Interactive Acoustic Transfer Approximation for Modal Sound

Dingzeyu Li
Yun Fei
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COLUMBIA UNIVERSITY
IN THE CITY OF NEW YORK

Rigid Body Sounds

Rigid Body Sounds



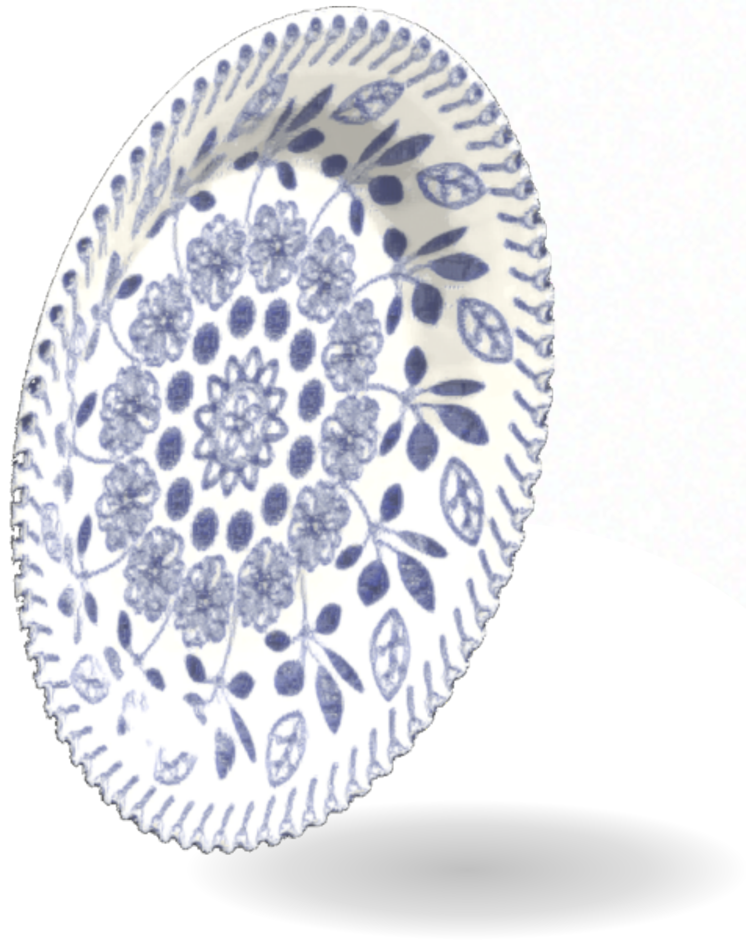


Modal Sound Synthesis

Modal Sound Synthesis

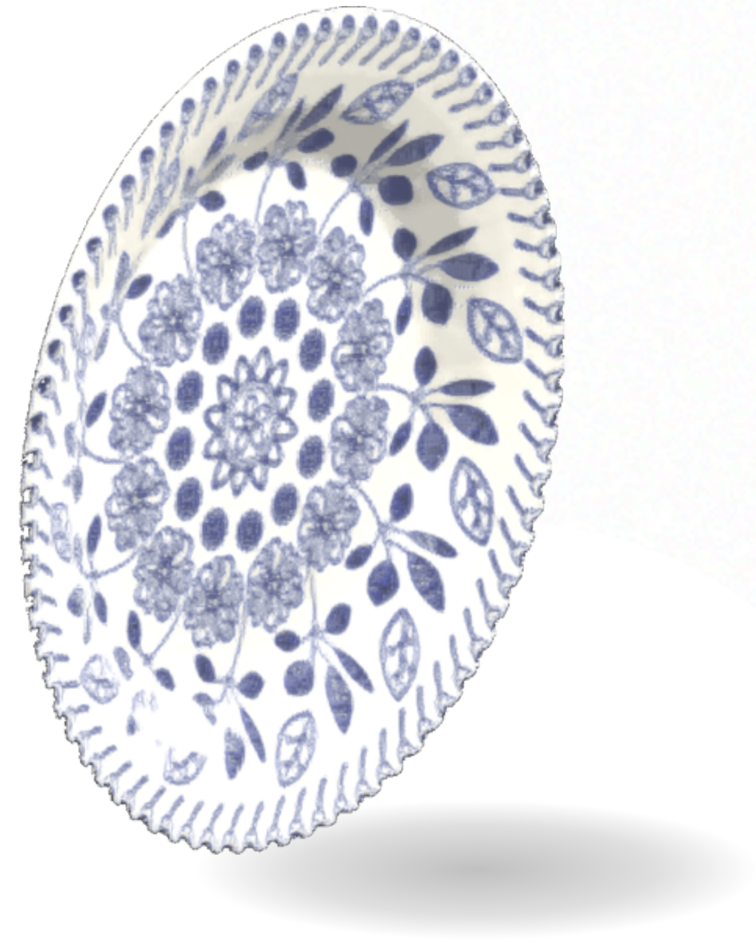
Linear Modal Analysis

Modal Vibrations



Linear Modal Analysis

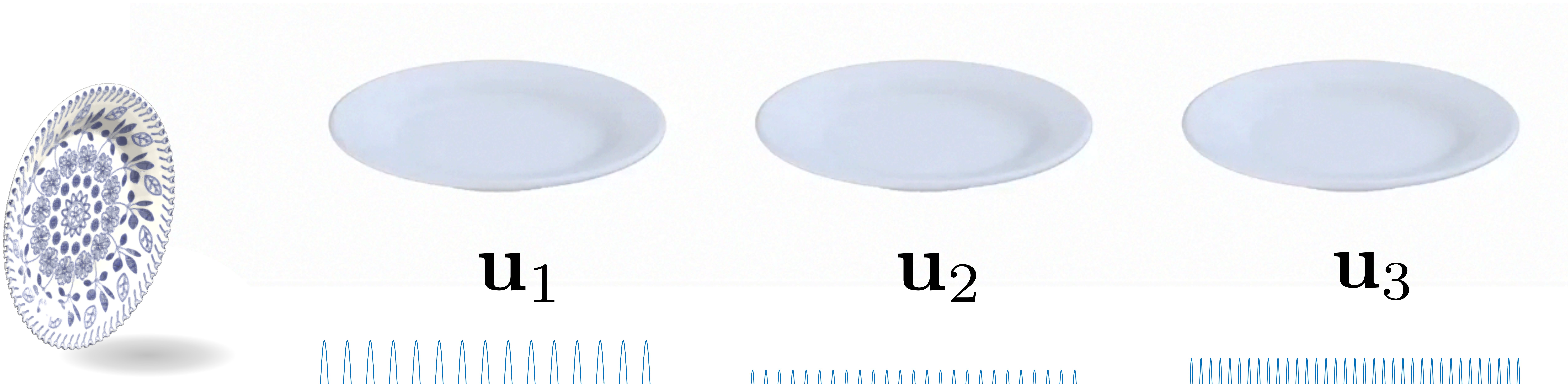
Modal Vibrations



$\mathbf{u}_1$ $\mathbf{u}_2$ $\mathbf{u}_3$

Linear Modal Analysis

Modal Vibrations



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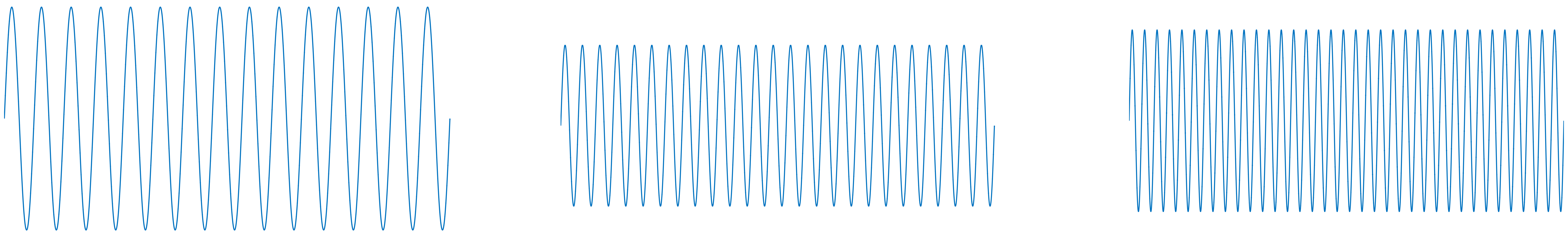
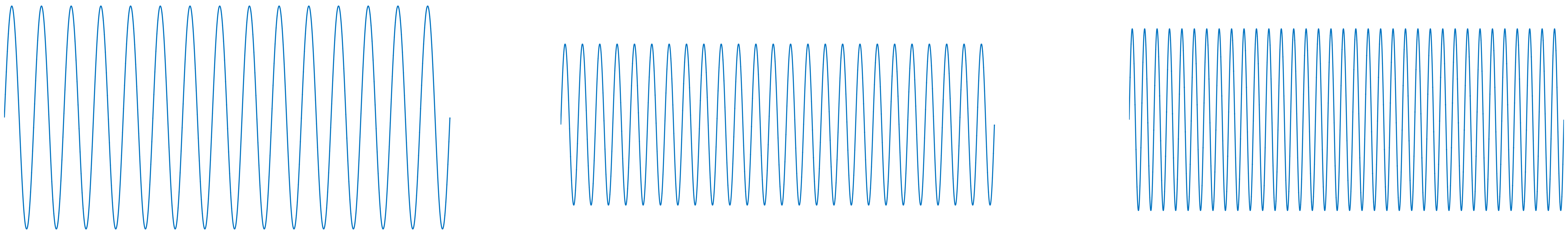


ω_1 ω_2 ω_3

Acoustic Transfer

Sound Propagation



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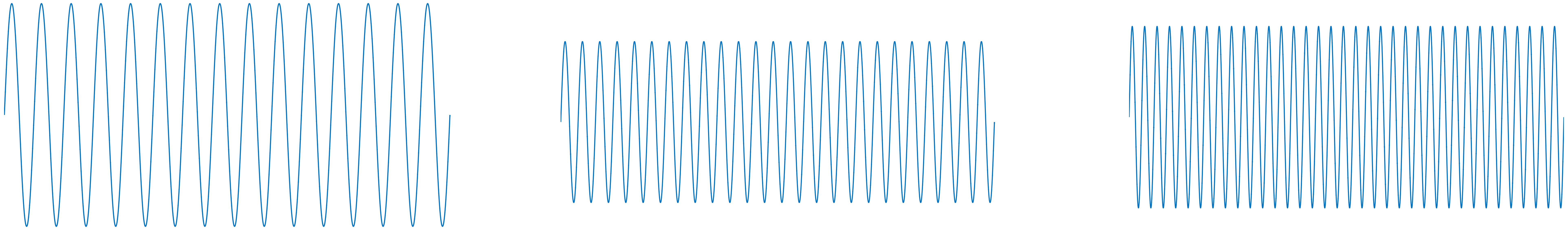

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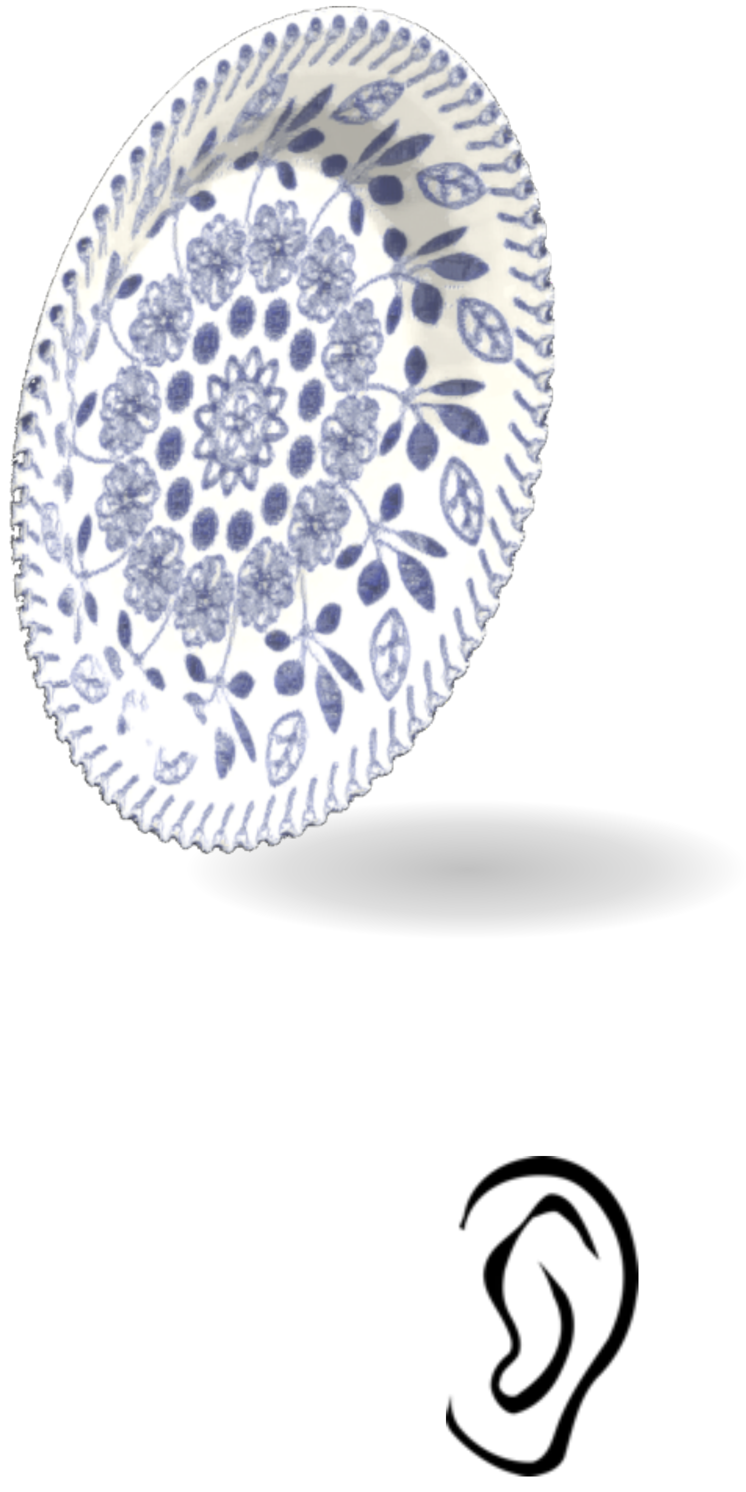

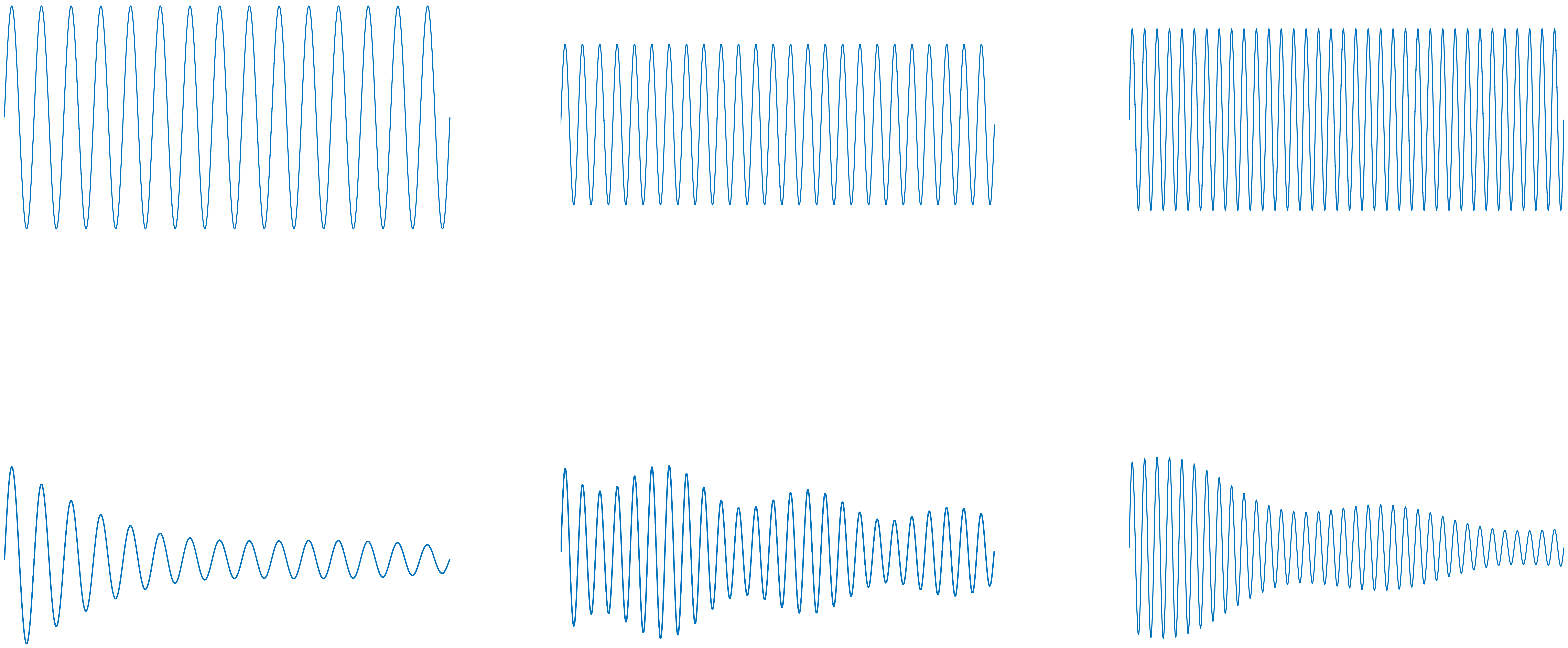

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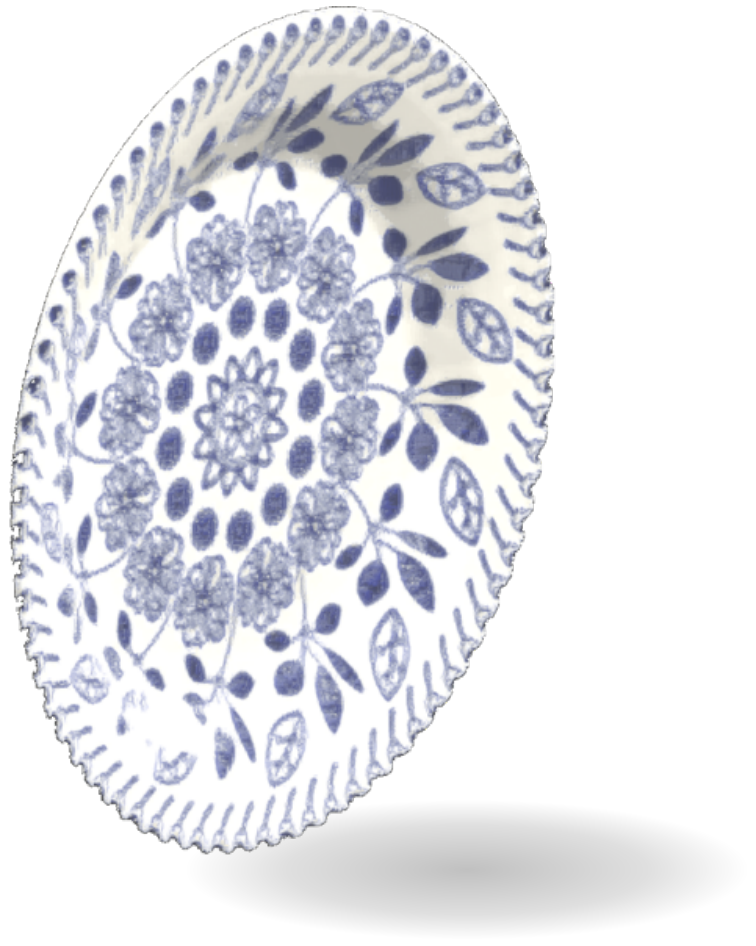
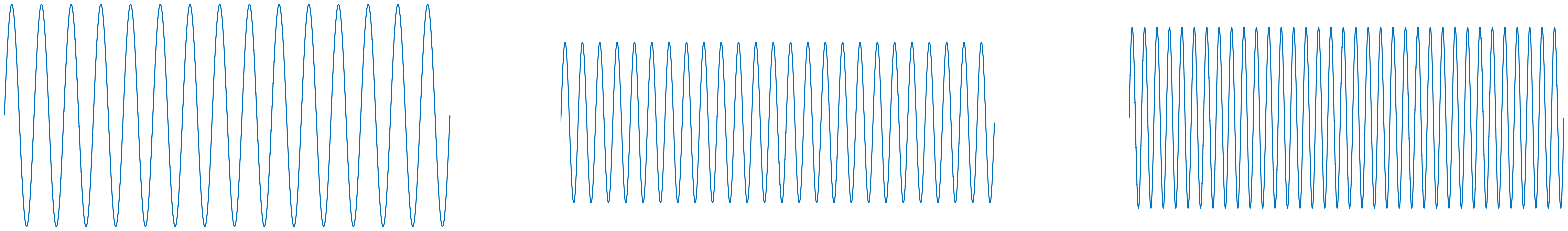
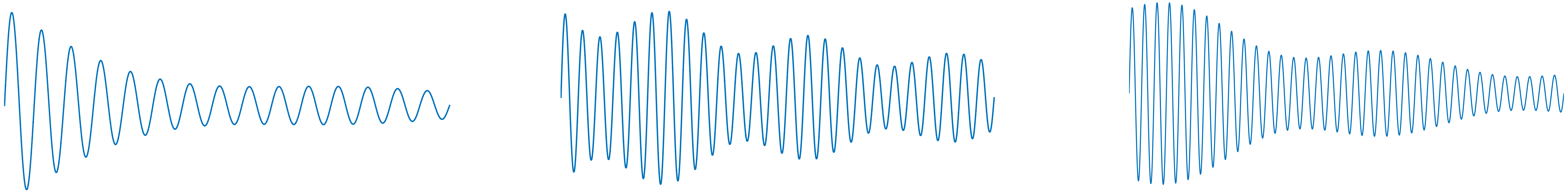




p_{ω_1} p_{ω_2} p_{ω_3}



Without Acoustic Transfer

Without Acoustic Transfer

Without Acoustic Transfer

Without Acoustic Transfer

With Acoustic Transfer

With Acoustic Transfer

With Acoustic Transfer

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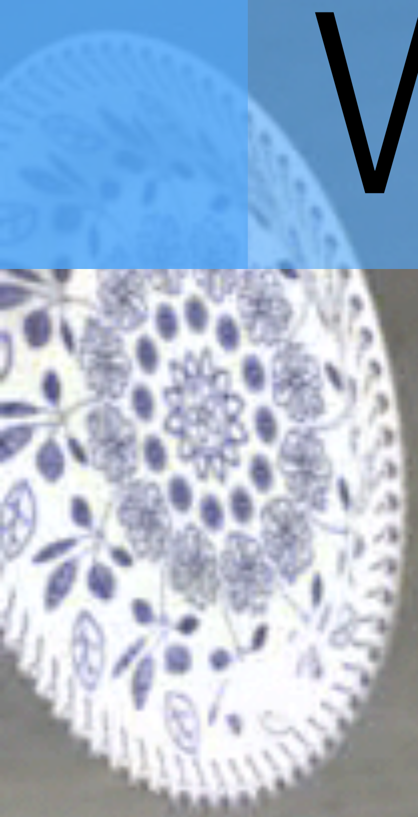

Interactive Acoustic Transfer Approximation

Helmholtz Equation

$$\nabla^2 p(\mathbf{x}, \omega) + k^2 p(\mathbf{x}, \omega) = 0$$

$$\text{s.t.} \quad \frac{\partial p}{\partial \mathbf{n}} = f(\mathbf{u}_\omega)$$

p acoustic transfer / pressure

$\mathbf{x}$ listening location

ω frequency

Helmholtz Equation

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wave equation

$$\nabla^2 u = \frac{1}{c^2} \frac{\partial^2 u}{\partial t^2}$$

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Basic Pipeline

Ceramics				
Glasses	Borosilicate Glass	61	-	64
	Glass Ceramic	64	-	110
	Silica Glass	68	-	74
	Soda-Lime Glass	68	-	72
Porous	Brick	10	-	50
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Technical	Alumina	215		413
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Material Parameters

Linear Modal Analysis

SLOW!

$$\nabla^2 p(\mathbf{x},\omega) + k^2 p(\mathbf{x},\omega) = 0$$

Helmholtz Solves

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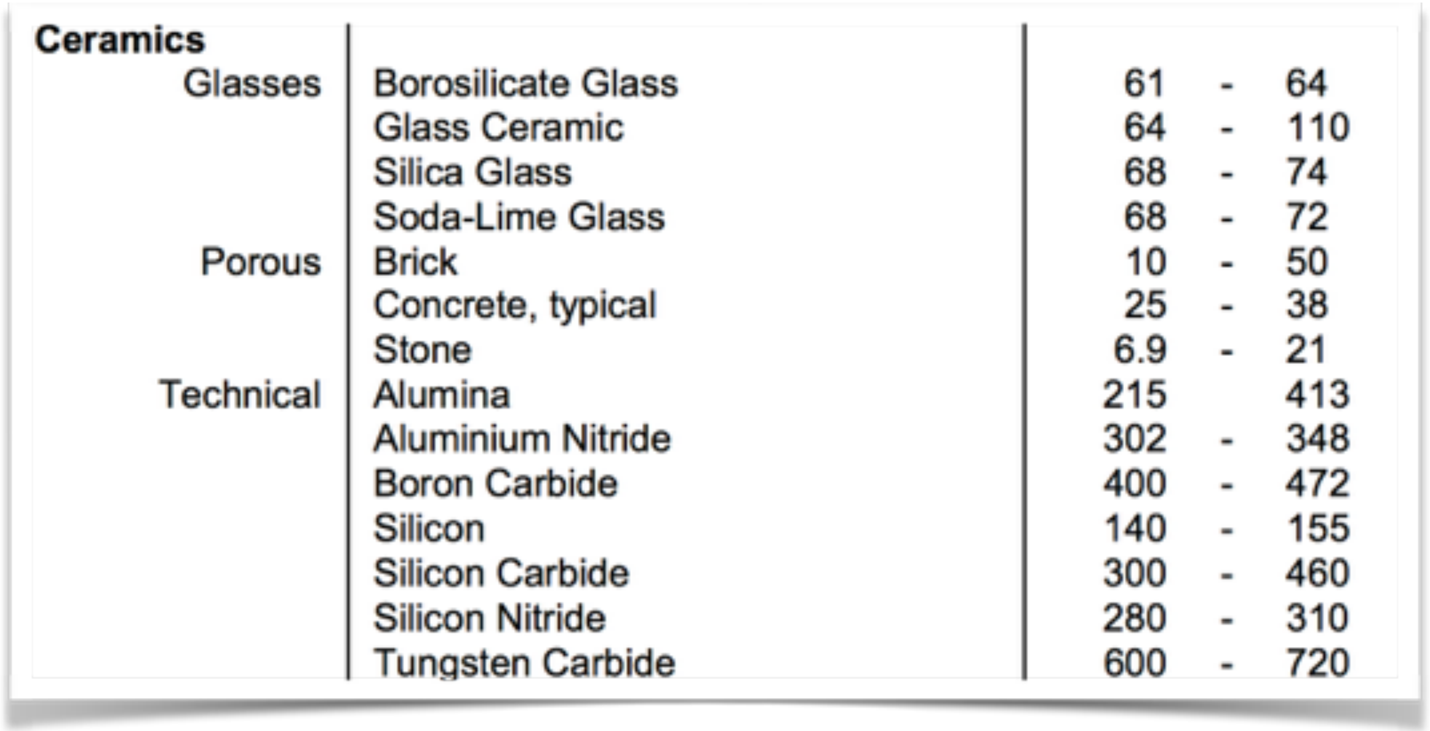

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Young's modulus
Material Data Book, University of Cambridge

A wide range of materials

No exact parameter

Possible range is large

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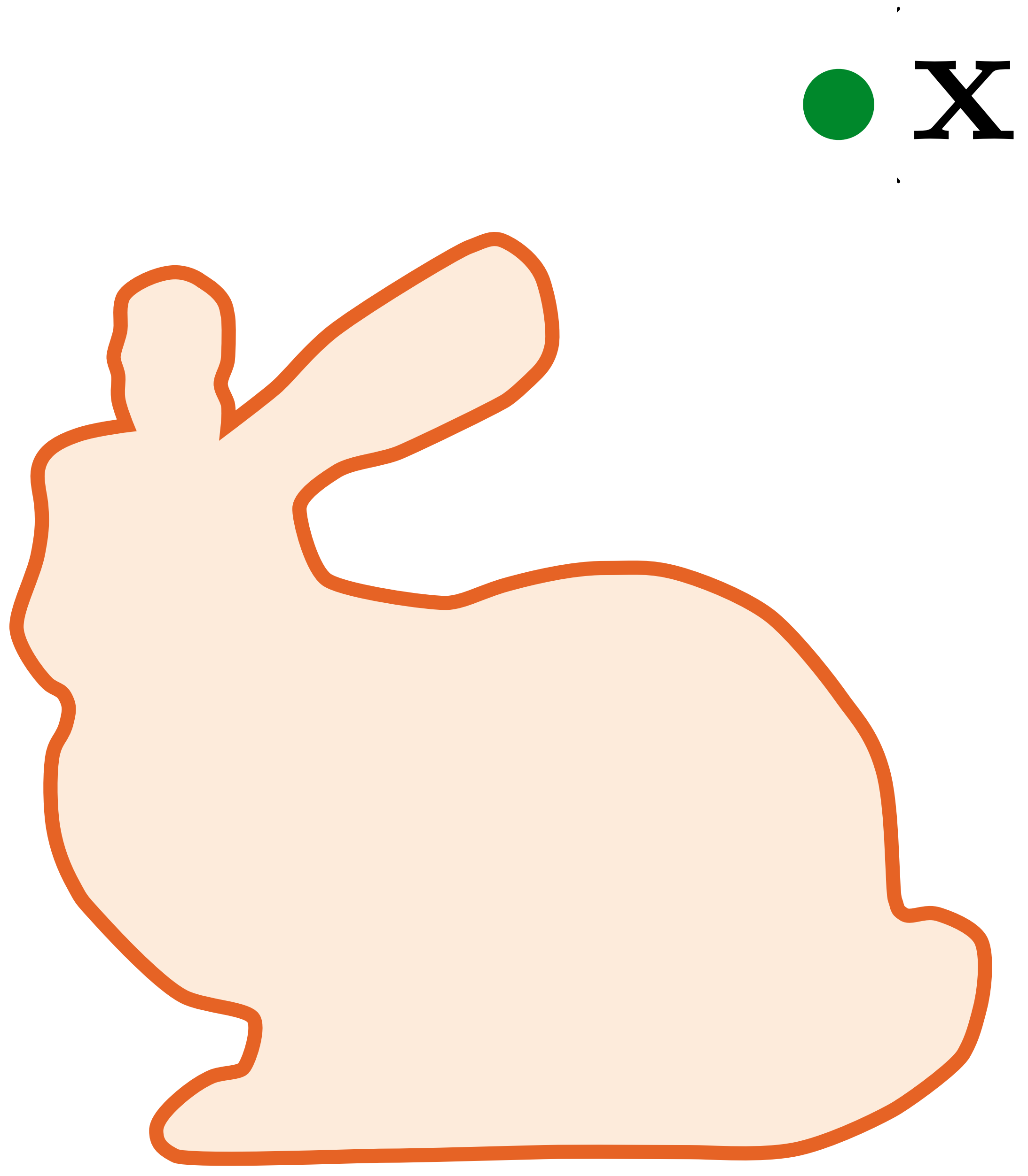
Problem Definition



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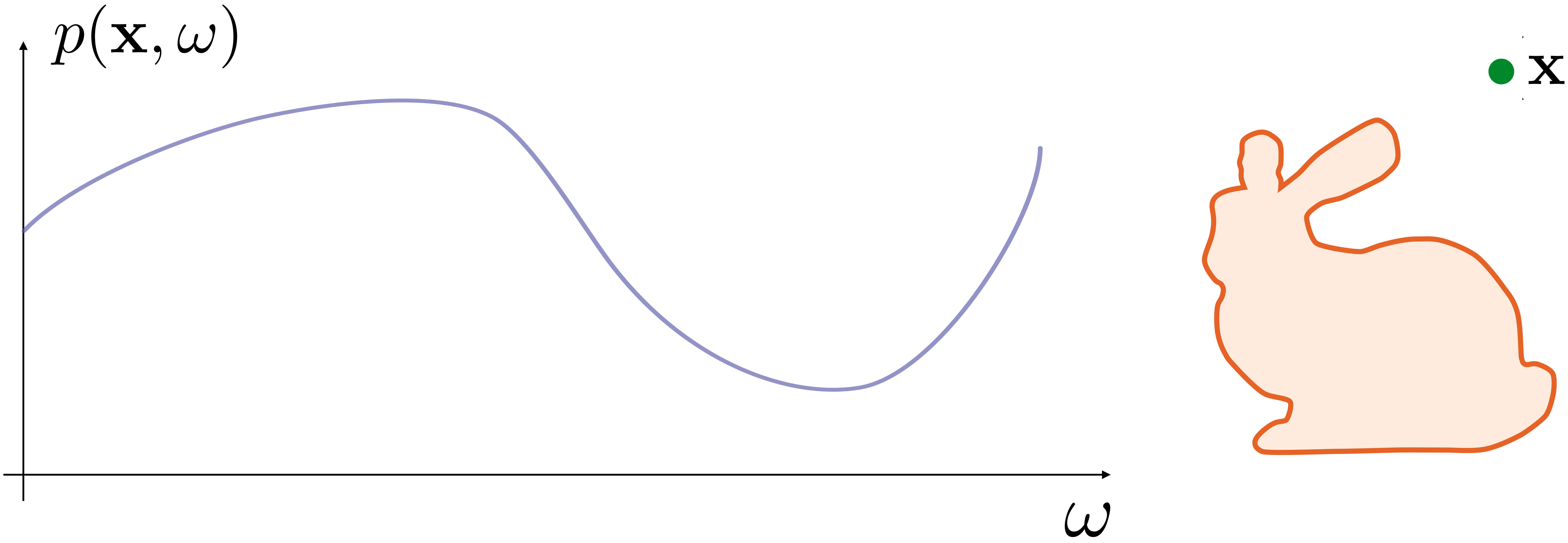

Related Work - Acoustic Simulation

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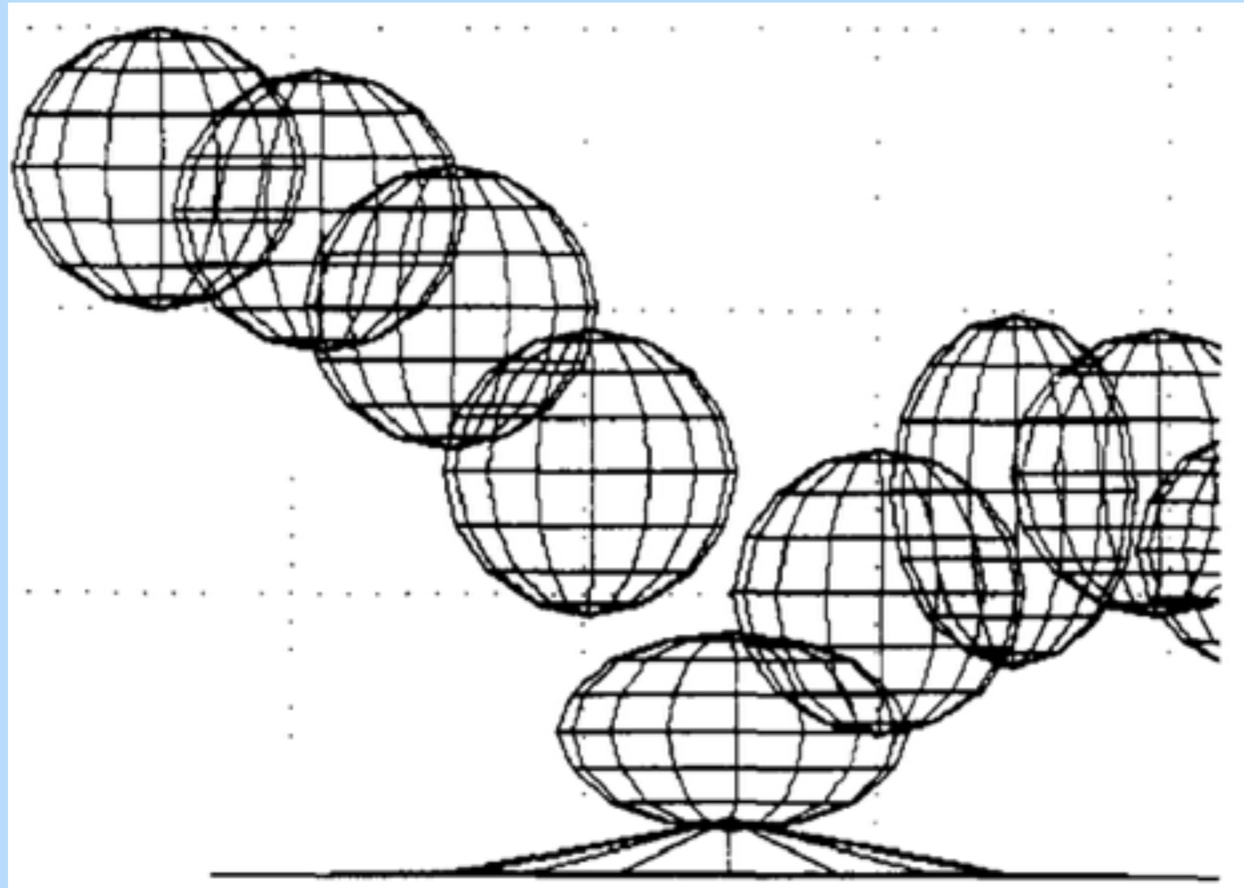

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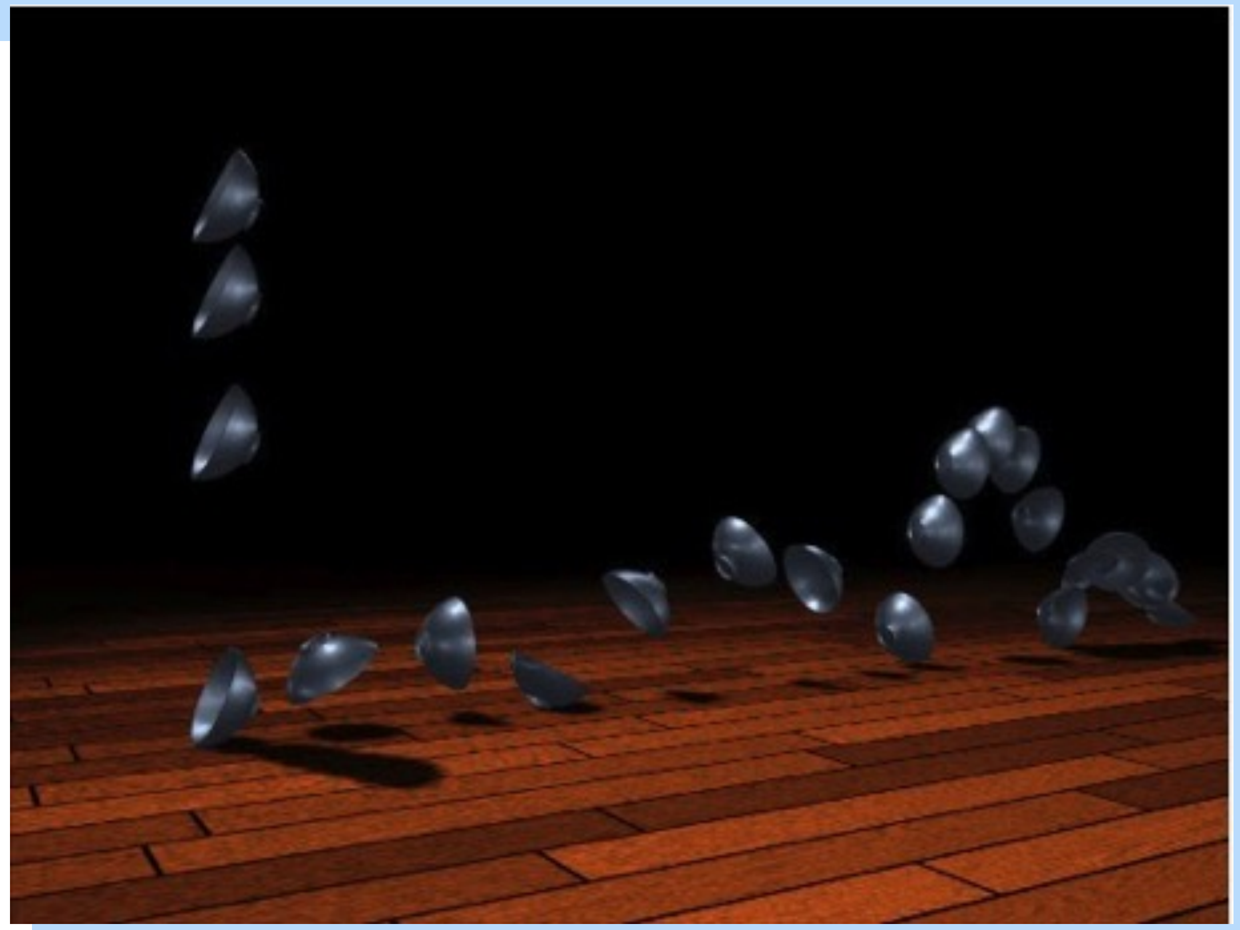

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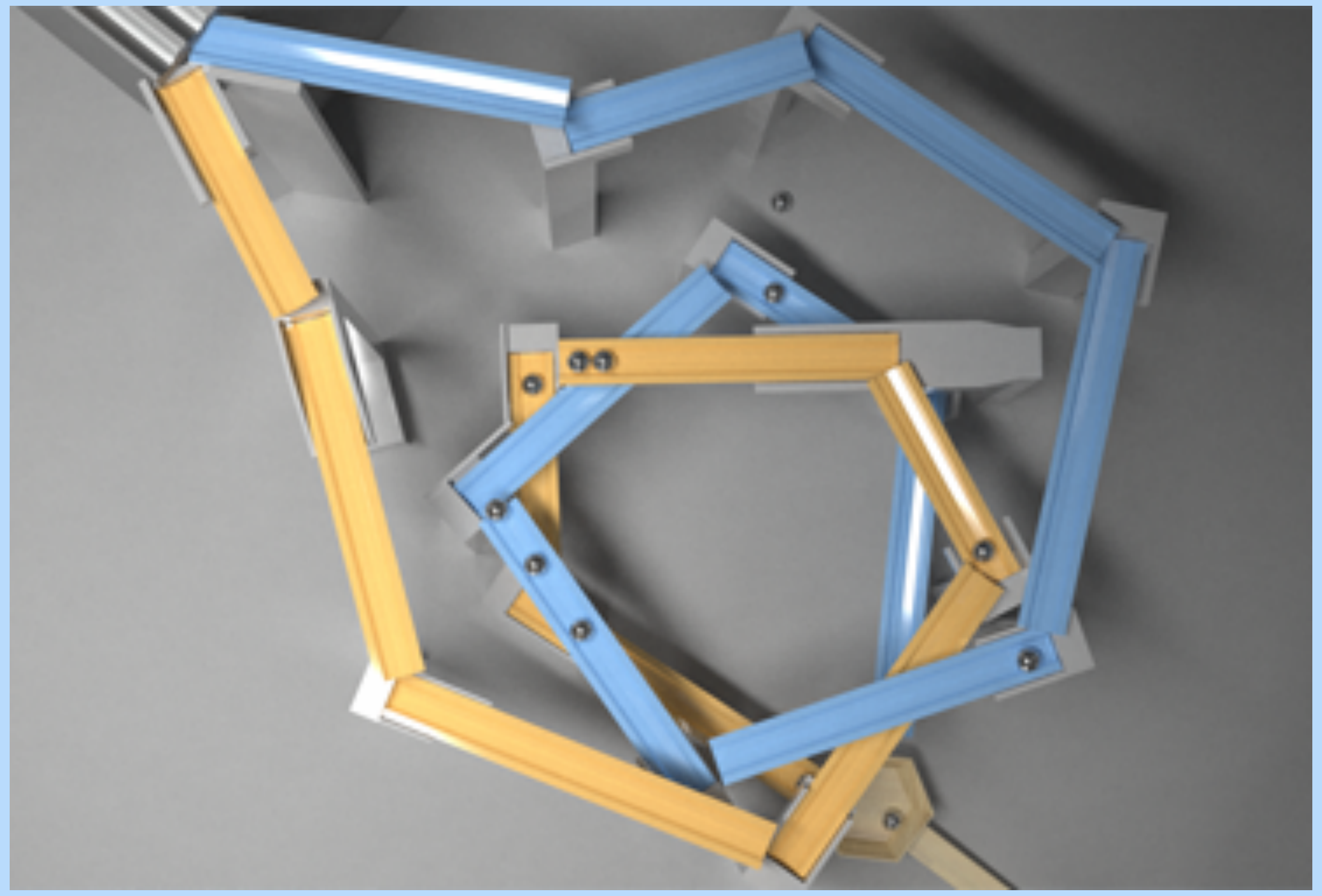

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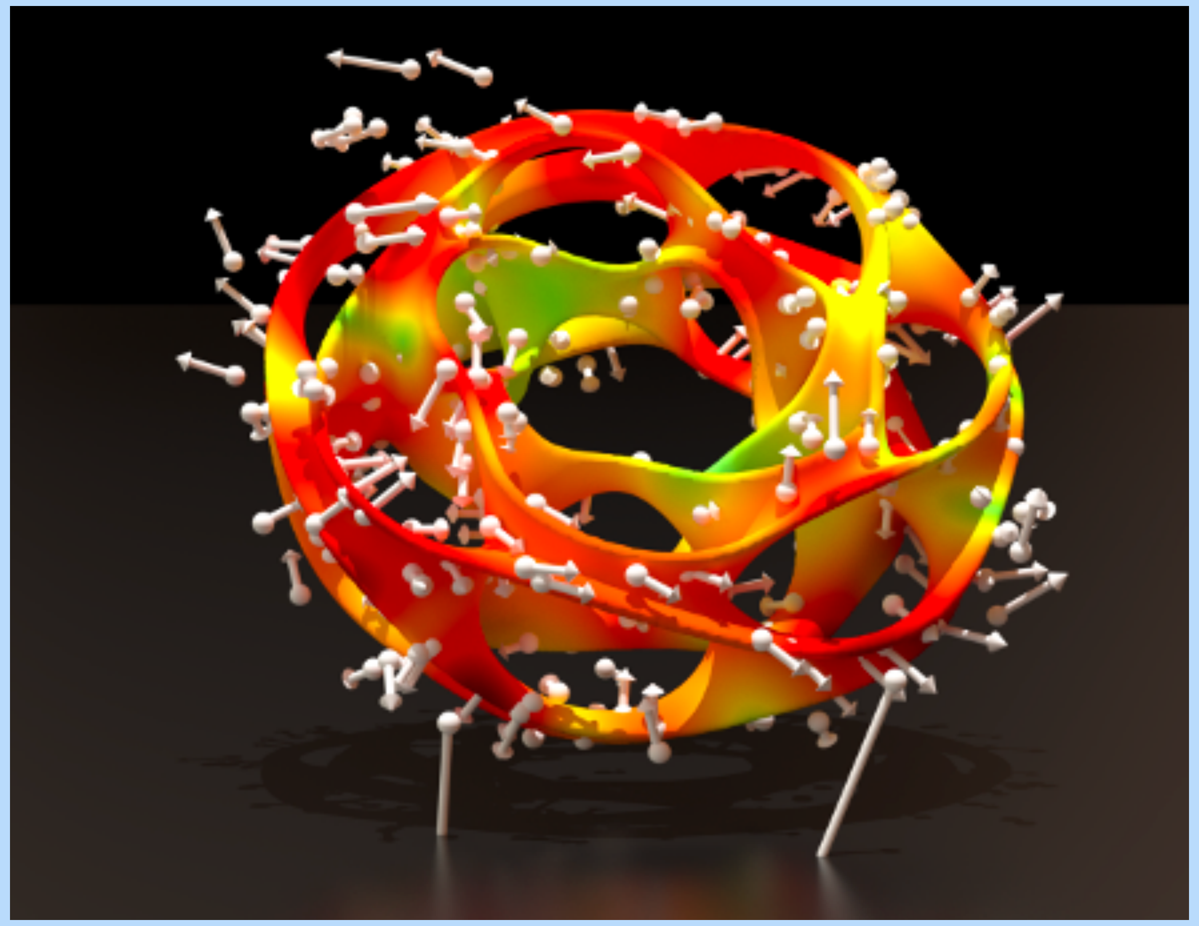

