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LeMo: an assembly kit for musical acoustics education

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ABSTRACT
Musical acoustics is a scientific field essential for an in-depth understanding of musical instruments and sounds. As such, it is relevant to wide audiences involved with music, including musicians, composers and even casual listeners. This work describes a twofold approach for introductory, hands-on education in musical acoustics. First, a concise classification approach for acoustic instruments is described. The approach consists of classifying instruments based on their fundamental acoustic properties of vibration generation, resonance and radiation. Then, an assembly kit of modular instrument components is described. The kit contains stand-alone resonator and radiator modules of various types, allowing the assembly of different fully functioning instrument prototypes. Students and general audiences, guided by educators, may use the kit to learn and experience the acoustic behaviour of musical instruments, as well as specific acoustic phenomena.

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Musical acoustics; education; instrument; instrumental acoustics; modular; kit

1. Introduction

Musical acoustics is a multidisciplinary field concerned with the research and description of the physics of music, and of musical instruments in particular. This field holds the answers to key questions regarding musical instruments: what causes an instrument to be perceived as good or bad? What makes one instrument sound brighter, warmer or louder than the other? What makes a banjo sound different than a guitar? As instrumental music is extremely widespread, these questions reach far beyond the confines of the scientific community, and are pertinent to general audiences such as musicians, instrument builders and even casual listeners.

Combining knowledge from various scientific fields with the popular appeal and familiarity of music, musical acoustics is an exemplary STEM subject (Science, Technology, Engineering and Mathematics) or even a STEAM subject, where the 'A' stands for Art. As such, musical acoustics could play a primary role in STEM education for general audiences.

Sonic differences between musical instruments are best explained by the instruments' acoustic properties, as they are conveniently reflected in existing systems of instrument classifications. Namely, the most pertinent properties defining an instrument's sound are the method of excitation (*generator*), the principal vibrating component's type (*resonator*) and the principal radiating component (*radiator*). Note that this classification is different from a typical classical orchestra instrument classification, with such categories as brass and woodwind.

This paper presents LeMo – an assembly kit for musical acoustics education. The kit consists of stand-alone modules of rudimentary instrument components, corresponding to common types of the above mentioned properties: generator, resonator and radiator. The modules are assembled by a simple magnetic fastener to create musical instrument prototypes representing various combinations of the three properties. Students and musicians may use the kit to explore the various instrument properties and their respective effects on the produced sounds. The kit offers a hands-on experiential approach, complementing theoretical musical acoustics education. The name LeMo is a wordplay on the kit's place of inception, Le Mans, France and the popular assembly toy Lego.

2. Related work

2.1. Music, acoustics and instrument making in education

Musical acoustics may serve two different pedagogical goals. First, it may enrich the musical experience of

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Supplemental data for this article can be accessed here. https://doi.org/10.1080/09298215.2022.2150651 music students. Second, it may serve as an attractive learning subject among STEM students. Various teaching programmes propose the use of musical acoustics for either goal. iMuSciCA is an online system for music based STEM education, created by a consortium of European universities and companies. The system offers various online activities blending music and science. One activity consists of 'designing' virtual musical instruments on a virtual lab bench using basic objects such as strings and weights. The project is targeted at secondary school children (Kritsis et al., 2019). Reflections on courses and topics for musical acoustics education are given by Rossing (2009). The courses are intended for university students from various disciplines, and leverage music's importance and attractiveness as a topic. According to Rossing, an understanding of musical acoustics can explicitly help musicians improve in their art. In addition, the importance of classroom demonstrations and experiments are acknowledged.

A review of teaching programmes involving instrument making is given by Matsunobu (2013), with a specific examination of adult shakuhachi flute makers and players. Incorporating instrument making as an integral part of the musical experience is found to foster attachment to the instrument, facilitate active engagement in music learning and enhance the player's understanding of instrument-specific techniques. Similar findings are reported by Smith (2018), who had incorporated instrument making in collegiate music education. Smith emphasises the re-connection between musician and instrument and the heightened awareness of instrument care, maintenance and appreciation. As digital fabrication technologies such as 3D printing are becoming more widespread, instrument making may be even taken up by musicians or students lacking technical training or specialised tools (Cottrell & Howell, 2019; Kolomiets et al., 2021).

Additional works also emphasise the educational importance of classroom experiments. Parikesit and Kusumaningtyas (2020) developed several methods of arousing the curiosity of undergraduate students using musical acoustics of the bundengan – a traditional Indonesian instrument. The methods include hands-on work with the instrument such as fabrication workshops, acoustic characterisation and modelling. Gazengel and Ayrault (2012) conduct short performances with musical instruments in the classroom, termed *scientific concerts* , to demonstrate basic concepts such as timbre and pitch to high school and university students.

The MERITE project is an educational toolkit consisting of a great variety of minimalist proto-instruments constructed from everyday objects (Gautier et al., 2019). This project makes a similar distinction between the three main acoustic functions of an instrument, generator, resonator and radiator, as done in the LeMo system. However, the MERITE project focuses mainly on the generation mechanisms, demonstrating plucking, rubbing, striking, whistling and blowing. The toolkit is intended for acoustics education for a popular audience, specifically children. The use of ready-made everyday objects is deliberate, arousing curiosity and assisting in the 'demystification' of musical instruments' methods of operation. Additional sources provide other novel ideas for instruments based on ready-made objects (Hopkin, 2009; Jeltsch & de Poorter, 2015; Vandervorst, 2006).

2.2. Classification systems

The LeMo kit was designed by identifying the properties of musical instruments most directly related to their sound production, and by classifying the variety of these properties in the world of existing musical instruments. This process was facilitated by the use of musical instrument classification systems.

The most widely used system in musical research is the Hornbostel-Sachs system (H–S) (Von Hornbostel & Sachs, 1961). The H–S system consists of classifying instruments into top-level categories, based on the initial sound-producing component: aerophones for an air column, chordophones for a string, membranophones for a membrane and idiophones for the instrument's solid body itself. Each category contains additional subcategories, based on various instrument properties, such as the excitation method and morphology. While the top-level categories pertain to an essential acoustic property of the instrument, some subcategories pertain to qualities, that while important from a classification perspective, are not acoustic in essence. For example, zithers are sub-classified by the string bearer's shape (tube, board, through etc.) and lutes are sub-classified by the angle of the string plane and soundboard (harp type, lute type etc.). Although the H–S system is extremely effective, this mixture of acoustic and non-acoustic properties causes it to overlook details relevant to this project's goal.

