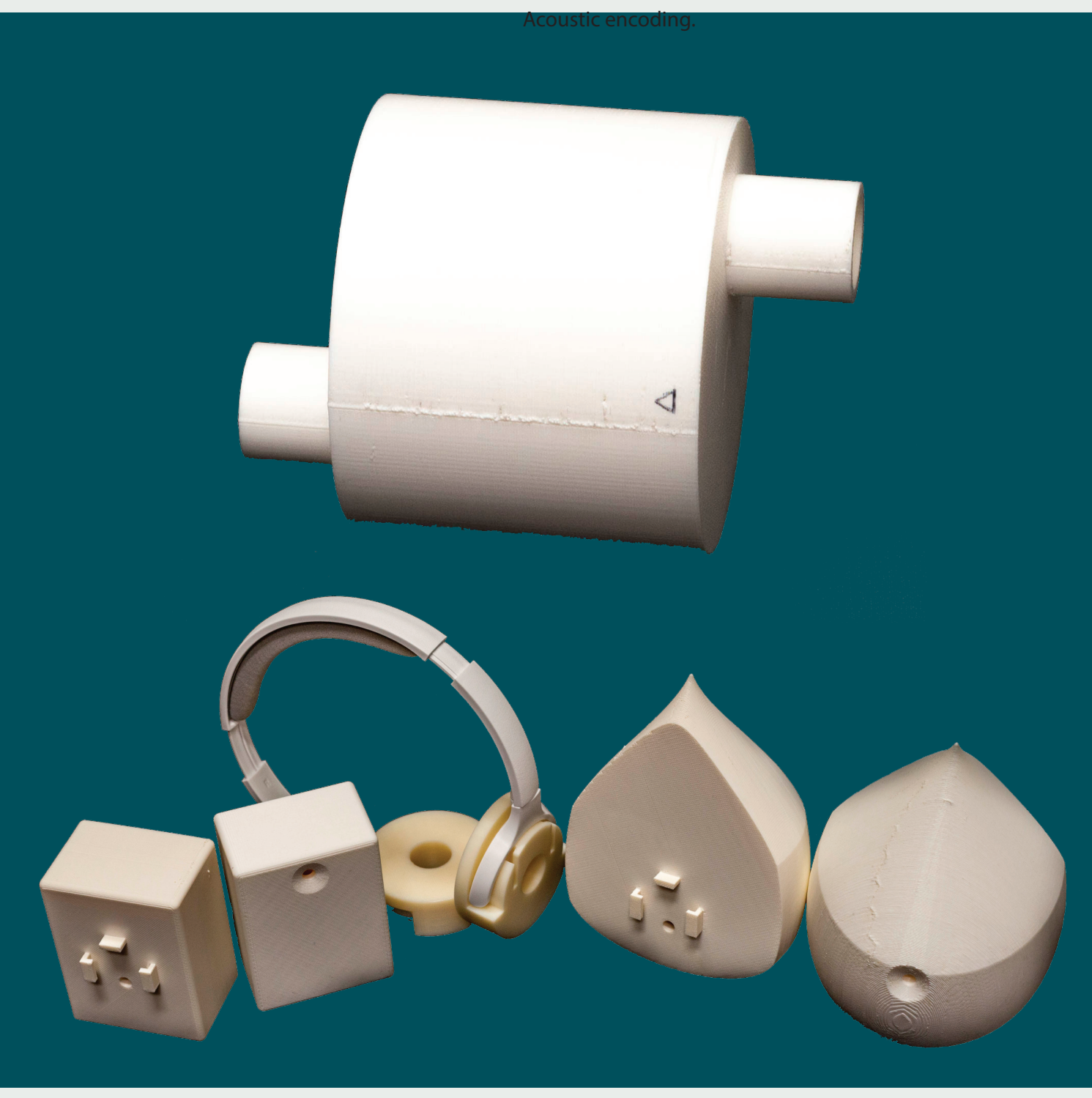
Acoustic Voxels:
Computational Optimization of Modular Acoustic Filters

Dingzeyu Li, David I.W. Levin, Wojciech Matusik, Changxi Zheng
Columbia University - Disney Research - MIT
SIGGRAPH 2016 - http://www.cs.columbia.edu/cg/lego/