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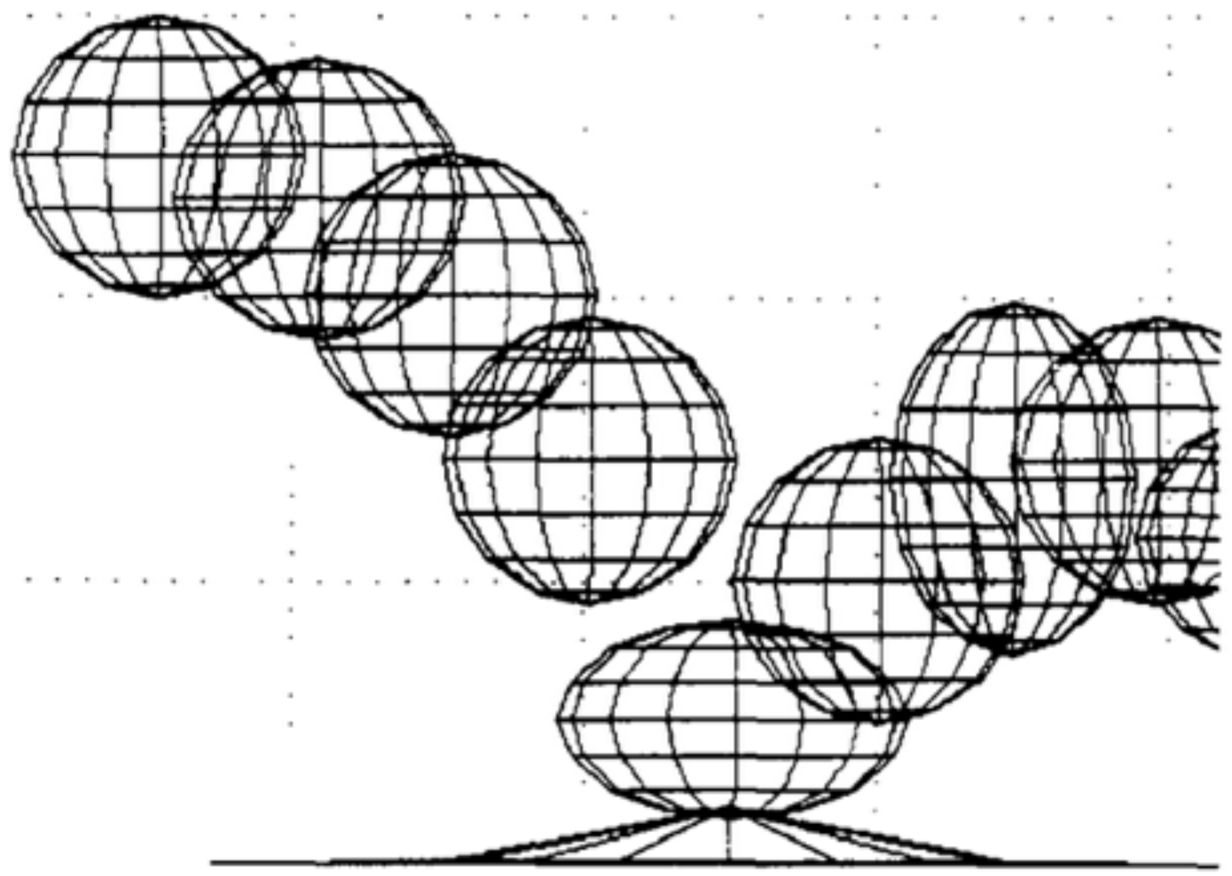

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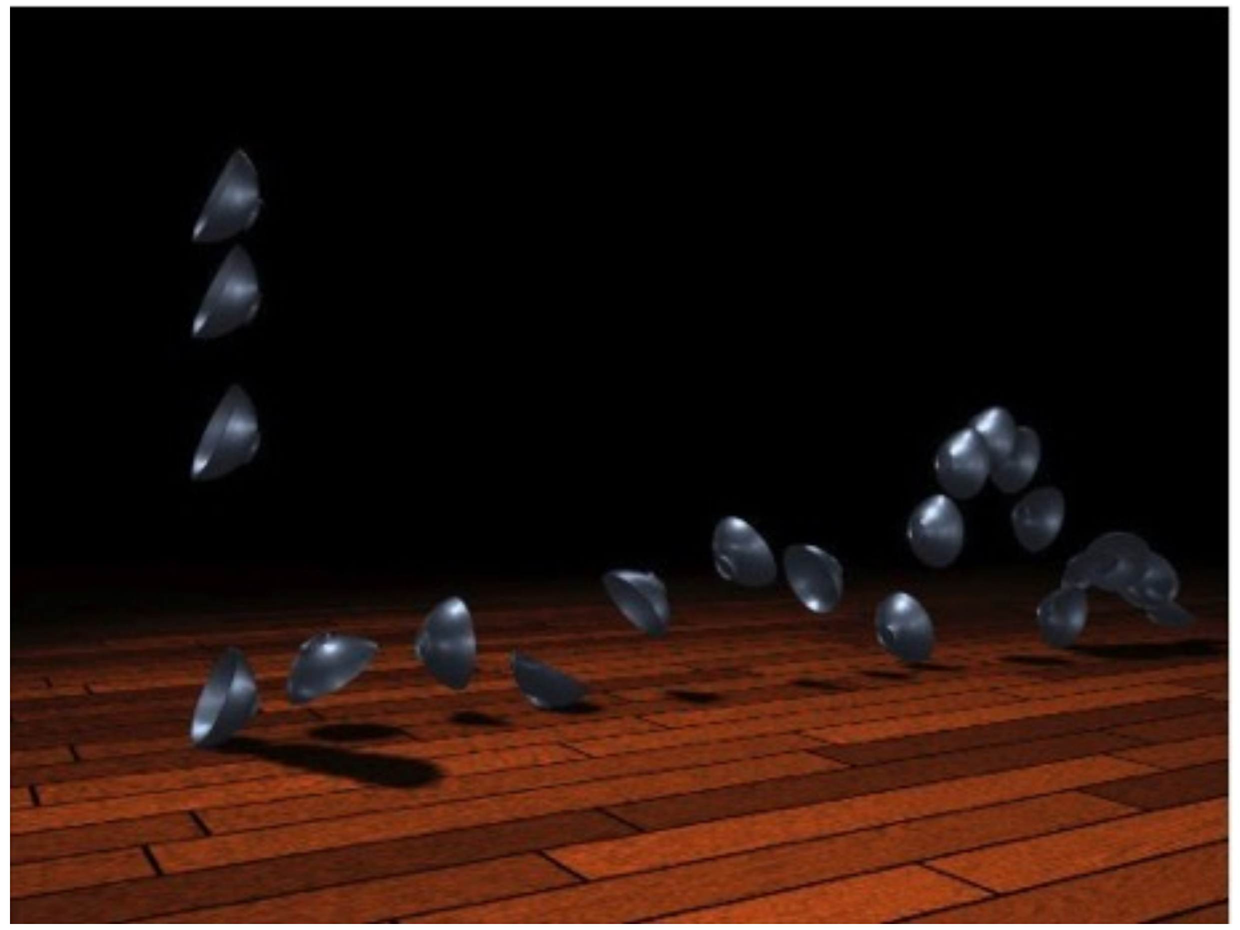

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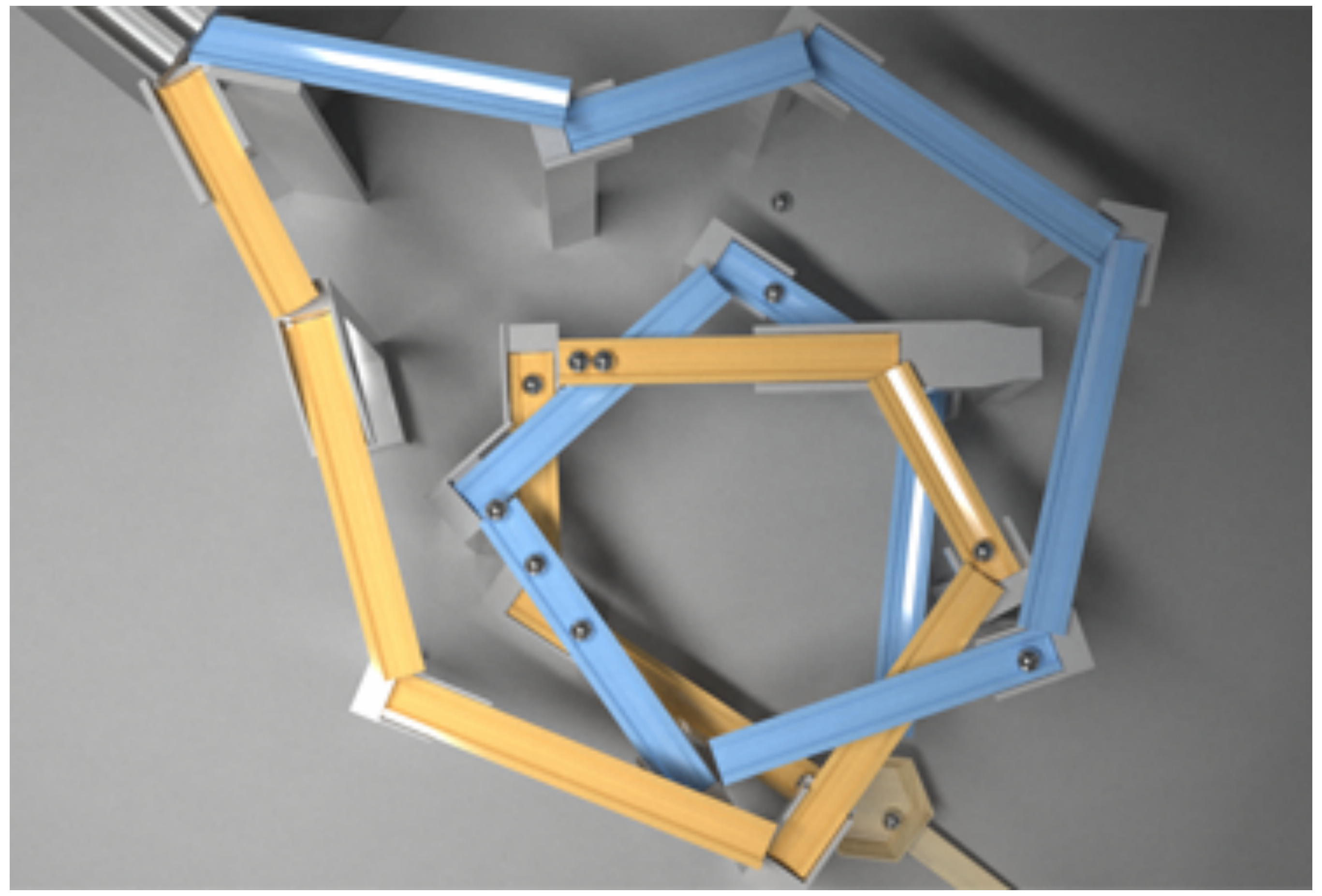

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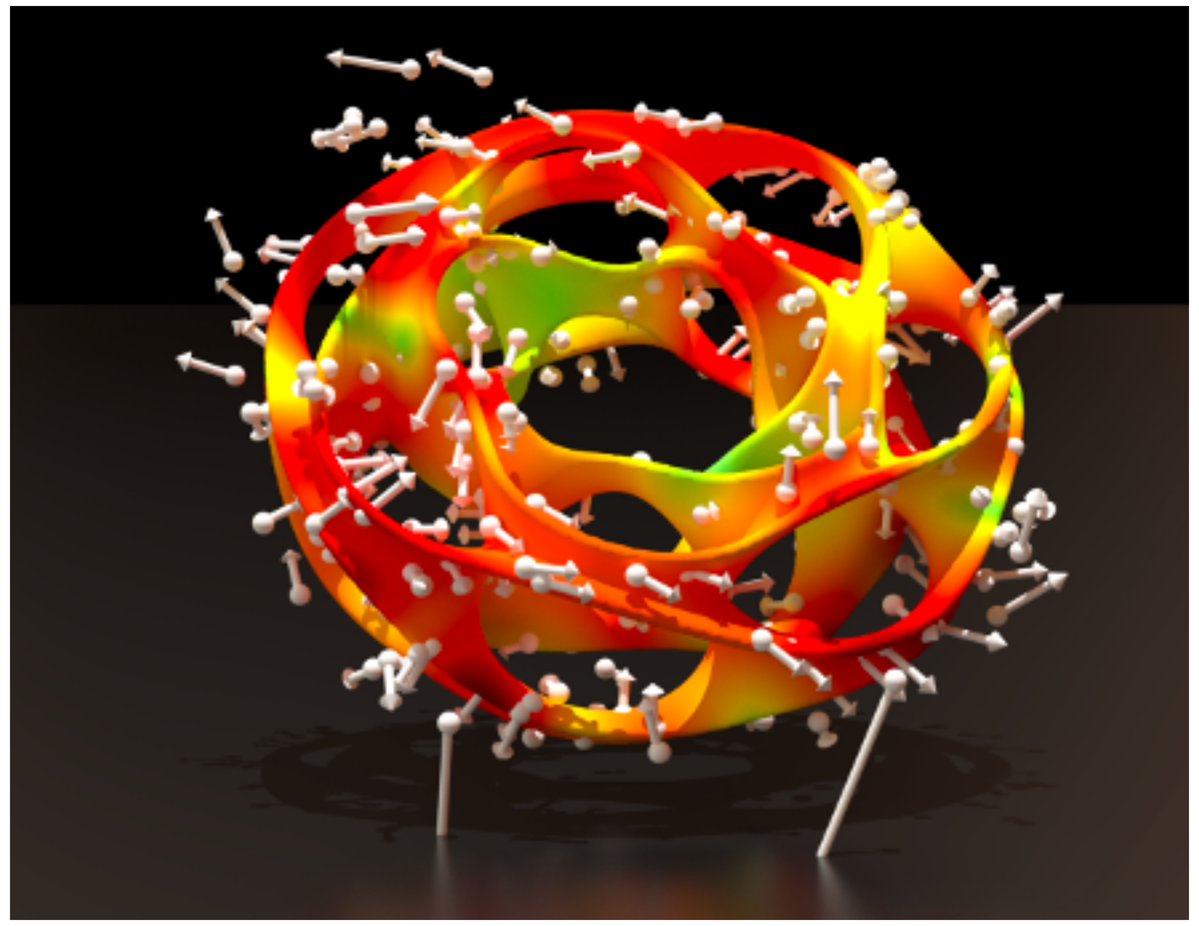

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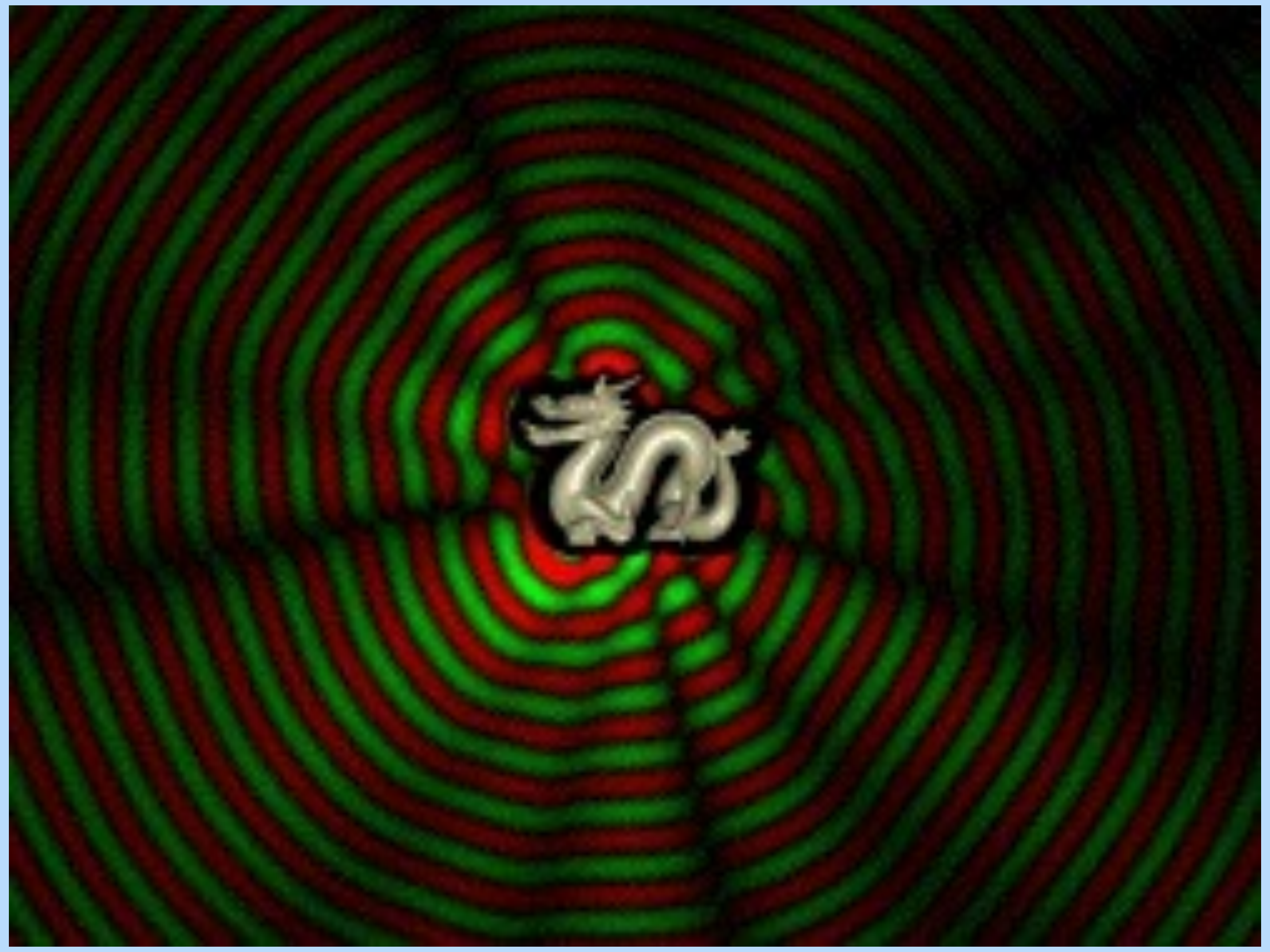

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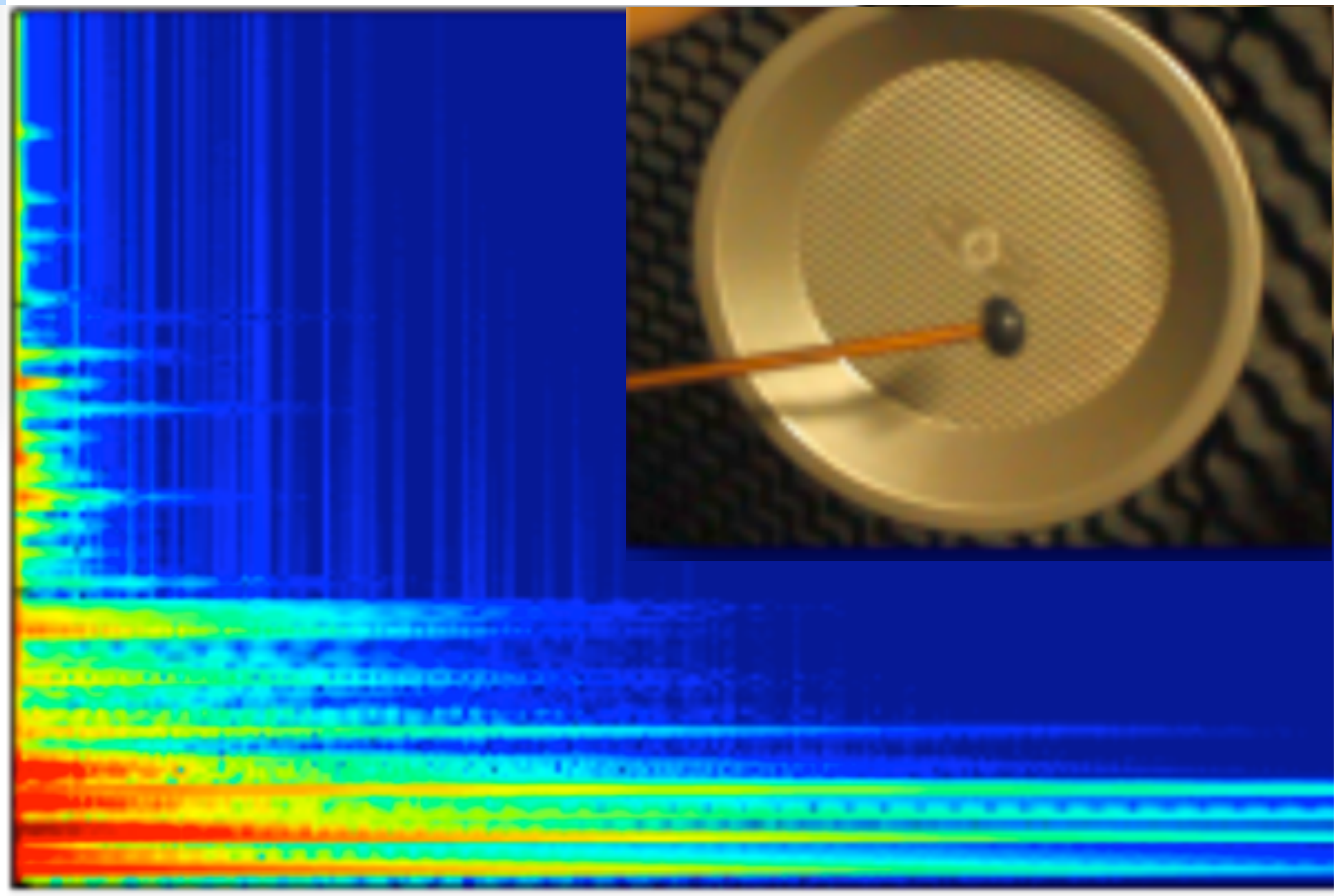

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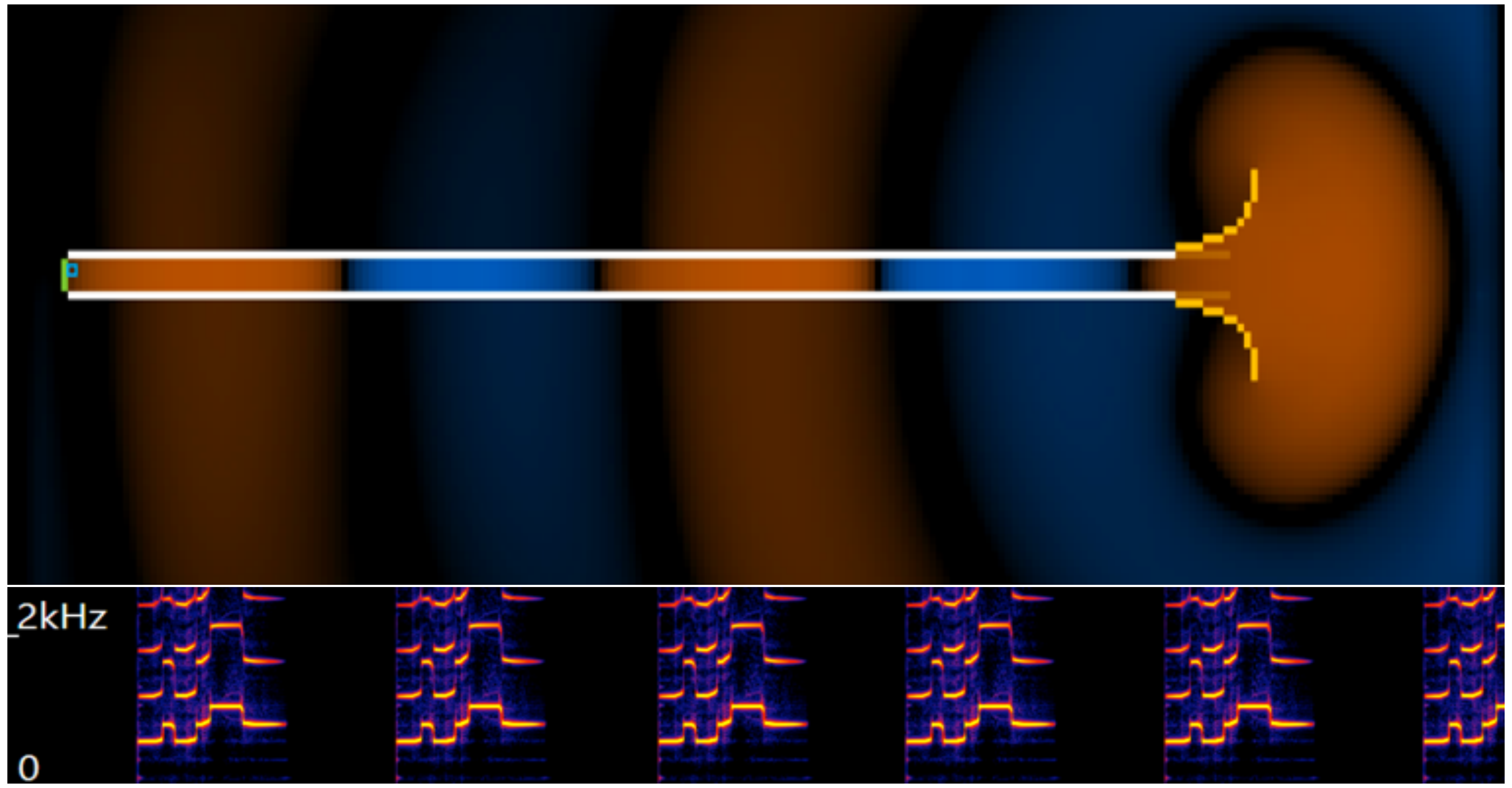

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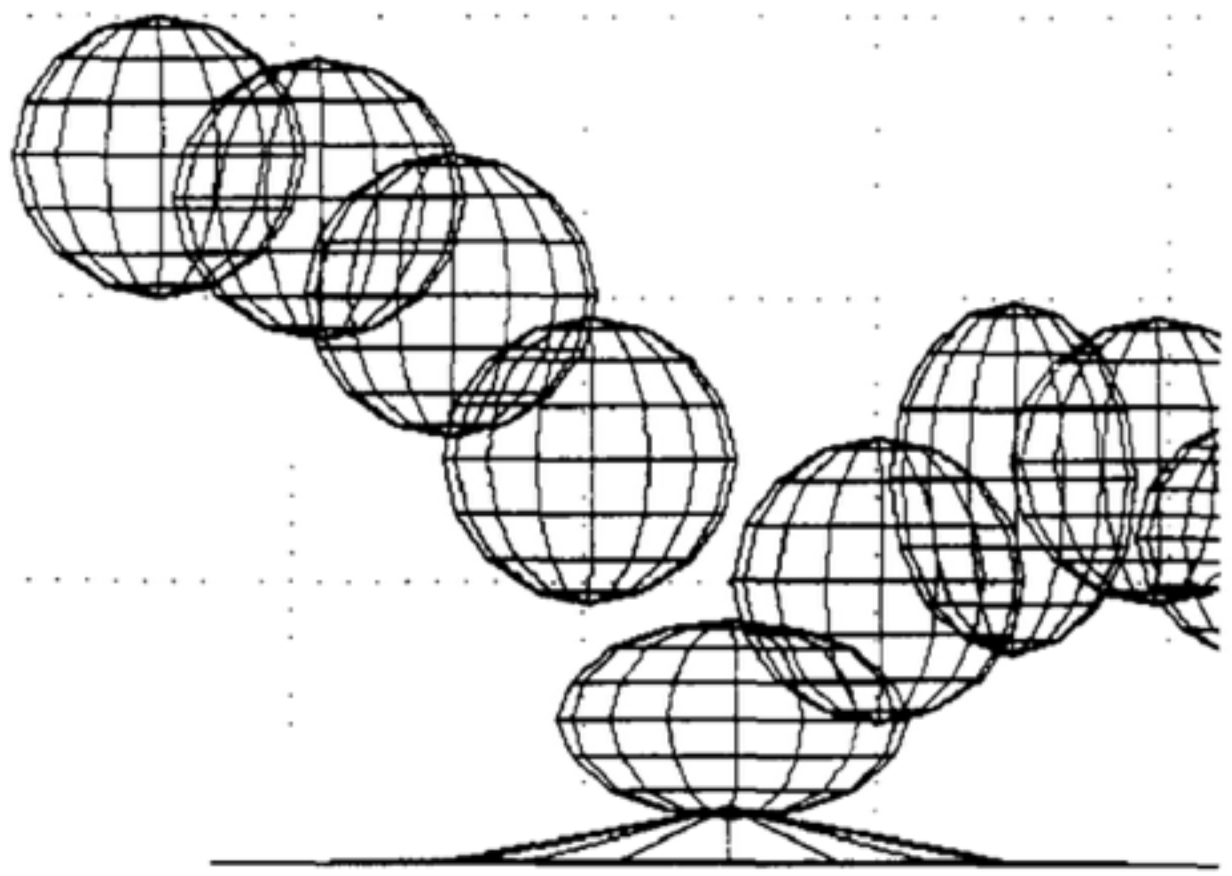
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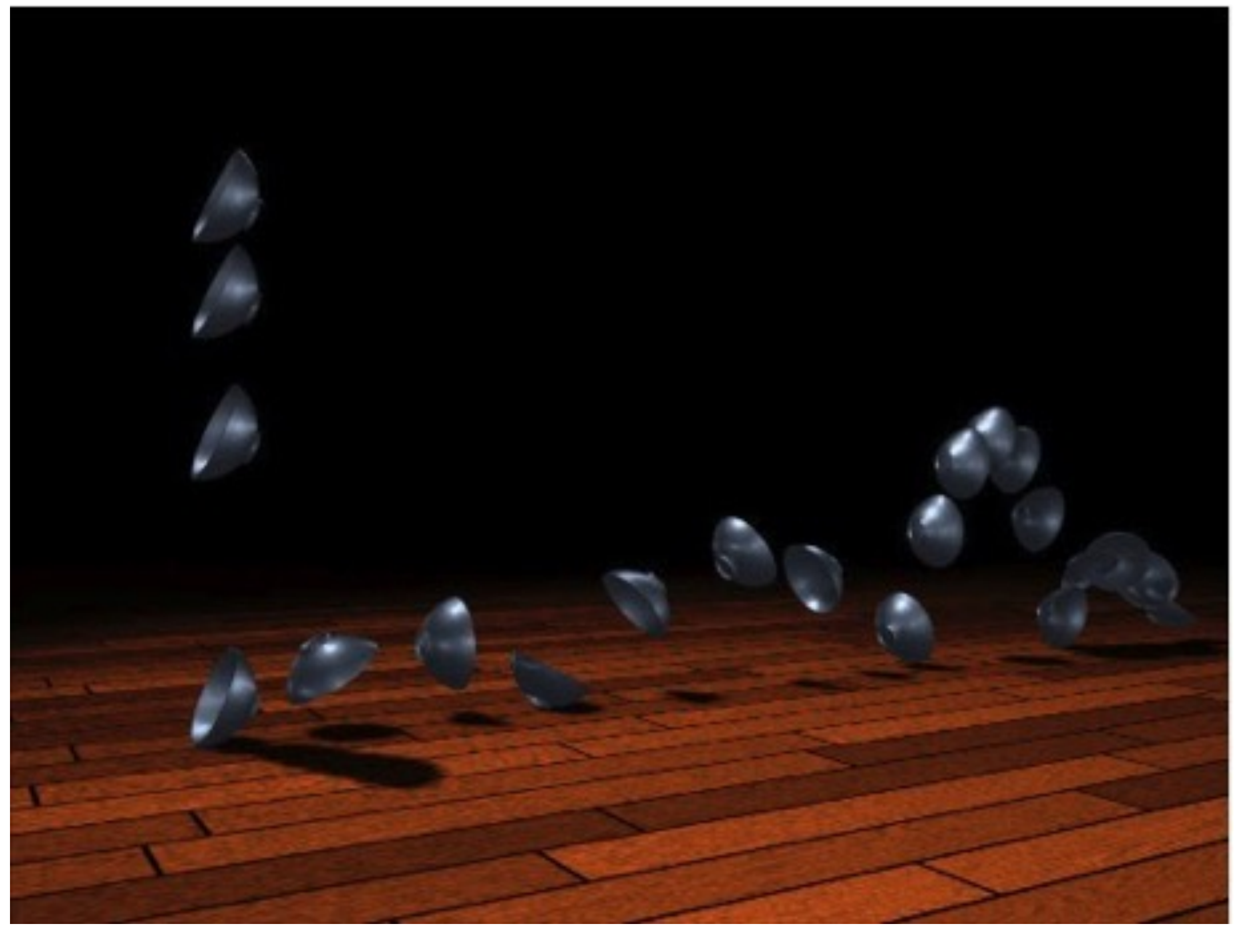
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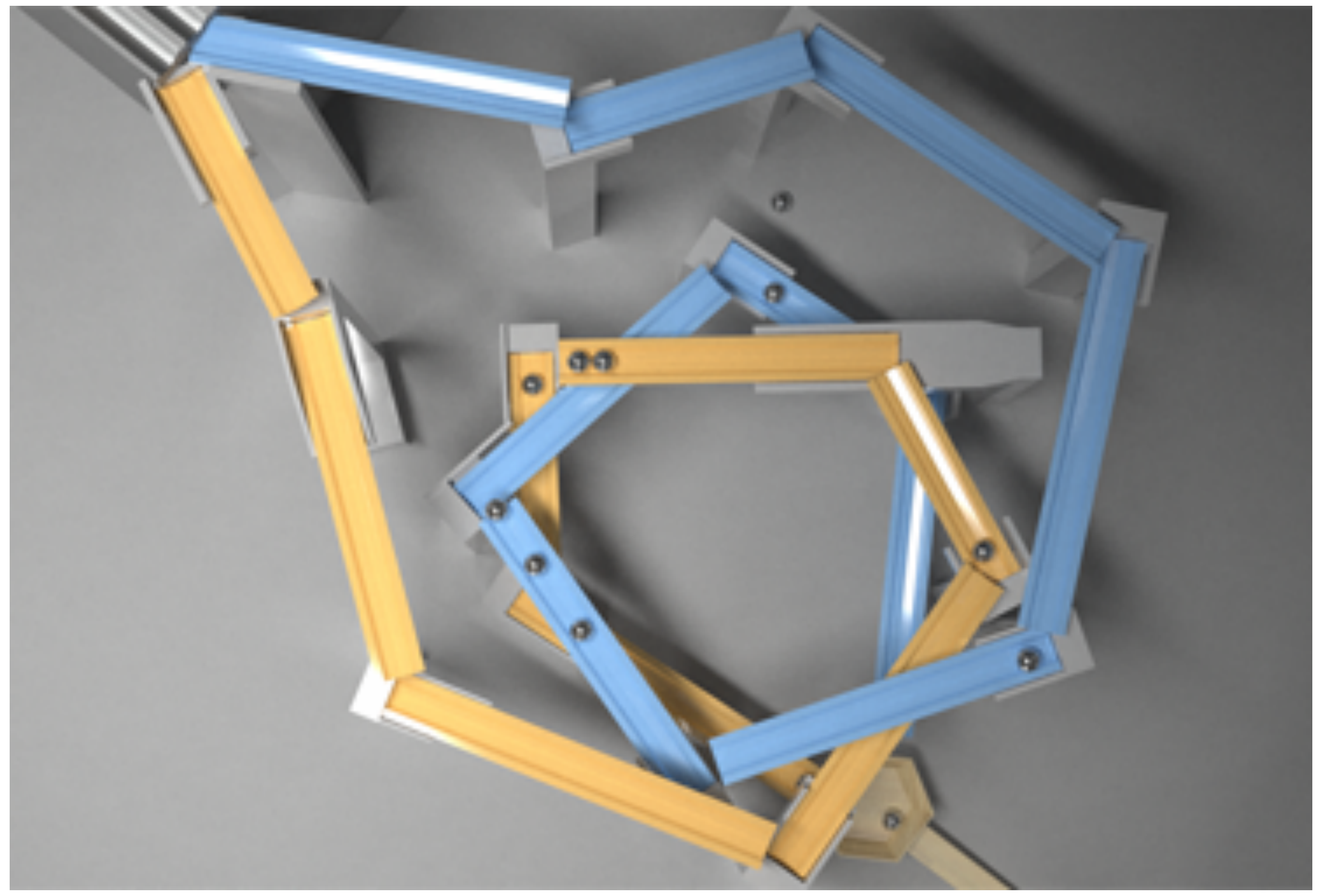
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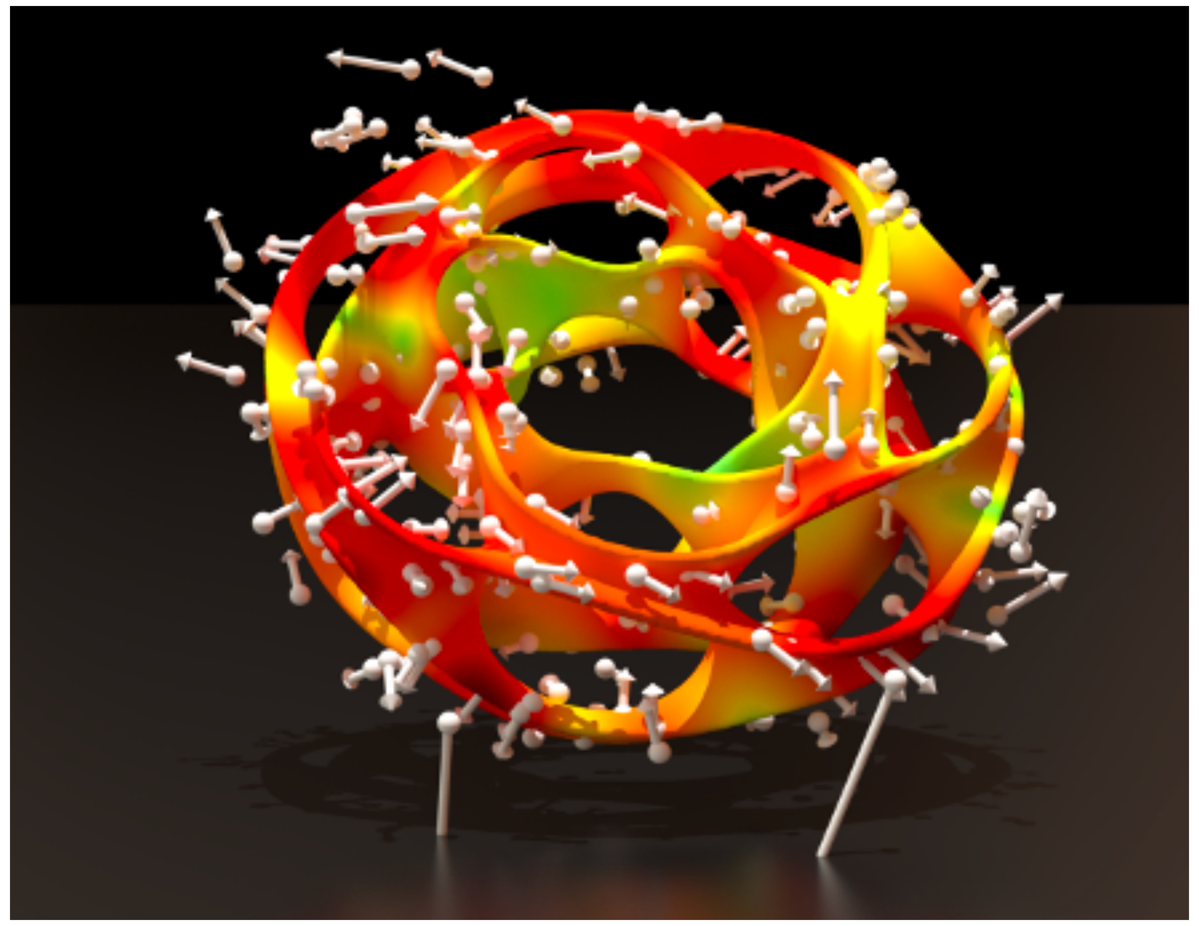
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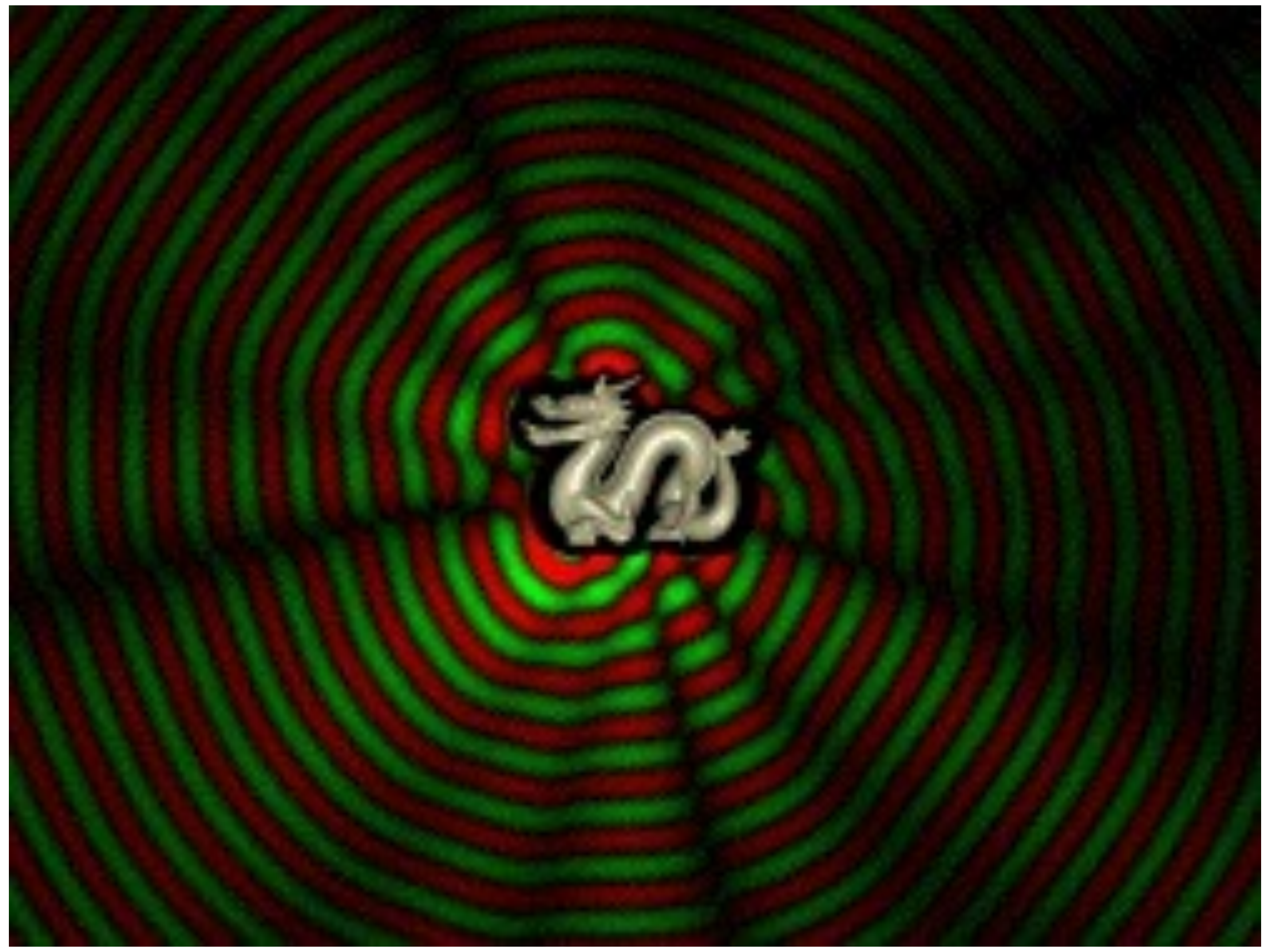
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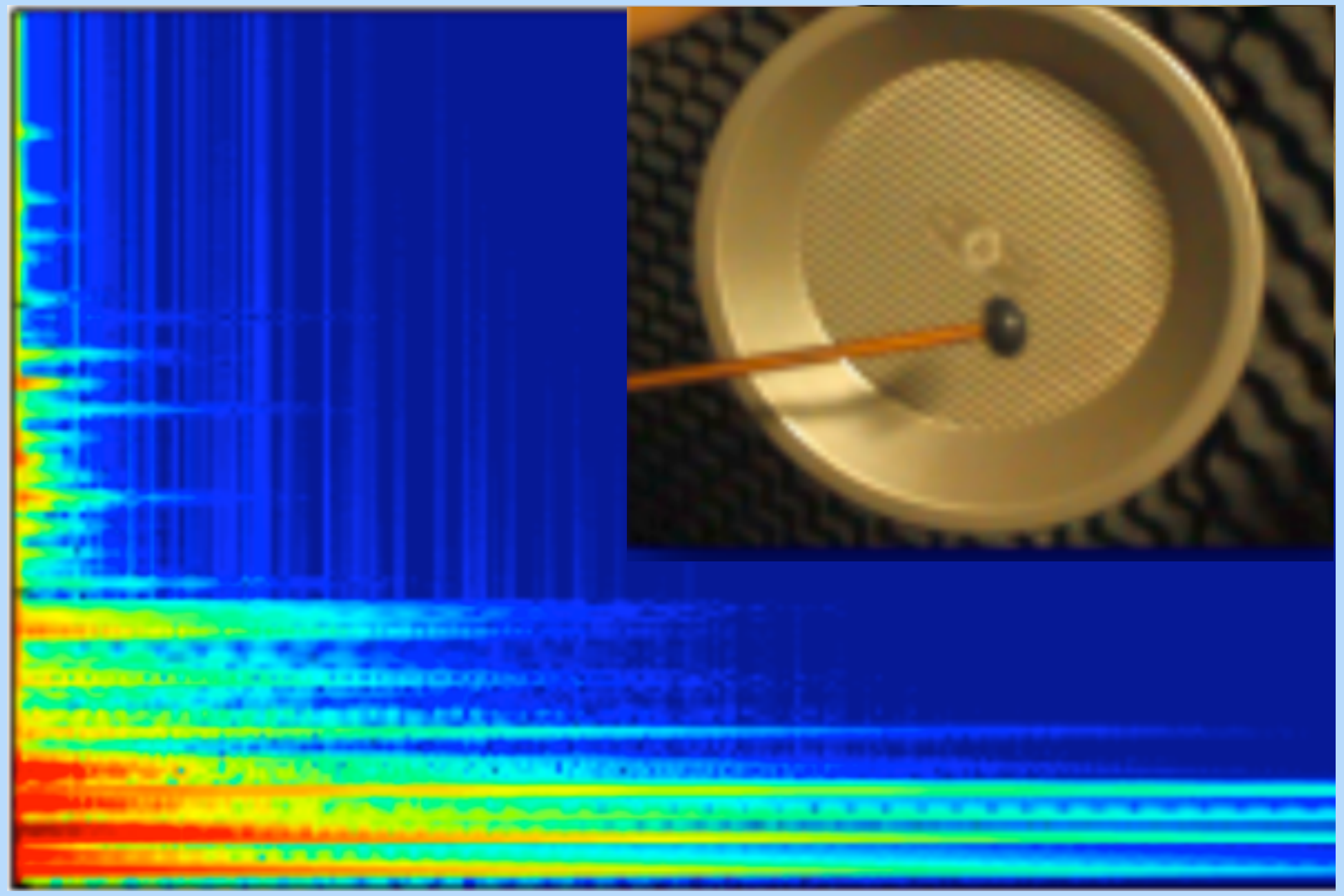
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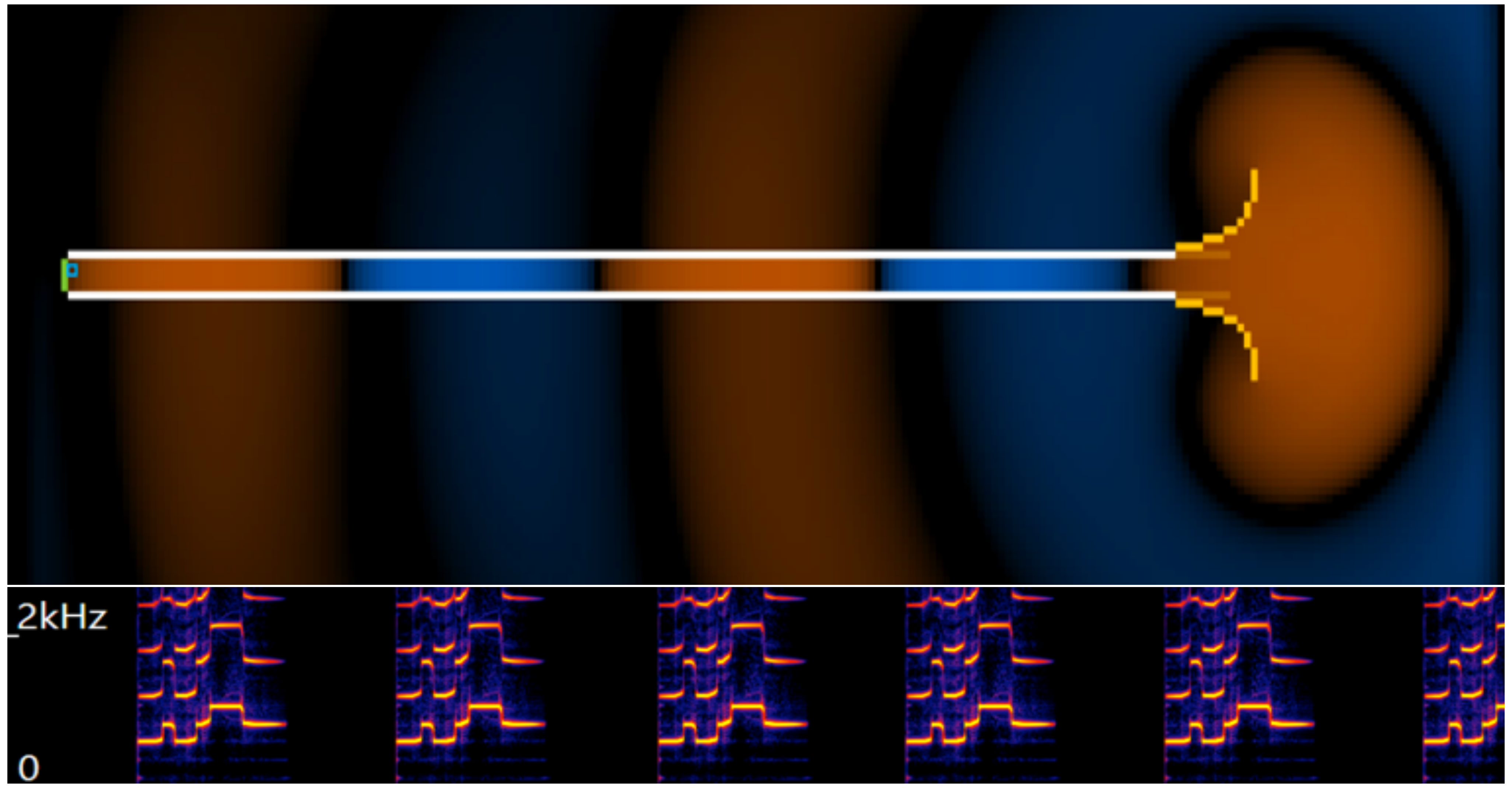

