



# Contactless Material Identification with Millimeter Wave Vibrometry

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\* indicates equal contribution.

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**ILLINOIS**  
URBANA - CHAMPAIGN

# Material sensing opens up many applications!

Robotic Grasping



Quality Control



Waste Sorting



Liquid & Food Control



# Material sensing opens up many applications!

Robotic Grasping



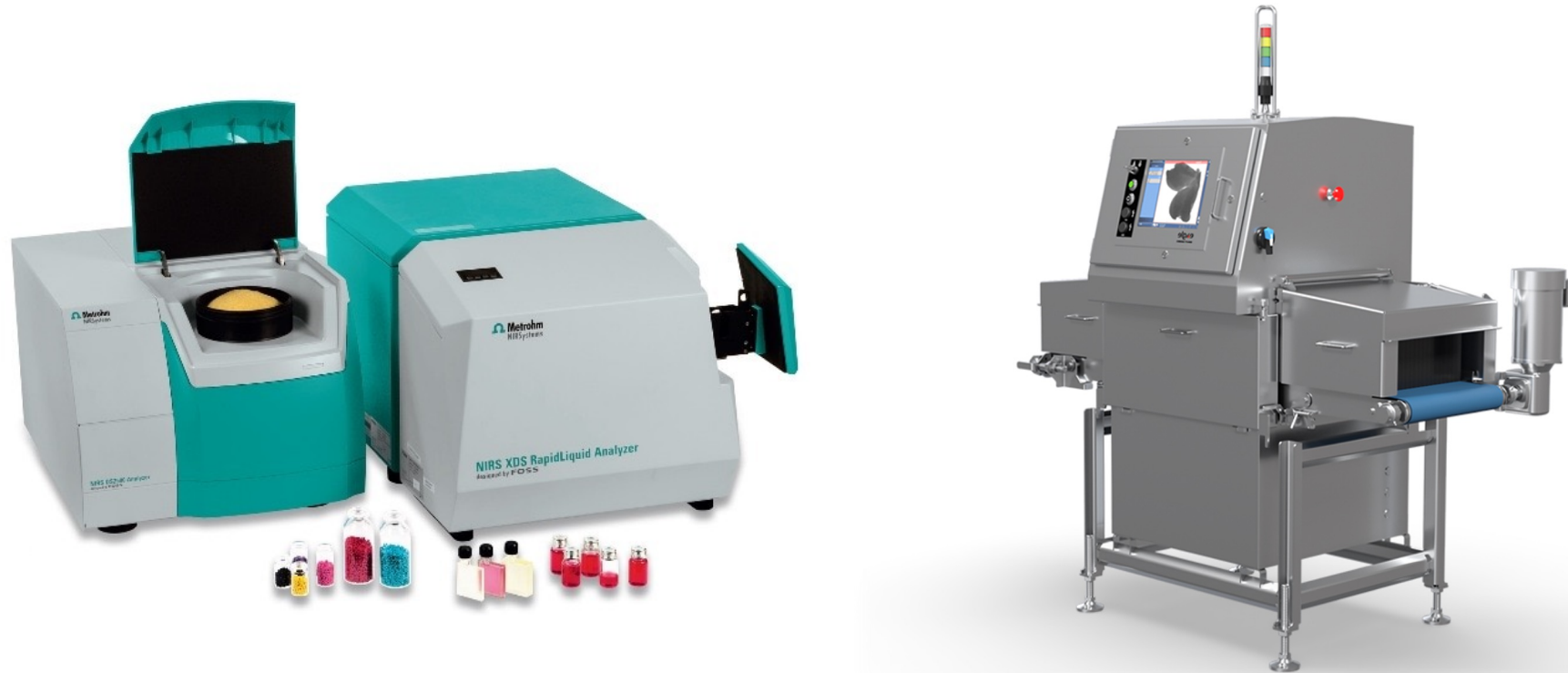
Quality Control



Practical & Scalable → Non-Invasive & Inexpensive!



# Systems used today

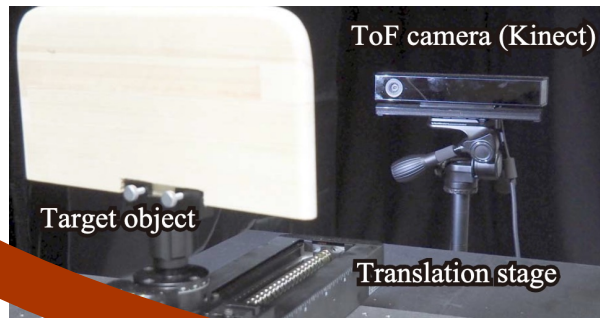
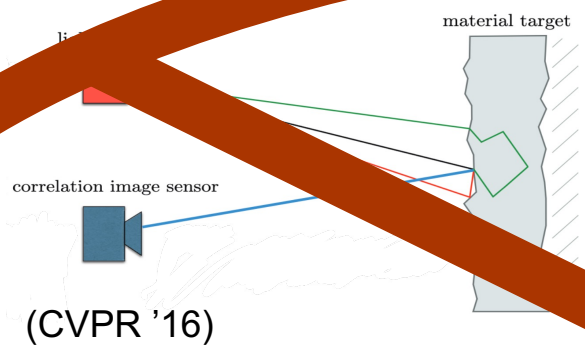


**Bulky and expensive!**



# Material sensing solutions...

vision solutions



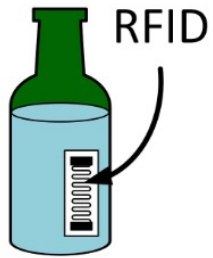
(CVPR '11)



# Material sensing solutions...

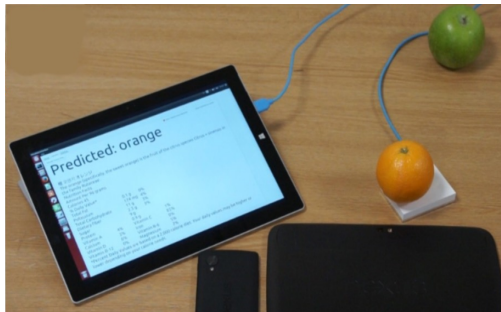
## Wireless Solutions

### RFID & Touch

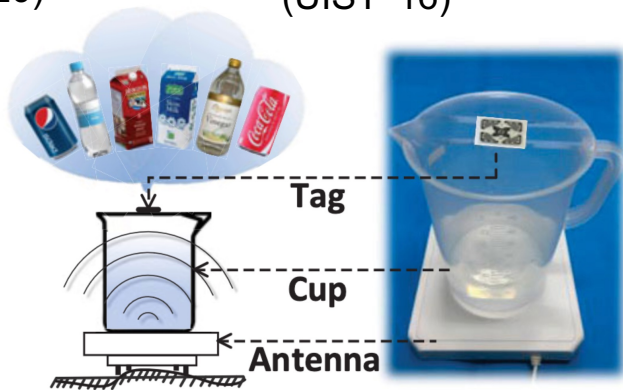


Sample

(NSDI '20)

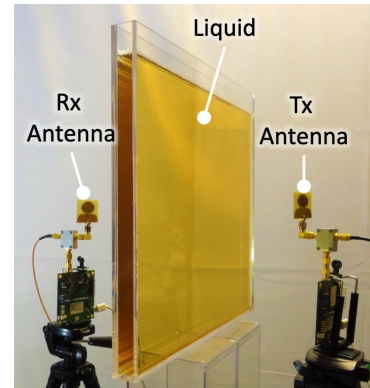


(UIST '16)

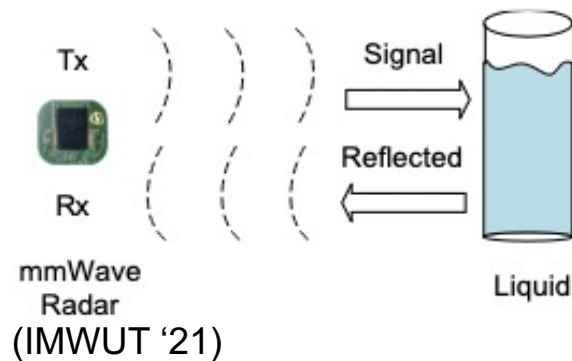


(MobiCom '17)

### Liquids

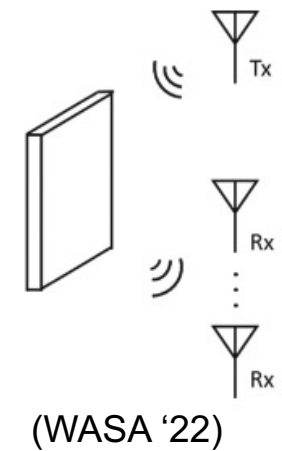
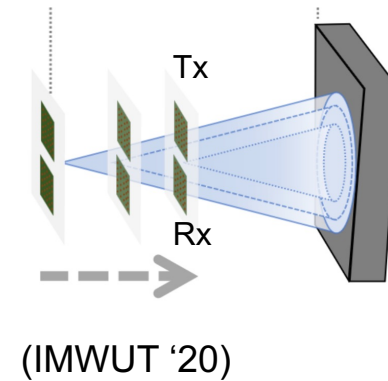


(MobiSys '16)



(IMWUT '21)

### Reflection Based



# Material sensing solutions...

## Wireless Solutions

RFID & Touch

Liquids

Reflection Based



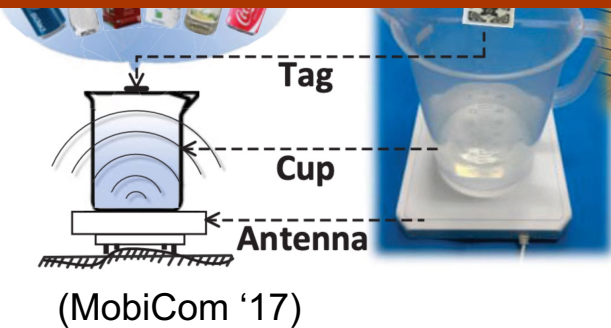
RFID



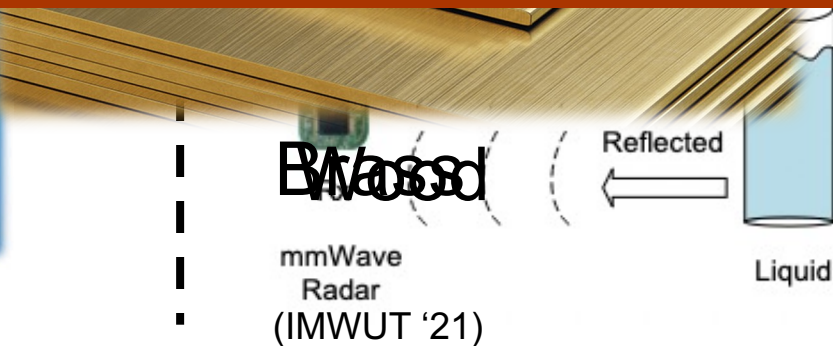
Liquid



Reflected power is not enough!



(MobiCom '17)



mmWave  
Radar  
(IMWUT '21)



Aluminum

(WASA '22)

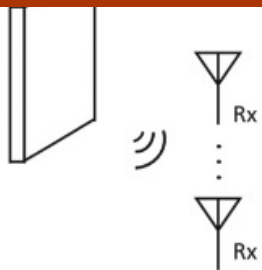
# Material sensing solutions...

Wireless Solutions

Reflection Based

Tx

Reflected power is not enough!



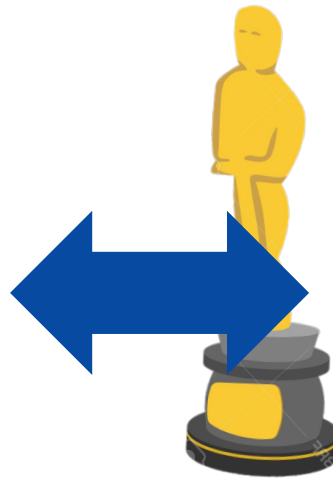
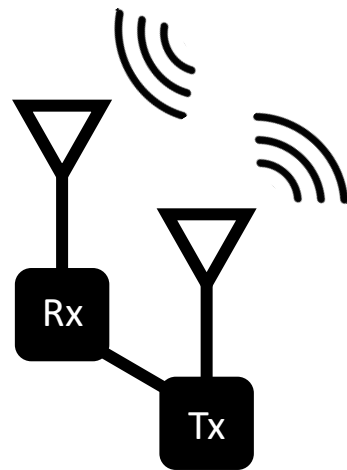
(WASA '22)