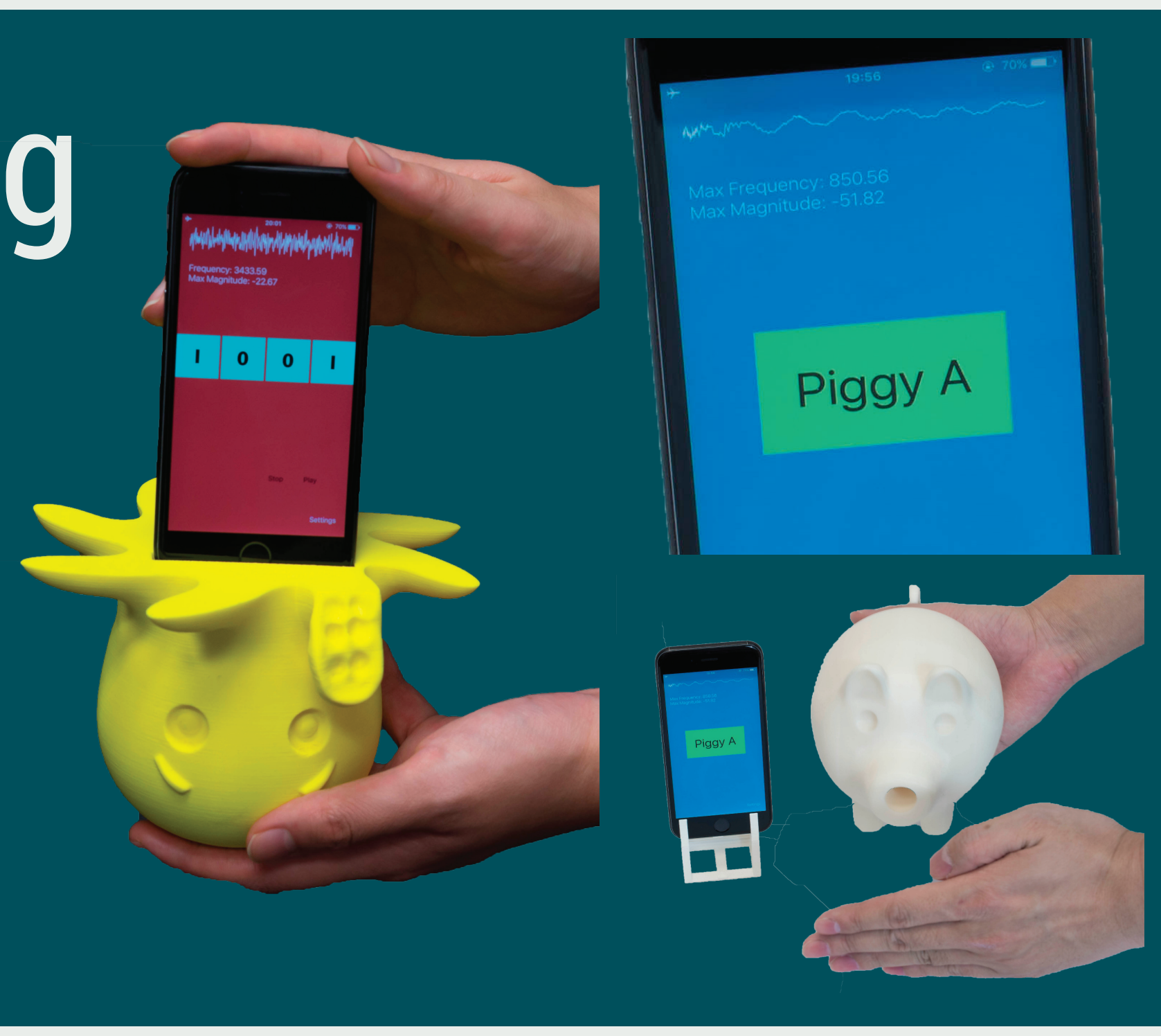


Muffler Design

- suppress peak frequencies from automobile/airplane engines

Wind Instrument Prototyping

- optimize the impedance curve to reach desired peaks for lip-reed instruments



Acoustic Signatures

- identify tapped objects via controlling the tapping sound
- encode bit strings by optimizing for the transmission loss

Motivation

Acoustic filters have a lots of applications:

car/airplane mufflers,
passtive ear aids,
wood-wind instruments,
acoustic tagging/signature,
and etc...

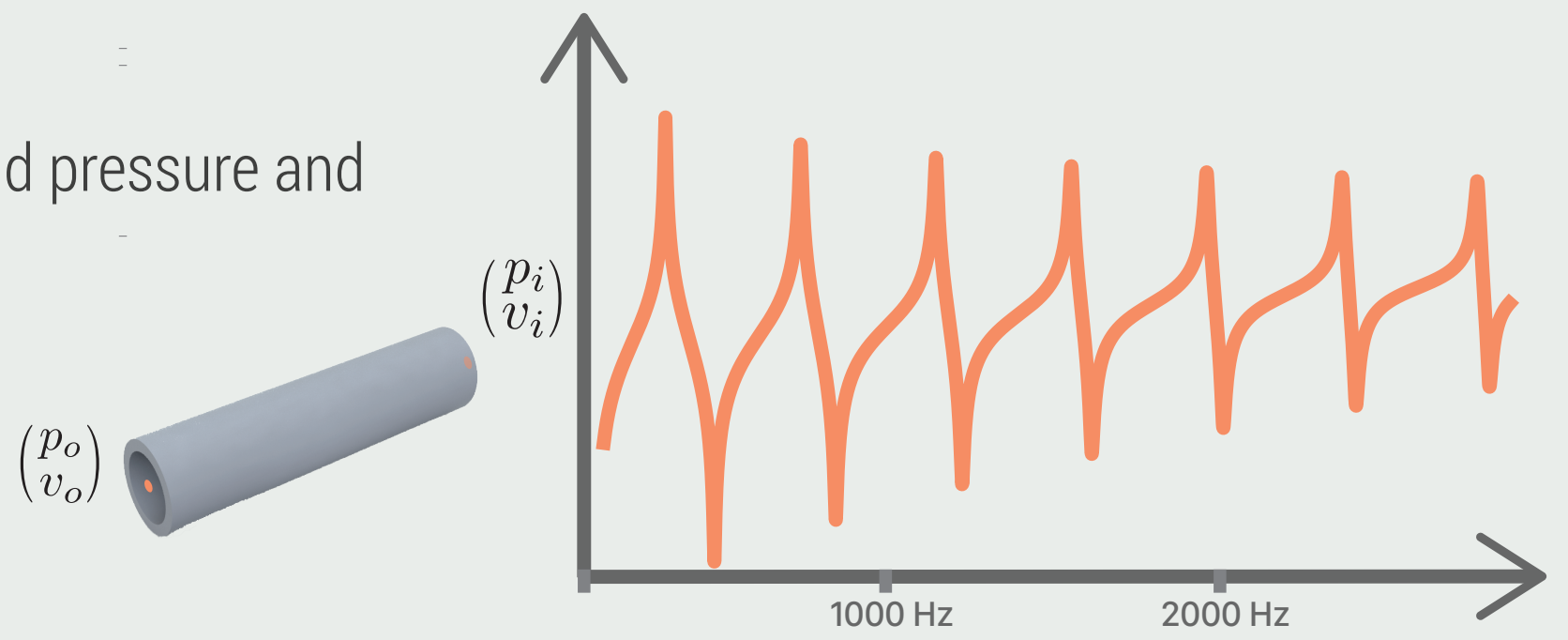
Yet, it is difficult to customize with desired properties.

