# *Introduction to Micro/Nanofluidics*

## Date: 2016/05/20

## Dr. Yi-Chung Tung

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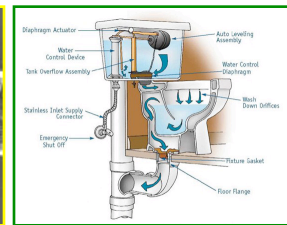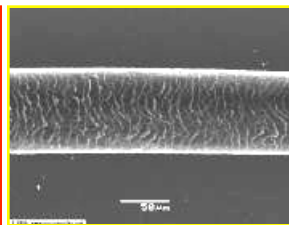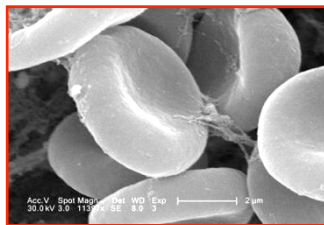# Outline

- Introduction to Microfluidics
- Basic Fluid Mechanics Concepts
- Equivalent Fluidic Circuit Model
- Conclusion

# What is Microfluidics

- ***Microfluidics*** = Micro + Fluidics
- ***Micro/Nano***: $10^{-6}$ , $10^{-9}$
  - Small size (sub-mm)
  - Small volumes ($\mu$l, nl, pl)
- ***Fluidics:*** handling of liquids and/or gases



# Advantages of Microfluidics

- The motivation for using a microfluidic system is analogous to the argument for using integrated circuits (IC) to replace the discrete component circuits.
- Advantages:
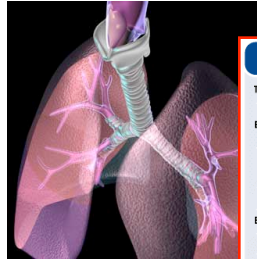
**Miniaturization: Portability (Lab-on-a-Chip)**

**Integration: Low Costs, Batch Fabrication**

**Automation: Simplicity of Operation**

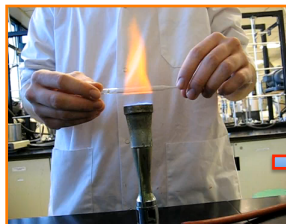## Microfluidics *in vivo*

- Circulating and Respiratory System



## Old School Microfluidics

- Historical Microfluidics: Glass capillary
- Glass Capillary has been broadly exploited in labs
- Capillary Electrophoresis (CE)

# Capillary Electrophoresis (CE)

- Introduced in the 1960s, the technique of capillary electrophoresis (CE) was designed to separate species based on their size to charge ratio in the interior of a small capillary filled with an electrolyte.
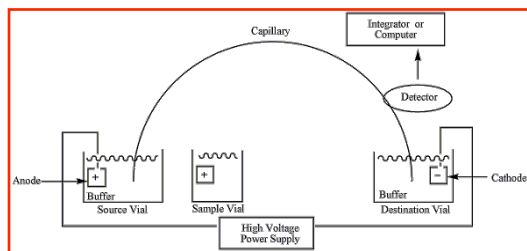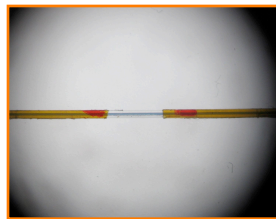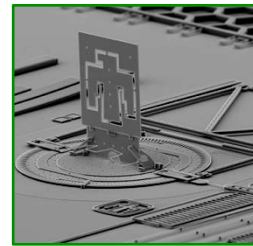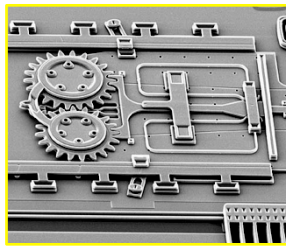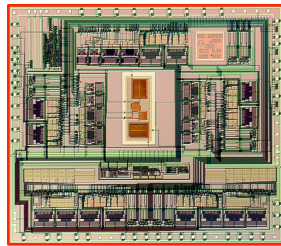


