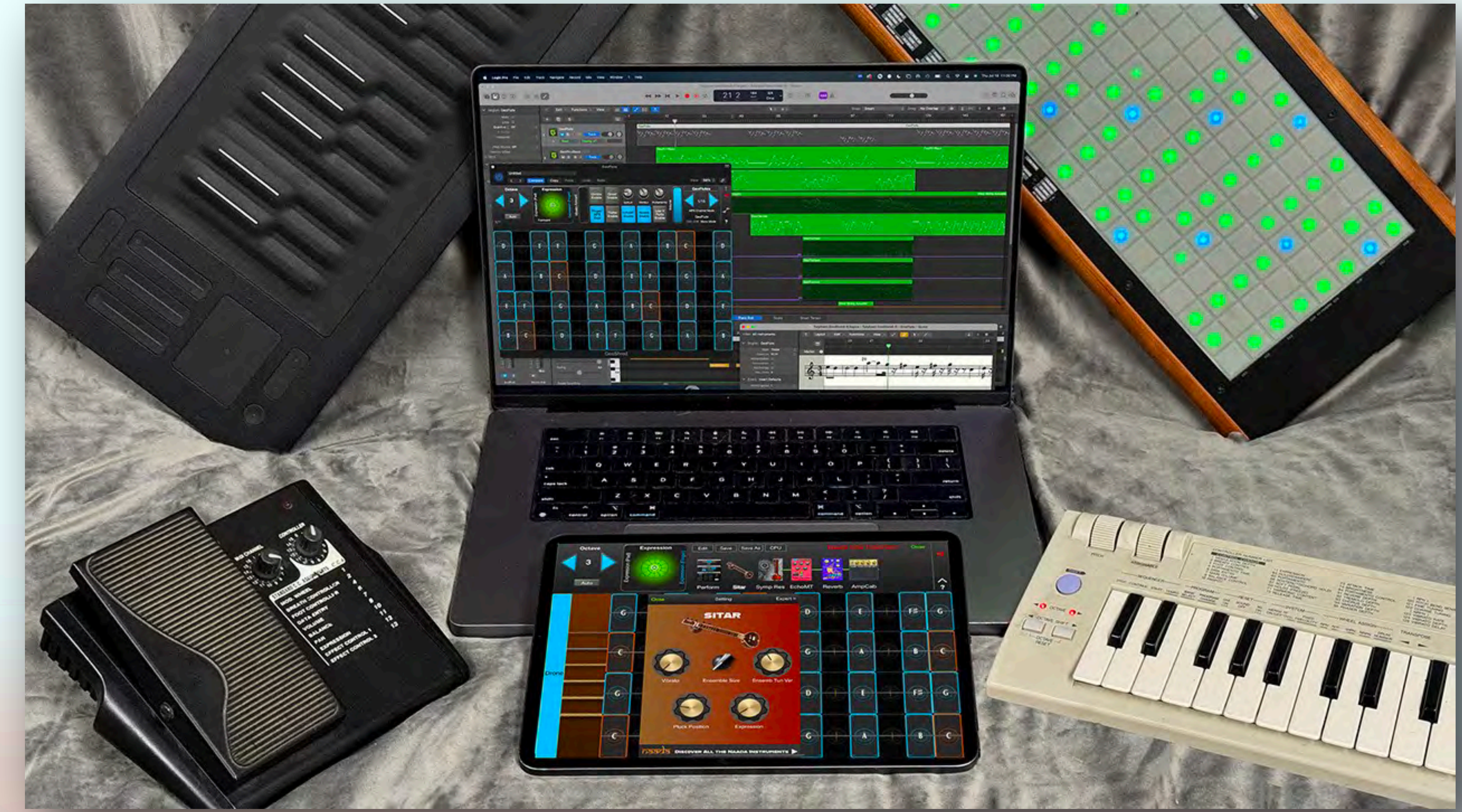
Physical Modeling Synthesis History and Applications

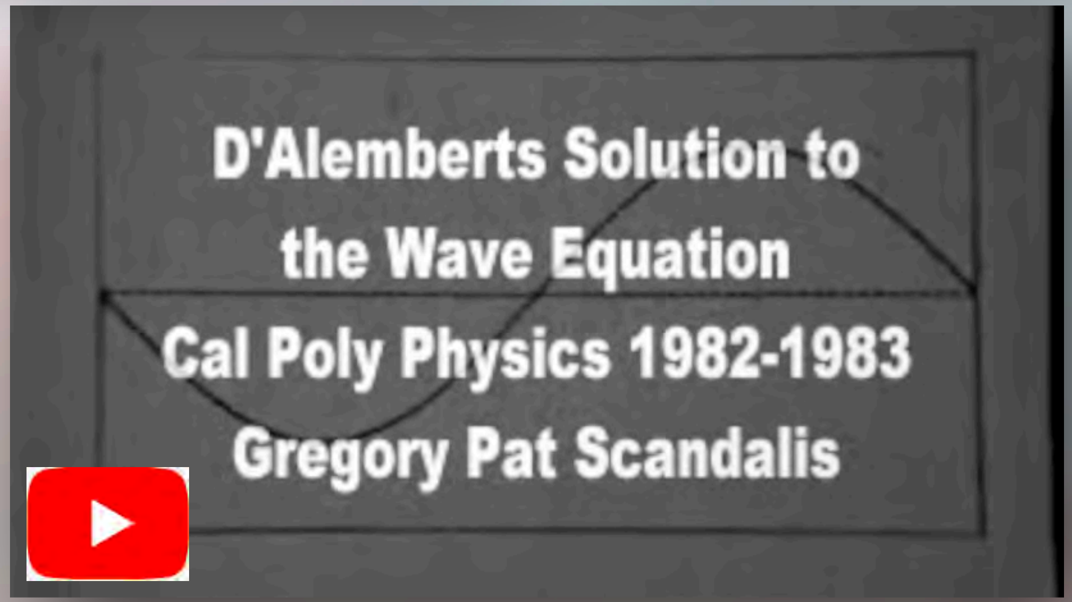
San Francisco Conservatory of Music, March 7, 2025



Gregory Pat Scandalis, Larry the O

About Pat

- 42 years in the Silicon Valley as an Engineer
- Built my first monophonic electronic instrument from a Radio Shack P-Box kit in 1970
- Gigged with an Arp Avatar guitar synth (1978)
- Guitar Player for Weird Al Band (1980)
- Computer modeling of vibrating strings and membranes for senior thesis in Physics (1982)
- Researcher in Physical Modeling at Stanford/ CCRMA (1994)
- CEO/CTO of moForte
  Chairman of the MPE Subcommittee MIDI Association

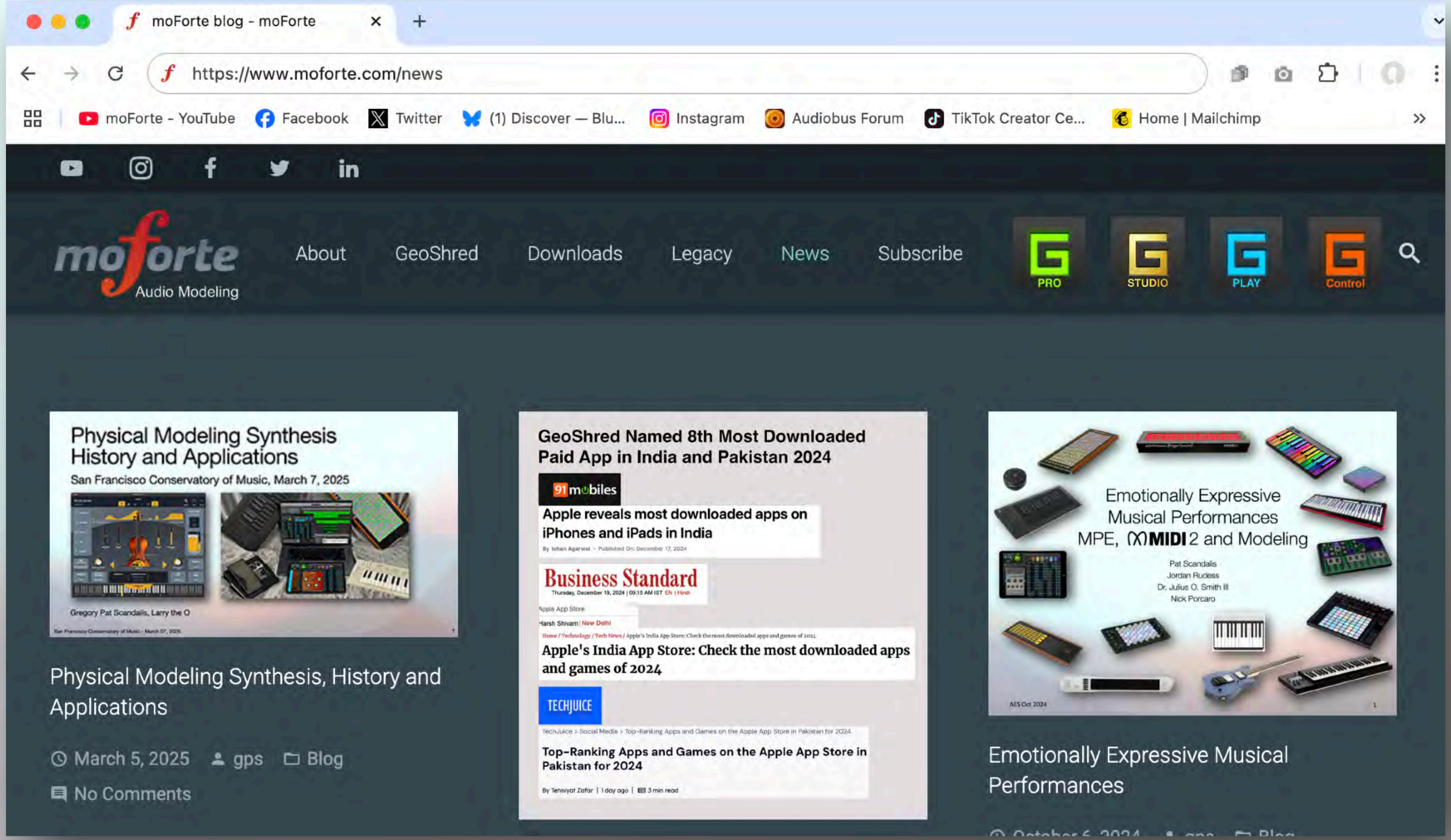


About Larry the O

- Worked as performer, composer, voiceover artist, sound designer, audio director, audio engineer, and producer for audio post-production for TV and film, album recording, live sound, video games, manufacturing, software development, publishing, and industrial sound design.
- Held positions at Lexicon, Russian Hill Recording, Focused Audio, LucasArts Entertainment, Electronic Arts, Meyer Sound, and BIAS
- More than 20 years as a Contributing Editor to Mix and Electronic Musician magazines.
- Graduated Berklee College of Music with a degree in Music Production, Summa Cum Laude, and was awarded Berklee's Distinguished Alumni Award.
- Creator of Ears Hear Now, a storytelling-meets-sound-art series with multiple festival placements.

This Presentation Can be Found at:

http://www.moforte.com/news



Outline of Topics

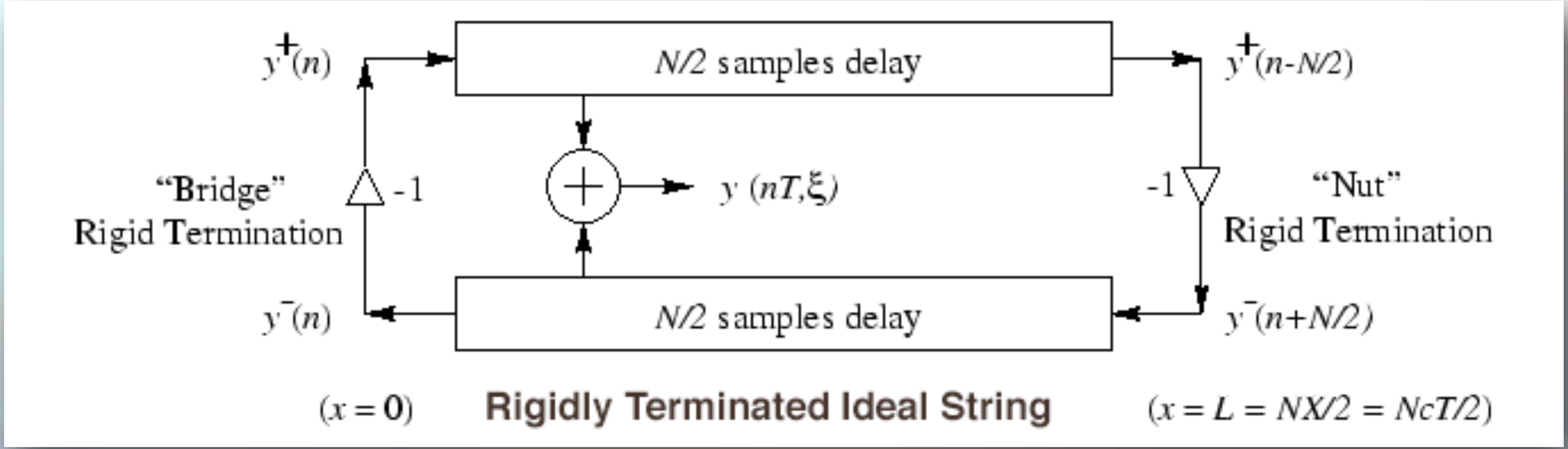
- Let's start with Video Demos!
- A Brief History of Physical Modeling Synthesis
- Physical Modeling and MPE MIDI
- PM Applications For Composers Using SWAM, GeoShred
- The Future, PM, MIDI 2, Orchestral Articulation
- Questions!

