can be described as the pressure change over a pipe of lenght l and average velocity $U = \frac{Q}{\pi r^2}$.

$$\Delta p = -\frac{8 \eta U l}{r^2} \tag{6}$$

2.5 Scaling of Thermal Effects

Thermal effects at small scales are mostly instant. This can be seen as the energy required to heat a volume scales with $\sim L^3$ but the heat transfer scales with $\sim L^2$ so the heat transfer is much bigger than the energy required. The time until thermal equilibrium is achieved scales with $\sim L^2$.
The Biot Numeber descirbes the ratio of convection and conduction.

$$Bi = \frac{R_{conv}}{R_{cond}} = \frac{hL}{k} \tag{7}$$

with L being the characteristic length, $h = \left[\frac{W}{m^2 K}\right]$ as the convection coefficient and $k = \left[\frac{W}{mK}\right]$ as the conduction coefficient. The Biot Number at the microscale is mostly $Bi \ll 1$.

Therfore we have. **At small scales thermal equilibrium happens almost instantaneously**. This can be used for thermal acuators.

2.5.1 Thermal Actuators

By heating a micromachined and thermally isolated structure, the object can easily be deforemd due to thermal expansion. This is also very efficient as the small thermal mass doesn't consume a lot of power. As the Biot Number is very small, the device can be switched on and off very quickle and there are no thermal gradients which could lead to the object cracking.

A thermal actuator ussually consist out of two U-shaped beams, that are anchored together. By heating the upper beam with a **flow of current** the actuator moves down. For upwards movement the bottom beam has to be heated. The maximal deflection is about $6 \mu m$ at a voltage difference of $9V$. This can actuator can then be used as a thermal relay, where the movement of the accutator opens and closes a electrical circuit. As the Biot Number is small, the closing time is less than $< 2ms$.

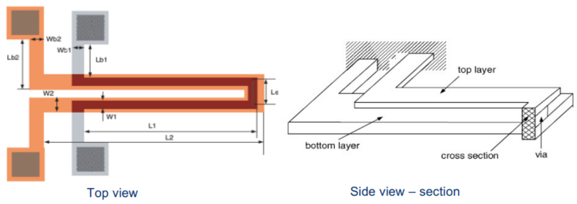


Figure 4: Thermal Actuator

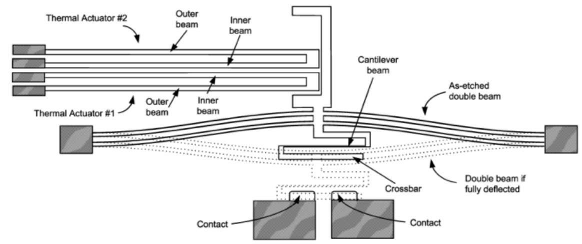


Figure 5: Thermal Relay

2.6 Scaling of Electrical Effects

The scaling of resistance, capacity and induction is as follows.

- Resistance scales with $R = \frac{L\rho}{A} \sim L^{-1}$, so the resistnace increases as the objec gets smaller.
- Capacity scales with $C = \varepsilon_0 \frac{A}{d} \sim L^1$ so the capacity decreases as the object gets smaller.
  - The Charge density is assumend to be constant $\frac{Q}{A} \sim L^0$
  - The Voltage of scales with $V = \frac{dQ}{dA} \sim L^1$, so it also decreases with as the objects size decreases. The Voltage is directly coupled to the Capcity.
  - The Electrostatic Force scales with $F = \frac{Q^2}{2\varepsilon A} \sim L^2$, so it decreases as the object gets smaller, but decreases slower then gravity.
- Induction is dependant on the change of magnetic flux over time.
  - The Voltage of a conductor loop inside a changing magnetic field with frequency f scales with

    $$U = BA(-2\pi f)\sin(2\pi ft) \sim L^2$$

  - Induction is directly dependent on the relative motion of the systems (Electrodynamics).

Even though the electrical froces get smaller, they are bigger than for example gravity, so the become dominant at suficiently small scales.

2.7 Scaling of Magnetic Effects

The scaling of magnetic effects is depending on the application.

- Magnetic Force between two wires $F \sim L^4$
- Magentic Force between a wire and a magnet $F \sim L^3$
- Torque between two magnets $T \sim L^3$
- Force between two magnets $F \sim L^2$

$$F_m = \mu_0 M v \left|\frac{\partial H}{\partial x}\right| = \frac{3\mu_0 M^2 v^2}{2\pi x^4}$$

- So the force ratio between two magnets and gravitiy scales with $\sim L^{-1}$

2.8 Scaling of Chemical Effexts

As most chemical reactions are surface reactions, a hihger S/V ratio increases the kinematics and efficeny. At the microscale the S/V is very hight, so chemical reactions are much faster.

2.9 Scaling of Power Density

As mentiond the problem of power delivery is one off the hardest nuts to crack in microrobotics. If the power is to low the device lacks activity but if the power is to high, the risk of material failure increases.
The powerdensity for different kind of forces scale differently.

Force Type	Scaling	Power Density
Weight/Elecromagnetic	L^3	$L^{0.5}$
Electrostatic/Fluid	L^2	L^-1
Surface Tension	L^1	$L^{-2.5}$

As we see electrostatic devices have a higher power density at smaller scale, therefore it is favorbale to use elctrostatic forces.

One problem in microrobotics is the good scaling of adhesive forces, so there is a need for a constant power supply.
The actual supply of power is a big challange, as batteries are a very bad idea, because they scale with volume and are therefore no suited for microscale power delivery. Alternatives include light, heat, electric and magnetic fields and chemical reactions.

2.9.1 Actuation Methods

The follwowing actuation methods are used on microrobots.

- Ligth Actuated Microrobots
  - Actuation is base on the light response of materials such as shape changing polymers or biomaterials
  - Optical responsive materials are usually soft and highly biocompatible, so they are good for biomedical applications
  - As Light can be focused very well and has a very small wavelength it si very good for nanoscale actuation
- Thermally Actuated Microrobots
  - Thermally induced material size change can be used to deform devices (as mentiond above)
  - At the small scale the S/V ratio is large, so the heat diffuses very rapid allowing for fast thermal responses
  - Thermally responsive biomaterial can be used, to accutate soft microrobots, as the swell if the are headed and thus can change their shape
- Magneticaly Actuated Microrobots
  - Magnetic fields allow for a very precise and wireless vontroll of devices (they can be biocompatible)
  - Different methods allow different motions
- Chemicaly Actuated Microrobots
  - Onboard chemical reactions allow for probulsion of the device. This can be achieved by release of kinetic energy in form of bubbles.
  - As they are self powerd, external conrol is very difficult

2.10 Micromanipulation

At microscale the objectmanipulation gets very difficult as different type of forces get more important. Thus the scaling law demand new types of force exertion, because classic gripping and pushing doesn't work at the microscale. Gravity becomes neglibile at a scale below $\sim 100\mu m$. Electromagnetic Forces start to dominate.

- Surface Tension cause by H_2O molecules and the resulting adhesion increase
- Electrostatic Forces dominate over gravitational forces
- Van der Waals Forces are dependante on the surface and thus increase in importance.

New contact and gripping methods have to developed.

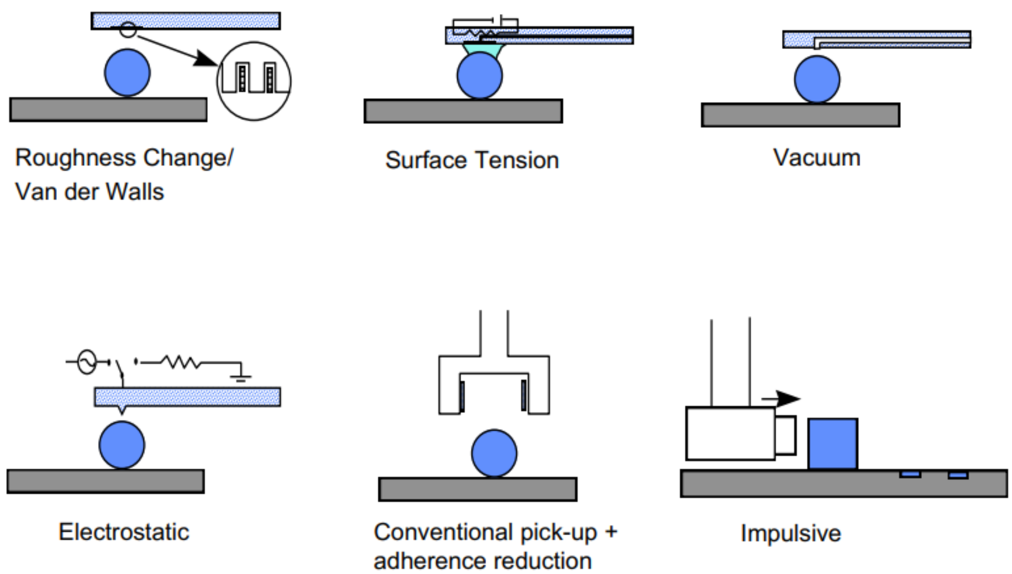


Figure 6: New Gripping Methods

Some Examples are on the Slides for Scaling.

2.11 Scaling Summary

- **Scaling at microscale is mostly non intuitive.**
- **Different forces scale differently**
  - Intertial forces become irrelevant while electromagnetic forces become increasingly important.
  - Thermal equilibrium is achieved very fast.
  - Laminar flow dominates the microscale
  - new actuators can and have to be used at the microscale.

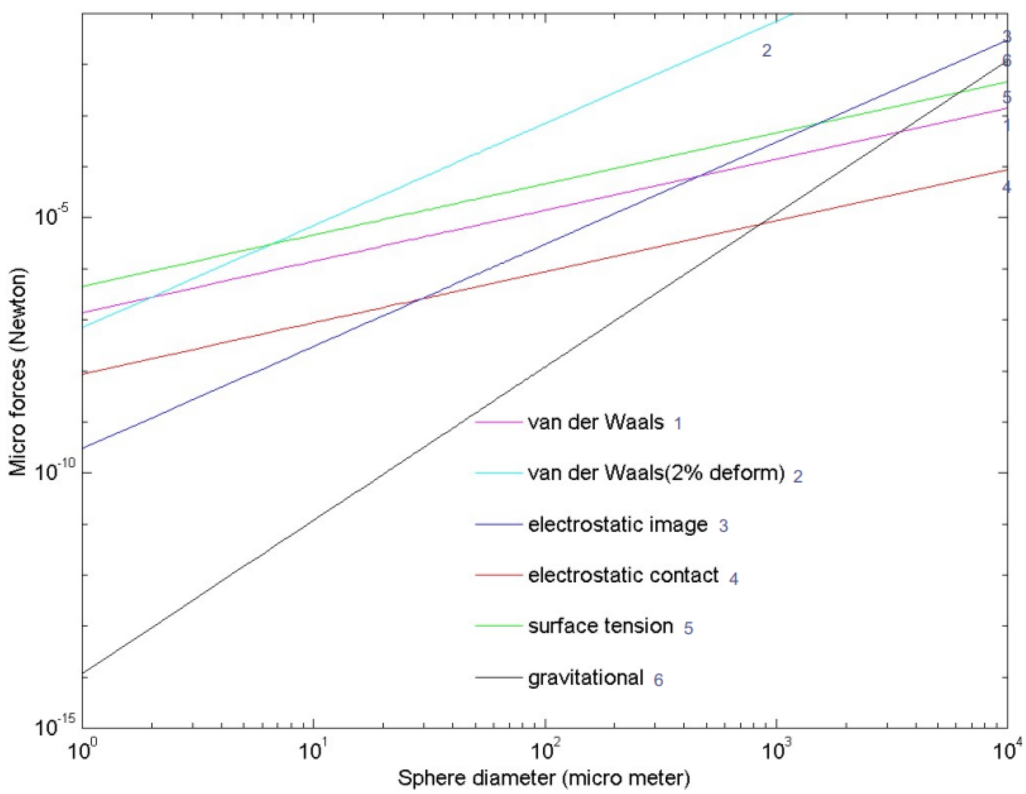


Figure 7: Plot of the Force Scaling

3 Electrostatics

As it can be seen in the Plot of Force Scaling, at small scales, electrostatci forces become increasingly important. A water strider for example can walk on water, because the surface tension(an electrostatic force) is higher than the weight of the strider. From the four force in physics (strong forces, weak forces, electromagnetic forces and gravity) at the microscale the electromagnetic forces are dominant.

3.1 Properties of Electrostatics

Electrostatic forces are a fundamental foce in nature and can have relatively long range interactions. As the forces are dependant on the charge and not the volume, they can be very strong even at small scales. Charges can easily be induced onto devices by ionization and polarization.
As they are used a lot at the microscale, **major function and failure mechansim of MEMS devices are dependant on electrostatic forces**.

3.2 Coulombs Law

In electrostatics, the electric charges do not move. Coulombs law describes the realtion between to charges.

$$F = \frac{1}{4\pi\varepsilon}\frac{q_1 q_2}{|r|^2}\vec{r} \tag{8}$$

As we can see the force is proportional to the product of the charges and inverse proportional to the square of the distance. Different to gravitational forces, electrostatic forces can be attractive or repulsive depending on the signs of the charges.

An more general way to describe the influence of a charge in space, we can have a look at the Electric field which descirbes the amount of force on a test particle of unit charge. The field lines of the electric field go from positive to negative charges and decay much more slowly than other intercations.

3.2.1 Potential Energy in Electrostatics

The electric field of multiple charges is just the superposition of the single charges and create a vector field.

$$\vec{E}(\vec{r}) = \sum_{i=1}^{N} \vec{E}_i(\vec{r}) \tag{9}$$

From the definition of the electric field, we get the force acting on an particel in an electric field.

$$\vec{F} = q \cdot \vec{E} \tag{10}$$

We can then insert the definition of work.

$$W_{AB} = \int_{r_A}^{r_b} -qE \cdot dr \tag{11}$$

The electric Potential is then Work per unit charge and the Voltage is then the difference of the electric potential between two points.

3.3 Piezoelectricity

Piezoelectricity is the interaction between mechanical stress and electrical charge. This phenomena mostly occurse in crystals and some cheramics. As the metrial is deformed a potentialdifference can be measured accors the axis of deformations. The phenomen is very usfull for example small force measurements for example microphones or they can be used as actuators, as the deforamtion is reversible. But the the stroke length is very short and a high amount of voltage is needed to deform the material.

3.4 Electromagnetic Forces at the Atomic Scale

Most atomic bonds and forces like ionic, metallic and covalend bonds or Van der Waals oder Surface Tension are based on electromagnetic forces and can mostly be described with cloulombs law.

3.4.1 Van der Waals Inercation

Even thought the ideal gas law is usefull $PV = nRT$ it is not accurate. We could instead use the Van der Waals interaction.

$$\left(P + \frac{an^2}{V^2}\right)(V - nb) = nRT \tag{12}$$

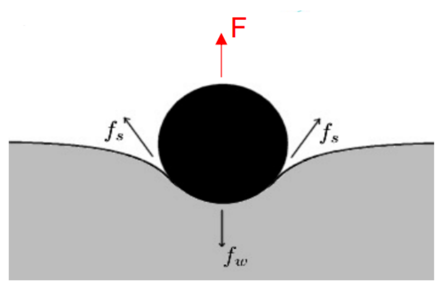
The Van der Waals forces do not only apply for gases but also for liquids and solids and are a result of the elctron charge distribution of two atoms. They are different from the three known bonds and are also relatively weak in comparison to the bonds. But they get significant in the interaction between molecules or surfaces. The Van der Waals Interactioin Force is an attraction Force.

On the Sildes have a look at the Potential Curve of Atoms.

Example of Van der Waals force:
Geckos can walk up vertical walls because their feet have very small lamella and thus a huge surface area. When thes small lamella come close to the wall Van der Walls forces attracte the small lamellas. The force of one lamella es tiny but adding all the small forces of the uncountable lamella results in a force big enough to hold the gecko on the wall.

3.4.2 Surface Tension

The surface tension is caused by the cohesive force within a liquid, that attract the molecules of the liquid by various intermolecular forces. Inside the liquid the forces cancle out and there is an equilibrium. But at the surface there is a net force point normally into the liquid. This force pushes the molecules into the liquid, resulting in surface tension. As a result of this attraction force the surface area of the liquid is being minimized.



Illustrative diagram of surface tension forces on a needle floating on the surface of water (shown in cross-section).

The force of the surface tension is always parralel to the surface, but when the surface get deformed this results in an upward force. The surface tension is denoted with $\gamma \left[\frac{N}{m} = \frac{J}{m^2}\right]$. The surface tension is measured by streching a membran until it breaks (see Slides).
Interface forces are observed between all three phases. Surface Tension describes the force between liquid and vapour.
The shape of a dropplet on a solid surface is determined by the relationship of the cohesive forces trying to minimze the surface area by trying to form a sphere and adhesive forces pull the liquid down and flattening the drop (see Slides). The shape of the droppled depends ond the surface properties. Hydrophobic surfaces result in a large contact angle and form a round dropplet. Hydrophiliy surfaces result in a small contact angle and fresult in a flat spread out dropplet.

3.4.3 Capillary Effect

Inside thin channels the surface tension results in a capillary effect.

With Gravity:
Strong adhesive forces pull up the liquid along side the channel against gravity. This is supported by the surface tension minimizing the surface area. The height difference achieved by the capilarry effect is inverse proprotional to the radius.

$$h = \frac{2\gamma\cos(\theta)}{r\rho g} \tag{13}$$

For Liquids with very high surface tension od hydrophobic channels, the liquid gets pushed down as the cohesive forces are stronger than the adhesive forces.

Without Gravity:
At some point gravity can be neglected and only the surface tension and capillary effects are relevant. This relation is described by the Bond Number.

$$Bo = \frac{r^2\rho g}{\gamma} = \frac{\text{Gravity}}{\text{Surface Tension}} \tag{14}$$

For small Bond numbers the surface tension is dominant. At the microscale r is usually small so gravity can be neglected. As a result hydrophilic micro-channels fill quickliy and hydrophobic micro-channels are difficult to full but empty easily.

3.4.4 Controlling the Surface Tension

As the surface tension is relevant at the microscale controlling the surface tension or hydrophilic properties is very important.
Surfaces can be made hydrophilic by hydrophilization by inducing polyrity on the surface. This is done by plasma activation or coating with hydrophilic materials.
It is also possible to change the surface tension of a liquid, for example by electrowetting. As the surface tension depends on the temperatur the surface tension can be changed by temperatur differences.

