Computing Sound: Physics-Based Parametric Sound Synthesis

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“Computing Sound”

• Physical Modeling Synthesis \((WG/WDF/FEM)\)
• Synthesis from Hybrid Time/Freq. Models \((Modal)\)
• Physically-Inspired/Controlled Sonic Models \((PhISM)\)
• Physically-Inspired Stochastic Event Models \((PhiSEM)\)
• Physically-Oriented Library of Interactive Sound Effects \((PhOLISE)\)
  Bill’s GaitLab: walking analysis/synthesis
• Examples, Controllers!!!, Demos, Movies
• (some on Voices, Speech, and Singing too)
Physical Modeling
(1 slide!)

Sound is Made…
• Striking, whacking, collisions
• Blowing, wind, flow, turbulence
• Bowing, rubbing, scraping
• Shaking, rattling, crunching

Sound is Perceived
• Auditory periphery
• Tonotopic mapping
• Rate/place (pitch)
• Spectral view

PLOrk: Non-Specific
Gamelan Taiko Fusion
PCM
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Modal Synthesis: The Missing Link
(Adrien, Vanden Doel, Cook …)
- Time/Frequency
- Impulse (or noise, other) generator excites filters
- Filters shape spectrum, model eigenmodes
- Filter parameters can be time-varying

\[ y[n] = g*x[n]; \]
\[ y[n] += b_1*y[n-1]; \]
\[ y[n] += b_2*y[n-2]; \]
\[ n++; \]
Modal: “Identity” Analysis and Resynthesis (“parametric sampling”)

Struck coffee mug

Identify modes
Model with filters (or sine oscs)

Remove modes to yield “residue”

Can re-excite modal filters for “identity resynthesis” (or modify!)

Parametric Modal Synthesis

- Physics
- Intuition
- Arbitrary!
- Random!

WiiDemo
The Wave Equation

\[ df = (T \sin \theta) x dx - (T \sin \theta) x \]  
(for each dx of string)

\[ f(x + dx) = f(x) + \delta f/\delta x dx + \ldots \]  
(Taylor’s series in space)

\[ \text{assume } \sin \theta = \theta \]  
(for small \( \theta \))

\[ F = ma = \rho dx \frac{d^2 y}{dt^2} \]  
(\( \rho = \text{mass/length} \))

Solution:
The wave equation
\[ (c^2 = T / \rho) \]

\[ \frac{d^2 y}{dx^2} = \frac{1}{c^2} \frac{d^2 y}{dt^2} \]

Traveling Wave String Solution(s)

D’ Alembert Solution of 2nd order wave equation (left and right going waves)

“Digital Waveguide Filter” Model (Smith)

- Bi-directional delay lines
- Filters for loss, radiation, other
Physical/Spatial Mesh/Modal Solutions

Modes of Plates are inharmonic

Modes problematic in higher dimensions and also for odd (non-analytical) shapes (impossible analytically except in very simple cases)

Finite Element Meshes
(SIGGRAPH 01 with O’ Brien and Essl)

“Synthesizing Sounds from Physically-Based Motion”
Tubes

- Open or closed at either end
- Wave equation solution same as strings
- Modes always harmonic because speed of sound is constant with frequency
- Solutions: Waveguide or Modal

Open + Closed: odd 1/4 wavelengths

Tubes and Air Chambers

Waveguide tube (with non-linear “reed”)

- Bulk Helmholtz Resonator with non-linear “reed”

Wang: Zelda

Simple clarinet model

Player breath pressure $P_b$
Non-linear reed model
"Bore" delay line
Reflection filter

Demo (SMELT)

Blown bottle

Demo (SMELT)
Data Driven, Physics-based Sound: “Music for Unprepared Piano”

SIGGRAPH 98
(with Bargar, Choi, Betts (NCSA))

The “Score”

Physical Models: Non-linearity in Solids (Scott VanDuyne)

Add spring(s) with position dependent constant
(one spring for positive displacement, another for negative)

Acts to spread spectral components
D’Alembert (Waveguide) (+ Stiffness)

All-pass waveguide (Smith & Jaffe)
- Acoustics View: Frequency dependent propagation c(f)
- Filter View: Stretch comb filter harmonics

Banded waveguides (Essl)
- Physical Acoustics: Wave train closures
- Filter View: Comb filters with one modal resonance each

Frictional Interactions
- Bow/String Models
  - friction “curve” \( m = f(\Delta v) \)
  - stick/slip based on \( \Delta v \)

Haptic Textures
- Minsky: functional surface forces
- Siira and Pai
- Fritz and Barner: Stochastic Haptic Textures
- Hayward and Armstrong: Haptic stick/slip springs

GameTrak Demo

Structured Friction (regular)
Physical Models: Particles

Whistle: Single particle influences physical (or other) oscillator

Homeraca: Many particles trigger parametric synthesis (or launch PCM)

Also good for “flock-like” sounds: applause, rain, birds, etc.

