ANDY CAVATORTA

technical curriculum vitae

As the principal engineer of Andy Cavatorta Studio, I specialize in bringing complex systems to life quickly. I produce the designs, software, circuits, mechanisms, structures, and interfaces. Some are solo projects. In others, others I lead multidisciplinary teams.

The works include a swarm of painting robots, the world's most complex arcade game, adaptive architectural acoustics, optical inventory systems, graphical user interfaces, specialized optical projectors, and more.

I navigate new territories using a combination of prolific prototyping and a knowledge of physics, algorithms, and math. I'm ideally suited for solving problems that are too new or obscure to have their own specialists.

This CV shares three examples of the breadth and depth of many of these projects.

Employment:

Principal
Andy Cavatorta Studio
2010-present

AR prototype engineer
Facebook
2018-19

Adjunct Professor
The Cooper Union,
2015, 2019

Selected Clients:
Björk
The MIT Museum
MoMA
TED

He/Him

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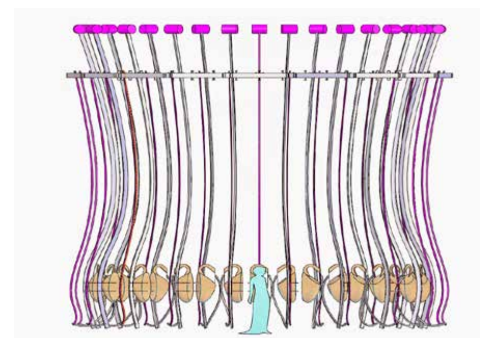
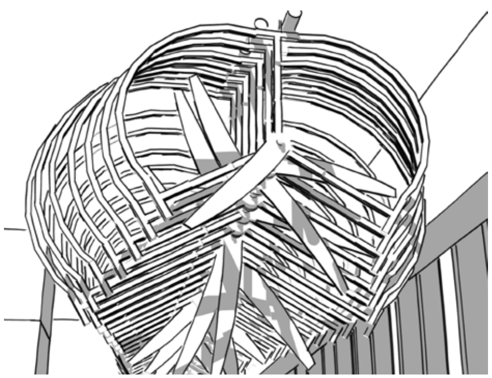
andycavatorta.com
ig: @andycavatorta
781.363.2181

Education:
Master of Arts and Sciences
MIT Media Lab,
2010



WHALE

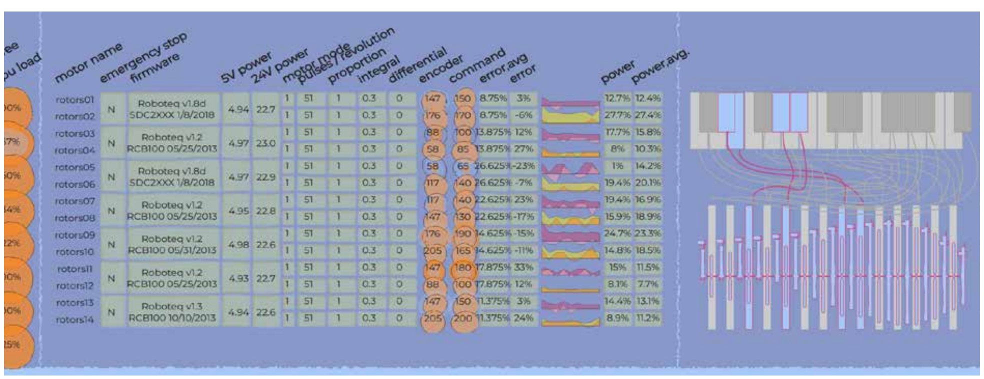
Whale is a large kinetic sculpture commissioned by The MIT Museum for their reopening in 2022. Its fourteen acoustic rotors spin at precise and ever-changing speeds to sing a 220-year-long song composed by a deep convolutional generative adversarial network.

The form, motions, and music are best seen in video:
https://vimeo.com/784666205

Whale is a solo project. The aesthetic design, CAD, fabrication, control system, and acoustic physics are covered on following pages.

All of the control software is written from whole cloth in Python. The software runs as 158 threads distributed across eight Raspberry Pi computers networked by Ethernet. This software uses network discovery, raw sockets, and a pub-sub model to assemble and syncronize all of the connections and threads. And it contains fourteen PID-based motor control systems.

The control interface is a blank SVG graphic containing four thousand lines of JavaScript and two WebSockets. It uses SVG's raw DOM interface to create a GUI.



TECHNOLOGIES USED:

Autodesk Fusion 360
CNC Steel-Cutting Tools
Manual Woodworking
Circuit Board Design
Manual Assembly
Acoustics (physics)

Python
- TensorFlow
- Network Discovery
- Raw Sockets
- Closed-Loop Motion Control
- Signal Processing Algorithms

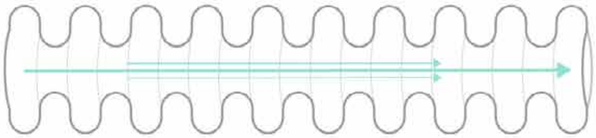
JavaScript (with no frameworks)
- Document Object Model
- WebSockets
- Generative SVG

Whale Tube Acoustics

WHY THE TUBES SING

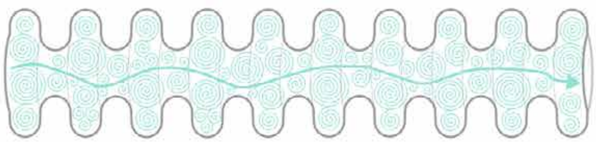
Laminar Flow

Air flowing through a corrugated tube at low speeds will mostly move in smooth, straight layers. The fastest layers are in the center of the cross-section. The outer layers near the corrugation will have minimal turbulence.



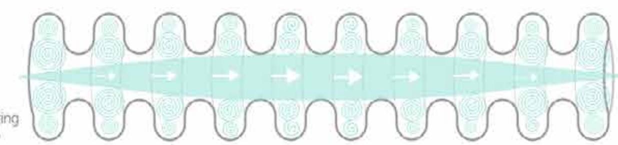
Turbulent Flow

At a higher flow rate, more vortices bloom in the moving air where it flows around the grooves. These vortices are chaotic and quiet.



Standing Waves & Entrainment

The chaotically vibrating vortices create a whispering cacophony of random sound waves within the tube. At certain rates of airflow, sound waves 1/2 as long as the tube will form and reflect back into the tube, creating a standing wave. The standing wave quickly organizes the chaotic vortices to match its frequency. The resulting reinforcing feedback loop causes the tube to sing. This loop is called entrainment.



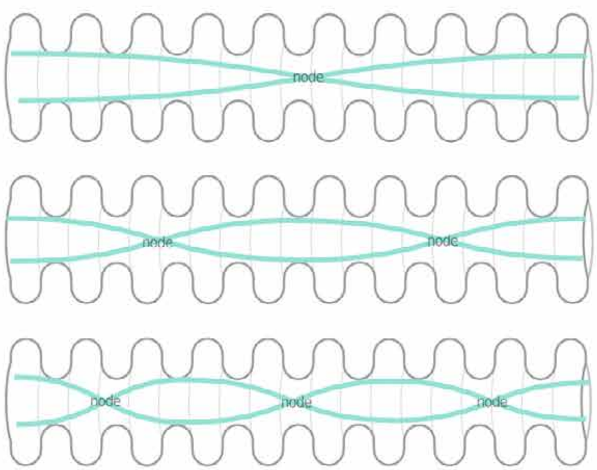
HARMONIC MODES

Each tube can sing at multiple pitches becasue standing waves can also form at shorter wavelengths when the airflow is increased.

Sound waves with a length of [3/2 | 5/2 | 7/2 | ...] the length of the tube will also cause standing waves and entrainment with the chaotic vortices.

