



Introduction to Microfluidics

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Dr. Yi-Chung Tung



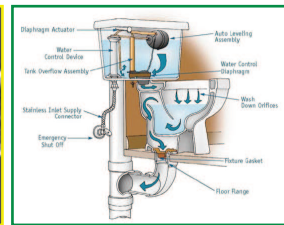
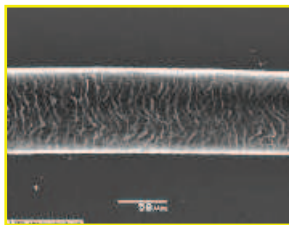
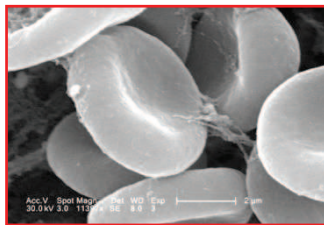
Outline

- 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 (μ 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)

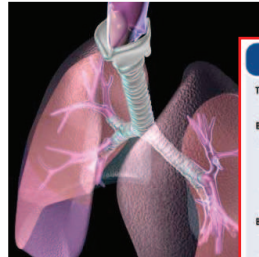
Integration: Low Costs, Batch Fabrication

Automation: Simplicity of Operation



Microfluidics *in vivo*

- Circulating and Respiratory System



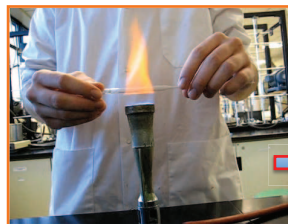
Location	Generation
Trachea	0
Bronchi	1
Bronchioles	2
Terminal bronchioles	3
Respiratory bronchioles	4
Alveolar ducts	5
Alveolar sacs	16
	17
	18
	19
	T, 20
	T, 21
	T, 22
	T, 23

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Old School Microfluidics

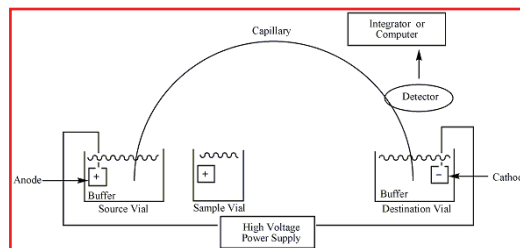
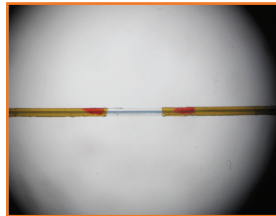
- Historical Microfluidics: Glass capillary
- Glass Capillary has been broadly exploited in labs
- Capillary Electrophoresis (CE)





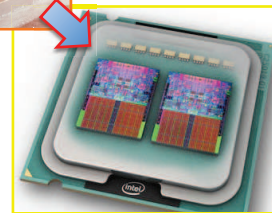
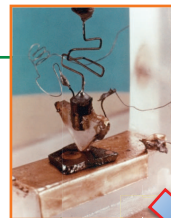
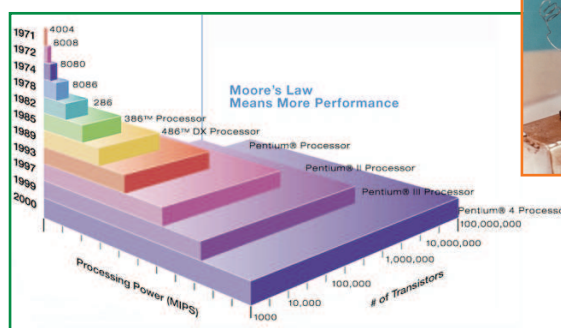
Capillary Electrophoresis (CE)

- 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

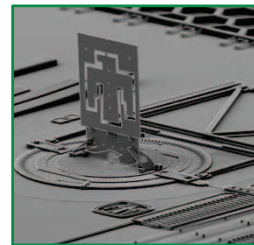
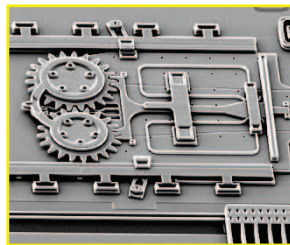
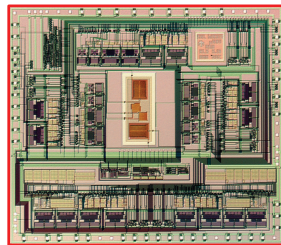
- Due to the advancement of micro/nano fabrication technology, “microfluidics” has been redefined.