The Story

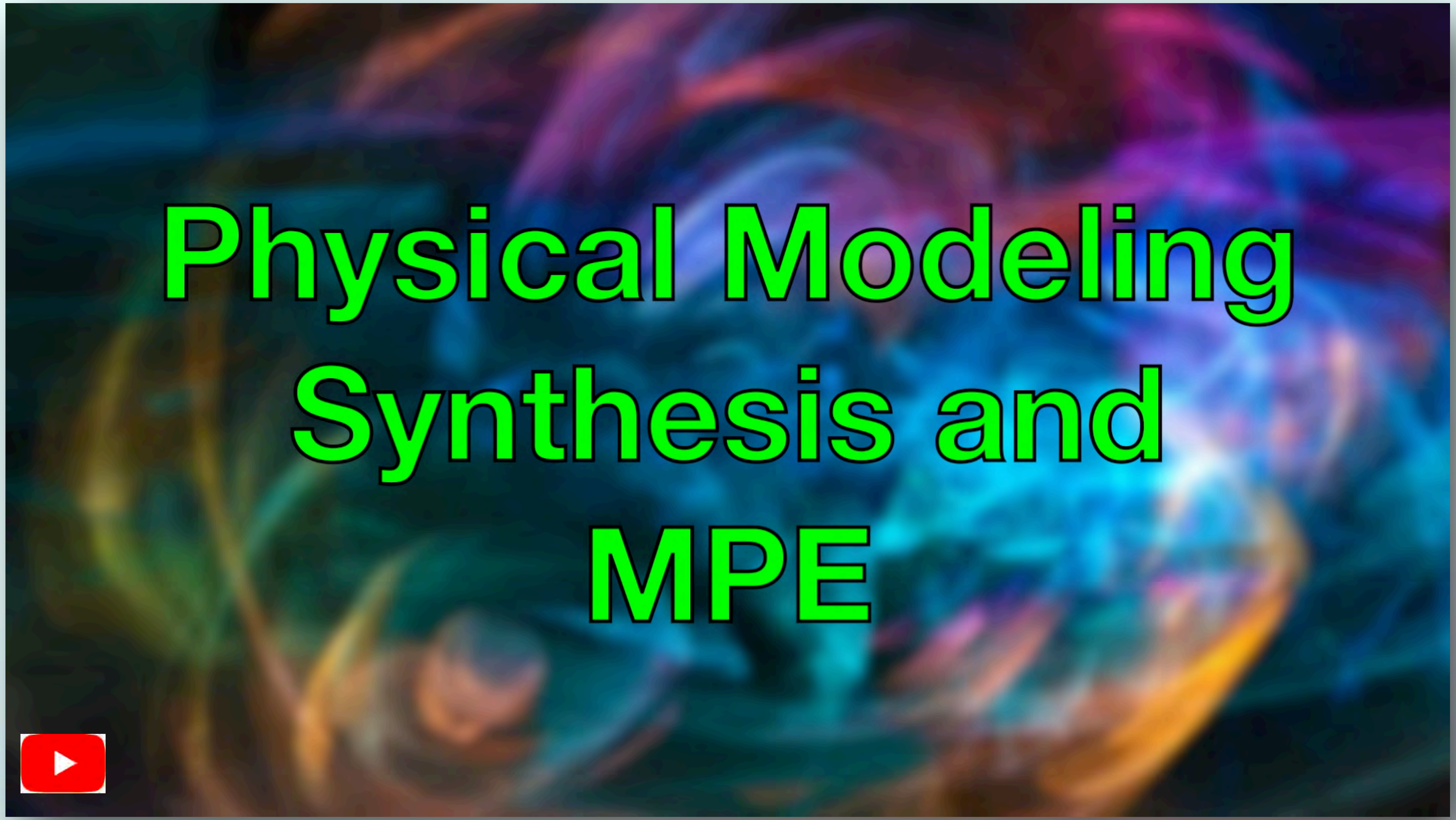
We find ourselves in a place where any of us can be Jimi Hendrix with just a small device in the palm of our hands. It’s a fun and deeply technical topic drawing on many fields including physics, acoustics, digital signal processing and music.

An abbreviated history of Physical Modeling Synthesis. Why in 1994, PM was poised to be the “Next Big Thing”. **And why it’s back!**

A Brief History of Physical Modeling Synthesis



Physical Modeling Demos



As performing musicians, our role is to transform emotions and feelings into musical expression. Physical modeling (PM) instrument models provide us with expressive controls that enhance our ability to convey emotion to an audience.

What is Physical Modeling Synthesis?

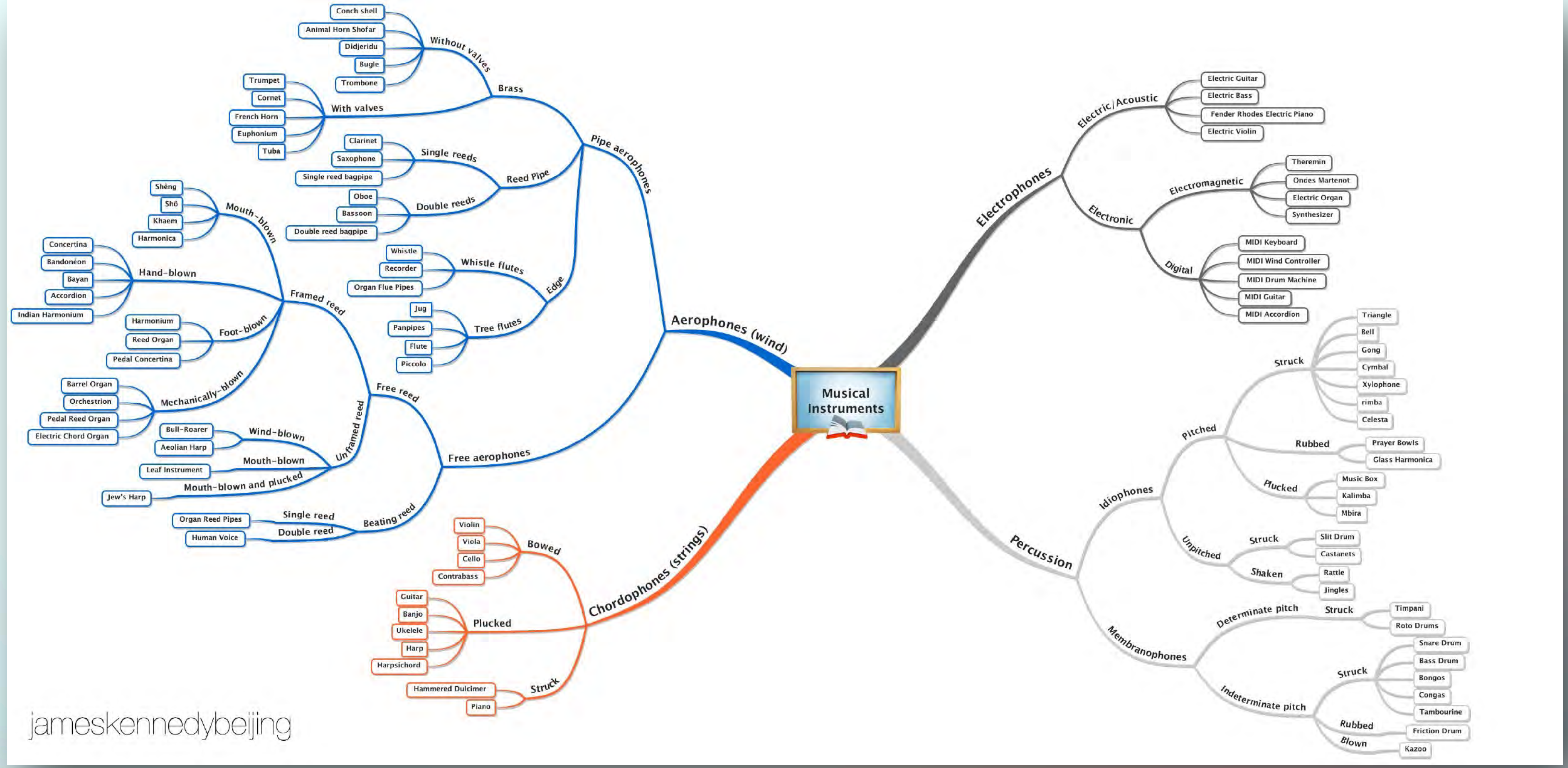
- Methods in which a sound is generated using a mathematical model of the physical source of sound.
- Any gestures that are used to interact with a real physical system can be mapped to parameters yielded an interactive and expressive performance experience.
- **Physical modeling is a collection of different techniques specific to each sound generation process.**

$$\frac{\partial^2 y}{\partial t^2} = \frac{1}{v_w^2}\frac{\partial^2 y}{dt^2}$$

Physics + Math
物理 + 數學

Taxonomy of Modeling Areas

Hornbostel–Sachs Classification

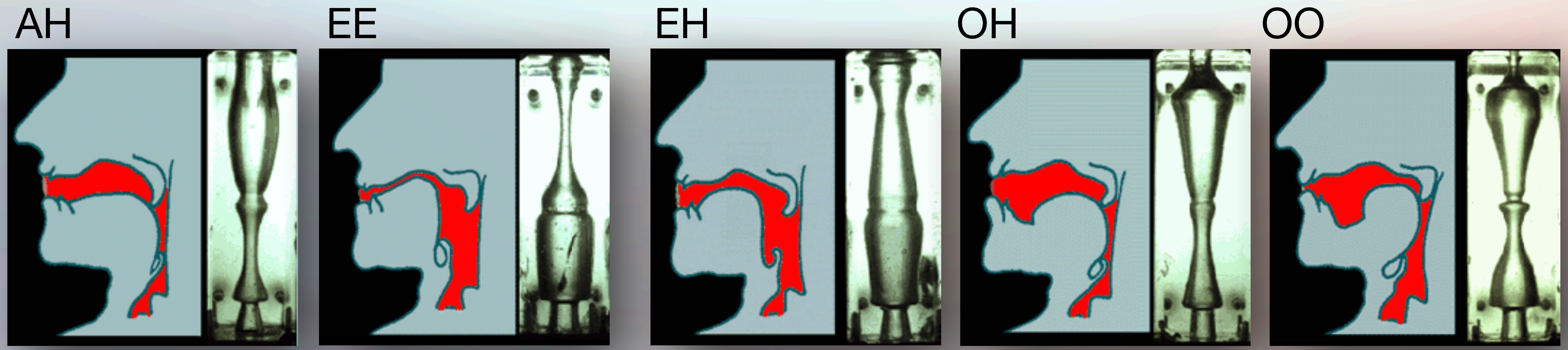


- Chordaphones - Guitars
- Aerophones - Woodwinds
- Membranophones - Drums
- Idiophones - Mallet Instruments
- Electrophones - Virtual Analog
- Game Sounds
- Human Voice

Early Mechanical Voice Synthesis

- 1000 -1200 ce - Speech Machines, Brazen Heads
- 1791 - Wolfgang Von Kempelin, speaking machine.
- 1857 - Joseph Faber, Euphonia (pictured)

Its been know for a long time that the vocal tract can be modeled with a bellows, a reed, a number of different size resonators and special elements for the tongue, the mouth. See Exploratorium Vocal Vowels.



The Voder (1937-39) - Homer Dudley

- Analog Electronic Speech Synthesis
- Analog model of the vocal tract. Tubes!
- Developed from research on voice compression at Bell Labs.
- Featured at the 1939 Worlds fair

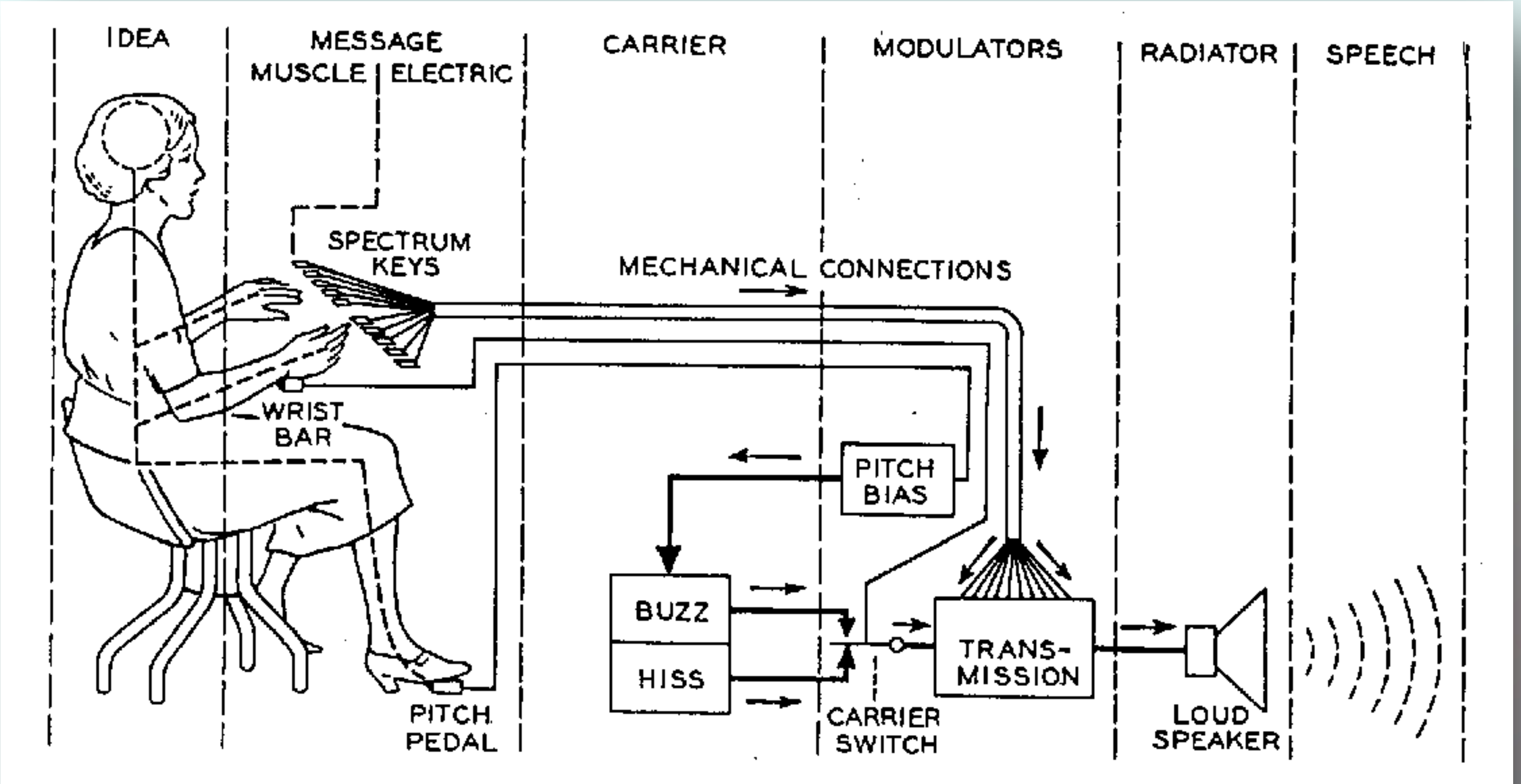
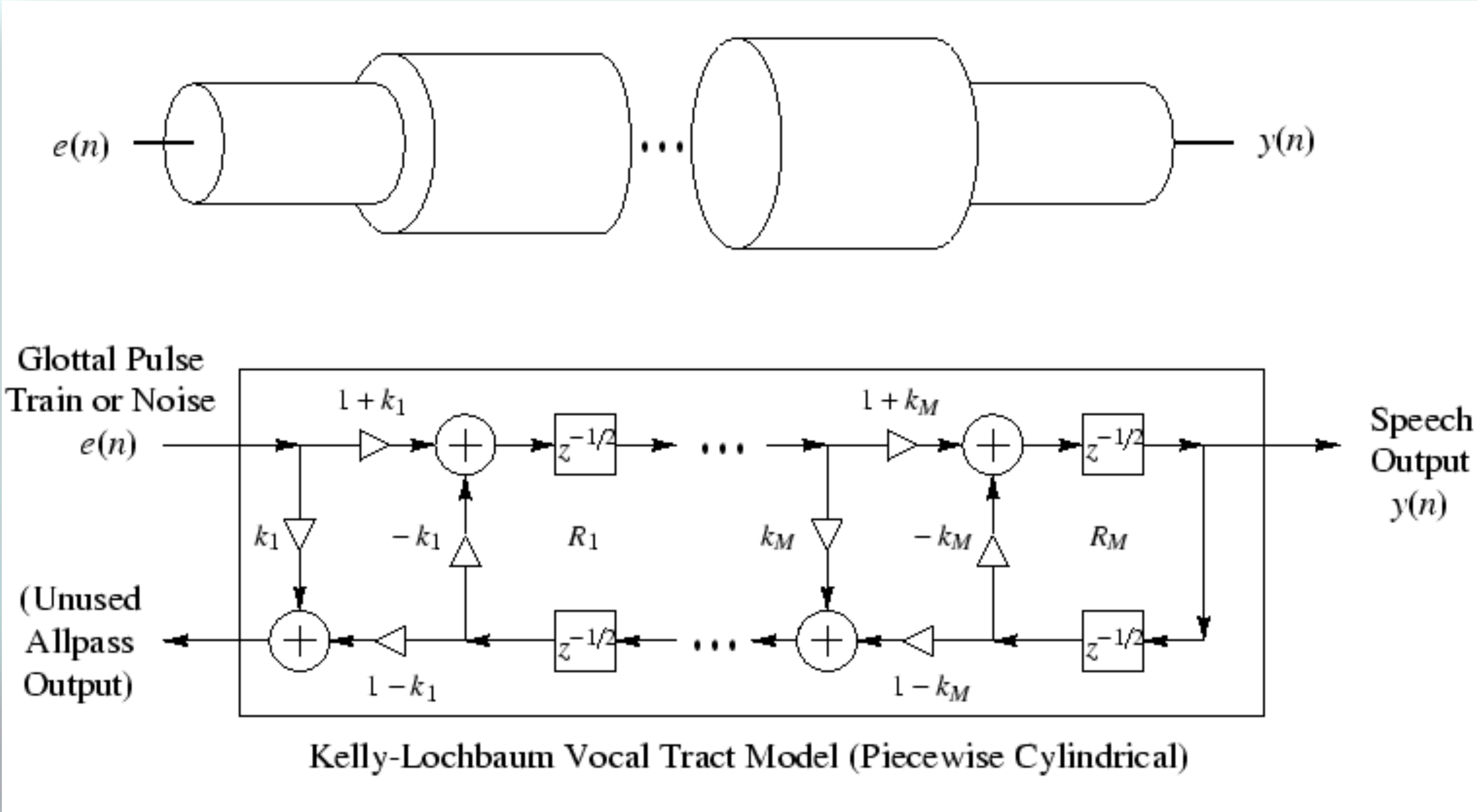


Fig. 8—Schematic circuit of the voder.

