Physics–Based Sound Synthesis for Graphics and Interactive Systems

Section Slides

James F. O'Brien
University of California, Berkeley

SIGGRAPH 2003
SAN DIEGO

Research Collaborators

Perry R. Cook (Princeton)
Georg Essl (University of Florida)
Christine M Gatchalian (U.C. Berkeley)
Kris K. Hauser (U.C. Berkeley)
Chen Shen (U.C. Berkeley)

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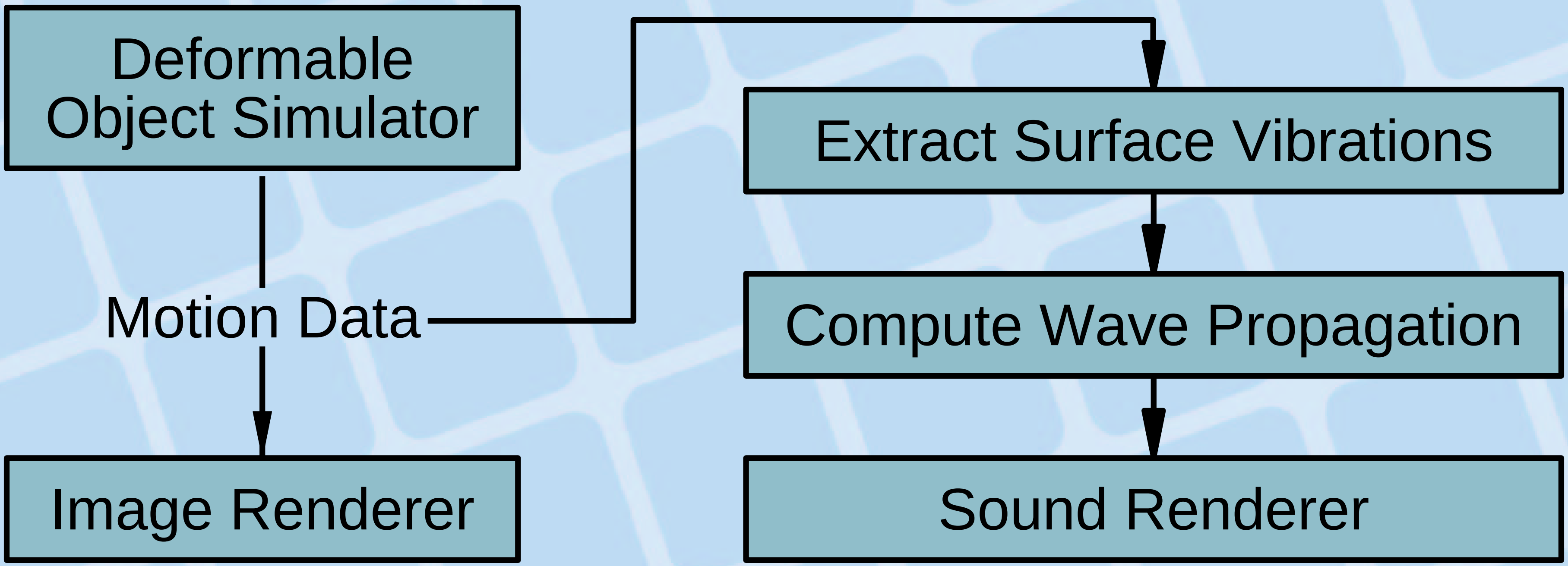
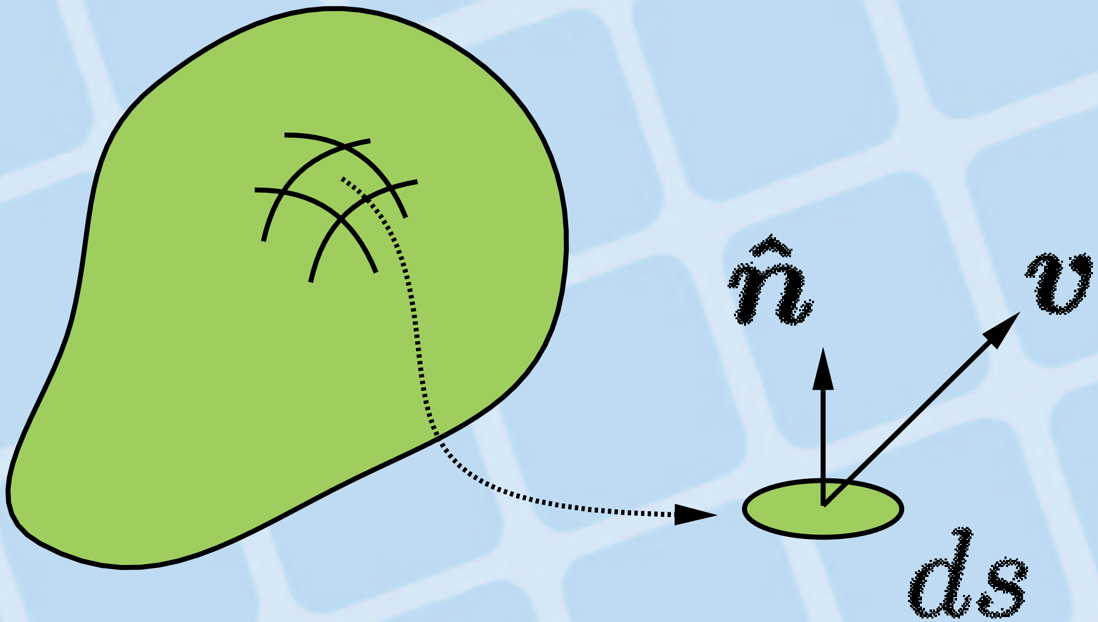
Surface Vibrations and Sound



Surface Vibrations

- **Relate surface movement to pressure**

$$p = z\boldsymbol{v} \cdot \hat{\boldsymbol{n}}$$



$$z = \rho c = 415\,\mathrm{Pa} \cdot \mathrm{s/m}$$

Specific acoustic impedance

- **Approximate p as const. over triangles**

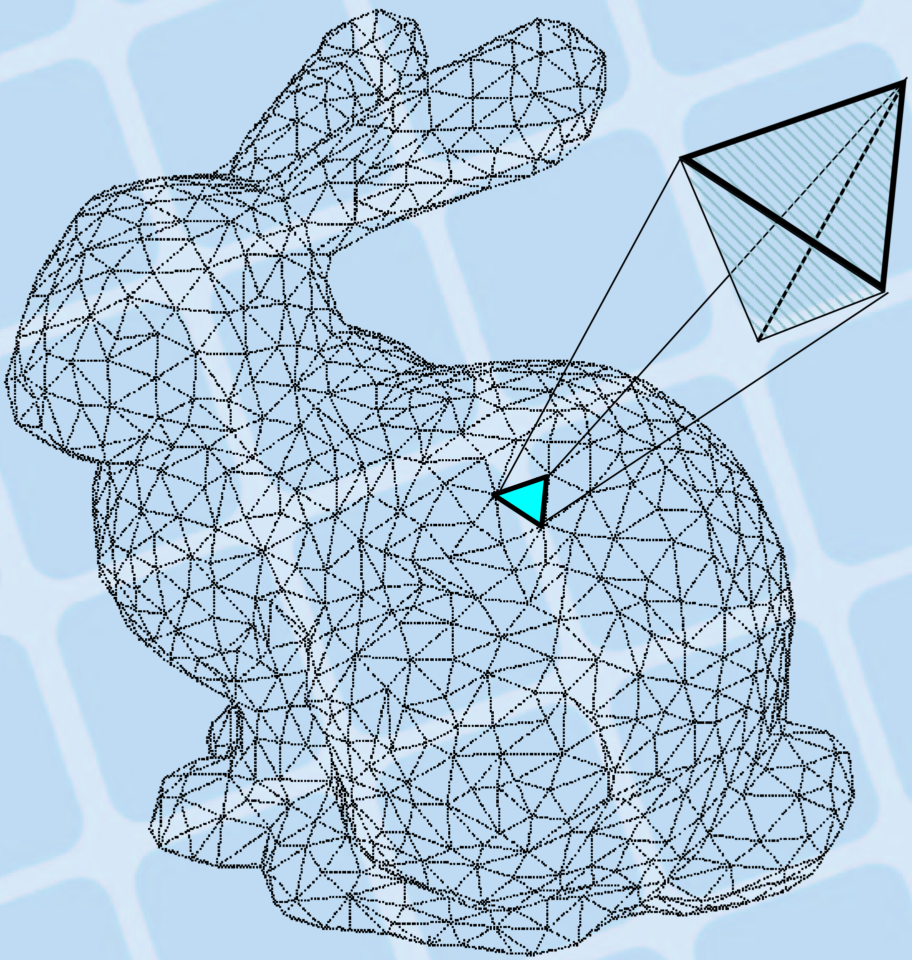
Simulation Requirements

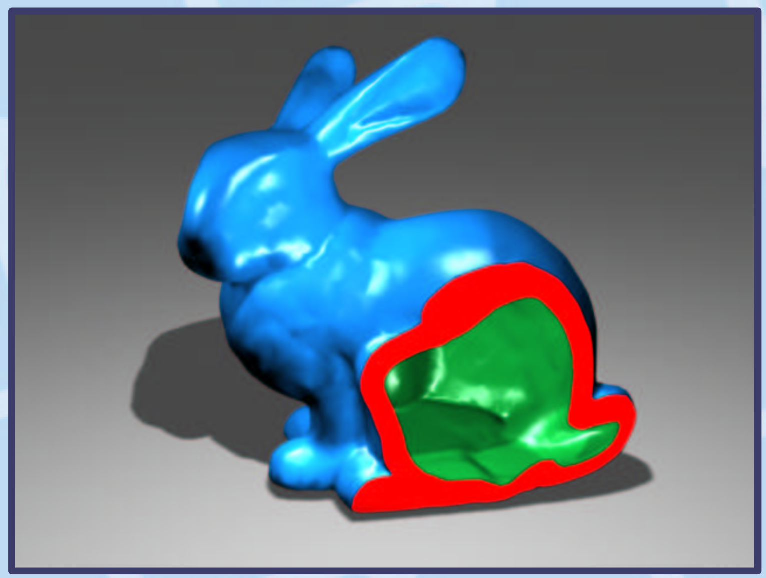
- Temporal Resolution
- Dynamic Deformation Modeling
- Boundary Representation
- Physical Realism