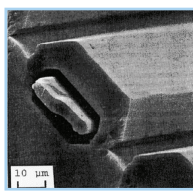


Microelectromechanical Systems

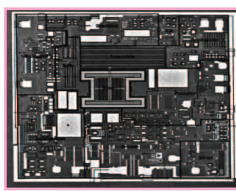
- Microelectromechanical Systems (MEMS).
- MEMS is the integration of *mechanical elements, sensors, actuators, and electronics* on a common silicon substrate through microfabrication technology.



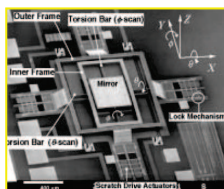
Advancement of MEMS



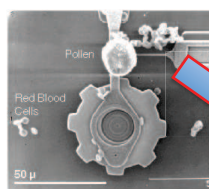
Ikeda et al. 1990 (Japan)



Analog Device ADXL50

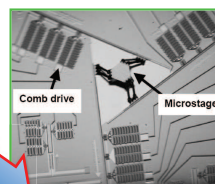


Toshiyoshi et al., 1998 (UCLA)

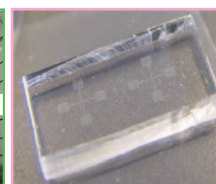


mems.sandia.gov

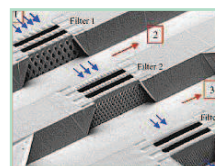
Polymer



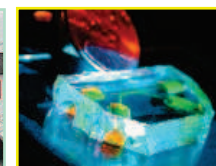
Walraven et al., 2003 (Sandia)



www.uni-ulm.de



www.mic.dtu.dk

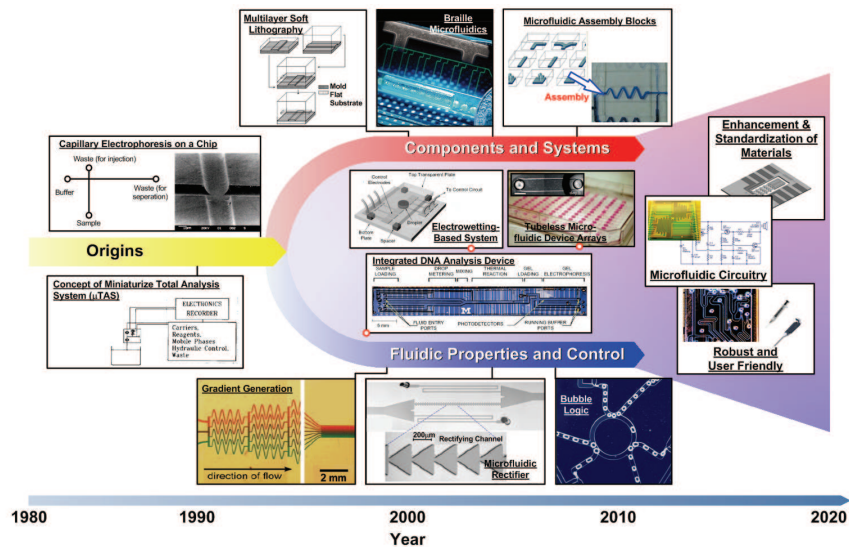


Takayama et al, 2003 (UM)