Acoustic background

Input Impedance

At frequency ω, the ratio of the sound pressure and acoustic velocity at a location x.

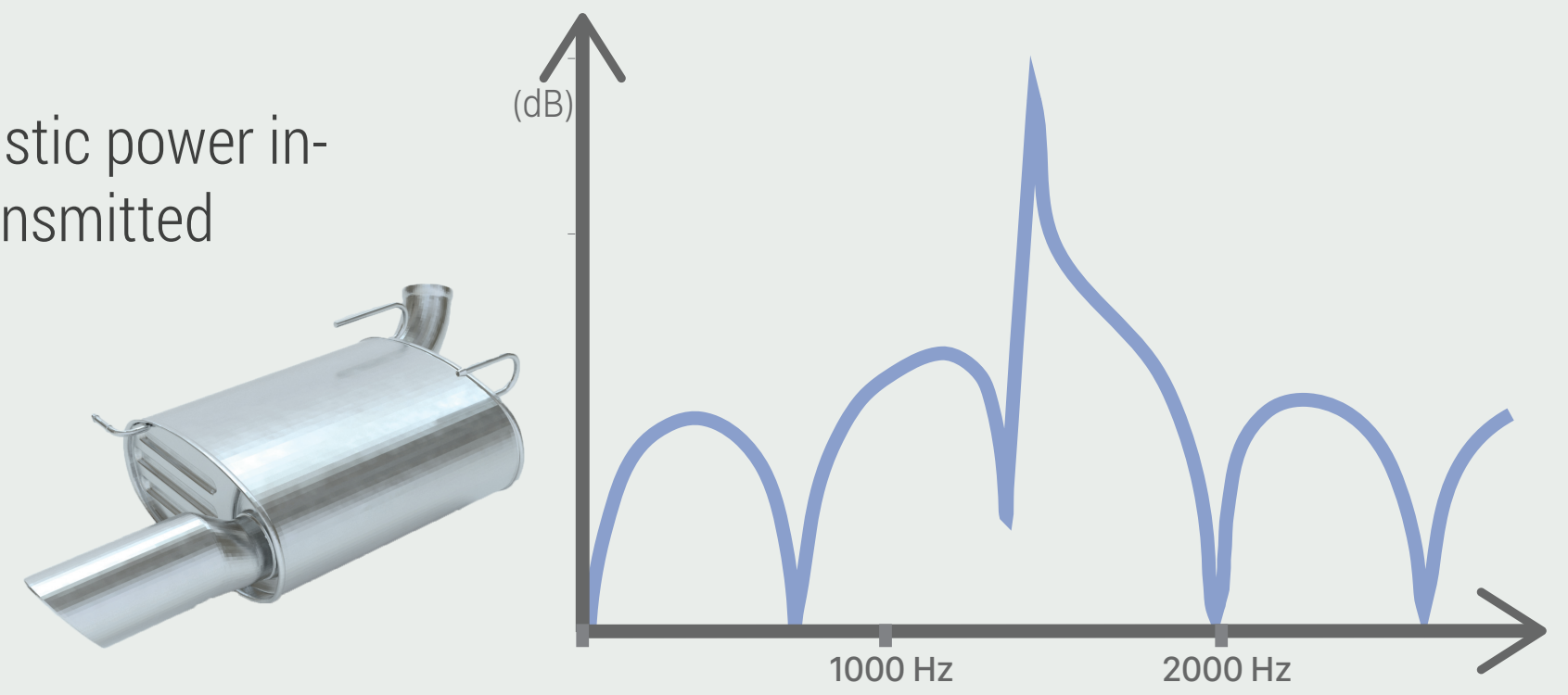
$$Z(x,\omega) = \frac{p(x,\omega)}{v(x,\omega)}$$



Transmission Loss

At frequency ω, the ratio of the acoustic power incident to the muffler to the power transmitted downstream into the environment.

$$L_{\mathrm{TL}}(\omega) = 10\log_{10}\left|\frac{S_{\mathrm{i}}p^2_{\mathrm{i}+}(\omega)}{S_{\mathrm{o}}p^2_{\mathrm{o}}(\omega)}\right|$$



Tranmission Matrices

Assume the acoustic pressure and velocity are both distributed uniformly over the cross-section, their relationship can be approximated linearly.

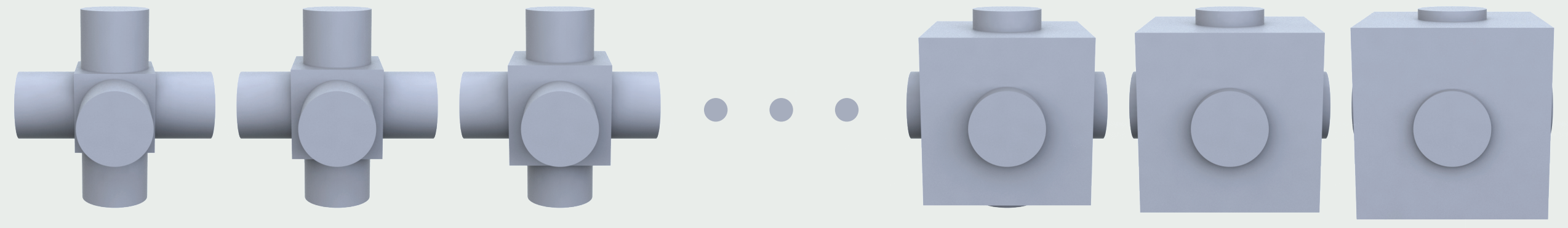
$$\begin{pmatrix} p_o(\omega) \\ v_o(\omega) \end{pmatrix} = \begin{pmatrix} T^\omega_{11} & T^\omega_{12} \\ T^\omega_{21} & T^\omega_{22} \end{pmatrix} \begin{pmatrix} p_i(\omega) \\ v_i(\omega) \end{pmatrix} \xrightarrow{\text{generalize}} \begin{pmatrix} p_1(\omega) \\ \vdots \\ p_n(\omega) \end{pmatrix} = \begin{pmatrix} T^\omega_{11} & \dots & T^\omega_{1n} \\ \vdots & \ddots & \vdots \\ T^\omega_{n1} & \dots & T^\omega_{nn} \end{pmatrix} \begin{pmatrix} v_1(\omega) \\ \vdots \\ v_n(\omega) \end{pmatrix}$$