Simulation Method

- Tetrahedral Finite Elements
  - Linear basis functions
  - Green's Strain
    (non−linear, finite deformation)
  - Rayleigh Damping
  - Explicit time integration
  - Details in O'Brien & Hodgins (SIGGRAPH 99)

Object Model





Surface Vibrations

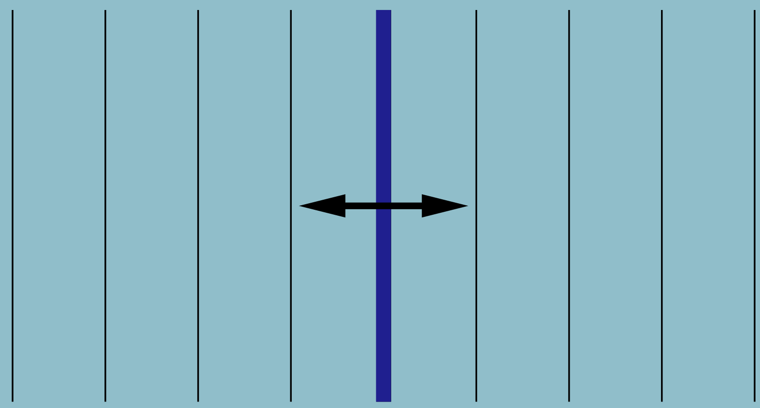
- For each triangle, band−pass filter to remove info outside audible range
  - Low−pass with windowed sinc function
  - High−pass with DC−Blocking filter
- Result: pressure as piece−wise const function over the surface(s)

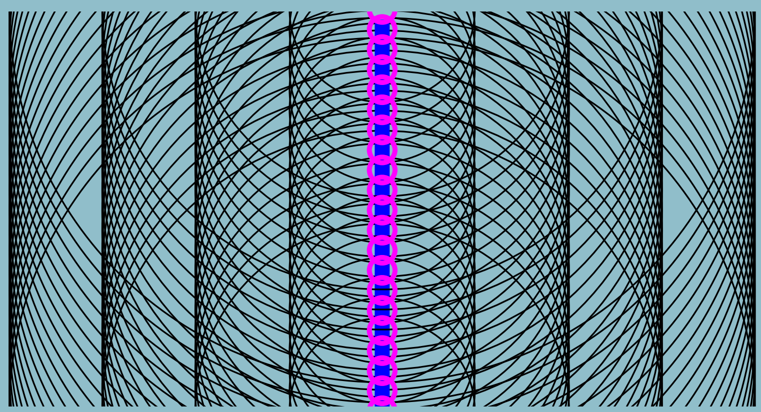
Radiation and Propagation

- Ignore reflection and diffraction
- Account for visibility
- Account for distance falloff

Radiation and Propagation

- **Model wavefront as sum of simple waves from each triangle (Huygen's principle)**





- **Simple wave for each triangle face (vibrating piston)**

Radiation and Propagation

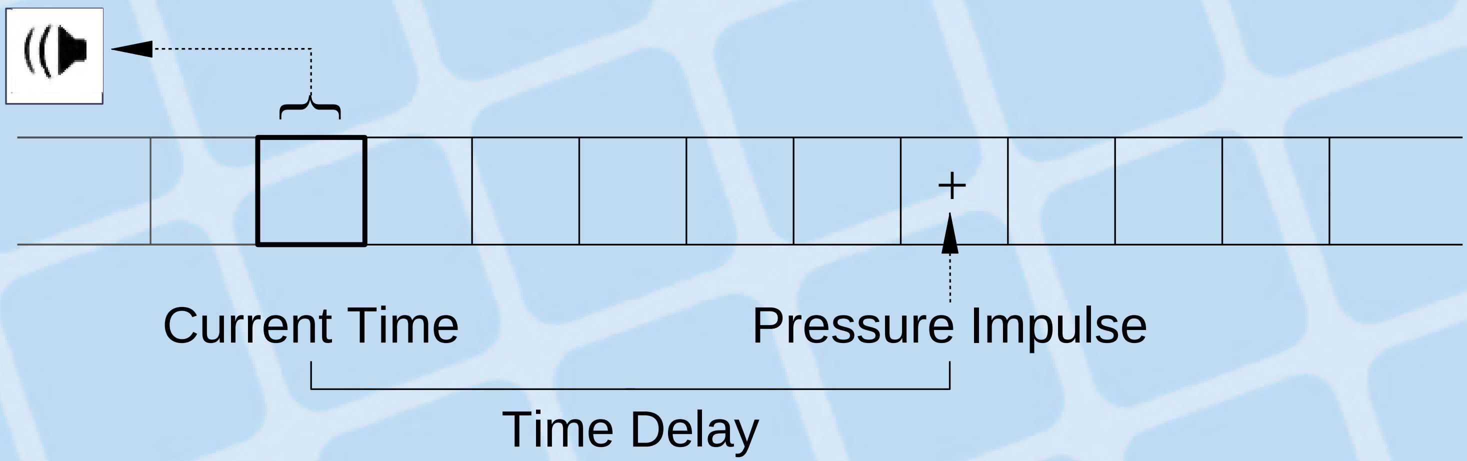
$$s = \frac{\tilde{p}\, a\, \delta_{\bar{x} \rightarrow r}}{\| \bar{\boldsymbol{x}} - \boldsymbol{r} \|} \cos(\theta)$$

- Signal at receiver
- Filtered pressure over triangle
- Area of triangle
- Visibility term
- Approximation of beam pattern
- Distance falloff

Radiation and Propagation

- **Account for travel time**

$$d = \frac{\|\bar{x} - r\|}{c}$$



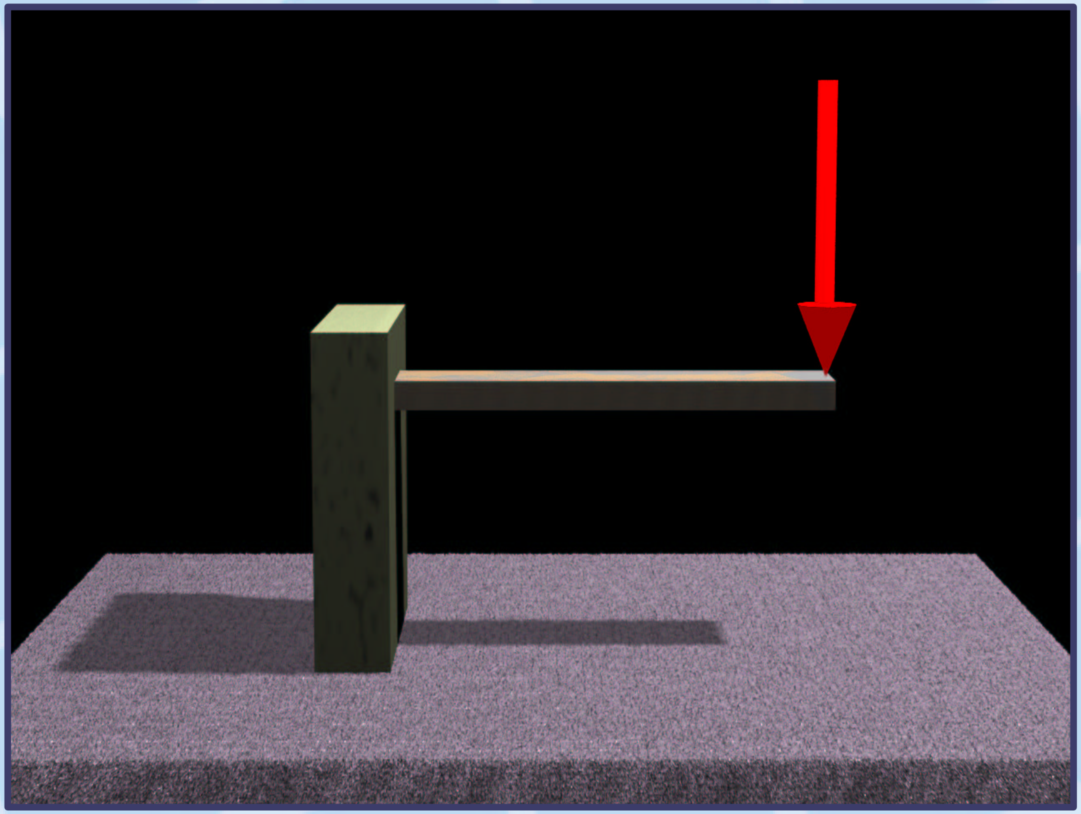
- **"Splat" into accumulation buffer**

Results

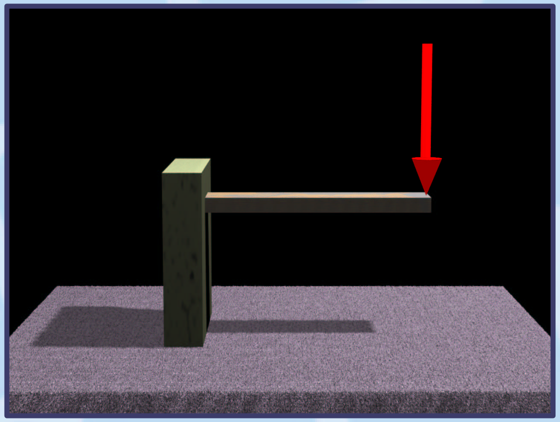
- Stereo from two listener locations
- Omni−directional receivers
- Located at rendering viewpoint
- 20 cm separation perpendicular to viewing and up directions
- 44.1 K Hz audio rate
- Simulation time−step between 10^{-5} and 10^{-7} seconds