A novel classification approach is presented by Lysloff and Matson (1985), which in some ways complements the H–S system. The alternative system consists of describing instruments by a set of 37 non-hierarchical parameters. The parameters pertain to various instrument aspects such as sound production, structure, material, tuning method and number of players. The parameter set describes a multi-dimensional space, in which instruments sharing many identical values are positioned in proximity. By focussing on a few specific parameters, the system facilitates drawing comparisons between instruments.

This work follows a similar approach to that of Lysloff and Matson (1985). However, since this work only seeks to explore the acoustic properties of instruments, it uses only the three well-defined acoustic parameters selected from the entire set.

2.3. Modular instruments

Many examples exist of modular instruments – musical instruments consisting of interchangeable components. The cümbüş is a Turkish banjo-like instrument, consisting of a membrane and an aluminum sound box with a detachable neck, allowing for easy neck replacement (Ederer, 2007). A selection of individual neck modules are available. The necks are modelled after existing lute-like instruments, such as a saz, a cura, a mandolin and a guitar. While most neck styles are plucked, the tanbur style neck is intended for bowing. Cümbüş sound boxes are also available as individual components, consisting of different sizes and materials.

The Fidular is a modular fiddle system somewhat resembling an erhu with detachable neck and sound box (Hantrakul, Lamtharn, n.d.). The system includes a selection of sound boxes, representing similar instruments of different musical cultures. The tuning pegs are designed to accommodate different string varieties. Somewhat similar in concept, the Chameleon guitar is an augmented guitar with a replaceable soundboard (Zoran & Paradiso, 2011). The soundboard availability offers sound augmentation, from a mild timbre modification to avant-garde sound effects. The soundboard's acoustic vibrations are picked up and further processed by DSP, simulating a sound box. This project was preceded by the reACOUSTIC eGUITAR, a conceptual proposal of a guitar where each string is coupled to a replaceable individual sound box (Zoran & Maes, 2008). Using sound boxes of different materials, shapes and sizes, the guitar's sound is altered.

3. Instrument classification: Generator/Resonator/Radiator

3.1. Overview

The classification approach used in this work consists of describing instruments by a set of three parameters, pertaining to their primary acoustic functions: generator, resonator and radiator. These parameters were identified using existing classification systems as described earlier. The parameters are defined as follows:

1. **Generator:** the primary tool or action used to excite initial mechanical vibrations in the instrument, such as striking with a hammer, rubbing with a bow and plucking by hand or plectrum.
2. **Resonator:** the primary sound producing component, such as a string, a membrane or an air column. The resonator's resonance frequencies determine the instrument's pitch.
3. **Radiator:** the primary component responsible for projecting the sound outwards, such as a soundboard, a membrane or an aperture. The radiator typically has little effect on the instrument's pitch, but it contributes to the timbre, radiation and loudness.

The authors had analysed several musical instrument databases, including MIMO (MIMO – Musical Instrument Museums Online, n.d.), online shops specialising in unusual and novel instruments (Lark in the Morning, n.d.), and miscellaneous instrument documentations found online. Several reoccurring values of the three parameters were identified, which the authors propose grouping into these categories:

- **Generator**
  1. Pluck: excitation consisting of displacing the resonator from equilibrium, followed by an abrupt release.
  2. Strike: striking the resonator, by hand or any kind of striker.
  3. Rub: rubbing the resonator as to induce a stick-slip motion, by a bow or a similar contraption, or by hand.
  4. Reed: excitation consisting of generating vibrations in a reed, or a double reed, by an air stream.
  5. Buzz: excitation consisting of generating vibrations directly in the player's lips by blowing, such as in playing a trumpet.
  6. Blow: excitation consisting of the production of an air stream, which does not incorporate a reed or a buzzing gesture, such as in playing a flute.
- **Resonator**
  1. String: any type of a thin flexible cord or band held under tension at both ends.
  2. Membrane: any type of a thin film held under tension.
  3. Solid body: any type of a rigid solid object or shell, not held under tension, such as bars and rods.
  4. Tube: a tube with any bore shape, open on both ends, in which air vibrates.
  5. Enclosure: any form of an enclosure or acoustic cavity with a single opening, in which air vibrates.
- **Radiator**
  1. Soundboard: a rigid surface, not held under tension, flat or mildly curved, such as a plate.

(2) Membrane: any type of a thin film held under tension.
(3) Solid body: any type of a rigid solid object or shell, not held under tension.
(4) Aperture: any form of an aperture in a solid material, through which air is guided from the instrument to the outside free air. This includes both tapered acoustic horns (such as in a trumpet) and a straight tube end (such as in a flute).

These categories may be further classified as either fluid or solid, based on their underlying physics. The fluid generators are reed, buzz and blow, the fluid resonators are tube and enclosure and the only fluid radiator is aperture. The rest of the categories are classified as solid. This distinction and its significance are detailed further in Section 3.2.

Throughout this paper, a concise instrument classification is notated by the corresponding values of the three parameters. For example, a violin is classified and notated as a rub/string/soundboard instrument, and a banjo is classified as a pluck/string/membrane instrument. Any combination of three values creates a category, or a 'family' of instruments. For example, the rub/string/soundboard category also contains the cello, hurdy gurdy and bowed clavier.

Figure 1 shows possible parameter combinations of instruments. First, a general distinction is made, outlining combinations of either solid and fluid resonators and radiators, as elaborated in Section 3.2. Then, examples of instruments with solid generators, resonators and radiators are shown, as these instruments are currently the focus of the LeMo kit. The examples appearing in each cell represent the authors' best efforts in locating instruments corresponding to each and every combination. In the case of common combinations, only a handful of examples are listed for brevity. Empty cells describe combinations for which the authors could find no examples. Given the immense variety of musical instruments, it is possible that such examples exist, but have eluded the authors.

The LeMo kit in its current form and the corresponding classification focus on instruments' fundamental acoustic functions. As such, they do not take into account non-primary acoustic components such as sympathetic strings or secondary resonators. For instance, a sitar is classified as pluck/string/soundboard instrument, much like a classical guitar, and this is despite the sitar having both sympathetic strings and a secondary cavity resonator. Note that in most instruments consisting of both a soundboard and a sound box, such as violins, the strings are directly coupled to the soundboard itself, while the soundboard is coupled to the sound box. Therefore, these instruments are classified as having soundboard radiators, while the sound box, a secondary resonator, is excluded from the classification.

