Printone: Interactive Resonance Simulation for Free-form Print-wind Instrument Design

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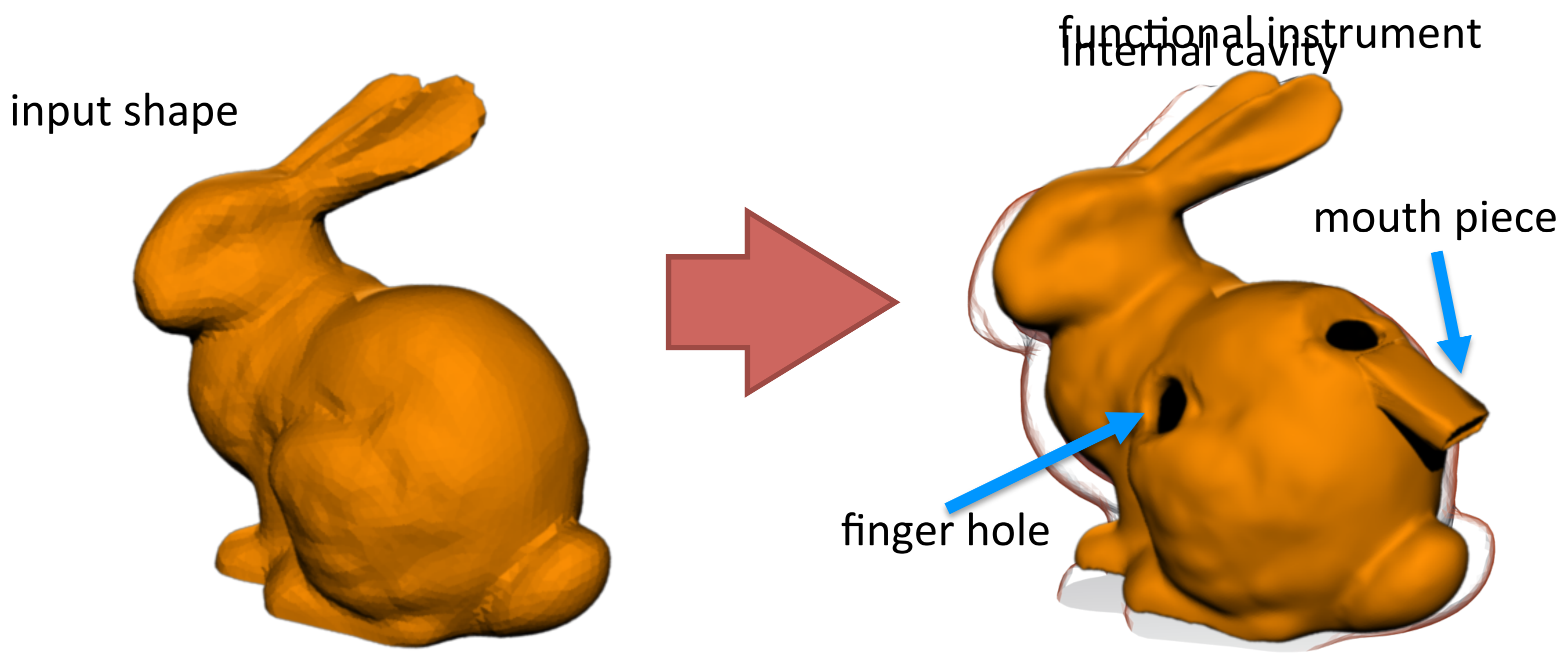
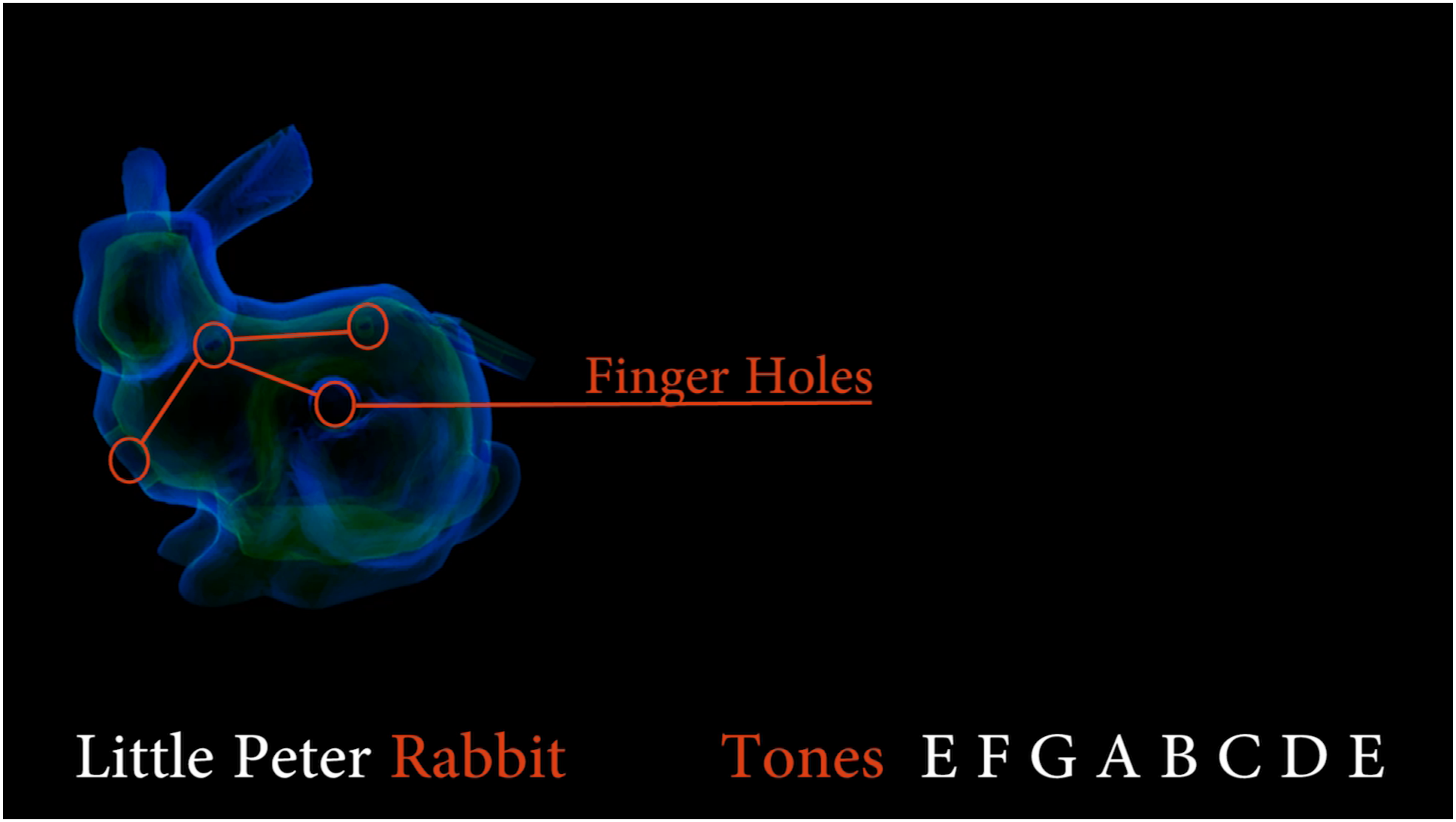
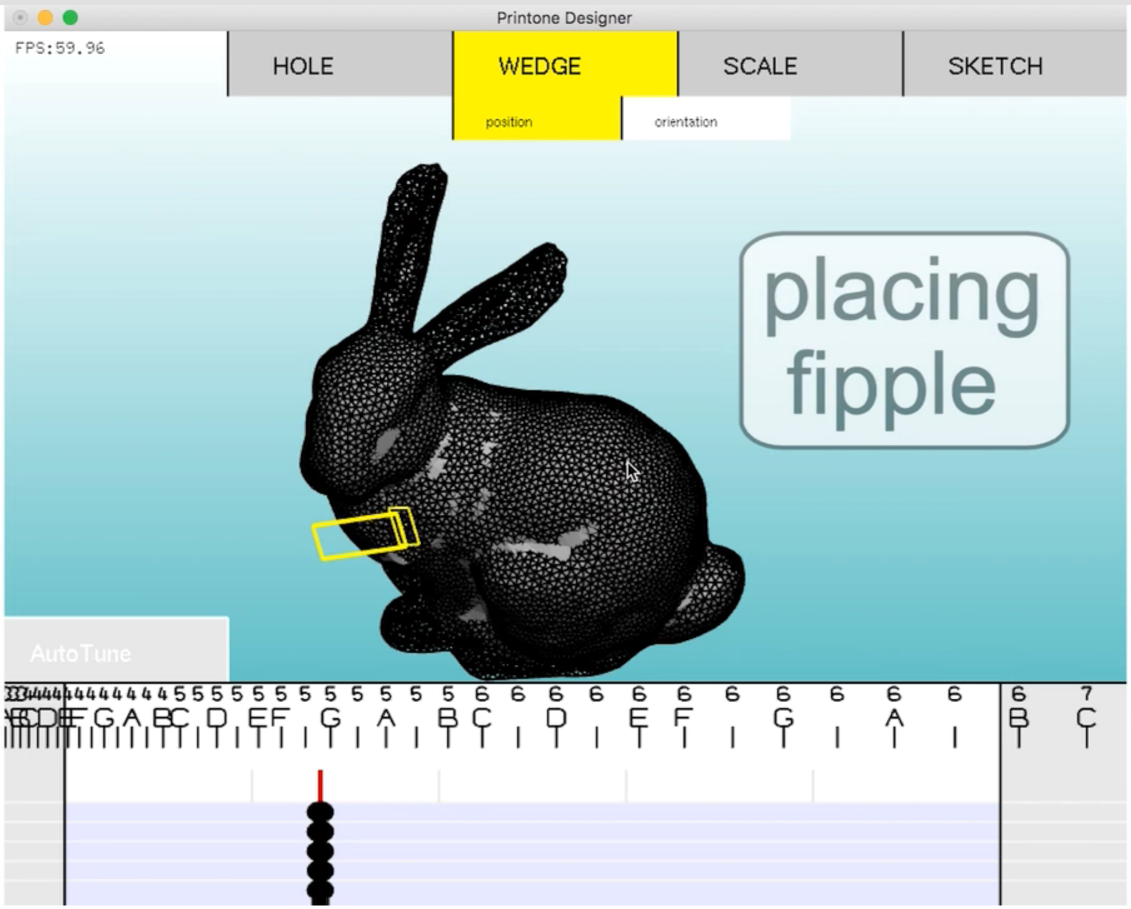
Free-form Wind-musical Instruments