3.5 Electrostatics Summary

- **At small scalles electromagnetic forces are dominant.**
- **Therefore they are the main force for robotic micromanipulation and locomotion.**

4 Magnetism

Another very important force in microrobotics is the magnetic force. Magnetism has it origin in electrodynamics and thus are connected to electrostatics. Since the scaling for magnetic forces are very good they are widly used in microrobotics. Therefore we will introduce the force and torque on ferromagentic materials in externally applied fields. We can then use magnetic fields and field gradients to control the microrobot wierelessly.

4.1 Fundamentals

A magentic field is generated by **moving electrical charges**. This magnetic field can then be detected by acceleration of an other moving electric charge, a current carrying conductor or by the force or torque on a magnetic dipole.

A very important difference to electrstatics is the fact, that **the smallest unit in magnetism is a magnetic dipol**. If you cut a magnetic dipol in half it will stay a magnetic dipol. The field lines from a magnetic dipole go from the north to the south pole. A electrical loop carrying a current creates a dipole and is thus often used as the smallest magnetic element.
The vector $\vec{m}$ points along the axis from south to north and is called magnetic moment. The value of $\vec{m}$ is called dipole strength with units $\left[Am^2\right]$.

4.1.1 Origin of Magnetism

Magnetism has it orgin on the atomic scale. An atom is made out of neutrons and protons in the nucleus and electrons are in motion around the nucleus. The electrons carrying a negative charge produce a magnetic dipole field as they spin around the nucleus. In most atoms the electrons come in pairs with different spins so the magnetid dipoles cancel. But in materials with unpaird electrons there is an net magnetic field.

Most material can thus be classified in one of the following categories

- Diamagnetic - no unpaired electrons, tiny attentuation (abschwächung) of the external field
- Paramagnetic - small number of unpaired electrons -¿ small intensification
- Ferromagntic - large number of unpaired electrons -¿ large intensification, some materials can even retain (behalten) the magentic field and are called permanent magnets

4.2 Gausss Law and Amperes and Faradays Laws

There are two ways to determine the magnetic field. We eather use Gausss Law, wich states that the magnetic flux is divergence free and electric fields are caused by electric charges.

$$\nabla \cdot \vec{B} = 0, \qquad \nabla \cdot \vec{D} = \rho \tag{15}$$

If we have a closed volume with surface area S we can use the integral form for the second equation.

$$\oint_S \vec{E} dA = \frac{\rho}{\varepsilon} \tag{16}$$

Gausses Laws are mainly used for electrostatics.

On the other hand we have Amperes Law and Faradays Law. Amperes Law states, that a moving current and changes in electric fields generate a rotational magentic field.

$$\nabla \times \vec{H} = \vec{J} + \frac{\partial D}{\partial t} \tag{17}$$

Faradays Law in contrast states that a change of the magnetic field generates a electric field.

$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t} \tag{18}$$

For microrobotics we only consider magnetics, so we only need Amperes Law and Gausss Law for magnetism.

$$\nabla \times \vec{H} = \vec{J} + \frac{\partial D}{\partial t}, \qquad \nabla \cdot \vec{B} = 0, \qquad \nabla \cdot \vec{D} = \rho \tag{19}$$

We will neclet the $\frac{\partial D}{\partial t}$ as it will only be relevant for very high frequencies.

The difference between $\vec{H}$ and $\vec{B}$

The magnetic field $\vec{H}\left[\frac{A}{m}\right]$ gives rise to a magnetid induction or flux densitiy $\vec{B}\,[T]$ in a medium with permeability μ.

$$\vec{B} = \mu \vec{H} \tag{20}$$

In general both $\vec{H}$ and $\vec{B}$ are vectors and μ would be a tensor and the relationship is nonlinear, anisotropic and temperatur dependent. We mostly look at the linear case.
$\vec{H}$ thus does not depend on the medium, whereas $\vec{B}$ does. $\vec{B}$ is a measure of how the material reacts to a magnetic field $\vec{H}$ and we can use μ to classify magnetic materials.

For linear and isotropic materials μ becomes a scalar and is definded as.

$$\mu = \mu_0 \cdot \mu_r, \qquad \mu_0 = 4\pi \cdot 10^{-7} \left[\frac{Tm}{A}\right] \tag{21}$$

The relative permeability μ_r can then be used to classify magnetic materials as introducecd in the beginning of this chapter.

- Diamagnetic: $\mu_r 1$
- Paramagnetic: $\mu_r = 1...10$
- Ferromagntic: $\mu_r \gg 10$
- For Vacuum or air we have: $\mu_r = 1$

We are mostly interessted in ferromagnetic materials as the can be used for magnetic locomotion. Some important ferromagentic materials are iron, nickle, cobalt and their alloys.

Example:

Insde an iron bar we have $|\vec{B}| = \mu_0 \mu_r |\vec{H}|$ with $\mu_r = 1000$. This means that for a given external field $\vec{H}$ iron concentrates the flux lines by a factor of 1000 than air. This is only true until $H < H_{sat}$. For $H > H_{sat}$ the material cannot handle more flux and the flux density stays the same.

4.2.1 Ferromagnetic Materials

Ferromagntic materials have unpaird electrons creating a magnetic dipole. Thes dipoles tend to spontaneously align without an external field, to reduce their exchange energy. In a unmagnetized material those aligned dipole units point in all directions and thus no net field can be detected. The dipol units containing organized dipoles are called **Weiss domains**. These Weiss domains are aligned at the short range, but over the whole material are anti-aligned.

But if a external field is applied the weiss domains move and they reorient parallel to the applied field, generating a net field intensifying the external field. This happens until all domains are oriented along the external field and saturation occurs.
The resulting magnetic filed generated by the weiss domains is called magnetization and is denoted with $\vec{M}$.

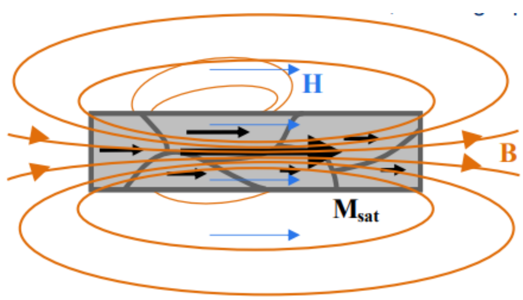


Figure 8: Magnetization of a Ferromagnetic Material

What happens after the external field is gone allows further classification of materials.

- Soft Magnetic Materials: the wiess domains reorient again and no or a weak field is observed
- Hard Magnetic Materials: the domains remain oriented creating a permanent magnet

4.2.2 Hysteresis Loop

The whole process of magnetization can be presented in a B-H or M-H diagramm (Hysteresis Loop).

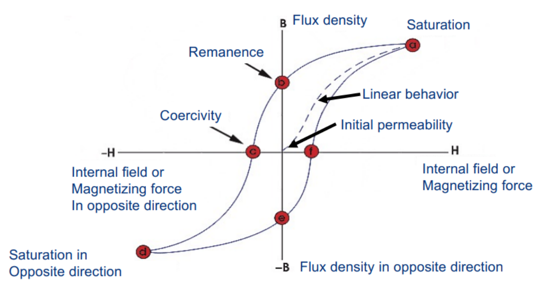


Figure 9: M-H Hysteresis Loop (wrong axis description in the figure)

The Remaining field after the external field is gone, is called remanence. The demagnetizing behavior describes the behavior when the H field is lowerd or turned around.

- Coercivity H_c is the negativ field required to demagnetize the material $B = 0$
- Hard magnetic materials: $|H_c| > 10000\,[A/m]$
- Soft magnetic materials: $|H_c| < 1000\,[A/m]$

These Hystersis Loops are very important in describing the magnetic behavior and thus the application of a material.

- Strong permanent magnets need a hight remanence
- For memory storage the material should have high coercivity(stability) and remanence
- For Transformers the material should be soft and have a small hysteresis loop (less energy loss in AC)
- For Electromagnets the behaviour should be soft and linear with a high permeability and saturation(amplification)

μ describes the relationship between $\vec{B}$ and $\vec{H}$ but it changes depending on the location on the hysteresis loop. So we have to introduce the magnetig susceptibility χ.

4.2.3 Magnetization

The magnetization captures the magnetic state of the material and is related to the magnetic moment $\vec{m} = v\vec{M}$ with v being the volume of the body. The magnetization is a vector field like $\vec{H}$ and $\vec{B}$. The relationship is as follows.

$$\vec{B} = \mu_0(\vec{H} + \vec{M}) = \mu_0\vec{H} + \mu_0\vec{M} \tag{22}$$

A visual description can be seen in the Figure 8.
In hard magnetic materials once the material is magnetized, the magnetization is independent of $\vec{H}$ with remanence $\vec{B}_r = \mu_0\vec{M}$. In soft materials on the other hand the magnetization and the external field are related by the susceptibility tensor. This is also true for hard magnetic materials until permanent magnetization is achieved.

$$\vec{M} = \chi\vec{H} \tag{23}$$

The relationship between μ_r and χ is derived by comparing the external field with the internal field in soft magnetic materials.

$$\vec{B} = \mu_0\vec{H} + \mu_0\vec{M} = \mu_0\vec{H} + \mu_0\chi\vec{H} = \mu_0(I + \chi)\vec{H} = \mu\vec{H} \tag{24}$$

Comparing the last two equalities we get.

$$\chi = \frac{\mu}{\mu_0} - I, \qquad \chi = \mu_r - 1 \quad \text{for lienar region with } \mu \text{ being a scalar} \tag{25}$$

4.3 Magnetic Forces and Torques

We knwo that a ferromagnetic material will magnetize if it is placed in a magnetic field. We also observe that a piece of iron (ferromagnetic material) rotates and moves in a magnetic field. We thus expect a relation between the magnetization and the force and torque a magnetic field field exerts onto the device. Magnets can be categorized into two categories.

4.3.1 Force

The force on a magnetic body is given by.

$$\vec{F} = \mu_0 \int_v (\vec{M} \cdot \nabla)H dv \approx \mu_0 v(\vec{M} \cdot \nabla)H \tag{26}$$

where v is the volume of the body, $\vec{M}$ is the magnetization of the body and $\vec{H}$ is the external magnetic field. The approximation can be done if the external field only acts on the center of mass of the body (only true for small bodies) and if we treat $\vec{M}$ as a single vector, wich is only true for ellipsoids.

If there are no currents flowing $\nabla \times \vec{H} = 0$ we can simplify the equation to.

$$\vec{F} = \mu_0 v \left[\vec{M} \cdot \frac{\partial\vec{H}}{\partial x}, \vec{M} \cdot \frac{\partial\vec{H}}{\partial y}, \vec{M} \cdot \frac{\partial\vec{H}}{\partial z}\right]^T \tag{27}$$

$$\vec{F} = \mu_0 v \begin{bmatrix} \frac{\partial}{\partial x}H_x & \frac{\partial}{\partial x}H_y & \frac{\partial}{\partial x}H_z \\ \frac{\partial}{\partial y}H_x & \frac{\partial}{\partial y}H_y & \frac{\partial}{\partial y}H_z \\ \frac{\partial}{\partial z}H_x & \frac{\partial}{\partial z}H_y & \frac{\partial}{\partial z}H_z \end{bmatrix} \tag{28}$$

We see that the force does not depend on the magnitude of $\vec{H}$ but only on the gradient. The force is maximal when the magnetization is aligned with the external field.

The magnetization $\vec{M}$ of a hard metalic material is independent of the applied field so the equation can be applied directly. For soft magnets the internal field depends on the external field so we have to look at extra relationships.

4.3.2 Torque

The torque on a magnetic body is given by.

$$\vec{\tau} = \mu_0 v \vec{M} \times \vec{H} \tag{29}$$

Observe that the torque is dependent on the magnitude of the applied field $\vec{H}$ and vanishes if $\vec{M}$ and $\vec{H}$ are aligned. The torque is maximal for a specific angle. For hard magnetic materials the magnetization is independent of the applied field, so the torque is maximal if $\vec{H}$ and $\vec{M}$ are prependicular.
For soft magnetic materials the specific angle dependas on the material as the relations ship between $\vec{M}$ and $\vec{H}$ is non linear.

4.4 Soft Metalic Materials

In soft metalic materials the magnetization $\vec{M}$ is not constant and depends on the magnetic field $\vec{H}$. There are two distincions.

- Linear Region: $\vec{M} = \chi \vec{H}$
- Saturation Region: $|\vec{M}| = m_s$

In this course we mostly assume we know $\vec{H}$ and it is applied at the center of mass of the body. With this assumptions we can determine the magnetization of the body.
The magnetization will minimze the total energy of the system. The relevant energys to minimize come from anisotropy and the zeeman energy.

The anisotropic energy comes from the fact, that material will be magenitsec along a given direction. The relevant anisotropy energy comes from the shape anisotropy. This shape anisotropy originates form the interaction between the dipoles in the material and tries to align the magnetizazion along the geometry of the body. There are two distinct directions along wich the body can be magnetized. The easiest axis is called **easy axis** and the hardes direction is called **hard axis**. So we will focus on how the shape of the device influences the magnetic proberties of the body.

We will look at the linear region $\vec{M} = \chi \vec{H}_i$, in this region the magnetization depends on the field inside the material. When a soft magnetic material is in a magnetic field there will be an internal field $\vec{H}_i$ and a demagnetizing field $\vec{H}_d$ insed the material. The internal field is the sum of the external field and the demagnetizing field.

$$\vec{H}_i = \vec{H} + \vec{H}_d \tag{30}$$

The demagnetizing field comes from the fact that the magnetization $\vec{M}$ results in two magnetic dipoles at the surface of the material.

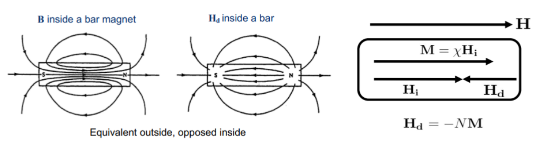


Figure 10: Demagnetizing Field

This results in a magnetic field $\vec{H}_d$ point in the opposite direction. The relationship between $\vec{M}$ and $\vec{H}_d$ is given by the demagnetizing tensor N.

$$\vec{H}_d = -N\vec{M} \tag{31}$$

If the bodies geometrical axis are aligned with the coordinate system, the tensor becomes diagonal.

$$N = \begin{bmatrix} n_x & 0 & 0 \\ 0 & n_y & 0 \\ 0 & 0 & n_z \end{bmatrix} \tag{32}$$

The tensor hase following properties.

- n_i are the eigenvalues of N with all $n_i > 0$
- N has trace 1: $tr(N) = n_x + n_x + n_z = 1$
- The smallest n_i represents the easy axis, wich corresponds to abig internal field and larger magnetization
- N is a simplification that can only be applied to fully magnetized shapes where the assumption of a single magnetization vector is good

The n_i can only b computed exactly for ellipsoids and mostly result in $n_a + 2n_r = 1$. For other shapes the computation is more complex and mostly done with numerical tools or tables.

We can now combine the demagnetizing tensor and the susceptibility tensor.

$$\vec{M} = \chi \vec{H}_i, \qquad \vec{H}_i = \vec{H} + \vec{H}_d = \vec{H} - N\vec{M} \tag{33}$$

comibining the equations

$$\vec{M} = \chi \vec{M} - \chi N \vec{M}, \qquad \vec{M} = \chi[I + \chi N]^{-1}\vec{H} = \chi_a \vec{H} \tag{34}$$

The external susceptibility tensor χ_a has the following form.

$$\chi_a = \begin{bmatrix} \frac{\chi}{1+n_x\chi} & 0 & 0 \\ 0 & \frac{\chi}{1+n_y\chi} & 0 \\ 0 & 0 & \frac{\chi}{1+n_z\chi} \end{bmatrix} \tag{35}$$

And becaus e soft magnetic materials ar ferromagnets $\chi \gg 10$ and we get $\chi_a = \text{diag}(\frac{1}{n_x}, \frac{1}{n_y}, \frac{1}{n_z})$. This result means that in the linear region the shape of the object is more important than the susceptibility.

Combining all the derivations gives us insight into the direction of magnetization inside a soft magnetic body. The magnetization vector of a soft magneitc body that is fixed lies in between the easy axis and the applied field. The direction depends on the level of anisotropy and the strength of the applied field.

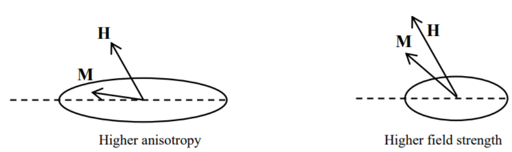


Figure 11: Magnetization of a Soft Magnetic Body

If the body is free to move, the torque will eventually align the easy axis and $\vec{H}$ as the body turns in the field and thus chaniging the direction of $\vec{M}$ and thus changing the torque etc..

4.5 Creating Magnetic Fields

We looked at how magnetic objects move inside a magnetic field. We now want to look at how we creat the external magnetic fields to move the robots. We will induce a magnetic field with a current carrying wire. The magnetic field induced by a wire can be calculated with the Biot-Savart Law.

$$d\vec{H} = \frac{1}{4\pi|r|^2} di\vec{l} \times \vec{r} \tag{36}$$

i being the current in the wire(assumed to be constant).

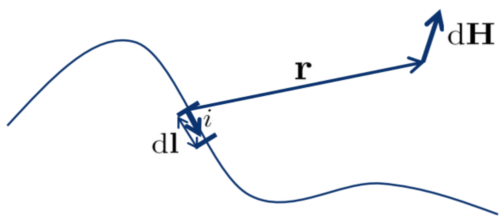


Figure 12: Biot-Savart Law

Integrating the equation over the whole wire results in the magnetic field. As this is quit tedeous we will mostly us known results, especially coils.

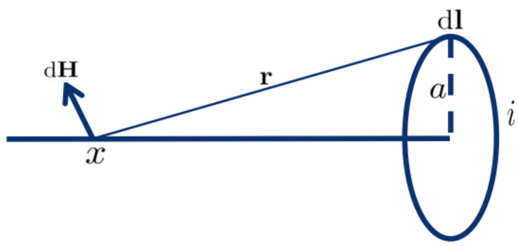


Figure 13: Magnetic Field from a Coil

The magnetic field from a coil centerd around the axis will have a magnetic field along that center axis with magnitude.

$$|\vec{H}| = \frac{ia^2}{2(a^2 + x^2)^{3/2}} \tag{37}$$

For the field off axis a numerical solution is required. For a coil with N turns, the magnitude can just be multiplied by N.

Combining two coils in a specific was results in controllable magnetic fields and field gradients.

4.5.1 Helmholtz Coils

A Helmholtz Coil consists of two parallel coils with common radius and seperation distance a. The current in the coil flows in the same direction.

