Introduction to Microfluidics

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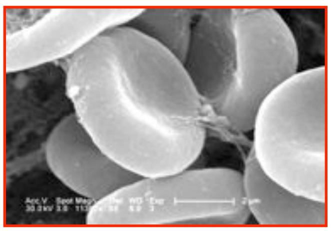
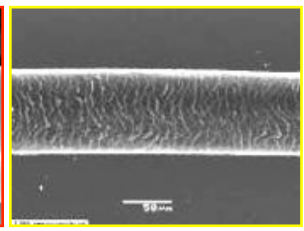
Outline

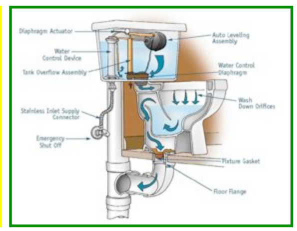
- Introduction to Microfluidics
- Basic Fluid Mechanics Concepts
- Equivalent Fluidic Circuit Model
- Conclusion

What is Microfluidics

- ***Microfluidics*** = Micro + Fluidics
- ***Micro**:* 10^{-6}
  - Small size (sub-mm)
  - Small volumes (μl, 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:

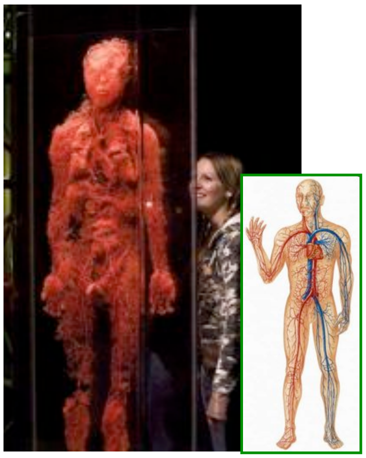
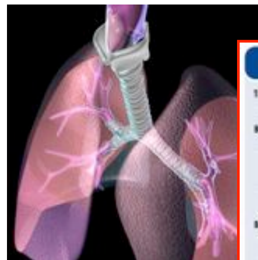
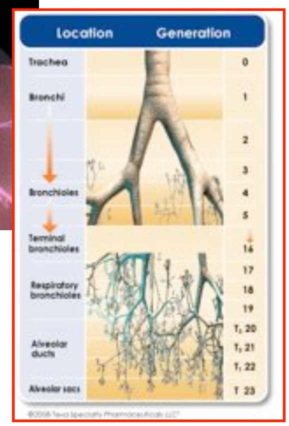
Miniaturization: Portability (Lab-on-a-Chip)

Integration: Low Costs, Batch Fabrication

Automation: Simplicity of Operation

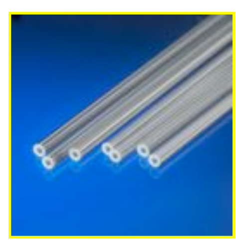
Microfluidics *in vivo*

- Circulating and Respiratory System

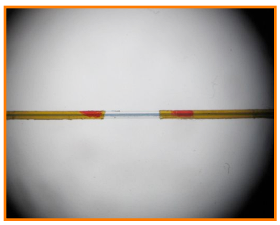
Old School Microfluidics

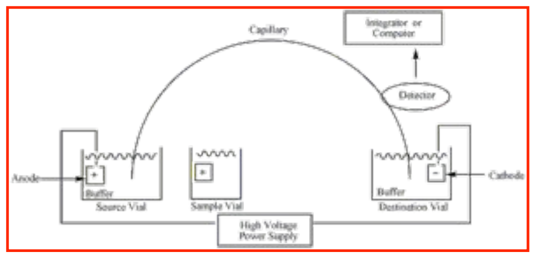
- Historical Microfluidics: Glass capillary
- Glass Capillary has been broadly exploited in labs
- Capillary Electrophoresis (CE)



Capillary Electrophoresis (CE)

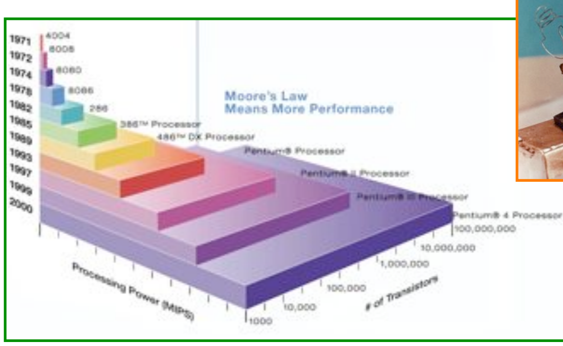
- Introduced in the 1960s, the technique of capillary electrophoresis (CE) was designed to separate species based on their size to charge ratio in the interior of a small capillary filled with an electrolyte.

