The enhancement of the intermolecular attractive forces at the surface is called surface tension.

- The cohesive forces between molecules down into a liquid are shared with all neighboring atoms.
- Those on the surface have no neighboring atoms above, and exhibit stronger attractive forces upon their nearest neighbors on the surface.

**Water Strider**
- The cohesive forces between liquid molecules are responsible for the phenomenon known as surface tension.
- The molecules at the surface do not have other like molecules on all sides of them and consequently they cohere more strongly to those directly associated with them on the surface.
- This forms a surface "film" which makes it more difficult to move an object through the surface than to move it when it is completely submerged.

**Surface Tension** (is typically measured in dynes/cm or N/m)
- The force in dynes required to break a film of length 1 cm.
- Water at 20°C has a surface tension of 72.8 dynes/cm compared to 22.3 for ethyl alcohol and 465 for mercury.

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**Capillary Action**
- Capillary action occurs when the adhesion to the walls is stronger than the cohesive forces between the liquid molecules. The height to which capillary action will take water in a uniform circular tube is limited by surface tension. Acting around the circumference, the upward force is

\[ T = 2\pi r \theta \gamma \]

- The height \( h \) to which capillary action will lift water depends upon the weight of water which the surface tension will lift:

\[ h = \frac{2T}{\rho g} \]

- The height to which the liquid can be lifted is given by

\[ h = \frac{2T}{\rho g} \]

**Contact Angle**
- Contact Angle at Equilibrium
  - Three phases system
  - Young Equation
    - The contact angle is related to the various interfacial energy densities (interfacial tensions) by the equation
    \[ \gamma_{SG} + \gamma_{SL} - \gamma_{LG} = \theta \]
    - where
      - \( \gamma_{SG} \) = the liquid-gas interface
      - \( \gamma_{SL} \) = the solid-liquid interface
      - \( \gamma_{LG} \) = the solid-gas interface
  - Measurement of wettability of surfaces
  - Wettability
    - Hydrophobic surfaces
      - Hate water
      - Wax, bare silicon wafer
    - Hydrophilic surfaces
      - Love water
      - Contact lens, bare glass wafer

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[Image of water droplets on a surface demonstrating surface tension and contact angle.]
**[Capillary] Contact Angle Measurement**

- **Contact Angle Analyzer**
  - (A) Static drop

- **Another Methods**
  - (A) Sessile or Static drop
  - (B) Wilhelmy plate method
  - (C) Captive air bubble method
  - (D) Capillary rise method
  - (E) Tilting substrate method

http://www.uweb.engr.washington.edu/research/tutorials/contact.html

**[Capillary] Capillary Pressure Drop**

\[
\frac{2\gamma_{LG} \cos \theta}{r_0} = \Delta p
\]

- \(\Delta p\): pressure drop across a liquid - gas interface in a capillary tube
- \(\gamma_{LG}\): the liquid – gas surface tension
- \(\theta\): the contact angle
- \(r_0\): the microchannel radius

**[Capillary] Filling Rate**

- **Filling Rate**
  - Filling rate = \(q(x(t)) = u(x(t)) \times \text{Area}\)
  - Capillary filling of micro channels
  - Assumption
    - (capillary pressure drop) = (viscous pressure loss)
    - At small sizes, fluid flow is dominated by viscous flow. Inertial flow is almost non-existent. This means the flow is “Laminar” with no turbulence.

- **Influences in the Filling Rate**
  - Increases with surface tension
  - Decreases with contact angle
  - Increases with radius
  - Decreases with viscosity

- **Filling Rate is an important parameter in capillary driven systems**

\[
x_0 = \frac{\pi \gamma_{LG} \cos \theta r_0^3}{4\eta x(t)}
\]

http://www.flow3d.com/app/CapillaryFilling.htm

**[Capillary] Test Strips**

- **Working Principle of Test Strips**
  - Reactants placed and immobilized on test stripes
  - Microstructures suck sample liquids through stripes by a capillary action
  - Sample liquid solutes and reacts with reactants in different ways

- **Strengths**
  - Robust microfluidics
  - Capillary forces
  - No external energy source needed
  - Avoiding unstable menisci
  - Timing
  - Rich field of commercialized applications
  - Simple color change reactions
  - Multi step immunoassays

- **Challenges**
  - Improvement of precision needed: 10 % → 2 - 5 % ...
  - e.g. metering structures needed with better accuracy
  - e.g. better control of incubation times needed (e.g. independent of Ambient temperature, ...)
  - Long term stability of wetting properties


http://www.mypharmacy.co.uk/health_products/products/a/ascensia/ascensia_contour.htm
**Case Study 1: Biosite Triage Cartridge**

1. A blood sample is taken and dropped onto test-chip opening. Filter separates blood cells from plasma, which then passes through into a reaction chamber.

