MNT-EC
Micro Nano Technology
Education Center

Microfluidics: A Multidisciplinary Concept

HI TEC 2024
Wednesday, 31 July

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Multi-disciplinary

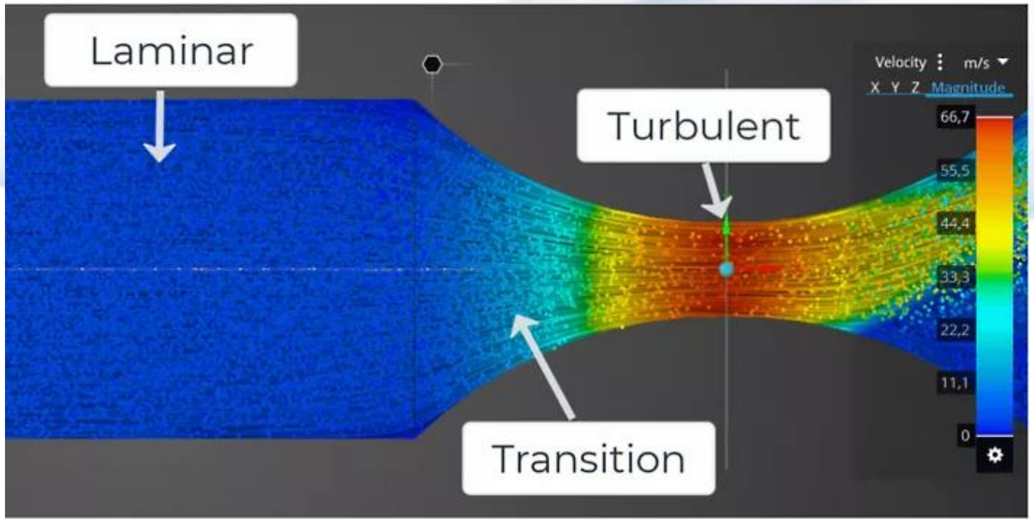
- Nuc. Physics, Chem. E, Mech. E, Elec. E, EMBA
- Scientist – Space radiation and weapon effects on electronic systems
- Executive – C and DH Systems (US and Int.)
- PI – Nano-Link NSF Nano education program
- Consultant/Advisor – Nano, biotech, space, workforce dev.

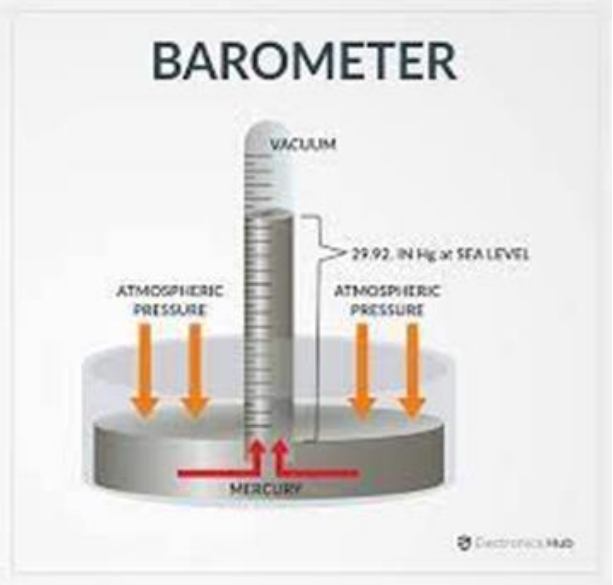
Newberry
Technology Associates™

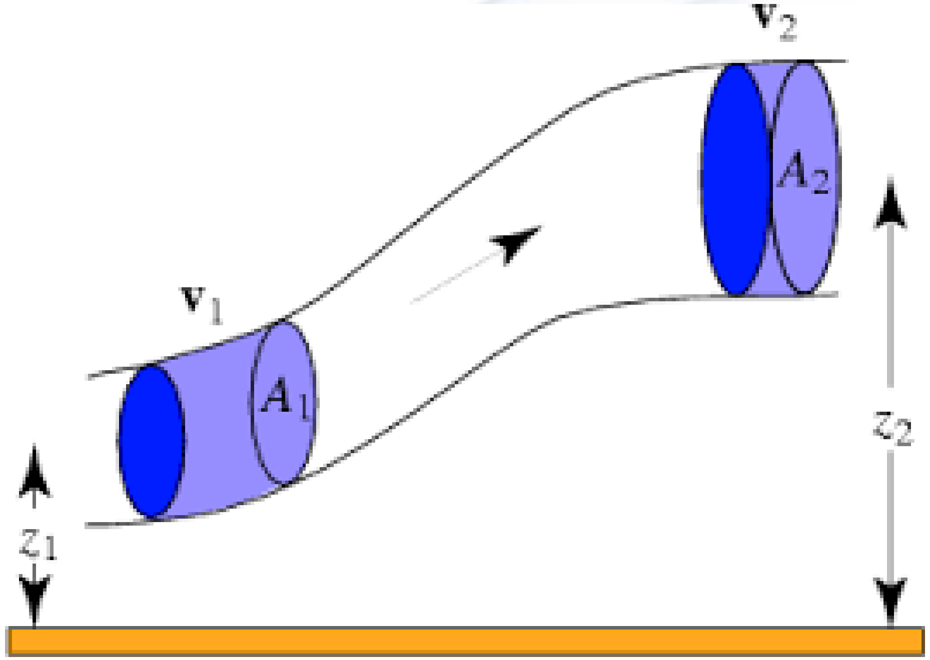
Agenda

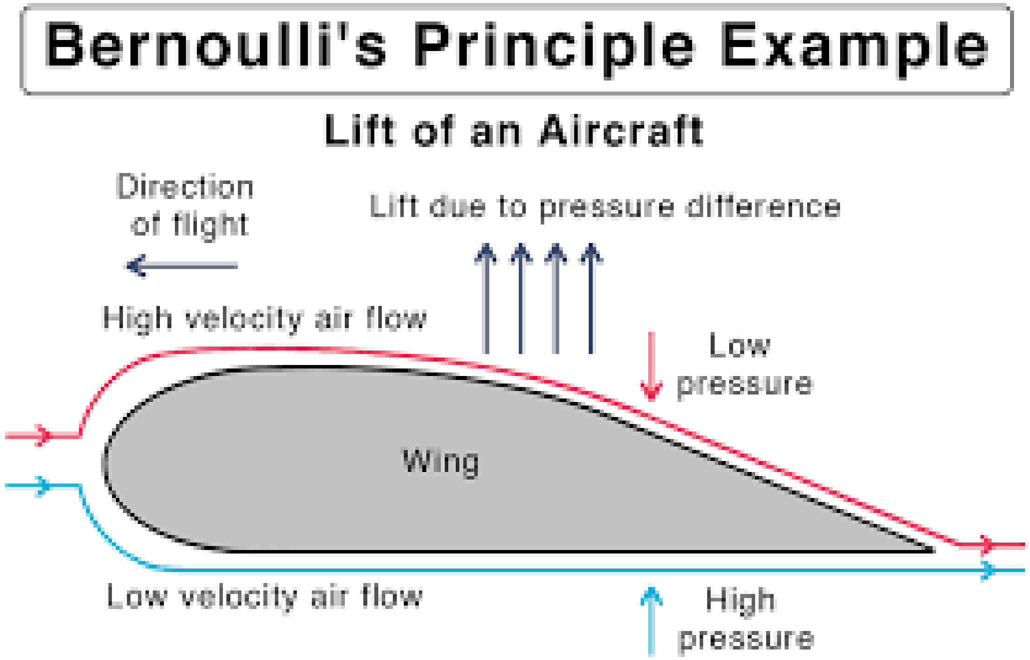
- Fluid flow we all know and love
- Why go smaller?
- We aren’t in Kansas anymore (pun intended)
- Fun with equations
- Applications of microfluidics
- An activity
- Thank you

When you think of Fluidics…

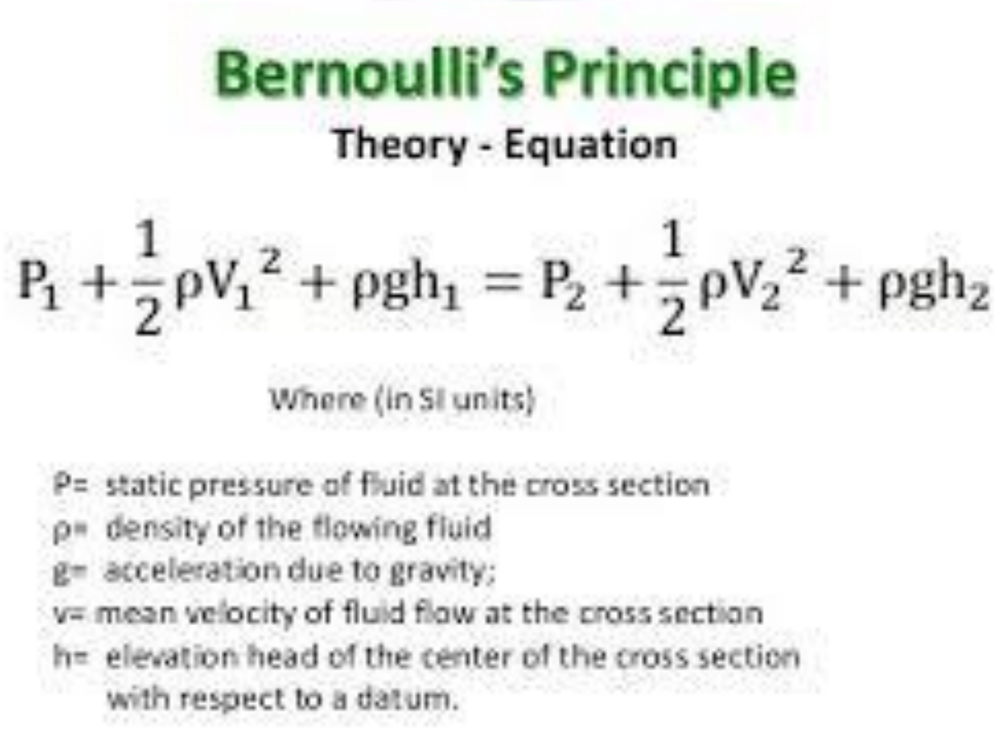





$\mathbf{v}_2$
A_2
$\mathbf{v}_1$
A_1
z_2
z_1


Bernoulli's Principle Example
Lift of an Aircraft
Direction of flight
Lift due to pressure difference
High velocity air flow
Low pressure
Wing
Low velocity air flow
High pressure

Bernoulli's principle is a key concept in fluid dynamics that relates pressure, speed and height. Bernoulli's principle states that an increase in the speed of a parcel of fluid occurs simultaneously with a decrease in either the pressure or the height above a datum.



