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Fluid Mechanics, 5th Ed. Kundu, Cohen, and Dowling

Exercise 1.1. Many centuries ago, a mariner poured 100 cm^3 of water into the ocean. As time passed, the action of currents, tides, and weather mixed the liquid uniformly throughout the earth's oceans, lakes, and rivers. Ignoring salinity, estimate the probability that the next cup of water you drink will contain at least one water molecule that was dumped by the mariner. Assess your chances of ever drinking truly pristine water. [Some possibly useful facts: M_w for water is 18.0 *kg* per *kg-mole*, the radius of the earth is 6370 *km*, the mean depth of the oceans is approximately 3.8 *km* and they cover 71% of the surface of the earth. One cup is ~240 *ml*.]

Solution 1.1. To get started, first list or determine the volumes involved:

$$\upsilon_d = \text{volume of water dumped} = 100\ \text{cm}^3,\ \upsilon_c = \text{volume of a cup} = 240\ \text{cm}^3, \text{ and}$$

$$V = \text{volume of water in the oceans} = 4\pi R^2 D\gamma,$$

where, R is the radius of the earth, D is the mean depth of the oceans, and γ is the oceans' coverage fraction. Here we've ignored the ocean volume occupied by salt and have assumed that the oceans' depth is small compared to the earth's diameter. Putting in the numbers produces:

$$V = 4\pi(6.37\times10^6 m)^2(3.8\times10^3 m)(0.71) = 1.376\times10^{18} m^3.$$

For well-mixed oceans, the probability P_o that any water molecule in the ocean came from the dumped water is:

$$P_o = \frac{(100\ \text{cm}^3 \text{ of water})}{(\text{oceans' volume})} = \frac{\upsilon_d}{V} = \frac{1.0\times10^{-4} m^3}{1.376\times10^{18} m^3} = 7.27\times10^{-23},$$

Denote the probability that at least one molecule from the dumped water is part of your next cup as P_1 (this is the answer to the question). Without a lot of combinatorial analysis, P_1 is not easy to calculate directly. It is easier to proceed by determining the probability P_2 that all the molecules in your cup are not from the dumped water. With these definitions, P_1 can be determined from: $P_1 = 1 - P_2$. Here, we can calculate P_2 from:

$$P_2 = (\text{the probability that a molecule was not in the dumped water})^{[\text{number of molecules in a cup}]}.$$

The number of molecules, N_c, in one cup of water is

$$N_c = 240 cm^3 \times \frac{1.00g}{cm^3} \times \frac{gmole}{18.0g} \times 6.023\times10^{23} \frac{molecules}{gmole} = 8.03\times10^{24} molecules$$

Thus, $P_2 = (1-P_o)^{N_c} = (1-7.27\times10^{-23})^{8.03\times10^{24}}$. Unfortunately, electronic calculators and modern computer math programs cannot evaluate this expression, so analytical techniques are required. First, take the natural log of both sides, i.e.

$$\ln(P_2) = N_c \ln(1-P_o) = 8.03\times10^{24} \ln(1-7.27\times10^{-23})$$

then expand the natural logarithm using $\ln(1-\varepsilon) \cong -\varepsilon$ (the first term of a standard Taylor series for $\varepsilon \to 0$)

$$\ln(P_2) \cong -N_c \cdot P_o = -8.03\times10^{24} \cdot 7.27\times10^{-23} = -584,$$

and exponentiate to find:

$$P_2 \cong e^{-584} \cong 10^{-254} \ldots (!)$$

Therefore, $P_1 = 1 - P_2$ is very-very close to unity, so there is a virtual certainty that the next cup of water you drink will have at least one molecule in it from the 100 cm^3 of water dumped many years ago. So, if one considers the rate at which they themselves and everyone else on the planet uses water it is essentially impossible to get a truly fresh cup to drink.

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