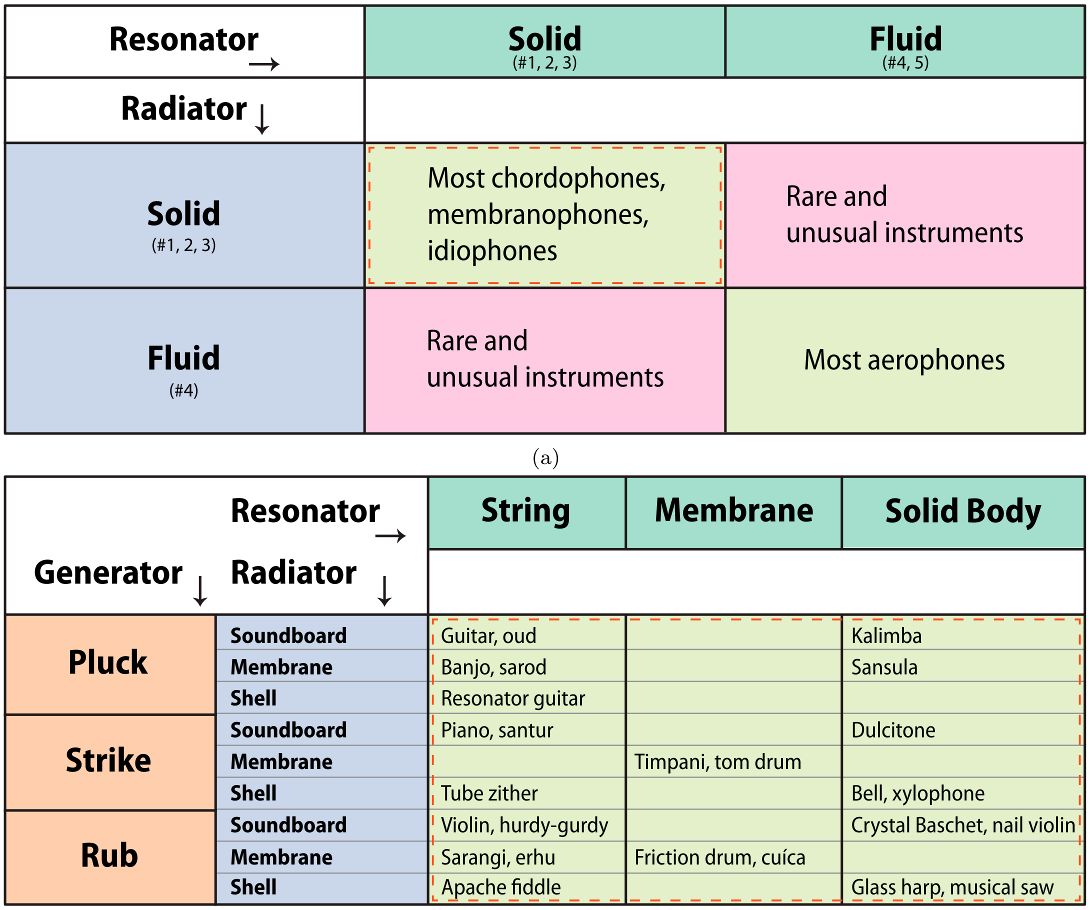
3.2. Solid and fluid acoustic elements

Resonators and radiators identified in existing instruments are based on either solid or fluid (air) acoustic elements. In most instruments, the resonator and radiator are either both solid or both fluid. The solid element instruments are typically excited by a pluck, strike or rub generator, while the fluid element instruments are typically excited by a reed, buzz or blow generator. These two groups are indicated in Figure 1 in green.

Some notable exceptions, where a solid and a fluid resonator or radiator are mixed, do in fact exist. The Stroh violin is a violin-like instrument, consisting of a metal horn radiator, resembling a brass instrument horn. As such, it is classified as a rub/string/aperture instrument, i.e. a solid acoustic elements resonator and a fluid radiator. The string is coupled to the horn via a metal membrane located at the small end of the horn (Zakharchuk, 2015). Similar horned versions of string instruments exist, such as the 'phono ukulele' and 'cellocordo' (horned cello).

Other notable exceptions pertain to combinations with a solid acoustic resonator excited by a generator mostly associated with a fluid element, or vice versa. The aeolian harp's strings are excited by wind (Selfridge et al., 2017), and is thus a blow/string/soundboard instrument. The wind wand, by Darrell De Vore, falls into a similar category, having rubber bands instead of strings (De Vore, 1989). An example of a solid generator acting on a fluid acoustic resonator is the thongophone, a plosive instrument where the end of a hollow tube is struck by a flat rubber clapper. The pitch of the resulting tone is determined by the air resonance inside the tube, rather then by the solid tube's resonance. The thongophone is therefore a strike/enclosure/aperture instrument.

Instruments consisting of a fluid resonator coupled to a solid radiator are specifically challenging to design. As the fluid and solid medium densities are considerably different, vibration transmission between the two elements is often inefficient. One successful example of such an instrument is La Tôle à Voix by the Baschet Brothers (Leloup, 2017). The instrument consists of a large contoured piece of sheet metal. The instrument is excited into vibration by a human singer's voice. Exhibiting non-linear vibration, the sheet metal acts as a solid radiator and enhances the singer's voice with inharmonic partials. While this instrument is more complex to fit into a simplistic generator/resonator/radiator scheme,



Resonator → / Radiator ↓	Solid (#1, 2, 3)	Fluid (#4, 5)
Solid (#1, 2, 3)	Most chordophones, membranophones, idiophones	Rare and unusual instruments
Fluid (#4)	Rare and unusual instruments	Most aerophones

(a)

Generator ↓	Resonator → / Radiator ↓	String	Membrane	Solid Body
Pluck	Soundboard	Guitar, oud		Kalimba
	Membrane	Banjo, sarod		Sansula
	Shell	Resonator guitar		
Strike	Soundboard	Piano, santur		Dulcitone
	Membrane		Timpani, tom drum	
	Shell	Tube zither		Bell, xylophone
Rub	Soundboard	Violin, hurdy-gurdy		Crystal Baschet, nail violin
	Membrane	Sarangi, erhu	Friction drum, cuíca	
	Shell	Apache fiddle		Glass harp, musical saw

(b)

Figure 1. A classification of instruments based on their generator, resonator and radiator properties. (a) The four general combinations of solid and fluid resonators and radiators, where most familiar instruments have either both solid or both fluid elements. (b) Breakdown of solid element instruments. Each generator and resonator combination is detailed with four radiator values.

instruments based on similar concepts may be conceived. For instance, a similar sheet metal radiator may be coupled to organ pipes, resulting in a reed/tube/soundboard instrument.