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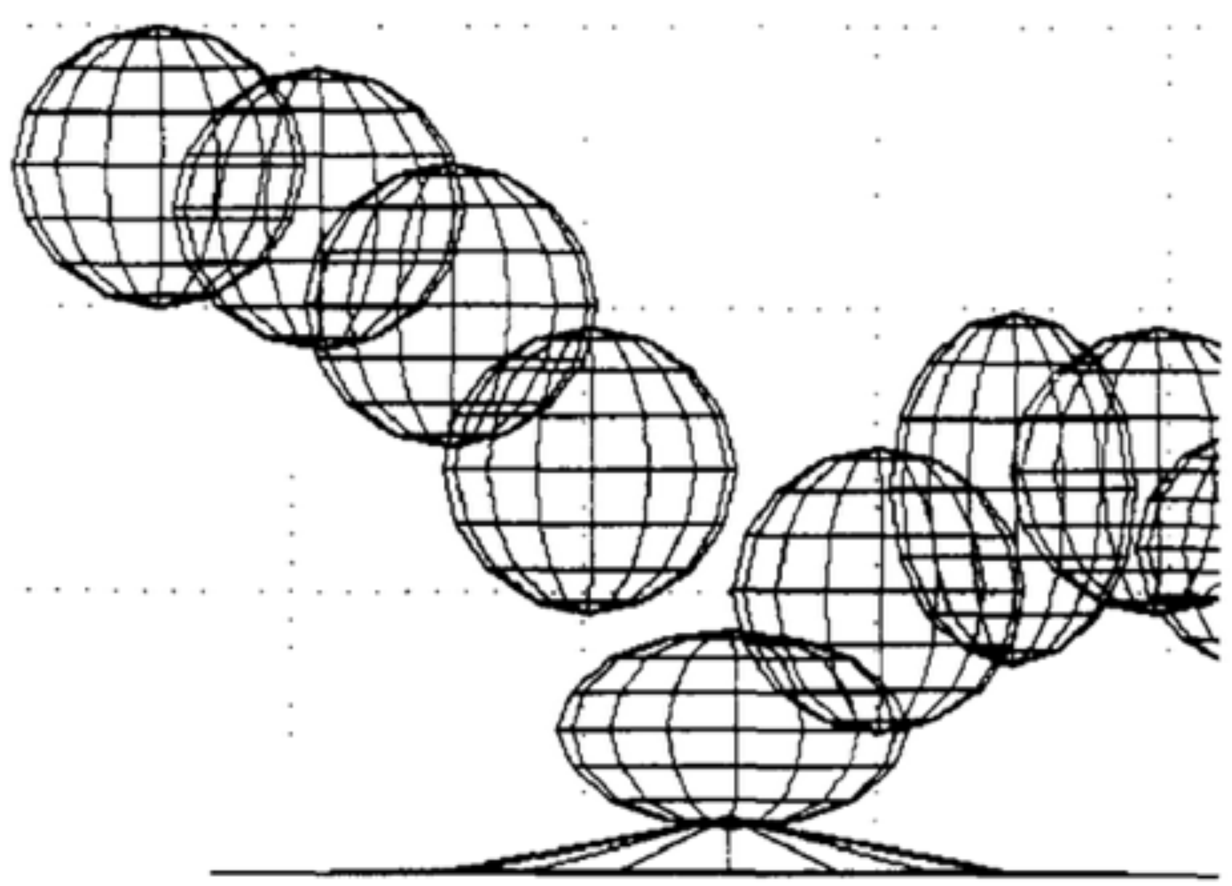

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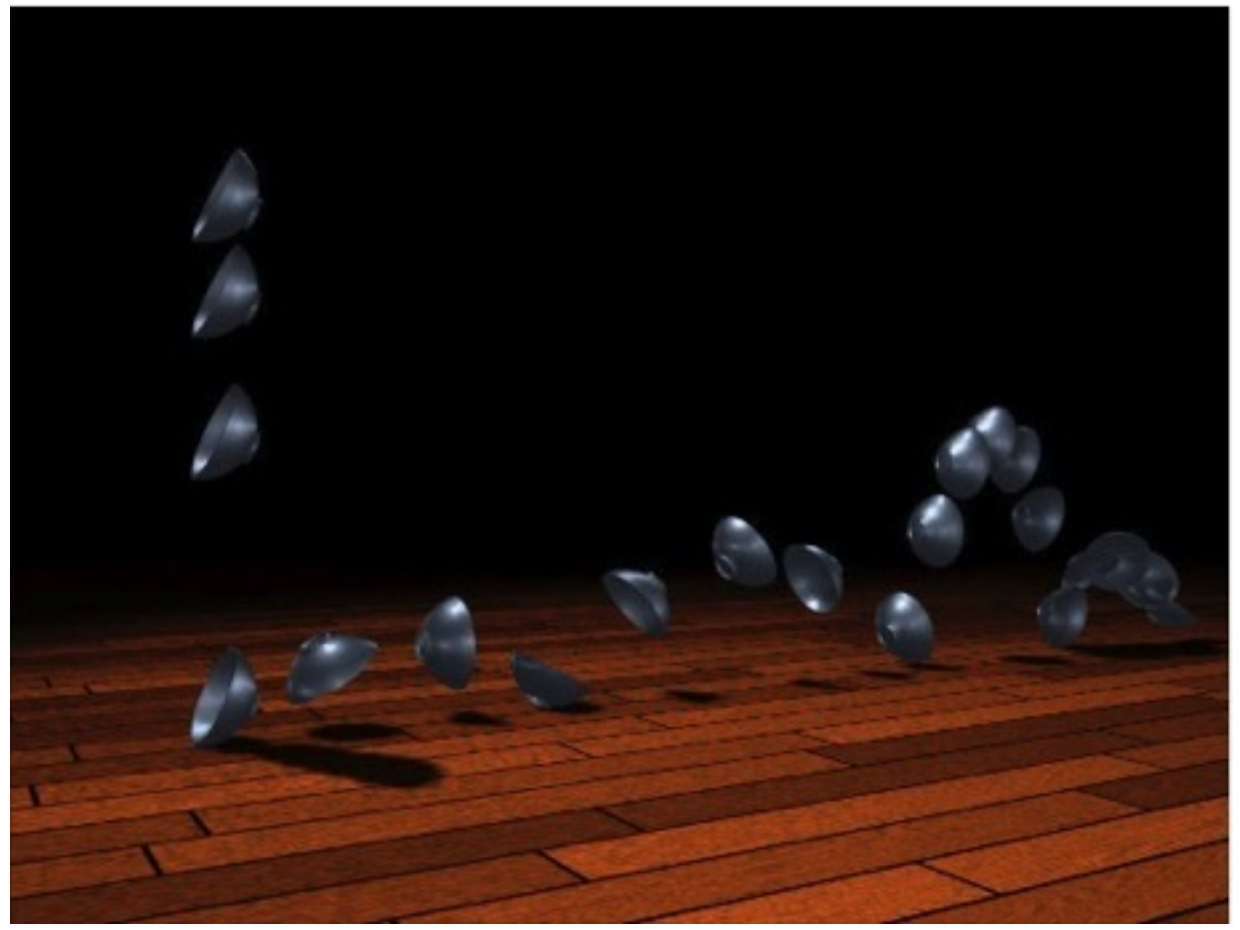

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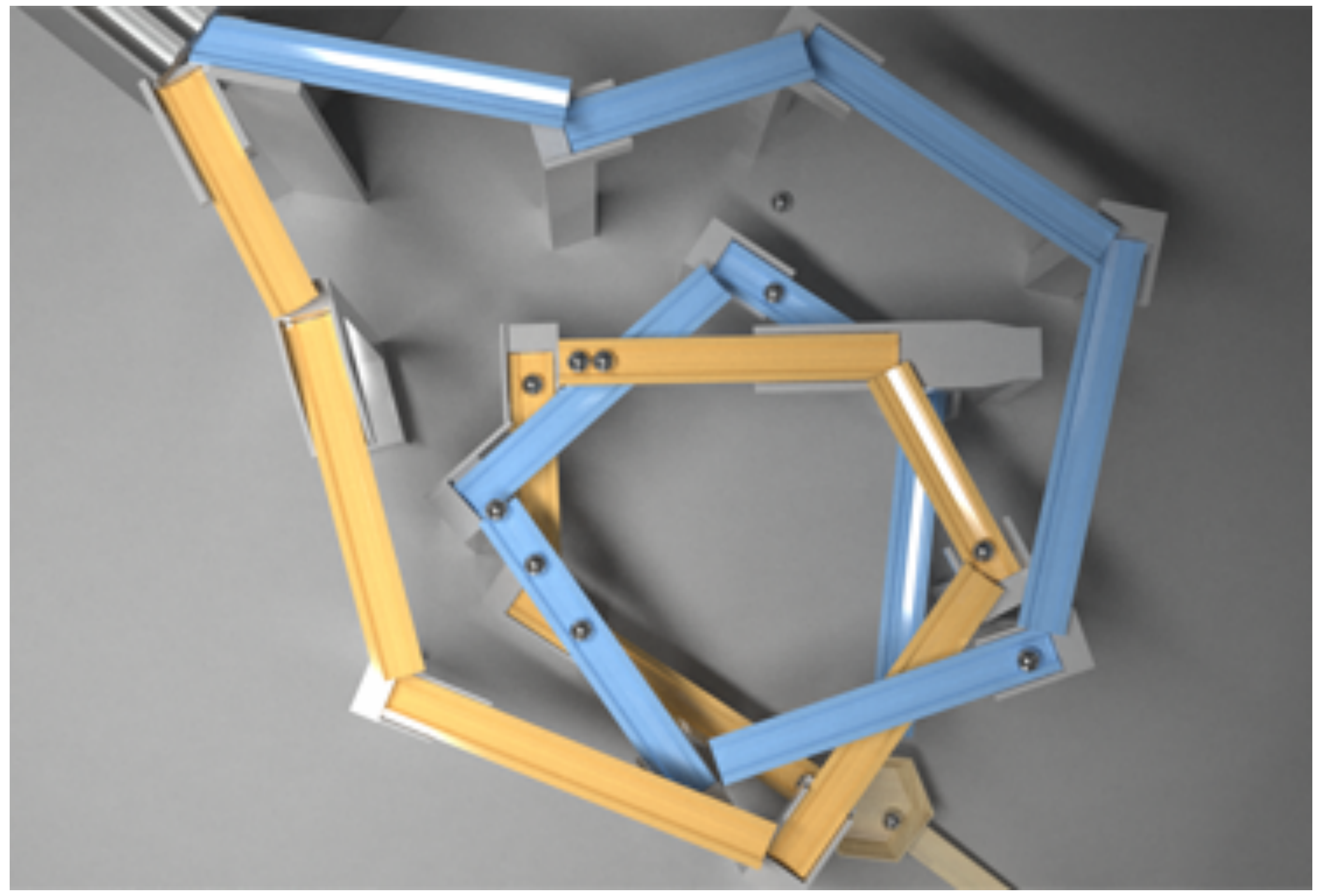

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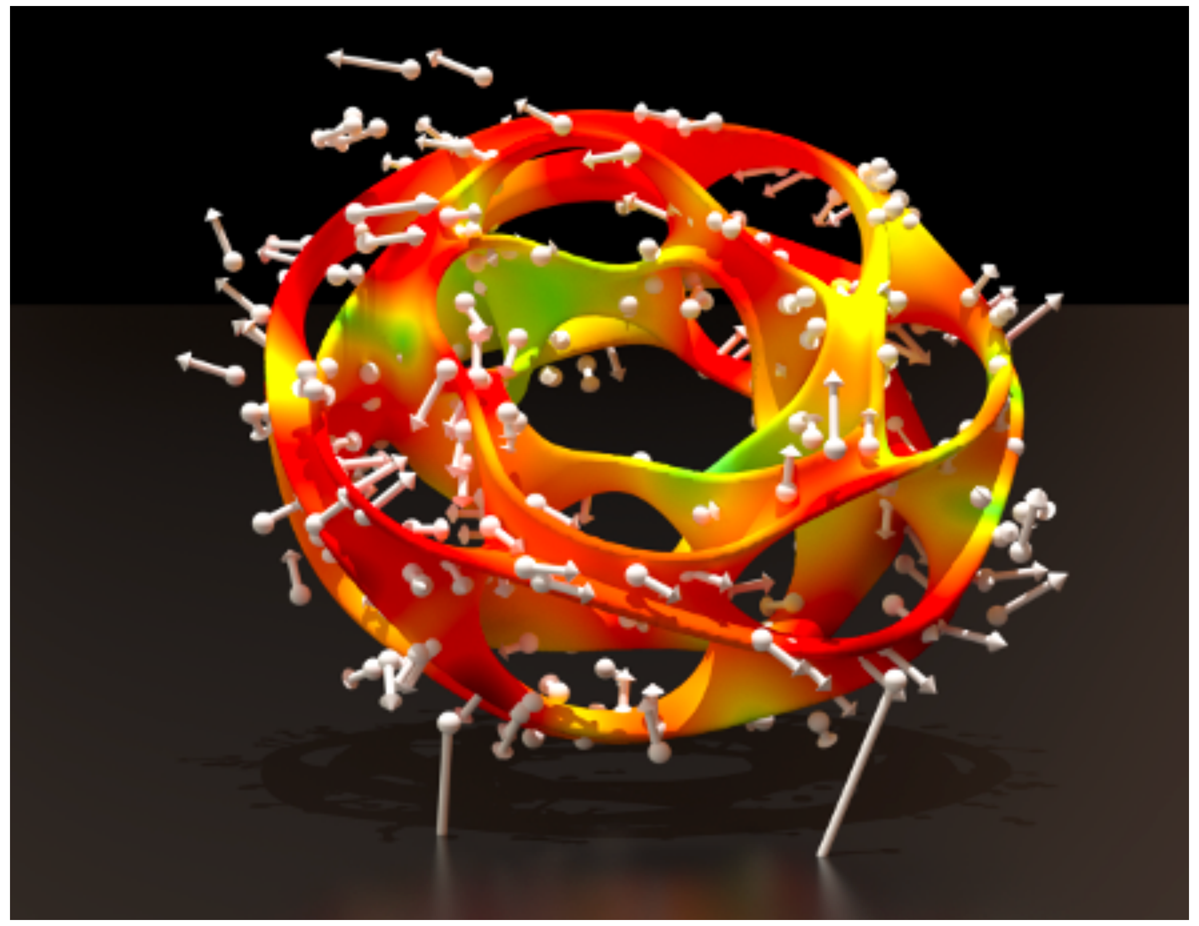

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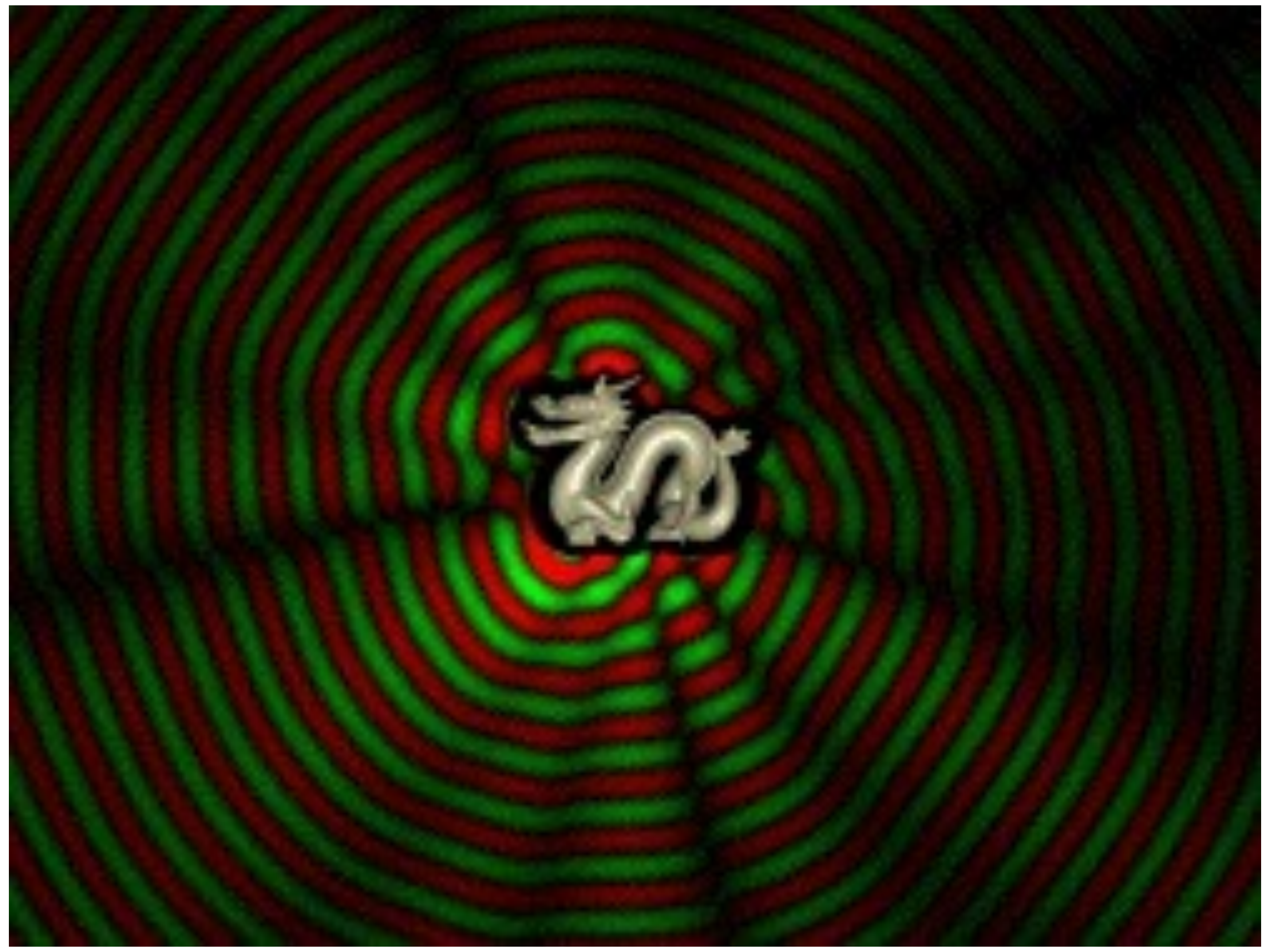

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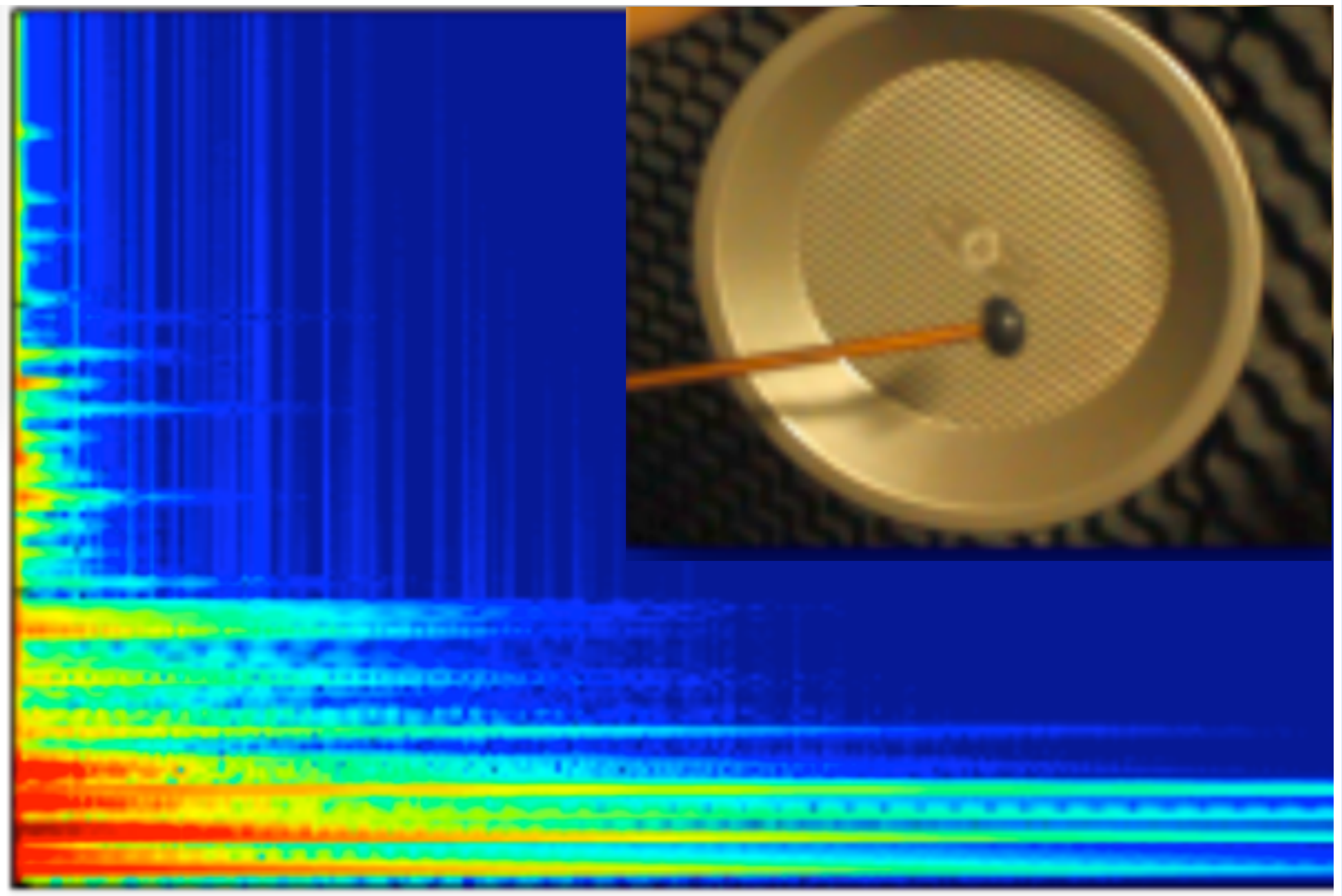

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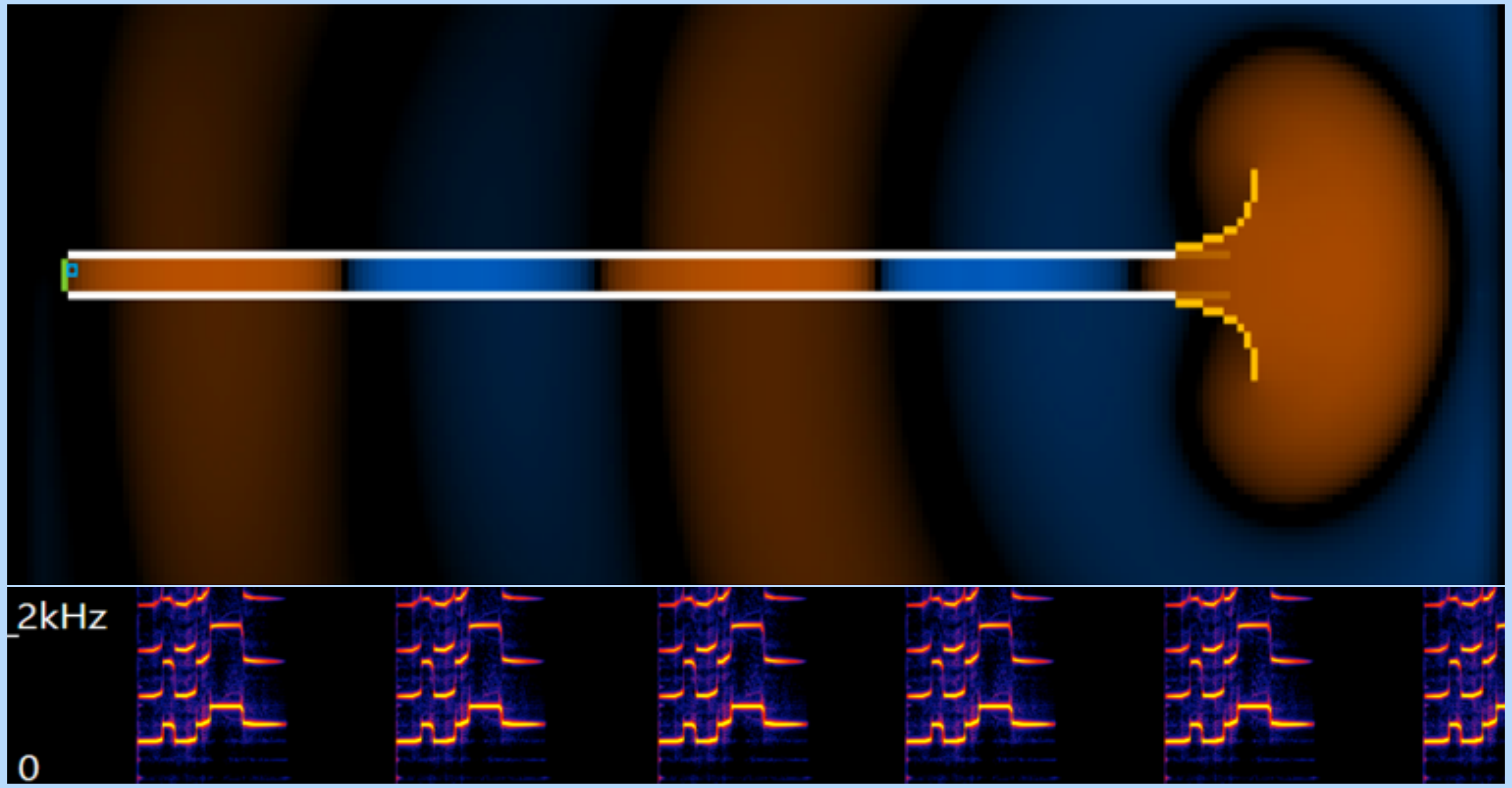

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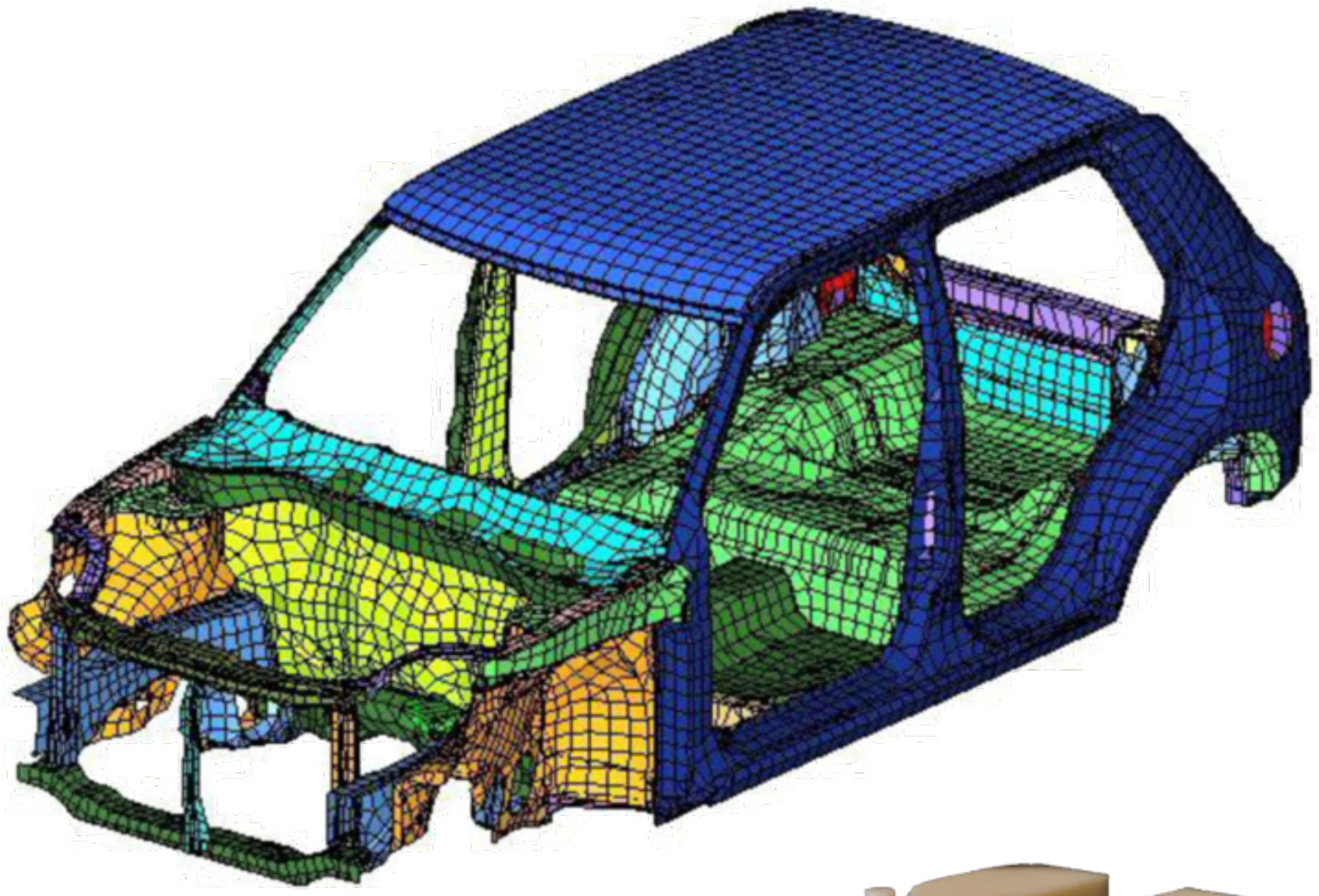
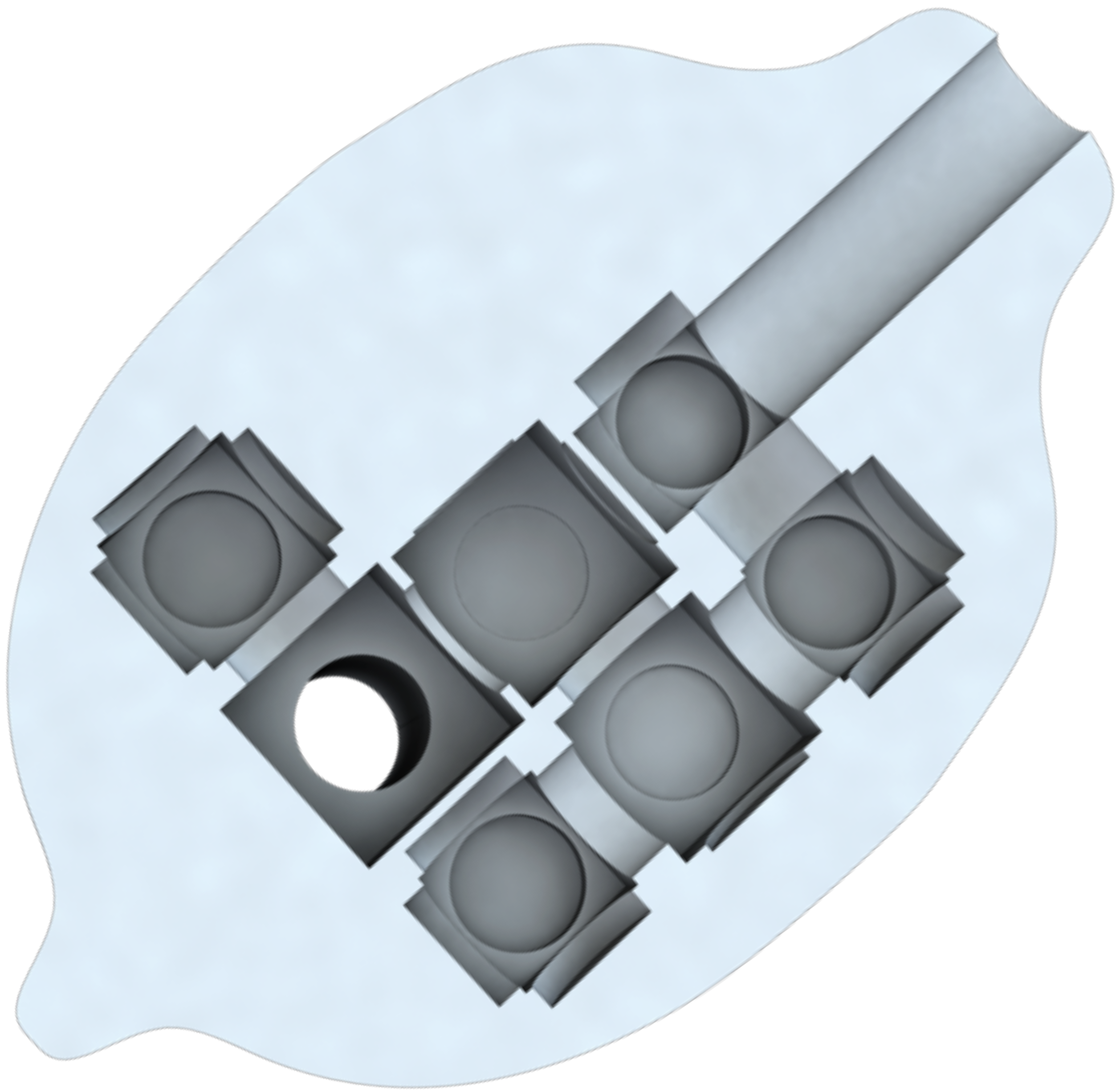
Applications beyond modal sound synthesis

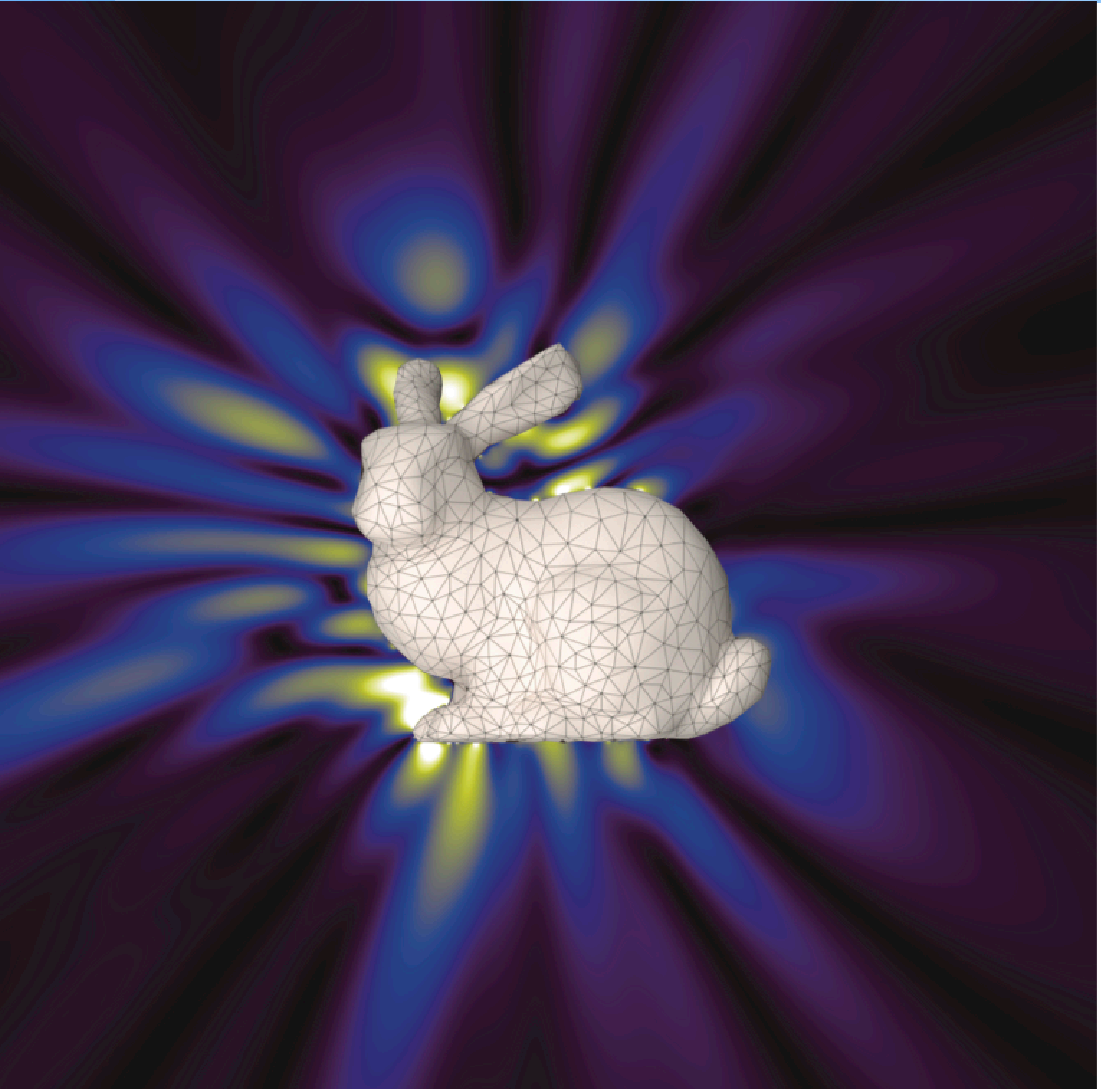




Acoustic Voxels
SIGGRAPH 2016
Li, Levin, Matusik, Zheng

Method Overview

Multipole Approximation for Helmholtz Eq.



$$\nabla^2 p(\mathbf{x}, \omega) + k^2 p(\mathbf{x}, \omega) = 0$$

$$p_i(\mathbf{x}, \omega) \approx ik \sum_{n=0}^{N} \sum_{m=-n}^{n} S_n^m(\mathbf{x}, \bar{\mathbf{x}}_0) M_n^m(\omega)$$

S_n^m : singular Helmholtz basis functions

$M_n^m(\omega)$: moments (depending on frequency)

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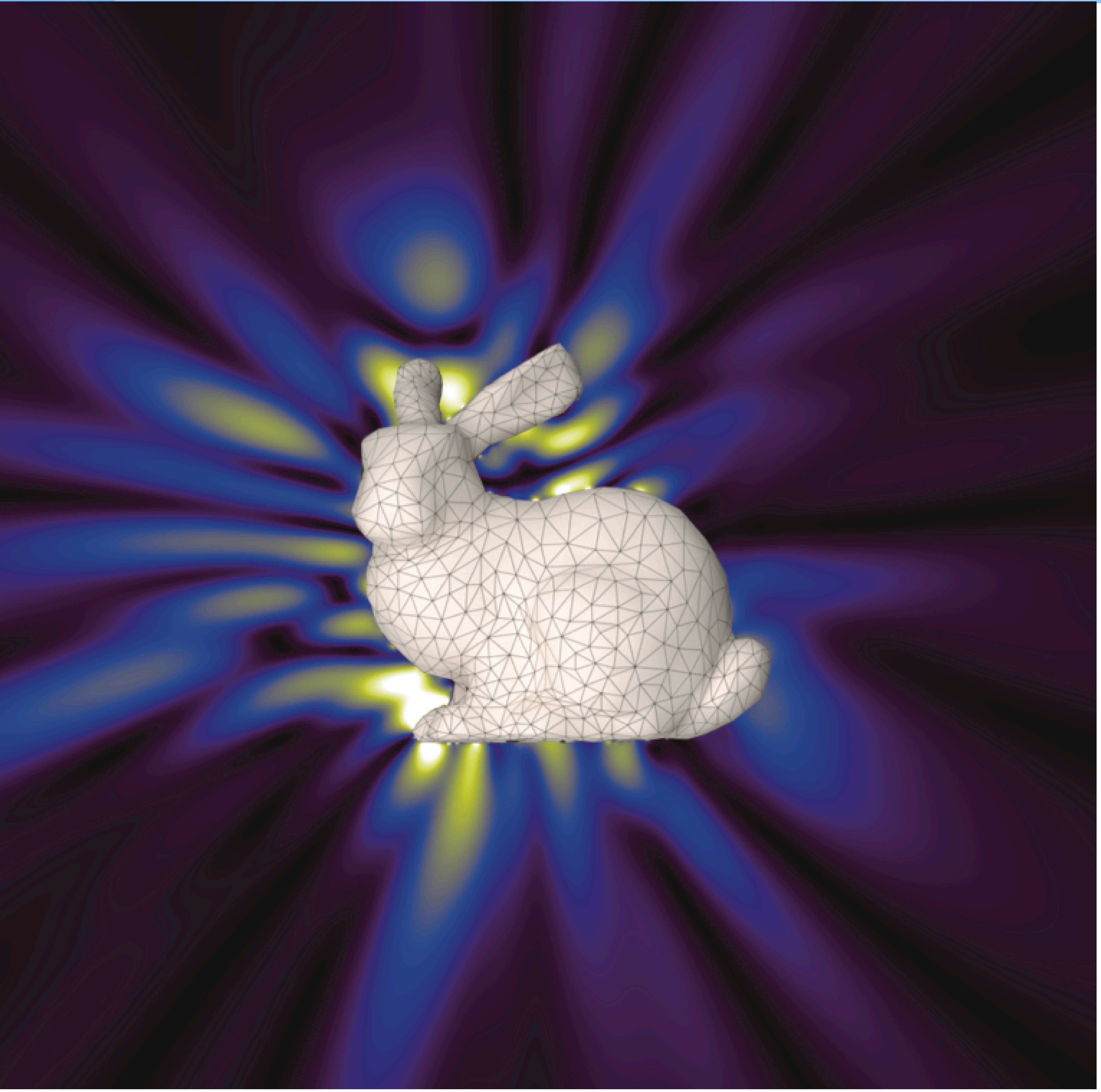