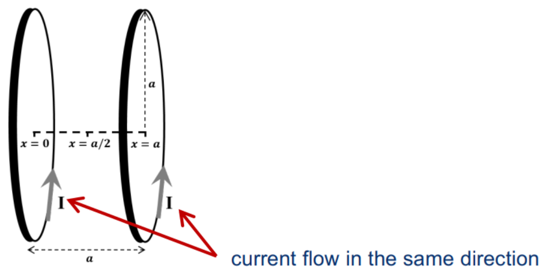


Figure 14: Helmholtz Coils Configuration

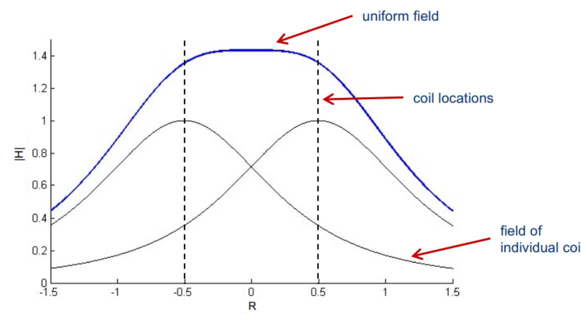


Figure 15: Helmholtz Coils Magnetic Field

The magnitude of the magnetic field between the two coils is almost constant with magnitude.

$$|\vec{H}| = (\frac{Ni}{2a})\left[\left(1+\frac{x^2}{a^2}\right)^{-1.5} + \left(1+\frac{(a-x)^2}{a^2}\right)^{-1.5}\right], \qquad |\vec{H}(x=\frac{a}{2})| = \frac{0.7155Ni}{a} \tag{38}$$

4.5.2 Maxwell Coils

A Maxwell Coil consists of two parallel coils with common radius and seperation distance a. But the current in the coils flow in opposite directions.

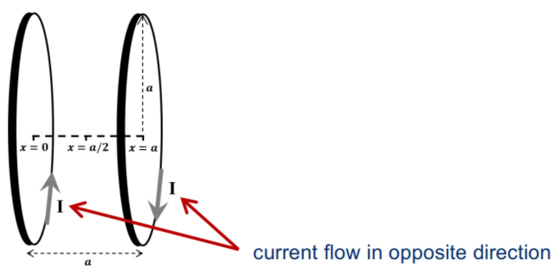


Figure 16: Maxwell Coils Configuration

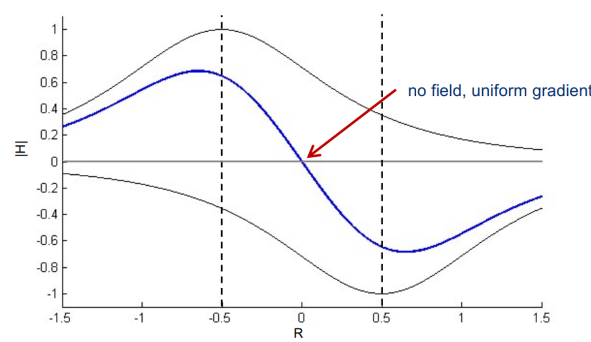


Figure 17: Maxwell Coils Magnetic Field

The field inside the coils is not constant but has a constant gradient $\frac{\partial \vec{H}}{\partial x} = const.$. The magnitude at the cender of the coil is 0.

$$|\vec{H}| = (\frac{Ni}{2a})\left[\left(1+\frac{x^2}{a^2}\right)^{-1.5} - \left(1+\frac{(a-x)^2}{a^2}\right)^{-1.5}\right], \qquad |\vec{H}(x=\frac{a}{2})| = 0 \tag{39}$$

4.5.3 Electromagnets

Another way to create a constant field by a solenoid. A solenoid is a long coil with lenght L, diameter D and N turns. The magnetic field inside a solenoid is uniform and at the center of a long solenoid the magnetic field simpliyfies to

$$|\vec{H}| = \frac{Ni}{L} \tag{40}$$

The field at the ends is half the value of the center $\frac{Ni}{2L}$. The magnetic field created by a solenoid is similar to that of a magnet and thus the solenoid is called electrmagnet. The stenght of the magnetic field can be increased by inserting a ferromagentic core inside the solenoid. The magnetic field from the solenoid magnetizes the core and thus increases the magnetic field.

4.6 Scaling of Magnetics

The scaling of magnetics can assesed by looking at a permanent magnet that can be described by a point dipole.

$$\vec{H}(\boldsymbol{P}) = \frac{1}{4\pi|\vec{P}|^3}\left(\frac{3(\vec{m}\cdot\vec{P})\vec{P}}{|\vec{P}|^2} - \vec{m}\right) \tag{41}$$

we use $\vec{m} = v\vec{M}$ as the connection between the magnetization $\vec{M}$, the volume v and the magnetic moment $\vec{m}$.
$\vec{P}$ is the position where the field is measured.
If all dimensions are scaled, the overall magnetic field stays constant. $\vec{m} \sim L^3$, $|\vec{P}| \sim L^1$ and thus $\vec{H} \sim L^0$.
This results in favorable scaling properties as the magnitude and the relative geometry stay the same.
The only thing that changes is the gradient. **The gradient increases** as we have smaller lengths.

The scaling of the Force/Torque per Volume stays constant $T/v, F/v \sim L^0$. This is better than gravity but other forces like surface tension scale better. If we can bring the magnet closer to the robot the scalling becomes better.

4.7 Benifits of Magnetic Interactions

Even thought the scaling is not the best magnetic interactions habe a lot of benifits.

- Permanent Forces: Permanent Magnets provide a constant magnetic field.
- Bistability Suspensions: Permanent magnets can keep a system in a given conifuration without energy consumption
- Remote stat switching is possible as external fields can magnetize soft magnets in MEMS devices an change the behavior
- Long Range Actuation: Magnetic fields and gradients can be effective even over long distances relative to the MEMS device and a big range of motion can be achieved
- Contactless Actuation can help locomotion inside the body
- Magnetic fields are considered safe for humanse (only high frequencies can be dangerous)

4.8 Magnetism Summary

- Electromagntic forces dominate at the microscale
- Magnetic manipulation is a powerful way to control microrobots
- A magnetic field is generated by a moving electrical charge
- The magnetic field gives rise to a magnetic flux wich is orders of magnitude denser in magnetic materials compared to air
- Magnetic Bodies experience forces and torques when exposed to a magnetic field
- We can compute these forces for both soft and hard magnets

5 Liquids

For microrobotics fluiddynamics is very important because nearly all applications at the sub milimeterscale are related to fluidynamics. This can for example be seen in nature as the smallest living organism living in a dry environement is about $30\mu m$. The main problem is to retain the fluid at smaller scales.

But wter allows both extremes as the smallest and largest animals live in water.

5.1 Navier Stokes Equation

The Navier Stokes Equation is the fluiddynamic equivalent to Newtons Second Law. It has to be used for incompressible fluids.

$$\underbrace{\rho\left(\frac{\partial\vec{v}}{\partial t}+(\vec{v}\cdot\nabla)\vec{v}\right)}_{\text{Inertial force per volume}(ma)} = \underbrace{\overbrace{-\nabla p}^{\text{pressure force}} + \overbrace{\mu\nabla^2\vec{v}}^{\text{viscous forces}}}_{\text{external forces}(F_{ext})} \tag{42}$$

An exact solution for the Navier Stokes Equation is very hard to find, so try to make simplifications for easier solutions. We start by introducing characteristic non-dimensional variables.

$$\tilde{\vec{x}} = \frac{\vec{x}}{L}, \quad \tilde{\vec{v}} = \frac{\vec{v}}{v_s}, \quad \tilde{t} = \frac{tv_s}{L}, \quad \tilde{p} = \frac{pL}{\mu v_s} \tag{43}$$

If we insert these variabels into the Navier Stokes Equation and simplyfie we get

$$\underbrace{\frac{\rho v_s L}{\mu}}_{\text{Reynolds Number}}\left(\frac{\partial\tilde{\vec{v}}}{\partial\tilde{t}}+(\tilde{\vec{v}}\cdot\tilde{\nabla})\tilde{\vec{v}}\right) = -\tilde{\nabla}\tilde{p}+\tilde{\nabla}^2\tilde{\vec{v}} \tag{44}$$

We thus see if the Reynolds Number has extremes values one of the sides can be neglected.

5.1.1 Reynolds Number

The Reynolds Number is a non dimensional number that describes the importance of intertial and viscous forces.

$$Re = \frac{\rho v_s L}{\mu} = \frac{\text{Interial Forces}}{\text{Viscous Forces}} \tag{45}$$

with ρ as the density, v_s the characteristic velocity, L the characteristic lenght and μ the fluid viscosity.
Note as the characteristic variables are not precisely defined, the Reynolds Number as a whole is not precisley defined and different conventions are used.

	Reynolds number
A large whale swimming at 10 m/s	300,000,000
A tuna swimming at the same speed	30,000,000
A duck flying at 20 m/s	300,000
A large dragon fly going 7 m/s	30,000
A copepod in a speed burst of 0.2 m/s	300
Flapping wings of the smallest flying insects	30
An invertebrate larva, 0.3 mm long, at 1 mm/s	0.3
A sea urchin sperm advancing the species at 0.2 mm/s	0.03
A bacterium, swimming at 0.01 mm/s	0.00001

Figure 18: Values of the Reynolds Number

5.1.2 Low Reynolds Numbers

As we see from the definition, the lenght and velocity are in the numerator. At the microscale these values are usually very small and as a result the Reynolds Number at the microscale is also very small $\rightarrow Re \ll 1$. This means that the viscous forces are more important than the inertial forces Viscous Forces $\gg$ Inertial Forces.
Because of that we can neglect the left side of the equation and we get the **Stokes Flow**.

$$\nabla p = \mu \nabla^2 \vec{v} \tag{46}$$

As we can see Stokes Flow is not time dependent and therefore reciprocal motion is not possible (every motion done for propulsion is reversed by moving in the other direction). At the macroscale a Low Reynolds Number can be achieved by a very hight viscosity $\mu \gg 1$.

5.1.3 Intermediate Reynolds Numbers

If the Reynlods Number is between $1 < Re <\sim 1000$ both inertial and viscous forces play an important role.

5.1.4 High Reynolds Numbers

If the Reynolds Number is higher than $Re \gg 10000$ the viscous forces can be neglected. This means we have nearly no friction and the flow is mostly turbulent.

5.1.5 Laminar and Turbulent Flow

The Reynolds Number also descirbes if the flow is laminar or turbulent (flow regime). Therefore a fluid mechanics model must consider the Reynolds Number. As the characteristic lenght can increase over the body the Reynolds Number can differ over the body and exceed the critical value. If this happens the laminar flow (small Reynolds Number) transitions ot a turbulent flow (high Reynolds Number).

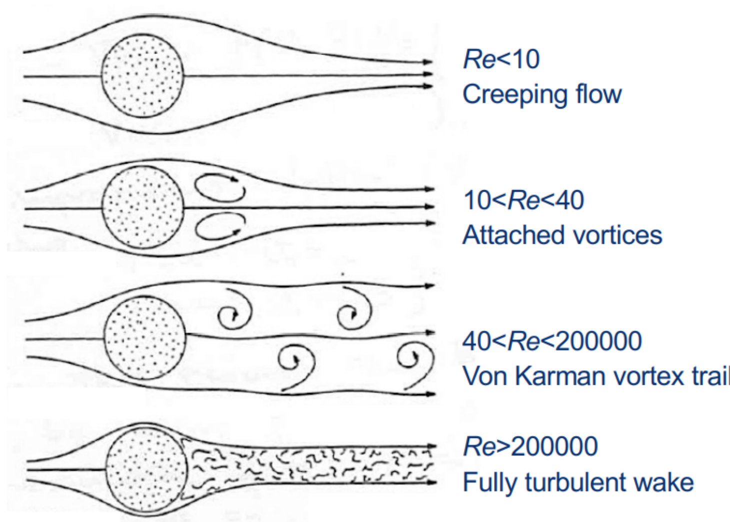


Figure 19: Transition from Laminar Flow to Turbulent Flow

5.2 Stokes Flow

As already mentioned at the microscale the flow is mostyl laminar and can be described by the Stokes Flow. An important value we need to knwo is the drag force in Stokes Flow. The drage force is given by.

$$\boxed{\vec{F}_{drag} = \underbrace{6\pi\mu R}_{=D_u}\vec{v}}, \quad D_u = \text{Drag Coefficient} \tag{47}$$

R is the Radius of the object.
This equation can be used to estimate the force needed to push/pull a micro-object.

For rotation we have a drag torque. This torque can be approximated by the following equation.

$$\vec{\tau}_d rag = 8\pi R^3 \vec{\omega} \tag{48}$$

We see the drag torque scales with R^3 so it is much smaller than the translational drag force.

5.2.1 Case Study

A microsphere $R = 1\mu m, \rho_s = 10^4 \frac{kg}{m^3}$ is pulled through water at a velocity $v = 10\frac{\mu m}{s}$. The pulling force in the steady state can be computed with the drag coefficient.

$$F_{pull} = F_{drag} = D_a v \approx 0.2pN = 0.2 \cdot 10^{-12} N \tag{49}$$

At $t = 0$ the drag force is released and we want to know the coasting distance and time of the spehere. To do this we use Newtons Second Law.

$$m\frac{d}{dt}v(t) + D_a v(t) = 0, \quad v(t = 0) = v_0 = 10\frac{\mu m}{s} \tag{50}$$

The solution to this ODE is an exponential.

$$v(t) = v_0 \exp\left(-\frac{D_a}{m}t\right) \tag{51}$$

If we want the coating distance of the spehere we have to integrate the speed over all time.

$$d_{coast} = \int_0^\infty v(t)dt = v_0 \frac{m}{D_a} \approx 2 \cdot 10^{-11} m, \qquad t_{coast} \approx 15\mu s \tag{52}$$

As a result we see that steady state is reached almost immediately. t_{coast} is defined as the time where $v(t) = 0.1\% \cdot v_0$.

5.3 Swimming at Low Reynolds Number

As we saw that Stokes Flow is independent of time swimming becomes a challange. Normal propulsion techniques we use as humens won't work because the motion to move us forward is counterd by the movment backwards.
In other wordes. A shape change generates a motion. When the shape is changed back to its original configuration with the exact reversed motion (independent of speed), the body is moved back to its original position. Such a motion is called **reciprocal motion**.
A micro-swimmer thus must generate a non-reciprocal motion in order to produce a net displacement. To create a non-reciprocal motion more than one degree of freedom (DOF) is necessary.

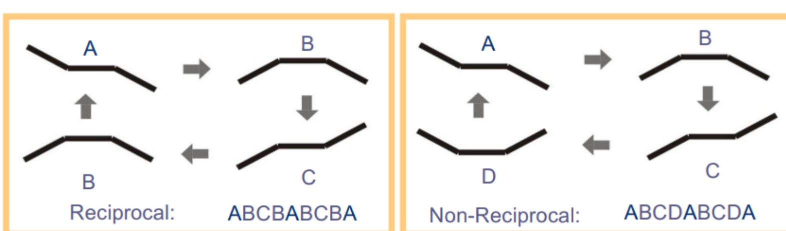


Figure 20: Figures of Reciprocal Motion(left) and Non Reciprocal Motion(right)

One way to produce a non-reciprocal motion is by having a turning tail(flagella with a corkscrew motion) like a sperm or with a cilia power stroke (see video on youtube or slides).

5.4 Propulsion Matrix - Artificial Bacterial Flagella (ABF)

A body namely a artificial bacterial flagella (ABF) trying to swim with a helical motion(rotation) will experience a linear relationship between the force, torque, velocity and rotational speed. This relationship can be represented in the **Propulsion Matrix**(PM).

$$\begin{bmatrix} F \\ \tau \end{bmatrix} = \underbrace{\begin{bmatrix} a & b \\ b & c \end{bmatrix}}_{PM} \cdot \begin{bmatrix} u \\ \omega \end{bmatrix} \tag{53}$$

$$a = A_t + A_h, \quad b = B_t, \quad c = C_t + C_h, \quad a, c > 0, b < 0 \tag{54}$$

F and τ are the external *non-fluidic* forces and torques applied onto the object. The drag force and torque are included in the propulsion matrix, where the index t and h stand for the tail and head respectively. Analytical models for a spehre and helical tail are avaliable bu they mostly have to be estimated experimentaly.

Figure 21: Helical Motion Sketch

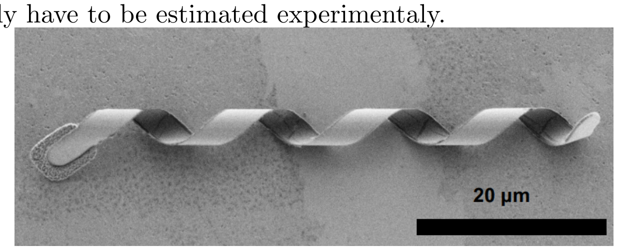


Figure 22: Helical Motion Real Robot

5.4.1 Controlling the ABF

A rotatiting magnetic field is used to control the rotational speed ω of the ABF. The torque τ is then given bay the external field H and the angle between the field and ABF.

$$\tau_m = V \cdot \vec{M} \times \vec{H} \stackrel{!}{=} \tau = b \cdot u + c \cdot \omega \tag{55}$$

An increase in rotational speed ω increases the forward velocity u (linear relationship).

$$u = \frac{F}{a} - \frac{b}{a}\omega, \quad b < 0 \tag{56}$$

If an external foce is applied the velocity is in- or decreased depending on the direction of the force.
Naturally if u and ω are increased, the drag force or torque is increased as well.

5.4.2 Finding the Propulsion Matrix PM

The PM can be found experimantally with 3 experiments.

Experiment 1: Vercial Balancing ($u = 0$)

The ABF is put in a vertical direction. Therefore we know the external force acting on the ABF.

$$F_{ext} = -F_{grav} + F_{buoy} \tag{57}$$

We now turn the ABF at the excat rotational speed ω that the velocity is zero $u = 0$. We can then get the value for b.

$$F = a \cdot u + b \cdot \omega \quad \stackrel{a=0}{\Rightarrow} \quad b = \frac{F_{ext}}{\omega} \tag{58}$$

Experiment 2: Horizontal Swimming $(F = 0)$

The ABF is put in a horizontal direction and then propulsed forward with a rotating magnetic field. We assume the axial force to be $F = 0$. We then measure the speed u of the ABF for different rotational speed ω. Plotting the data gives a linear relationship from which we extract the slope to get a.

$$F = a \cdot u + b \cdot \omega \quad \overset{F=0}{\Rightarrow} \quad u = -\frac{b}{a}\omega \tag{59}$$

Experiment 3: Vertical Free-Fall $(\tau = 0)$

The ABF is put in a vertical position. We then let it go and measure the free-fall velocity. With this we get the rotational speed ω

$$u = \frac{F_{ext} - b\omega}{a} \quad \Rightarrow \quad \omega = \frac{F_{ext} - u \cdot a}{b} \tag{60}$$

As we assume there is no torque acting on the body $\tau = 0$ we get.

$$\tau = b \cdot u + c \cdot \omega \quad \overset{\tau=0}{\Rightarrow} \quad c = -\frac{b \cdot u}{\omega} \tag{61}$$

We can also just measure both velocitys and insert them into the equation.