Simulation & optimization to guide the instrument design with correct tones




Finger Holes
Little Peter Rabbit
Tones E F G A B C D E

Interactive Design Interface

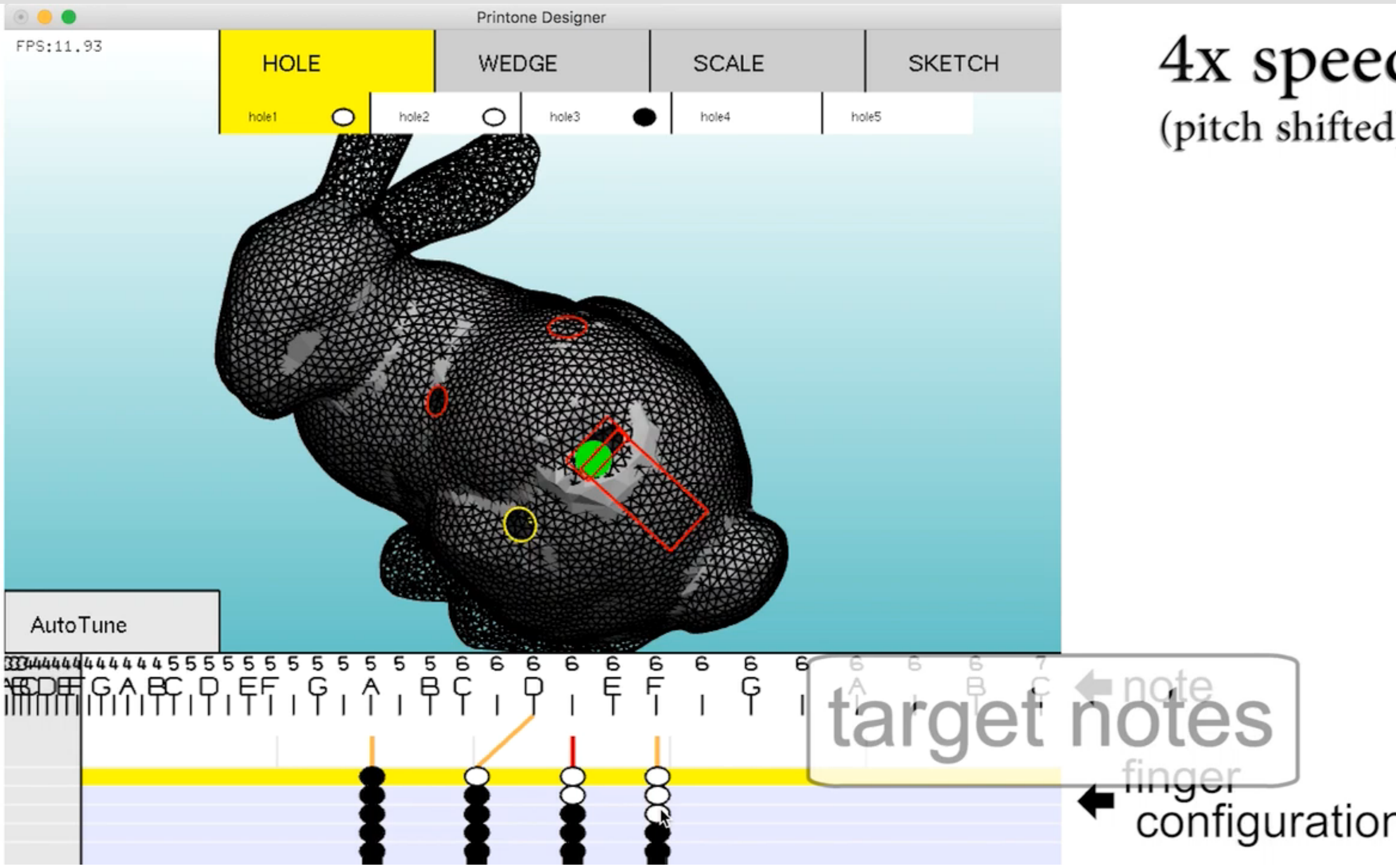


2x speed
(pitch shifted)

note

finger configuration

Interactive Hole-size Optimization



4x speed

(pitch shifted)

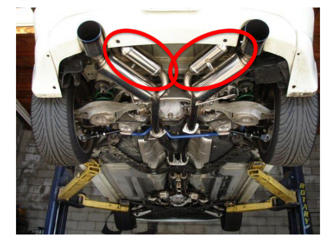
Why Musical Instruments?

- It is fun to play with sounds!!

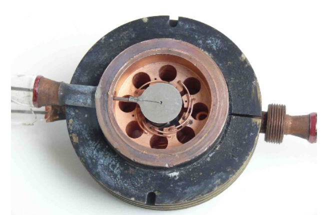
- There are many practical applications

speaker
housing

resonator

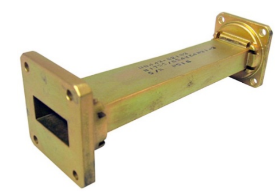


muffler



magnetron

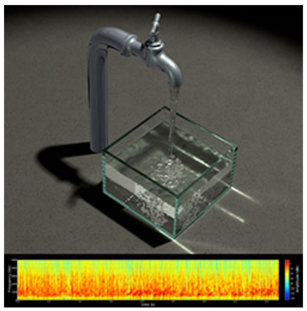
antenna



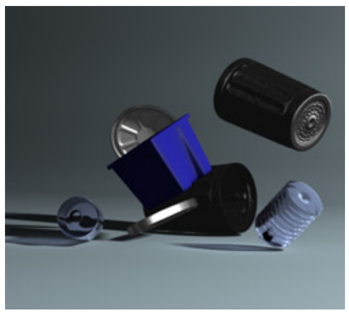
wave guide

Related Work: Sound Simulation

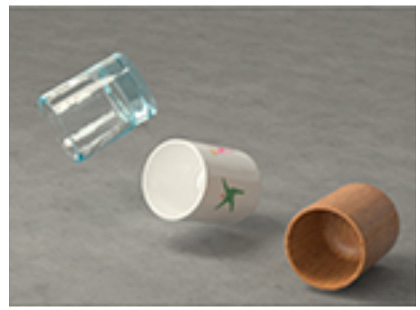
Computing acoustic transfer for solid vibration



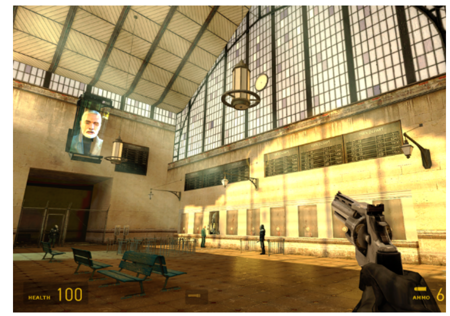
[Zhang et al. 2009]



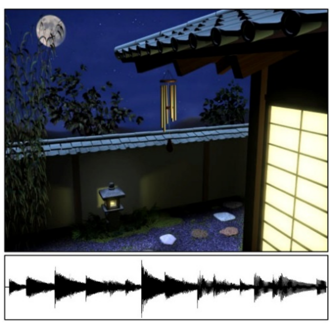
[Chadwick et al. 2009]



[Li et al. 2015]



[Raghuvanshi et al. 2010]



[O'Brien et al. 2002]

[James et al. 2006]

[Bonneel et al. 2008]

[Dobashi et al. 2003]

Related Works: Contact Sound Design

Our goal is interactive design of wind-instrument

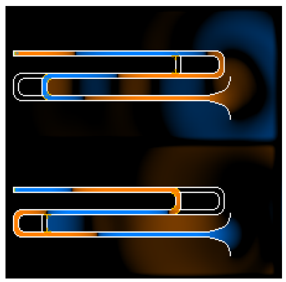
[Umetani et al. 2010]

[Bharaj et al. 2015]

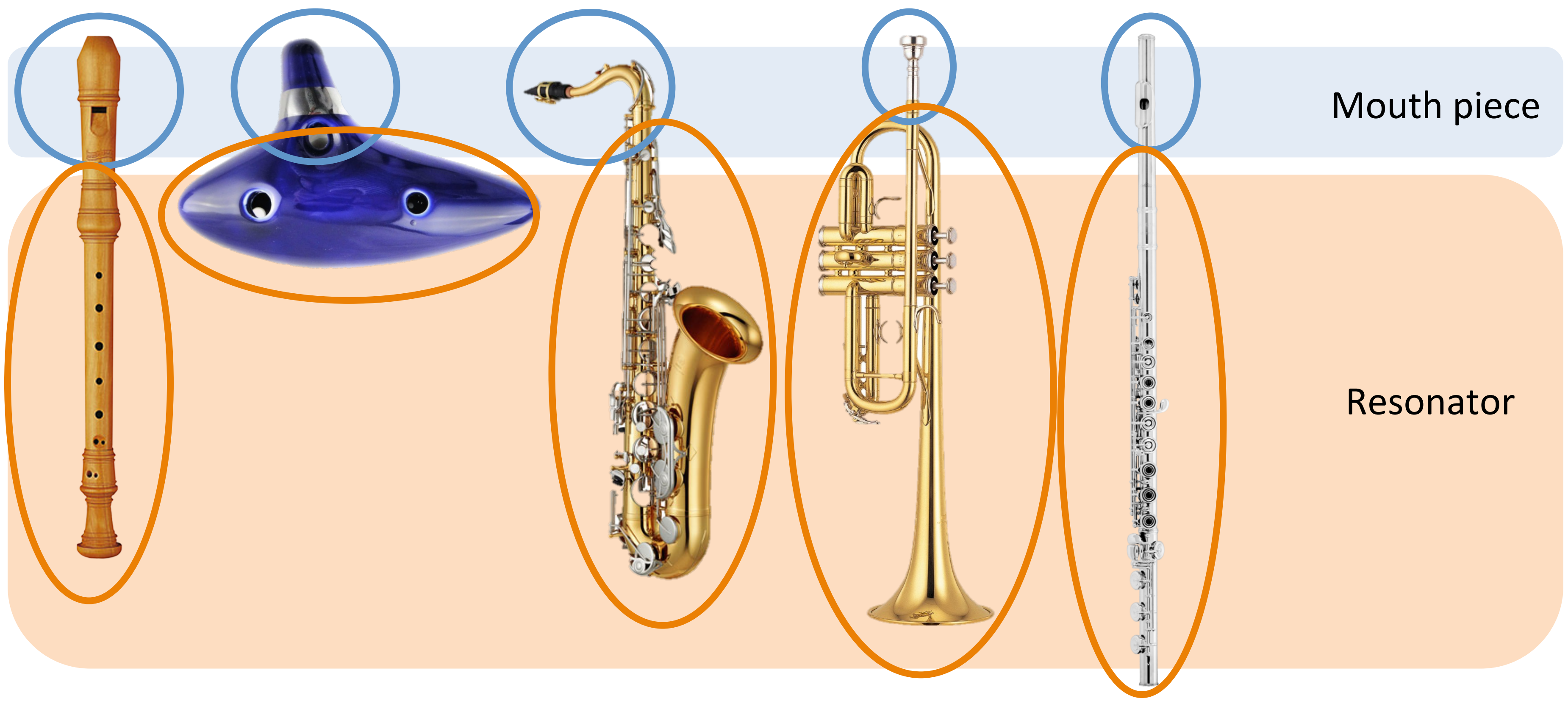
[Musialski et al. 2016]