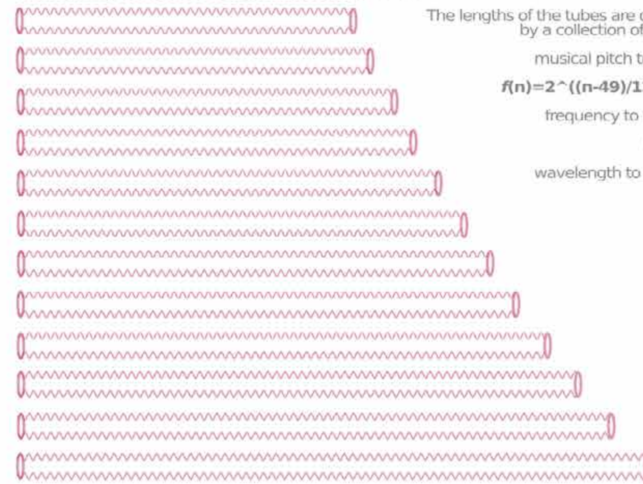
The single half-wave standing wave is called the fundamental mode or the first harmonic mode. The table below shows how properties change as harmonic modes increase.

harmonic	1	2	3	4
wavelength	λ m	$\lambda/2$ m	$\lambda/3$ m	$\lambda/4$ m
frequency	f_0 Hz	$2 \cdot f_0$ Hz	$3 \cdot f_0$ Hz	$4 \cdot f_0$ Hz
nodes	1	2	3	4
semitones	p_0	p_0+12	p_0+18	p_0+24



TUBE LENGTH	WAVE-LENGTH	FREQ.	PITCH
413mm	826mm	415.30Hz	G# 3
437mm	875mm	392.00Hz	G 3
463mm	927mm	369.99Hz	F# 3
491mm	982mm	349.23Hz	F 3
520mm	1040mm	329.63Hz	E 3
551mm	1102mm	311.13Hz	D# 3
584mm	1168mm	293.66Hz	D 3
618mm	1237mm	277.18Hz	C# 3
655mm	1311mm	261.63Hz	C 3
686mm	1372mm	249.94Hz	B 2
735mm	1471mm	233.08Hz	A# 2
779mm	1559mm	220Hz	A 2

TUBE LENGTH & FUNDAMENTAL PITCH



The lengths of the tubes are determined by a collection of equations.

musical pitch to frequency

$f(n)=2$^$((n-49)/12)$ * 440Hz

frequency to wavelength

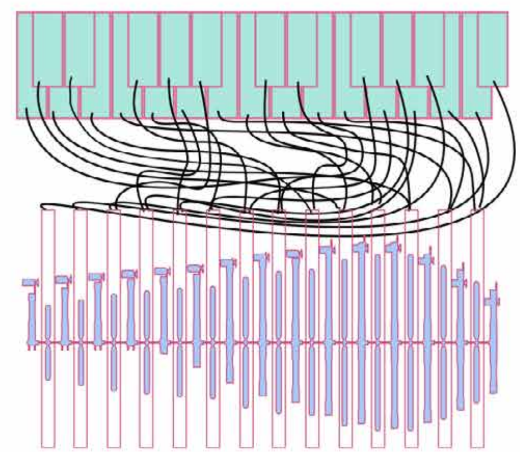
$w=(f\&\lambda)/v$

wavelength to tube length

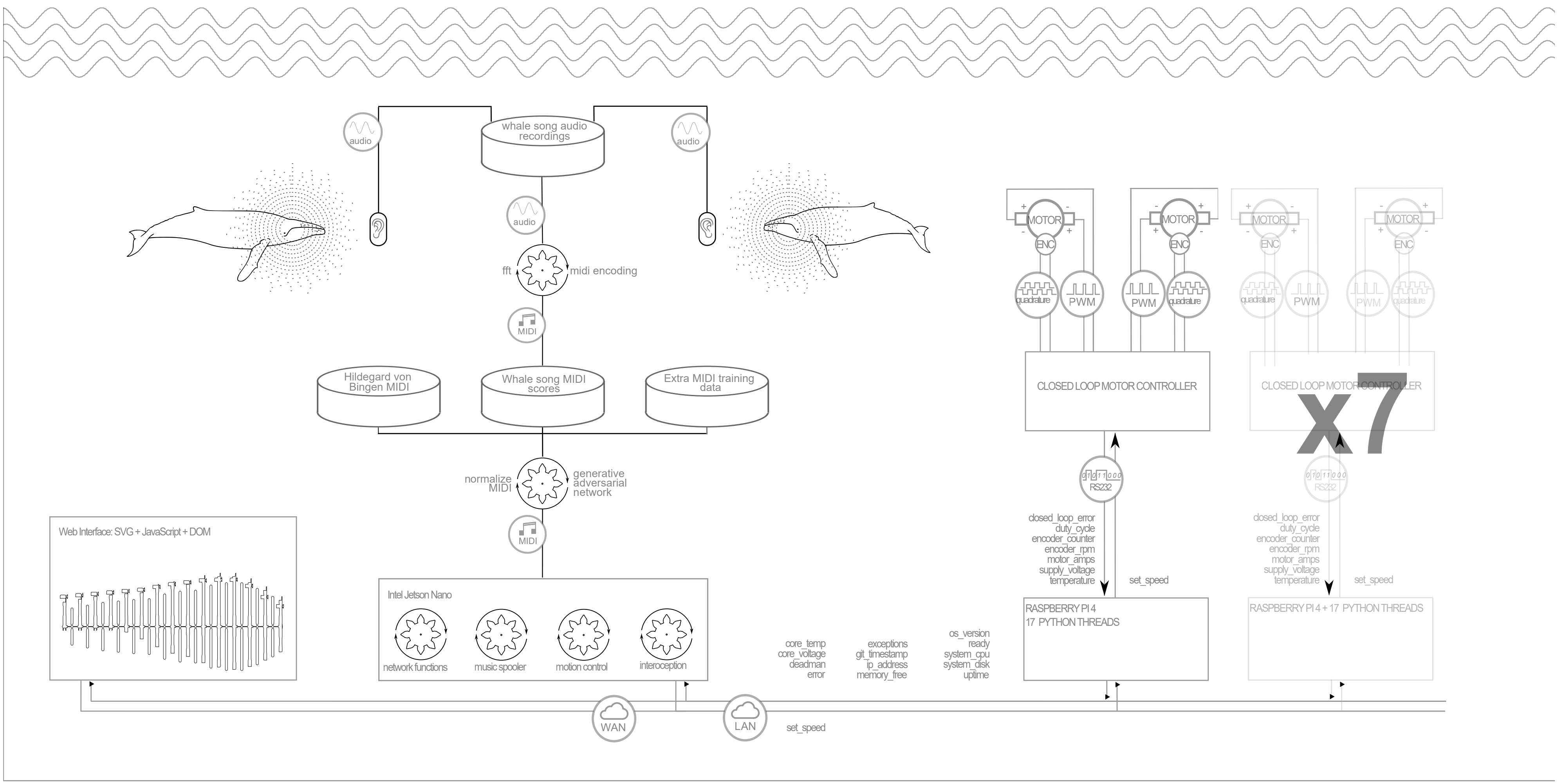
$l = w/2$

CHROMATIC COVERAGE

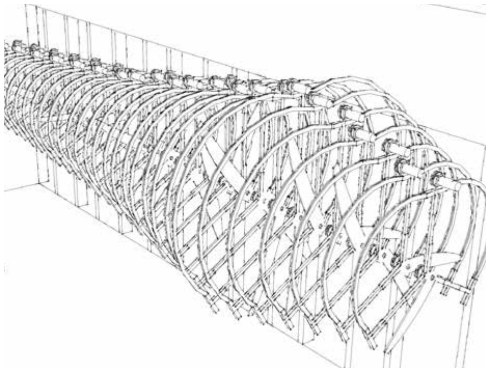
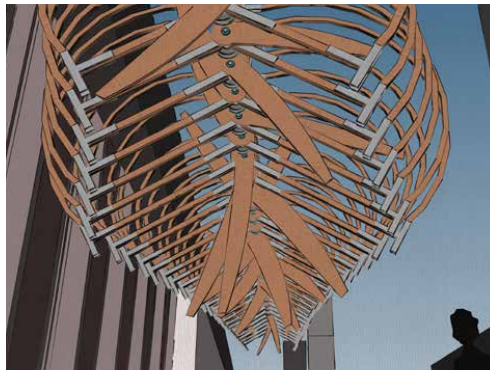
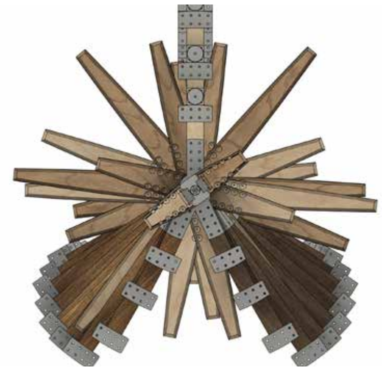
Using a combination of different tube lengths and harmonic modes, Whale can comfortably produce a range of 25 chromatic pitches. It's possible to play a whole octave of pitches above this range. But this requires the rotors to spin at a speed that may be hazardous.



