Computing Sound: Physics-Based Parametric Sound Synthesis

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GameSoundCon, 2014

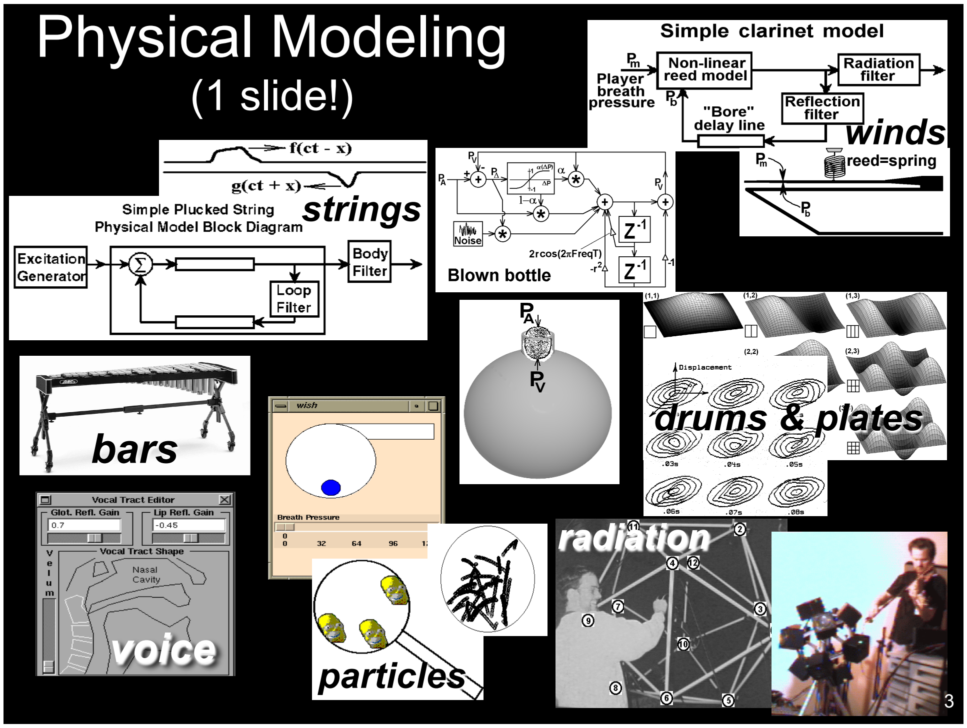
1

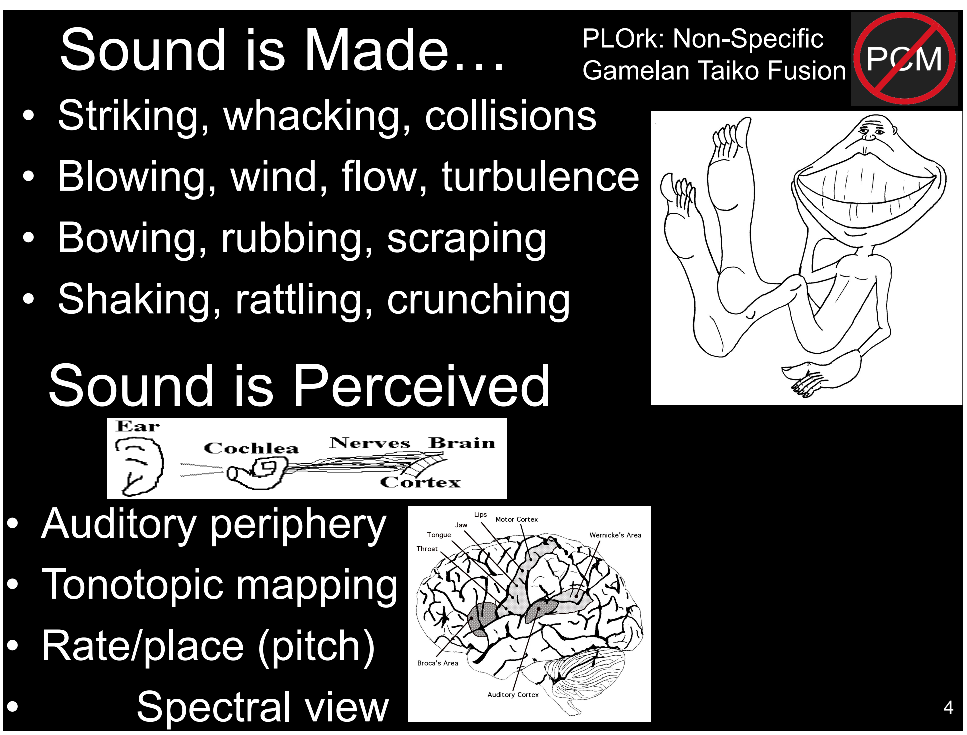
"Computing Sound"

~~PCM~~

- 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)

2

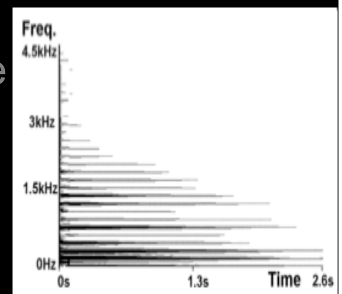

Physical Modeling
(1 slide!)
Simple clarinet model
Player breath pressure
Non-linear reed model
Radiation filter
Reflection filter
"Bore" delay line
winds
reed=spring
f(ct - x)
g(ct + x)
Simple Plucked String Physical Model Block Diagram
strings
Excitation Generator
Loop Filter
Body Filter
Noise
Blown bottle
bars
Breath Pressure
drums & plates
Displacement
Vocal Tract Editor
Glot. Refl. Gain
Lip Refl. Gain
Vocal Tract Shape
Nasal Cavity
voice
particles
radiation
3


Sound is Made…
PLOrk: Non-Specific
Gamelan Taiko Fusion
PCM
• Striking, whacking, collisions
• Blowing, wind, flow, turbulence
• Bowing, rubbing, scraping
• Shaking, rattling, crunching
Sound is Perceived
Ear
Cochlea
Nerves
Brain
Cortex
• Auditory periphery
• Tonotopic mapping
• Rate/place (pitch)
• Spectral view
Lips
Jaw
Motor Cortex
Tongue
Wernicke's Area
Throat
Broca's Area
Auditory Cortex
4

Sound is Made…

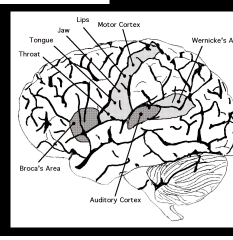
PLOrk: Non-Specific Gamelan Taiko Fusion