Bernoulli's Principle

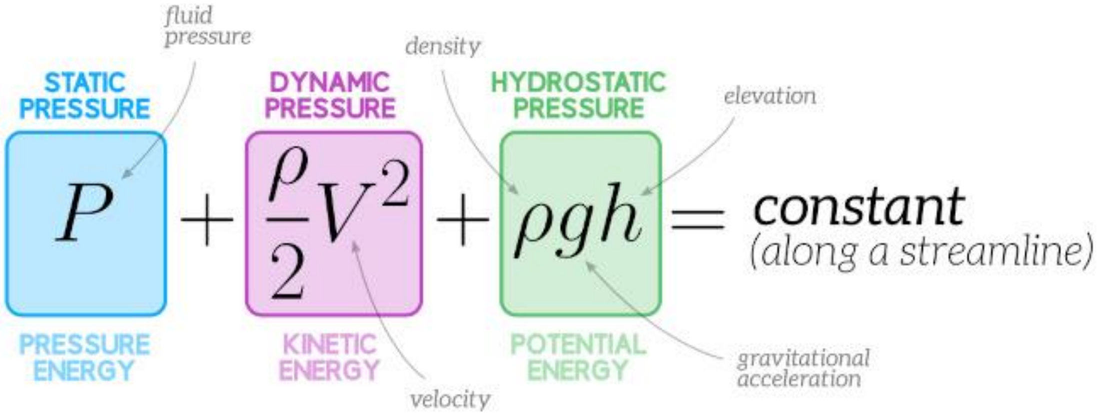
Theory - Equation

$$P_1 + \frac{1}{2}\rho V_1^{\,2} + \rho g h_1 = P_2 + \frac{1}{2}\rho V_2^{\,2} + \rho g h_2$$

Where (in SI units)

P= static pressure of fluid at the cross section
ρ= density of the flowing fluid
g= acceleration due to gravity;
v= mean velocity of fluid flow at the cross section
h= elevation head of the center of the cross section with respect to a datum.

Conservation of Energy



$$P + \frac{\rho}{2}V^2 + \rho g h = \text{constant}$$

(along a streamline)

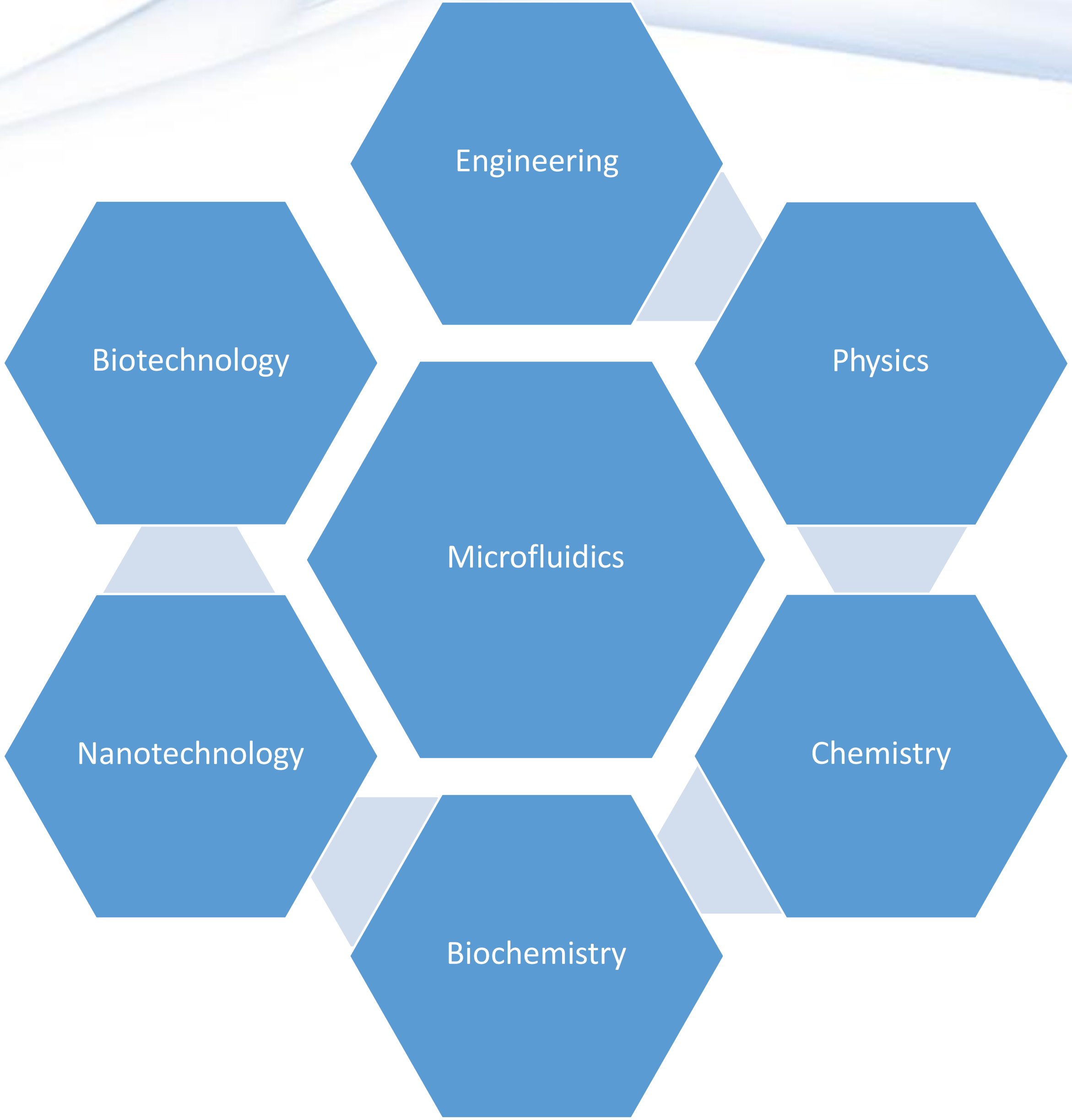
Motivation for Miniaturization

- Micro scale = laminar flow
- Laminar flow allows controlled mixing
- Low thermal mass
- Efficient mass transport (speedy diffusion)
- Good (large) ratio of channel surface area: channel volume
- Single cell and molecule manipulations
- Protection against contamination and evaporation
- Kinetics easy to study

Benefits of size reduction

1. Decreased reagent consumption
2. Small economic footprint
3. Rapid heat transfer and catalysis
4. Fast diffusive mixing
5. Automation and integration
6. **Faster result determination**
    - **Point of care**
    - **Home detection**
    - **Water assessment**
    - **Agriculture health**