Whale System Diagram



Whale CAD and Fabrication

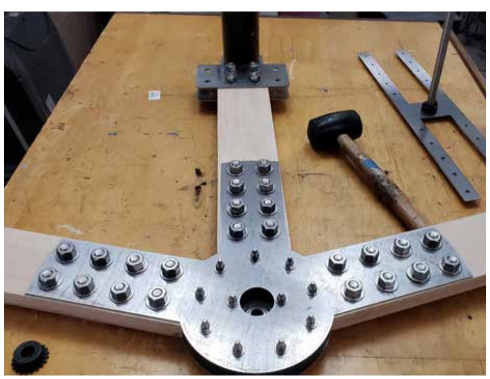
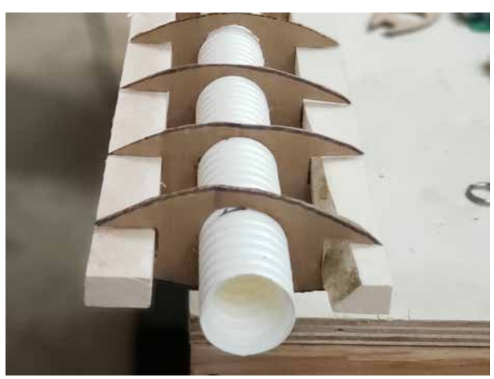




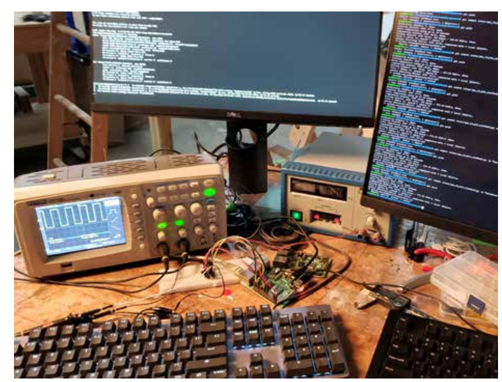

Whale began as many aesthetic sketches in 3D modeling programs. It later became a variety of CAD designs created with Fusion 360.

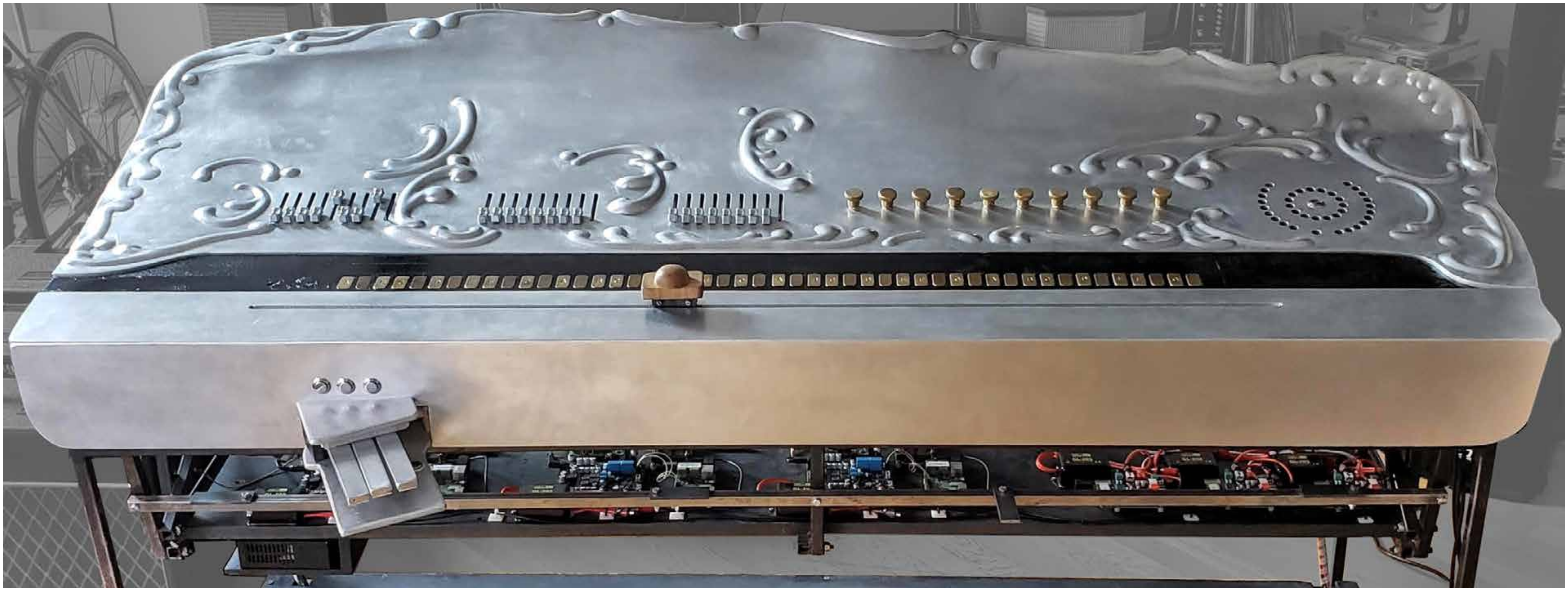
The steel parts were cut with high-powered CNC lasers. The wood parts were cut with a CNC router and shaped with hand tools. Paper sections were cut with a standard laser cutter.

The tubes were tuned by hand using a vintage stroboscopic tuner because its instantaneous readings could handle the constant Doppler vibrato.

The final assembly feaured nearly one thousand fasteners, dozens of custom cables, many chains, sprockets, and custom tensioners.





THE IRVINE

The Irvine is an artifact from a re-imagined history of electronic music in which electrophones entered the symphony orchestra before its menagerie of instruments became fixed. Symphonic electrophones would last for decades and reward long relationships. Rather than controlling processes that crank out automatic music, performers would need to craft every nuance with their hands, ears, technique, and musicality.

Advanced players may develop unique and recognizable voices on the instruments.

The Irvine is intended to play as expressively as singing, with continuous and discrete expression in pitch, dynamics, and timbre.

As part of this imagined history, the design of the Irvine ignores the standard vocabulary of analog synthesizers. It uses crystals and two stages of signal heterodyning to shape its voices. It has a fully-analog signal path from the crystals to the output lines.

Its playing interface is inspired by the lovely 1928 Ondes Martenot. But the Irvine introduces far more musical dimensions. It has three voices instead of just one, enabling a single note to change timbre. And it produces vowel formants and has a three-channel tape-loop-like feature for layering voices and articulatily dropping them in and out while playing.

More info can be found here: https://andycavatorta.com/irvine.html

Irvine Signal Concepts

GALLIUM PHOSPHATE & OSCILLATORS

The Irvine's analog signal path starts with six gallium phosphate crystals. Gallium phosphate is similar to quartz but oscillates at higher temperatures and pressures. These crystals do not occur in nature. They are grown using a proprietray process invented at AVL in Graz.

Each crystal is used as a resonator in a Colpitts oscillator circuit. These six oscillators produce six signals oscillating in a range of ~6MHz±2kHz.

