Physics-Based Sound Synthesis Introduction/Overview

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TODAY

1. The role of ‘Physics’ in Sound Synthesis
2. Overview of Resonator Modelling Paradigms
3. Some Examples
4. Course Overview
5. Introduction to Matlab

1. THE ROLE OF PHYSICS IN SOUND SYNTHESIS

- Modelling “Acoustic Sound”
- Physical Modelling Features
- Phycics and Perception
- Physical Model Applications
- Physical Model Definitions, Structure, Procedure

Abstract versus Natural Sound, Historically

artificial/
abstract

natural/
acoustic

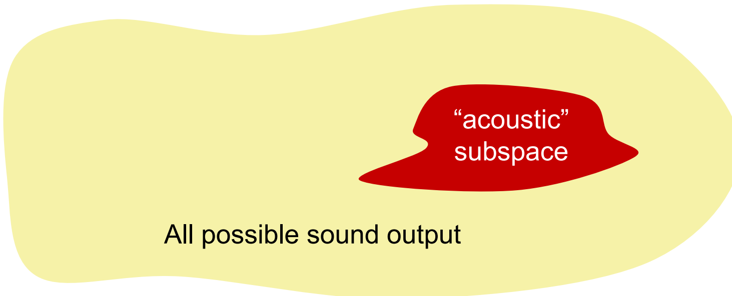
“perceptual continuum”

Mathetical model (Additive, FM)	Sampling/recording + transformation (filtering, modulating)
Elementary wavevorms (sine, block)	acoustically produced sound
Elektronische Musik Koln	Musique Concrete Paris

“Kontakte” (Stockhausen, 1960)

Can models be made to sound natural/acoustic?

Constraining the sonoric output to an “acoustic” subspace that matches with natural sounding systems.

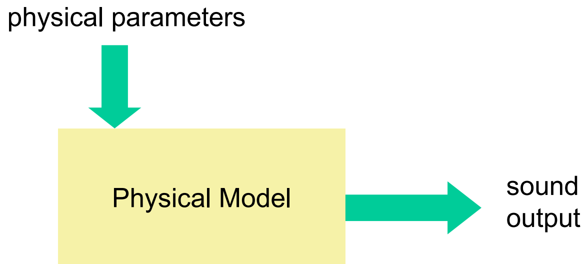


Answer 1: Analysis / Re-Synthesis

recorded sound → (analysis) → model parameters → (re-synthesis) → synthesised sound

Additive:	(FFT)	frequencies amplitudes phases	(identity property)
FM:		carrier freq modulation freq modulation index	

Answer 2: Physical Modelling



- Formulates a causal relationship between audio and the physical parameters that constrain and drive it
- Mimics behaviour of natural sound sources

Physical Modelling: Main Advantages

- Output is (within certain limits) restricted to ‘acoustic, natural’ output. (quality depends on accuracy of physical model).
- Control parameters are intuitive.
- Dynamic parameter control generates realistic dynamic output (for example, fast transients).
- Knowledge of physics of vibrating systems can be used to build and develop models.

Physical modelling: Main Disadvantages

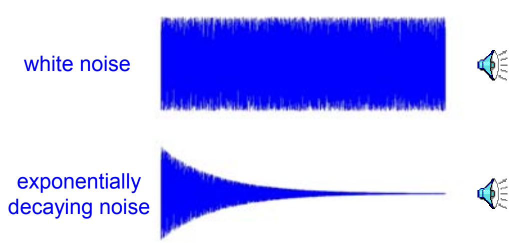
- Precise models for high-quality synthesis are usually computationally expensive.
- Models tend to require some understanding of physics from the user. User interface can still be a problem.
- Parameter estimation is often difficult, no uniform methods for analysis are available.

Perceiving Physical Properties/Behaviour

Can we perceive physical properties or behaviour from **sound**?

Experiment:

Free, linear system vibrations decay exponentially



Physical and Perceptual Parameters

input-side:

physical parameters

driving, propagating, reflecting, resonating, constraining, production

Physical Model

output-side:

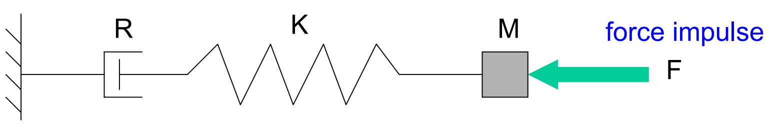
perceptual parameters

audible sound, listening, experiencing

What causes the sound?

What does it sound like?

