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Developing and Popularizing STEM Online Tools: The Case of 'Listening to Waves' Tools for the Science of Music

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Abstract.

Music is a source of joy and identity formation in all cultures and socio-economic strata, and its connections with science, technology, engineering, and math are numerous. One important connection is with the physics of waves. Listening to Waves (LTW) is a program designed to increase adolescents' interest in STEM through the science of sound and music. Based on LTW's early experience performing STEM outreach activities in schools, LTW recognized the need to create easily accessible tools for visualizing and manipulating sound. In particular, LTW has been developing browser-based implementations of a signal generator, an oscilloscope, and a spectrogram. These tools, commonly used in physics and engineering laboratories, represent and analyze data gathered through the computer microphone and sent to the speaker. LTW has modified them and added functionalities that allow students to deepen their engagement by playfully creating sound and music. For example, the oscilloscope tool also functions as a simple sound editor with which students can apply signal-processing effects and record their creations. The tools' are being used thousands of times each month throughout the United States' school system. Here, I give an account of the development of the online tools and the elements that lead to their widespread adoption, hoping that this account can benefit other teams creating interactive STEM-oriented applications. This project is funded through NSF's Innovative Technology Experiences for Students and Teachers (ITEST), Division of Research on Learning in Formal and Informal Settings

Introduction.

STEM professionals interested in developing outreach programs are often fascinated by their scientific domains and passionate about sharing that fascination with new generations. As such, many of us embark on outreach activities that can impact the lives of the direct recipients, soon discovering that our time availability imposes a narrow limit on the number of children we can serve, so the question arises of how we can scale up these activities to make a larger impact on society. Listening to Waves, the program I created, is successfully navigating the transition from a "garage-operation" to a mid-scale educational program, powered by a set of web-applications that are being used by thousands of students weekly. Therefore, it is a good time to share LTW's story and highlight the strategies that, I think, contributed to the tools' widespread adoption.

No matter the strategy a program uses to popularize its product, its plan will fail if the product does not connect with the stakeholders' interests and needs. By creating tools to explore the science of music, LTW connects with the children and educators' innate interest in music, and the schools' need for hands-on, engaging science activities. There are several other reported experiences connecting music with STEM. Most of them have required heavy support from STEM professionals [1]–[6] and consequently have not gone beyond a few implementations, whereas some others requiring less training have become more popular [7], [8]. Given the inherent interest in music on the part of both educators and students, I think it is possible to envision a much larger and broader integration of music into STEM than currently exists. Web-based applications can significantly contribute to this spread, as they allow easy access to interactive hands-on experiences.

LTW development went through three main stages. It started in a very small scale through personal connections with teachers. Then, it moved to large public schools with heavy support from LTW's team. Finally, LTW created web-applications and curriculum to be used by teachers anywhere in the world with internet access. In this paper, I expand on the details of these stages and offer general advice for developing impactful programs. To learn more about LTW, watch tutorials, and play with the web-applications, the reader is encouraged to visit the program's website *www.listeningtowaves.com*.

Previous literature has established several dimensions associated with a successful scale-up of technology-based education programs [9]. Those dimensions are *depth*, associated with the effectiveness of a program; *sustainability*, associated with the program's robustness to be implemented across contexts and time; *spread*, associated with the ease of implementation that allows users to adopt the technology; *shift*, associated with the users' ownership of the innovation; and *evolution*, associated with the developers' iteration of the tool based on user experience and feedback. That literature is based on well-established programs. Although LTW is in a more incipient stage of development, it is being developed to grow along those dimensions, as discussed in the conclusions. The goal with this account, however, is not to reiterate that literature. Rather, I intend to share practical strategies that are appropriate for an earlier stage of spread and development of technology-based educational programs.

Stage 1. Small scale. Training wheels.

Trying radically new activities with children is always a surprise, and not always a pleasant one, as it is impossible to guess what children will find engaging, what they know, what they will be able to understand, and how fast. This lack of knowledge can lead to distressful situations in which students are frustrated, and the program's team is disheartened. Therefore, it is advantageous to start working with students in a very "safe" environment and working in close collaboration with teaching experts (experienced teachers) that are very familiar with their students. Working in collaboration with teachers might be the only way to effectively begin an outreach program, as schools are reluctant to let strangers in unless they have clearly proved the value of what they have to offer.