3.3. Features of the classification approach

The classification approach used in this work offers a methodological process for creating comparisons between existing instruments and identifying their similarities and differences. The comparisons are made by describing the generator/resonator/radiator properties of existing instruments. Different property combinations may describe not only instrument families in existence, but also possible theoretical instruments. As such, the classification approach may also serve instrument inventors seeking to create instruments with novel acoustic properties.

These features of the classification approach are best demonstrated with an example. A classical guitar is classified as a pluck/string/soundboard instrument. Similarly, a banjo and a resonator guitar are both pluck/string instruments, but with different radiators – membrane and solid body, respectively. A kalimba also shares the guitar's generator and radiator, but consists of a solid body resonator in the form of metal tines. While a kalimba and a classical guitar would not usually be compared, one being an idiophone and one a chordophone, a parallel is drawn here, resulting from the classification approach itself. This parallel, and the consideration of the banjo and resonator guitar, directly leads to the conception of other possible kalimbas, having membrane or solid body radiators. A kalimba with a membrane radiator, termed 'sansula', was indeed invented in 2001 by Peter Hokema (Hokema Kalimbas, n.d.). However, we could find no documentation of a kalimba with a solid body resonator. Using this process of mixing possible generator/resonator/radiator properties, instrument inventors may come up with ideas for novel instruments, potentially 'filling in' some of the blank cells in Figure 1. Such novel instruments may be prototyped by using or by extending the LeMo kit, as described in Section 5.

3.4. Prevalence of combinations

The classification approach may also be used to identify how common each generator/resonator/radiator combination is. The most widespread combinations are quite obvious. Many chordophones, such as various guitars, mandolins and lutes, are pluck/string/soundboard instruments. Strike/string/soundboard instruments, like some tube zithers, are also widespread, though somewhat less so. Pluck/string/membrane combinations, such as a banjo, are quite common as well, especially among traditional instruments. Most membranophones are struck, and have the membrane itself acting as the radiator, as discussed in Section 4.2. Idiophones are commonly struck as well, such as in a cymbal and cajon, and only a few are plucked (kalimba) or rubbed (glass harp, Cristal Baschet). Here too, the idiophone's solid body is typically also the radiator. Therefore, strike/solid body/solid body and strike/membrane/membrane combinations are extremely widespread. Aerophones almost exclusively have a reed, a buzz or a blow generator, and an aperture radiator.

Uncommon combinations include string resonators and solid body radiators. Some examples of this combination are the resonator guitar, using an aluminum cone radiator, and many tube zithers, using a bamboo shell radiator. While most membranophones are struck, the friction drum is excited by rubbing. Hence, it is a rub/membrane/membrane instrument. A peculiar example of a strike/solid body/soundboard instrument is the dulcitone – a piano-like instrument with tuning forks in place of strings. The tuning forks are coupled to a soundboard radiator (Maor, 2018). The Cristal Baschet is a unique and successful example of a rub/solid body/soundboard instrument, consisting of metal rod resonators coupled to large sheet metal radiators. While not a musical instrument, the auxetophone is a record player consisting of a compressed air amplifier (Hawley, 1978). The player's needle controls a sensitive valve. As the valve opens, a stream of compressed air is passed to the auxetophone's horn, significantly amplifying the sound. The valve's function is similar to that of a trumpet player's buzzing lips, while the vibrating needle is a solid body resonator. While the auxetophone is too complex to fit into a generator/resonator/radiator scheme, it does consist of an unusual buzz generator and a solid body resonator combination.

3.5. Undocumented combinations

There are some combinations for which the authors could find no documented examples, though the existence of similar combinations indirectly implies their feasibility. These combinations may offer musical acoustics practitioners and instrument inventors avenues for exploration. The combinations, with an abstract description of possible corresponding instruments, are:

1. Rub/string/solid body: A bowed string instrument, such as a violin, with a solid body radiator, such as a cone or a shell.
2. Strike/string/membrane: A hammered string instrument, such as a dulcimer, with a membrane radiator.
3. Pluck/solid body/solid body: A plucked solid body instrument, such as a kalimba, with a solid body radiator, such as a shell.
4. Strike/solid body/membrane: A hammered solid body instrument, such as a dulcitone (consisting of hammered tuning forks), coupled to a membrane radiator.
5. Rub/solid body/membrane: A rubbed solid body instrument, such as a Cristal Baschet (consisting of rubbed glass rods), coupled to a membrane radiator.

In addition, there are more general observations worth noting. All documented Stroh-like instruments consist of a string resonator, but a similar coupling of an aperture radiator may also work with a solid body resonator (such as kalimba tines). Membrane resonators are typically struck, but the authors are familiar with a method of plucking a membrane. The method consists of placing two small magnets on opposite sides of the membrane and then gently pulling one of the magnets. No documentations of pluck/membrane instruments were found. Finally, the existence of the aeolian harp, where strings are activated by the wind (a blow/string/soundboard combination), leads to the theoretical conception of a wind activated membranophone (blow/membrane/membrane). Exploration of some of these combinations by the authors is discussed in Section 4.

3.6. Notable exceptions

While the classification approach encompasses many familiar acoustic instruments, there are some notable exceptions of instruments for which no combination applies. The pyrophone is a 19th century instrument consisting of a set of glass tubes operated by a piano-like keyboard. The sound is generated by the combustion produced by the burning of hydrogen gas inside the tubes (Peacock, 1988). The calliope is a somewhat related instrument, where fipple pipes are excited with gas or steam. Another example is the bullroarer which doesn't seem to fit any combination. The bullroarer consists of a slab of wood tied to a string, rotated in the air

Figure 2. The LeMo kit modules. From top left corner, the radiators: soundboard, membrane (fastener shown on top), cone, horn, and the resonators: strings, clamped bars, free bars, perforated cymbal.

above the players head. The sound is produced by an acoustic dipole, generated across the slab due to its complex movement (Fletcher, 2003). While the bullroarer may be described as having a blow generator, as the initial excitation is caused by a relative movement of air, none of the classified resonator and radiator values are suitable. These examples demonstrate that while the generator/resonator/radiator classification approach covers many musical instruments, exceptions do exist.

