Physically Based Sound for Computer Animation and Virtual Environments

Fire

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“Fire” Reference:

- Jeffrey N. Chadwick and Doug L. James,
  Animating Fire with Sound, *ACM Transactions on Graphics (SIGGRAPH 2011 Conference Proceedings)*, August 2011.

Jeff Chadwick

[Nguyen et al. 2002]

[Hong et al. 2007]

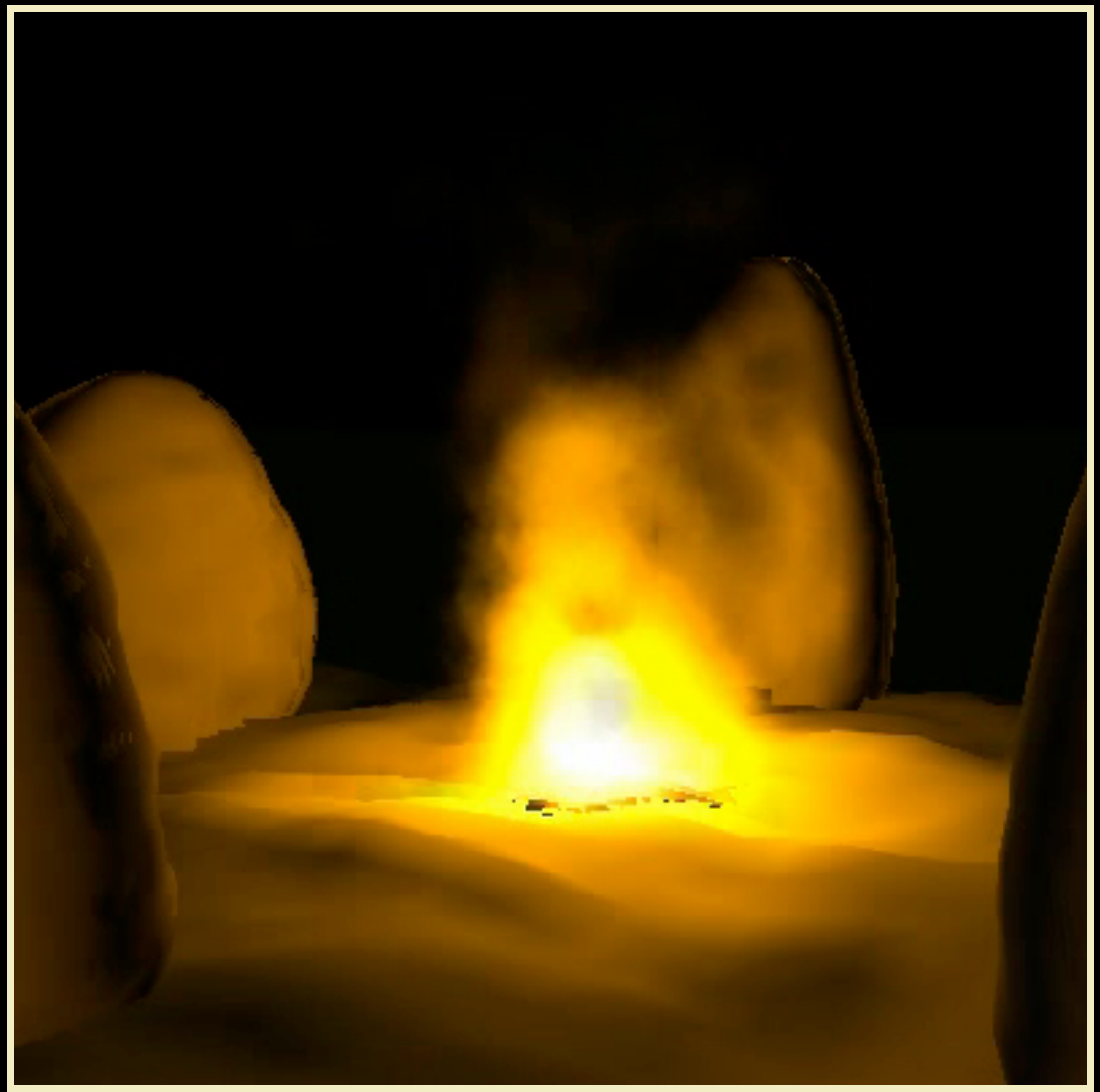
[Feldman et al. 2003]

[Horvath and Geiger 2009]

Sound Synthesis

Aerodynamic Sound

[Dobashi et al. 2003]



[Dobashi et al. 2004]

Preview

Background

- Combustion sound components [Chrighton et al. 1992; Poinsot and Veynante 2005]
  - Aerodynamic noise (eg. [Dobashi et al. 2003])
    - Resulting from turbulent flow
  - “Direct combustion noise”
    - Produced by density fluctuations resulting from heat release
    - Dominant source of combustion sound [Ihme et al. 2009]

Background

Combustion heat release rate

- Combustion sound wave equation

$$\frac{1}{c_0^2}\frac{\partial^2 p}{\partial t^2} - \nabla^2 p = -C\frac{\partial \boxed{q}}{\partial t}$$

- Convert to integral equation

$$p(\mathbf{x}, t) = \frac{C}{4\pi}\frac{\partial}{\partial t}\int_{\mathbb{R}^3}\frac{1}{r}q\left(\mathbf{y}, t - r/c_0\right)d^3\mathbf{y}$$

$$sound \approx \frac{d}{dt}\boxed{\int_{\mathbb{R}^3} q(\mathbf{y}, t)d^3\mathbf{y}}$$