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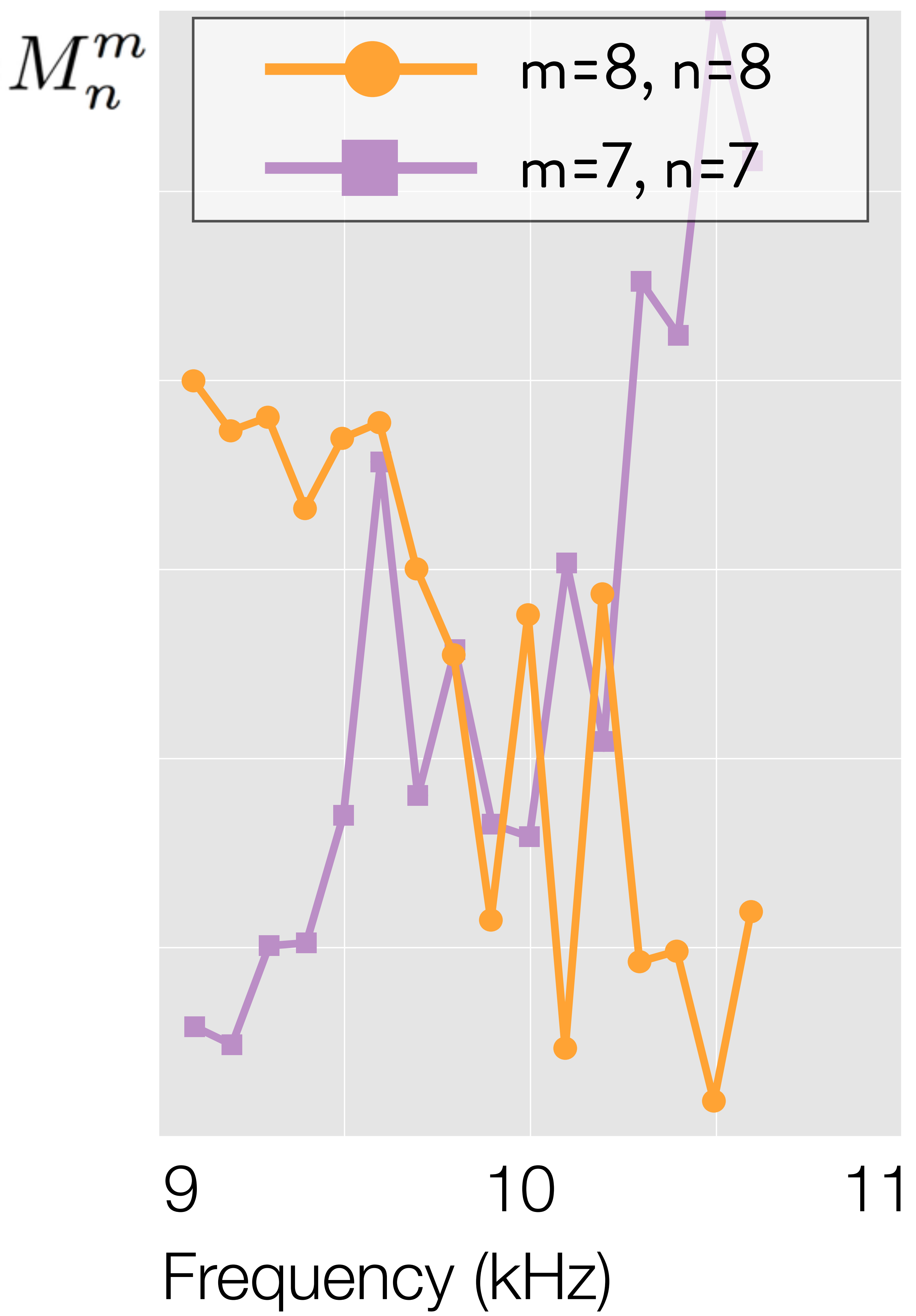
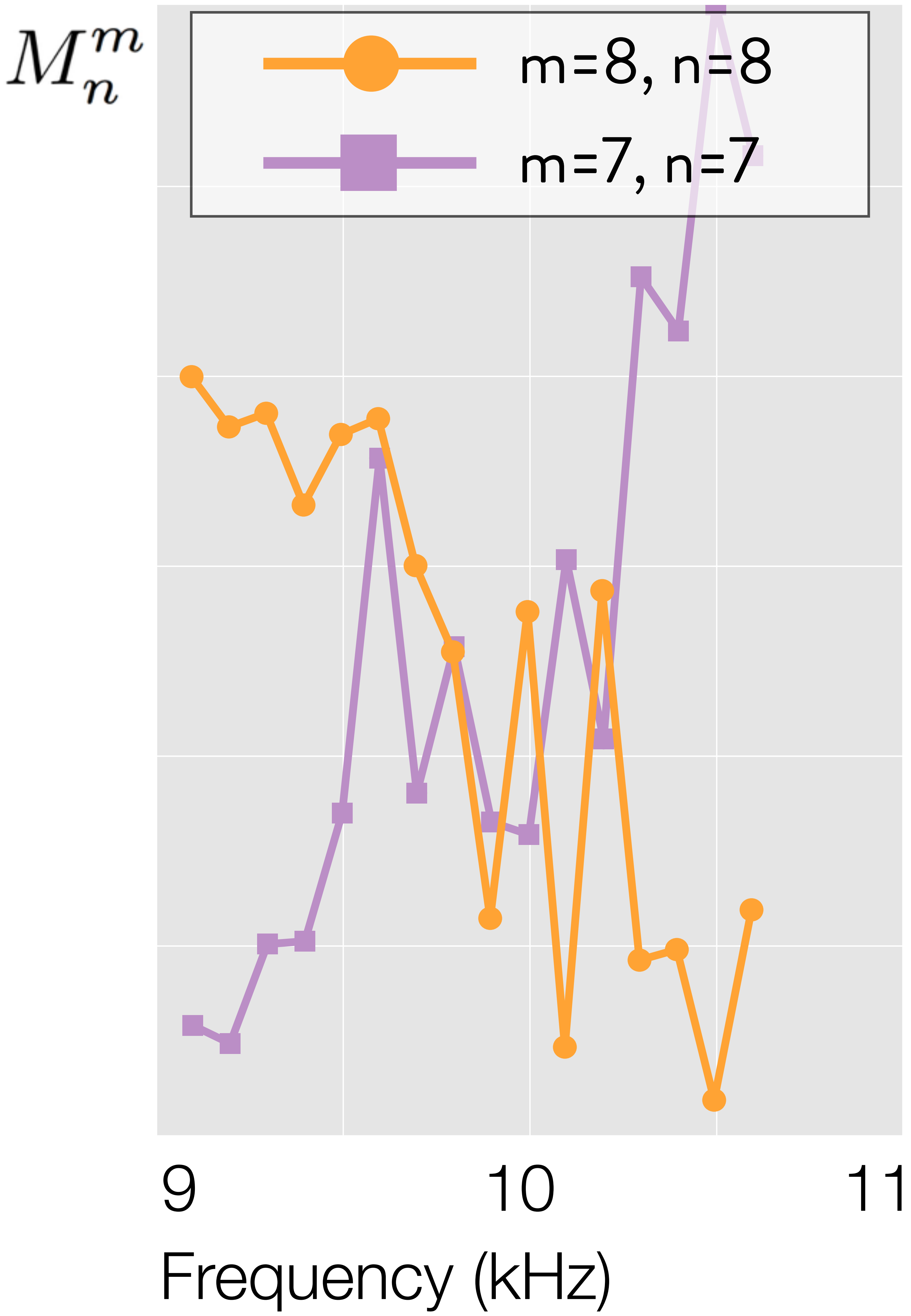
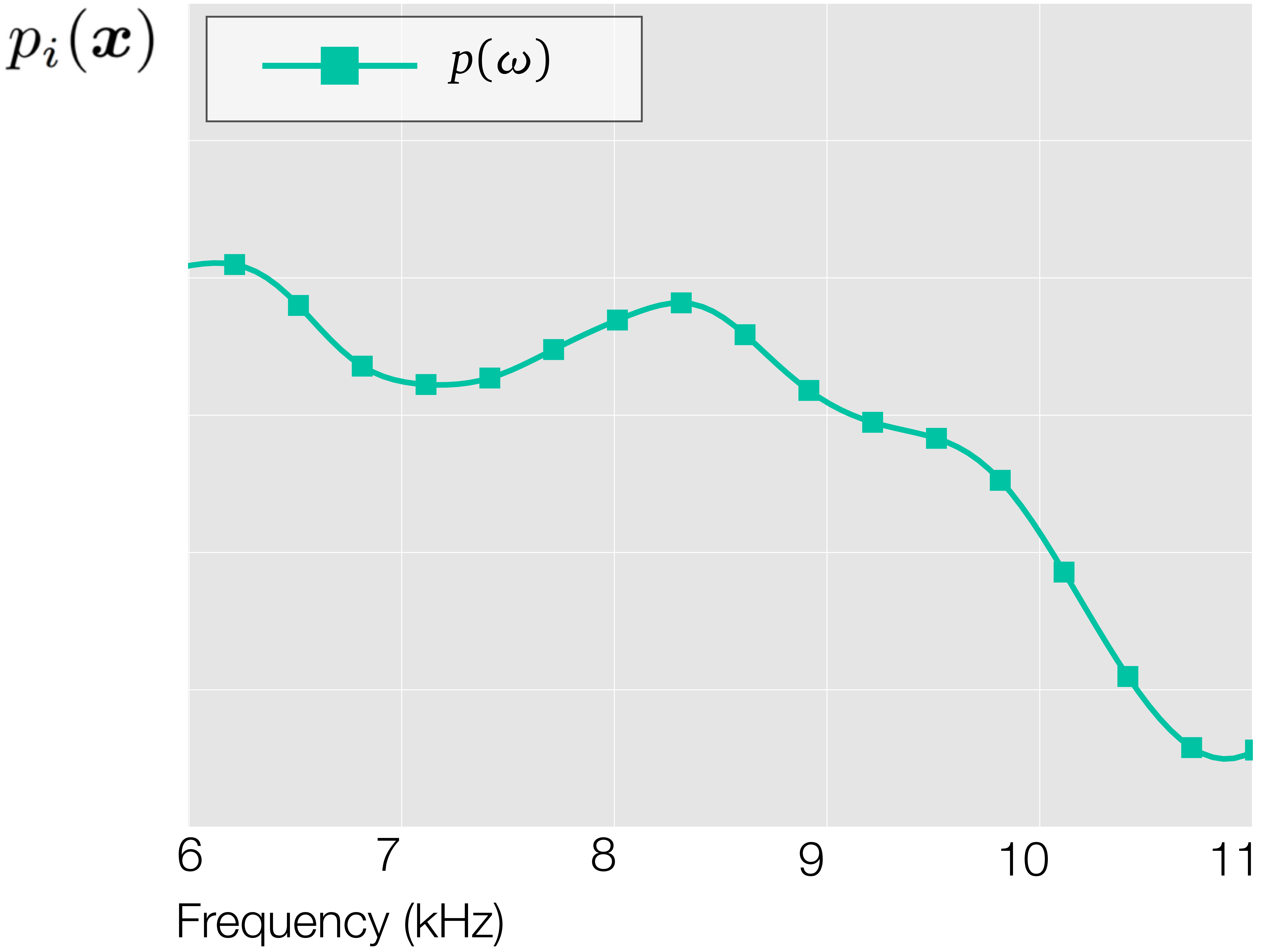
Irregularity of Moments



Pressure to Moments





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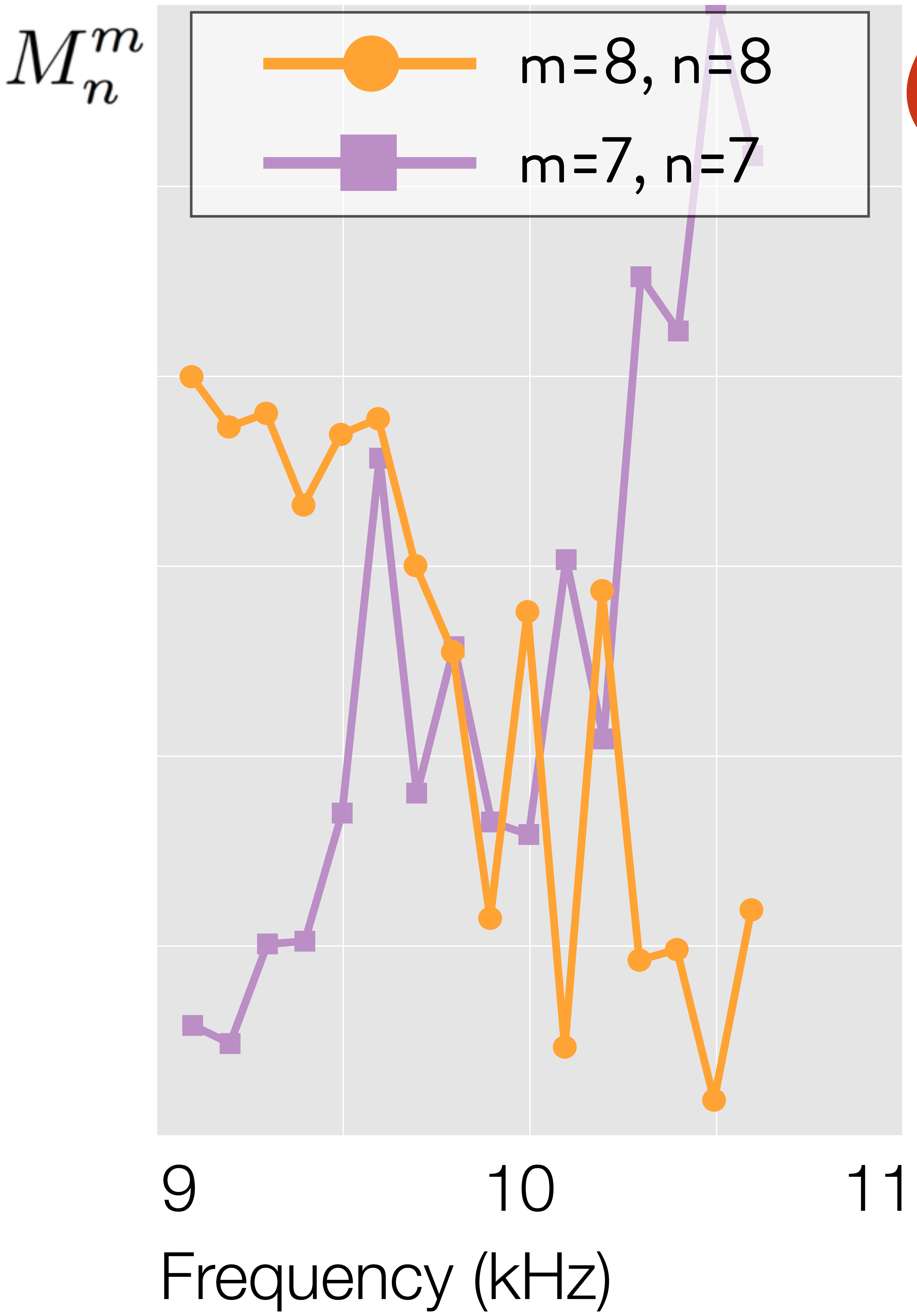
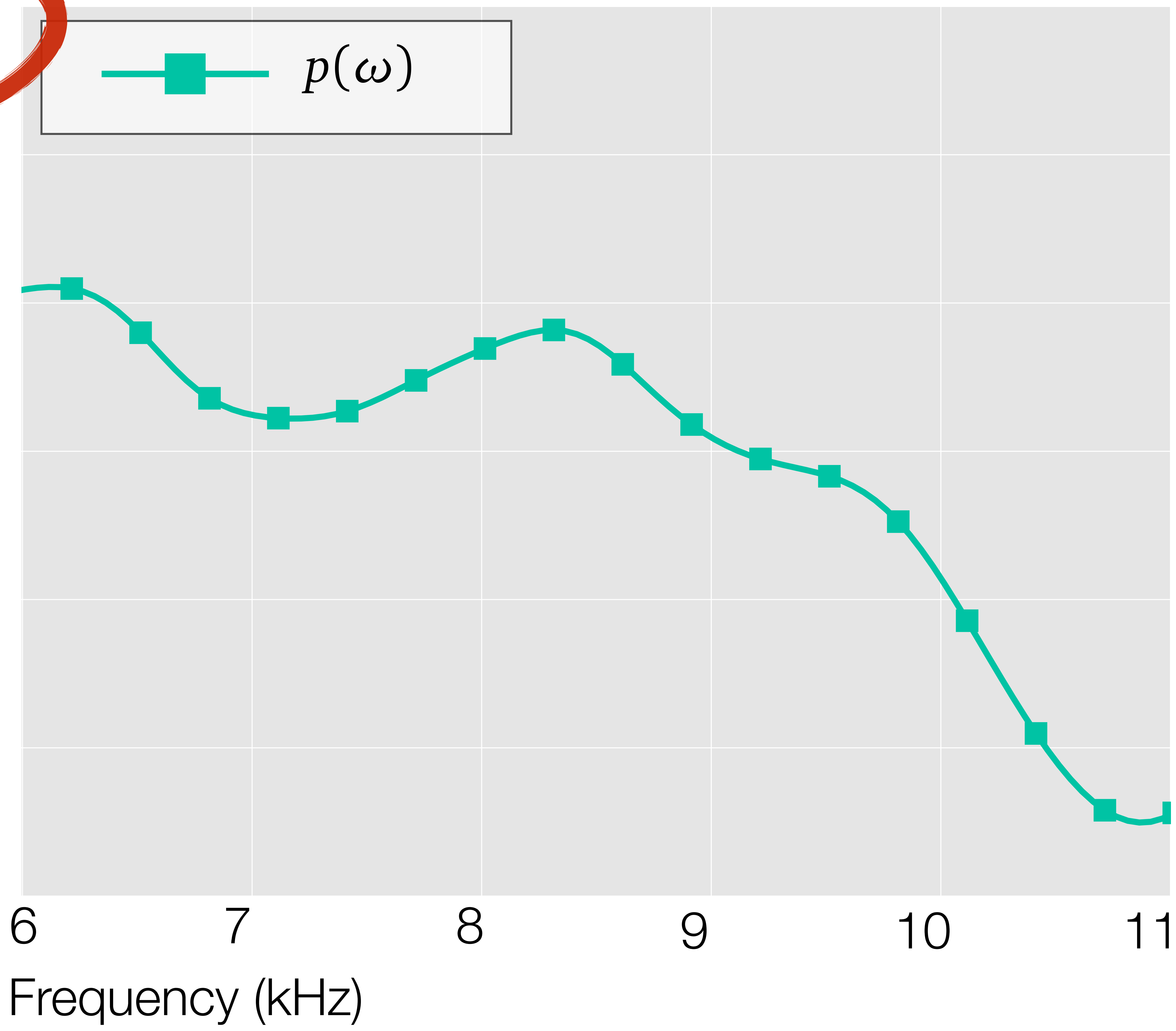
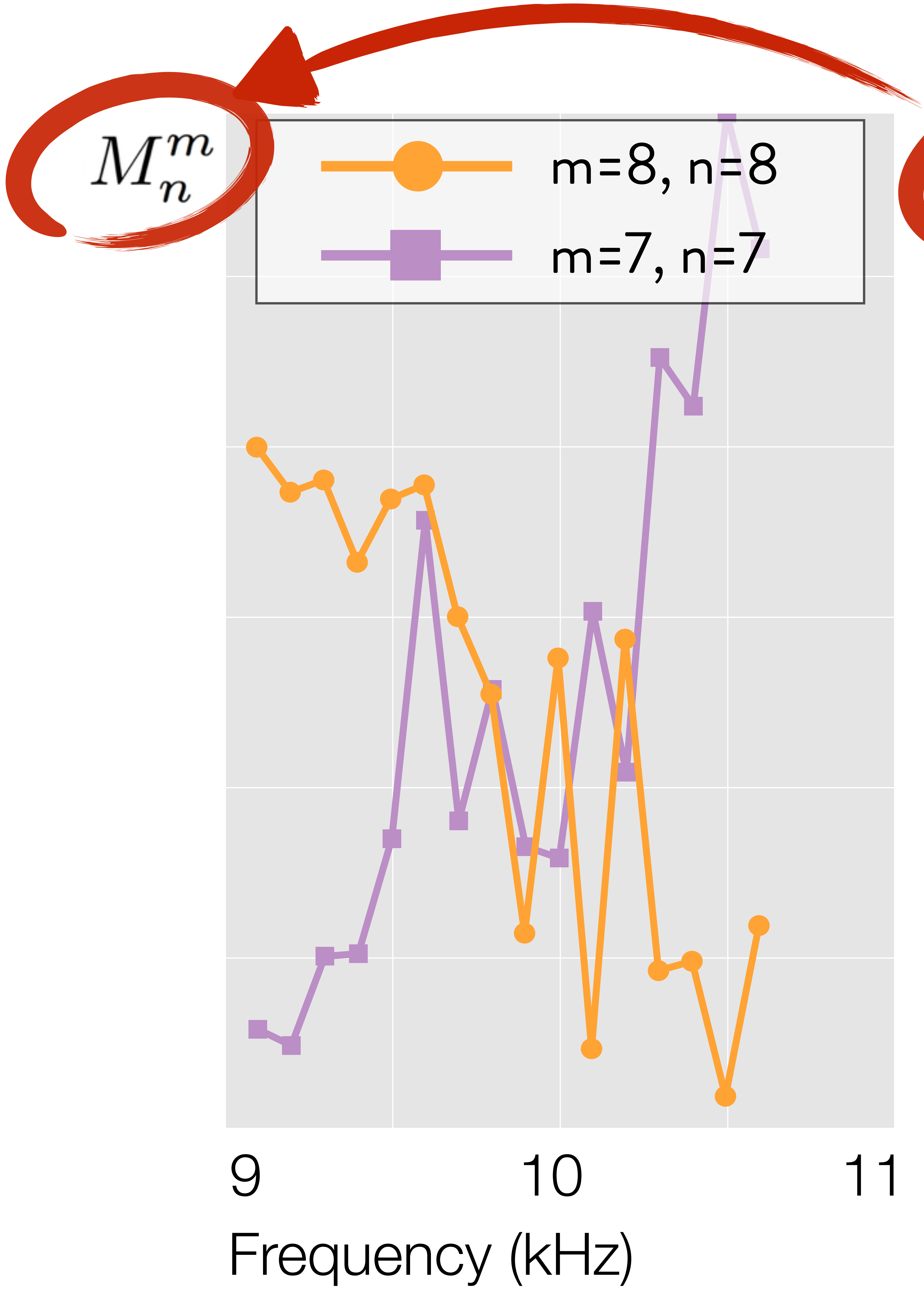
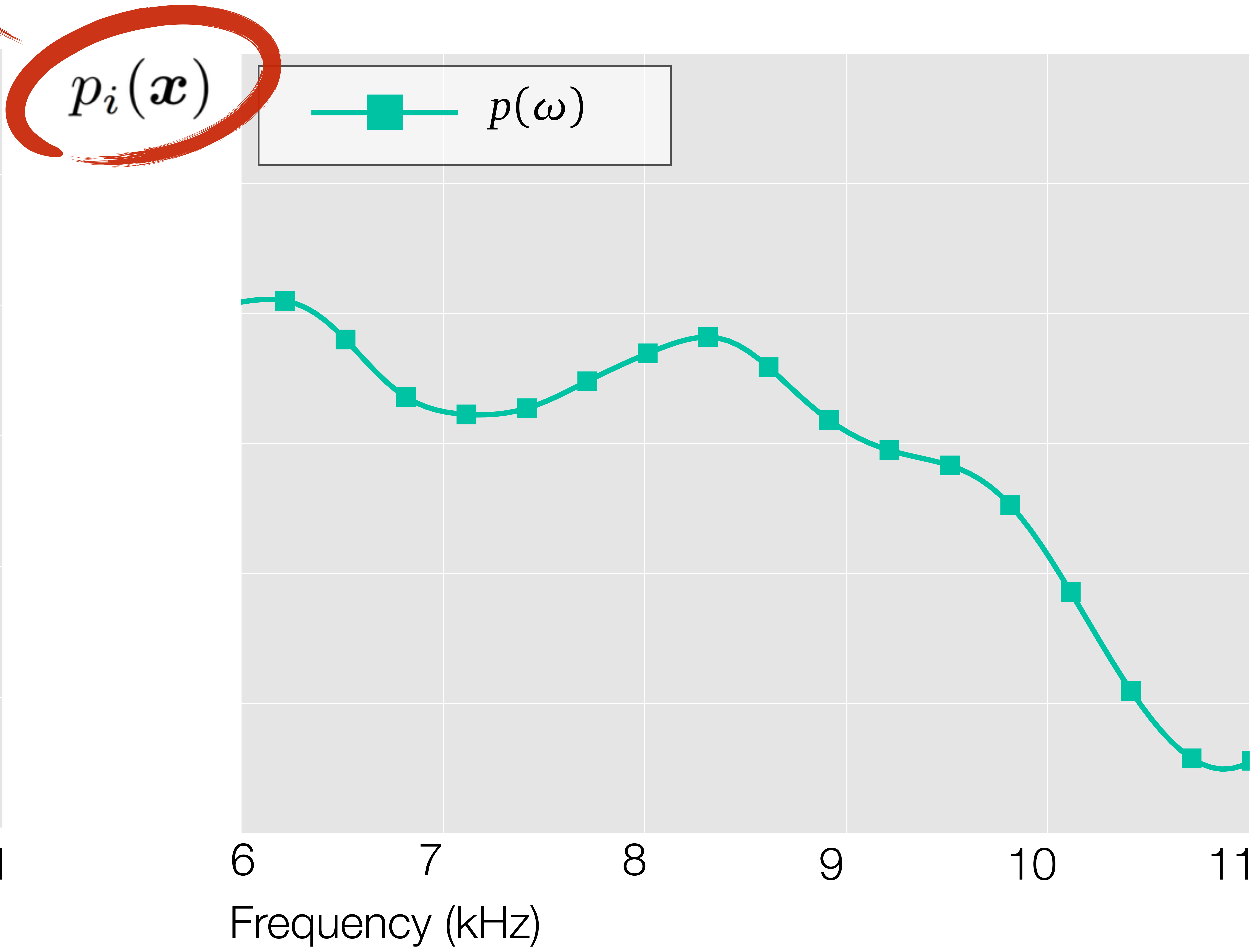


$p_i(\boldsymbol{x})$



Pressure to Moments

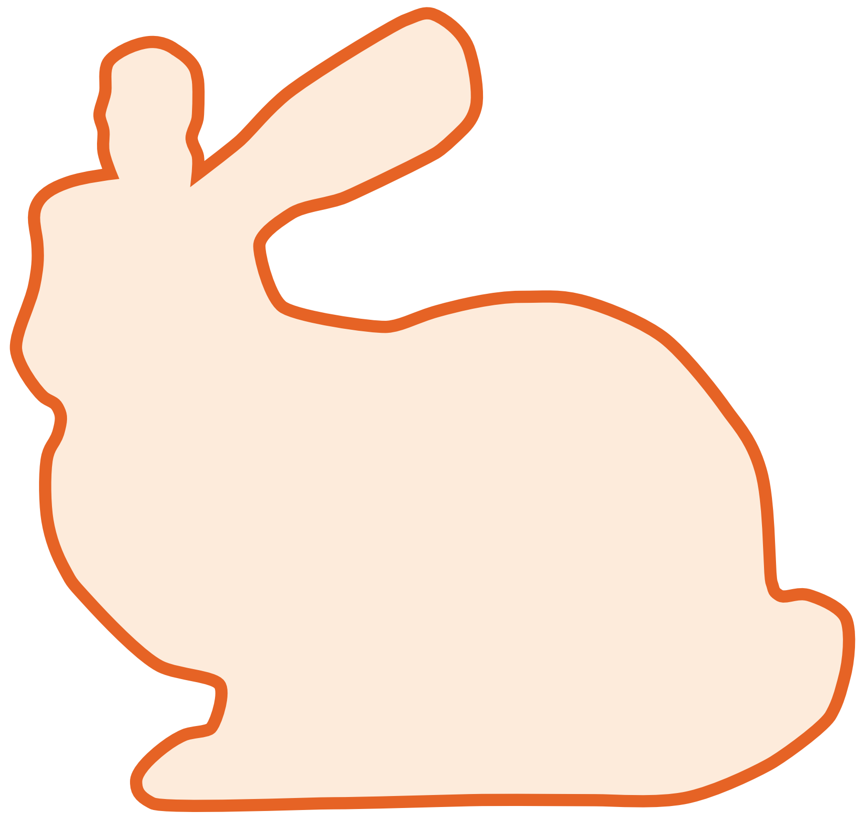




Algorithm in Brief

$$p_i(\mathbf{x}, \omega) \approx ik \sum_{n=0}^{N} \sum_{m=-n}^{n} S_n^m(\mathbf{x}, \bar{\mathbf{x}}_0) M_n^m(\omega)$$

● $\boldsymbol{x}$



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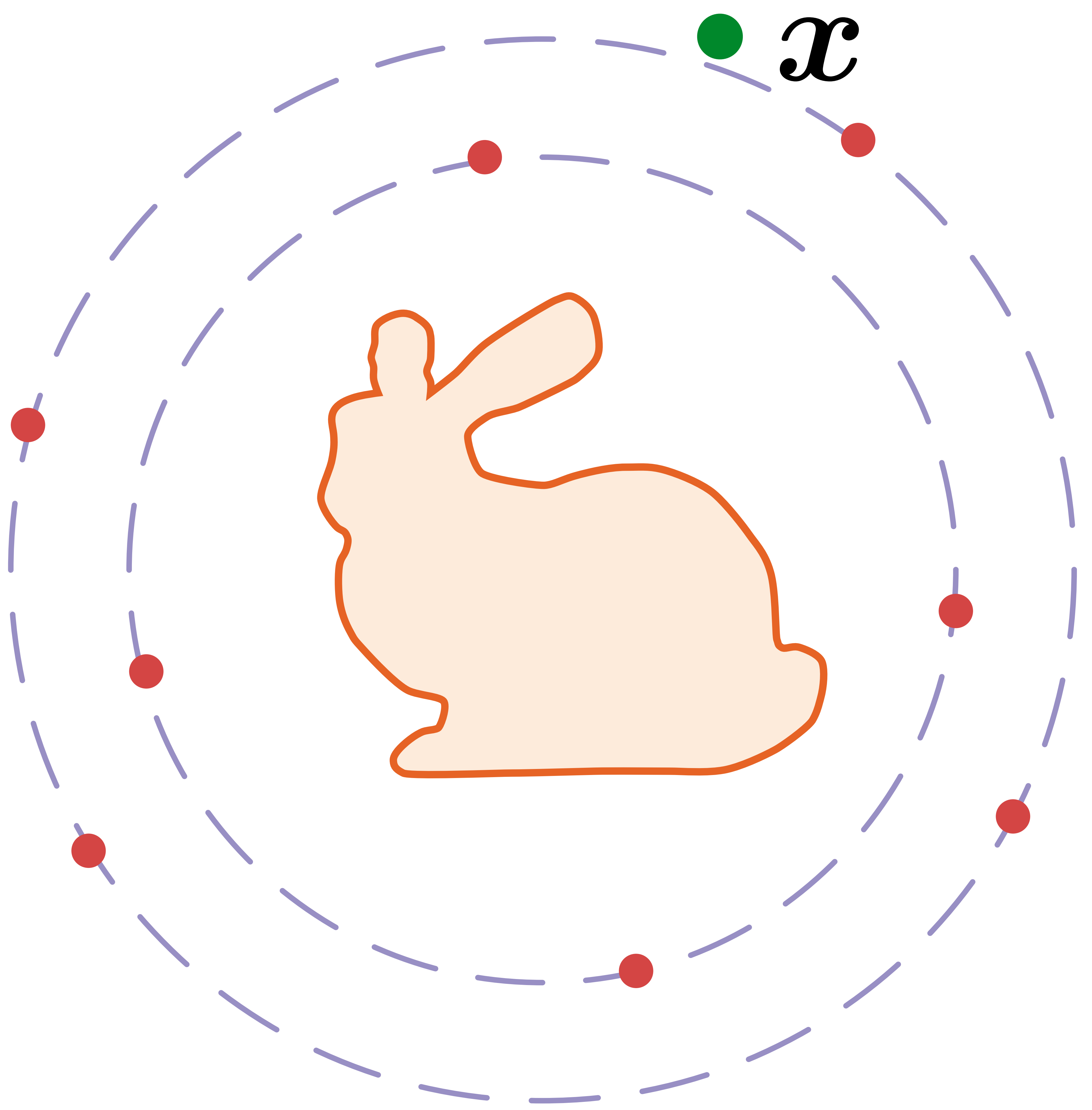

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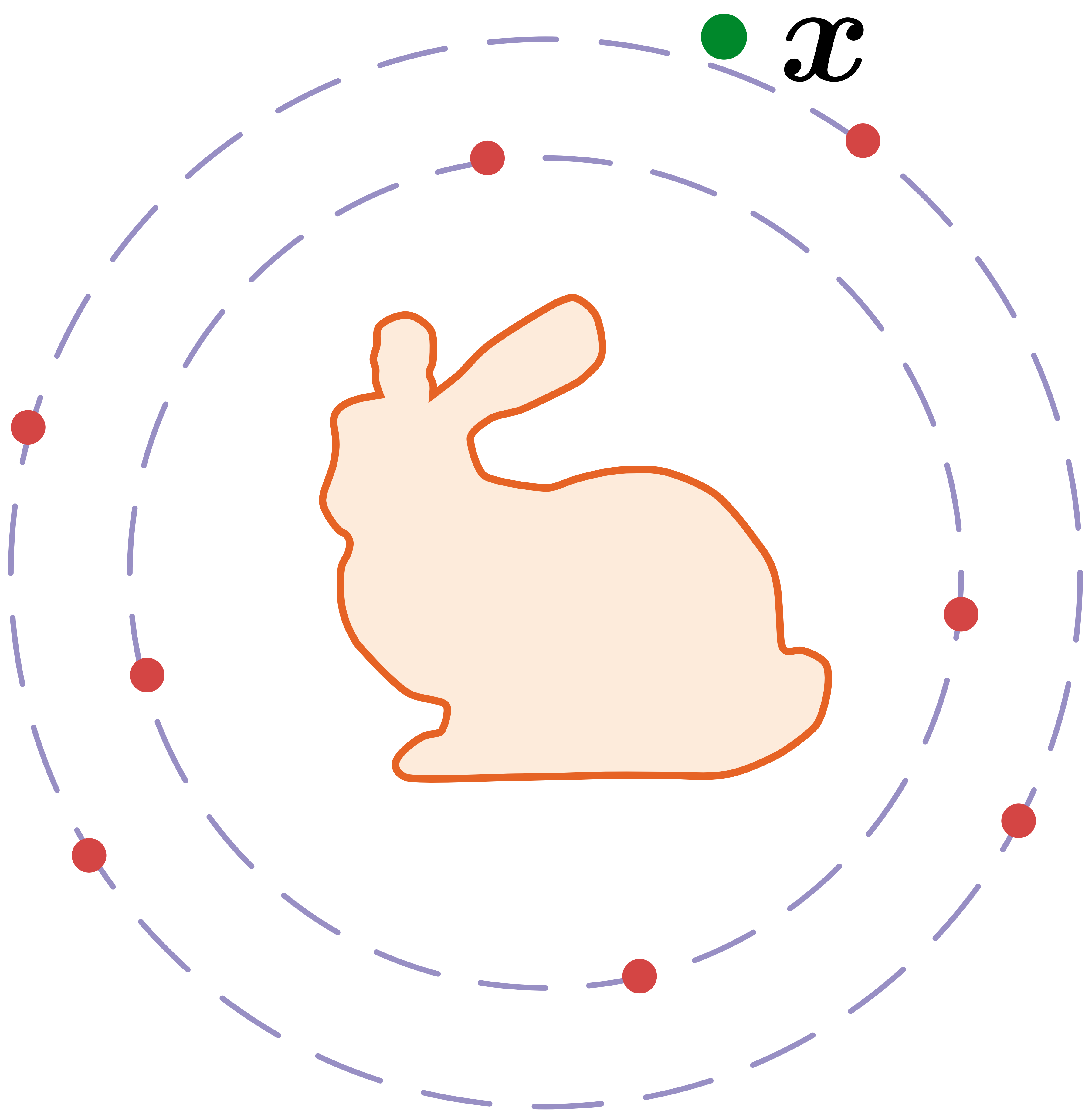
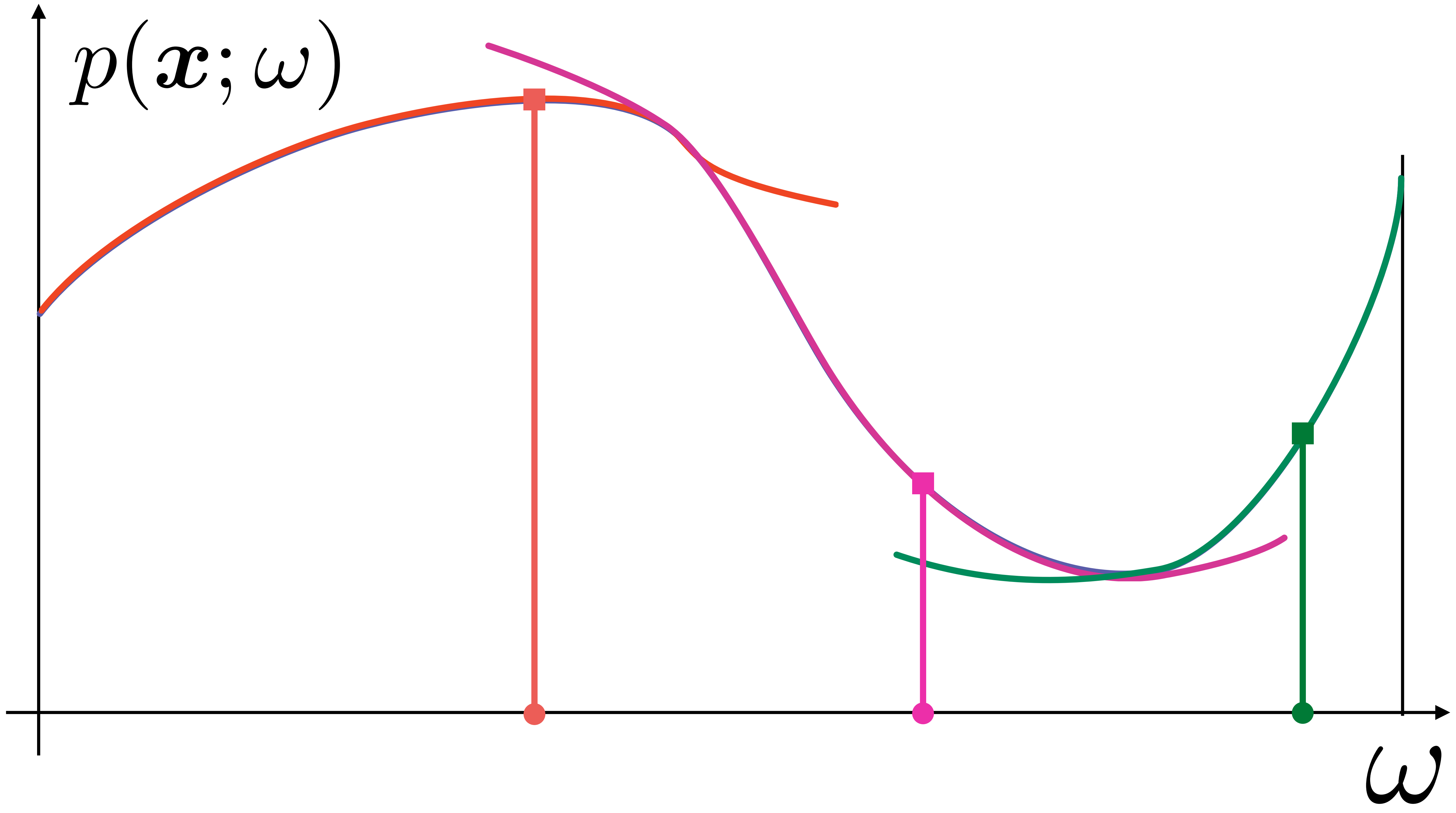
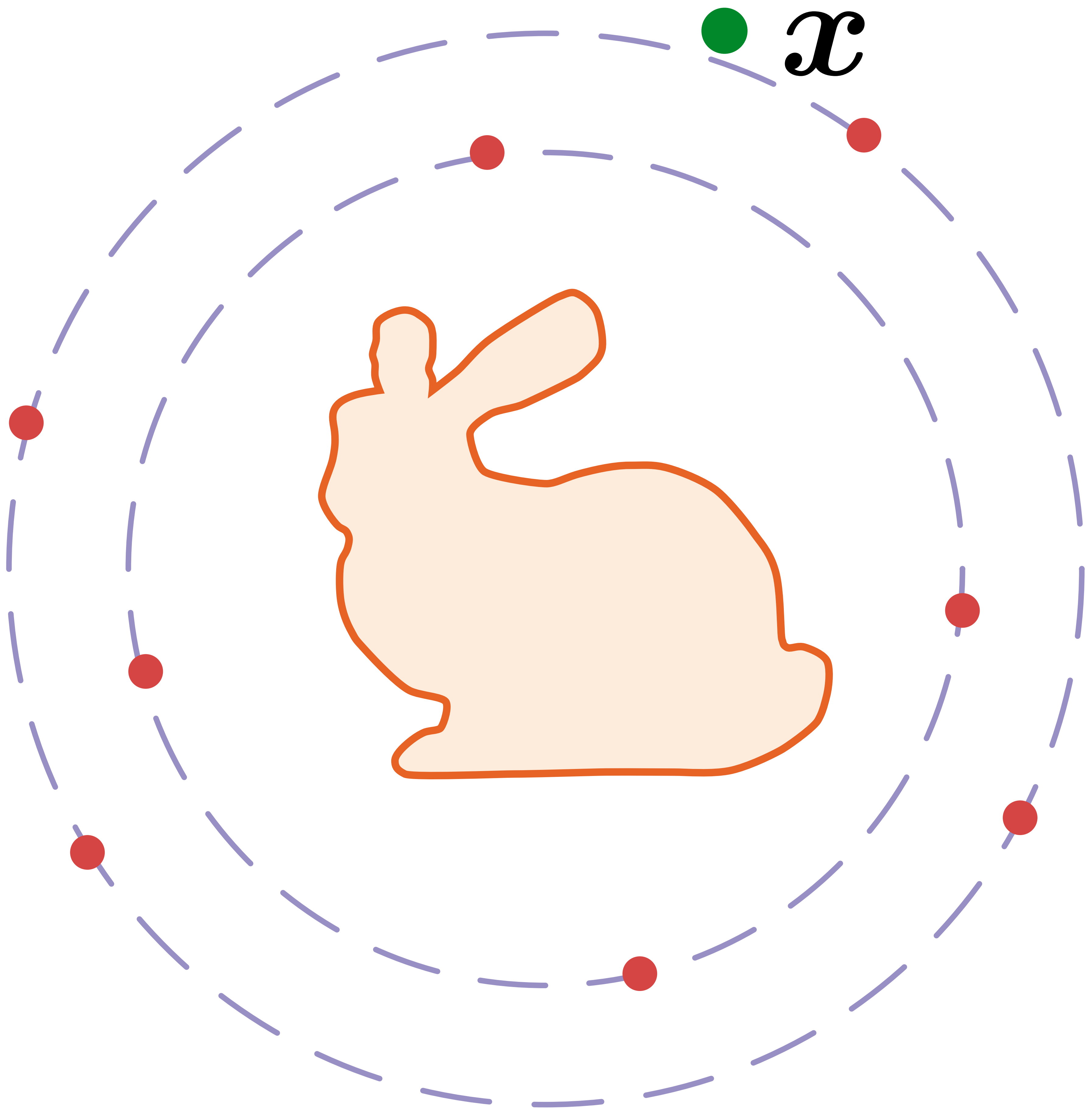


Contributions



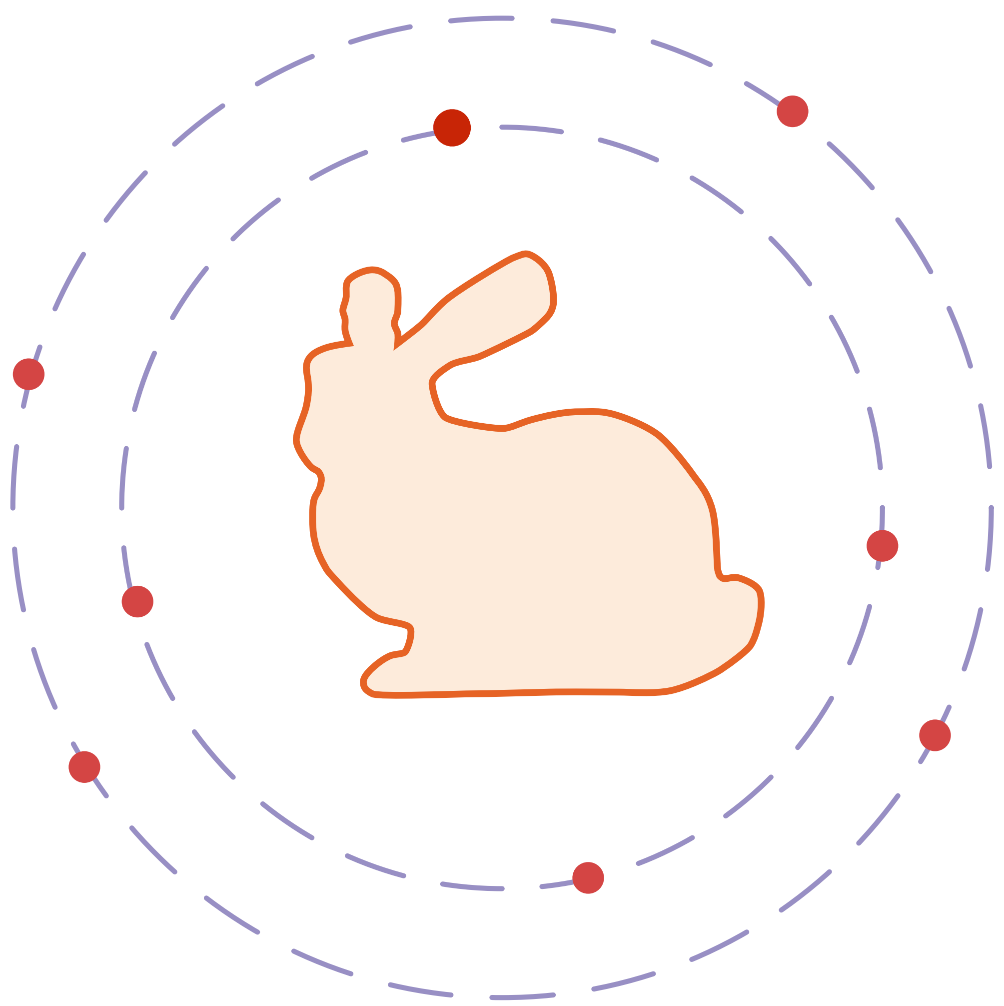


Fast Helmholtz Precomputation

Interactive Runtime Solve

Fast Helmholtz Precomputation

Pressure Frequency Sweep



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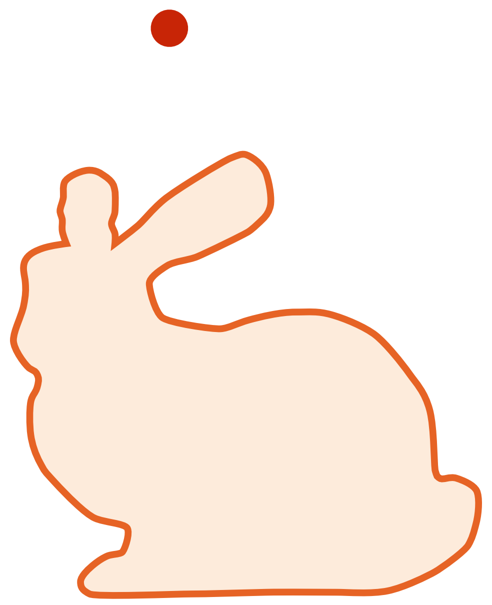