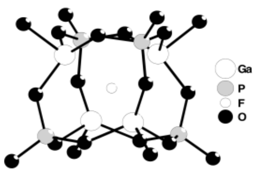


fig 1: Gallium Phosphate crystal structure

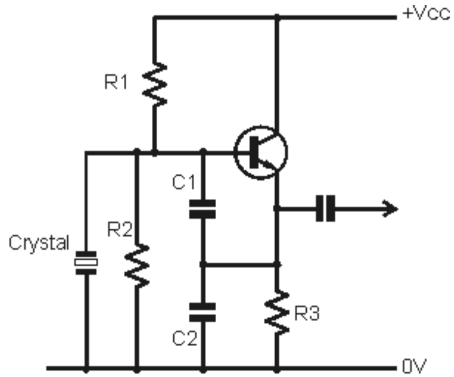


fig 2: Crystal-based Colpitts Oscillator

HETERODYNE

The all-analog signal path of the Irvine starts with gallium phosphate resonators oscillating at ~6MHz and ends with complex signals in the audible range of 20Hz to 20kHz. This is achieved with multiple stages of heterodyning.

A heterodyne is a signal frequency that is created by combining or mixing two higher frequencies.

Figure 3 shows two signals of similar frequency.

Figure 4 shows how the signals align or negate.

Figure 5 shows the superposition of the two signals, the amplitude periodically doubling or canceling to zero.

Figure 6 shows the beat frequency isolated from the original signals by using a low-pass filter.

This final signal is called the heterodyne. Its frequency is equal to the difference between the frequencies of the two original frequencies.

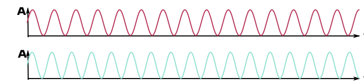


fig 3: two signals of slightly different frequency

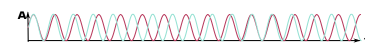


fig 4: two different signals superimposed

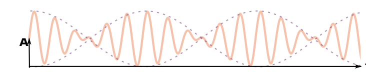


fig 5: beat frequency from superposition

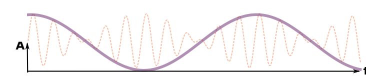


fig 6: beat frequency isolated by low-pass filter

HARMONICS & TIMBRE

A musical note with a pitch of A440 sounds very different when played on a violin and on a kazoo. This difference is a complex subject called timbre. Timbre is all properties other than pitch and loudness.

The largest contributor to timbre is harmonics. Harmonics are additional frequencies that are a natural part of most musical sounds. They tend to fall near a pattern called the harmonic series, shown in Figure 7 on the right. The table above lists the ideal harmonics of a note with pitch A220.

The circuits of the Irvine can add three harmonics to each of its three voices. The harmonic mode, amplitude, and sharpness/flatness are all adjustable.

mode	*f*	*f2*	*f3*	*f4*	*f5*	*f6*	*f7*
frequency(Hz)	220	440	880	1760	3520	7040	14080
ratio	1:1	2:1	5:2	3:1	13:4	7:2	15:4
just interval	unison	octave	5th	octave	M 3rd	fifth	m 7th
pitch	A3	A4	F5	A5	Db5	F5	A5

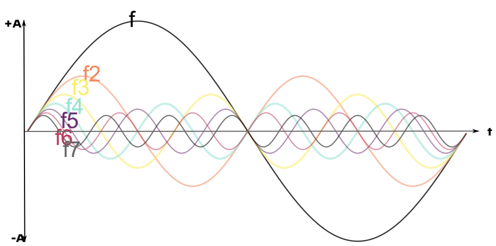


fig 7: Ideal pattern of musical harmonics.

VOWEL FORMANTS

The Irvine's three voices achieve their voicelike properties by emulating the vowels of speech.

Vowels are formed by peaks in the frequency spectrum called formants.

The Irvine uses heterodyning to add formants to each voice. These enable the player to create complex and wordlike phrases out of each note.

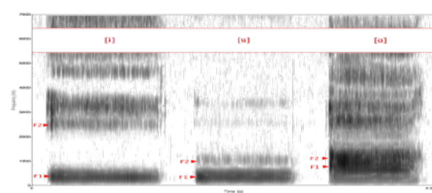


fig 8: Spectrogram showing energy peaks for three vowels

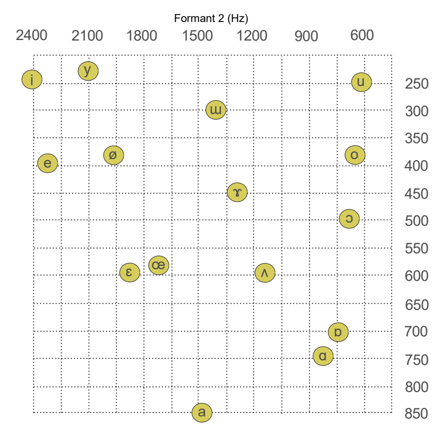
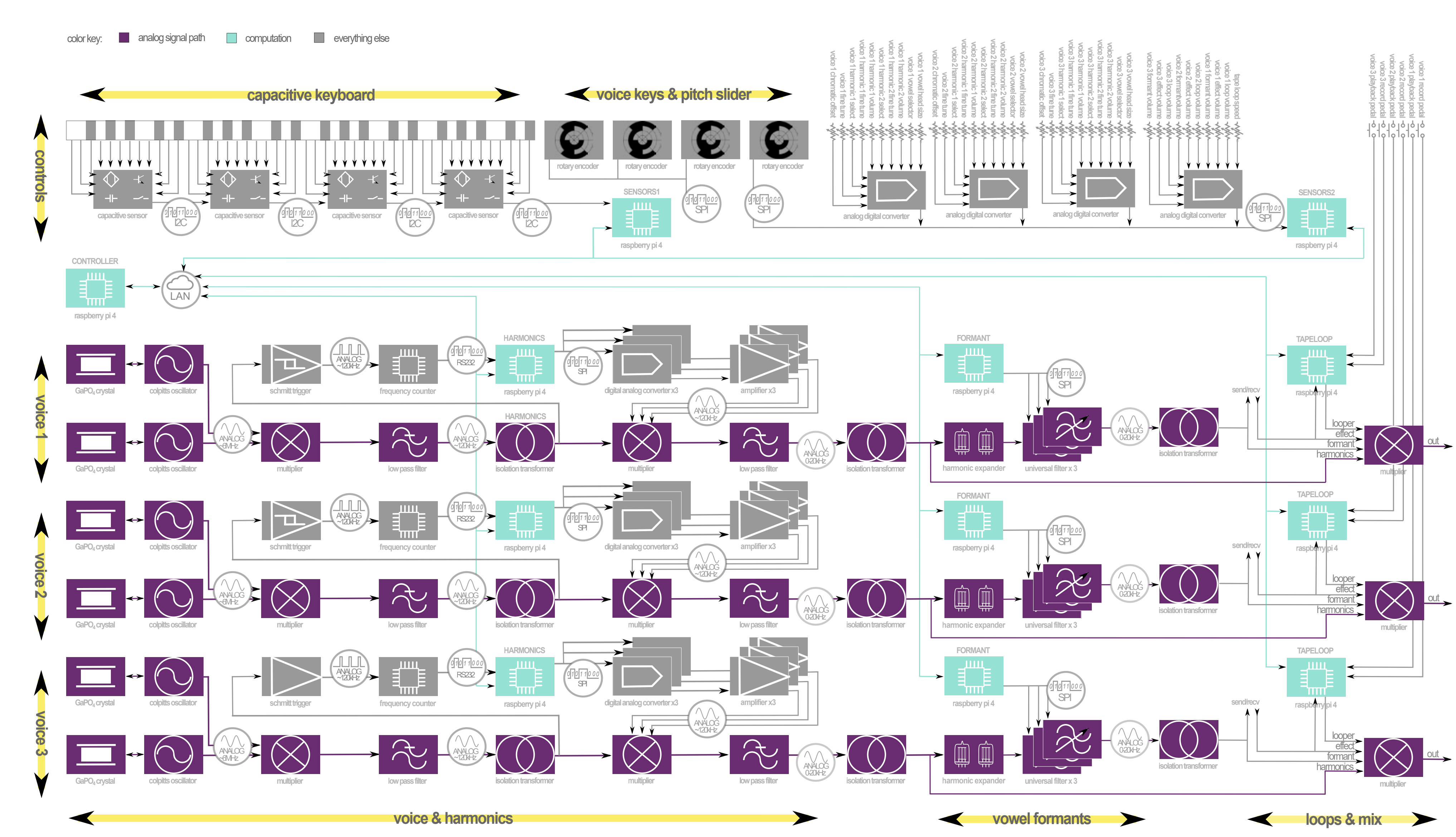
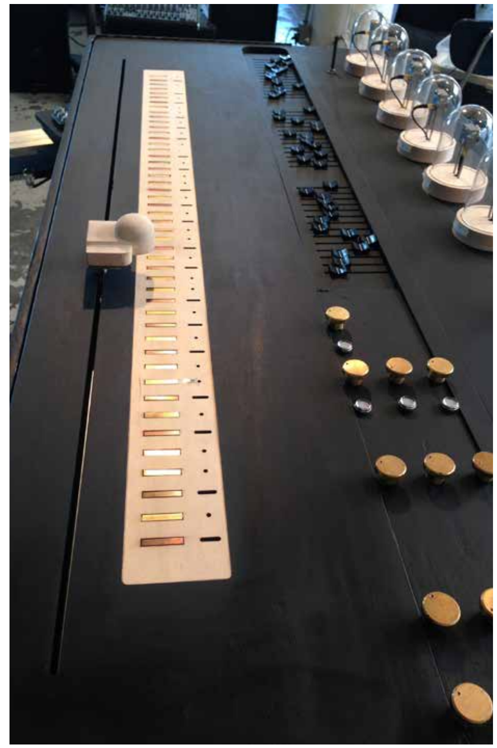


