Two-Phase Microfluidic Devices: Theory and Applications

Todd Thorsen
Dept. of Mechanical Engineering
M.I.T.

Panamerican Advanced Studies Institute
Micro-Electro-Mechanical Systems
San Carlos de Bariloche, Argentina
25 de Junio, 2004

Outline for the Talk

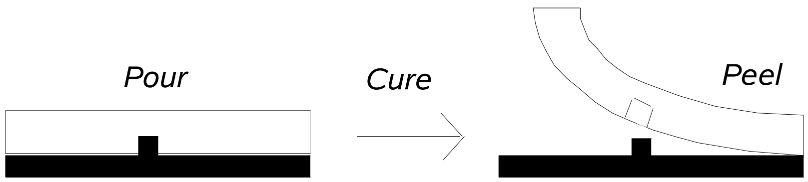
- Introduction to Soft Lithography
  - Chip Fabrication
- Droplet Formation and Pattern Generation
  - Principles
  - Theory
  - Crossflow-based devices
  - In-line devices

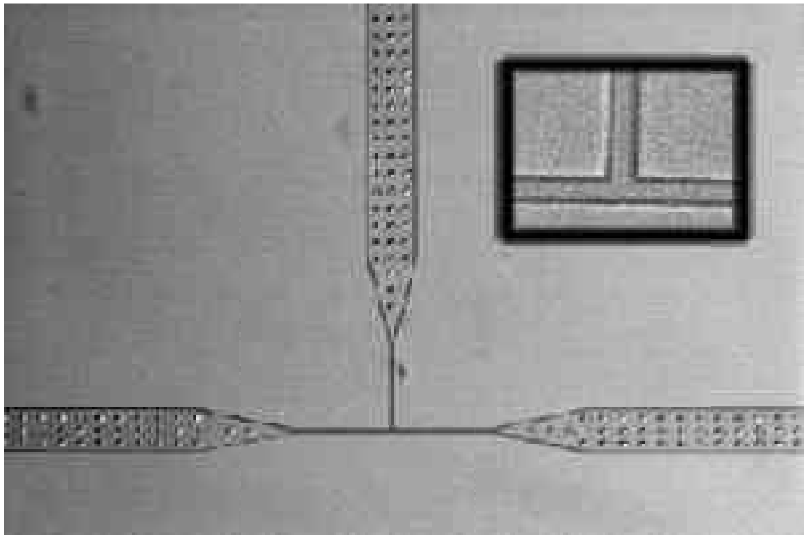
Introduction to Soft Lithography

- Inexpensive and rugged elastomeric materials: PDMS, polyurethane, etc.
- Easy and Forgiving Manufacturing Process
- Disposable and thus no cross contamination
- Simple Flow Design and Integration

Microfabrication

- Mold: Photoresist-patterned silicon wafer
  - Positive relief channel template
- Device: Elastomer
  - Cured on silicon mold
  - High fidelity negative replica of channels
  - Hermetically seals to coverslip





Liquid Metering: Introduction

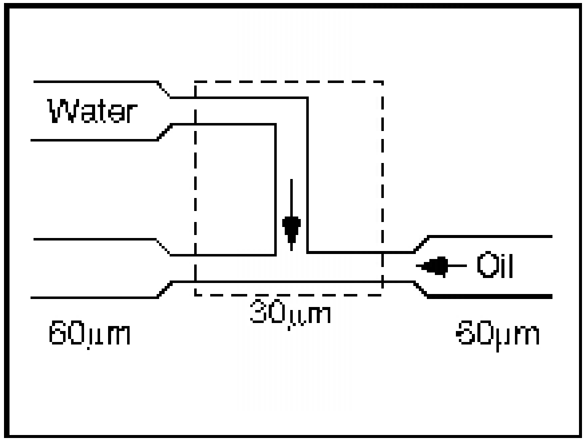
-Picoliter droplet formation driven by surface tension and shear forces and tension at the interface of two immiscible phases

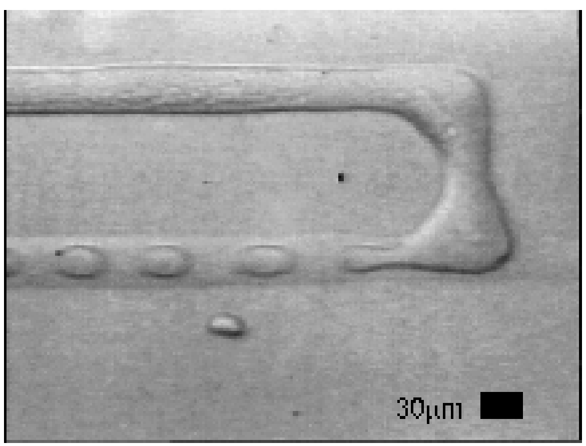
-Precise control of droplet volume, frequency and pattern formation by pressure manipulation

Emulsification

- Batch method (propeller)
- Microfluidic/ capillary crossflow
  - Extruded capillaries
  - Microporous glass (Japan)
  - Microfluidic devices
- Hydrodynamic focusing
  - Liquid ‘squeezed’ between inmiscible phase

Crossflow Dynamics





- Water enters oil perpendicular to the output flow direction
- Precise control of flow rate and droplet size determined by relative pressures of oil and water as well as the channel geometry
- Surfactant in oil phase stabilizes droplets