Related Works: Acoustic Sound Design

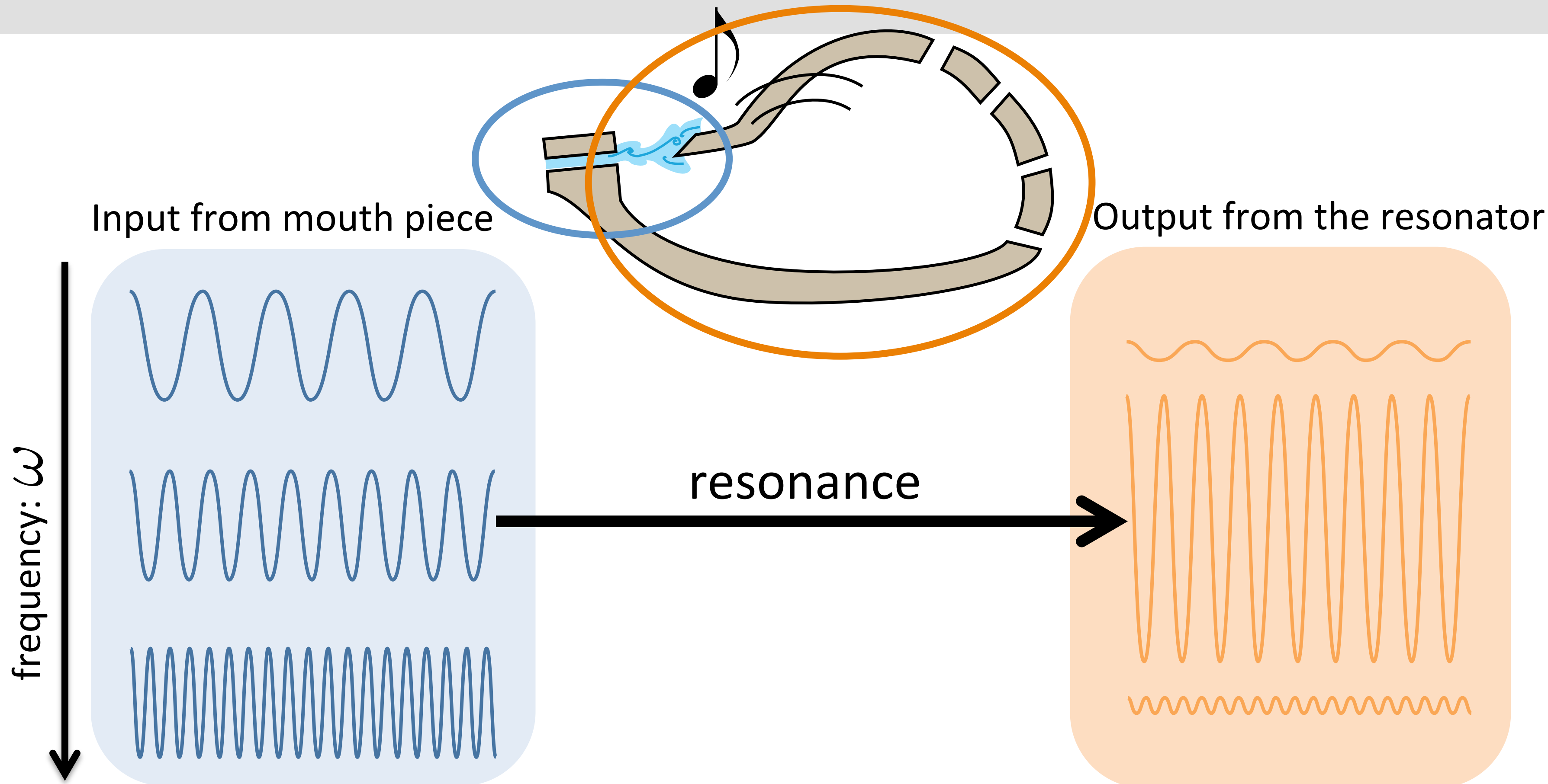
Our goal is 3D functional interactive design

	 [Allen et al. 2015]	 [li et al. 2016]	 our work
Interactivity	Interactive	Offline optimization	Interactive
Simulation DoF	2D	3D: Concatenations of parameterized voxel	3D: free-form

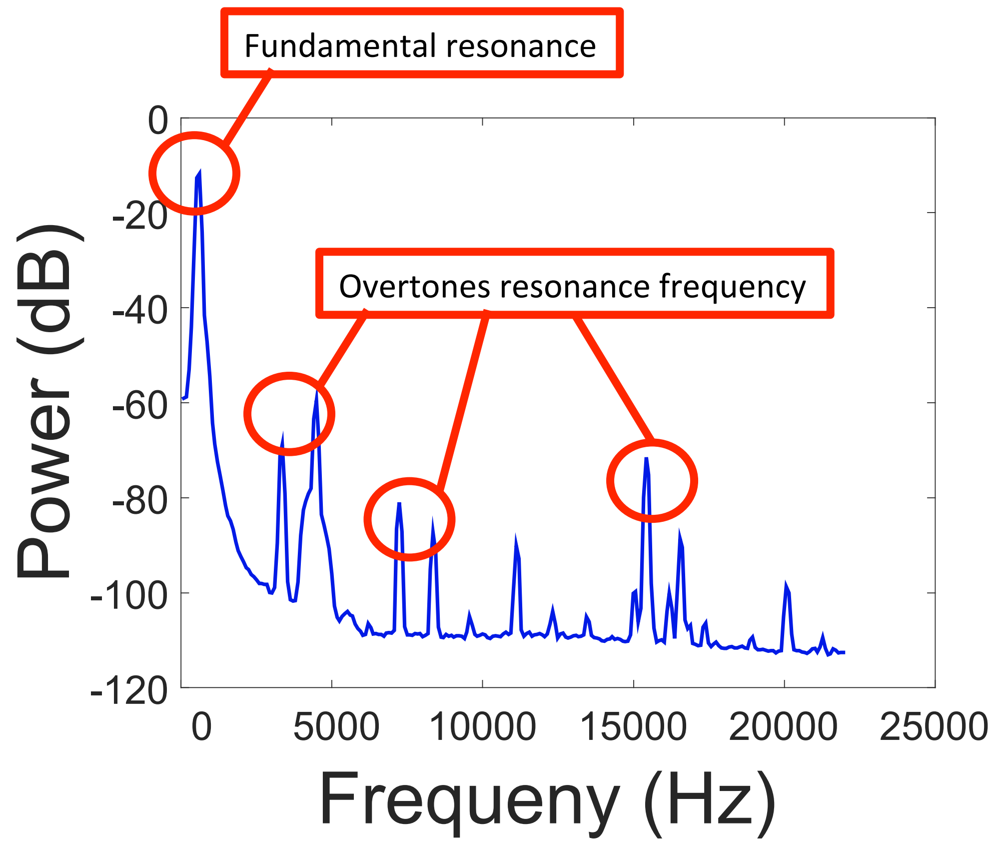
Anatomy of Wind-Musical Instruments



Output Becomes Large at Resonance Freq.

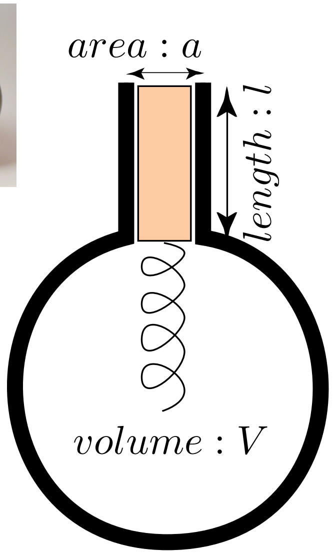


Lowest Resonance Frequency Determines the Tone



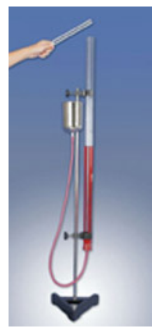
Design of Free-form Resonator is Difficult