5.5 Viscosity

If a fluid is subjected to a force it starts to flow unlike a solid that deformes. The **viscosity** μ **measures the resistance to flow** and is a property of liquids and gases.

$$\mu = \frac{\tau}{\dot{\gamma}} = \frac{\text{shear stress}}{\text{shear rate}}, \quad \dot{\gamma} = \frac{du}{dy} \tag{62}$$

5.5.1 Newtonian Fluids

Newtonian Fluids are the simpler fluids as their viscosity is independent of shear rate and velocity. Newtonian fluids are purely viscous fluids. The viscosity from Newtonian Fluids is alterd by the material components and temperature.

5.5.2 Non Newtonian Fluids

Non Newtonian Fluids are more complicated as their viscosity depends on the shear rate. This means that the stress depends non linear in stain or strain rate.

Figure 23: Non Newtonian Fluids

Even thought we said the stokes flow is time independent, if we insert a device in a non-newtionian fluid we can utilise the non linear relationship between viscosity and shear rate.

The properties of non-newtionian fluids can also differ.

- Non-Newtonian Fluids are *viscoelastic* if they are *time-dependent* and their shear rate and shear strain arr related to the shear stress
- Non-Newtonian Fluids are *inelastic or purly viscous* if they are *time-independent* and their shear strain is a unique non-linear function of shear stress

These viscoelastic materials/fluids/gels have a few common properties.

- Relaxation: time-dependent stress decrease for a constant strain
- Creep: time-dependent strain increase for a constanr stress
- Effective stiffness is a function of strain rate
- Hysteresis: phase lag is observed during cyclic loading, which leads to energy dissipation
- Frictional resistance during rolling and atentuation of acousitc waves.

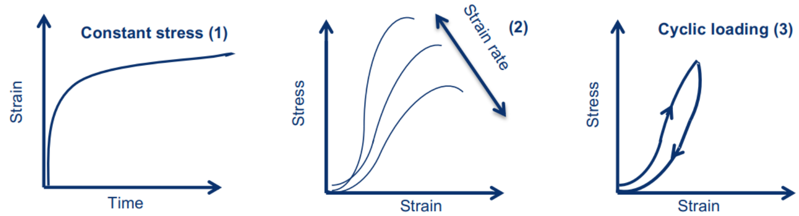


Figure 24: Properties of Viscoelastic materials

5.5.3 Non-Newtonian Biofluids

As one big application of microrobotics is biology, we need to look at biofluids. In biology there is a wide variety of different types of liquids. The most important bodily fluids have the following characteristics.

- Blood
  - In arteris: modeled as Newtonian Fluid
  - In capillaries: Non Newtonian Fluid
- Vitreous body of the eye (important as a lot of application are for the eye)
  - Comination of several Non-Newtonian components

5.6 Random Walks and Brownian Motion

At the microscale diffusion is very relevant. To descirbe the diffusion of a particle we introduce Brownian Motion and Random Walks.
The position of a Random Walk can iteratively be described by the following equation.

$$x_i(n) = x_i(n-1) \pm \delta \tag{63}$$

The mean squared displacement for brownain motion can then be calculated.

$$\underbrace{\langle r^2 \rangle = 2Dt,}_{1D} \quad \underbrace{\langle r^2 \rangle = 4Dt,}_{2D} \quad \underbrace{\langle r^2 \rangle = 6Dt}_{3D} \tag{64}$$

With D being the Diffusivity.

$$D = \frac{kT}{6\pi R\mu} \sim \frac{1}{\text{viscosity}} \tag{65}$$

Important is that in $1D$ and $2D$ a particle will always come back to start state. In $3D$ this is not guarenteed.

Brownian Motion is the motion of a particel in a medium due to atoms bumping into the particel and moving it. The mean displacement is then a function of time as seen in equation (64).
We can then extend this motion to the macroscopic scale and introduce Diffusion and Ficks Law.

5.6.1 Fick's Law

Fick's Law describse the number of particles crossing an area A per unit time.

$$\frac{dn}{dt} = -DA\frac{dc}{dx} \tag{66}$$

With D as the diffusion coefficient, A the cross sectional area and $\frac{dc}{dx}$ as the concentration gradient. We can then be introduce the diffusion flux $J = \frac{dn}{Adt}\left[\frac{mol}{m^2 s}\right]$ and rewrite the above equation to get Fick's First Law.

$$J = -D\frac{dc}{dx}, \qquad J = -D\nabla c \tag{67}$$

The diffusion will then determine how a particel or microrobot is moved around because of diffuion. But it can also help organism to find certain things based on a concentration gradient and follow that gradient (Chemotaxis).

Biased-Random Walks:

If there is a temperature gradient a partcile expereinces a force towards the lower temperature.

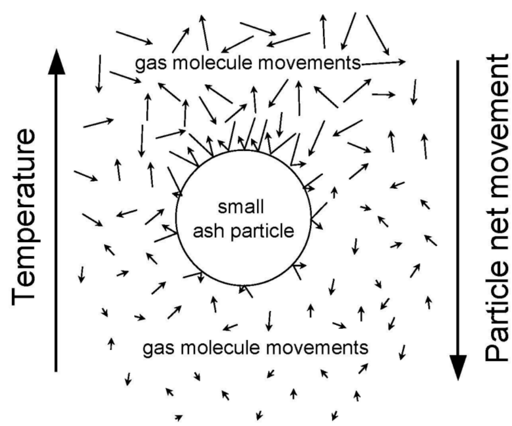


Figure 25: Thermophoresis

The same reasoning can also be used for electropheresis, but the gradient is an electric field and the particle is electricaly charged.
Or dielectrophoresis where a dielectric particle is in a non uniform electric field also expiriences a force uses the same reasoning.

5.7 Liquids Summary

- Microrobots operate in a Low Reynolds Number regime
- Therefore laminar flow is dominant
- As Stokes Flow is time independent a microrobot must have a non-reciprocal motion for propulsion
- Some of these motion can be copied from nature
- Diffusion and Brownian Motion needs to be considerd at the microscale

6 Observation Tools

After watching at the governing physics at the microscale, we will have a look at how we can actually see at the microscale.
We humans can see up things down to about $200\mu m = 0.2mm$ without any aid. As microrobs are smaller than 200 μm we need obeservation tools.
An important distincion we have to make is if we want to see the robot outside or inside the body as this changes the method drastically.

6.1 Seeing and Light

The ability to see things is based on light reaching our eyes. Light is an electrmagnetic wave that propagates through space. Electromagnetic waves come in huge spectrum, where the visible light has wavelengths about $400nm - 700nm$.

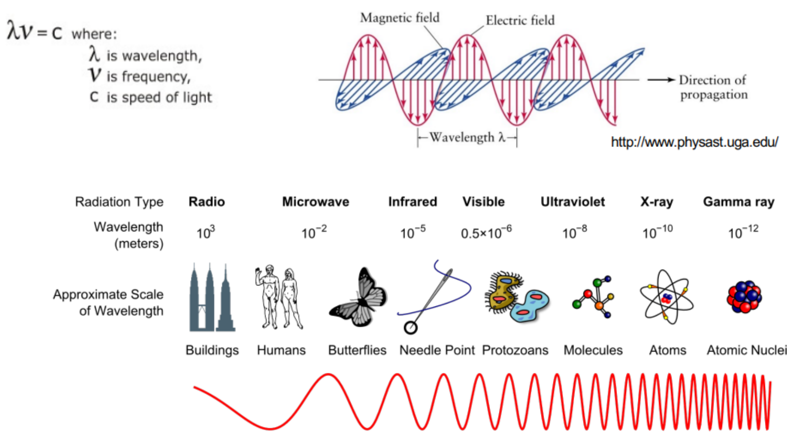


Figure 26: Light

6.2 Optical Microscope

The first microscope was made by Leeuwenhoek who solved the problems of holding the lends, keepin ghte specimen within the focal length, focusing the specimen, retaining the focus, makeing the lens and keeping his hands free. Leeuwenhoek reached a magnification of 275x.

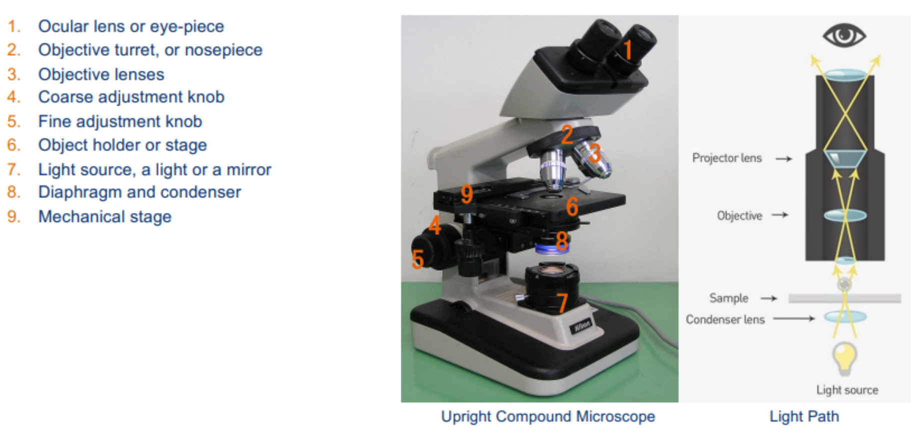


Figure 27: Bacis Setup of an Optical Microscope

The main problem we have to solve is the resolution. The resolution indicates if we can preceive two adjoining points as seperat or as one. For human eye the resolution is about $0.15mm - 0.2mm$ at a distance of $250mm$. Lenses in microscopes can have magnifications of $4x$, $10x$, $40x$, $100x$ and even higher.
The overall magnification of a micrscope is the product of the objective magnification and the ocular (eye-piece) magnification.

$$M = M_1 \cdot M_2 \tag{68}$$

With this mulicplication magnification up to $1000x$ is possible. But seeing smaller things comes with a drawback. The higher the magnification is, the smaller is the depth of field and working distance. The depth of field is the field at which the specimen is in focus. The working distance is the distance between the microscope and the surface of the specimen.

To fully understand how microscopes work, we need to look at the properties of light.
Light being a wave has 4 typicall wave properties.

Reflection:
When light (a wave) hits a surface between two dissimilar medias, the light retruns into the medium from which it oridinated (e.g. mirror). The incoming angle is then the same as the outgoing angle.

Refraction:
If light (a wave) passes from one transparent medium to another transperent medium the light will change its direction. Light coming from a less dense medium will bend prependicular to the surface (Richtung Lot), with greater deviation for shorter wavelengths. The angle is determined by Snells law.

Dispersion:
Seperation of light into its constituent wavelengths when entering a transparent medium. This effect is due to different refractive indices for different wavelenghts. An example of dispresion is the spectrum produce by a prism or the rainbow caused by waterdroplets.

Diffraction:
Ligth can bend around edges as new wavefronts are generated at sharp edges. The smaller the aperatur is (smaller gap), the higher is the diffraction.

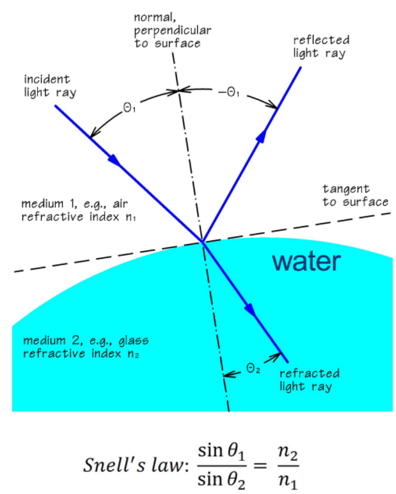


Figure 28: Reflection and Refraction

6.2.1 Optical Resolution

The theoretical fineness that can be distinguished with light is given by the following equation.

$$d = 0.61 \frac{\lambda}{n \sin(\alpha)} \tag{69}$$

d minimum resolving distance, λ wavelength of the used light, n index of refraction of the embedding medium, α is the acceptance angle of the objective lens.
If the objects are closer than d light/microscope can't "display" the two objects as seperate.
The denominator of the left side is a property of the microscope used, so we can define it as microscope characteristic. We thus introduce the numerical aperature.

$$NA = n \sin(\alpha) \tag{70}$$

The highest practical numerical aperature are around 0.95 - 1.50 or $\alpha = 72°$ with air $n = 1$ or oil $n = 1.5$. We normally assume a wavelenght of $\lambda = 550nm$. With these values we get the best optical resolution of about $d \sim 0.2\mu m = 200nm$.

6.2.2 Contrtast on a Microscope

Optical Microscope require a good illumination to work properly. There are two methods used. The commonly used **bright field** microscope and the **dark field** microscope.

Brith Field:
The full aperature is illuminated from below. This method does not reveal differences in brigthness between structural details, which means the contrast is low. Additionally the smaple can absorbe light.

Dark Field:
A central obstruction blocks the central ligth cone (the central lightcone illuminates the specimen in the bright field micriscope). This method enhances the contrast of the image but ligth can get scatterd at the object.

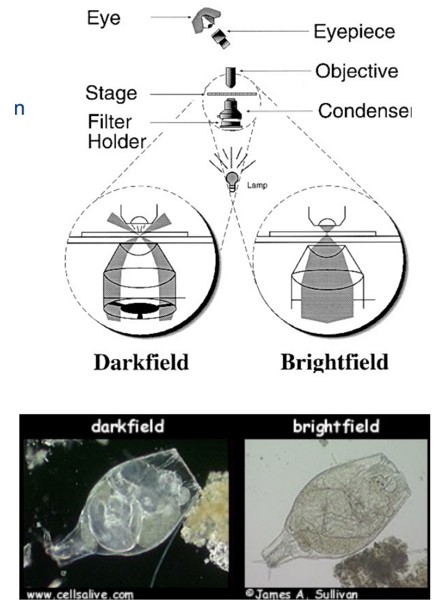


Figure 29: Dark and Bright Field

6.2.3 Aberration

For a perfectly sharp image the light should be concentrated to one point (the optimal focalpoint). But this is not always the case and thus we introduce the term aberration which describes the phenomena of non optimal focusing of light.

Sperical Aberration:
When the light passes trough a not perfectly corrected convex lens, the light is not focused onto the optimal focal-point but rather sactterd along the optical axis.

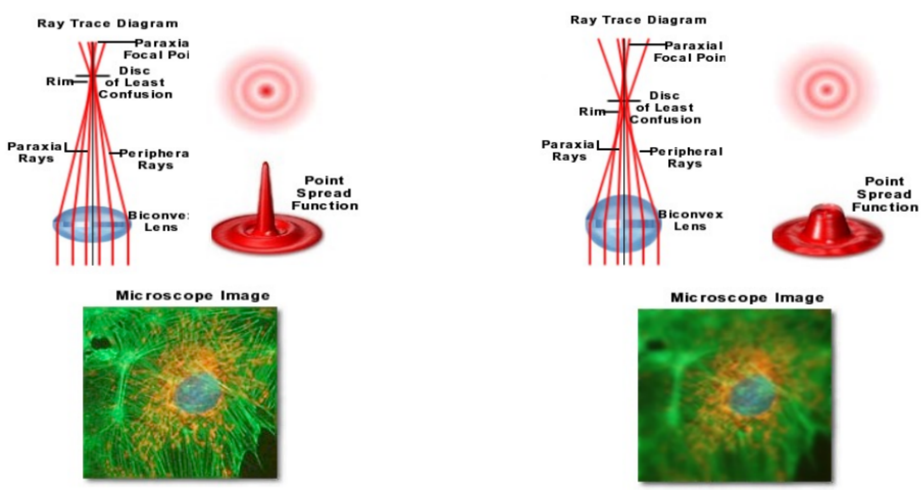


Figure 30: Spherical Aberration

Chromatic Aberration:
When ligh passes through a optical lens that has different refractive indices for different wavelenghts, the different wavelengths are not focused on the same point. This results in a one colored image. This can effect can be reversed by two or more lenses to correct for chromatic aberrations.

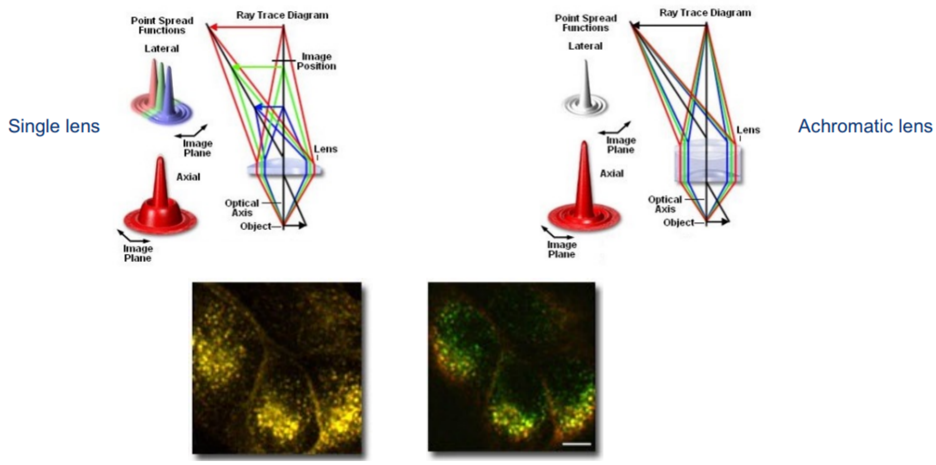


Figure 31: Chromatic Aberration

Astigmatism:
If the lense or the whole optical system is not axissymmetric not all light is focused on the same point.

