NSF 2002 Summer School (Urbana-Champaign)

Microfluidics

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Brown University

- Basic Concepts and Applications
- Gas Flows
- Liquid Flows
- Particulate Flows
- Moving Domains and Applications

Reference: *G.E. Karniadakis & A. Beskok*
Micro Flows: Fundamentals and Simulation,
Springer, 2002.

Microfluidics:

Emerging technology that allows development of new approaches to synthesize, purify, and rapidly screen chemicals, biologicals, and materials using integrated, massively parallel miniaturized platforms.

- **Microfluidics is *Interdisciplinary*:**
  - Micro-Fabrication
  - Chemistry
  - Biology
  - Mechanics
  - Control Systems
  - Micro-Scale Physics and Thermal/Fluidic Transport
  - Numerical Modeling
  - Material Science
  - System Integration and Packaging
  - Validation & Experimentation
  - Reliability Engineering
  - …

Microfluidic Devices

Sensors & Actuators:

Pressure, Temperature, Shear Stress,
Biological & Chemical Sensors

Fluidic Components:

Channels, Pumps, Membranes
Valves,
Nozzles, Diffusers and Mixers

Motion Generation:

Micro-Motors, Turbines,
Steam Engines, Gears, Pistons, Links

Micro-Total-Analysis-Systems (μ -TAS) seamlessly integrate sample collection and separation units, biological and chemical sensors, fluid pumping and flow control elements, and electronics on a single microchip.

Microfluidic Applications:

Defense Applications:

- Lab on a chip: μ-TAS

Bio-Medical Applications:

- Drug Delivery Systems
- DNA Analyzers
- Human Health Monitoring
- Artificial Organs

Environmental Monitoring:

- Water & Air Pollution Sensing
- Gas/Liquid Filtration Systems

Microelectronics:

- Thermal Management
- Bubble-Jet Printers

Aerospace Industry:

- Drag & Stall Control

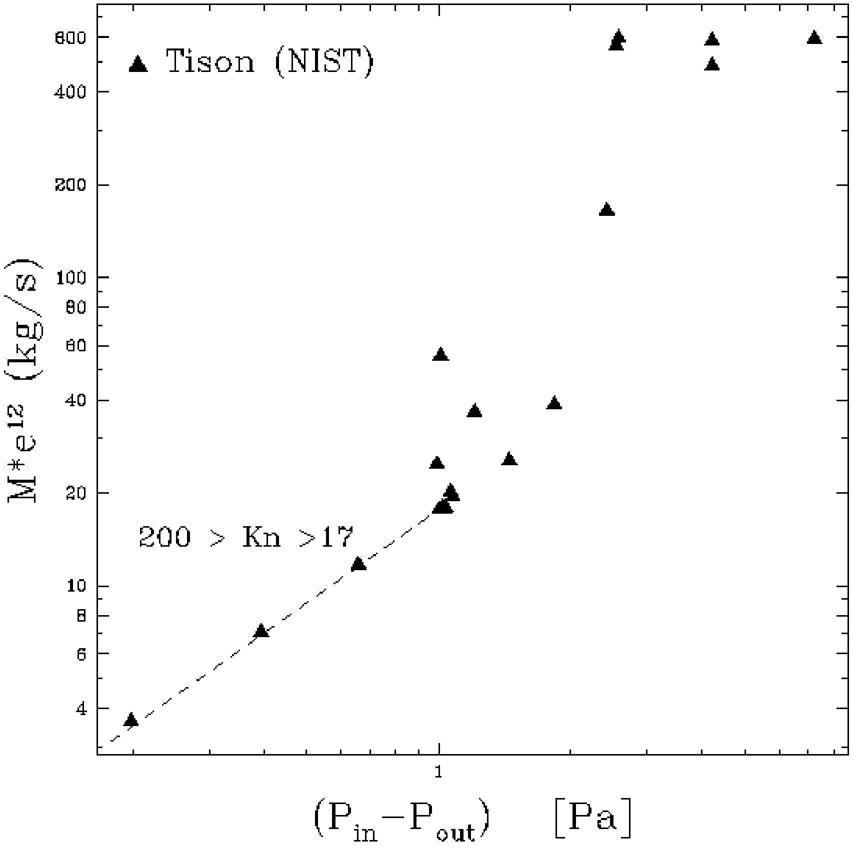
Scientific & Technological Challenges

- Development of *new* concepts that are *specifically designed* to take advantage of the small scale of microfluidic devices,

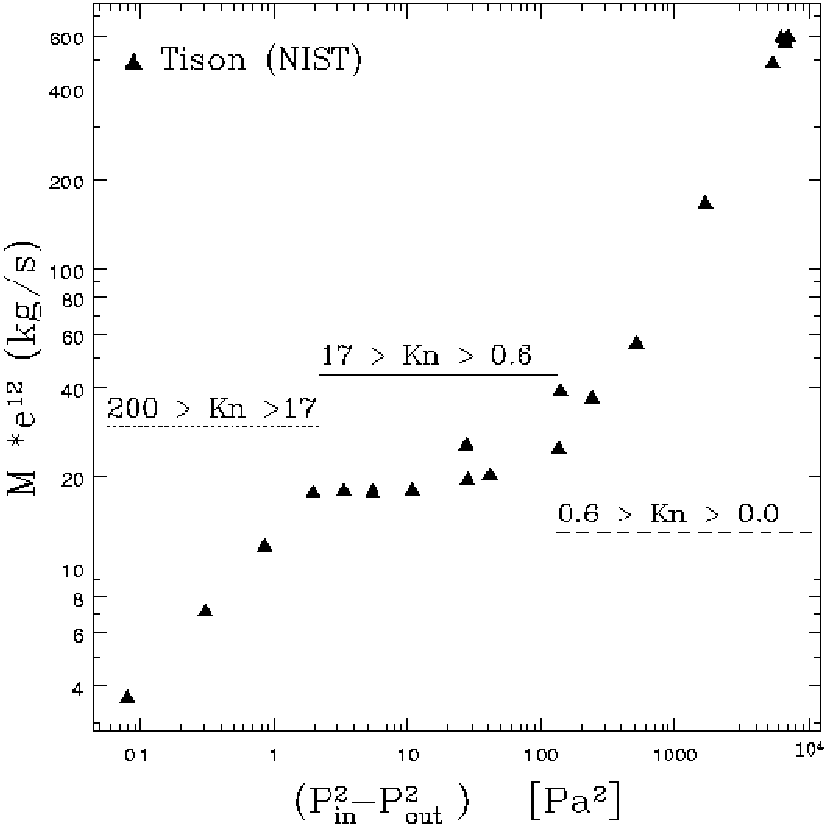
- To impart unique new functions that are not simply miniaturized versions of existing systems and components.

Mass Flow Rate versus Pressure Drop

- Pipe Flow (2mm x 200 mm; gas at low pressure)