Brass

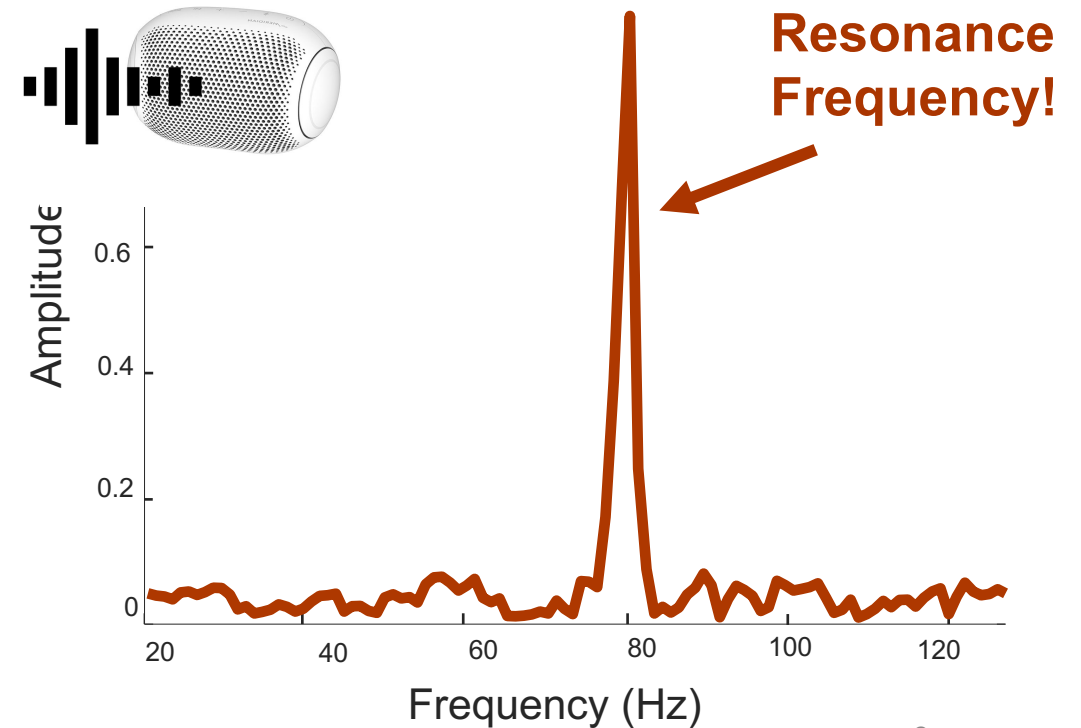
Aluminum



# Combine acoustics and RF!

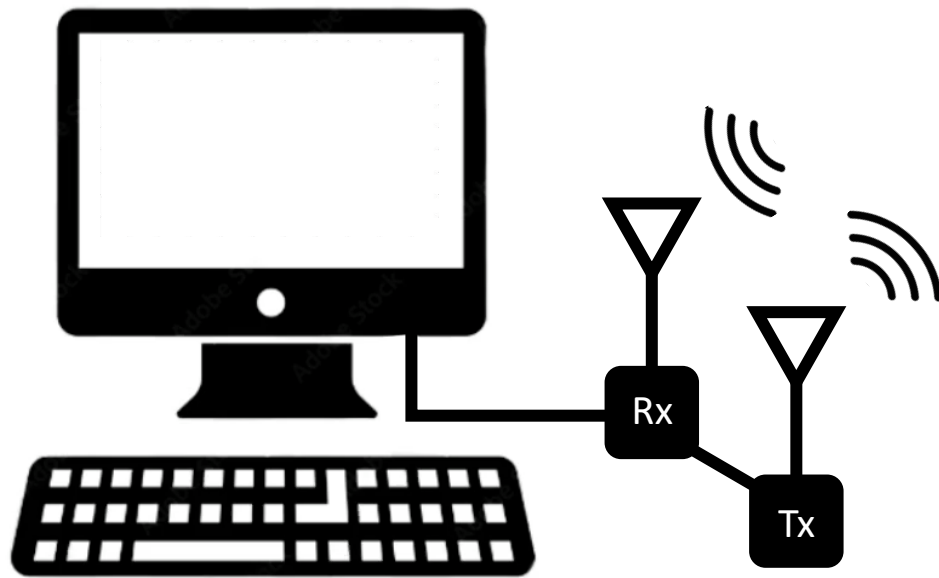


Visible Vibration Frequencies



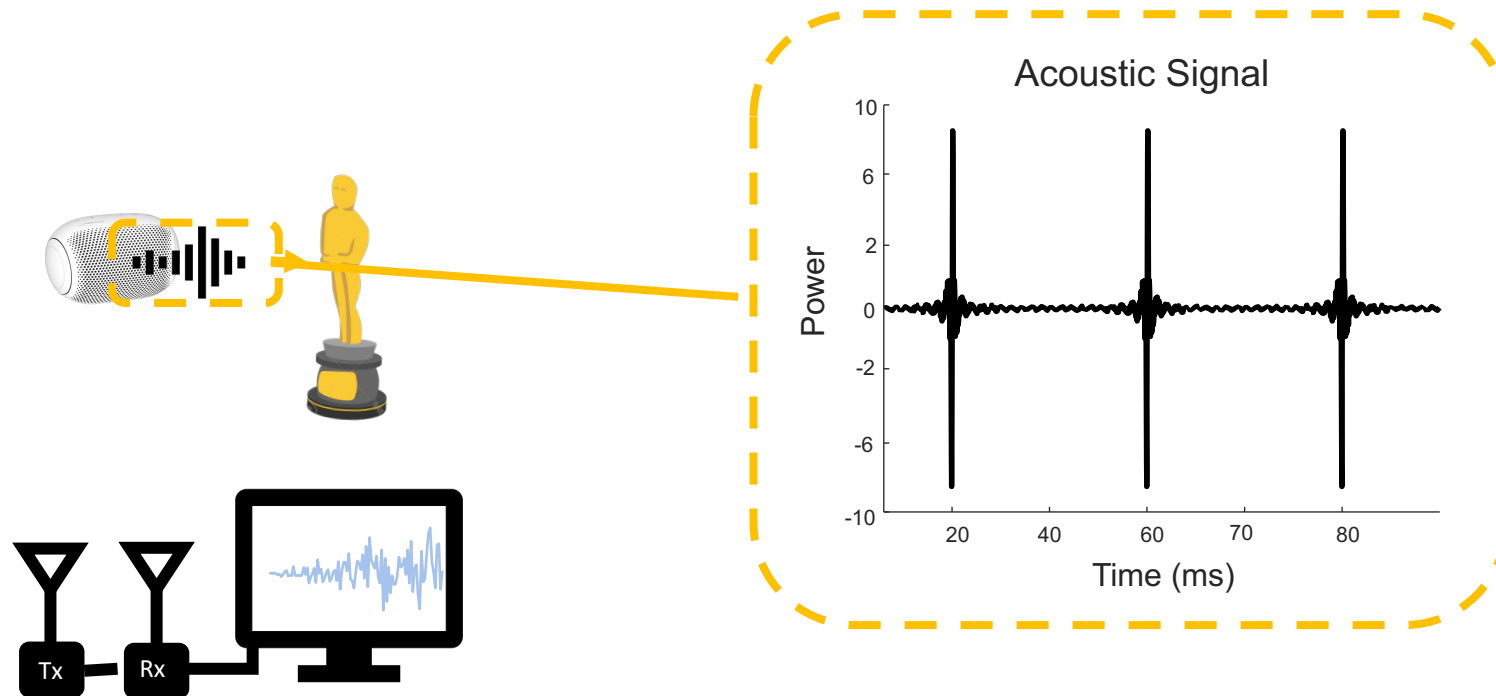
# We present RFVibe...

Is this gold?  
Gold  Fake Gold



# Challenges

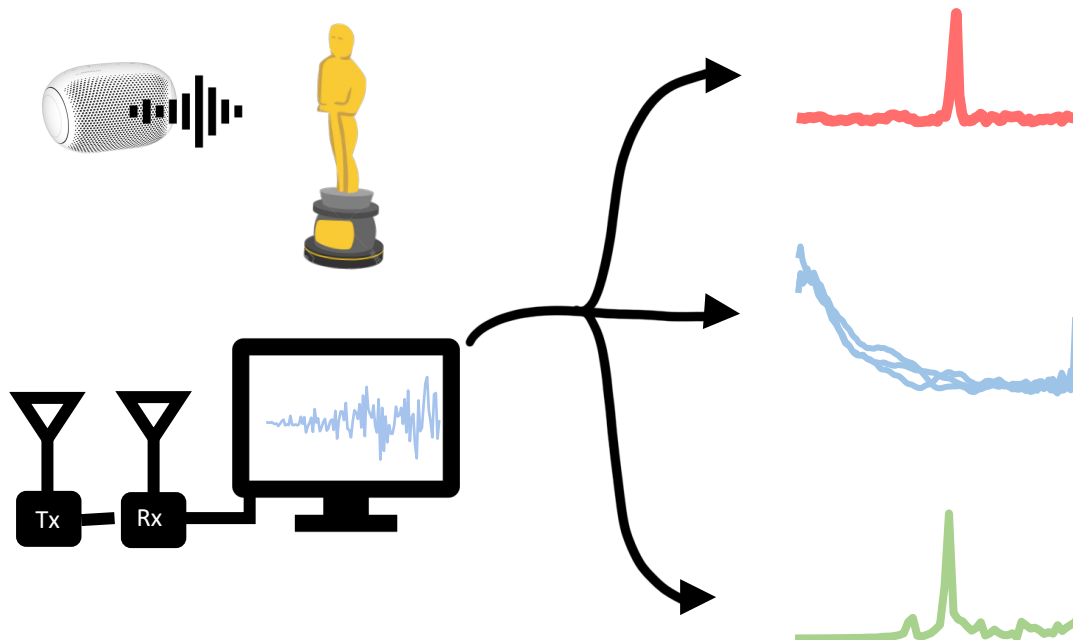
1. What acoustic source to extract vibrations?



# Challenges

1. What acoustic source to extract vibrations?

2. How to process the raw data to get useful information?



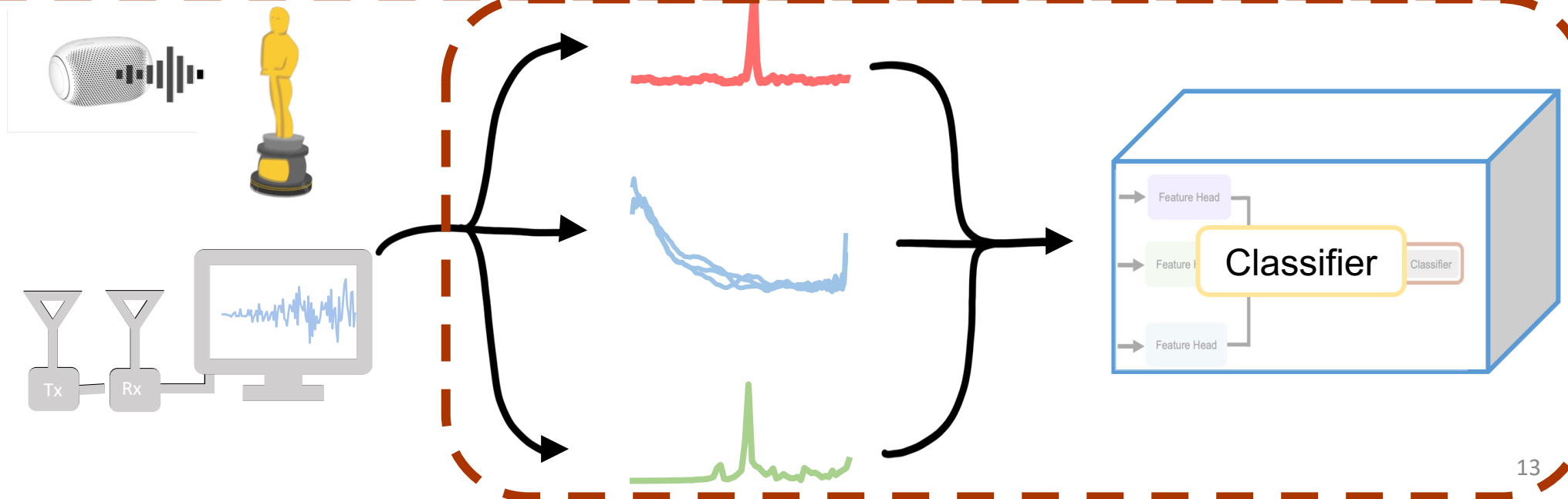


# Challenges

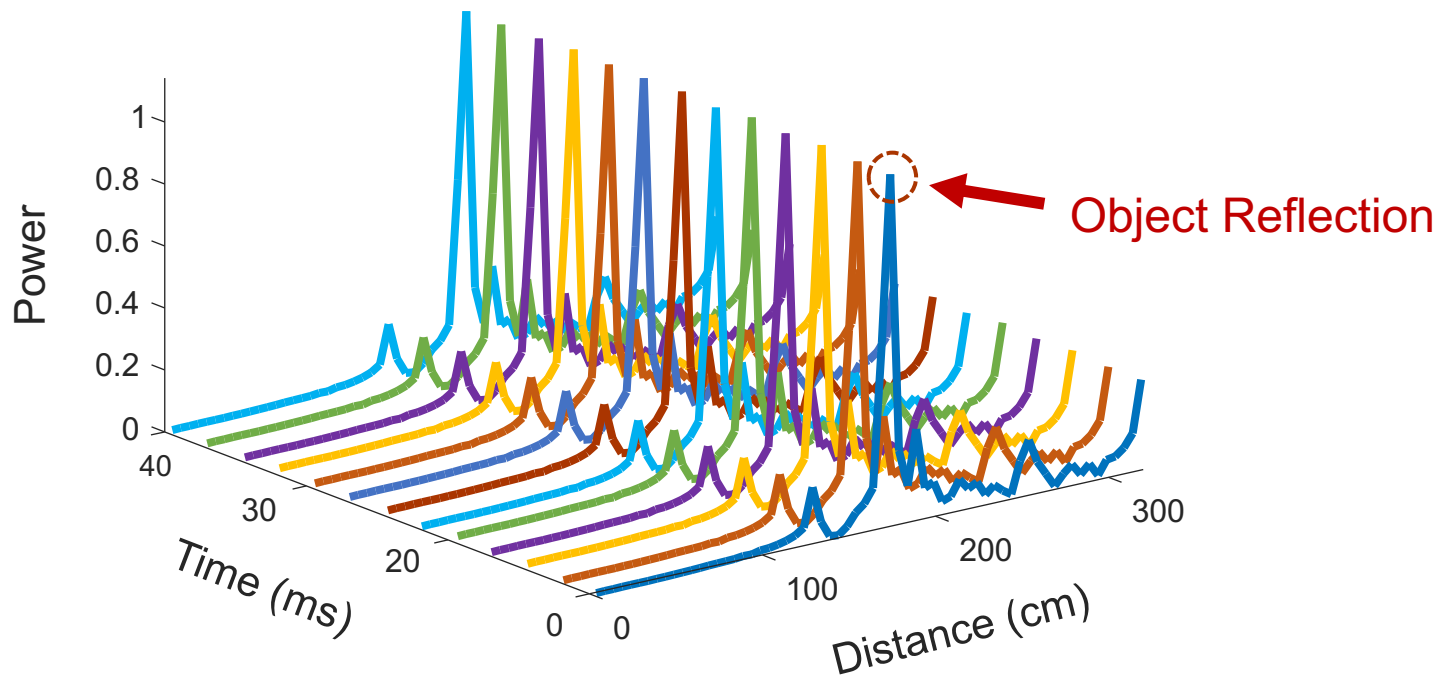
1. What acoustic source to extract vibrations?

2. How to process the raw data to get useful information?

3. How to combine the extracted information for material classification?



## Reflected Power



coarse-grained

fine-grained

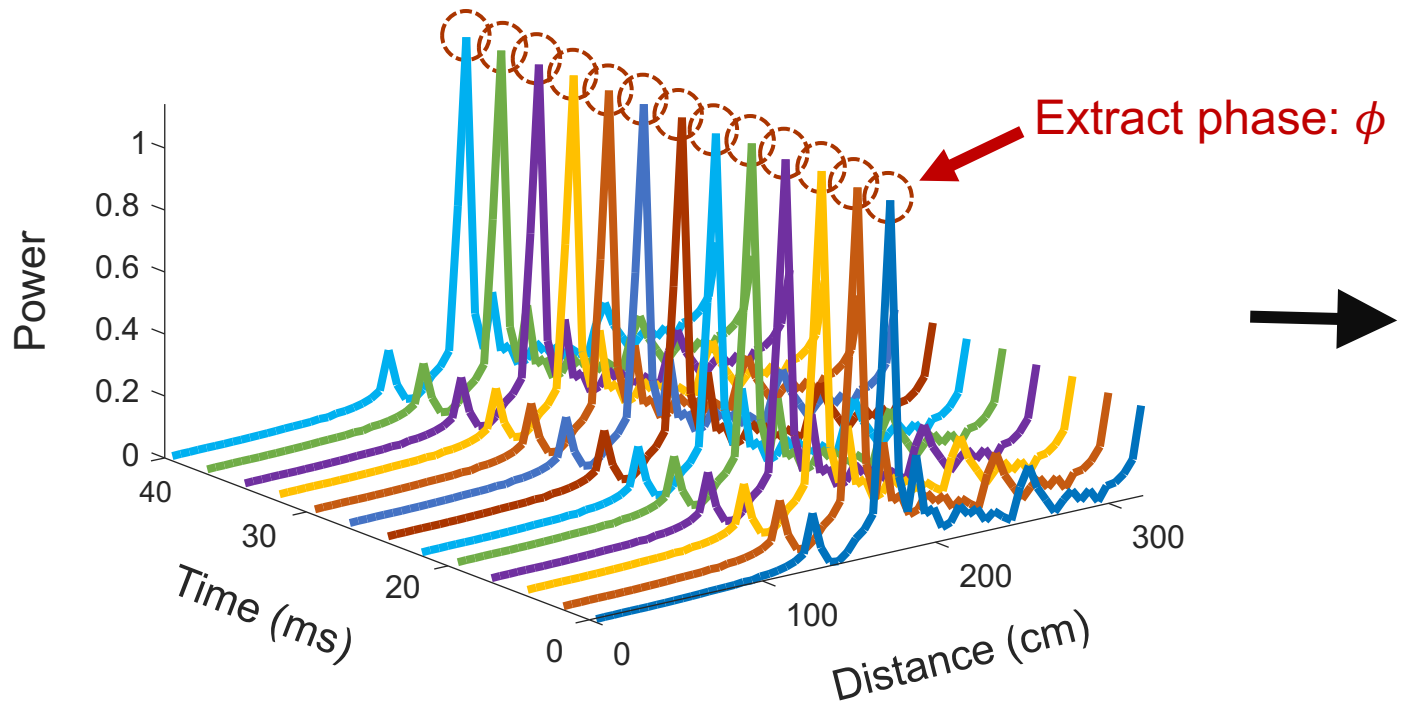
Object reflects  $\rightarrow Ae^{\phi}$

$$\phi = \frac{2\pi d}{\lambda} \propto d = \text{distance of object}$$

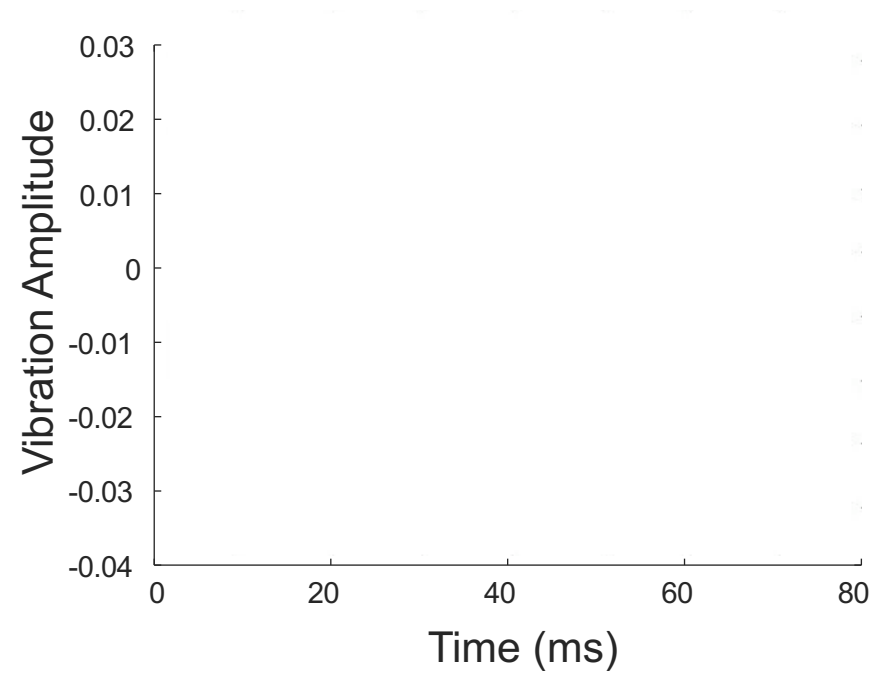
# Vibrations are reflected in the phase!