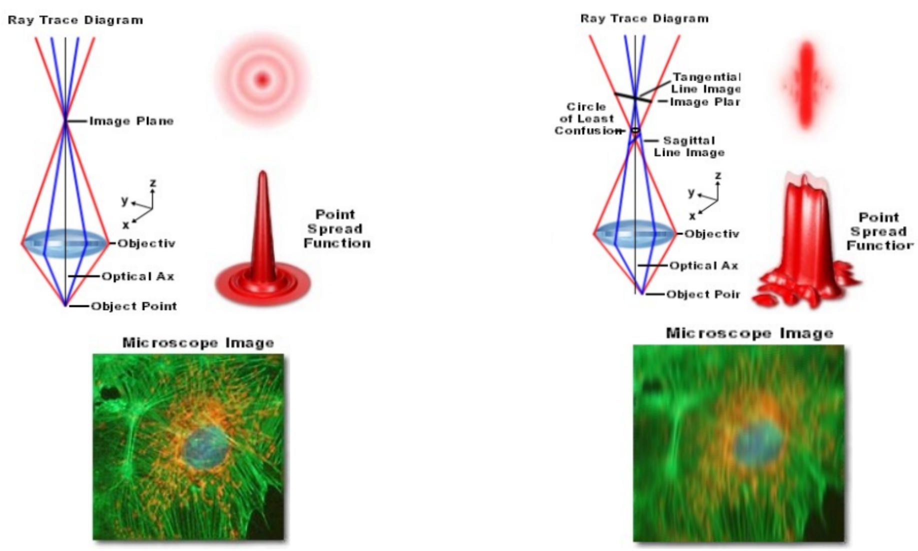


Figure 32: Astigmatism

6.2.4 Enhancment of the Optical Resolution

To improve the optical resolution of a micriscope one can use **Fluorescence Microscopy**. A fluorescent microscope shines high energy light beams (UV light) at molecules. This molecules then get excited an emit visible light. For this selective fluorophores (chemical markers) or quantum dots can be used as thes "shining" markers. As the excitation and emission occur at different wavelengths they can be seperated with filters so we only see the emitted ligth. This important technique can enhance tjhe resolution upto single molecules of about $d = 2nm - 5nm$.

6.2.5 Confocal Laser Scanning Microscope

The problem with optical microscope is, that we can only se 2D images in a plane and have a very bad conception about depth. To get a 3D image with a microscope one can use CLS.
This method works similar to a 3D-Printer as it collects the light from songle planes by scanning it with a laser point by point. A pinhole conjugated to the focal plaen keeps light from the detector that didn't come from the scanning/focal plane. All the slices are then added together to get a 3D render of the object.

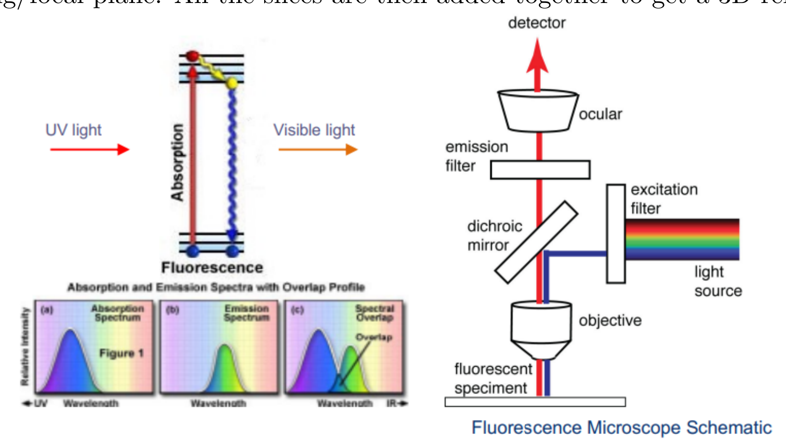


Figure 33: Fluerescent Microscope

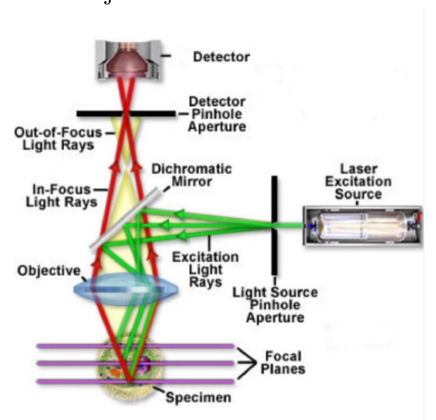


Figure 34: Confocal Laser Scanning Microscope

6.3 Electron Microscopy

If we want to see things below $2nm$ light doesn't work. We therefore use electrons as the wave nature of electrons can achieve smaller wavelengths. The wavelength of a moving electron is described by de Broglie $\lambda = \frac{h}{mv}$ and is inverse proportional to the momentum of the electron. The energy of an electron is given by $eV = 0.5mv^2$, with V being the acceleration voltage. If we then combine the two equations we get the wavelength of an electron.

$$\lambda = \frac{h}{\sqrt{2meV}} = \frac{12.3}{\sqrt{V}} \tag{71}$$

As a result we can tune the wavelenght of the electron by adjusting the acceleration voltage V.

As electrons are charged particles and not a light wave we need to find new lenses. We can make us of the fact, that moving charges can be accelerated in magnetic fields. Thus the new lenses for electron microscopes are coils instead of glas.

The new theoretical resolution of electron microscope is much smaller than for optical microscopes.

$$d = 0.6 \cdot \lambda_e \tag{72}$$

with values as low as $\lambda_e = 1.968pm$. In reality this resolution is not possible due to various aberration effects and is normally around $d = 0.2nm$.

Electrons interact in various ways with the material. For the microscope we are only interessted in electrons reflecting (directly oft via scattering) from the material or electrons being transmitted through the material. The interactions can be split into elastic and inelastic interactions. The elastic interaction (green) occur without an energy transfer from the electron to the material. The inelastic interactions (red) occur with energy transfer form the electron to the material. This inelastic interactions cause various unwanted effects.

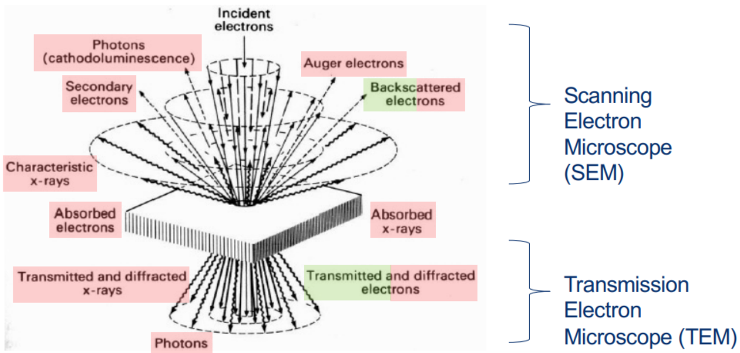


Figure 35: Different Kind of Electron Interactions

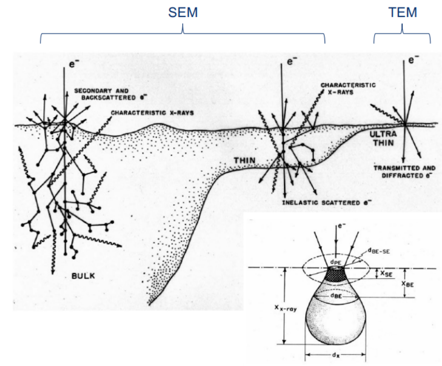


Figure 36: Different Kind of Electron Interactions depending on the thickness

The thickness of the specimen is also important for the choice of microscope as the amount of electrons transmitted is very dependent on the thickness.

6.3.1 Scanning Electron Microscopy (SEM)

In a SEM an electron gun emits electrons which are then focused on a small point by two ord more condenser lenses. Scanning Coils are used to move the focus of the eletron beam over the sample surface.
A Detector then detects back-scattered electron and secondary electrons. The signal is then amplified and every pixels brightness is tehn determined by the number of detected electrons.

SEM Detectors:
The detectors in SEM play an important role as they detemine the image quality. A normal SEM has 3 main detectros.
SE Detector: SE (Secondary Electrons) are low energy electrons emitted from the top layer of the material. They usualy scatter in a high-angle (in respect to the incoming direction). The SE provide usfull information on the surface of the sample (topography). SE detector need low acceleration voltage ($1kV - 5kV$).
BSE Detector: BSE (Backscattered Electrons) are generated form a deeper layer of the sample and provide material contrasts of a specimen. BSE Detector also require low acceleration voltages ($3kV - 5kV$).
In-Lnes Detector: In-Lens detectors also detect SE but only those generated by a low energy primary beam (up to $20keV$). The In-Lens detector provides information on the surface of the specimen. The need very low acceleration voltages $0.1kV - 3kV$.

6.3.2 Transmission Electron Microscope (TEM)

In contrast to the SEM Microscope a TEM detects the transmitted electrons. This method is only possible if the specimen is very thin. As the steup is similar to an optical microscope there are also two imaging modes (bright field and dark field imaging).
But there is also a second imaging mode. The Diffraction mode makes use of the fact, that if a crystalline solid produces a certain diffraction patter we can deduce the underlying crystalline strucure.

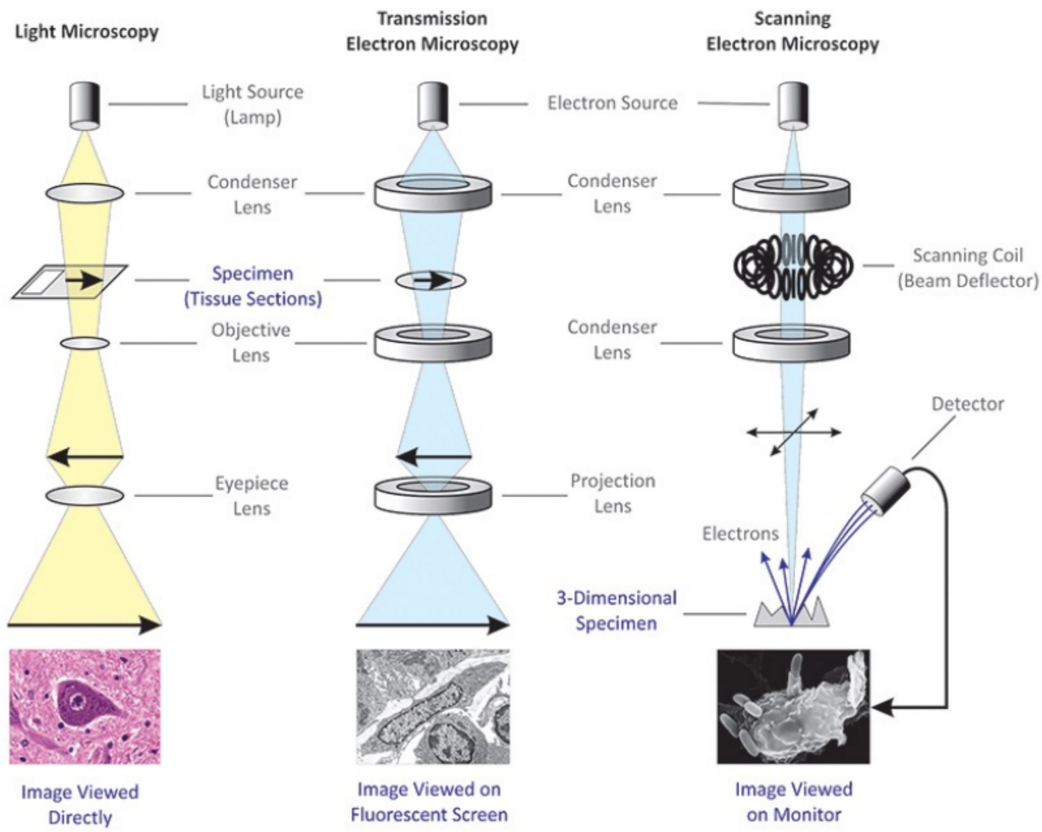


Figure 37: The different setups for electron microscopes compared to a optical microscope

6.4 Scanning Probe Microscopy (SPM)

Even thought Electron Microscopes have a good resolution we can achieve even higher resolutions with SPMs. SPMs is the collection of techniques for scanning the specimen with a scanning probe and measuring the probe-surface interaction.

The most dominant method is the Atomic Force Microscopy (AFM). AFM probes the surface with a sharp tipped cantilever. The atomic force between the tip and the surface cause the cantilever to bend or vibrate. This bending or vibration can then be measured and turned into an image.

AFM works in two regimes. The *contact regime* uses the repulsive Coulomb force at a distance of a few hunderd picometers. The *Non contact regime* uses the attractive Van der Waals forces at a distance of a few nanmeters.

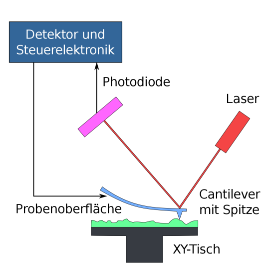


Figure 38: Setup of AFM

There are three imaging modes namely contact mode, tapping mode and non-contact mode.

6.4.1 Contact Mode

In contact mode a tip is scanned over the sample and the deflection of the cantilever is monitored (not measured). A constant deflection of the cantilever is then achieved by a feedback loop thats moves the scanner up and down depending on the force exerted by the cantilever. The movement of the scanner required to keep a constant deflection is then measured to create a image.
Contact mode works in ambient and liquid environements.

6.4.2 Tapping Mode

Tapping Mode works by oscillating a cantilever near its resonance frequency with typiycal amplitudes from $20-100nm$. The tip then ligthly taps the surface of the sample. Similar to contact mode a feedback loop keeps the amplitude constant by moving the scanner up or down. The movement of the scanner required to keep a constant deflection is then measured to create a image.
Tapping mode works in ambient and liquid environements. This method has a higher resolution compared to contact mode, since no lateral forces occur.

6.4.3 No-Contact Mode

Non-Contact Mode workes the same way as tapping mode with the only difference that the cantilever is slightly above the sample in a fluidic layer. The cantilevers frequency is then decreased by Van der Waals forces. A feedback loop keeps the amplitude constant by moving the scanner up or down. The movement of the scanner required to keep a constant deflection is then measured to create a image.
Non-Contact mode only works in a liquid environement.

	Contact Mode	Tapping Mode	Non-Contact Mode
Advantages	▪ High scan speeds (throughout) ▪ Rough samples with extreme changes in vertical topography can sometimes be scanned more easily in contact mode	▪ Higher lateral resolution on most samples ▪ Lower forces and less damage to soft samples ▪ Lateral forces are virtually eliminated, so there is no scraping	▪ No force exerted on the sample surface
Disadvantages	▪ Lateral (shear forces can distort features in the image ▪ The combination of lateral forces and high normal forces can result in reduced spatial resolution and may damage soft samples due to scraping between the tip and sample	▪ Slightly slower scan speed than contact mode AFM	▪ Lower lateral resolution, limited by the tip-sample separation ▪ Slower scan speed than Tapping Mode and Contact Mode ▪ Non-contact usually only works on extremely hydrophobic samples, where the adsorbed fluid layer is at a minimum

Figure 39: Comparison of the 3 AFM modes

6.4.4 Magnetic Force Microscopy(MFM)

MFM is basically the same as AFM but it uses a tip coated with a magnetic material. Then two scans are made. The first scan with tapping mode is used to determine the topology of the sample. Then a second scan is done with the cantilever lifted ”far” away from the sample. The second scan is used to scan the magnetic properties of the sample.

6.5 Observation Tools for Objects inside the Body

All the introduced observations tools can only be used for things that can be put into the microscope and are therefore useless for seeing things inside the body.

6.6 Near Infra-Red Imaging

Light usually can't penetrate our skin. But near infra-red light can sometimes penetrate our skin and we can use that to see things close under the skin.

6.7 Magnetic Resonance Imaging (MRI)

MRI makes us of the spin of hydrogen atoms. The MRI-tube creates a strong magnetic field B that alignes the spin of most of the hydrogen atoms. Then an electric field is sent into the body with a certain frequency (Lamor Frequency) $\omega = \gamma B$. This electric field then dealignes the spins of the weak hydrogen atoms. As they realigne they send of a signal that can be detected by coils. The main trick is to have a small magnetic field gradient along the body to vary the Lamor Frequency. Then small sections of the body can be scanned.

6.8 Magnetic Particle Imaging (MPI)

The MPI functions similar to MRI but instead of using the hydrogen atomes as magnets small ferromagnetic nanoparicles are used to detectet different things in the body. The applications are promising but no human MPI exists yet.

6.9 Observation Tools Summary

- Optical Microscopes are limited in their resolution
- NA describes the possible resolution of the microscope
- Electron Microscope increas the resolution as the wavelength of an electron can be tuned with the acceleration voltage
- There are two electron microscopes SEM and TEM
- To get even higher resolutions we need AFMs or MFMs
- They scan the probe with a cantilever and relie on atomic forces
- The can be operated in three modes: Contact, Tapping and Non-Concact
- Contact and Tapping can be used in dry and wet environements, while No-Contact can only be used in wet environements
- MFM can also scan the magnetic proberties of the sample
- Imaging techniques inside the body include near infrared, MRI and MPI

7 Microorganisms and Bio-Inspired Robots

Humans have often looked at nature for inspiration to solve engineering problems. The main goal of bio-inspired robots is to reproduce functions or mechanisms found in biological systems. The hardest part is to simplify the biological mechanisms as they are usually very complex.

Teh reasen looking at nature is simple. Artificial and natural devices often operate with the same environemental constraints, so the challenges are often the same. Nature had millions of years to solve the problems so we can have a look at the solution for inspiration.
Secondly biology and robotics can often benefit from each other. New microtechnologies offer a better way to research biological systems. And better understaning of biological systems lead the better bio-inspired technologies.

7.1 Biorobotics

Biorobots can be put into three categories.

- Biomimetics: An engineered device exactly reproducing the target biological system
- Bioinspired: An engineered device borrowing some concepts from biology but having some freedom in its implementation
- Biological Robots: An emulation of a biological system used to understand the real biological system.

	Advantages	Dangers
Biomimetics	Nature has millions of years of experience	An exact copy of Nature is almost always impossible => most "biomimetics" are actually "bioinspired"
Bioinspired	Nature's solutions offer a good starting point	There is the risk of taking Nature's example out of context or tweaking it to the point where it becomes meaningless
Biological robotics	Allows testing of a hypothesis in conditions impossible or unpractical to test on the actual organism	Errors in the transfer from biological to artificial system may lead to false scientific claims

Figure 40: Comparison between the three categories

When implementing a bioinspired robot one has to be careful as the task is not easy. Some dangerous repercussions of wrong implementation are:

- False biomimetic claims, meaning we wrongly copy nature or dont fully understand nature.
- Falsely assuming the biolocigal solution is the best possible solution for the problem at hand
- False scientific claims when using biological robots can be made.

To minimize risk of wrong implementation one can follow a specific scheme.

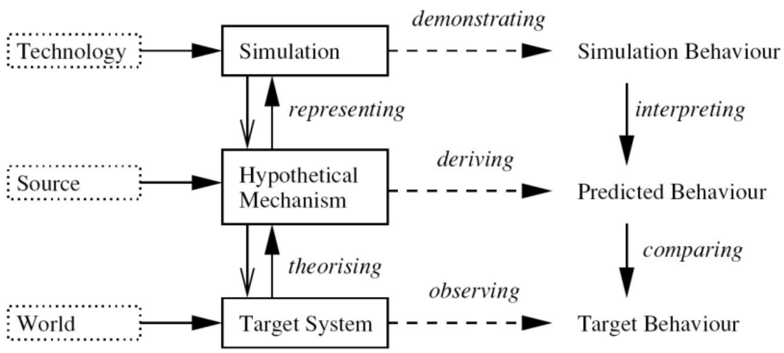


Figure 41: Possible scheme to avoid wrong implementation

If the goal is to copy nature we start at the bottom and work ourselfes up the diagramm. This is no guarantee but it can help reduce the risk of some pitfalls.
While implementing a biorobotic system two key points have to be considered.