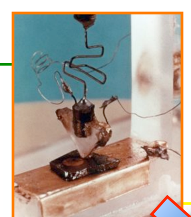


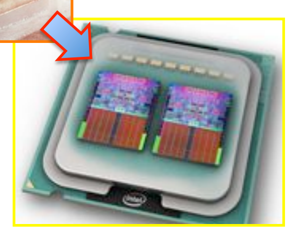


New Era of Microfluidics

- Due to the advancement of micro/nano fabrication technology, “microfluidics” has been redefined.

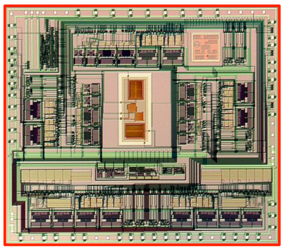
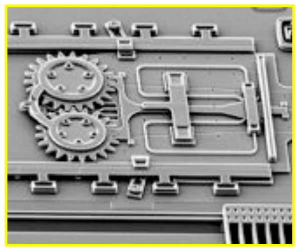
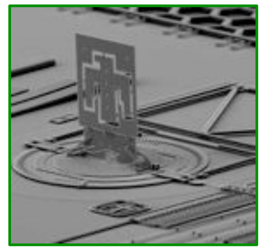




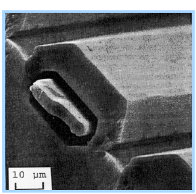


Microelectromechanical Systems

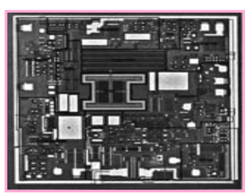
- Microelectromechanical Systems (MEMS).
- MEMS is is the integration of *mechanical elements, sensors, actuators, and electronics* on a common silicon substrate through microfabrication technology.

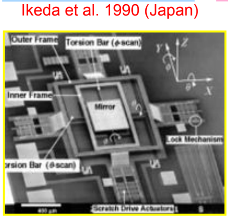




Advancement of MEMS

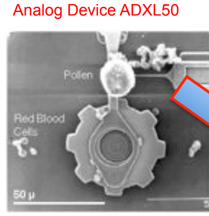


Ikeda et al. 1990 (Japan)


Analog Device ADXL50



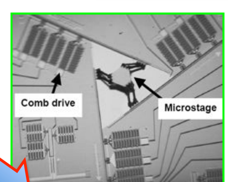
Toshiyoshi et al., 1998 (UCLA)



mems.andia.gov

Silicon-Based

Polymer



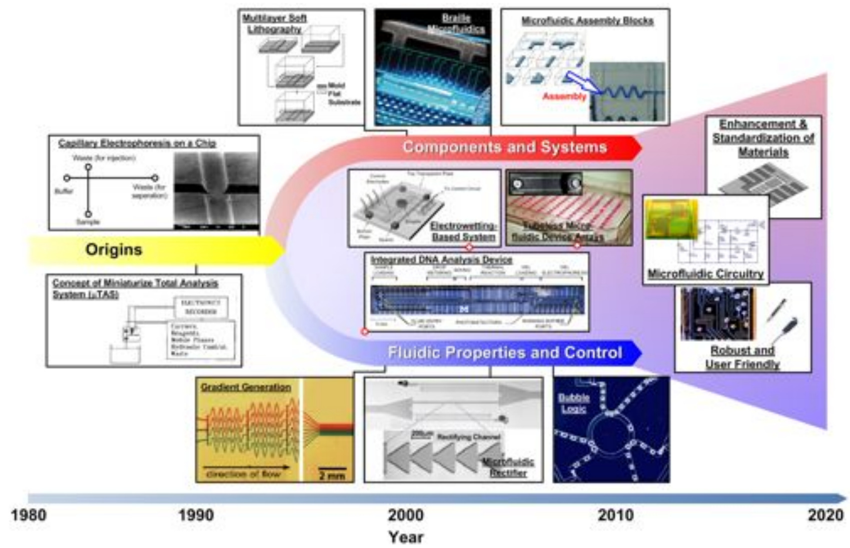
Walraven et al., 2003 (Sandia)