# New Era of Microfluidics

- Due to the advancement of micro/nano fabrication technology, "microfluidics" has been redefined.
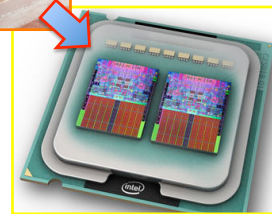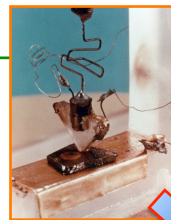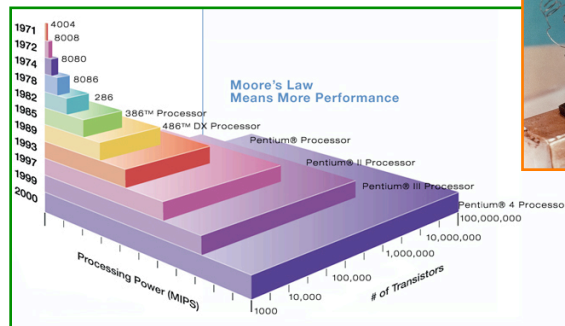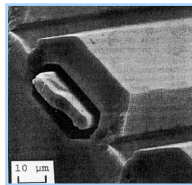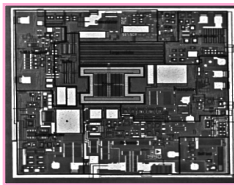
# Microelectromechanical Systems

- Microelectromechanical Systems (MEMS).
- MEMS is is the integration of *mechanical elements, sensors, actuators, and electronics* on a common silicon substrate through microfabrication technology.



# Advancement of MEMS



Ikeda et al. 1990 (Japan)

Analog Device ADXL50

**Polymer**

Comb drive

Microstage
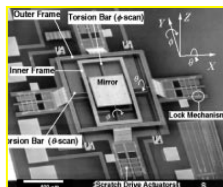
Toshiyoshi et al., 1998 (UCLA)
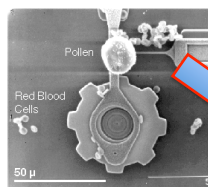
mems.andia.gov

Walraven et al., 2003 (Sandia)
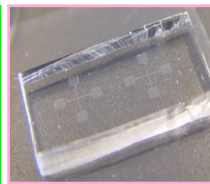
www.uni-ulm.de
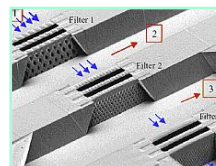
**Silicon-Based**

www.mic.dtu.dk

Takayama et al, 2003 (UM)