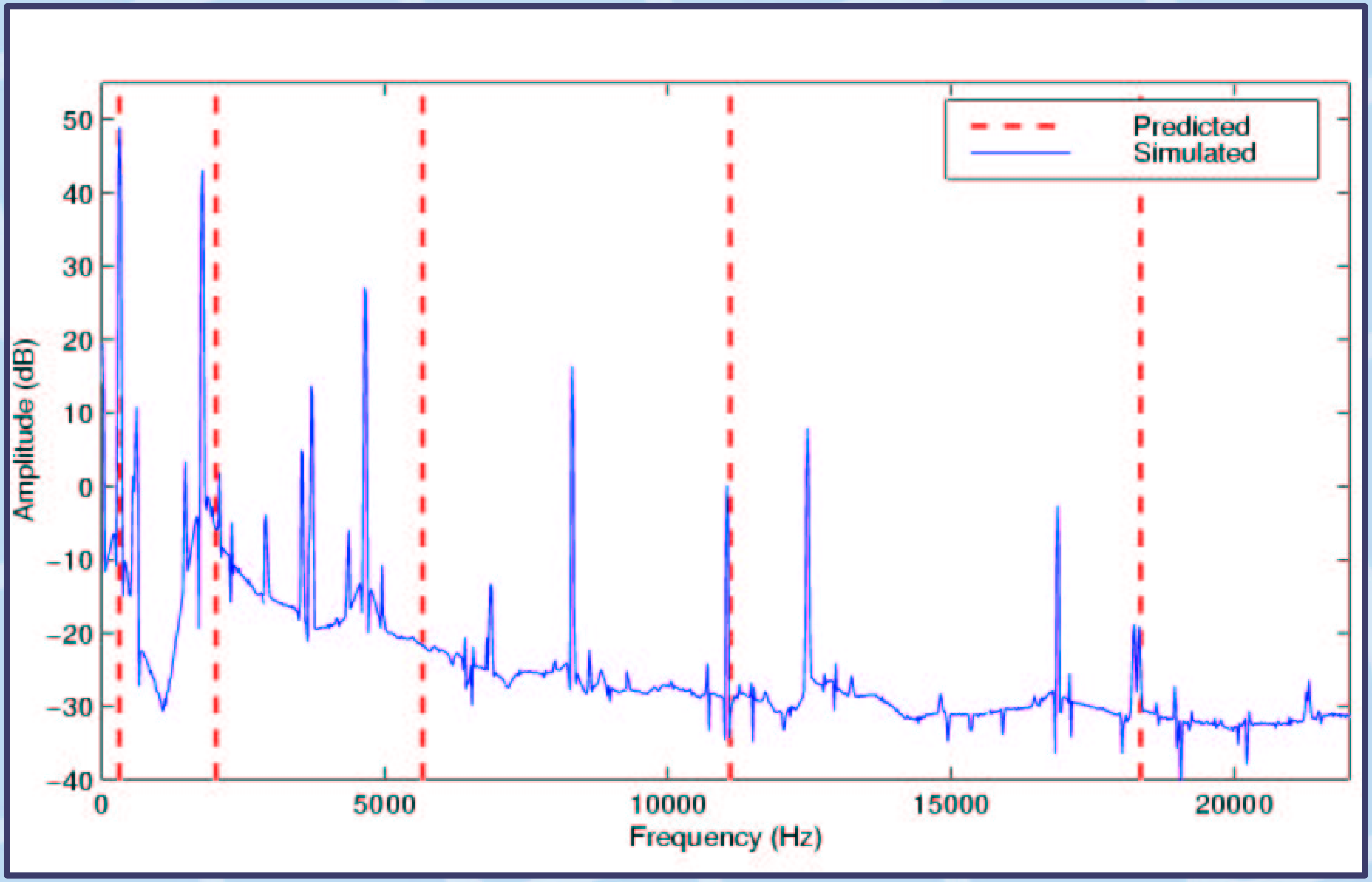
Plucked Bar

- Fixed at one end
- Impulse applied at the other



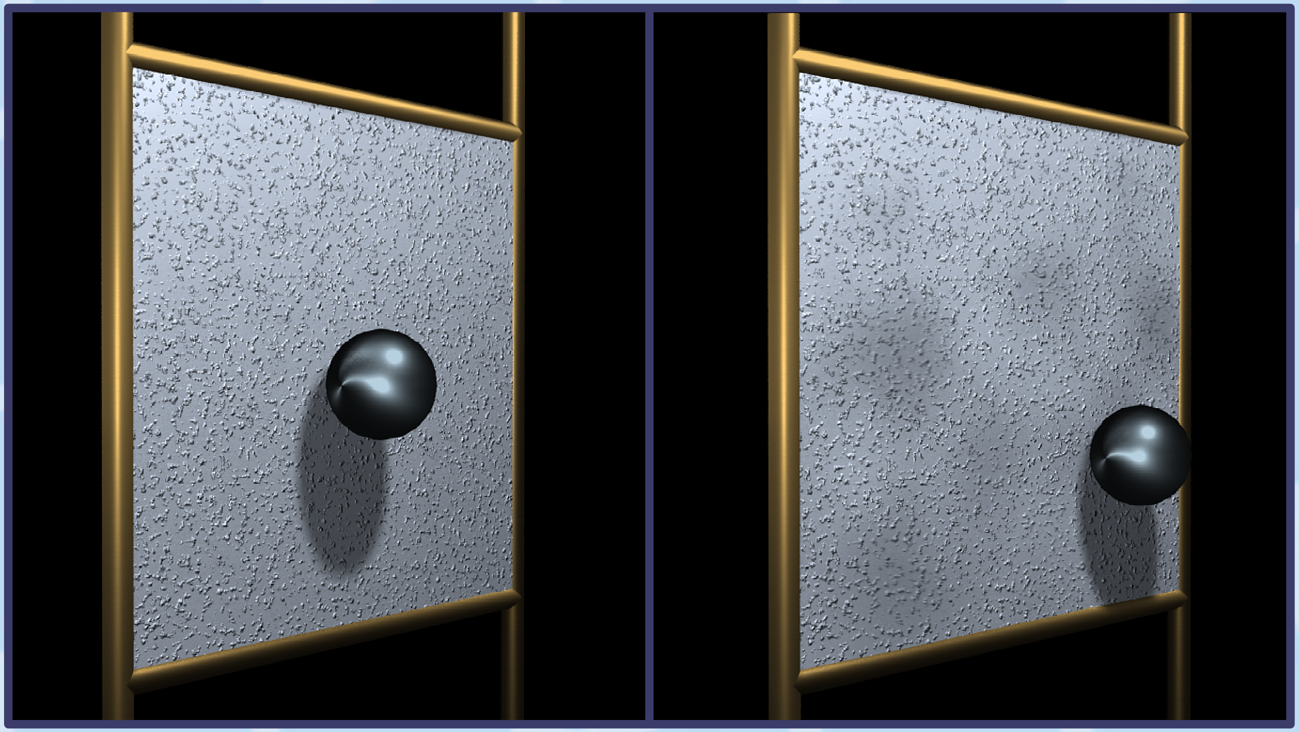
Plucked Bar





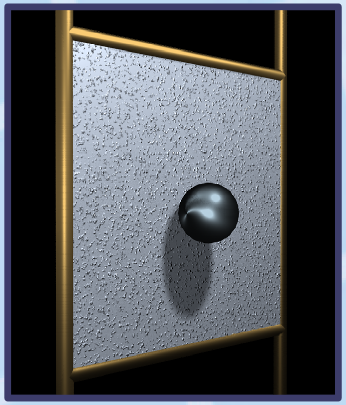
Predicted
Simulated
Amplitude (dB)
Frequency (Hz)
50
40
30
20
10
0
−10
−20
−30
−40
0
5000
10000
15000
20000

