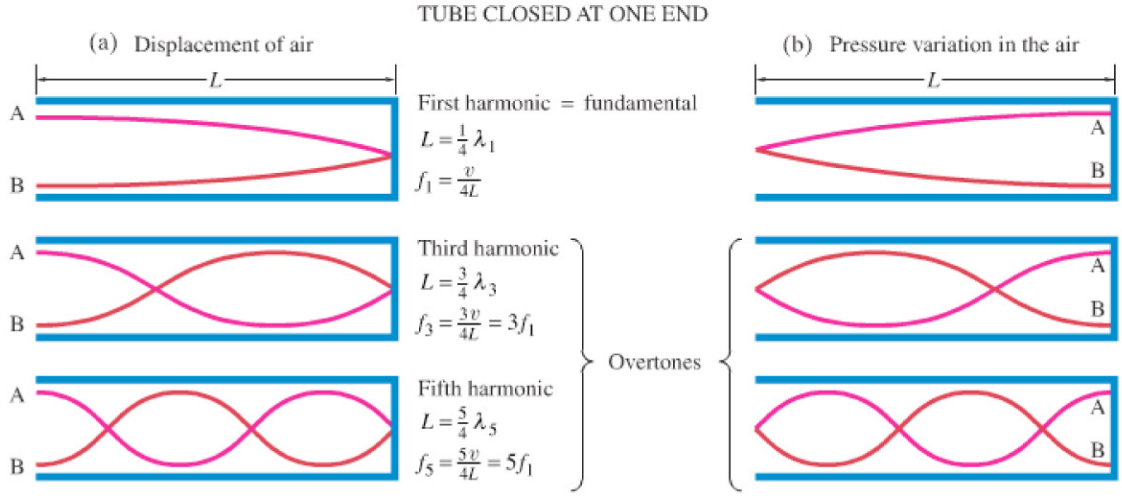


**FIGURE 12–12** Modes of vibration (standing waves) for a tube closed at one end ("closed tube"). See caption for Fig. 12–11.

*Closed tube*

For a closed tube, shown in Fig. 12–12a, which could be an organ pipe, there is always a displacement node at the closed end (because the air is not free to move) and an antinode at the open end (where the air can move freely). Since the distance between a node and the nearest antinode is $\frac{1}{4}\lambda$, we see that the fundamental in a closed tube corresponds to only one-fourth of a wavelength within the length of the tube: $L = \lambda/4$, and $\lambda = 4L$. The fundamental frequency is thus $f_1 = v/4L$, or half that for an open pipe of the same length. There is another difference, for as we can see from Fig. 12–12a, only the odd harmonics are present in a closed tube: the overtones have frequencies equal to $3, 5, 7, \cdots$ times the fundamental frequency. There is no way for waves with $2, 4, 6, \cdots$ times the fundamental frequency to have a node at one end and an antinode at the other, and thus they cannot exist as standing waves in a closed tube.

*Closed tubes produce only odd harmonics*

Another way to analyze the vibrations in a uniform tube is to consider a description in terms of the *pressure* in the air, shown in part (b) of Figs. 12–11 and 12–12 (right-hand sides). Where the air in a wave is compressed, the pressure is higher, whereas in a wave expansion (or rarefaction), the pressure is less than normal. The open end of a tube is open to the atmosphere. Hence the pressure variation at an open end must be a *node*: the pressure doesn't alternate, but remains at the outside atmospheric pressure. If a tube has a closed end, the pressure at that closed end can readily alternate to be above or below atmospheric pressure. Hence there is a pressure *antinode* at a closed end of a tube. There can be pressure nodes and antinodes within the tube. Some of the possible vibrational modes in terms of pressure for an open tube are shown in Fig. 12–11b, and for a closed tube are shown in Fig. 12–12b.

**EXAMPLE 12–9** **Organ pipes.** What will be the fundamental frequency and first three overtones for a 26-cm-long organ pipe at 20°C if it is (*a*) open and (*b*) closed?

**APPROACH** All our calculations can be based on Figs. 12–11a and 12–12a.

**SOLUTION** (*a*) For the open pipe, Fig. 12–11a, the fundamental frequency is

$$f_1 = \frac{v}{2L} = \frac{343\text{ m/s}}{2(0.26\text{ m})} = 660\text{ Hz}.$$

The speed $v$ is the speed of sound in air (the air vibrating in the pipe). The overtones include all harmonics: 1320 Hz, 1980 Hz, 2640 Hz, and so on.
(*b*) For a closed pipe, Fig. 12–12a, the fundamental frequency is

$$f_1 = \frac{v}{4L} = \frac{343\text{ m/s}}{4(0.26\text{ m})} = 330\text{ Hz}.$$

Only odd harmonics are present: the first three overtones are 990 Hz, 1650 Hz, and 2310 Hz.

**NOTE** The closed pipe plays 330 Hz, which, from Table 12–3, is E above middle C, whereas the open pipe of the same length plays 660 Hz, an octave higher.