Example: Driven Harmonic Oscillator



physical level:

$$M\frac{d^2y}{dt^2}+R\frac{dy}{dt}+Ky=F$$

$M=$ mass

$R=$ damping

$K=$ stiffness

perceptual level:

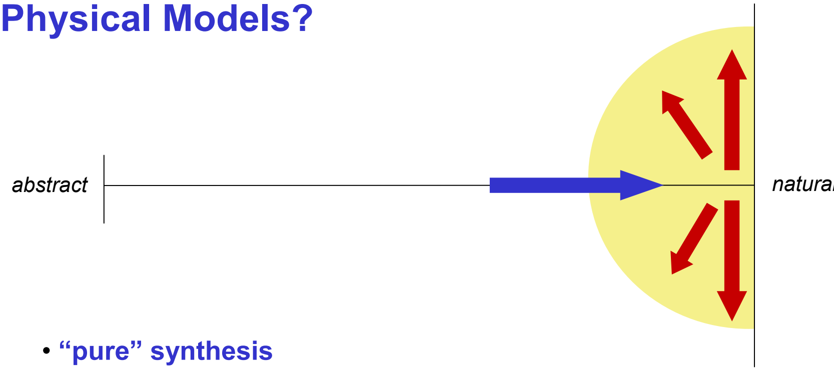
$$\frac{d^2y}{dt^2}+2\alpha\frac{dy}{dt}+\omega_0^2 y=A\,F$$

$\omega_0=\sqrt{\frac{K}{M}}=$ resonance frequency

$\alpha=\frac{R}{2M}=$ decay rate

$A=\frac{1}{M}=$ amplitude

So what can we do with Physical Models?



- **"pure" synthesis**
  (better "presets", novel virtual instruments)

- **analysis/re-synthesis**

  (physical parameterisation of recorded sound)

A Strict Definition of a Physical Model

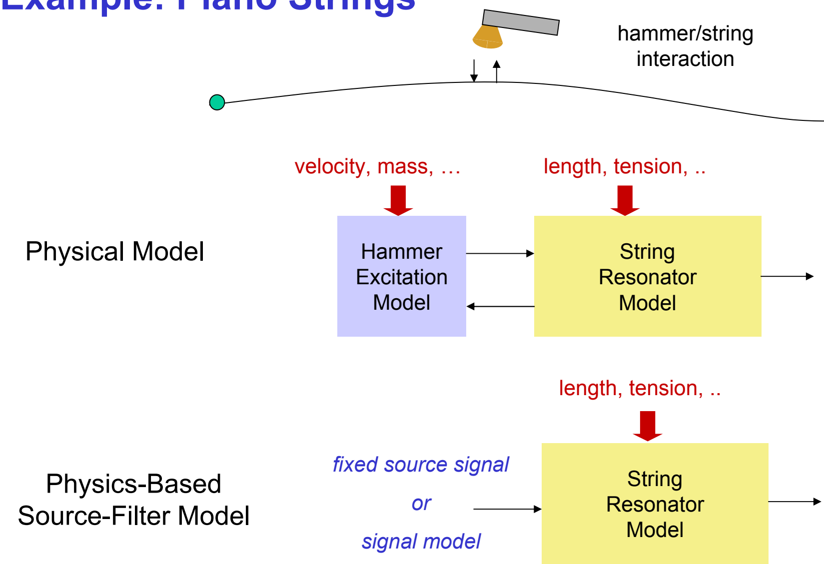
A model is called **physical** if:

- all model equations are based on physical laws.
- all model parameters are physical
  (except numerical parameters such as the sample rate).
- all parameters are parameters, not variables that fluctuate at the same rate as the oscillations produced.

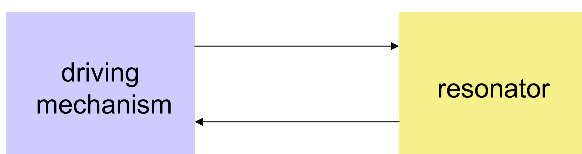
If these are not strictly met, one tends to speak of:

- a **physics-based** model
- a **physically-informed** model
- a **physically-inspired** model

Example: Piano Strings



Excitation



Impulsive excitation:	plucking a string mallet impact	guitar string + body xylophone bar
sustained excitation	bowing a string reed blowing	violin string + body woodwind bore
many-particle interaction		e.g. maracas shell