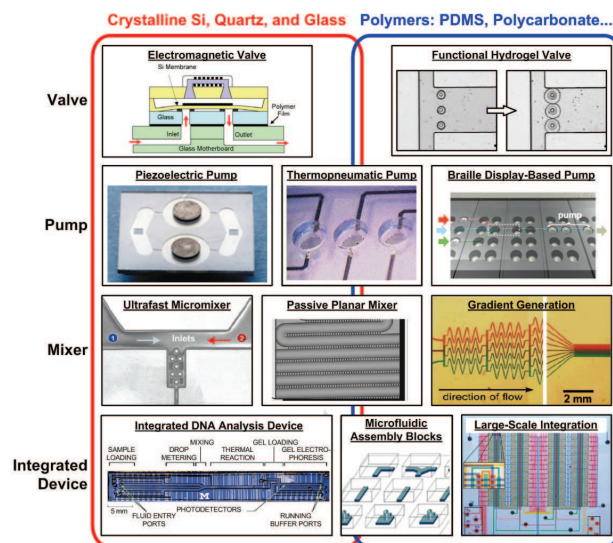
Silicon-Based



Development of Microfluidics



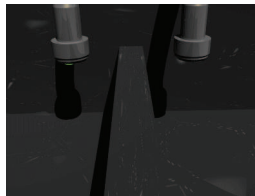
Materials of Microfluidic Devices





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 ($^{\circ}\text{C}$)	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](#).



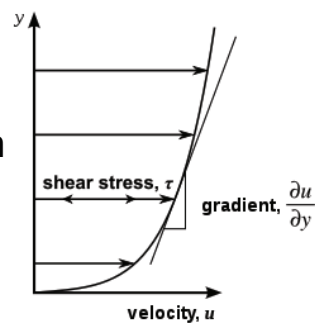
Fluid Mechanics

- **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).
- **Newtonian Fluids.**





Fluid Mechanics

- **Viscosity (η):**

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

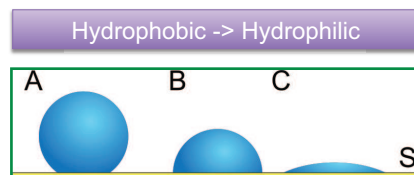
Temperature [°C]	Viscosity [mPa·s]
10	1.308
20	1.002
30	0.7978
40	0.6531
50	0.5471
60	0.4668
70	0.4044
80	0.3550
90	0.3150
100	0.2822



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).

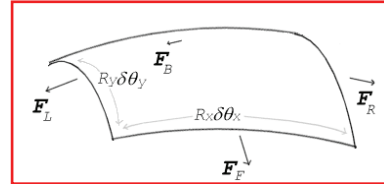




Fluid Mechanics

- **Surface Tension (γ):**
Young-Laplace 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.

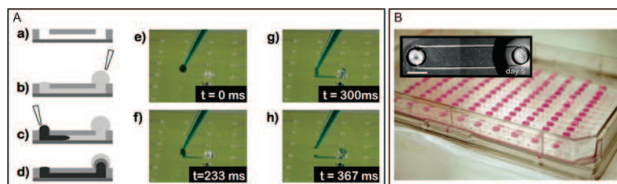
Water at 25°C, $\gamma = 71.97$ (dyn/cm)

Δp for water drops of different radii at STP				
Droplet radius	1 mm	0.1 mm	1 μ m	10 nm
Δp (atm)	0.0014	0.0144	1.436	143.6