www.uni-ulm.de

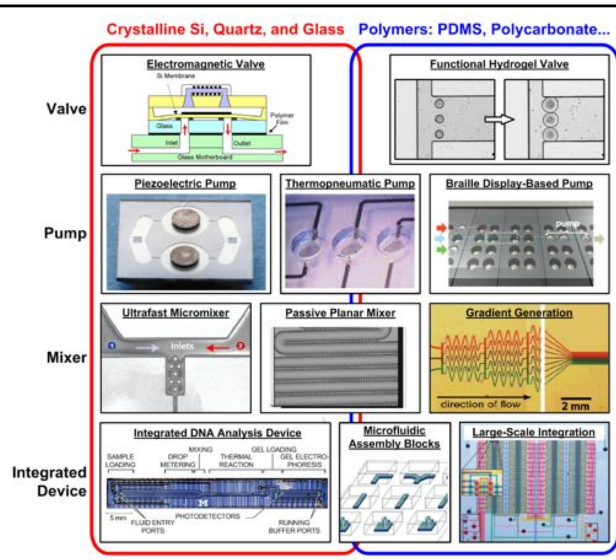

www.mic.dtu.dk


Takayama et al, 2003 (UM)

Development of Microfluidics



Materials of Microfluidic Devices

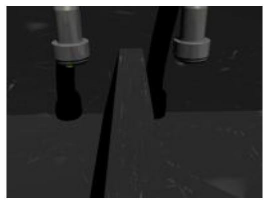


Fluid Mechanics

- **Density (ρ):**
  Density = Mass/Volume (kg/m^3)
- **Dynamic Viscosity (Viscosity, μ):**
  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.

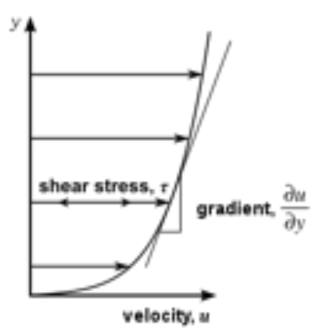


Fluid Mechanics

- **Viscosity (μ) – Newton's Theory:**

$$\tau = \mu \frac{du}{dy}$$

  where τ is Fluid Shear Stress
  where *(du/dy)* is change of fluid velocity in *y* direction
- This is a constitutive equation (a reasonable first approximation).
- **<u>Newtonian Fluids.</u>**



Fluid Mechanics

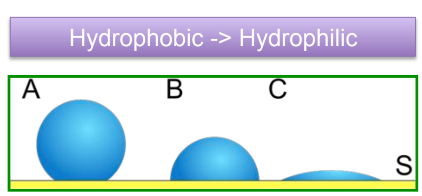
- **Viscosity (μ):**
  - Unit: kg/(m.s) = Pa.s = 10 Poise
  - Viscosity of Water at 20°C
    = 0.01002 Poise
    = 1.002 cP (centipoise)
    = 1.002 mPa.s
  - Viscosity of SAE 30 oil at 20°C
    = 2.9 Poise

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

Fluid Mechanics

- **Surface Tension (γ):**

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

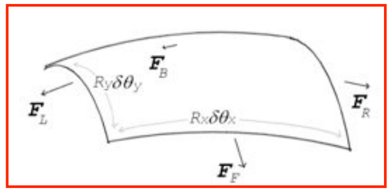


Fluid Mechanics

- **Surface Tension (γ):**

  Young-Lapalace Equation:

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



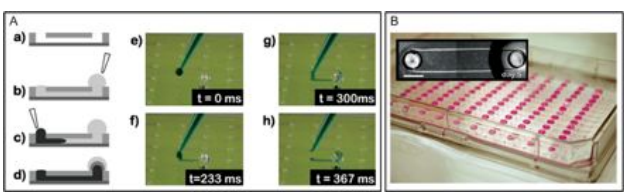
Where Δp is the pressure difference, γ is surface tension, R_x and R_y are radii of curvature in each of the axes that are parallel to the surface.