General Derivation Procedure

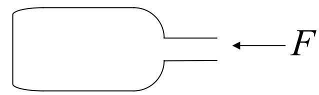
Acoustic Theories

simplifications ↓

Acoustic Model

discretisation ↓

Discrete-Time Model



Helmholz resonator

$$M\frac{d^2y}{dt^2}+R\frac{dy}{dt}+Ky=F$$

e.g., impulse-invariant method

$$y_{n+1}=b_1F_n+a_1y_n+a_2y_{n-1}$$

2.Overwiew of Resonator Modelling Paradigms

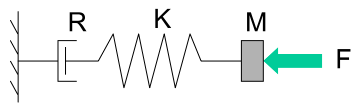
- Mass-Spring-Damper / Finite Elements
- Finite Differences
- Wave-Based Approach
- Modal Synthesis

Resonators: Linear Systems

simulating resonators = solving physical equations numerically

LUMPED: one point in space, and time: ODE

$$M\frac{d^2y}{dt^2}+R\frac{dy}{dt}+Ky=F$$

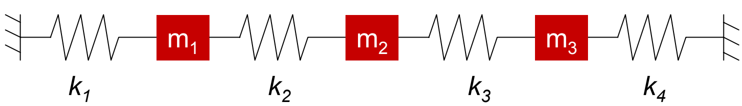


mass-spring-damper

DISTRIBUTED: space and time: PDE

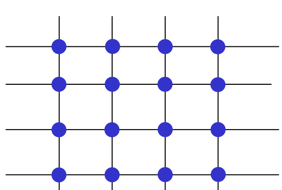
$$\frac{\partial^2 y}{\partial x^2}=\frac{1}{c^2}\frac{\partial^2 y}{\partial t^2}$$

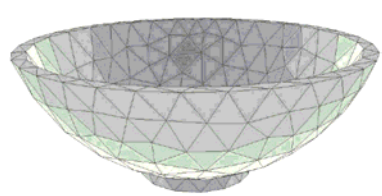
Mass-Spring-Damper Systems / Finite Elements (FE)



$$\begin{bmatrix} m_1 & 0 & 0 \\ 0 & m_2 & 0 \\ 0 & 0 & m_3 \end{bmatrix}\begin{Bmatrix} \ddot{x}_1 \\ \ddot{x}_2 \\ \ddot{x}_3 \end{Bmatrix}+\begin{bmatrix} (k_1+k_2) & -k_2 & 0 \\ -k2 & (k_2+k_3) & -k3 \\ 0 & -k3 & (k_3+k_4) \end{bmatrix}\begin{Bmatrix} x_1 \\ x_2 \\ x_3 \end{Bmatrix}=\begin{Bmatrix} F_1 \\ F_2 \\ F_3 \end{Bmatrix}$$

higher dimensional topologies



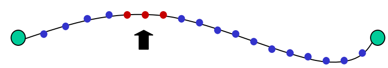


Transformation to global coordinates: Finite Element Method (FEM)

Finite Differences (FD)

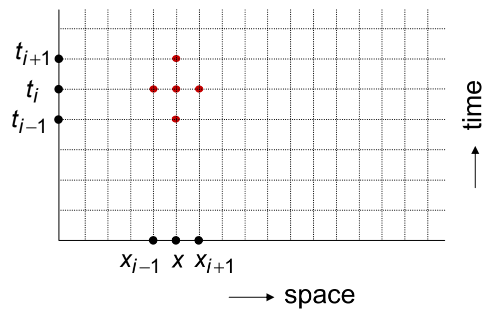
Approximating derivatives with a weighted combination of space-time grid-point values

$$\frac{\partial^2 y}{\partial x^2} = \frac{1}{c^2}\frac{\partial^2 y}{\partial t^2}$$



$$\left[\frac{\partial^2 y}{\partial x^2}\right]_i^n \approx \frac{y_{i+1}^n - 2y_i^n + y_{i-1}^n}{\Delta x^2}$$

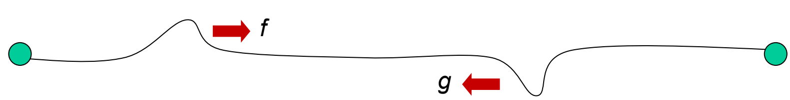
$$\left[\frac{\partial^2 y}{\partial t^2}\right]_i^n \approx \frac{y_i^{n+1} - 2y_i^n + y_i^{n-1}}{\Delta t^2}$$