2-port version — generalize → n-port version

Methods

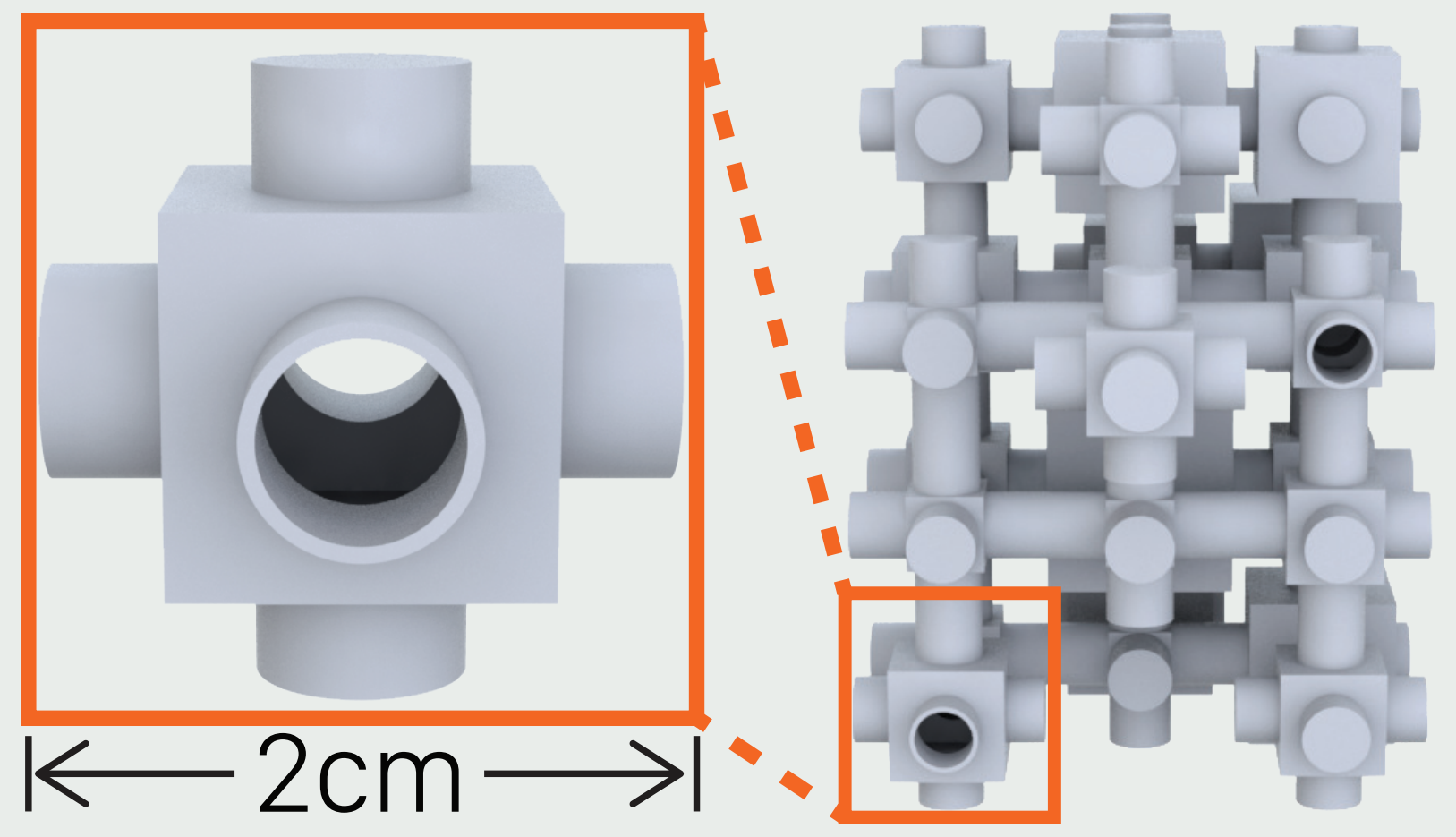
To construct acoustic filters, we propose 3 key steps:

(1) use modular primitive resonators



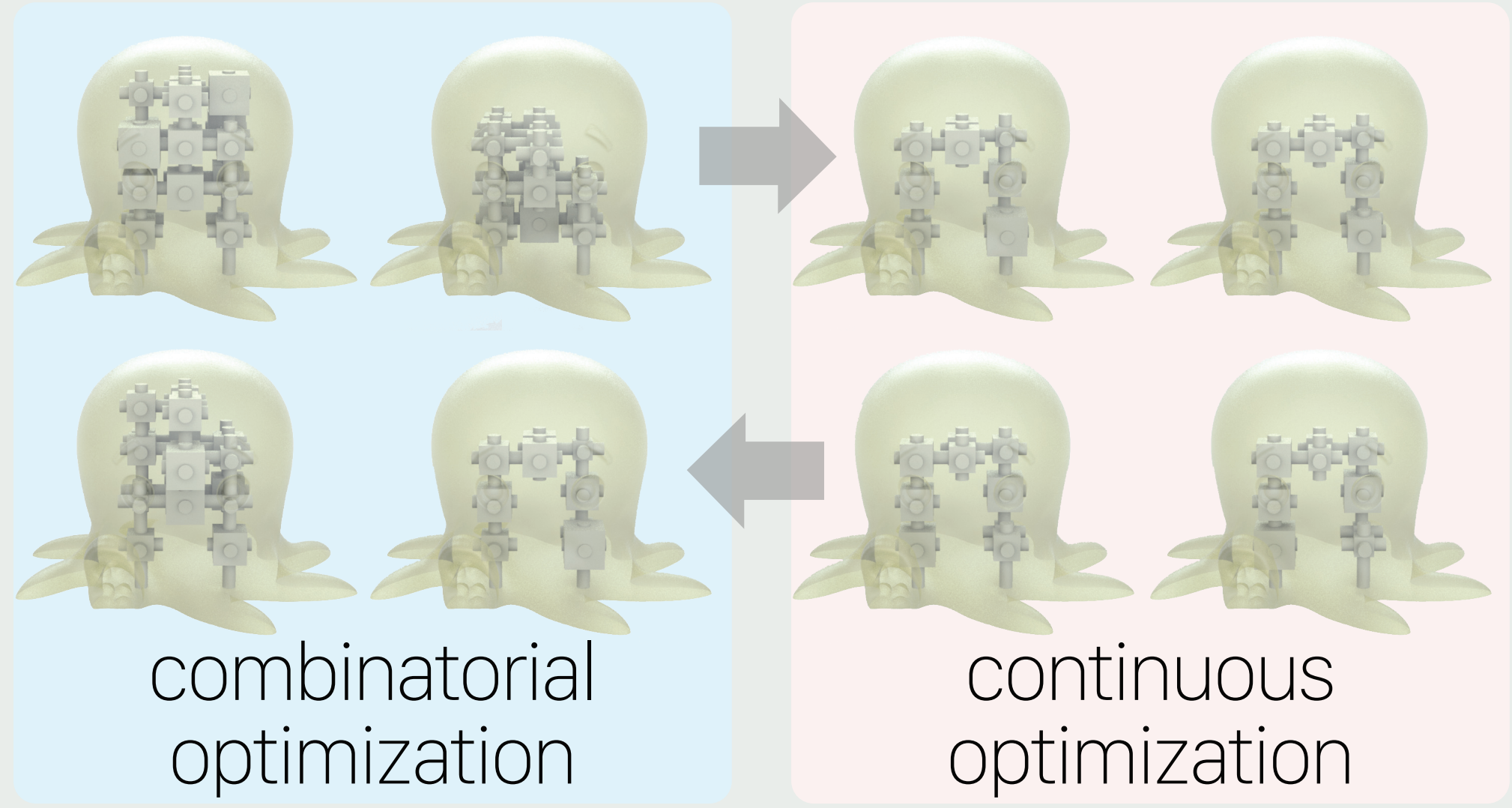
We use a simple shape as our primitive resonator hollow cube with extruded cylinders on its six faces. All the cylindrical extrusions have the same radius and length and therefore the bounding boxes of all primitives stay the same.

(2) assemble primitives together



The primitives can be composed together at their faces by connecting an inlet and an outlet to form a complex structure.

(3) iteratively optimize the assembly connectivity and individual primitive parameters

