# Music in the making at the Yale CEID

ISAM 2019 Paper No.: 17

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**Introduction**

Musical Acoustics and Instrument Design, a course taught in the Yale Center for Engineering Innovation and Design (CEID), explores the principles of acoustic and electronic musical instruments using a highly interactive hands-on approach that takes optimal advantage of the resources available in an academic makerspace. Targeting undergraduate students with a wide range of backgrounds in music and engineering, the course provides an understanding of the theory of musical instruments, how they are designed, and a practical knowledge of the tools and technology used to build them. The culmination of the course is the design and construction of an original instrument by each student. We present some of the outstanding student results from spring 2019. The course was co-taught by Larry Wilen and Konrad Kaczmarek, faculty in Mechanical Engineering and the Department of Music, respectively. Shai Gertler was the teaching fellow and Antonio Medina was a student in the class, now a Design Fellow in the CEID.

**Course model details**

The first half of the course includes lectures on the physical theory of waves and vibration as they relate to musical instruments, musical tuning systems, as well the theory and application of electromechanical design and digital music synthesis. The lectures are paired with labs that reinforce the theoretical concepts as well as teach specific manufacturing and design skills such as CAD, 3D printing, laser-cutting, hand tools, electronics, and microprocessors. Each lab consists of building a different musical instrument ranging across the spectrum of string, wind, percussion, electronic and digital. Some labs incorporate a “mini design challenge” whereby students may modify aspects of their instruments to enhance some musical component.

With 5 weeks left in the term, the students are challenged to conceive of and build an instrument of their own, using the new skills they have learned, and leveraging the diverse tools and resources of the CEID. An informal iterative design process is followed whereby students alternately brainstorm design concepts and build successively more complex prototypes. Technical and logistical challenges and interaction with simple prototypes lead to further understanding of musical concepts, new skill development, as well as highly creative invention.

We have found that the above curricular formula weaves together diverse aspects of iterative design, fosters a unique environment for interactive learning, and results in highly creative outputs that also naturally produce a high degree of student satisfaction with, and engagement in, the learning process. An earlier paper[1] describes in some detail the pedagogical model for the course, as well as some of the final projects from the first year the course was taught (fall 2014).

In this poster, we highlight and discuss some projects from the past year (spring 2019), along with live demonstrations. While the projects mostly speak for themselves as unique creations, we specifically emphasize here examples where the iterative making process itself provided inspiration for unusual creative elements, and in particular where difficulties or constraints in the process led to unexpected innovative surprises or directions. We strive to demonstrate these creative flashes through a brief narrative of the student’s design journey along with the musical outcome.

More generally, we present these project outcomes to make the case that the curricular model we describe, whether applied to musical instruments, (ENAS344/MUSI316) introductory engineering, (ENAS118) the design of medical devices, (MENG404) the design of consumer products, (ENAS400) or other topics, is a special kind of learning laboratory somewhat unique to the academic makerspace environment at Yale.[2]

**Highlighted Projects, spring 2019:**

Four E-Motions: Milo Brandt, class of 2019

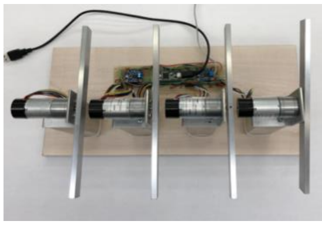

*Figure 1 . Milo Brandt's Four E-Motions. Each key has a different physical feel and maps to a different musical function*

Milo was a music and math major, and a carillon aficionado. His initial idea was to create a set of keys that looked like a carillon keyboard, but could also simulate the feel of playing a carillon, with lower notes having a different resistance and inertia compared to higher ones. He experimented with various electromechanical systems and eventually settled upon a simple geared motor with a built in encoder, with a metal bar (the "key") attached to the motor shaft. The system was interfaced to a teensy microprocessor and motor drivers. By employing feedback and physical modeling in his code, he could simulate just about any mechanical system; for example, a key could feel light or heavy, could have a small or large restoring restoring force to an equilibrium position, or might experience more or less friction. At this point, Milo was poised to add 24 more motor units and create his carillon keyboard. Unfortunately, there was little time left, and Milo was constrained to work with only four units, so he was forced to think in new directions. The result is shown here: One motor obeys a physical model with multiple potential minima plus inertia and friction, a second acts like a lever with a simple linear spring and friction, the third and fourth act like frictionless systems with inertia and and a torsional spring and hence go into sustained rotational oscillations. All the "key" motions are mapped into different musical effects which are demonstrated here. Had Milo been allowed to work with 25 motors, he certainly would have achieved a really amazing carillon keyboard, but one might argue that his 4 e-motions are way more interesting!

DNO ("d-eye-noh"): Antonio Medina, class of 2019

*Figure 2. Antonio Medina's DNO (Directionally Nuanced Orbital). Built in the shape of a bowling ball, the DNO allows the user to produce musical notes that are affected by the instrument's orientation in a spherical coordinate system as well as inputs from buttons positioned in a format based on a saxophone.*

Antonio, a mechanical engineering major, had also studied saxophone for 12 years. His goal was to create an instrument that, like a saxophone, incorporated an array of buttons that mapped to discrete pitches. The DNO also uses measurements of directional orientations to affect other parameters of the resulting sound. Design challenges such as the limitations of space for internal audio led to an implementation of wireless solutions that allowed for more versatile audio outputs.

Built with programmability and visual aesthetics, Antonio's instrument will be highlighted in more detail in the student poster session at ISAM 2019.

Analog Sympathizer: Nash Keyes, class of 2021

*Figure 3. Nash Keyes' Analog Sympathizer. Six sympathetic strings with amplified pickups create unique spatial audio effects.*

Inspired by a class visit to the Yale Collection of Musical Instruments and the Viola d'Amore displayed there, Nash decided to apply the concept of sympathetic strings to a guitar and to experiment with different tunings for these additional strings. An early prototype showed promise but exhibited a fairly subtle sympathetic response. A large improvement resulted from using a modified violin bridge to couple the strings, but the effect was still relatively difficult to hear and the number of sympathetic notes was limited. Nash's original plan was to use a larger number of sympathetic strings and to invent a damper mechanism that could select which strings were activated to bring out specific resonant effects. Pressed for time and constrained by the space on the instrument, they instead experimented with piezoelectric pickups that principally amplified only the sympathetic vibrations. They also invented a prototype mechanical device based on the action of a retractable pen, that could divide a string into two different lengths to produce a different set of frequencies available for the sympathetic response. While originally conceived to be a "backup" idea given the limited time remaining, this solution was realized to be potentially even richer and mathematically more interesting than the original plan. Another interesting feature that was conceived in the building process was simply that the two pickups (one on each set of 3 strings) could be sent to different stereo speakers, resulting in a unique spatial quality to the audio effects.

**References**


[1] Thibault Bertrand, Konrad Kaczmarek, and Larry Wilen, "Musical Acoustics & Instrument Design: When Engineering meets music." In *Proceedings of the 41st International Computer Music Conference, University of North Texas, Denton, TX.* (2015).

[2] V. Wilczynski, L. Wilen, J. Zinter, "Teaching Engineering Design in a Higher Education Makerspace," In *American Society for Engineering Education Annual Conference Proceedings* (2016).