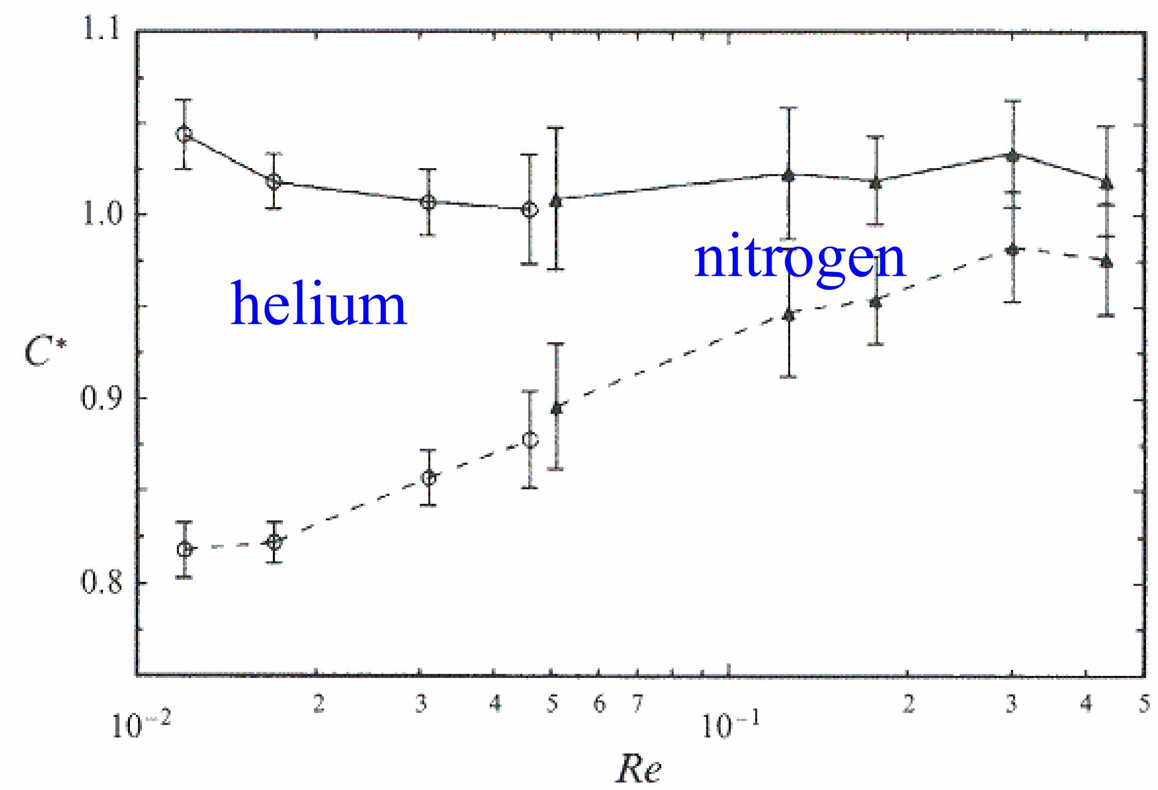


- Linear Scaling



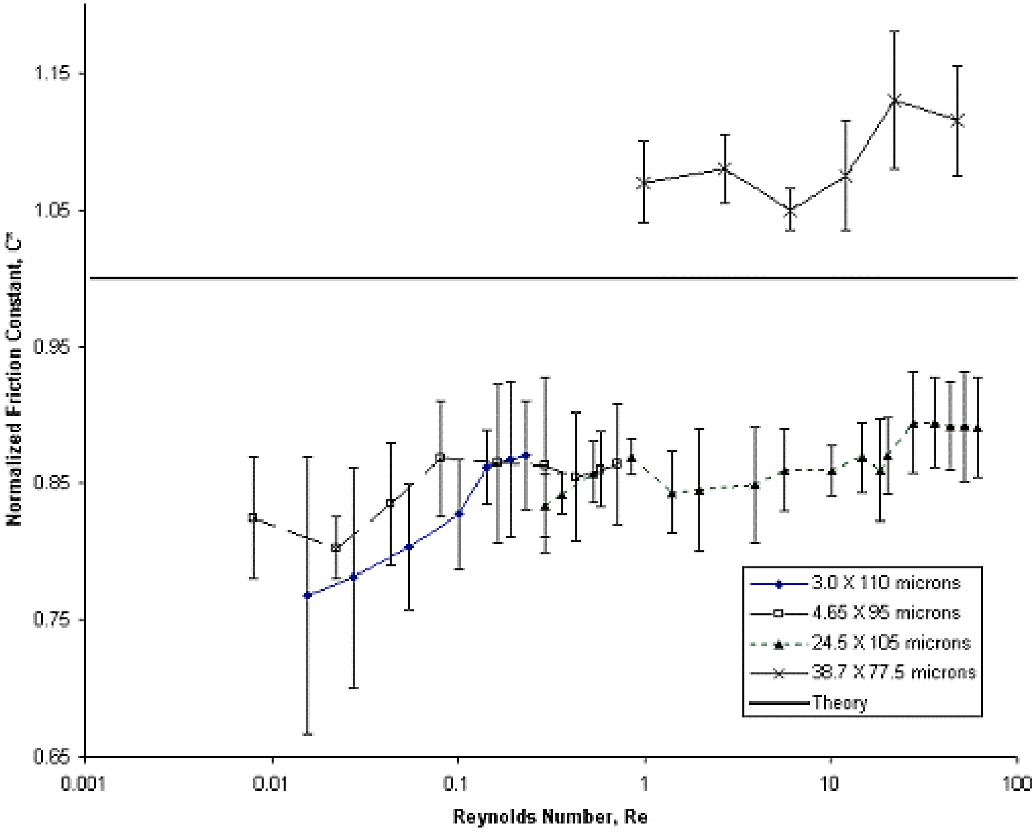
- Quadratic Scaling

Deviations from Continuum - Gases



- ***Microchannel***: 0.51 microns (Bau et al., U Penn, 1988)
  - $C^* = Po_{ex}/Po_{th}$ *where* $Po = C_f Re$
  - $Po = 64$ *(pipe)*
  - $Po = 96$ *(2D channel)*

Deviations from Continuum - Liquids

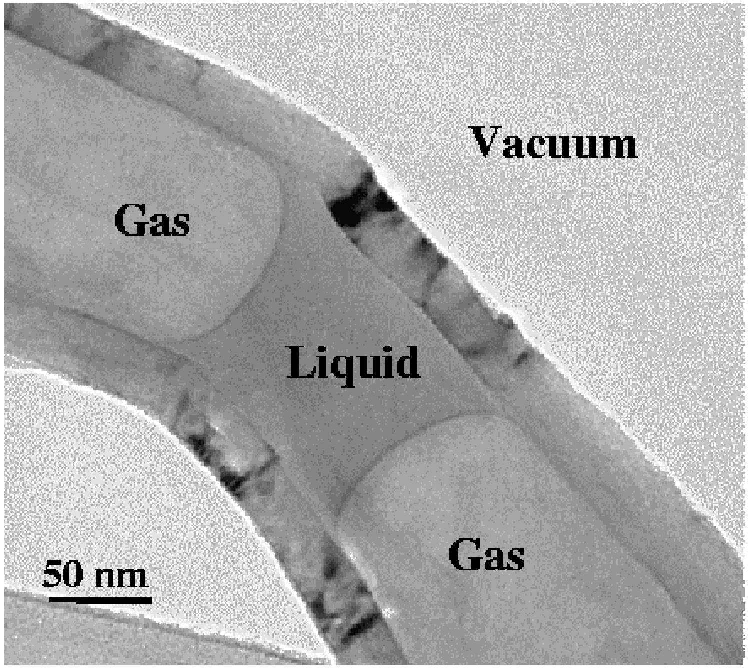


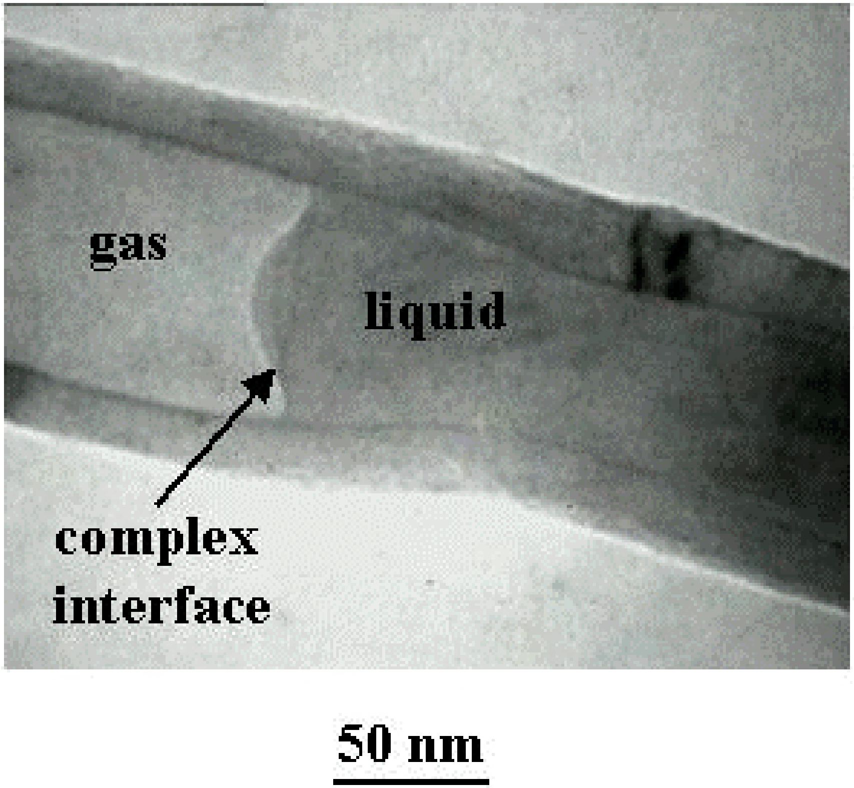
- *Microducts* (Bau & Pfahler, 2001)
- **Silicone oil**

- Question: Anomalous Diffusion or something else?

