SIGGRAPH2015

Xroads of Discovery

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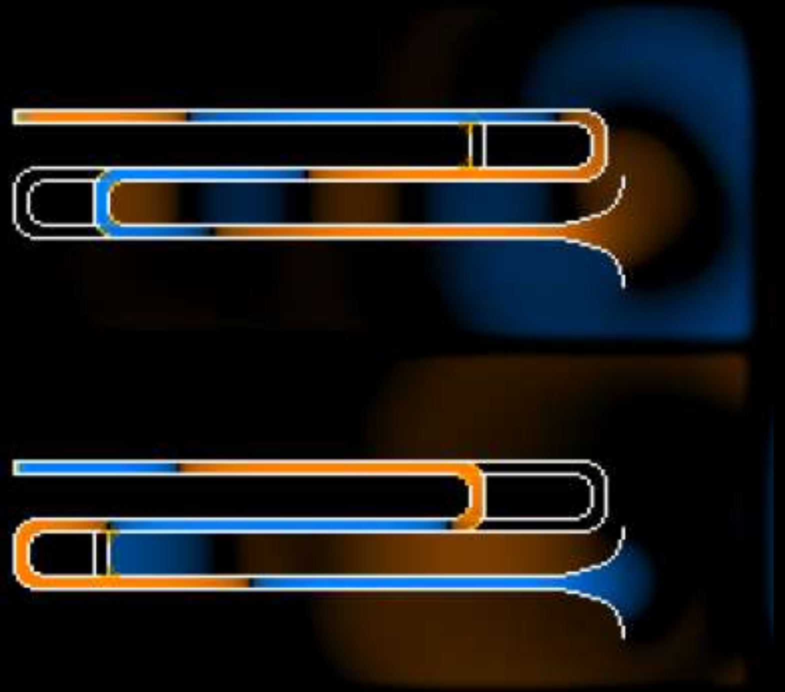
The 42nd International Conference and Exhibition
on Computer Graphics and Interactive Techniques