- Spatiotemporal Scale Difference: Natural devices are often much smaller and faster as the engineered counterpart
- Level of Abstraction: Nature is too complex to fully copy and the building blocks of engineering and nature are different so some sort of abstraction has to be done

To also increase the effectiveness of biorobots a close biologist/engineer interaction is crucial.
Intersting Case Study in the Slides demonstrate the right use of the scheme.

7.2 Bio-Inspired Microrobotic Locomotion

One of the biggest challenges for microrobots is locomotion. So looking at biological solutions can yield promising results or ideas.

7.2.1 Locomotion on a Surface

Nature has three main methods on locomotion on a surface. We will look at a few examples.

Crawling:
Inchworms move by drawing its hind end forward while holding the front. Once it is "folded" the front end is moved forward while holding on the back end.
This principal was copied by a microrobot. A polymer shaped like a table had a magnet attached to it. The magnet being relatively heavy bent the polymer beam so the legs would extend outwards. Changing the magnetic field and lifting the magnet up the legs moved inwards. Doing that over and over again the microrobot moved.

Figure 42: Crawling of an Inchworm

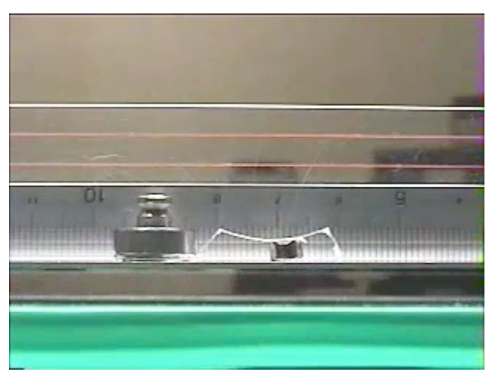


Figure 43: Crawling of a microrobot

Walking:
The main challenge was trying to walk on water. Engineers therefore looked at the water strider walking on water. The water strider can walk on water as the feet are superhydrophobic and the surface tension holds the strider afloat. The superhydrophobic legs are due to a large number of tiny oriented hairs (microsetae) with fine nanogrooves.
The engineered strider-like robot had ten supporting legs with two small dc motor connected to two actuating "legs"(corkscrew like). The supporting legs made it float and the motors served as driving systm. The supporitng legs had a microstructure with nanoribbons similar to the water strider leg. These nanoribbons made the supporting legs superhydrophobic.

Figure 44: Water Strider

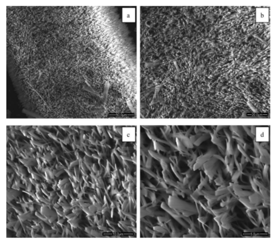


Figure 45: Nanoribbons of the Engineerd Robot

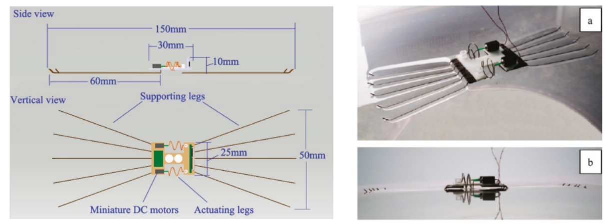


Figure 46: Engineerd Strider Like Robot

Jumping:
A excellent excellent example for an jumping animal is the locust (Heuschrecke). Engineers built a jumping locust inspired jumping robot.

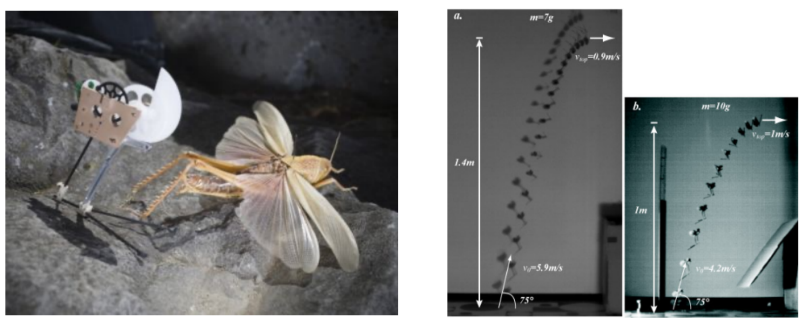


Figure 47: Locust Inspired Jumping Robot

7.2.2 Flying

The mechanisms for moving through a liquid depend on the liquid properties. If the liquid is more dense and has an higher density we usually name it swimming. If the liquid is less dense and has lower density we call it flying.

Flying:
When research flying at a microscale engineers and biologist look at eh fruit flie (Drosophila Melanogaster). Looking at the fruit flie has many advantages. Fruit flies have outstanding flight preformacne, is completely autonomous, they are very small and are well research (over many decades).
Biologist were even able to measure the flight controlling mechanosensory feedback system of the fruit flies. The lab also measured the flight forces by glueing the flie to MEMS force sensors.

The goal of studying fruit flies is to come up with solutions and knowledge for Micro Aerial Vehicles (MAVs). They have many advantages as they are very small and fast, they are very quiet (stealth) and can access very small cavitys. With these advantages the application range from military to search and rescue to inspection and even toys. But there are also disadvantages like the payload limitation, the difficulty of powersupply as they mostly have to be powered by a wire and thus are not autonomous and their fragility is also a problem for everyday use.

Swimming vs. Flysing:
What is actually the difference between flying and swimming?
For a given object flying at a given speed swimming and flying can be destinguished by the following characteristics.

- Swimming: During swimming the intertial and viscous forces are 100-1000 times higher. The Reynolds Number is usually higher than for swimming. Swimming is usually slower than flying.
- Fyling: Smaller inertial and viscous forces result in higher flying speeds.

For microflyers these characteristics can change. The Reynolds Number for microflyers are similar to certain swimmers, so viscosity plays a more important role for microflyers than for macroflyers like airplanes. Additionaly for swimmers the buoynacy is much higher due to the higher density of water. Therefore a wing must move much faster than a fin to generate lift.

7.2.3 Swimming

As most microrobts are submerged in a liquid with a viscosity equal to water, swimming is the most interessting locomotion to look at.

Stroke Swimming:
Stroke swimming is characterised by a strong powerstroke for propulsion and a slow recovery stroke. Jellyfish for example use strokes to swim. Engineeris designed a jellyfish like propulsionsystem called Medusoid. The Medusoid consisted of a elastic front and a rat muclecells as motors. The belly contraction for the fast stroke was induced by the cardiomyocytes of rats. The recoil stroke was then induced by the PDMS (a polymer) that was elastically stretched during the powerstroke.

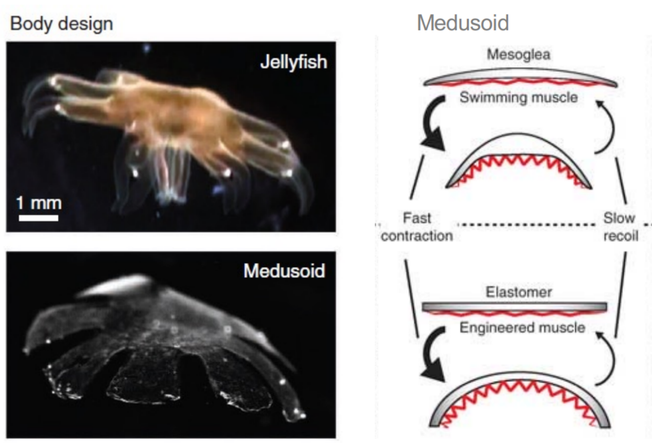


Figure 48: Jellyfish Inspired Medusoid

The Medusoid was able to mimic the stroke very good and was able to swim very well.

Flagella Rotation/Beating:
The most common locomotion at the microscale is done by flagella rotation or beating. Falgella rotation works like a corkscrew. As the flagella rotates the microorganism is propulsed forward (E. Coli). Flagella beating uses a non-reciprocal beating motion to propell the microorganism at the strokes (Sperm).
The third flagella based locomotion is with cilia. Cilia are small hearlike flagellas around the body of the microorganism. Through a non-reciprocal motion of the cilia the microorganism can be propulsed forward.
These flagella motors are driven by a rotary engine made of proteins. The flagellas can reach rotational speeds up to 200-1000 rpm.
Microorganism can navigate through chemotaxis. Chemotaxis is the presence of a concentration gradient. The microorganism follows this concentration gradient.

7.3 ABF Locomotion

The flagella rotation is one of the easiest ways for microrobot propulsion. Therefore engineers came up with the ABF an artificial bacterial flagellum.
An ABF consists of a soft magnetic head and an mostly non magentic tial. The soft magnetic head is used to induce a rotation of the ABF through a magnetic and this rotation is then turned into a forward translation throught spinning of the helical tail.
It is therefore beneficial to have a better understanding of these ABF.
Assumptions:

- The whole ABF is one dimensional, meaning the rotation is around the helical axis and the translation is along the helical axis.
- The Tail is a slender helix with circular cross-section
- The head is a sphere
- Flow fields of the head and tail dont influence each other so the can be computed separately and then superimposed

The basics of how ABF move were already introduced in the chapter Liquids. We know look at desinge specifications.

Step-Out Fequency:
The rotational speed is limited y the maximal magnetic torque on the ABF (assuming $F = 0$).

$$\omega_{max} = \frac{a}{ac - b^2}\tau_{m,max} \tag{73}$$

since ω and u are linearly dependent, we get the maximal velocity.

$$u_{max} = -\frac{b}{a}\omega_{max} = \frac{b}{b^2 - ac}\tau_{m,max} \tag{74}$$

If the frequency of the rotating field is increased above ω_{max} the ABF can't follow the rotation of the magnetic field and is thus called the step-out frequency.
The step-out frequency can be increased by increasing the magnetic torque, which in turn can be increased by increasing the volume of the head.
Increasing the volume of the head will increase ω_{max} but not necessarily u_{max} as the drag will increase with a bigger head. u_{max} can even be decreased with a bigger head volume.

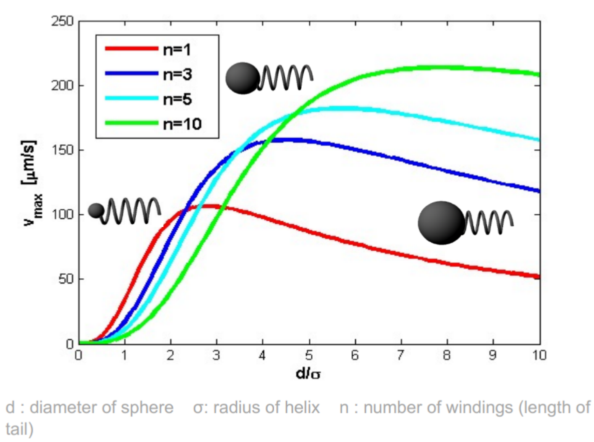


Figure 49: u_{max} as a function of the diameter

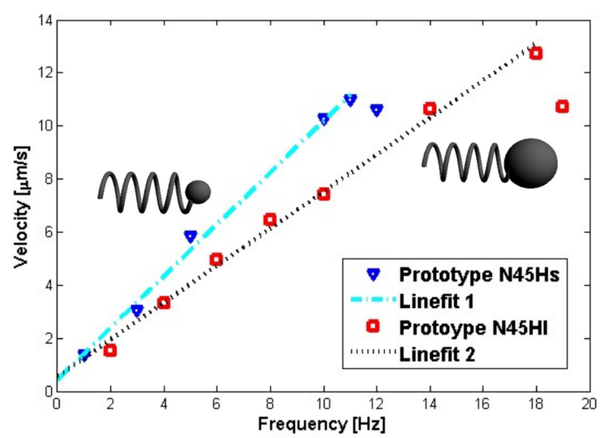


Figure 50: Velocity-Frequency curve for two ABF

As we can see we have to make a trade off between fluiddynamics favorable effects and magnetic favorable effects. The influence of the head size for

- Fluiddynamics:
  - Head does not directly contribute to forward propulsion
  - Creates additionl drag
  - Decreases swimming speed at given ω
  - $\rightarrow$ Smaller is better
- Magnetics:
  - Volume is related to the magnetic torque
  - Bigger head means higher torque
  - Bigger head means higher step-out frequency
  - $\rightarrow$ Bigger is better

The tail also has two contradictory properties.

- Tail should be short for less drag and weight
- Tail should be long for better stability

Our job is to find a optimal trade-off between these properties.

7.3.1 Controling a Swarm of ABF

When we want to control a swarm of ABF and want to target single ABF we can decouple them by different head sizes and thus different step-out frequencies.

- small head $\rightarrow$ low step-out frequency
- big head $\rightarrow$ high step-out frequency

We can then controll one of the ABF by either increasing the frequency from f_1 to f_2 so $f_1 < f_{out,1} < f_2 < f_{out,2}$ or by decreasing the magnetic field at a constant frequency so $f_{out,1,2} < f < f_{out,1,1} < f_{out,2,2}$.

7.3.2 Wall Effects

Ar low Reynolds Numbers wall effects have a large influence in the behaviour of ABFs. Near walls the drag between the wall and the ABF is higher than on the other side. As a result the ABF starts rolling along the wall prependicular to the desired forward motion. As the ABF is also moving forward the ABF net direction is a sidewise drift.

7.3.3 Flexible Tails

There are also some concepts of using flexibale ABF tails like microorganisms (e.g. bull sperm). These ABF consist of small magnetic particles connecte by DNA. The ABF tail was then attached to a red blood cell and the tail was guided by magnetic fields.

7.4 Bio-Inspored Robotics Summary

- Nature provides good solutions or starting points for engineering problems.
- Robotics can hlep biologist and visversa
- The transfer from biology to robotics is non-trivial

8 Materials

We now want to look at how we can fabricate microrobots. We therefore wil first look ate how materials behave at the microscale.

8.1 Types of Solid Materials

There are 4 main types of solid materials formed by different bonds.

Type of Solid	**Form of Unit Particles**	**Force between the Particles**	**Examples**
Molecular	Atom or Molecules	Van der Waals or Hydrogen Bridges	Iodine, Glycine,Sulfur
Covalent Network	Atoms	Covalent Bonds	Carbon, SiO_2, H_2O
Ionic	positive and negative Ions	Electrostatic Attraction	Na^+Sl^-, KCl, $MgBr_2$
Metallic	Atoms	Metallic Bonds	Ni, Fe

At the microscale we have to introduce some new nanscale materials or structures.

Nanoparticle:
A nanoparticle is a particle having on or more dimensions of the order of $100nm$ or less that behaves as awhole unit in terms of properties and transport.

Nanowire:
A nanowire is a structure with a diameter or thickness constrained to $\sim 10nm$ and a unconstrained length, resulting in length to width ratio of over 1000 and more.

Nanorods:
Nanorods are nanowires with an aspect ratio of only $3-5$.

Nanotubes:
Nanotubes are organic or inorganic tubular structures with an inner diameter in the nanometer range. These nanotubes can either be single wall or multiwall tubes. Nanotubes usually have a huge surfaces to volume (S/V) ratio.

Nanoporous Materials:
A nanoporous material is usually a bulk material supported by a porous framework, with pores in the nanometer range. The nanoporous materials can be organic or inorganic.

8.1.1 Carbon Nanostructures

As it turned out carbon is a atom capable of building many different stable nanostructures. Carbon thus can have allotropic forms, meaning carbon (one element) can occur in different strucutres/forms.
The different structures carbon can create are Diamond, Graphite consisting of layers of *Graphene*, Lonsdaleite, Fullerene C_{60}, C_{540} and C_{70}, Amorphous Carbon and Carbon Nanotubs. Even though nanotubes are very usefull for microengineering things they ar not very good for biological systems as they are not polar.

The most promising material is **Graphene** which was discovered in 2004. Graphene is a 2D carbon sheet and the fundamental form of graphite (stacked) or nanotubes (rolled). Graphene is most reactive form of carbon as it has a huge surface area. It is also very highly electrical and thermaly conductive. As a result of the high electrical conductivity electrons travel through graphene as if they had no mass $\rightarrow v \approx 10^6 \frac{m}{s}$ (Fermi Velocity). And to all these properties graphene is very hard (harder than diamond and 300 times harder than steel).
Graphene is used today in new graphics cards for better heat dissipation and stability. New graphene base touchscreens are in development. These touchscreens are bendable, unbreakable, transparrent and most importantly touchsensitive.
Funfact: Graphene can be harvested by scotchtabe from graphite.

8.1.2 Difference between nano/micro and macroscale materials

The five most important differences between materials at the nano-/microscale and macroscale(bulk materials) are:

- Gravitational forces can be neglected at the nanoscale and electromagnetic forces begin to dominate
- Greater surface-to-volume (S/V) ratio
- Random molecular motion becomes important
- Quantum mechanics has to be used to describe motion and energy (only at the nanoscale)
- Stochsticaly isentropic behaviour cant be assumed

Examples:

High Surface to Volume Ratio:
The high surface to volume ratio at small scales offers a large area for different coatings of the microrobot. With these coating one can tune the magnetic properties (e.g. nickel coating) or chemical properties (e.g. hydrophilic coating). The large surface area can also be used for drug delivery by coating the microrobot with polymeres that contain the drug.

Magnetic Properties at the Nanoscale:
At very small scales ferromagnetic materials behave differently than at the macroscale. As the size of the object decreases magnetic domai wall rearrangements become restriced but there are still multile domains.. This forces the spin rotations to occur uniformly trhoughout each domain. As a result the coercivity of a material is incread until a maxima is reached.
This maxima occures at the critical diameter D_C. If the object is smaller than D_C multiple magnetic domains is energetically unfavorable. Therefore the objec only consists of only one magnetic domain with an aligned magnetic spin. D_C depends ond the anisotropy K and the magnetig saturation value of the material.
If the size is even decrease more the anisotropic energy decreases resulting in a decreasing energy barrier between magnetic stable states. The material will randomly and spontaneously flip between magnetic stable states. This random flips of the magnetization direction under the influence of temerature is called **Superparamagnetism**.
The Stoner Wohlfarth Model describes that the energy barrier between magnetic stable states is directly dependetn on it anisotropic energy. With decreasing particle size this energy barrier shrinks. Below D_S the thermal energy of the surrounding is enough to overcome that barrier.