# Development of Microfluidics



# Materials of Microfluidic Devices



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## Fluid Mechanics

- **Density ($\rho$):**
  Density = Mass/Volume (kg/m$^3$)
- **Dynamic Viscosity (Viscosity, $\mu$):**
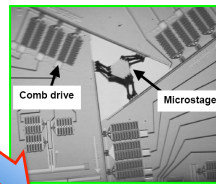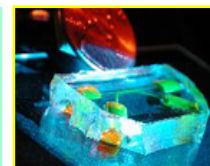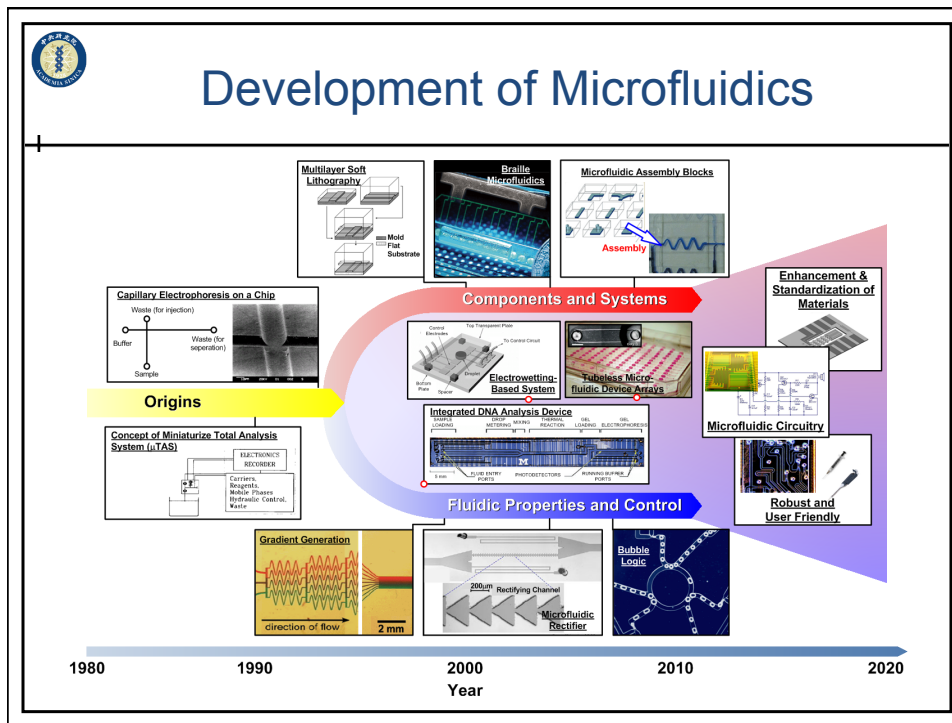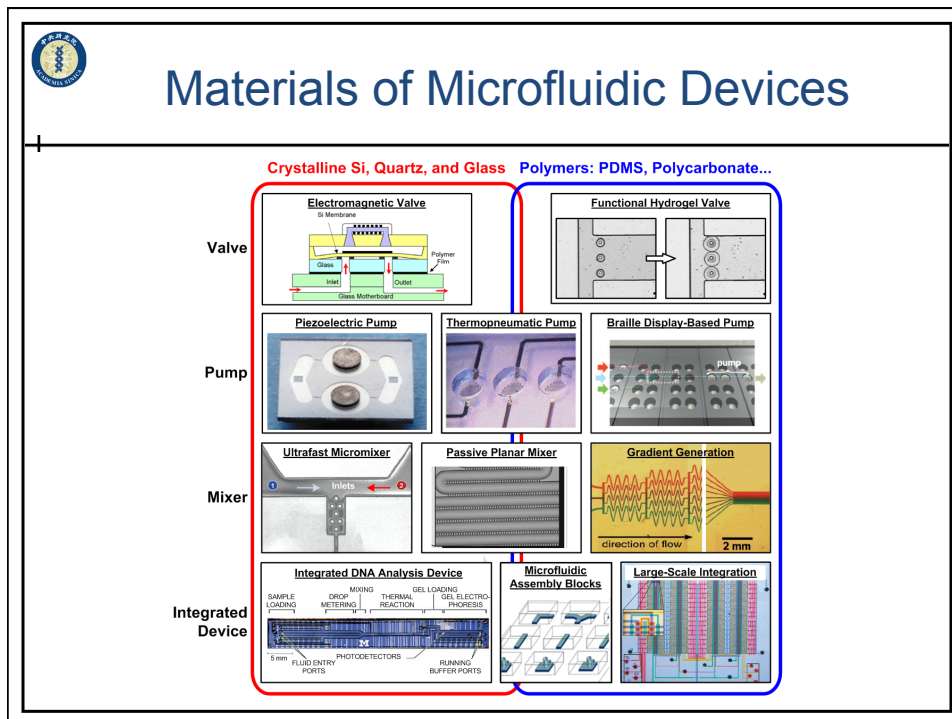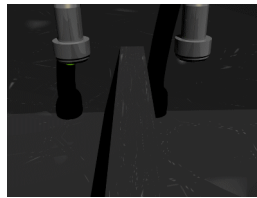  Viscosity is a measure of the resistance of a fluid which is being deformed by either shear stress or tensional stress.