4. The LeMo kit

This Section describes the LeMo assembly kit, a collection of standalone modules consisting of generators, resonators and radiators, shown in Figure 2. The kit's purpose is to allow musicians, students, researchers, inventors and general audiences to explore and experiment with different musical instruments. The kit is used by assembling different generator/resonator/radiator combinations. The acoustic function of each component is demonstrated by replacing that component and observing the resulting differences. In addition, the kit may be expanded with customised modules, as described in Section 5. Currently, the kit contains only solid vibration modules, with the single exception of a horn radiator. It is hoped that the kit would be complemented with fluid vibration modules in later stages.

All resonator and radiator modules incorporate a standard fastener used for assembly. The fastener consists of a flat square area of approximately 7 cm by 7 cm. On the resonator side, three neodymium magnets are embedded in the module. On the radiator side, three matching steel discs are embedded in the module. The modules are assembled by fixing both fasteners together, allowing the magnets and steel discs to attach. The resulting connection is sufficiently strong to hold both pieces together and provide acoustic coupling. The modules are disassembled by simply pulling apart the fastener.

While the kit's resonators and radiators are custom designed to be suitable for assembly, generators don't require such customisation as they are naturally detached from the instrument itself. As such, the generator portion of the kit consist of a collection of standard plectrums, beaters and bows.


(a) (b)

Figure 3. The fastener used to assemble resonator and radiator modules. The fastener consists of neodymium magnets (resonator side) and matching steel discs (radiator side). (a) Fastener - resonator side; (b) Fastener – radiator side.

4.1. Description of the modules

The kit currently consists of four resonator and four radiator modules, corresponding to the classification described earlier, and two additional resonators conceived by the authors, which demonstrate less common acoustic features. The existing standard modules are:

- **Resonators**
  1. Strings ('Ukulele'): a module resembling a ukulele's neck, representing a string resonator, consisting of a fretboard and four strings.
  2. Clamped bars ('Kalimba'): a module resembling a kalimba, consisting of 17 metal tines. This module represents a plucked idiophone.
  3. Free bars ('Xylophone'): a module resembling a rudimentary xylophone, consisting of circular rods. This module best represents a struck idiophone. The bars are placed on foam board supports which permit some acoustic coupling to a radiator while only mildly damping the bars.
  4. Perforated cymbal: a module consisting of a standard perforated cymbal, typically used as a practice cymbal with a decreased loudness. Due to the decreased loudness, the module is better suited for coupling to a radiator. This module best represents a struck or rubbed idiophone. The cymbal is acoustically coupled to a radiator via a metal stand at its centre.
- **Radiators**
  1. Soundboard: a module consisting of an oval wooden soundboard.
  2. Membrane: a module consisting of a standard frame drum. A standard fastener, printed in 3D, is attached to the membrane's underside.
  3. Cone: a module consisting of a standard aluminum 'cone resonator' of a resonator guitar, representing a solid body radiator.
  4. Horn: a module consisting of a metal horn, representing an aperture radiator. The horn is fitted with a coupling mechanism resembling a Stroh violin's mechanism, for transmitting vibrations from solid resonators to the air column: a fastener is attached to the horn via a ball bearing, allowing rotational movements. An arm extends from the bottom of the fastener to a metal membrane sealing the narrow end of the horn. Vibrations at the fastener are translated to the metal membrane, which are then radiated through the horn.

All resonators and radiators contain a standard fastener, and thus can be assembled together to create a unique acoustic prototype, with a total of 16 different assemblies. Some assemblies are shown in Figure 4. The applicable generators vary per resonator. The ukulele's strings may be plucked, hammered and rubbed. The kalimba's tines may be plucked and hammered. The cymbal may be hammered and rubbed, and the xylophone's bars may be hammered. Sound Samples 9–13 demonstrate a chord progression on the strings module coupled to different radiators, played by an amateur player.

4.2. Resonator – radiator separation

Resonators also have some radiation properties, depending on their surface area. Resonators with a small surface area, such as strings and tines, have poor radiation properties and are therefore suitable to be coupled to radiators. However, resonators with large surface areas,

Figure 4. Several LeMo kit assemblies, showing combinations of all standard resonator and radiator modules. Each assembly produces a sound with unique acoustic properties, based on its components.

such as membranes and shells, are usually also effective as radiators. Thus, in most instruments with a membrane or solid body resonators, such as drums, bells and marimbas, the resonator itself also acts as the radiator, producing sufficiently loud sounds. No designated radiator is implemented in these instrument, as such an implementation would be mostly inaudible.

However, the concept of a large solid body resonator, such as a cymbal, radiating through a non-solid body radiator, may be interesting to demonstrate. In order for such an assembly to be effective, a unique solid body resonator with sufficiently low loudness levels is required. Such a solid body resonator is found in the practice cymbal – a cymbal perforated with a multitude of small holes throughout its surface. The perforated cymbal's vibration and produced sound are similar to that of a standard cymbal, dominated by strong non-linear couplings in the thin shell. However, the perforated cymbal's radiated sound loudness is significantly reduced by the smaller surface area due to the perforations. Thus, the practice cymbal allows the separation of resonator and radiator functions, and the coupling to a separate radiator.

The perforated cymbal module consists of a practice cymbal mounted on a steel rod, fixed at its bottom to a wooden fastener. The cymbal's vibrations are transmitted to a radiator, coupled via the rod and fastener. Ultimately, the sound produced by the coupled radiator is sufficiently loud to be audible over the cymbal's sound. The specific choice of the radiator – soundboard, membrane, cone or horn – significantly affects the resulting sound's timbre. This module demonstrates the effect of a resonator's surface area on its radiation and loudness.

Similar in concept to practice cymbals, practice drums are membrane instruments designed to produce acoustic drum sounds with a decreased loudness. A common design for a practice drum consists of a metal mesh instead of a membrane. Having a smaller surface area, the mesh produces significantly quieter sounds. The authors considered using a practice drum as a membrane resonator module, in a similar fashion to the perforated cymbal module. However, a sufficiently effective method for coupling the mesh's vibrations to a radiator module was not yet developed. Therefore, a membrane resonator is currently not implemented in the kit.