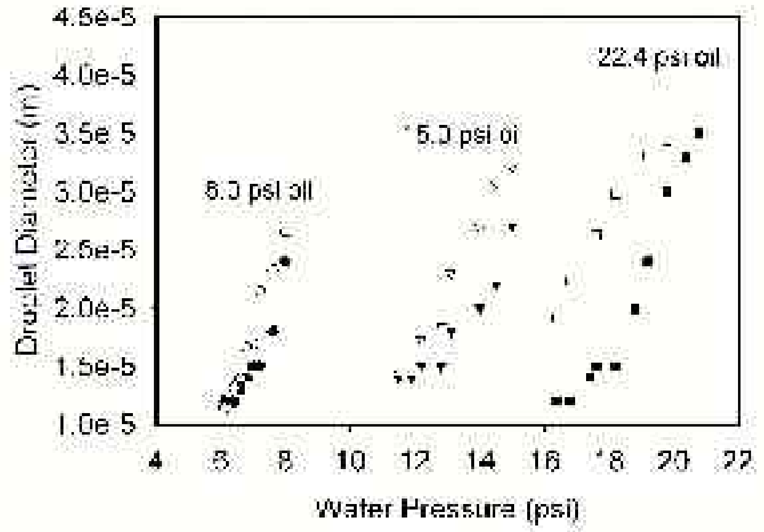
T. Thorsen, R.W. Roberts, F.H. Arnold and S.R. Quake, *Phys.Rev. Lett.* **86**: 4163 (2001)

Nontrivial physics in a microfluidic device

- Microfluidic flow is at low Reynolds' number, i.e. simple linear Stokes flow.
- The interaction between two immiscible fluids introduces nonlinearity and instability.
- These are essential ingredients for pattern formation in dynamical systems.

Physics of Crossflow Droplet Formation

- Droplet formation is a balance between the interfacial tension and the shear force present in the system



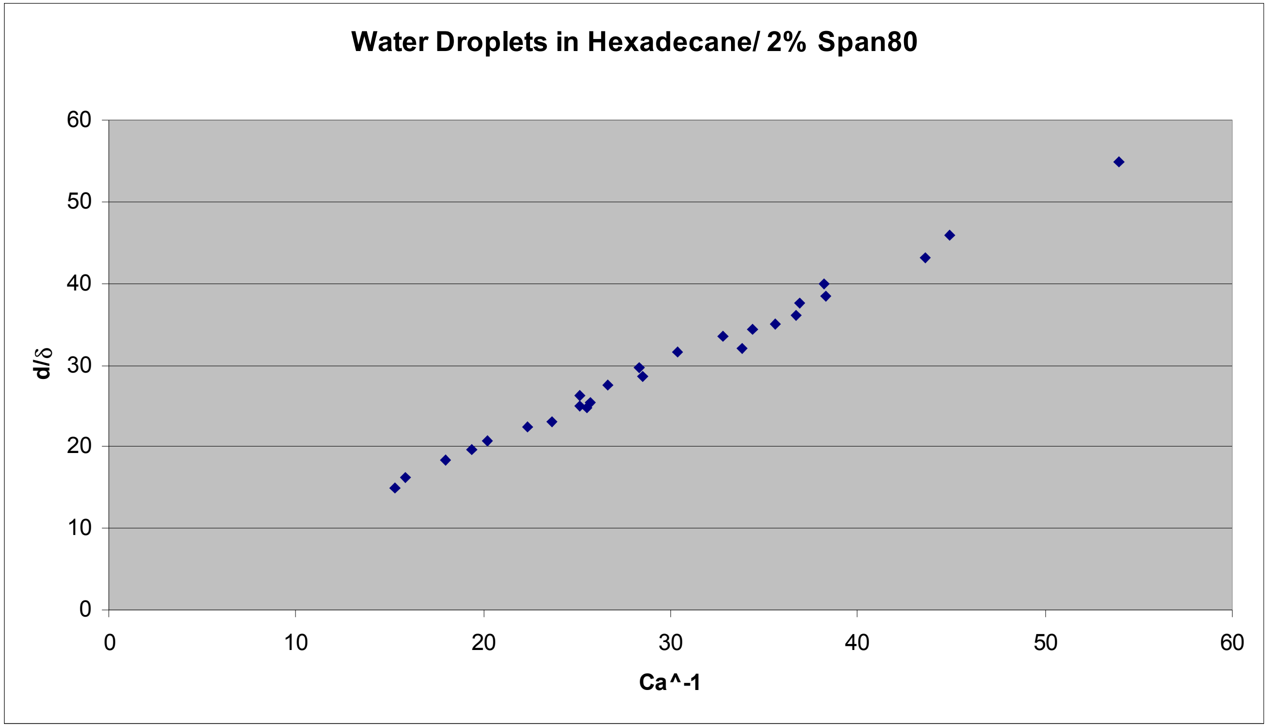
- Droplet radius=$\sigma/\eta\varepsilon$