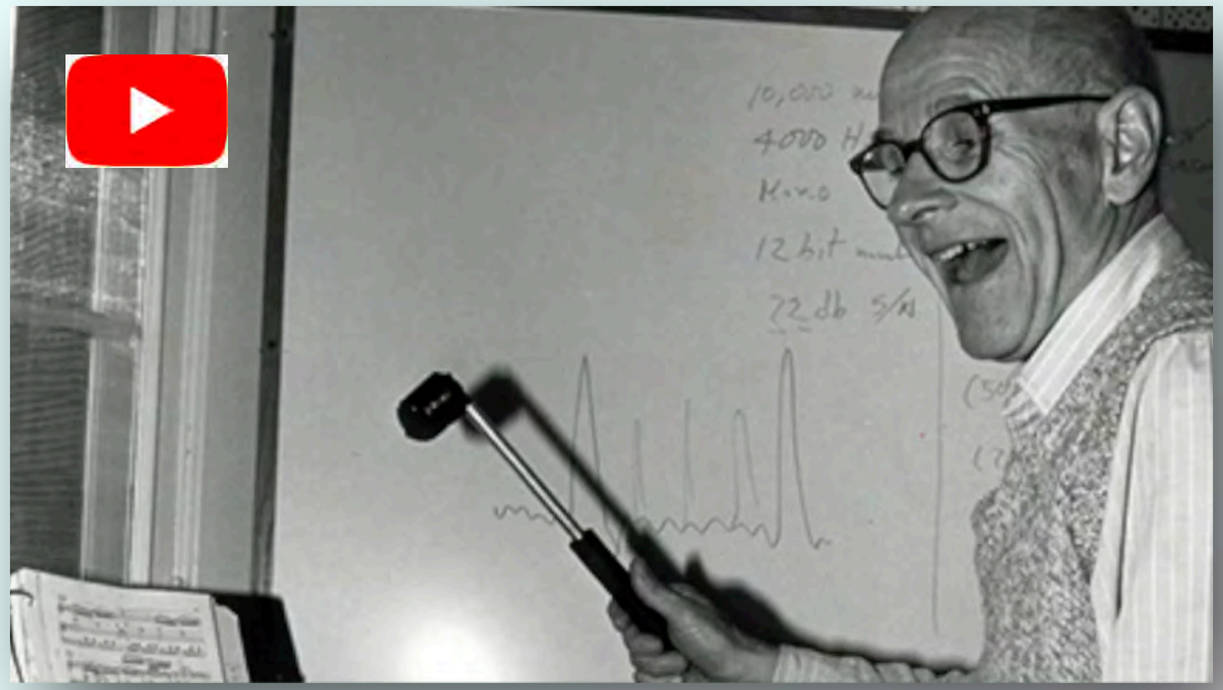
The Voder as demonstrated by Mrs. Harper at The Franklin Institute.

Kelly-Lochbaum Vocal Tract Model (1961)

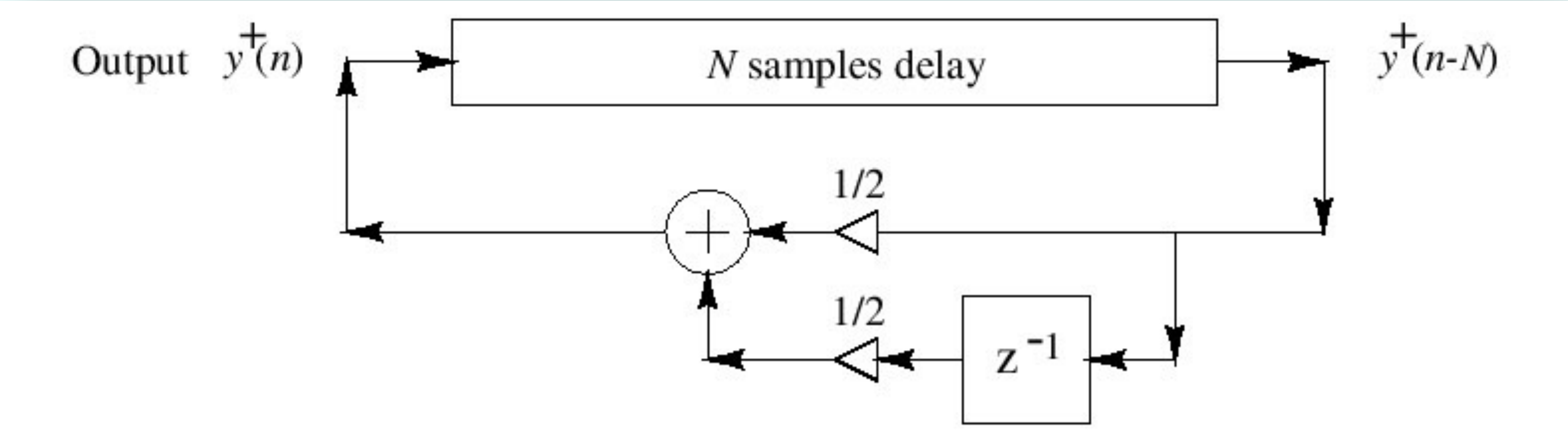


Daisy Bell (1961)

- Daisy Bell
- Vocal part by Kelly and Lochbaum (1961)
- Musical accompaniment by Max Mathews
- Computed on an IBM 704
- Based on Russian speech-vowel data from Gunnar Fant’s book
- Probably the first digital physical-modeling synthesis sound example by any method
- Inspired Arthur C. Clarke to adapt it for “2001: A Space Odyssey” the Hal 9000’s “first song”

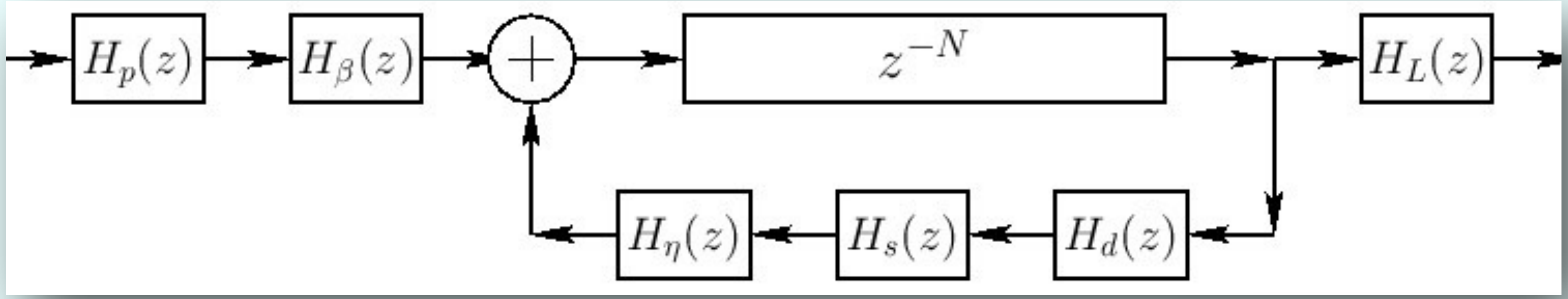


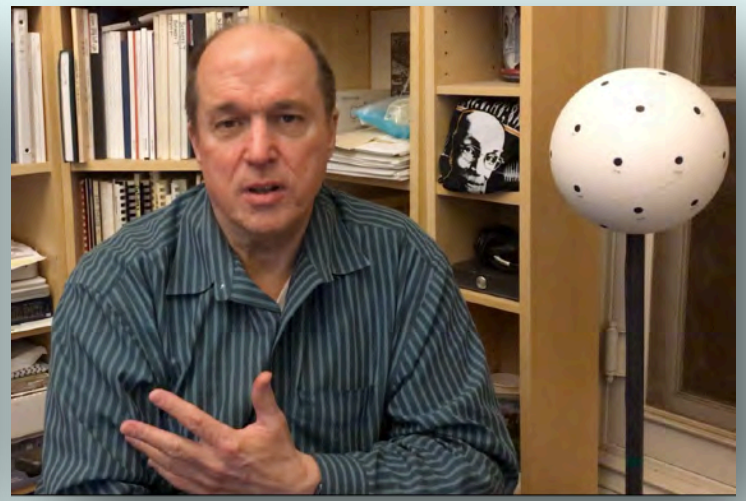
Karplus-Strong (KS) Algorithm (1978)



- Discovered (1978) as “self-modifying wavetable synthesis”
- Wavetable is preferably initialized with random numbers
- Licensed to Mattel
- The first musical use of the algorithm was in the work “*May All Your Children Be Acrobats”* written in 1981 by David A. Jaffe.

EKS Algorithm (Jaffe-Smith 1983)





$$
\begin{aligned}
H_p(z) &= \frac{1-p}{1-p\,z^{-1}} = \text{pick-direction lowpass filter} \\
H_\beta(z) &= 1 - z^{-\lfloor \beta N + 1/2 \rfloor} = \text{pick-position comb filter, } \beta \in (0,1) \\
H_d(z) &= \text{string-damping filter (one/two poles/zeros typical)} \\
H_s(z) &= \text{string-stiffness allpass filter (several poles and zeros)} \\
H_\eta(z) &= -\frac{\eta(N) - z^{-1}}{1-\eta(N)\,z^{-1}} = \text{first-order string-tuning allpass filter} \\
H_L(z) &= \frac{1-R_L}{1-R_L\,z^{-1}} = \text{dynamic-level lowpass filter}
\end{aligned}
$$

- Musical Example “Silicon Valley Breakdown” (Jaffe 1992)
- Musical Example BWV-1041 (used to intro the NeXT machine 1988)

The KS and EKS Papers Were Published Simultaneously in the Computer Music Journal (CMJ) (1983)

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Digital Synthesis of Plucked-String and Drum Timbres

Introduction

There are many techniques currently used for digital music synthesis, including frequency modulation (FM) synthesis, waveshaping, additive synthesis, and subtractive synthesis. To achieve rich, natural sounds, all of them require fast arithmetic capability, such as is found on expensive computers or digital synthesizers. For musicians and experimenters without access to these machines, musically interesting digital synthesis has been almost impossible.

The techniques described in this paper can be implemented quite cheaply on almost any computer. Real-time synthesis implementations have been done for Intel 8080A (by Alex Strong), Texas Instruments TMS9900 (by Kevin Karplus), and SC/MP (by Mike Plass) microprocessors. David Jaffe and Julius Smith have programmed the Systems Concept Digital Synthesizer at the Center for Computer Research in Music and Acoustics (CCRMA) to perform several variants of the algorithms (Jaffe and Smith 1983).

Not only are the algorithms simple to implement in software, but hardware realizations are easily done. The authors have designed and tested a custom *n*-channel metal-oxide semiconductor (*n*MOS) chip (the Digitar chip), which computes 16 independent notes, each with a sampling rate of 20 KHz.

Despite the simplicity of the techniques, the sound is surprisingly rich and natural. When the plucked-string algorithm was compared with additive synthesis at Bell Laboratories, it was found that as many as 30 sine wave oscillators were needed to produce a similarly realistic timbre (Sleator 1981). The entire plucked-string algorithm requires only as much computation as one or two sine wave oscillators.

The parameters available for control are pitch, amplitude, and decay time. The pitch is specified by an integer that is approximately the period of the sound, in samples (periodicity parameter p). Amplitude is specified as the initial peak amplitude A. Decay time is determined by the pitch and by a decay stretch factor S.

The algorithms in this paper lack the versatility of FM synthesis, additive synthesis, or subtractive synthesis. They are, however, cheap to implement, easy to control, and pleasant to hear. For musicians interested primarily in performing and composing music, rather than designing instruments, these algorithms provide a welcome new technique. For those interested in instrument design, they open a new field of effective techniques to explore.

Wavetable Synthesis

One standard synthesis technique is the *wavetable synthesis* algorithm. It consists of repeating a number of samples over and over, thus producing a purely periodic signal. If we let Y_t be the value of the t^{th} sample, the algorithm can be written mathematically as

$$Y_t = Y_{t-p}.$$

The parameter p is called the *wavetable length* or *periodicity parameter*. It represents the amount of memory needed and the period of the tone (in sam-

This research was supported in part by the Fannie and John Hertz Foundation.

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Summer 1983, 0148-9267/83/020043-13 $04.00/0,

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Extensions of the Karplus-Strong Plucked-String Algorithm

Introduction

In 1960, an efficient computational model for vibrating strings, based on physical resonating, was proposed by McIntyre and Woodhouse (1960). This model plays a crucial role in their recent work on bowed strings (McIntyre, Schumacher, and Woodhouse 1981; 1983), and methods for calibrating the model to recorded data have been developed (Smith 1983).

Independently, in 1978, Alex Strong devised an efficient special case of the McIntyre-Woodhouse string model that produces remarkably rich and realistic timbres despite its simplicity (Karplus and Strong 1983). Since then, Strong and Kevin Karplus have explored several variations and refinements of the algorithm, with an emphasis on small-system implementations. We have found that the Karplus-Strong algorithm can be used with equally impressive results on fast, high-power equipment. The availability of multiplies, for example, allows several modifications and extensions that increase its usefulness and flexibility. These extensions are described in this paper. The developments were motivated by musical needs that arose during the composition of *May All Your Children Be Acrobats* (1981) for computer-generated tape, eight guitars, and voice and *Silicon Valley Breakdown* (1982) for four-channel, computer-generated tape, both written by David Jaffe. Our theoretical approach and the extensions based on it have also been applied to the McIntyre-Woodhouse algorithm (Smith 1983).