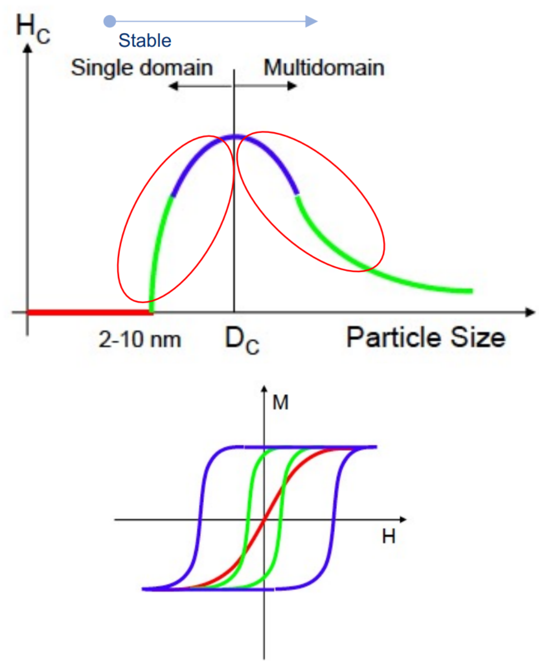


Figure 51: Magnetic Properties at the Nanoscale

The random flips occur randomly at a frequency defined by the objects Neel relaxation time $\tau = \tau_0 \exp\left(\frac{\Delta E}{k_b T}\right)$. If the temperatur of the surrounding is to low the particle behaves like a normal ferromagnet again.
If we decrease the size even more below $7nm$ the magnetic properties are determined by the atomic spin structure of the particle. Below $7nm$ the S/V ration is so big, that surface related effects dominate the magnetic behaviour. **Spin-Canting** is the effect of non-symmetric exchange interactions of the surface atoms with partially exposed ions and disorder or non-complete atomic unit cells. Spin-Canting leads to a decrease of magnetic susceptibility and stauration. This also explains the limitation for a magnetic recording (HDD) device as the storage particals cant be smaller than a given diameter.

Electrical Properties at the Nanoscale:
At the nanoscale the conductance of a 1D wire can only take discrete values due to quantum effects, which are a multple of the conductance quantum G_0.

Optical Propeteis at the Nanoscale:
The size of a particle can determine its color. For example the size of gold particles in a solution determine the color of that solution. This is due to fact that only the light that matches the resonant frequency of the surface electrons is scattered out. Different particle sizes give rise to different electron resonant frequencies and therefore different colors.

8.2 Materials Summary

- A wide variaty of materials are avaliable to use for micro and nanorobots
- Most commonly used materials are Silicon, Iron, Cobalt, Nickel, Titatnium and Carbon
- The properties of the materials at the nanoscale are different than for bulk materials
- The properties can be advantages or not
- The shape and the chemical composition of the material coupled with the nanostructure provide powerful tools for microrobots

9 Microfabrication

9.1 Top-Down and Bottom-Up

There are two main approches for building things including microrobots.

9.1.1 Top-Down Approach

The Top-Down Approach is motivated by the manufacturing industry. The Top-Down Approach works by taking a bigger building block and reducing it size by cutting the unwanted parts. Examples at the macroscale are CNC machining. The big disadvanatge of the Top-Down Approach is the big amount of waste.
For microscale objects the top-down approach is well established as we can use the techniques from microship manufacturing. At the microscale we mostly use deposite a thin film and then remove the unwanted parts by photolithography or etching. The resolution for the top-down apporaches is limited (e.g. photolithography $1\mu m$.)

9.1.2 Bottom-Up Approach

The Bottom-Up Approach is mainly inspired by nature and works by building a bigger structure by small building blocks. The Bottom-Up Approach is mainly used in nanofabrication. For the nanofabrication bottom-up approach selected atoms or molecules are added together to create bigger structures. Nanofabrication makes us of nanomanipulation, self-assembly and chemical methods as physical interactions are very difficult. At the nanoscale a long range order is very hard to achieve.

9.2 Substrates

Even though many materials can be used for microrobots silicon is the mosted used one today. Silicon is mostly used as we can preciesly control its properties by creating single cristal silicon wafers. We can then cut these silicon wafers in a prefered crystal orientation defined by the miller indeces.
The miller indeces define the given plane by a coordinate system $[x, y, z]$. The miller indeces $[h, k, l]$ are obtained by taking the reciprocal value of the intercepts of the plane with the coordinate axis. The reciprocal values are then multiplied by their least common multiple.
A silicon crystel can be seen as two overlapping FCC (face centered crystal) unit cells offset by $a/4$ with a being the unit lengths. Depending on the plane (miller indices) there are more or fewer atoms on the surface, resulting in different chemical and mechanical properties.
More atoms mean higher oxidation rate but slower etching and cutting.
The one crystal silicons are grown by inserting a seed crystal in molten silicion and then pulling on the hardening silicion.

9.2.1 Oxidation Layer

An oxidation layer on the surface of a silicon wafer is often required for protection and insulation. The oxidation layer is very inmportant for microelectronics as it is non conductive. The layer can be grown in an oxidation chamber by consuming the silicon. The thickeness of the layer also determines the color of the wafer.

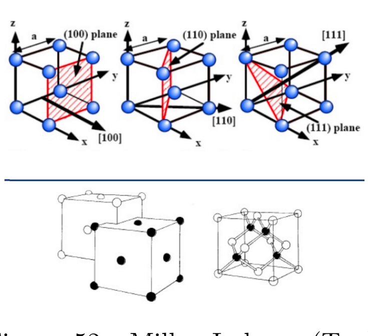


Figure 52: Miller Indeces (Top), Silicon Crystel (Bottom)

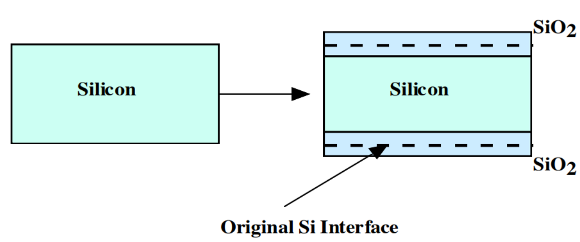


Figure 53: Oxidation Layer of a Silicon Wafer

9.3 Additive Processes

9.3.1 Physical Vapor Deposition (PVD)

Thermal Evaporation:
The source material (material we want to deposit on the substrate) is heated until it evaporates. The evaporated material then travels to the cooler substrates and condenses and is deposited onto it.
Thermals Evaporation is quite fast and cheap, but the challange is to find the correct heating source.

Heat Source	Advantages	Disadvantages
Resistance Heating	No Radiation	Contamination
Electron Beam	Low Contamination	Radiation
Radio Frequency (RF)	No Radiation	Contamination
Laser Heating	No Radiation and Contamination	Expensive

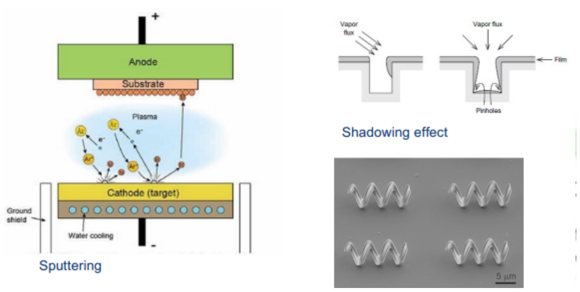


Figure 54: Sputtering (Left), Shadowing (Right Top), ABS Sputter Coated with Ni(Right Bottom)

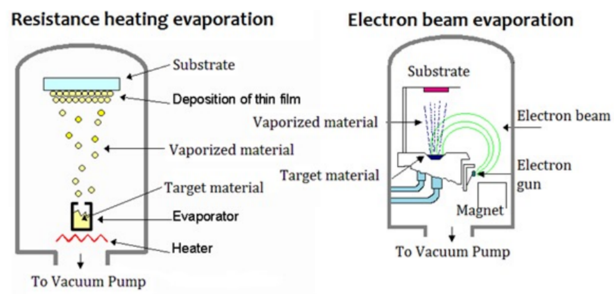


Figure 55: Thermal Evaporation

Sputtering:
During sputtering Argon Ar molecules are ionized by a strong potential difference. These Argon ions are then accelerated towards the target material (material with which we want to coat our substrate). The Argone ions release atoms from the target after impact. These atoms then travel to the substrate and form a layer of atoms.

A problem these PVD methods face are the shadwoing effect, where the substrate is not unifromaly coated in cavitys due to the straight trajectory of vapor molecuels.

9.3.2 Chemical Vapor Deposition CVD

During a gas containing the target material is transportet over the substrate. The atom then diffuse to the surface of the substrate (boundary layer) and are then deposited onto the substrate. The method is very usefule as it can deposit silicion or other polycrystaline materials. The big disadvantage is that CVD is very slow and expensive.

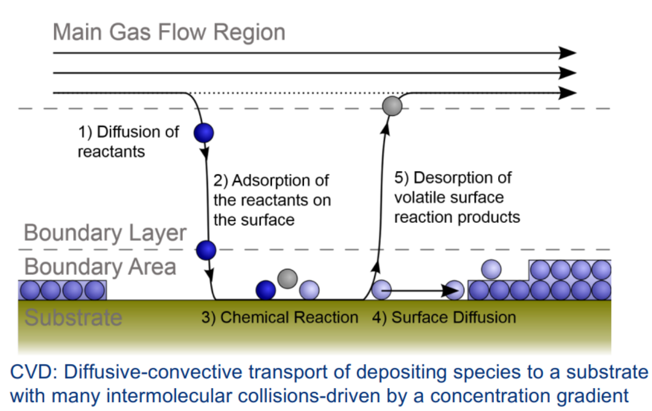


Figure 56: CVD

9.3.3 Electrodeposition

The main principle of electrodeposition is that the target material and the substrate are charged differently. This is done in a electrochemical cell. The cell is filled with a solution containing the target material. The substrate is then inserted into the solution and negativaly or positivaly charged. The target material is then charged opposite of is already charged and then sticks to the substrate. This process looks similar to a battery. The big advantage of electrodeposition is the scaleability as it can be used at the macro and microscale. It is also cheap, simple and highly tunable.

9.4 Lithography

Lithography basicaly works by exposing a photoresist to UV light to change its properties. Which areas are exposed can be controlled by a mask that transferes the pattern onto the wafer.

Lithography Process:

1. Coating the wafer with a photosensitive polymer and pre-bake to evaporate the solvent in the photoresist
2. Align wafer with the mask patterns in a mask aligner
3. Expose the photoresist to UV-light trhough the mask (the mask shields certain areas)
4. Remove the photoresist with a developer.
    - Remove Exposed Resist = Positive Resist: Light degrades the polymers resulting in a more soluble resist
    - Remove Unexposed Resist = Negative Resist: Light polymerizes the rubber in the photoresist and strengthens the resist
5. Post-Bake to harden the wafer and photoresist
6. After Lithography the pattern is then used to either deposit material onto the pattern or remove material of the pattern by etching

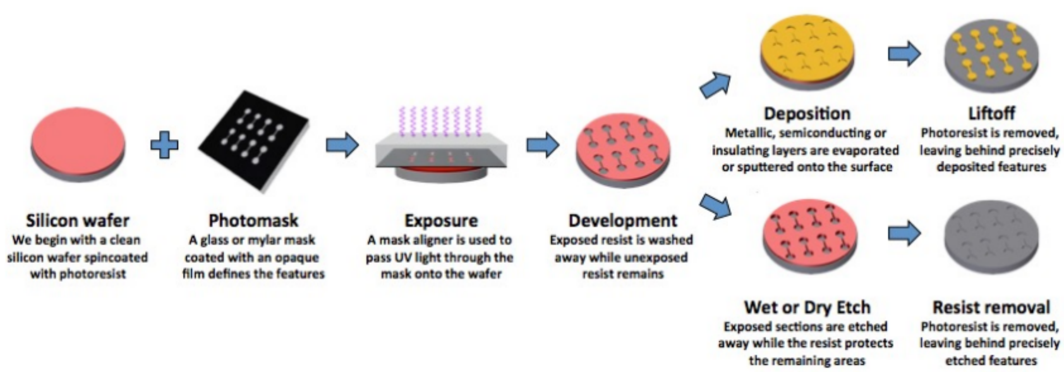


Figure 57: Complete Lithography with Etching or Deposition

Mask:
The Mask is a stencil used to generate the patterns. It is usually made out of optically flat glass or quartz and then coated with chorme to generate the pattern. We use two mask polyrities:

- Clear Field: Area of Interest is coated (light cant pass)
- Dark Field: Area of Interest is uncoeted (light can pass)

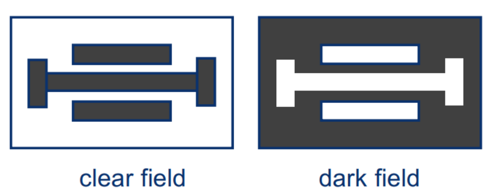


Figure 58: Different Mask Types

Aligment:
If multiple masks are used to generate the pattern, the mask have to be aligned perfectly to guarantee a good matching between the different patterns. To achieve a goog aligment, aligment markers are used. As there will always be some aligment error, these erros should be accounted for when designing a chip of microrobot.

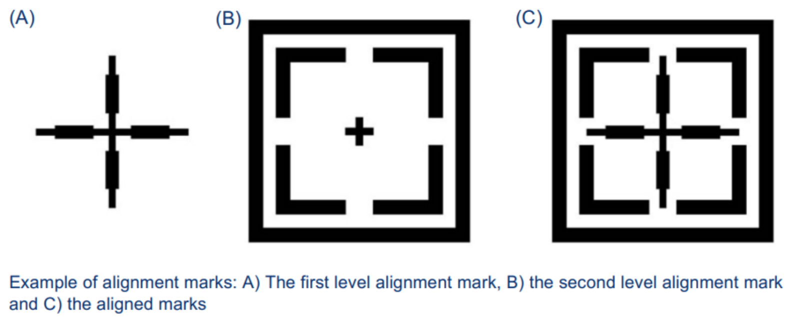


Figure 59: Alignement Markers

Exposure:
Different Exposure Techniques can be used to expose the photoresist.

- Contact Printing:
  - The mask is in contact with the resist
  - Pro: High Resolution $< 0.5\mu m$
  - Con: Mask and Wafer can easily be damaged
  - Resolution: $2b_{min} = 3\sqrt{\lambda \frac{d}{2}}$
- Proximity Printing:
  - The mask is slightly above the resist
  - Pro: Long Mask Life due to the $10 - 25\mu m$ gap
  - Con: Lower Resolution due to diffraction effects $(2 - 4\mu m)$
  - Resolution: $2b_{min} \approx 3\sqrt{\lambda s}$
- Projection Printing:
  - The Image of the Mask is reduced to a point and then the whole mask and wafer are scanned
  - Pro: High Resolution $\leq 0.2\mu m$, Long Mask Life
  - Con: Very Complicated and Expensive
  - Resolution: $b_{min} = \frac{k\lambda}{NA}$, NA = Numerical Apperature

d is the thickness of the resist, b_{min} is the minimal width that can be printed.

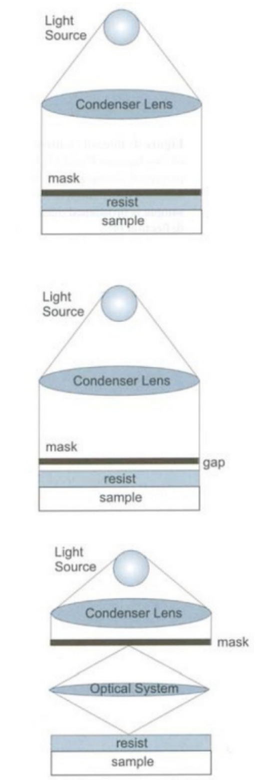


Figure 60: Different Exposure Techniques

9.5 Subtractive Processes

We now want to look at how we can remove material from the substrate. The main method to remove material is etching (ätzen). We can destinguisch between dry and wet etching.

9.5.1 Wet Etching

During Wet Etching the solid material is removed using **liquid** etchants. The Etching rate depends on various factors like etchant concentration, temperature, crystal orientation ord agitation (Umrühren).
There are two different wet etchant types. Isotropic and anisotropic etchants.

Isotropic Etchant:
An isotropic etchant etches in all crystallographic directions at the same rate, creating rounded shapes. Isotropic etchants are usually acidic for example HNA, HF, HNO_3 or CH_3COOH. Isotropic etchants are very fast und undercut the mask. Often used mask is SiO_2.

Anisotropic Etchant:
An anisotropic etchant etches at a different rate depending on the crystal orientation of the exposed crystal plane. Anisotropic etchants are usually alkaline (basisch) $pH > 12$ for example KOH. Aniotropic etchatns usually need a higher temperatur to work $> 50C°$. The reaction rate is limited and usually slower than for isentropic etchants. A big advantage of anisotropic etchants is that they dont undercut the mask and agitation is not relevant. Often used mask is Si_3N_4.

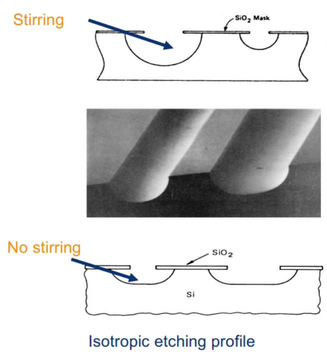


Figure 61: Isotropic Etching

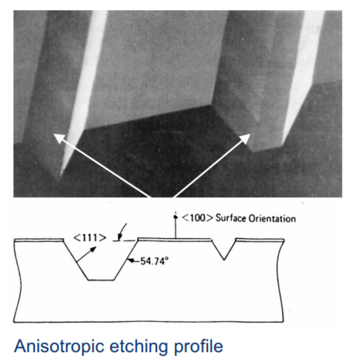


Figure 62: Anisotropic Etching

9.5.2 Dry Etching

During Dry Etching the solid material is removed using **gaseous** etchants (mostly in the plasma state). There are three main methods for dry etching.

Sputter Etching:
High energy particles are bombared at the substrate and removing material.

Plasma Etching:
Plasma etching works through chemical etching. A chemical reaction between the gas molecules and sample surface remoce material.

Reactive Etching:
Combination of Sputter Etching and Reactive Etching.

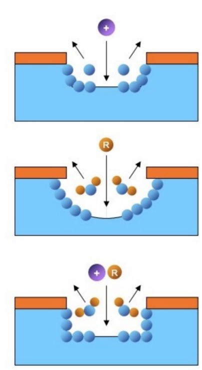


Figure 63: Dry Etching Methods

9.6 Other Manufacturing Techniques

9.6.1 Ultra High Precision Machining

This manufacturing technique is a scaled down version of CNC machinging, achieved by better controls and more stable lathes (Drehmaschinen) through better beating, laser interferometry and better temperatur control.