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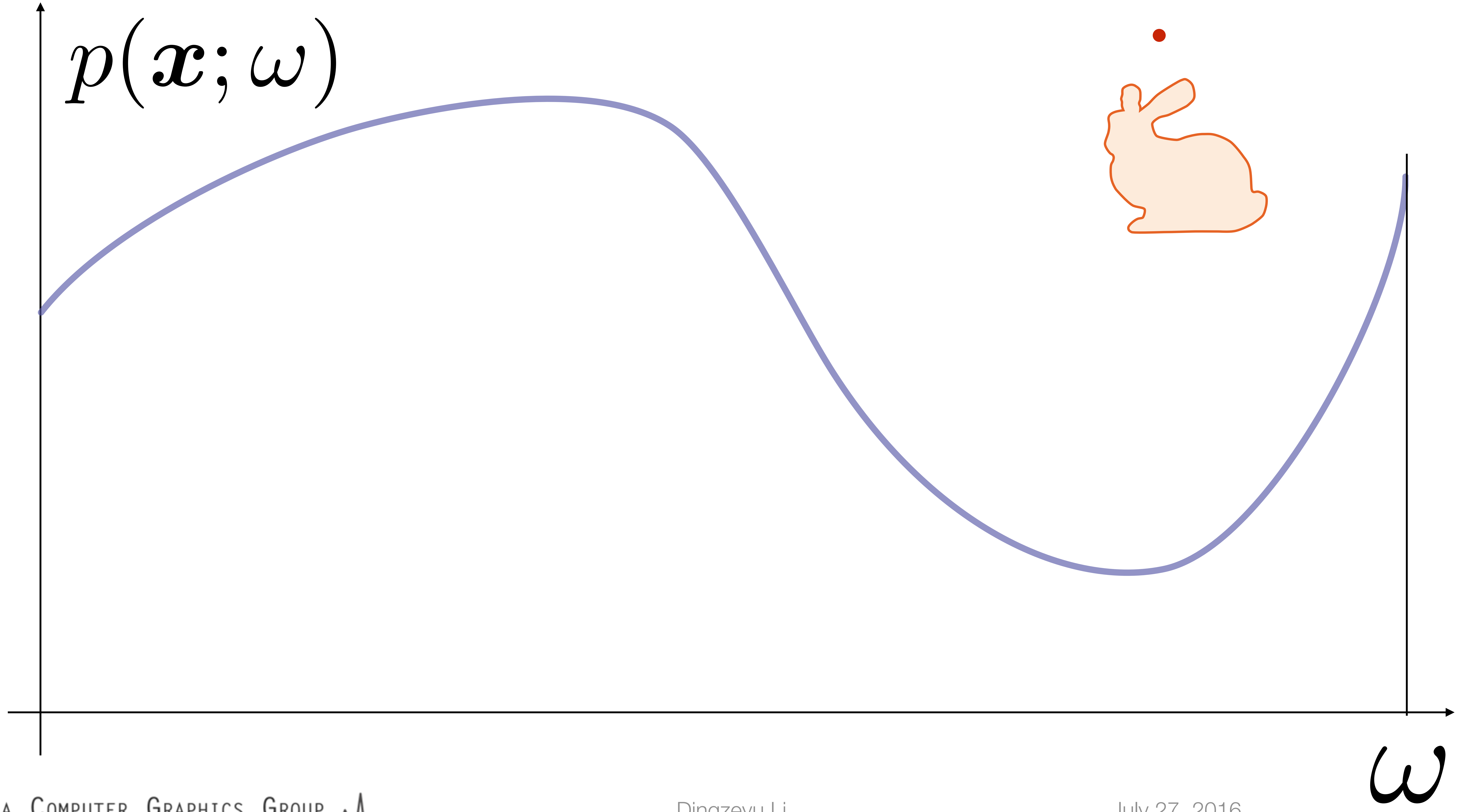
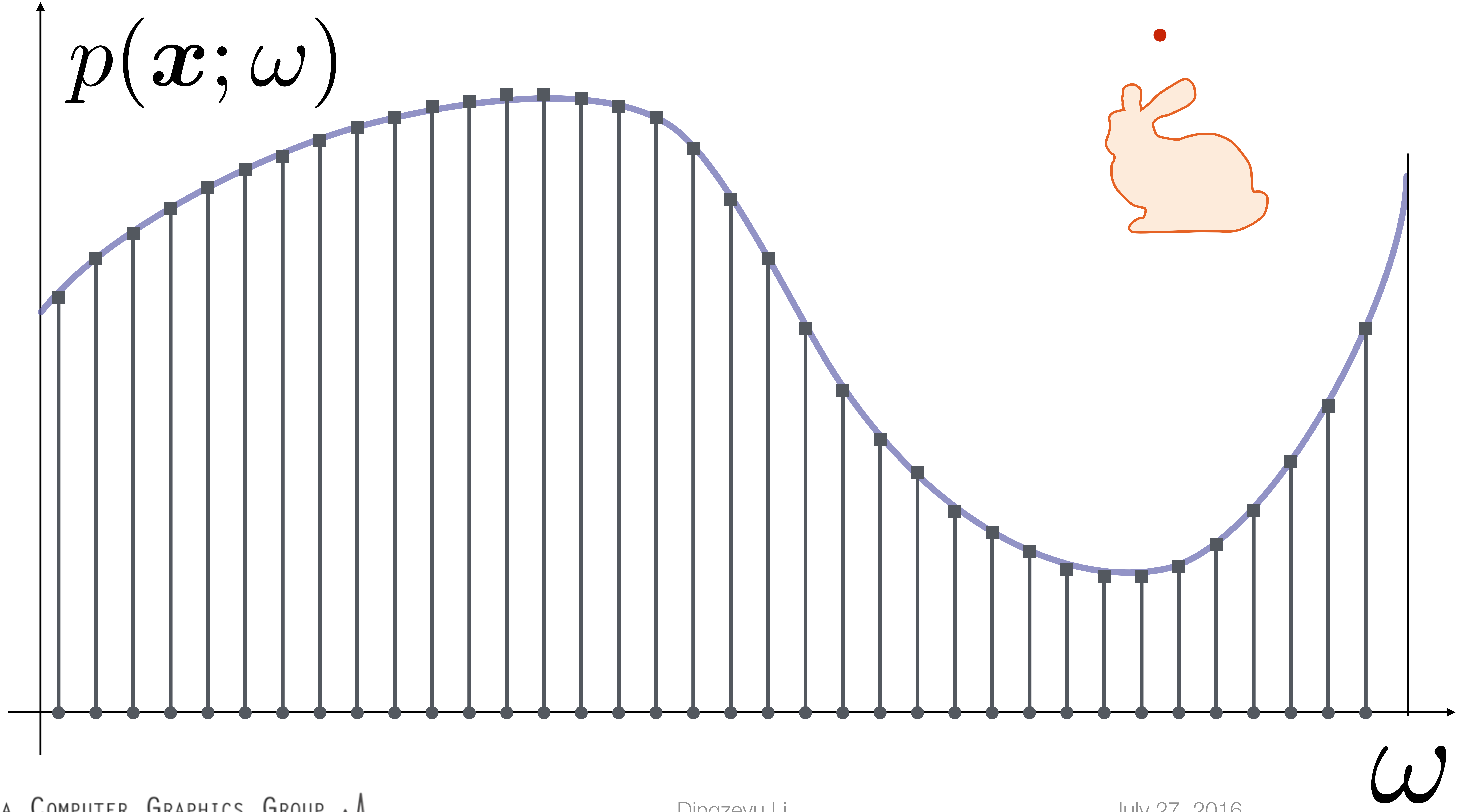
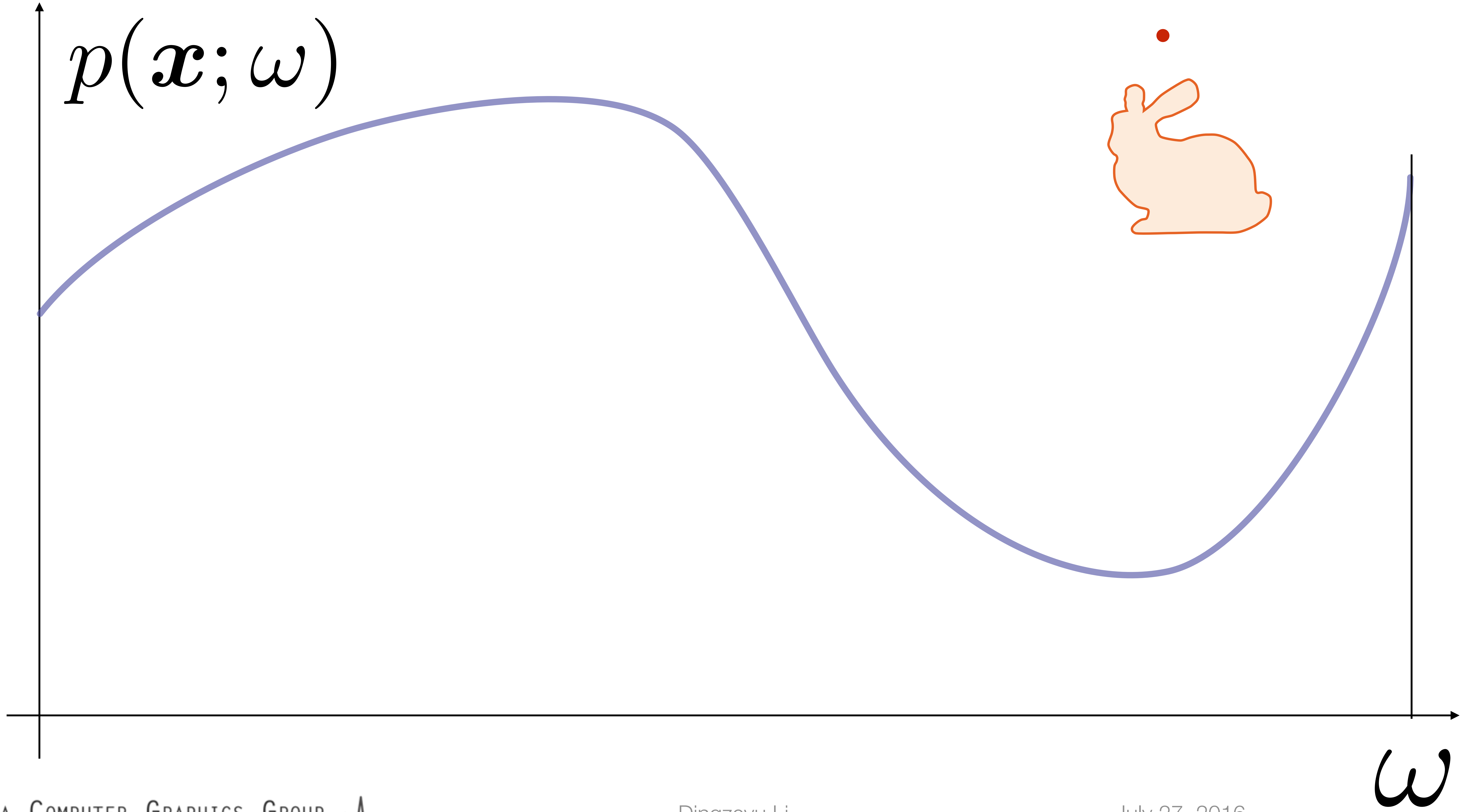


Pressure Frequency Sweep



Asymptotic Expansion



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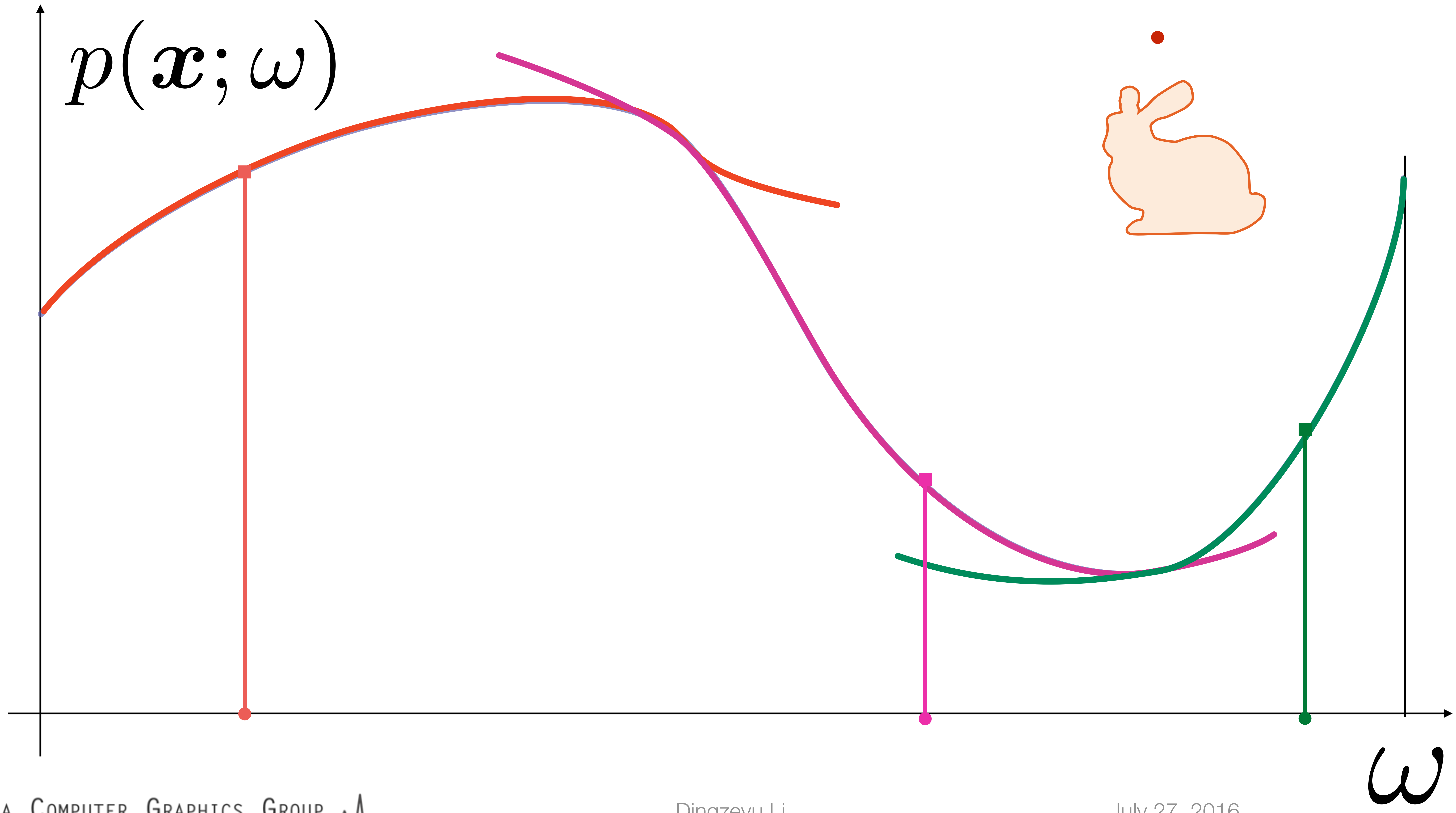

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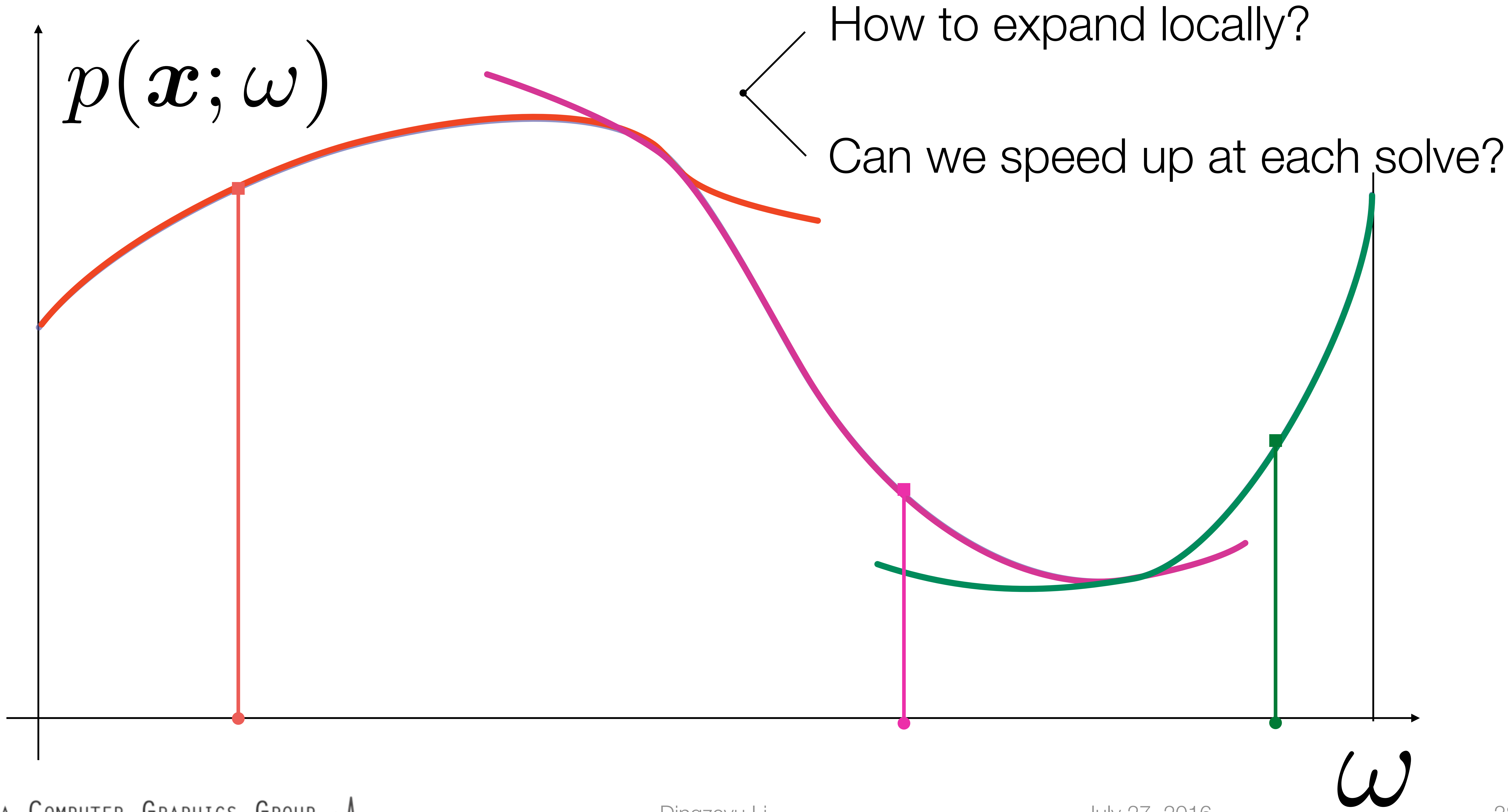
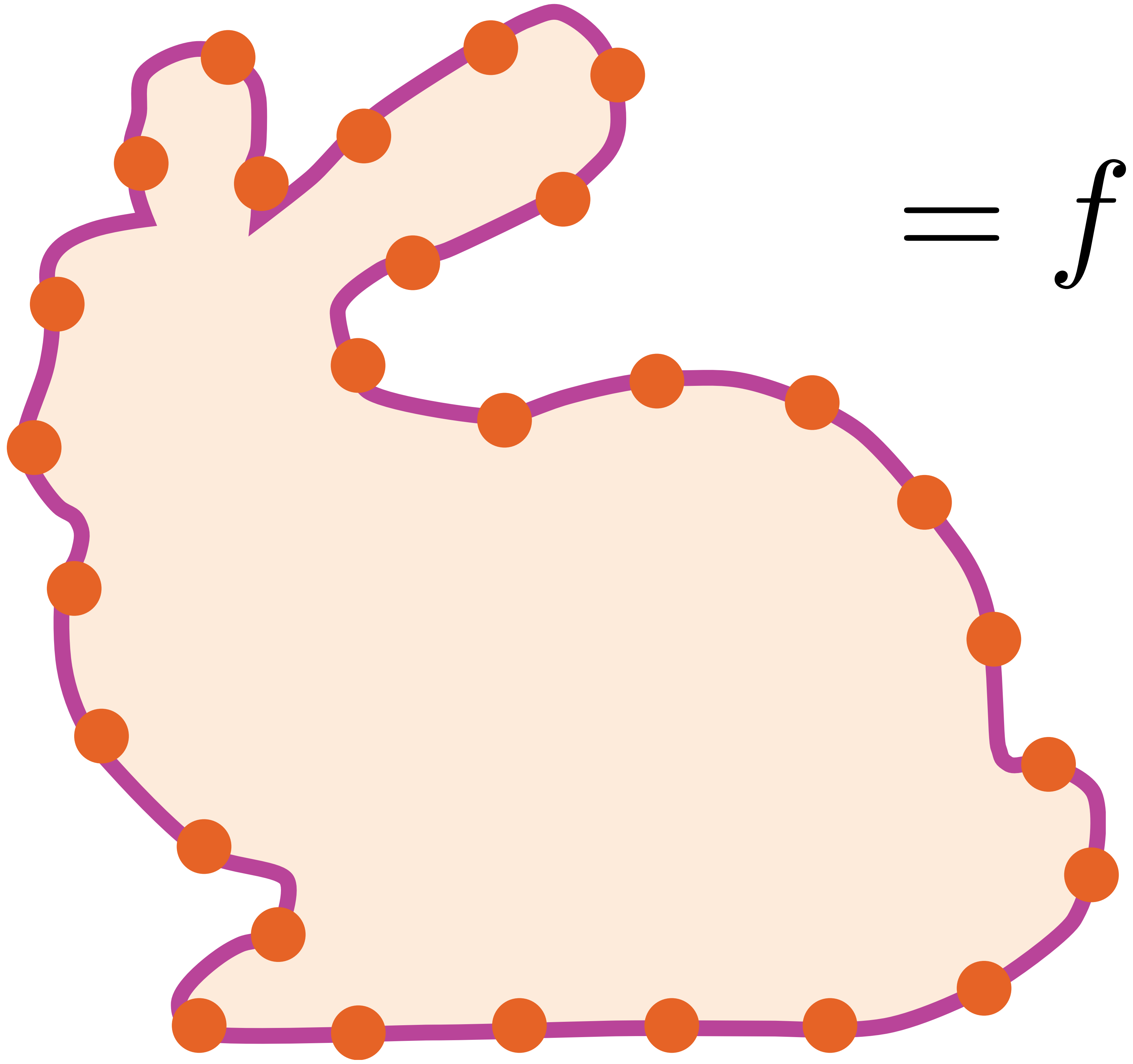


Boundary Integral

- $$p(\mathbf{x}, \omega) = \int_S \left[G(\mathbf{x}; \mathbf{y}) \frac{\partial \phi_\omega}{\partial \mathbf{n}}(\mathbf{y}) - \frac{\partial G}{\partial \mathbf{n}}(\mathbf{x}; \mathbf{y}) \phi_\omega(\mathbf{y}) \right] dS(\mathbf{y})$$

$$= f(\phi_w)$$



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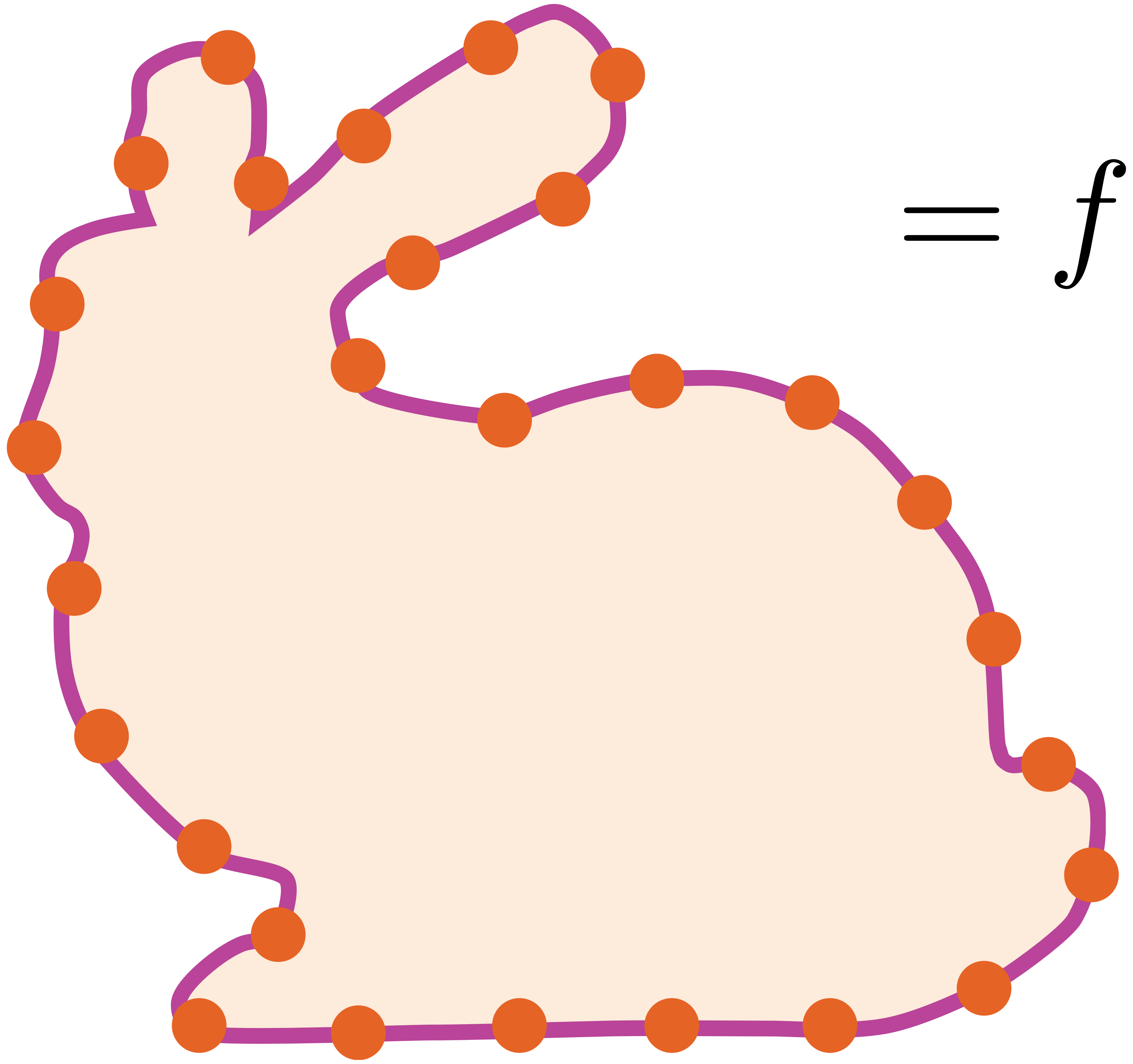

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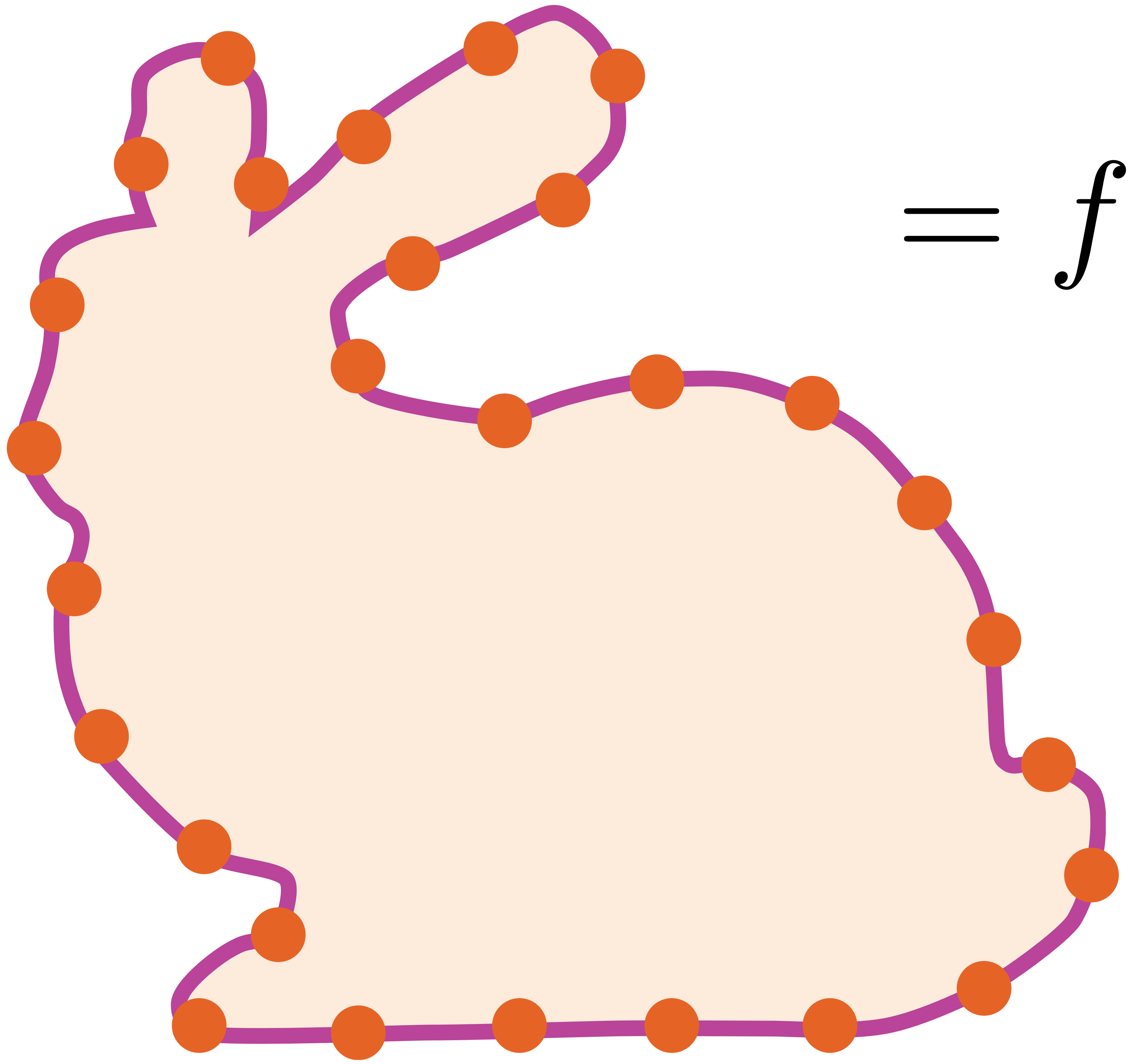

$$\mathsf{A}(\omega)\phi(\omega) = \mathbf{b}(\omega)$$

Polynomial Expansion

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• • •

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$$\cdots$$

$$n!\mathsf{A}(\omega_0)\phi_n = \mathbf{b}^{(n)}(\omega_0) - \sum_{i=1}^{n}(n-i)!C_n^i\mathsf{A}^{(i)}(\omega_0)\phi_{n-i}$$

Polynomial Expansion

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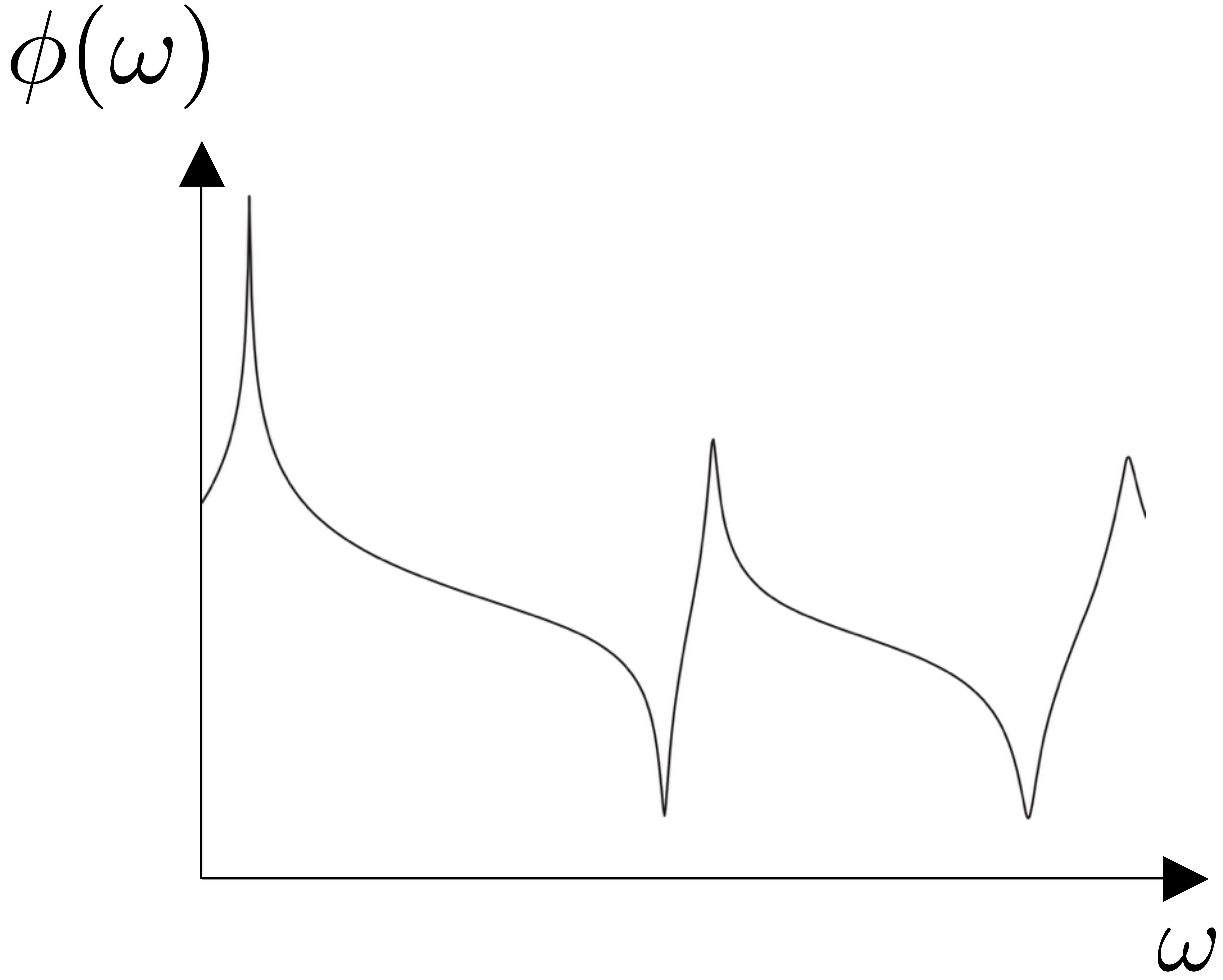
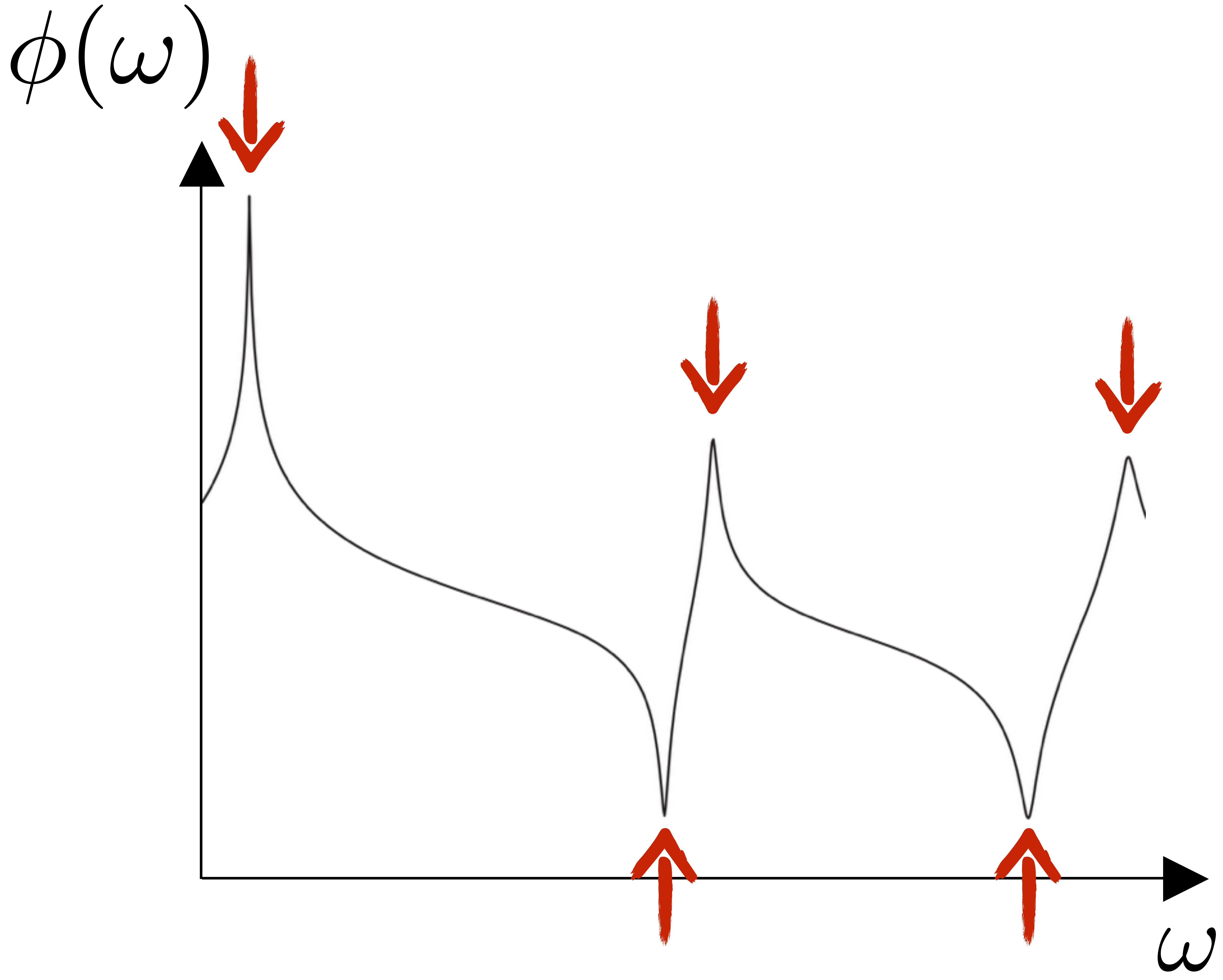
Padé Approximant for Better Convergence



Singularities [Lenzi et al. 2013]

Polynomial expansion

Padé Approximant for Better Convergence



Singularities [Lenzi et al. 2013]

Polynomial expansion ✗

Padé Approximant ✓

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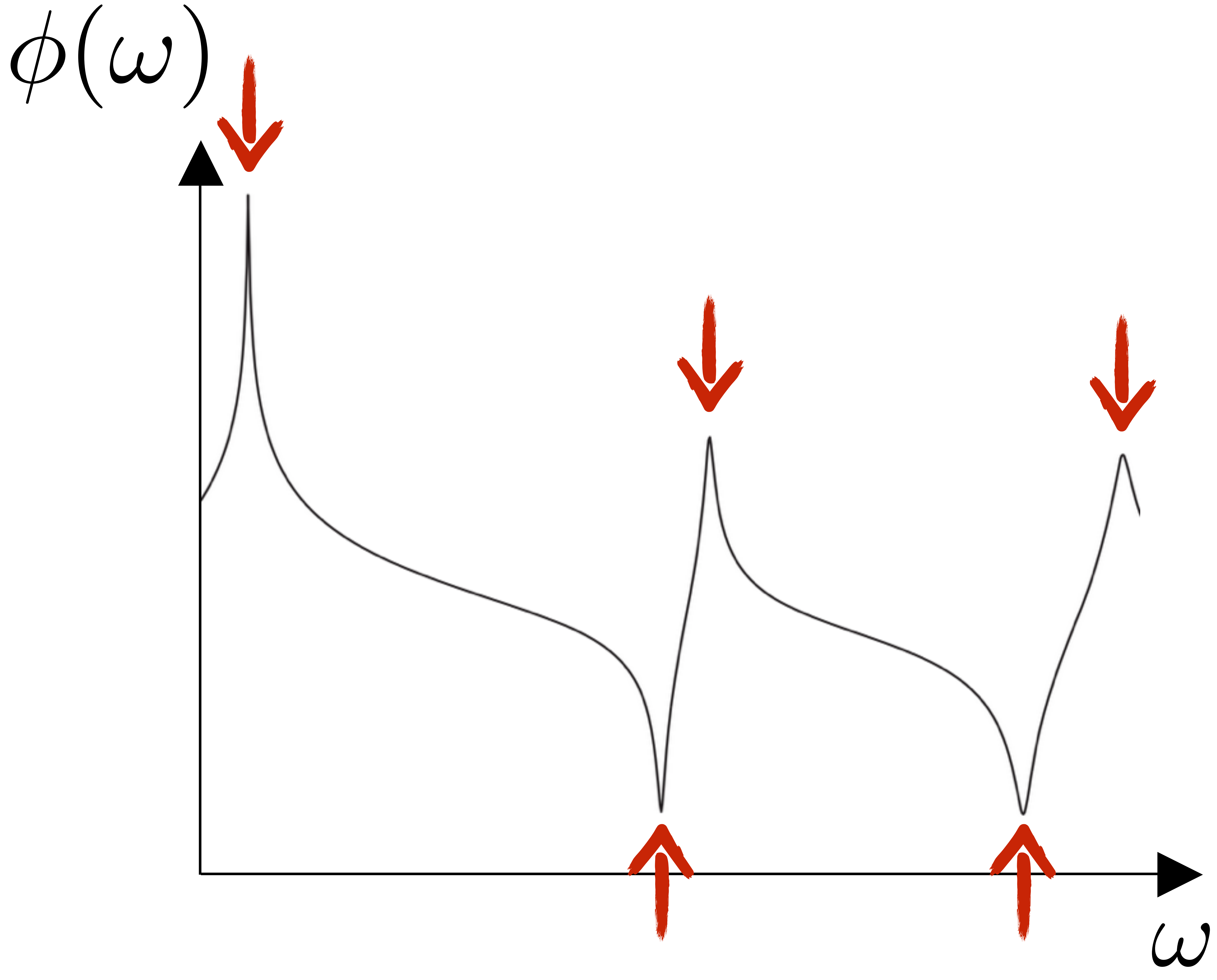


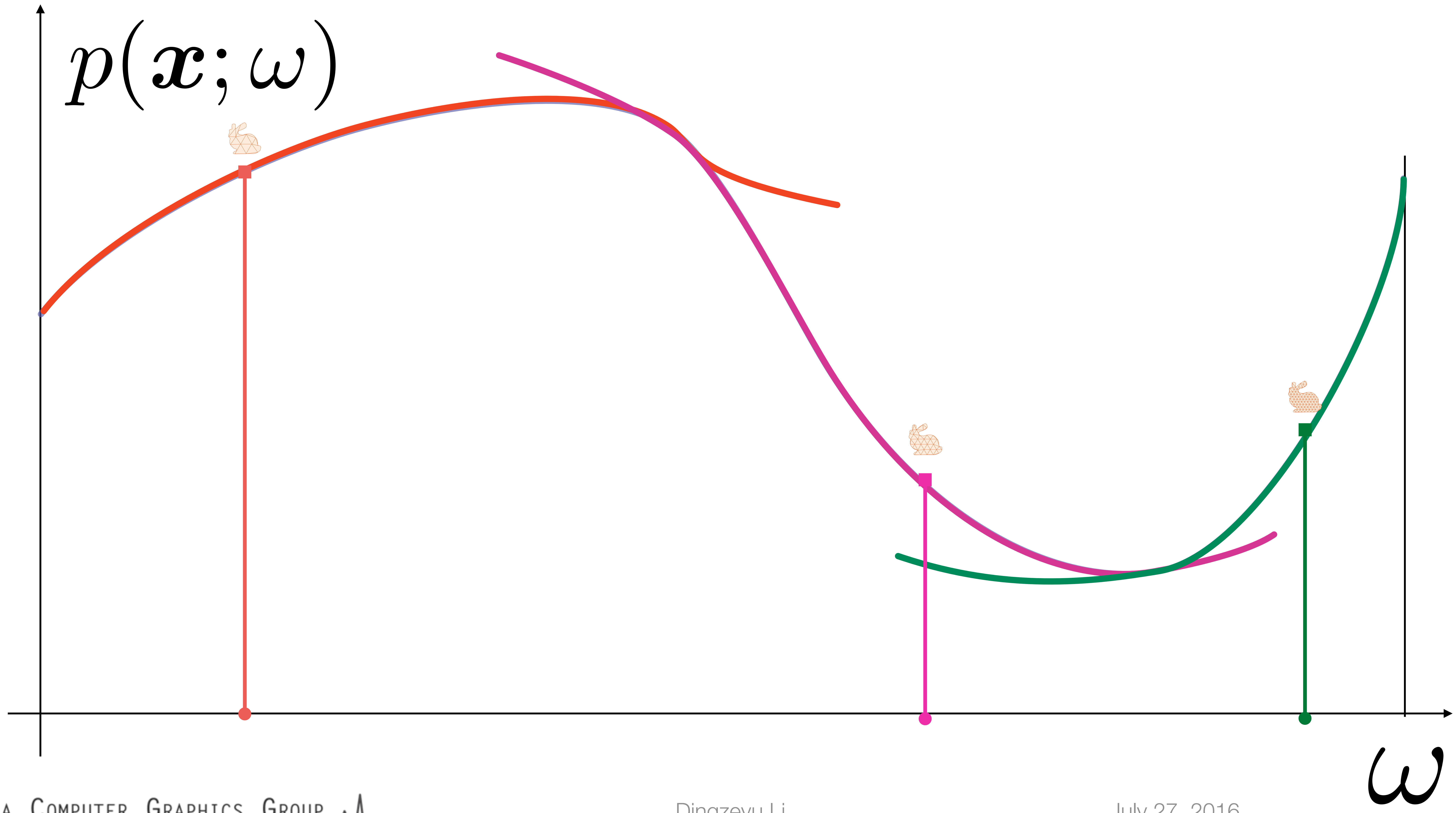
Singularities [Lenzi et al. 2013]