The String-Simulation Algorithm

The Karplus-Strong plucked-string algorithm is presented in this issue of *Computer Music Journal*. From our point of view, the algorithm consists of a high-order *digital filter*, which represents the string; and a short *noise burst*, which represents the "pluck."[1] The digital filter is given by the difference equation

$$y_n = x_n + \frac{y_{n-N} + y_{n-(N+1)}}{2}, \qquad (1)$$

where x_n is the input signal amplitude at sample n, y_n is the output amplitude at sample n, and N is the (approximate) desired pitch period of the note in samples. The noise burst is defined by

$$x_n = \begin{cases} Au_n, & n = 0, 1, 2, \ldots, N-1 \\ 0, & n \geq N, \end{cases}$$

where A is the desired amplitude, and $u_n \in [-1,1]$ is the output of a random-number generator. The output y_n is taken beginning at time $n = N$ in our implementation.

Analysis of the String Simulator

Before proceeding to practical extensions of the algorithm, we will describe the theory on which many of them are based. Various concepts from digital filter theory are employed. For a tutorial introduction to digital filter theory, see the works by Smith (1982b) and Steiglitz (1974).

The input-output relation of Eq. (1) may be ex-

David A. Jaffe is also affiliated with the Music Department at Stanford University, and Julius O. Smith is also affiliated with the Electrical Engineering Department there.

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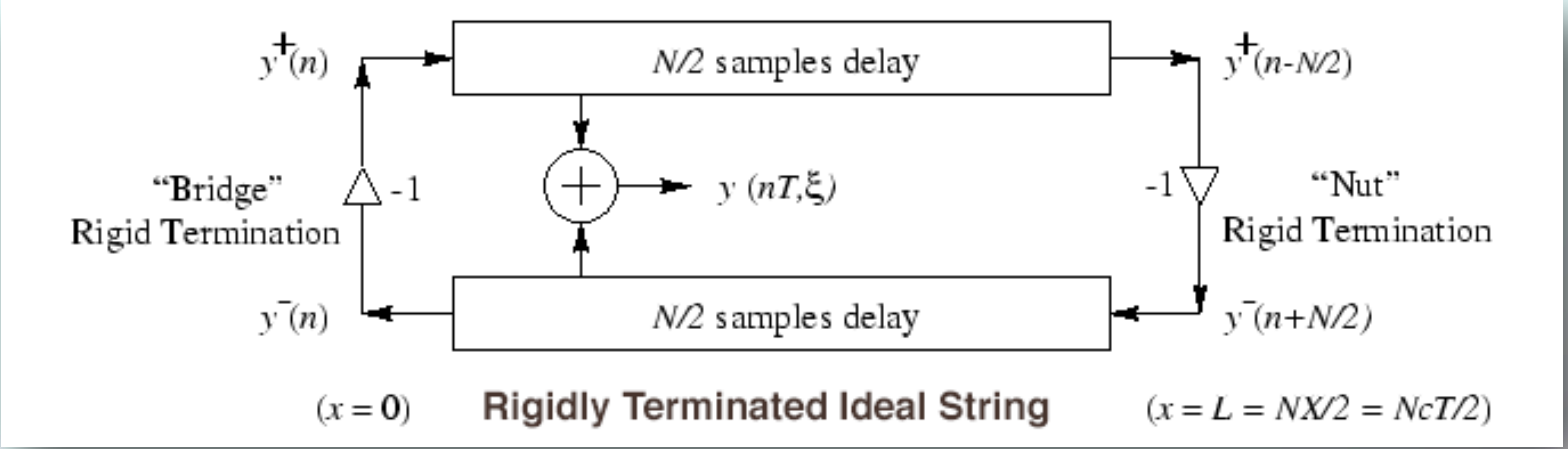
Summer 1983, 0148-9267/83/020056-14 $04.00/0,

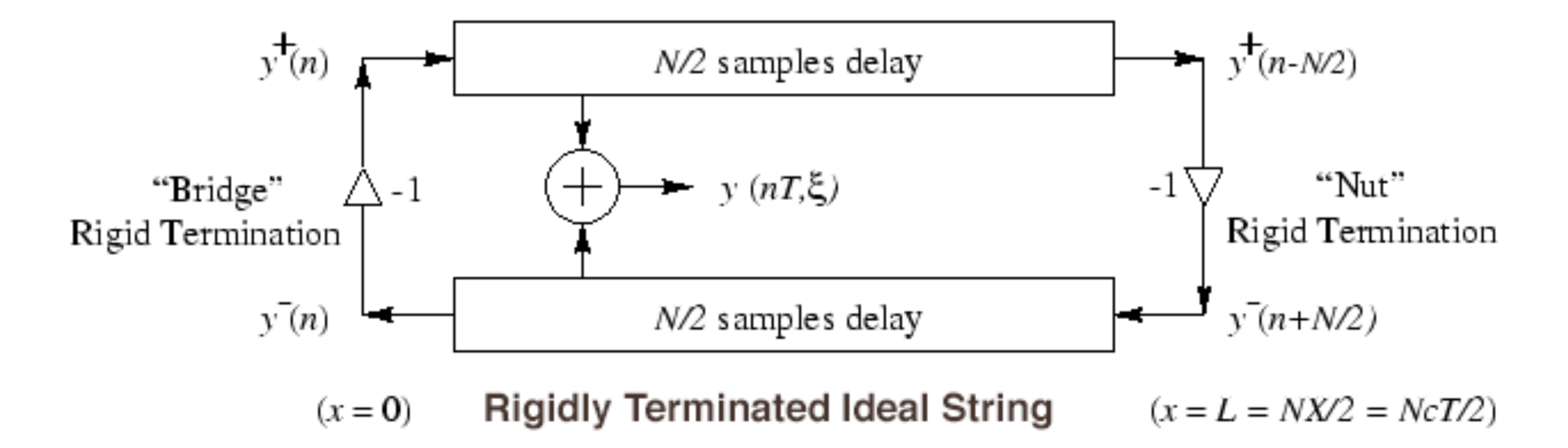
1. In some situations, the sound more closely resembles a string struck with a hammer or mallet than one plucked with a pick, but we will always use the term *pluck* when referring to the excitation.

Digital Waveguide Models (Smith 1985)



- Equivalent to d'Alembert's Solution to the Partial Differential Equation for a string (1747)
- Used for the Yamaha VL Family (1994)
- Shakuhachi, Tenor Sax

Digital Waveguide Models (Smith 1985)



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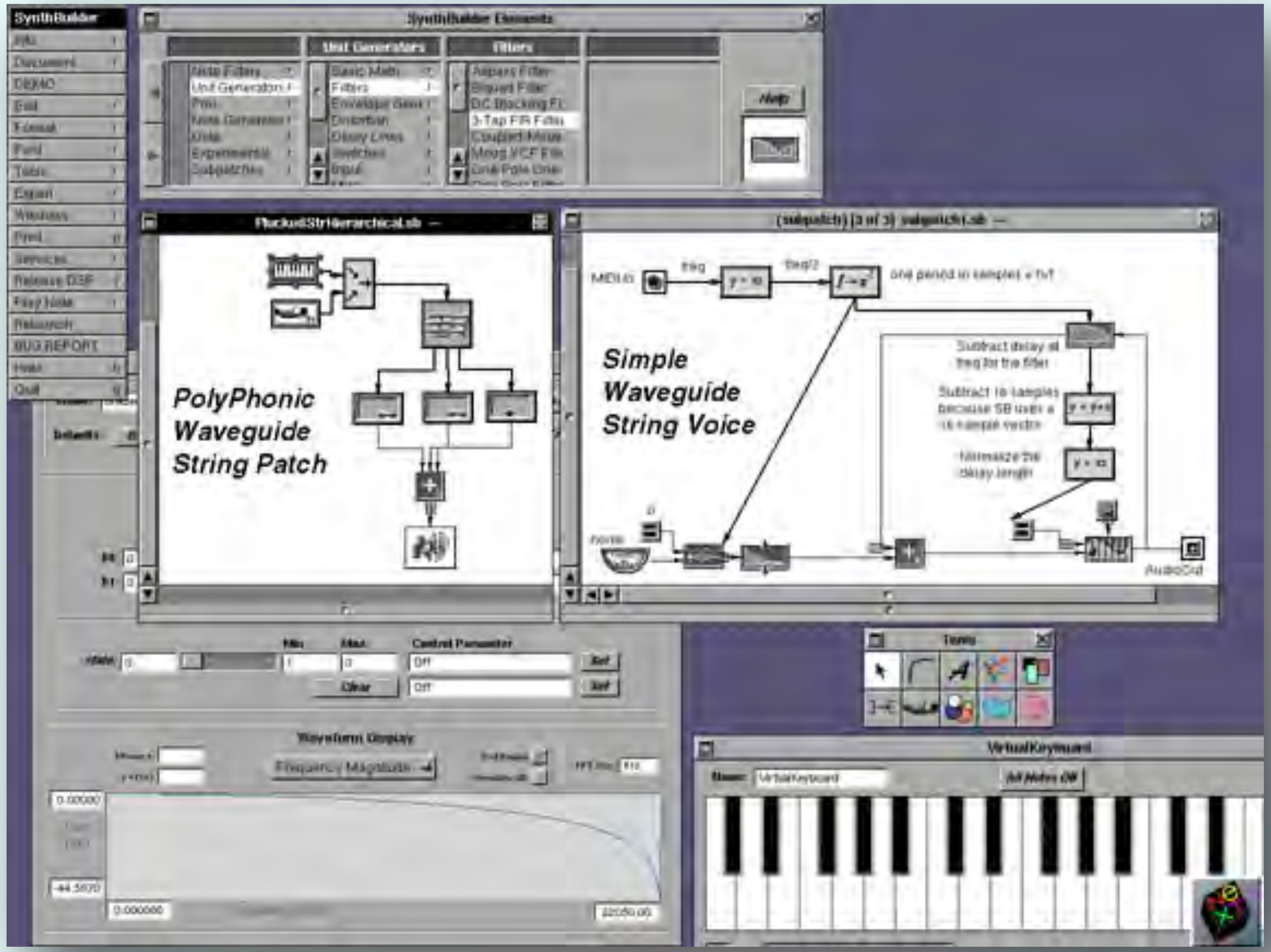
SynthBuilder (Porcaro et al 1993-1997)

- SynthBuilder was a rapid-prototyping tool on the NeXT machine for the development of music synthesis and effects patches. Initially for the 56k DSP and later for SynthServer/ SynthScript.
- Leveraged the NeXT Music Kit and the source code for the NeXT Draw Program.
- It played a major role in the development of physical models including Coupled Mode Synthesis (Van Duyne), Virtual Analog (Stilson, Smith) Sondius Program.
- SynthBuilder was written by Nick Porcaro with significant contributions from David Jaffe and Pat Scandalis, Julius Smith, Tim Stinson and Scott Van Dyne.



1997 SynthBuilder won the Grand Prize in the Bourges International Music Software Competition

Coupled Mode Synthesis (CMS) (Van Duyne 1996)

- Modeling of percussion sounds
- Modal technique with coupling
- Tibetan Bell Model
- Wind Chime Model
- Tubular Bells Model
- Percussion Ensemble
- Taiko Ensemble

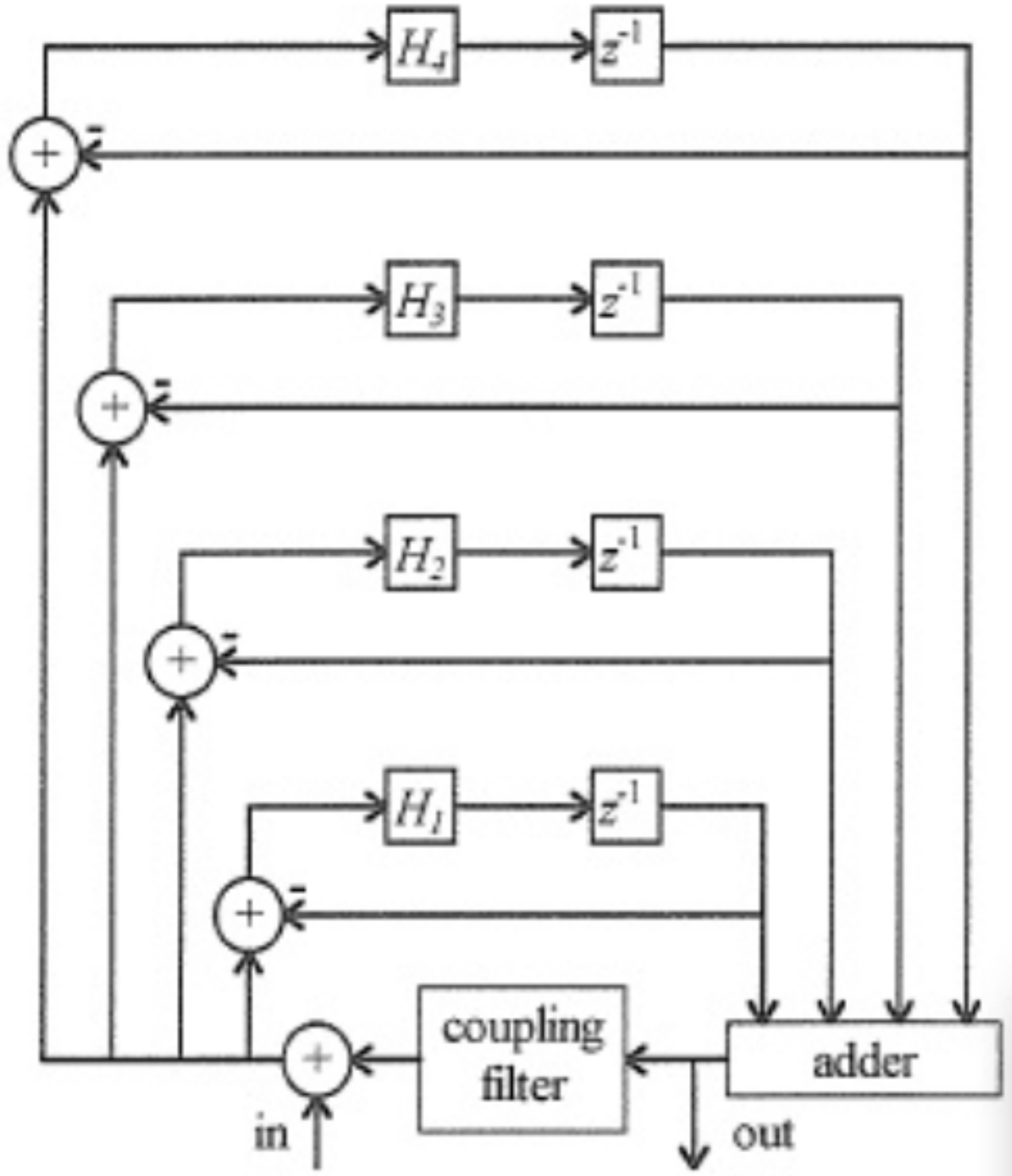
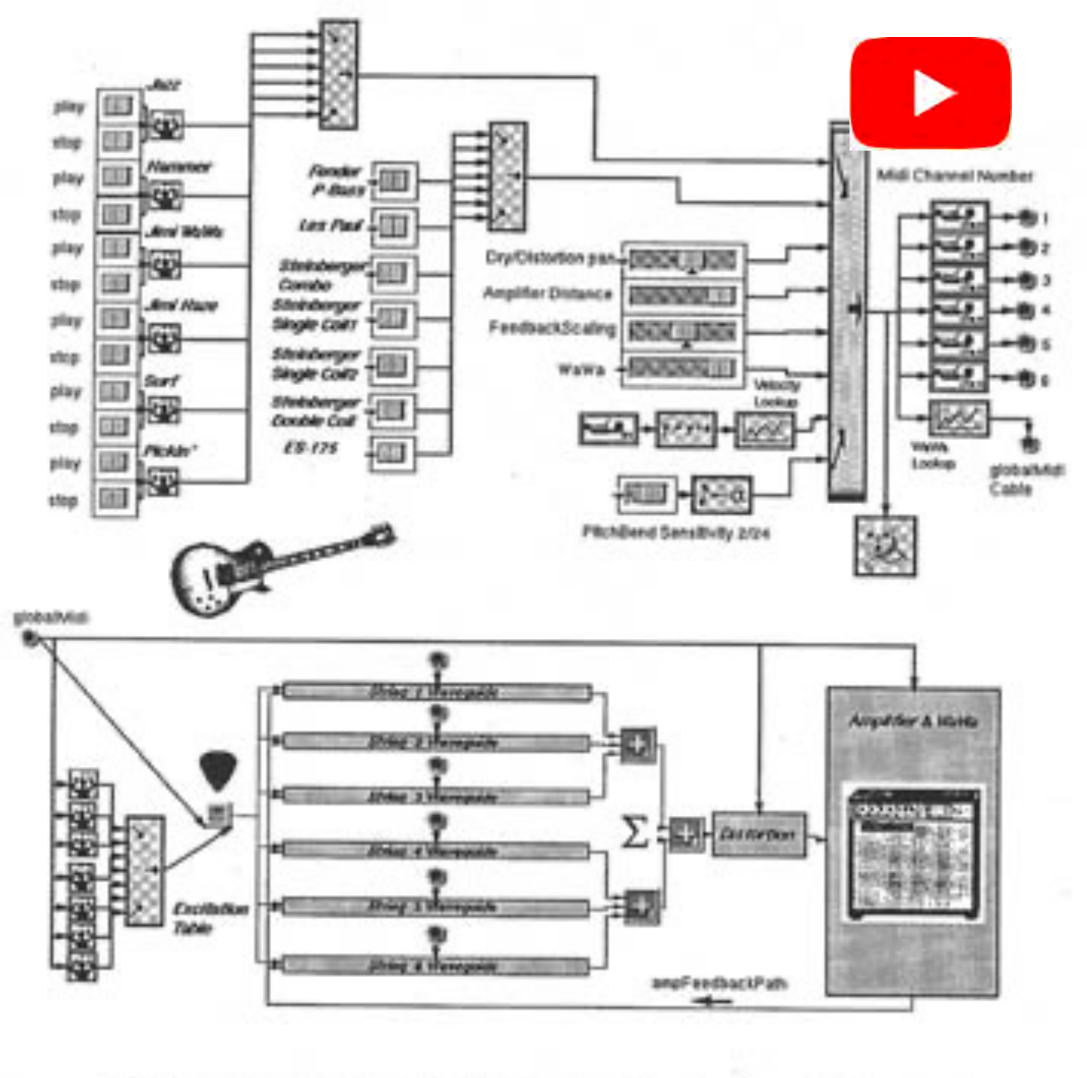