Water at 25^{o}C, γ = 71.97 (dyn/cm)

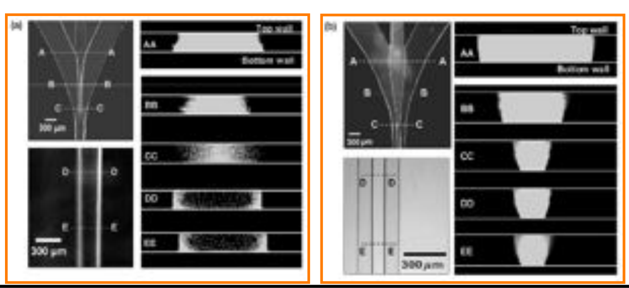
Δ*p* for water drops of different radii at STP				
Droplet radius	1 mm	0.1 mm	1 µm	10 nm
Δ*p* (atm)	0.0014	0.0144	1.436	143.6

Fluid Mechanics

- Utilize Surface Tension in Microfluidics



Surface Tension Driven Flow

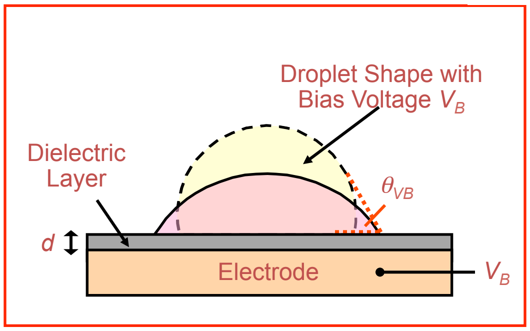


Air-Liquid Two Phase Flow

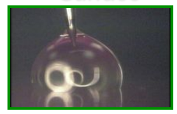
Fluid Mechanics

- Control Surface Tension in Microfluidics: Electro-Wetting

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



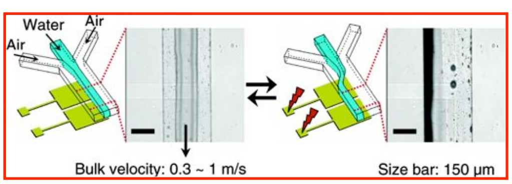
Hydrophobic Surface

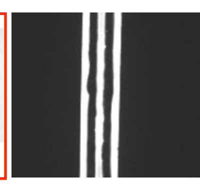


Hydrophilic Surface

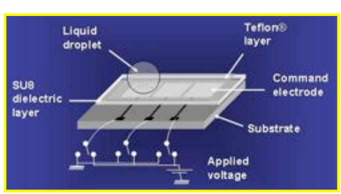
Fluid Mechanics

- Electro-Wetting Microfluidics





Switchable Surface for Air-Liquid Flow



Digital Microfluidics

Fluid Mechanics

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

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

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

  V is the mean fluid velocity (m/s)

  L is the a characteristic linear dimension (m)

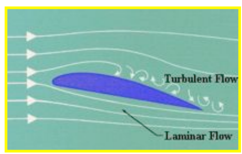
  (traveled length of fluid or hydarulic diameter etc.)

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, laminar flow occurs when *Re* < 2300, and turbulent flow occurs when *Re* > 4000.
  - In the interval between 2300 and 4000: **Transition Flow.**

Fluid Mechanics

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



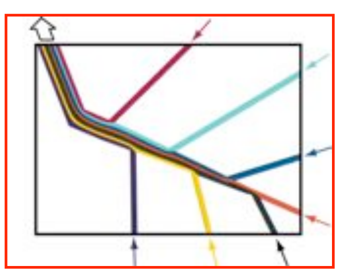
Fluid Mechanics

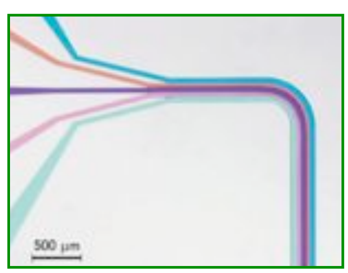
- Microfluidics (Laminar or Turbulent?)