Object reflects  $\rightarrow Ae^{\phi}$

Reflected Power

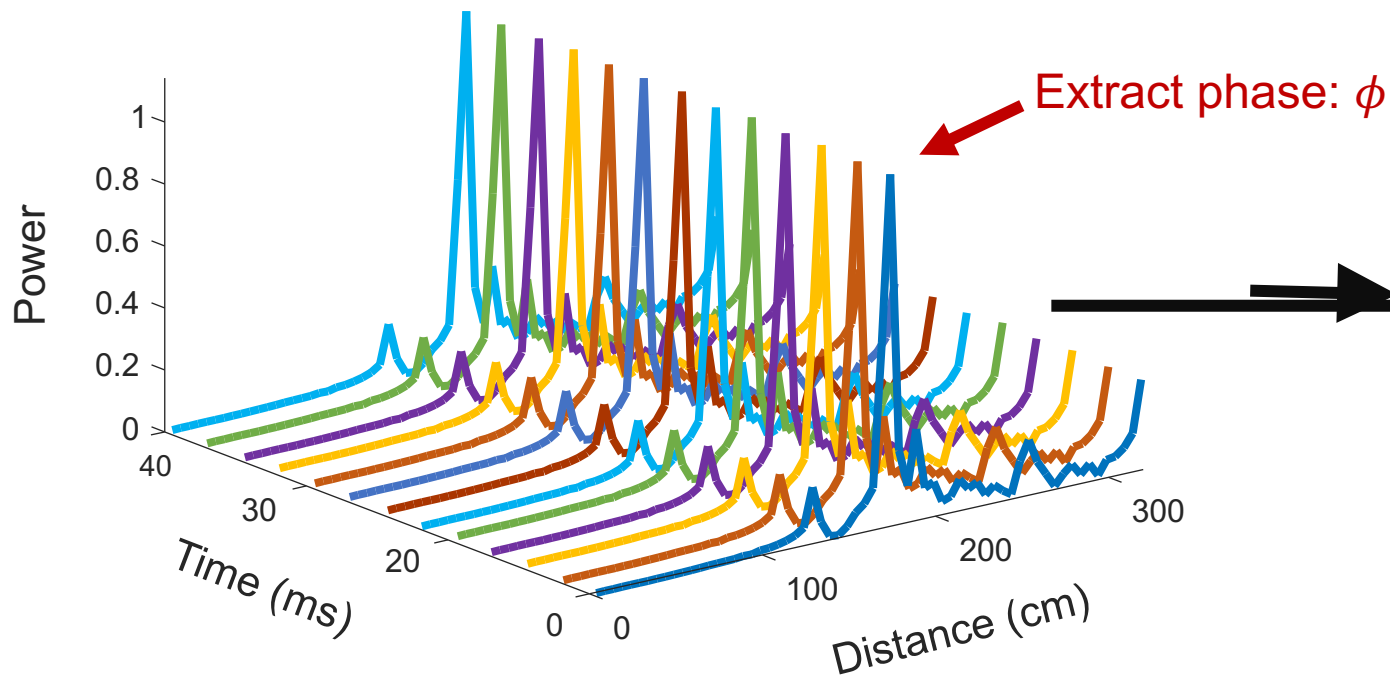


Phase

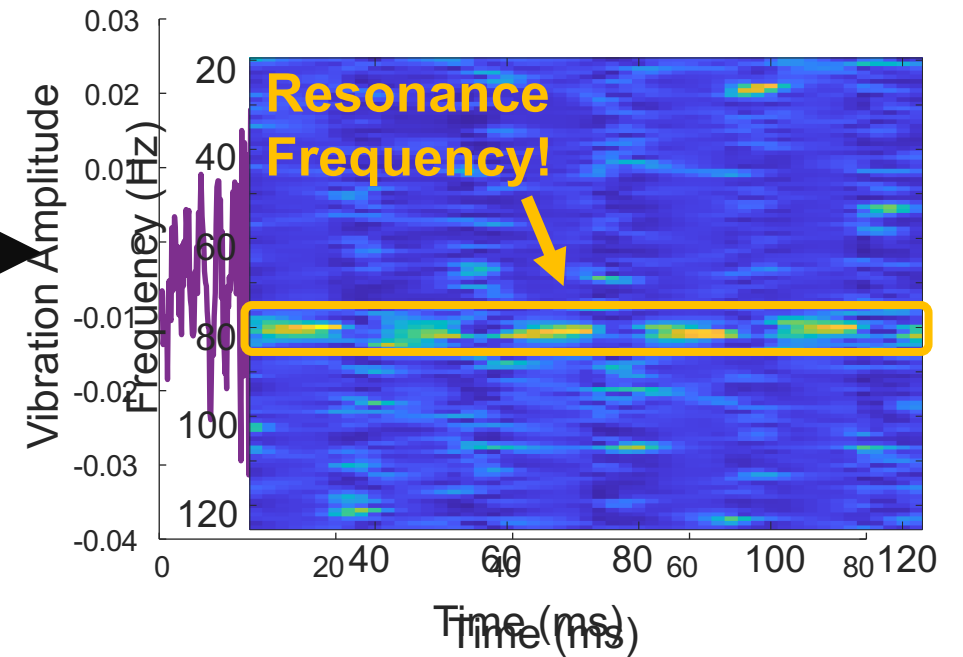


# Feature 1: Resonance Frequency

Reflected Power



Short Time Fourier Transform

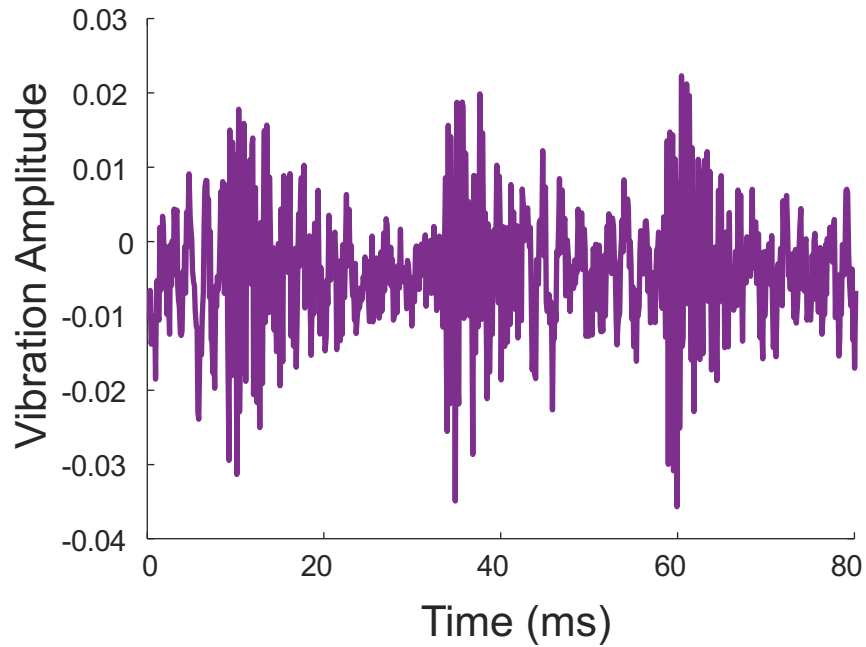


Visible frequencies are noisy!

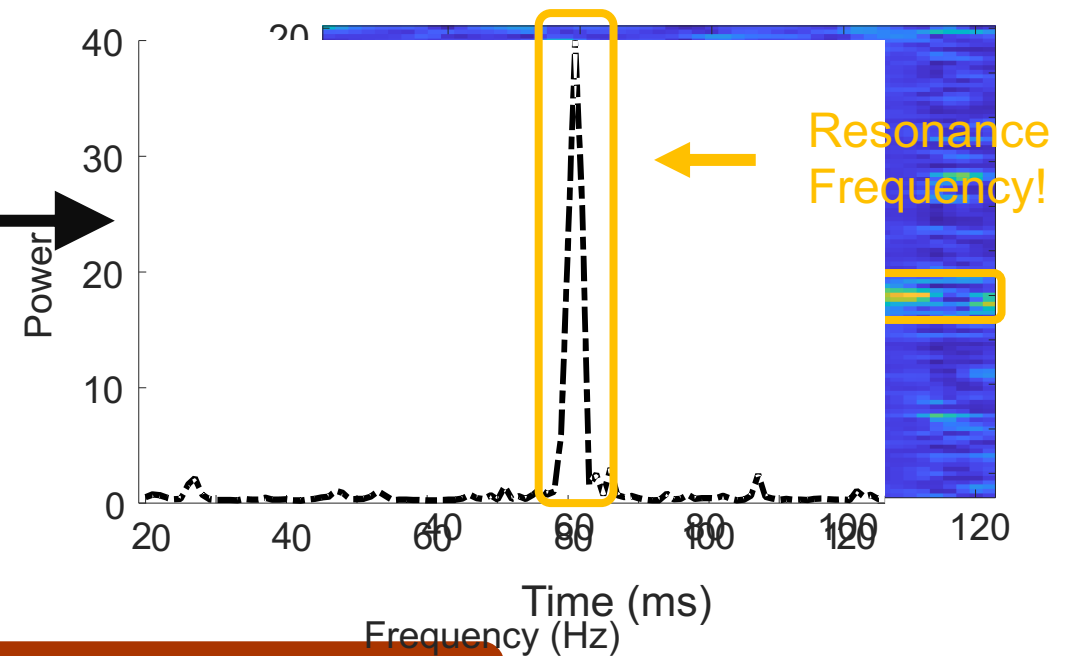


# Feature 1: Resonance Frequency

Phase



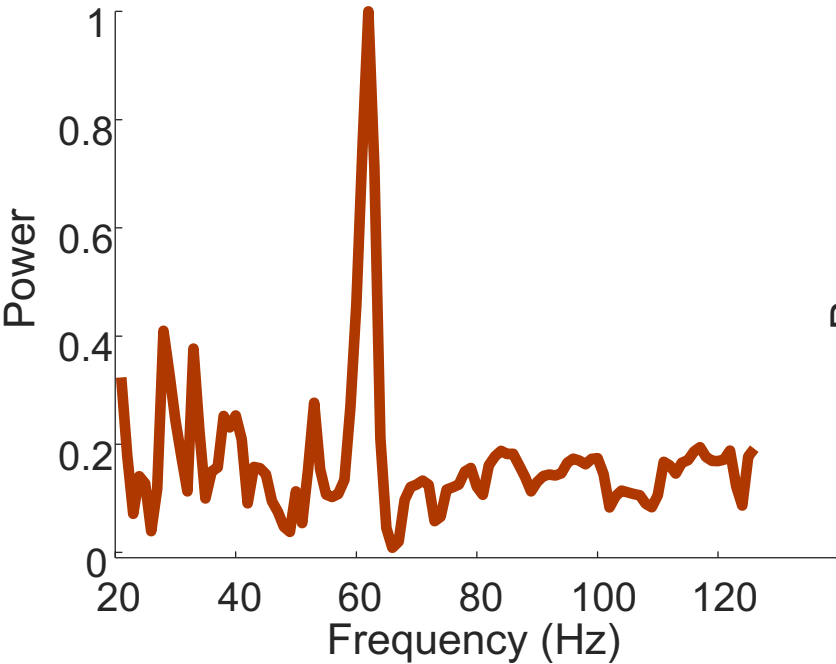
Resonance Short Time Frequency Transform



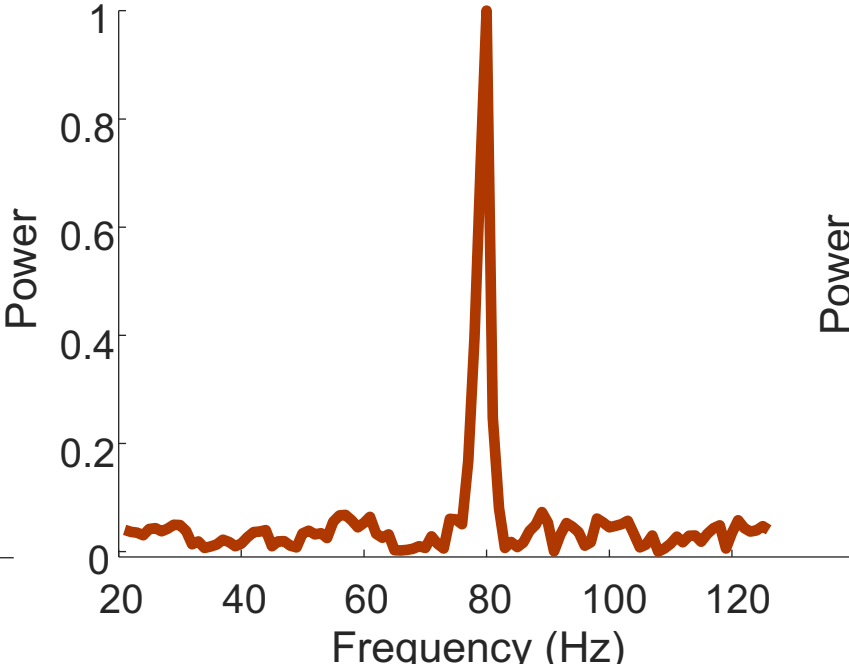
Visible frequencies are noisy!