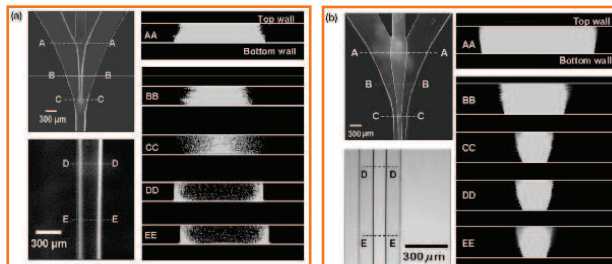
Fluid Mechanics

- **Utilize Surface Tension in Microfluidics**



Surface Tension Driven Flow

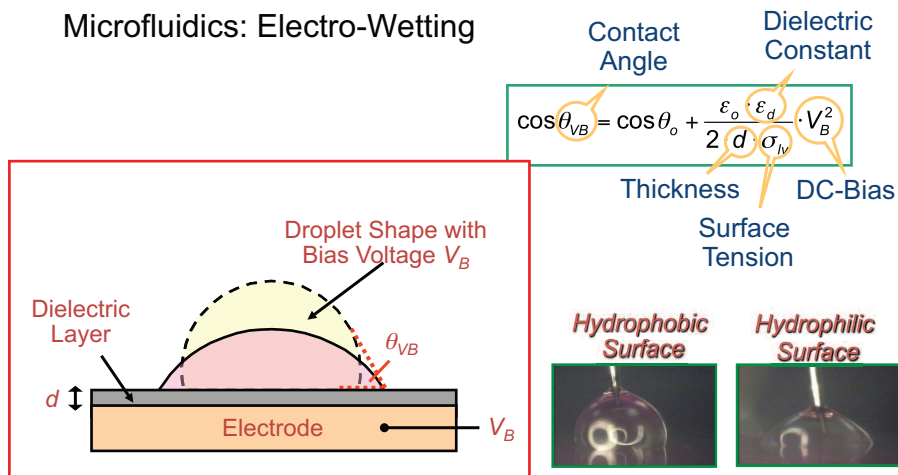
Air-Liquid Two Phase Flow





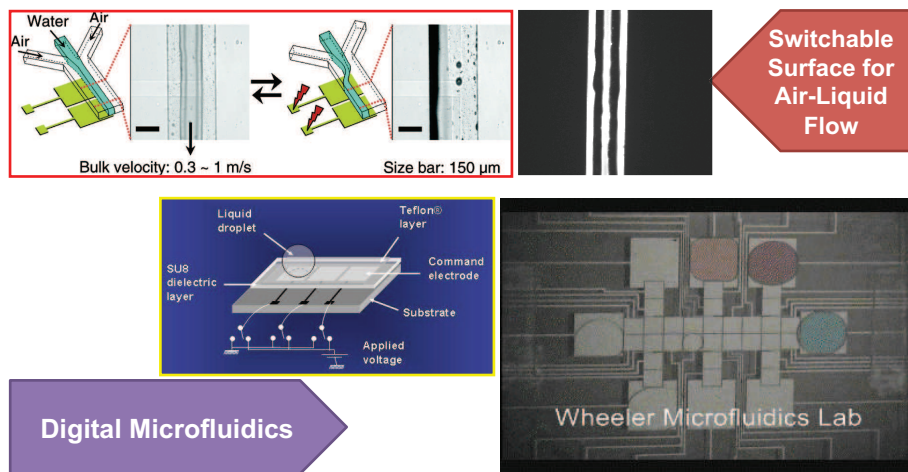
Fluid Mechanics

- Control Surface Tension in Microfluidics: Electro-Wetting



Fluid Mechanics

- Electro-Wetting Microfluidics





Fluid Mechanics

- **Reynolds Number (Re):**

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

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

V is the mean fluid velocity (m/s)

L is the a characteristic linear dimension (m)
(traveled length of fluid or hydraulic 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 $Re > 4000$.

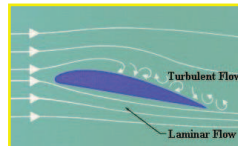
- In the interval between 2300 and 4000:
Transition Flow.



Fluid Mechanics

- **Laminar Flow vs. Turbulent Flow**

- Blood Flow in brain $\sim 1 \times 10^2$
- Blood flow in aorta $\sim 1 \times 10^3$
- Typical pitch in Major League Baseball $\sim 2 \times 10^5$
- Person swimming $\sim 4 \times 10^6$



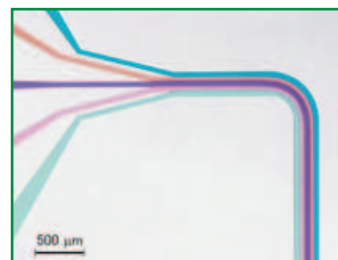
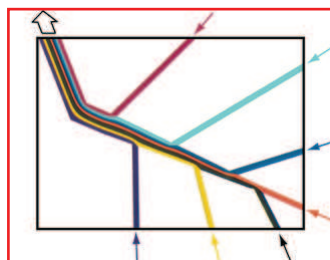
Fluid Mechanics