fig 9: The first two frequencies for each vowel (International Phonetic Alphabet)

Block-Level System Diagram for the Irvine

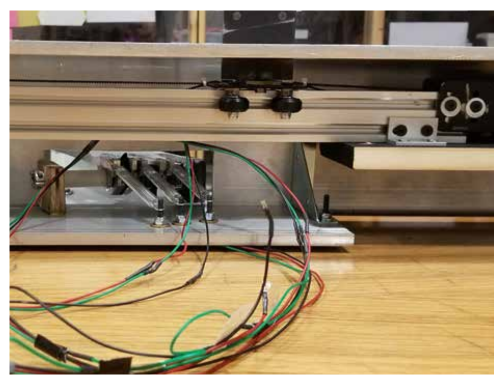


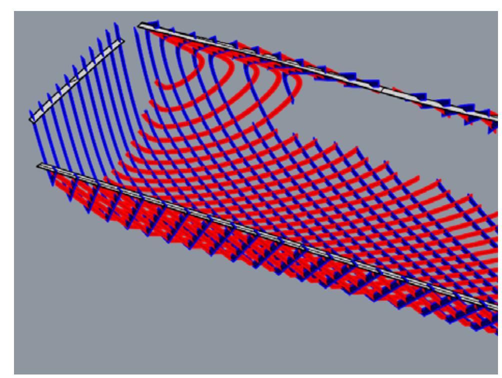
Irvine Prototyping and Process



The Irvine and all of its systems were completely refactored seven times over its 30-week development. This included its custom circuit boards, distributed software, human interfaces, structures and forms, mechanisms, materials, and musical voices. Some of the processes were unusual, including clay sculpting, experiments with liquid nitrogen, glass circuit boards, and metal-forming processes that required six strong hands at once.

More details can be found at https://andycavatorta.com/irvine.html



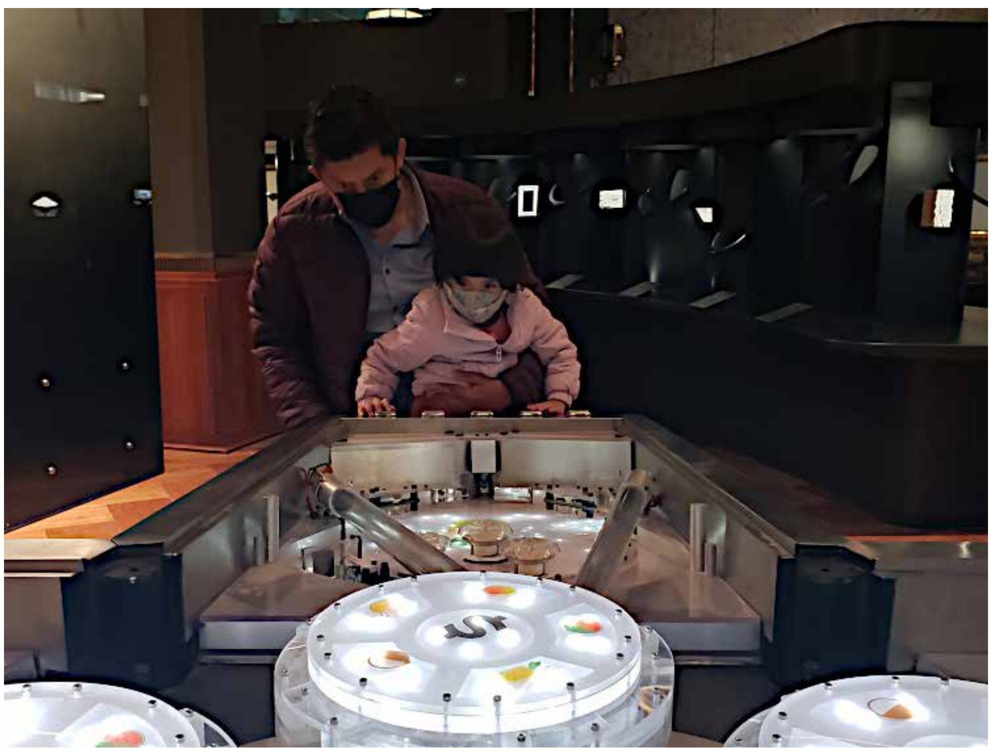


DUAL COINCIDENCE

Dual Coincidence is a multiplayer electromechanical arcade game created as a fine art commission for Museo de Banco de México (the museum of the central bank of Mexico). It is my first game design project and also the most complex arcade game in the world.

The game incorporates 17 computer, six servo motors, 132 sensors, 115 solenoid actuators, 704 channels of lighting, and about 12,000 lines of code.

You can see tha game in action here: https://andycavatorta.com/dual.html



The software runs as ~500 concurrent threads of Python. These two files provide a peek into how it is structured.

The central controller:
https://github.com/andycavatorta/pinball/tree/master/roles/controller/main.py

Each of the pinball playfields:
https://github.com/andycavatorta/pinball/blob/master/roles/gamestation/main.py