As a complement of my work investigating the cognitive science of music and its influence on education, I, in collaboration with Dr. Khalil, set out to perform outreach activities teaching school children about the science of music. For this, I tapped into my personal and professional network to find possible collaborators in schools. Through a friend, I was introduced to the 9th-grade science teachers at High Tech High North County (HTHNC) in San Marcos, California. This grassroots approach cemented a personal connection with the teachers, which helped create a comfortable working environment. The characteristics of the school were also beneficial. HTH is a charter school system known worldwide for its project-based education approach [10] and whose teachers, who often have experience working in STEM fields, are expected to be innovative. HTH's flexibility allowed for our work in the classroom to last for a few months. This long time allowed for a great deal of trial and error, a pressure-free environment to test ideas and gain plenty of feedback from both teachers and students.

In this first experience, we and the teacher coordinated several lessons in which we used free software to introduce the science of waves. After this introduction, students developed a project in which they created sound installations and reflected on how their installations vibrated and generated sound [2].

We used free sound editor *Audacity* [11] for students to visualize waveforms (as an oscilloscope), create pure tones (as a signal generator), and create sound compositions. For a spectrogram, we used free software *UltimaSound* (See Figure 1). Using and installing the software on the school's computers was possible because we were working with a teacher that had the resources to learn how to use the software and have it installed in the schools' computers. This luxury was not available in later experiences.

We documented the experience in two ways. 1) We used HTH students' media skills to film the classes and the installations' design process, creating a video presentation showcasing students working and having fun. 2) After the experience, we surveyed students and used the data in a publication [2]. The publication and surveys were instrumental in obtaining funding to further develop the project, and the media piece acted as a presentation letter to introduce our program to other venues.

HTHNC is a relatively small school serving approximately 40% low-income students, with considerable material and human resources. The HTH system is unique, even for a charter school, and it is renowned around the world for its innovative pedagogy. Even if this environment is an excellent breeding ground for new programs, the activities carried out there cannot be easily scaled up. For spreading such activities to low-income communities, it is necessary to target and adapt to institutions serving those communities.

Stage 2. Large public schools with heavy involvement from the program's team.

If a goal is to create a program reaching a vast number of students, public schools are an ideal venue. Even when the activities need to be heavily supported by the program's team, a single public school offers the opportunity to reach low-income students in the hundreds. Furthermore, there are thousands of public schools that share culture, goals, and curriculum. Because public schools form an extensive and heavily interconnected network, if a program works in a school, it can be easy to "spread the word" to other schools in the district, county, and state.

The first challenge of working with public schools is getting through the door, as schools can be wary of strangers, of draining their teachers' precious time, and that the time commitment required isn't aligned or commensurate with their intended outcomes. Armed with the confidence of my HTH experience and with the media created by the students, I contacted a large district's STEAM coordinator, who in turn connected me with the science team at two of their schools (90% Latinx, 95% low-income, serving 850 8th-grade students). Because of the time constraints and the large number of students to be served, in these schools we implemented a more streamlined version of the program, in which the collaboration with the teachers was not as deep, and the student activities were more narrowly guided. The experience involved some of the online tools as well as hands-on physical sound exploration activities. For a better idea of the program's implementation, please see (https://listeningtowaves.com/ltwvideo). The relationship with these schools has lasted for four years, and it is ongoing because the teachers perceive the value of the activities, becoming increasingly comfortable to implement them on their own. A more detailed account of the experience, including survey results that demonstrate an improvement of students' attitudes towards science, can be found in [12].

Working with large public schools presents many challenges beyond getting through the door, particularly in low-income areas, where schools have meager budgets and where teachers are often overwhelmed by large class sizes. In these schools, teachers focus a lot of their time and attention on classroom management and they have little additional time-availablity to learn the materials to support the program's implementation. Working in such an environment offers little room for failure, as a disengaged classroom can soon become chaotic, and the developer might not be invited a second time. Therefore, I recommend that developers only reach this stage once they are confident that the materials they bring are engaging. Spending time in a public school allows a program's team to understand the teachers' and schools' needs and limitations, which is necessary for the program to create the mechanisms of support that are needed to ensure that a program can grow beyond the direct participation and physical presence of its founders. One significant limitation, upon which I expand below, is the access to technology.