# Resonance frequency shows up differently in different materials!

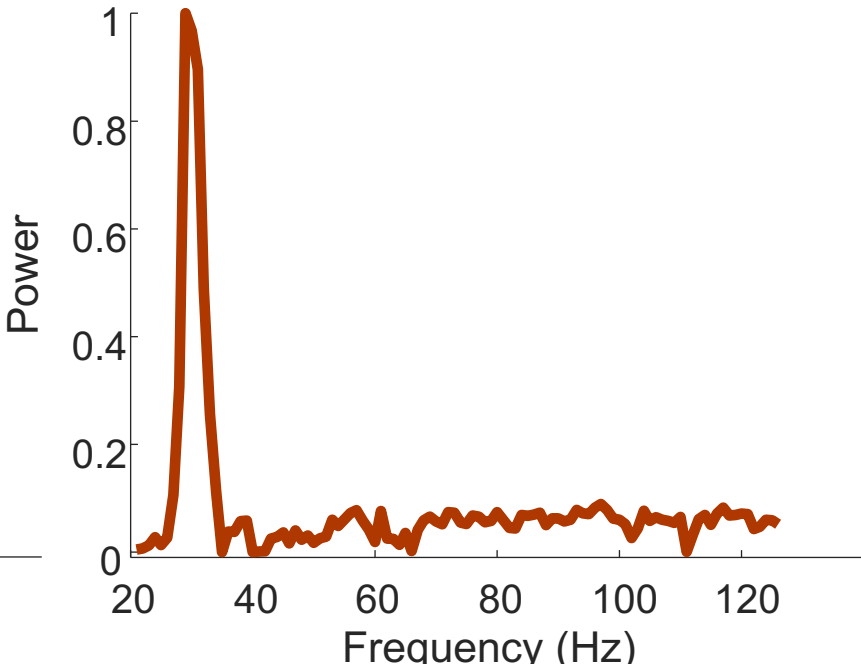
Plastic



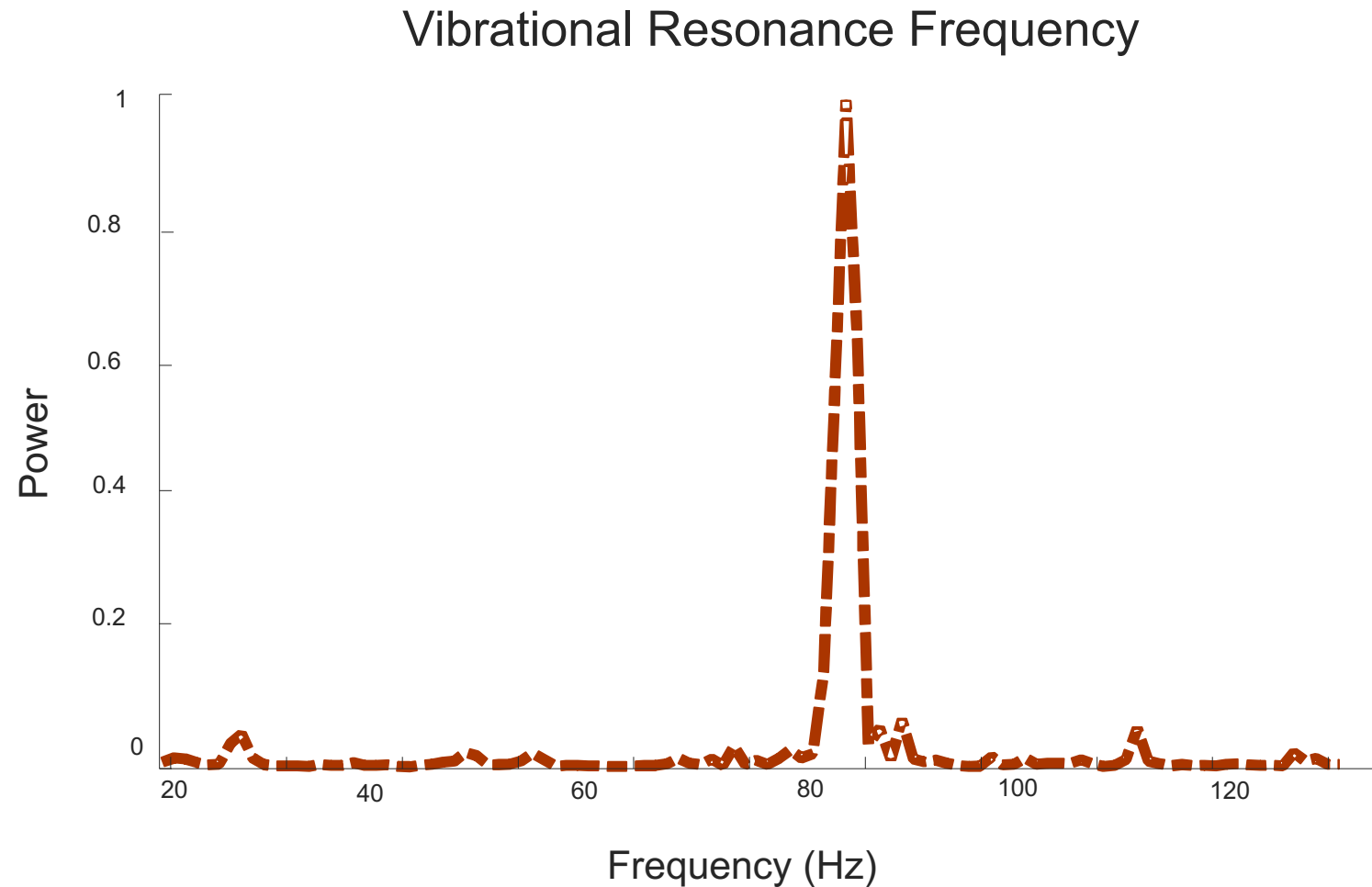
Aluminum



Wood

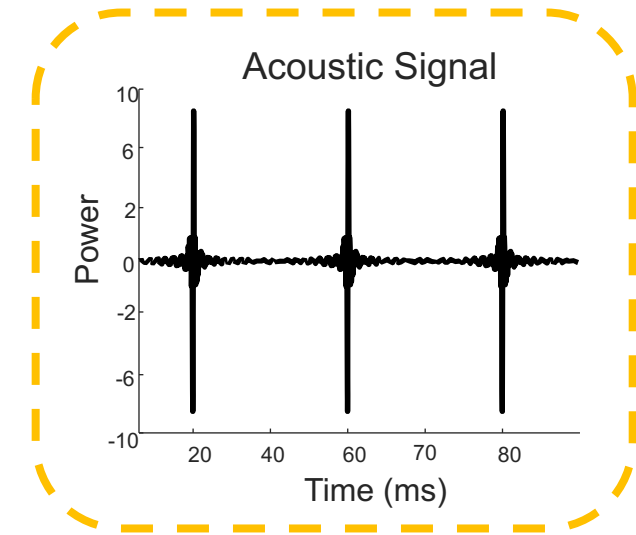
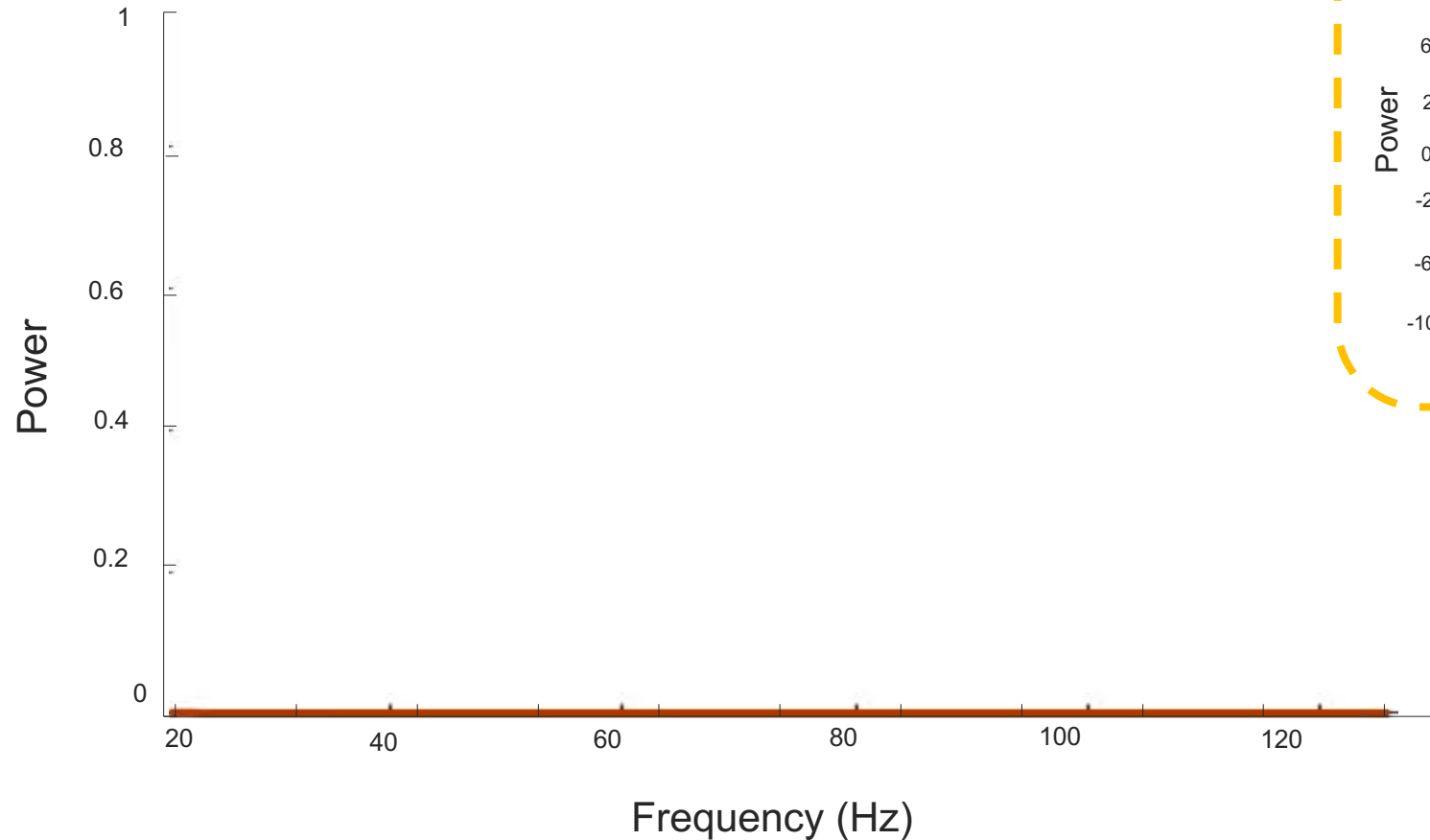