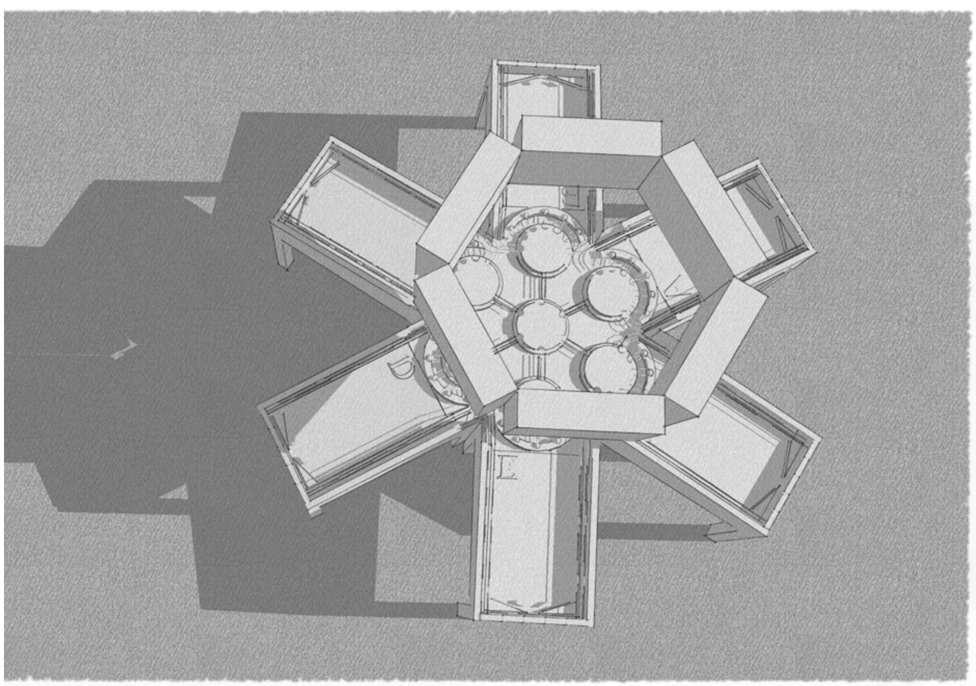
The Game Concept

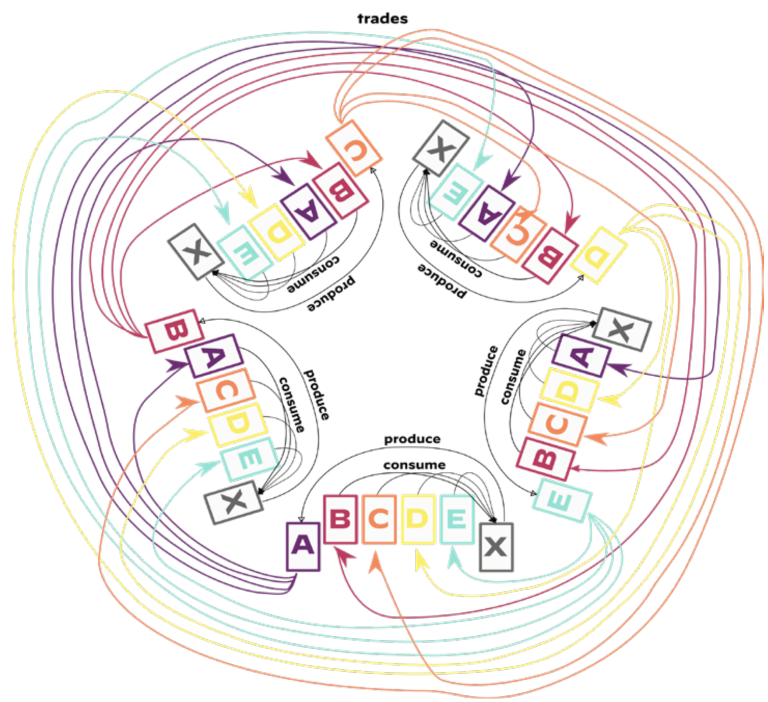
The client asked for a piece that would illustrate the Double Coincidence of Wants, an economic concept related to the dynamics and limitations of barter. It claims that barter is limited to two parties who are both willing to trade something the other wants.

I chose to present the concept as a game so visitors could get inside the forces and dynamics to experience the complexity themselves. And I chose to include pinball as a component because even people who have never played pinball know how to play pinball.

In my design, the game is a village. Each player creates a resource they trade with others: maize, shoes, home repairs, medicine, and transportation. Each player starts with a stock of resources from others. And each player earns their designated resource when they earn points in pinball. But each ball they use costs resources. As a player's stock of resources from others dwindles, the game will incentivize players to try to trade.

But trading is a matter of timing. Other players may not need to trade at the same time. And this is the dual coincidence.





One System in Detail: The Exchange Matrix

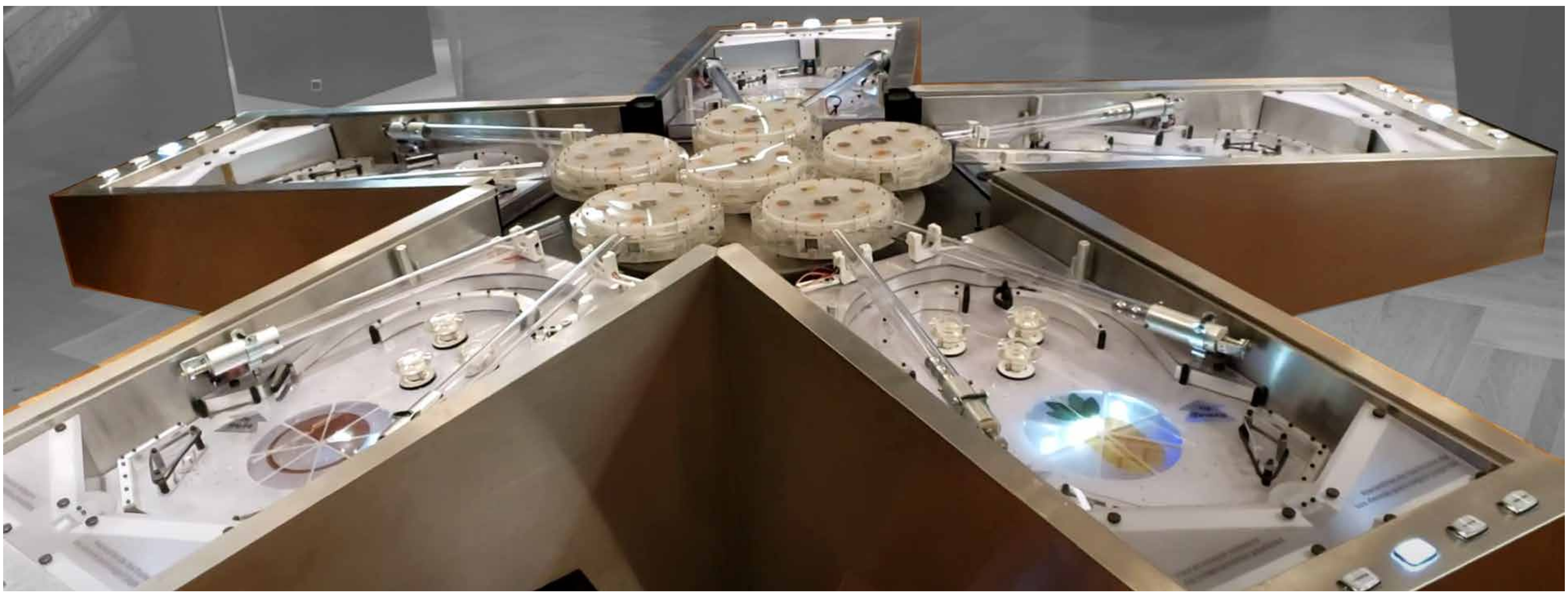
The whole game has many systems, including the five pinball playfields, 25 physical chimes, and acrylic displays featuring 175 channels of edge-lit acrylic. This document will focus on the system that performs trades by passing balls between pinball playfields: The Exchange Matrix.

The Exchange Matrix is made of ten *accumulator tubes* and six rotating carousels. The tubes represent local resources and can each receive, store, and eject balls. The rotating carousels each have five pockets that can receive, store, and eject balls into tubes or other carousels.

The carousels represent each player's stock of resources from other players. And they work together to pass balls between tubes anywhere on the table.

The carousels also have 144 channels of lighting that animate collectively.