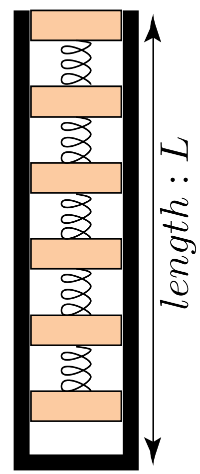
cavity-neck shape
Helmholtz resonator



0D mass-spring model

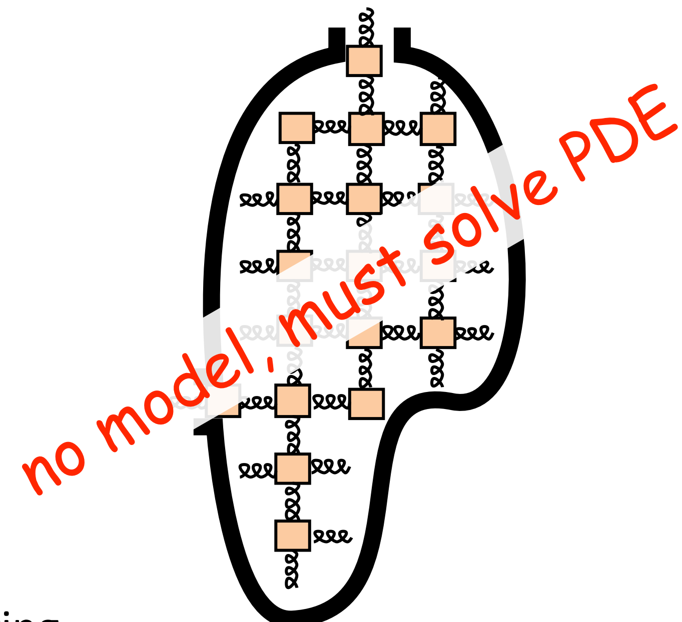
tube-like shape
air-column resonator





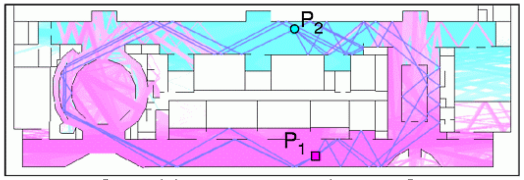
1D distributed mass-spring

free-form shape



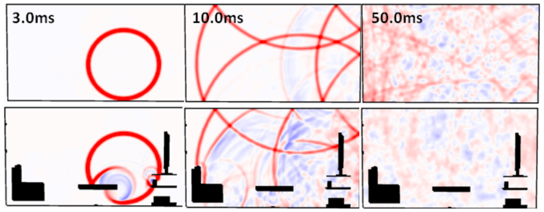
Methods to Compute Acoustics for 3D Shapes

- Geometric – Path Tracing
  - ☹inaccurate for resonance



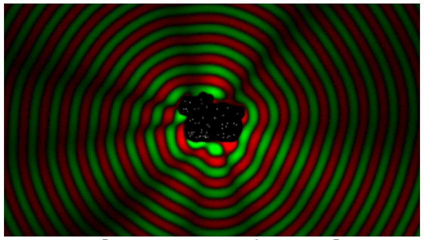
[Funkhouser et. al 2002]

- Time Domain – FTDT,FEM
  - ☹inefficient for stationary response



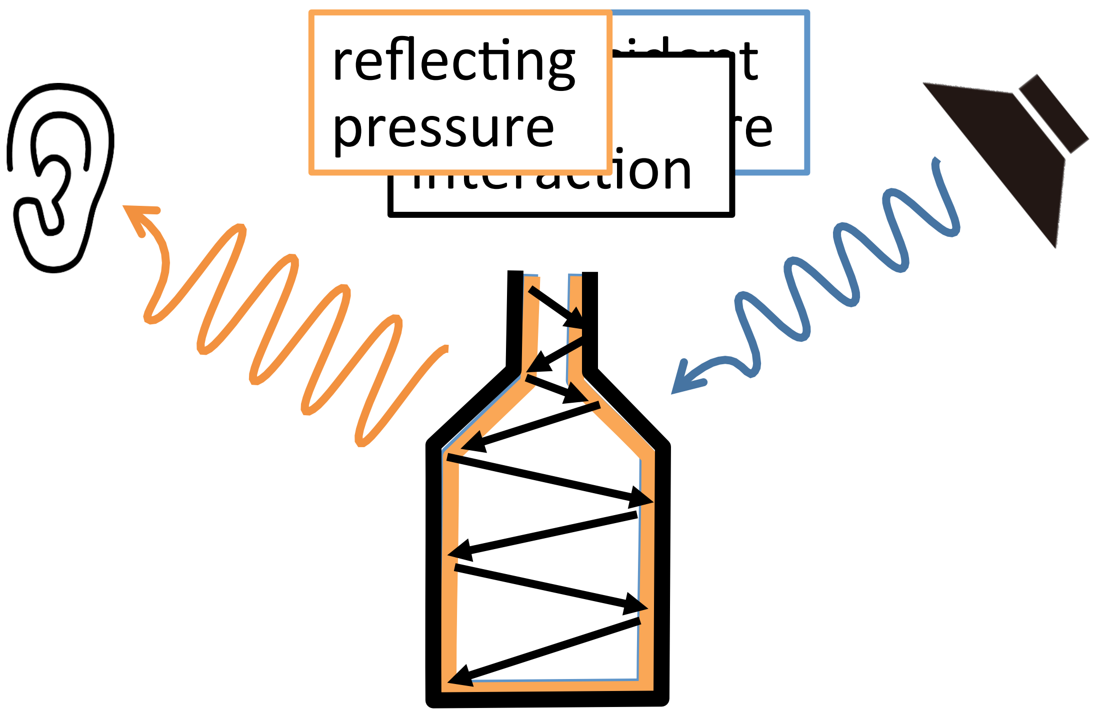
[Raghuvanshi et. al 2010]

- Frequency Domain – FEM, BEM
  - ☺efficient for stationary response
  - ☺accurate

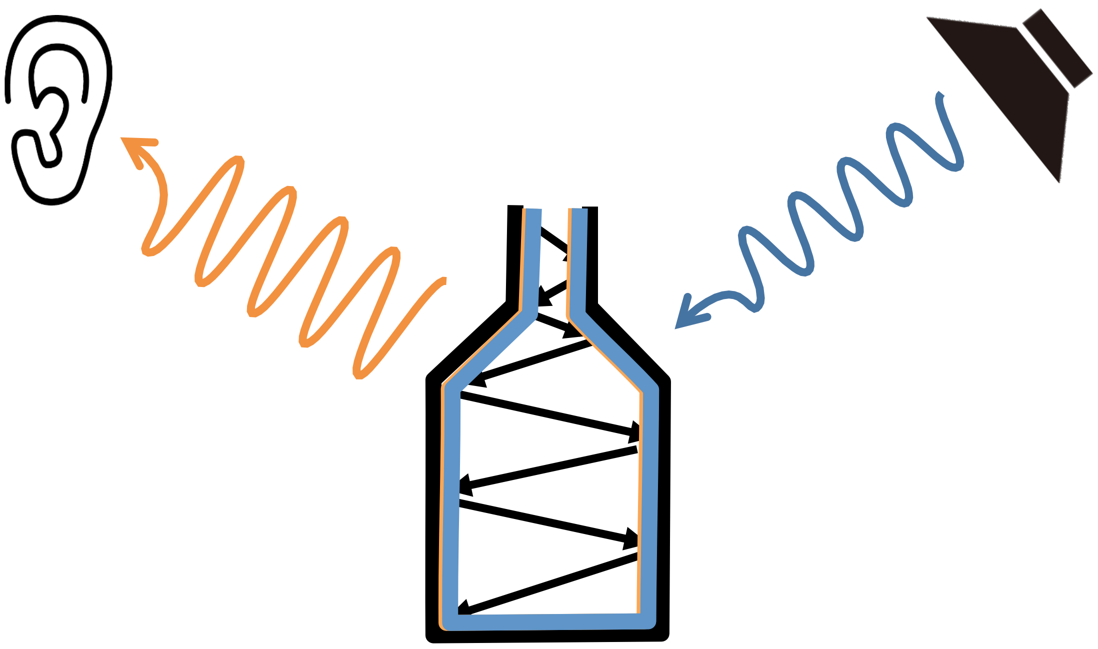

[James et. al 2006]

What is the Acoustic Resonance?