Background

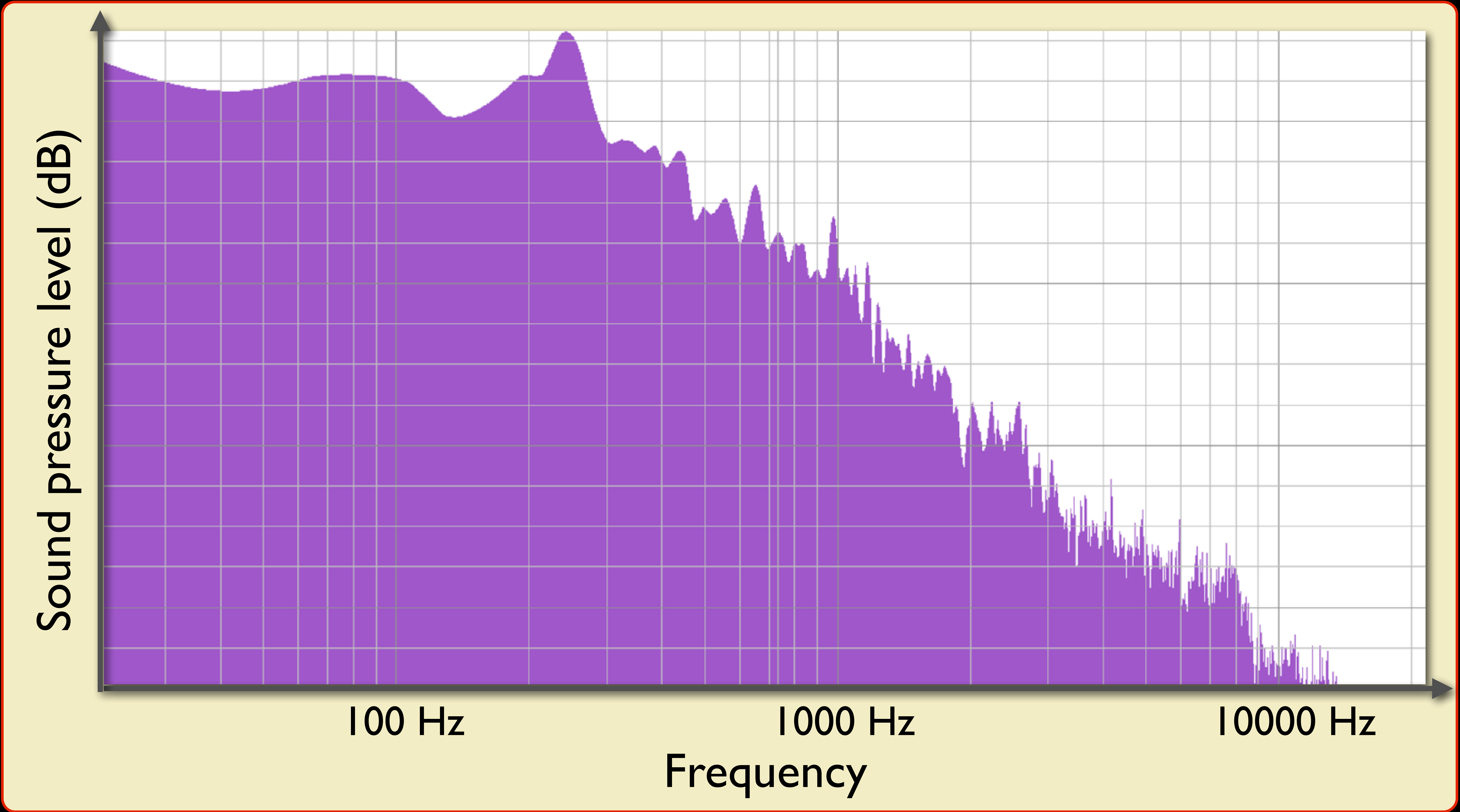
$$sound \approx \frac{d}{dt}\int_{\mathbb{R}^3} q(\mathbf{y},t)d^3\mathbf{y}$$

- **Problem:** Flame solvers from the graphics community do not realistically model heat release
  - Heat release modeled artistically, via simple functions, etc.
  - **Goal:** express heat release in terms of quantities we have access to