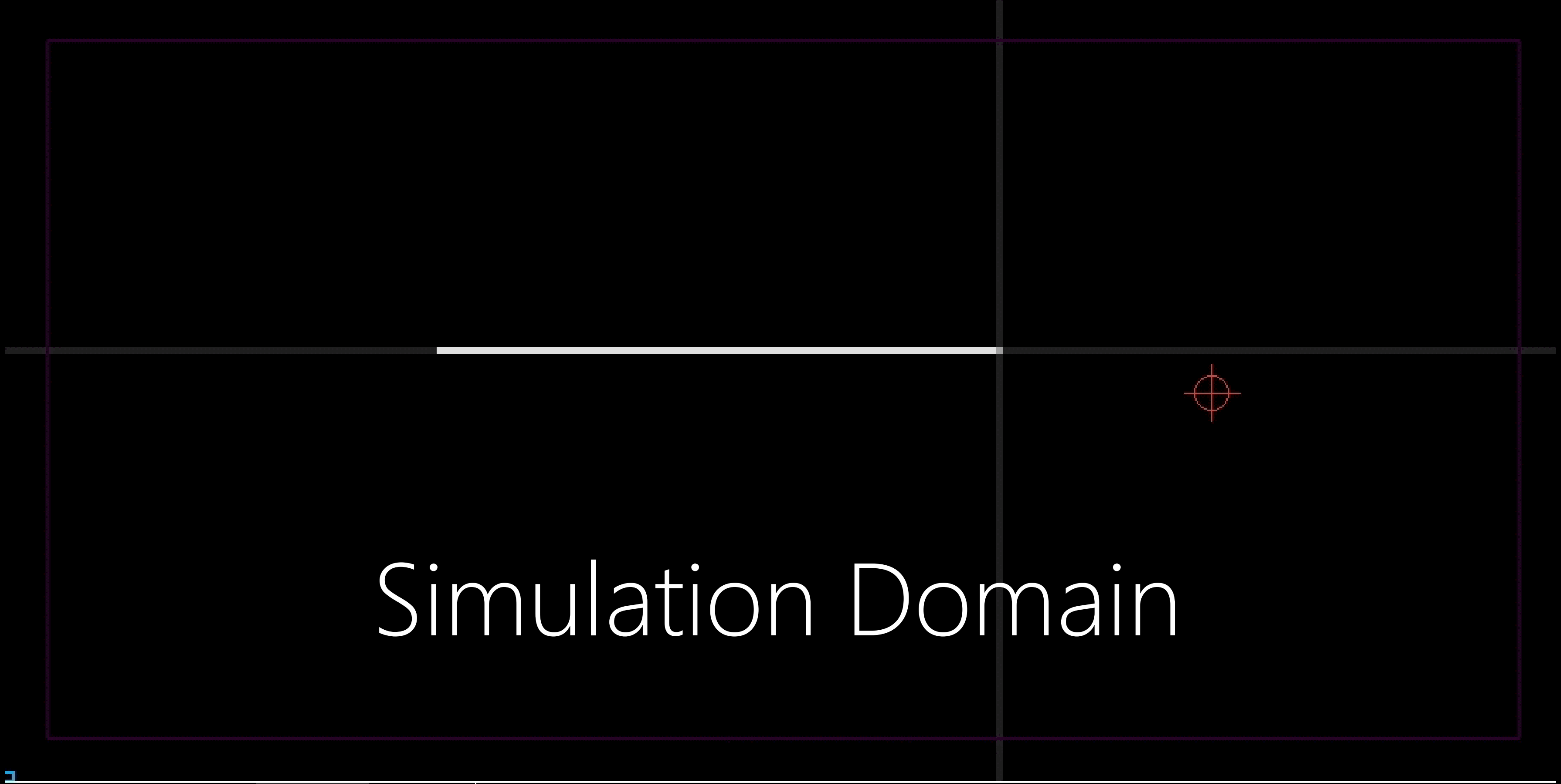


Aerophones in Flatland

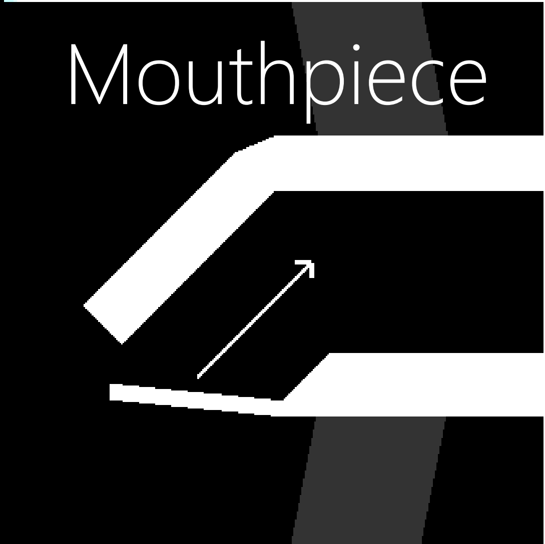
Interactive Wave Simulation of Wind Instruments