| Temp (°C) | Density (kg/m$^3$) |
|---|---|
| 100 | 958.4 |
| 80 | 971.8 |
| 60 | 983.2 |
| 40 | 992.2 |
| 30 | 995.6502 |
| 25 | 997.0479 |
| 22 | 997.7735 |
| 20 | 998.2071 |
| 15 | 999.1026 |
| 10 | 999.7026 |
| 4 | 999.9720 |
| 0 | 999.8395 |
| −10 | 998.117 |
| −20 | 993.547 |
| −30 | 983.854 |

The density of water in kilograms per cubic meter (SI unit) at various temperatures in degrees Celsius. The values below 0 °C refer to supercooled water.
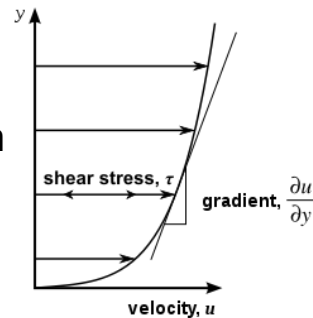
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## Fluid Mechanics

- **Viscosity ($\mu$) – Newton's Theory:**
$$\tau = \mu \frac{du}{dy}$$

where $\tau$ is Fluid Shear Stress
where $(du/dy)$ is change of fluid velocity in $y$ direction

- This is a constitutive equation (a reasonable first approximation).
- **Newtonian Fluids.**

# Fluid Mechanics

- **Viscosity ($\mu$):**
  - Unit: kg/(m.s) = Pa.s = 10 Poise
  - Viscosity of Water at 20°C
    = 0.01002 Poise
    = 1.002 cP (centipoise)
    = 1.002 mPa.s
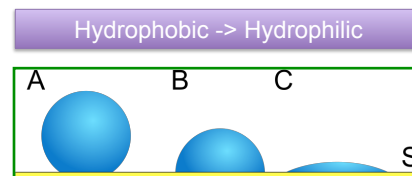  - Viscosity of SAE 30 oil at 20°C
    = 2.9 Poise

| Temperature [°C] | Viscosity [mPa·s] |
|---|---|
| 10 | 1.308 |
| 20 | 1.002 |
| 30 | 0.7978 |
| 40 | 0.6531 |
| 50 | 0.5471 |
| 60 | 0.4668 |
| 70 | 0.4044 |
| 80 | 0.3550 |
| 90 | 0.3150 |
| 100 | 0.2822 |

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# Fluid Mechanics

- **Surface Tension ($\gamma$):**

  **Surface tension** is a property of the surface of a liquid. Surface tension is caused by cohesion (the attraction of molecules to like molecules).
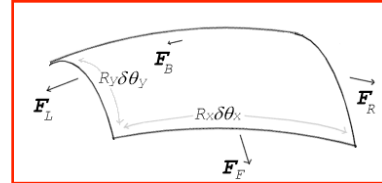


Hydrophobic -> Hydrophilic

A    B    C    S

# Fluid Mechanics

- **Surface Tension ($\gamma$):**
  **Young-Lapalace Equation:**

$$\Delta p = \gamma \left( \frac{1}{R_x} + \frac{1}{R_y} \right)$$

Where $\Delta p$ is the pressure difference, $\gamma$ is surface tension, $R_x$ and $R_y$ are radii of curvature in each of the axes that are parallel to the surface.
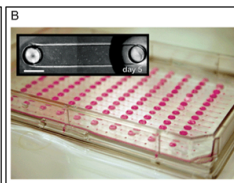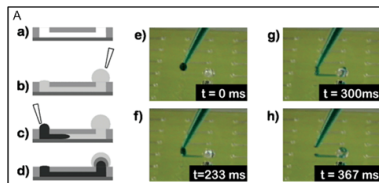
Water at 25°C, $\gamma$ = 71.97 (dyn/cm)

| $\Delta p$ for water drops of different radii at STP | | | | |
|---|---|---|---|---|
| Droplet radius | 1 mm | 0.1 mm | 1 μm | 10 nm |
| $\Delta p$ (atm) | 0.0014 | 0.0144 | 1.436 | 143.6 |