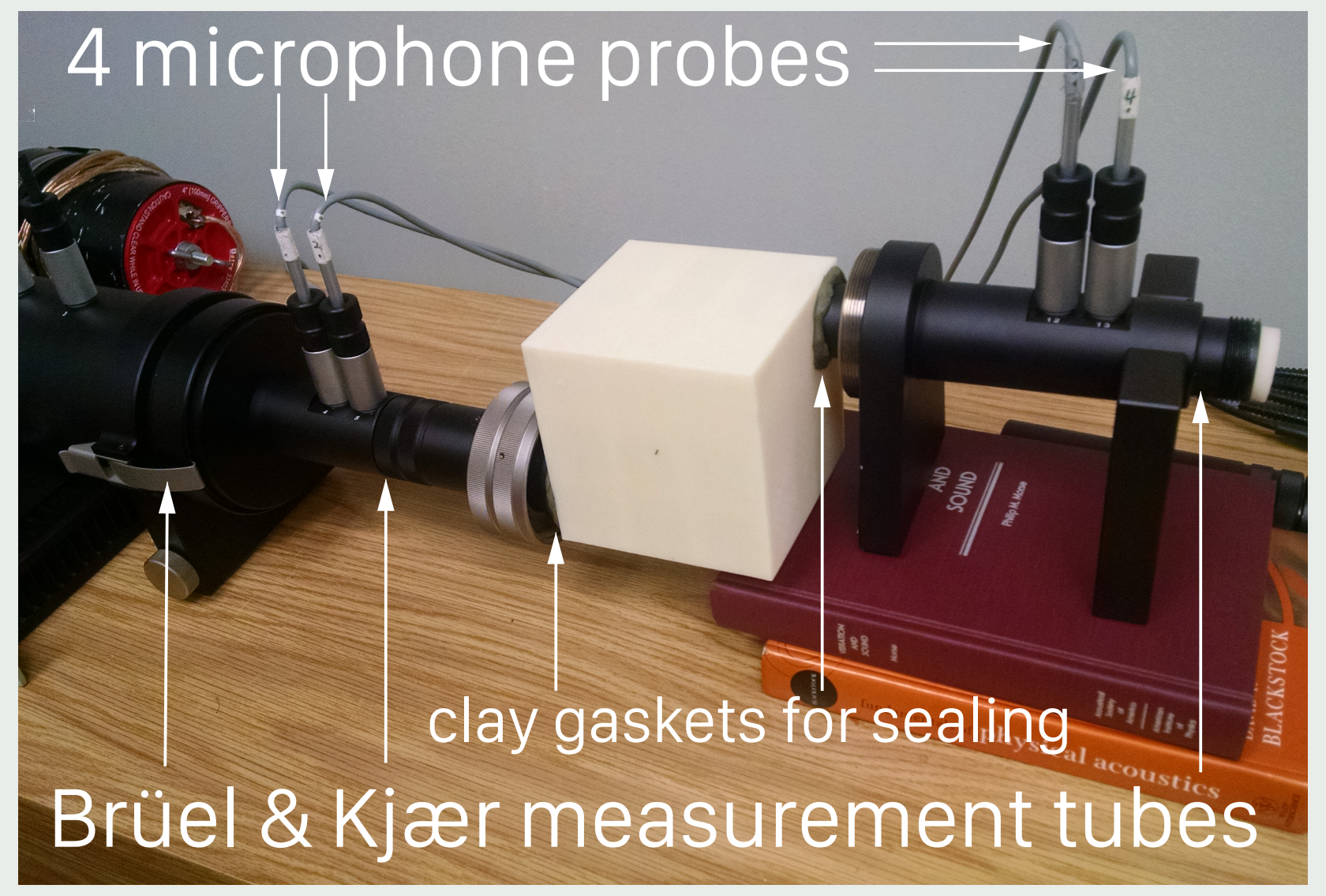


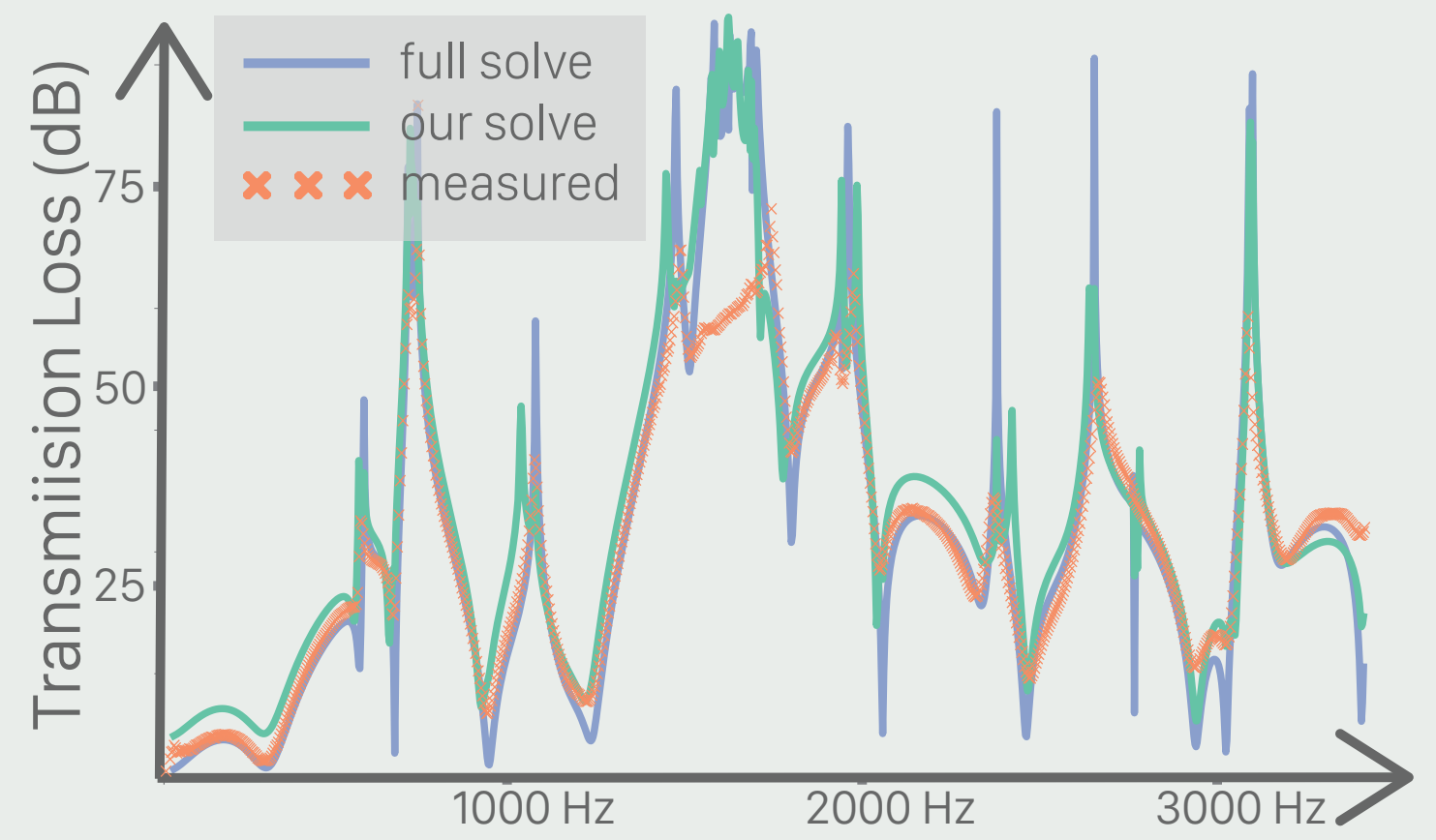
In the optimization, we take random samples for the connectivity of the resonators. We also continuous change the size of each hollow cube. Our novel optimization framework iterates between these two combinatorial (SMC) and continuous (BFGS) stages, in order to satisfy the desired acoustic goals.

Results

We fabricated our designs using Stratasys uPrint SE Plus, a filament-based 3D printer with a layer resolution at 0.254mm. We use ABS-P430 plastic as the model material and a dissolvable support material which can be washed away upon finish. The fabrication time varies from a few hours to a day.

