
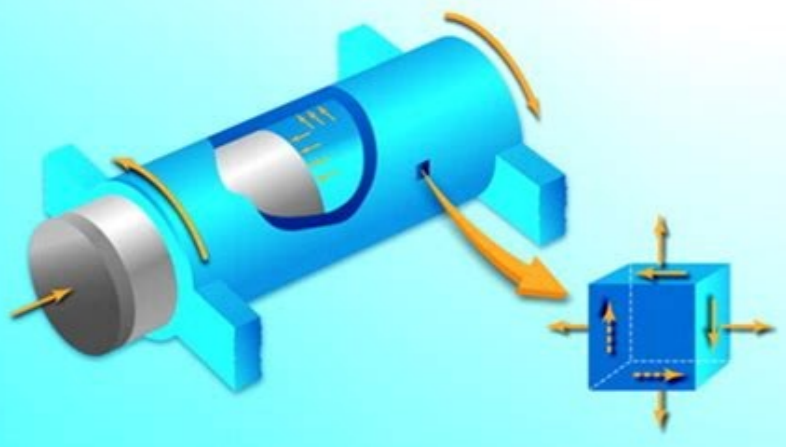


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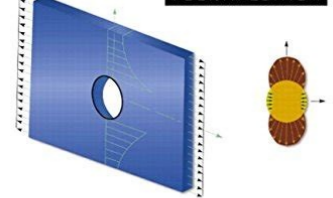
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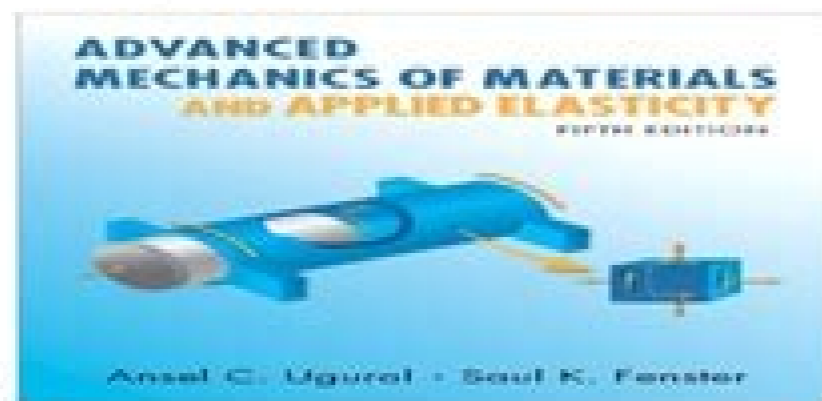
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Fluid Mechanics, 5th Ed. Kundu, Cohen, and Dowling

**Exercise 1.1.** Many centuries ago, a mariner poured 100 cm<sup>3</sup> 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:  
 $u_d$  = volume of water dumped = 100 cm<sup>3</sup>,  $u_c$  = volume of a cup = 240 cm<sup>3</sup>, and  
 $V$  = 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  $\gamma$  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:

$$V = 4\pi(6.37 \times 10^6 \text{ m})^2(3.8 \times 10^3 \text{ m})(0.71) = 1.376 \times 10^{20} \text{ m}^3$$

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

$$P_c = \frac{(100 \text{ cm}^3 \text{ of water})}{(\text{oceans' volume})} = \frac{u_d}{V} = \frac{1.0 \times 10^{-4} \text{ m}^3}{1.376 \times 10^{20} \text{ m}^3} = 7.27 \times 10^{-25}$$

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:

$P_2$  = (the probability that a molecule was not in the dumped water)<sup>number of molecules in a cup</sup>

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

$$N_c = 240 \text{ cm}^3 \times \frac{1.00 \text{ g}}{\text{cm}^3} \times \frac{\text{gmole}}{18.0 \text{ g}} \times 6.023 \times 10^{23} \frac{\text{molecules}}{\text{gmole}} = 8.03 \times 10^{23} \text{ molecules}$$

Thus,  $P_2 = (1 - P_c)^{N_c} = (1 - 7.27 \times 10^{-25})^{8.03 \times 10^{23}}$ . 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.

$$\ln(P_2) = N_c \ln(1 - P_c) = 8.03 \times 10^{23} \ln(1 - 7.27 \times 10^{-25})$$

then expand the natural logarithm using  $\ln(1 - \epsilon) \approx -\epsilon$  (the first term of a standard Taylor series for  $\epsilon \rightarrow 0$ )

$$\ln(P_2) \approx -N_c \cdot P_c = -8.03 \times 10^{24} \cdot 7.27 \times 10^{-25} = -584,$$

and exponentiate to find:

$$P_2 \approx e^{-584} \approx 10^{-254} \dots (1)$$

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<sup>3</sup> 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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