Polynomial expansion ✗

Padé Approximant ✓

$$\phi(\omega) = \frac{\sum_{i=0}^{L} \alpha_i (\omega - \omega_0)^i}{1 + \sum_{j=1}^{M} \beta_j (\omega - \omega_0)^j}$$

Mesh Simplification for Pressure Solves



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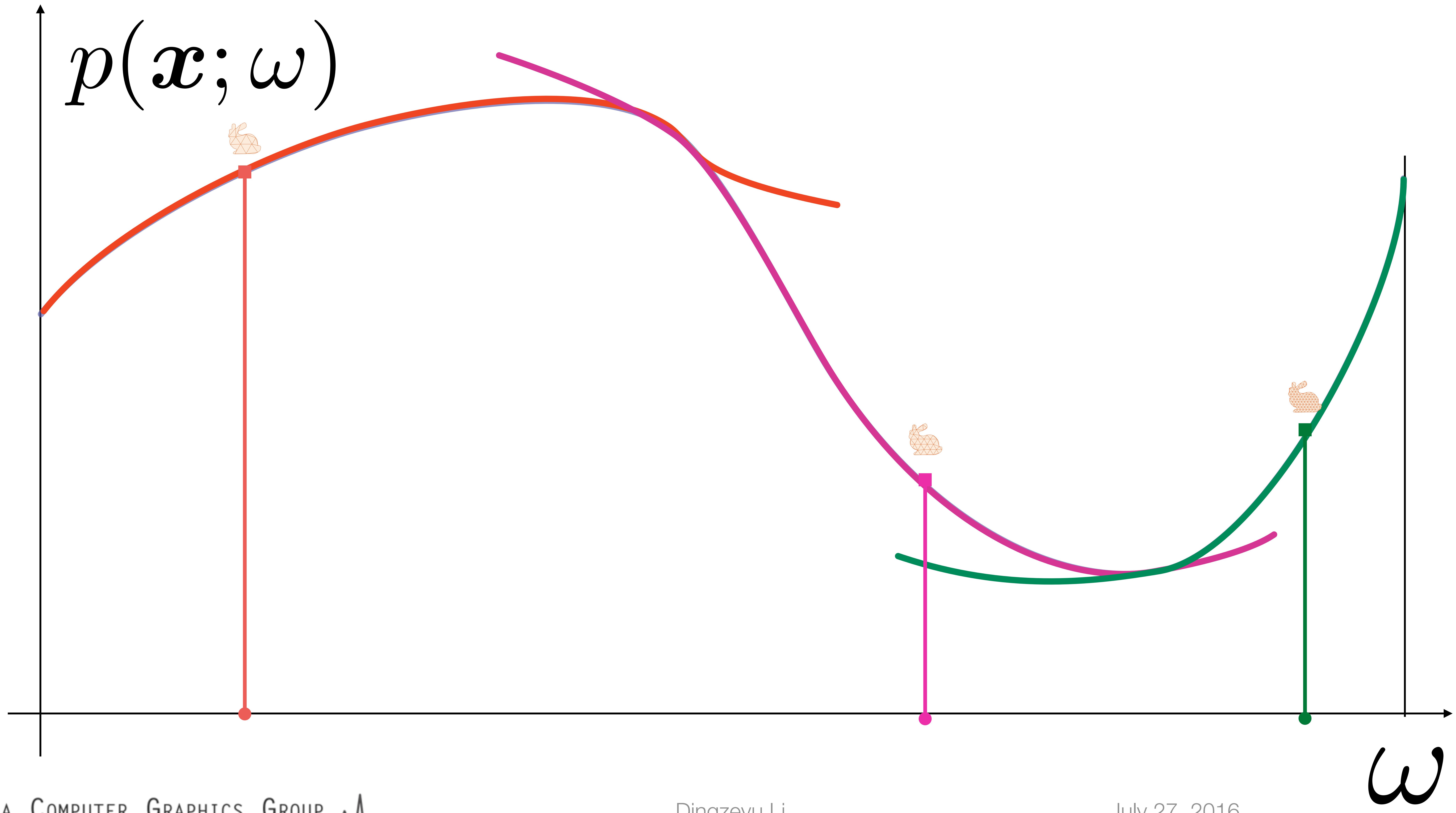

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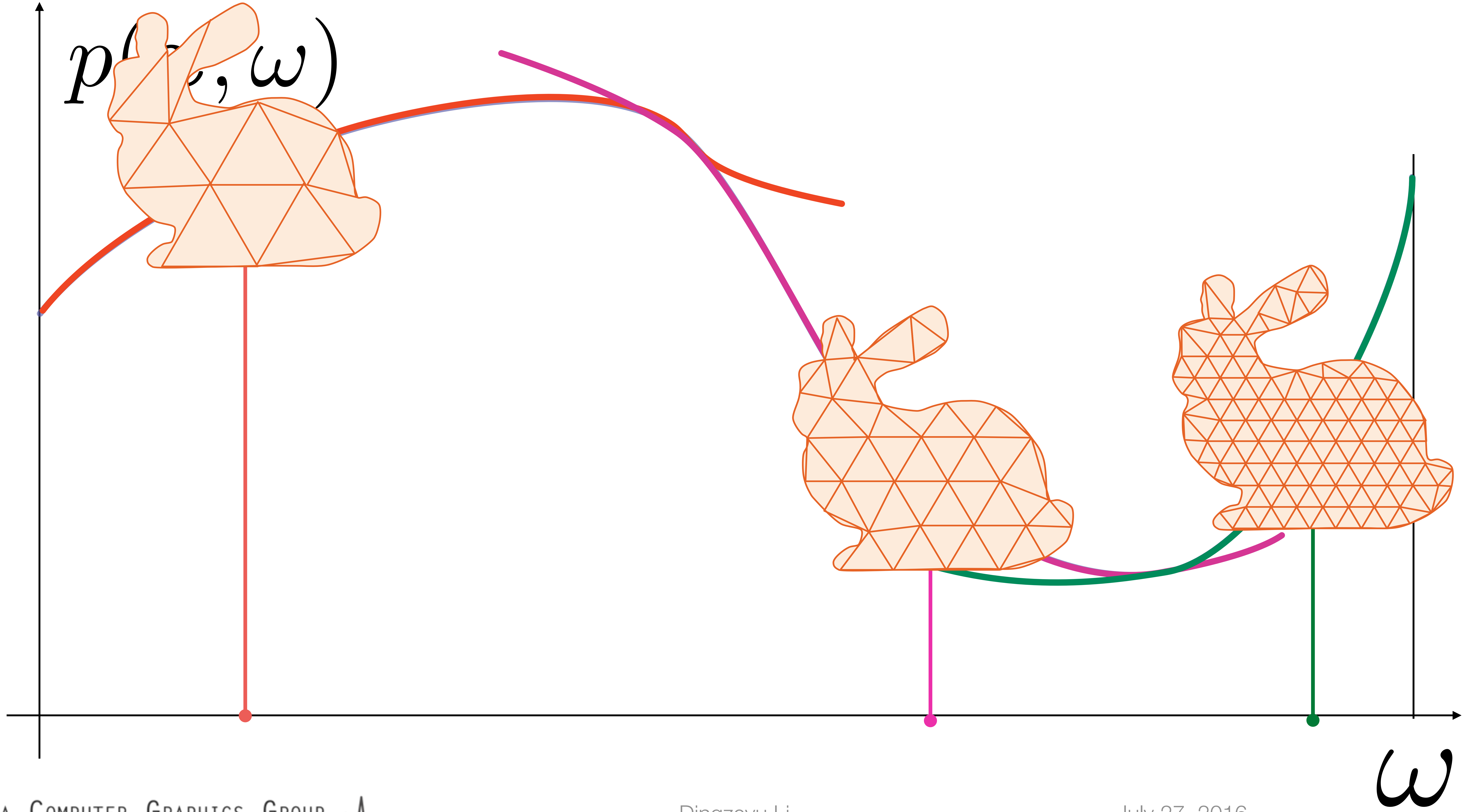
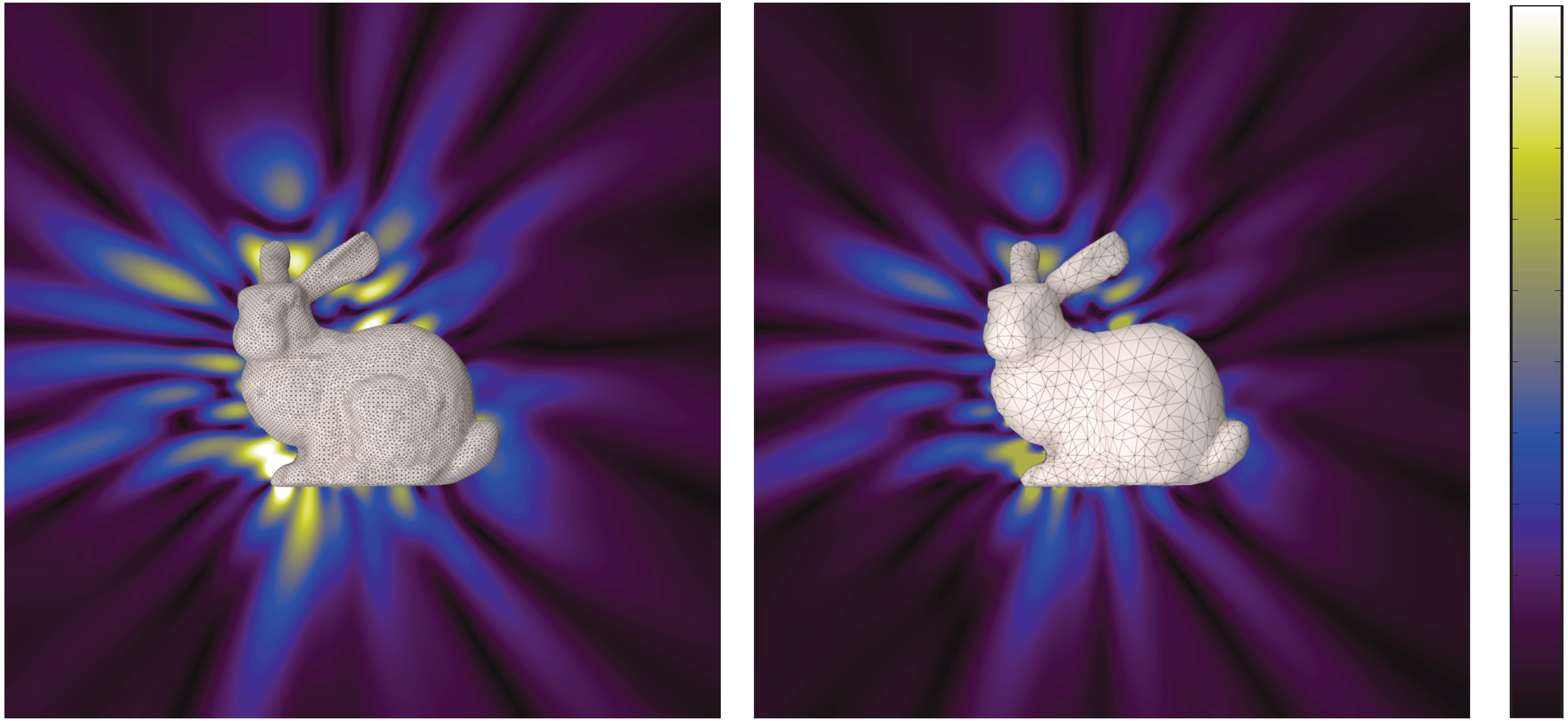


Existing approach loses acoustic pressure.

Original
30k triangles

Simplified [Hoppe 1999]
2k triangles



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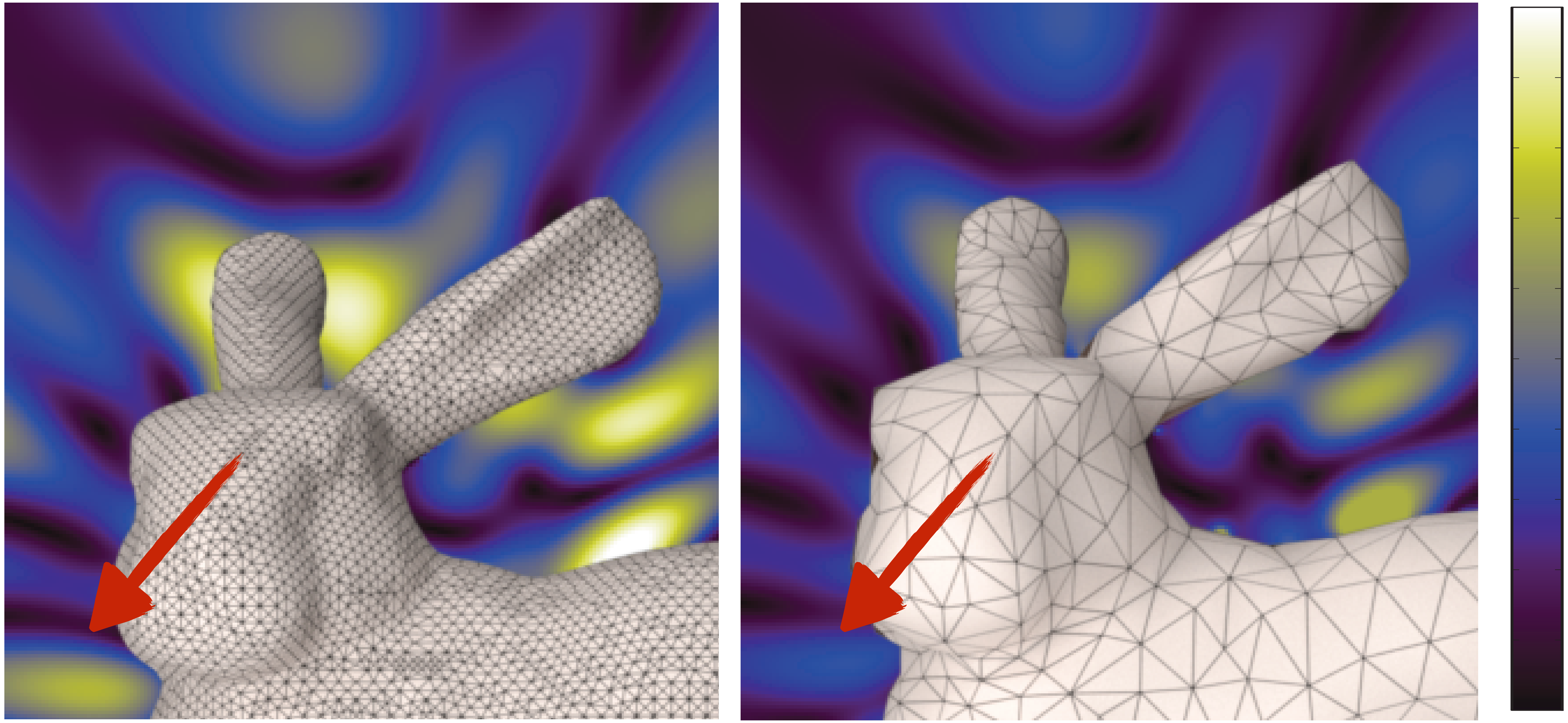
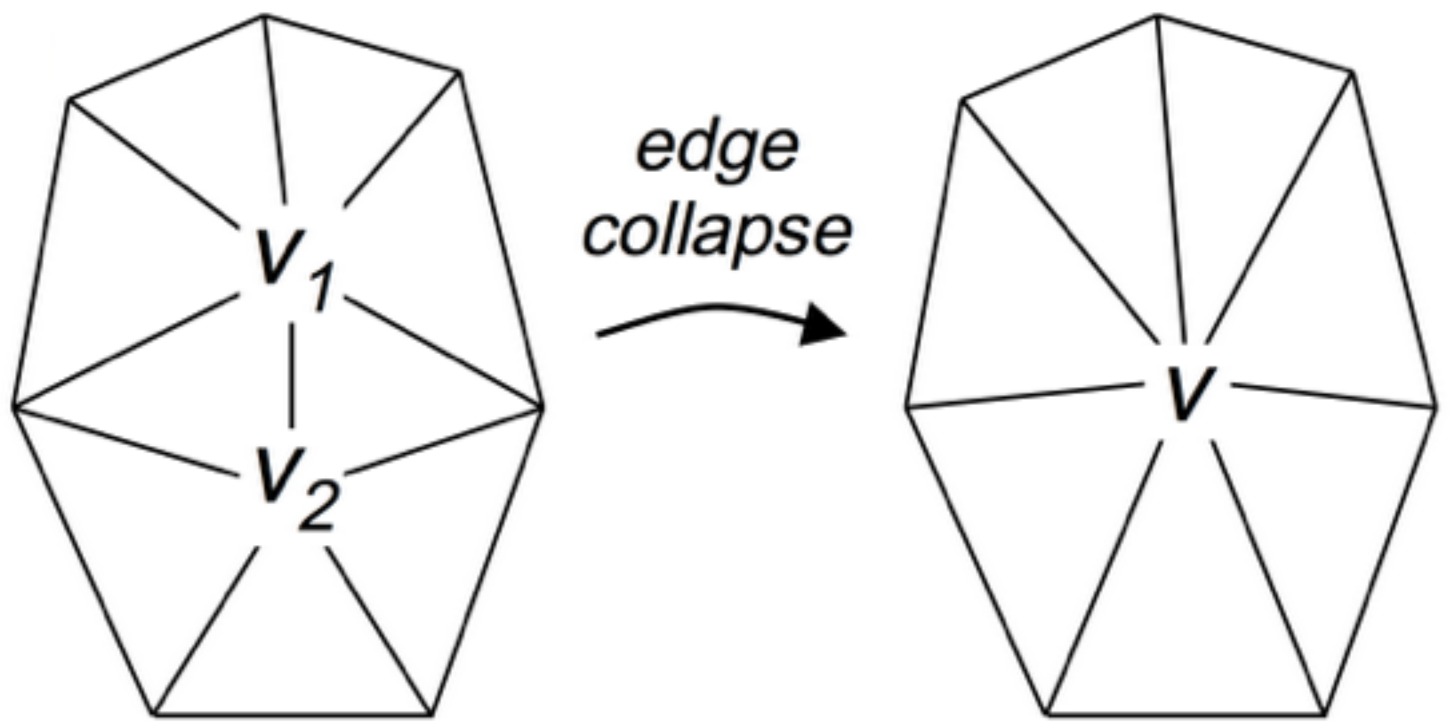


Acoustic Transfer Preserving Simplification

Edge Collapse Algorithm [Hoppe 1999]



$$\mathbf{v}_{new} = \arg\min_{\mathbf{v}} Q^{v_1}(\mathbf{v}) + Q^{v_2}(\mathbf{v})$$

$$\text{s.t.} \quad \mathbf{g}_{vol}^T \mathbf{v} + d_{vol} = 0$$ Volume Constraint

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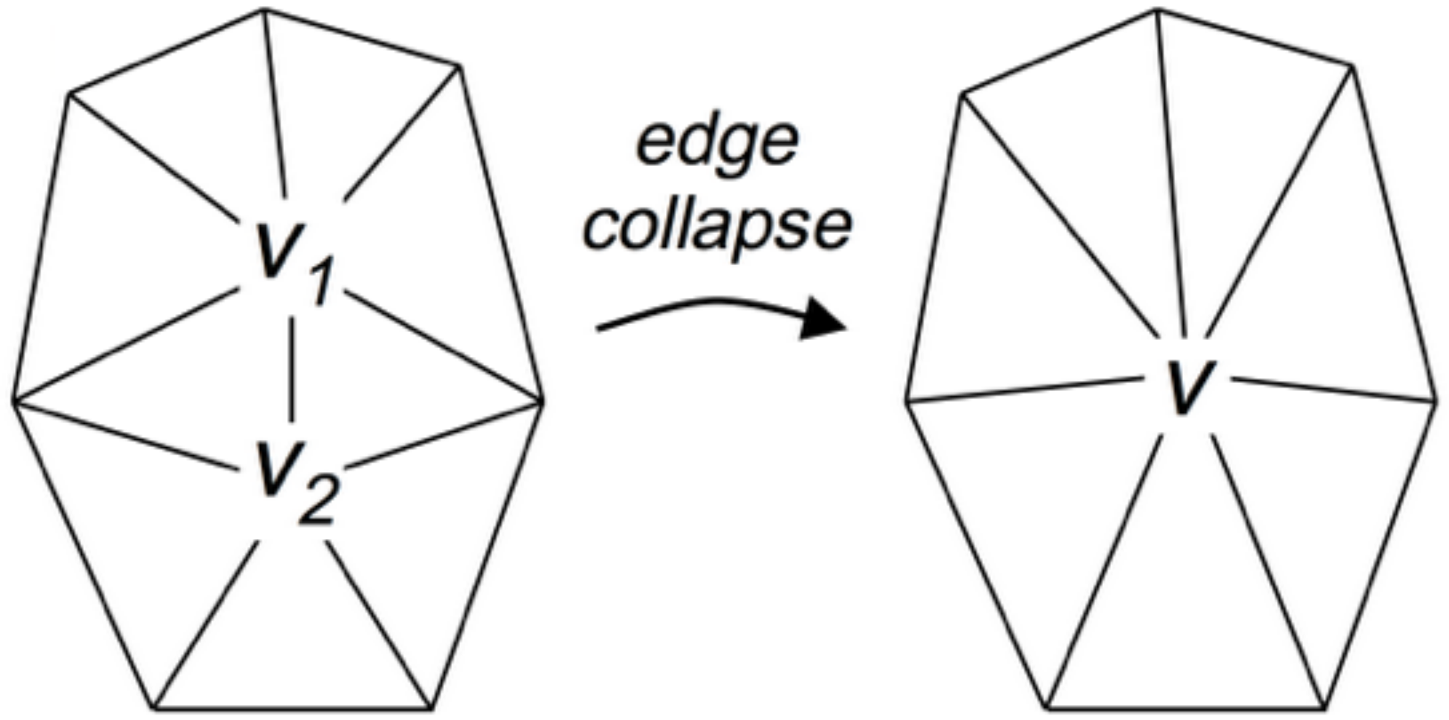

$$\nabla^2 p(\mathbf{x}, \omega) + k^2 p(\mathbf{x}, \omega) = 0$$

$$\text{s.t.} \quad \frac{\partial p}{\partial \mathbf{n}} = f(\mathbf{u}_\omega)$$

Acoustic Transfer Preserving Simplification

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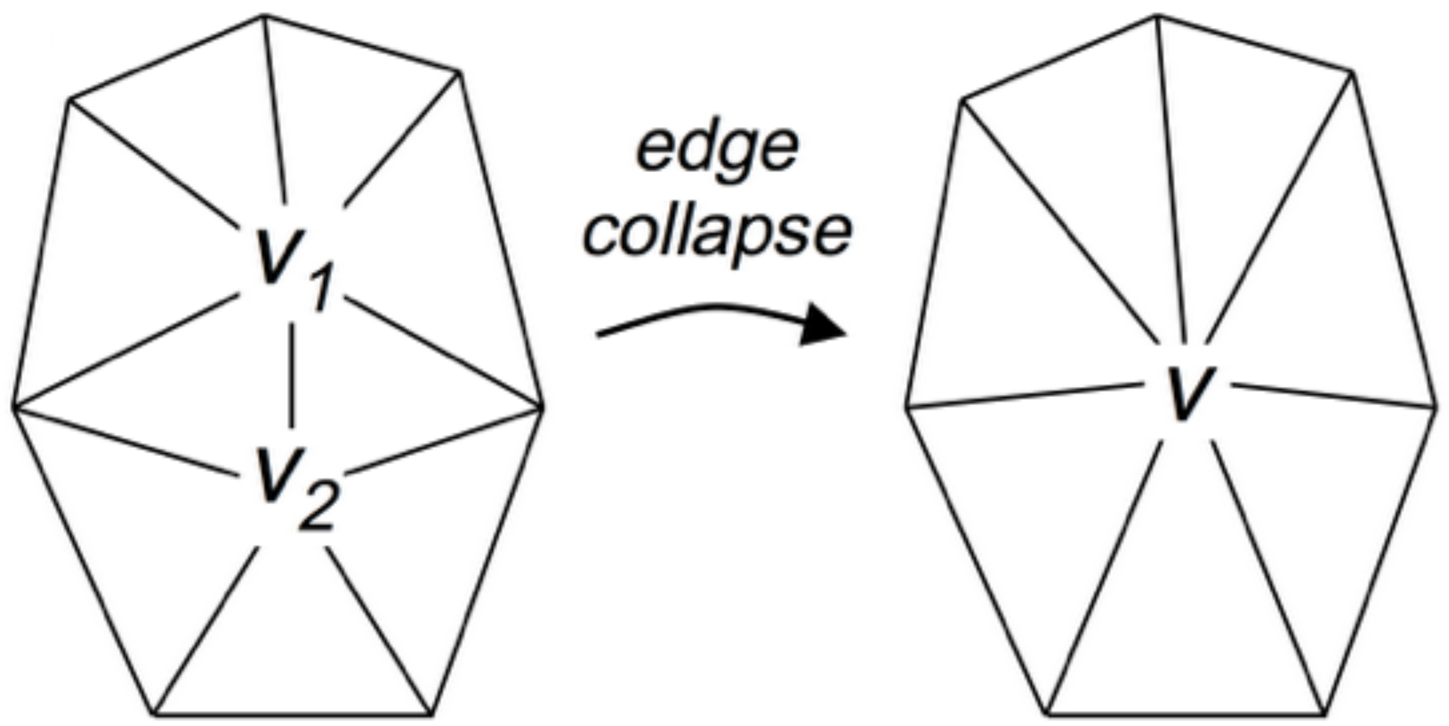

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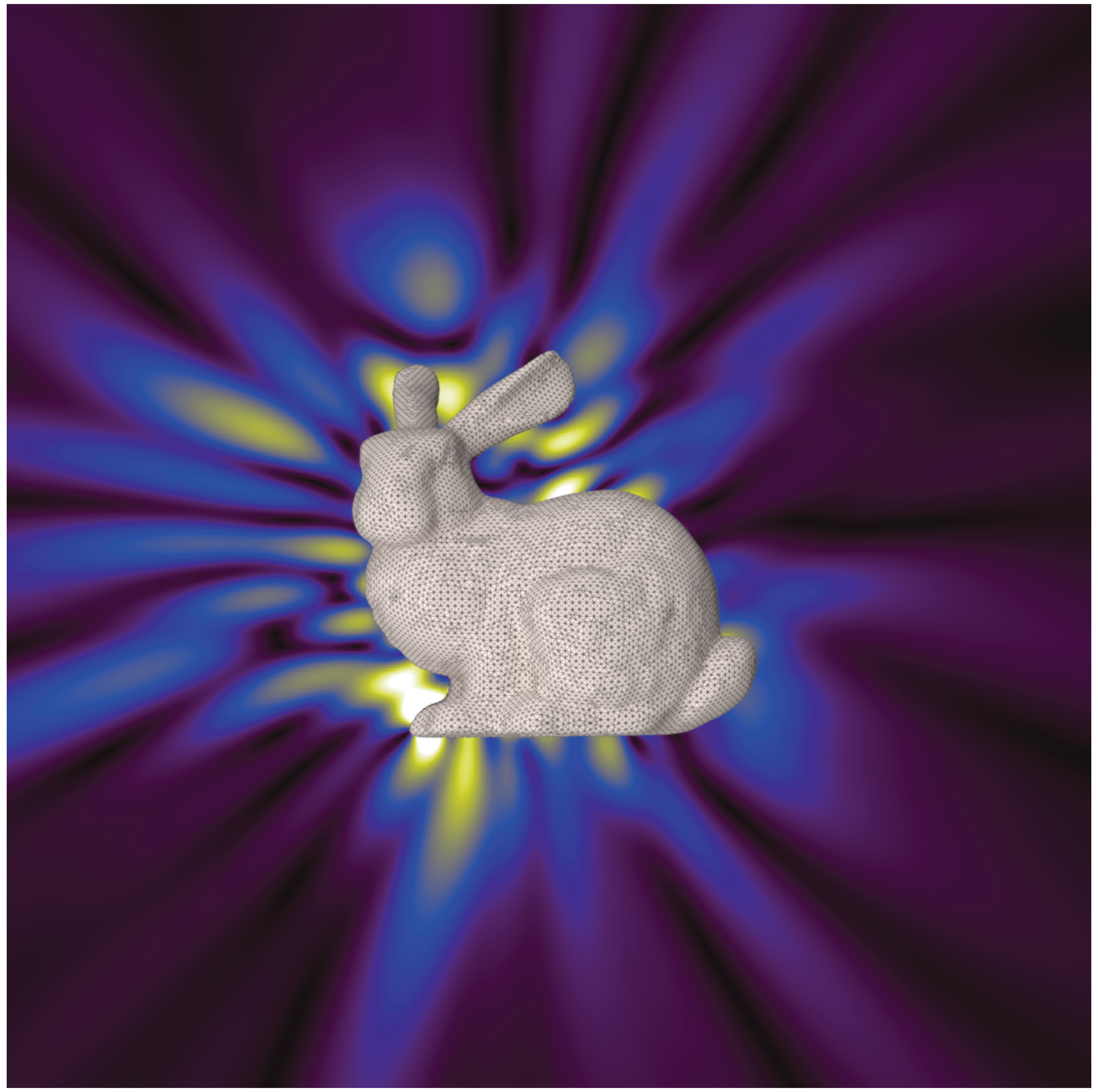
$$\frac{1}{6} \sum_{f \in \mathcal{N}(v)} \left[(\mathbf{v} - \mathbf{v}_{f1}) \times (\mathbf{v} - \mathbf{v}_{f2})\right]^T (\mathbf{u} + \mathbf{u}_{f1} + \mathbf{m}u_{f2}) = C_v$$

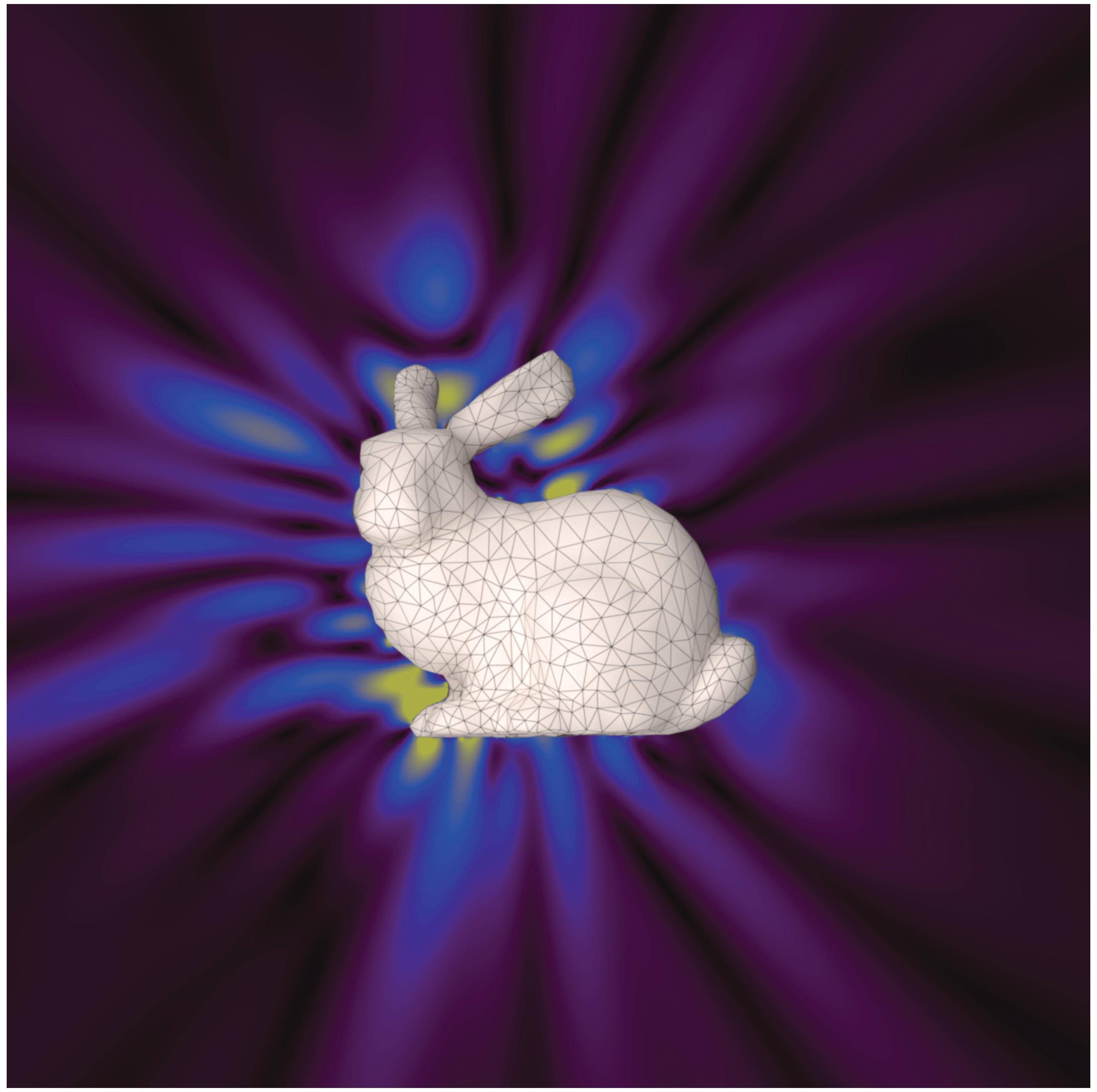
Acoustic Transfer Constraint

Our approach *preserves* acoustic pressure.

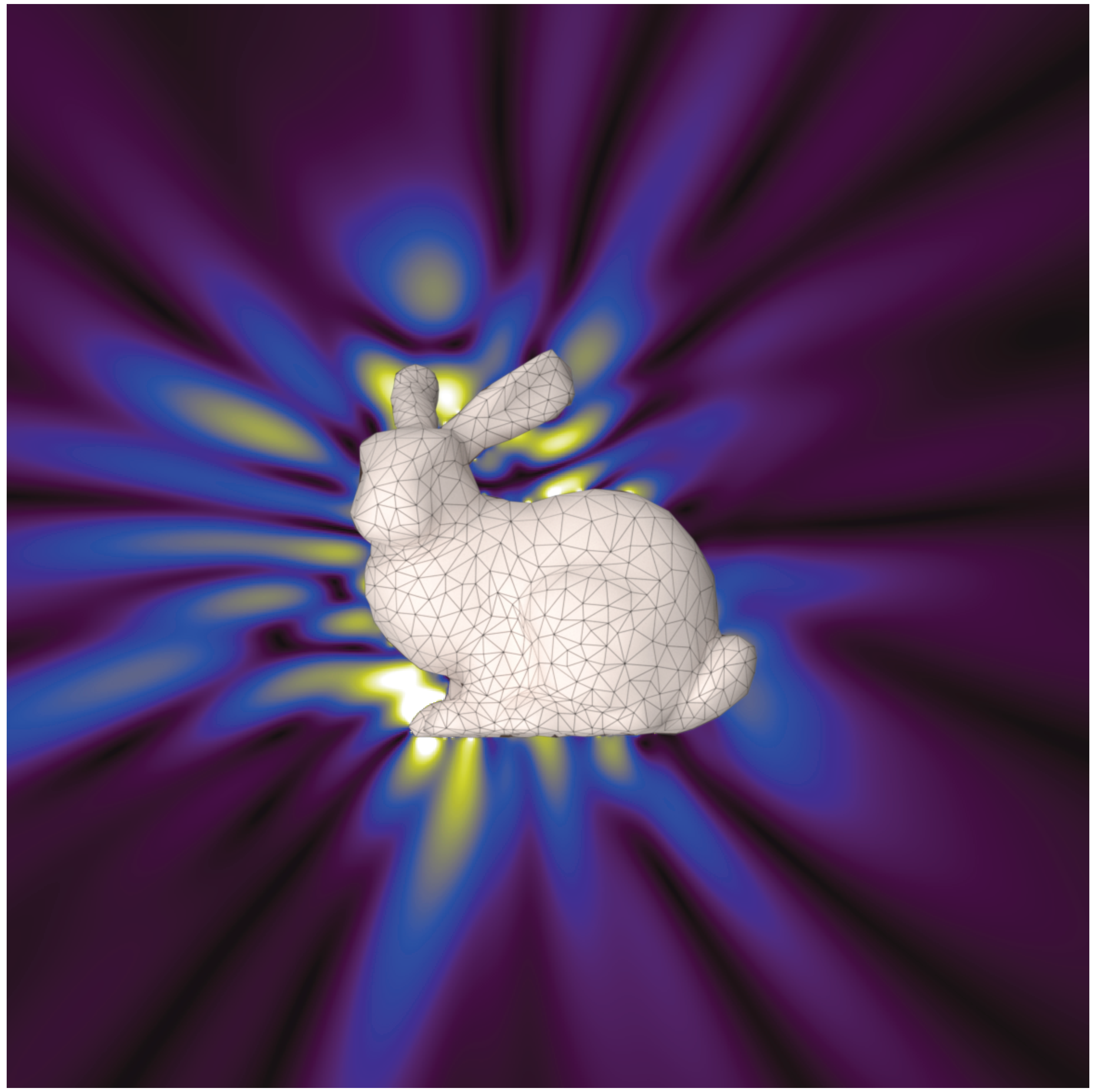
Original
30k triangles



Simplified [Hoppe 1999]
2k triangles



Simplified (Ours)
2k triangles



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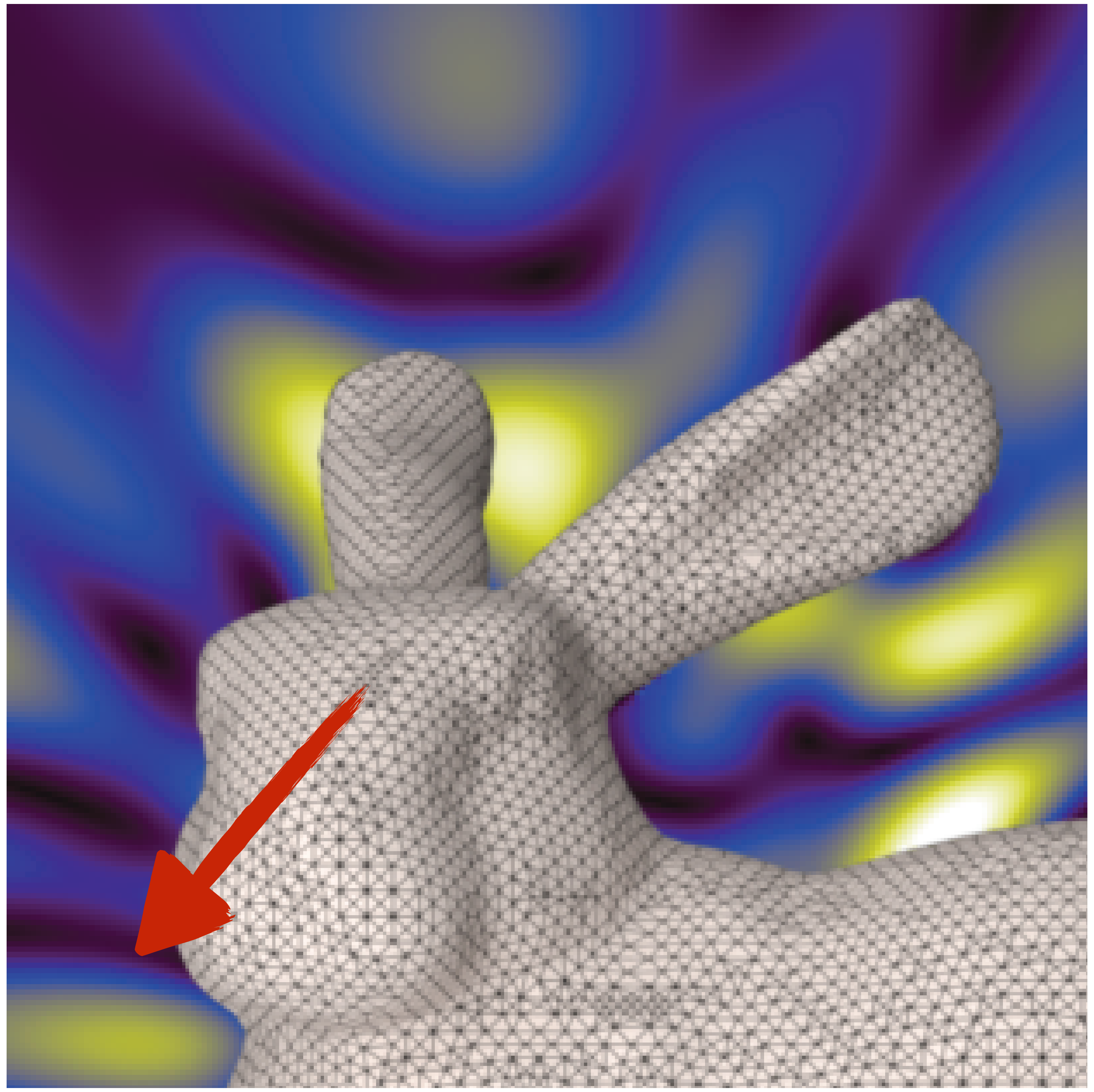

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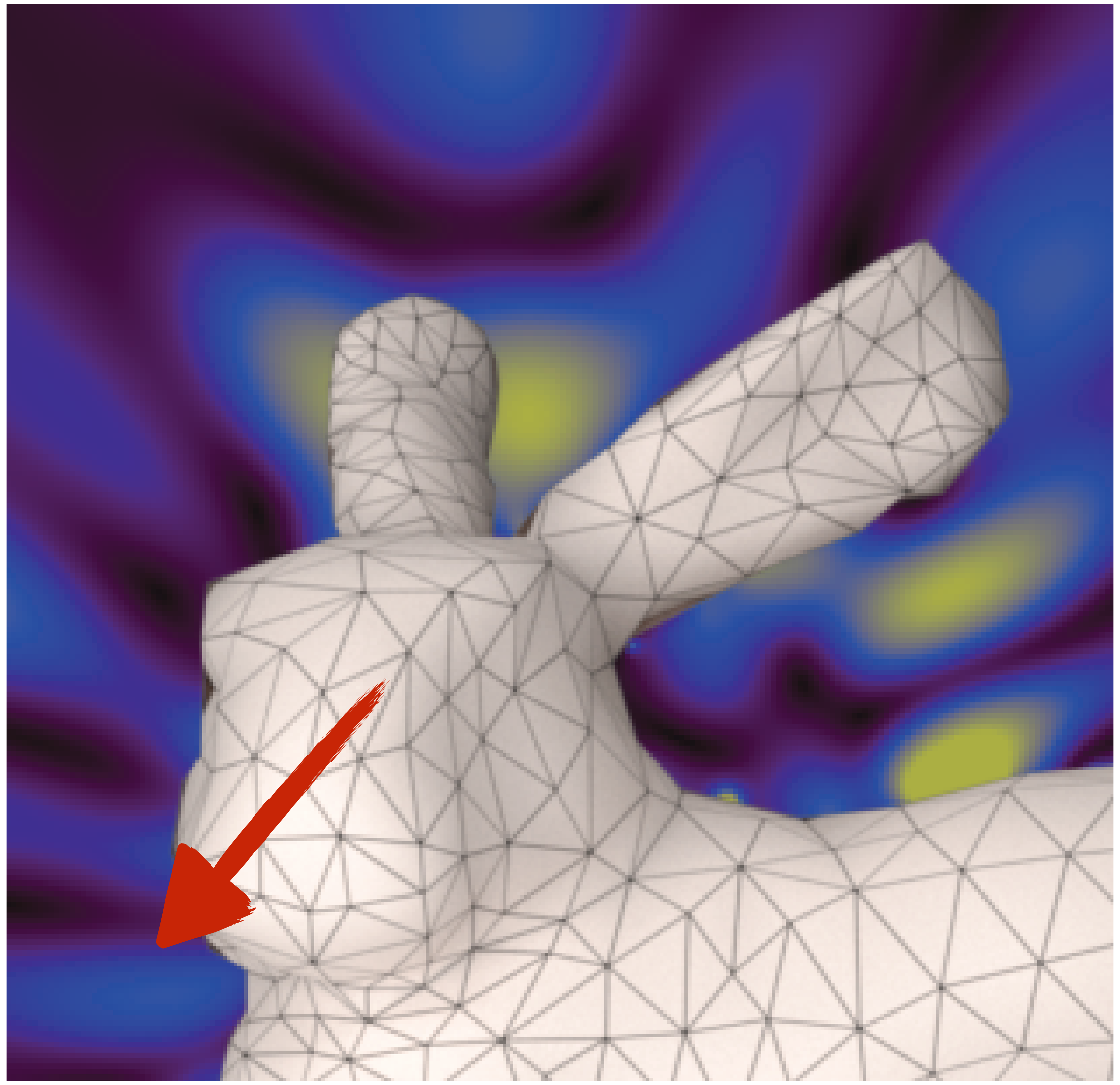