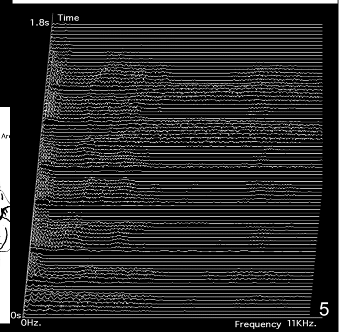
- Striking, whacking, collisions
- Blowing, wind, flow, turbulence
- Bowing, rubbing, scraping
- Shaking, rattling, crunching



Sound is Perceived

- Auditory periphery
- Tonotopic mapping
- Rate/place (pitch)
- Spectral view



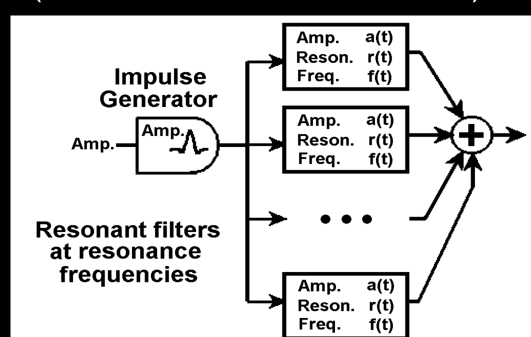


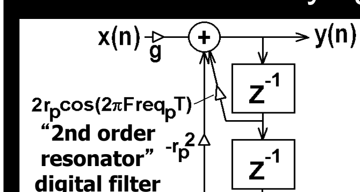
5

Modal Synthesis: The Missing Link

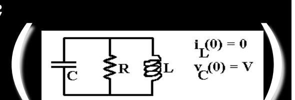
(Adrien, Vanden Doel, Cook …)

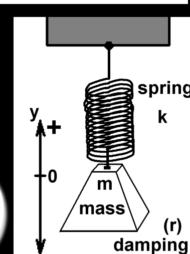
– Time/Frequency
– Impulse (or noise, other) generator excites filters
– Filters shape spectrum, model eigen<u>modes</u>
– Filter parameters can be time-varying






```
y[n] = g*x[n];
y[n] += b1*y[n-1];
y[n] += b2*y[n-2];
n++;
```

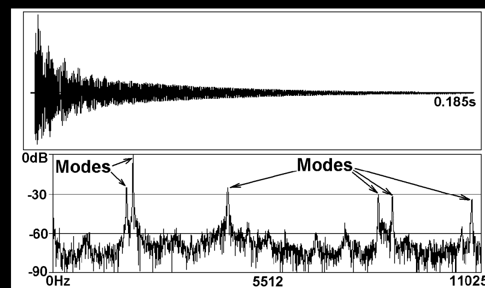




6

Modal: "Identity" Analysis and Resynthesis ("parametric sampling")

Struck coffee mug

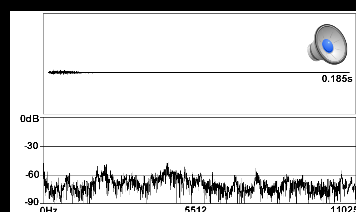


Identify modes

Model with filters

(or sine oscs)

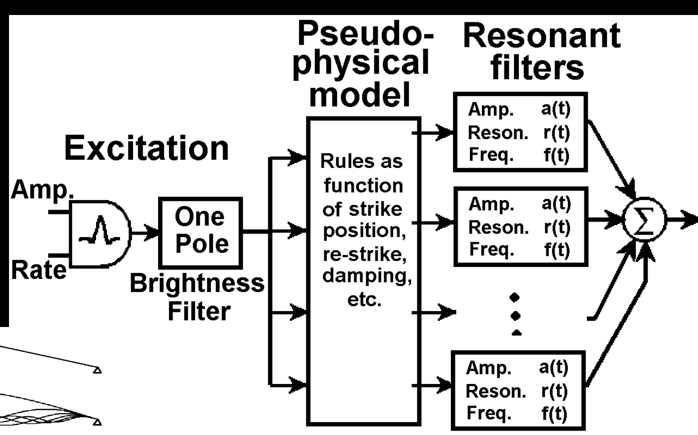
Remove modes to yield "residue"

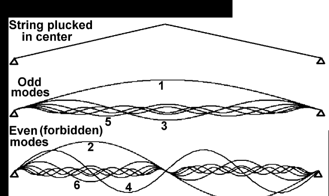


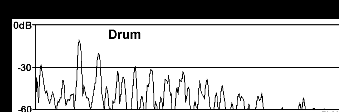
Can re-excite modal filters for "identity resynthesis" (or modify!)

Parametric Modal Synthesis

- Physics
- Intuition
- Arbitrary!
- Random!

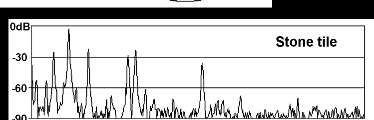






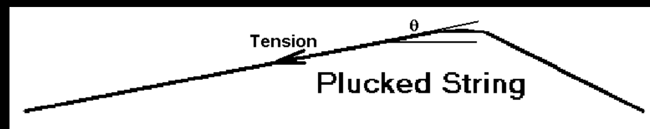
Metal

Wood



WiiDemo

The Wave Equation



$df\ = (T\ \sin\ \ )_{x+dx} - (T\sin\ \ )_x$ (for each dx of string)

$f(x+dx) = f(x) + \delta f/\delta x\ dx + \ldots$ (Taylor's series in space)

assume $\sin\theta = \theta$ (for small θ)

$F = ma = \rho\ dx\ d^2y/dt^2$ (ρ = mass/length)

Solution:

The wave equation

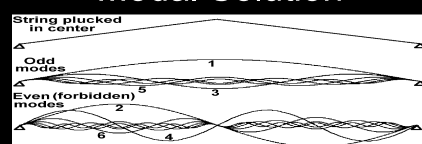
$(c^2 = T / \rho)$

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

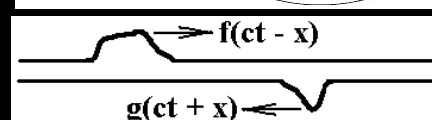
9

Traveling Wave String Solution(s)

Modal Solution

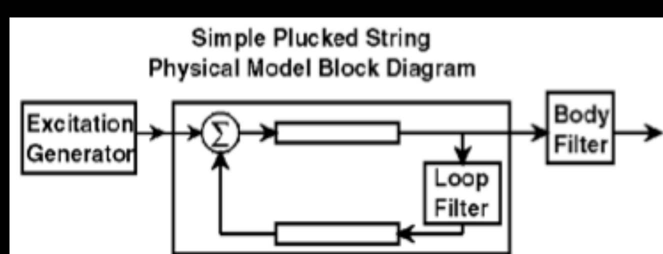


D' Alembert Solution of 2nd order wave equation (left and right going waves)



"Digital Waveguide Filter" Model (Smith)