As we started working in public schools, it became apparent that the use of software, even if free, presents a significant hurdle. Installing software on the students' school-provided devices might not be practical or even allowed, and installing software on the public schools' computers needs approval and heavy support from the IT personnel. Although this is possible when working at one or two schools and with the support of the school's administration, it is not a scalable model. If one expects an educational program to be widely adopted, it has to be extremely easy for overburdened schools to do so. This is why, after our first experience using downloadable software, I decided that if LTW was to reach a broader audience, the tools needed to be web-based so they could be accessed without the need of installation.

Another hurdle is that the software we were using had not been designed for educational purposes, therefore it was too complex to be quickly deployed in the classrooms. For example, the sound editor *Audacity* needs users to adjust a few settings before they can start recording. In my experience, guiding students to collectively adjust such settings is impossible, as a large class easily loses focus with this kind of a task in less than 20 seconds.. Therefore, the persons guiding the learning need to visit each working group helping students and verifying that the program's settings are appropriate. This personalized service is easy in a small classroom, with a lot of time, and with several instructors, as we experienced in HTH, but it becomes challenging under more typical conditions. Another problem is that *Audacity* has too many buttons. If the user presses the wrong button (for example changing a selection tool), they will not be able to continue with the activities. This complexity also makes it difficult to guide students towards an activity with a specific learning outcome. For example, our intention using Audacity was to allow students to create sine waves of different amplitudes and frequencies, comparing their waveforms with their sound to understand the relationship between frequency, pitch, amplitude, and volume. Creating and visualizing those waves in *Audacity* requires students to perform many steps that they might find meaningless, which causes them to disengage rapidly. This experience led me to realize that for a platform to be adopted in classrooms it has to be immediately engaging (at the press of a single button), it has to be simple enough that pressing the wrong button will not cause a catastrophic failure, and it has to make it very easy to perform the activities associated with the learning goals.

Even though it was cumbersome, using the free software allowed me to understand how to frame the learning goals to be palatable for schools (see *Stage 3*), to understand what the students were capable of understanding, and to evaluate what features in the software they found engaging. In general, students much enjoyed not only the capacity to visualize sound, but also the capacity to create and record sound, and playfully transform and re-arrange sound, activities that connect with the larger fields of sound-engineering and signal processing and with the US standards' for *analyzing and interpreting data*. Based on this experience, while developing the online tools I attempted to keep some of the sound playfulness that *Audacity* allowed for. In particular, the applications replicated some of the features that I noticed were very engaging for the students, but simplifying the interfase so students could more easily experience those features. For example, they much enjoyed using *Audacity* to create sounds looped at different length selections, from long selections creating repeating phrases, to shorter selections creating slow rhythms, to faster selections creating fast danceable rhythms – to which they usually bobbed their heads—, to very short selections creating pitch. Accordingly, besides allowing students to visualize waveforms at different time scales, as oscilloscopes do, LTW's online oscilloscope allows students to very easily create loops of varying lengths, as well as other engaging sound manipulations.

Stage 3. Online tools. Going beyond the team.

Curriculum development. As soon as we started pitching the program to schools, it became apparent that, although schools would be happy with a short visit from a STEM professional, for them to commit the teachers' time and effort to implement a learning program they needed for the program to satisfy the curricular goals, as dictated by the New Generation Science Standards (NGSS, a framework for K-12 education). The physics of waves is one of the *core ideas* covered in the standards, and the software tools that we used are intentionally designed for teaching the required concepts. Although the domain-kowledge concepts that NGSS requires—named *core ideas* in the NGSS—are relatively simple, the standards are rather complex, including not only *core ideas* but also *crosscutting concepts* and *science and engineering practices*. Because of that complexity, creating an NGSS-aligned lesson plan needs the participation of a teaching professional, who not only knows the intricacies of NGSS, but understands the teachers' culture and language. To align LTW's tools to the standards, we partnered with the San Diego County of Education (SDCOE), which is in charge of providing training and resources—including for NGSS implementation--to 42 districts throughout San Diego County. The collaboration followed a teacher action research model [13], in which *teacher-leaders*—practicing teachers who are experts in curriculum development—work with subject-domain experts to create relevant learning modules, which are then implemented in the *teacher-leaders'* classrooms, and iterated accordingly. The work we did with SDCOE went beyond creating lessons that used the online tools, extending to an 11-lesson learning sequence incorporating publicly available videos and physical simulations [14].