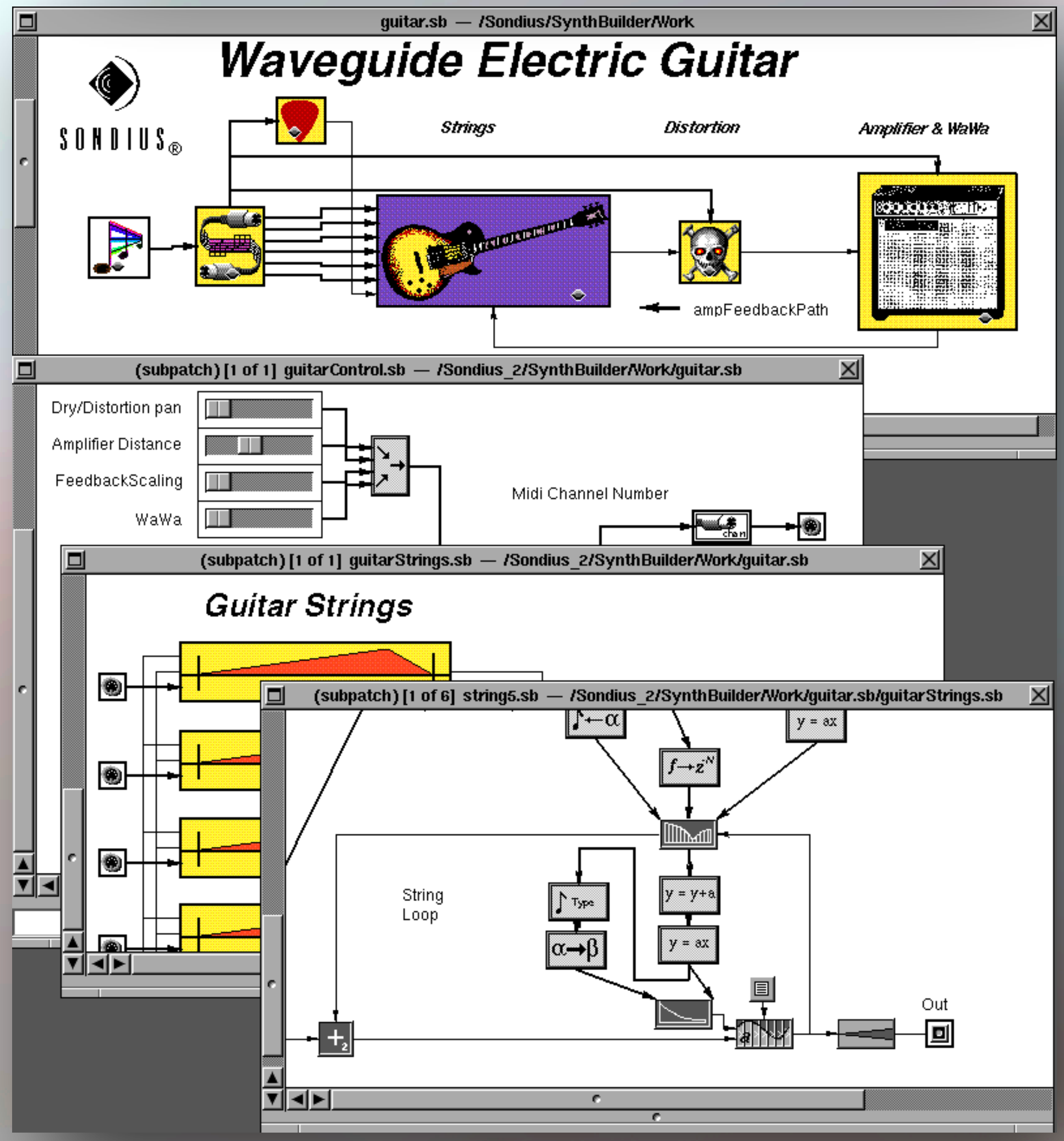
Figure 2: The Coupled Mode Filter Structure

Guitar Model (Scandalis 1996)

- Distortion, feedback and effects.
- Initial period excitations to capture the sound of different guitars.
- Controlled with Yamaha G10 guitar controller similar to today's MPE.

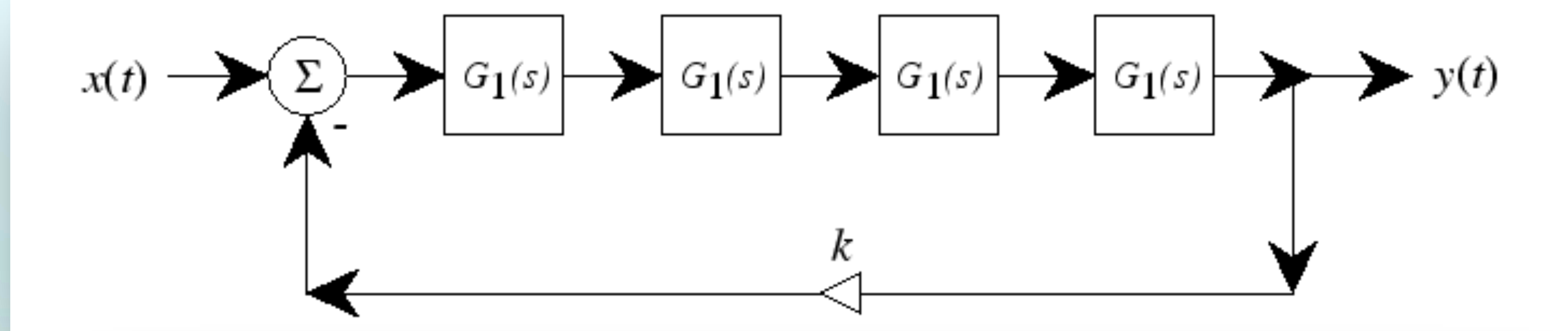


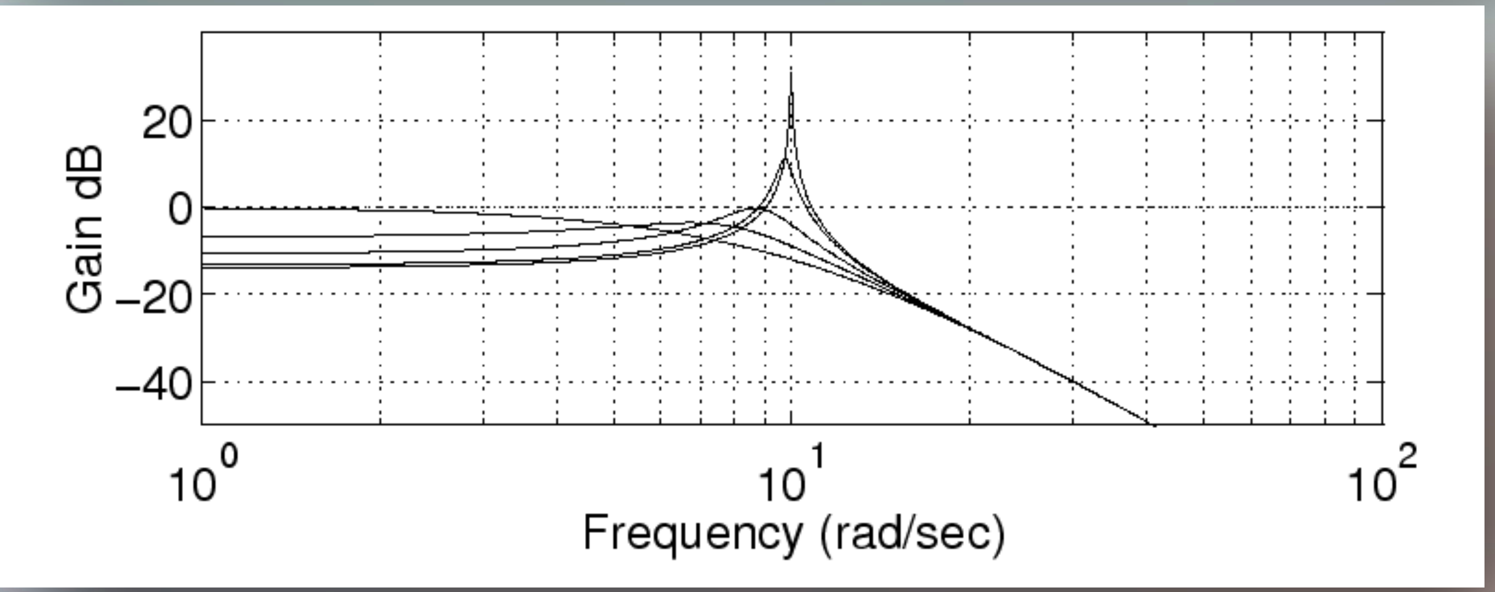
A six string electric guitar model with distortion, feedback and wawa, implemented in SynthBuilder. This model runs on on a single 72Mhz Motorola 56002 DSP.

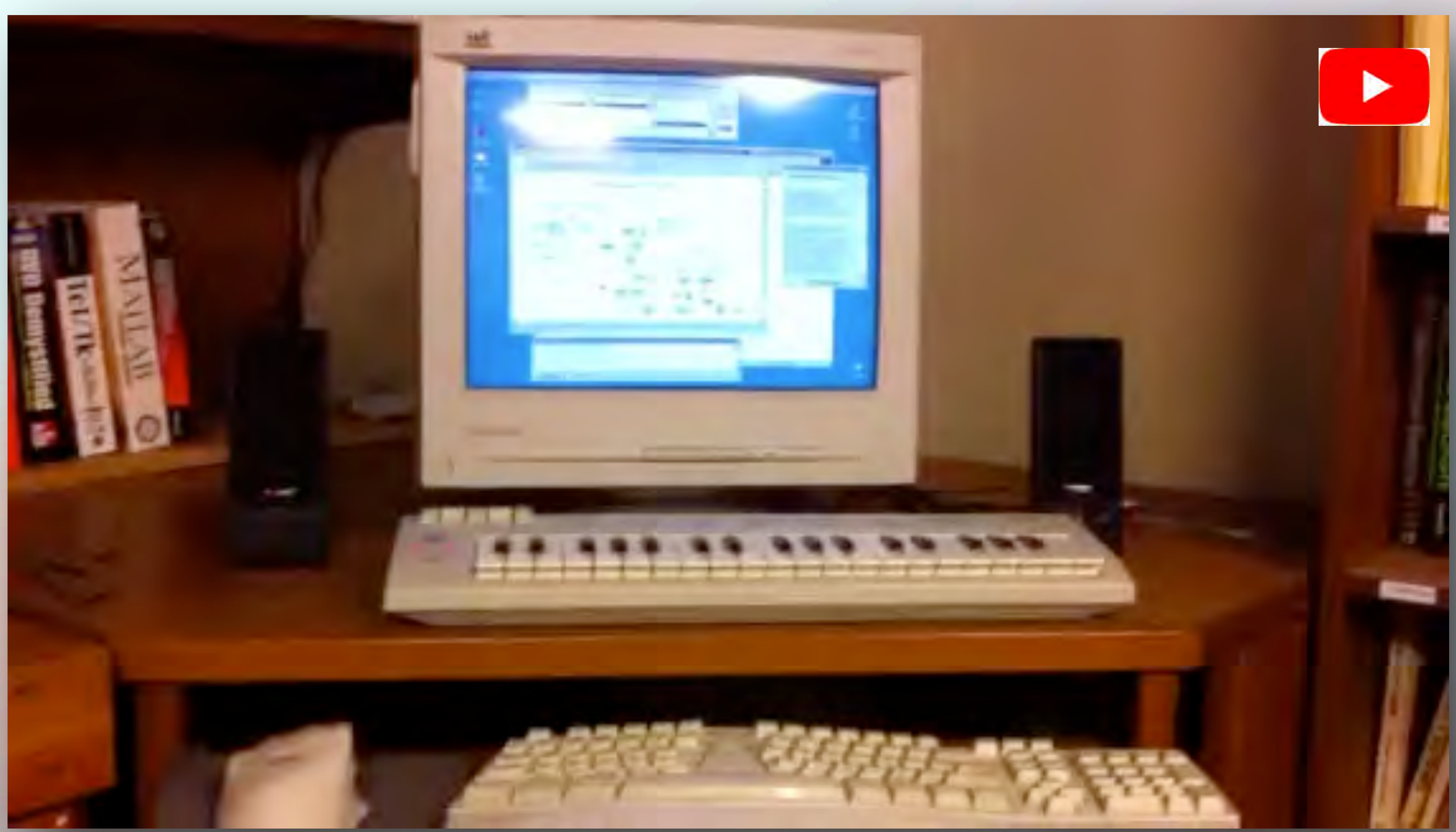


Virtual Analog (Stilson-Smith 1996)

- Alias-Free Digital Synthesis of Classic Analog Waveforms
- Digital implementation of the Moog VCF. Four identical one-poles in series with a feedback loop.
- Sounds great!