Flame Recording

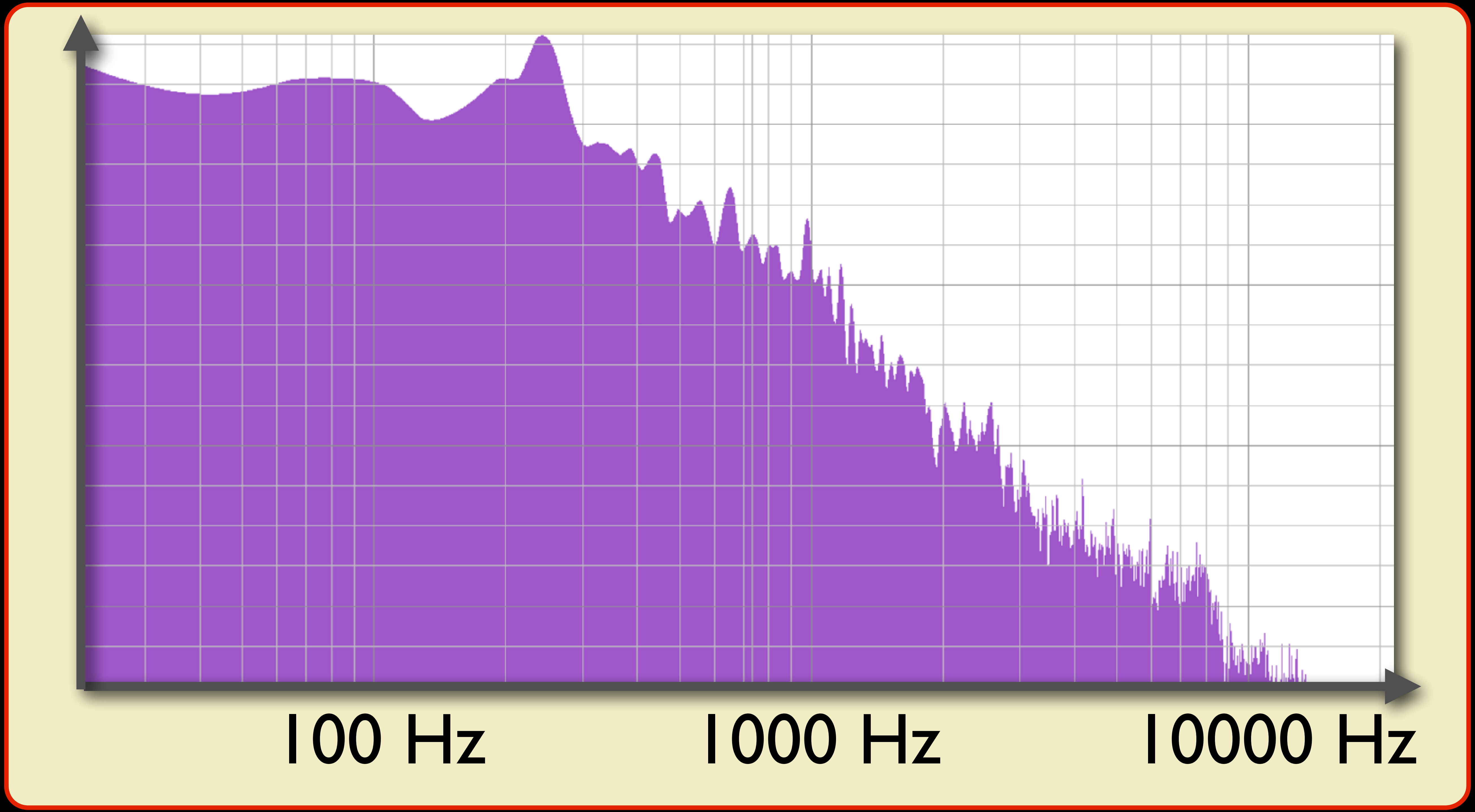
1/10th speed

Flame Recording


Sound pressure level (dB)
100 Hz
1000 Hz
10000 Hz
Frequency

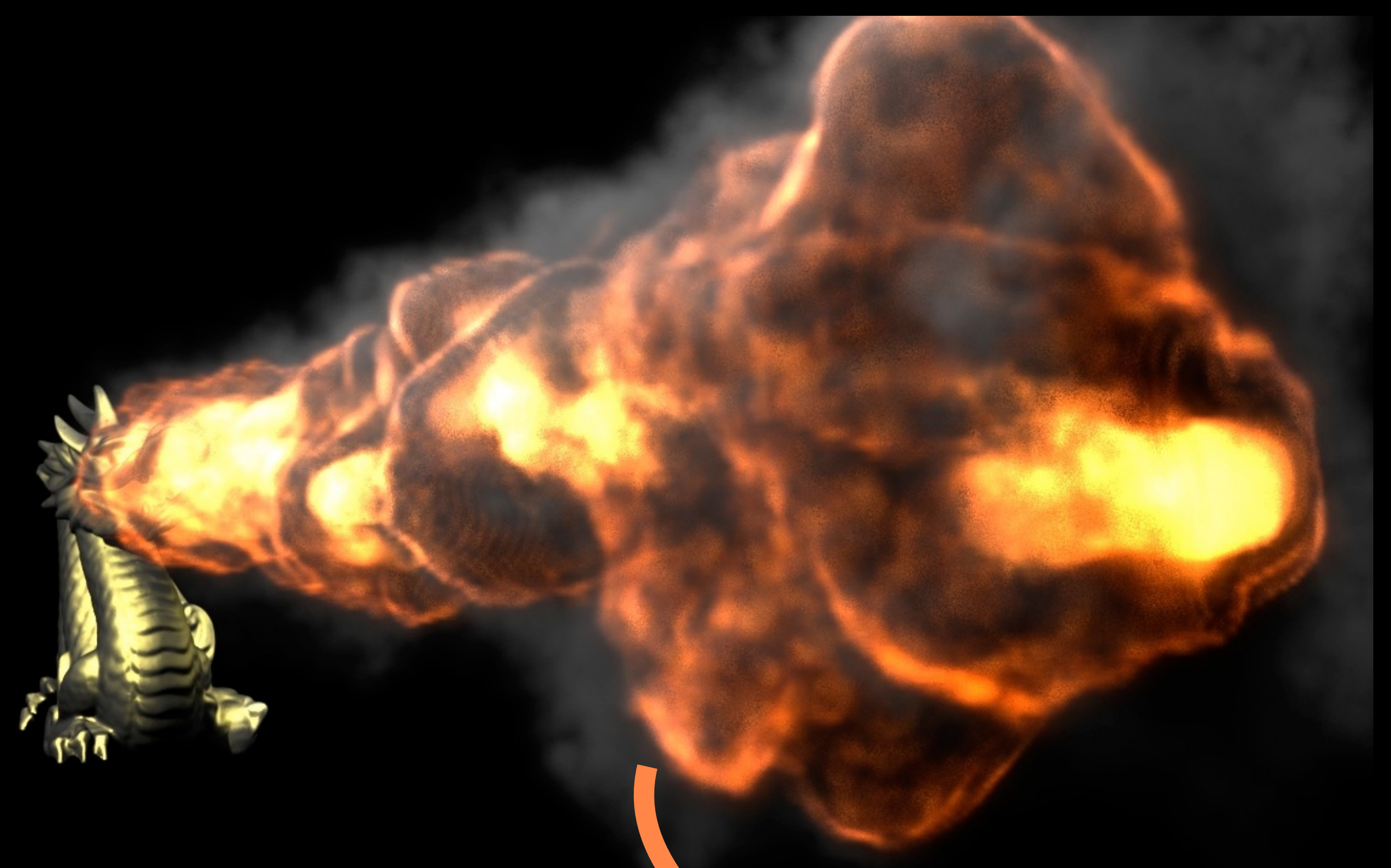
Problem Statement

- Time stepping 3D fluid simulation to resolve all frequency content impractical

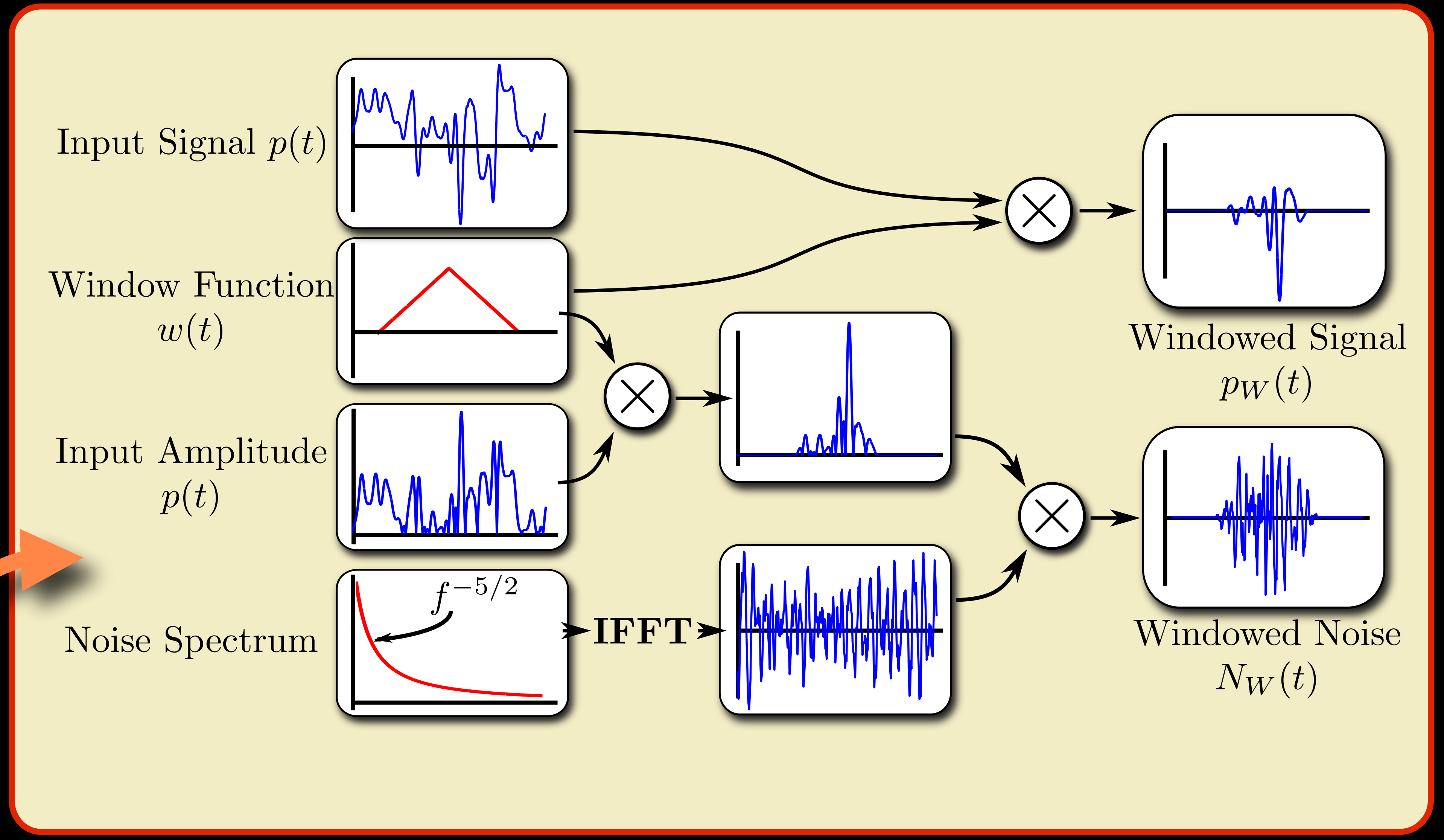


- Flame solvers used in the graphics community do not model complex combustion chemistry
  - Increasing temporal resolution would not be effective

