Visualization of Flow Inside a Small Evaporating Droplet

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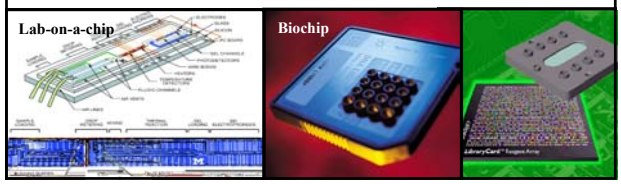
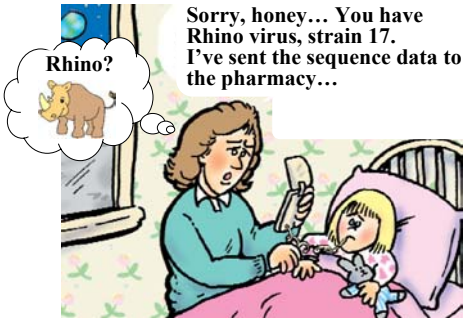
Motivation

- Growing interest in controlling microscale flow such as in Lab-on-a-chip.
- Fabrication of 3D microstructures is very difficult and expensive.



Everyone's a (future) doctor.



(from M. Burns 2002, Science)

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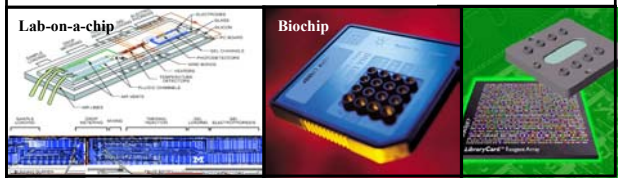
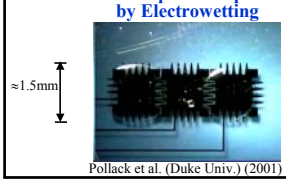


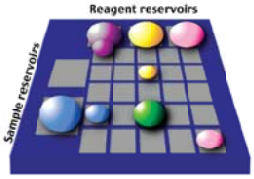
Motivation

- Droplet-based microfluidic operations
  - By programmed electric signals rather than by complex physical structures.
  - Fabrication process becomes very simple.

Micro-droplet manipulation by Electrowetting



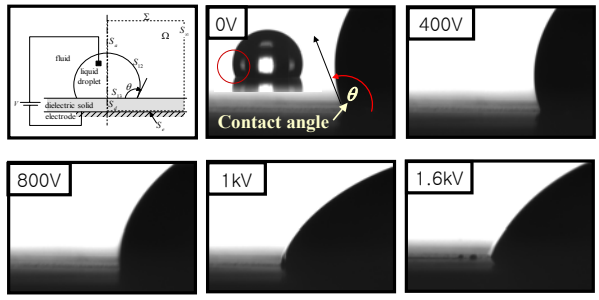
Pollack et al. (Duke Univ.) (2001)



C.-J. Kim et al. (UCLA) (2002)

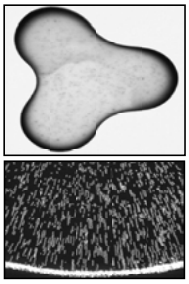
Motivation

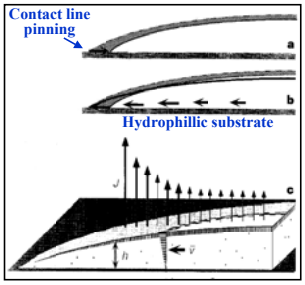
- Contact angle control by electrowetting



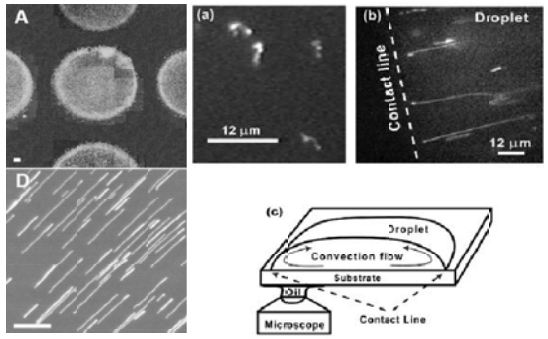
Backgrounds

- Formation of ring strains of a coffee droplet

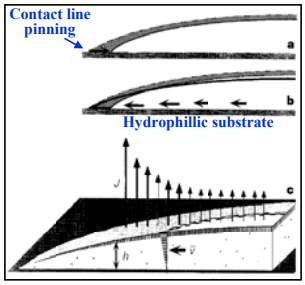




DNA stretching by the droplet flow



On a hydrophillic surface (small contact angle)



