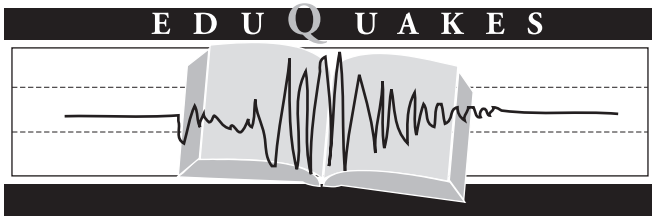

Seismic Waves and Sound Waves: From Earthquakes to Music

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Online Material: Workshop presentations.

INTRODUCTION

Art is one of the main tools through which humans have, since their origins, chosen to interpret reality and to communicate. At the present time, however, the intellectual spheres of arts and science remain as far apart as they were when, in 1959, C. P. Snow delivered the Rede lecture in Cambridge under the title *The Two Cultures and the Scientific Revolution* (Snow, 1993). The lecture ignited a debate that rapidly extended outside Britain's borders. In Italy, for example, the writer and scientist Primo Levi argued that the divide between the sciences and humanities was not known to Galileo, da Vinci, Descartes, and Goethe, who were simultaneously scientists and humanists (Levi, 1989). C. P. Snow (1993) argues in the Rede lecture that "the total incomprehension of science radiates its influence on all the rest. It gives, much more persuasively than we realize, an unscientific flavor to the whole traditional culture… and it is the traditional culture which manages the western world."

This divide, which remains despite 50 years of deprecation, is particularly dangerous in the field of seismology, because the subject of earthquakes strongly links a scientific topic to the life, history, and culture of millions of people living in seismically active regions. The lack of seismological education at all levels, in any region, translates into an insufficient awareness of seismic hazard. With the aim of crossing this cultural divide, we have built and tested a format for conveying scientific information about earthquakes through the medium of music. Clearly, it is essential for any country that includes a seismically active region to educate the greatest possible number of people about where, how, and why earthquakes occur. Our goal is to increase resilience to earthquakes and their related hazards by educating people who are, perhaps, impervious to conventional scientific exegesis but respond readily to explanations grounded in the humanities.

"Seismic Waves and Sound Waves: From Earthquakes to Music" is a 2-hour interactive program that we use to present seismology in an approachable way. It is intended to give the audience an in-depth explanation about earthquake physics and how energy is carried through the Earth by seismic waves. The project was inspired by three considerations. First, an interactive session requires and enables the participants to be involved more deeply than they would be if they were simply listening to a lesson. Second, seismic *P* waves and sound waves share the same nature, both being mechanical longitudinal waves. The third consideration is the power of music to communicate in deep, non-verbal ways.

The first consideration arises from our conviction that public communication of science must involve more than laying out its concepts and rules, which can often be counterintuitive or obscure to a general audience. In everyday life, people integrate new knowledge into their accumulated sum of real-life experiences, which are made up of memories, images, and emotions. Communication of science is therefore much more efficient if it can engage the emotions of an audience in the transfer of knowledge. Feelings and emotions are also conducive to active learning during an educational workshop because they sustain curiosity, a vital ingredient in scientific progress, as in most worthwhile human endeavors (Vygotskij, 1986).

The congruence between *P* waves and sound waves allows us to draw parallels between an apparently esoteric science and the audience's everyday experience. We explain the physical properties of seismic waves through enjoyable experiments that draw upon concepts that both are familiar to the audience and are fundamentally linked to music, something to which most people respond.

Maestro José Antonio Abreu, founder of the National System of Youth and Children's Orchestras of Venezuela, identifies "the huge spiritual world that music produces in itself [which] ends up fostering ethical values and overcoming material poverty" (Abreu, 2009). An equally powerful conviction underlies the West-Eastern Divan Orchestra, founded by Edward Said and Daniel Barenboim, and consisting of musicians from Israel, Palestine, and other Arab countries. We exploit this capacity of music, at a much more modest level, to bond scientists and lay people during our workshops. The emotional empathy that evolves during our concerts, we believe, helps to fix in the audience's memory lessons that they have learned about scientific concepts, which are themselves connected to music.