# Resonance frequency shows up differently in different materials!



# Speed of damping can help characterize materials!

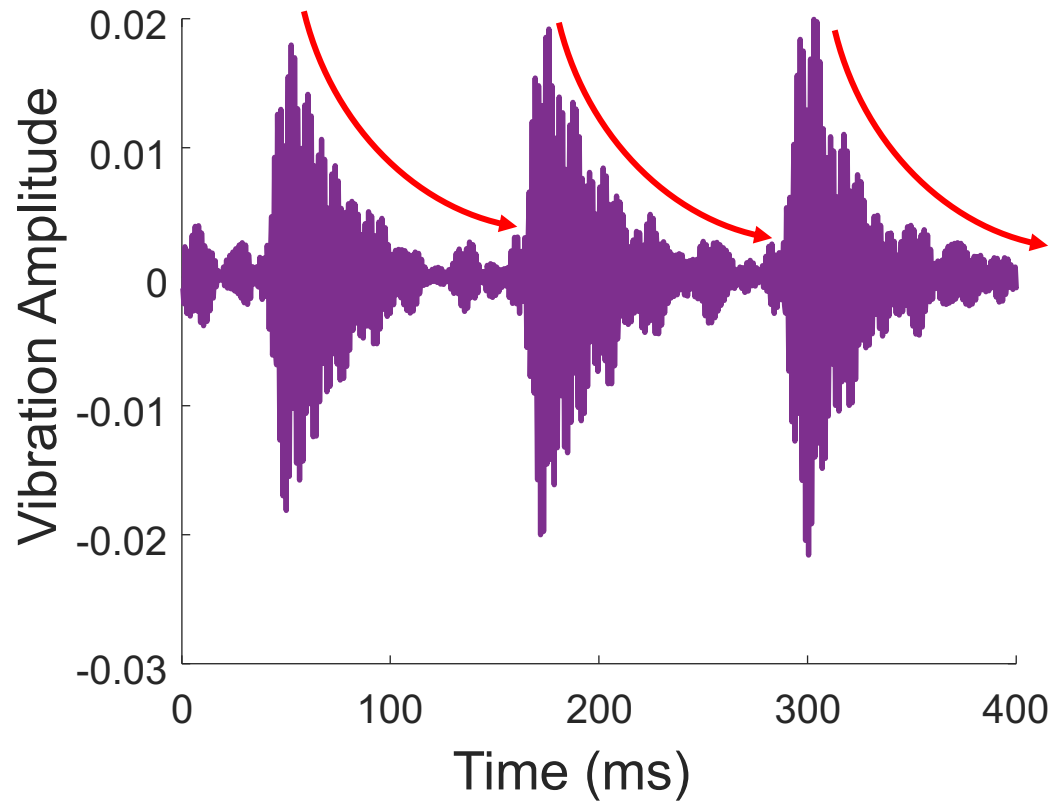
Resonance Frequency Over Time



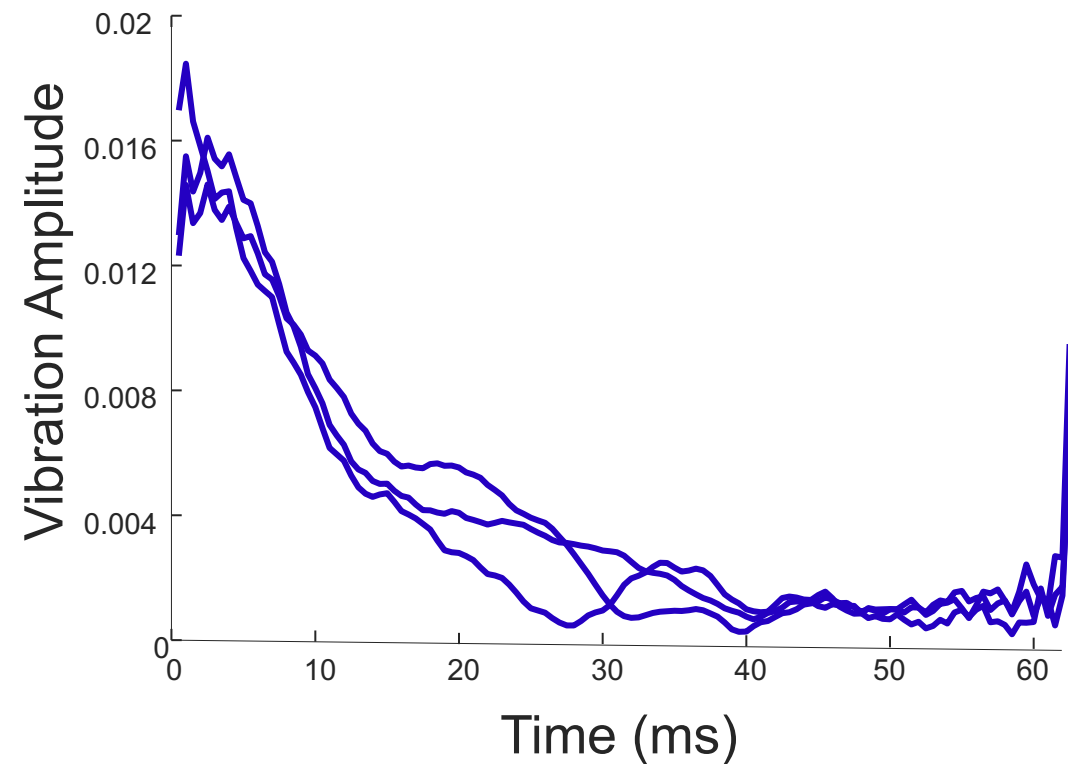


# Feature 2: Damping

Filtered Vibration Signal

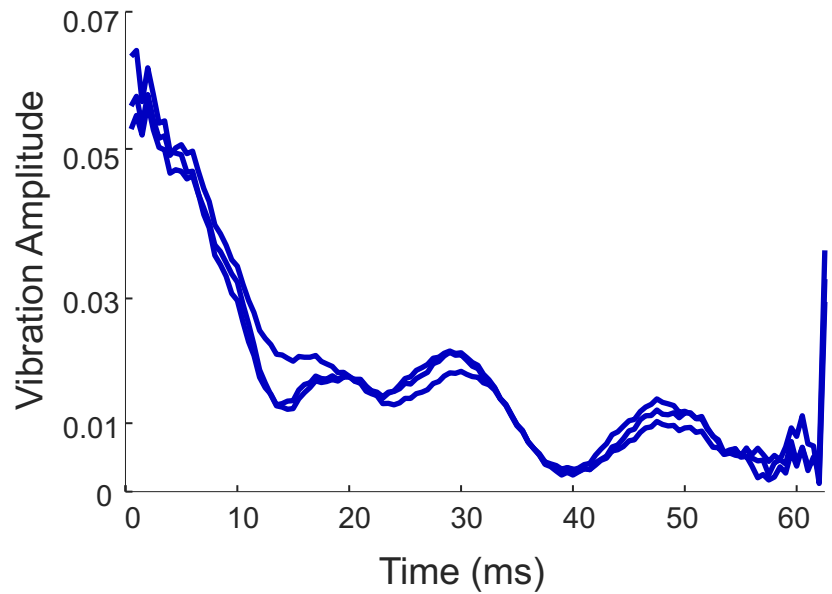


Damping Feature

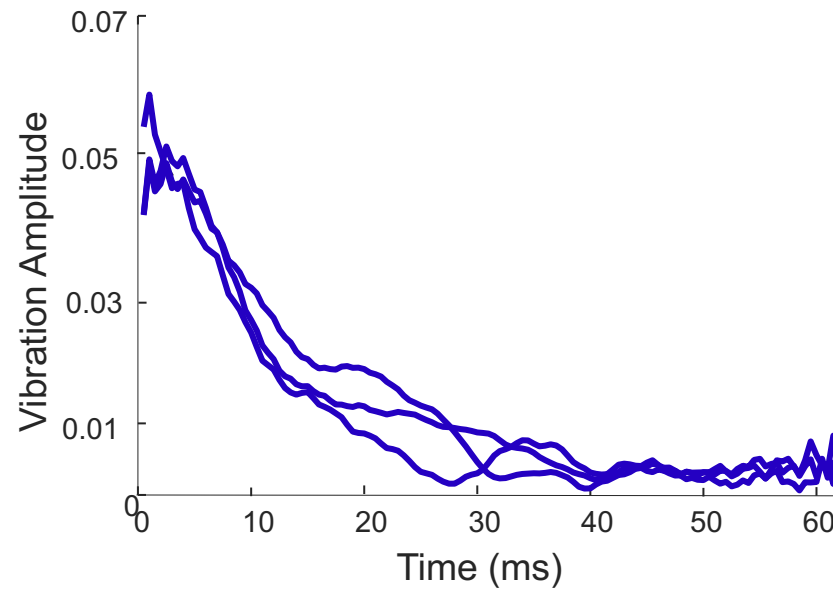


# Damping speeds vary based on material!

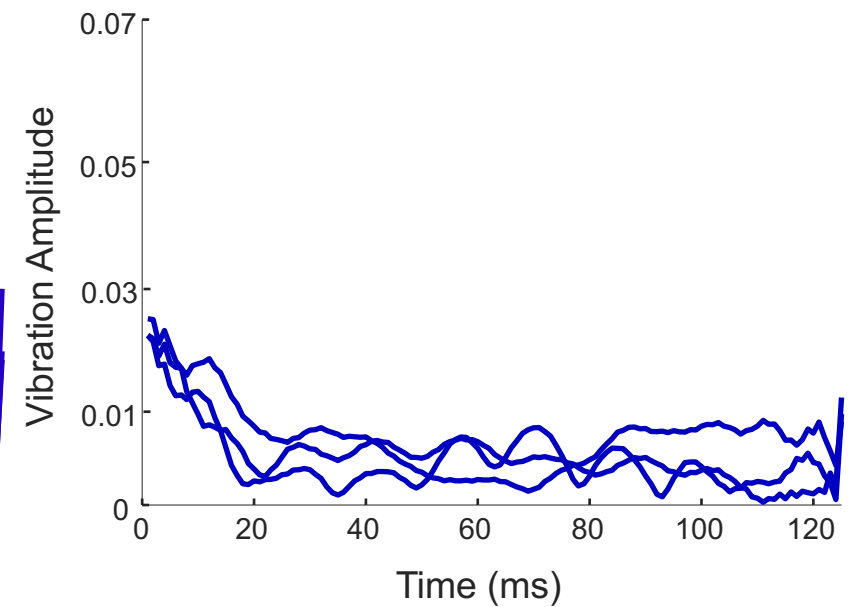
Plastic



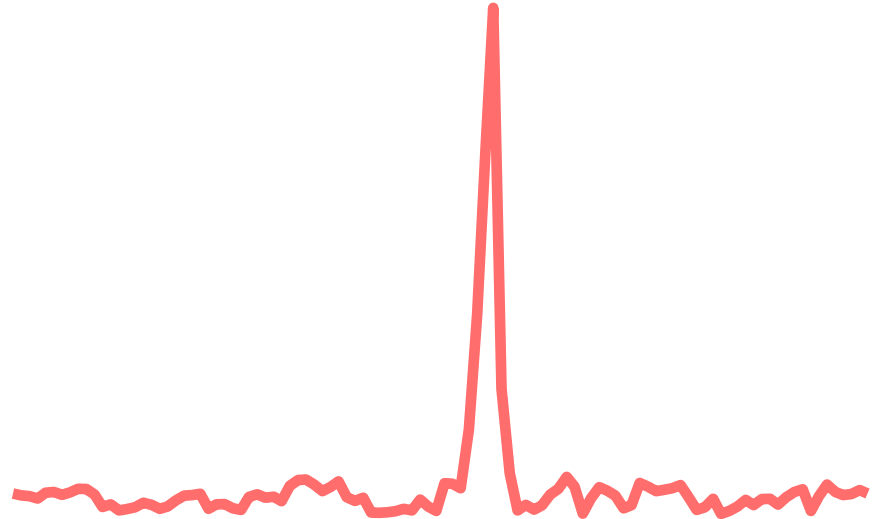
Aluminum



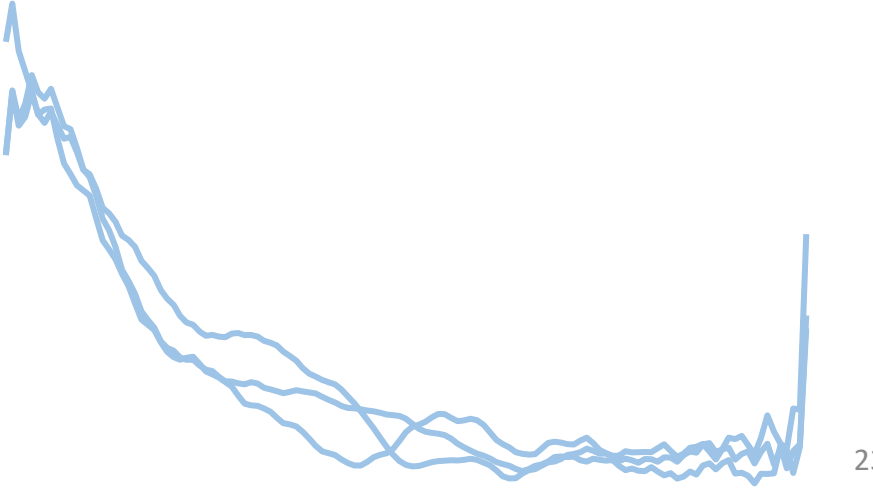
Wood



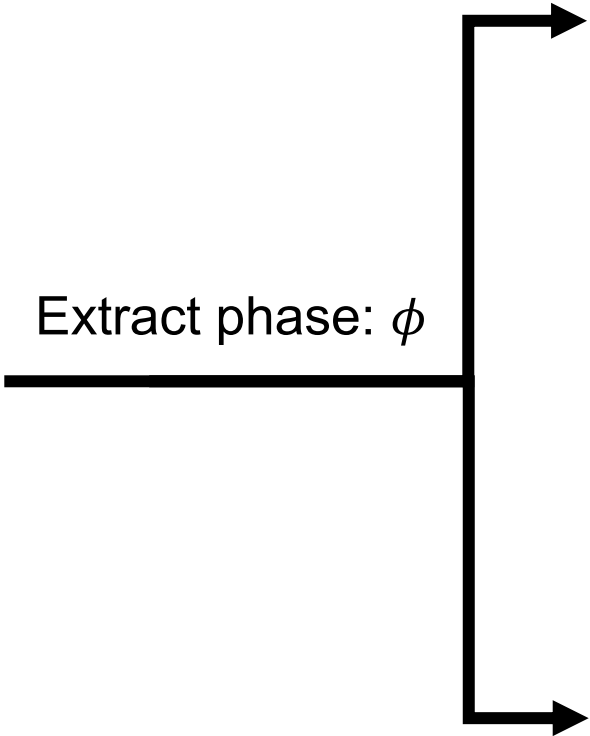
# Resonance Frequency



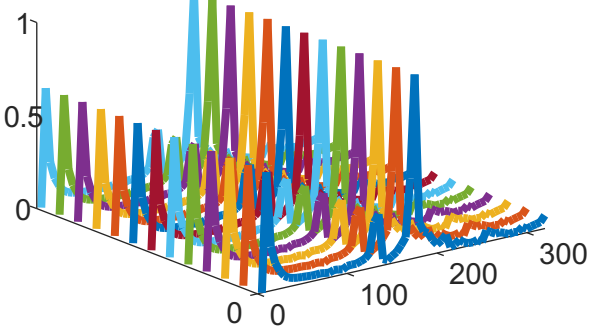
# Damping Speed



Extract phase:  $\phi$



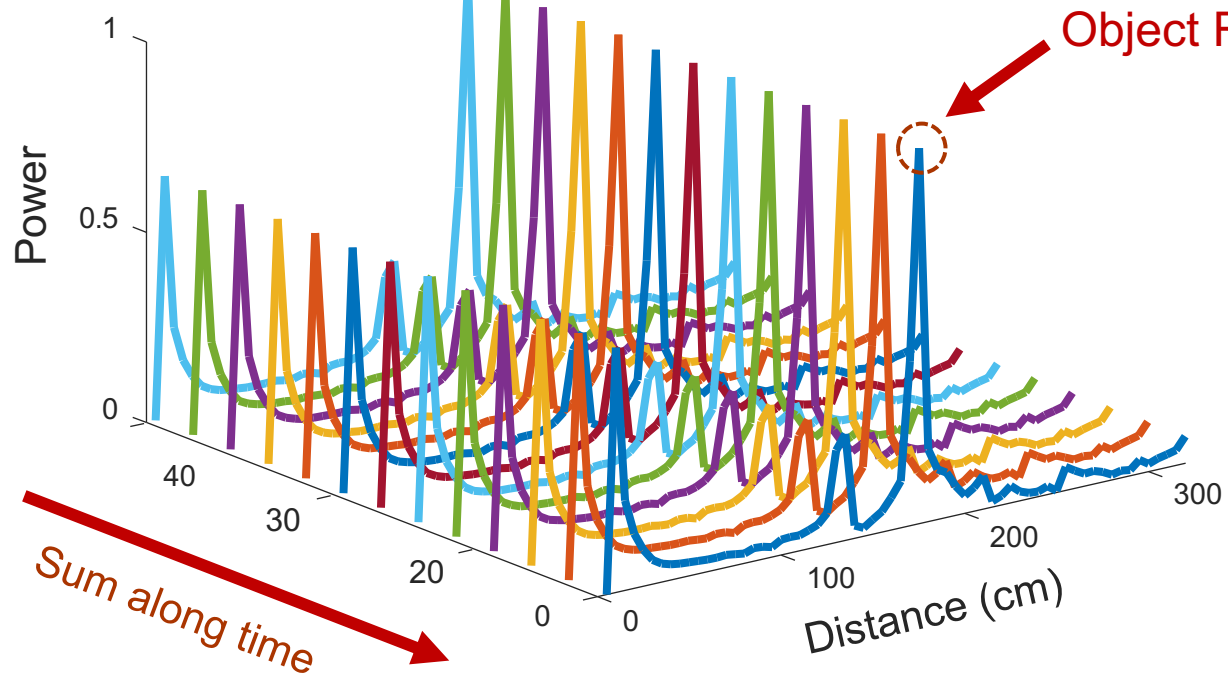