2. The plasma combines with reagents (antibodies bound to fluorescent particles) to form a reaction mixture, which incubates before flowing into a diagnostic lane. Steps 1 and 2 take approximately 12 minutes.

3. The test chip is inserted into the Triage MeterPlus.

4. The meter then measures the fluorescent intensity of the sample—markers that indicate a disease or drug overdose—using a laser diode, and prints out those measurements after a couple of minutes.

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**Transport Balance in a Test Stripe**

- total input volume spreads to wetting parts
  - filter
  - reaction zone
  - transport parts
  - waste chamber

\[ V_{\text{input}} > V_{\text{filter}} + V_{\text{react}} + V_{\text{transport}} + V_{\text{waste}} \]

- move all reacted sample through readout

\[ V_{\text{waste}} > V_{\text{transport}} + V_{\text{react}} \]

\[ V_{\text{react}} > 2V_{\text{filter}} \]

- example Biosite Triage

\[ V_{\text{react}} = 3V_{\text{filter}} + V_{\text{cont}} = 20\mu l \]
**Case Study 1: Biosite Triage Cartridge**

- **Setting up incubation Time**
  - incubation time requirements:
    - incubation times up to 10 minutes necessary
    - stop or slow down capillary flow for a defined period of time
  - physical approach to extend incubation time:
    - different contact angle
    - small diameter
  
  \[ q(x) \propto \frac{\gamma_{LG} \cos \theta_0}{\eta x} \]

  - total volume flow negligible whileManicuous in time gap. After manicuous leaves time gap capillary force increases again.

  - very small and long capillaries
  - high contact angles lead to possibility of stop of capillary flow

**Case Study 2: Liquid Handling for the Life Sciences**

- **TopSpot®-technology**
  - Self-filling due to capillary pressure
  - Ejection due to pneumatic actuation
  - Individual droplets on the slide having a pitch of about 500 µm

**Capillary Effects**

- **Passive Capillary Effect**
  - Utilizes dependence on the geometry
  - Utilizes surfaces with wettability gradients

- **Electrocapillary Effect**
  - Electrowetting
  - Changes the surface tension by varying their potential difference

- **Thermocapillary Effect**
  - Thermowetting
  - Marangoni Effect
  - Caused by the temperature dependence of the surface tension
  - At a higher temperature, the molecules of the liquid move faster and their attractive force becomes smaller

**Electrocapillary Effect**

- Also known as "Electrowetting"
- Changes the surface tension between two immiscible, conductive liquids or between a solid surface and a liquid by varying their potential difference
- The effect is based on the adsorption characteristics of ions in the wetting interface
- This interface is an electrical double layer (typically 10 Å to 100 Å thick)
- By changing the electrical potential across this double layer, the surface tension is controllable

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**References:**

- Science, 291, 277-280, 2001
[Capillary] Electrocapillary Effect

- \( \text{Capillary} \) Electrocapillary Effect

[Capillary] Thermocapillary Effect

- **Thermowetting (in hydrophilic)**
  - Hot: weak surface tension (weak wettability)
  - Cold: strong surface tension (strong wettability)

- **Marangoni Convection**
  - the surface is pulled towards the surface with a lower temperature when differences exist in the interface temperature between the gas and liquid, thus causing convection. This convection is the Marangoni convection.

[Capillary] Microcapillary Pumping

- Driving droplet motion with gradients in solid-liquid interfacial energy driven by:
  - (a) thermal gradients (thermowetting),
  - (b) droplets that contain a chemical that reacts to decrease surface wettability,
  - (c) liquid bi-slugs that leave a coating film that lowers the overall surface energy, and
  - (d) light-induced reactions that create wettability gradients (optowetting).