Interface Inside Carbon Nano-Tubes

(transmission electron micrographs)

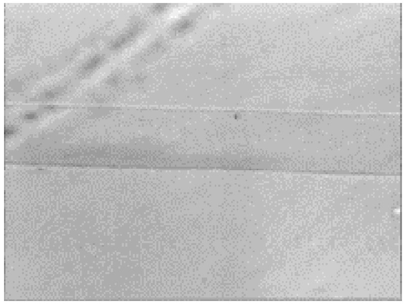


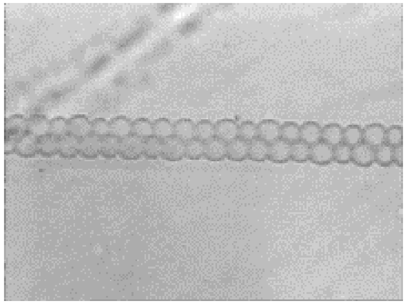


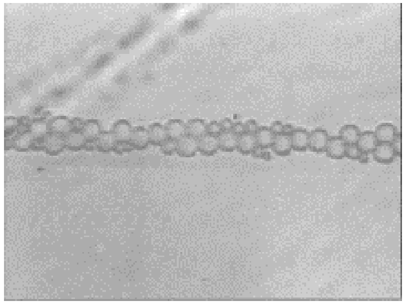
Courtesy of Megaridis & Gogotsi, UIC

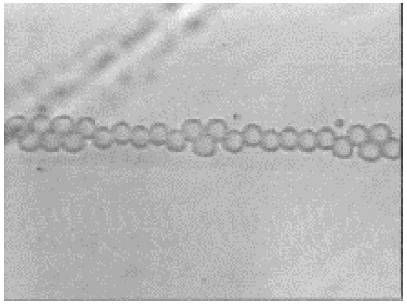
Reverse Micelle Formation in Microchannels Containing Hexadecane/ 2% Span80