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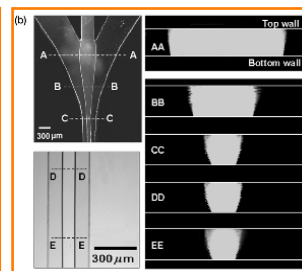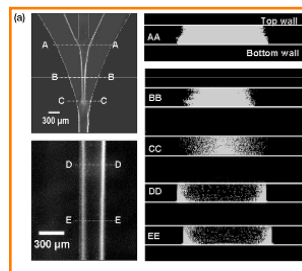# Fluid Mechanics

- Utilize Surface Tension in Microfluidics
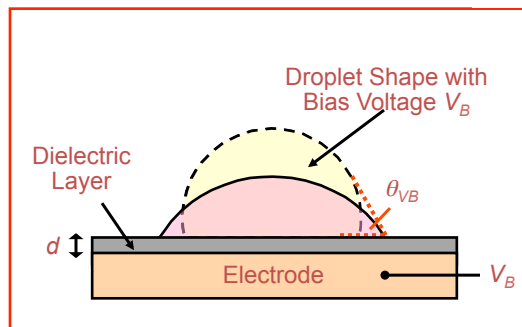
**Surface Tension Driven Flow**
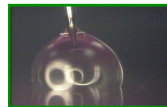
**Air-Liquid Two Phase Flow**

# Fluid Mechanics

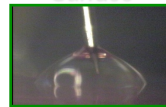- Control Surface Tension in
  Microfluidics: Electro-Wetting

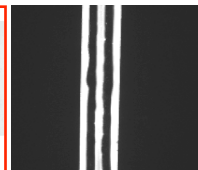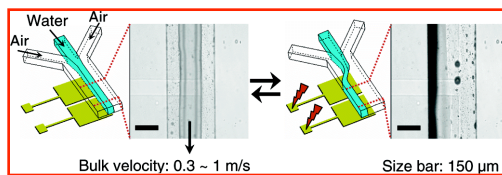$$\cos\theta_V = \cos\theta_o + \frac{1}{2}\frac{\varepsilon\varepsilon_o}{\gamma_{LV}t}V^2$$

Droplet Shape with
Bias Voltage $V_B$

Dielectric
Layer

$\theta_{VB}$

$d$

Electrode — $V_B$

*Hydrophobic
Surface*

*Hydrophilic
Surface*

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# Fluid Mechanics

- ## Electro-Wetting Microfluidics

Water  Air
Air

⇄

Bulk velocity: 0.3 ~ 1 m/s        Size bar: 150 µm

**Switchable
Surface for
Air-Liquid
Flow**

Liquid
droplet

Teflon®
layer

SU8
dielectric
layer

Command
electrode

Substrate

Applied
voltage

**Digital Microfluidics**

Wheeler Microfluidics Lab

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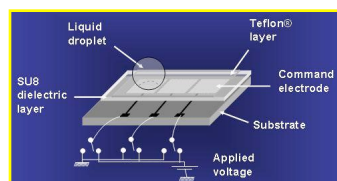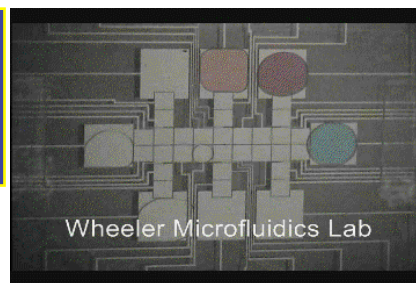
## Fluid Mechanics

- **Reynolds Number (*Re*):**

  *Re* is a <u>dimensionless number</u> that gives a measure of the ratio of inertial forces to viscous forces**.**

  $$\text{Re} = \frac{\rho VL}{\mu}$$

  *V* is the mean fluid velocity (m/s)

  *L* is the a characteristic linear dimension (m)
    (traveled length of fluid or hydarulic diameter etc.)