Microfluidics Impact



Engineering

Biotechnology

Physics

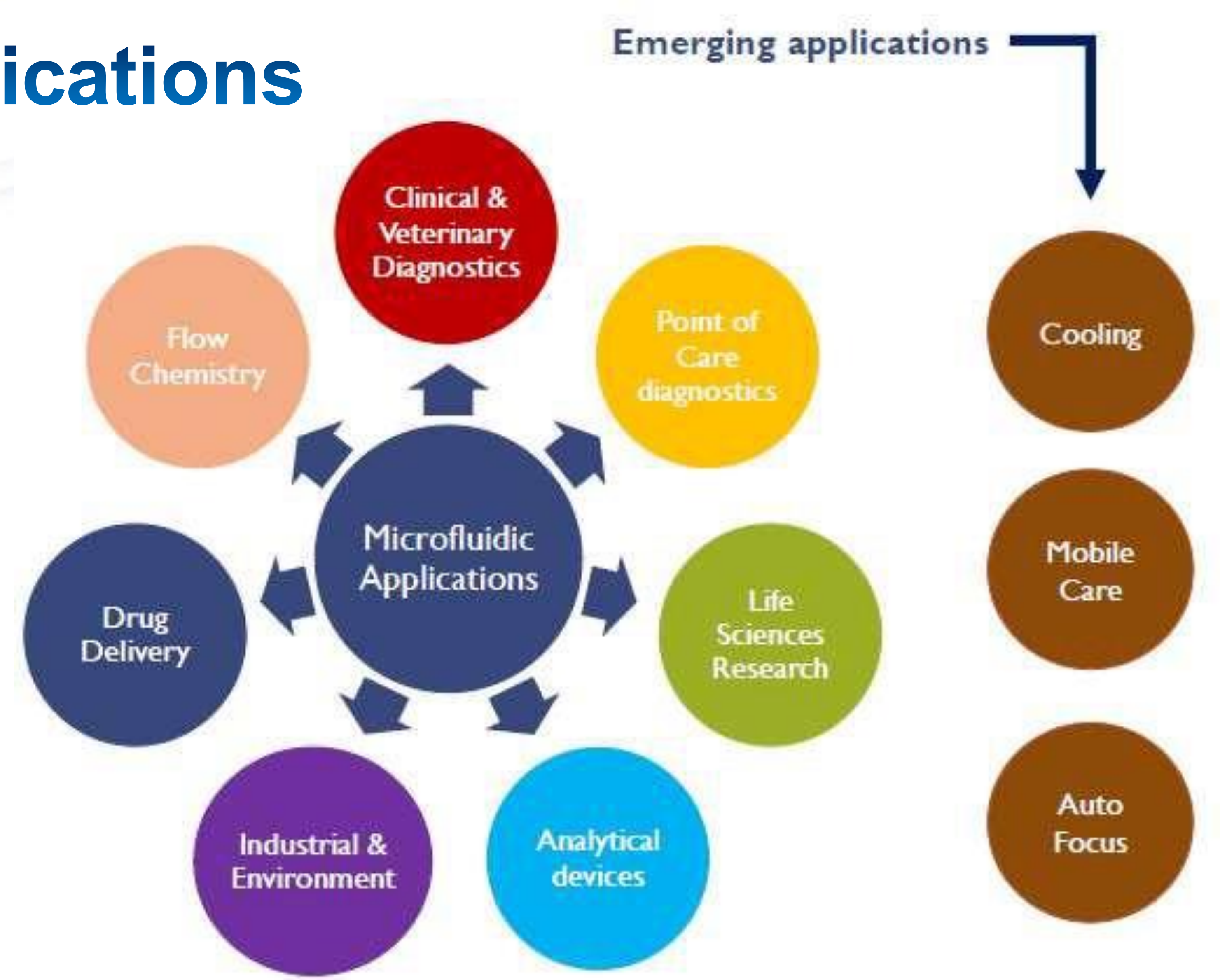
Microfluidics

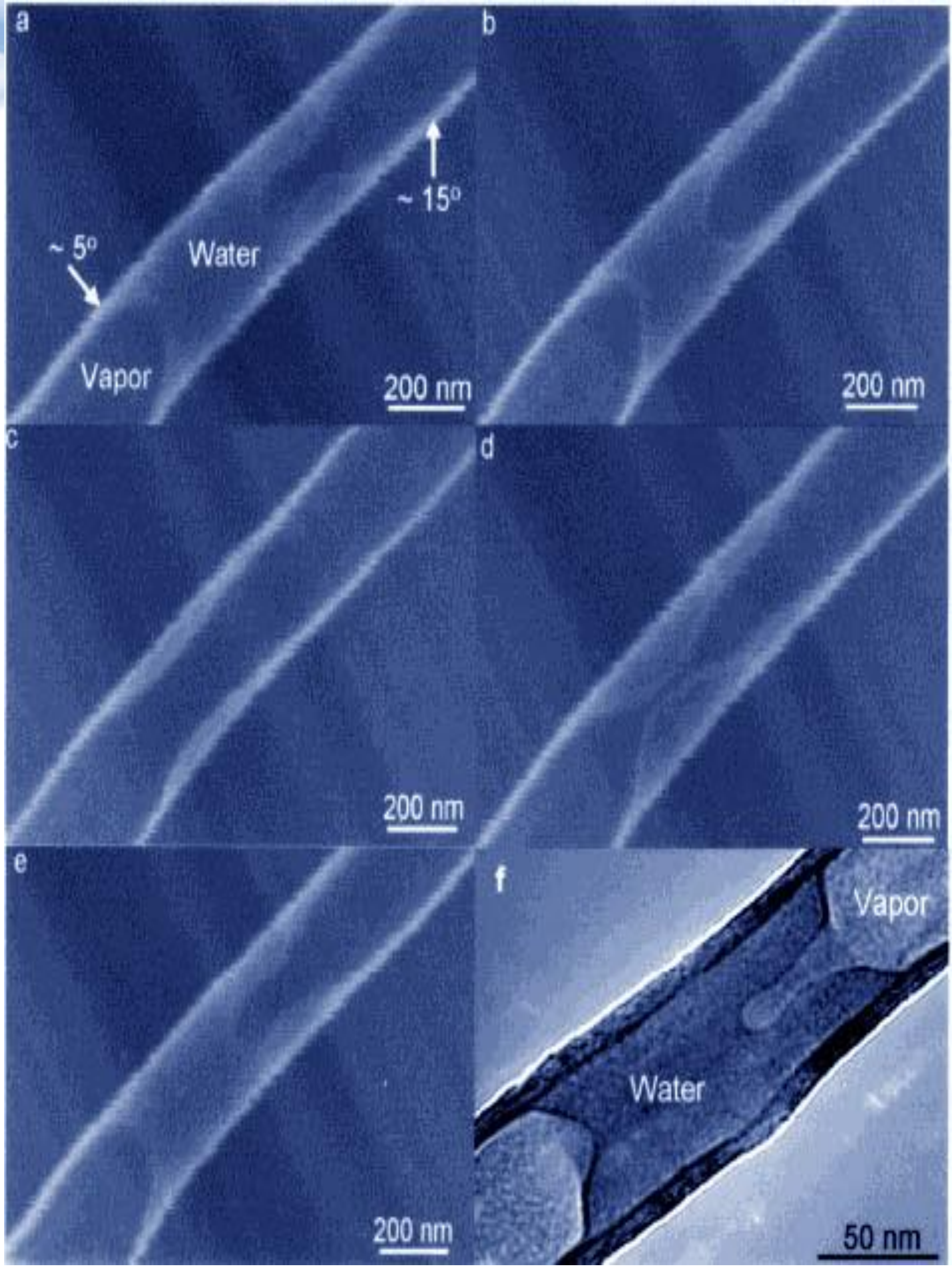
Nanotechnology

Chemistry

Biochemistry

Microfluidic Applications



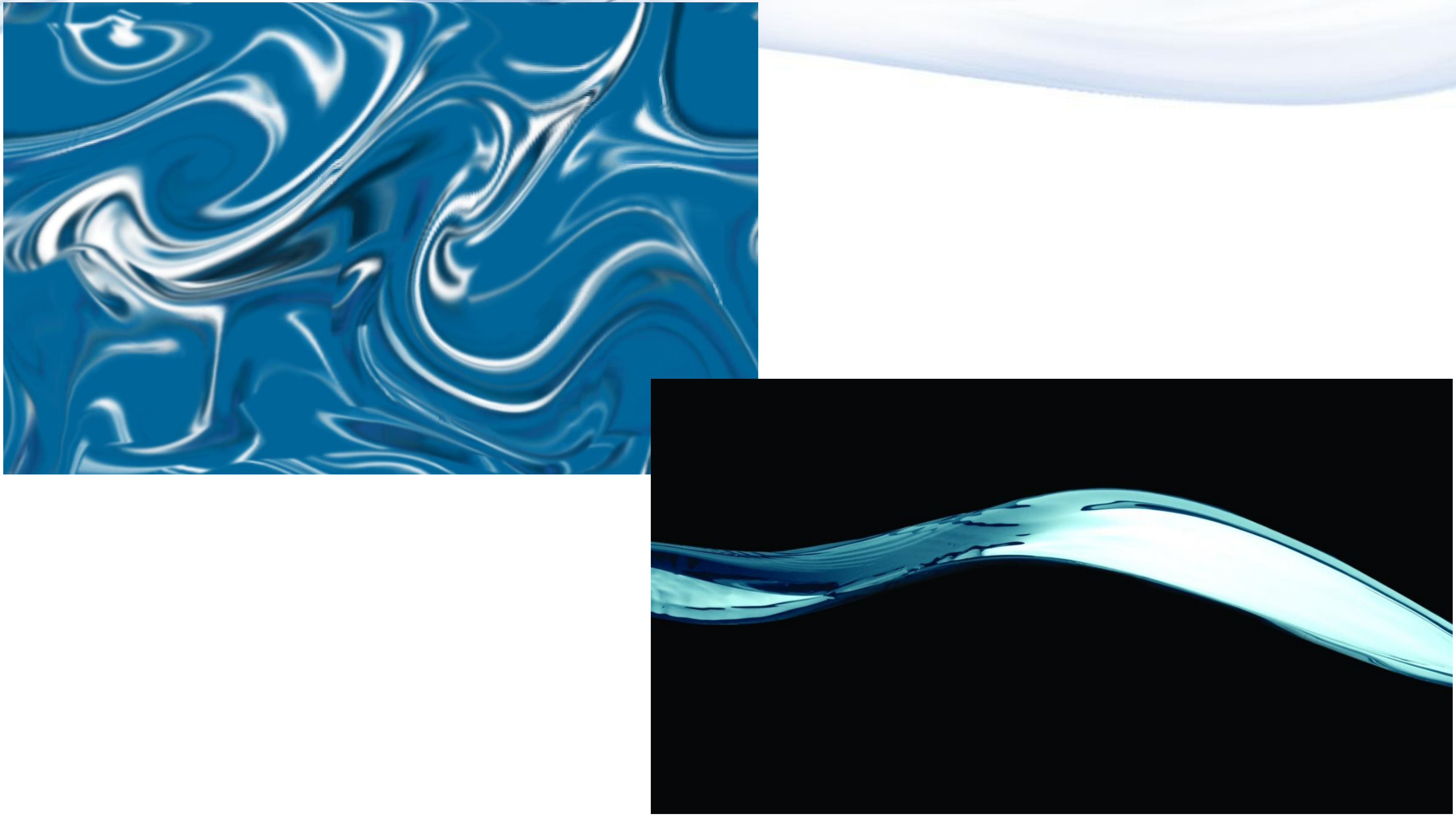


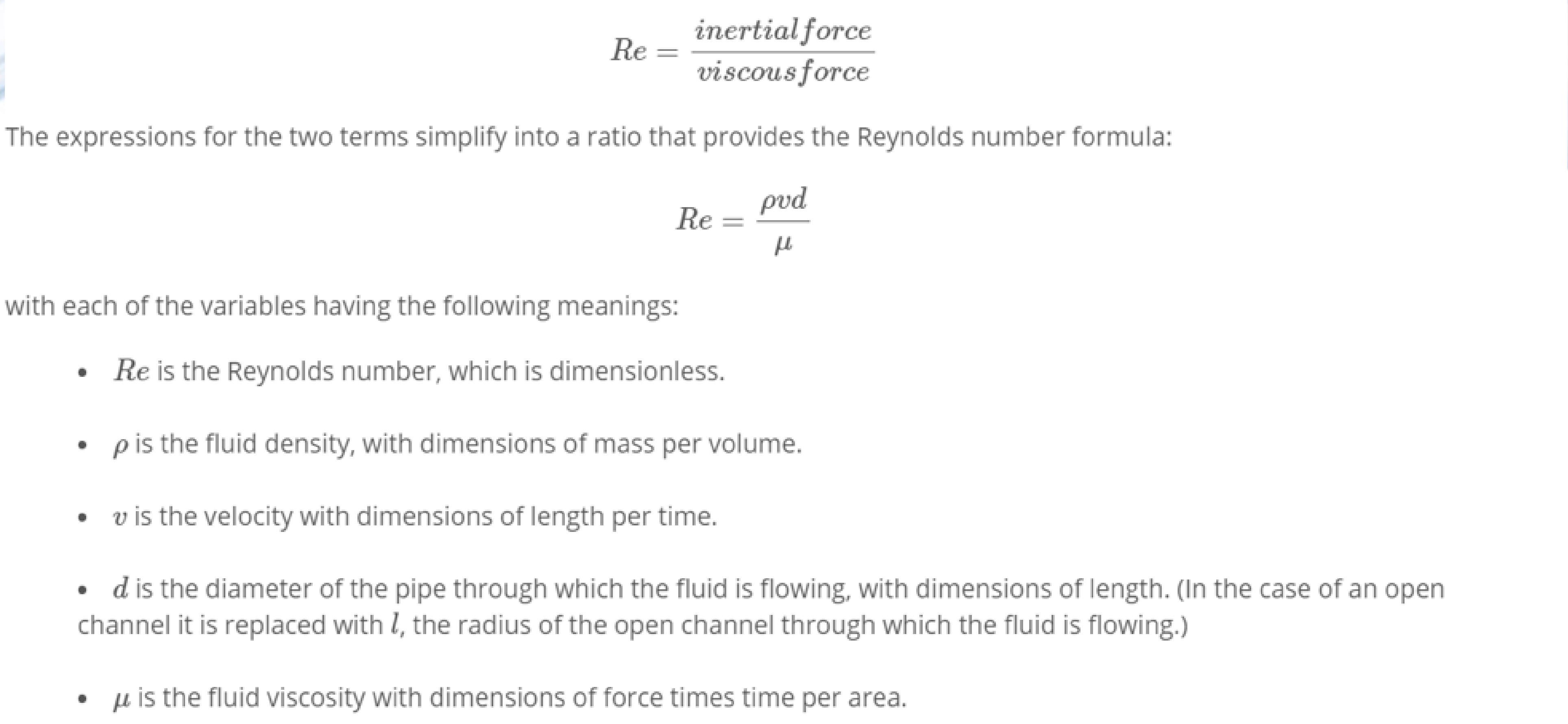
Water in Nanotube
Source: Yury Gogotsi

References:
Environmental Scanning Electron Microscopy Study of Water in Carbon Nanopipes M. Pía Rossi, Haihui Ye, Yury Gogotsi, Sundar Babu, Patrick Ndungu, and Jean-Claude Bradley *Nano Lett.*; 2004; ASAP Web Release Date: 15-Apr-2004; (Letter) DOI: 10.1021/nl049688u

Description:
The ability of the Environmental Scanning Electron Microscope (ESEM) to condense and evaporate liquids has enabled the in situ dynamic study of condensation, evaporation and transport of water inside carbon nanotubes. It has been possible to see liquid menisci inside straight, CVD-fabricated carbon nanotubes (CNTs) having disordered walls. From the measured contact angles, it is clear that these CNTs are hydrophilic. Complex meniscus shapes and slow liquid dynamics due to water confinement and strong interaction with tube walls have been observed.

The above ESEM images show the dynamic behavior of a water plug close to the open end of a nanotube. The meniscus shape changes when, at a constant stage temperature, the vapor pressure of water in the chamber is changed (a) 5.5 Torr, (b) 5.8 Torr, (c) 6.0 Torr, (d) 5.8 Torr and (e) 5.7 Torr, where the meniscus returns to the shape seen in (a). The asymmetrical shape of the meniscus, especially the complex shape of the meniscus on the right side in (a, e), is a result of the difference in the vapor pressure caused by the open left end and closed right end of the tube. (f) TEM image showing a similar plug shape in a closed CNT under pressure.





$$Re = \frac{inertial\,force}{viscous\,force}$$

The expressions for the two terms simplify into a ratio that provides the Reynolds number formula:

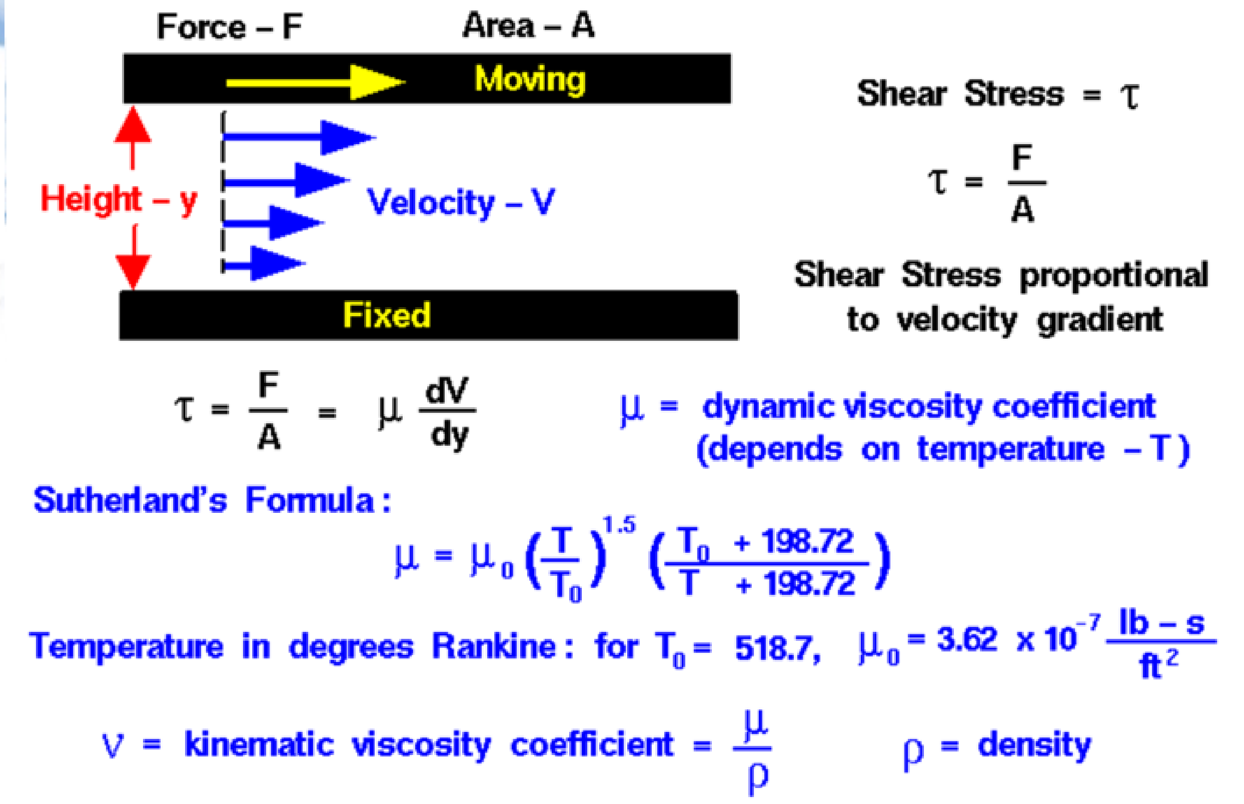
$$Re = \frac{\rho v d}{\mu}$$

with each of the variables having the following meanings:

- Re is the Reynolds number, which is dimensionless.
- ρ is the fluid density, with dimensions of mass per volume.
- v is the velocity with dimensions of length per time.
- d is the diameter of the pipe through which the fluid is flowing, with dimensions of length. (In the case of an open channel it is replaced with l, the radius of the open channel through which the fluid is flowing.)