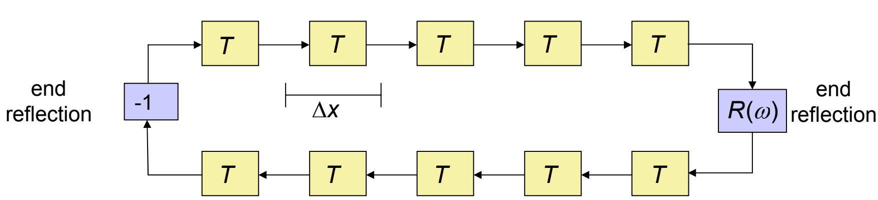
Travelling Waves

Travelling wave solution (d'Alembert, 1747):

$$y(x,t) = y^+(x,t) + y^-(x,t) = f(ct+x) + g(ct-x)$$

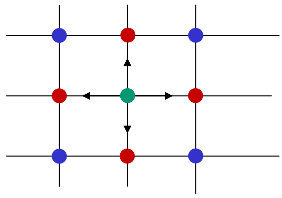


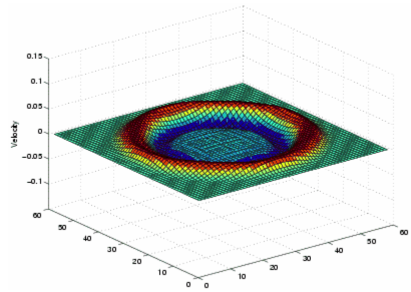
Sample travelling waves : $\Delta x = cT$ **(Digital Waveguide)**



Travelling Waves 2D/3D: Waveguide Meshes

2D Mesh



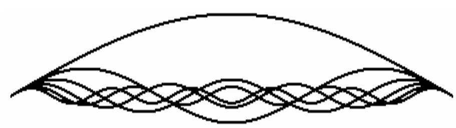


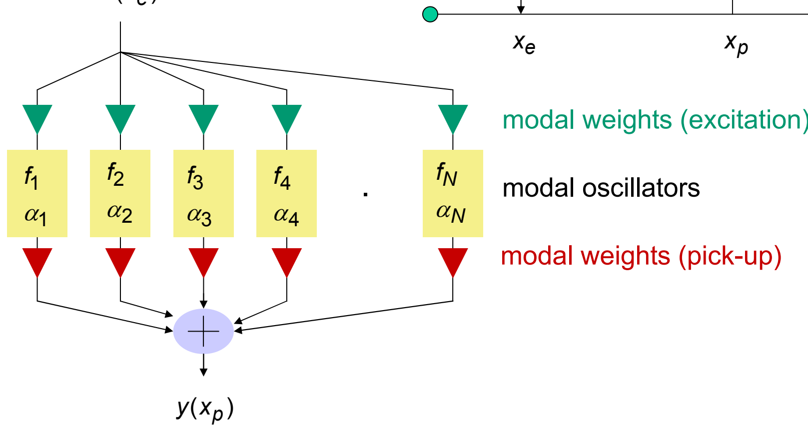
Wave Digital Models & Networks

- Decomposition into ‘non-physical’ wave variables
- choose `port-resistance’ to avoid delay-free loops
- Great for lumped elements (for example, toneholes)
- Multi-dimensional WD networks (Bilbao)

Modal Synthesis

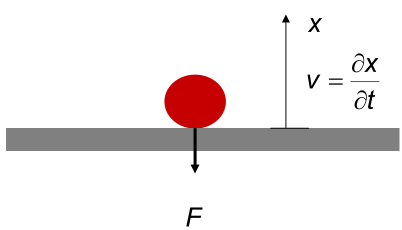
Decomposition into **modes of vibration** (natural resonances)





3.Some Examples

[EXAMPLE:] Impulsive Excitation Of Objects



Contact laws:

$$F = \begin{cases} -kx^{\alpha} - \lambda x^{\alpha} v & x > 0 \\ 0 & x \leq 0 \end{cases}$$

Musical Instrument Example:

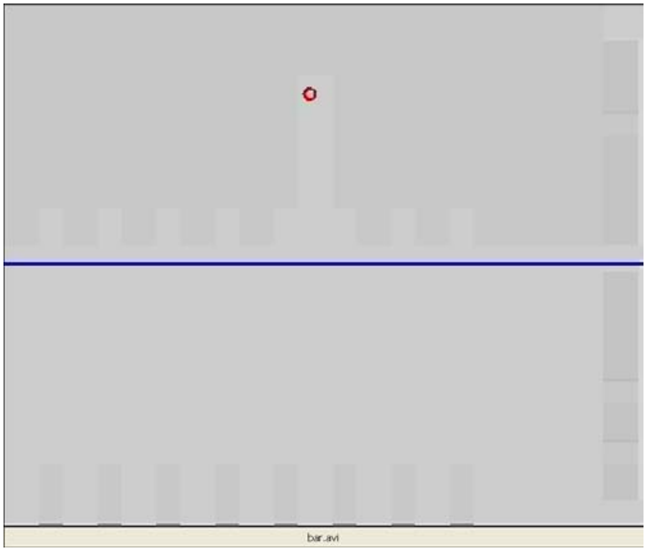
Metal bar mallet strikes rubber mallet wooden mallet