Overview

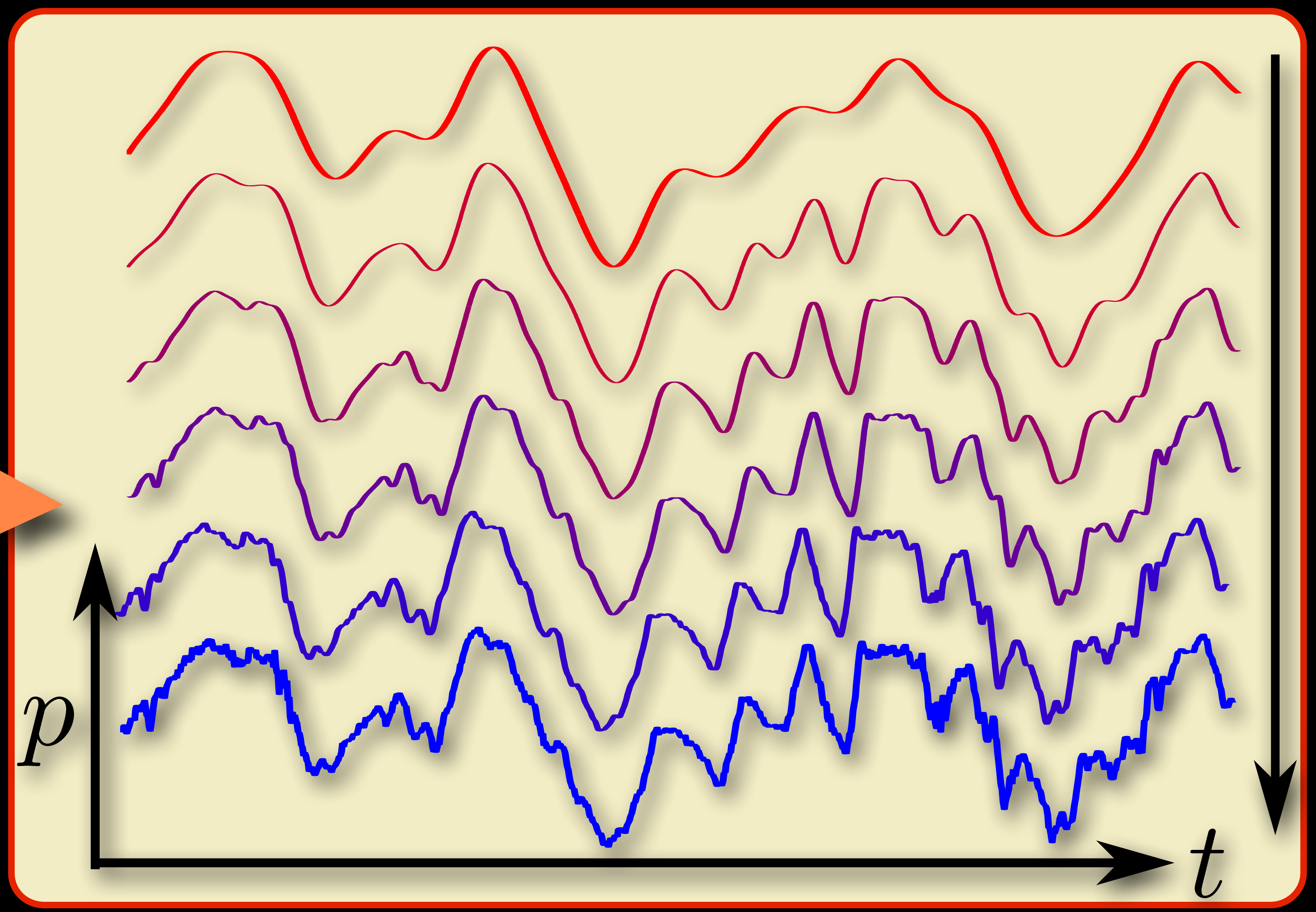


Spectral Bandwidth Extension



OR

Sound Texture Synthesis



Low-frequency Sound Model

Low-frequency Sound Model

$$sound \approx \frac{d}{dt} \int_{\mathbb{R}^3} q(\mathbf{y}, t) d^3\mathbf{y}$$

- **Problem:** Flame solvers from the graphics community do not realistically model heat release
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Low-frequency Sound Model

Modeling Heat Release

- Premixed flame assumption:
  - Reactants mixed prior to combustion
  - Combustion occurs rapidly when ignition temperature is reached
  - **Result:** heat release confined to "flame front" separating burnt and unburnt gasses

Low-frequency Sound Model

Modeling Heat Release

$$sound \approx \frac{d}{dt}\int_{\mathbb{R}^3} q(\mathbf{y},t)d^3\mathbf{y}$$

$$sound \approx \frac{d}{dt}\int_{S(t)} q\ dS$$

Low-frequency Sound Model

Modeling Heat Release

- Approximate heat release with velocity flux [Strahle 1972; Clavin and Siggia 1991; Chrighton et al. 1992]

$$sound \approx \frac{d}{dt}\int_{S(t)} q\, dS \approx \frac{d}{dt}\int_{S(t)} \mathbf{u}\cdot\mathbf{n}\, dS$$

Low-frequency Sound Model

Flame Front Surface

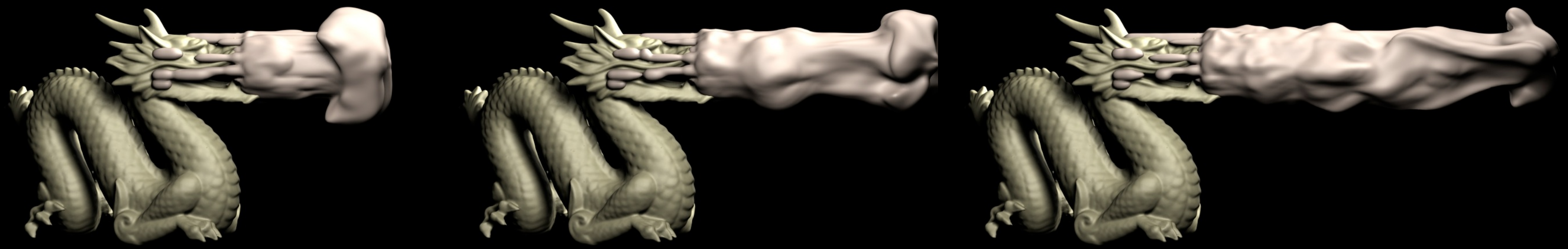
$$sound \approx \frac{d}{dt} \int_{S(t)} \mathbf{u} \cdot \mathbf{n} \, dS$$