- μ is the fluid viscosity with dimensions of force times time per area.

Re = inertial forces (ρv)/ viscous forces ($\eta/2r$) = $2r\rho v/\eta$

Here: r is the radius and η is viscosity



Shear Stress = τ

$$\tau = \frac{F}{A}$$

Shear Stress proportional to velocity gradient

$$\tau = \frac{F}{A} = \mu \frac{dV}{dy}$$

μ = dynamic viscosity coefficient (depends on temperature – T)

Sutherland's Formula :

$$\mu = \mu_0 \left(\frac{T}{T_0}\right)^{1.5} \left(\frac{T_0 + 198.72}{T + 198.72}\right)$$

Temperature in degrees Rankine : for $T_0 = 518.7$, $\mu_0 = 3.62 \times 10^{-7} \frac{lb - s}{ft^2}$

ν = kinematic viscosity coefficient = $\frac{\mu}{\rho}$

ρ = density

FYI: The Rankine temperature scale relates to the absolute scale of thermodynamic temperature.
It is similar to the Fahrenheit scale but starts at absolute zero and 1 R = -458.67 F (absolute zero = - 459.67 F)

Ref. https://www.tutco.com/insights/journey-through-temperature-scales-from-fahrenheit-to-kelvin-and-beyond/

Viscosity is normally “defined” in relation to the amount of force require to move an object (sphere) through a medium of a given viscosity

For example: Dropping a sphere of mass m into a beaker of liquid

Stoke’s Law

$F = 6\pi\eta r v$

η viscosity
r radius
v velocity

When the sphere reaches terminal velocity the force due to gravity, mg, is balanced by the retarding force of the liquid

$V_t = mg/6\pi\eta r = 4/3\ \pi r^3 \rho g/6\pi\eta r = 2\rho g r^2/9\eta$ which is proportional to r^2

Re = inertial forces (ρv)/ viscous forces ($\eta/2r$) = $2r\rho v/\eta$

As size, r, decreases, the ratio of inertial to viscous forces (Reynolds number) decreases and viscosity dominates.

As a result, micro or nano sized objects moving through fluids are dominated by viscous forces.

For example,
consider an iron sphere moving through water

$r = 1$ mm $v_t = 1$ m/s
$r = 1$ µm $v_t = 1$ µm/s
$r = 1$ nm $v_t = 1$ pm/s

Ponder: If you could toss a nanoparticle off the edge of your desk,
how long would it take to reach the floor?

Capillary Viscometer

Hagen-Poiseuille Equation – defining fluids in circular tubes

The volume flow rate, q_m is…

- directly proportional to the pressure difference (ΔP) between the ends of the tube
- inversely proportional to the length (ℓ) of the tube
- inversely proportional to the viscosity (η) of the fluid
- proportional to the fourth power of the radius (r^4) of the tube

$$q_m = \frac{\pi \Delta P r^4}{8 \eta \ell}$$

Solve for viscosity if that's what you want to know.