The creation of the lesson plans coincided with the beginning of the COVID-19 pandemic and the schools' move to virtual learning, with the consequent increased demand for the kind of engaging online activities that LTW web applications offer. The NGSS-aligned curriculum, with its adaptability to remote learning, provided an incentive for schools to adopt LTW's activities. This, however, was not enough for adoption, as the time cost of implementing a new program could be high for teachers, who were overburdened by the schools' move to distance-learning. Following LTW's general policy of facilitating the teachers' work as much as possible, LTW worked with a teacher consultant to format the lessons as a series of google slides, which teachers typically use to present their classes, and that teachers could administer remotely. Along with the lesson slides, we also provided student worksheets and lesson briefs detailing the standards' alignment. Importantly, the lessons are independent, so that even if a teacher does not have the time or interest to implement them all, they can use the ones that best suit their classrooms. This lesson structure follows the low-floor-high-ceiling approach [15], in which participants have both easy access to an activity or tool, and the possibility of deepening their engagement over time.

Dissemination. Working in partnership with SDCOE had the triple benefit of 1) accessing an expert team which created meaningful lesson plans, 2) bringing a "stamp of approval" from a recognized institution, and 3) offering an extensive professional network to spread the activities (SDCOE is in charge of providing resources to the large community of schools throughout San Diego County and its well-known science resource center website, which features our activities, is accessed 170,000 times yearly nationwide).

The lesson plans were also disseminated through Facebook advertising, which was very effective when teachers were scouring the internet for remote learning resources and sharing those resources with other teachers. Facebook offers the opportunity of creating targeted advertising, for example, showing an ad only to people that follow National Science Teachers Association (NSTA). This targeting allowed LTW to reach key "customers" with a relatively small budget. For example, $100 worth of targeted advertising created dozens of shares, mainly by teachers, which brought hundreds of viewers to the teacher-resources page on LTW's website.

The activities were also disseminated through professional development. Teachers were recruited through email chains distributed through our professional network, and through word of mouth from the teacher-participants themselves, who invited their colleagues. Typically, teachers were compensated for a two hour teleconference session, a one hour pre-conference homework 'assignment' of exploring LTW's website, and a one hour post-conference homework assignment in which teachers meet with us after implementation to report on their experience and provide feedback. The advanced homework was implemented so teachers could get a more in-depth exposure while minimizing the meeting time. The follow up homework was implemented to stimulate teachers to use the resources and for LTW to better understand how the resources work in the classroom. Offering remote professional development allowed LTW not only to reach more people but also to access diverse environments that are typically hard to reach. For example, there were many participants working in rural areas and Tribal lands. During and after participation, I followed up with teachers to suggest they introduce the activities to their colleagues, which many did.

A life of their own. The web applications replicate tools that are standard in science and engineering laboratories. Although we have created specific lesson plans associated with them, they can be used in several other ways, and we encourage teachers to be creative. I am aware that a few efforts exist in this direction, 1) one teacher in a Tribal Land is currently working on a project using the oscilloscope to gather natural sounds and mix them with poetry and drumming; 2) one teacher working with gifted students modified a lesson plan in which students measure themselves and their relatives' hearing ranges, so they would graph age vs. maximum hearing frequency to observe a trend; 3) science curriculum developers at San Diego Unified School District are adapting the spectrogram tool to study sounds of nature; and 4) the oscilloscope tool was used as part of a program in Kerala, India, that demonstrated to increase students' data literacy [16].

Successful strategies.

Based on this experience, I enumerate the salient features that I think should be considered in developing a program:

1- Time in the classroom. Working in close collaboration with students will help developers understand their interests and capabilities, which will help to create engaging learning experiences. Working with teachers will help developers understand their culture, capabilities, and needs and create tools that teachers can eventually implement without the developers' direct support. In the initial stage, it is useful to work in a very controlled environment. Ultimately, the work should be carried out in the environment that will be the focus of the spread. Because of their demographics and shared culture, large public schools present an environment that can allow a program to eventually reach a vast number of low-income students.