# Raw Signal



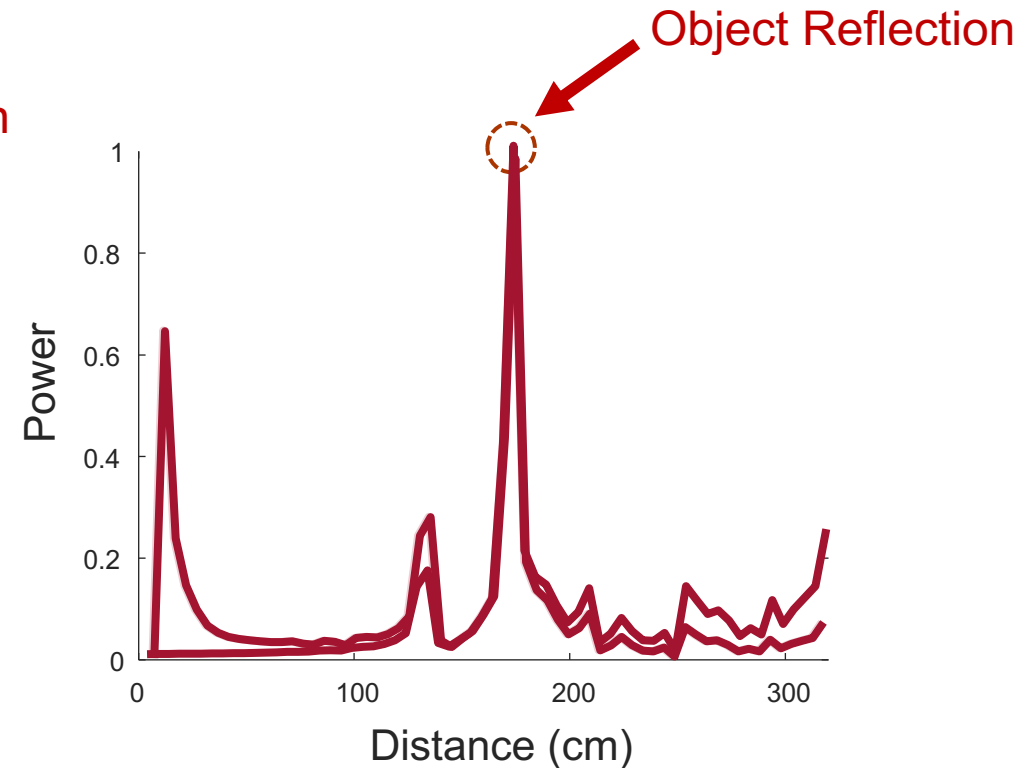
# Feature 3: Reflection Power

Object reflects  $\rightarrow Ae^\phi$

Reflected Power

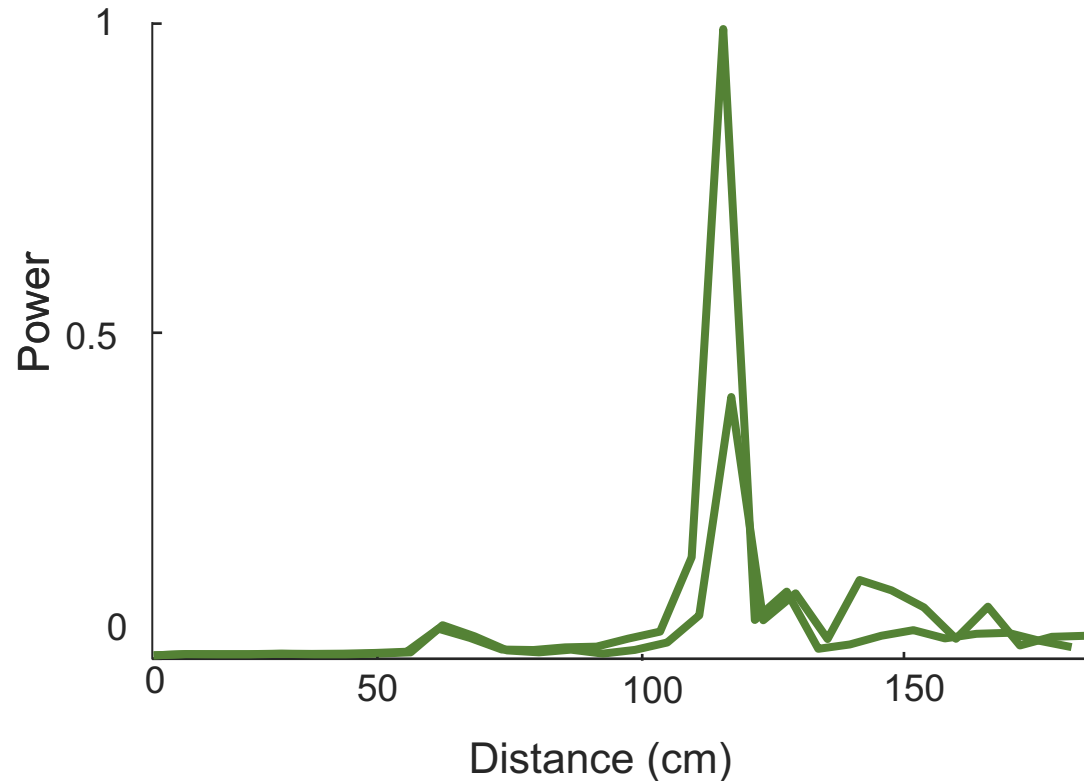


Reflected Power Feature

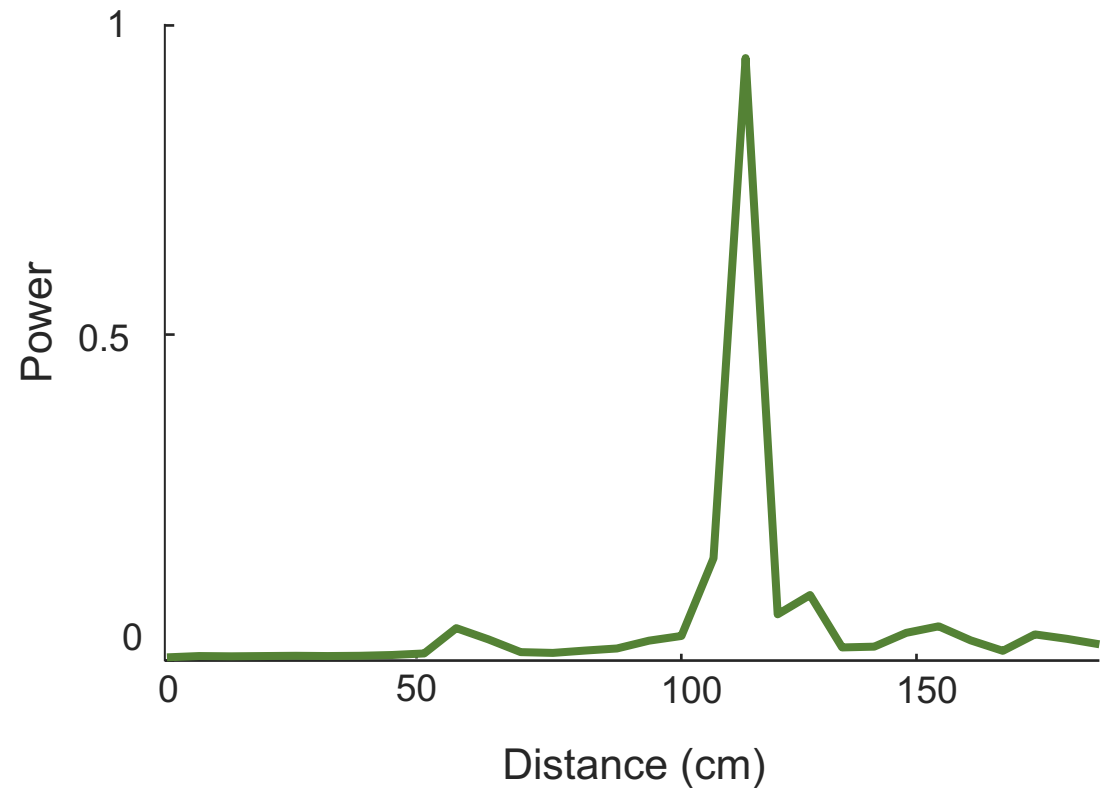


# Reflection powers vary based on material, but is not enough!

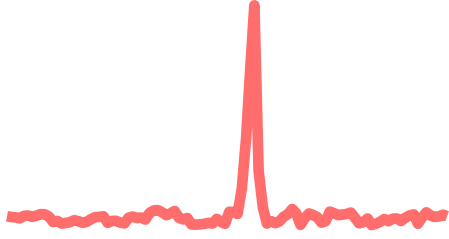
Brass



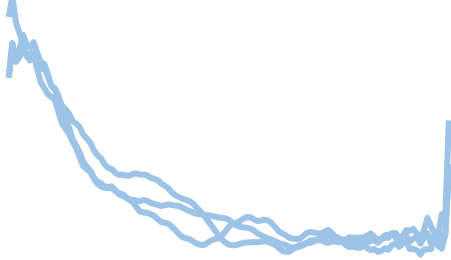
Aluminum



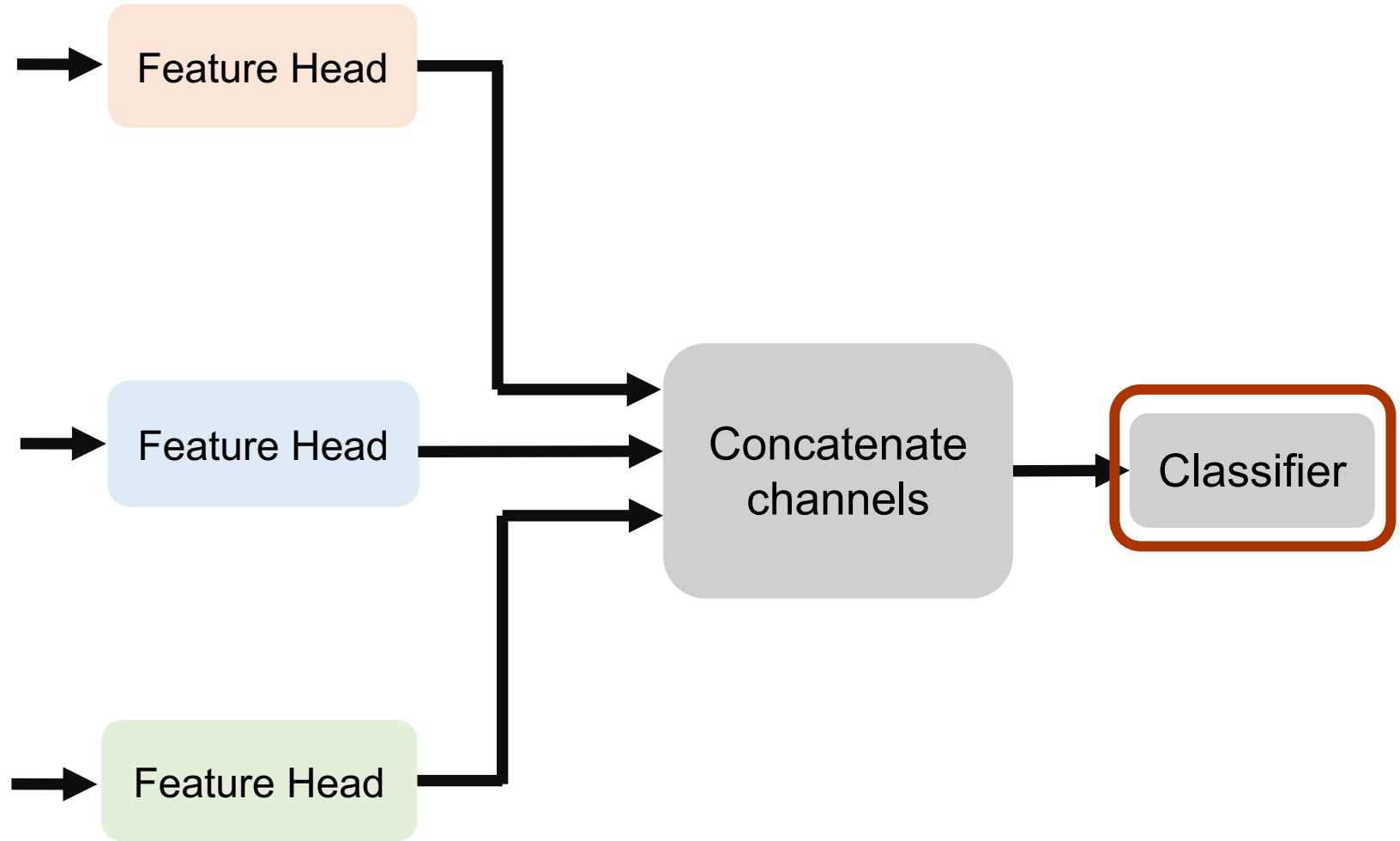
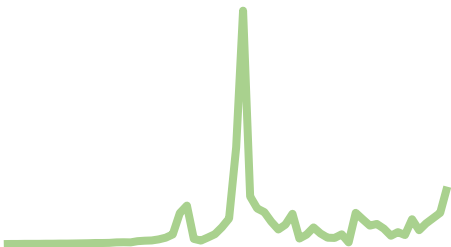
Resonance Frequency

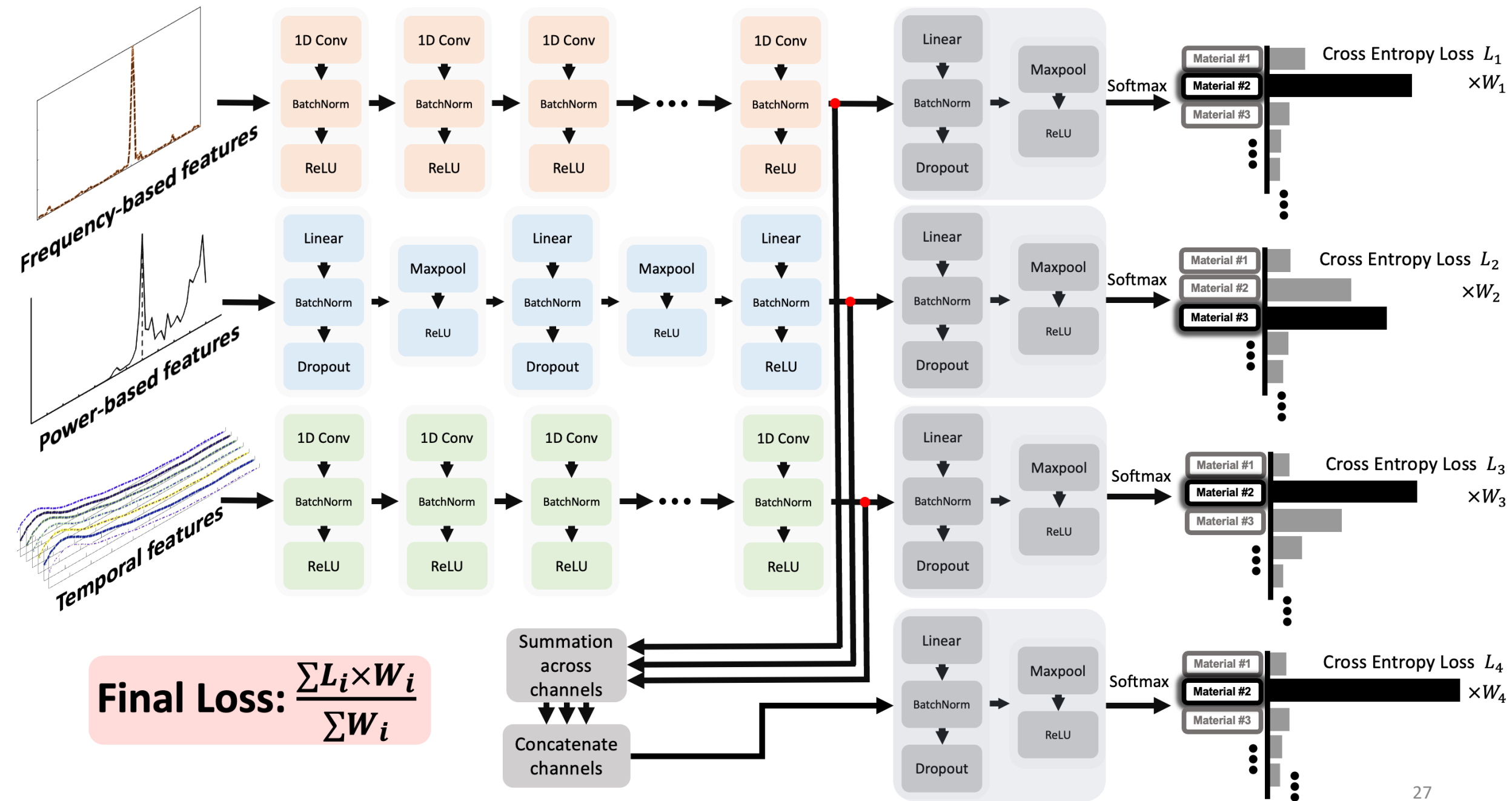


Damping Speed

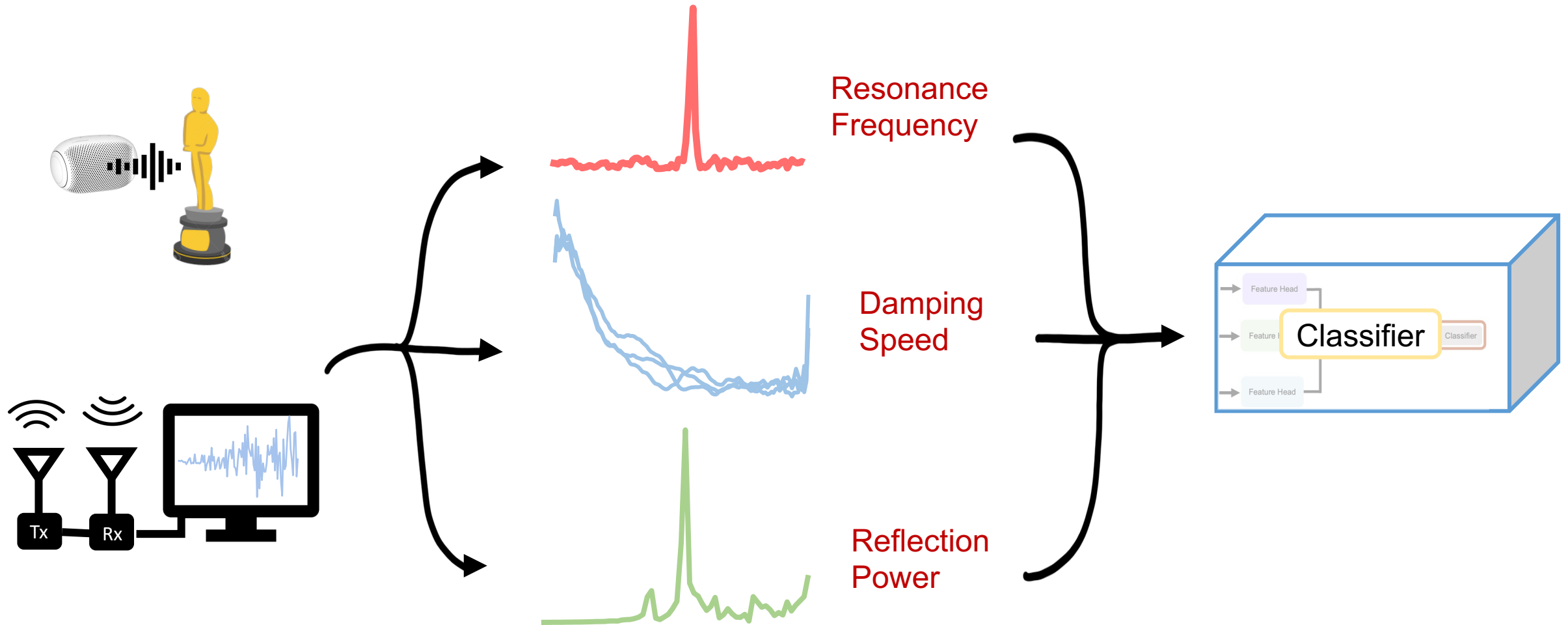


Reflection Power





# Putting it all together...





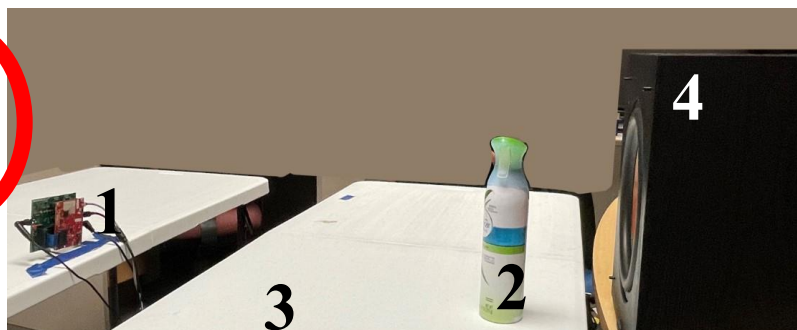
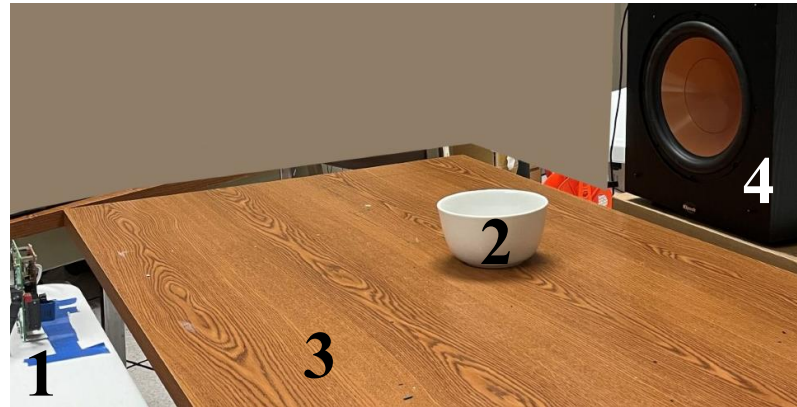
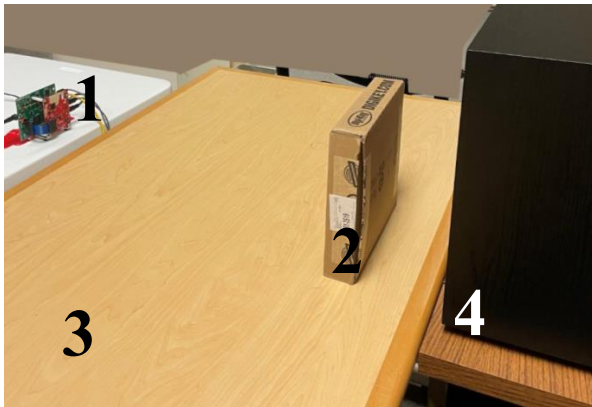
# Experimental Setup