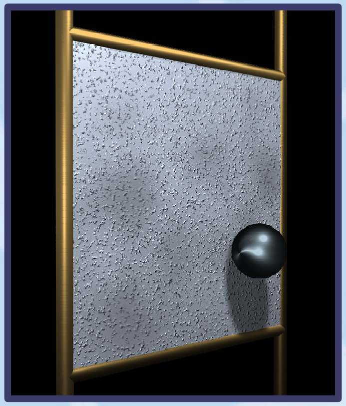
Square Plates

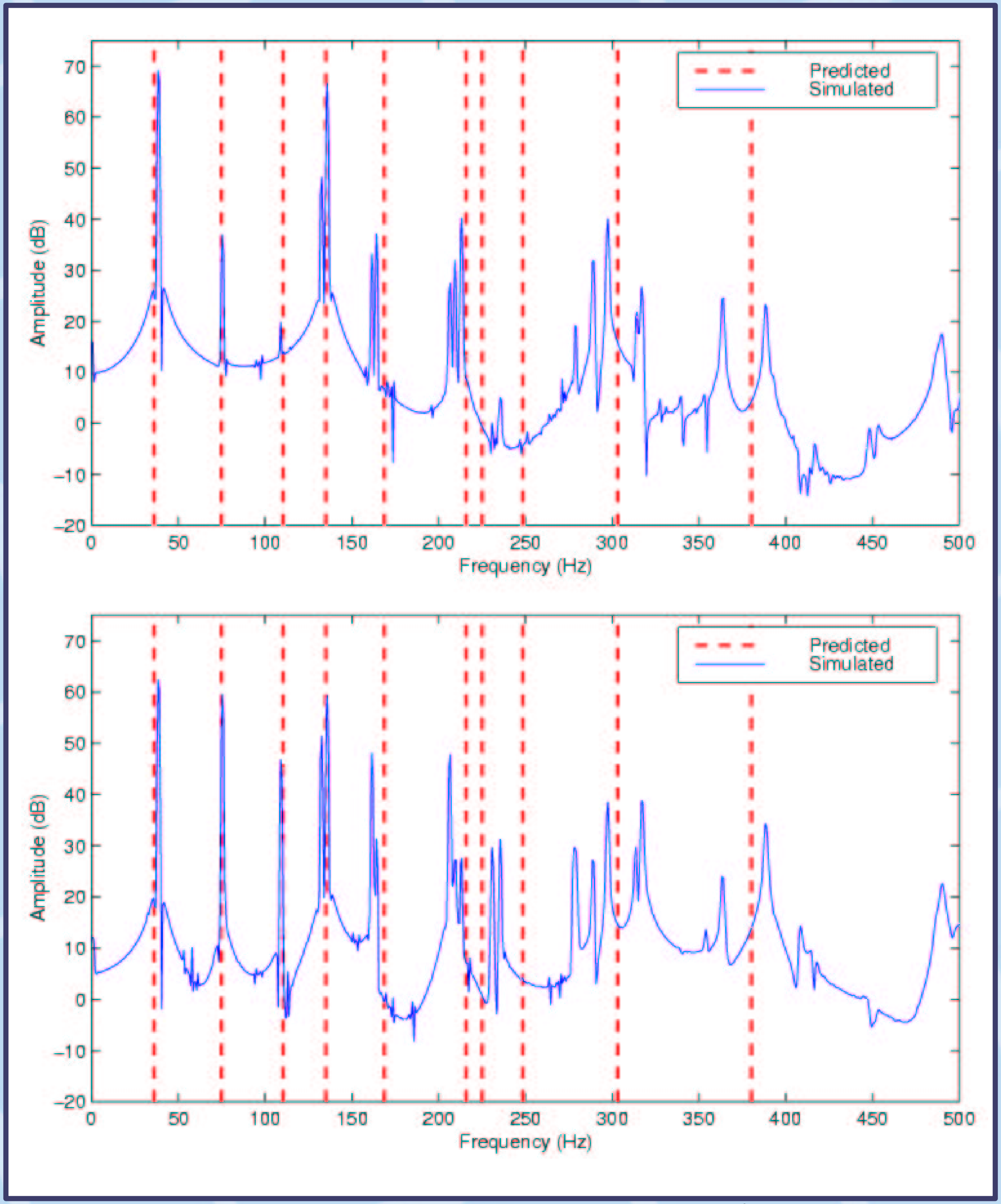


- Fixed along edges
- Struck by mass at different locations

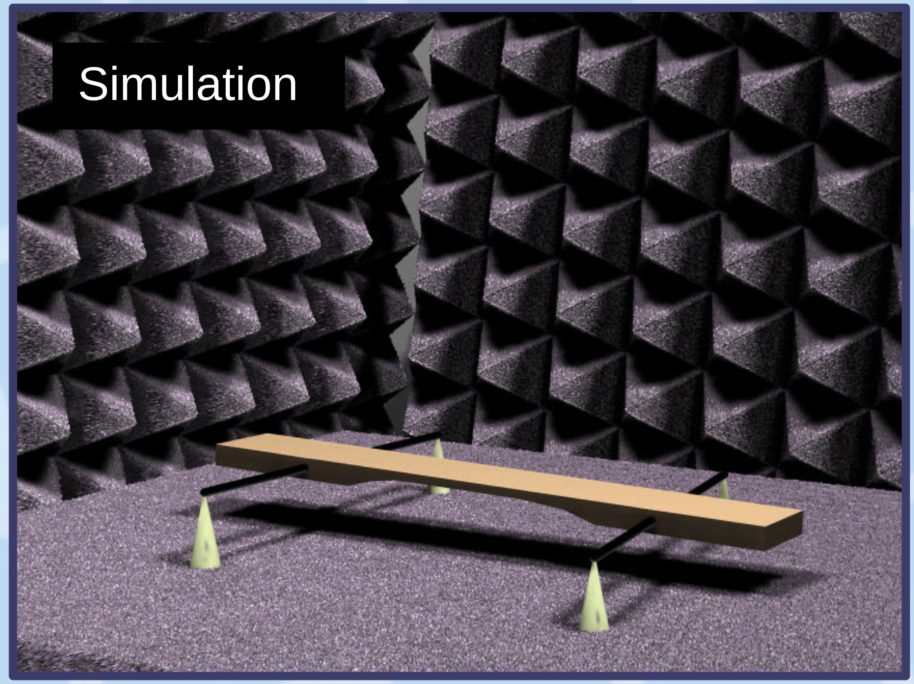
Square Plates





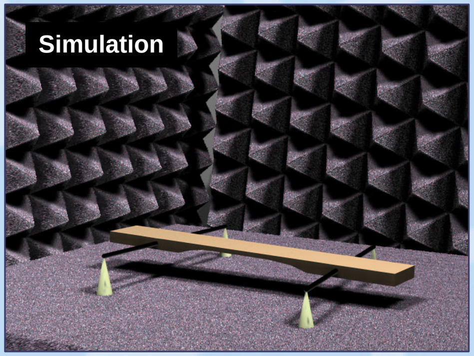


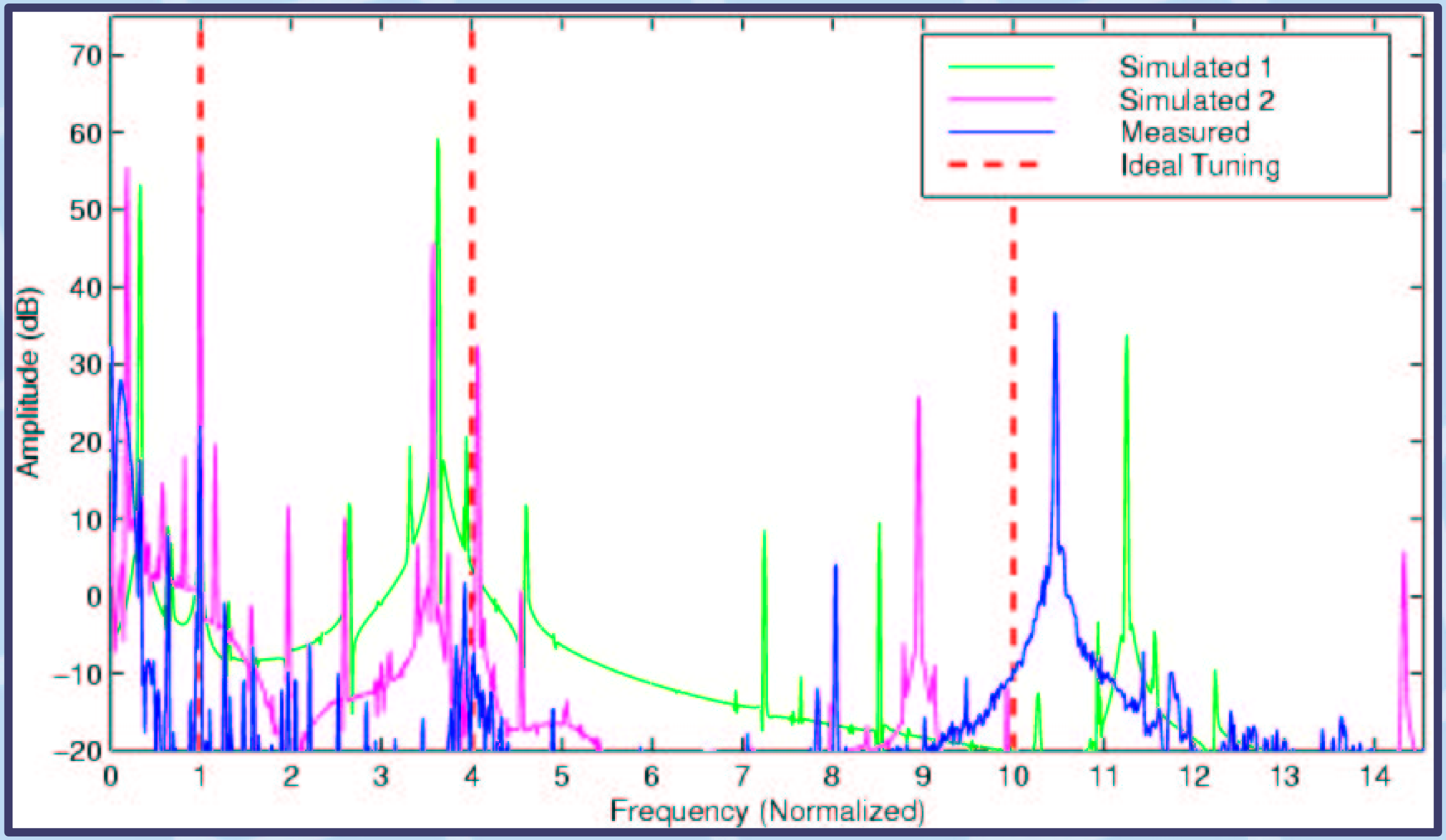
Vibraphone Bar



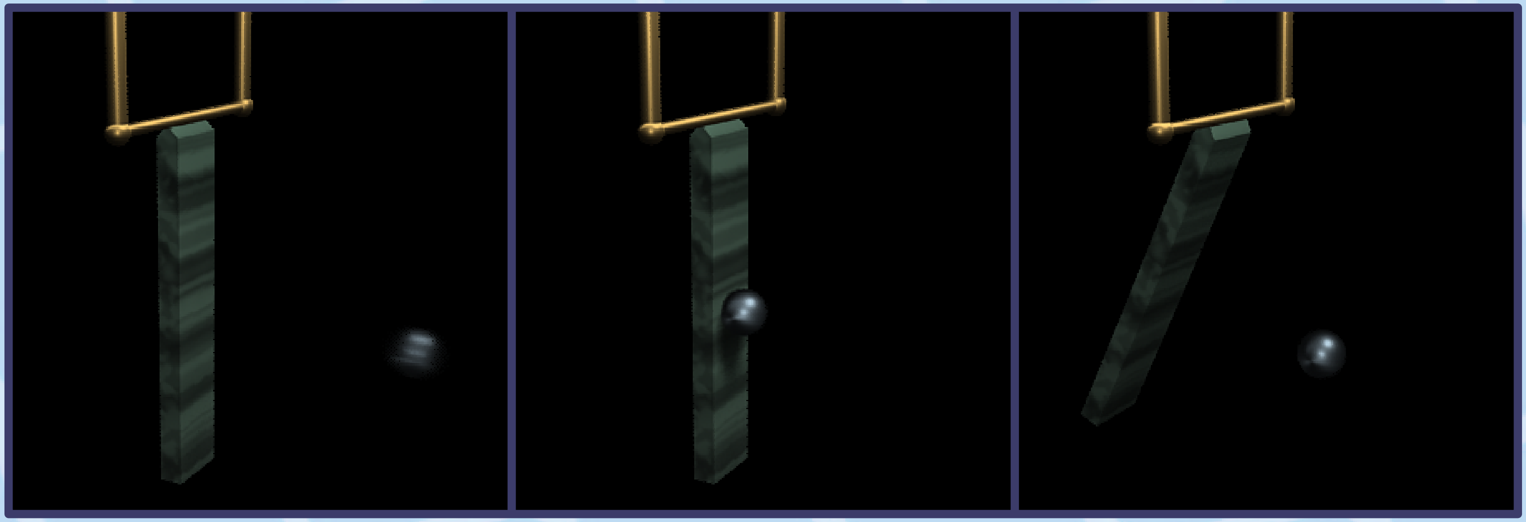
- **Spring mounted at nodes of first mode**
- **Compared to real bar and ideal tunning**

