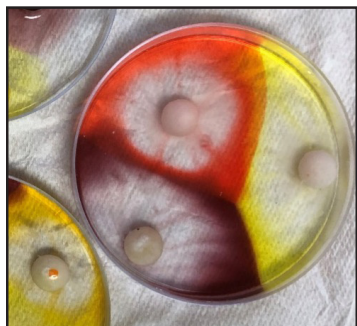


## Visualizing Bulk Flow in Mass Transfer with Dissolving Candy

Elementary school teachers and chemical engineering professors agree that watching Skittles™ dissolve into water provides a beautiful visualization of diffusion with only a few minutes of waiting.<sup>[1]</sup> But upon deeper examination, Fick's Law cannot explain this demonstration! Typical liquid-phase diffusivities of small molecules are  $10^{-6} - 10^{-7} \frac{\text{cm}^2}{\text{s}}$ ; even a proton with its Grotthus mechanism reaches only  $D_{H^+} = 9.3 \times 10^{-5} \frac{\text{cm}^2}{\text{s}}$ . Observing visible color changes over a centimeter should therefore take  $\tau = \frac{l^2}{D} \approx 10^5 \text{s}$ , over an hour. Furthermore, if the demonstration goes longer, the candy colors will diffuse up the concentration gradient to form a concentrated ring of food dye, as shown in Figure 1! What is happening?



**Figure 1.** Formation of a concentrated ring of food dye due to bulk flow from a concentrated sugar solution.

The answer lies in a nuanced concept that often challenges undergraduates: bulk flow. The magnitude of dye flux,  $N_{\text{dye}}$ , demands bulk fluid flow that drives the flux outward faster than diffusion alone (Eq. 1).

$$N_{\text{dye}} = -D_{\text{dye}} \nabla c_{\text{dye}} + c_{\text{dye}} \mathbf{v} \quad (1)$$

Considering that the water is initially quiescent, there are three possible explanations: Marangoni flow, thermophoresis, or density-driven flow. Marangoni flow is caused by a gradient in surface tension at liquid interfaces. It can be discounted because the effect occurs regardless of the liquid depth above the submerged candy. Thermophoresis is caused by thermal diffusion along concentration gradients, whereby light and heavy molecules move to regions of lower and higher temperatures, respectively. As the candy coating (composed of dye, sucrose, and corn syrup) dissolves, the heat of mixing causes a slight change in temperature. For pure sucrose, the heat of mixing is endothermic with a value of 17.61 J/g. If we assume that 0.01 g of sugar dissolves in 0.005 g of water adiabatically, the water temperature would change by  $-7.7^\circ\text{C}$  at the candy surface. This value, which is

certainly overestimated, is still too small to explain the phenomenon.

The only satisfactory explanation for the counter-intuitive observation is gravity-driven bulk flow. The dissolved sugar forms a three-dimensional transient gradient in density,  $\rho(r, \theta, z, t)$ , that induces a velocity,  $\mathbf{v}$ , (Eq. 2), due to gravitational effects.

$$\frac{\partial \rho}{\partial t} + \mathbf{v} \cdot \nabla \rho = \rho \nabla \cdot \mathbf{v} \quad (2)$$

The flow field can be determined from solving the continuity equation coupled with Navier-Stokes (not shown) considering the geometry of the Skittle and its orientation in the bath, which gives rise to the initial  $\rho(r, \theta, z, t = 0)$ . The gravitational flow contribution to  $N_{\text{dye}}$  explains both the unexpected speed of dye movement and its *apparent* diffusion “uphill”, against the concentration gradient.

These subtleties of concentrated solution transport and characteristic time constants are not appropriate for the first week of an undergraduate transport class. However, the demonstration still provides an extremely effective visualization of bulk flow. Students immediately recognize that *something* must be pushing the dye away from the candy. We use this activity to introduce the concepts of concentration gradients, flux, and coordinate systems. While all the students can recognize positive and negative slopes, very few intuitively connect slopes to gradients at this stage in their career. Students also have not yet learned (or forgotten) that flux is positive when moving from low to high position and negative when moving high to low, and this convention needs to be drilled throughout the course. Worksheets and solutions for this activity are available at *Engineering Unleashed*.<sup>[2]</sup> This work was supported by the National Science Foundation, under award number CBET-1929755.

In summary, watching candy dissolve visualizes more than diffusion. From this activity, students can understand why mass transfer and heat transfer are often taught separately, why choosing a flux equation requires thought and domain knowledge, and how to define the directions of the flux and concentration gradient. Most of all, the demonstration encourages students to train their intuition and capacity for critical thinking by comparing expectations with observations.

## REFERENCES

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— MAUREEN H. TANG AND NICOLAS J. ALVAREZ, Drexel University • Philadelphia, PA 19104

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