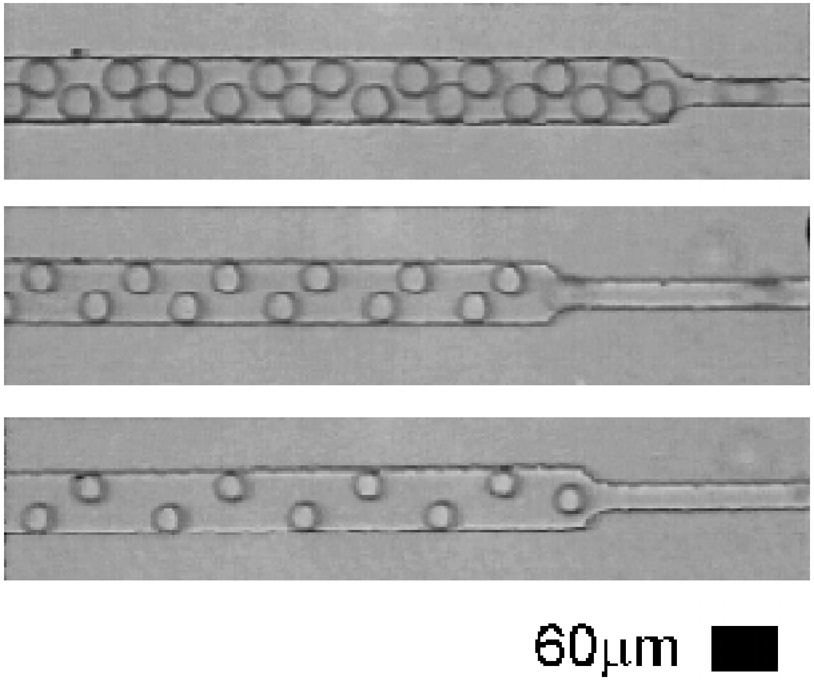
Physics of Droplet Formation 2

- As the impinging water stream never blocks the continuous oil/surfactant solution at the crossflow junction, high shear forces are generated
- Droplet deformation occurs only when the viscous shear stress of the continuous phase, $\eta_e \varepsilon$, overcomes the characteristic Laplace pressure, σ/d, where η_e is the viscosity of the continuous phase, ε is the shear rate, d is the droplet diameter and σ is the interfacial tension between the water/oil/surfactant.
- Rupturing occurs when the Capillary number, $Ca = \eta_e d/2\sigma$, exceeds a critical value less than order unity under simple shear flow, which implies that a droplet has been elongated by viscous shear before rupturing

Physics of Droplet Formation 3

- Estimating the shear rate by $2\nu/\delta$, where $\delta \sim$ the minimal channel dimension and ν is the velocity of the fluid in the gap, droplet diameter is simply inversely proportional to the Capillary number…….. $d/\delta = Ca^{-1}$

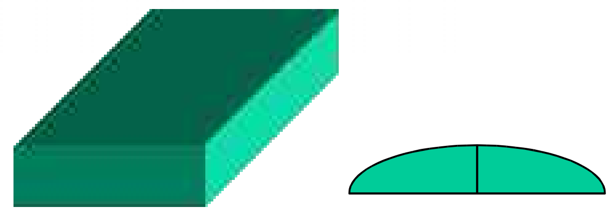




13.1/12.4

12.1/12.4

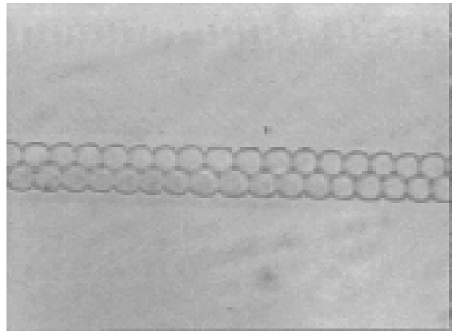
11.1/12.4



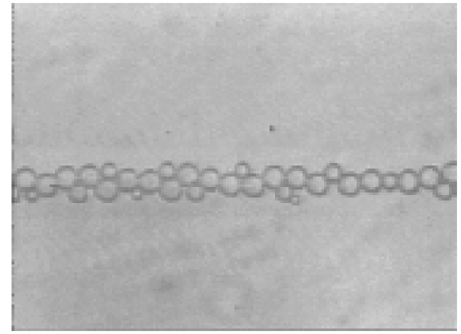
In channels with square cross-sections, the droplets associate with one of the walls and are always spatially separated.

But when the cross section is curved...

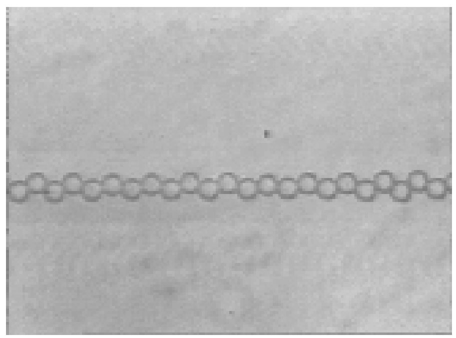
Reverse Micelle Formation in Microchannels Containing Hexadecane/ 2% Span80