## Fluid Mechanics

- **Reynolds Number (*Re*):**

  – Large *Re* means inertial force dominates: **Turbulent Flow (unsteady flow stream, i.e. swirls and vortices).**

  – Small *Re* means viscosity force dominates: **Laminar Flow (fluid stream follows regular paths, i.e. streamlines).**

  – For flow in a pipe, <u>laminar flow</u> occurs when *Re* < 2300, and <u>turbulent flow</u> occurs when *Re* > 4000.
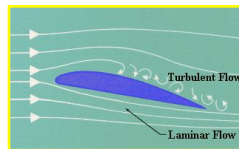
  – In the interval between 2300 and 4000: **Transition Flow.**

# Fluid Mechanics

- **Laminar Flow vs. Turbulent Flow**
  - Blood Flow in brain ~ $1 \times 10^2$
  - Blood flow in aorta ~ $1 \times 10^3$
  - Typical pitch in Major League Baseball ~ $2 \times 10^5$
  - Person swimming ~ $4 \times 10^6$

Turbulent Flow

Laminar Flow

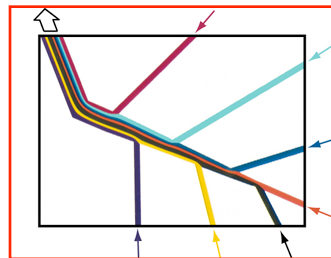| Low Speed Laminar small $Re$ | High Speed Turbulent high $Re$ |

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# Fluid Mechanics

- Microfluidics (Laminar or Turbulent?)

$$\mathrm{Re} = \frac{\rho V L}{\mu}$$

For example: $V = 1$ (mm/s), $L = 100$ $\mu$m

$$\mathrm{Re} = \frac{\rho V L}{\mu} = \frac{1000(kg/m^3) \times 10^{-3}(m/s) \times 100 \cdot 10^{-6}(m)}{0.001(kg/m \cdot s)} = 0.1$$
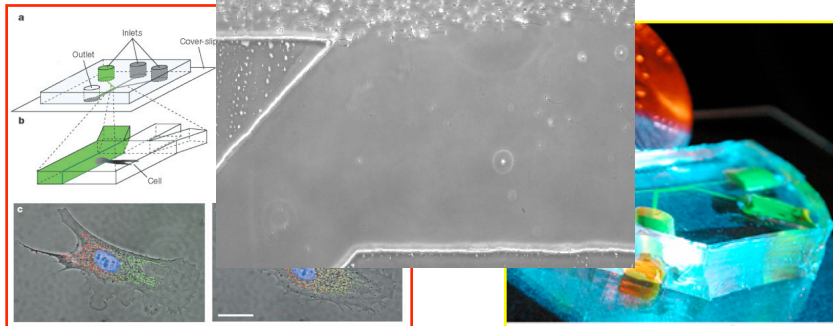
500 μm
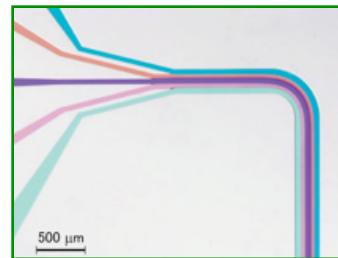
# Fluid Mechanics