TALKING ABOUT WAVES

The program is organized in two main sections; the first is "Talking about Waves" and the second is "Listening to Waves."

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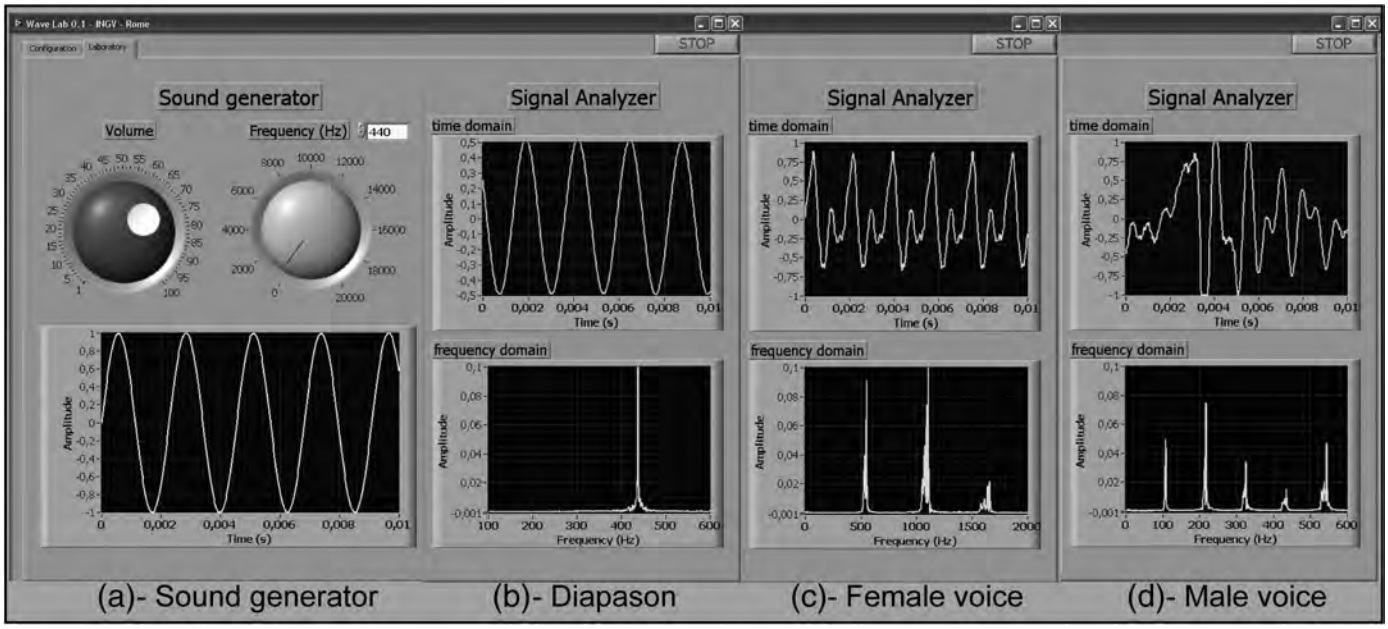


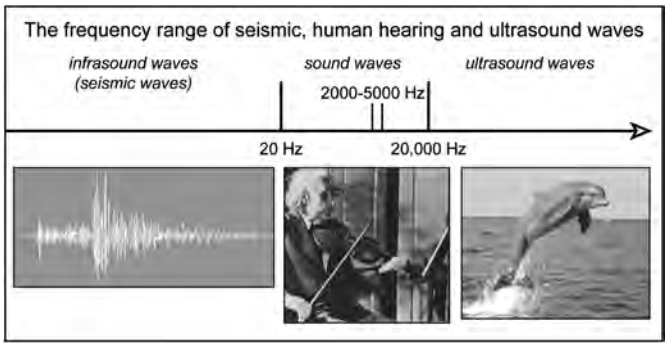
▲ **Figure 1.** The Wave Lab, a tone generator and signal-analysis software. (a) A synthetic 440-Hz sound; (b) the signal analysis of the sound produced by a diapason in both time and frequency domains; (c) female voice shown in time and frequency domains; (d) male voice shown in time and frequency domains.