Vibraphone Bar



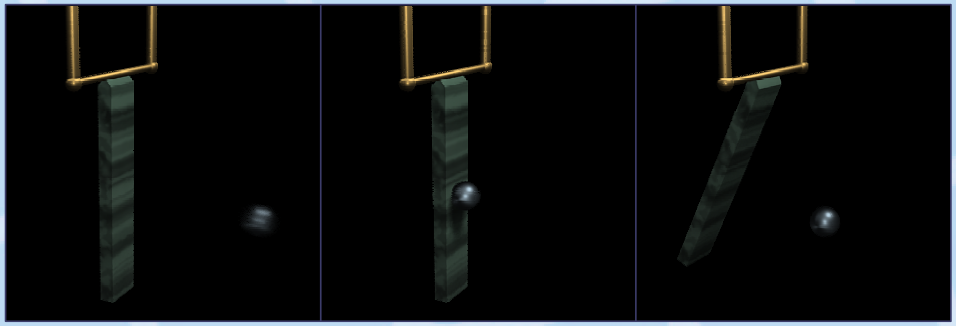


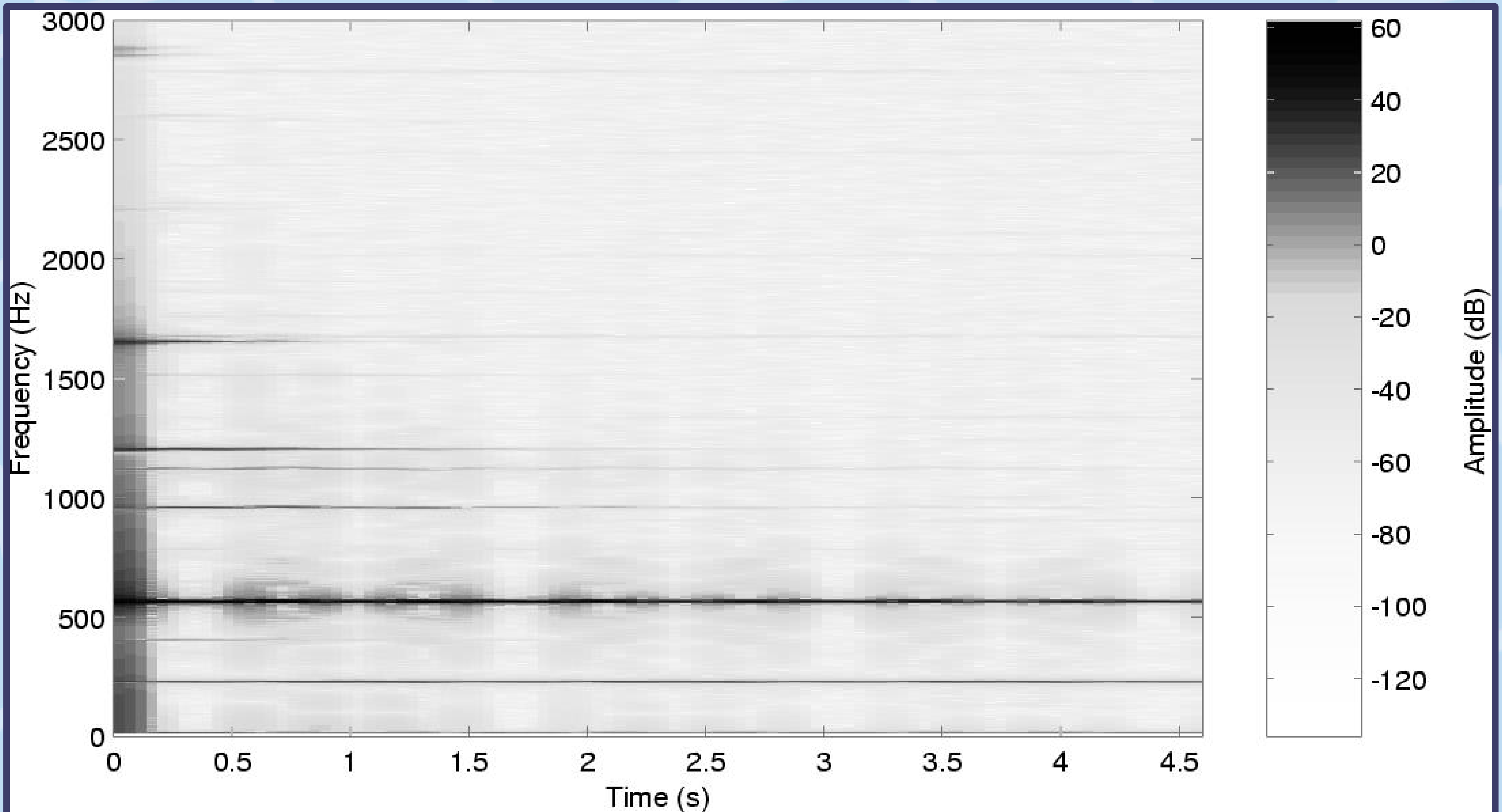
Swinging Bar



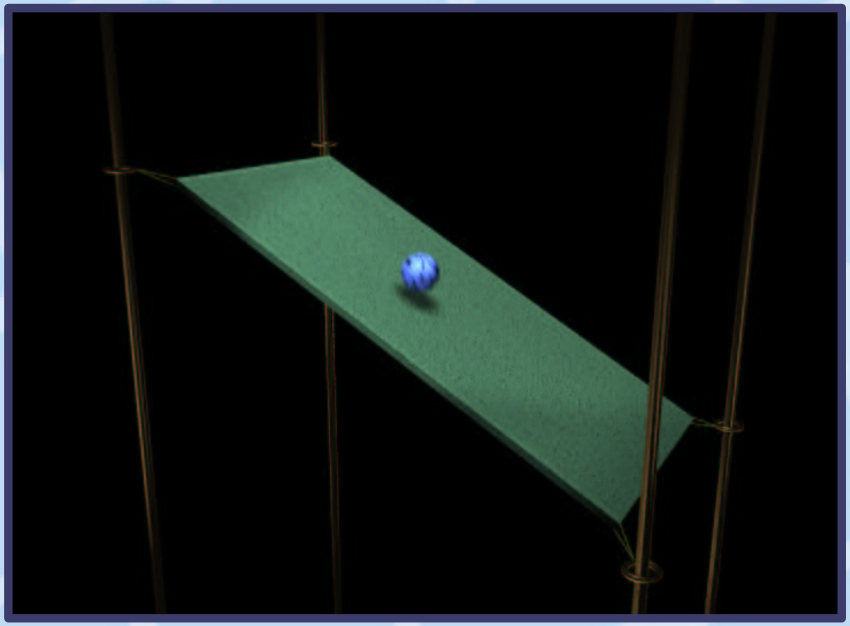
- **Doppler effects**

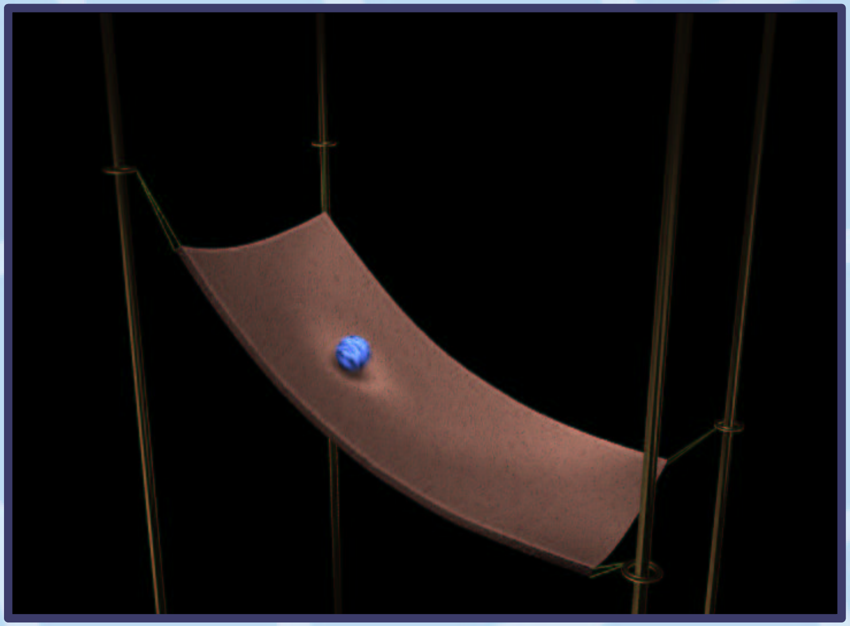
Swinging Bar





Slab and Ball



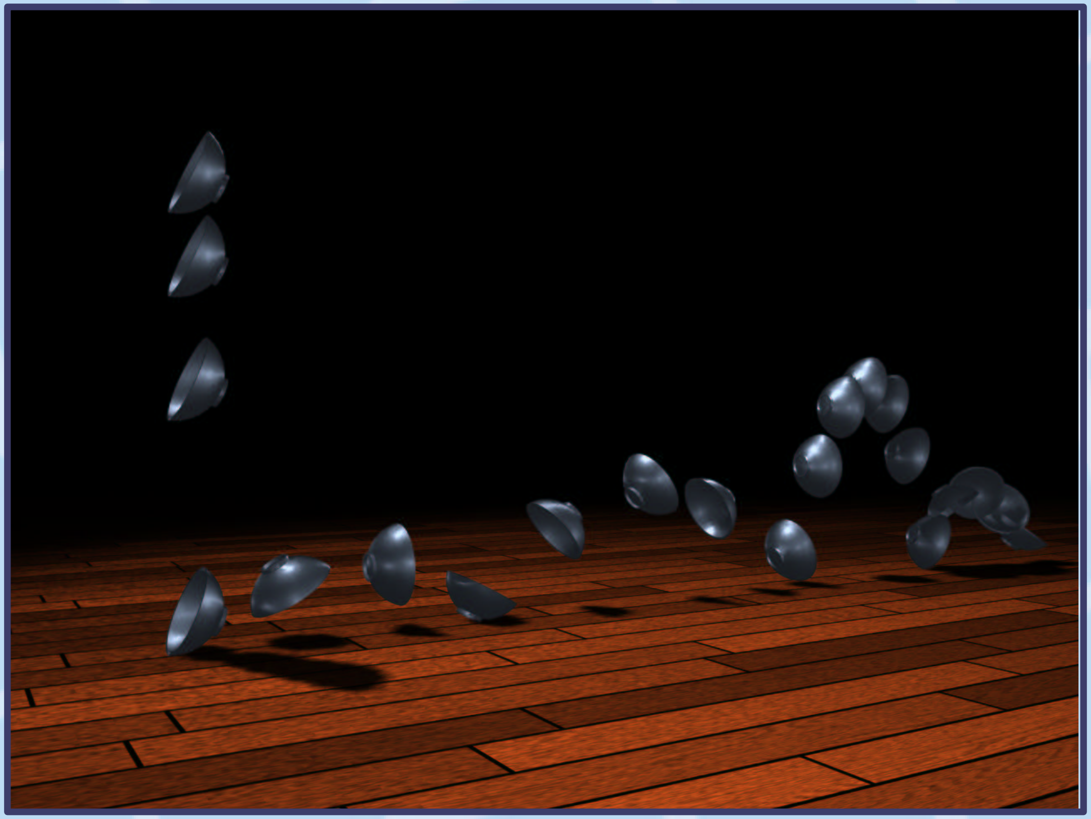


- Both objects sounding
- Mounted on springs

Stiff Sheet