Stochastic Event Synthesis: Building a synthesis model

Run model w/ lots of particles

Collect statistics -> Poisson

System energy decays exponentially.
Particle collision causes decaying burst of filtered noise
PhISEM Algorithm

- Exponentially decaying system energy

- Particle sound energy is exponentially (fast) decaying white noise. Sum of exponentially decaying noises is an exponentially decaying noise.

- Each time step, compute likelihood (based on #of particles) of new sound-producing event
  - If so, add to net particle sound envelope energy

- Filter result with system resonances/modes, with reallocation if needed

PhISEM Code Example

```c
#define SOUND_DECAY 0.95
#define SYSTEM_DECAY 0.999

EACH SAMPLE:

shakeEnergy *= SYSTEM_DECAY; // Exponential system decay
if (random(1024) < num_beans) // If collision
    sndLevel += gain * shakeEnergy; // add energy
input = sndLevel * noise_tick(); // Actual Sound is Random
sndLevel *= SOUND_DECAY; // Exponential Sound decay
input -= output[0]*coeffs[0]; // Do simple
input -= output[1]*coeffs[1]; // system resonance
output[1] = output[0]; // filter
output[0] = input; // calculations
```
PhISEM: Stochastic Modal Synthesis

Stochastic resonances
Modal PhISEM examples

- Allow resonances to vary randomly (or not) on each excitation
- Each resonance can have own distribution
- Can reallocate one, two, ..., all each collision

Tambourine
Sleighbells
Bamboo Wind Chimes
Coin(s) in a Cup
Socket Wrench
Related techniques

- Wavelets (background sounds) (Miner)
- Independent Components Analysis (Casey)
- Stochastic Multi-Pulse LPC (Zhu & Wyse)
- Sampled Wavelet Trees (Dubnov, Misra)

- My interest: things that we directly excite/control, and how to control them

- Interactive Digital Foley:
  Analyze walking sounds for higher-level structure/parameters

Interactive Digital Foley → PhOLISE: “Real-world” PhISEM

Physically Oriented Library of Interactive Sound Effects

Interaction sounds, including

Walking!
Modeling Bill’s Gait (AES02)

- Segment sound files
- Extract temporal structure & features
- Do PhISEM analysis
- Resynthesize
- Parametric Synthesis
- ClapLab, Flox, … Analysis(SysID)?
Data Driven Sound (PhISM): “Seen in Shadow”

SIGGRAPH 2000
with Grady Klein,
Adam Finkelstein,
Petrovic, Fujito

Music:
Trueman, Mugan

PhISM Controllers

PhOLIEMat

Picos

TapShoe
**Synthesis ToolKit in C++ (STK)**

- STK: a set of classes in C++ for rapid experimentation with sound synthesis. Available for free (source, multi-platform)
  - [http://www.cs.princeton.edu/~prc](http://www.cs.princeton.edu/~prc)
  - [http://www-ccrma.stanford.edu/software/stk](http://www-ccrma.stanford.edu/software/stk)
- Based on “Unit Generators,” the classical computer music/sound building blocks:
- Oscillators, Filters, Delay Lines, etc.
- Build your own algorithms from these

**ChucK: On-the-fly Programming Language**

- Open source
- On-the-fly (VM)
- Extensible
- Fun
- Not efficient!!

**Book on interactive sound synthesis**

- Many examples, figures, soundfiles, and open-source code!

**OTHERS: Sounding Object, DAFX, some SIGGRAPH, other**

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**More Resources and References**

- **ChucK**: On-the-fly Programming Language
  - Open source
  - On-the-fly (VM)
  - Extensible
  - Fun
  - Not efficient!!
  - Contains STK and lots more
    (sensors, MIDI, OSC, HID, networking)
  - Based on “Unit Generators,” the classical computer music/sound building blocks:
    - Oscillators, Filters, Delay Lines, etc.
    - Build your own algorithms from these

**ChucK Book!!**

- Many examples, figures, and open-source code!
Upcoming Voice/Tech Book:

La Bella Voce et la Macchina
(the beautiful voice and the machine)

A History of Technology
and the Expressive Voice

Technology: Any human-fashioned
tool, technique, method, law,
notation, enhancement, etc.