Andrew Allen
Nikunj Raghuvanshi

Microsoft Research



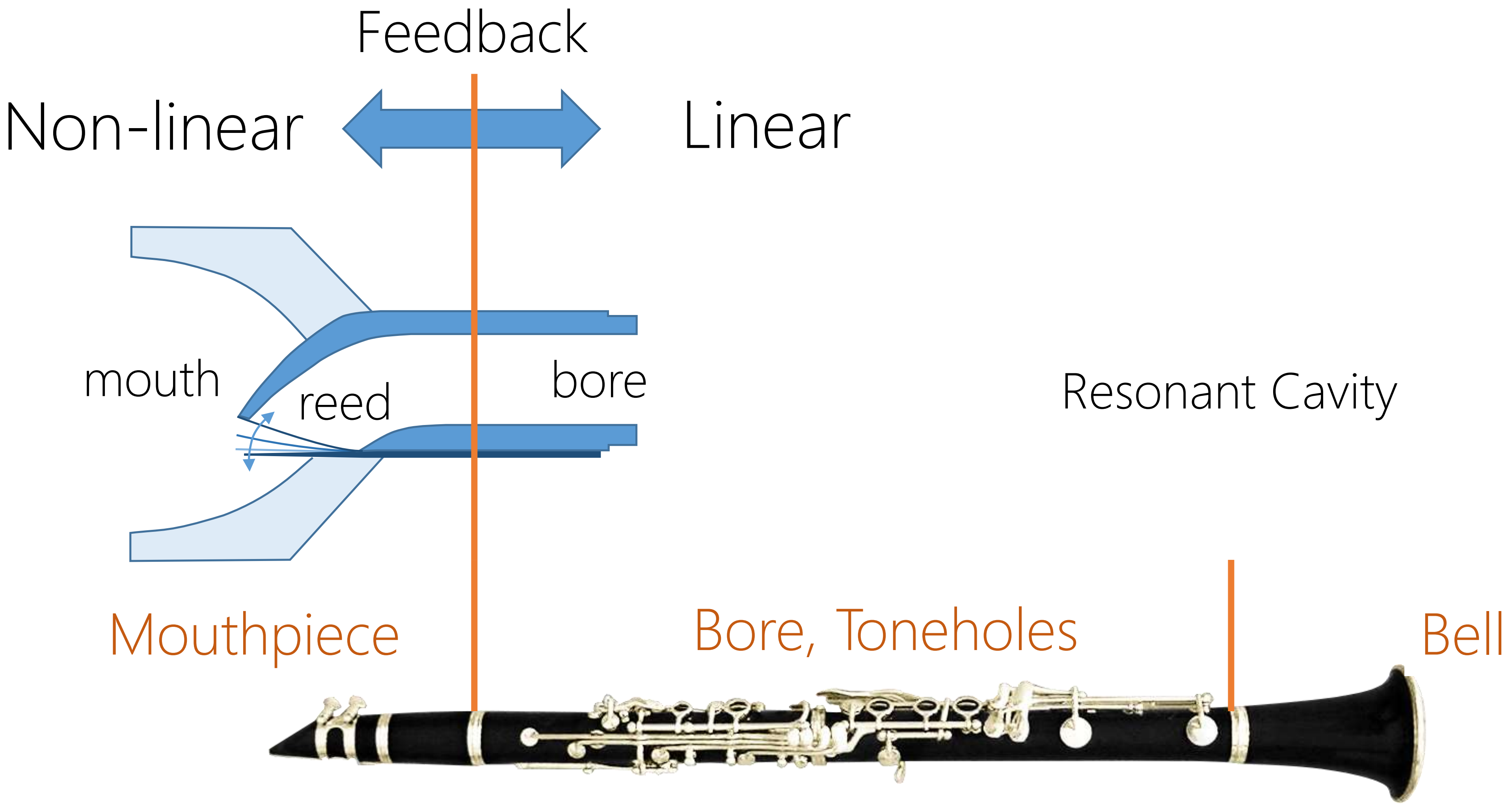
Simulation Domain



Mouthpiece