$$\eta = \frac{\pi \Delta P r^4}{8 q_m \ell}$$

An aside: reminders of *hidden* dependencies

Consider viscosity

Maple syrup, water, honey, oil – inherent understanding of viscosity

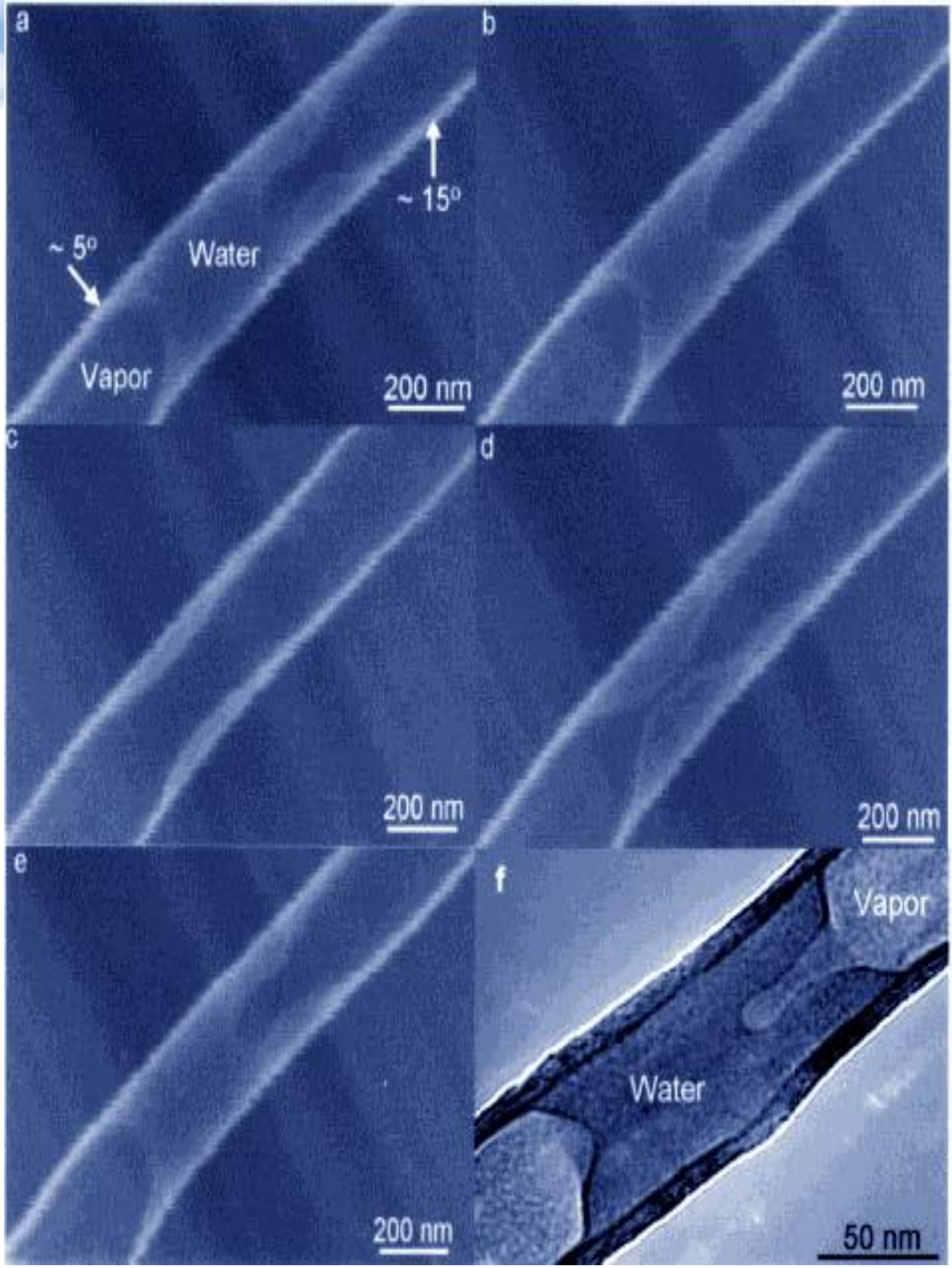
We also all have experience of the effect of a temperature change on the viscosity of a material………

$$\text{viscosity} = \eta = \frac{2(\Delta\rho)ga^2}{9v}$$

? Where is the temperature dependence in this equation ?

It is “hidden” in the density

Ref: Density tables



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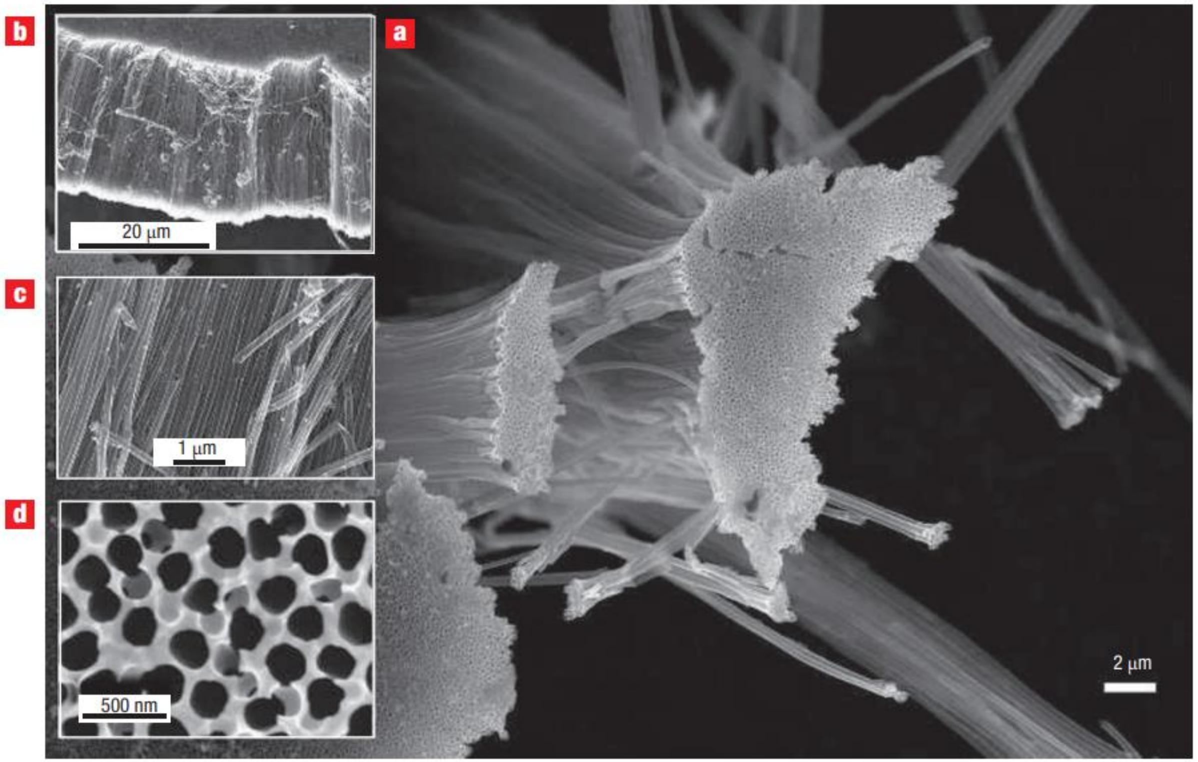
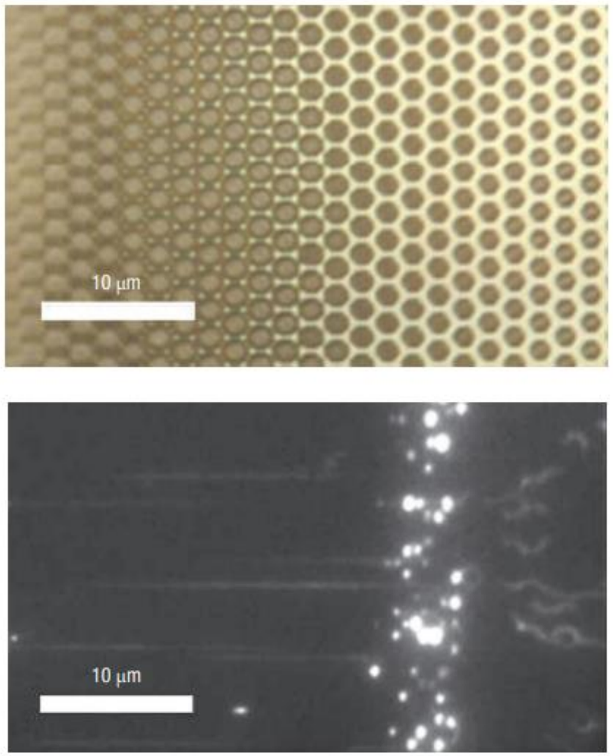




Fluid flow in carbon nanotubes and nanopipes
Nature Nanotechnology 2007

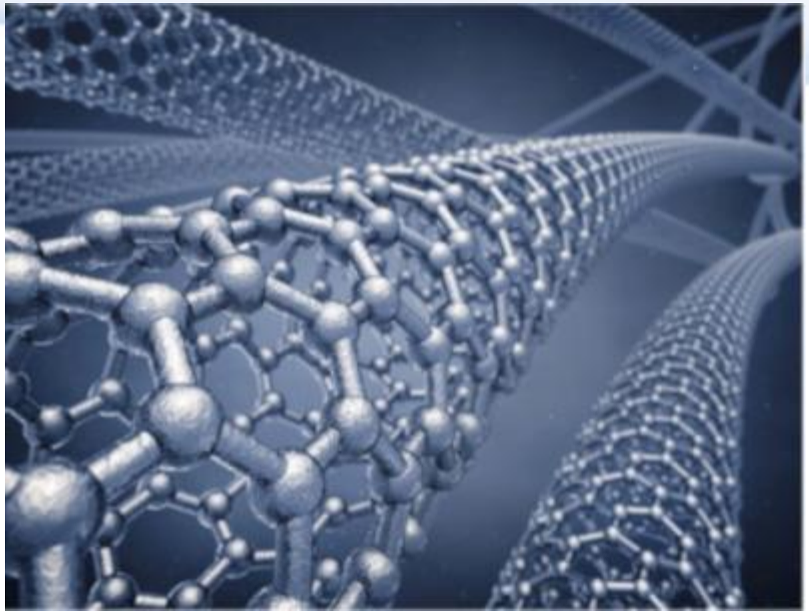
Remember it is not only the *size* of the system that defines operation…

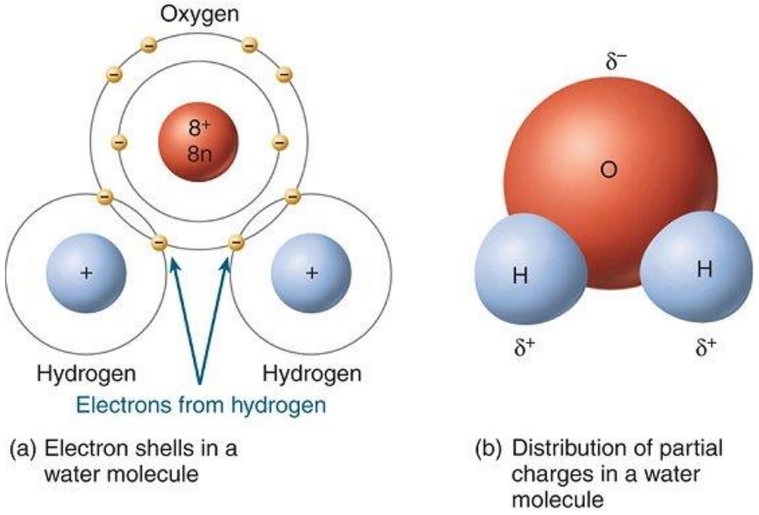
It is both *density* and *viscosity* of the system fluid