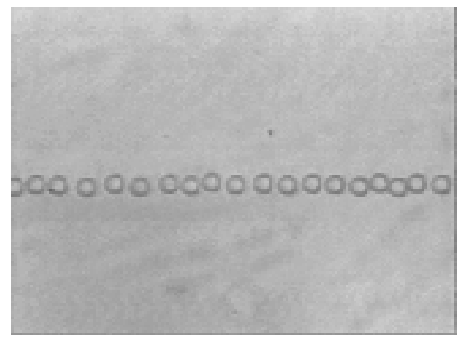
9.1/8.0 psi w/o-s



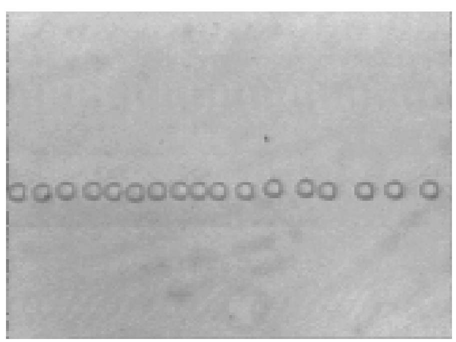
8.4/8.0 psi w/o-s



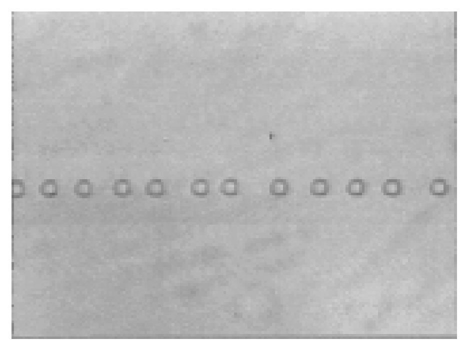
8.0/8.0 psi w/o-s



7.6/8.0 psi w/o-s



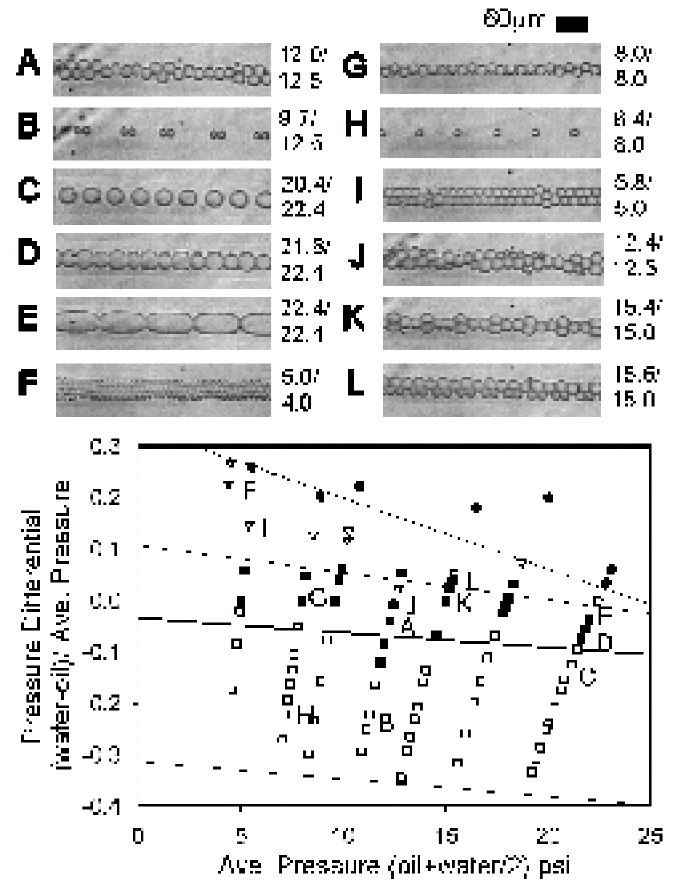
7.2/8.0 psi w/o-s



7.0/8.0 psi w/o-s

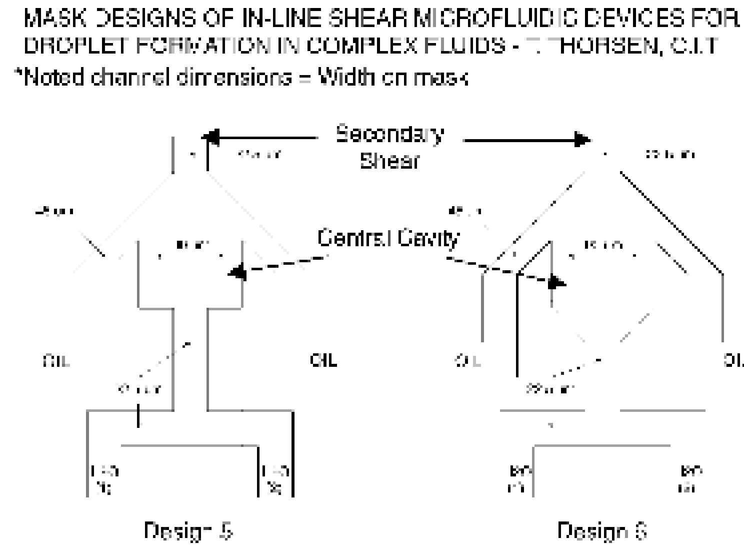
Dynamic Pattern Formation

- Droplet become locked in metastable patterns, reminiscent of "jamming" phenomena of granular systems
- Patters range from monodisperse droplets to complex ribbons