How Boundary Element Simulation Works

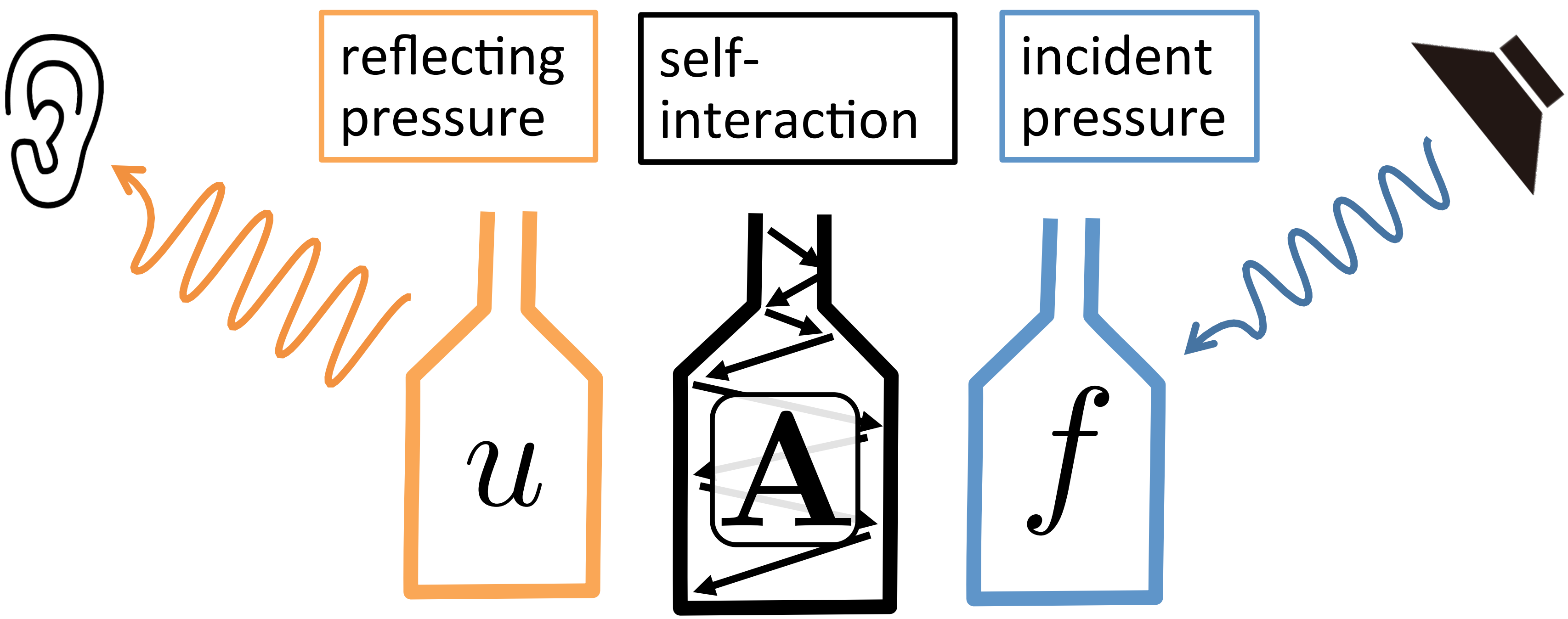


How Boundary Element Simulation Works



How Boundary Element Simulation Works

$$\mathbf{A}u = f$$



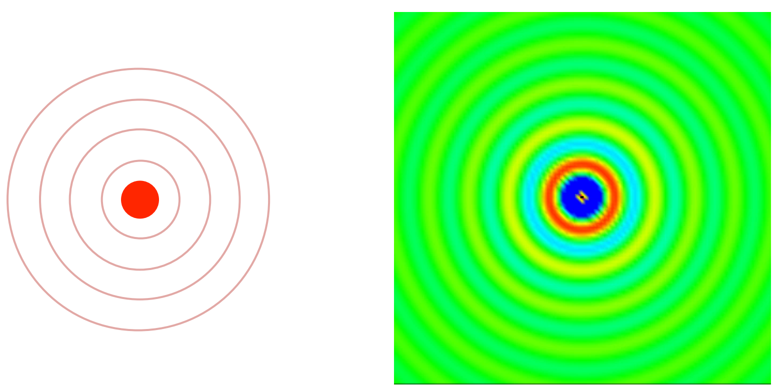
Solving Helmholtz Equation with BEM

Helmholtz equation

$$(\nabla^2 + k)u(x) = \delta(x)$$

Solution is a combination of kernels

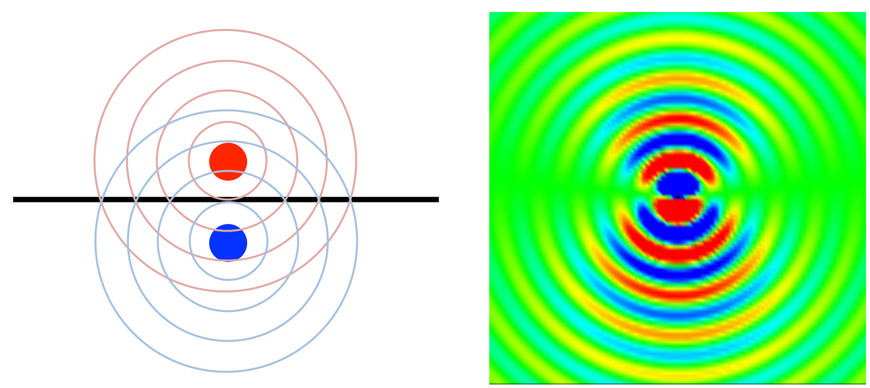
$$u(r) = e^{-ikr}/4\pi r$$



Total reflection boundary condition

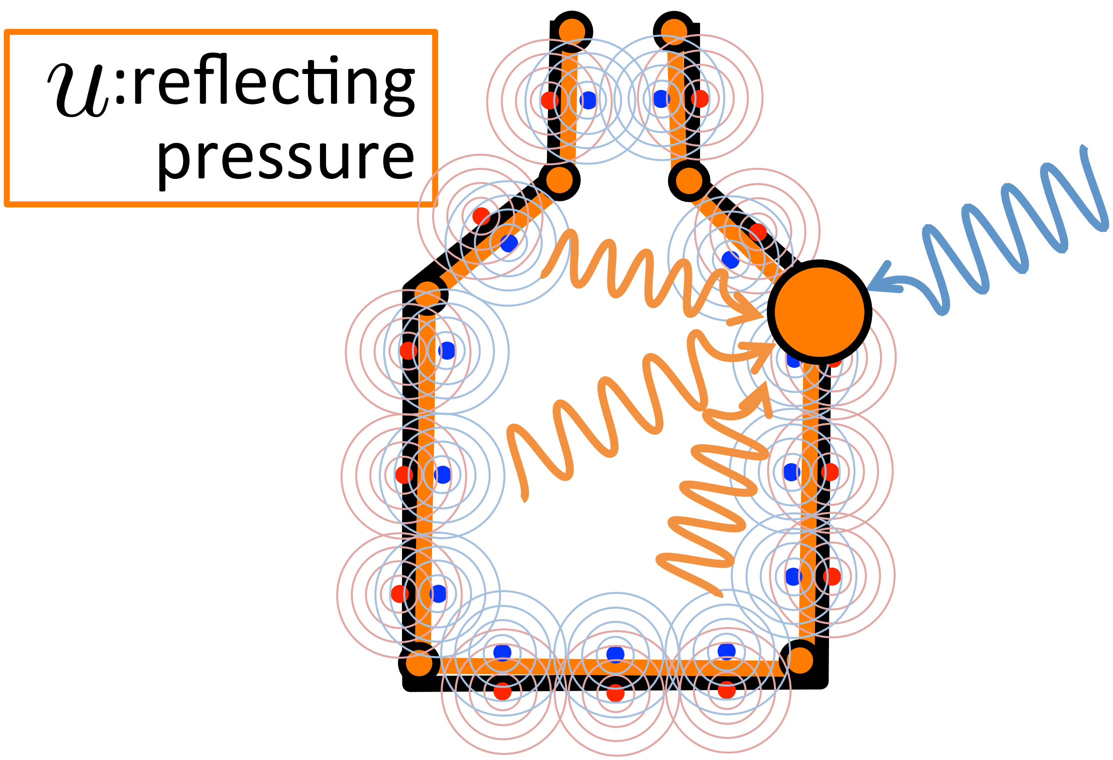
$$\partial u(x)/\partial x = 0$$

Dipole distribution on the surface

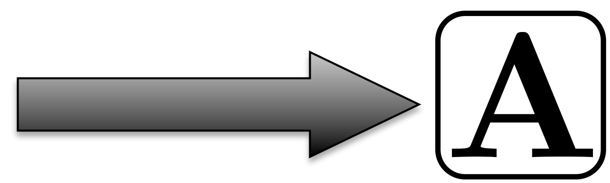


Solving Helmholtz Equation with BEM

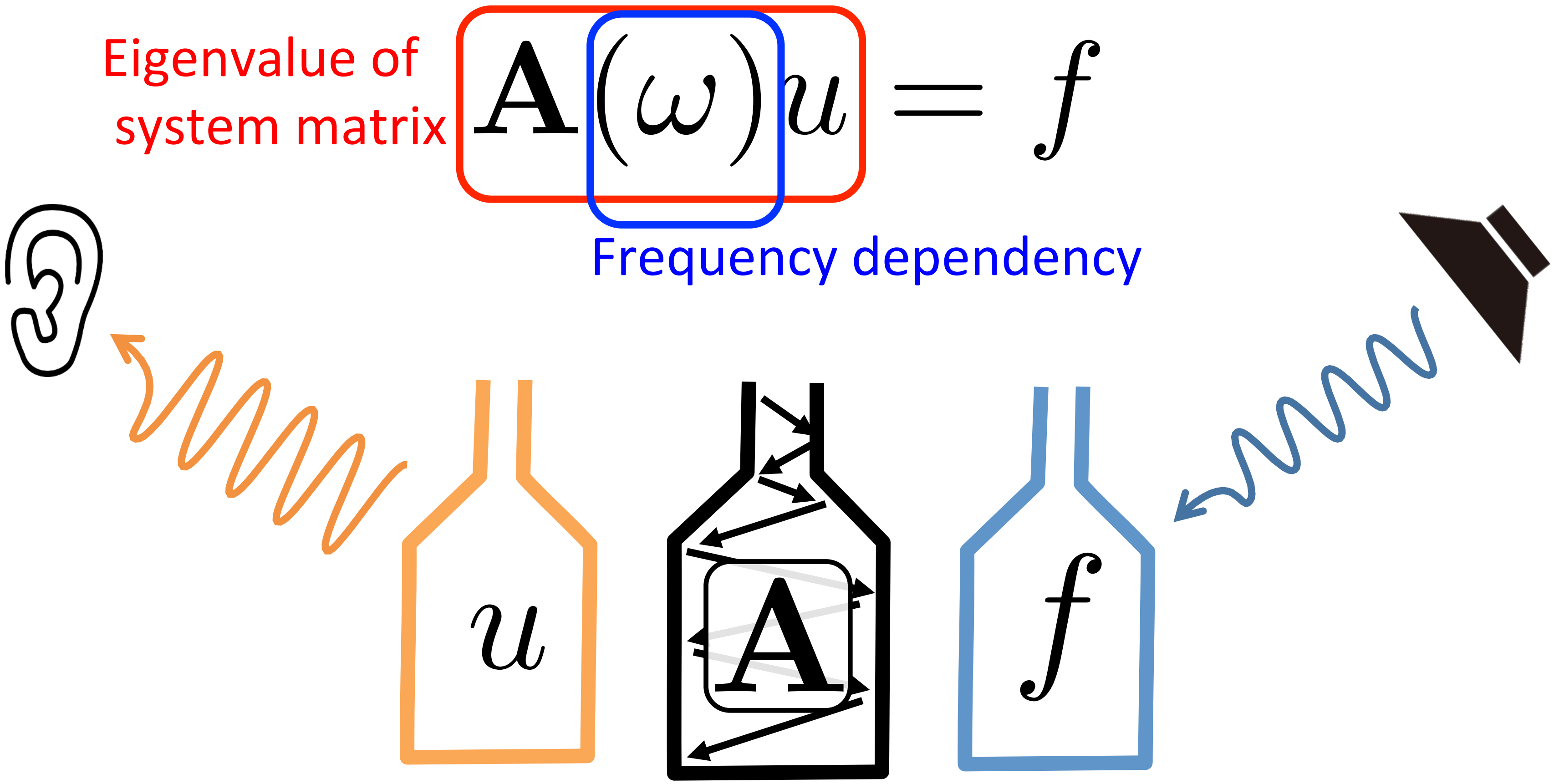
We assemble matrix to capture interplay of reflecting pressure