- **Microfluidics (Laminar or Turbulent?)**

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

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

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



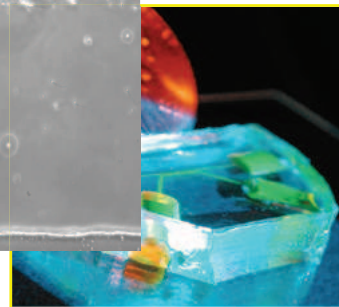
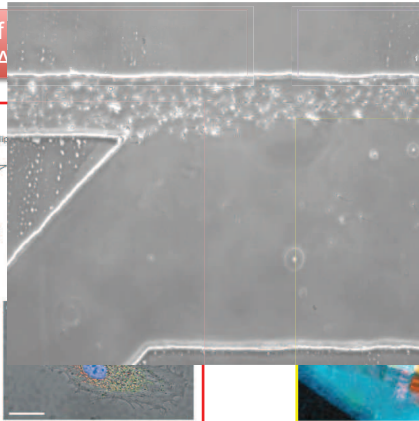
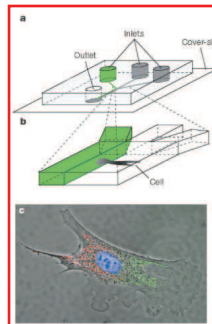


Fluid Mechanics

- Laminar Flow in Microfluidic Channel

Partial Treatment of
Flows (PA)

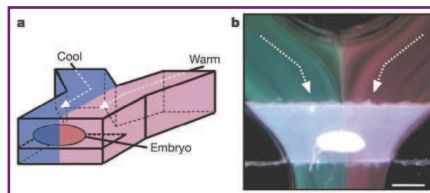
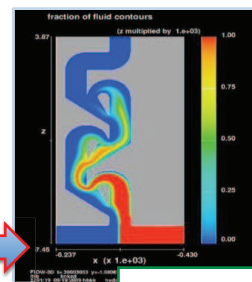
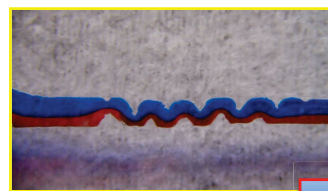
Term Sorter
ar vs. Diffusion)



Fluid Mechanics

- Limits in Microfluidic Channel

Gradients Generation – Difficult to Mix





Fluid Mechanics

- **Reynolds Number (Re):**

The ratio of inertial forces to viscous forces.

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

- **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.

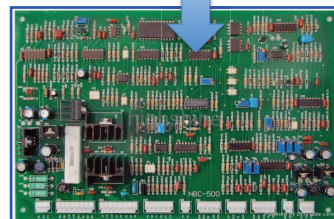
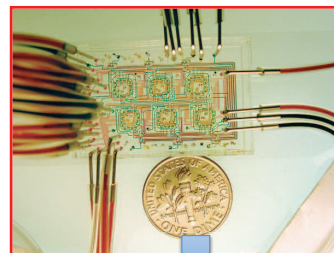
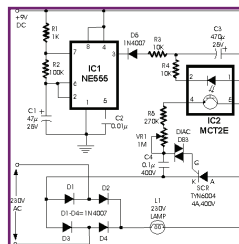
$$Bo = \frac{\rho a L^2}{\gamma}$$



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

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

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 ν 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)