4.3. Acoustic analysis

Coupling a radiator to a resonator is likely to have two effects on the produced tone. First, the amplitude and duration of each partial produced by the resonator itself may change. More pronounced changes are likely to occur where a resonator's resonance frequency coincides with a radiator's resonance frequency. Second, resonance frequencies of the radiator itself may be excited and appear in the tone. These radiator partials typically have shorter decay times, due to higher internal damping in the radiator. Thus, the radiator's partials are expected to be present mostly in the attack transient at the beginning of the tone. As the attack transient is known to be perceptually significant and to have a major effect on tone quality assessment (Cassidy & Schlegel, 2016), the radiator resonances may be expected to have a considerable effect on the tone.

An acoustical characterisation was performed on the LeMo kit to investigate the effects of different coupled radiators. First, the mobility of each radiator module was measured using an impact hammer and an accelerometer. The impact was induced at the fastener's centre, and the accelerometer was located within several millimetres of the impact point. The mobility is defined as the ratio of the vibration velocity to the impact force, in the frequency domain. In the context of the study, this measurement configuration is known to be sufficiently accurate up to 4 kHz. Subsequently, tones produced by the resonator modules and by different resonator–radiator assemblies were recorded by a near-field microphone. The modules were excited by manually plucking or striking.

Figure 5 shows the spectrograms of several resonator module tones, compared to tones produced by the same resonators with different coupled radiators (see complementary Sound Samples 5(a–f)). Each tone was normalised by its RMS value. A plot of the radiator module's mobility at the coupling point is shown above each spectrogram of the assembly tone.

The radiator's effect is clearly demonstrated by Figure 5(a ,d), relating to a kalimba and a cone radiator assembly. With the cone radiator coupled, the relative magnitude of the second harmonic at 522 Hz is significantly increased. This harmonic is barely noticeable without a radiator. In addition, new partials appear between 1200 to 1350 Hz. It is reasonable to assume that these partials stem from the radiator itself, which has several significant resonance frequencies at this range, as visible in the mobility plot.

A similar occurrence is visible in Figure 5(b ,e), showing the string module and a string module-plate radiator assembly. The plate radiator decreases the fundamental frequency's relative magnitude at 261 Hz and accentuates the second harmonic at 522 Hz. Additional differences are observable in the decay times of some higher harmonics, and a slight increase in relative energy in various frequencies in the attack transient. All of these differences contribute to an audible change of timbre. A significant change in tone is also noticeable in the perforated cymbal module's case, coupled to a membrane radiator, as shown in Figure 5(c ,f). The membrane radiator causes an increase of relative magnitude of several partials between 550 to 1350 Hz and two partials around 1950 Hz, while decreasing the relative magnitude of some specific partials above 3000 Hz.

Compared to the other radiators, the horn radiator's effects were not equally noticeable. In most assemblies, the horn radiator mainly contributed to the radiation's directivity pattern. While the acoustic radiation was not measured, an informal impression is that the horn does create a noticeable directivity in the direction in front of the horn's aperture. However, in terms of timbre, in most cases the horn radiator did not create significant differences. Possible reasons for this inefficacy are explored in Section 6. Figure 6 shows the spectrogram of a string module–horn radiator assembly's tone, a specific horn assembly where the effect on timbre was noticeable (see complementary Sound Sample 6). Here, the horn amplifies the second and third harmonics at 522 and 783 Hz, attenuates the fifth harmonic at 1305 Hz and shortens the decay time of several harmonics above 2500 Hz.

5. Novel resonators

The LeMo kit may be useful for exploring acoustic phenomena or prototyping novel musical instruments. For instance, the existing modules may assemble a kalimba with a solid body radiator prototype, an instrument for which we could find no documentation, as described in Section 3.3 and shown in Figure 4.

In addition to the existing modules, the kit may be easily extended with new modules, providing users and inventors a platform for even further exploration. The only technical requirement of additional modules is the implementation of a suitable fastener. The following subsections describe two novel resonator modules developed by the authors, demonstrating the kit's capabilities.

5.1. Slinky resonator

Slinky is an off-the-shelf steel spring toy, most known for its ability to 'travel' down a flight of stairs. The spring is dispersive, with a faster propagation time of high frequencies. When hammered or plucked, the spring