- Laminar Flow in Microfluidic Channel



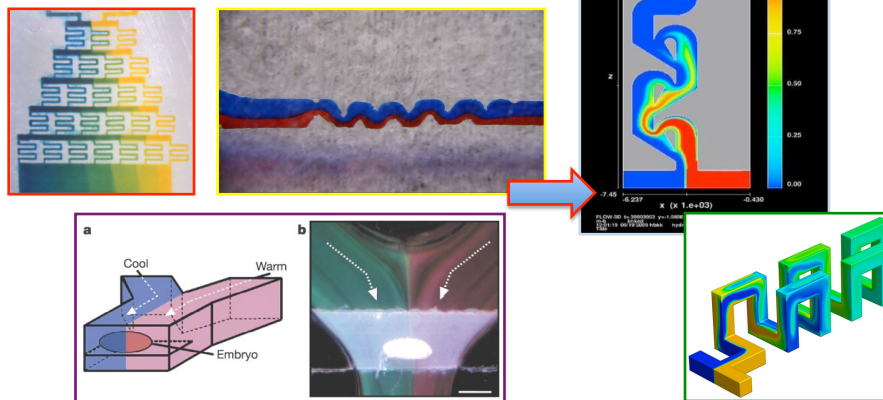Partial Treatment of ... Flows (PA...

...erm Sorter ...ar vs. Diffusion)

# Fluid Mechanics

- Limits in Microfluidic Channel



Gradients Generation – Difficult to Mix

# Fluid Mechanics

- **Reynolds Number ($Re$):**

  The ratio of inertial forces to viscous forces.

  $$\mathrm{Re} = \frac{\rho V L}{\mu}$$

- **Weber Number ($We$):**

  The ratio of inertia forces to surface tension forces.

  $$We = \frac{\rho V^2 L}{\sigma}$$

- **Bond Number ($Bo$):**

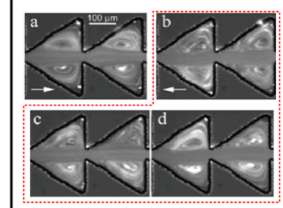  The ratio of body forces to surface tension forces.
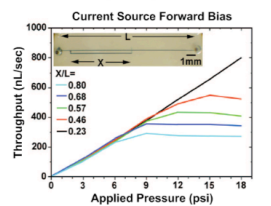
  $$Bo = \frac{\rho a L^2}{\gamma}$$
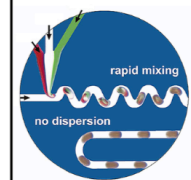
# Other Microfluidic Devices
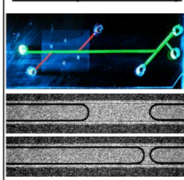
# Conclusion



Surface Tension — Electrowetting System

Laminar Flow — H-Filter: Buffer, Sample, Diffusion of small analytes, Retention of large components, Extract, Waste
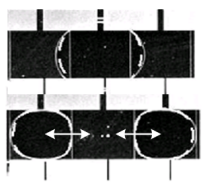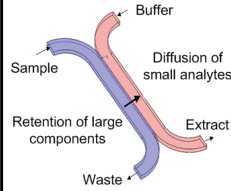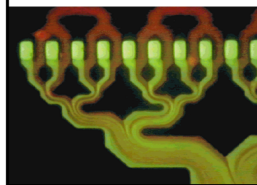
Partial Treatment of Cells: Fluid Inlets, Outlet
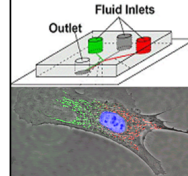
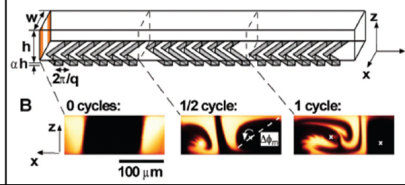Diffusion vs. Convection — Diffusion Mixer, Chaotic Mixer

# Conclusion

- Advantages and Limitations of Microfluidics
- Challenges
- Future Directions