The smooth and regular curve that results from sounding a tuning fork (or from the motion of a pendulum) is a simple \textit{sine wave}, or a waveform of a single constant frequency and amplitude.
Whereas the air particles disturbed by a tuning fork move in simple and uncomplicated ways - merely back and forth - most sources of sound disturb the air in far more complex ways.

Complex waves result when the air particles vibrate in more than one way at the same time and are therefore composed of more than one frequency.
Complex Waves

For example, the striking of a note on a piano engenders very different wave patterns than the simple pattern of the tuning fork that we saw earlier.

From Ladefoged EAP, p. 25
So, different instruments produce different patterns of complex waves: e.g., violins, pianos, and the human voice.

⇒ The reason the same note originating from any of these sources sounds different is that each source produces a different shaped complex wave.

⇒ That is, the *difference in quality* between sounds from a violin, from a piano, and from the voice is due to the difference in the complexity of the waveform produced.

**Complex Waves and Quality**
**Excursus: Some Terms**

**Period**: measurement of the time it takes for completion. In this case, the period = .01 sec.

Recall that the frequency of a sound is the rate at which cycles occur per second.

So if you know the period (the time for one cycle), you can calculate the frequency (the number of cycles per second) and vice versa.

\[
\text{Frequency} = \frac{1}{\text{Period}}
\]

Period = .01

Frequency = 1/.01 = 100 Hz

Figures from http://www.clas.ufl.edu/users/ratree/Lin_6932/Week%201/Wave%20Characteristics.ppt
Period versus Frequency

Frequency = 1/0.5 SEC or 2 cycles/SEC (2 Hz)

Period = 0.5 SEC

Amplitude

0 0.5 SEC 1.0 SEC

Figure adapted from Ferrand (2001). *Speech Science An Integrated Approach to Theory and Clinical Practice*, p. 20.
A wave in which each cycle takes the same amount of time as the proceeding and following cycles is called a **periodic wave**.

⇒ In speech, vowels are generally characterized by periodic waves.

A wave in which each cycle takes a different amount of time (a wave with an irregular series of cycles) is called an **aperiodic wave**.

⇒ In speech, some consonants are characterized by aperiodic waves.
The Complex Shape of Vowels

[\textit{\texttt{\textbf{\textit{\texttt{}}} as in caught}]

[\textit{\texttt{\textbf{\textit{\texttt{}}} as in who}]

[\textit{\texttt{\textbf{\textit{\texttt{}}} as in see}]

Time in seconds
Combining Waves

300 Hz

500 Hz

300 + 500 Hz

Figures from http://www.clas.ufl.edu/users/ratree/Lin_6932/Week%201Wave%20Characteristics.ppt
Combining Waves

300 + 500 Hz

One repetition of the complex wave

Highest peaks in the complex wave result from both tones working together to increase air pressure

Lowest troughs in the complex wave result from both tones working together to decrease air pressure

The pressure is between these two extremes when the two tones are working against each other
Fourier Analysis

Given any number of pure tones, it is possible to combine them to produce any number of synthesized waveforms.

By adding the increases in air pressure and subtracting the decreases in air pressure at any one point in time across a number of simple waves, we can synthesize a waveform that would be the result of combining them.

The mathematical analysis involved in combining pure tones to produce complex waves (and vice versa) is called Fourier Analysis, after the man who discovered the concept.

Fig. 4.1. A combination of 100 Hz, 200 Hz, and 300 Hz waves forming a complex wave.
The frequency of repetition of the complex waveform (the main pattern) is referred to as the **fundamental frequency** (or F0).

F0 corresponds to the lowest frequency among the individual components of the complex wave.
**Harmonics** are the set of additional tones (or component waves) present in the complex wave.

Harmonics are always at frequencies above - and are whole number multiples of - the fundamental.
A diagram of the relative amplitudes of the component waves in any complex wave is called a spectrum (pl. spectra) - a spectrum allows us to easily see the harmonics.
Spectra

Unlike with waveforms, the spectrum of any sound is relatively straightforward even when there are lots of component waves (and therefore lots of harmonics).

Fig. 3.1. The waveform of the C below middle C on a piano.

Fig. 4.4. The spectrum of the waveform illustrated in fig. 3.1, the C below middle C on a piano.
Interestingly, two sounds can have the same spectrum and be composed of the same frequencies (and be perceived as essentially the same sound) - but if the component parts are not combined in the same way (at the same points in time), the waveforms will be different.

Differences in the timing of components is referred to as a difference in phase (e.g., one frequency may start before the other).

**Spectra and Waveforms**

![Graph showing same spectrum](image)

**Same spectrum**

![Graph showing different waveforms](image)

**Different waveforms**

Fig. 4.1. A combination of 100 Hz, 200 Hz, and 300 Hz waves forming a complex wave.

Fig. 4.5. A combination of 100 Hz, 200 Hz, and 300 Hz waves, differing from the combination in fig. 4.1 with respect to their relative timing, and consequently forming a different complex wave.