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

For example: V = 1 (mm/s), L = 100 μm

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



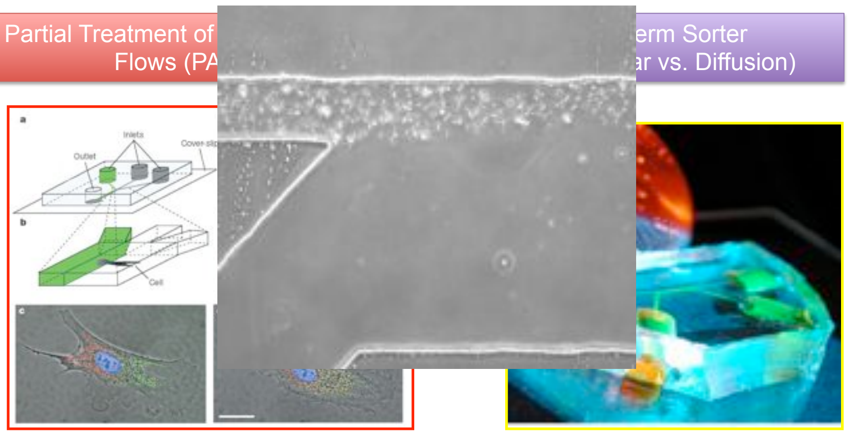


Fluid Mechanics

- Laminar Flow in Microfluidic Channel

Partial Treatment of
Flows (PA

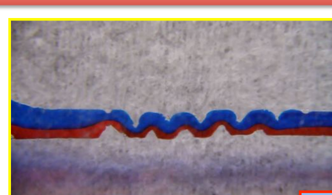
erm Sorter
ar vs. Diffusion)

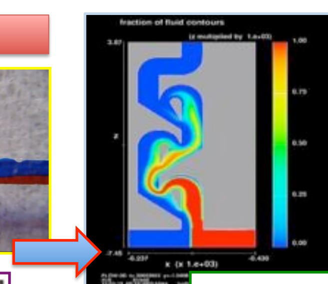


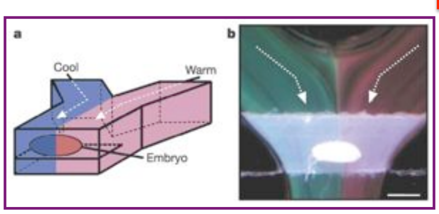
Fluid Mechanics

- 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.

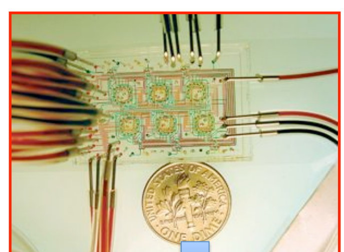
$$Bo = \frac{\rho a L^2}{\gamma}$$

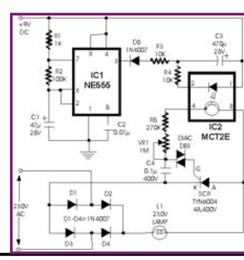
Equivalent Fluidic Circuit Model

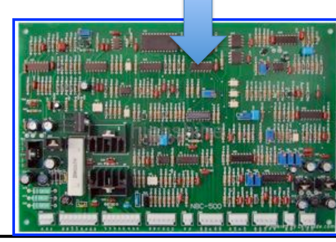
- **Equivalent Circuit Model:**

Voltage -> Pressure

Current -> Flow Rate







Equivalent Fluidic Circuit Model

- **Equivalent Circuit Model (Resistance, R):**

Analogous to electrical resistance, fluid resistance is defined as the ratio of pressure drop over flow rate,

$$R = \frac{\Delta P}{Q} \text{ in } \frac{N \cdot s}{m^5}$$

where ΔP is the pressure difference, in N/m^2, and Q is the volume flow rate, in m^3/s.

For a pipe with a rectangular cross section with width w, and depth h, and assuming both, laminar flow and Newtonian fluid, the resistance is

$$R = \frac{12\mu L}{w \cdot h^3}\left[1 - \frac{h}{w}\left(\frac{192}{\pi^5}\sum_{n=1}^{\infty}\frac{1}{n^5}\tanh\left(\frac{n\pi w}{h}\right)\right)\right]^{-1}$$

Equivalent Fluidic Circuit Model

- **Equivalent Circuit Model (Capacitance, C):**

Compliant elements of a fluidic system exhibit the fluidic equivalent of capacitance as a pressure-dependent volume change

$$C = \frac{dV}{dP} \text{ in } \frac{m^5}{N}$$

The fluidic capacitance for a square membrane can be derived by plate theory as

$$C = \frac{6a^6(1-v^2)}{\pi^4 E t^3}$$

where a is membrane width, in m, E is Young's modulus of membrane, in N/m^2, t is membrane thickness, in m, and v is Poisson's ratio of membrane (dimensionless.)