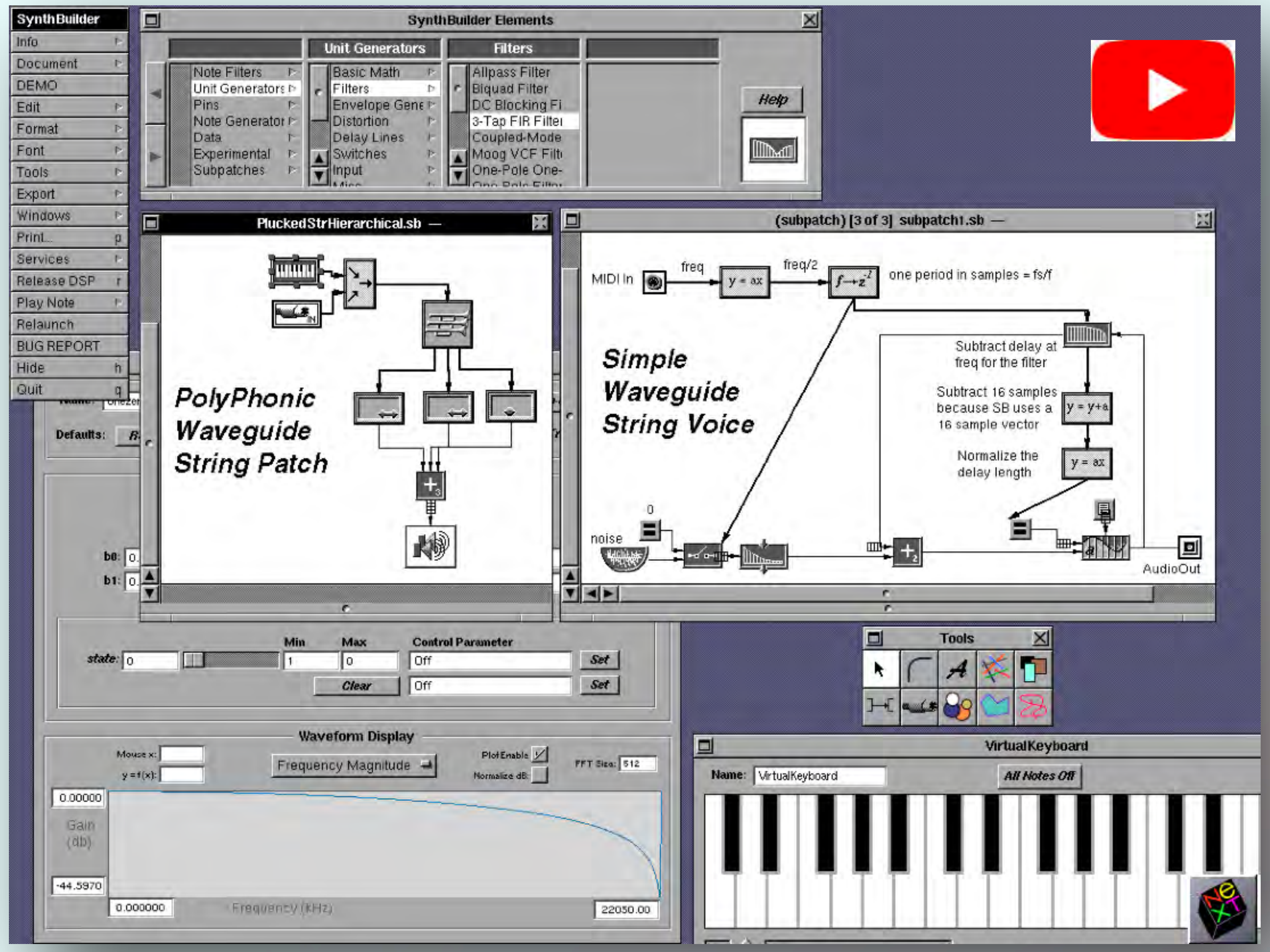


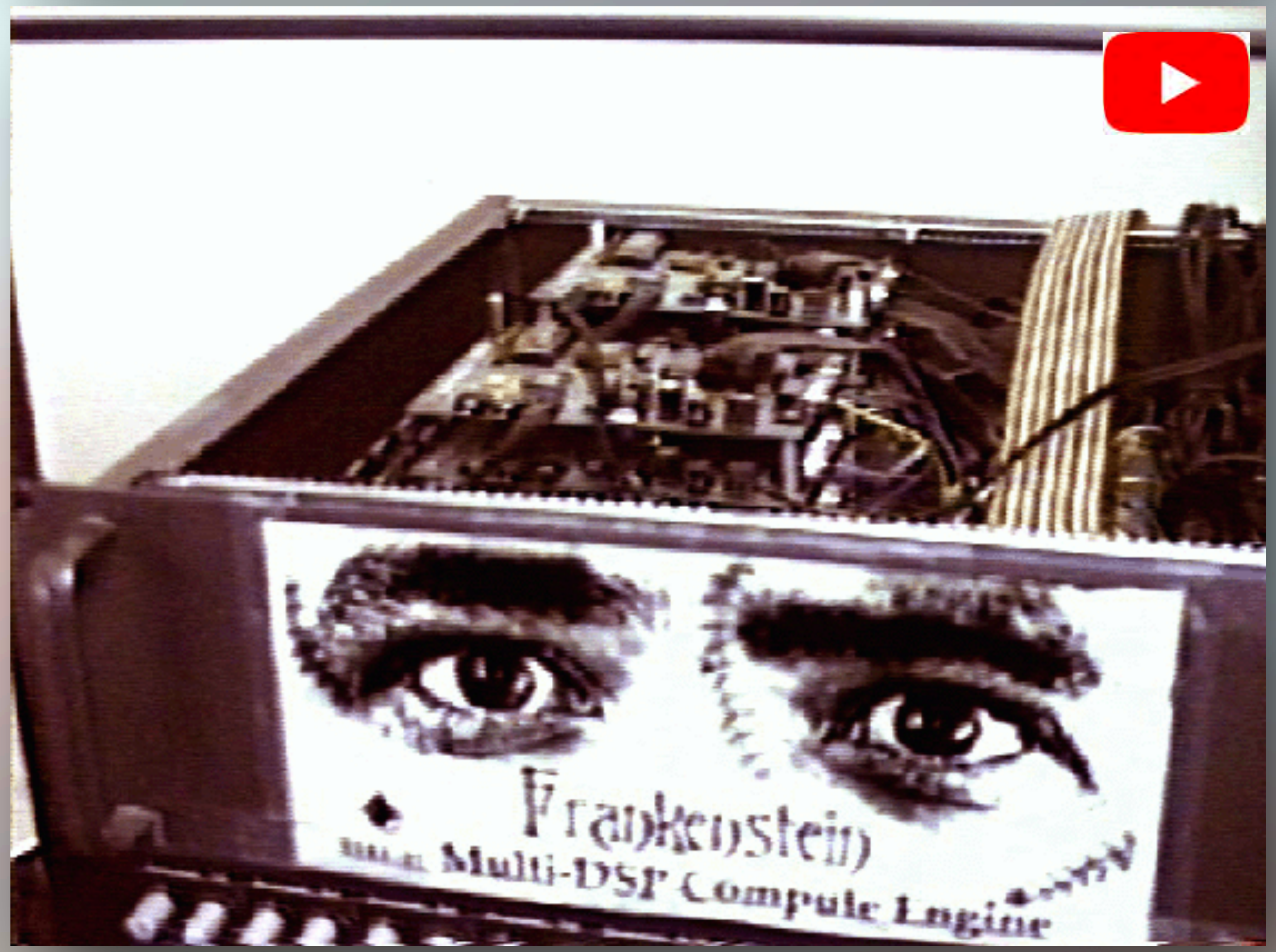




Full Ensembles all Physical Modeling (1997)

- Stanford OTL/CCRMA created the Sondius project to assist with commercializing physical modeling technologies.
- The result was a modeling tool, SynthBuilder, a DSP farm called Frankenstein, and a set of models covering about two thirds of the General MIDI set.
- Many modeling techniques were used including EKS, Waveguide, Commuted Synthesis, Coupled Mode Synthesis, Virtual Analog.





First Generation PM Products

- Yamaha VL-1 + Chipsets (1994-2000)
- Korg SynthKit … Kronos (1994-present)
- Seer Systems Reality (1997)
- Aureal ASP 301 Chip (1995-1997)
- Staccato SynthCore Sondius Models (1997-2001)

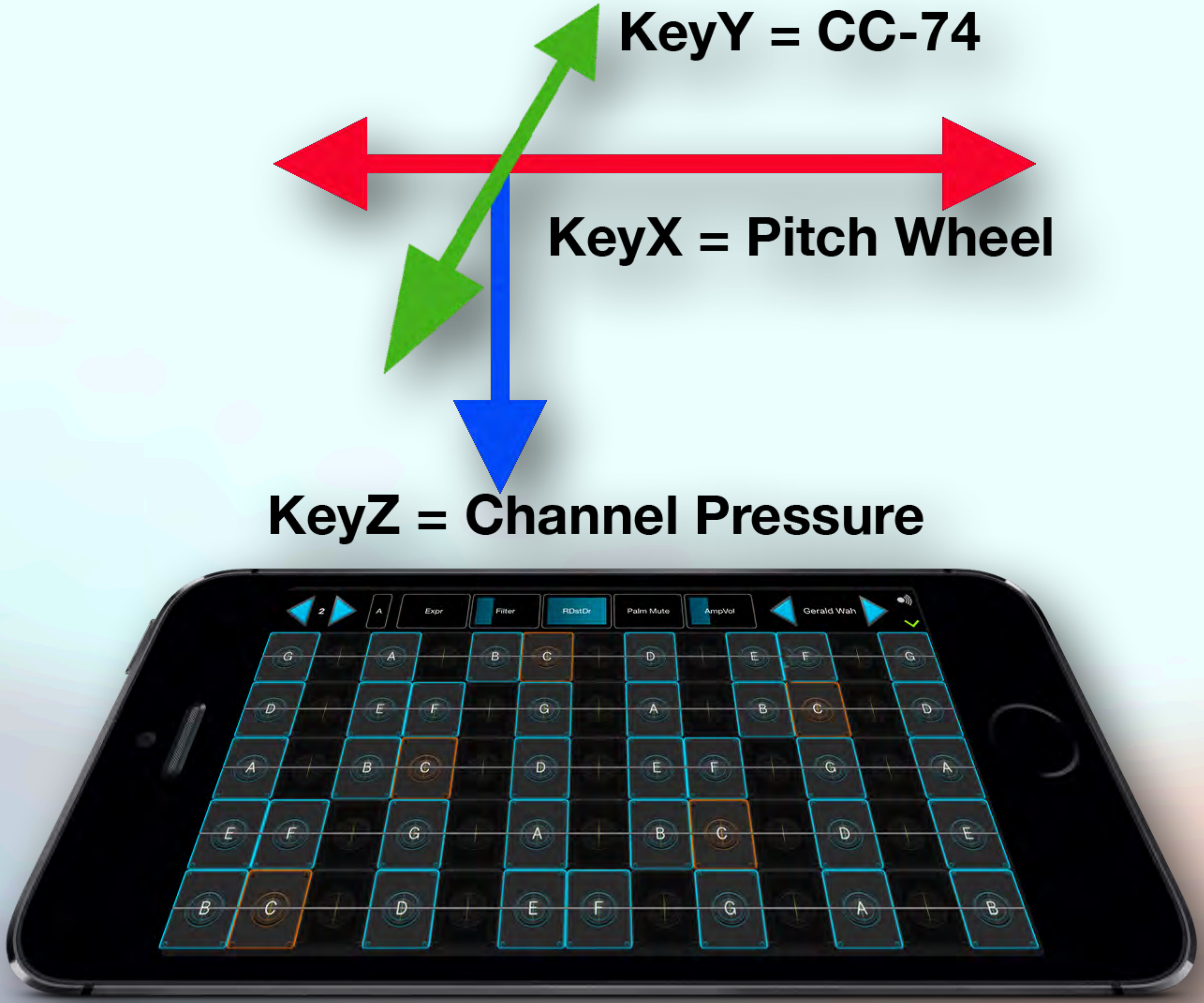
In 1994 Physical Modeling Was Poised to be the "Next Big Thing", So What Happened?

- By 1994, FM was the standard for PC Game Music. In part due to it's small memory footprint.
- PM was seen by Yamaha as the successor to FM (John Chowning's pioneer FM patent was expiring).
- The cost of memory starting plummeting in 1996. Sampling became common.
- Some expressivity could be achieved with extensively interpolated samples.
- Voicing PM is difficult (like FM), voicing samples is more direct.
- Controllers that could express multiple dimensions were not common.

Why is PM Back?

- **Compute Power** - A DSP Farm is no longer needed.
- **Lots of Models Now** - Models require research to create and calibrate.
- **MPE** - There is a new generation of polyphonic expressive controllers based on the new MIDI MPE spec.