Spectrogram

Wind Instruments



Feedback

Non-linear

Linear

mouth

reed

bore

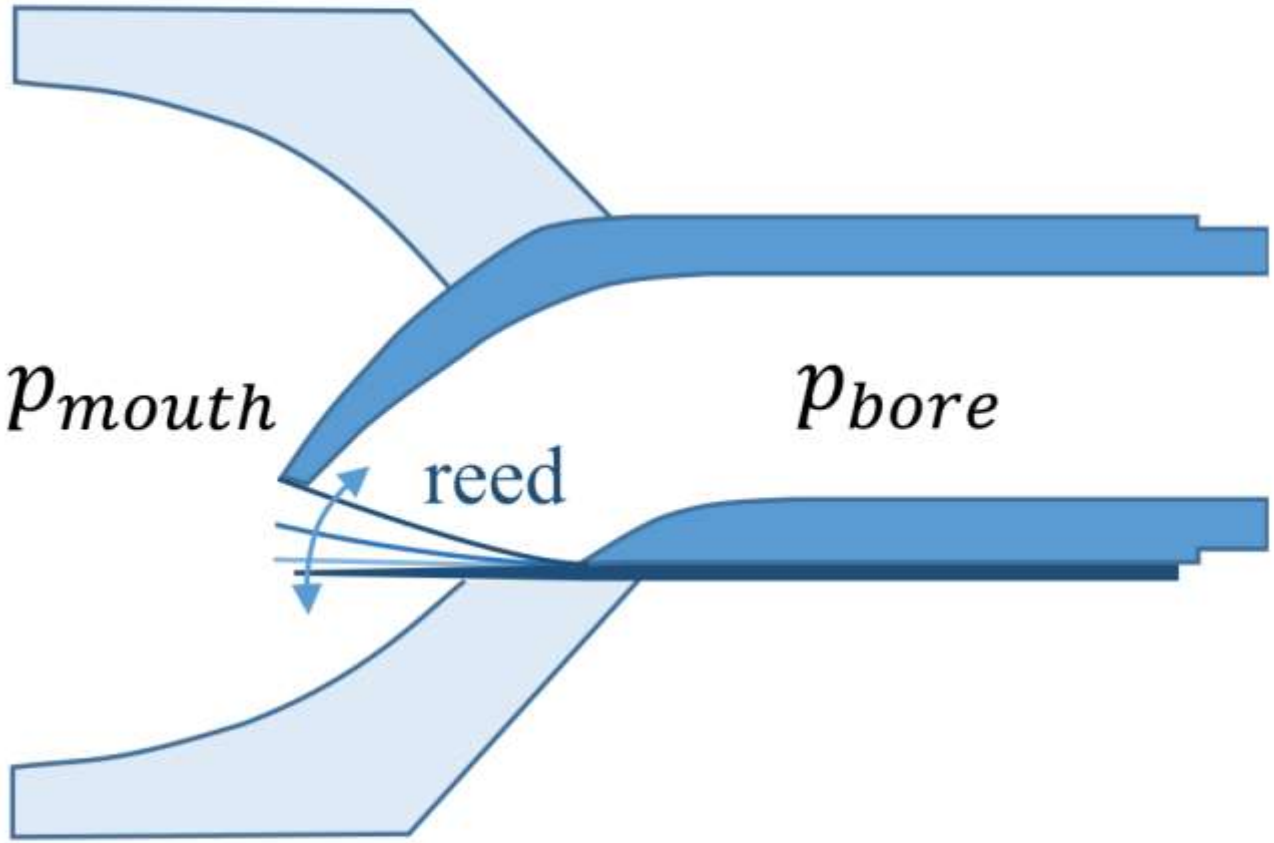