9.6.2 Laser Machining

Lasers are used ina lot of different manufacturing techniques like heat treatment, welding, ablation, deposition, etching, lithopraphy, microelectroformin, focused beam milling and stereo lithography.

Laser machining can be used for subtractive machinging by burnign away material. But it can also be used for additive processes like 3D printing or 3D lithography.

9.6.3 3D Laser Lithography

3D Laser Lithopraphy uses lasers to "draw" 3D structures into a transparent material (photoresist). This is achieved by exactly timing two photons arriving at the desired location. If the photons arrive at nearly the same time the energy absorbed by the photoresist is high enough to polymerize the photoresist (one photon would not be enough). The resolution of 3D laser lithography is about $150 - 450nm$. But it is very slow at the moment.
This method can also be used to create metal-organic micromachines. A positive photoresist is used to create mold. This is then partially electrodeposited and partially not. Then we polymer cast the whole thing and we have interconnecten metalic and non metalic structures.

9.7 Surface and Bulk Machining

Bulk Micromachining removes big parts (bulks) of silicon to define the device structure throuhg dry or wet etching. Surface Micromachining adds layers onto the wafer surface to create strucutres (thin film deposition).

10 Nanofabrication

For Nanofabrication most microfabrication techniques are used as well but some additional techniques are required in order to acheivestructures with nanoscale features.

10.1 Electron Beam Lithography

Similar to the observation tools we can achieve better resolution if we use electrons instead of light, as the wavelenght of light puts an upper limit on the resolution. E-beam lithography usese a electron sensetive resist. The patterns are directly written into the resist by a scanning electron beam(SEM) and do not require a mask.
E-beam lithogrpahy combined with lift-off is currently the main way to fabricate nanostructures.
Lift-off describes the process after e-beam lithography. The pattern created by the e-beam lithography is then filled with material. When the resist is then removed (lift-off) the desired pattern remains.
Even though we can theoreticaly achieve much higher resolution with e-beam lithography electron scattering in the resist limits the practical resolution. Back scattered and secondary electrons expose the resist and lower the resolution. Scattering reduce the resolution form $0.1\mu m$ to $0.2\mu m$.

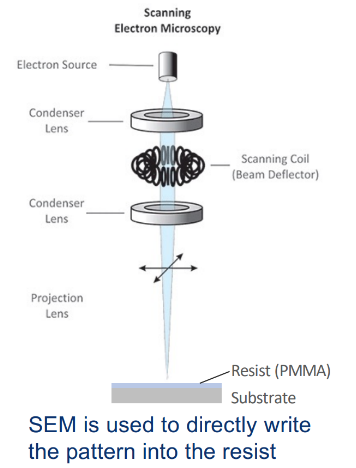


Figure 64: Electron Beam Lithography

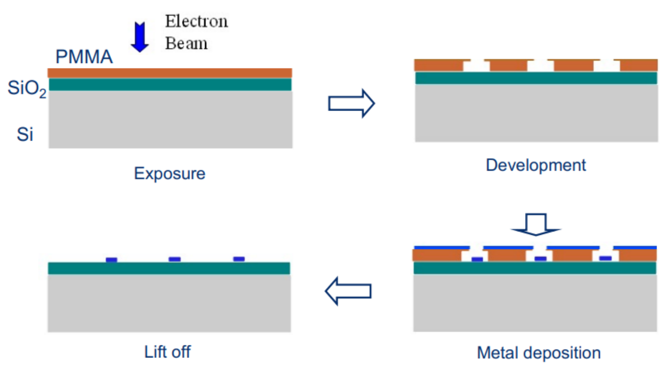


Figure 65: Whole Lift-Off Process

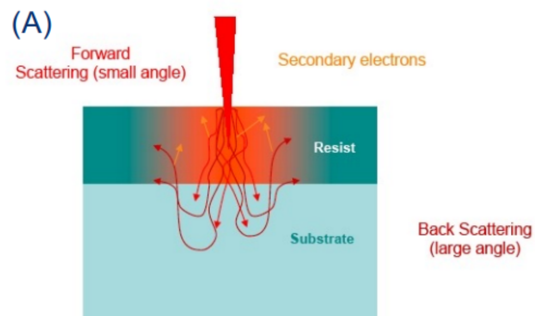


Figure 66: Electron Beam Scattering

10.2 Other Nanolithography Methods

There are other nanolithography methods used to achieve even smaller resolutions

10.2.1 Extrem UV Lithography

Extrem UV Lithography is currently the state of the art method for nanofabrication, with wavelengths of $\lambda \sim 13.5nm$ resulting in resolutions upto $7nm$. As it is the method with the highest resolution it also has some disadvantages. As EUV light is stongly absorbed by all materials the lithography has to be done in a vacuum. A special mask is required mad out of multilayer Si or glass and special mirrors are needed. Because of the challanges EUVL is very expensive and at the moment only one company(ASML) is able to preform it.

10.2.2 X-Ray Lithography

X-Ray lithography uses x-rays $\lambda \sim 1nm$ generated by a synchrotron storage ring. The rest workes similar Photolithography. With x-ray lithography large aspect ratios (seitenverhältnisse) are possible.
The challenges for this technique are the masks as most materials hav low transparency at $\lambda = 1nm$. The mask must thus be very thin $1 - 2\mu m$ and $0.5\mu m$ for the pattern. This thin masks are very hard to fabricate.

10.3 Scanning Probe Techniques

Scanning probe techniques are characterized by the use of a tip that is eather in contact or nearly in contact with the substrate. There are different ways to implement scanning probe techniques.

10.3.1 AFM Based Exposure and Lithography

AFM-base exposure and lithography also useses electrons. The resist is exposed to the electrons from a biased AFM tip. It uses the Non-Contact mode from AFM. As electrons are used the same resists as for e-beam lithography can be used. The advantages of AFM-based lithography are a more detailed image and precise alignement between substrate and AFM tip. AFM based techniques are also relatively cheap as there are desktop sized AFMs.

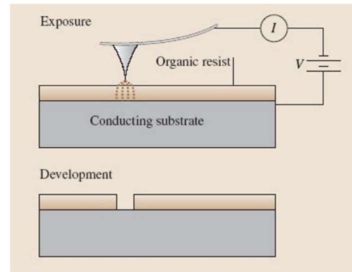


Figure 67: AFM Lithography with electrons

10.3.2 NanoFrazer

A heated cnatilever tip evaporates the thermally responsive resist. this technique is very fast as only small exposure times are reqiured.

10.3.3 Dip-Pen Nanolithography

The Dip-Pen technique useses a ARM tip, that is inked with a solution containing small concentrations of the molecula of interest. The AFM tip is then brought into contact with the surface and the ink molecules flow from the tip onto the surface like pen. The water meniscues that naturally forms between the tip and the surface enables the diffusion and transport of the molecules. As thsi technique uses water it cant be done in a vacuum. Some examples for dip-penned species are polymers, gold, dendrimers, DNA, organic dyes, antibodies and alkanethiols.

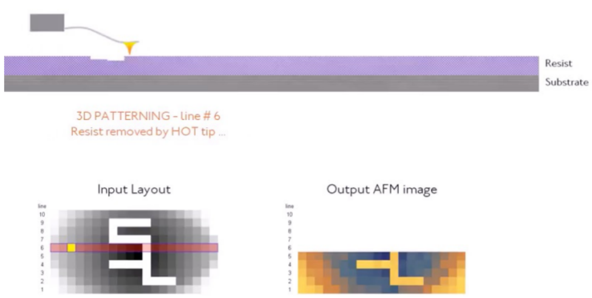


Figure 68: NanoFrazer

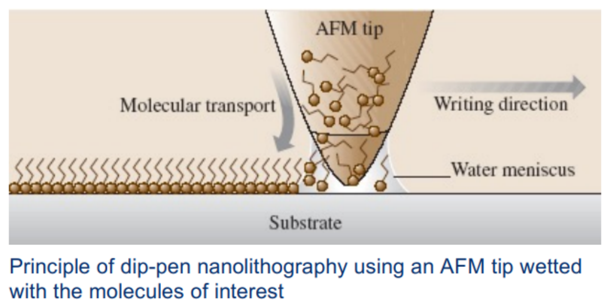


Figure 69: Dip Pen Nanolithography

10.4 Localized Electrochemical Deposition

In LECD the current required for electrodecomposition is localized onto a sharp tip. Then only material is deposited near the sharp tip. By moving across the sample in a desired trajectory a pattern can be draw onto the sample. Through changing the current density of additives to the electrolyte different surface roughness can (un-)willfully be achieved. As only one layer at a time can be deposited the process is very time consuming. Only materials that can form electrlytes can be used.

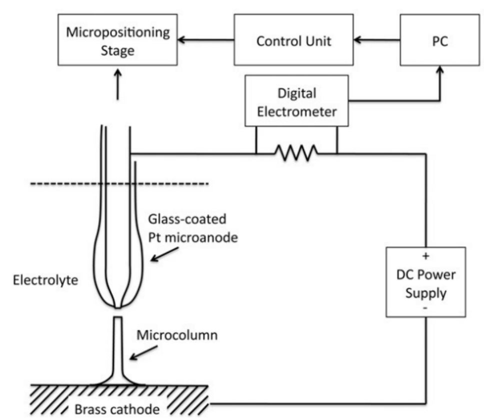


Figure 70: LECD Setup

10.5 Focused-Ion-Beam Etching/Milling

FIB etching works with a similar setup as SEM, but instead of electrons heavy ions (usually Ga^+) are used. The ions are bombarded onto the substraate to remove material. As FIB uses large ions they do not penetrate much into the substrate.

10.6 FIB Chemical Vapor Deposition (FIB-CVD)

When combining FIB with a gas source wich delivers reactants to the surface a deposition of material can be achieved. The adsorbed reactants react with the ion-beam and secondary electrons to form a deposit. As the ion beam only has a short penetration depth the depostion area is limited to a small area on the surface. The FIB-CVD technique is used to fabricate 3D nanostructures.

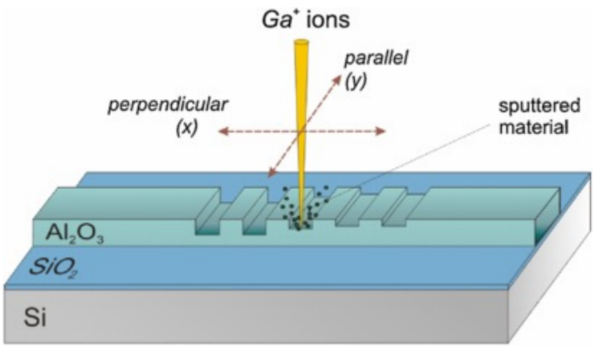


Figure 71: FIB

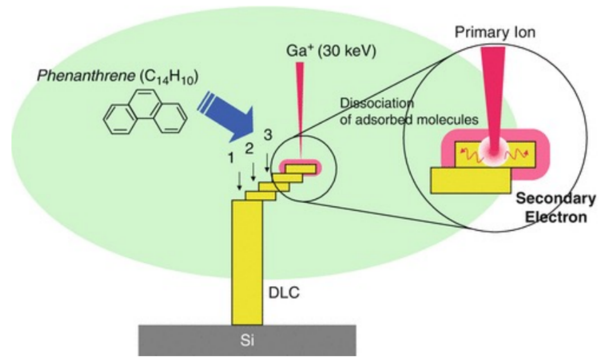


Figure 72: FIB-CVD

10.7 Self-Assembly

As micro-/nanomanipulation is inherently difficult self-assembly can have a huge impact on microrobotics.
The definition of self-assembly:

Self-assembly is the structural self-organization of physical entities without external guidance. It is a reversible process in which disordered pre-existing components form stable and well-defined patterns or structures of higher order.

or

Self-assembly is the spontaneous formation of organized structures from many discrete components that interact with one another directly and/or indirectly through their environment. In addition, the assembling components may also be subject to global potentials such as externally imposed EM fields or chemical potentials.

Self-assembly is a fundamental and omnipresent principle in nature at all scales. Self-assemby creats complex phenomena ranging from crystal formation to solar systems to life itself.
Self-assembly has a huge potential in microrobotics for bottom-up processes.

Self-assembly is often fast but can't create very complex structurs. In contrast controlled robotic assemply is often slow but can form very complex strucutres. We can now combine the two to get optimal results from hybrid assembly.

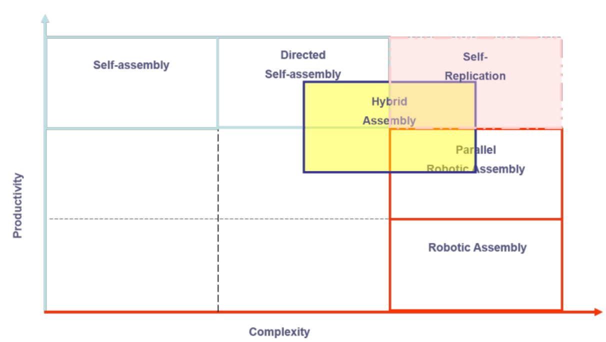


Figure 73: Assembly Productivity vs. Complexity

10.7.1 Static Self-Assembly

In static SA the order state is formed at an equilibrium of the syste. Through static SA the system is at a global or local equilibrium and does not dissipate heat. Forming the order structure may reqiure energy, but once order is formed no energy is needed as the system is stable.
Some examples of static AS are crystalin structures of a ribosome, self-assembled nanofibers, an array of millimeter-sized polymeric plates assembled at a water interface by cpillary interactions, thin film of a nematic liquid crystal on a isotropic substrate, micrometer-sized metallic polyhedra folded from planar substrate or a three dimensional aggregate of micrometer plates assembled by capillary forces.

10.7.2 Dynamic Self-Assembly

In dynamic SA the structures are formed by local interactions. As it is not stable and uses energy it is sometime reffered to as self-organization. Dynamic SA only happens if the interactions responsible for the formation of a structure between the components dissipate energy to the environement.
Some Examples of dynamic SA are an optical micrograph of a cell with fluorescently labled cytoskeleton and nucleus, reaction-diffusion waves in a petri dish, a simple aggregate of three milimeter sized rotating magnetized disks interacting with eachother, a school of fish, concentric rings formed by charged metallic beads rolling in a circualr path or convection cells formed above a micropatterned metallic support.

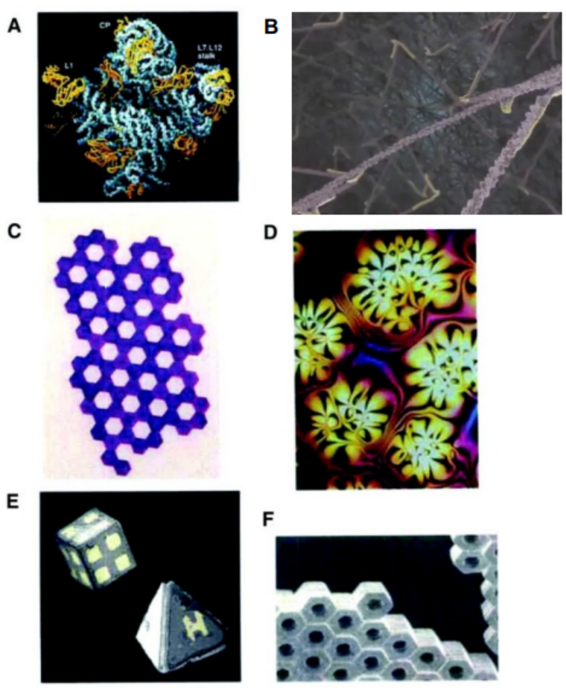


Figure 74: Examples of Static SA

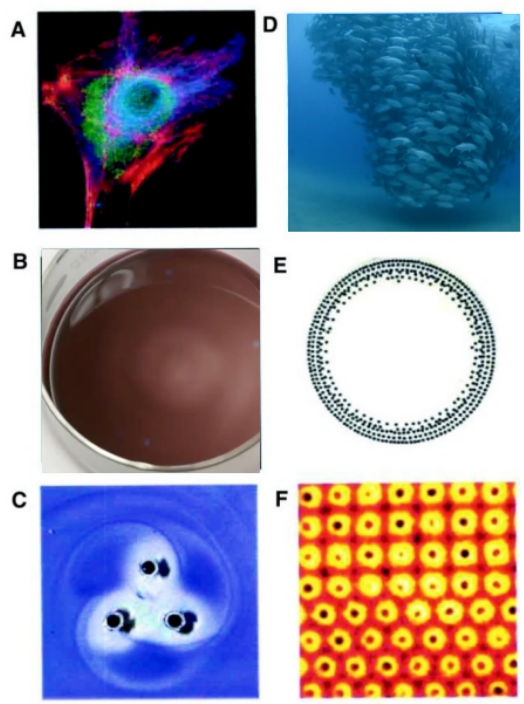


Figure 75: Dynamic of Static SA

10.7.3 Interaction Foces

The forces which drive the SA are relatively weak in comparison to the scale of the components. On the molecular level mostly non covalent forces like Van der Waals, electrostatic, hydrogen bonds or hydropobic-/phillic interactions are involved.
On the macroscale often other types of forces like magnetic, capillary, electrostatic and gravitational forces are involved.
It is beneficial that the assembly is reversible, so in a case of misconfiguration the connections can be broken an reconfigured.

10.7.4 Intrinsic Stress

A commonly used SA method for microrobots are intrinsic stresses. Intrinsic stress in a 2D structure can lead to folding or bending ot hte component to a lower energy state. The intrinsic stress can then be used to create 3D structures.
A good example of this method is the fabrication of ABF. First special substrate containg galliumarsenid and different alloys of it is produced. Then with a positive photoresist and etching a first pattern is created (long thin tails). Then with a negative photoresist, PVD and lift-off a soft magnetic head is added to the tail patterns. The last step is wet etching to release the ABF. The patterns were made in such a way that through intrinsic stresses a helical structur is formed.

Intrinsic stresses can also be used in batch production of nanocoils with contacts.
First a "normal" rod is fabricated. Then through anisotropic wet etching the coil is formed with the help of intrinsic stresses. And the last step uses LECD to deposit coils and pads.

10.7.5 Field Gradient Assisted SA

Using external electric or magnetic fields we can easiyl orient objects. This is done by using the fact that if a non polarizable object is placed in a non-uniform electric field, charges accumulate along the longest axis and a depole is induced. This depole expiriences a torque along the field. If the object is more polarizable than the medium it will travel to the field maxima and if the object is less polarizable the object moves towards the field minima.

10.7.6 Applications of Self-Assembly

On example where SA could be beneficial is a Endoscopy Capsule. An Endoscopy Capsule is a big pill a patient can swallow that goes through the digestive tract to make measurements. This pill cant be very big as the patient has to swallow it. IF we could swallow seperate part to build the device inside our stomach we could maybe implement more advanced technologies into that pill.