MPE = MIDI Polyphonic Expression
MPE + Modeling = BIG DEAL

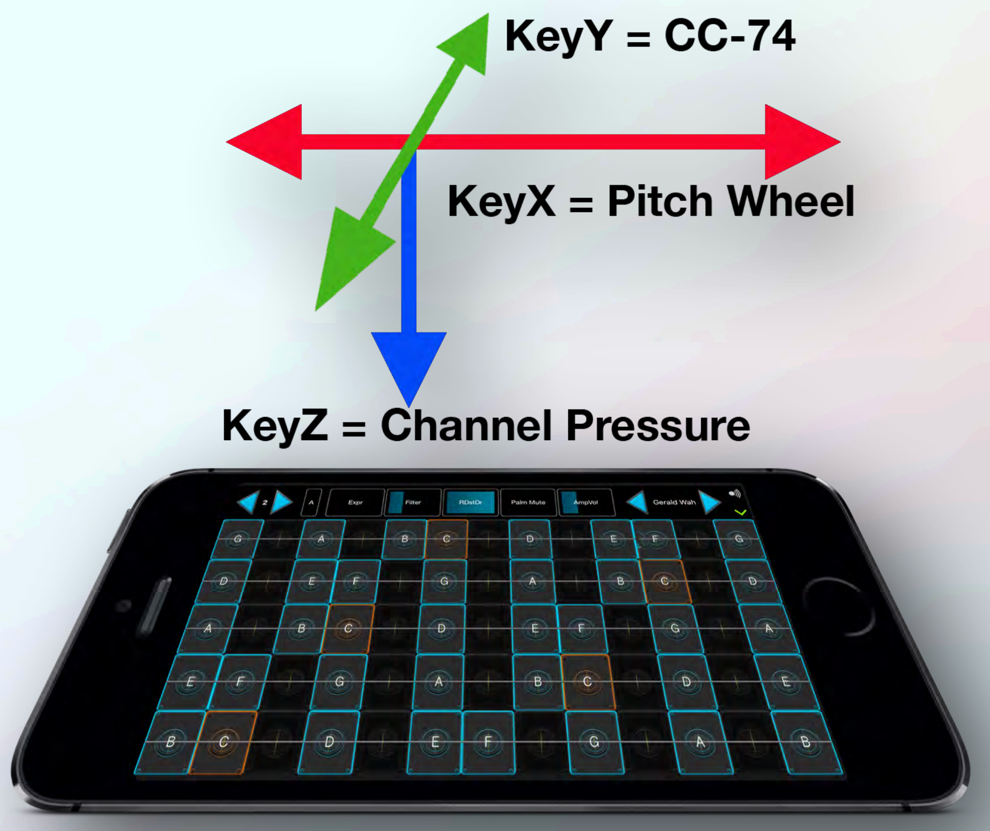


MPE in a Nutshell

- Derivative of MIDI Modes 3/4; enabled with RPN-6/0

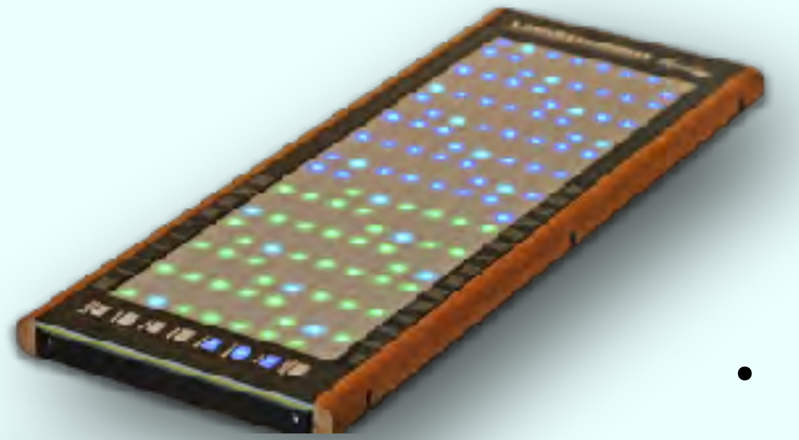
- Can be Channel-Per-Note (for Keyboards, like the Seaboard) or Channel-Per-Row (String) (GeoShred, LinnStrument, Guitar Controller).

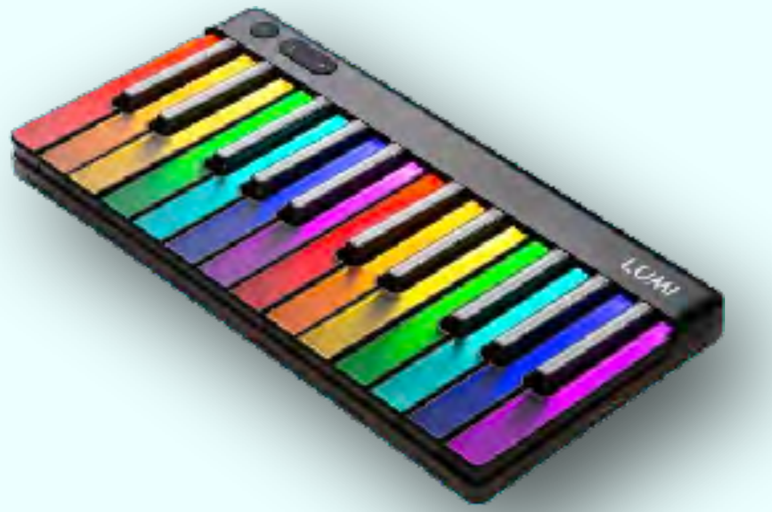
- Expression Control Conventions (per Channel)
  - o KeyX – Pitch Bend (Roli calls this *Glide*)
  - o KeyY – CC-74 (Roli calls this *Slide*)
  - o KeyZ – Channel Pressure (Roli calls this *Press*)

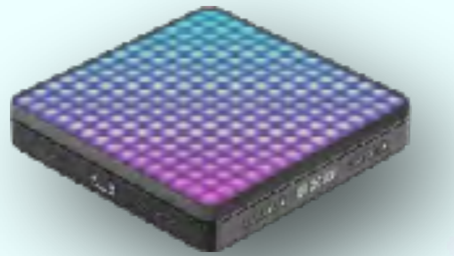


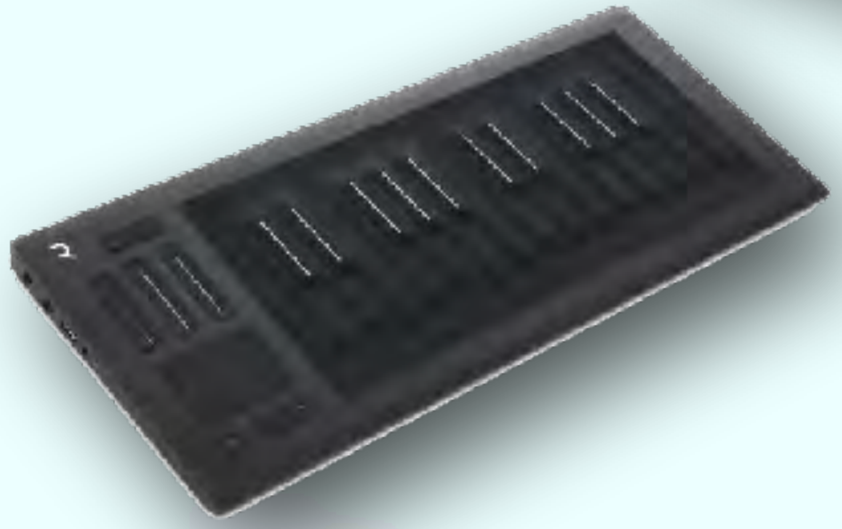
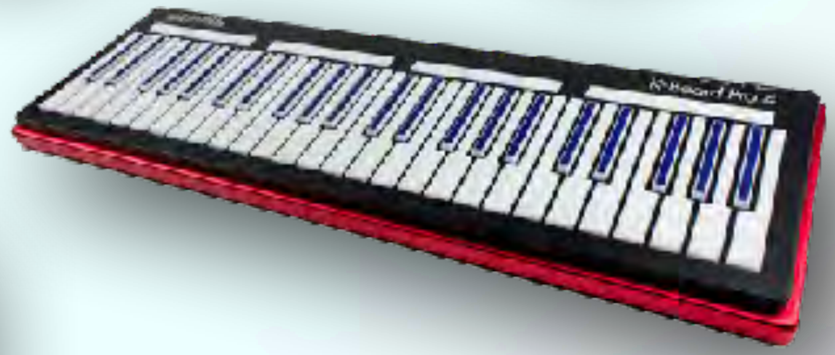
- Provides for Manager Channel (typically 1 or 16) that globally controls the MPE Member Channels (ie modWheel to all Member Channels)

Some MPE Controllers



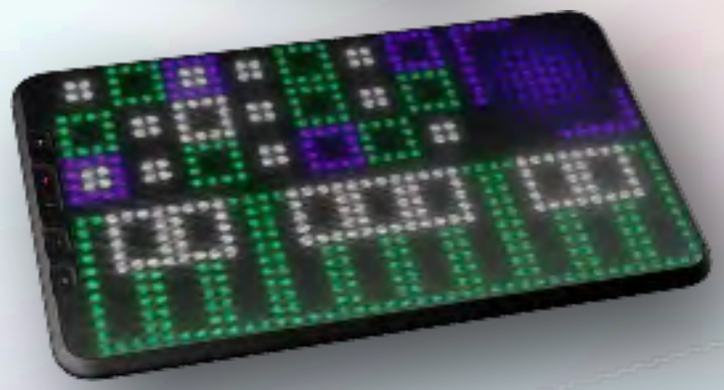



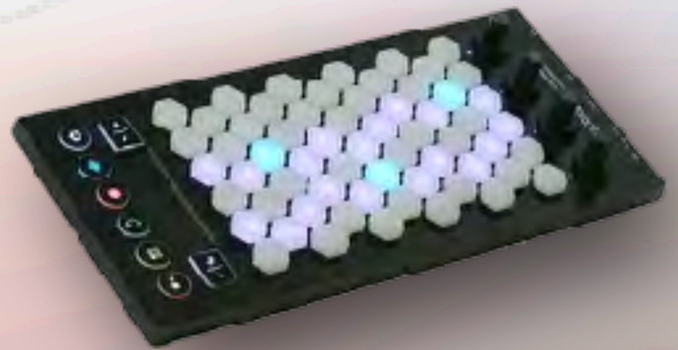
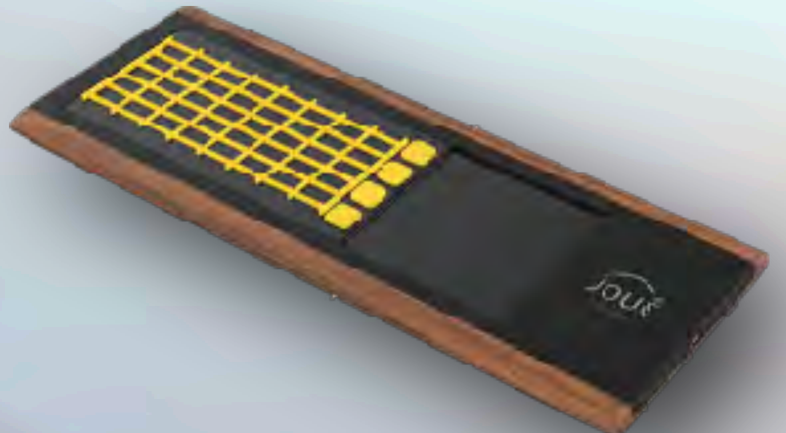
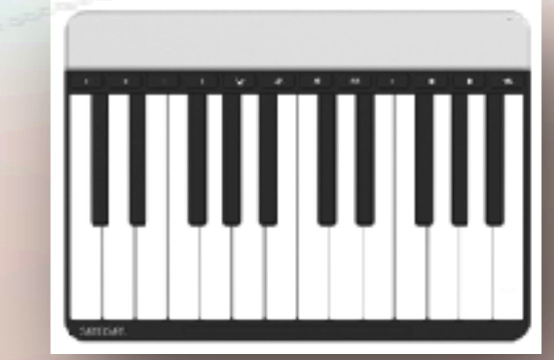


- Haken Continuum
- Lumi Keys
- Roli Blocks
- KMI K-Board Pro 4
- Ere Touch
- Ableton Push 2
- Exquis
- Osmose
- Guitar Controllers
- Sensel Morph
- Artiphon INSTRUMENT 1
- Joué
- GeoShred
- Roli Seaboard
- LinnStrument

MPE makes a whole new generation of controllers possible. **Whatever instrument makers dream up!**

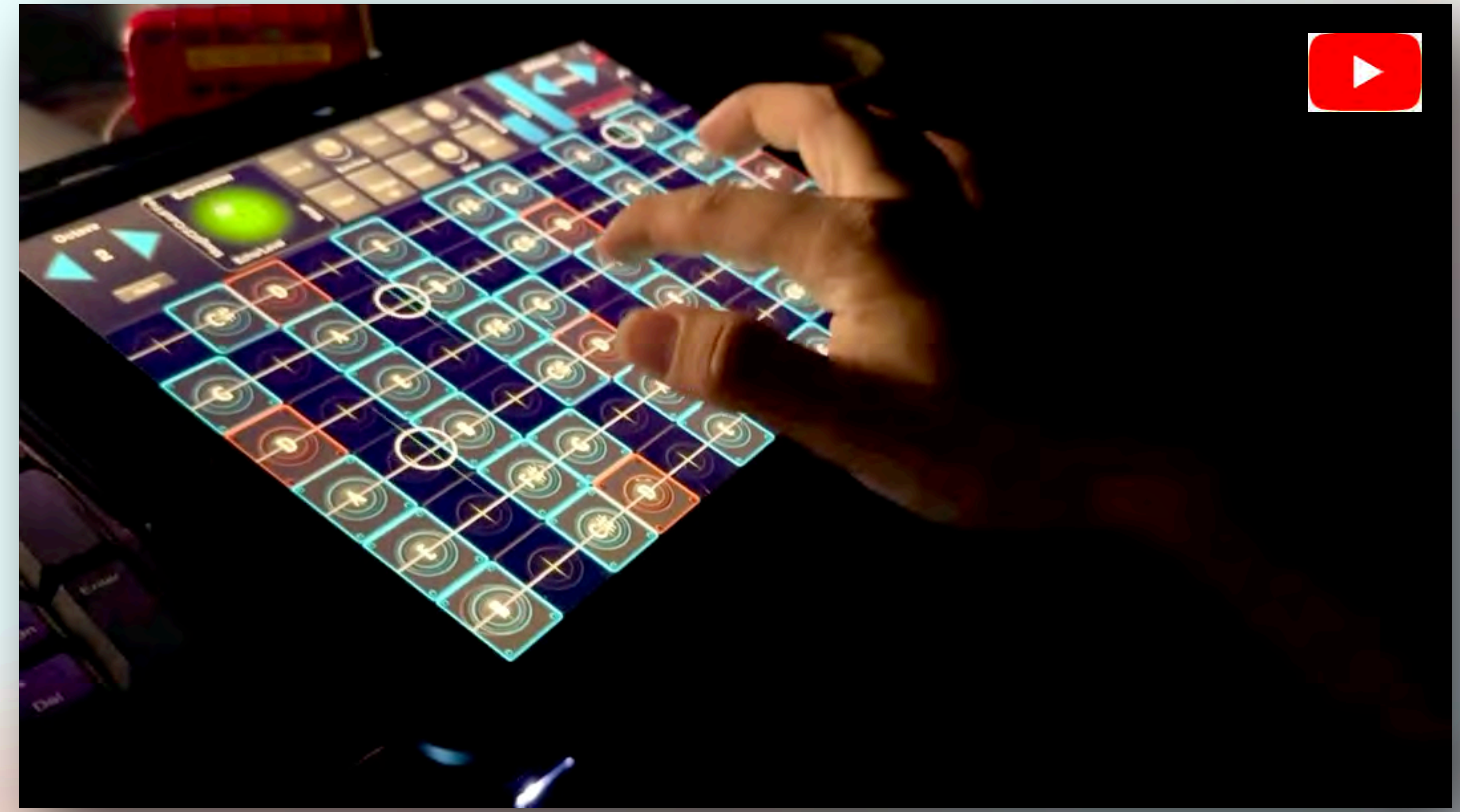





MPE and The Importance of Pitch Fluidity

- Pitch Fluidity is an essential expressive metaphor for musical performances around the world.