- **Bi-directional delay lines**
- **Filters for loss, radiation, other**

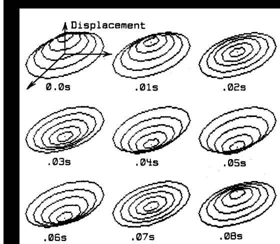


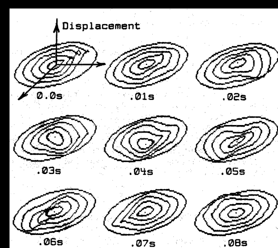
Plucked, Mandolin

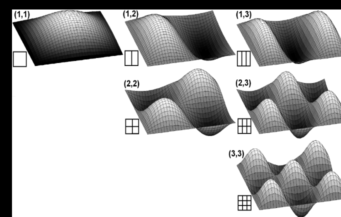
10

Physical/Spatial Mesh/Modal Solutions

Modes of Plates are inharmonic







Center strike **Edge strike**
round = Bessel function roots

Rectangular Plate Modes
= sqrt(i,j) factors

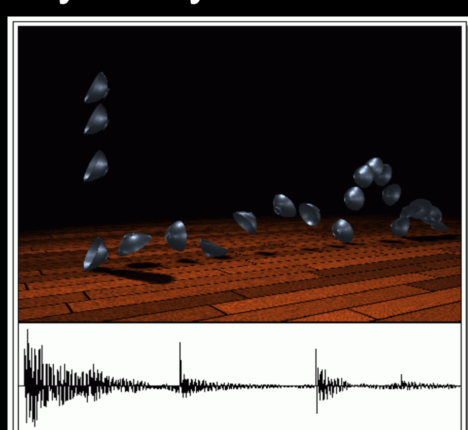
Modes problematic in higher dimensions and also for odd (non-analytical) shapes
(impossible analytically except in very simple cases)

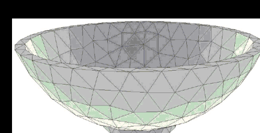
Mesh2D 11

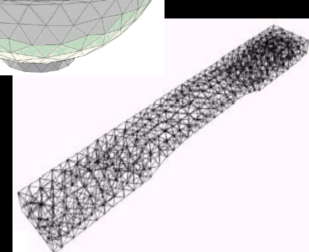
Finite Element Meshes

(SIGGRAPH 01 with O' Brien and Essl)

"Synthesizing Sounds from Physically-Based Motion"



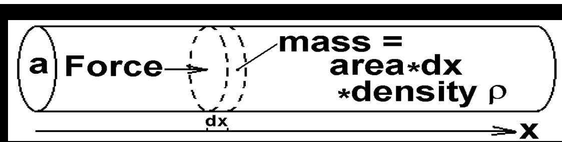




MOVIE

12

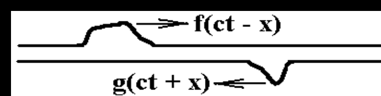
Tubes



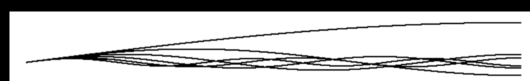
Lansky:
Still Time

- 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



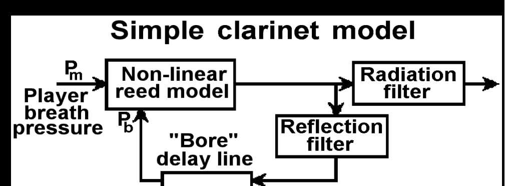
Open + Closed: odd 1/4 wavelengths

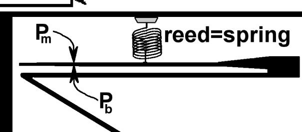
Clar/Flute 13

Tubes and Air Chambers

Wang:
Zelda

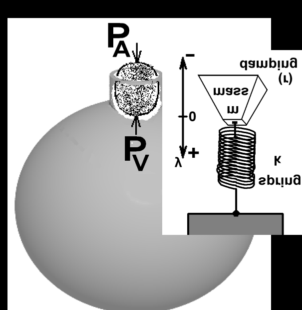
Waveguide tube
(with non-linear "reed")





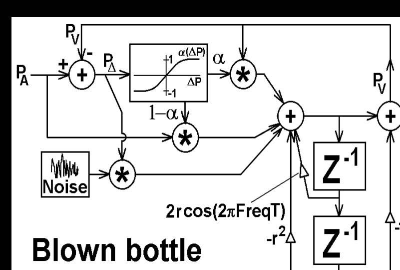
- Bulk Helmholtz Resonator

with non-linear "reed"



pre

Demo
(SMELT)



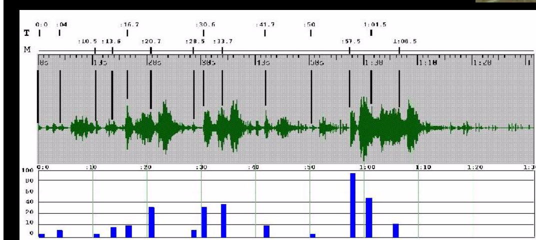
14

Data Driven, Physics-based Sound: "Music for Unprepared Piano"

SIGGRAPH 98

(with Bargar, Choi, Betts (NCSA))

The "Score"



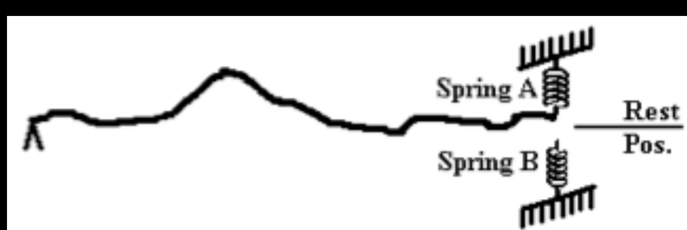
15

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

Sitar

Add spring(s) with position dependent constant

(one spring for positive displacement, another for negative)

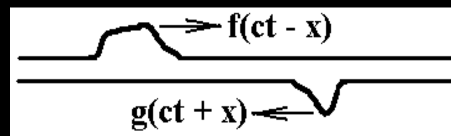


Also for Meshes

Acts to spread spectral components

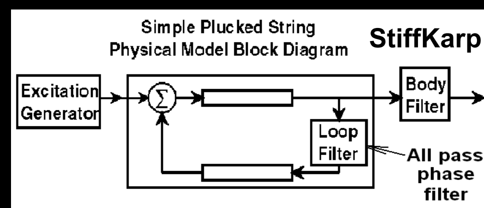
16

D' Alembert (Waveguide) (+ Stiffness)



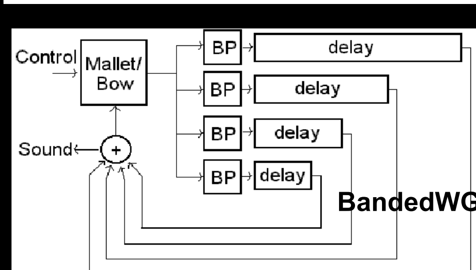
All-pass waveguide (Smith & Jaffe)