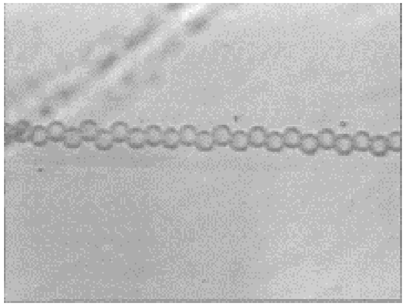
* Quake, Caltech

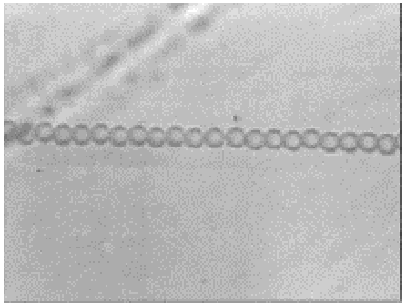

13.2/12.5 psi w/o-s


12.8/12.5 psi w/o-s

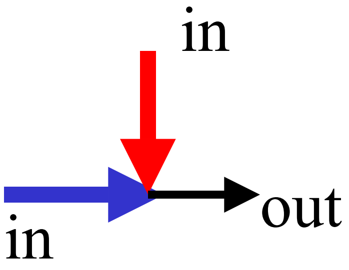

12.4/12.5 psi w/o-s


12.0/12.5 psi w/o-s


11.5/12.5 psi w/o-s


11.1/12.5 psi w/o-s

T-junction

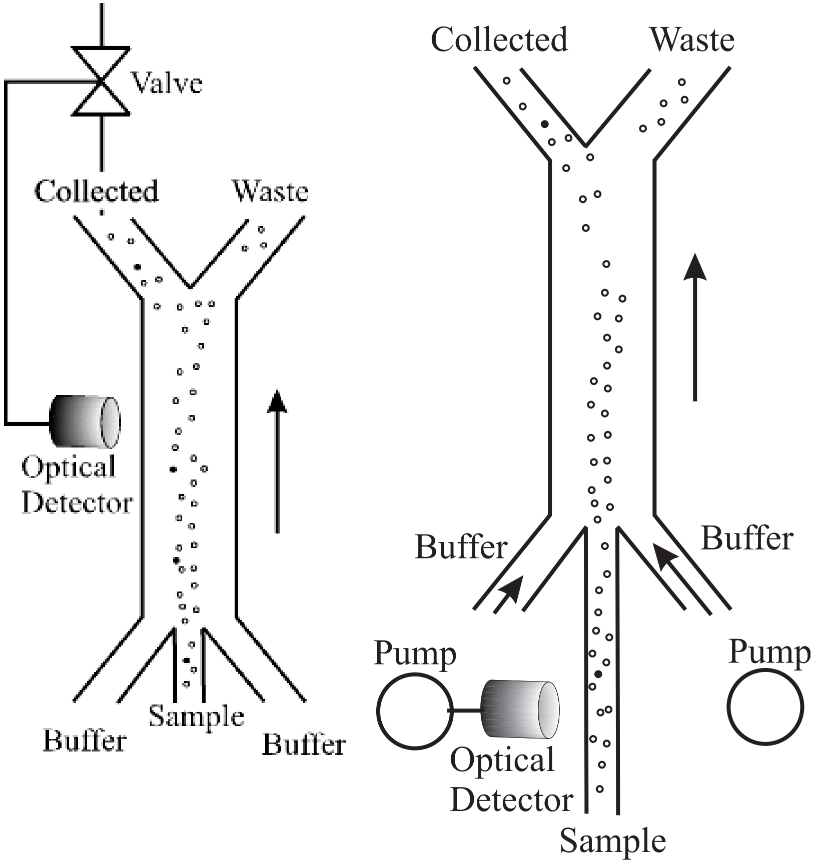


Liquids + Gas

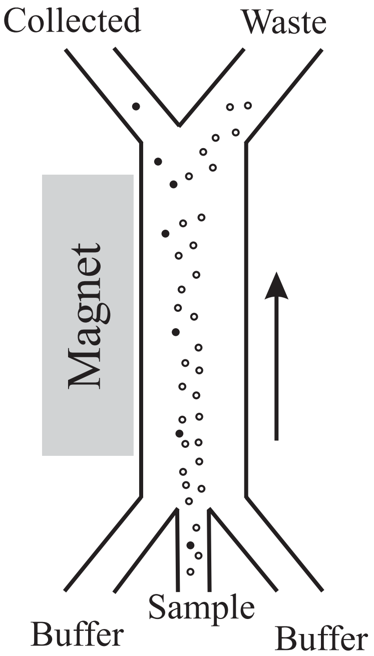
Applications of Particulate Microflows

-Sorting
-Analyzing Of
-Removal

- Cells
- Particles
- Embryos



Micro fluorescent activated cell sorting
μFACS

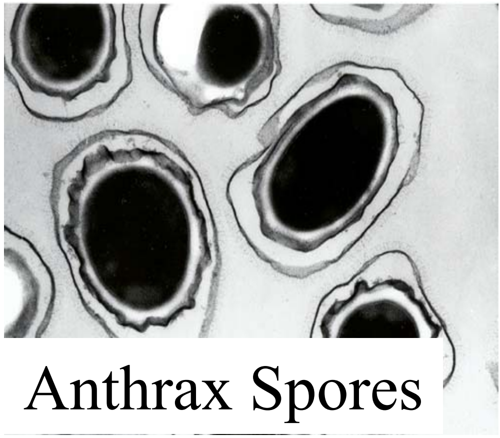


Micro magnetic activated cell sorting

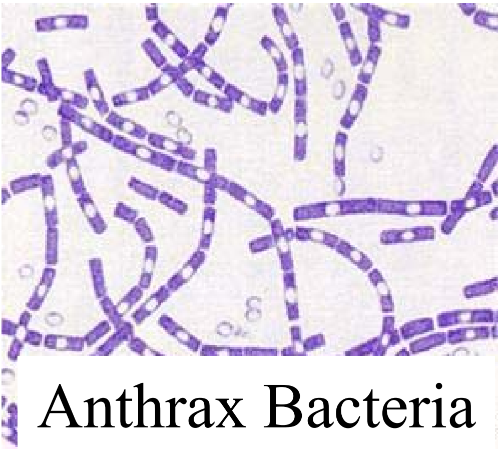
μMACS

* *Telleman et al.*

Characterization of Airborne Particles



Anthrax Spores

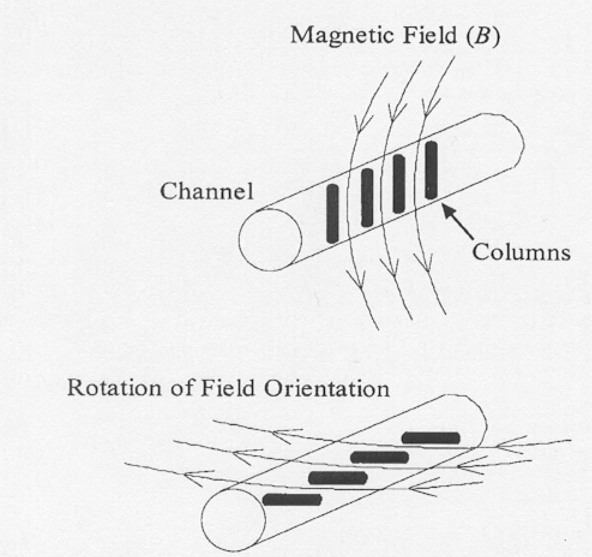


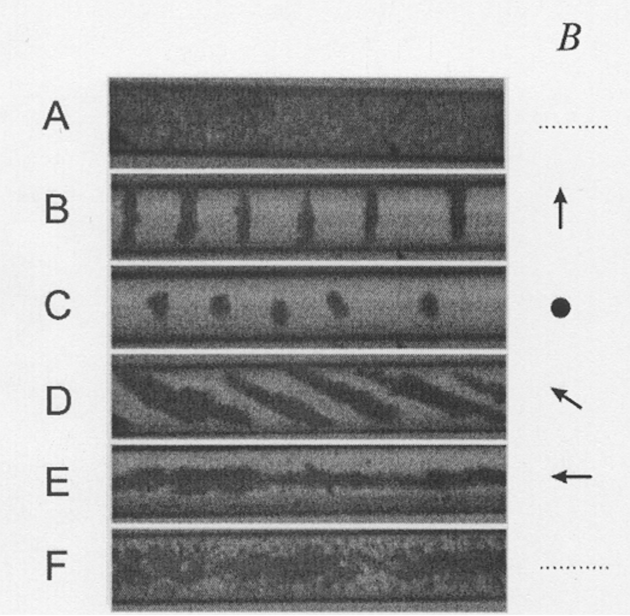
Anthrax Bacteria

Size, Shape & Orientation

Active Control of Supraparticle Structures Microchannels

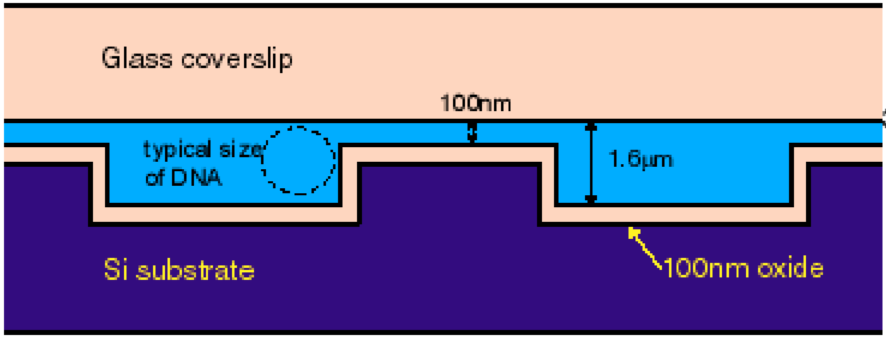
Hayes et al. *Langmuir* (2001)

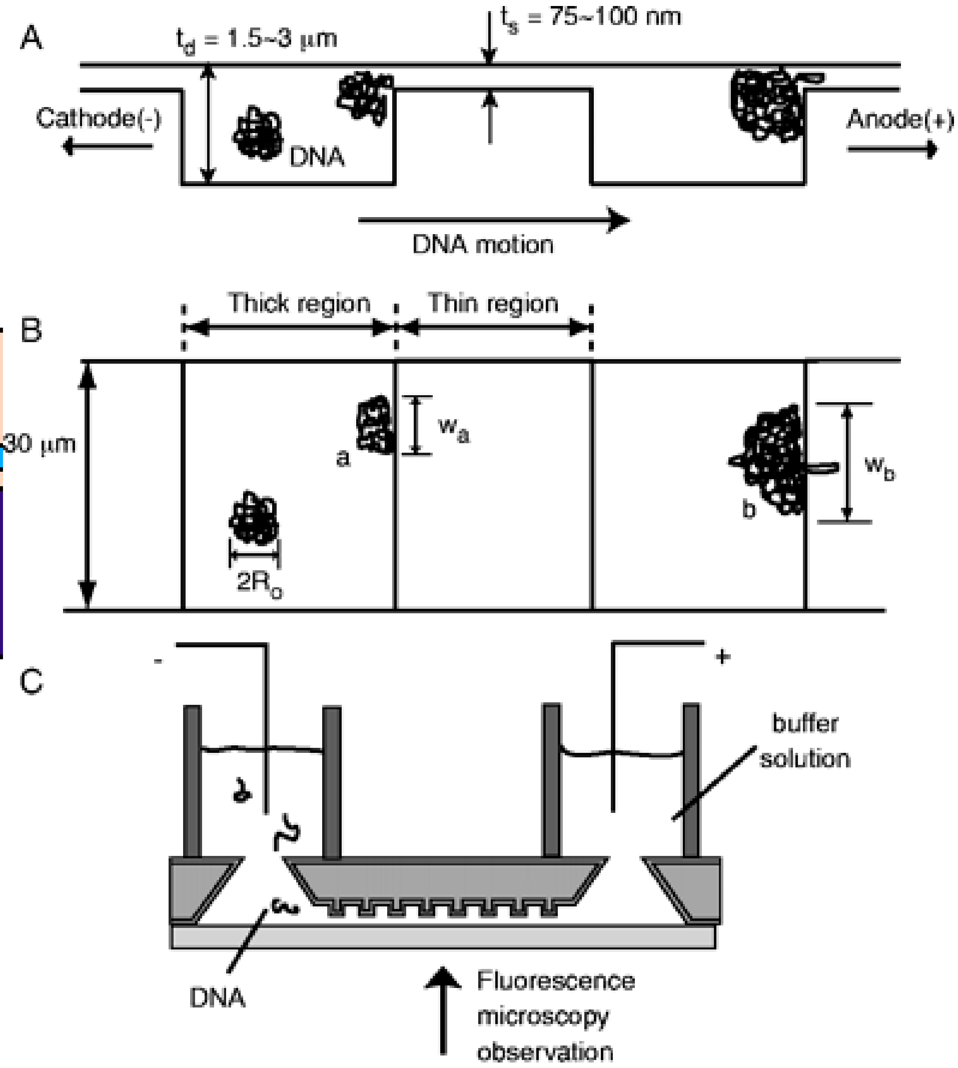




Entropic Trapping and Seiving of DNA in Nanofluidic Channels

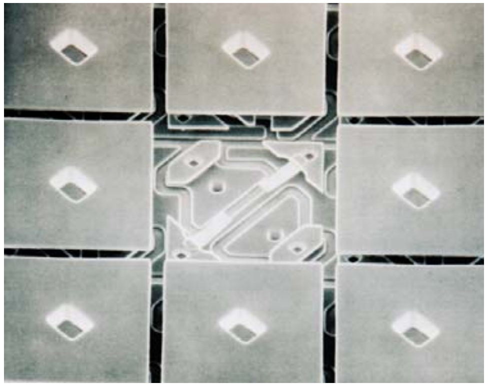
Han & Craighead, *Science*, (2000)

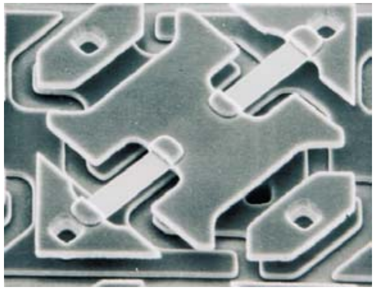


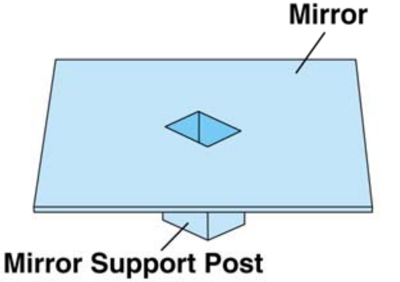


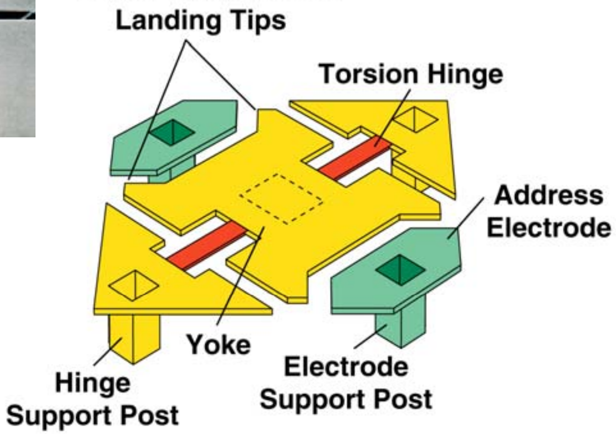
Digital Micro-Mirror Device™

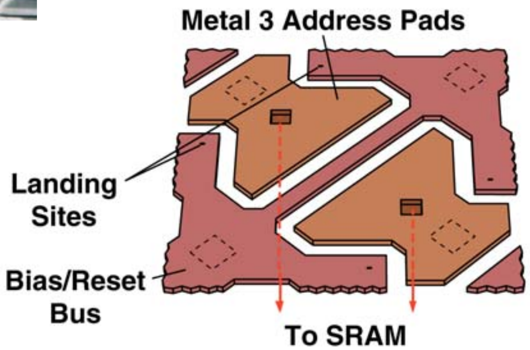
Digital Light Processing ™:
848 x 600 pixels
1280 x 1024 pixels
16µm x 16µm w/ 1 µm separation