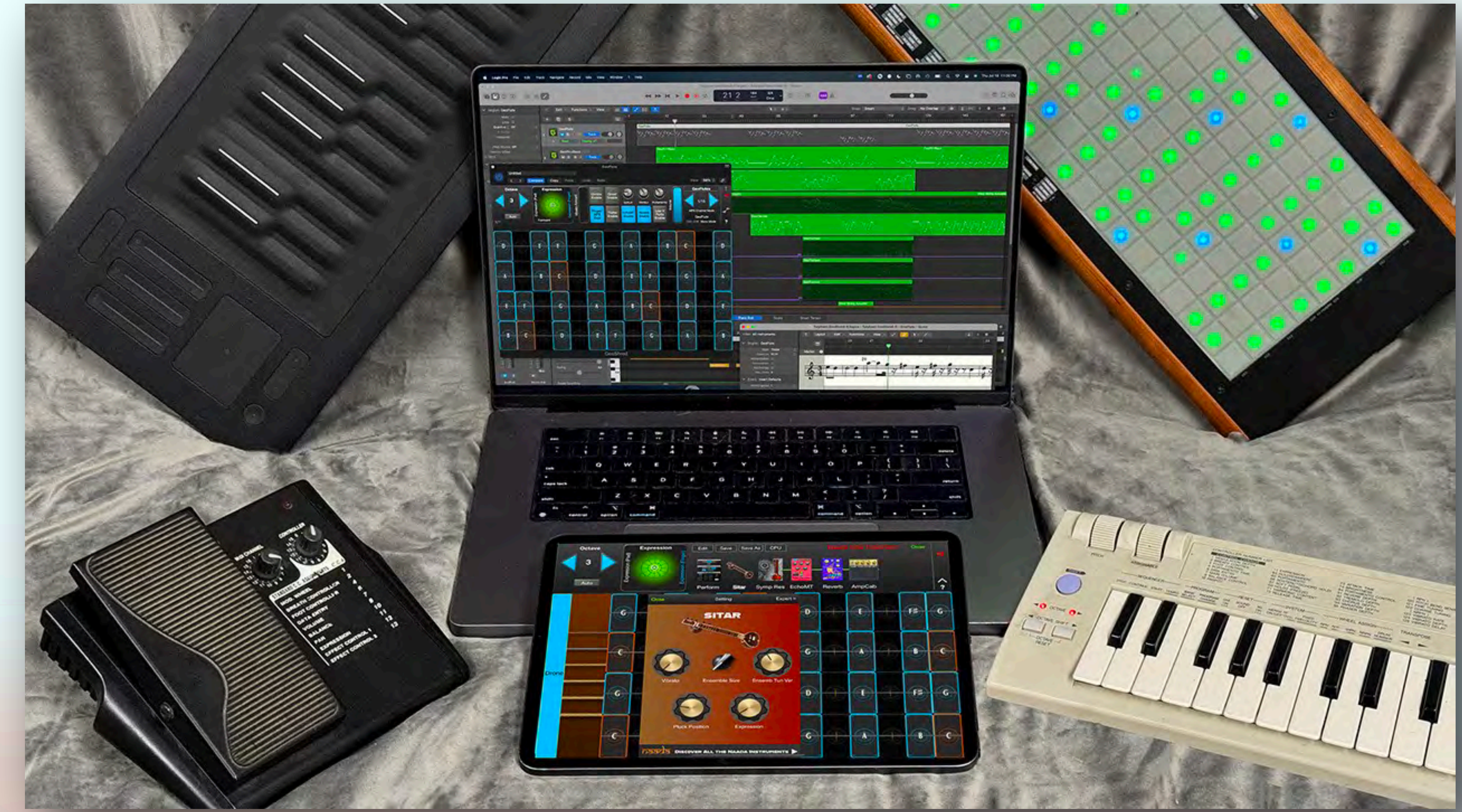
- MPE directly addresses Pitch Fluidity by supporting per-note, multi octave pitch Bending.

- Though not a part of MPE, Pitch Rounding is essential to enable performers to play in-tun in any given temperament. Roli Seaboard, LinnStrument, GeoShred, et al support pitch rounding.



Full Musical Ensembles 2025

PM Applications Using SWAM, GeoShred



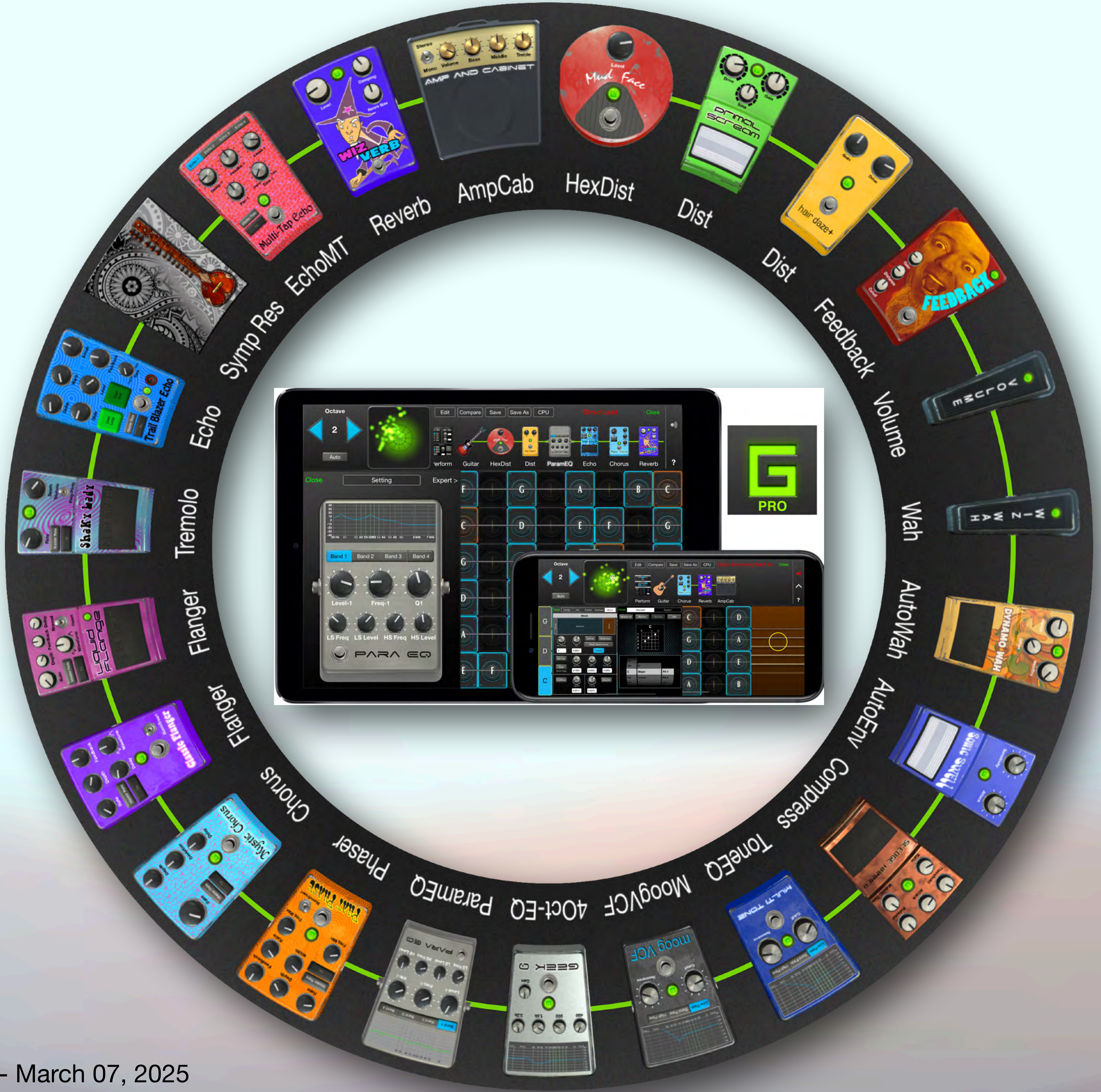
About SWAM

- Created and sold since 2017 by Audio Modeling, an Italian company run by Stefano Lucato, Emanuele Parravicini, and Simone Capitani.
- SWAM instruments model 33 string, woodwind, and brass instruments. They are fundamentally based on digital waveguide synthesis technology.
- Performable, real-time synthesis instruments with many MIDI-controllable parameters. Parameters can be mapped to curves that optimize their response in performance.
- Highly expressive, lifelike, and MPE-capable.
- Have MUCH smaller RAM and disk footprints than sample instruments and can load presets nearly instantly.
- Can run standalone or as plugins in DAWs, and also come in iOS versions. GeoSWAM is a family of SWAM instruments built to run in MoForte GeoShred.

GeoShred

- iOS/iPadOS and MacOS. Windows Late 2025
- 250k users world wide in 120+ countries. 30% of users are in India
- Unique isomorphic MPE keyboard with “Almost Magic” Pitch Rounding.
- GeoShred Keyboard has XY expression on iPad and XYZ on iPhone 8,9,10.
- Supports GeoShred Keyboard, MPE Controllers, Conventional MIDI Controllers and Wind Controllers.

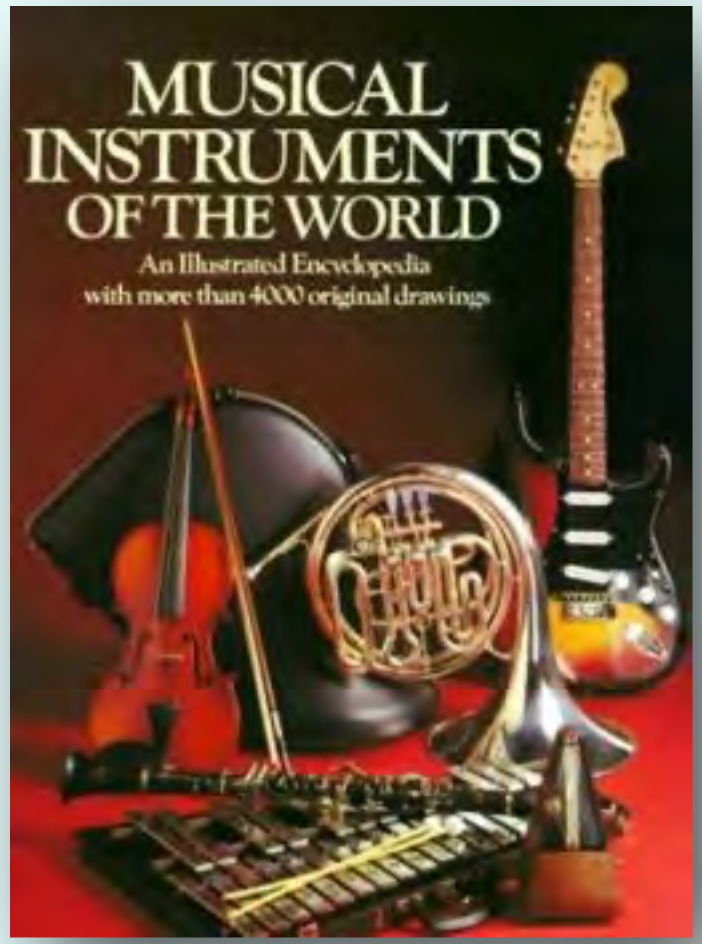
22 Modeled Effects

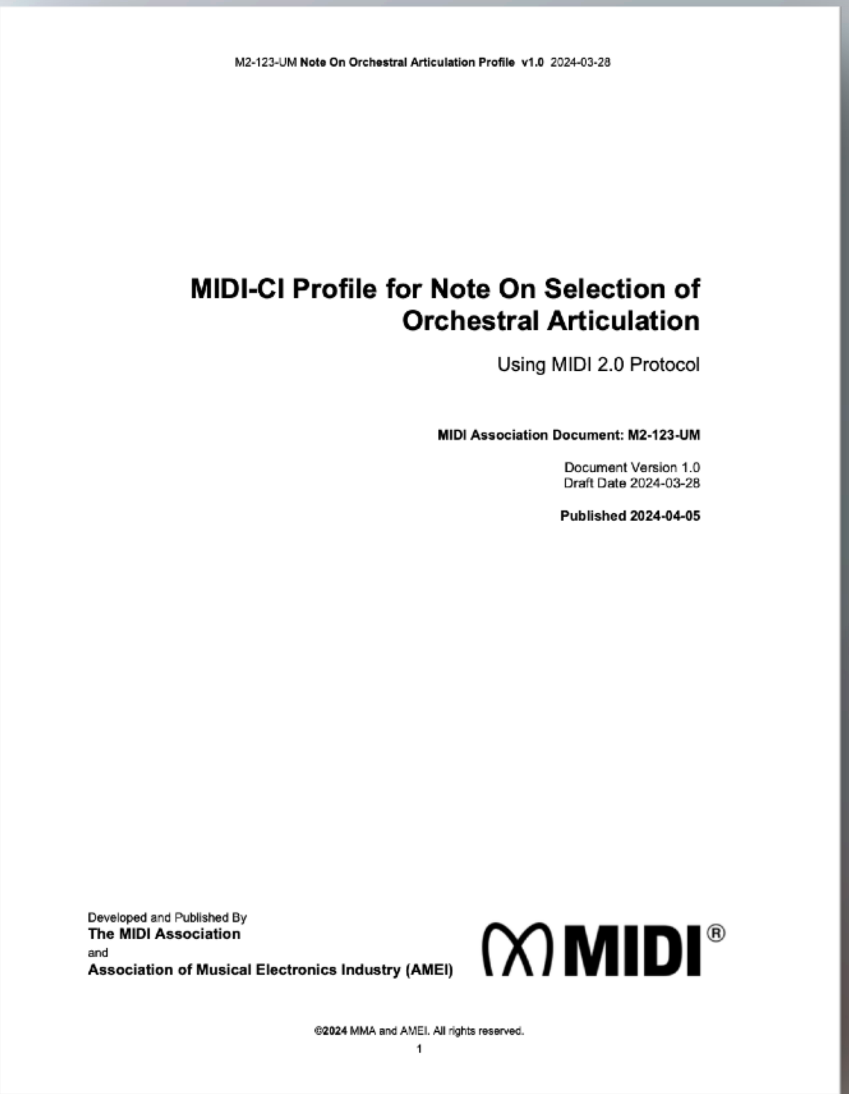


Currently 33 Physically Modeled Instruments

The Future

- More models
- MIDI 2.0
- Orchestral Articulation in MIDI 2, and the potential for fully articulated ensemble scores using PM.
- AI for Articulation and Model Calibration




M2-123-UM **Note On Orchestral Articulation Profile v1.0** 2024-03-28

MIDI-CI Profile for Note On Selection of Orchestral Articulation

Using MIDI 2.0 Protocol

MIDI Association Document: M2-123-UM

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MIDI®

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Physical Modeling Collaborators

wizdom music

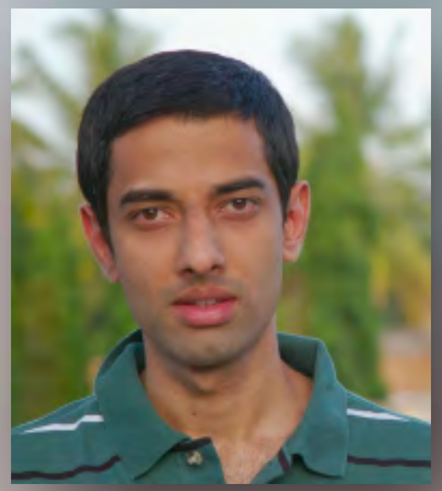
moforte
Audio Modeling

Audio Modeling

GeoShred is a collaboration between Rock Star and mobile music innovator Jordan Rudess, Stanford/CCRMA Professor Dr. Julius O. Smith III, Nick Porcaro, Pat Scandalis

Additional models developed by Audio Modeling/ SWAM (Stefano Lucato, Lele Parravicini) and AccelMatrix/Naada (Suthambhara Nagaraj)

naada



Gratitude

Mary Albertson
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Simone Capitani
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Perry Cook
Jon Dattorro
David Jaffe
Mike Kent
Joe Koepnick
Max Matthews (RIP)
Romain Michon
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Scott Levine
Roger Linn
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Keith McMillen (RIP)
Yann Orlarey
Stephane Letz
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Danny Petkevich
Nick Porcaro
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