2- High value and low cost. For a program to spread, it needs to fulfill the schools' necessities and be easy to implement. The school *necessities* are for the activities to be engaging and to be aligned with the curriculum. The *cost* includes the monetary cost and the cost in terms of time and effort from teachers and school employees. Web-applications can be free or inexpensive, and they do not require support from IT personnel, which makes them very low cost. It is also useful for the lesson plans to be very clearly organized, for example, structured as a set of slides with associated student worksheets.

3- Partnerships. Partnering with institutions that are well inserted in the educational system can help a program create relevant resources and, once the resources are created, help spread them through the community.

4- Dissemination. Materials can be dissemanted by aggresively tapping the developers' professional networks (including partnerships), through paid professional development, and through targeted online advertising. After an initial stage in which the program starts gaining visibility, dissemination can occur organically through its website, as it becomes more visible in search engines. A well-curated, attractively designed, and organized website can be very instrumental in providing a program credibility in the public's eyes. Undergraduates can be of great help for developing a website. Creating media that profiles the program is also very useful to share the content and gain visibility.

5-Breath vs. depth. For a developer passionate about their field, it can be easy to go down the rabbit hole of depth, creating very long and detailed learning experiences touching on many corners of that field. Although this depth can be appropriate when working for a long time with a small group of motivated students, as is often the case in selective (or self-selective) after school programs, it can conspire against the broad adoption of the program, as it requires a lot of training by the instructors or the direct participation of the developer. This does not mean that depth should be renounced, but that the program developers need to be strategic about growth. If the developer's goal is to achieve both depth and breadth, the choice has to be made of which dimension to target first. In developing LTW, I put a lot of effort into creating experiences that I soon realized were not easily scalable. Although those experiences contributed to my learning and reached several students, in retrospect I understand I should have been more strategic in deciding what aspects of the program to focus on in order to maximize its breadth. Ultimately, I decided to focus on breadth because I believe it is more democratic. Even if focusing on underrepresented students, small in-depth programs end up reaching the most motivated, the most supported, or just the luckiest. An initial focus on breadth can be regarded as a strategic choice, as the activities can be improved over time to provide more depth. We observed this to happen when our partner teachers became more comfortable with the materials as they engaged with the program year after year and independently implemented more activities.

Conclussions and future directions:

This work recounts LTW's strategies to grow from a small "boutique-style" outreach program to more widespread adoption. The transition involved observing student use of available software for analyzing and creating sound, and adapting the software to maximize the users' access, both in terms of technology and usability. At the present moment, LTW has been growing organically through a bottom-up strategy focusing on teachers' networks, rather than under a top-down "school-reform" model, which has been the focus of scale-up research [9], [17]. Nevertheless, LTW develops along the dimensions identified in that literature: LTW's early success in improving students' attitudes towards science signals its potential for *depth*. The online tools have been developed to be robust, thus targeting the dimension of *sustainability*. The ease of use of the online tools and associated curriculum targets the dimension of *spread*, and is likely to have lead to their widespread adoption. The fact that teachers are adapting the lesson plans or repurposing the online tools indicates the programs' *shift*. Through the professional development structure and the teacher action model implemented with the San Diego County Office of

Education, the program's continuous communication with its users targets the dimension of *evolution*.

So far, the research about the program’s effect on students’ attitudes towards science has been limited to an experience that counted with the program team's heavy involvement. The next step will be to investigate how the program is being adopted by teachers, the effect on teacher and student attitudes toward science, and how the activities are sustained over time. This research will help reveal the scope of LTW’s value and guide iterations of the online tools and curriculum.

On a more general level, I envision that LTW will contribute to a deeper integration of music in the schools’ curriculum, for example by incorporating other subjects such as the creation of electronic music through computing, and the relations between music and data science, history, literature, foreign lenguages, and world-culture.

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Figures.