- ***Acoustics View: Frequency dependent propagation c(f)***
- ***Filter View: Stretch comb filter harmonics***



Banded waveguides (Essl)

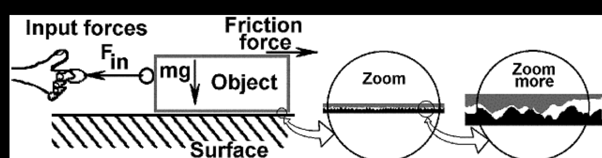
- ***Physical Acoustics: Wave train closures***
- ***Filter View: Comb filters with one modal resonance each***



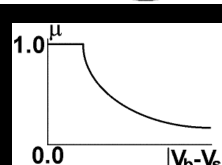
17

Frictional Interactions

- Bow/String Models



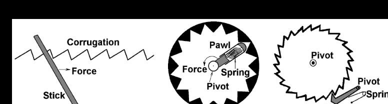
  - friction "curve" m = f (Δv)
  - stick/slip based on Δv



GameTrak *Demo*

Haptic Textures

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

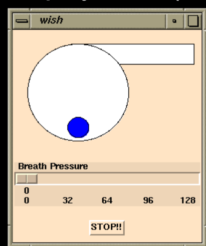


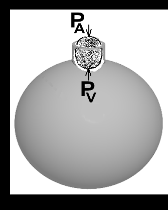
Structured (regular) Friction

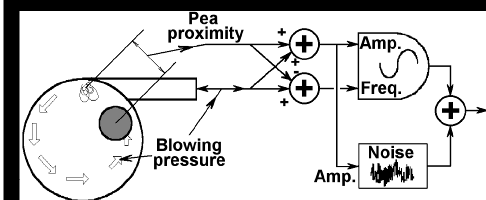
18

Physical Models: Particles

Whistle: Single particle influences physical (or other) oscillator

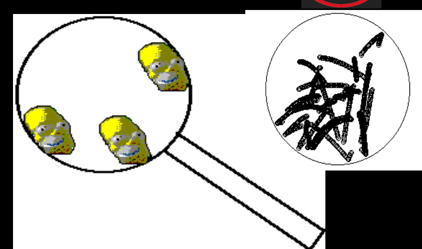






Whistle Demo (SMELT)

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



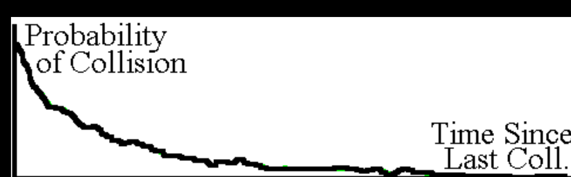
Also good for "flock-like" sounds: applause, rain, birds, etc.

19

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

20

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

21

PhISEM Code Example

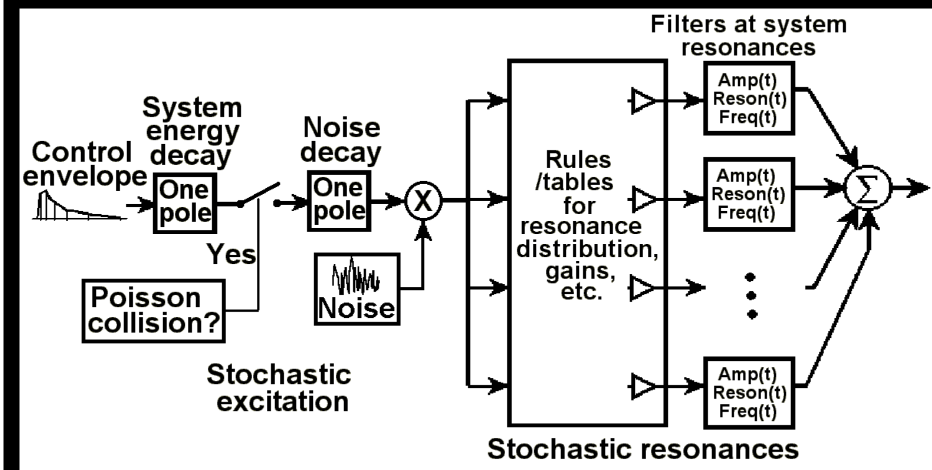
```
#define SOUND_DECAY 0.95
#define SYSTEM_DECAY 0.999

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
```

22

PhISEM: Stochastic Modal Synthesis



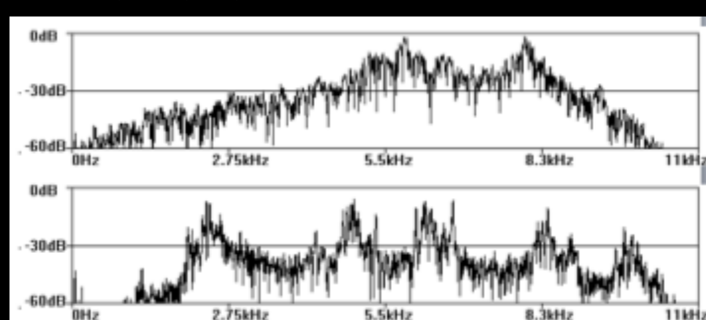
OSC Shaker Demos

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

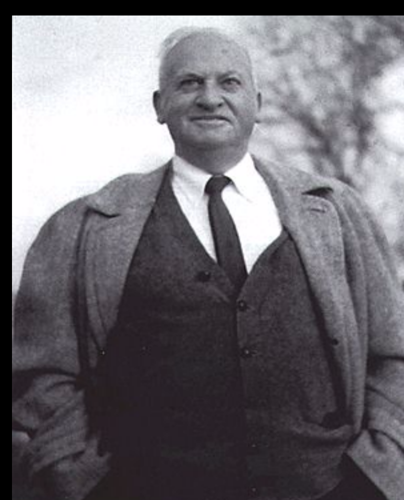
25

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

Physically Oriented Library of Interactive Sound Effects

Interaction sounds, including

Walking!



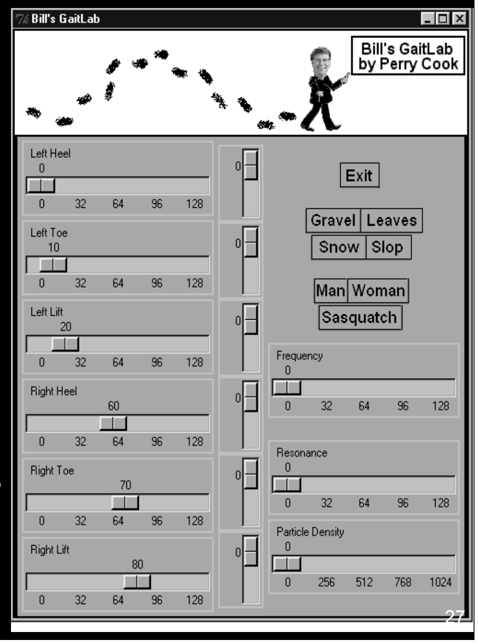
JACK DONOVAN FOLEY

6

Modeling Bill's Gait (AES02)

- Segment sound files
- Extract temporal structure & features
- Do PhISEM analysis
- Resynthesize
- Parametric Synthesis
- ClapLab, Flox, …

Analysis(SysID)?