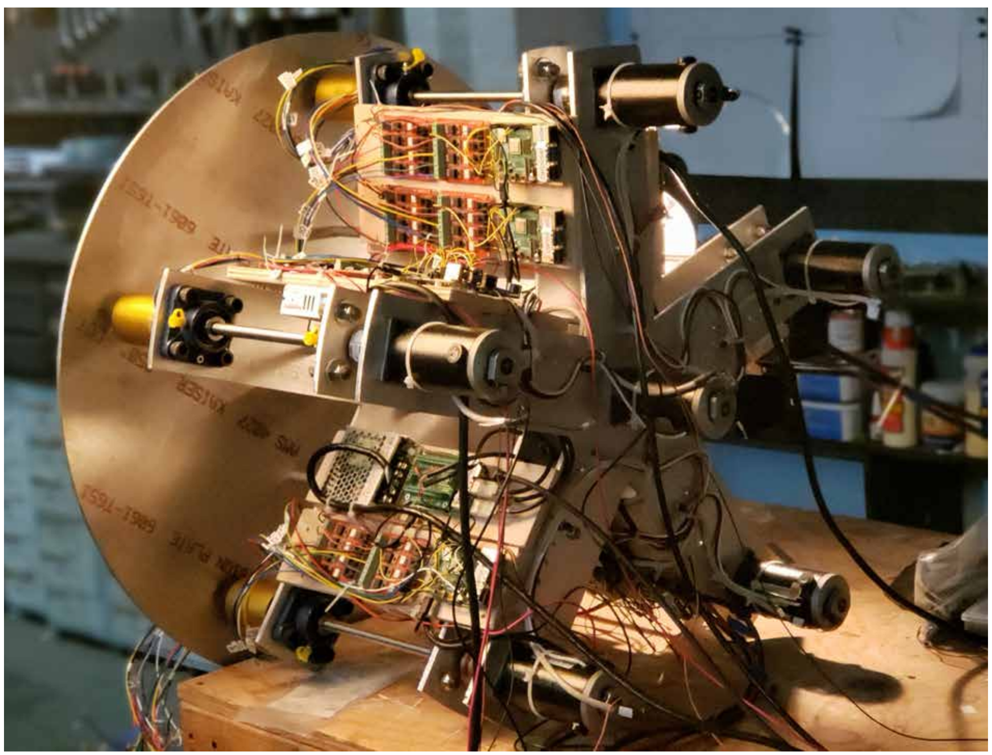
Video shows this better than words.
https://vimeo.com/761179206

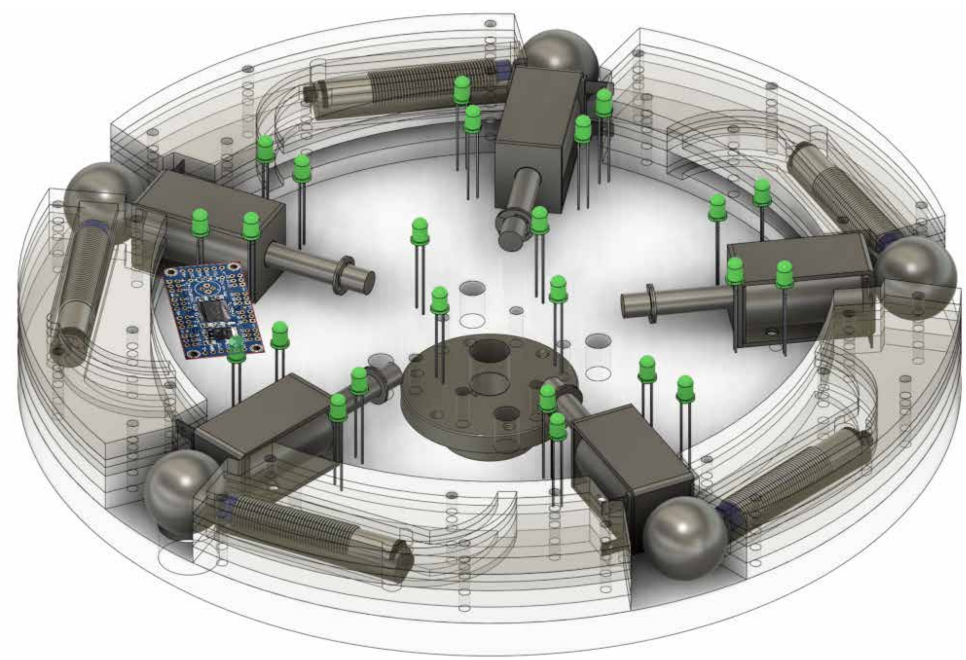


The Exchange Matrix

The Exchange Matrix is complex under the surface. Its structure is made of precise layers of 6mm aluminum plate. It contains hundreds of circuits and nine computers. The carousels are rotated into precise positions by six closed-loop servo motor systems.

Each of the six carousels contains five solenoid actuators for ejecting a ball, five inductive sensors for detecting the presence of a ball, and 24 LEDs for displaying game status and processes.





INSTRUMENT DESIGN COMMISSIONS


The Irvine
AVL, 2017
https://andycavatorta.com/irvine.html


The Dervishes
TED & Lincoln, 2013
https://andycavatorta.com/dervishes.html


Magnetic Resonance Harp
Molly Herron, 2014
https://andycavatorta.com/overtoneharp.html


Chalice Symphony
Stella Artois (AB-InBev), 2014
https://andycavatorta.com/chalicesymphony.html


Gravity Harps
Björk, 2011 & 2016
https://andycavatorta.com/gravityharps.html

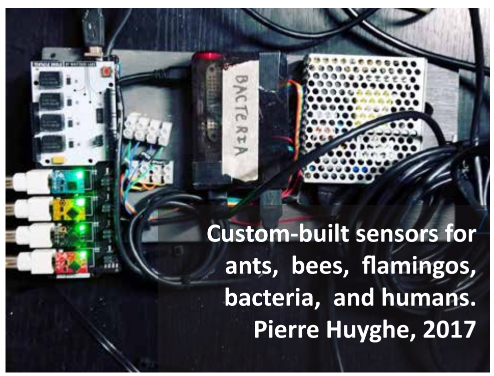

Rotacorda and Crystallophone
Between Music, 2015
https://andycavatorta.com/aquasonic.html

R&D COMMISSIONS FOR ARTISTS

Control Systems for Articulated Architecture
Pierre Huyghe, 2017

Distributed Control System, Pierre Huyghe, 2017
https://www.artnews.com/art-news/artists/constant-displacement-pierre-huyghe-on-his-work-at-skulptur-projekte-munster-2017-8602/

Machine Vision HeLa Cell Tracker
w/ Flourescence Microscope
Pierre Huyghe, 2017



Custom-built sensors for ants, bees, flamingos, bacteria, and humans.
Pierre Huyghe, 2017

Motion Control Hardware & Software
Nick Cave & Barneys New York, 2016

Swarm of 24 Autonomous Robots
Sougwen Chung, 2018
https://sougwen.com/project/omniaperomnia

Control system and authoring interface
Daniel Arsham, 2012
https://content.jwplatform.com/previews/0mJ4Ydzi

TEACHING @ THE COOPER UNION

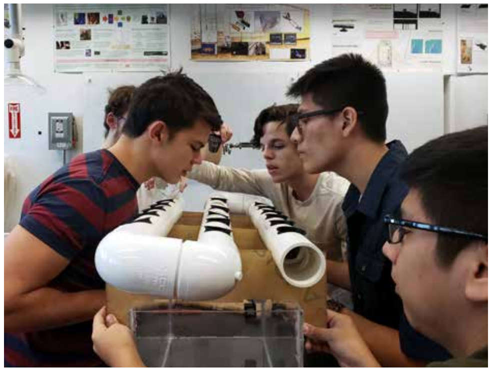
In 2015 and 2019, I created and taught curriculums for ***EID101 Engineering Design & Problem Solving***.

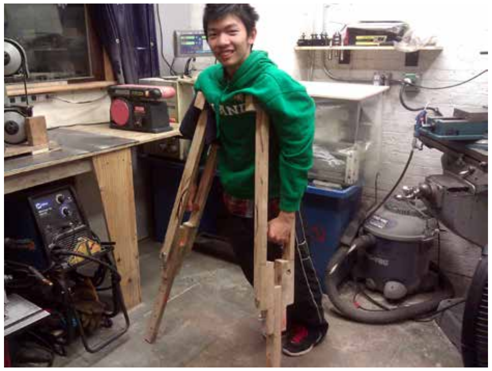
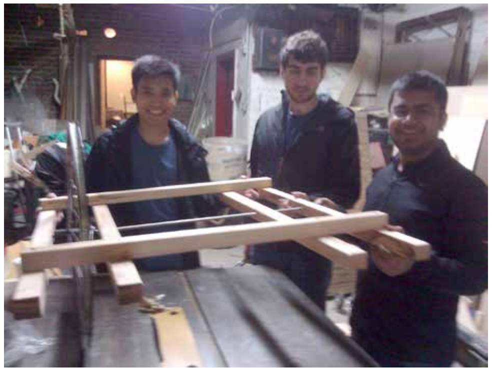
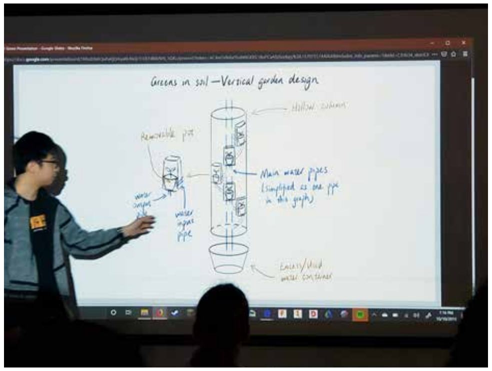
The first curriculum tasked students with inventing mobility devices for environments with limited resources. It was inspired the ingenuity I witnessed in homemade mobiity devices in Niger.

