



# Dye Flow through a Paper Microfluidic Chip

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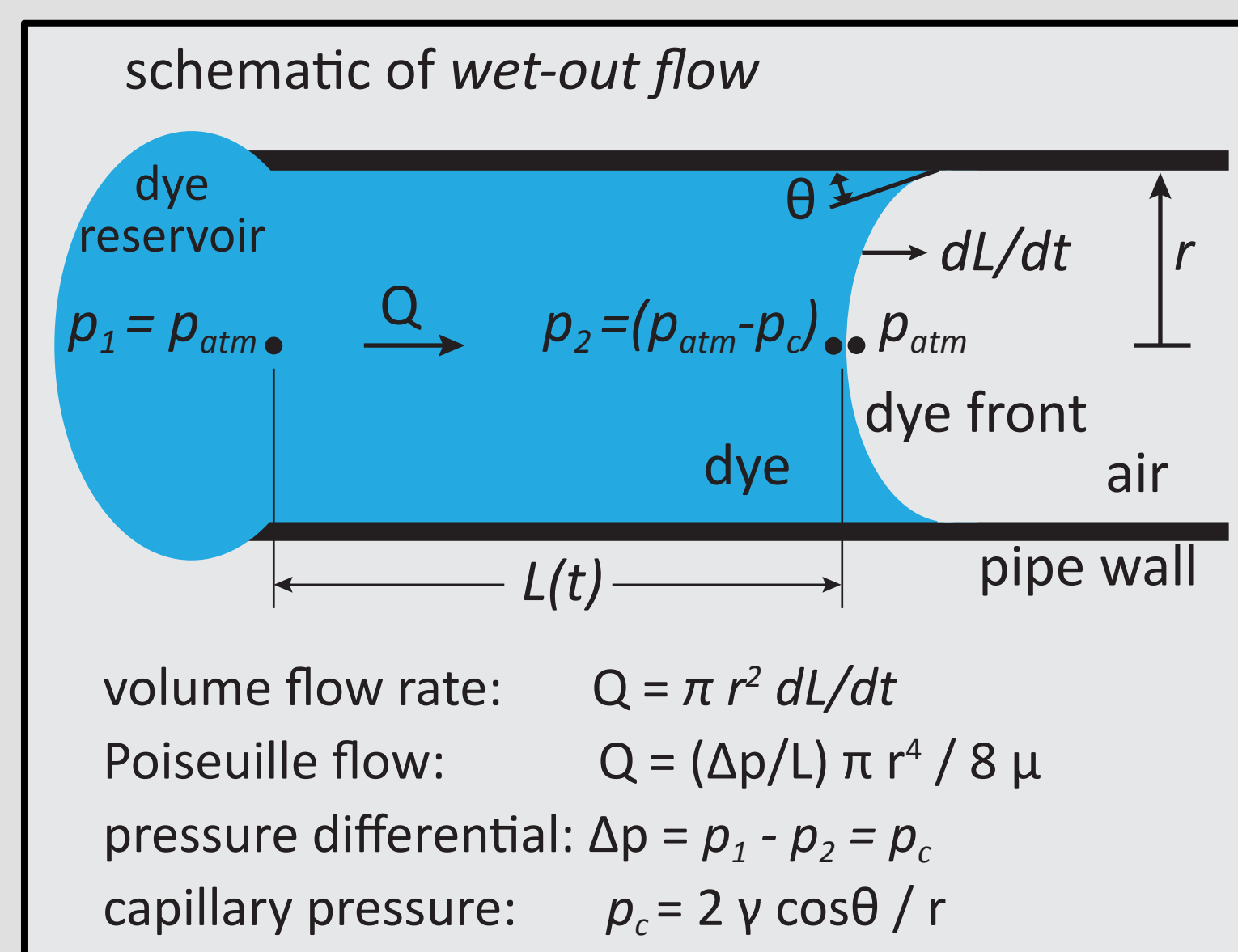
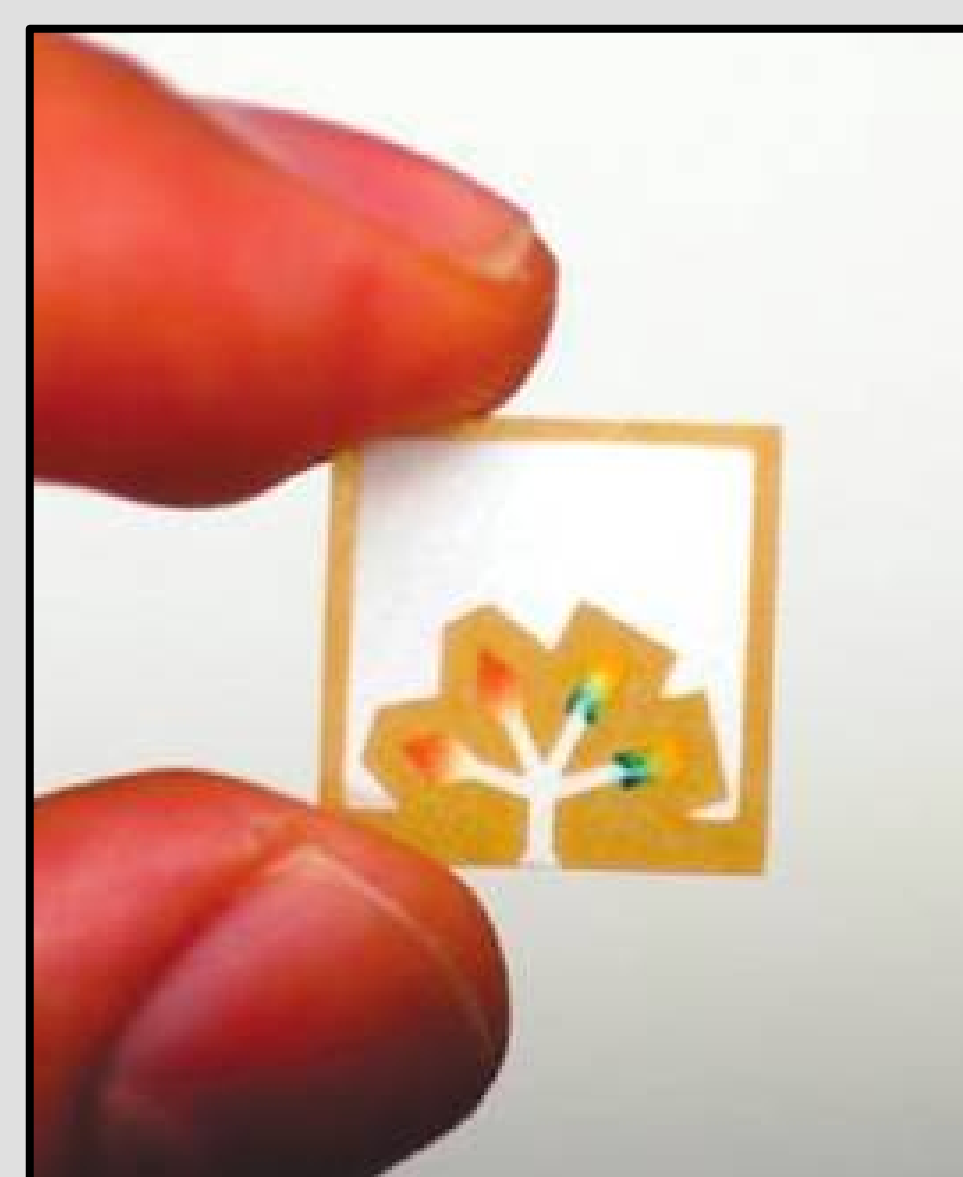
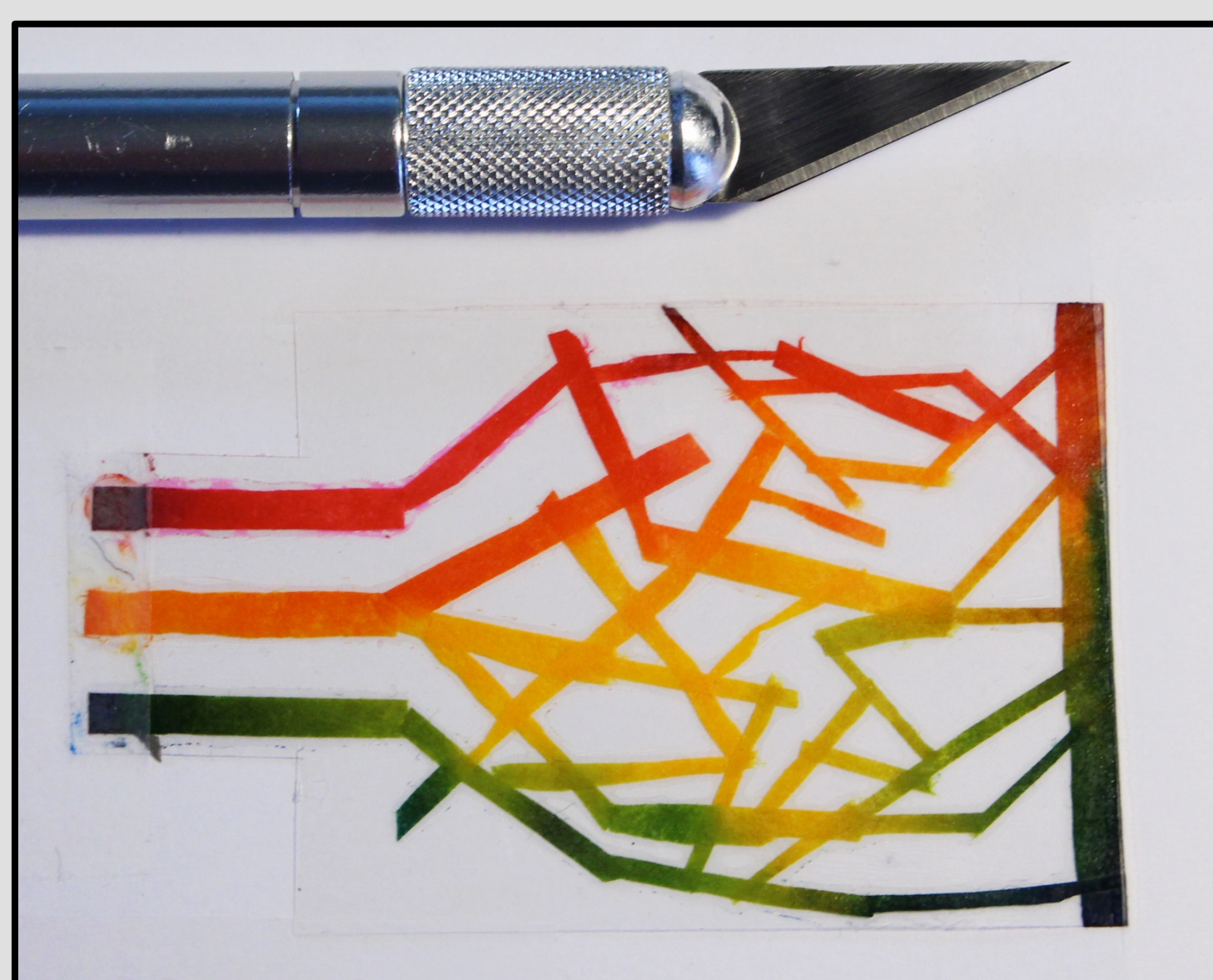
Microfluidic devices can enable quantitative analysis of very small samples of liquids in applications such as healthcare [1], environmental monitoring [2], and food safety [3]. Common devices include the home pregnancy test and the blood glucose meter. Paper-based diagnostic test strips are a low-cost, lightweight, and disposable technology, making them viable for use in developing countries [1]. The physical principle underlying these devices is that of capillary action.