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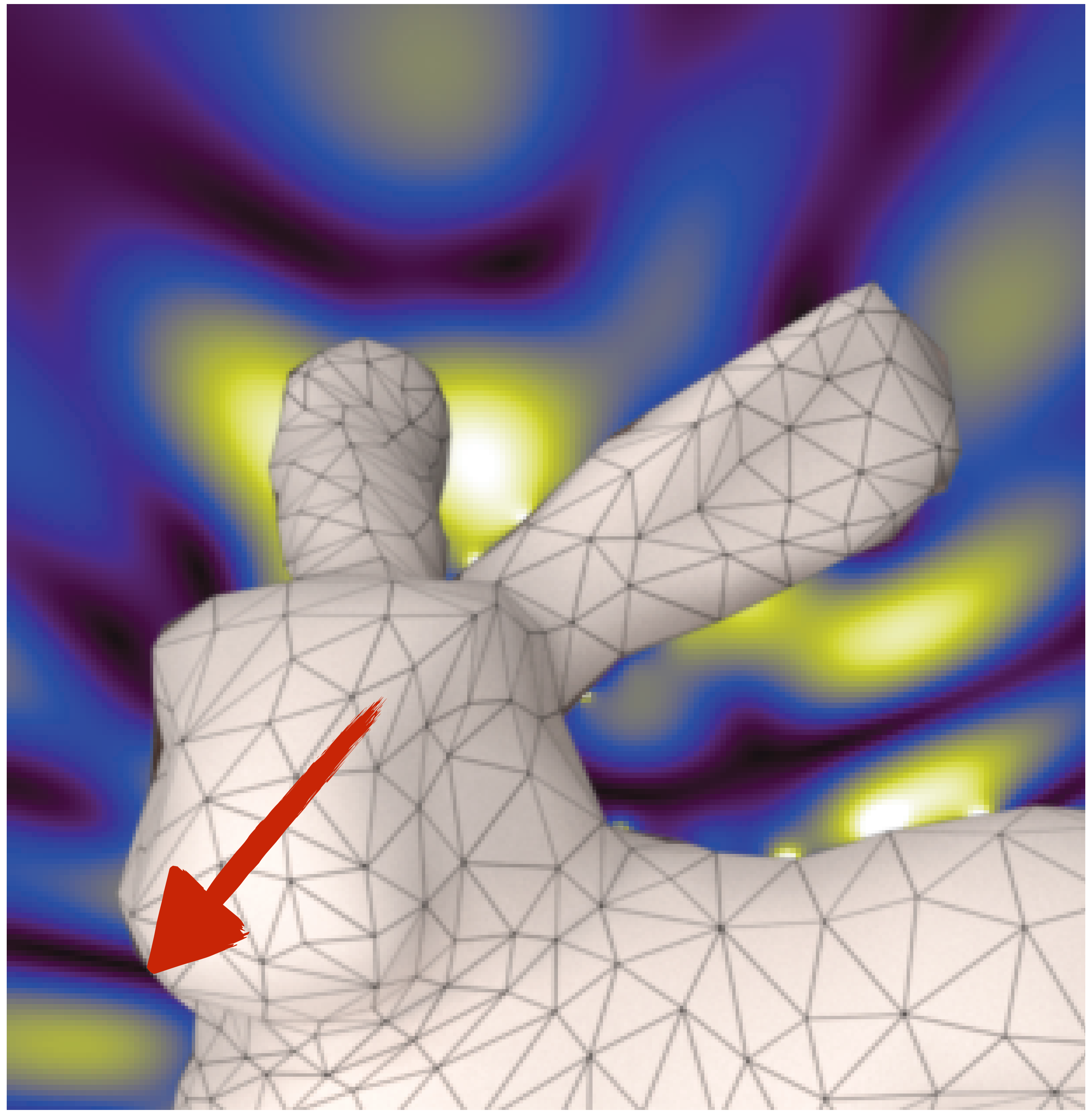
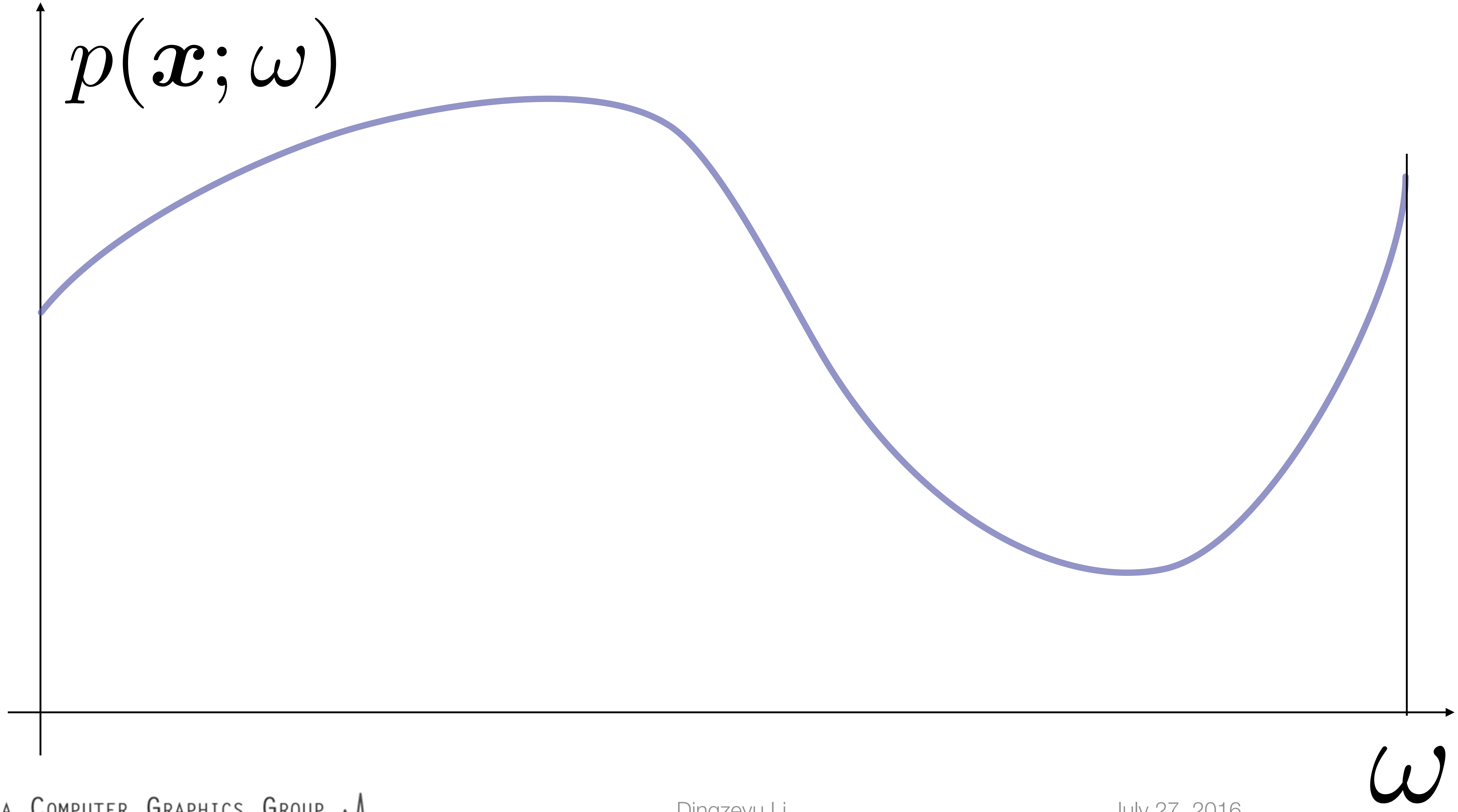


Recap: Fast Helmholtz Precomputation



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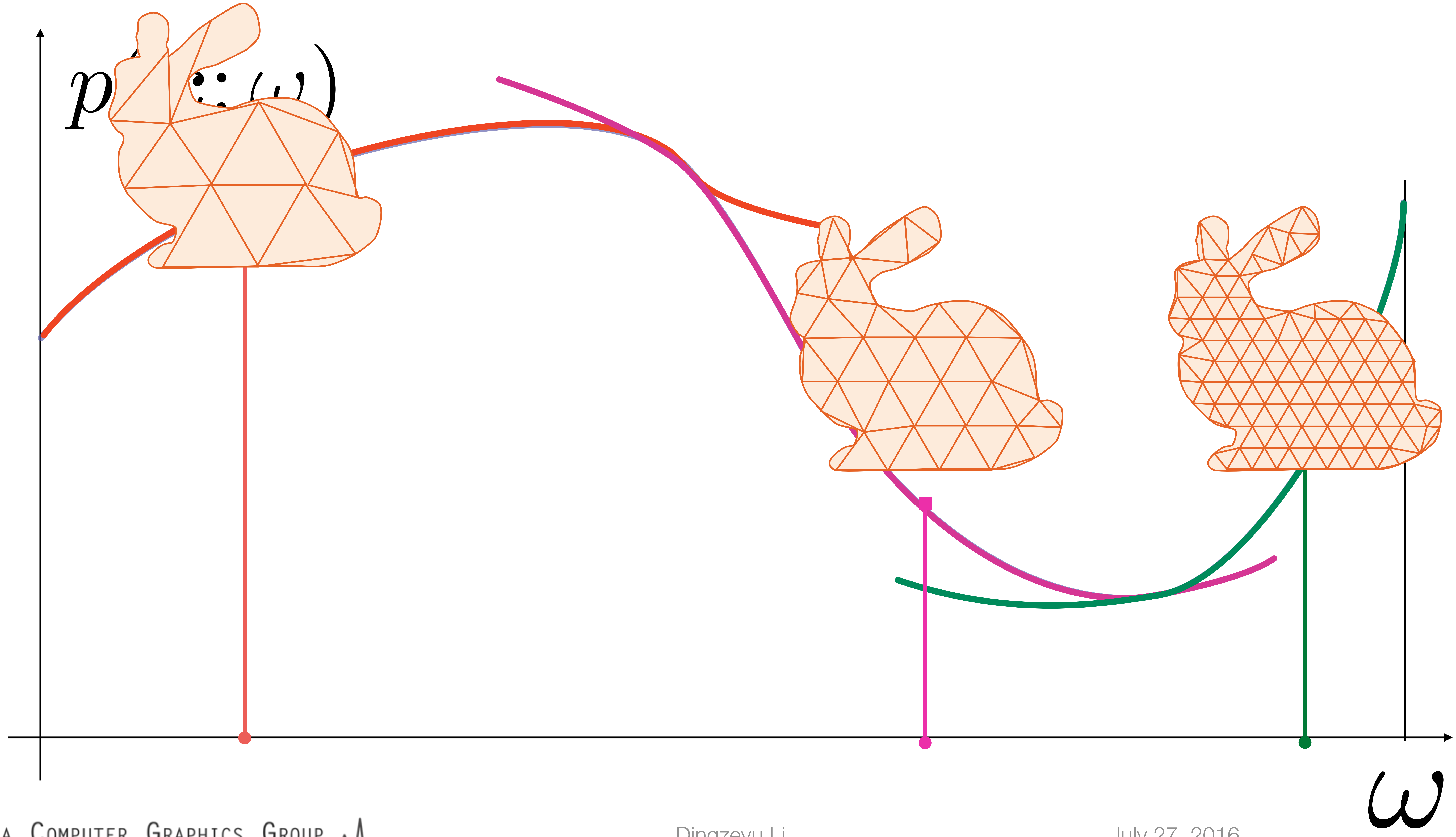

Interactive Runtime Solve

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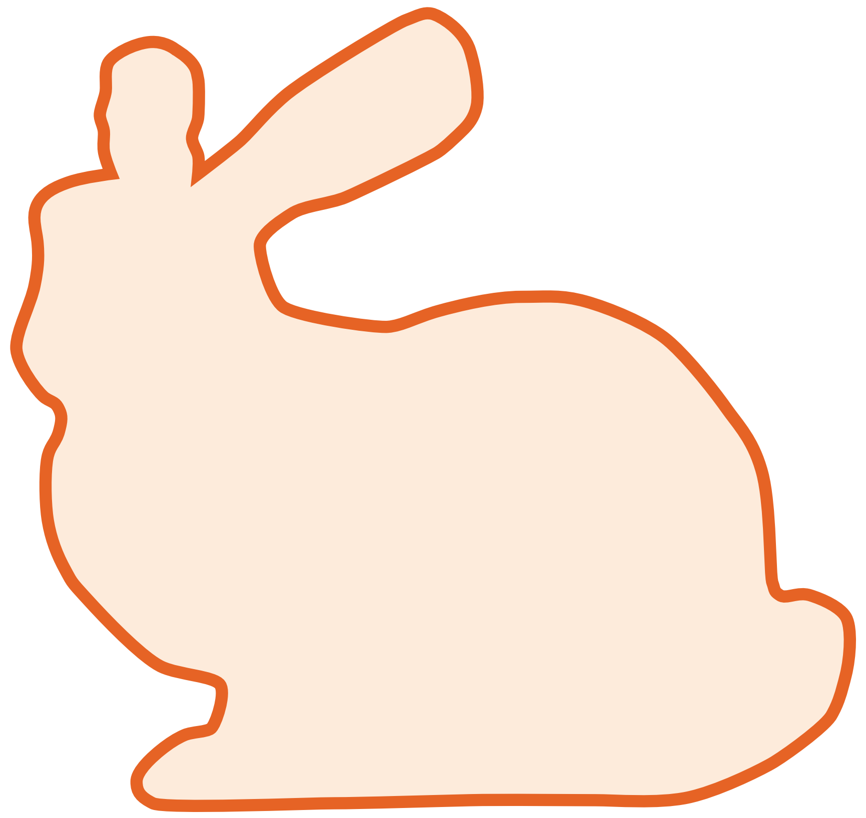

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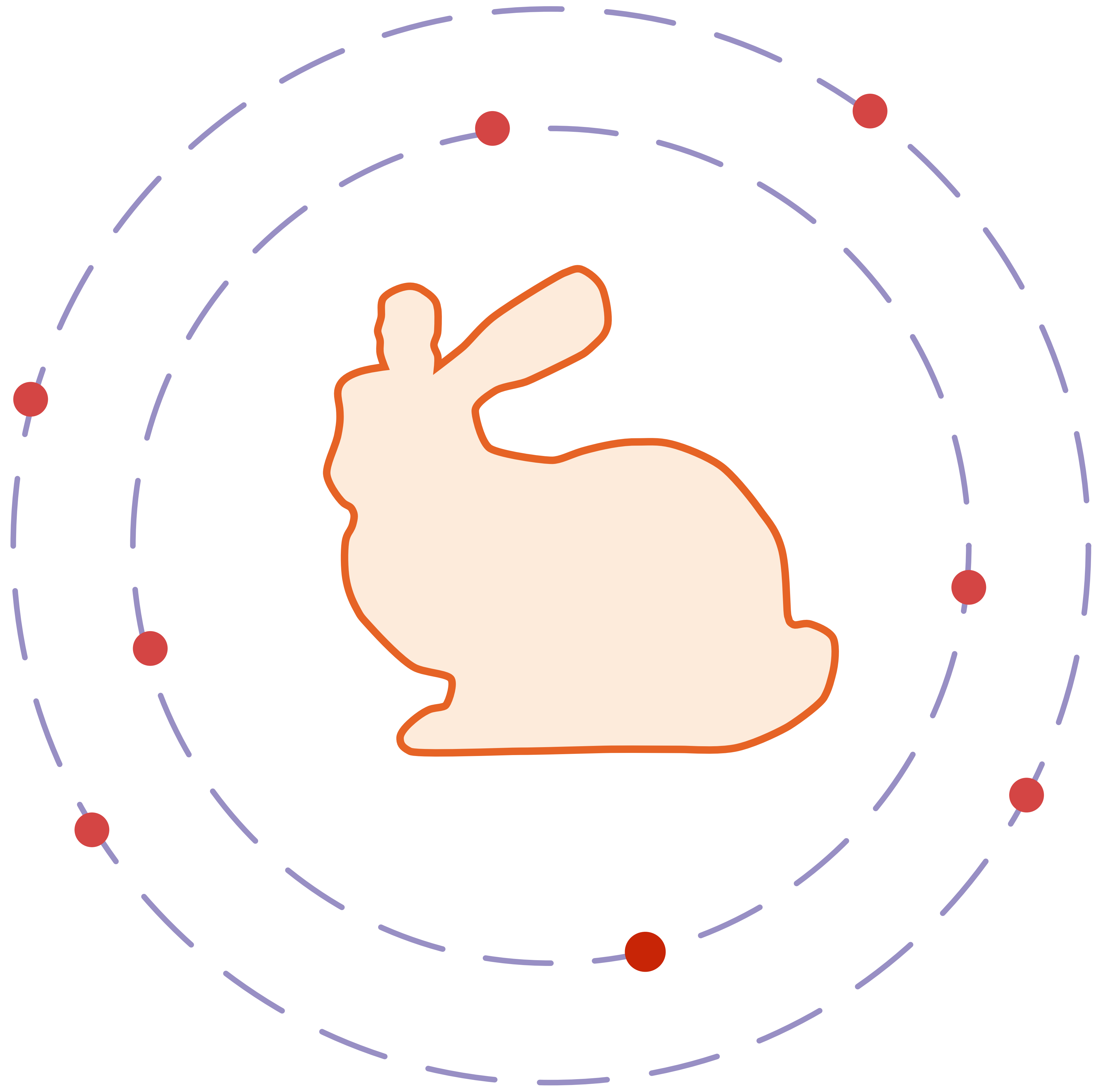

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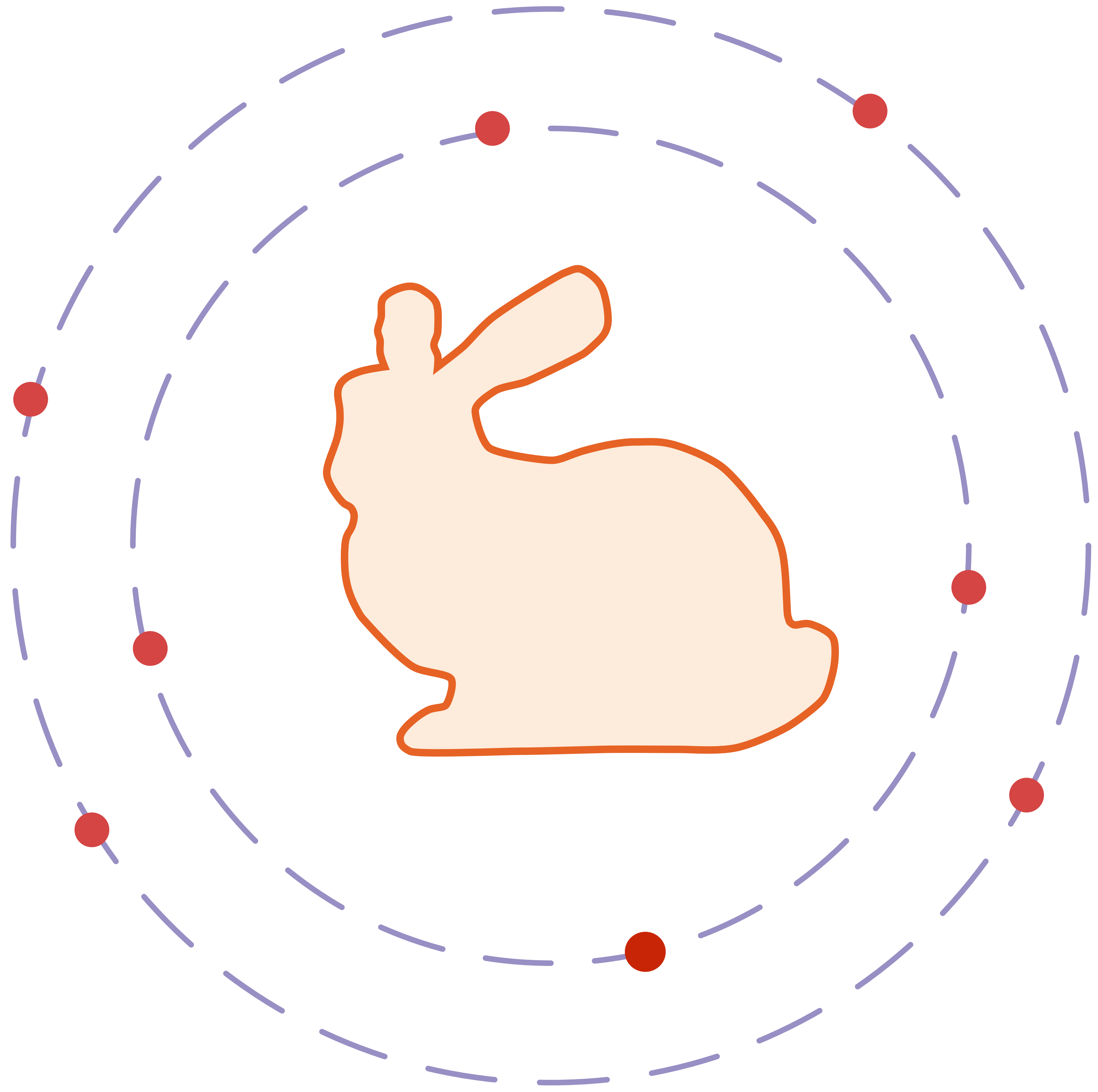

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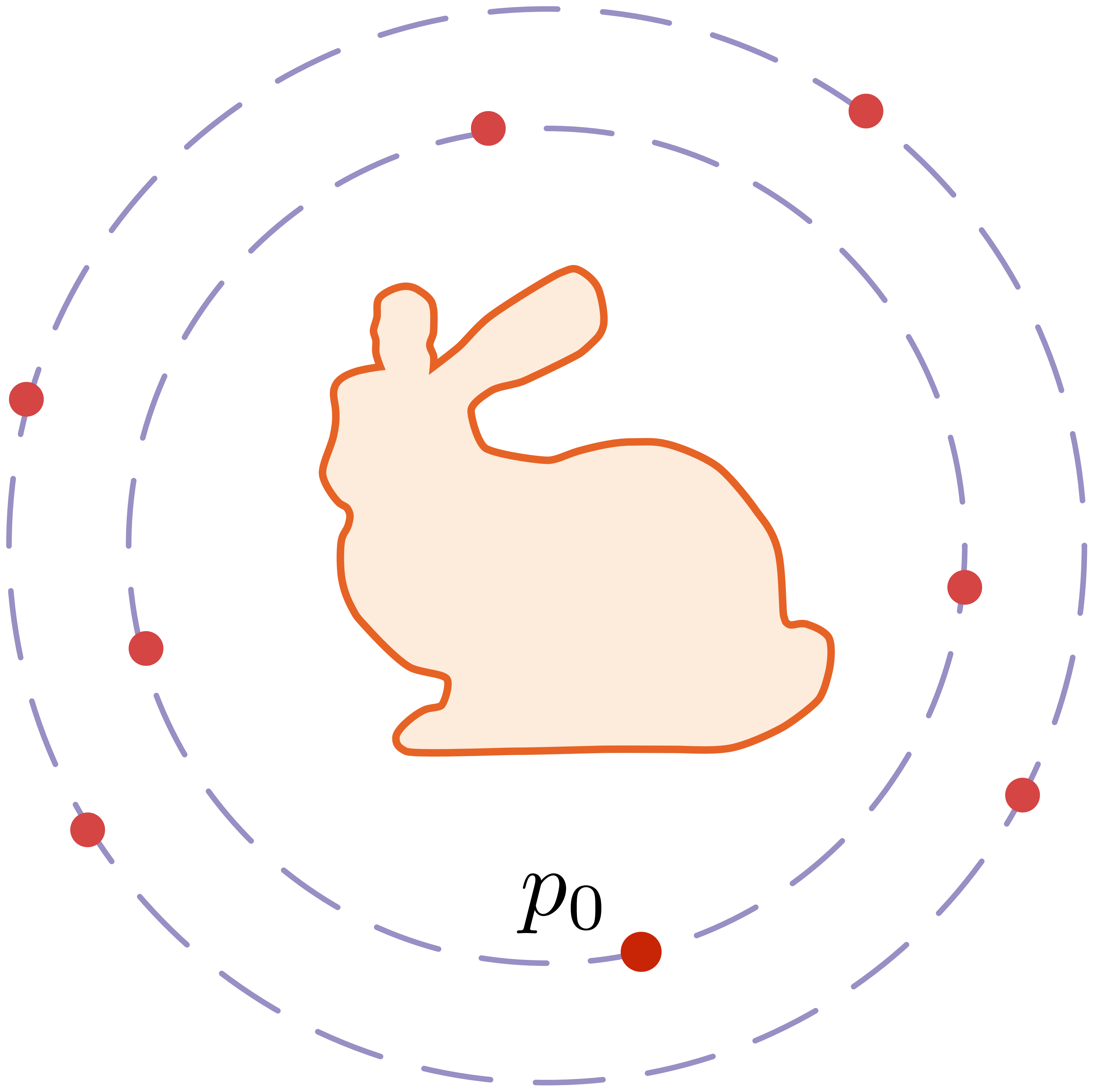

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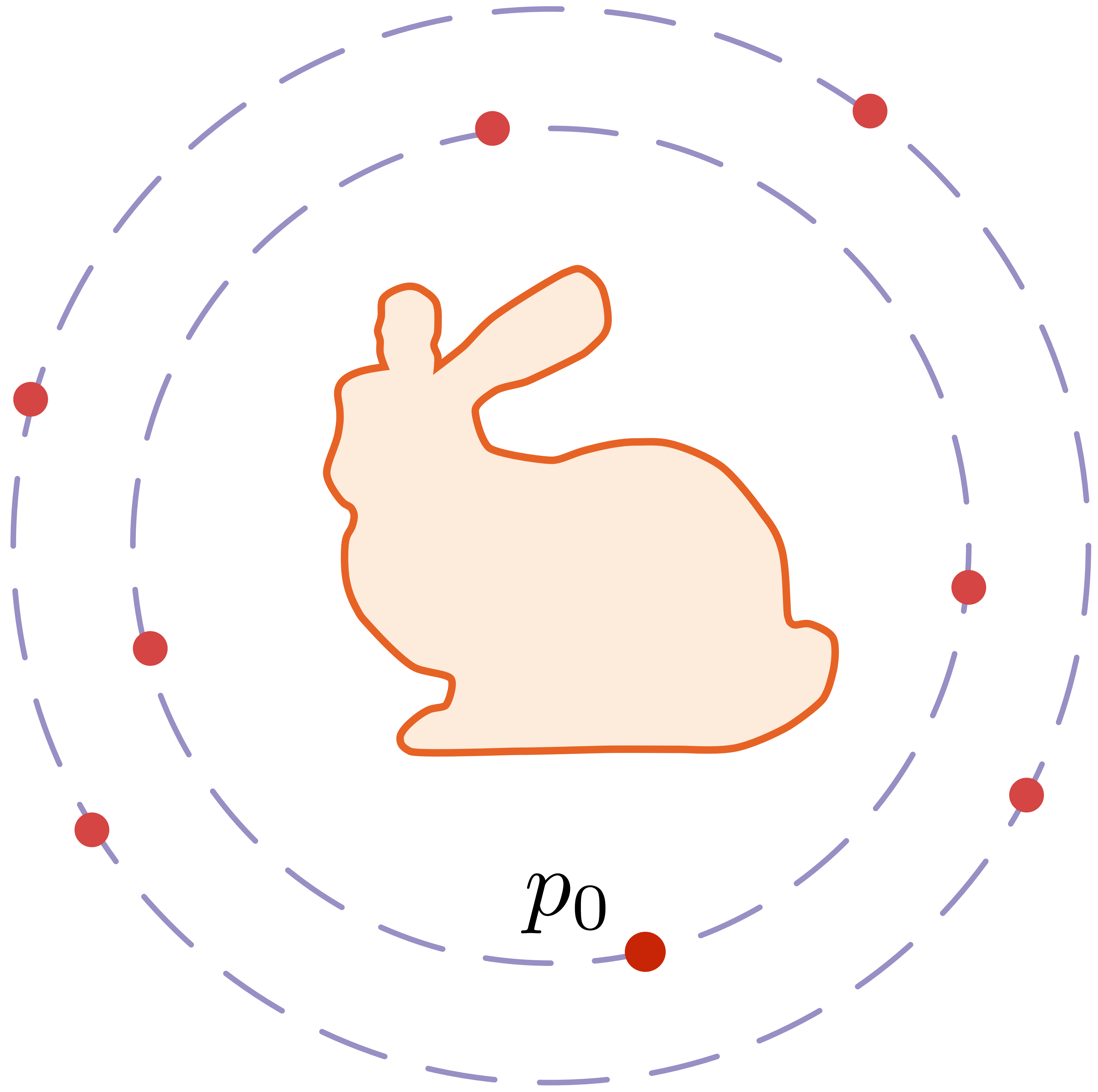

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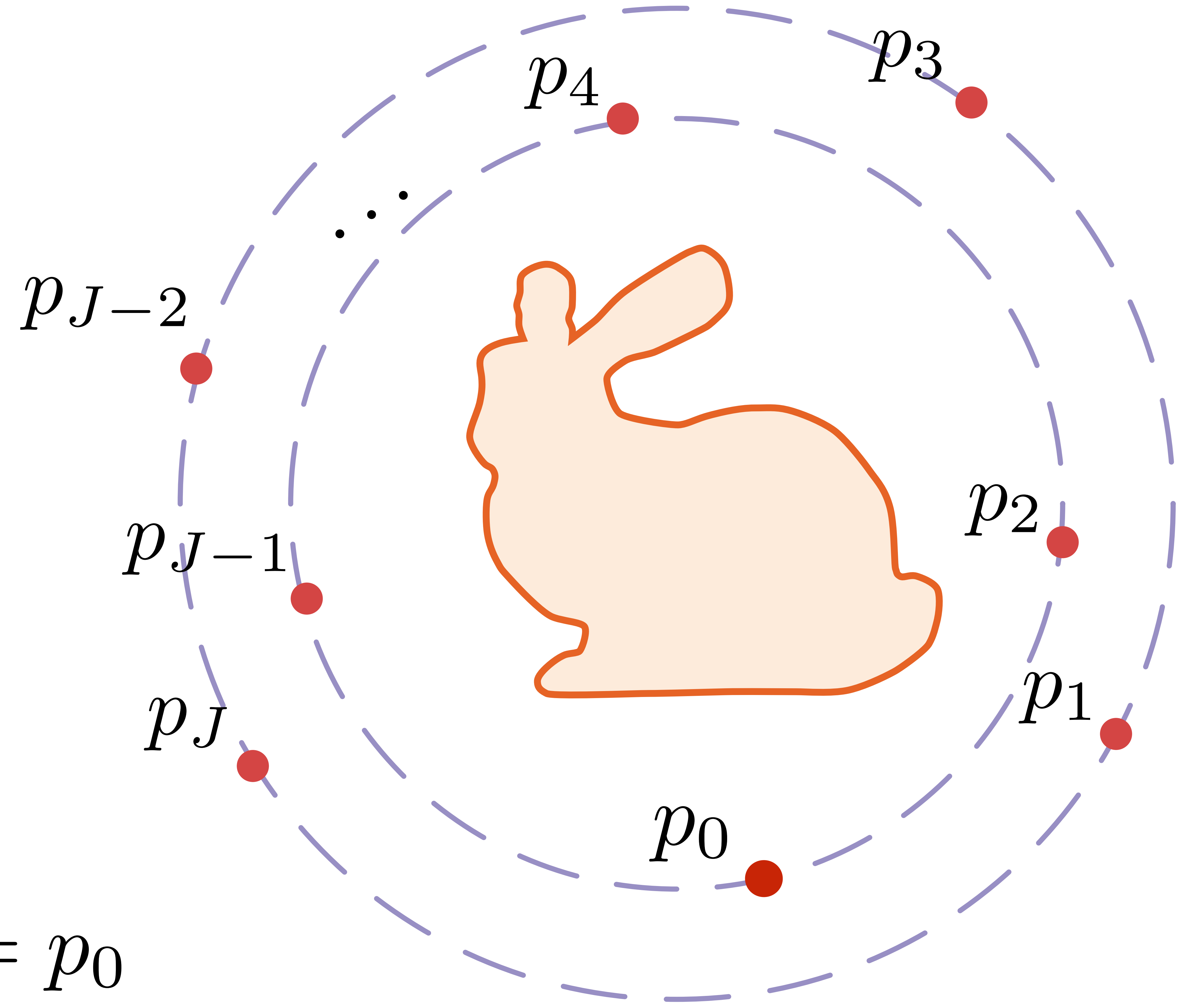

Least Squares Solve for Moments

$$\left[S_0^0(x_1, \bar{x}_0) \quad \ldots \quad S_N^N(x_1, \bar{x}_0)\right] \begin{bmatrix} M_0^0 \\ \vdots \\ M_N^N \end{bmatrix} = p_0$$

Least Squares Solve for Moments

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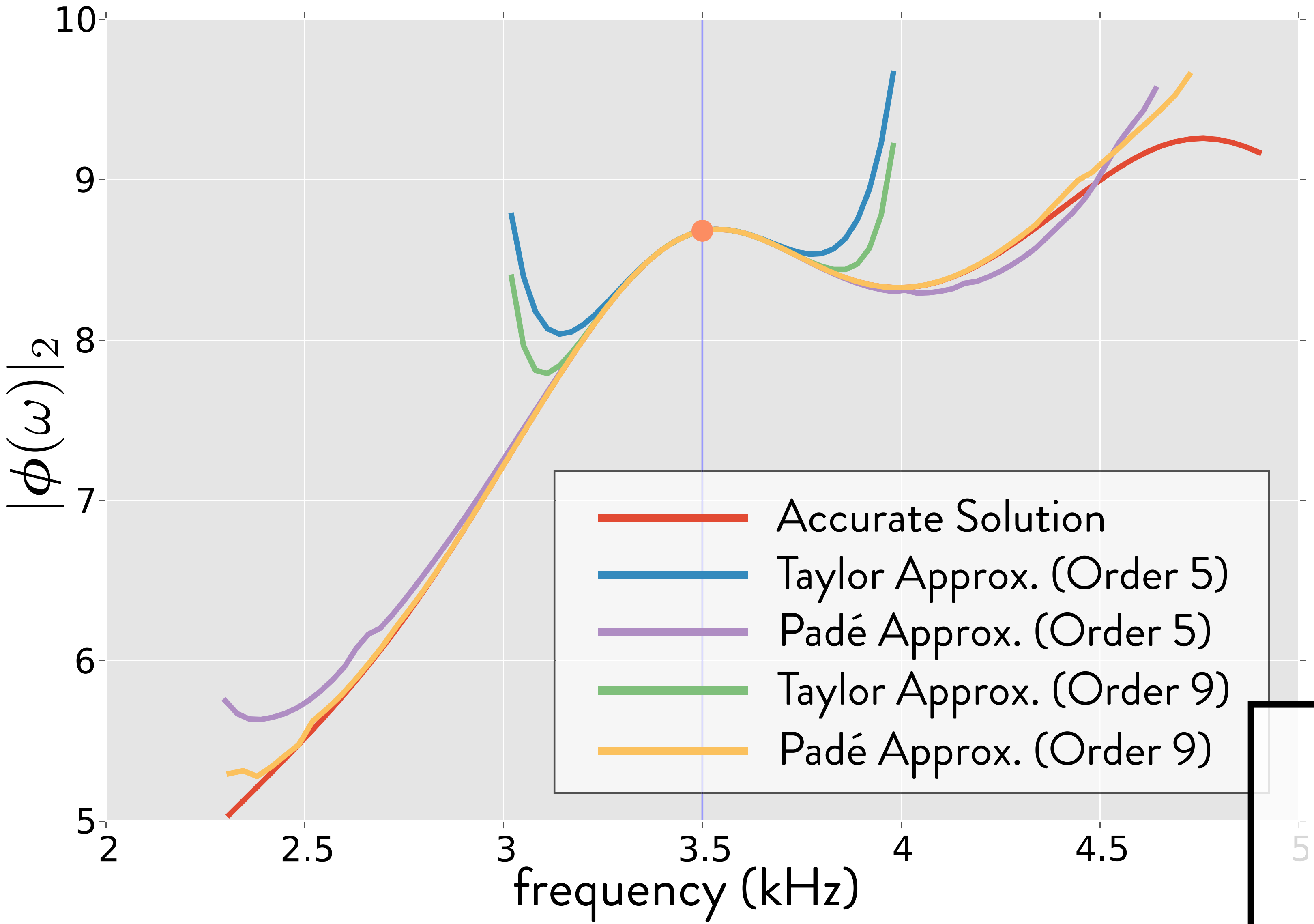
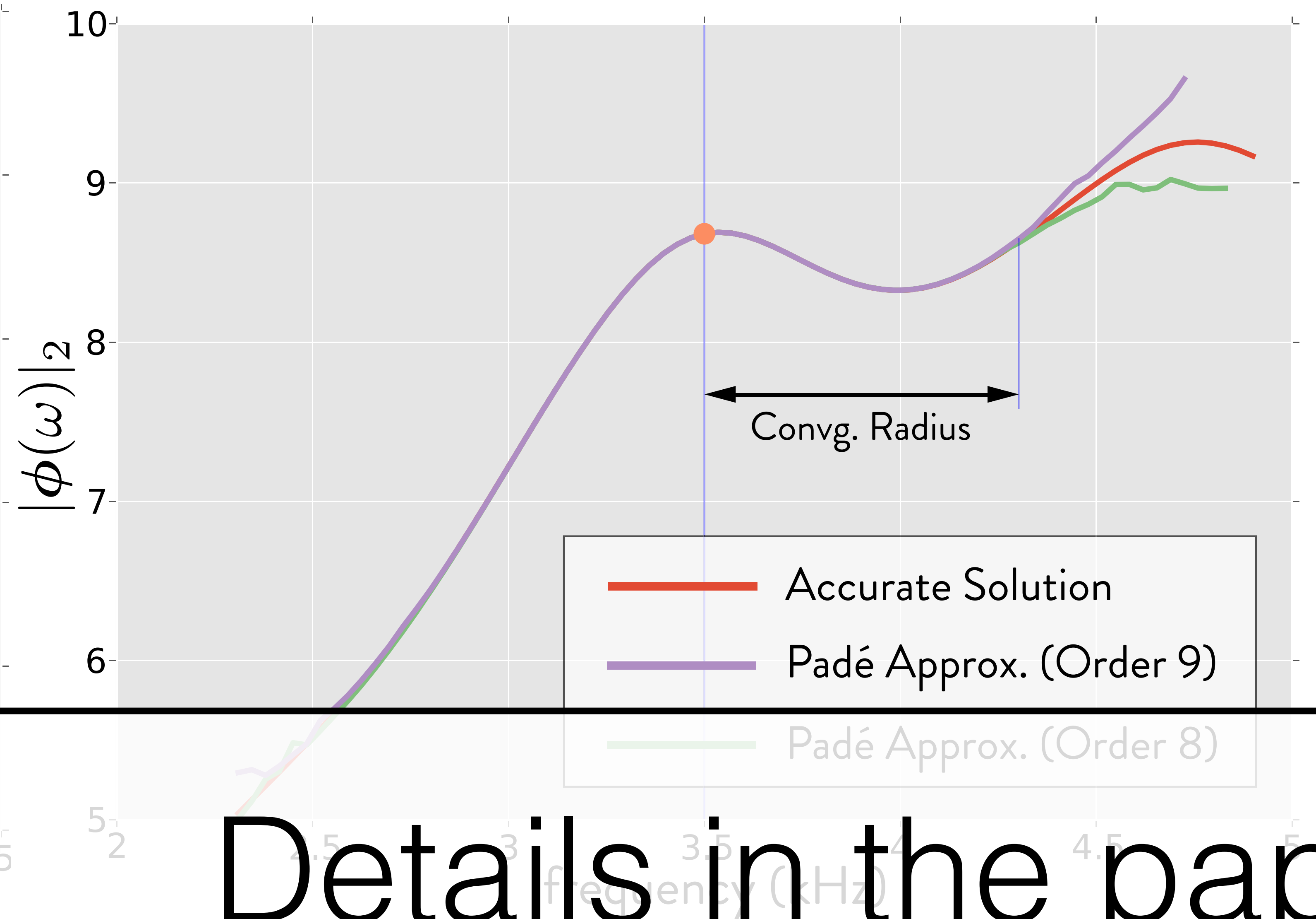
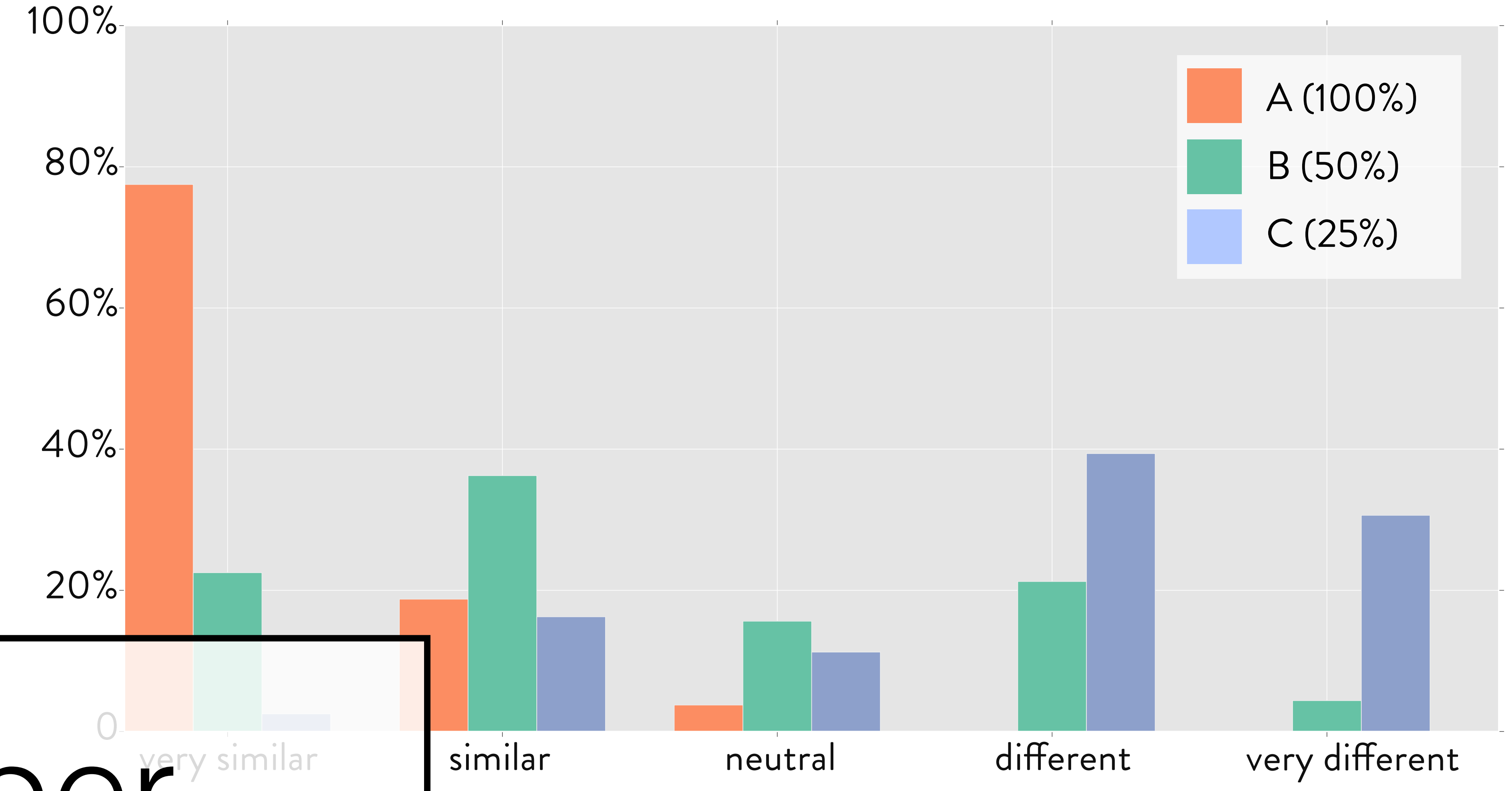
$$\begin{bmatrix} S_0^0(x_1,\bar{x}_0) & \dots & S_N^N(x_1,\bar{x}_0) \\ \vdots & \ddots & \vdots \\ S_0^0(x_J,\bar{x}_0) & \dots & S_N^N(x_J,\bar{x}_0) \end{bmatrix} \begin{bmatrix} M_0^0 \\ \vdots \\ M_N^N \end{bmatrix} = \begin{bmatrix} p_0 \\ \vdots \\ p_J \end{bmatrix}$$