- "Blue core" flame solvers [Nguyen et al. 2002; Hong et al. 2007]
  - Explicitly model flame front surface level set
- Other solvers which explicitly model fuel (eg. Houdini's *Pyro FX* solver)
  - Track rate at which fuel is consumed at each voxel and build an iso-surface

Low-frequency Sound Model

Results

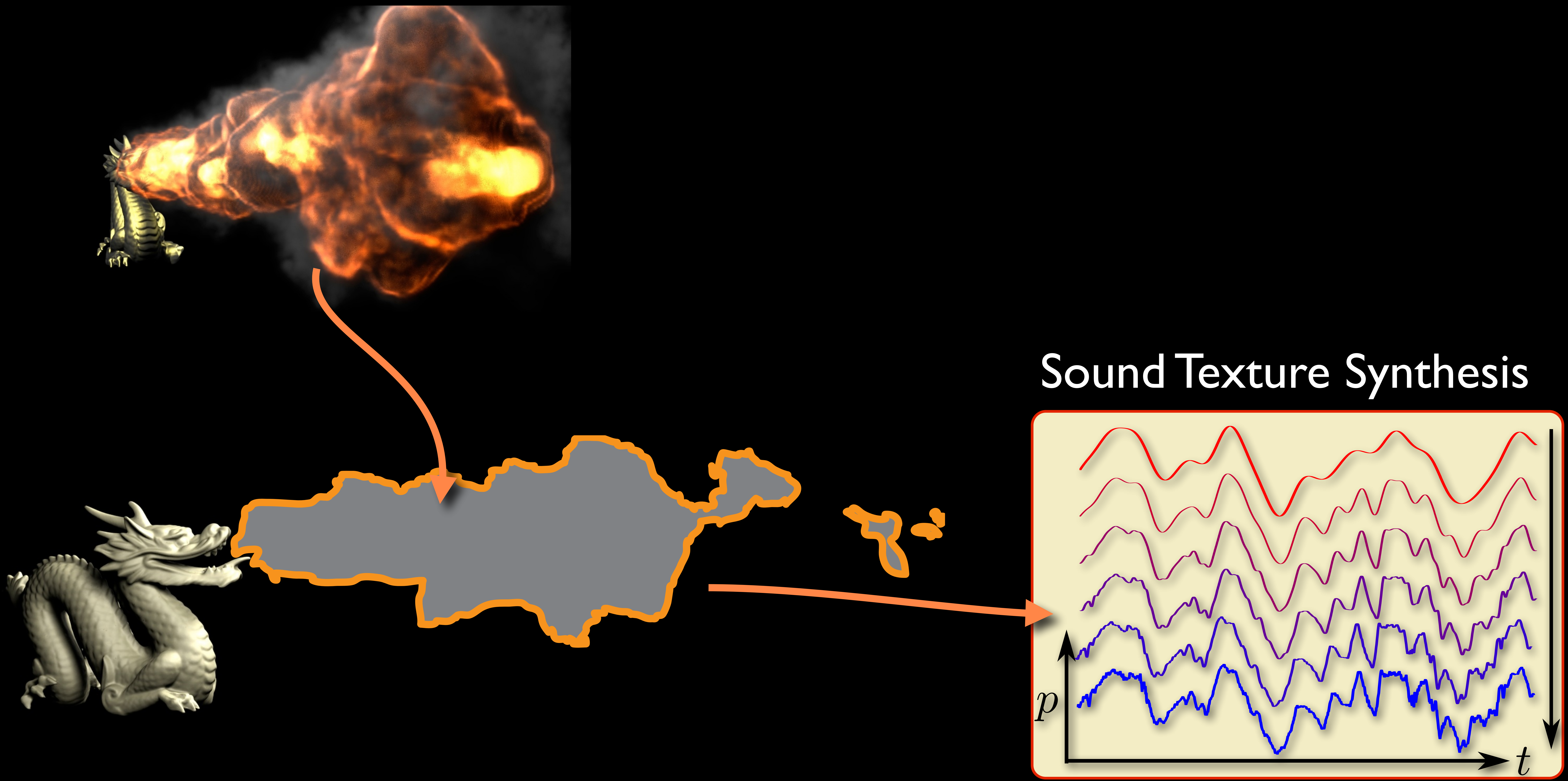
$$sound \approx \frac{d}{dt}\boxed{\int_{S(t)} \mathbf{u}\cdot\mathbf{n}\,dS} = \frac{d}{dt}\boxed{I(t)}$$



Compute $I(t_0), \quad I(t_1), \quad I(t_2), \ldots$

Simulation time steps

Overview



Sound Texture Synthesis

Motivation

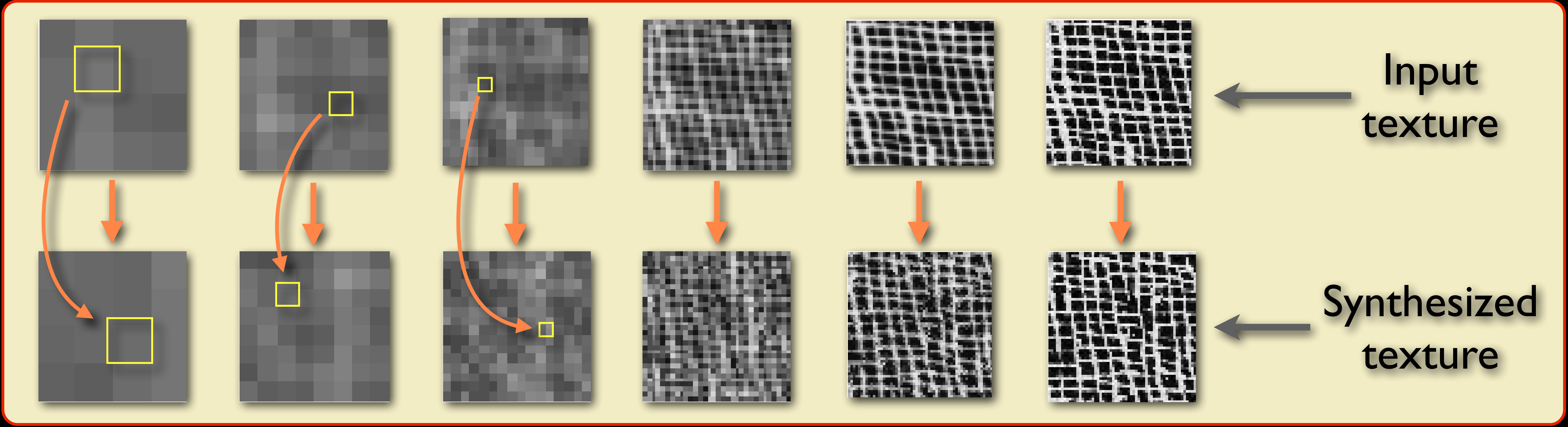
- Noise-based bandwidth extension introduces higher frequencies
  - Missing temporal structure present in real flame sounds
  - No "style control"
- **Idea:** Using low-frequency results as a guide, introduce high-frequency detail based on recorded flame sounds