1: Radar

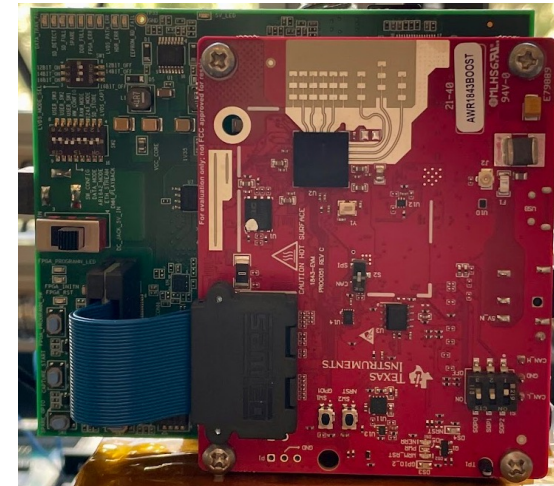
2: Object of Interest

3: Base Table

4: Speaker



TI's AWR1843 Radar



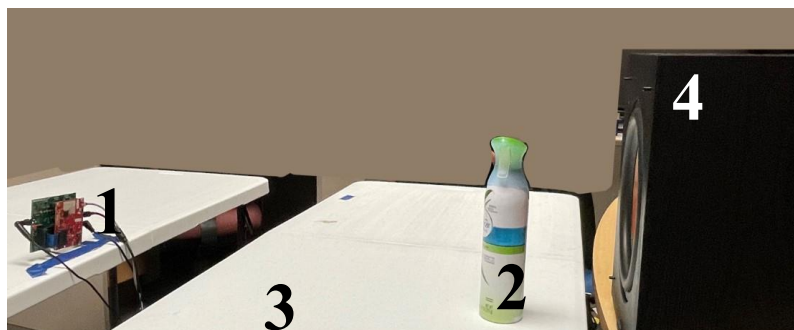
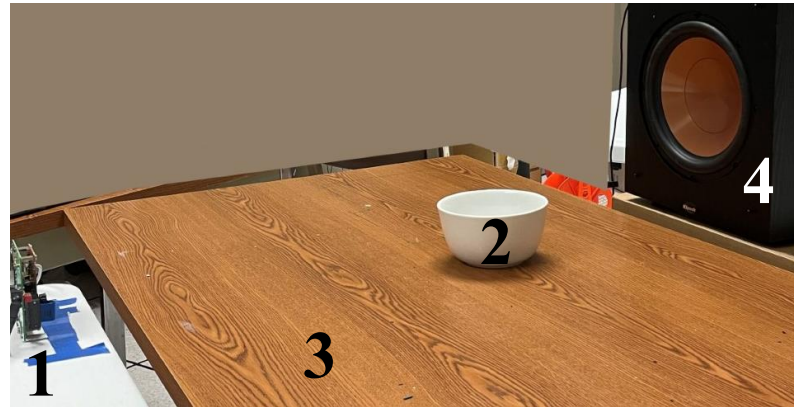
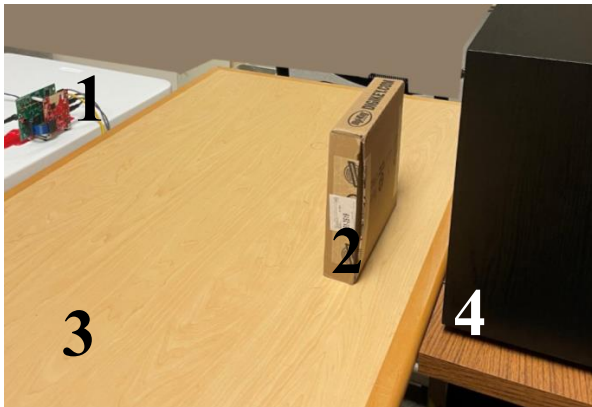
# Experimental Setup

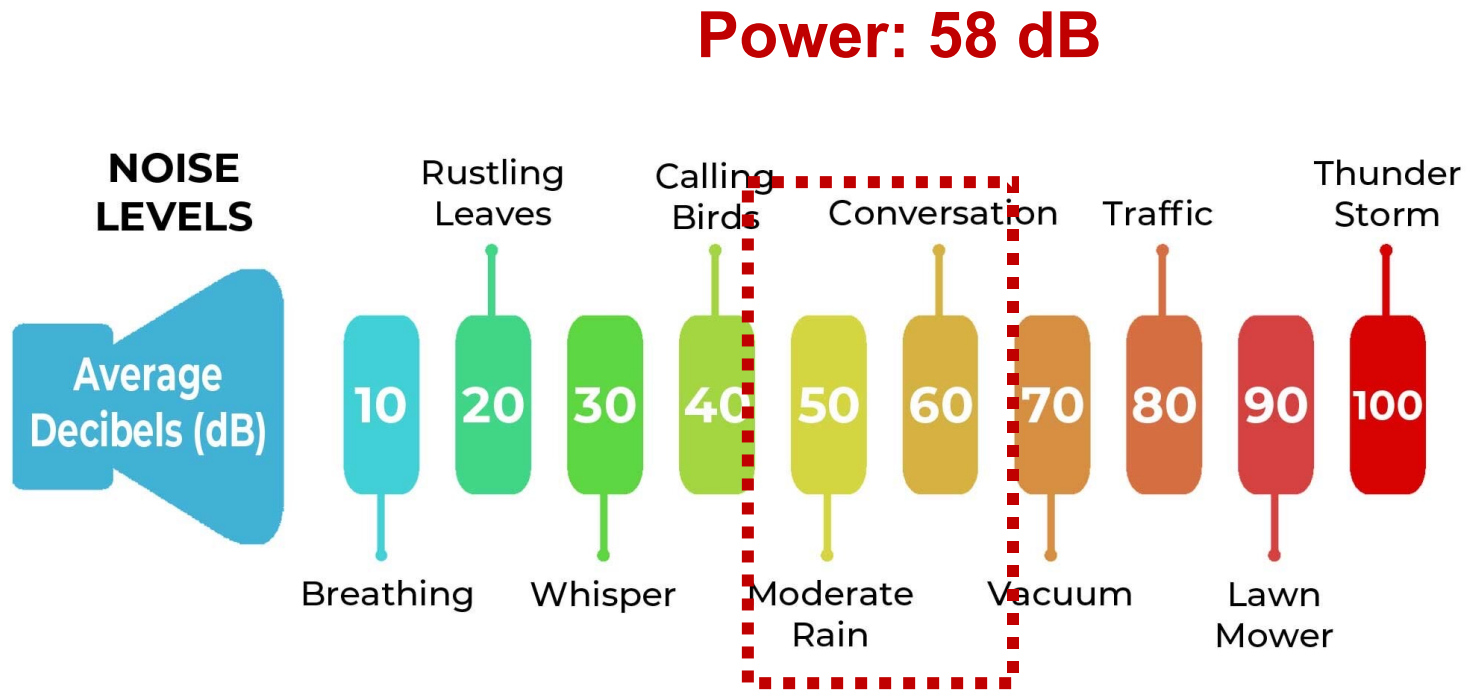
1: Radar

2: Object of Interest

3: Base Table

4: Speaker

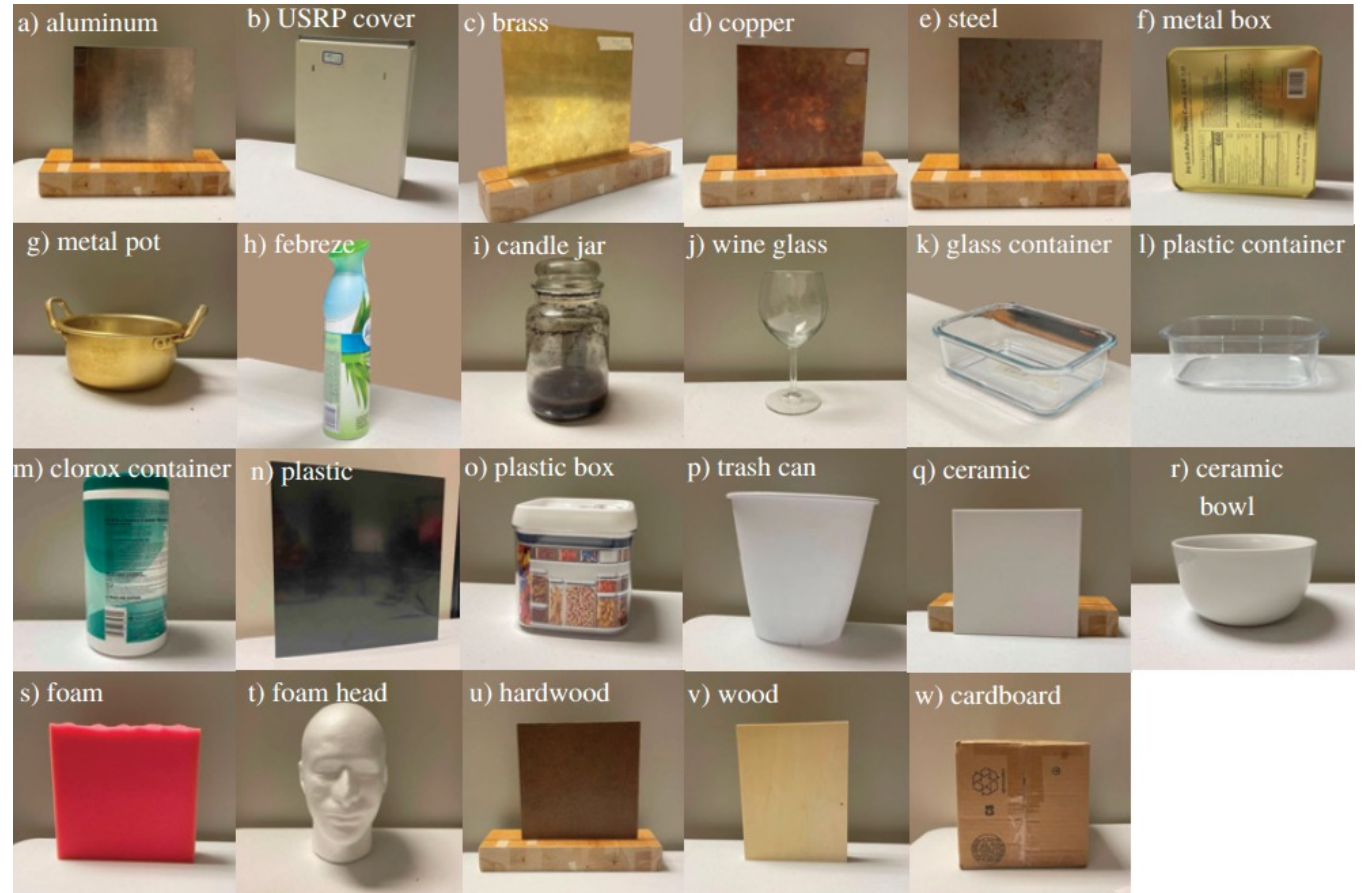




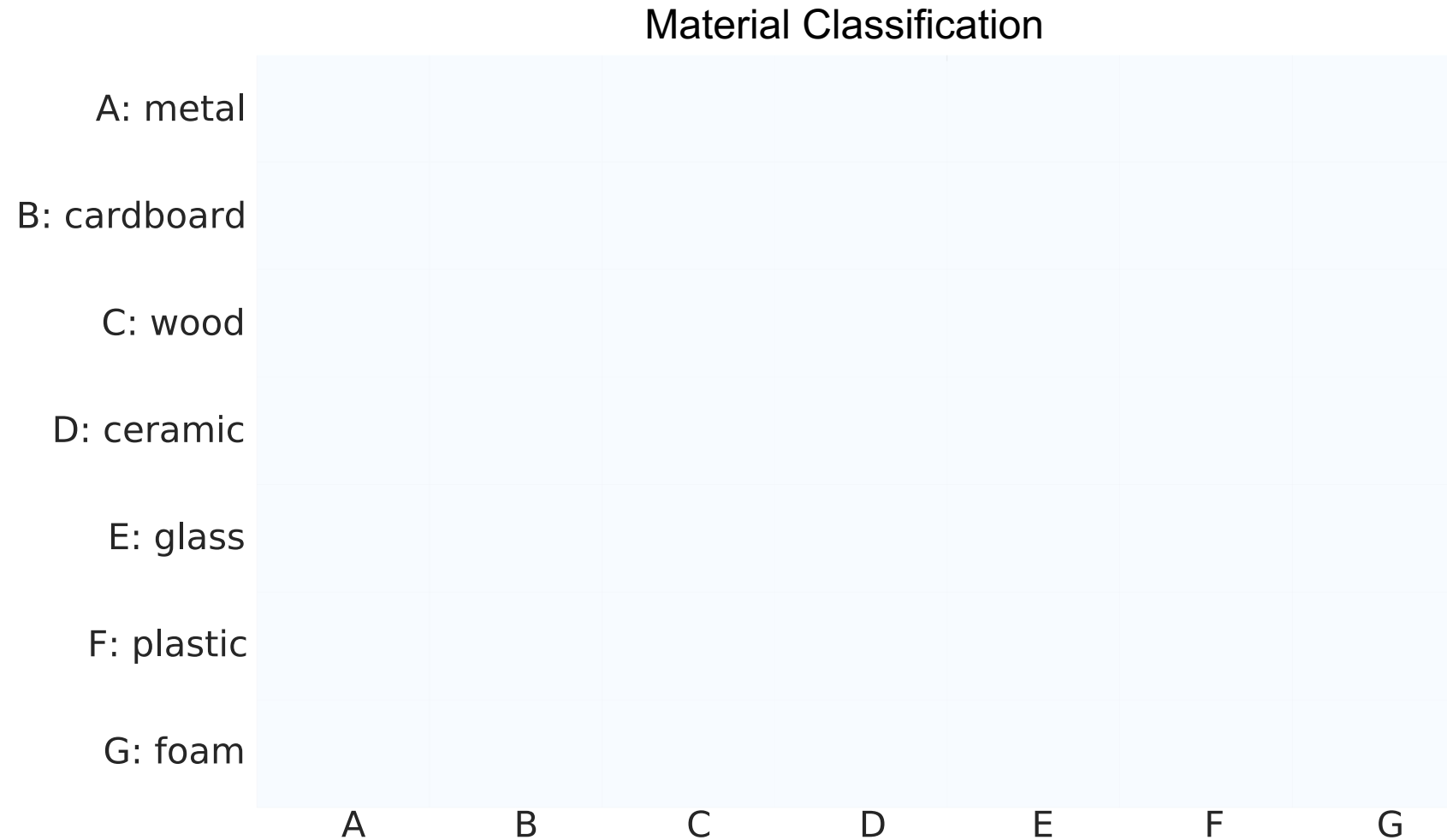


# Evaluation Details

- Experiment Objects:
  - 23 everyday objects, including curved and small objects
  - 7 different materials
- Environment
  - 3 different room: 2 office spaces, 1 lab space