In turn, "Talking about Waves" is split into three phases: (1) Earthquakes: why and how they happen; (2) From seismic waves to sound waves; (3) The chorus of the Earth (see Ⓔ file available in the electronic supplement to this article).

During "Earthquakes: why and how they happen," we explain the origins of plate motion. We show how the associated forces lead to deformation in narrow zones at plate boundaries and in diffuse networks of faults in plate interiors. Once the cause of the earthquakes is explained, we are in a position to show how the energy released by an earthquake is carried through the Earth by seismic waves. We then describe *P*, *S*, and surface waves, showing how they appear on a seismogram and how humans perceive each type of wave, particularly in the near-field. A teaching animation shows how the waves travel through the Earth.

During the second phase, "From seismic waves to sound waves," researchers guide the audience through the introduction of essential knowledge about waves. Again we use teaching animations to explain that a wave represents transport of energy, and that *P* waves carry energy in the same way that sound does, even though in the former case the source of energy is the earthquake, whereas in the latter the source may be our voice or an instrument. This phase requires the public to interact with the Wave Lab, a tone generator and signal analysis software (Fig. 1). The Wave Lab first generates monochromatic sound waves at different frequencies from the center to the limit of human hearing, and we ask the audience to recognize them. This experiment proves that human listening capability is in theory as wide as 20 Hz to 20 kHz, but it can slightly change with individual sensibility and age (Fig. 2). In general, young people can hear the whole frequency range whereas old people usually do not. Some people with a different tone of voice (for example, adult males, adult females, and children) are asked to sing a note into the Wave Lab microphone, showing the time and frequency diagrams in real time (signal analysis). The same experiment is repeated with a xylophone, a diapason, or other available instruments, to show some basic acoustic principles. This phase helps the audience to become familiar with scientific terms such as frequency, period, amplitude, and resonance, which are all important quantities in understanding waves and how they relate to seismic hazard.

The last phase of the section "Talking about Waves" is "The chorus of the Earth." In addition to earthquakes, the Earth emits waves in different frequency ranges as a consequence of other natural phenomena. These very low frequency



▲ **Figure 2.** An example of slide used during the workshop. It shows that the only difference between longitudinal sound waves and seismic *P* waves is the frequency, and that the voice of some animals, such as dolphins, is an ultrasound wave.

waves, in the range 10^{-7}–50 Hz, are mostly out of the hearing range of humans (Fig. 2), but are recorded by very broad broadband seismometers. We compare the Earth's natural vibrations with the singing of a polyphonic chorus by dividing these waves into five groups: soprano, contralto, tenor, baritone, and bass (Table 1). This analogy places the waves into a common life experience, allowing the audience to understand that the Earth can vibrate like a giant bell (baritone in Table 1), that the moon's tide (bass in Table 1) produces waves (Wahr, 1995), that atmospheric pressure changes transmit waves to the solid earth (tenor in Table 1), and that the vibration produced by the sea waves can be seen on the seismograms (contralto in Table 1). The participants come to realize that the seismometer is our artificial ear, which hears, so to speak, the very low frequency waves outside human-hearing range. These examples emphasize that waves generated by natural physical phenomena in the bass to contralto ranges are, in principle, very similar to our daily experience and perception of waves, but just occur at lower frequencies.

LISTENING TO WAVES

The last section of our program, "Listening to Waves," is a one-hour concert during which music becomes the protagonist. During the experimental phase of our project, we tailored the music of each workshop to the type of audience, which ranged from young students to adults; the genres included music for strings played by youngsters, a young polyphonic choir, and jazz and blues groups. We found that music is important not only in raising the sensitivity of the audience to the scientific message; the promise of a musical component to the workshop can itself induce people to participate who would otherwise have regarded the scientific subject as inaccessible.