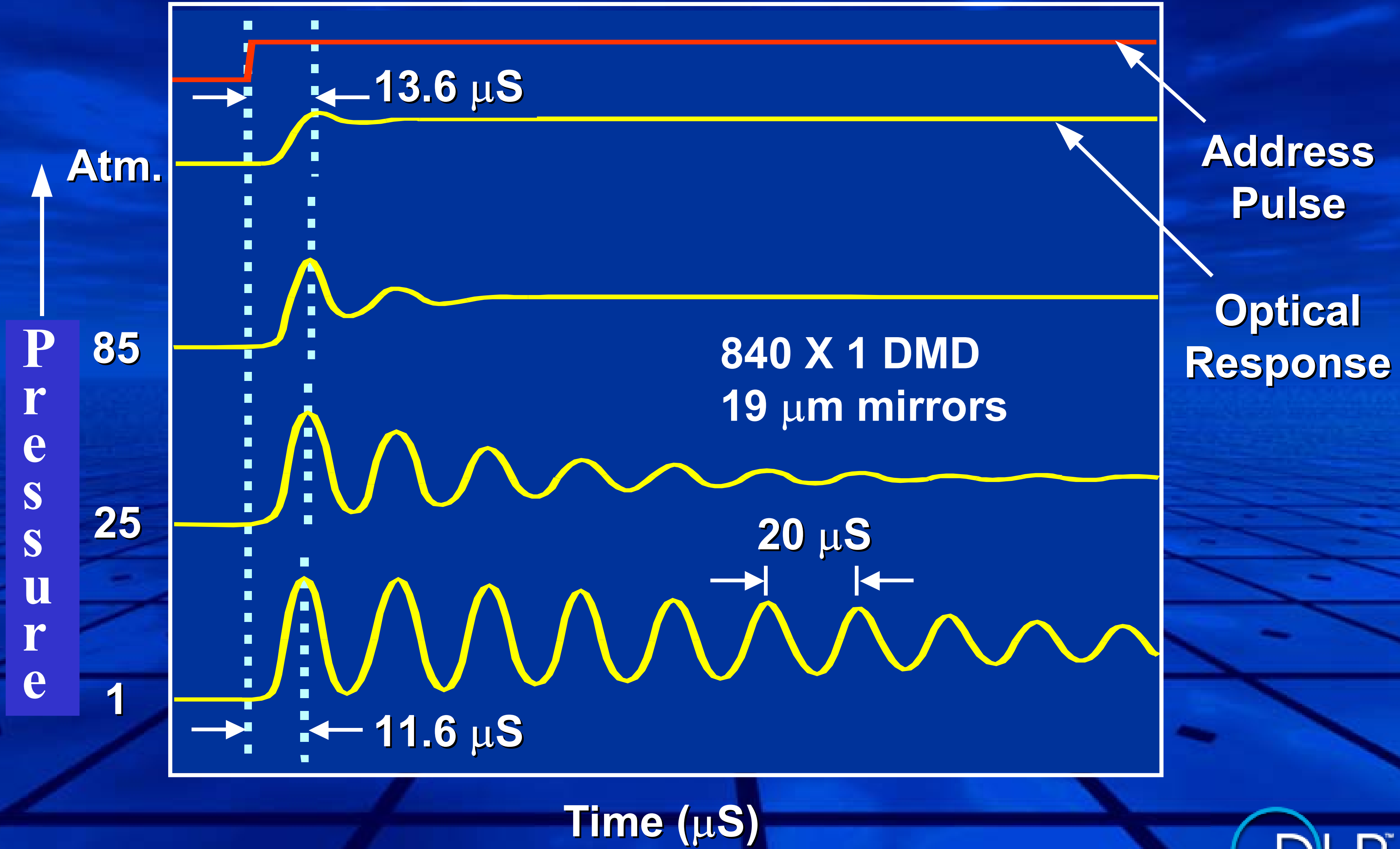




Courtesy of Texas Instruments

DMD™ Air Damping Effects & Transient Response

Courtesy of Texas Instruments

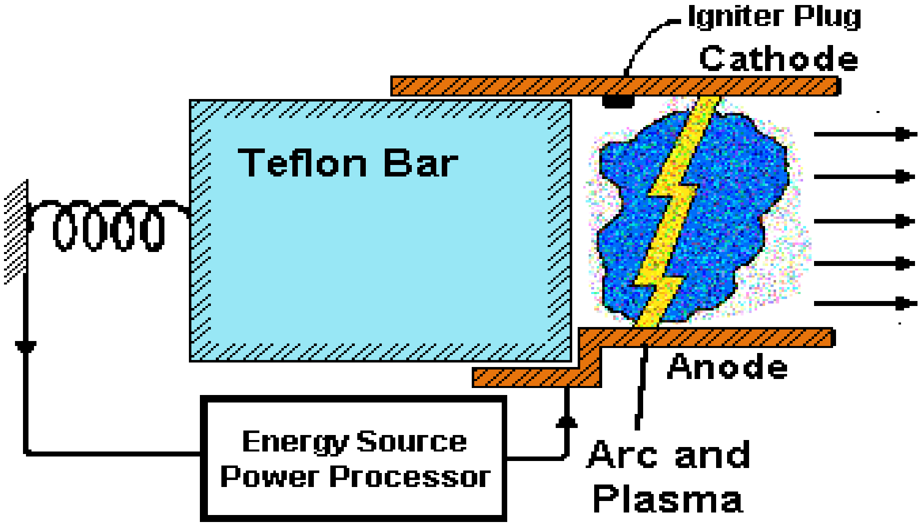


Simulation of Micro-Pulse-Plasma Thrusters (micro-PPT)

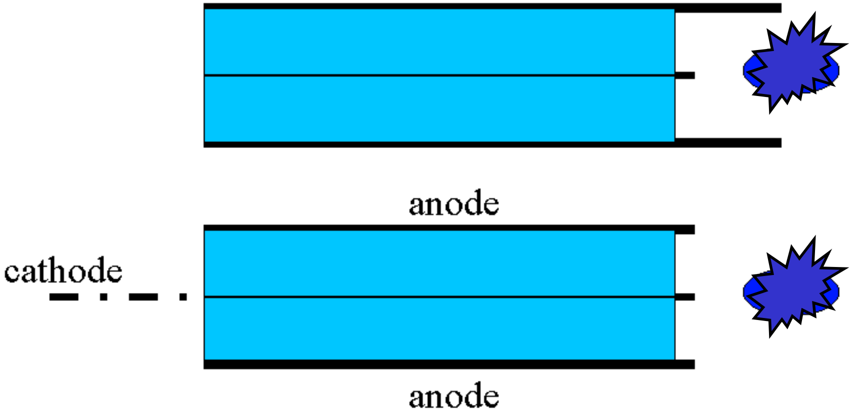
- New issues arise in simulating plasma microthrusters that are an order of magnitude smaller than the existing state-of-the art.
  - Current simulation technologies are based on mathematical models and assumptions that break down in microscales and, therefore, cannot treat these microflows comprehensively.

- Microspacercaft are currently considered by Air Force, NASA and industry for a variety of applications.
  - L<10 cm, W< 1 kg, and P< 10 W.
  - Need for micropropulsion.
  - Plasma microthrusters introduce an additional complexity in their analysis due to the overlap of electrodynamic and gasdynamic scales.

Physical Processes in a micro-PPT



AFRL micro-PPTs

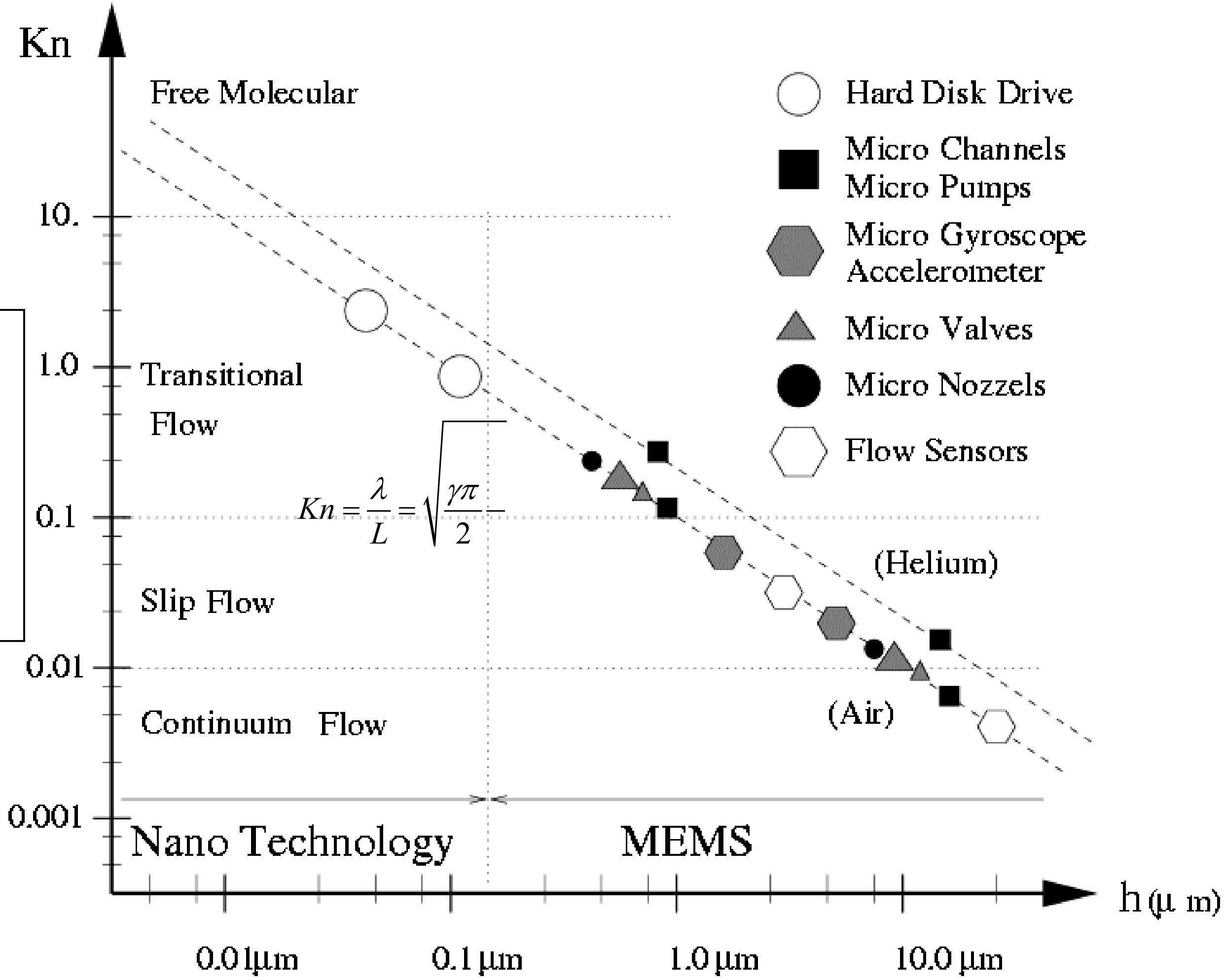


- Gas Discharge Processes
- Teflon Ablation
- Magnetogasdynamic Acceleration
- Coupling with External Circuit