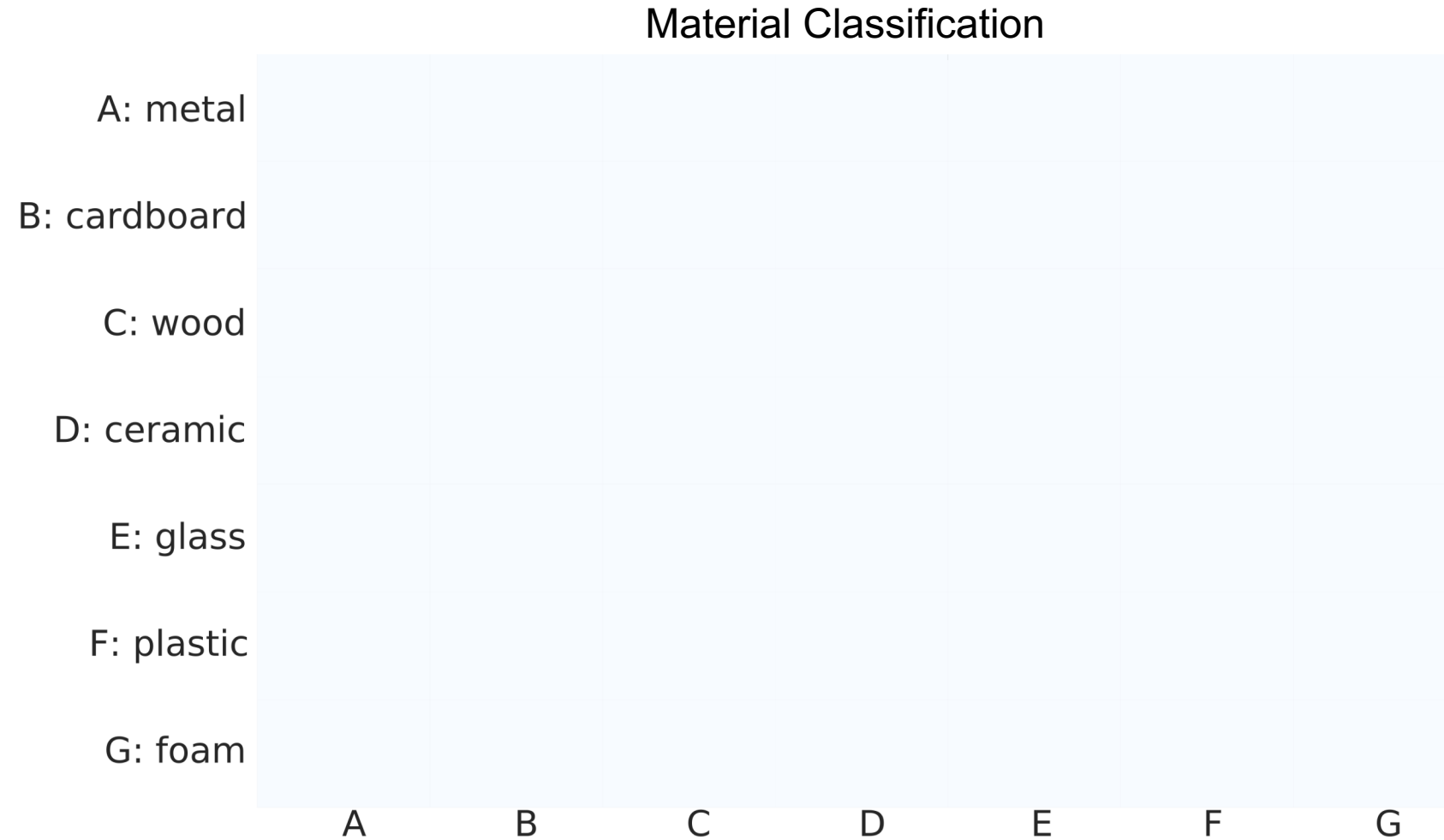


# Main Results



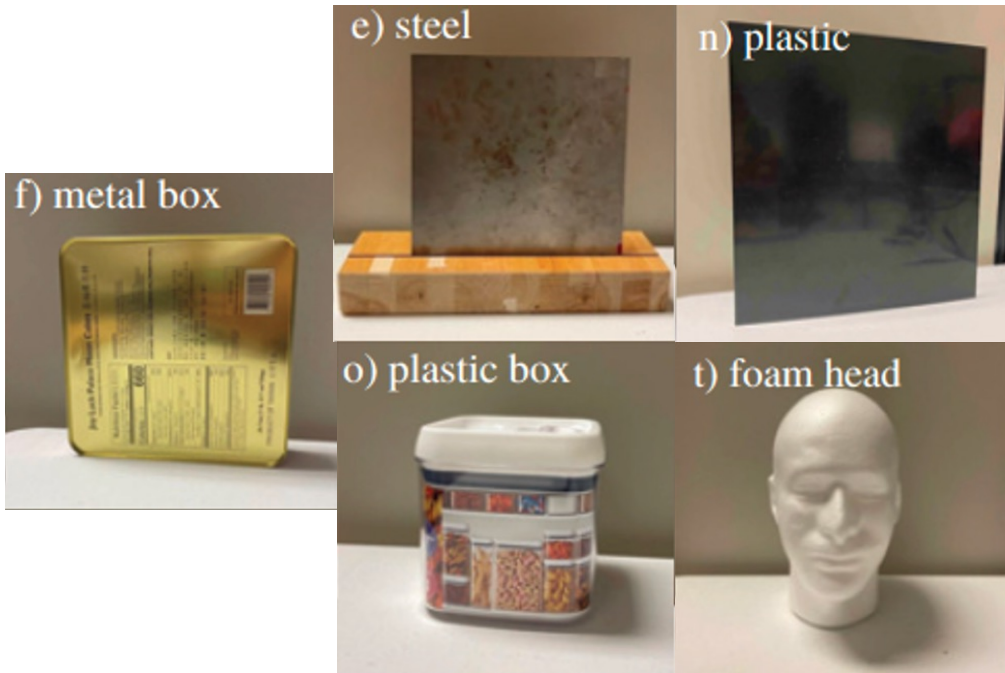
**Accuracy: 81%, 4 materials have over 90%**

# Main Results – Different Train/Test Environments



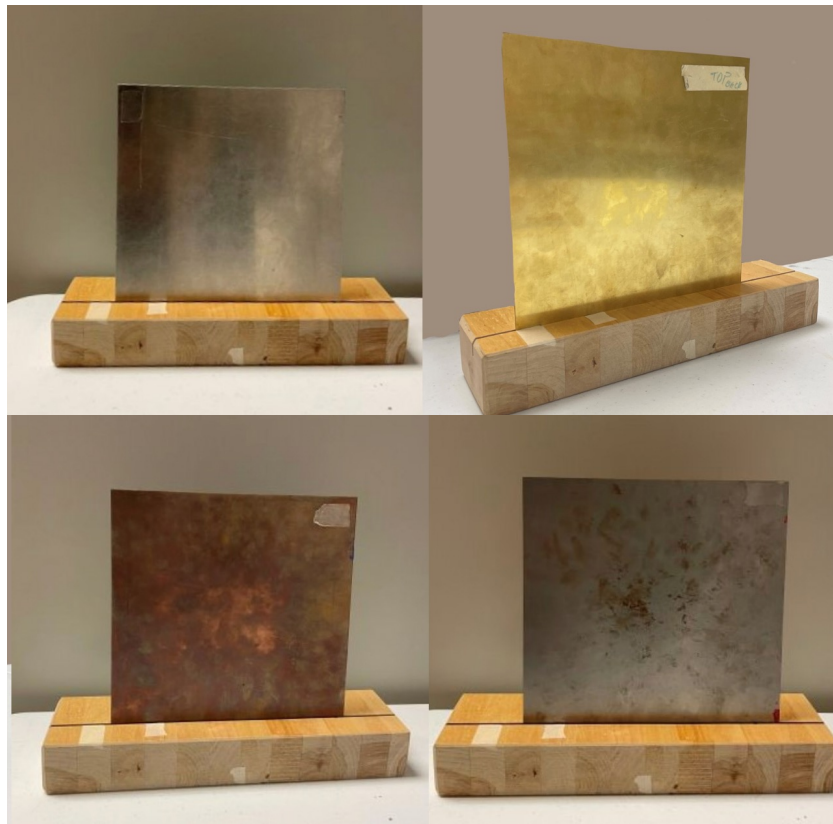
**Accuracy: 73%, 3 materials have over 80%**

# Objects not seen by the network



Unseen Object	Acc (%)	STD
Steel	99.9	0.01
Plastic Sheet	90.5	13.3
Metal Box	80.7	10.3
Plastic Box	53.5	6.0
Foam Head	47.0	9.5

# Metal Classification

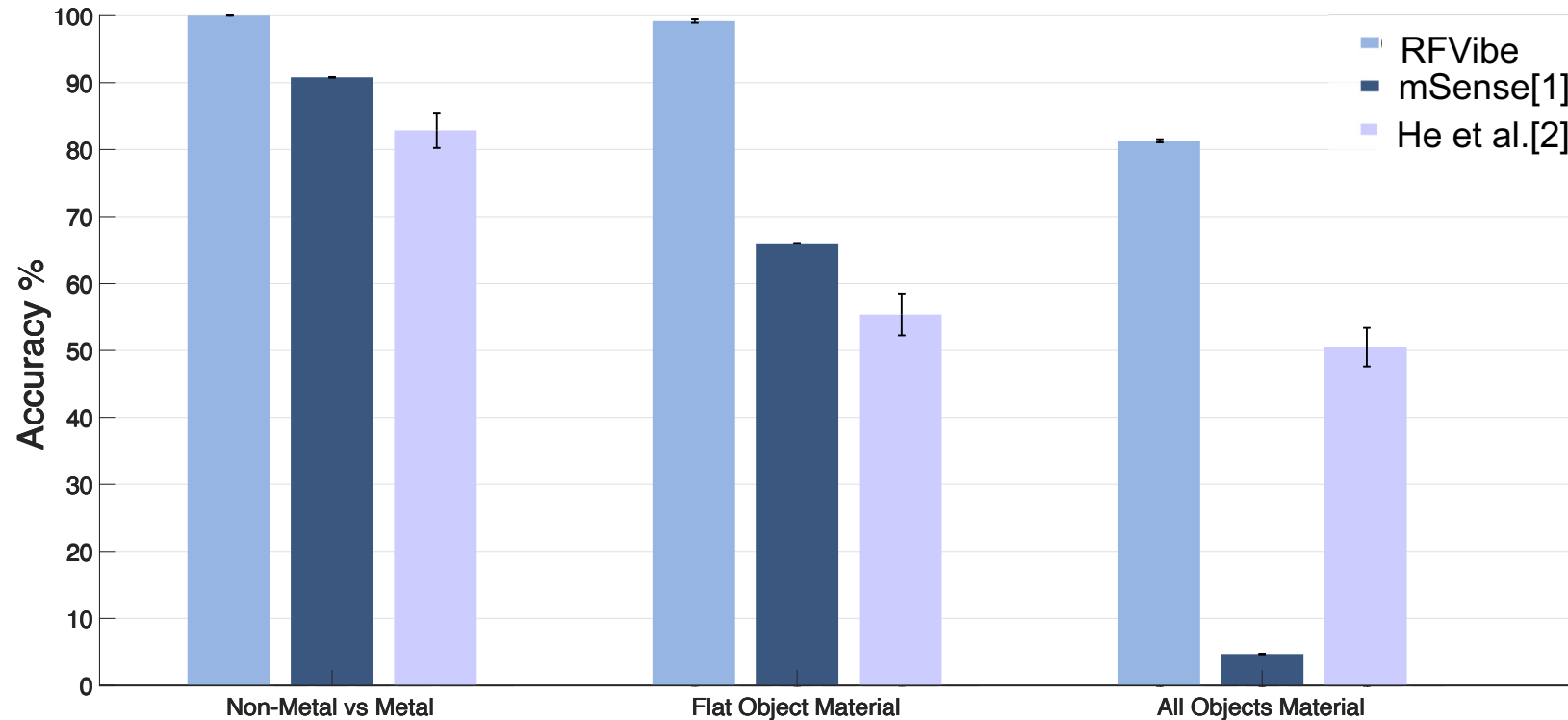


Metal Name	Acc (%)	STD
Aluminum	98.7	5.6
Brass	68.4	7.1
Copper	58.6	10.1
Steel	98.0	0.8

**Accuracy: 83%**



# Comparison with Baselines



[1] C. Wu, F. Zhang, B. Wang, and K. R. Liu. msense: Towards mobile material sensing with a single millimeter-wave radio. *IMWUT '20*

[2] S. He, Y. Qian, H. Zhang, G. Zhang, M. Xu, L. Fu, X. Cheng, H. Wang, and P. Hu. Accurate contact-free material recognition with millimeter wave and machine learning. *WASA '2022*

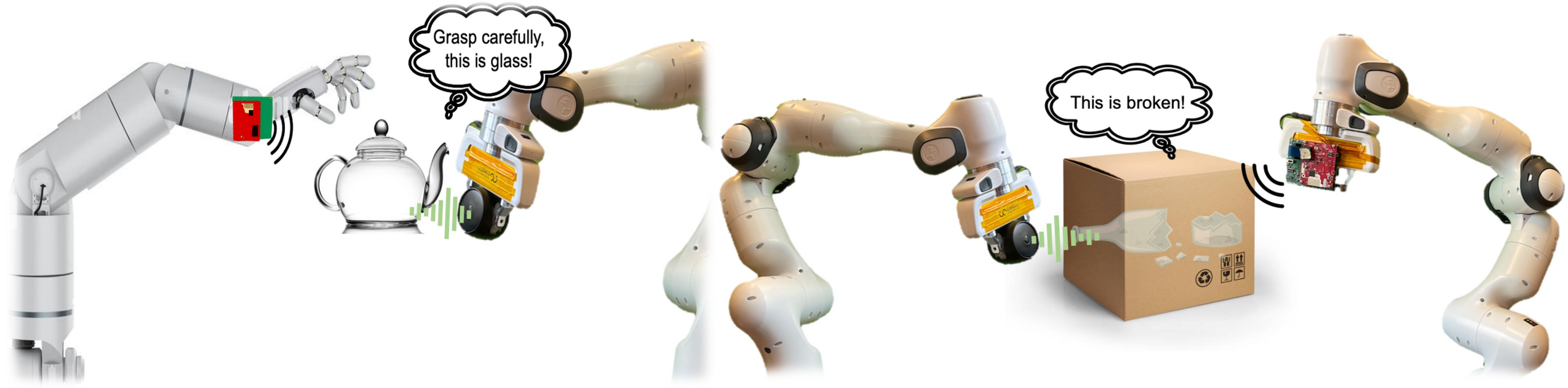
# Hidden Objects



Hidden Method	Acc (%)	STD
Uncovered	83.2	3.3
Paper Cover	70.0	4.4
In Bag	73.0	4.8
Painted	69.8	3.6

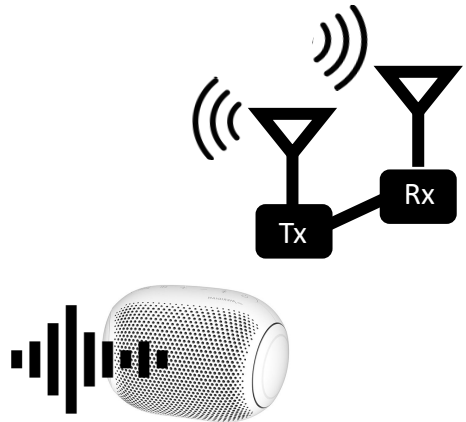
# More microbechmarks in the paper!

- *Unseen Boundary Conditions*
- *Unseen Rotation*
- *Unseen Distance of Object to Speaker*
- *Object Classification*
- *Different Speakers*
- *Impact of Individual Features*
- *Length of Vibration Time Used*
- *Comparison with Basic Classifiers*
- *Effect of Weight*
- *Background Noise*

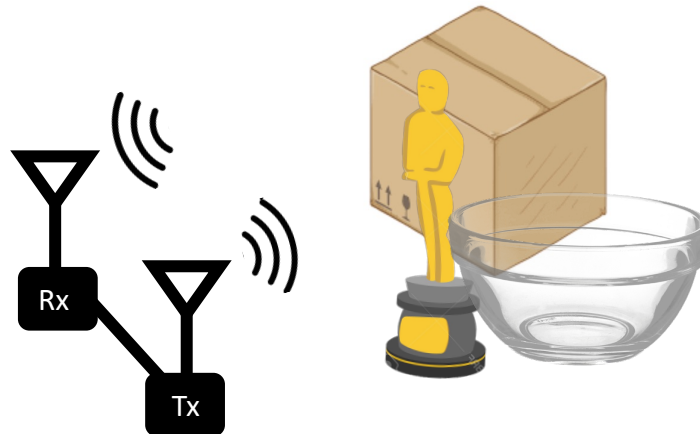


# Limitations

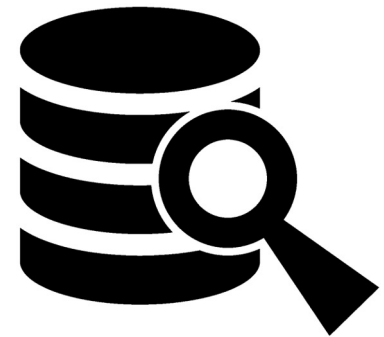
Speaker Location



Multiple Objects



More Data





- Material sensing system combining RF and acoustics to achieve high accuracy
- Resonance frequency, damping speeds and reflection power contain unique information about material properties
- Opens up the door for many applications in wireless material sensing

**Please see our code & dataset at:  
[https://github.com/hailanzs/contactless-mat-id.](https://github.com/hailanzs/contactless-mat-id)**