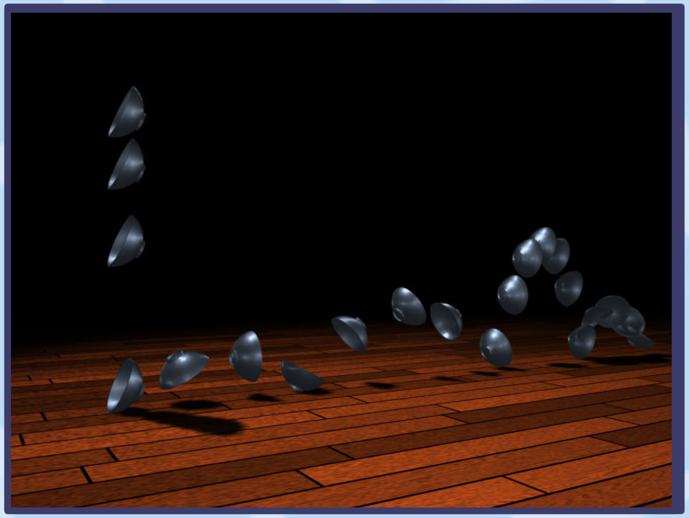
- **Non–linear deformation**

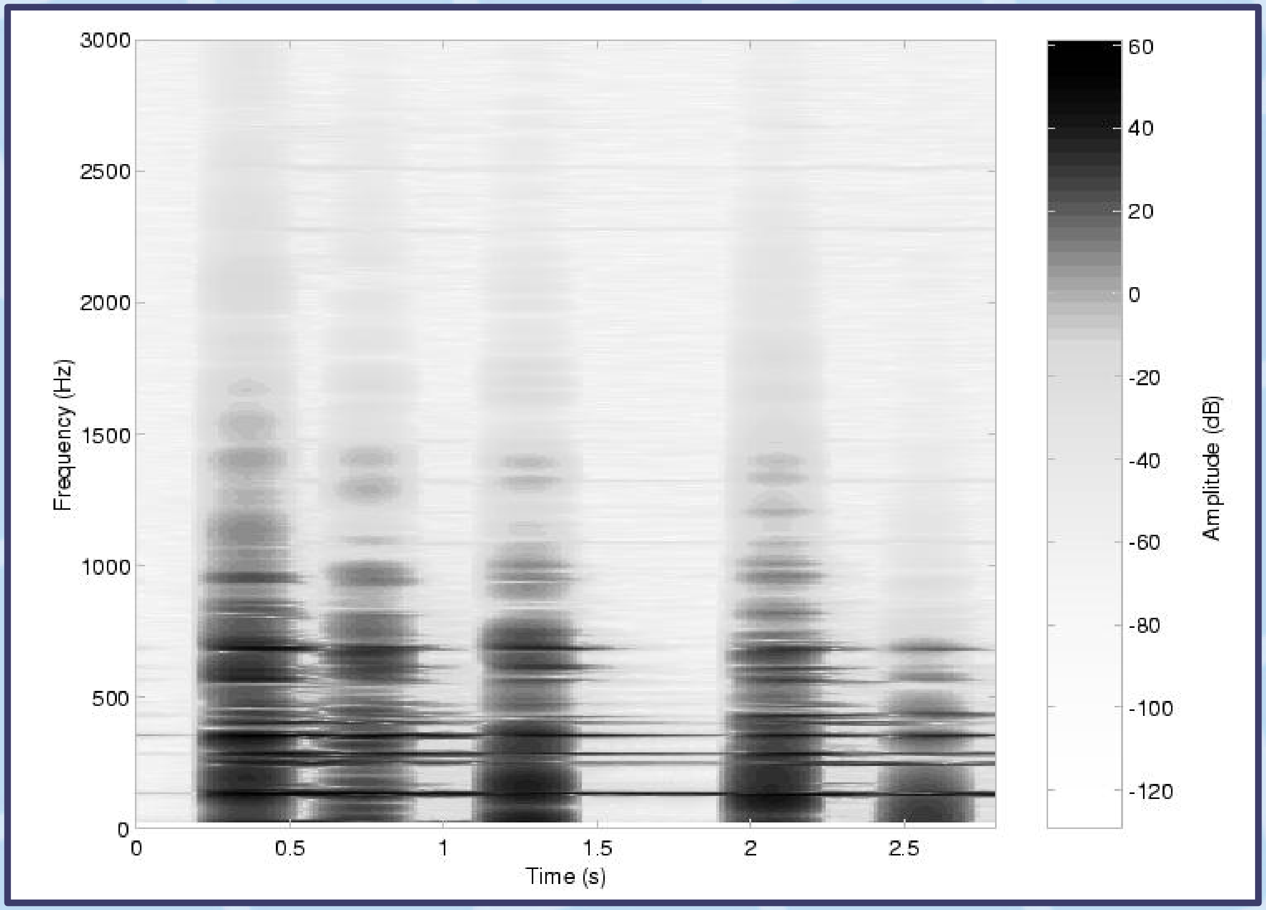
Bowls



- Only bowl is sounding
- Bounces excite different modes

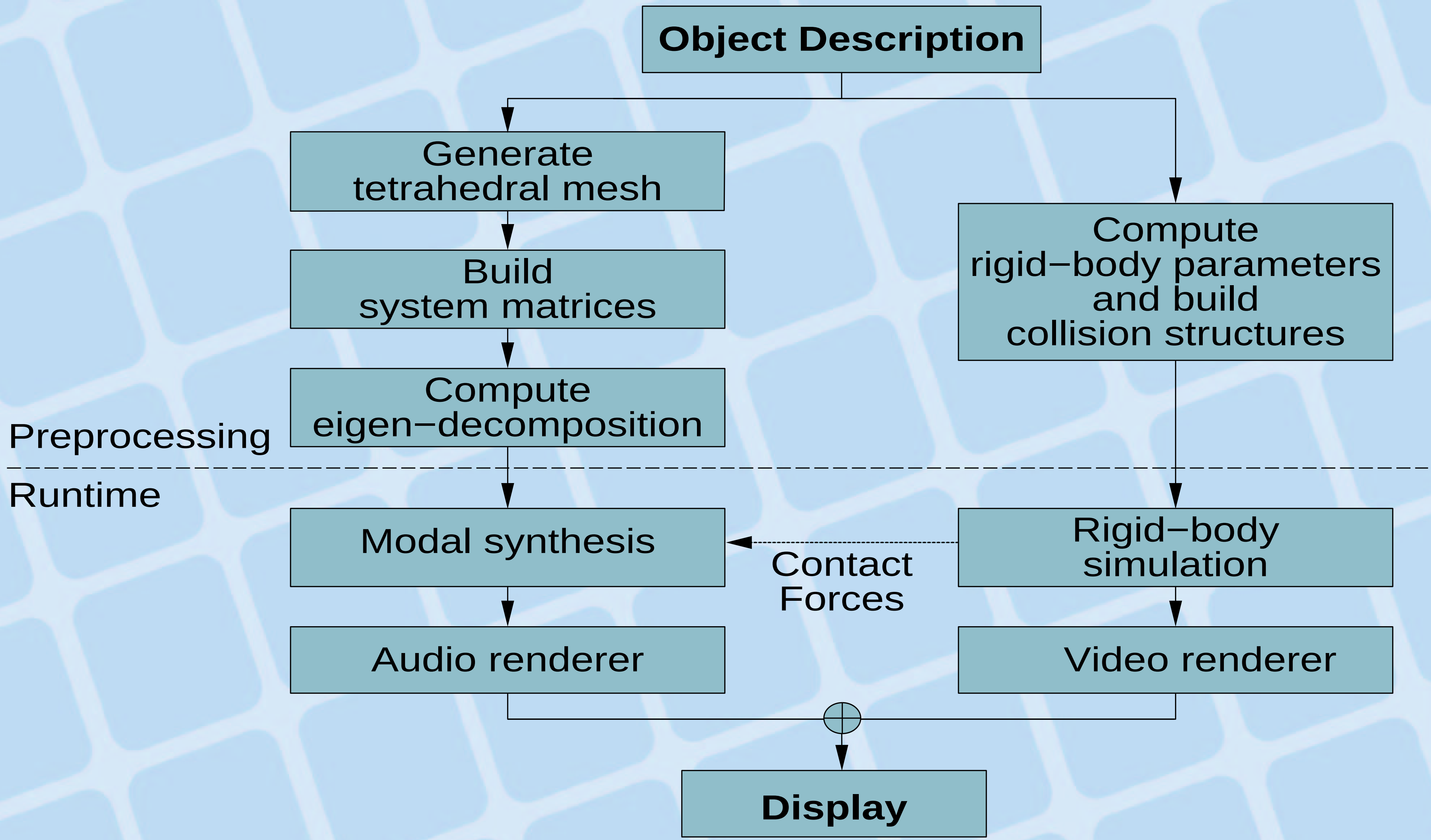
Bowls





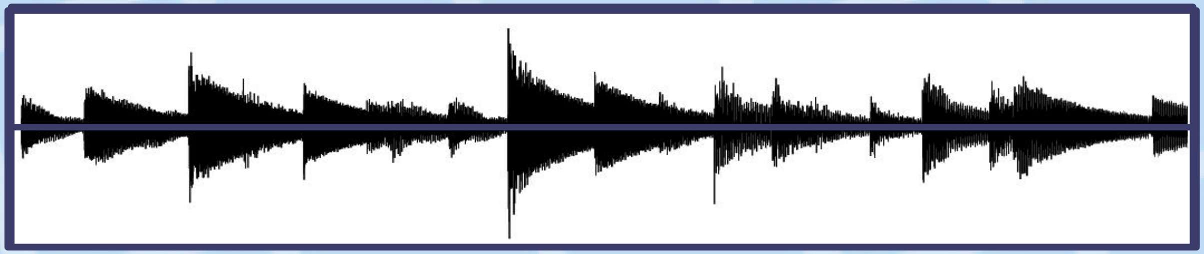
3000
2500
2000
1500
1000
500
0
Frequency (Hz)
0
0.5
1
1.5
2
2.5
Time (s)
60
40
20
0
-20
-40
-60
-80
-100
-120
Amplitude (dB)