(Finite Difference Model)

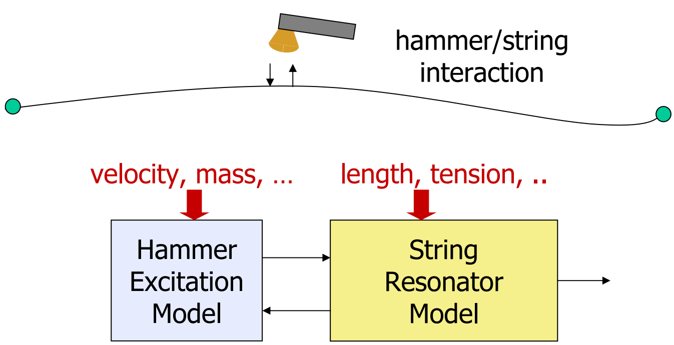
Environmental Sound Example:

Bouncing/colliding objects falling mass

(Modal Synthesis)



[EXAMPLE:] Piano/Hammer Interaction



Increasing striking velocity (Bank, 1999):

(Digital Waveguide Model)

[EXAMPLE:] Brass Instrument Tones

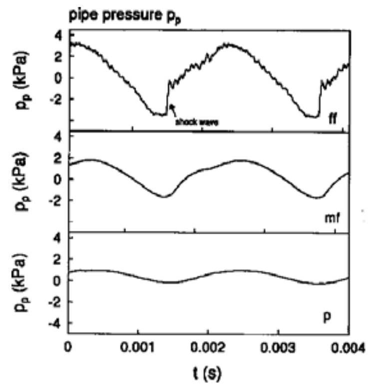
Non-Linear Wave Propagation in Acoustics Tubes:

Non-linear acoustic wave propagation occurs in many brass instrument air columns at high dynamic playing levels.

Trombone simulation
(Msallam,2000)

Linear wave propagation

Non-linear wave propagation



Pressure levels in trombones for different blowing pressures.
(Hirschberg et al, 1995)

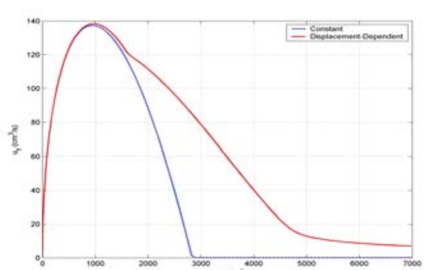
[EXAMPLE:] Woodwind Instruments

Modelling includes:

- Wave propagation in acoustic bore, including toneholes.
- Reed Excitation mechanism.

Clarinet simulation (1994)

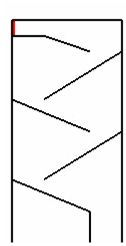
(Digital Waveguide Model)



Clarinet Reed: Flow vs Pressure Drop

[EXAMPLE:] Interacting Particles

- Shakers
- Water (rain, river, snow)
- Surface texture interaction
- Group interaction (flocking birds, crowd noises)



Related to:

- Discrete-event modelling
- Granular Synthesis

Synthesis by physically-informed stochastic parameters

Physically-Inspired Stochastic Event Modelling (PhISEM) (Cook, 1997)

Large simulation of many particles interacting between themselves and the wall of a 'container'

statistics collection

PhISEM Synthesizer

4. COURSE OVERVIEW

Week	Session	Lectures	Topics	Tutorials
A	1	Introduction	Concepts in physics-based synthesis. Course Overview, Introduction to Matlab	X
B	2	Math Review	Complex Numbers, Differentiation	X
C	3	Vibration of Point Masses	Newton's laws, one-mass systems differential equation, resonance, damping, two-mass systems, normal modes	X
D	4	Discretisation of the Harmonic Oscillator	Finite differences, impulse-invariant method, stability, discretisation artefacts	X
E	*ASSIGNMENT 1*			
F	5	Vibration of Strings and Membranes	Wave equation & solutions for transversal motion in ideal strings & rectangular membranes, modal synthesis.	X
G	6	Finite Difference Simulation	Finite difference method, simulation of strings, 2D mesh.	X
H	*ASSIGNMENT 2*			
I	7	Wave-Based String Instrument Synthesis	Digital Waveguide Modelling, Commuted Synthesis, SDL string model	X
J	8	DSP Elements in Max/MSP	Filters & delay lines, SDL	X
K	*ASSIGNMENT 3*			