assembling relationships at all points



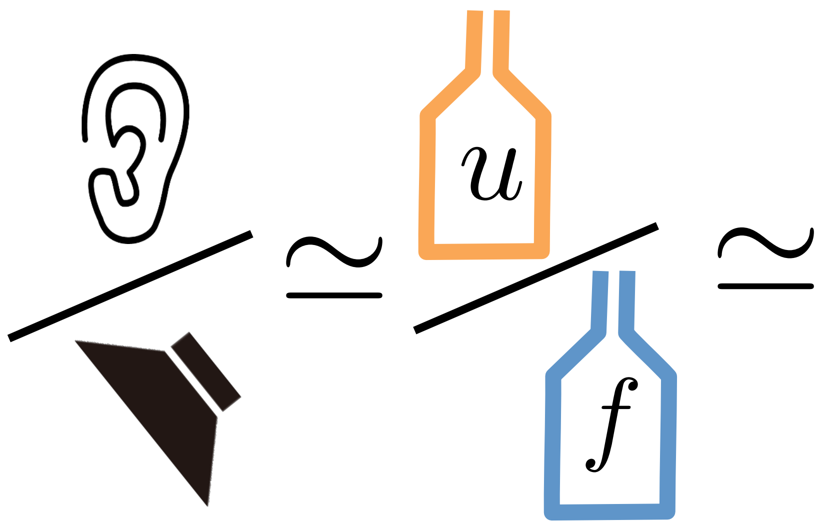
How Boundary Element Simulation Works



Small min. Eigenvalue gives a Large Amplification

Our goal is to find a frequency ω that makes $\lambda_{min}(\mathbf{A})$ nearly zero

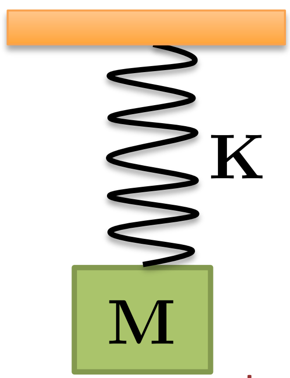
Amplify ratio =



$$\simeq \frac{1}{\lambda_{min}(\mathbf{A}(\omega))}$$

Eigen Analysis in Resonance Simulation

Simple harmonic oscillation problem

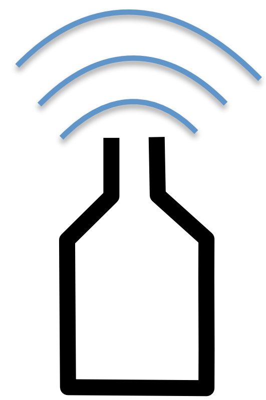


decomposable

$$\mathbf{A}(\omega) = \boxed{\mathbf{K}} - \omega^2 \boxed{\mathbf{M}}$$

$\lambda(\mathbf{A}) = 0$ ➡ Solution with General Eigenvalue Problem

Acoustic resonance simulation

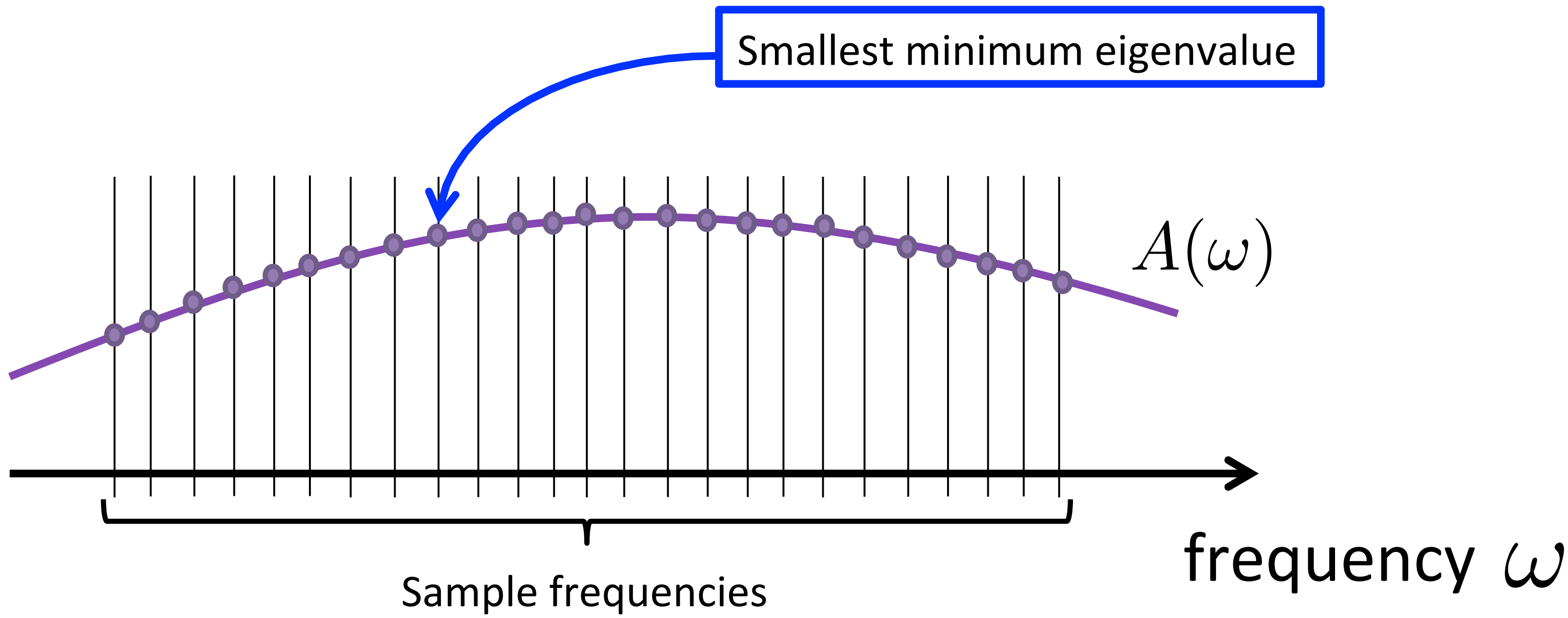


$\mathbf{A}(\omega)$ ➡ No decomposition available

$\lambda(\mathbf{A}) = 0$ ➡ No easy solution!

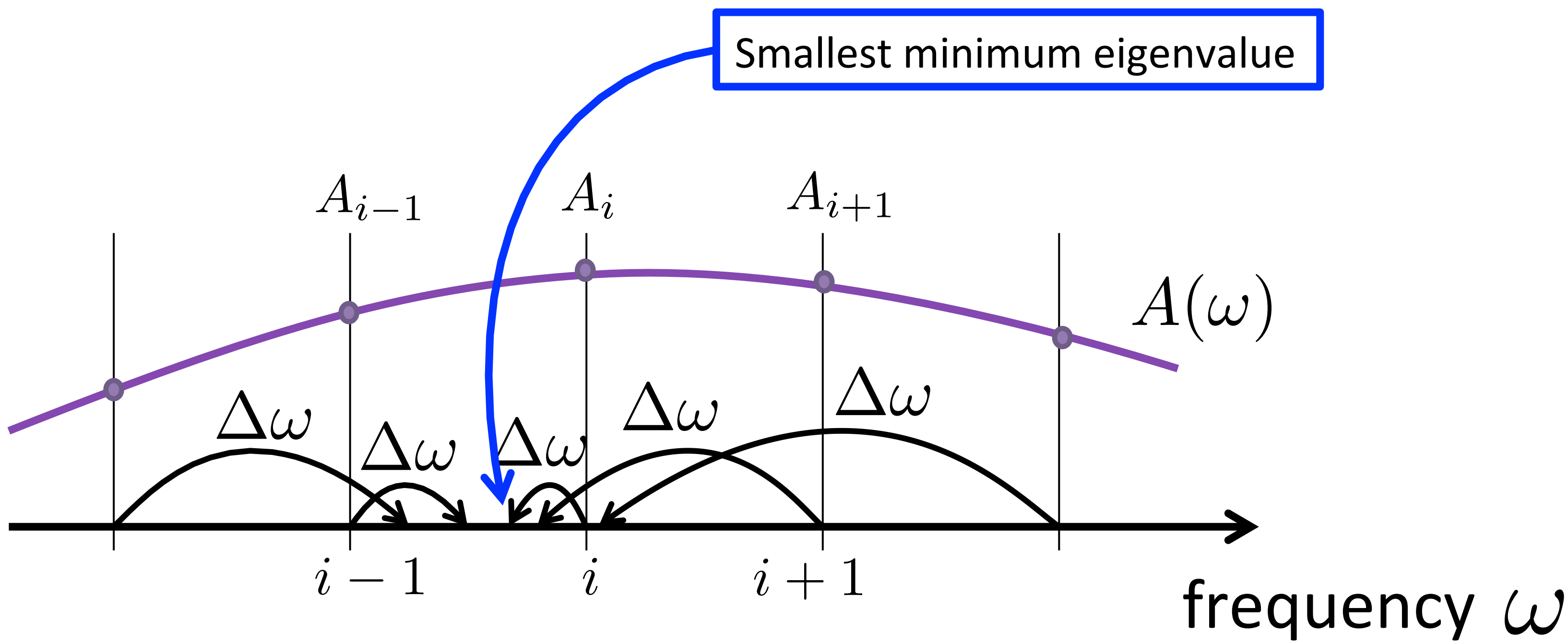
Traditional Frequency Sweep Method is Very Slow

Find smallest min. eigenvalue by computing matrices and their eigenvalue for many sampled frequencies



We Propose "Sparse Matrix Sampling"