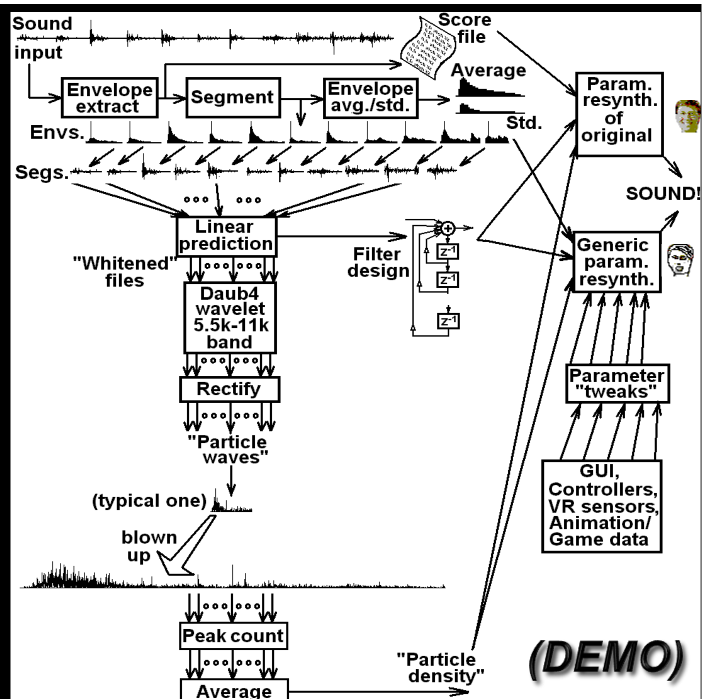


Walking analysis

Identify Filter(s)+ Residue

Wavelets

Count Peaks



Data Driven Sound (PhISM): “Seen in Shadow”

SIGGRAPH 2000

with Grady Klein,
Adam Finkelstein,
Petrovic, Fujito

Music:
Trueman, Mugan

MOVIE

29

PhISM Controllers

PhOLIEMat

Picos

TapShoe

30

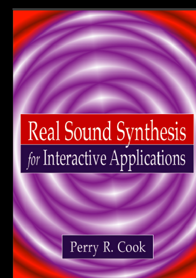
Resources, References, Code

PLOrk:
Take it for Granite

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-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

Book on interactive sound synthesis



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

OTHERS: Sounding Object, DAFX, some SIGGRAPH, other

31

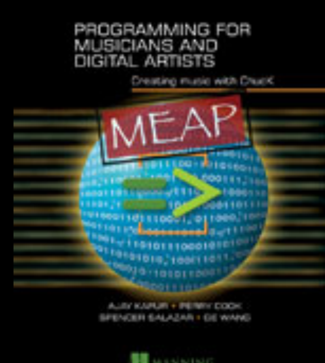
More Resources and References

- **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

Everybody Hack ChucK Tonight!!

ChucK Book!!



Many examples, figures, and open-source code!

32

Upcoming Voice/Tech Book:

www.vocebella.org

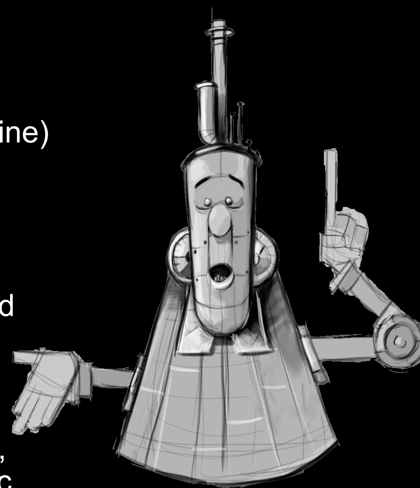
La Bella Voce
et la Macchina

(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.

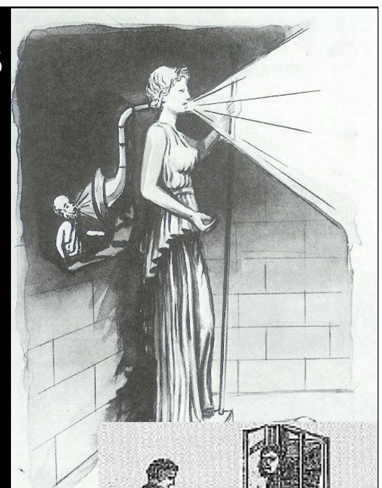


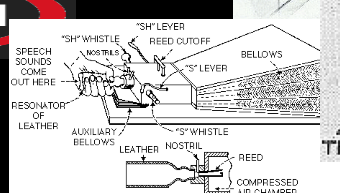
"Steamo"

33

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



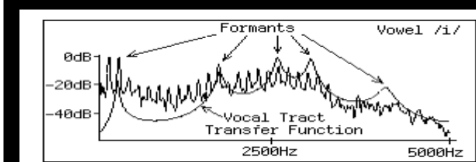


34

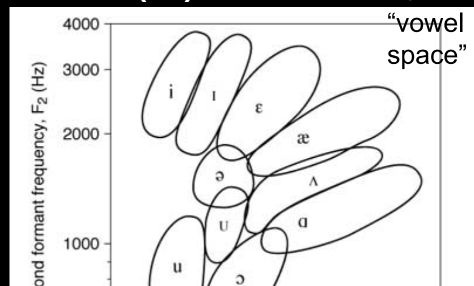
A Note (or 2) on Voices (2)

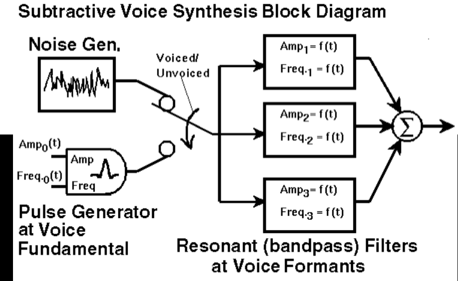
- Rich history of speaking machines
- And controllers for vocal models (Von Kempelen 1791, Faber 1840, Dudley 1939 ++)

- Formant Source/Filter



f1/f2 "vowel space"