Because the music in our process taps into the emotions of our audiences, they leave the workshops with deeper engagement with the scientific message than, perhaps, would have resulted from a purely rational exposition (Hein, 1998). Surprisingly, we found that this engagement could also modulate our audience's emotional responses to earthquakes. Leaving the workshops, members of our audiences expressed a realization that earthquakes not only are events that have tragic consequences when they interact with society (and the built environment), but they also are manifestations of the workings of the planet on which we live that have a beauty of their own, and we must therefore learn to live with them.

COOPERATION WITH YOUTH ORCHESTRAS AND CHOIRS

It's widely recognized that education is central to raising awareness of, and favoring actions to mitigate, seismic hazard. But the same could be said of any society's response to many of its ills. The uniqueness of our program is that we are able to direct a powerful general educational tool, music, towards a specific goal, seismic hazard, because the physics of the two phenomena is the same.

Maestro Abreu, founder of the National System of Youth and Children's Orchestras of Venezuela (commonly known as El Sistema), reminds us that "education is the synthesis of wisdom and knowledge; it's the means to strive for a more perfect, more aware, nobler and more just society" (Borzacchini, 2010). El Sistema has shown that a music program can both create great musicians and dramatically change the life

Table 1
The Chorus of the Earth

Frequency Range (Hz)	Period Range (time)	Phenomena	Voice in the Choir of the Earth
10^{-7}–10^{-4}	3 months–3 hours	Solid tide (caused by gravitational forces among the Earth, the moon and the sun)	Bass
3×10^{-4}–3×10^{-3}	1 hour–5 min	Normal mode of the Earth (free oscillations of the Earth excited by very strong earthquakes)	Baritone
10^{-3}–10^{-1}	15 min–10 s	Atmospheric pressure changes	Tenor
		Most energetic waves of strong earthquakes	
0.03–1	30 s–1 s	Sea waves	Contralto
		Most energetic waves of Intermediate earthquakes	
1–50	1 s–0.02 s	Human activity	Soprano
		Rain	
		Wind	
		Weak earthquakes	

Phenomena at various frequencies cause mechanical waves to travel through the Earth, waves which can be registered by seismometers exactly like seismic waves. In the last column is indicated the parallel with the choristers in terms of voices in the Chorus of the Earth.

trajectory of hundreds of thousands of a nation's neediest children. The value of El Sistema is now widely understood, particularly in countries that seek to increase the levels of literacy among their young populations. Among the twenty-six countries that have joined El Sistema many, such as Chile, Colombia, India, Mexico, Nicaragua, Peru, Italy, and the United States, are seismically active.

We believe that science must serve society, its children, and its weakest members, in the same way that Maestro Abreu envisages for music. By aligning our seismic-hazard educational experience to the philosophy of El Sistema we can give rising generations the skills to improve resilience to earthquakes in their own countries.

The three evenings of the experimental phase of our format were attended by about 500 people. Our next target is to reach out to the roughly 6,500 children of the Youth Orchestras and Choirs within Italy and educate through our program not only the children themselves, but their families and friends. The young musicians will be the protagonists of the phase "Listening to Waves" in the workshops. We believe that with the same spontaneity that they bring to the playing of music, the children will absorb understanding and awareness of seismic hazard, and that this understanding will be an effective resource to their society. Furthermore, this cohort will grow every year as new children join the system, and the older children graduate to become mature and effective advocates for all that they have learned from their experience.

Our hope is that in the future, through Youth Orchestras and Choirs in seismically active countries, our workshop will be able to reach many thousands of children, helping them to foster their appreciation of the natural world, and to develop their critical thinking skills so that they can help their societies to respond effectively to the hazards, and opportunities, that nature presents to them.

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