Gas Microflows: Typical Applications

$$Kn = \frac{\lambda}{L} = \sqrt{\frac{\gamma\pi}{2}}\,\frac{M}{\mathrm{Re}}$$

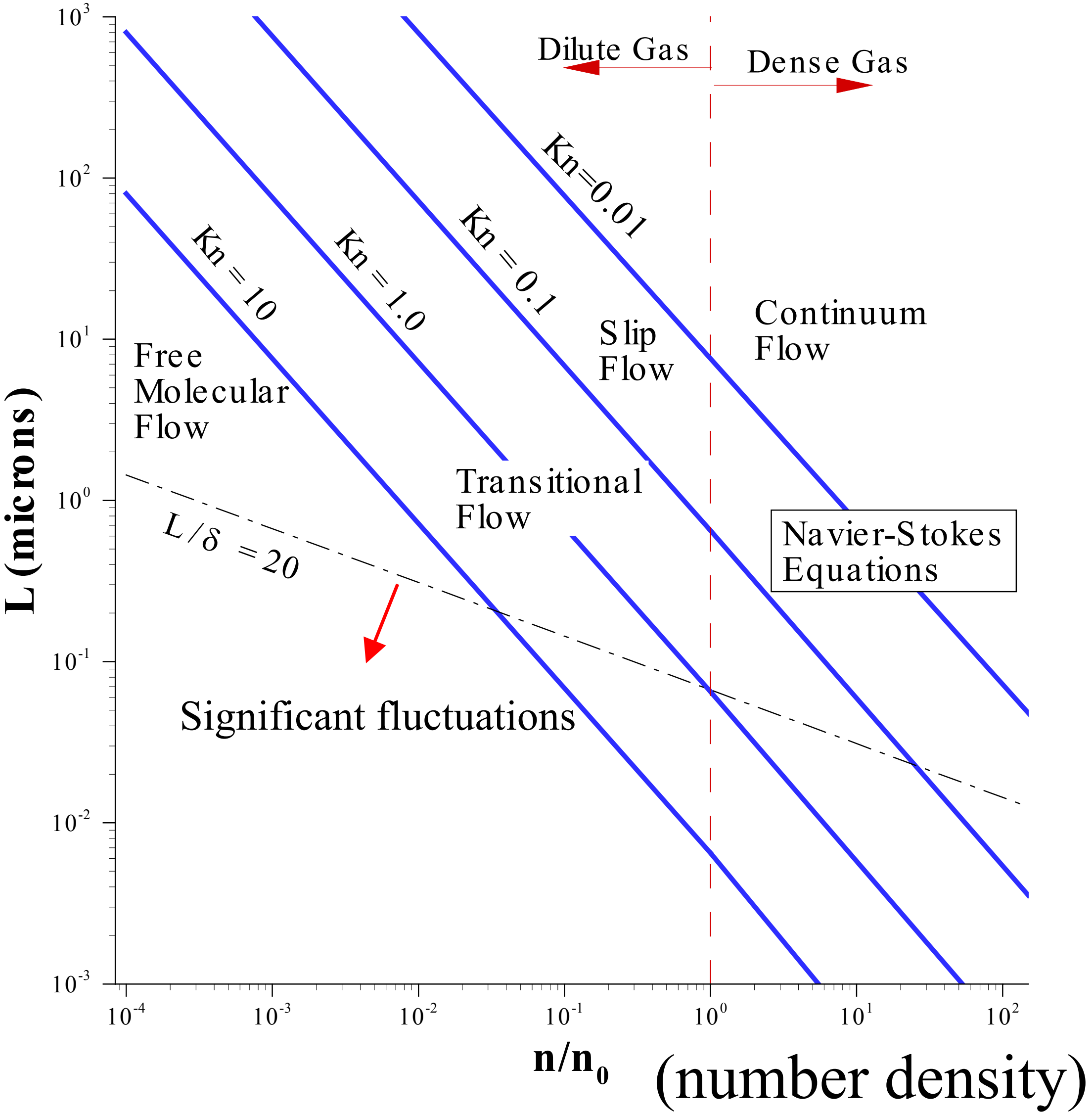
Knudsen number



The Continuum Hypothesis

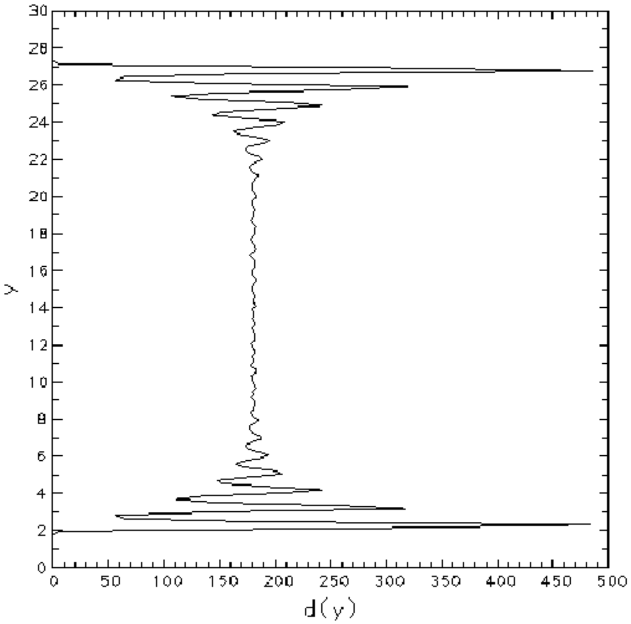
- How small should a volume of fluid be so that we can assign it *mean* properties?
- At what scales will the statistical fluctuations be significant?
- Are the low-pressure rarefied gas flows dynamically similar to the gas micro-flows?

The Continuum Hypothesis

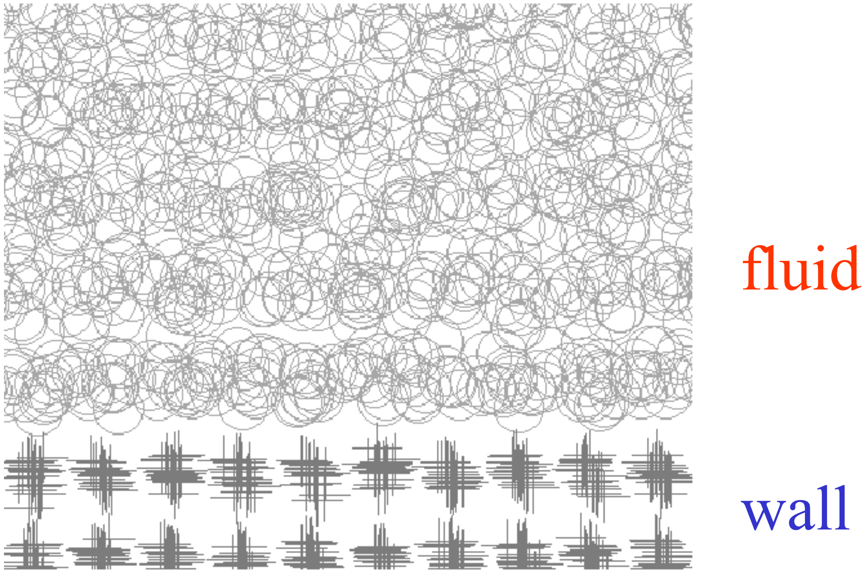


LIQUIDS: Nano-Scale Behavior

MD Simulations (*Koplik & Banavar, ARFM 1995*)



Density fluctuations across a nano-channel.