Overview



Object Description
Generate tetrahedral mesh
Build system matrices
Compute eigen−decomposition
Compute rigid−body parameters and build collision structures
Preprocessing
Runtime
Modal synthesis
Contact Forces
Rigid−body simulation
Audio renderer
Video renderer
Display

Example: Wind Chimes



Linearization

$$\mathcal{K}(\boldsymbol{d}) + \mathcal{C}(\boldsymbol{d},\dot{\boldsymbol{d}}) + \mathcal{M}(\ddot{\boldsymbol{d}}) = \boldsymbol{f}$$

$$\Downarrow$$

$$\boldsymbol{K}\boldsymbol{d} + \boldsymbol{C}\dot{\boldsymbol{d}} + \boldsymbol{M}\ddot{\boldsymbol{d}} = \boldsymbol{f}$$

$$\Downarrow$$

$$\boldsymbol{K}(\boldsymbol{d} + \alpha_1\dot{\boldsymbol{d}}) + \boldsymbol{M}(\alpha_2\dot{\boldsymbol{d}} + \ddot{\boldsymbol{d}}) = \boldsymbol{f}$$

$$\boldsymbol{C} = \alpha_1\boldsymbol{K} + \alpha_2\boldsymbol{M}$$

Normalize for Mass

- Normalize for mass by change of coordinates
  - Cholesky decomposition $\boldsymbol{M} = \boldsymbol{L}\boldsymbol{L}^{\mathsf{T}}$
  - Change coordinates $\boldsymbol{y} = \boldsymbol{L}^{\mathsf{T}}\boldsymbol{d}$

$$\boldsymbol{K}(\boldsymbol{d} + \alpha_1 \dot{\boldsymbol{d}}) + \boldsymbol{M}(\alpha_2 \dot{\boldsymbol{d}} + \ddot{\boldsymbol{d}}) = \boldsymbol{f}$$

$$\Downarrow$$

$$\boldsymbol{L}^{-1}\boldsymbol{K}\boldsymbol{L}^{-\mathsf{T}}(\boldsymbol{y} + \alpha_1 \dot{\boldsymbol{y}}) + (\alpha_2 \dot{\boldsymbol{y}} + \ddot{\boldsymbol{y}}) = \boldsymbol{L}^{-1}\boldsymbol{f}$$

Diagonalize

- Diagonalize with second change of coordinates
  - Eigen decomposition $\boldsymbol{L}^{-1}\boldsymbol{K}\boldsymbol{L}^{-\mathsf{T}} = \boldsymbol{V}\boldsymbol{\Lambda}\boldsymbol{V}^{\mathsf{T}}$
  - Change coordinates $\boldsymbol{z} = \boldsymbol{V}^{\mathsf{T}}\boldsymbol{y}$

$$\boldsymbol{L}^{-1}\boldsymbol{K}\boldsymbol{L}^{-\mathsf{T}}(\boldsymbol{y} + \alpha_1\dot{\boldsymbol{y}}) + (\alpha_2\dot{\boldsymbol{y}} + \ddot{\boldsymbol{y}}) = \boldsymbol{L}^{-1}\boldsymbol{f}$$

$$\Downarrow$$

$$\boldsymbol{\Lambda}(\boldsymbol{z} + \alpha_1\dot{\boldsymbol{z}}) + (\alpha_2\dot{\boldsymbol{z}} + \ddot{\boldsymbol{z}}) = \boldsymbol{V}^{\mathsf{T}}\boldsymbol{L}^{-1}\boldsymbol{f}$$

$$\Downarrow$$

$$\boldsymbol{\Lambda}\boldsymbol{z} + (\alpha_1\boldsymbol{\Lambda} + \alpha_2\boldsymbol{I})\dot{\boldsymbol{z}} + \ddot{\boldsymbol{z}} = \boldsymbol{g}$$

Diagonalize

$$\boldsymbol{K}\boldsymbol{d} + \boldsymbol{C}\dot{\boldsymbol{d}} + \boldsymbol{M}\ddot{\boldsymbol{d}} = \boldsymbol{f}$$

$$\Downarrow$$

$$\boldsymbol{\Lambda}\boldsymbol{z} + (\alpha_1\boldsymbol{\Lambda} + \alpha_2\boldsymbol{I})\dot{\boldsymbol{z}} + \ddot{\boldsymbol{z}} = \boldsymbol{g}$$

$$\boldsymbol{z} = \boldsymbol{V}^{\mathsf{T}}\boldsymbol{L}^{\mathsf{T}}\boldsymbol{d}$$

$$\boldsymbol{d} = \boldsymbol{L}^{-\mathsf{T}}\boldsymbol{V}\boldsymbol{z}$$

$$\boldsymbol{g} = \boldsymbol{V}^{\mathsf{T}}\boldsymbol{L}^{-1}\boldsymbol{f} = (\boldsymbol{L}^{-\mathsf{T}}\boldsymbol{V})^{\mathsf{T}}\boldsymbol{f}$$

Diagonalize

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$$\boldsymbol{K}\boldsymbol{d} + \boldsymbol{C}\dot{\boldsymbol{d}} + \boldsymbol{M}\ddot{\boldsymbol{d}} = \boldsymbol{f}$$

$$\Downarrow$$

$$\lambda_i z_i + (\alpha_1 \lambda_i + \alpha_2)\dot{z}_i + \ddot{z}_i = g_i$$

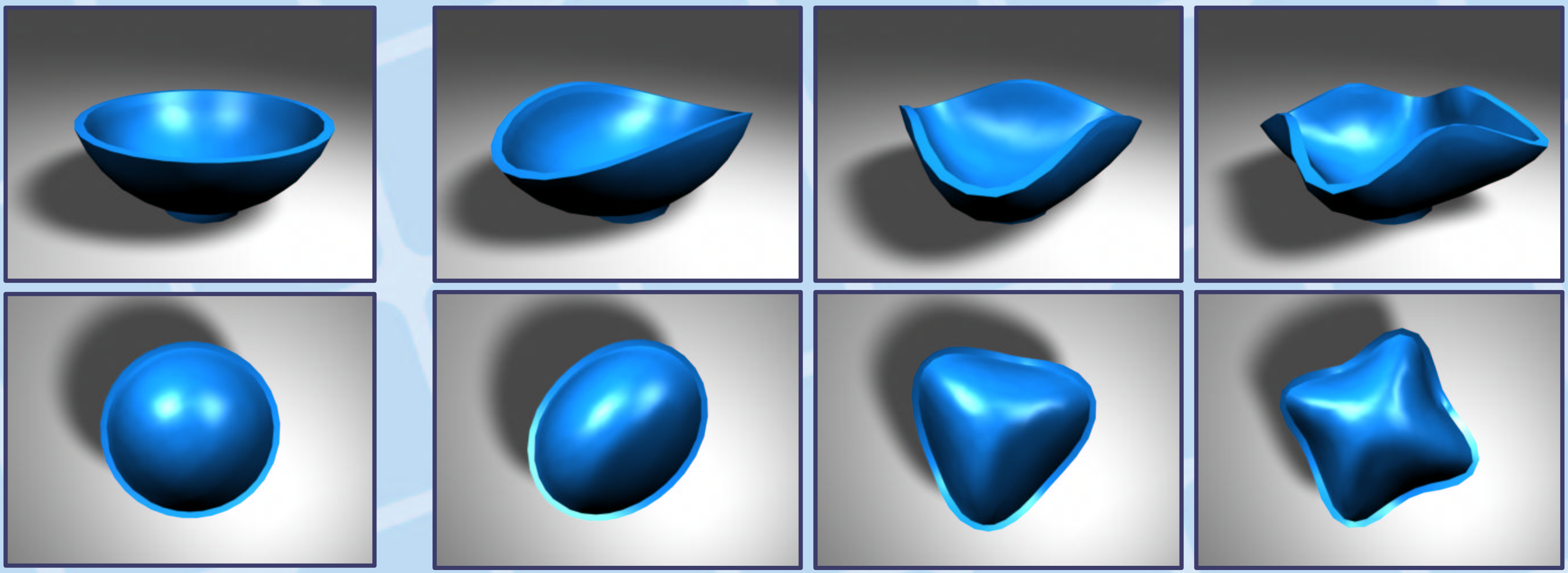
$$\boldsymbol{z} = \boldsymbol{V}^{\mathsf{T}} \boldsymbol{L}^{\mathsf{T}} \boldsymbol{d}$$

$$\boldsymbol{d} = \boldsymbol{L}^{-\mathsf{T}} \boldsymbol{V} \boldsymbol{z}$$

$$\boldsymbol{g} = \boldsymbol{V}^{\mathsf{T}} \boldsymbol{L}^{-1} \boldsymbol{f} = (\boldsymbol{L}^{-\mathsf{T}} \boldsymbol{V})^{\mathsf{T}} \boldsymbol{f}$$

Modes

- Columns of $\boldsymbol{L}^{-\top}\boldsymbol{V}$ are shapes of object's vibrational modes



Modes

- Each scalar ODE has analytical solution

$$z_i = c_1 e^{t\omega_i^+} + c_2 e^{t\omega_i^-}$$

$$\omega_i^{\pm} = \frac{-(\alpha_1\lambda_i + \alpha_2) \pm \sqrt{(\alpha_1\lambda_i + \alpha_2)^2 - 4\lambda_i}}{2}$$