Resonant Cavity

Mouthpiece

Bore, Toneholes

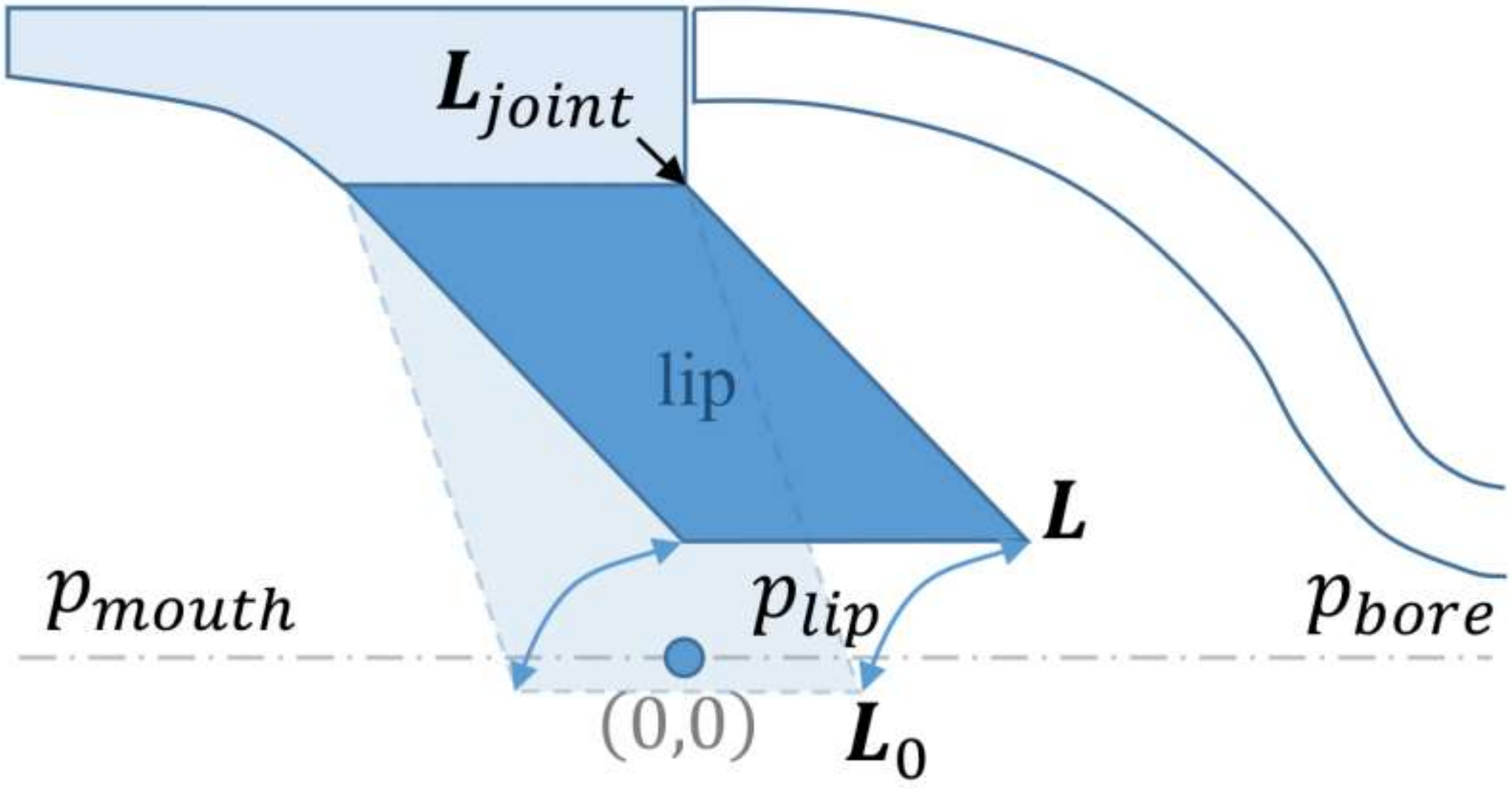
Bell

Excitation models: Single Reed (Clarinet)