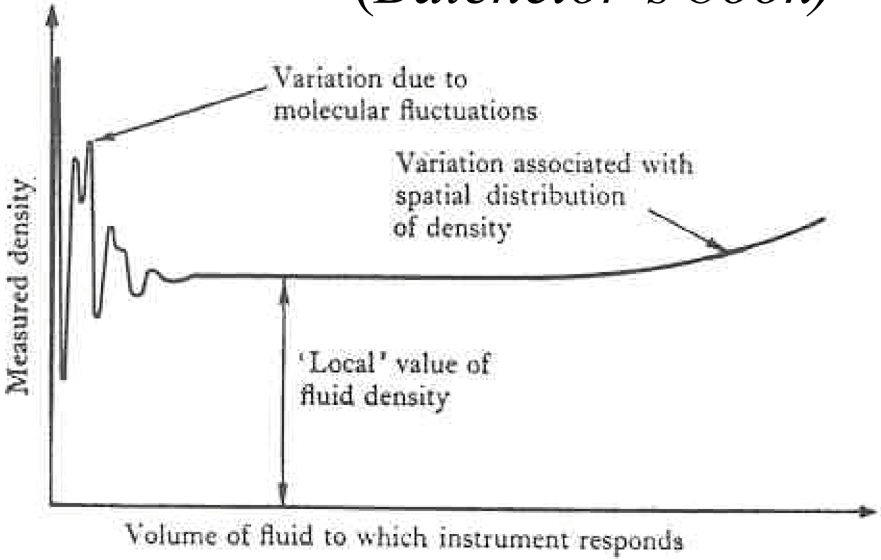


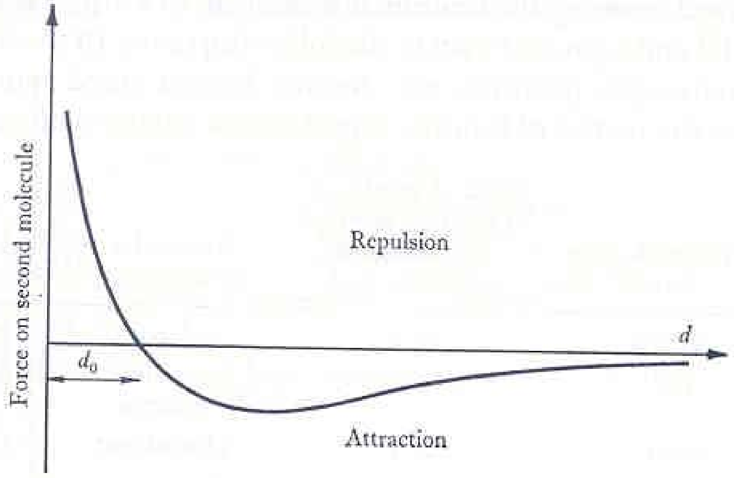
Layering of Lennard-Jones molecules near a smooth surface.

- *3D periodic channel 51.30x29.7x25.65 (molecular units)*
- *27,000 number of atoms*
- *2,592 atoms of each wall (FCC lattice type)*
- *1 atom = 1 unit*

The Continuum Hypothesis

- *(Batchelor's book)*



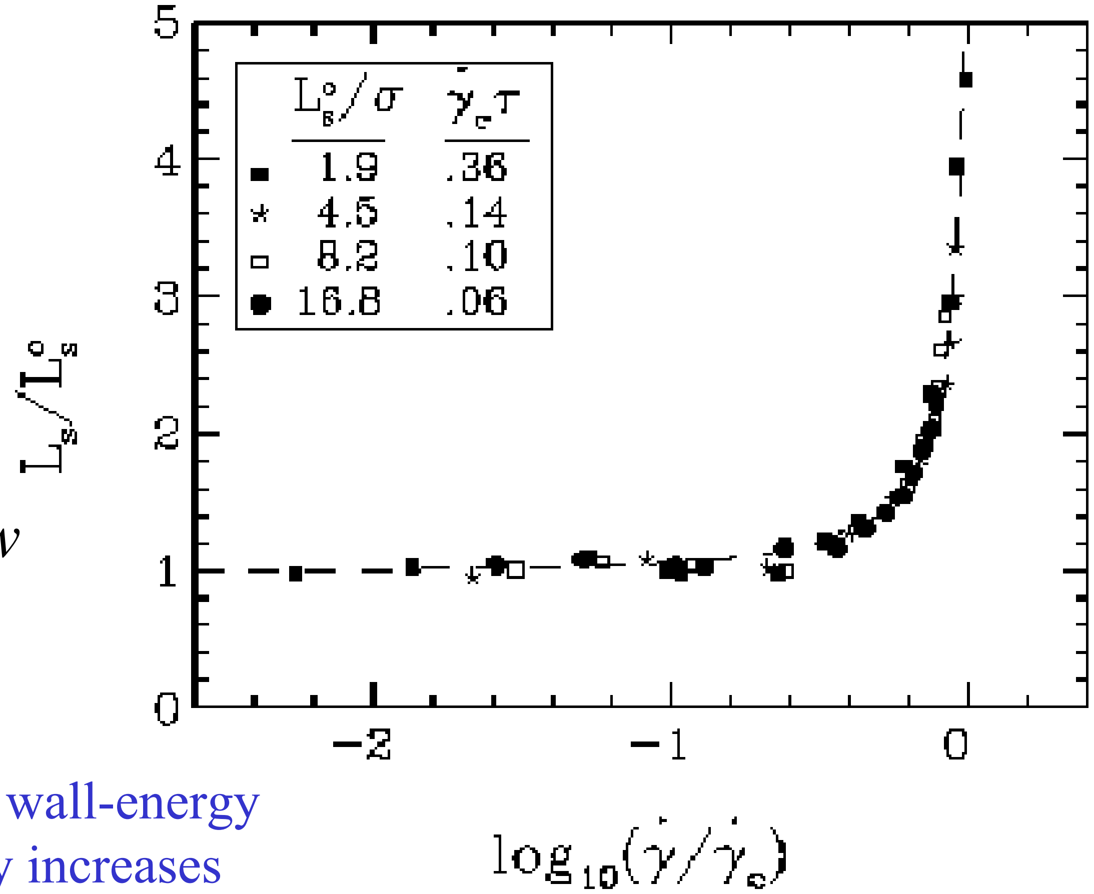


Type	Force (molec)	Motion (d_0)	Structure (molec)	statistics
Solid	Strong	<<1	ordered	quantum
Liquid	Medium	O(1)	Semi-order	quantum+ classical
gas	weak	>>1	disordered	classical

Slip Length in Complex Liquids

(Thompson & Troian, Nature, 1998)

$$\frac{L_s}{L_s^0} = [1 - \frac{\dot{\gamma}}{\dot{\gamma}_c}]^{\alpha}$$



- *MD of Couette flow*
- *Lennard-Jones*
- *$H=25.57\sigma$*

- Slip length increases as wall-energy decreases or wall-density increases
- For slip length > 17σ *:*
strong nonlinear response?

<u>Question:</u> At high shear rates, is the liquid behavior near the wall non-Newtonian<u>?</u>

Physical Challenges of Micro-Scale Transport

- *Gas Flows*
  - Compressibility
  - *Rarefaction*
    - Slip
    - Transition
    - Free Molecular
    - Thermally Induced Motion
  - Surface & Roughness
  - Viscous Heating
  - Incomplete Similitude
  - …

- *Liquid Flows*
  - Wetting
  - Adsorption
  - Slip
  - *Electrokinetics*
  - Polarity
  - Coulomb & van der Waals Forces
  - Capillary Forces
  - Roughness
  - …

Constitutive Laws, Boundary Conditions, Surface, Interface and Body Forces

Micro Flows: Fundamentals & Simulation

Karniadakis & Beskok, Springer, New York, 2001

ISBN 0-387-95324-8

Numerical Modeling Challenges

- Multi Physical Phenomenon (Thermal, Fluidic, Mechanical, Biological, Chemical, Electrical)
- Multi Scale (Atomistic, Continuum)
- Complex Geometry