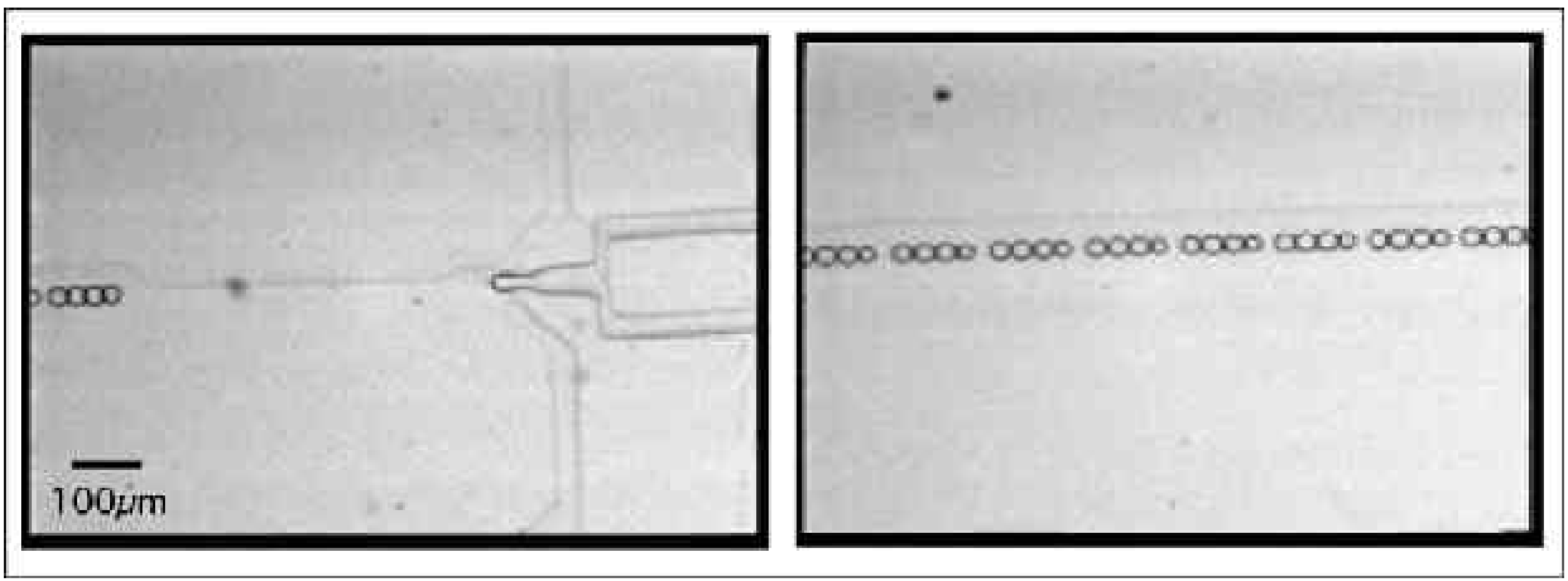
In-line Microfluidic Devices: Hydrodynamic Focusing

- In contrast with crossflow-based microfluidic droplet formation, disperse phase is squeezed by the continuous phase, generating thread instability and subsequent drop formation



Viscosity Mismatch and Front Propagation

- Focused water stream retracts as water droplets are sheared off in clusters with regular periodicity
- Behavior resembles ‘front propagation’ of viscous Rayleigh capillary instability of a cylindrical surface.

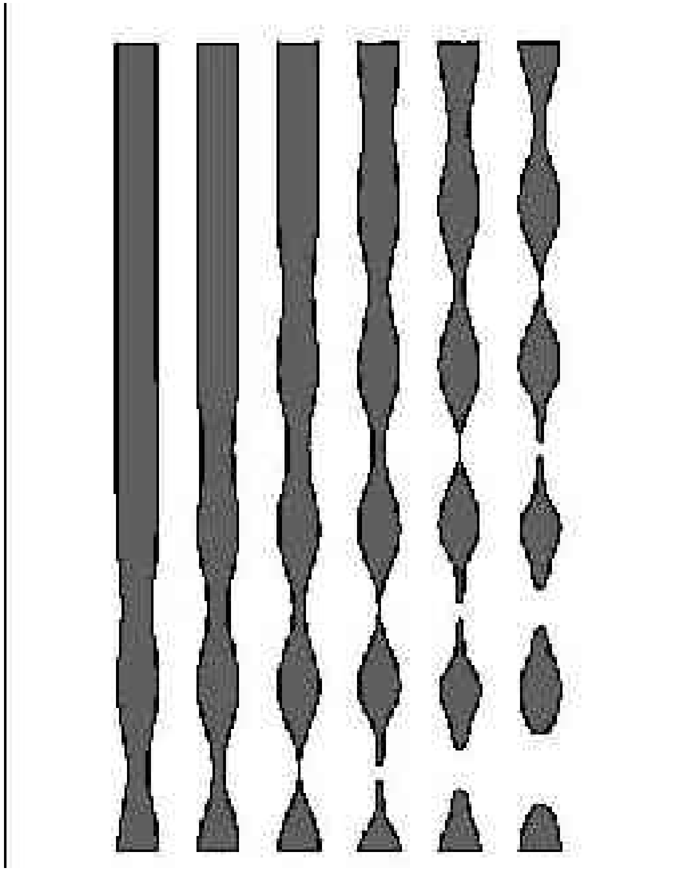


Front Propagation Theory

- Capillary instability occurs as liquid is subjected to destabilizing forces
- Front propagation of the Rayleigh instability, suggested by mathematical modeling studies of two immiscible fluids, occurs as the instability generated at a droplet tip propagates faster than the liquid thread can retract.
- Observed for intermediate λ values ($.001 < \lambda < 0.1$)