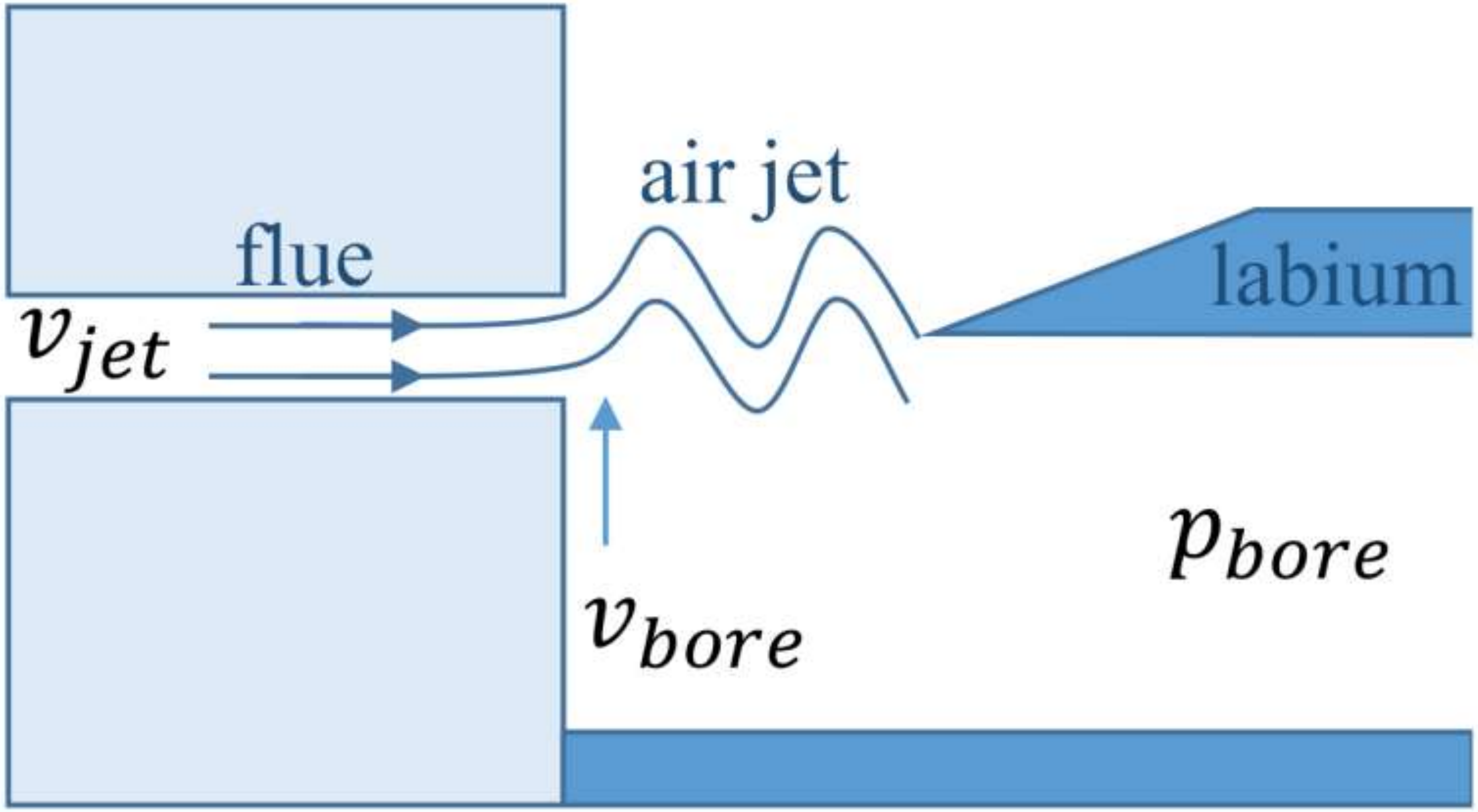
Dalmont, J.P., Gilbert J., and Ollivier, S. 2003.

Excitation models: Lips (Trumpet)



Adachi and Sato. 1996.