Related work on texture synthesis:

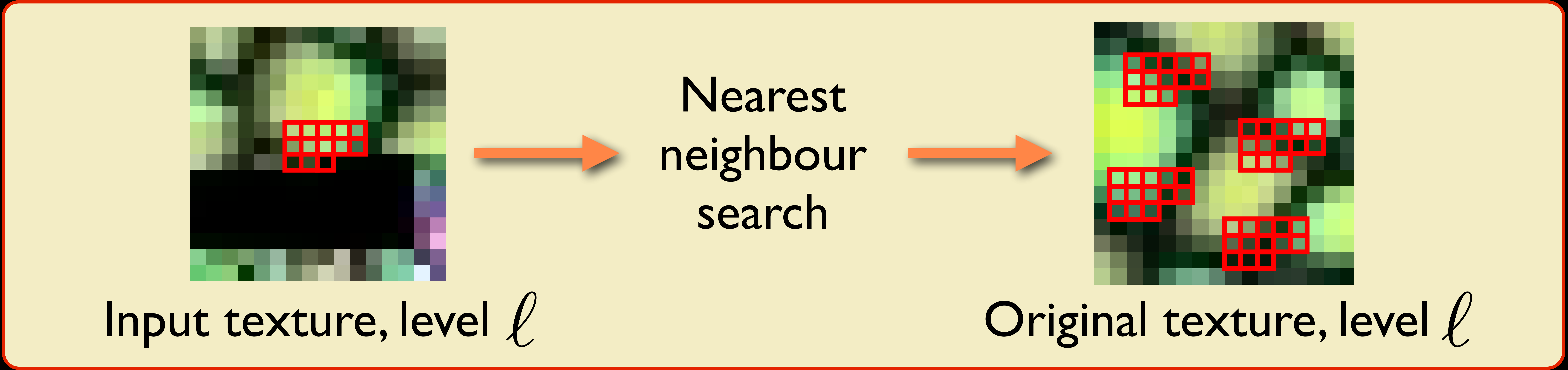
- Images: [Heeger and Bergen 1995; Efros and Leung 1999; Wei and Levoy 2000; Efros and Freeman 2001] (and many others)
- Sounds: [Dubnov et al. 2002; Strobl et al. 2006; McDermott et al 2009; Marelli et al. 2010]

Texture Synthesis Basics

[Wei and Levoy 2000]



Images from [Wei 1999]

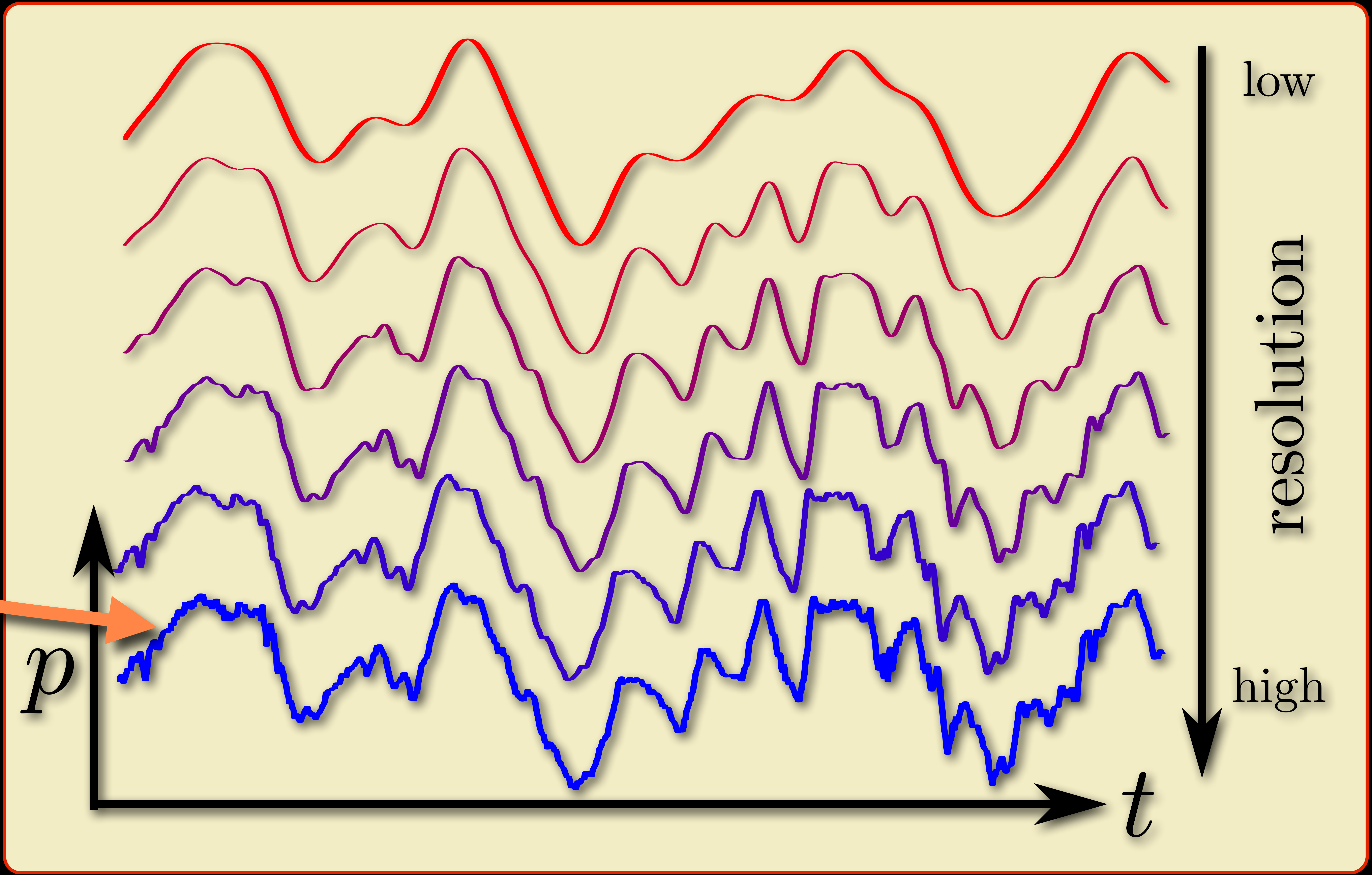


Images from [Wei and Levoy 2000]

Sound Texture Synthesis

Feature Training

Training sound (eg. recorded flame sound)