We incrementally solve from sparsely sampled frequency

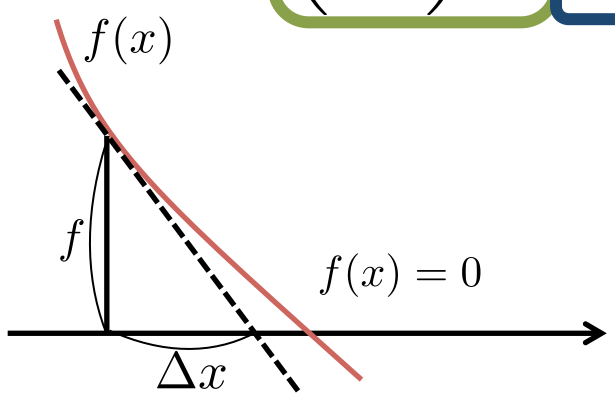


Computing Resonance Incrementally

Newton-Raphson

$$f(x) = 0$$

$$\Delta x = \left(\frac{df}{dx}\right)^{-1} f$$



Our scheme

$$\lambda_{min}\left[\mathbf{A}(\omega)\right] = 0$$

central difference

$$\frac{A_{i+1} - A_{i-1}}{\omega_{i+1} - \omega_{i-1}}$$

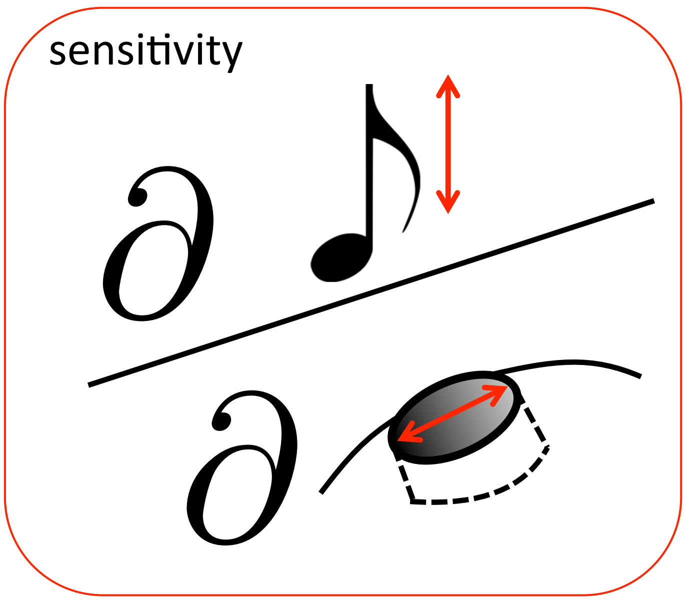
$$\Delta\omega = \lambda_{min}\left[\left(\frac{d\mathbf{A}}{d\omega}\right)^{-1}\mathbf{A}\right]$$

$$= \lambda_{max}\left[\frac{d\mathbf{A}}{d\omega}\mathbf{A}^{-1}\right]$$

We use the power method to find the maximum eigenvalue

AutoTune: Automatic Hole-size Optimization

Analytically computing the sensitivity of the tone with respect to the hole size



Iterative minimization of difference between simulated and goal frequencies

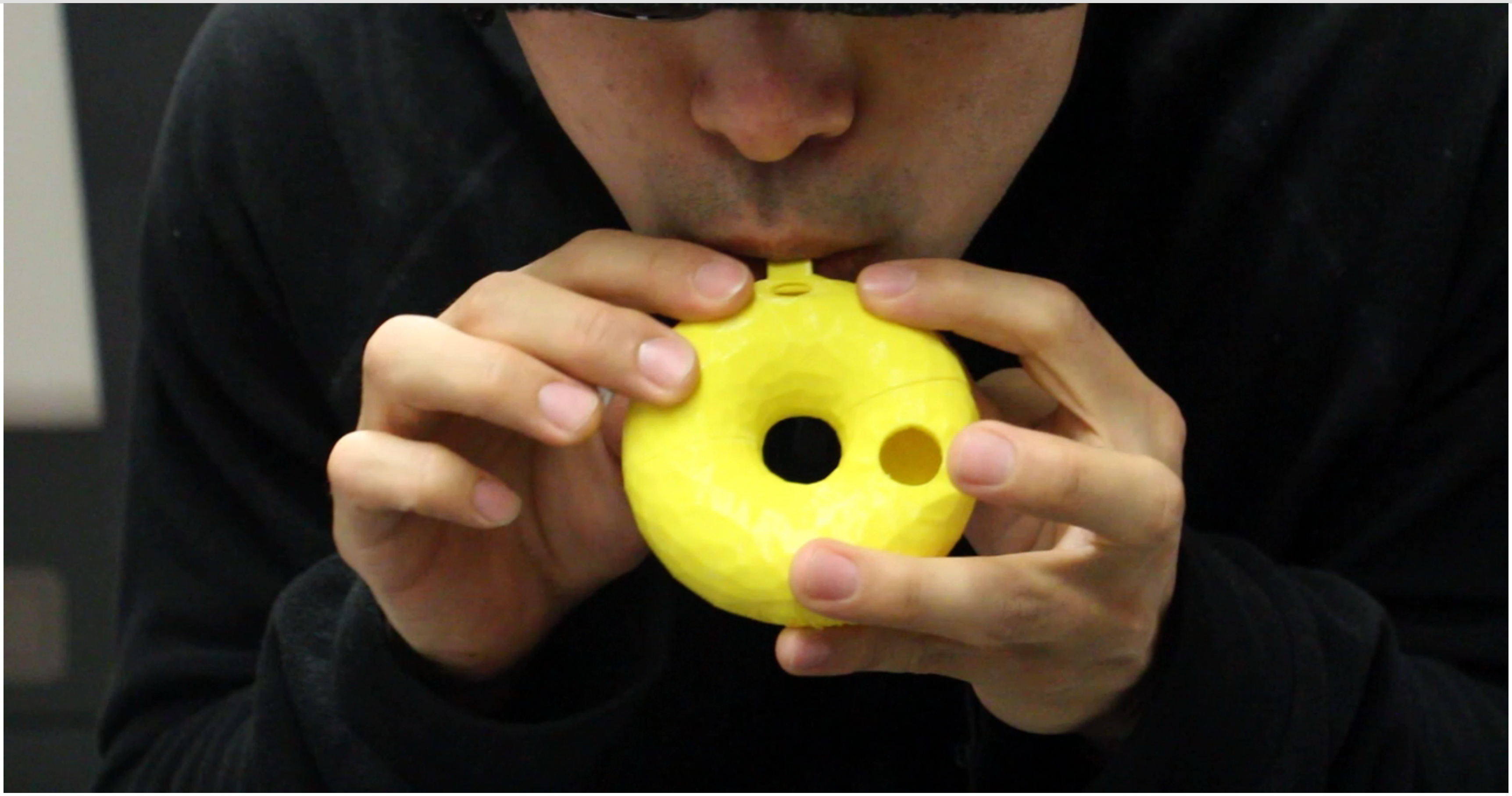
1st order real-time estimation
[Umetani et al 2011]

Live Demo!