Equivalent Fluidic Circuit Model

- **Equivalent Circuit Model (Inductance, H):**

In a manner analogous to electrical inductance, fluidic systems are capable of storing kinetic energy in fluidic inductance, H (in kg/m^4)

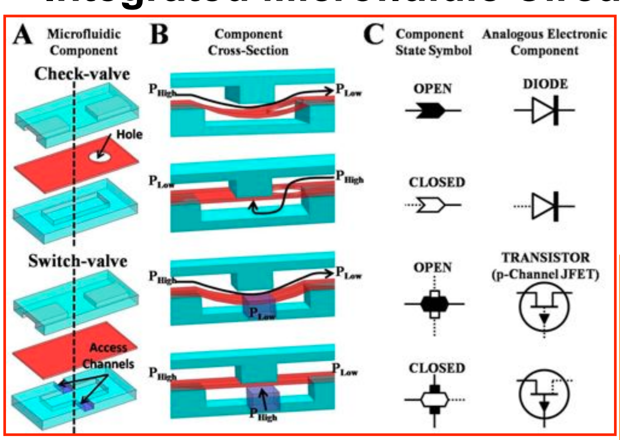
$$\Delta P = H \frac{dQ}{dt}$$

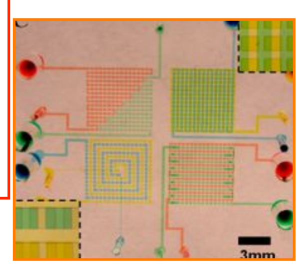
For incompressible and inert fluidics in tubes of constant cross section A, the fluidic inductance is given by

$$H = \frac{\rho L}{A}$$

Equivalent Fluidic Circuit Model

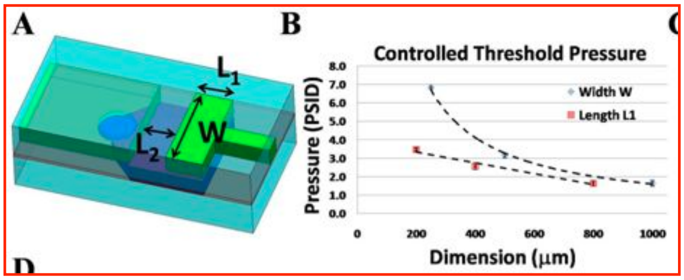
- **Integrated Microfluidic Circuitry Device:**

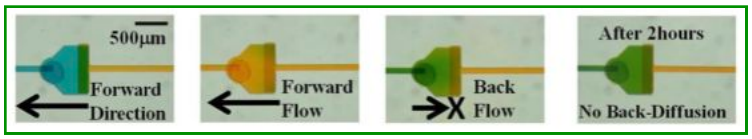




Equivalent Fluidic Circuit Model

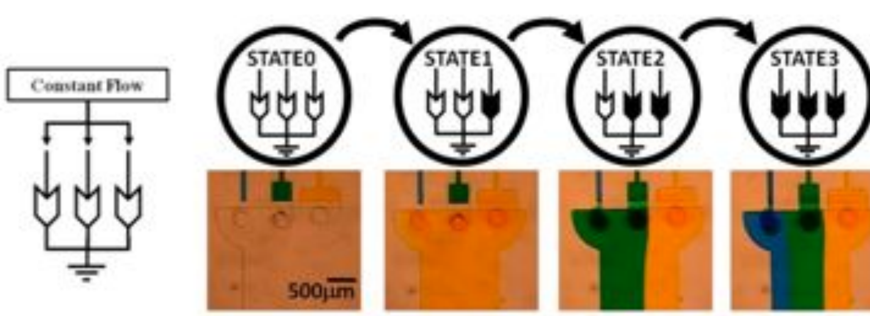
- **Integrated Microfluidic Circuitry Device:**