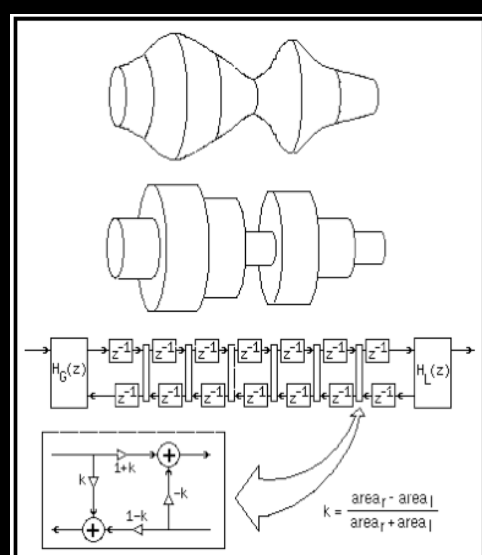
osc DEMO

35

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, ++)



36

Controlling electronic voice synth: Dudley's Voder

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

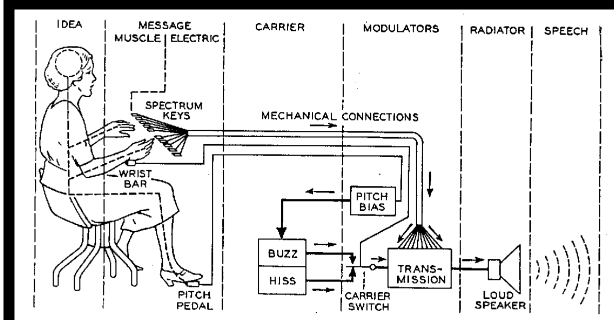
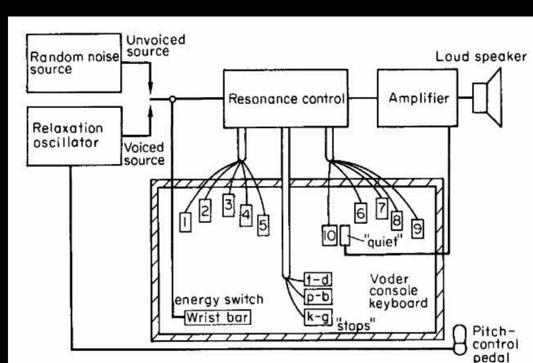


Fig. 8—Schematic circuit of the voder.

37

Voder: Source/Filter Model

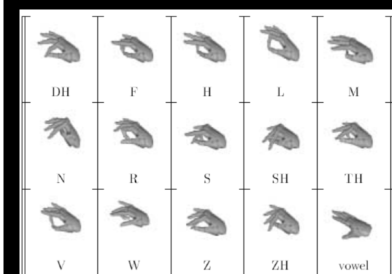
- Noise/Pulse (wrist bar)
- Pitch control (foot pedal)
- Resonances (10 finger sliders)
- Consonant/Stop Presets (thumb buttons)



38

GloveTalk (Fels and Hinton, 1990+)

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



39

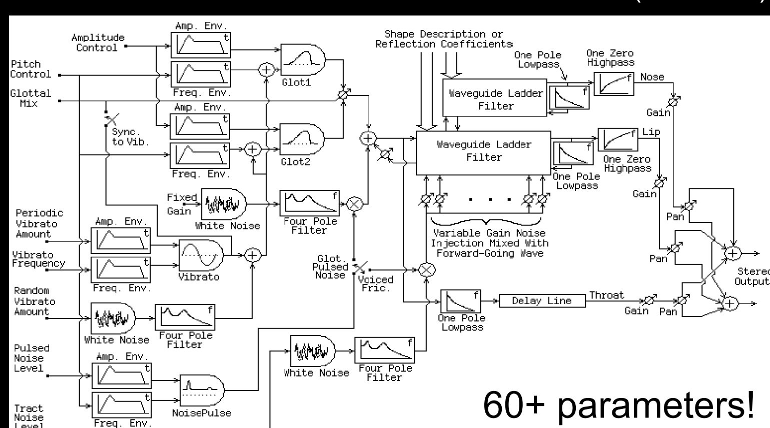
Articulatory (physical) Voice Synth (SPASM)

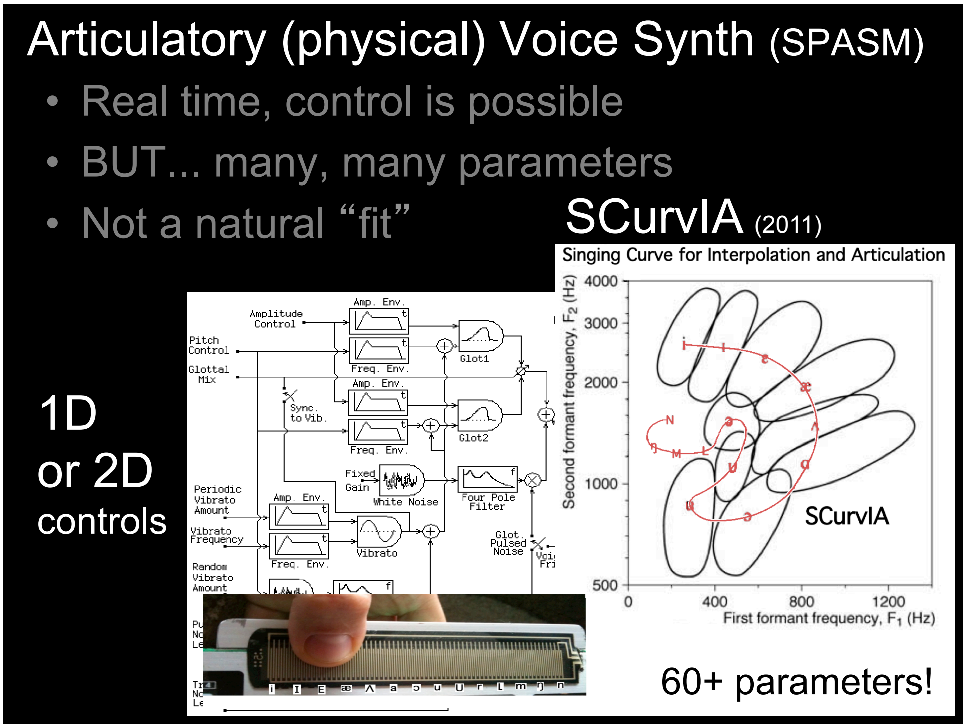
- Real time, control is possible
- BUT... many, many parameters
- Not a natural "fit"