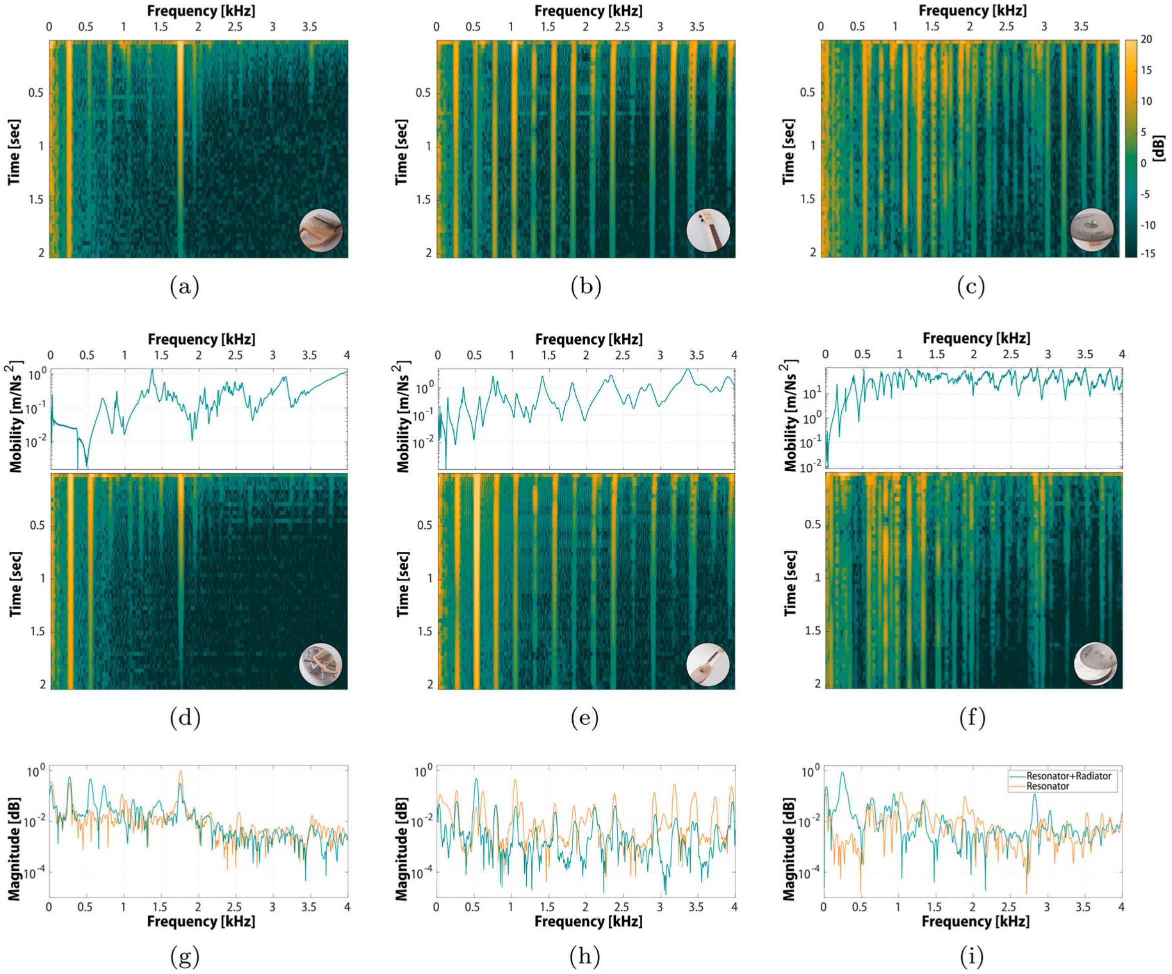


Figure 5. Spectrograms of tones produced by standalone LeMo resonators (top) compared to the same resonators coupled to radiators (middle). The radiators' mobilities are plotted above the spectrograms. The spectra of the same tones' attack transients appear at the bottom. Coupling a radiator amplifies and attenuates different existing partials, and adds additional partials to the tone at some radiator resonance frequencies. (a) Kalimba resonator without a radiator; (b) String resonator without a radiator; (c) Perforated cymbal resonator without a radiator; (d) Kalimba resonator coupled to a cone radiator; (e) String resonator coupled to a soundboard radiator; (f) Perforated cymbal resonator coupled to a membrane radiator; (g) Kalimba resonator coupled to a cone radiator, transient tone; (h) String resonator coupled to a soundboard radiator, transient tone; (i) Perforated cymbal resonator coupled to a membrane radiator, transient tone.

produces a metallic-sounding descending chirp (Crawford, 1987). Thus, the Slinky may be a familiar and appealing means for the demonstration of acoustic dispersion. Due to the springs's small surface area, the produced sounds are of low loudness, and most acoustic demonstrations involving the Slinky seem to require amplification.

The Slinky resonator module, shown in Figure 7, consists of a standard Slinky attached to a steel plate and a magnet at one end, enabling coupling to a radiator module. Any radiator considerably increases the loudness, preventing the need for amplification. Specifically, coupling the Slinky to the cone radiator module accentuates the sound's 'metallic' qualities. This is most likely due to the existence of effective cone mid-range resonance frequencies. An assembly consisting of the Slinky resonator and a membrane radiator represents a crude prototype of a Yaybahar or of a thunder drum (Ballora, 2014; Gorkem Sen, n.d.) (see Sound Sample 7).

5.2. Loose strings resonator

While strings are a very common resonator in musical instruments, they are almost exclusively used under tension. While not under tension, strings still produce sounds, albeit barely audible. The loose strings resonator utilises the sound produced by strings not under tension.

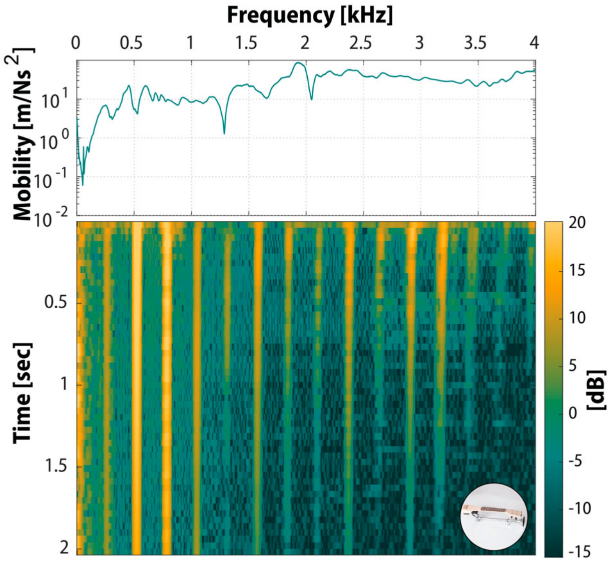


Figure 6. Spectrogram of a tone produced by the string resonator coupled to the horn radiator. The radiator's mobility is plotted above the spectrogram.

Figure 7. The Slinky resonator module. The magnetic fastener is located at the right end.

These sounds, of a naturally very low loudness, are made audible by coupling to any radiator module.

The loose strings module, shown in Figure 8, consists of four ball-end wound bass guitar strings. The strings are fitted with two steel plates and a magnet, such that the ball-ends are firmly clamped between the plates. The plate is held so that the strings are hanging vertically, free at the bottom end. The strings are excited by striking or scratching the windings. Vibrations in the strings are transmitted to the radiator via the clamped ball-ends and the steel plate, resulting in loud audible sounds. The strike sounds are short and percussive, with a subtle pitch quality, akin to a mixture of a string and a metal shaker. This module serves as a means for the demonstration of wave propagation and vibration transmission. In addition, increasing the strings' tightness by tugging or attaching weights to the free ends allows for exploring the relation between string tension and pitch (see Sound Sample 8 – loose strings resonator coupled to a cone radiator).

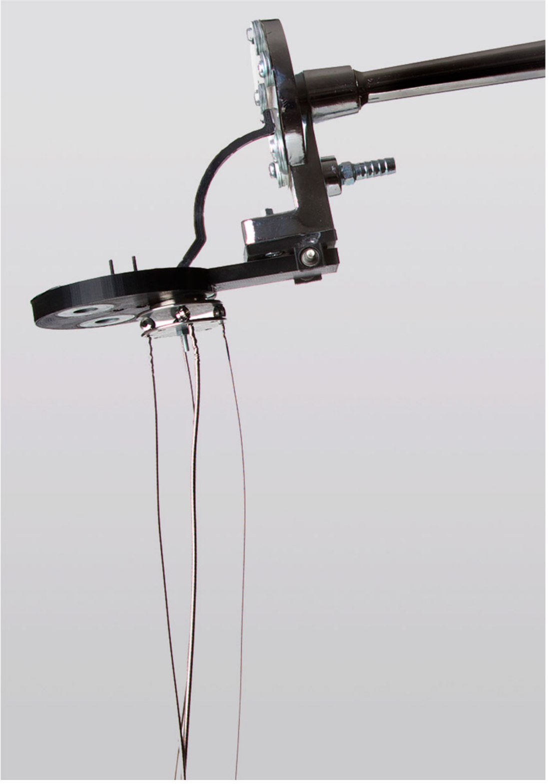


Figure 8. The loose strings resonator module, shown attached to the horn radiator.The strings extend downwards to their normal length (cropped).