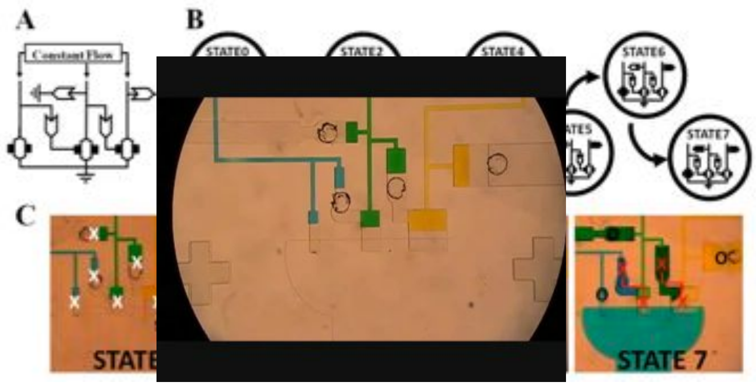
Equivalent Fluidic Circuit Model

- **Integrated Microfluidic Circuitry Device – <u>Time Release</u>**



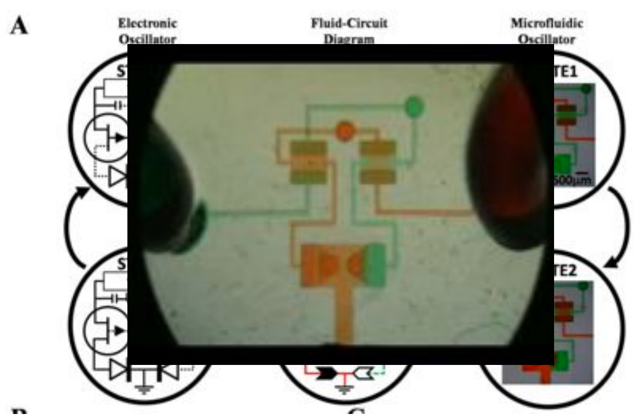
Equivalent Fluidic Circuit Model

- **Integrated Microfluidic Circuitry Device – <u>Time Switch</u>**



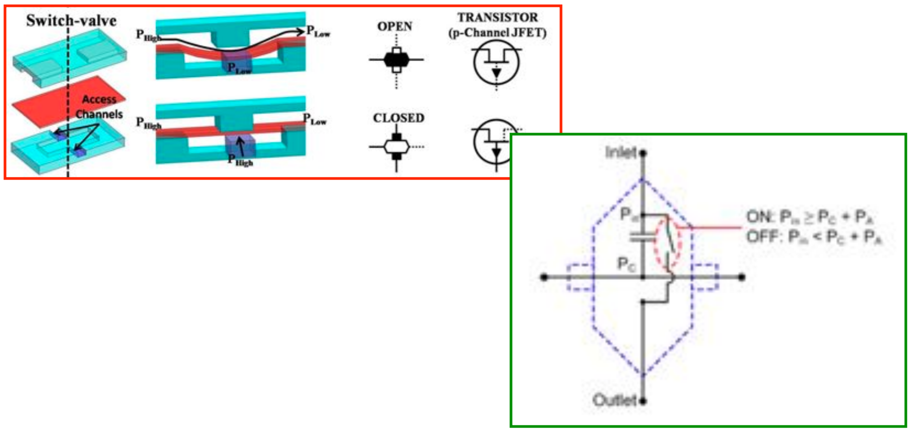
Equivalent Fluidic Circuit Model

- **Integrated Microfluidic Circuitry Device – <u>Oscillator</u>**



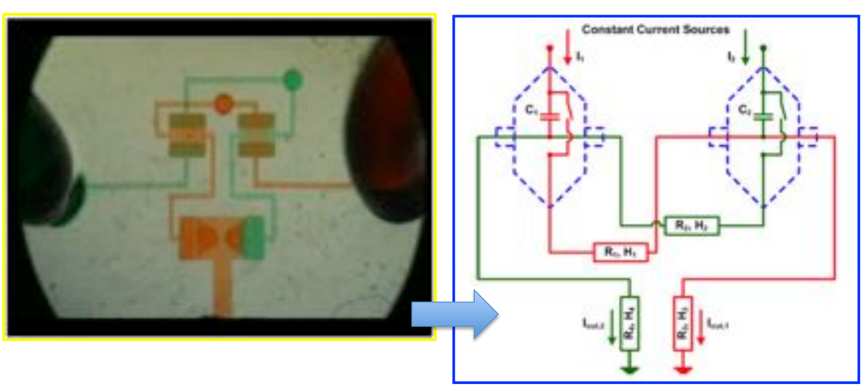
Equivalent Fluidic Circuit Model

- **Integrated Microfluidic Circuitry Device – <u>Oscillator</u>**