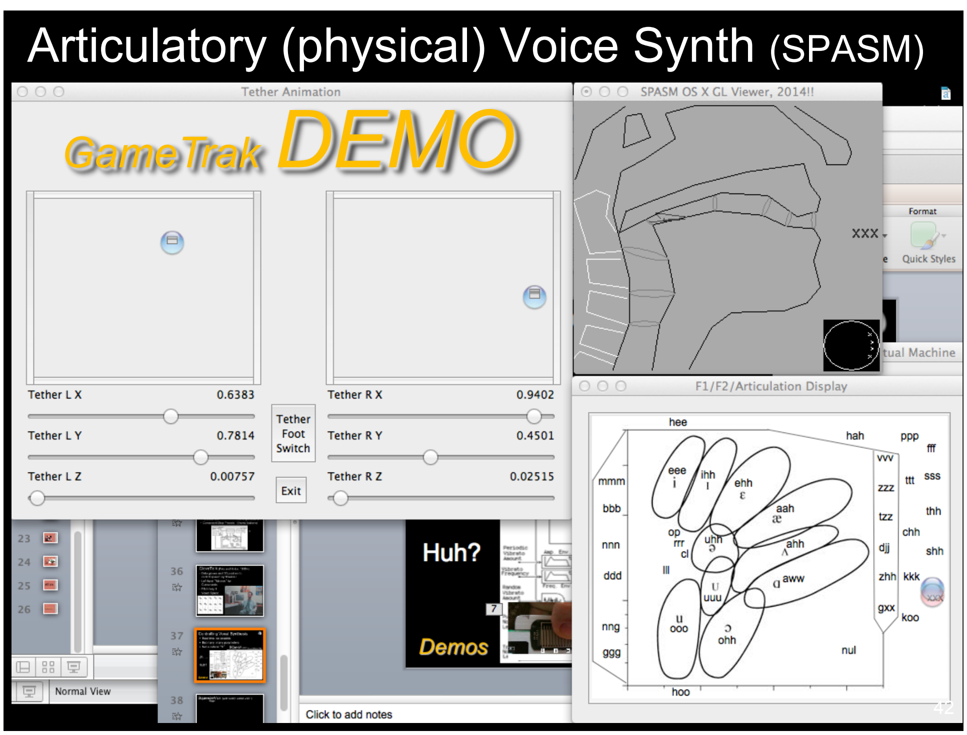
Cook (Shiela '89)

Uh….

Huh?




Articulatory (physical) Voice Synth (SPASM)
• Real time, control is possible
• BUT... many, many parameters
• Not a natural "fit"
SCurvIA (2011)
Singing Curve for Interpolation and Articulation
1D
or 2D
controls
Amplitude Control
Pitch Control
Glottal Mix
Sync. to Vib.
Amp. Env.
Freq. Env.
Glot1
Glot2
Fixed Gain
White Noise
Four Pole Filter
Periodic Vibrato Amount
Vibrato Frequency
Random Vibrato Amount
Vibrato
Glot. Pulsed Noise
Second formant frequency, F2 (Hz)
First formant frequency, F1 (Hz)
SCurvIA
60+ parameters!


Articulatory (physical) Voice Synth (SPASM)
Tether Animation
GameTrak DEMO
Tether L X 0.6383
Tether L Y 0.7814
Tether L Z 0.00757
Tether Foot Switch
Exit
Tether R X 0.9402
Tether R Y 0.4501
Tether R Z 0.02515
SPASM OS X GL Viewer, 2014!!
F1/F2/Articulation Display
hee
hah
eee
ihh
ehh
aah
ahh
aww
uhh
uuu
ooo
ohh
hoo
nul
mmm
bbb
nnn
ddd
nng
ggg
ppp
fff
ttt
sss
thh
chh
shh
zzz
tzz
djj
zhh
kkk
gxx
koo
Huh?
Demos
Click to add notes

SqueezeVox (with Colby Leider 2001)

Maggie

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

Lisa

Maggie

Colby's Bart

43

Physical Models in Performance

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

- Tomie Hahn: Streams

- Shakers/Bamboo + vocal formant filters

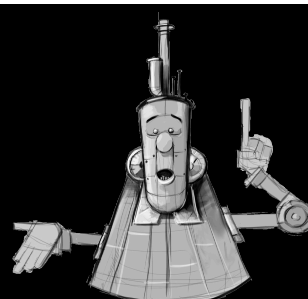
- Pikapika (Tomie Hahn)

Shakers + "Blotar" (non-linear feedback waveguide flute)

44

(PL)Orkestra(s) of the Future!

45



Whew!!!!

46

ACKs

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Princeton SEAS (Maria Klawe**)
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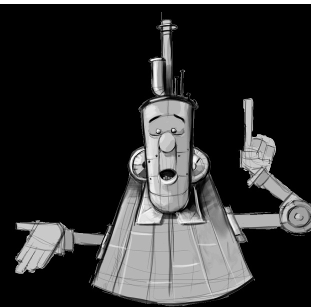
Princeton Sophomore Initiative
Guggenheim Foundation
MacArthur Foundation
Ariel Foundation
David A. Gardner ’69 Magic Fund (Princeton Humanities Council)
Kimberly and Frank H. Moss ’71 Research Innovation Fund (Princeton SEAS).



Props

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

47

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

48

References: Waveguide & FE Modeling

Computer Music Journal, 1992-3, Two Special Issues on Physical Modeling, MIT Press, Vol. 16 No. 4 & Vol. 17 No. 1, Winter 92, Spring 93.

Van Duyne, S. and J. Smith 1993. "Physical Modeling with the 2-D Digital Waveguide Mesh." In Proceedings of the ICMC, Tokyo, pp. 40-47.

J.O. Smith, 1997, "Acoustic Modeling Using Digital Waveguides," in Roads et. al. eds., *Musical Signal Processing*, NL, Swets and Zeitlinger.

Pierce, J. R. and van Duyne, S. A. 1997, A passive non-linear digital filter design which facilitates physics-based sound synthesis of highly nonlinear musical instruments. Journal of the Acoustical Society of America, 101(2): 1120-1126.

Essl, G. and Cook, P., 2000, "Measurements and efficient simulations of bowed bars," Journal of the Acoustical Society of America, 108:1, 379-388.

O'Brien, J.F., Cook, P.R., Essl, G., 2001, "Synthesizing Sound from Physically Based Motion," In Proc. SIGGRAPH 2001, Los Angeles, CA, 529-536, 2001.

49

References: Friction

Siira J. and Pai D.K. 1996, "Haptic Textures, A Stochastic Approach," IEEE International Conference on Robotics and Automation.

Fritz, J.P and Barner K. E. 1996, "Stochastic Models for Haptic Texture," Proceedings SPIE Intl. Symposium on Intelligent Systems and Advanced Manufacturing.

Hayward, V., Armstrong, B. 1999. A new computational model of friction applied to haptic rendering. Preprints of ISER'99 (6th Int. Symp. on Experimental Robotics).

References: Confined Turbulence

Verge, M. 1995. Aeroacoustics of Confined Jets, with Applications to the Physics of Recorder-Like Instruments. Thesis, Technical University of Eindhoven.