“Puff the Magic Dragon”with the Stanford Dragon

Beethoven Symphony #9

Ocarina with Genus 1 topology

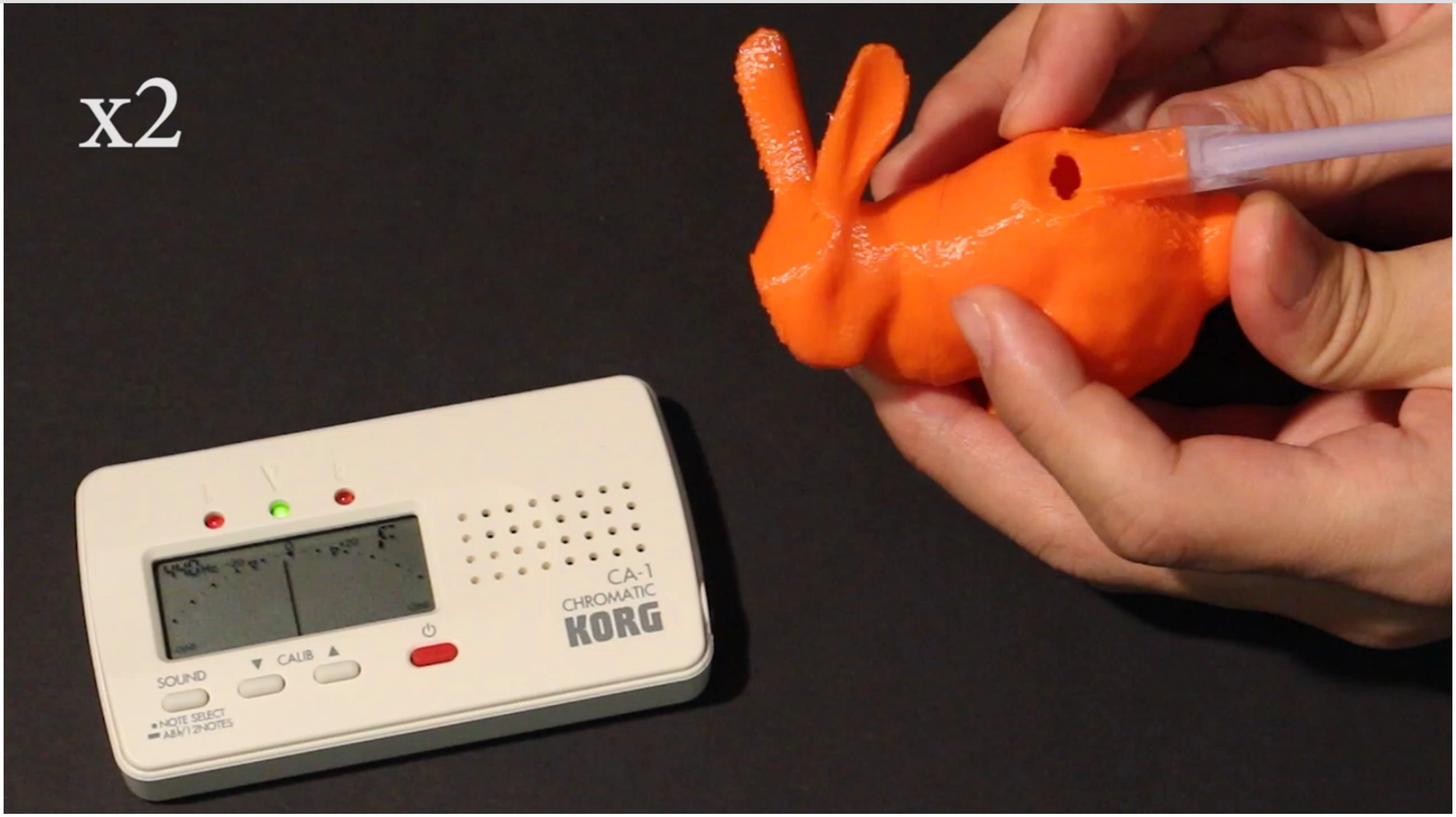


Flute

Big Ocarina

Saxophone

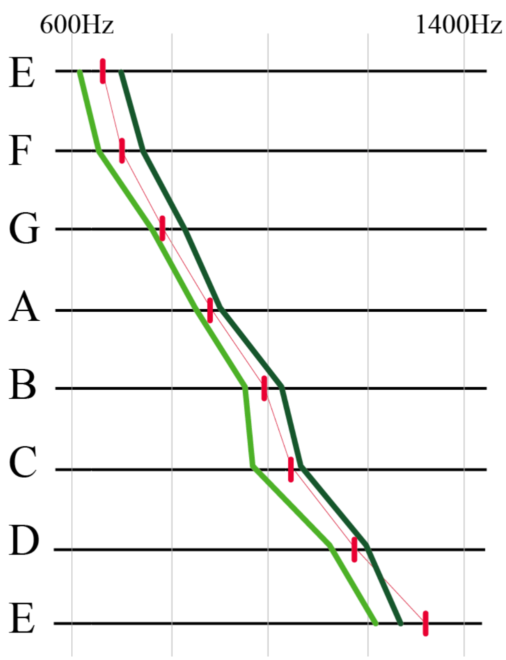
Chromatic Tuner Test

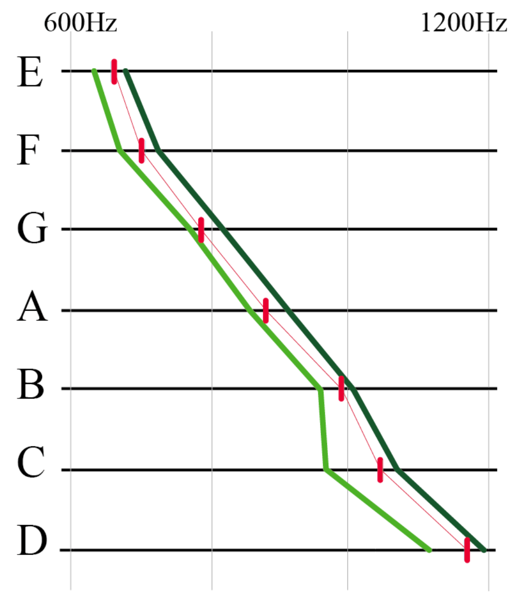


Accuracy: Instrument can Produce Right Tones

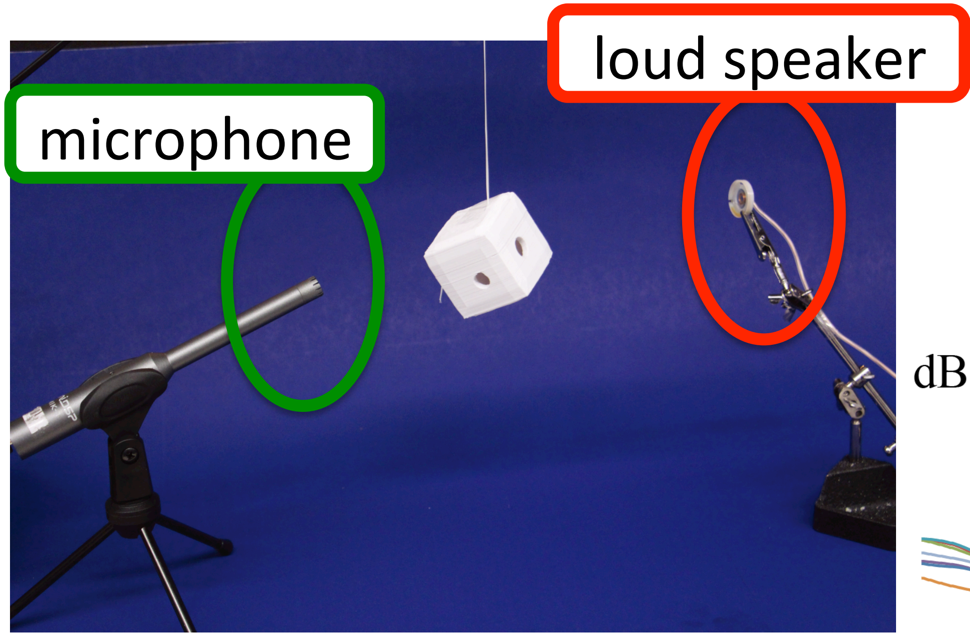
The target tone and the lower & higher bound of sound

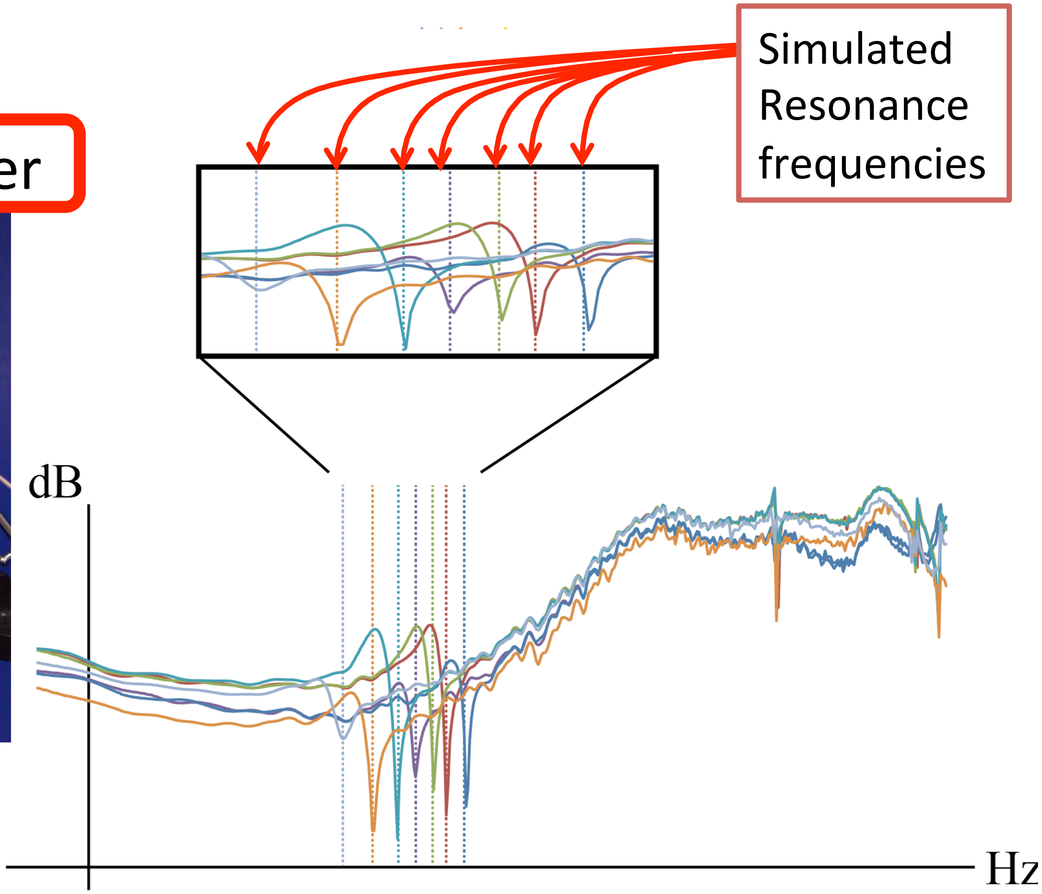
Only 4 cases in 104 target tones are out of tune





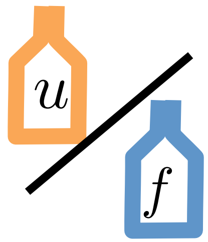
Passive Resonance Measurement: (<10Hz error)



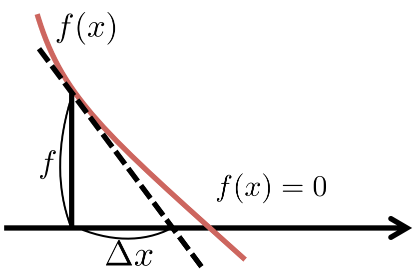


Key Contributions

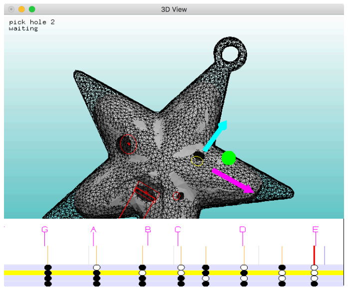
- Eigenvalue modeling of acoustic resonance



- Fast small minimum eigenvalue search

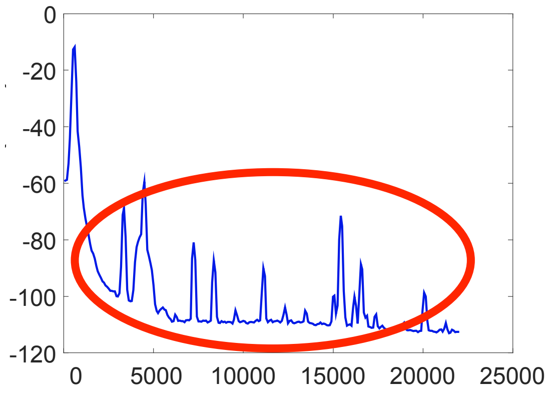


- Interface to design wind instrument



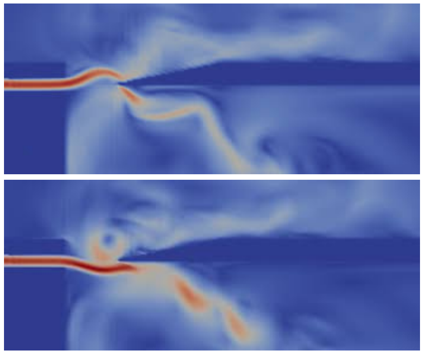
Limitation: Simulating Timbre (Sound Quality)

Simulating overtones



mouthpiece modeling

turbulence simulation



[N Giordano 2013]

Thank You for Your Attention!

Acknowledgements
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- Alexander Barnett at Dartmouth College
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