Validation via industrial laboratory test

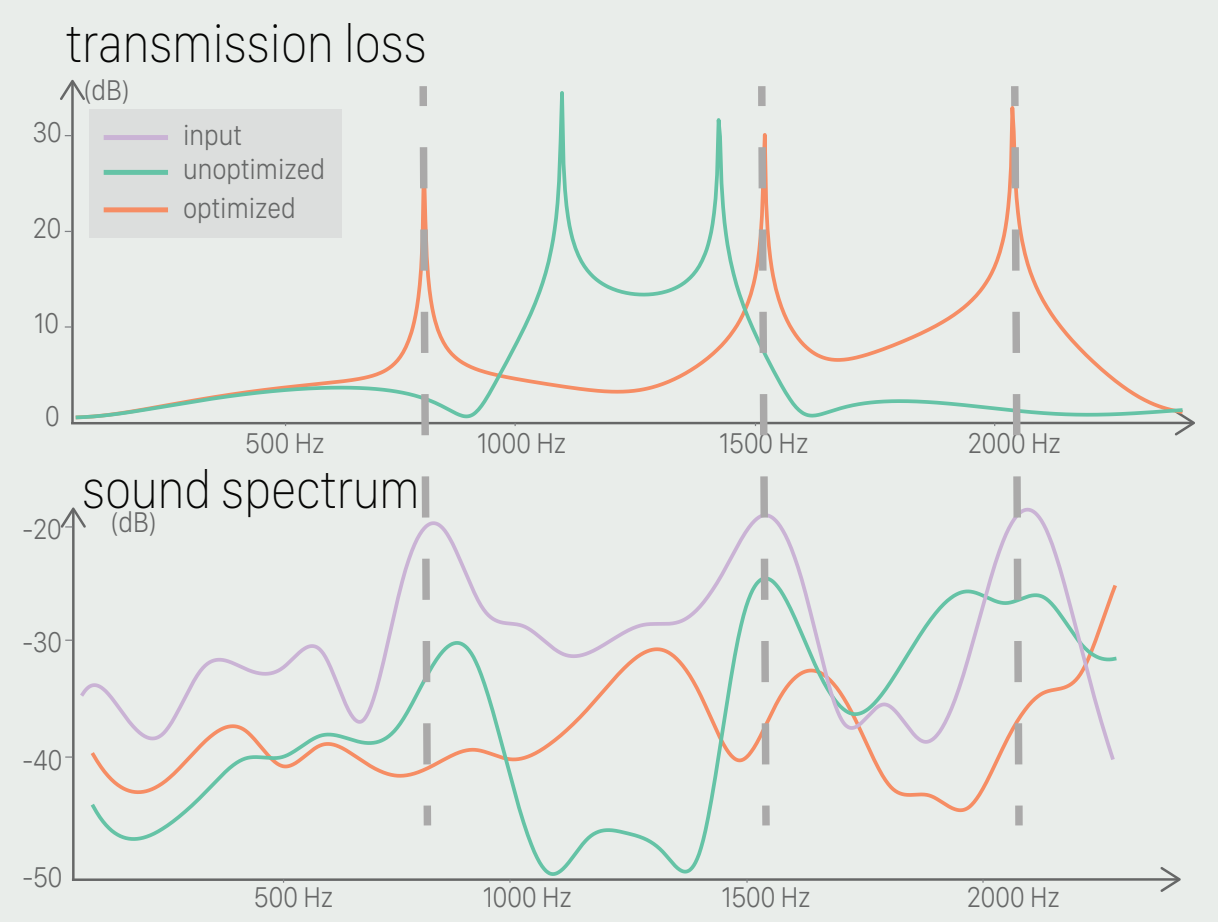




We measured the transmission loss (TL) of our prints using Brüel & Kjær 4206-T measurement tubes with the 4-microphone technique [Tao and Seybert 2003].