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

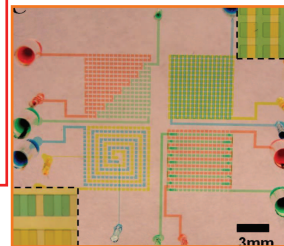
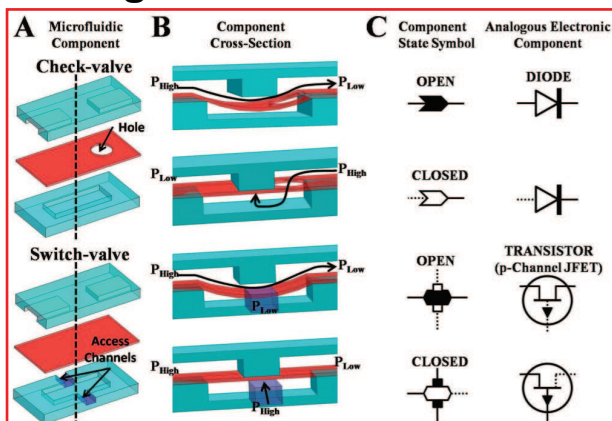
For incompressible and inert fluidics in tubes of constant cross section A , the fluidic inductance is given by

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



Equivalent Fluidic Circuit Model

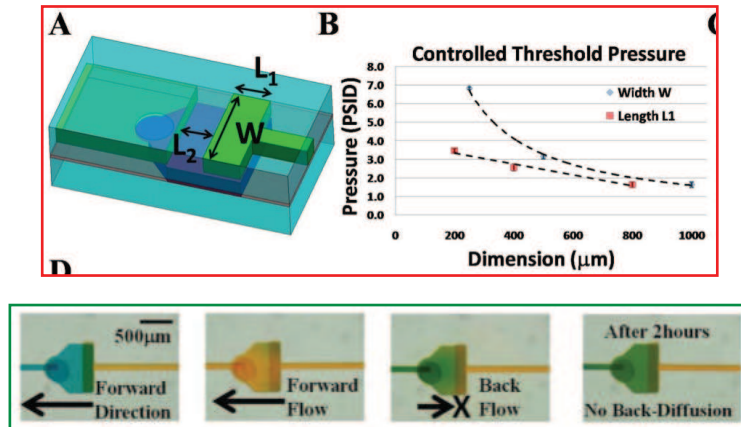
• Integrated Microfluidic Circuitry Device:





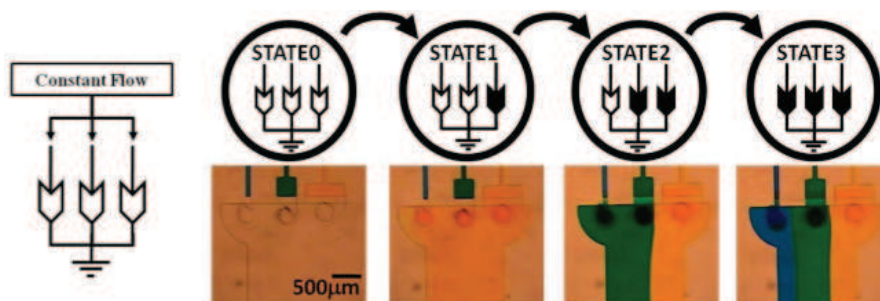
Equivalent Fluidic Circuit Model

- Integrated Microfluidic Circuitry Device:



Equivalent Fluidic Circuit Model

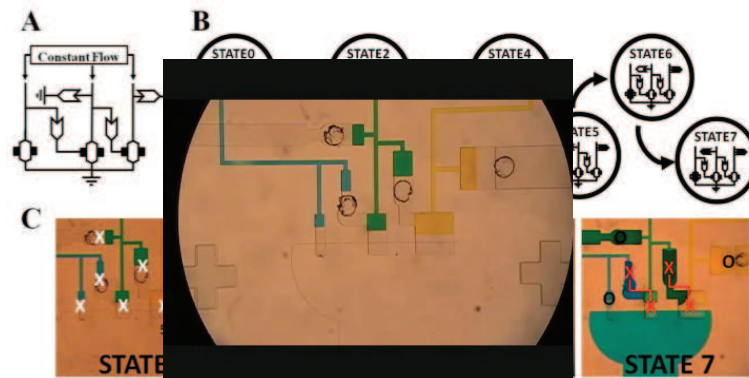
- Integrated Microfluidic Circuitry Device –
Time Release