Pelorson, X., A. Hirschberg, R. van Hassell, A. Wijnands, and Y Auregan, 1994, "Theoretical and experimental study of quasisteady-flow separation within the glottis during phonation. Application to a two-mass model," Journal of the Acoustical Society of America, 96(6), pp. 3416-3431.

50

References: LPC and Subtractive

Atal, B. 1970. "Speech Analysis and Synthesis by Linear Prediction of the Speech Wave." Journal of the Acoustical Society of America 47.65(A).

Markel, J. and A. Gray, 1976, Linear Prediction of Speech, New York, Springer.

Moorer, A. 1979, "The Use of Linear Prediction of Speech in Computer Music Applications," Journal of the Audio Engineering Society 27(3): pp. 134-140.

Rabiner, L. 1968. "Digital Formant Synthesizer" Journal of the Acoustical Society of America 43(4), pp. 822-828.

Klatt, D. 1980. "Software for a Cascade/Parallel Formant Synthesizer," Journal of the Acoustical Society of America 67(3), pp. 971-995.

Carlson, G., Ternström, S., Sundberg, J. and T. Ungvary 1991. "A New Digital System for Singing Synthesis Allowing Expressive Control." Proc. of the International Computer Music Conference, Montreal, pp. 315-318.

Kelly, J., and C. Lochbaum. 1962. "Speech Synthesis." Proc . Fourth Intern. Congr. Acoust. Paper G42: pp. 1-4.

Cook, P. 1992. "SPASM: a Real-Time Vocal Tract Physical Model Editor/Controller and Singer: the Companion Software Synthesis System," Computer Music Journal, 17: 1, pp. 30-44.

51

References: Modal Synthesis

Rossing, T. 2000, *The Science of Percussion Instruments*, World Scientific, Singapore.

Serra, X. 1986. "A Computer Model for Bar Percussion Instruments," Proc. ICMC, The Hague, pp. 257-262.

Wawrzynek, J. 1989. "VLSI Models for Sound Synthesis," in Current Directions in Computer Music Research, M. Mathews and J. Pierce Eds., Cambridge, MIT Press.

Adrien, J.M. 1991, "The Missing Link: Modal Synthesis", in: G. De Poli, A. Picalli, and C. Roads, eds. Representations of Musical Signals. MIT Press, Cambridge, MA.

Doutaut V. & A. Chaigne 1993. "Time Domain Simulations of Xylophone Bars," Stockholm Music Acoustics Conference, pp. 574-579.

Larouche, J. & J. Meillier 1994. "Multichannel Excitation/Filter Modeling of Percussive Sounds with Application to the Piano," IEEE Trans. Speech and Audio, pp. 329-344.

P. Cook 1997, "Physically Inspired Sonic Modeling: (PhISM): Synthesis of Percussive Sounds," Computer Music Journal, 21:3 (expanded from ICMC 1996).

K. Van den Doel and D. Pai, "Synthesis of Shape Dependent Sounds with Physical Modeling," Proc. Intl. Conference on Auditory Display, Santa Clara, CA, 1997.

K. van den Doel, P. G. Kry and D. K. Pai, 2001, "FoleyAutomatic: Physically-based Sound Effects for Interactive Simulation and Animation,'' in *Computer Graphics (ACM SIGGRAPH 2001 Conference Proceedings)*.

O'Brien, J. F., Shen, C., Gatchalian, C. M., 2002, "Synthesizing Sounds from Rigid-Body Simulations." *ACM SIGGRAPH Symposium on Computer Animation*.

52

References: Sinusoidal Models

Dudley, H. 1939, "The Vocoder," Bell Laboratories Record, December.

Moorer, A. 1978. "The Use of the Phase Vocoder in Computer Music Applications." Journal of the Audio Engineering Society, 26 (1/2), pp. 42-45.

Dolson, M. 1986, "The Phase Vocoder: A Tutorial," CMJ, 10 (4), pp. 14-27.

Robert J. McAulay and Thomas Quatieri 1986, "Speech Analysis/Synthesis Based on a Sinusoidal Representation," IEEE Trans. ASSP-34, pp. 744-754.

Xavier Serra, 1989, "A System for Sound Analysis/Transformation/Synthesis Based on a Deterministic Plus Stochastic Decomposition," Ph.D. dissertation, Dept. of Music, Stanford University, Stanford CA.

Kelly Fitz, Lippold Haken, and Bryan Holloway,1995, "Lemur - A Tool for Timbre Manipulation ," Proc. Intl. Computer Music Conf.

Adrian Freed, Xavier Rodet, and Phillipe Depalle 1993, "Synthesis and Control of Hundreds of Sinusoidal Partials on a Desktop Computer without Custom Hardware," Proc. ICSPAT.

T. Verma, T. Meng, 1998 "An Analysis/Synthesis Tool for Transient Signals that Allows a Flexible Sines+Transients+Noise Model for Audio," 1998 IEEE ICASSP-98. Seattle, WA.

SMS Web site. URL:http://www.iua.upf.es/~sms.

53

Refs: PhISEM, Wavelets, Grains

Rodet, X. 1984. "Time-Domain Formant-Wave-Function Synthesis," Computer Music Journal 8 (3), pp 9-14.

Roads, C. 1991. "Asynchronous Granular Synthesis" In G. De Poli, A. Piccialli, and C. Roads, eds. 1991. Representations of Musical Signals. Cambridge, Mass: The MIT Press, pp. 143-185.

C. Cadoz, A. Luciani and J. Florens, 1993, "CORDIS-ANIMA: A Modeling and Simulation System for Sound Image Synthesis-The General Formalization" Computer Music Journal, Vol. 17, No. 1, pp. 21 - 29.

P. Cook, 1997, "Physically Inspired Sonic Modeling: (PhISM): Synthesis of Percussive Sounds," Computer Music Journal, 21:3.

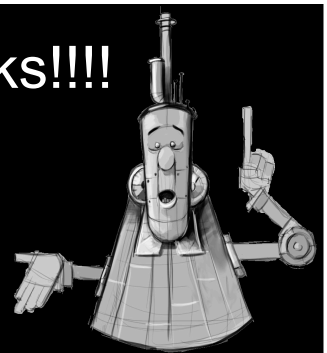
N. Miner, 1998, Creating Wavelet-based Models for Real-time Synthesis of Perceptually Convincing Environmental Sounds, Ph.D. Diss., Univ. New Mexico.

M. Casey, 1998, Auditory Group Theory with Applications to Statistical Basis Methods for Structured Audio, Ph.D. Dissertation, MIT Media Lab.

S. Dubnov, Z. Bar-Joseph, R. El-Yaniv, D. Lischinski, M. Werman, 2002, "Synthesizing Sound Textures Through Wavelet Tree Learning," *IEEE CG&A special issue on "Virtual Worlds, Real Sounds,"* 22(4).

54

The End: Thanks!!!!



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)

55