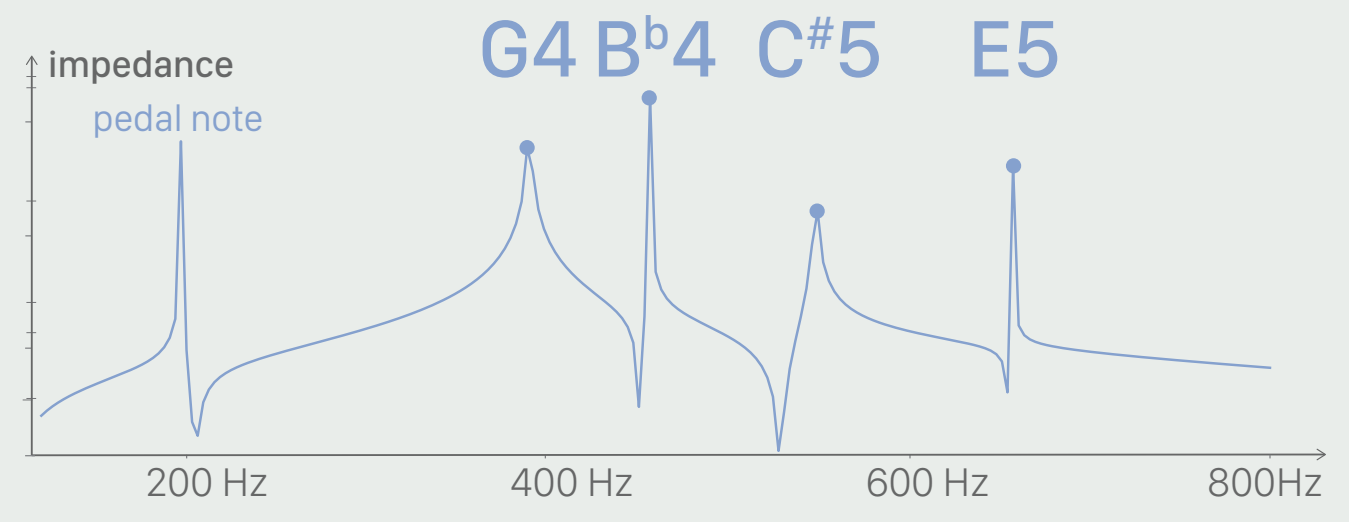
Application 1: Muffler Design

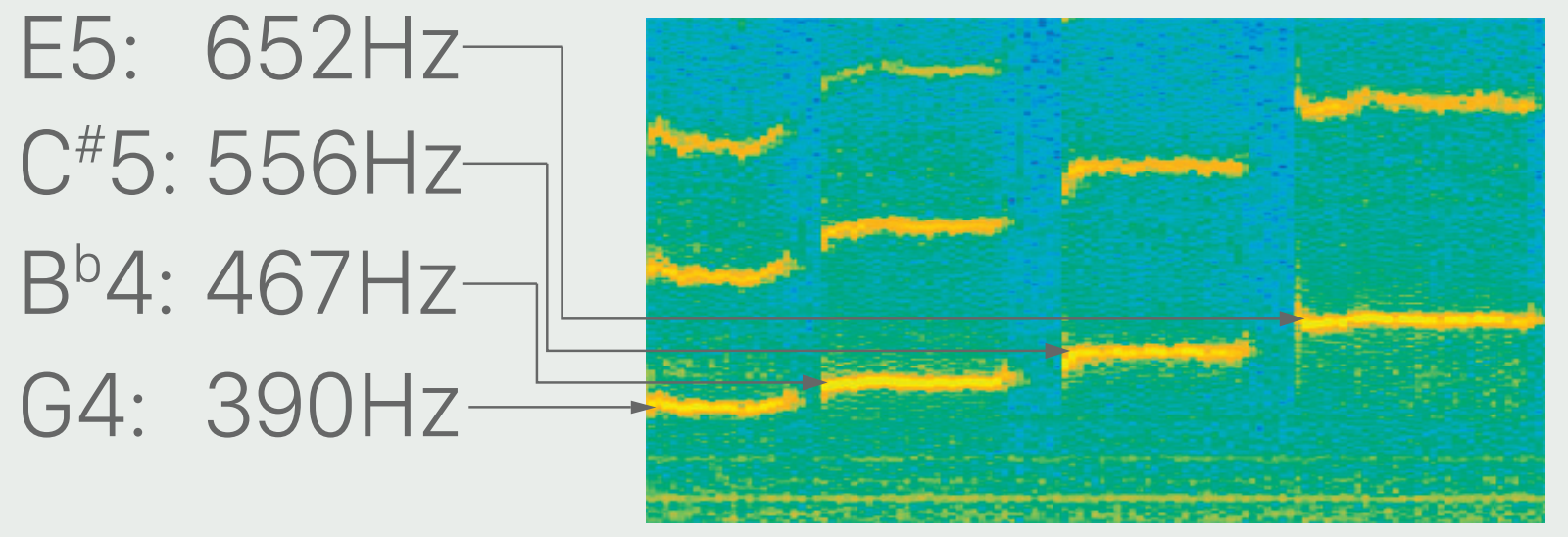
We demonstrate the possibility of controlling muffler behavior at finer granularity using our modular filter, because of its ability to construct complex muffler structures. We aim to construct mufflers that selectively attenuate sound near a set of discrete frequency values. Our first example is to attenuate a recorded engine noise, which has peaks in frequency domain at 850Hz, 1550Hz, and 2100Hz.



Application 2: Wind Instruments Prototyping

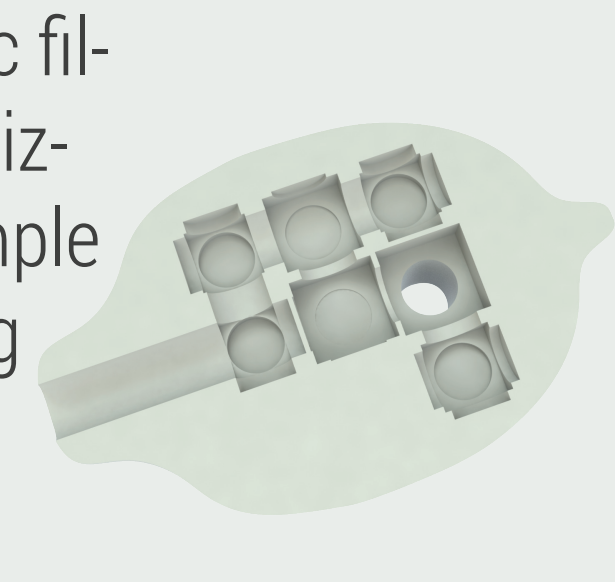
Acoustic resonator is a key part of wind instruments.We applied our method to customize trumpets, for which the customization is twofold: control the set of notes that a trumpet can play and customize its shape, which in our case is a cartoon hippopotamus shape. The resulting trumpet relies on the standard mouthpiece for excitation. We define an objective functions that maximizes the impedance values at the frequencies of those notes.





Application 3: Acoustic Signatures

Acoustic tagging. We embed tags into the acoustic filtering effects of a shape, by computationally optimizing its internal structure. We have implmened a simple iPhone application that decodes a recorded tapping sound and identifies the PIGGY. Note the tapping sound corresponds to the resonant frequencies.



Acoustic encoding. Taking one step further, we demonstrate the ability to encode bit strings, akin to the idea of QR code but without visual distraction. We fabricated three OCTOPUSES with identical surface shape, and use them to encode different 4-bit strings, including 0000, 1001, and 0111.

Acknowledgements

We thank the anonymous reviewers for their feedback. We are grateful to Jui-Hsien Wang for early discussion, Ioannis Kymissis and Andrei Shylo for supporting 3D printing facilities, Chang Xiao for iOS development help, Yonghao Yue for rendering advices, Yun Fei for improving the video, Timothy Sun for video narrative, Henrique Maia for proofreading, and Alec Jacobson for discussion on wind instrument examples. We also thank Syed Haris Ali for open sourcing EZAudio library. Meshs for PIGGY, OCTOPUS, and BOB are provided by courtesy of www.craftsmanspace.com, Makerbot, and Keenan Crane, respectively. This research was supported in part by the National Science Foundation (CREER-1453101) and donations from Adobe.

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Contact:

Dingzeyu Li
dli@cs.columbia.edu