Students worked in groups to make many iterations of prototypes using only materials scavenged for free in NYC. They evaluted the designs by using them for transport and transactions in the chaotic neighborhood around Cooper Union.

The second curriculum tasked students with creating food technologies for changing or precarious environments. Students created closed-loop aquaponic systems and cricket habitats, mirrored arrays to amplify sunlight, steel tools for non-destructive harvesting, and more.

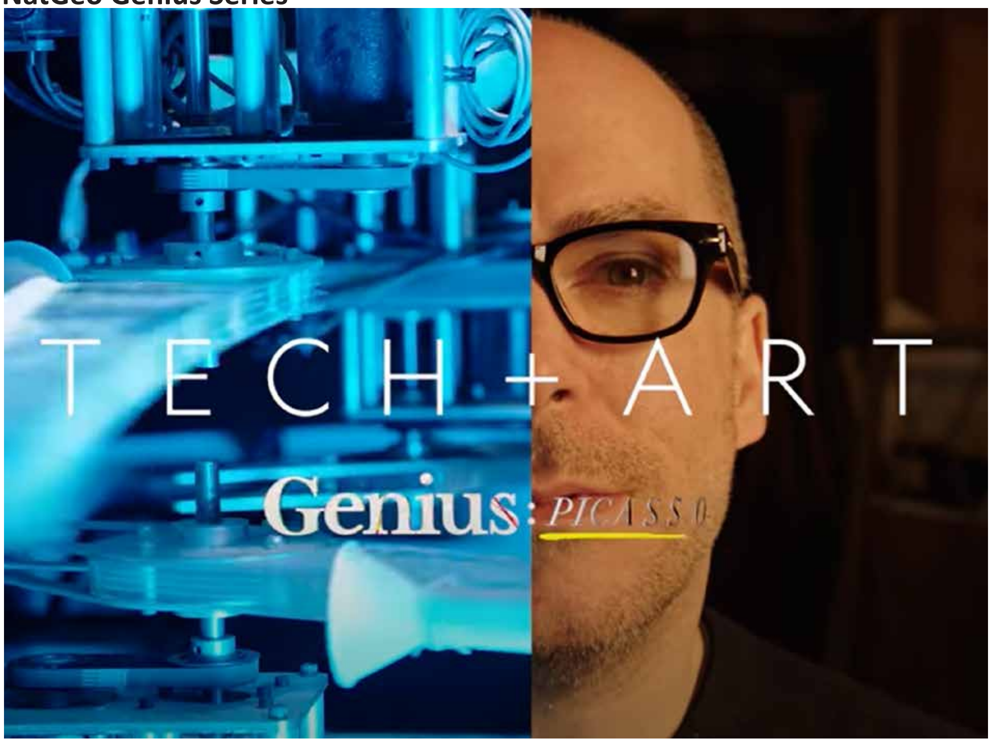
It also served as a survey class for using tools and materials. Students created CAD models, cast metals, grew biomaterials, used CNC tools, welded, and were introduced to embedded systems.



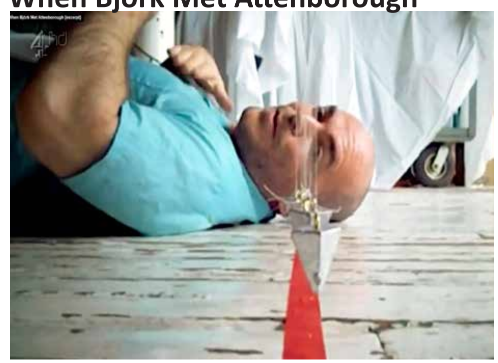

SELECTED DOCUMENTARIES

NatGeo Genius Series



Chalice Symphony Documentary

When Björk Met Attenborough



Great Big Story

Motherboard TV

TED + Lincoln

Sounds Like Art

Vernissage TV

SELECTED PRESS & INTERVIEWS

2023		
	New Atlas	Dual Coincidence is likely the world's most complex electromechanical game
2022		
	Fast Company	MIT's new museum demystifies the world's most complex technologies
2021		
	Ripley's Believe It Or Not	THE CURIOUS HISTORY AND REMARKABLE REINVENTION OF THE PYROPHONE
2017		
	The Quietus	Water, Water, Everywhere: Sonica Festival Reviewed
2016		
	White Rabbit Project	Invented Before Its Time?
	Mysteries at the Museum	Dawn of the Synth
	Popular Science	Q&A With An Insane Instrument Inventor
	Huffington Post	This Band Plays Music Underwater, And It's Hauntingly Gorgeous
	New Scientist	Making a splash: Let's hear it for the first underwater band
2015		
	Atlas Obscura	The Telharmonium Was the Spotify of 1906
	The New Yorker	Turning Bridges Into Music
	The O'Reilly Solid Podcast	Tying software and hardware together through art
2014		
	Vice	How to Build a Magnetized Piano Harp
	POPSOP	Stella Artois plays the symphony of glass
2013		
	Core 77	Creating Beats with the Speed of Raindrops
	Acrhinect	Gravity Harps is a Robotic Musical Instrument Built for Björk's Biophilia Tour
2012		
	Make Magazine	Make: Talk 010 – Andy Cavatorta, Bjork's Musical Roboticist
	The New Yorker	Inventing Björk's Gravity Harp
2011		
	Core 77	Bjork's Biophilia: An Ambitious New Album Experience
	Wired	In depth: How Björk's 'Biophilia' album fuses music with iPad apps
	Vice	Instruments Of Change: The Engineering Behind Bjork's Musical Robots
2009		
	Art In New York City	Luis Blackaller and Andy Cavatorta

LECTURES

2023	
The MIT Museum	Live Q&A: **Whale**
UMass Composers Seminar	Lecture: **Early Electrophones**
2022	
NYU ITP	Lecture: **The Design of Good Instruments**
2021	
NYU ITP	Lecture: **The Design of Good Instruments**
2019	
NYU ITP	Lecture: **The Design of Good Instruments**
Acoustical Society of America	Keynote: **Acoustic Sound and Meaning**
Atlas Obscura @SXSW	Panelist: **In the Element**
2018	
Mid American College Art Association Conference	Keynote: **Prototypes and Creative Process**
FAB14, Toulouse	Lecture: **Music, Machines, and Meaning**
FAB14, Toulouse	Keynote Panel
2017	
MoogFest	Lecture: **Music, Machines, and Meaning**
MoogFest	Workshop: **Physical Oscillators and Expressive Dimensions**
Boyer College of Music and Dance	Lecture: **Music, Machines, and Meaning**
2016	
Technical University, Graz	Lecture: **Music Has Always Been Technological**
Atlas Obscura Talks	Lecture: **The Telharmonium**
2015	
School of Visual Arts	Lecture: **Recent Work and Findings**
Spotify NYC	Lecture: **Recent Work and Findings**
O'Reilly Solid Conference	Lecture: **Music, Machines, and Meaning**
Disruption Day, London	Closer: **Music, Machines, and Meaning**
2014	
Design Leadership Conference	Closer: **Music, Machines, and Meaning**
MIT CAST	Lecture: **Gravity Harps and New Works**
MIT Media Lab	Lecture:**Music Has Always Been Technological**
UPenn Music Department	Lecture: **Gravity Harps and New Works**
St. Mary's University, London UK	Lecture: **Music, Machines, and Meaning**
Spotify USA	Lecture: **Gravity Harps and New Works**