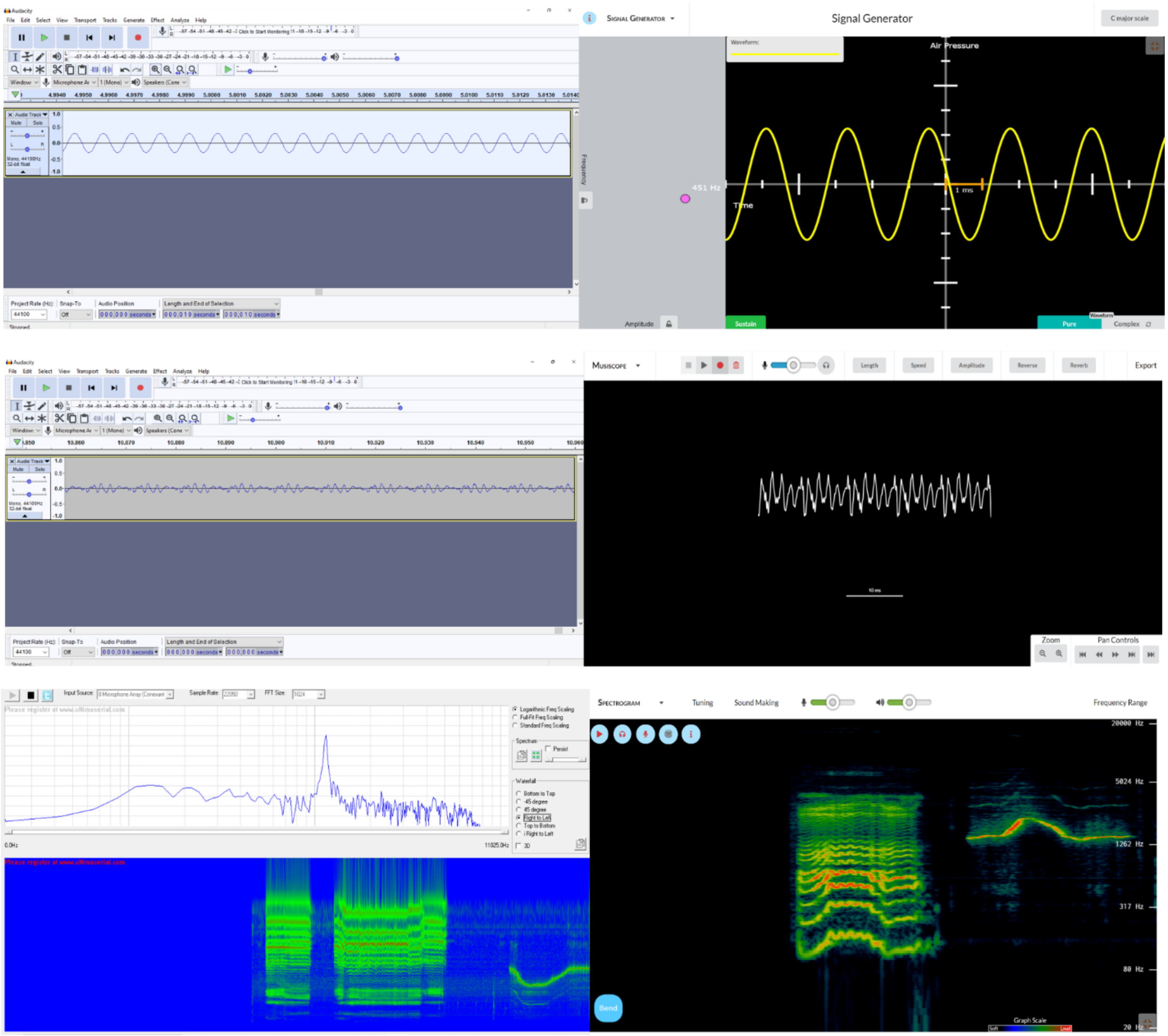

Figure 1. Listening to Waves' web applications facilitate the public's access to laboratory tools. The applications appeal to a broad audience because they are web-based and they present a simplified user experience catered to specific learning goals. LTW's web applications also seek to increase the user's engagement by allowing them to playfully create sound and music. The left figures represent software used in early instantiations of the program. The right figures represent LTW's current web applications. Creating a pure tone or visualizing a waveform with the free audio editor *Audacity* (top and middle left) involves a long series of steps and setting of parameters. In contrast, LTW's users can easily create and visualize a pure tone with the signal generator (top right), or easily visualize a sound's waveform in real time with the oscilloscope (middle right). Similarly, spectrum analyzer UltimaSound (bottom left) presents a complicated user interface, as compared to LTW's spectrogram, which also allows users to play musical scales and add sound effects (bottom right). To use the tools see https://listeningtowaves.com/sound-exploration.