Not “just” a single size consideration and more

Measurements of interest for consideration of water in a CNT

Length of C-C bond in graphene	0.142 nm
C atomic radius	0.070 nm
O atomic radius (covalent bond)	0.073 nm
H atomic radius (covalent bond)	0.032 nm
Water base of “triangle”	0.280 nm
Water height of “triangle”	0.098 nm



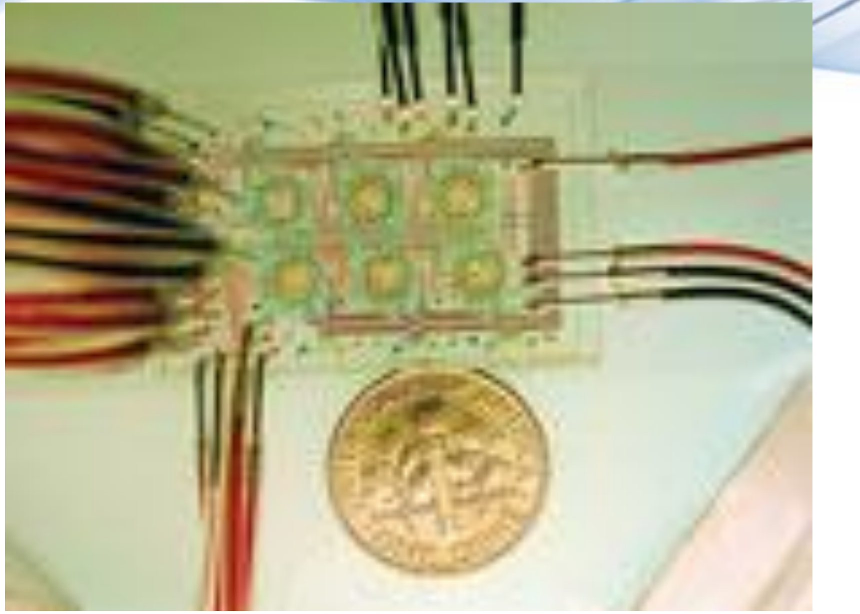


(a) Electron shells in a water molecule

(b) Distribution of partial charges in a water molecule

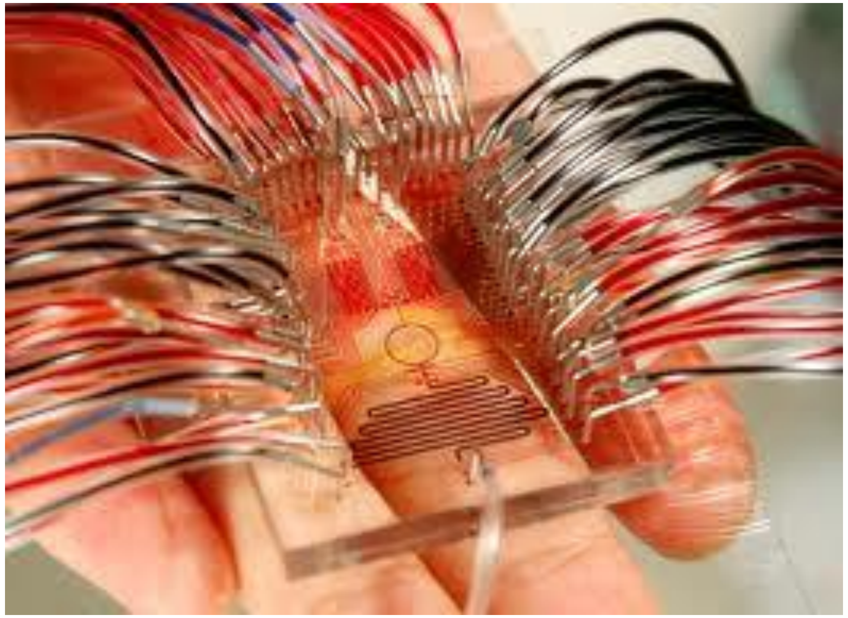
Ref: alevelnotes.com

REMEMBER:
True size consideration…
Molecular charge…
Nonuniform charge density…
Temperature



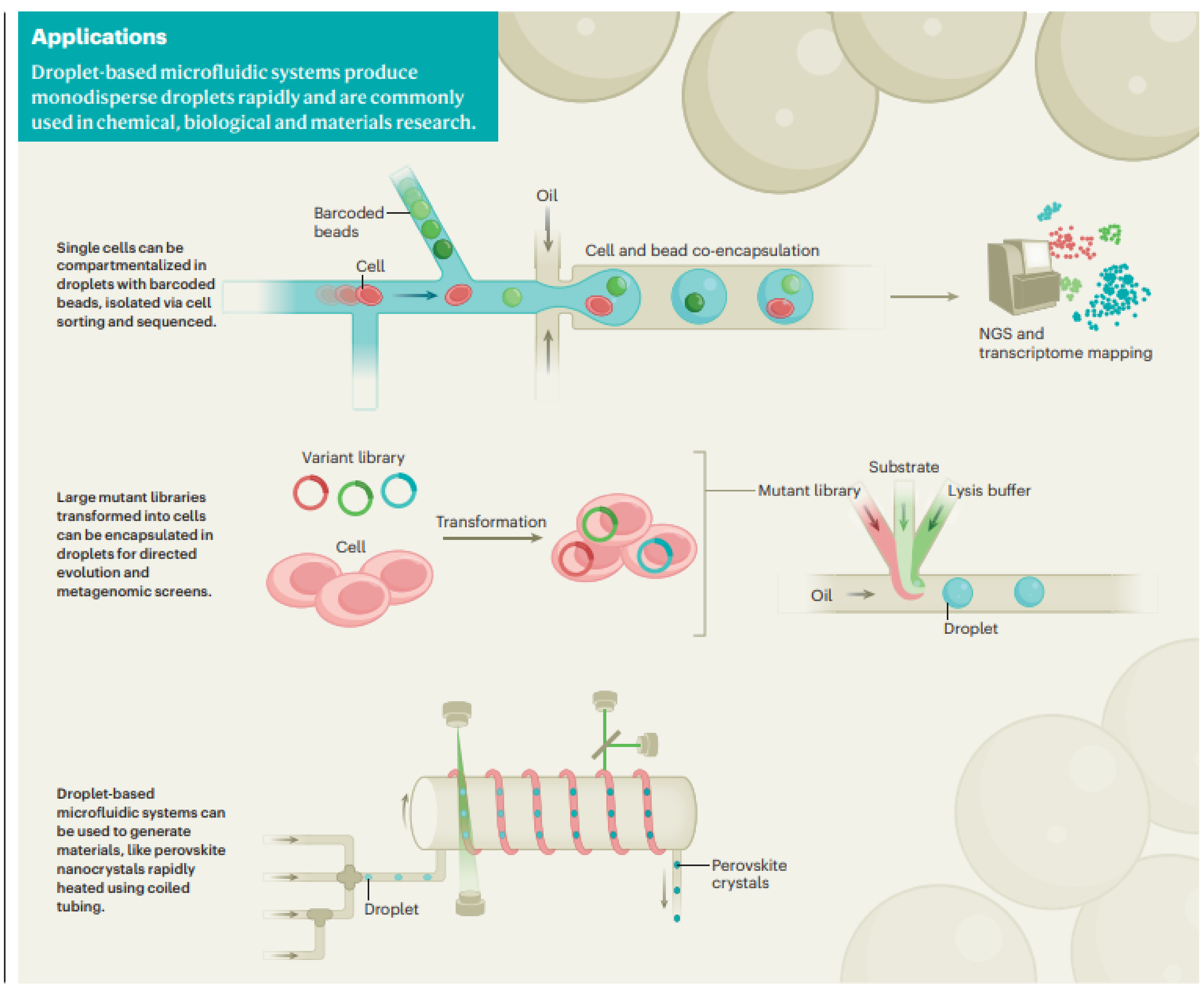
Lab on A Chip

Nursing point of care assessment
Remote use environmental sensors
Drug development



Key Application Areas

- Polymerase Chain Reactions
- Immunoassays
- Drug Screening
- Electrophoretic separations
- Analysis of unpurified blood samples
- DNA sequencing
- Single Cell manipulation
- Screens for protein crystallization conditions
- Cell culture studies



Applications

Droplet-based microfluidic systems produce monodisperse droplets rapidly and are commonly used in chemical, biological and materials research.

Single cells can be compartmentalized in droplets with barcoded beads, isolated via cell sorting and sequenced.

Large mutant libraries transformed into cells can be encapsulated in droplets for directed evolution and metagenomic screens.

Droplet-based microfluidic systems can be used to generate materials, like perovskite nanocrystals rapidly heated using coiled tubing.

