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Bell Labs and the Case of the Missing Fundamental

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So how can you tell if it's a man's voice on the phone when the phone only has an effective bandwidth of 340-3400 Hz and most men's voices have a fundamental frequency of about 125-150 Hz? Elementary, my dear reader! Dr. Chasin retells this Bell Labs mystery and provides the answer.

Way back in the mid-1950s (and it was a dark and stormy night), two researchers—we will call them Miller and Licklider (actually those are their real names)—had a request from Bell Labs to define the best frequency response for their telephones. They were cautioned not to say "from 20 Hz to 20,000 Hz," which is the hearing range of normal-hearing young adults, because this would be incredibly expensive to accomplish. They instead were asked, "How poor can the frequency response be and still be adequate to convey speech through a telephone with good intelligibility?" The Bell engineers quite understandably wanted to know what corners they could cut in order to save money, channel carrying capacity, and still end up with a telephone signal that was "good enough."

Most of the work of Miller and Licklider focused on the higher frequency end, and they found that, for normal-hearing people in relatively quiet locations, we only needed to transmit sounds up to 3400 Hz and it was "good enough." The energy of sibilants such as the "s" has most of its energy above 3400 Hz, but they found that the appearance of "s" was quite predictable, and while there were some transmission errors, telephone users could "fill in the blanks."

This "filling in the blanks" strategy *does* work well for normal-hearing people, but occasionally we need to clarify whether a person said "fix" or "six." However, for the most part, it worked (and still does work) well. For hard-of-hearing people who have an effective hearing range of only up to 2000 or 3000 Hz, telephone use—partly because of this relatively narrow range—is a problem.

Miller and Licklider, having convinced themselves that 3400 Hz was a sufficient upper end for the phone, were very surprised to see that the lower end of the phone system could be as high as 340 Hz. It was known that the fundamental frequency (also known as the pitch) of a man's voice was about 125-150 Hz, and a woman's voice was perhaps an octave higher, so having a phone system that did not transmit these lower frequencies was very odd. When listening to their experimental phone system (essentially a master hearing aid) that was set to a frequency response of 340-3400 Hz—a response that still exists today with modern technology—they were still able to identify a male voice despite the fundamental frequency or pitch not being in the bandwidth of the phone. If the phone only transmitted sounds above 340 Hz, how can 125 Hz be heard?

The Plot Thickens...

Well, Miller and Licklider were understandably confused, so they thought that they would take a break and walk down to their local pub. (Actually I am making this part up but it sounds better.) After a few beers and listening to some great jazz, they came to a realization that a person's pitch or fundamental frequency of their voice is not the fundamental frequency. The pitch is the *difference* between any two harmonics and this "difference-information" is well within the range of the telephone.

The human voice functions identically to a violin or guitar; the vocal chords are held tightly at both ends like the strings of a violin or a guitar. In acoustics, we call this a half wavelength resonator. Well, actually, even if it is not in acoustics, it is still called a *half wavelength resonator*. This means that not only is there the fundamental frequency (the lowest note, which musicians may refer to as the tonic or the note name), but also *integer multiples* of the fundamental frequency.

In a man's voice (the example here being my voice), the fundamental frequency is 125 Hz. The first harmonic is 250 Hz (2 x 125 Hz); the next harmonic is 375 Hz (3 x 125 Hz); the next is 500 Hz (4 x 125 Hz); and so on. The harmonics at 375 Hz and 500 Hz, as well as higher frequency multiples, are well within the frequency response of the telephone. Notice that the difference between 375 Hz and 500 Hz is exactly 125 Hz, and the difference or spacing between all speech harmonics in this example will also be exactly 125 Hz.

We don't need to hear the very low frequency 125 Hz, just the higher frequency "differences," which we call pitch. The fundamental frequency is indeed missing on the telephone (and in most well-fit hearing aids), but the higher frequency harmonic structure is really what we need to hear.

Miller and Licklider's concern about not hearing the fundamental was misplaced. We don't need to hear the fundamental—just the higher frequency harmonics (actually their differences) that are the result of the fundamental frequency.

When it comes to music, there indeed may be a note played at two octaves below middle C (65 Hz), but this same 65 Hz difference is heard also between 524 Hz and 589 Hz, which are two of the harmonics of C (65 Hz). Both 524 Hz and 589 Hz, and most of the other higher frequency harmonics of C (65 Hz), are well within the amplification range of modern hearing aids (and telephones).

The Case of the Missing Fundamental has been solved and our intrepid researchers can go back to drinking beer and listening to jazz, even while wearing their relatively narrowband hearing aids.

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