Front Propagation 2

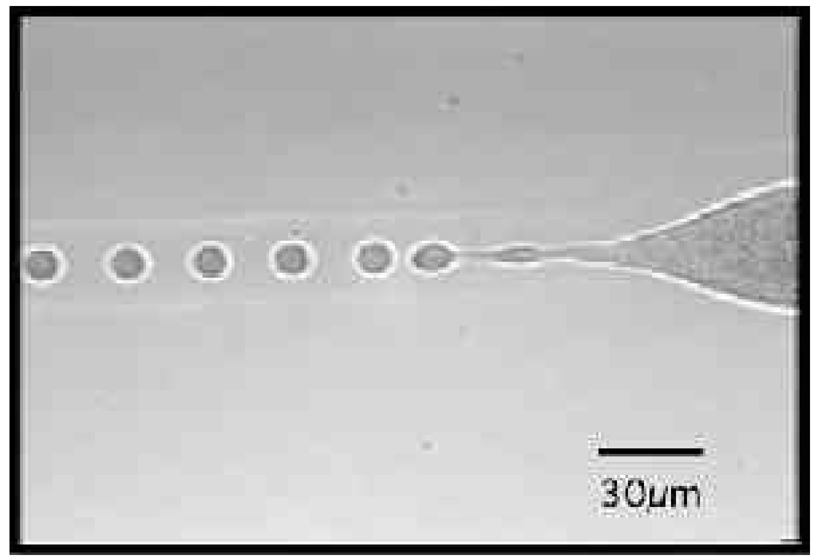
- Pinching occurs faster than thread retraction, releasing a burst of droplets
- For λ<.001, droplets break off before end retracts
- For large λ….



Powers, T.R. and Goldstein, R.E. *Phys. Rev. Lett.* 78 (13): 2555-2558

Matched Viscosity Systems

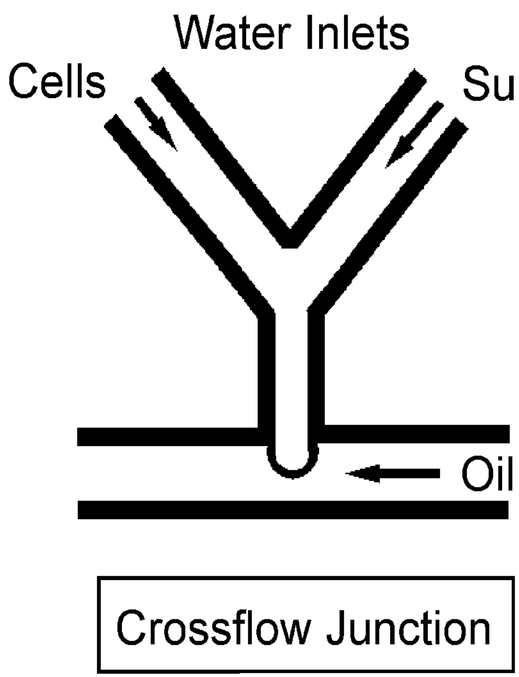
- N-hexane/ DMF (λ=0.3)
- Tip stream regularly expands and contracts, producing regular, monodisperse droplets



Applications

- Biochemical screening
  - Single-cell assay system
- Generation of uniform colloidal assemblies
- Photonic ball synthesis