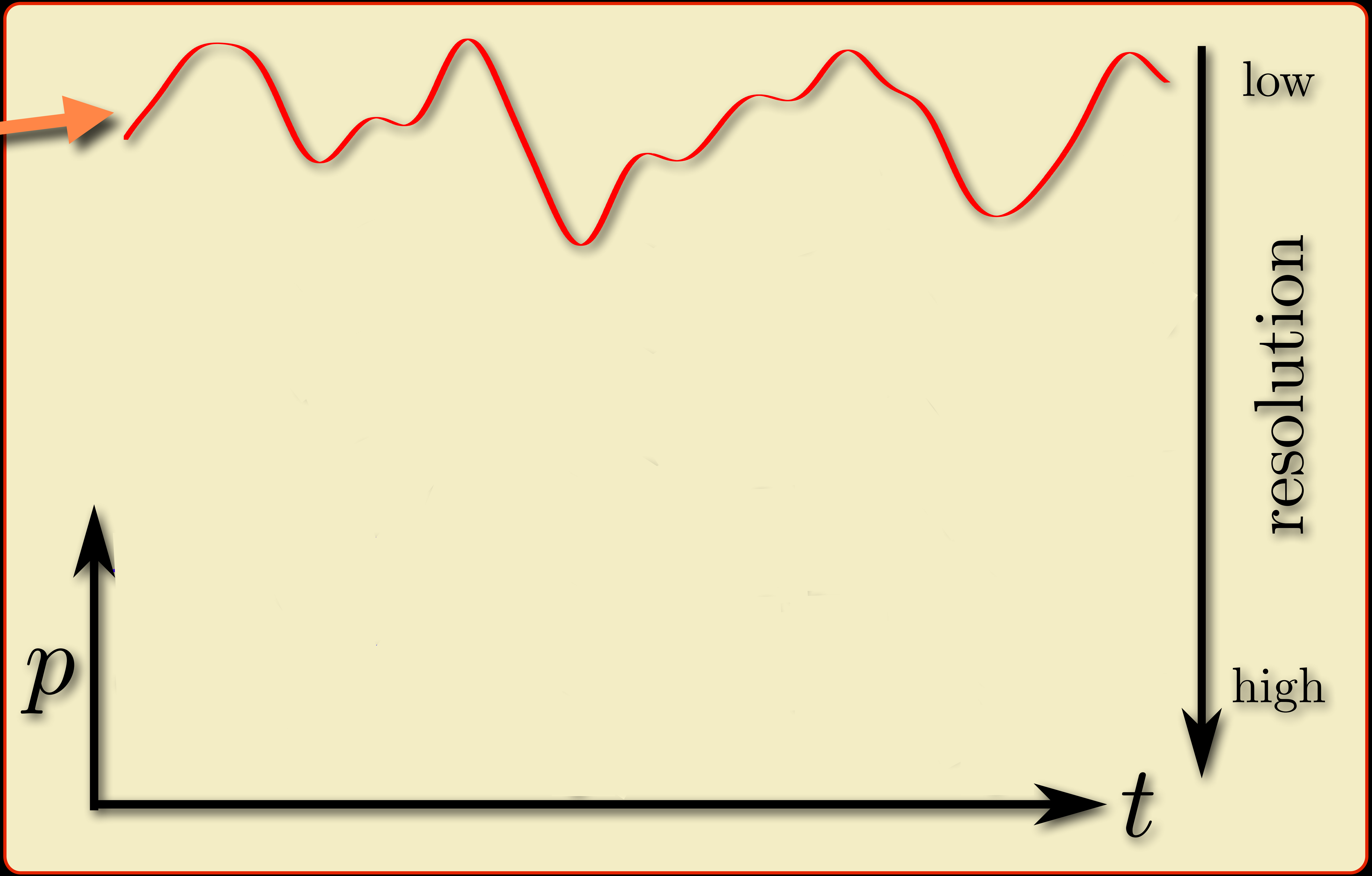


1D Gaussian pyramid

Sound Texture Synthesis

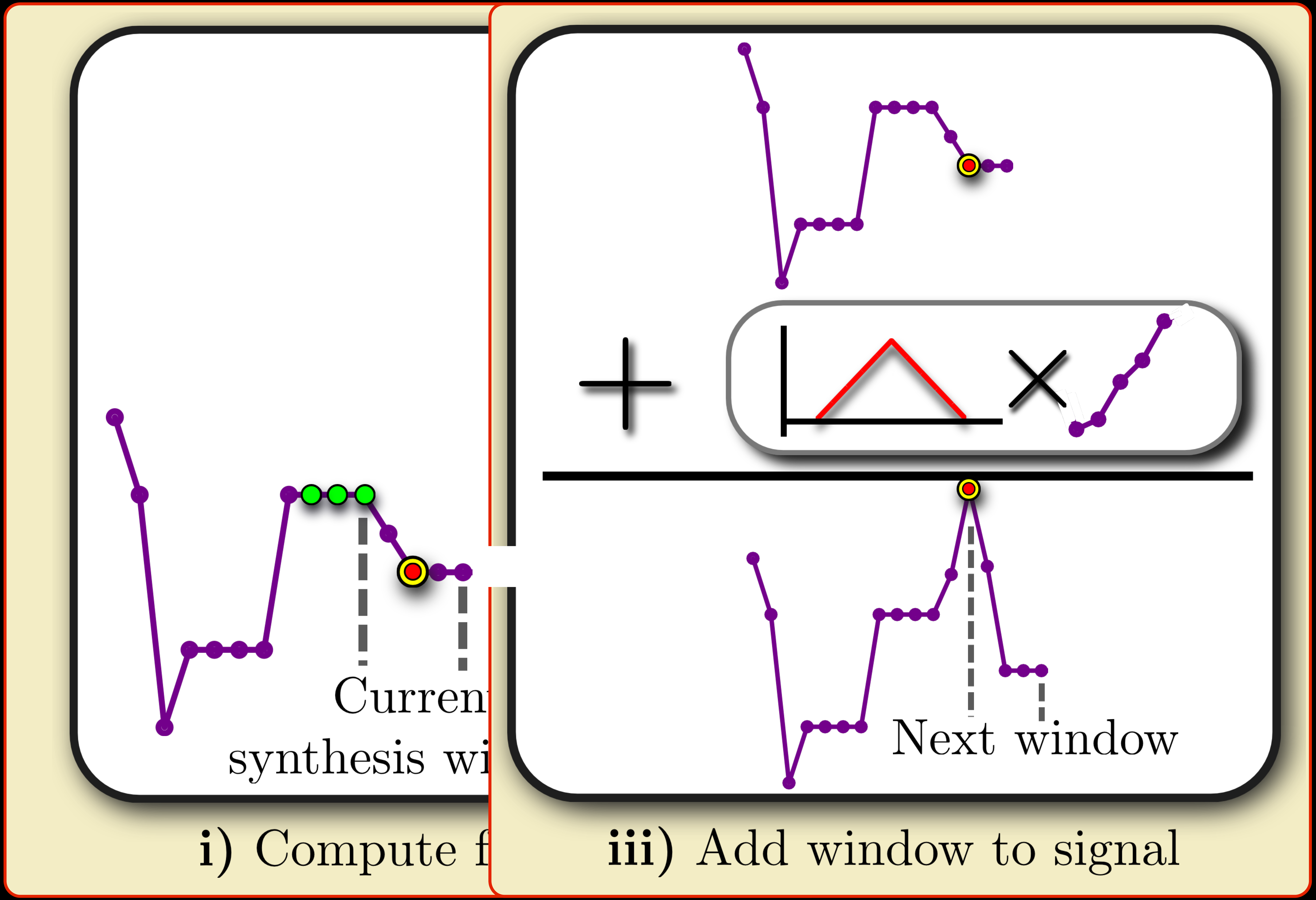
Low to High Frequency Synthesis

Physically based low frequency sound



1D Gaussian pyramid

Sound Texture Synthesis: Signal Synthesis



Sound Texture Synthesis

Results

Dragon

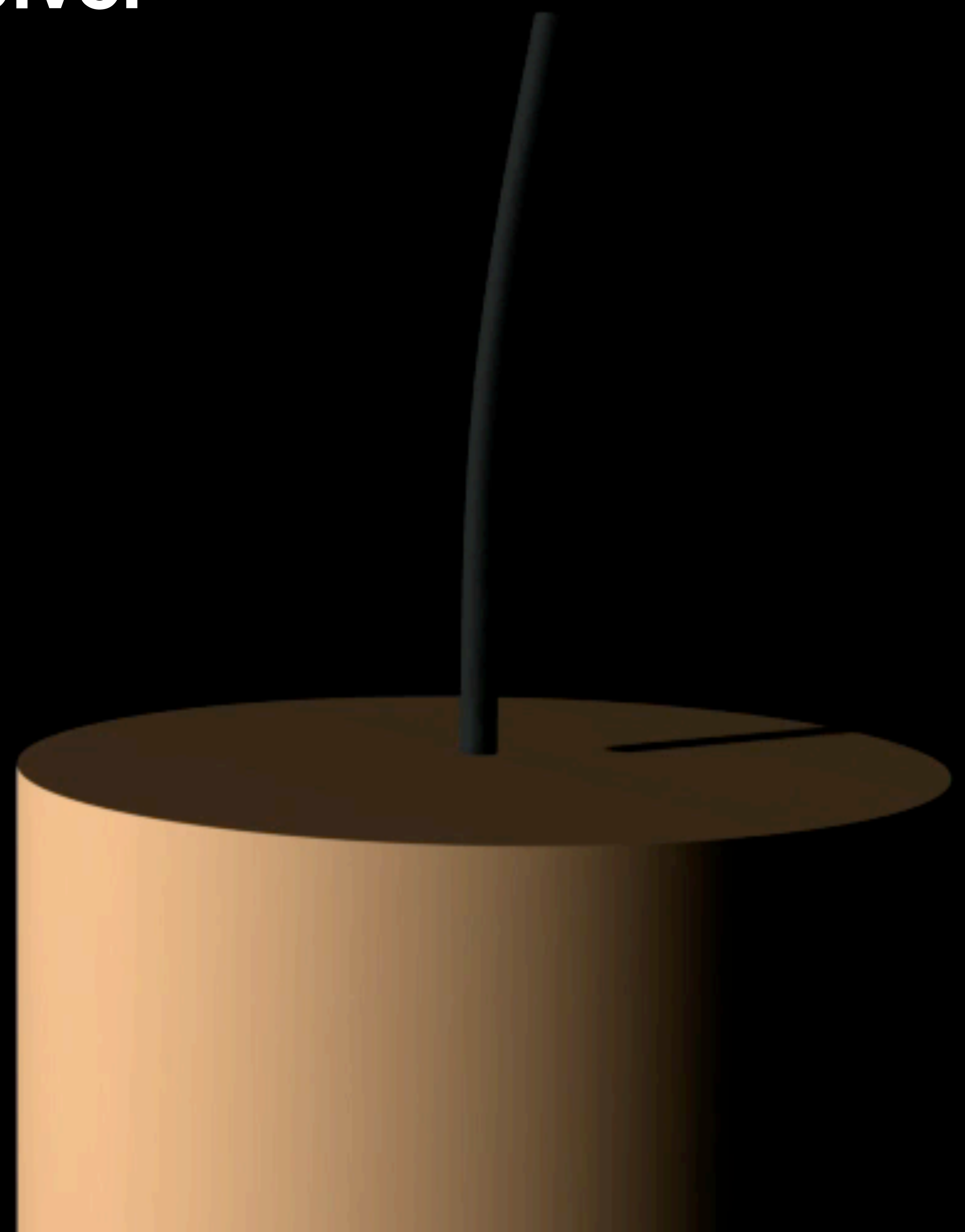
Dragon height: 1.15m

Simulated with: Houdini *Pyro FX* solver

Candle

Wick height: 4cm

Simulated with: Houdini *Pyro FX* solver



Burning Brick

Brick width: 20cm

Simulated with: Houdini *Pyro FX* solver

Style Control

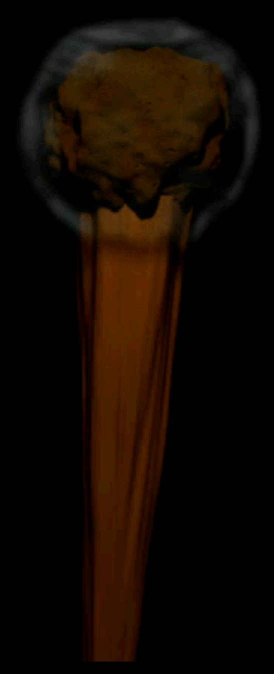
Torch

Torch length: 70cm
Simulated with: Houdini fire solver (blue core model with detonation shock dynamics [Nguyen et al. 2002; Hong et al. 2007])

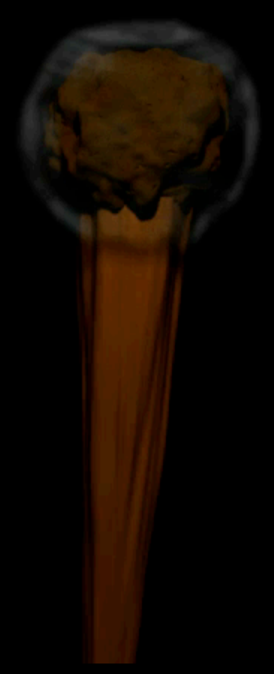
Training clips taken from *Ultimate Fire* sound library

http://www.therecordist.com

Training clip #1



Training clip #2



Training clip #3

Simulation/Timing data

Simulation times: ~2-3 hours

Iso-surface construction times: ~10s per time step

Scene	Domain size (m)	Domain resolution (voxels)	Animation length (s)	Bandwidth extension time (s)	Sound texture synthesis time (s)
Burning brick	2.0x1.7x0.9	180x151x78	5	64	20
Candle	0.15x0.15x0.12	115x120x96	6	151	86
Dragon	4.1x2.9x2.1	200x142x102	9	223	56
Flame jet	1.5x1.4x0.69	140x134x65	10	256	54
Torch	1.5x1.4x1.8	104x100x128	5	63	41

Acknowledgements

Webpage (with code) http://www.cs.cornell.edu/~chadwick/fire

Renderer Side Effects Software's *Mantra*

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Autodesk
Vision Research