Decay rate

Frequency

Overview

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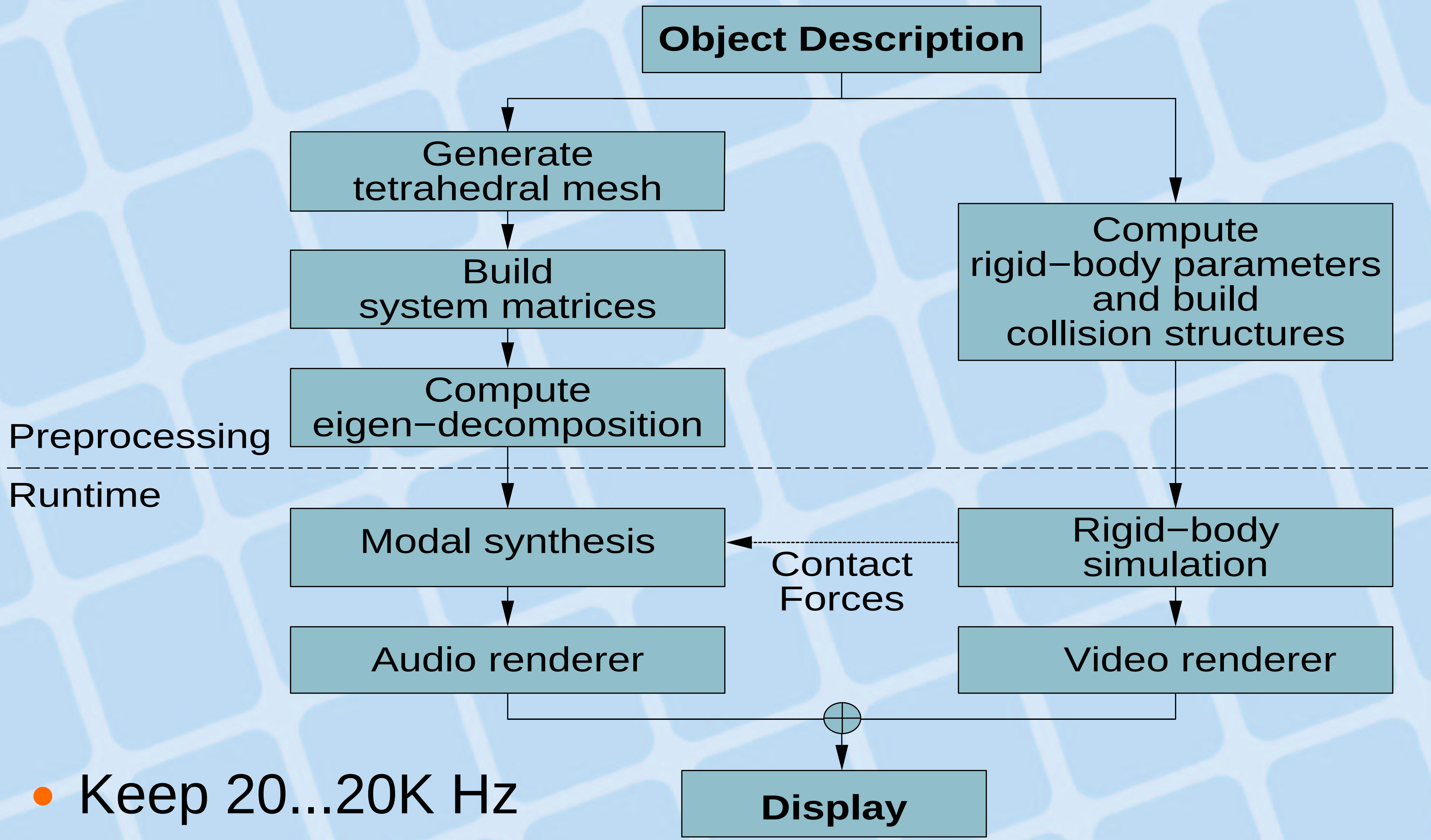
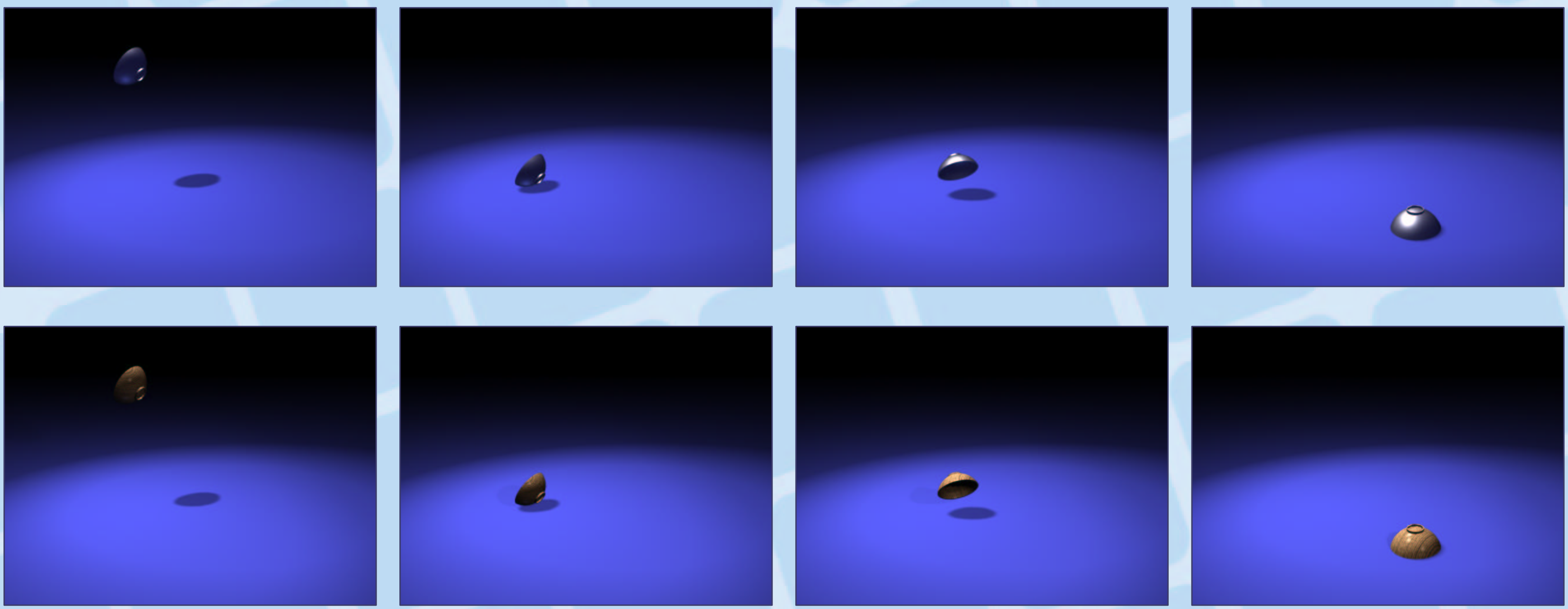


- Keep 20...20K Hz

Results

- Sound for different materials
  - Same geometry and motion
  - Different materials

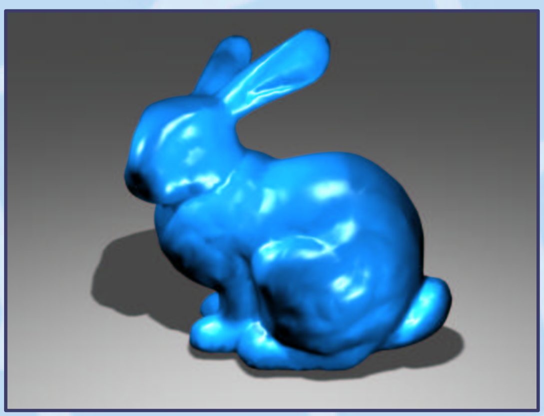


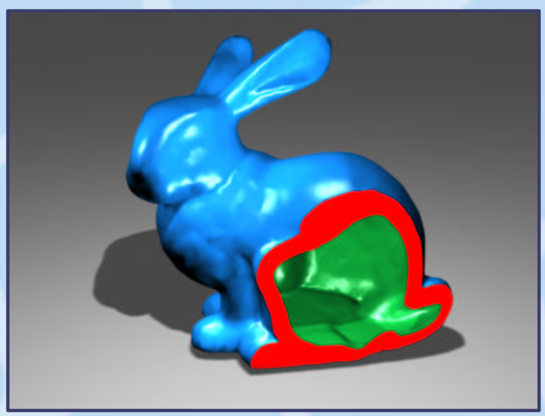
Results

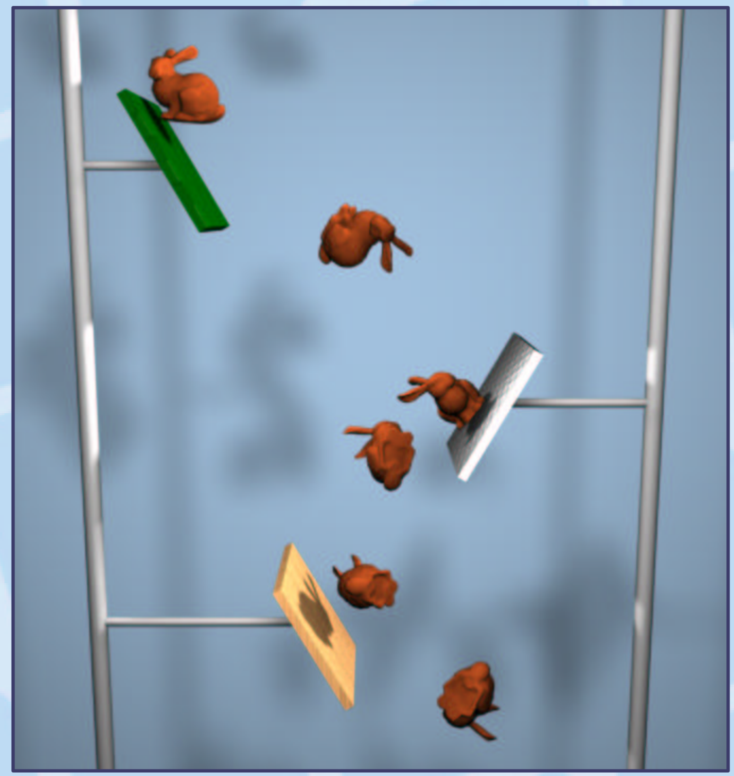
- Sound consistent with geometry
  - Geometrically similar shapes
  - Scaled by 10x

Results

- Complex geometry
  - Use sparse methods for decomposition
  - Does not impact runtime cost







Results

- Preprocessing times

Example	Num. Nodes	Method	Precompute
Chime(D3)	18796	Sparse	2h 24min
Bowl #1	387	Dense	4min 12sec
Bowl #2	387	Dense	4min 12sec
Bunny (Ceramic)	37114	Sparse	4h 40min
Plastic Shelf	361	Sparse	30sec
Aluminum Shelf	361	Sparse	30sec
Wood Shelf	361	Sparse	30sec
Bunny (Metal)	37114	Sparse	4h 40min
Blocks	1160	Dense	5h 28min
Boxes	1160	Dense	5h 28min
The End (T)	71	Dense	42sec

Results

- Comparison with real chimes

Note	Ideal Freq.	Measured Length	Measured Freq.	Computed Freq.
D3	587.33	.505	585.8	589.17
E3	659.26	.475	656.0	665.03
G3	783.99	.435	781.8	787.01
A4	880.00	.410	877.5	884.70
B4	987.77	.388	982.5	984.75
D4	1174.66	.353	1167.0	1186.88

- Primary modes match with < 2% error