The top image depicts a *wet-out flow*, in which an advancing dye front fills a paper microfluidic chip. The front is pulled ahead by surface tension forces, with the flow rate limited by viscous friction. An elegant model of the wet-out flow was proposed by Washburn [4], who assumed that a porous medium could be modeled as a collection of circular cylinders. Assuming Poiseuille flow in a cylinder of radius  $r$  currently filled to length  $L$  by a liquid with dynamic viscosity  $\mu$ , the speed of advance of the front is  $dL/dt = (\Delta p/L)(r^2/8\mu)$ . The pressure differential driving the flow is the capillary pressure:  $\Delta p = 2 \gamma \cos\theta / r$ , where  $\gamma$  is the surface tension and  $\theta$  is the contact angle. Integrating yields the length of pipe filled with fluid:  $L^2 = (\gamma \cos\theta r / 2 \mu) t$ . For a porous medium assumed to be composed of many cylinders of various lengths and radii, an effective radius  $R$  can be formed, such that in general:

$$L^2 = (\gamma \cos\theta R / \mu) t.$$

Interestingly, although the wet-out flow is *not* a diffusion process, this equation resembles the general form for a diffusion process:  $L^2 \sim (\text{constant}) t$ . For example, momentum diffusion is governed by  $L^2 \sim \nu t$ , and heat diffusion by  $L^2 \sim \alpha t$ , where  $\nu$  is the kinematic viscosity (momentum diffusivity) and  $\alpha$  is the thermal diffusivity. The quantity  $(\gamma \cos\theta R / \mu)$  has the units of diffusivity, but it represents the macroscopic balance between surface tension and viscous forces.

The paper microfluidic chip imaged herein was created using coffee filter paper and clear tape. Red, yellow, and blue food coloring highlight different pathways through the circuit, with orange and green sections indicating where dye has mixed. The three dyes advance through the paper at different rates, resulting in a beautiful blend of colors.



**Figure:** (top) artistic visualization of flow through a paper microfluidic chip using colored dye (image enhanced by adjustment of color saturation and tone as well as digital image filtering); (left) microfluidic chip with X-Acto knife for scale; (center) paper-based analytic device for point-of-care medical diagnostics (image copied from [1]); (right) schematic of *wet-out flow*.

## References:

1. A.W. Martinez, S.T. Phillips, G.M. Whitesides, and E. Carrilho, "Diagnostics for the Developing World: Microfluidic Paper-Based Analytical Devices", *Analytical Chemistry*, **82**:3–10, 2010.
2. R. Rusconi, M.S. Garren, and R. Stocker, "Microfluidics expanding the frontiers of microbial ecology", *Annual Review of Biophysics*, **43**:2.1-2.27, 2014.
3. A. Escarpa, "Lights and Shadows on Food Microfluidics", *Lab on a Chip*, **14**:3213, 2014.
4. E.W. Washburn, "The Dynamics of Capillary Flow", *Physical Review*, **17**:273, 1921.