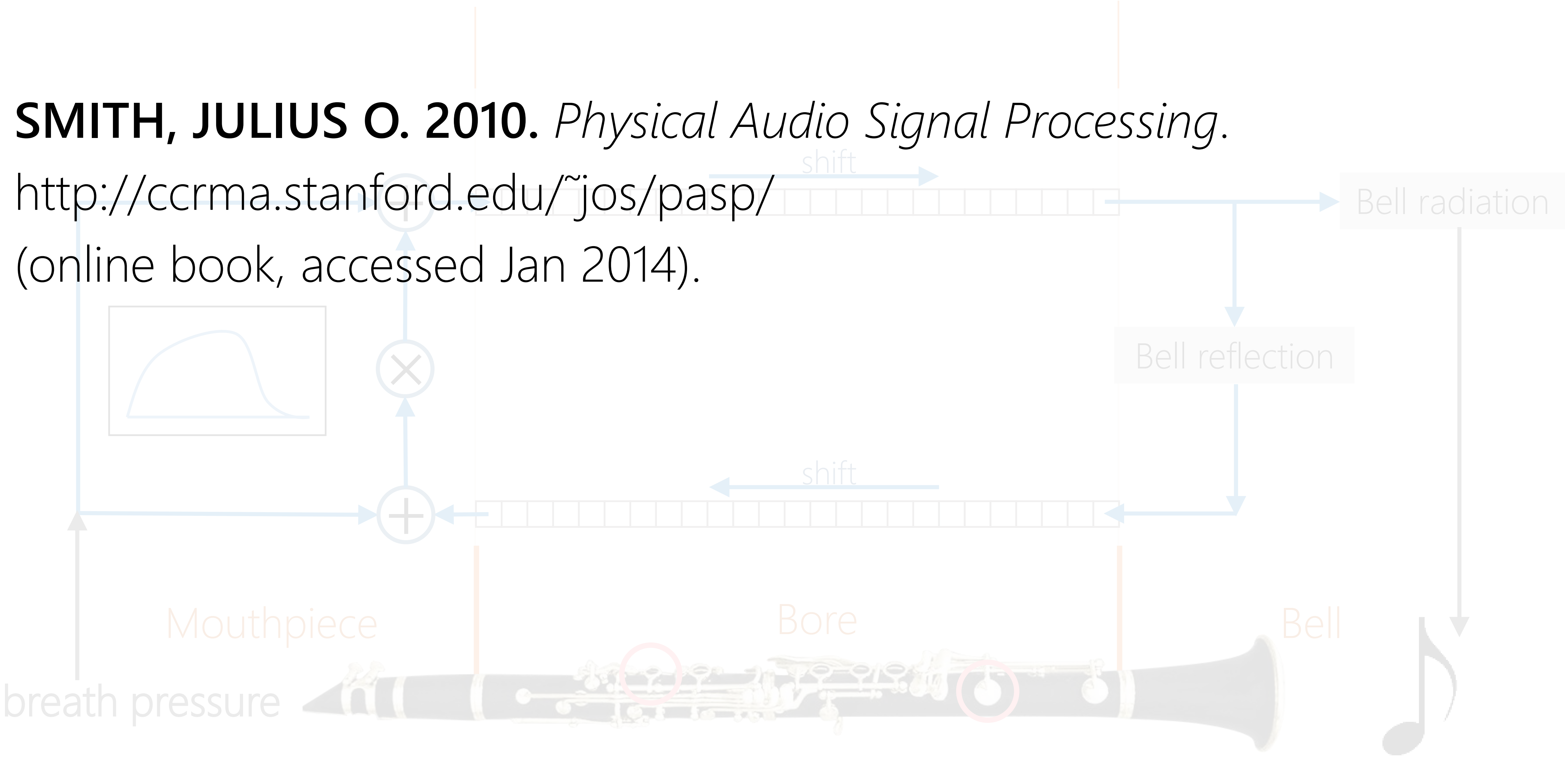
Excitation models: Air Jet (Flute)