Equivalent Fluidic Circuit Model

- **Integrated Microfluidic Circuitry Device – <u>Oscillator</u>**



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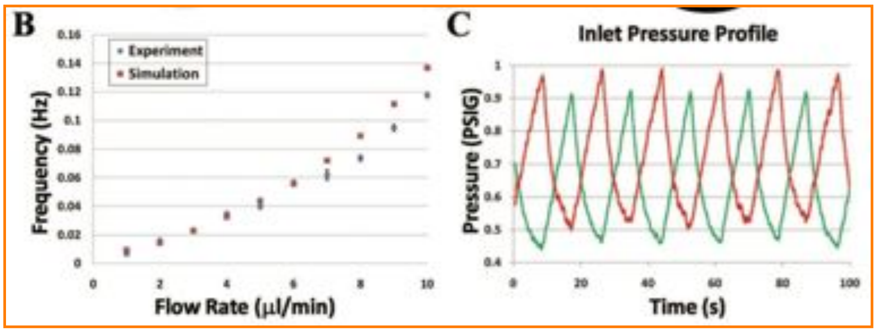

Equivalent Fluidic Circuit Model

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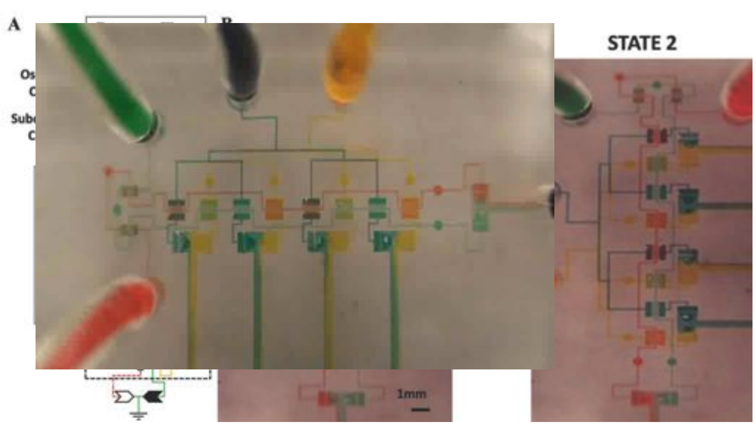
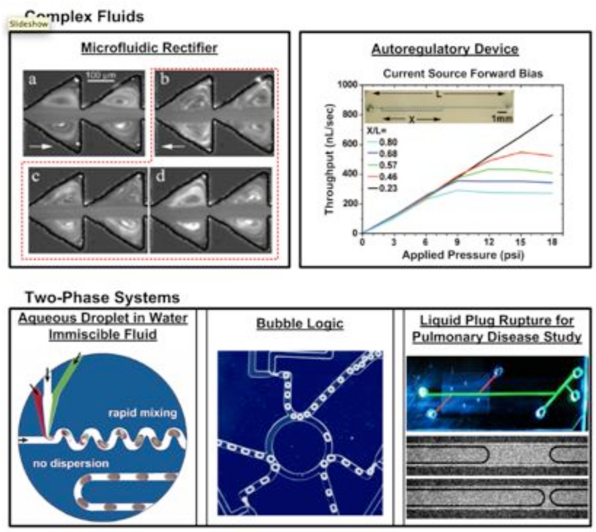
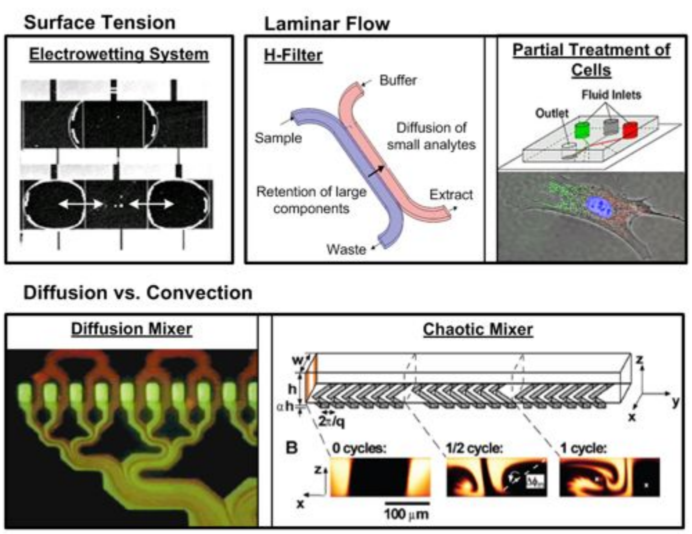


Other Microfluidic Devices



Conclusion



Conclusion

- Advantages and Limitations of Microfluidics
- Challenges
- Future Directions