Numerical Simulation Strategies

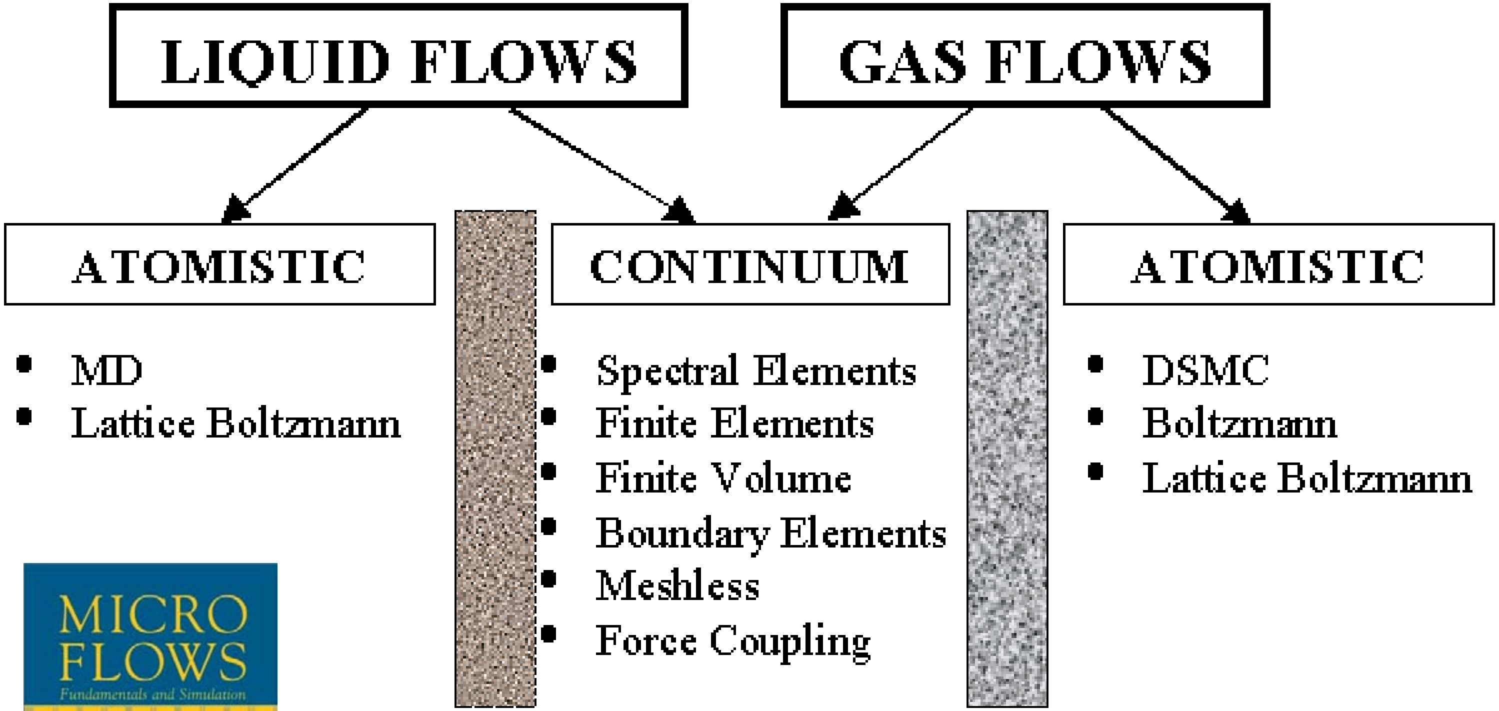
- **Scientific Simulations:**
  - Multi Scale
  - Simpler Geometry
  - Accurate (error < 1 %)
- **Engineering Simulations:**
  - Multi Scale
  - Multi Physics
  - Complex Geometry
  - Accurate (error < 5~10 %)
- **Low Order Models:**
  - Multi Physics
  - Full Device Simulation
  - Lower Accuracy, but Fast (error ~10 %)

Challenges of Microscale Research

- **Small Scale Physics**
  - **Governing Equations Breakdown**
    - **Constitutive Laws**
    - **Boundary Conditions**
  - **Microscopic Effects**
    - **Dominance of Surface Forces**
    - **Coulomb Forces**
    - **Van der Waals Forces**
    - **Capillary Forces**
    - **Importance of Molecular Structure**

- **Detection & Experimental Verification**
    - **Micro Particle Image Velocimetry**
    - **Molecular Fluorescence Velocimetry**

Numerical Modeling Methods



LIQUID FLOWS

GAS FLOWS

ATOMISTIC

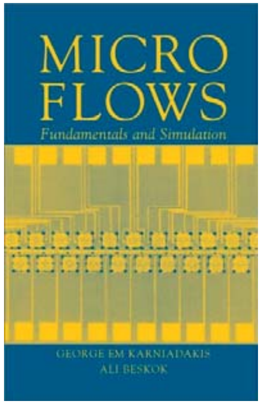
- MD
- Lattice Boltzmann

CONTINUUM

- Spectral Elements
- Finite Elements
- Finite Volume
- Boundary Elements
- Meshless
- Force Coupling

ATOMISTIC

- DSMC
- Boltzmann
- Lattice Boltzmann



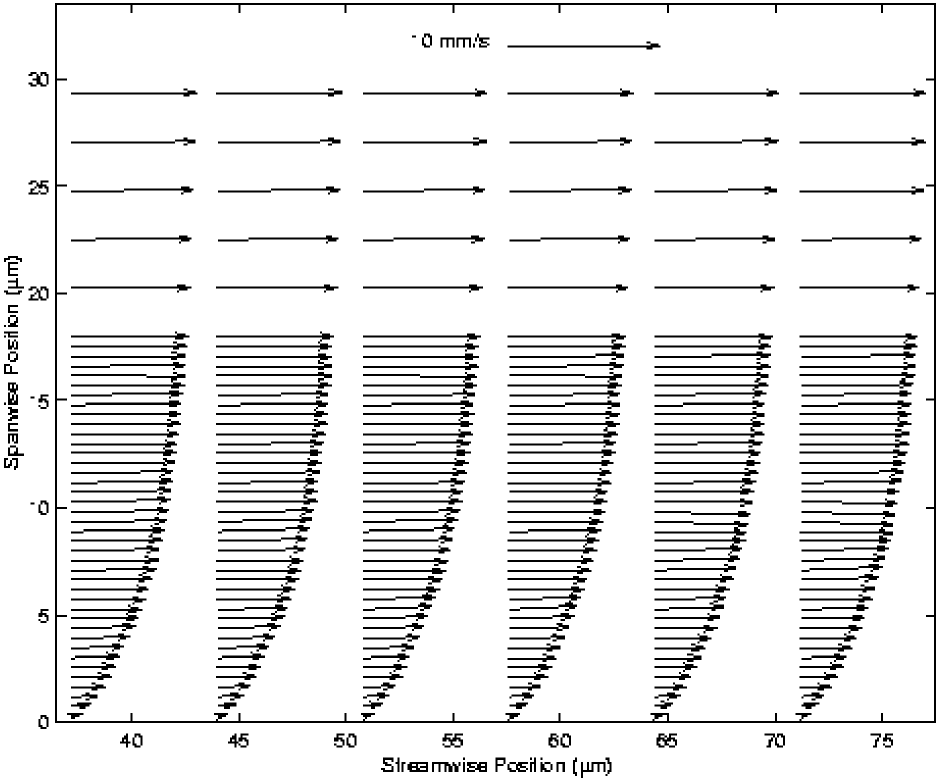
MICRO FLOWS

Fundamentals and Simulation

GEORGE EM KARNIADAKIS
ALI BESKOK

Experimental Limitations

- Micro-Particle-Image-Velocimetry (*Meinhart et al.*)



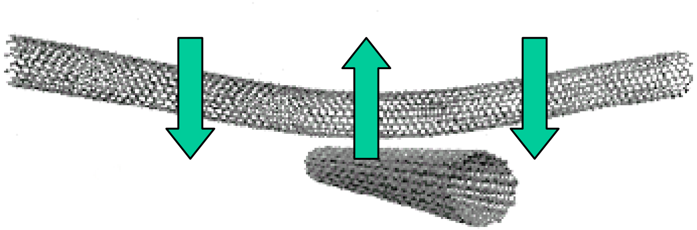
- 30 x 300 microns channel
- Resolution: 450 nm in the wall-normal

- Overlapped windows
- Specialied interrogation algorithms

Prototype Flows

- Pressure-Driven Flows
  - Poieseuille flow
- Shear-Driven Flows
  - Couette flow
  - Cavity flow
- Squeezed Film – Lubrication
  - Reynolds equation
- Electrokinetically-Driven Flows
  - Dielectrophoresis
- Thermal Creep
  - Knudsen compressors
- Surface-Tension-Driven Flows
  - routing of droplets

FUTURE



- Microfluidics:

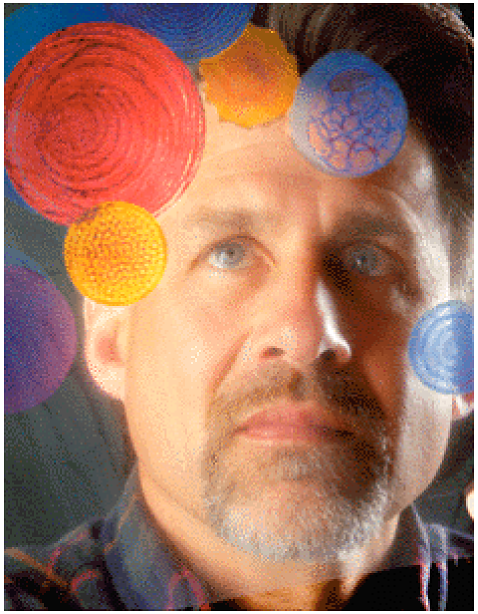
  The path and link to nanotechnology

- The wet circuit → liquid circuit + element

- Fluidic Self Assembly – Massively Parallel VLSI-like, programmable fluidic networks with logic

- Fluids with more than Viscosity – MOEMS

- Complex Fluids
  - Magnetorheological fluids
  - Magnetic (high-frequency) microfluidics
  - Dynamic reconfiguration, use **E** to change properties



Sandia nanospheres

- Wall-less fluidics/interfaces (Bebe, Whitesides)

- Smart dust – Biomimetic sensors