Flow: nonuniform evaporation + mass conservation

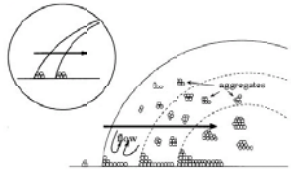
↑ McHale et al. (1998)

Contact angle

↑ Uno et al. (2002)

Particle accumulation

On a *hydrophobic* surface (large contact angle)



Uno et al. (2002) Colloid Polym Sci. 276.

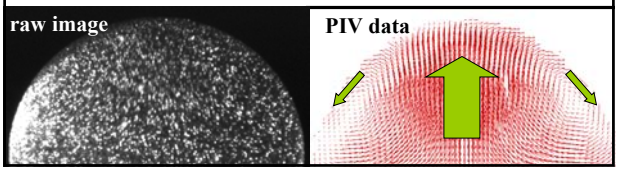
Evaporation

?

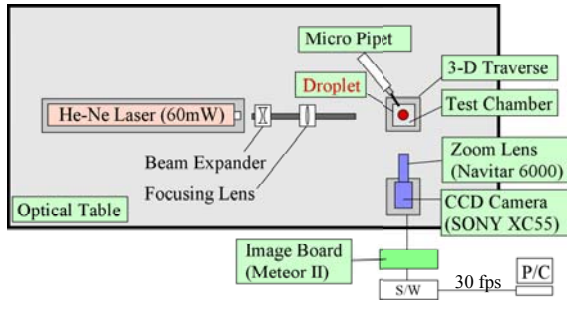
Flow?

Objectives

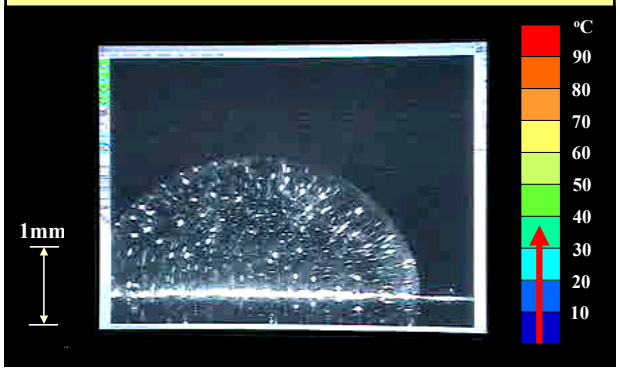
- Flow pattern and generation mechanism on a hydrophobic surface.
- Develop a method to compensate for the *light refraction effect*.



Experimental setup



Flow inside a droplet on a heated plate



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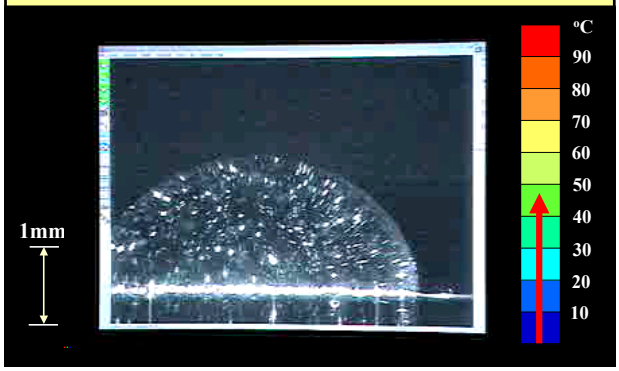