nature reviews methods primers 2023

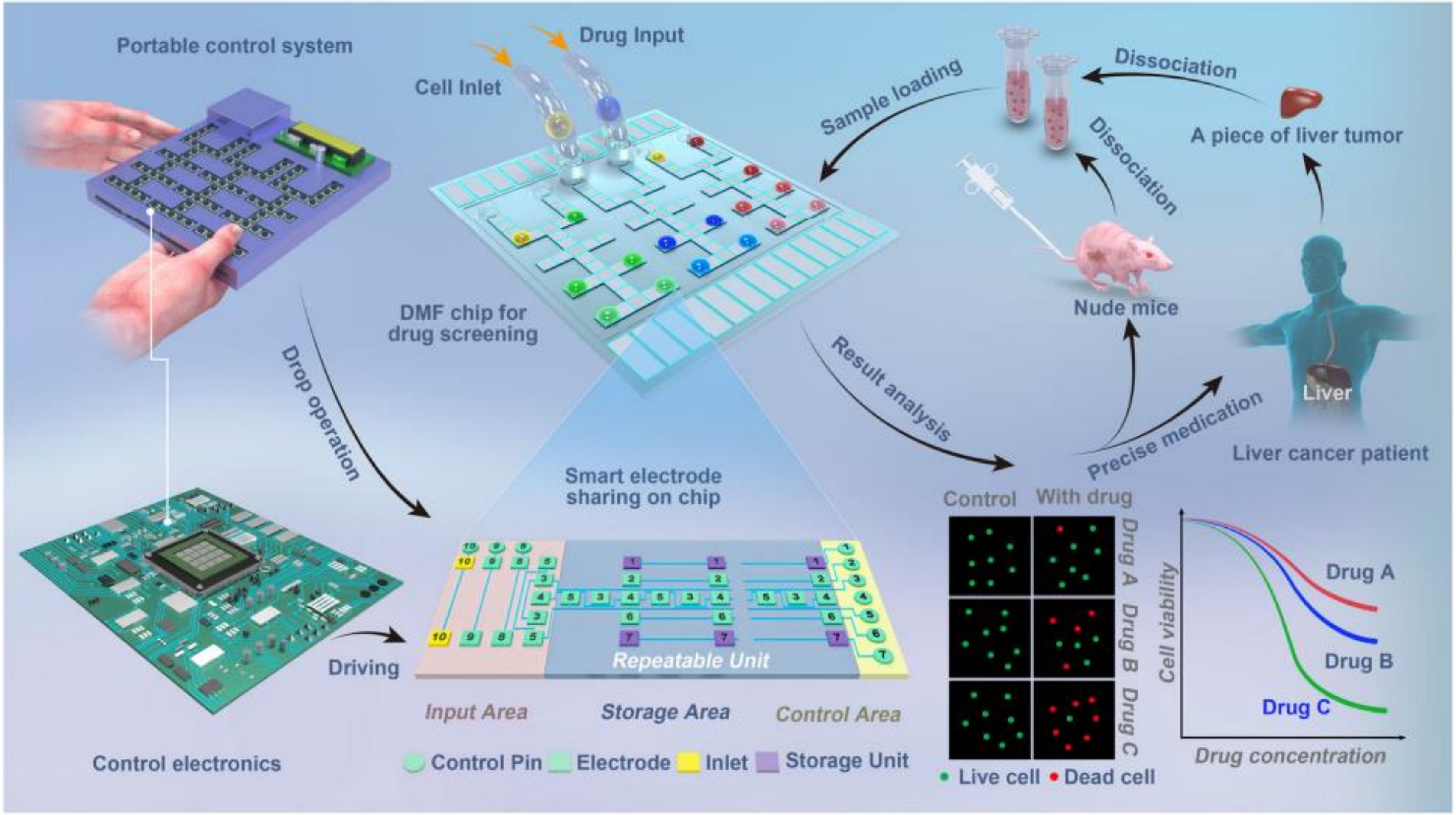
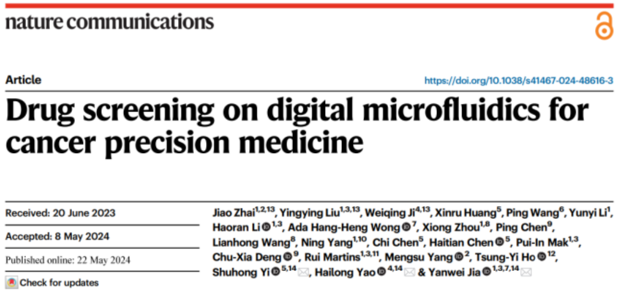


Fig. 1 | Schematic of drug screening on digital microfluidics for cancer precision medicine. Schematic of the digital microfluidic (DMF) system for drug screening of biopsy samples from MDA-MB-231 breast cancer xenograft mouse model and patients with liver cancer.



nature communications

Article

https://doi.org/10.1038/s41467-024-48616-3

Drug screening on digital microfluidics for cancer precision medicine

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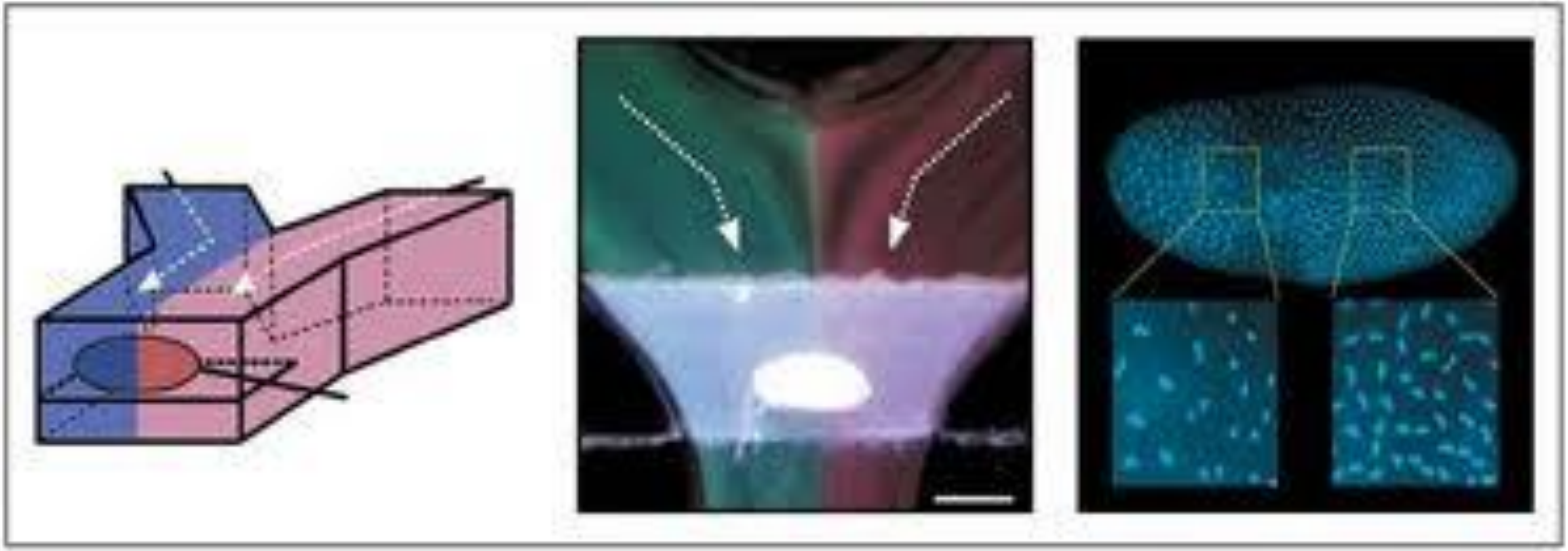
Accepted: 8 May 2024

Jiao Zhai[1,2,13], Yingying Liu[1,3,13], Weiqing Ji[4,13], Xinru Huang[5], Ping Wang[6], Yunyi Li[1], Haoran Li[1,3], Ada Hang-Heng Wong[7], Xiong Zhou[1,8], Ping Chen[9], Lianhong Wang[8], Ning Yang[1,10], Chi Chen[5], Haitian Chen[5], Pui-In Mak[1,3], Chu-Xia Deng[9], Rui Martins[1,3,11], Mengsu Yang[2], Tsung-Yi Ho[12], Shuhong Yi[5,14] ✉, Hailong Yao[4,14] ✉ & Yanwei Jia[1,3,7,14] ✉