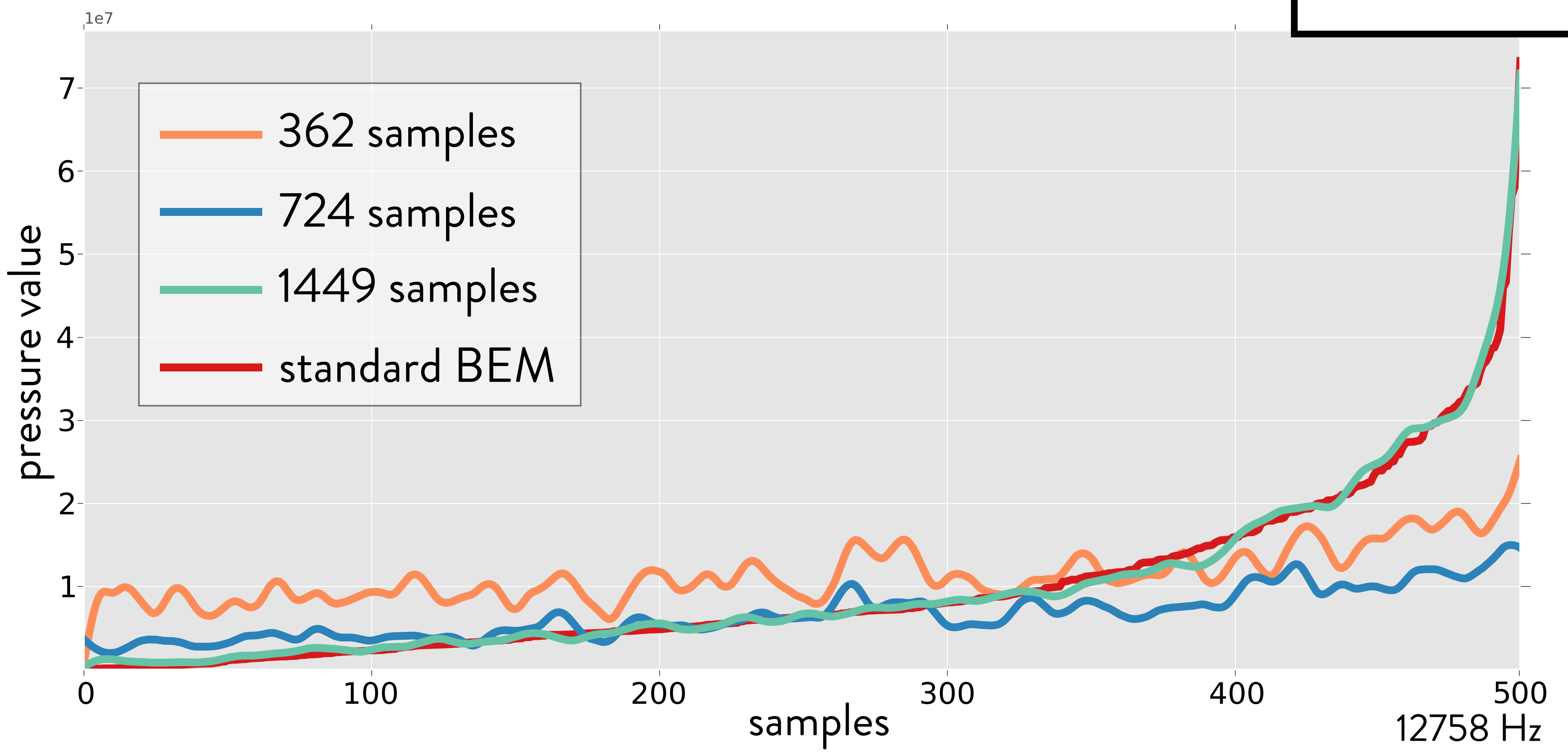
Evaluation

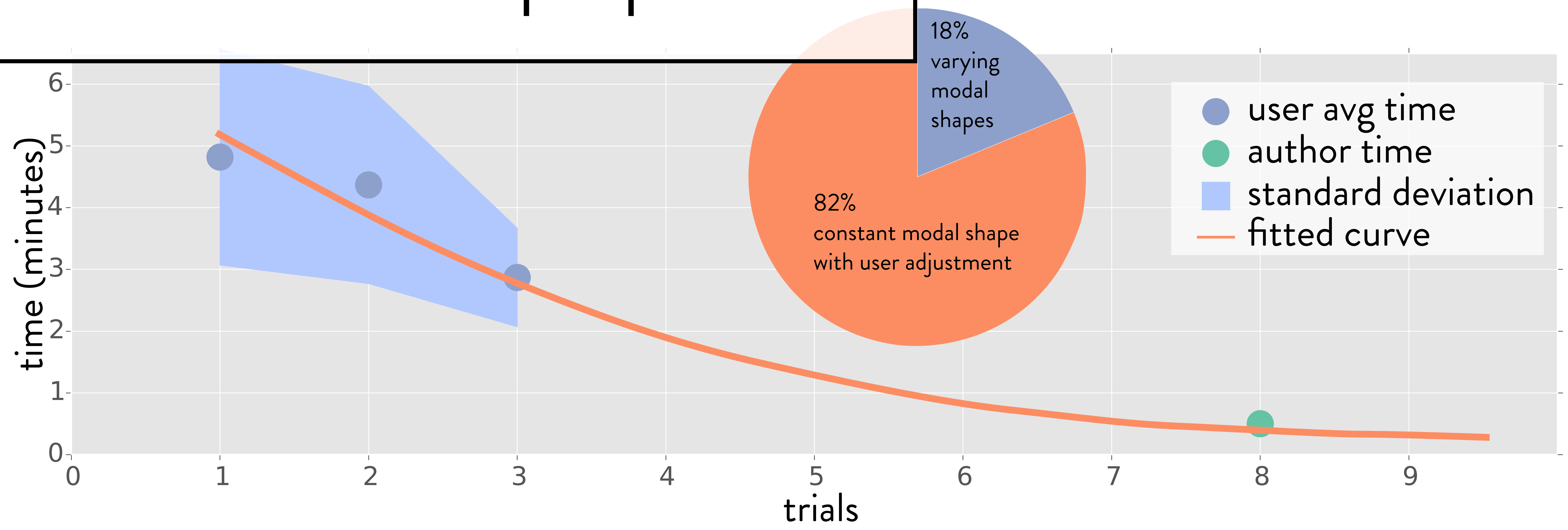






Details in the paper





Timing Statistics

ii) Mesh Simplification					(iii) Adaptive Freq. Sweep			(iv) Runtime Evaluation				
	after (avg.)		simp.	speedup	before	after	speedup	before		after		speedup
e	# tri.	BE Solve	time		# solves	# solves		size	time	size	time	
	5750	4.2m	16.8m	4.2×	4740	253	17.2×	8.1MB	59m	5.1MB	12.9s	274×
	7255	6.1m	14.7m	5.5×	4492	379	11.3×	8.7MB	96m	5.4MB	13.6s	424×
	4297	4.6m	10.2m	10.1×	3360	198	14.5×	7.7MB	132m	4.8MB	22.2s	356×
	4139	4.1m	30.6m	4.9×	13396	1068	10.4×	30.2MB	237m	22.1MB	28.9s	492×
	3123	3.8m	6.5m	3.7×	5075	267	17.6×	9.2MB	96m	6.0MB	24.8s	232×
	5425	5.8m	21.2m	2.9×	3626	221	13.2×	6.7MB	38m	4.2MB	11.6s	197×
	7841	5.6m	28.4m	4.9×	12623	715	17.1×	62.4MB	258m	26.1MB	12.2s	1270×
	6406	5.1m	40.3m	7.8×	14131	624	22.2×	61.2MB	312m	25.7MB	23.8s	785×
	5364	4.7m	36.6m	4.4×	9246	436	20.5×	42.7MB	186m	19.9MB	19.4s	575×

Timing Statistics

(ii) Mesh Simplification					(iii) Adaptive Freq. Sweep			(iv) Runtime Evaluation				
	after (avg.)		simp.		before	after		before		after		
e	# tri.	BE Solve	time	speedup	# solves	# solves	speedup	size	time	size	time	speedup
[illegible]	5750	[illegible]	[illegible]	[illegible]	[illegible]	253	17.2×	8.1MB	59m	5.1MB	12.9s	274×
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	379	11.3×	8.7MB	96m	5.4MB	13.6s	424×
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	14.5×	7.7MB	132m	4.8MB	22.2s	356×
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	30.2MB	237m	22.1MB	28.9s	492×
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	267	17.6×	9.2MB	96m	6.0MB	24.8s	232×
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	6.7MB	38m	4.2MB	11.6s	197×
[illegible]	7841	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	17.1×	62.4MB	258m	26.1MB	12.2s	1270×
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	22.2×	61.2MB	312m	25.7MB	23.8s	785×
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	9246	436	20.5×	42.7MB	186m	19.9MB	19.4s	575×

100X SPEEDUP

Fast Helmholtz Precomputation

Timing Statistics

(ii) Mesh Simplification | (iii) Adaptive Freq. Sweep | (iv) Runtime Evaluation

100X SPEEDUP

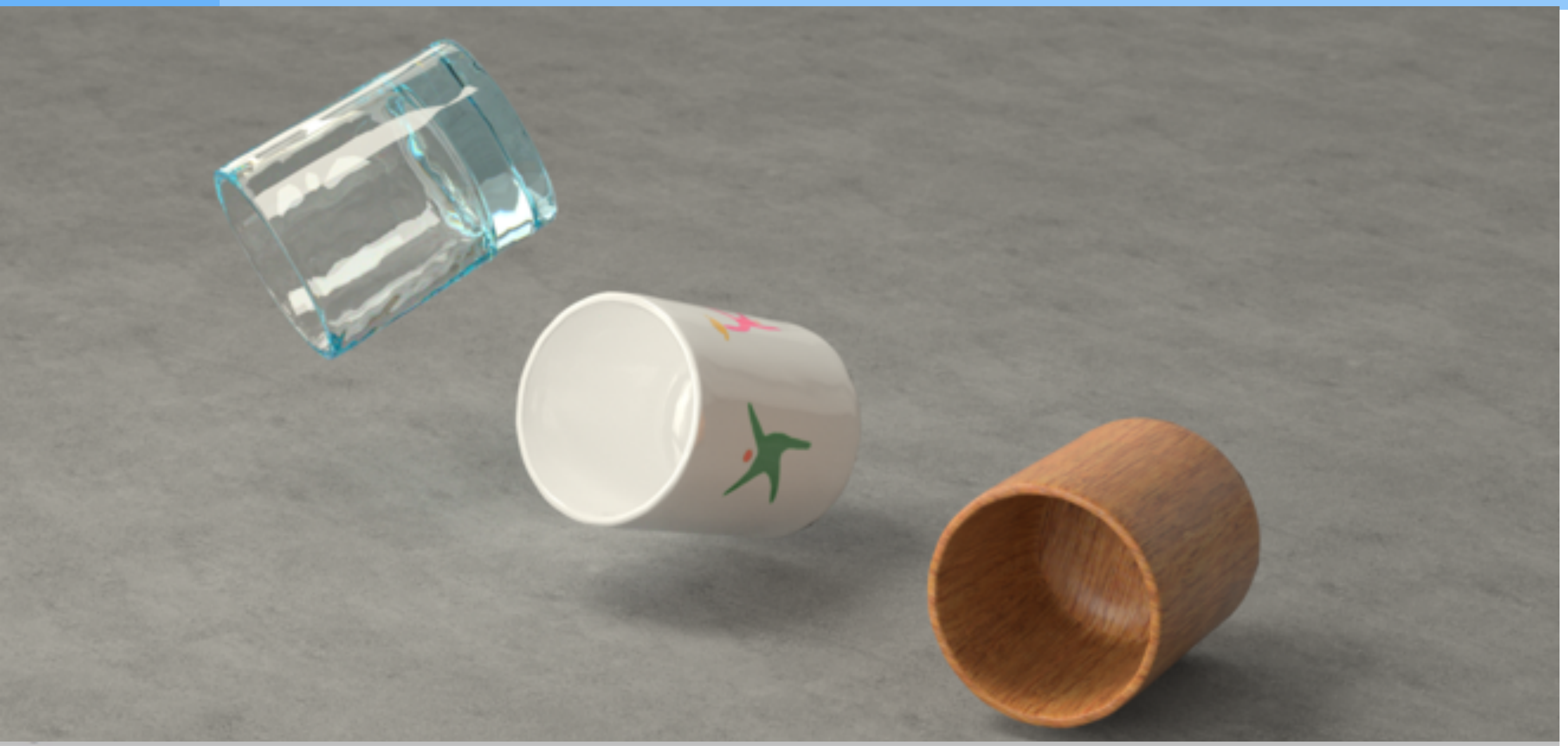
Fast Helmholtz Precomputation

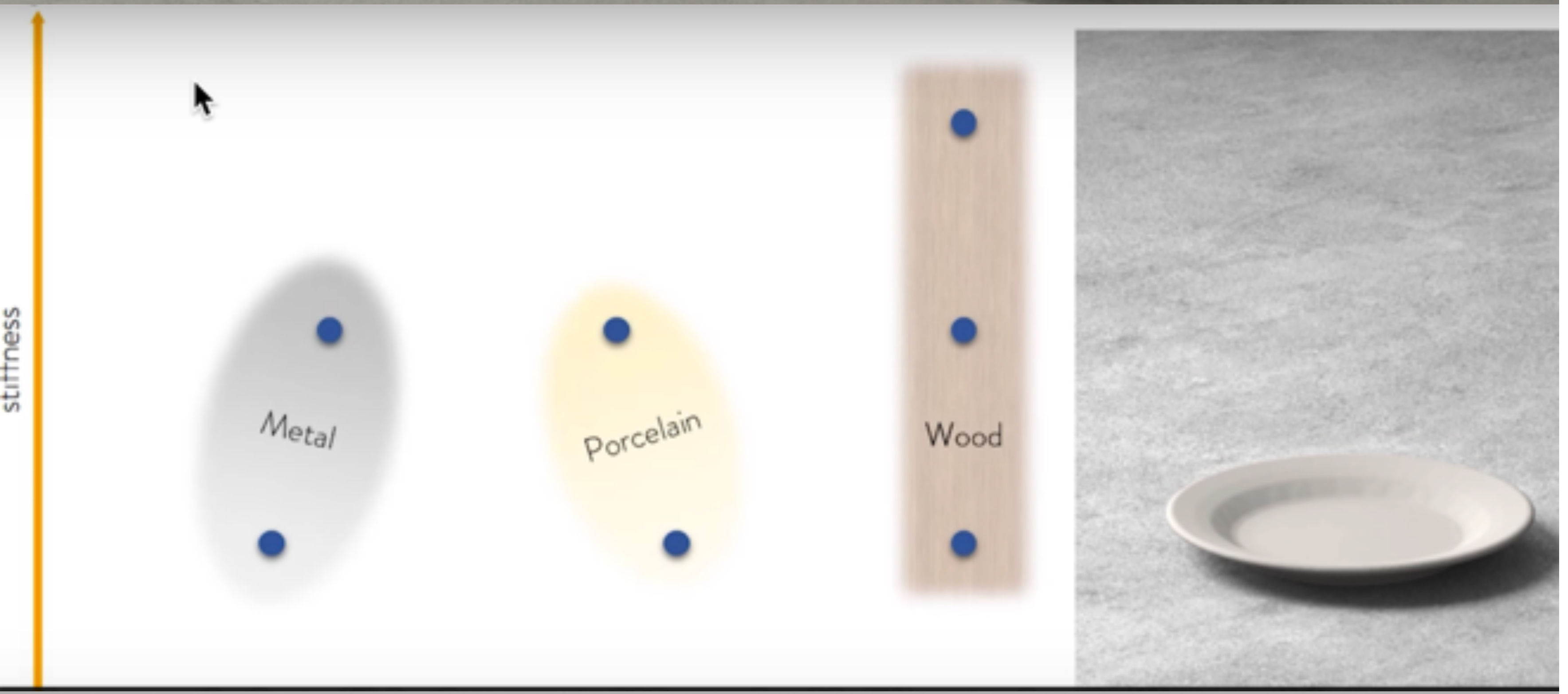
200X SPEEDUP

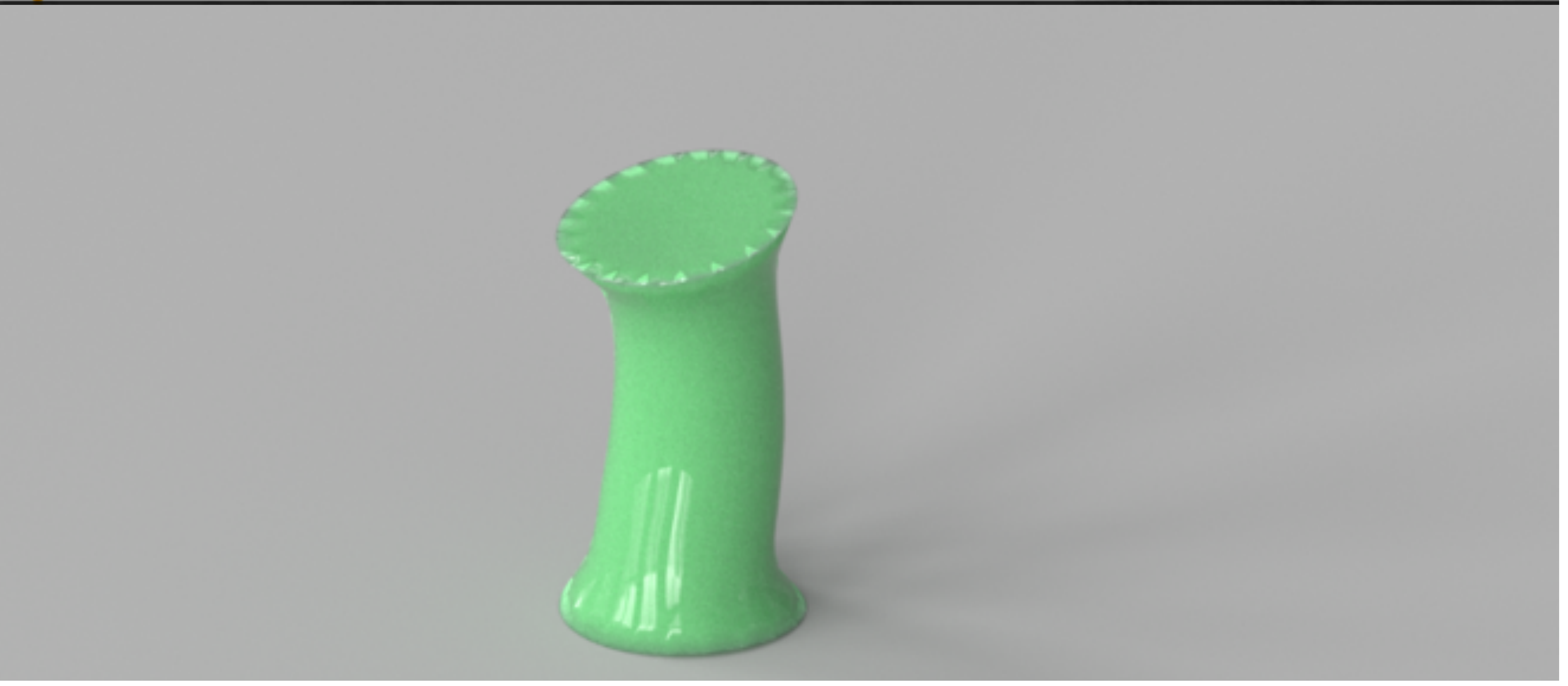
Interactive Runtime Solve

Results

Results







Fast Parameter Editing

Parameter Space Exploration

Time-varying Frequency Effects

Fast Parameter Editing

Mug

porcelain

glass

wood

Fast Parameter Editing

Mug

porcelain

glass

wood

Fast Parameter Editing

PLATE

porcelain

wood

metal

Fast Parameter Editing

Plate

porcelain

wood

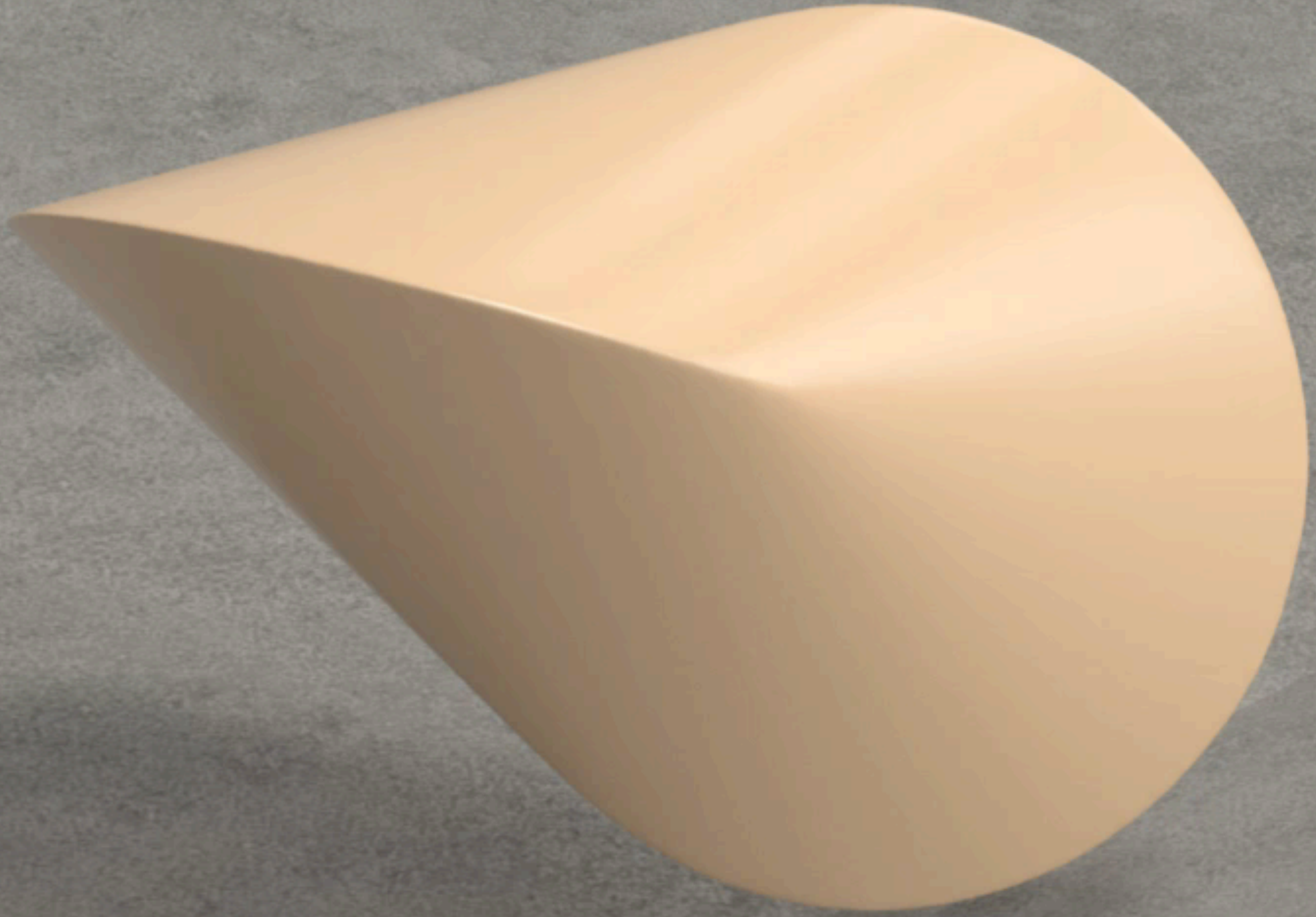
metal

Fast Parameter Editing

OLOID

ivory

metal

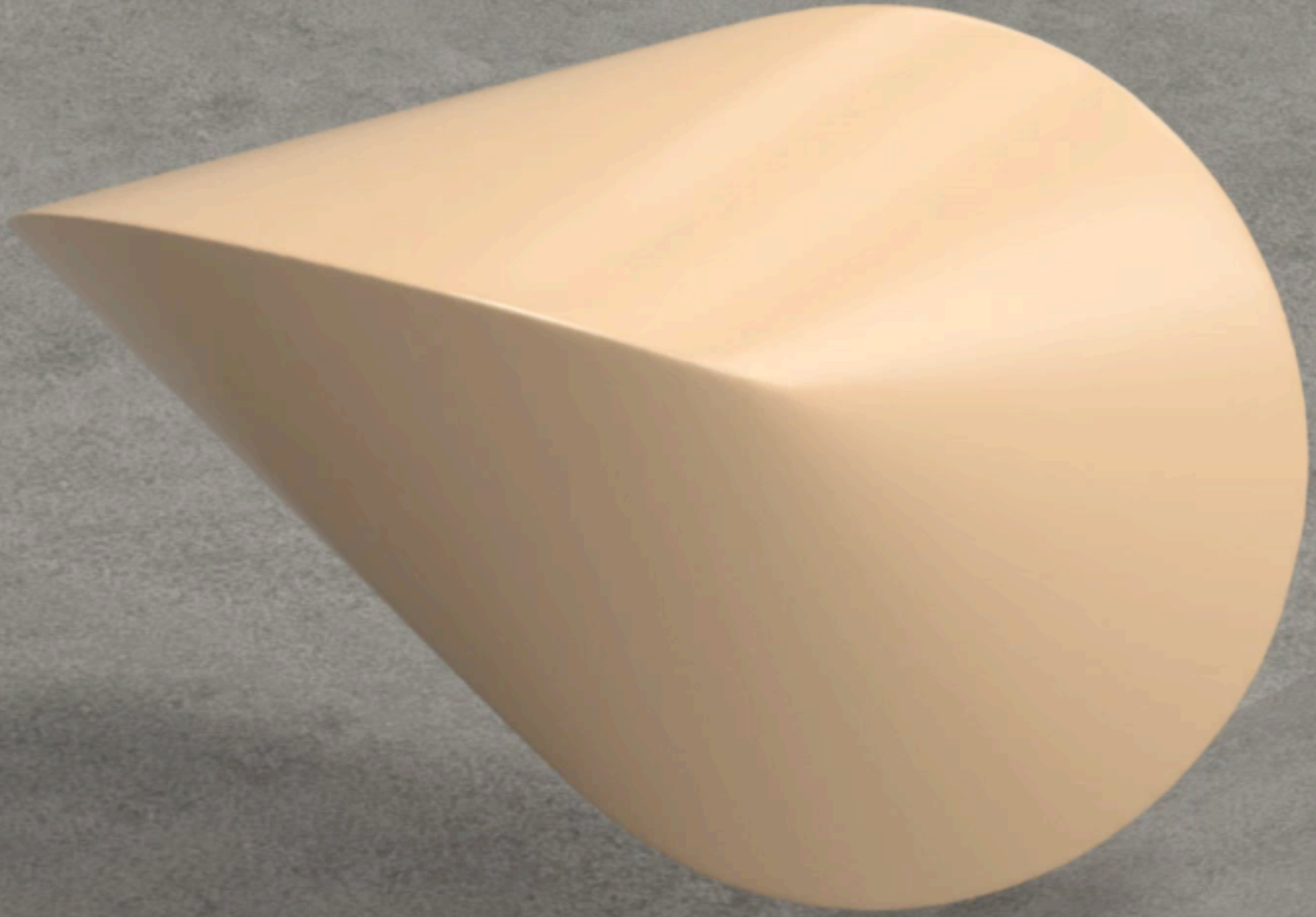


Fast Parameter Editing

Oloid

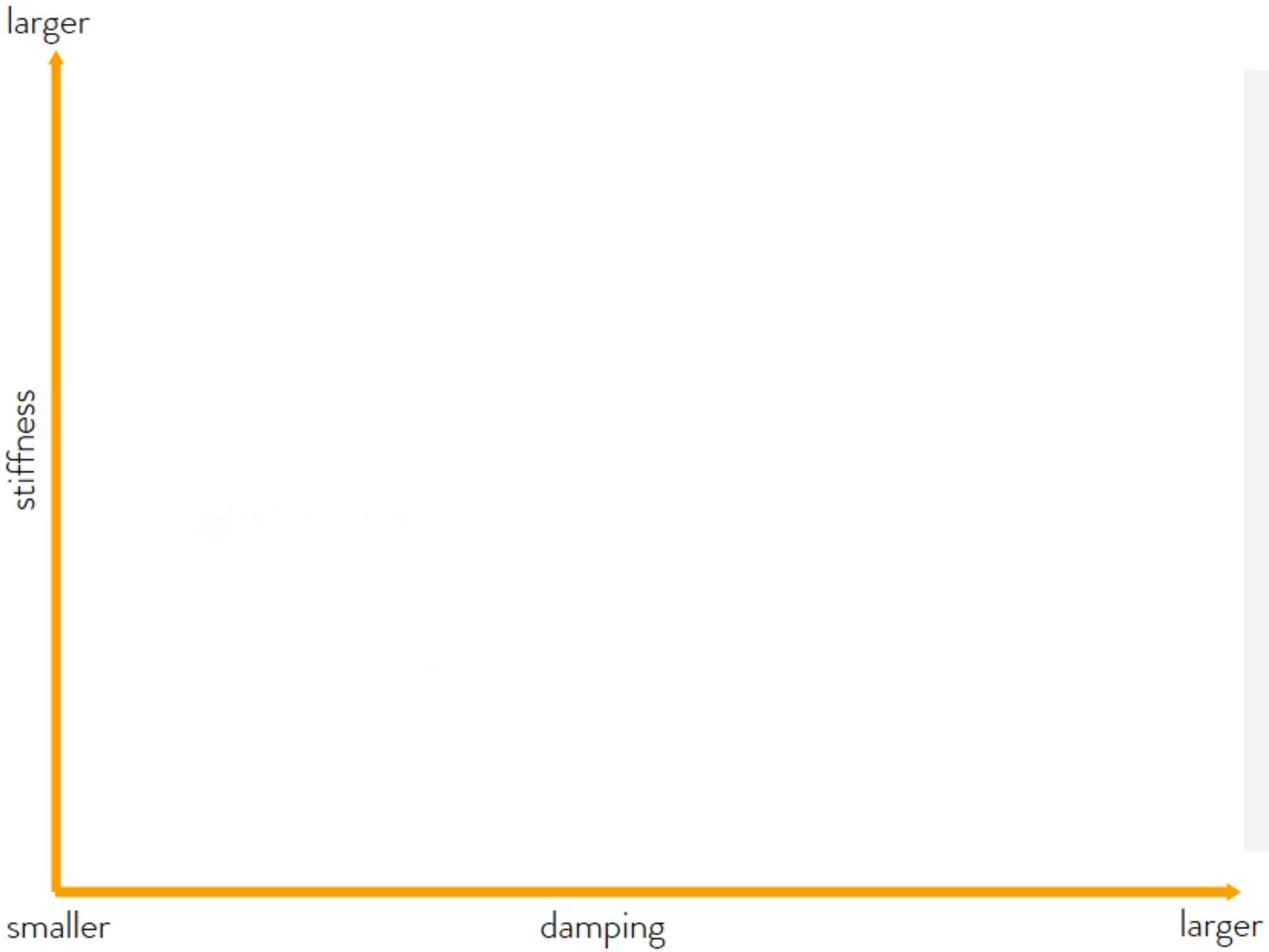
ivory

metal



Parameter Space Exploration

Parameter Space Exploration

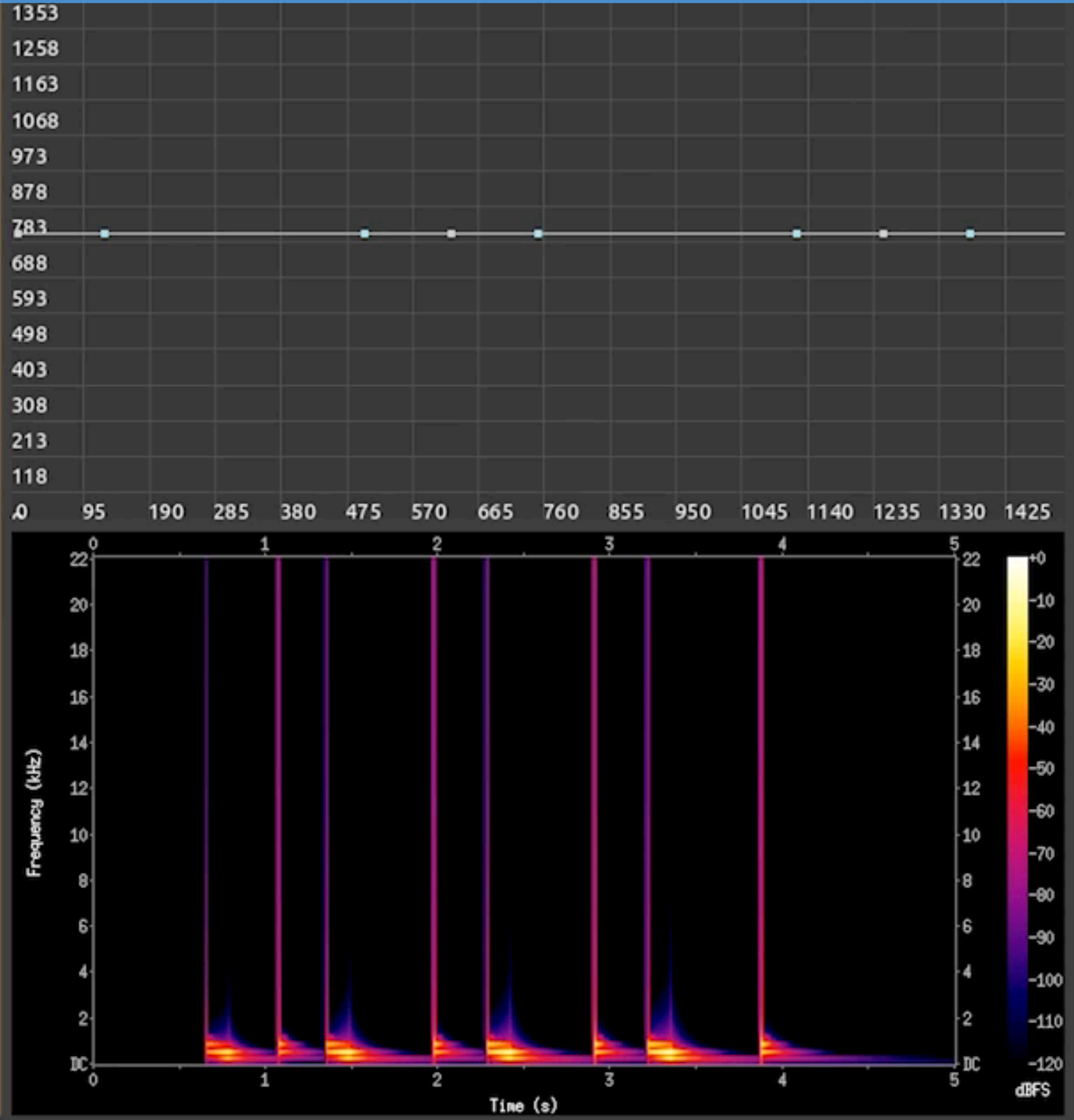


Time-Varying Frequency Effects

Time-Varying Frequency Effects

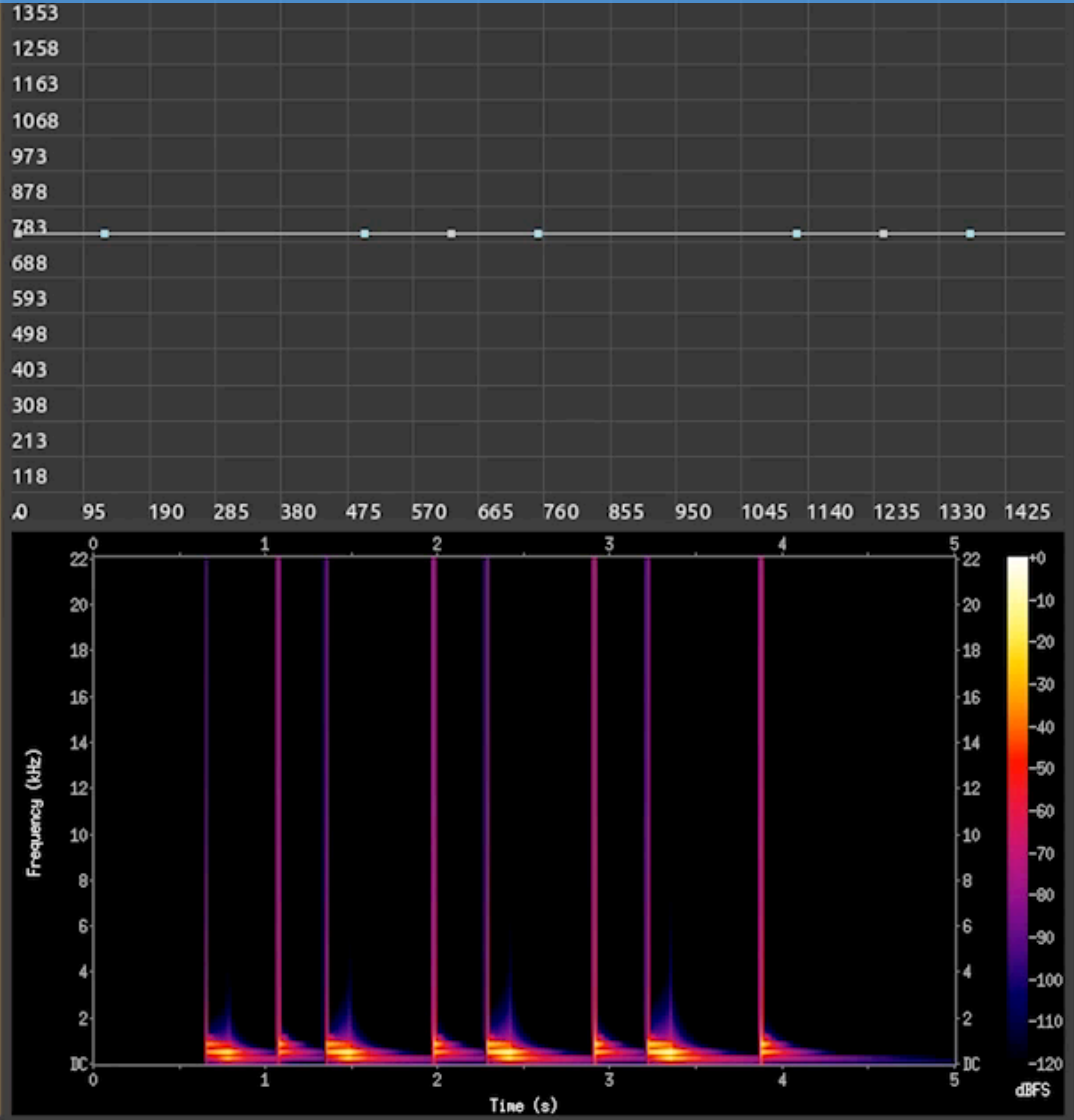
Time-Varying Frequency Effects

animation courtesy of [Tan et al. 2012]



Time-Varying Frequency Effects

animation courtesy of [Tan et al. 2012]



Conclusion

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A Numerical Method for Interactive Acoustic Transfer Approximation

- modal sound synthesis
- interactive parameter editing
- efficient precomputation

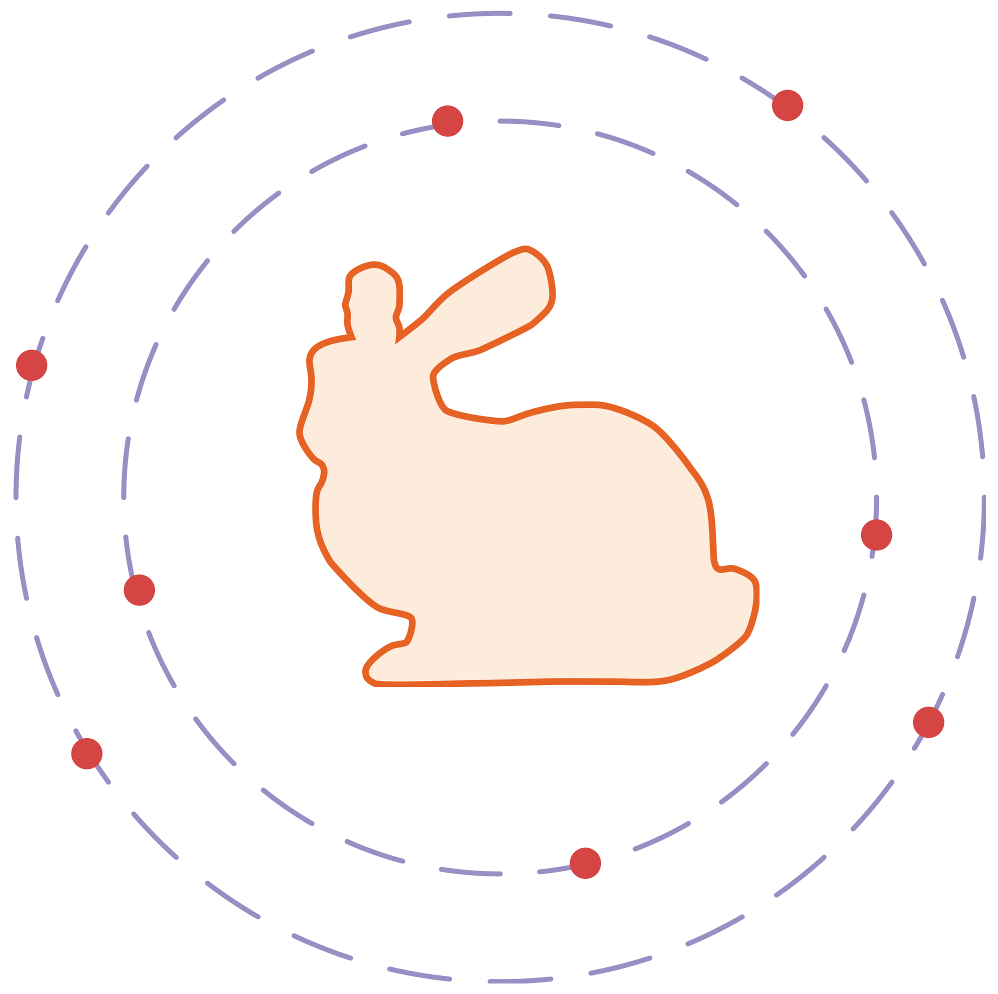
Conclusion

A Numerical Method for Interactive Acoustic Transfer Approximation

modal sound synthesis

interactive parameter editing

efficient precomputation



Future Work

better keypoint selection algorithm

Conclusion

A Numerical Method for Interactive Acoustic Transfer Approximation

- modal sound synthesis
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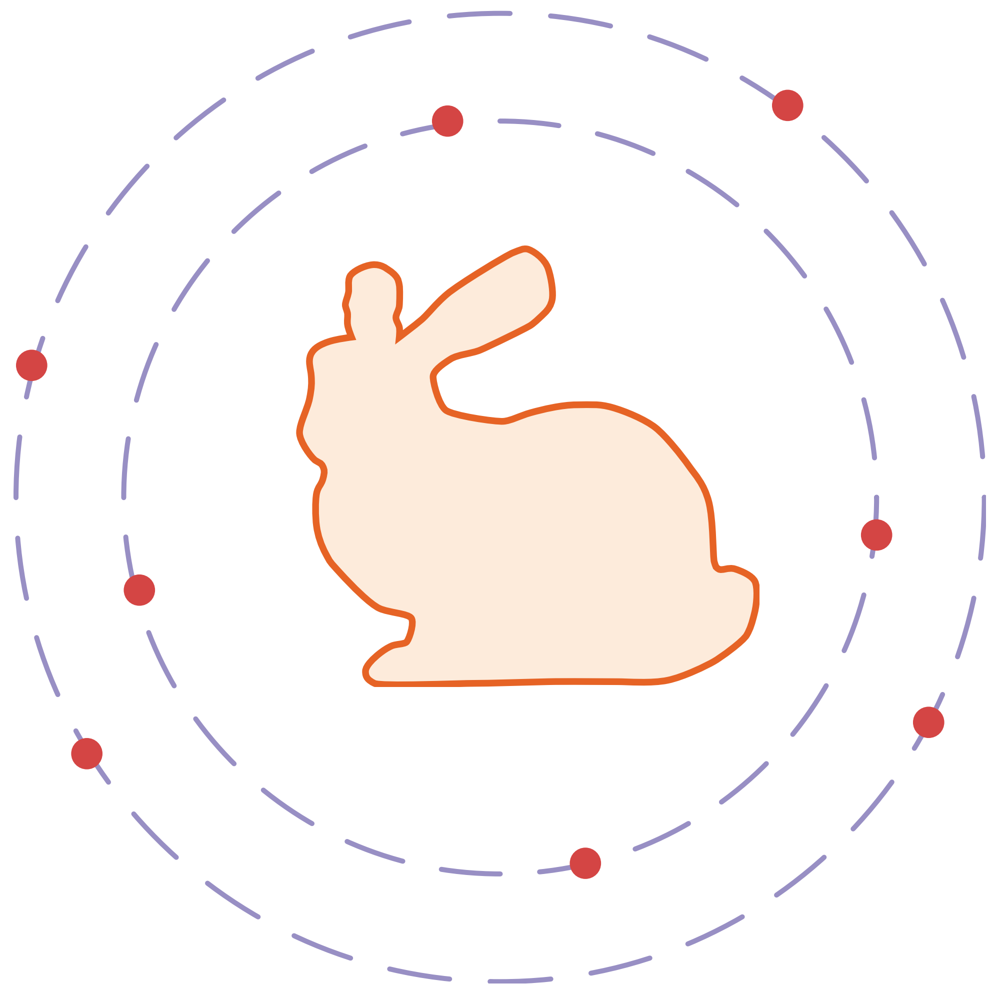
- efficient precomputation



Future Work

- better keypoint selection algorithm
- geometry-independent parameters

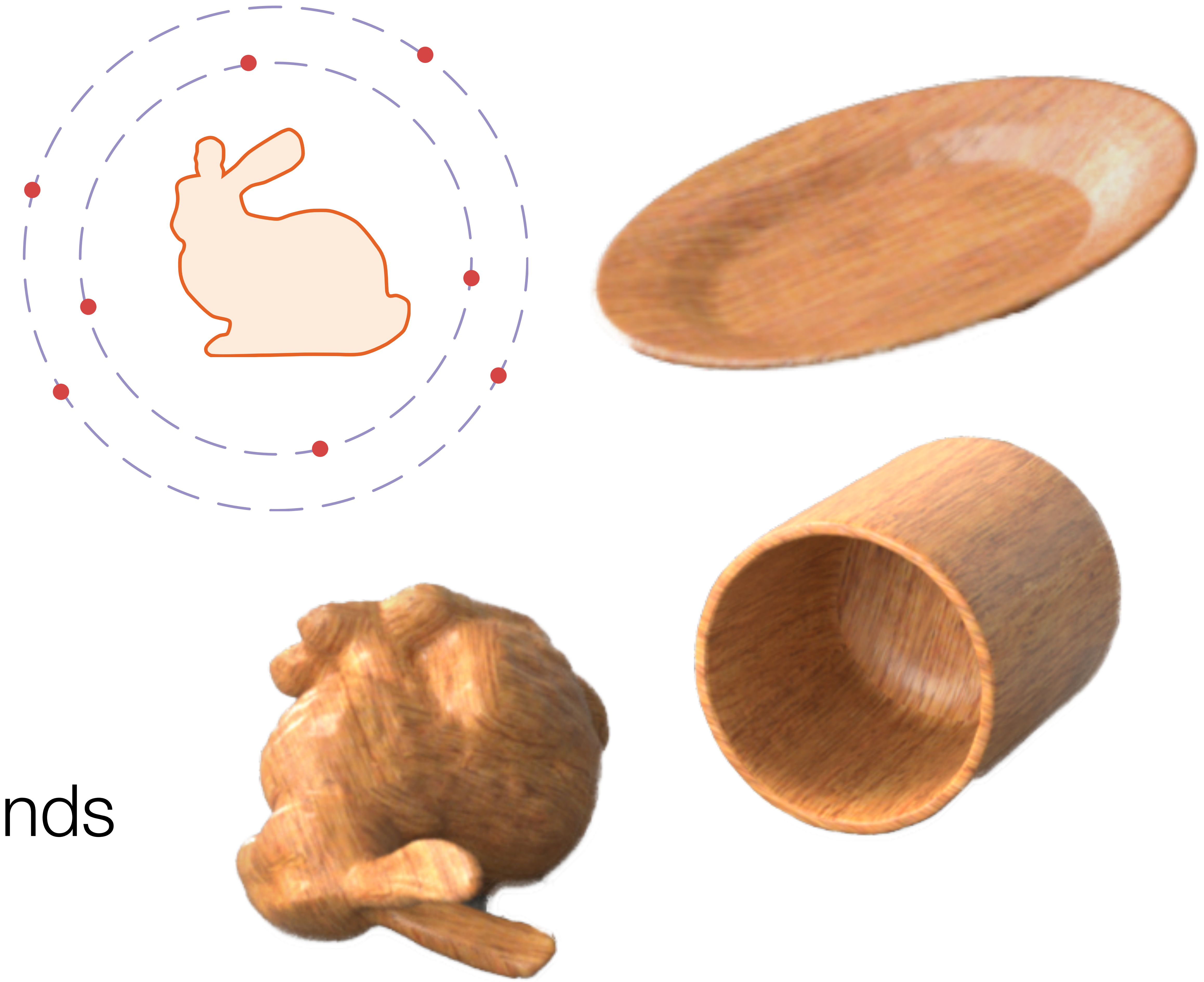
Conclusion

A Numerical Method for Interactive Acoustic Transfer Approximation

modal sound synthesis

interactive parameter editing

efficient precomputation



Future Work

better keypoint selection algorithm

geometry-independent parameters

other applications beyond modal sounds

Acknowledgement

Jeff Chadwick, Jie Tan, Timothy Sun, Breannan Smith, Henrique Maia

National Science Foundation (CAREER-1453101)

Intel

Interactive Acoustic Transfer Approximation for Modal Sound

http://www.cs.columbia.edu/cg/transfer/ (or Google “interactive acoustic transfer”)

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Yun Fei
Changxi Zheng

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