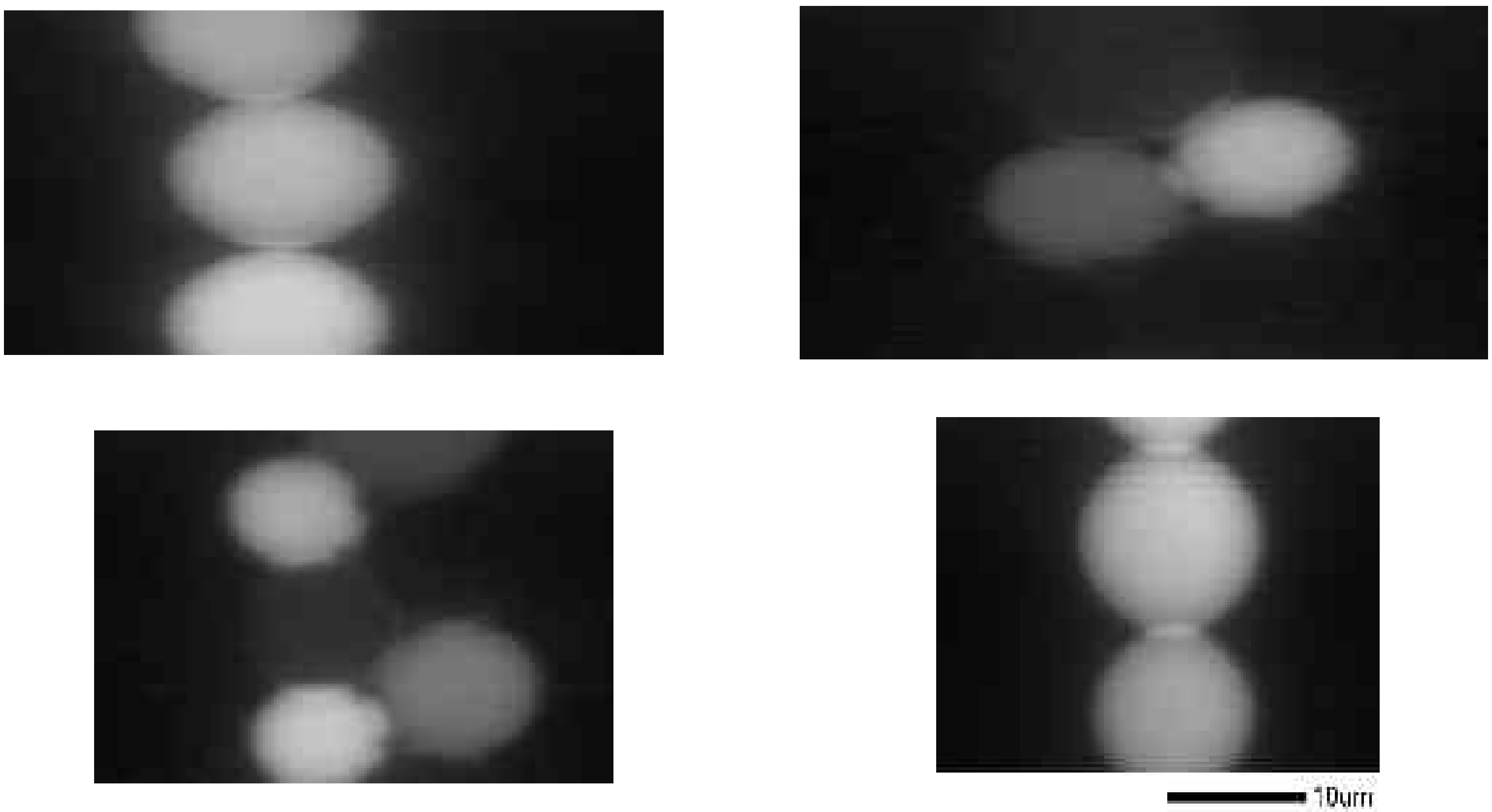
Reverse Micelles as Bioreactors



- *E.coli* expressing enzyme injected into one water channel
- Substrate introduced in separate water channel
- *E.coli*/substrate mix at crossflow junction and are compartmentalized into droplets in the oil stream
- Product visualized as substrate is converted to product inside of the droplets