Expressive Voice: Singing, acting,
preaching, rapping, praying, etc.

“Steamo”

A Note (or 2) on Voices

• Rich history of speaking machines
• And controllers for vocal models (Von Kempelen 1791, Faber 1840, Dudley 1939 ++)
• Concatenative PCM
A Note (or 2) on Voices (2)

- Rich history of speaking machines
- And controllers for vocal models (Von Kempelen 1791, Faber 1840, Dudley 1939 ++)

• Formant Source/Filter

A Note (or 2) on Voices (3)

- Rich history of speaking machines
- And controllers for vocal models (Von Kempelen 1791, Faber 1840, Dudley 1939 ++)

• Formant Source/Filter
• Physical Articulatory (acoustic tube, Kelly/Lochbaum, Mathews 1960, Cook 1989, ++)
Controlling electronic voice synth: Dudley’s Voder

- 1939 World’s Fair
- Operators (female) manipulate console

Voder: Source/Filter Model

- Noise/Pulse (wrist bar)
- Pitch control (foot pedal)
- Resonances (10 finger sliders)
- Consonant/Stop Presets (thumb buttons)
GloveTalk (Fels and Hinton, 1990+)

- Data gloves and 3D position to control speech synthesizer
- Left Hand “Macros” for Consonants
- Pitch height
- Vowel Space

Articulatory (physical) Voice Synth (SPASM)

- Real time, control is possible
- BUT... many, many parameters
- Not a natural “fit”

Uh....

Huh?

60+ parameters!
Articulatory (physical) Voice Synth (SPASM)

- Real time, control is possible
- BUT... many, many parameters
- Not a natural “fit”

SCurvIA (2011)

1D or 2D controls

60+ parameters!

GameTrak DEMO
**SqueezeVox** (with Colby Leider 2001)

- Voice Control Issues:
  - Pitch
  - Breathing
  - Articulation
  - etc.
- Fix: Accordiae?

**Physical Models in Performance**

*Interface: Dan Trueman, Curtis Bahn, Tomie Hahn, Perry Cook, Others*

- Tomie Hahn: Streams
  - Pikapika (Tomie Hahn)
- Shakers/Bamboo + vocal formant filters
  - Shakers + "Blotar" (non-linear feedback waveguide flute)
(PL)Orkestra(s) of the Future!

Whew!!!!
ACKs

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Props

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LAP, Colby Leider, Dan Trueman, Ajay Kapur, Ben Knapp, Curtis Bahn, Ge Wang, Rebecca Fiebrink,
Princeton Undergrads, CS and Music Grad Students.

Some others in this space:

• Julius Smith (Stanford/CCRMA): Waveguides++
• Stefan Bilbao (Edinburgh): Wave Digital Filters
• Dinesh Pai (Rutgers), and Kees van den Doel (UBC)
• IRCAM: Rodet, Depalle (McGill), many others
• McGill: Scavone, others
• Sounding Object (SOB, EU consortium):
  – Rocchesso, Avanzini, Bresin, Serafin, Rath, Bernardini,
    Borin, Fontana, Ottaviani
• Marsailles: Korland-Martinet, Ystad, Guillemain
• Andy Farnell: “Procedural Audio” (PD to Wwise plugins)
• Doug James (Cornell) James O’Brien (Berkley)
• Valimaki, Karjalainen, others (Helsinki U T)

Conferences: DAFX,ICMC,ASA,WASPAA,NIME,AES,SIGGRAPH,ISMIR
References: Waveguide & FE Modeling


References: Friction


References: Confined Turbulence


References: LPC and Subtractive


References: Modal Synthesis

References: Sinusoidal Models

Dudley, H. 1939, "The Vocoder," Bell Laboratories Record, December.
SMS Web site. URL: http://www.iua.upf.es/~sms

Refs: PhISEM, Wavelets, Grains

The End:

Consider parametric, physically-motivated sound synthesis

Lots of public domain (unpatented or patents expired) open source code is available

It’s Fun!!

www.chucku.org
(www.vocebella.org)