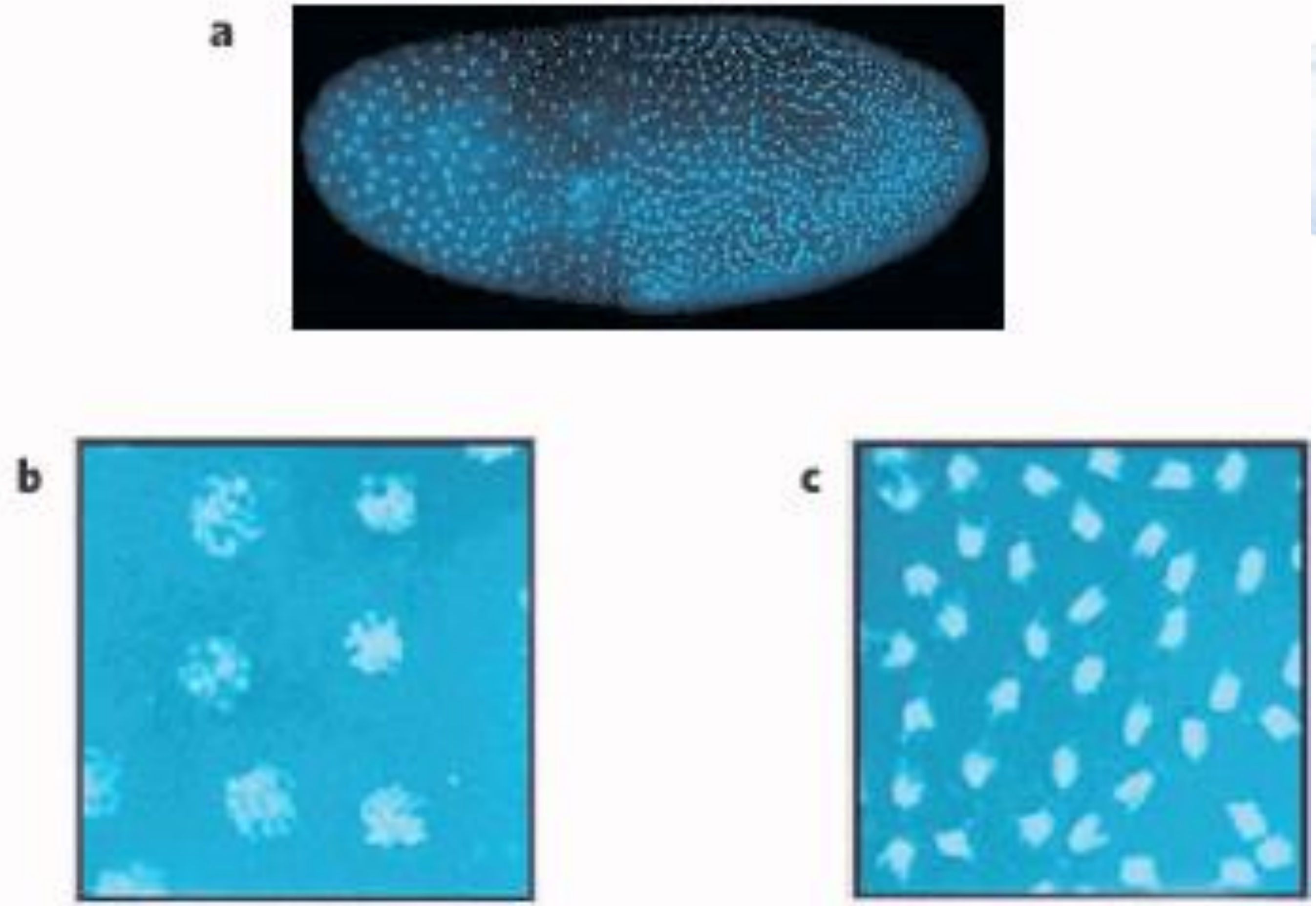
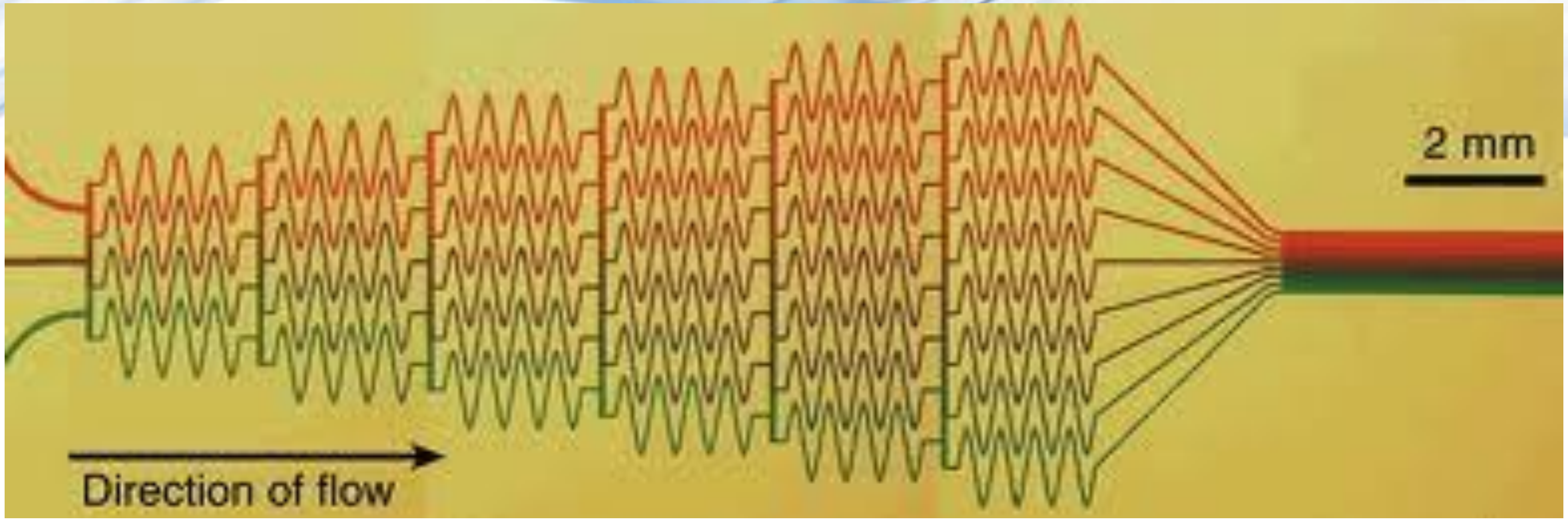
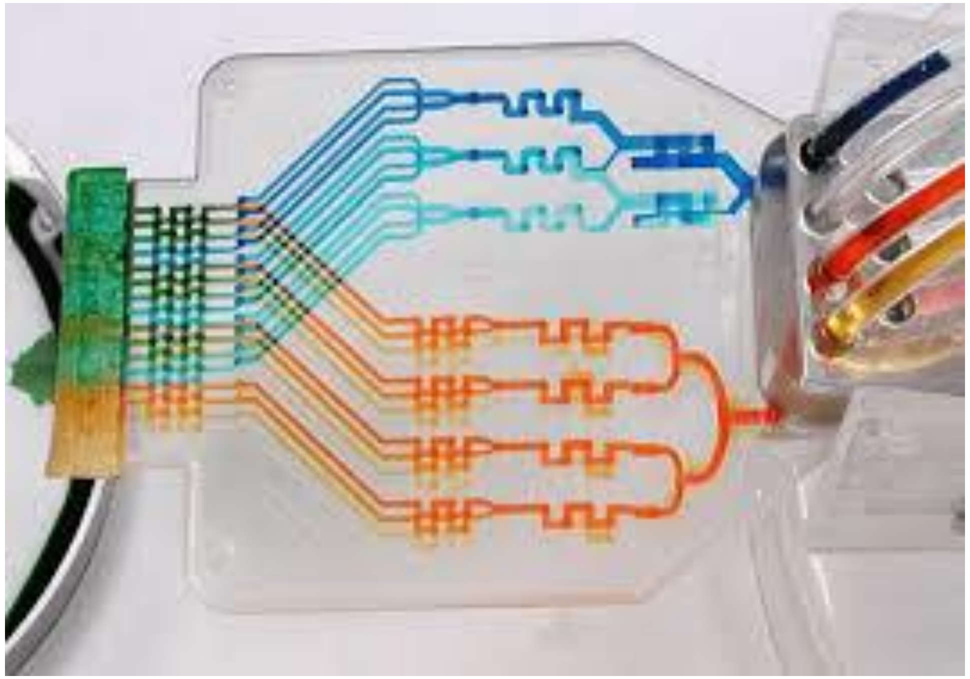


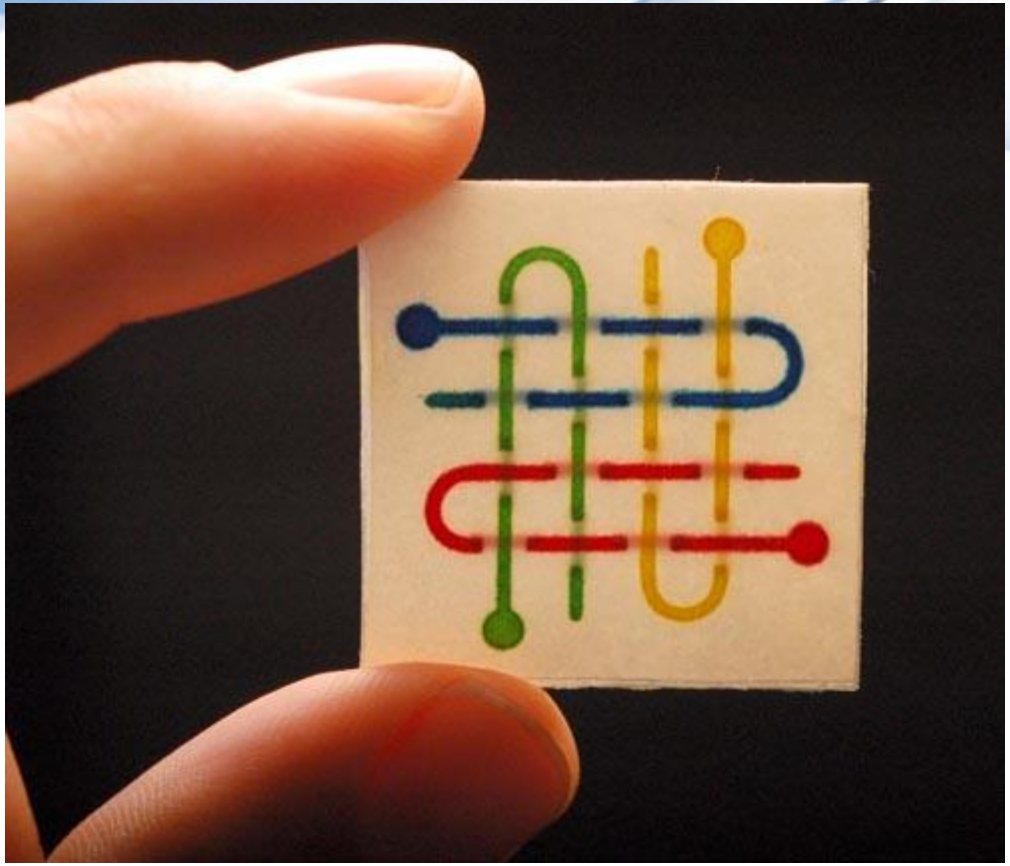
Figure 4 | A new platform for cellular and developmental biology. Laminar flow in microchannels, together with the biocompatibility of PDMS, enable new methods of studying cellular and developmental biology. One system examines the effect of temperature on the development of a fruitfly embryo[55]. The embryo (the large oval in **a**) is immobilized in the middle of a microchannel. Aqueous streams of two different temperatures flow over the halves of the embryo (**b** shows the cold half, **c** the warm half); the differences in the embryo are reflected in the density of cells (marked by the light-blue nuclei). The embryo is ~500 μm wide.

Nature. July 2006. Whitesides. p. 371





www.nature.com



The device was made from two layers of patterned paper and one layer of double-sided tape, and it measures 3 cm x 3 cm. (Credit: Whitesides lab)

Wyss.harvard.edu

Results and Discussion

Figure 1: Laminar flow in water (left) and isopropanol (right).

Laminar Flow

The forces of gravity and capillary action were not enough to draw the single drops of fluid into the channels in this experiment. However, when forced through the channels by squeezing the fluids in with the pipettes, laminar flow could be observed in with both the water and isopropanol (fig. 1).

Activity

Materials

- PDMS: Dupont Sylgard 184 Silicone Elastomer Kit (makes 50+)
- “puffy” paint (3D paint)
- Petri Dished 100mm width, 15 mm height, plastic
- Glass slides 76 mm X 52 mm
- Hole creator – Biopsy punch, mechanical punch, power drill
- Scissors, straight edge
- Pipettes
- Food coloring
- Water
- Other fluids (optional)

Activity

Process

- Using the puffy paint make your designs in the petri dishes (can use top and bottom)
  - Careful – make sure design ends are large enough for your fluid entry/exit holes
  - Careful - partially empty puffy paint squirt bottles can produce puffs of air and not paint
- Wait about 24 hours
- Mix up the PDMS – 10:1 mixture, stir for at least 5 minutes, let set 30 minutes
  - Note: Bubbles will go away
- Pour PDMS over designs, enough to cover well
- Wait 2.5 to 3 days
- Remove PDMS from petri dish and puffy paint design. The “extra” PDMS provides a location for holding
- Punch fluid entry holes into the PDMS
  - Careful – Make sure your punch size is appropriate for the pipettes you are using (PDMS will draw in a bit from the punched hole)
- Place PDMS punched design on glass slide
- If desired, trim excess PDMS away from slide using scissors or straight edge
- Press PDMS onto glass slide to ensure sealed channel edges
- Using 2 pipettes with different colored water, squeeze water into the channels
- Ta Da!!!
- Note: this activity and the PDMS is very forgiving, can rinse and repeat many times

Thank You --- now let's play

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