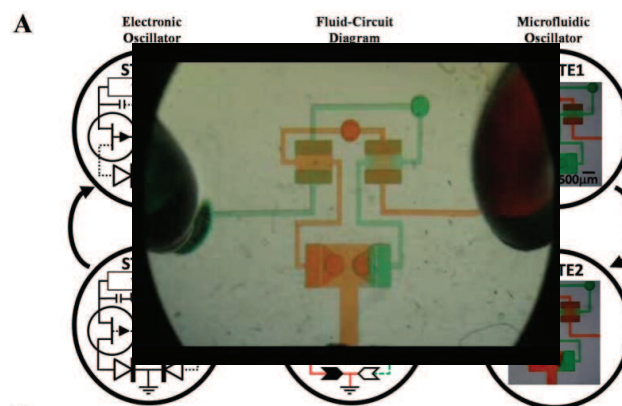
Equivalent Fluidic Circuit Model

- **Integrated Microfluidic Circuitry Device – Time Switch**



Equivalent Fluidic Circuit Model

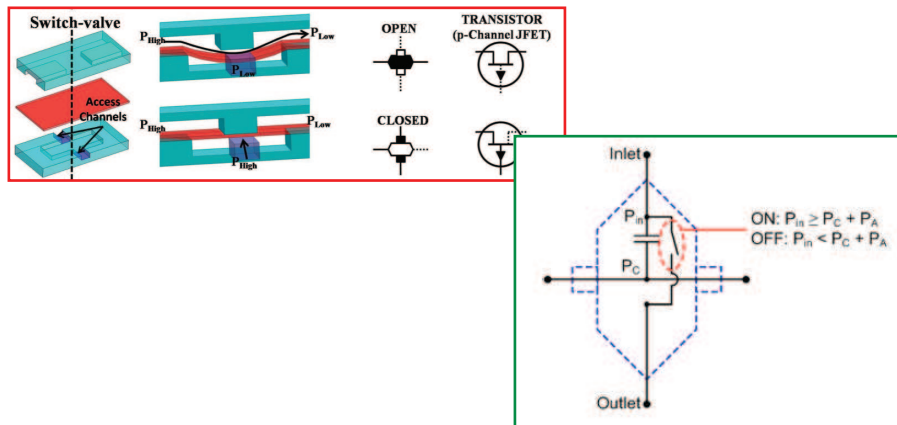
- **Integrated Microfluidic Circuitry Device – Oscillator**