6. Discussion

The LeMo kit allows musicians, students and general audiences to explore the acoustic properties of various musical instruments and to get an intuitive hands-on understanding of the workings of musical instruments. Furthermore, the kit may demonstrate various acoustic phenomena, both trivial and advanced, such as frequency, timbre, mode, vibration transmission, radiation, loudness, dispersion, damping and non-linear vibration. The kit first presents the audience with a conceptual approach for the consideration of musical instruments as combinations of generator/resonator/radiator elements. Various combinations are described, and combinations for which no actual instruments exist are noted. Then, some combinations are demonstrated using kit assemblies.

The kit's current form consists of only solid vibration modules, with the exception of the horn radiator, and therefore represents some chordophones and idiophones.

Two additional novel resonator modules demonstrate the concepts of dispersion and string tension. Acoustic analysis has shown that the coupling of different radiators to the resonator modules altered the produced tone, thus effectively demonstrating some basic acoustic differences between instruments. All modules were designed to be suitable for children, and are durable, easy to use and assemble, and do not contain complex mechanical parts.

6.1. Drawbacks of the current implementation

One major trade-off in the kit's specification is the very fact that it consists of physical objects, rather than virtual representations. The direct experience offered by physical objects may be attractive to various audiences, and to children especially. However, physical objects are far more complicated to replicate and share than virtual online tools. The authors wish to facilitate the replication of the LeMo kit by making its fabrication plans publicly available. Nonetheless, its replication would still require skills, materials and tools.

The current implementation also has some technical issues. The coupling fastener seems to create decent acoustic coupling, but the mechanical connection it forms could be stronger, especially when the assemblies are moved. Future versions of the kit could incorporate an improvement over the magnetic fastener, perhaps including a locking latch mechanism.

As previously described, the horn radiator was found to be somewhat less effective than the other radiators. The authors tend to attribute this to the resonator modules' bridge design. The mechanism for the horn radiator was based on a Stroh violin coupling mechanism, where the violin bridge is mounted on a pivot, allowing for a considerable range of motion. However, in LeMo's resonators, the bridges and supports are mounted directly on the modules' bodies, without pivot-equivalent mechanisms. Thus, the resonator bridges allow for smaller ranges of motion, which seem to be insufficient for the horn radiator. In addition, as the bridges are mounted directly on the modules' solid bodies, the vibration is further dampened by the user's grip. Lastly, the horn mechanism consists of 3D printed plastic. It is possible that by using different bridge designs, allowing for more bridge-to-body movement, and by fabricating the horn mechanism from metal, better coupling may be achieved.

Another somewhat ineffective module is the xylophone resonator. This module produces sufficiently loud sounds by itself, diminishing the effects of a coupled radiator. For future implementations, bars with reduced surface areas could be considered. Such a reduction may be achieved by various means, such as by using flat thin bars, circular bars with smaller diameters or perforated bars in the fashion of the perforated cymbal. In addition, the coupling between the bars and the coupled radiator seems to be weak. Creating an effective coupling method turned out to be a challenging trade-off between allowing sufficiently low bar damping to effective vibration transmission. The authors' best effort, consisting of plastic foam supports, seems to be insufficiently effective. It is possible that a better design of the entire module, combined with a better mounting mechanism, could overcome this problem.

6.2. Future work

Further technical development of the kit is still warranted. First and foremost, the kit should be expanded to include fluid vibration modules. These modules would consist of all fluid elements described in Section 3.1: reed, buzz and blow generators (technically, mouthpieces), tube and enclosure resonators in various shapes, and aperture radiators. Once these modules are incorporated, the kit would be able to represent many aerophones, thus encompassing most everyday instruments. Later expansions of the kit may attempt to implement solid-fluid coupling, as described in Section 3.2, in order to represent instruments such as La Tôle à Voix. Implementation of solid-fluid coupling may be more complex, and may require the design of customised coupling adapters for the existing modules, or a complete redesign of the solid modules. Another challenging expansion could be the design of a tuning feature for resonators that are not typically tunable, such as bars or cymbals. Such a tuning feature would allow users to precisely examine how the interaction of resonator–radiator resonance frequencies affects the produced tones, as is currently only possible with the strings module.

The variety of solid instruments represented by the kit may also be expanded to include more complex combinations. The kit's current implementation is deliberately concise, focussing on the fundamental acoustic properties of musical instruments. However, this simplicity comes at a trade-off, overlooking some instruments' acoustic properties which may be both essential and educational. Many instruments consist of several resonators. For example, a marimba incorporates tube resonators placed underneath the bars. As the kit consists of only primary resonators, a marimba can only be partly represented. The sympathetic strings of many instruments are similarly overlooked. For representing these instruments, more complex modules, incorporating secondary resonators or sympathetic strings, may be developed in the future. In addition, a membrane resonator with sufficiently low loudness levels should be developed in order to represent membranophones suitable for coupling to a radiator.

Future research of the kit should also include a user study, to examine the kit's various use cases as a teaching aid. Thus far, the kit is described as intended for broad audiences and purposes. However, it is possible that specific cases within these broad definitions are preferable. For instance, future research may investigate for which ages and educational backgrounds the kit is mostly suitable. Also, a user study should determine if the kit is only useful as a hands-on teaching aid, or also for frontal instruction, with the audience only seeing and hearing the modules.

7. Conclusion

An assembly kit for popular musical acoustics education was presented. The kit is based on a simplistic classification approach of musical instruments by three parameters: method of excitation (generator), initial sound producing component (resonator) and the primary sound radiating component (radiator). The classification approach allows for comparisons to be easily drawn between instruments. The kit consists of modular resonators and radiators, and allows for prototypes of musical instruments to be easily assembled. The instruments' acoustic properties are explored by replacing the modules, as well as by exciting sounds using different standard generators, such as plectrums and bows. The kit currently represents various idiophones and chordophones, and also demonstrates the concepts of dispersion and string tension using two novel resonator modules. Different resonator/radiator assemblies were acoustically characterised and shown to produce noticeable differences in the produced sounds.

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