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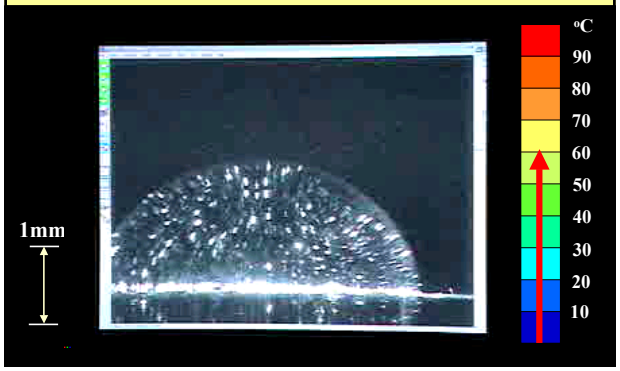
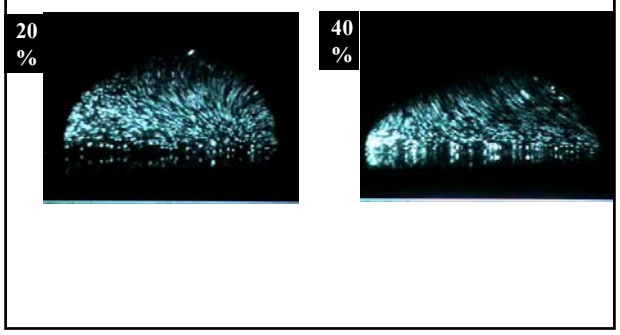


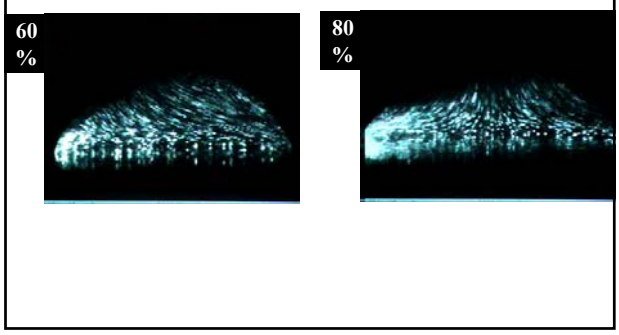
Flow inside a two-component droplet

- Case of heated droplets
  - Sophisticated temperature control devices are necessary.
  - Contact angle is a function of temperature.
- Case of evaporating (two-comp.) droplets
  - Almost spontaneous flow.
  - Easy to generate.

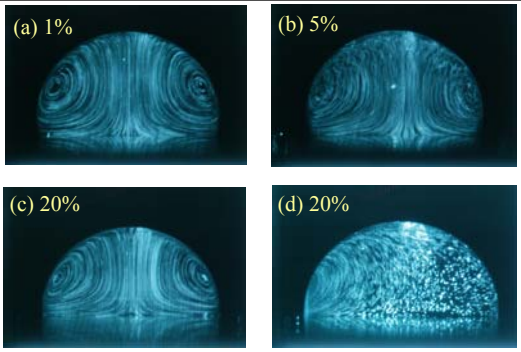
Flow inside an alcoholic droplet



Flow inside an alcoholic droplet

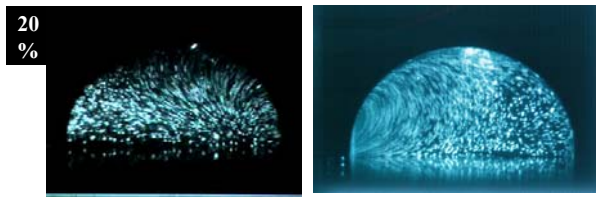


Typical flow patterns

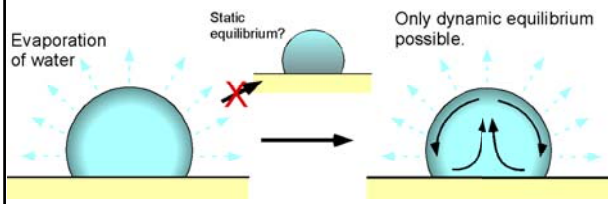


How does the flow generated?

- For *high* evaporation rate: *Marangoni convection*

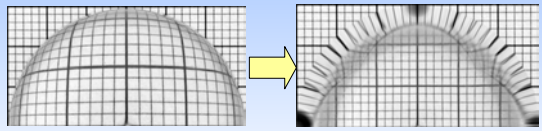


How does the flow generated?