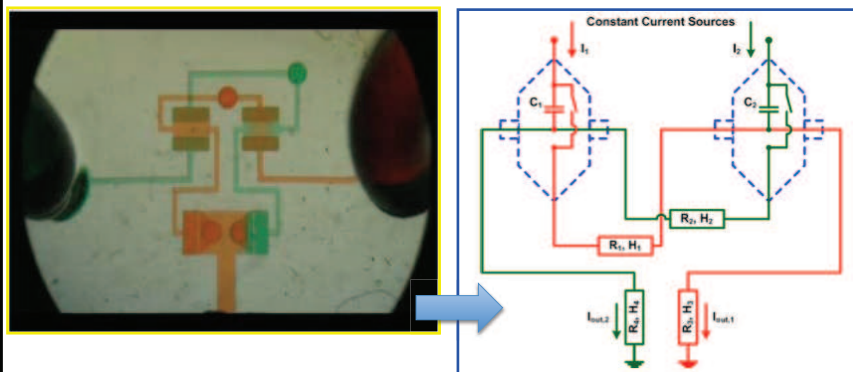
Equivalent Fluidic Circuit Model

- **Integrated Microfluidic Circuitry Device – Oscillator**



Equivalent Fluidic Circuit Model

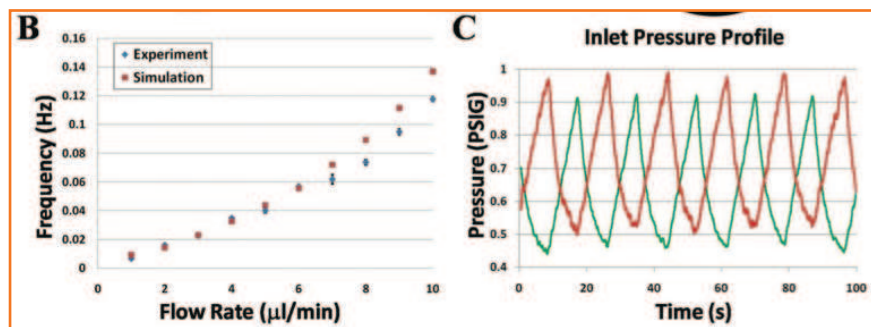
- **Integrated Microfluidic Circuitry Device – Oscillator**





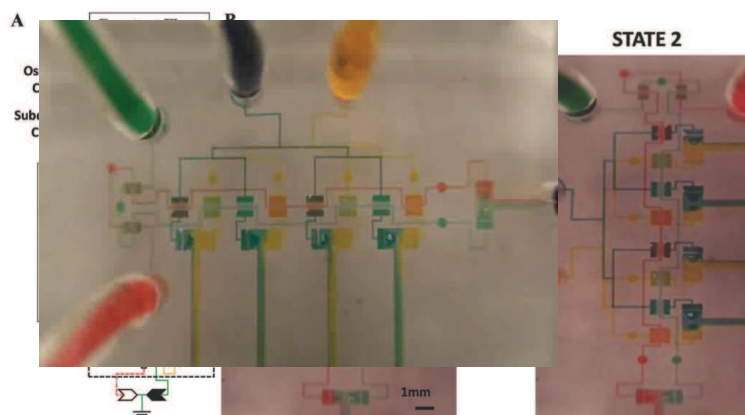
Equivalent Fluidic Circuit Model

- **Integrated Microfluidic Circuitry Device – Oscillator**



Equivalent Fluidic Circuit Model

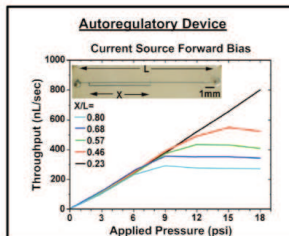
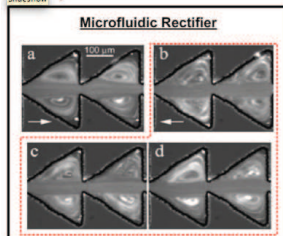
- **Integrated Microfluidic Circuitry Device – Oscillator**



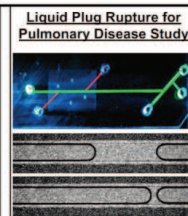
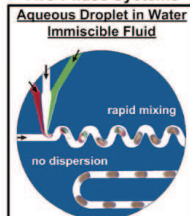


Other Microfluidic Devices

Complex Fluids

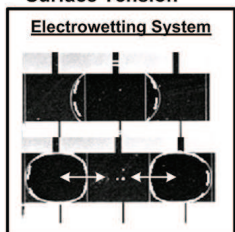


Two-Phase Systems

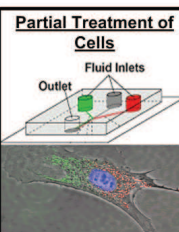
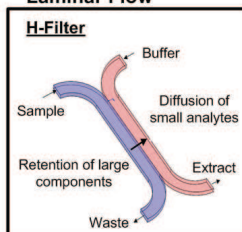


Conclusion

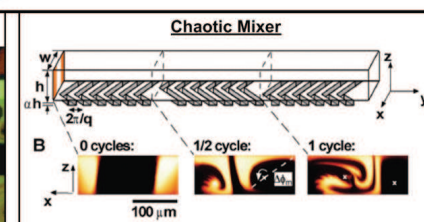
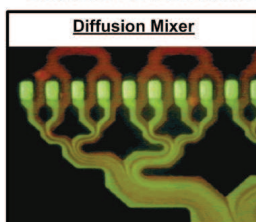
Surface Tension



Laminar Flow



Diffusion vs. Convection





Conclusion

- Advantages and Limitations of Microfluidics
- Challenges
- Future Directions