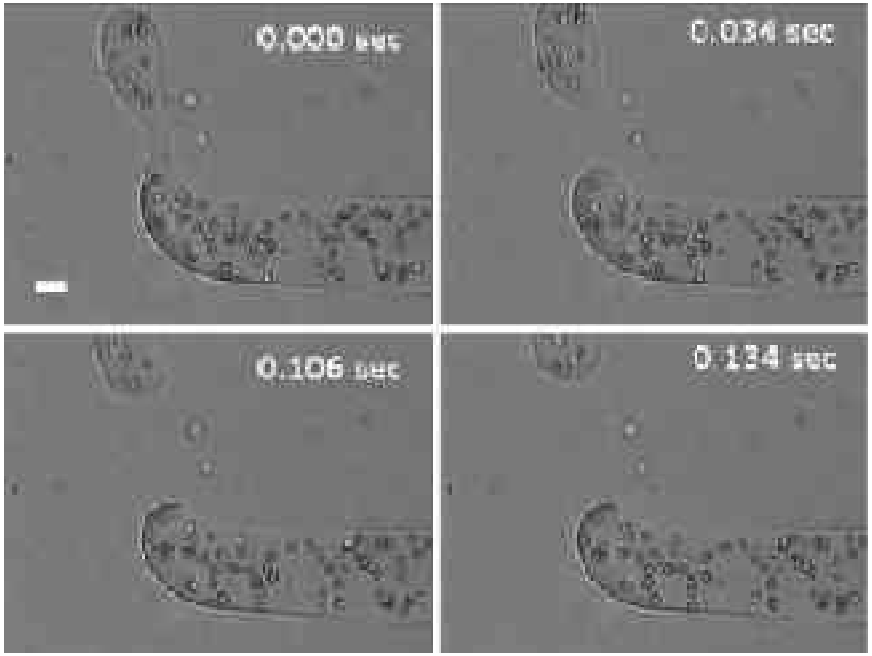
Reverse Micelles in PDMS Microchannels

Encapsulated *E.coli p*NB esterase with fluorescein diacetate substrate



Colloidal Assembly

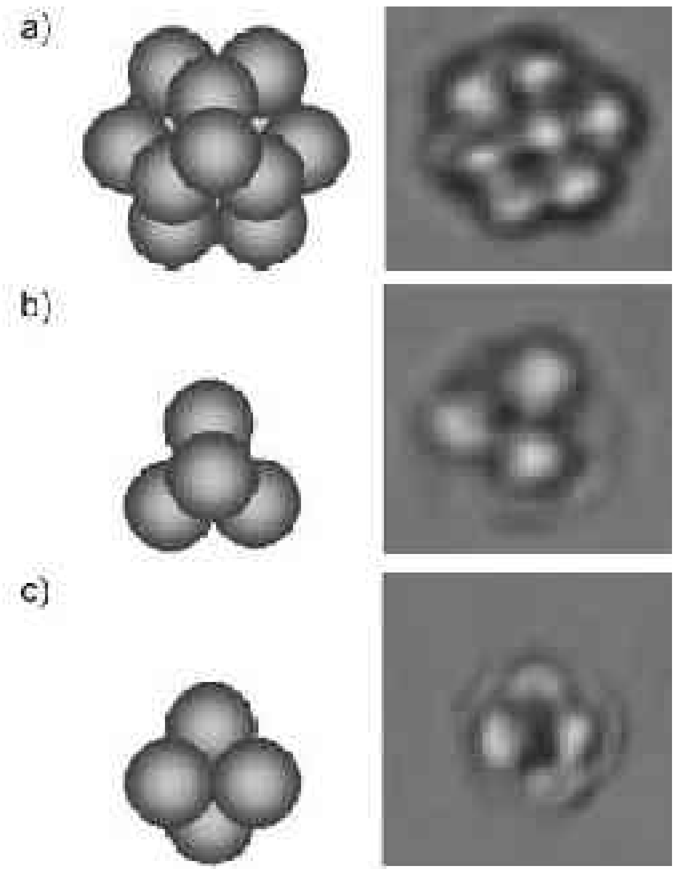
- Potential applications in:
  - Display technology
  - Nanobarcoding
  - Photonic bandgap materials



Yi, G.-R., Thorsen, T., Manoharan, V.*et al.* *Adv. Materials*. **15** (15): 1300 –1304 (2003)

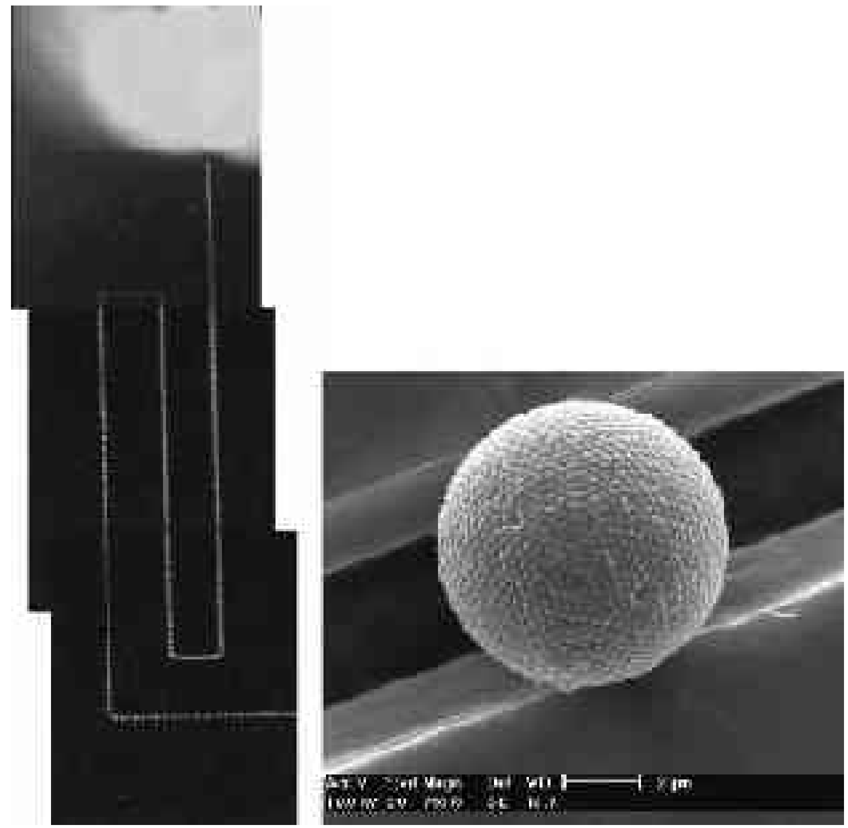
Model colloidal assemblies

- Volatile disperse phase mixed with beads allows beads to be shrink-wrapped as solvent is drawn out of the droplet in the microchannels



Uniform Photonic Ball Synthesis

- 230 nm poly (styrene/styrene sulfonate particles)
- Monodisperse
- Particles adopt forced geometry which may have interesting photonic properties



Yi, G.-R., Jeon, S.-J., Thorsen, T.*et al.* *Synthetic Materials* ***139****(3) 803-806 (2003)*

Summary

- Two-phase microfluidic systems have interesting properties which lend themselves to both theoretical and applied research applications
- Future work
  - Advanced modeling/ flow analysis
  - Applied systems with both biological
  and engineering applications

Acknowledgements

- Thorsen Laboratory at M.I.T.
  - J.P. Urbanski, Graduate Student
- Dr. Stephen Quake and group members at Caltech
- Dr. David Pine and group members at UCSB
- Dr. Ronald Probstein, Mechanical Engineering, M.I.T.