- For *low* evaporation rate: *Rayleigh convection*
  - Concentration gradient by evaporation

Image Correction by Ray Tracing Method



Ray tracing method – simulation

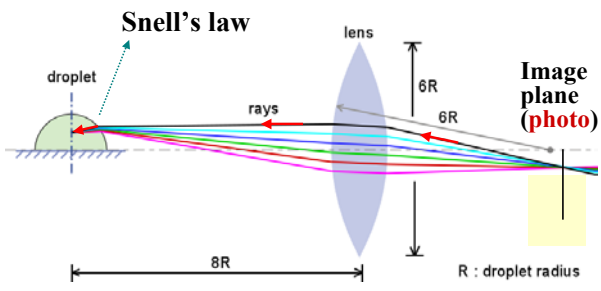
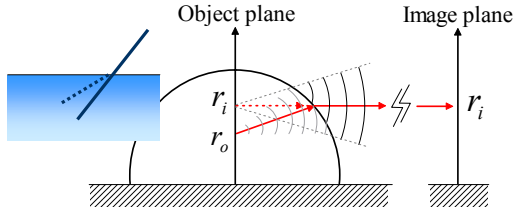
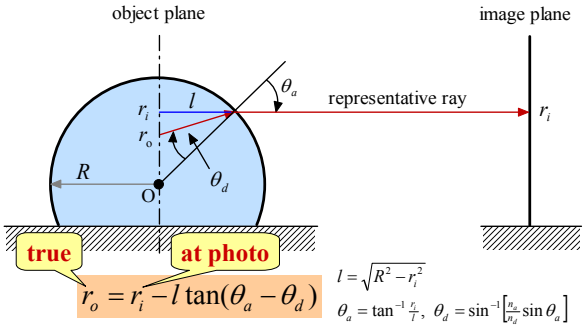


Image restoration: ray tracing method

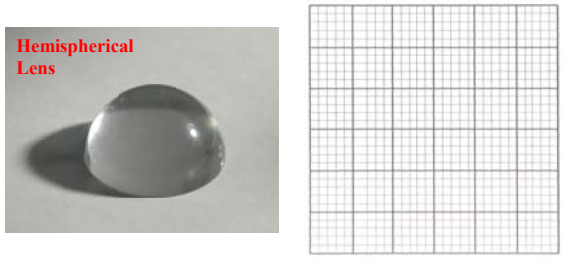


A object at r_o is seen as if it is at r_o due to refraction effect.

Image restoration: ray tracing method



Simulation of lens effect of hemispherical lenses



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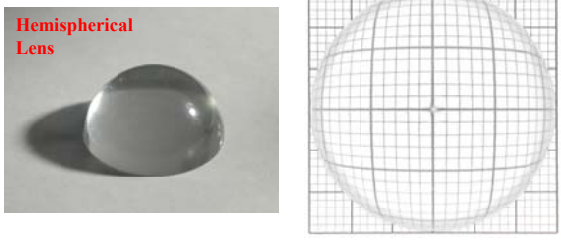

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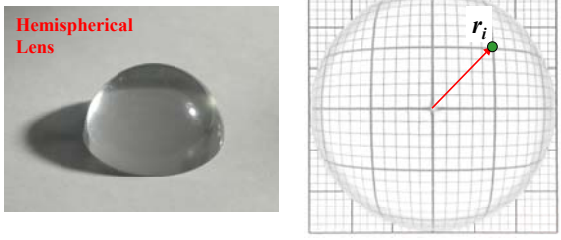


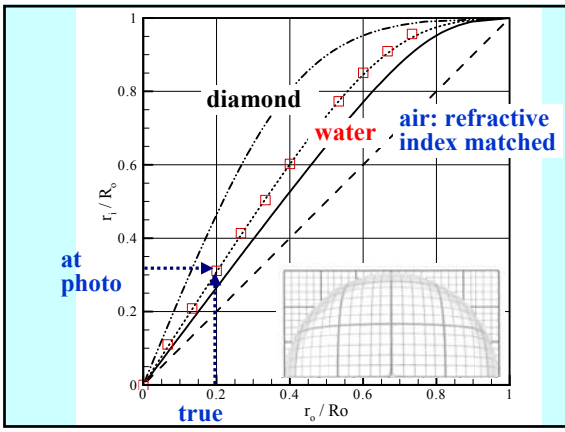
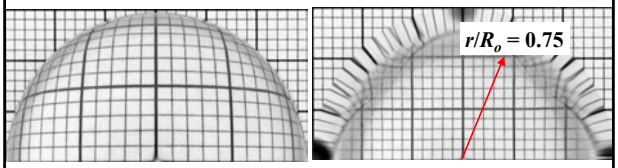


Image restoration by ray tacing method

- Center region is satisfactory ($r/R_o < 0.75$).
- At the edge, poor performance due to jamming of rays.

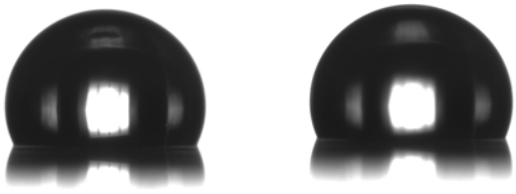


(a) raw image of regular mesh (b) restored image of (a)

Image Correction and PIV

Evaporation of droplet

KCl 1M 5μl Deionized water (pure water)



1mm Time: 0 min

Evaporation of droplet

KCl 1M 5μl Deionized water (pure water)

1mm Time: 10 min

Evaporation of droplet

KCl 1M 5μl Deionized water (pure water)

1mm Time: 20 min

Evaporation of droplet

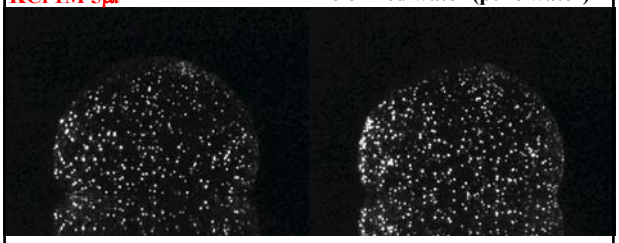
KCl 1M 5μl Deionized water (pure water)

1mm Time: 30 min

Flow inside evaporating droplets

KCl 1M 5μl

Deionized water (pure water)



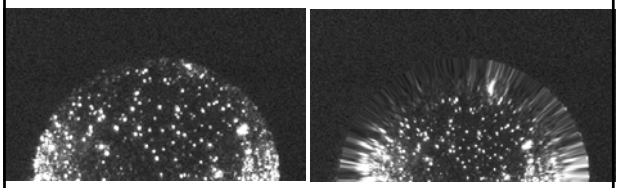
1mm

Seeding particle
- polystyrene (3μm), 0.5% in volume ratio

Image restoration and PIV

Raw image 1

Transformed image 1

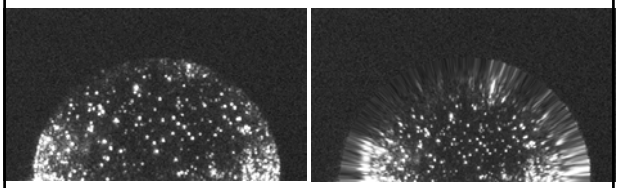


PIV algorithm: Two-Frame PIV

Image restoration and PIV

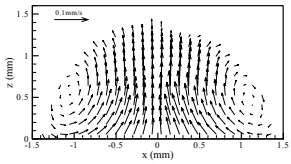
Raw image 2

Transformed image 2

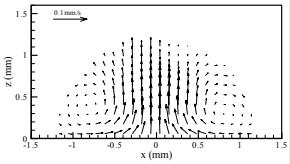


PIV algorithm: Two-Frame PIV

Effect of image restoration on velocity vectors (KCl 1M)



(a) before image restoration



(b) after image restoration

Concluding remarks

- Existence of a flow inside *two-component* droplets is firstly shown.

  No flow inside a pure liquid droplet!

- *Quantitative visualization* method for flow inside a droplet is developed.
  - -Edge region is not corrected well.
  - -Provides useful data for numerical investigations.

Concluding remarks

- Further study is necessary.
  - *Inter-relationship with contact angle.*
  - Effect of colloidal particle on flow.