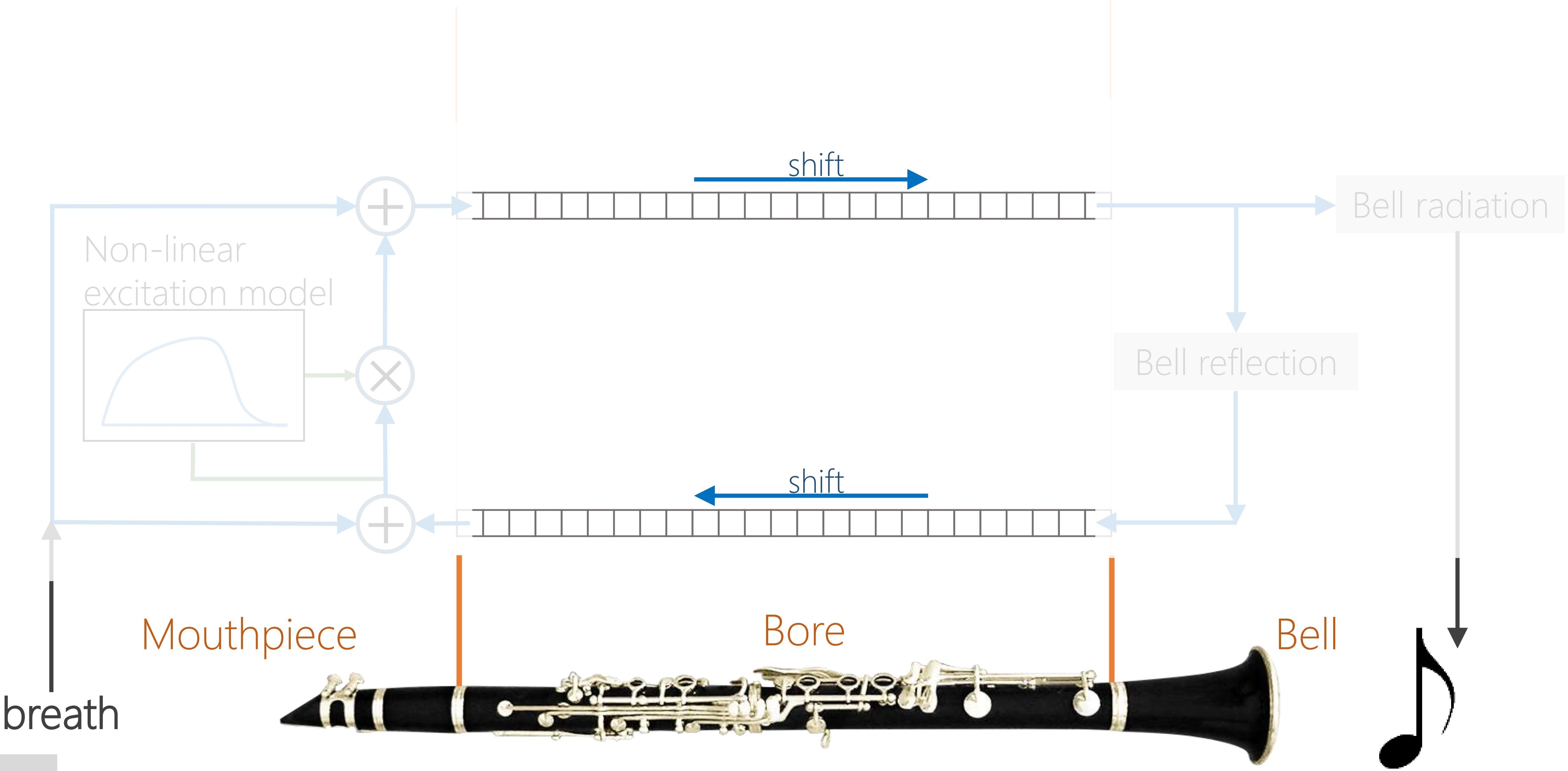
de La Cuadra. 2006.

Realtime synthesis: Digital Waveguides

SMITH, JULIUS O. 2010. *Physical Audio Signal Processing*.
http://ccrma.stanford.edu/~jos/pasp/
(online book, accessed Jan 2014).

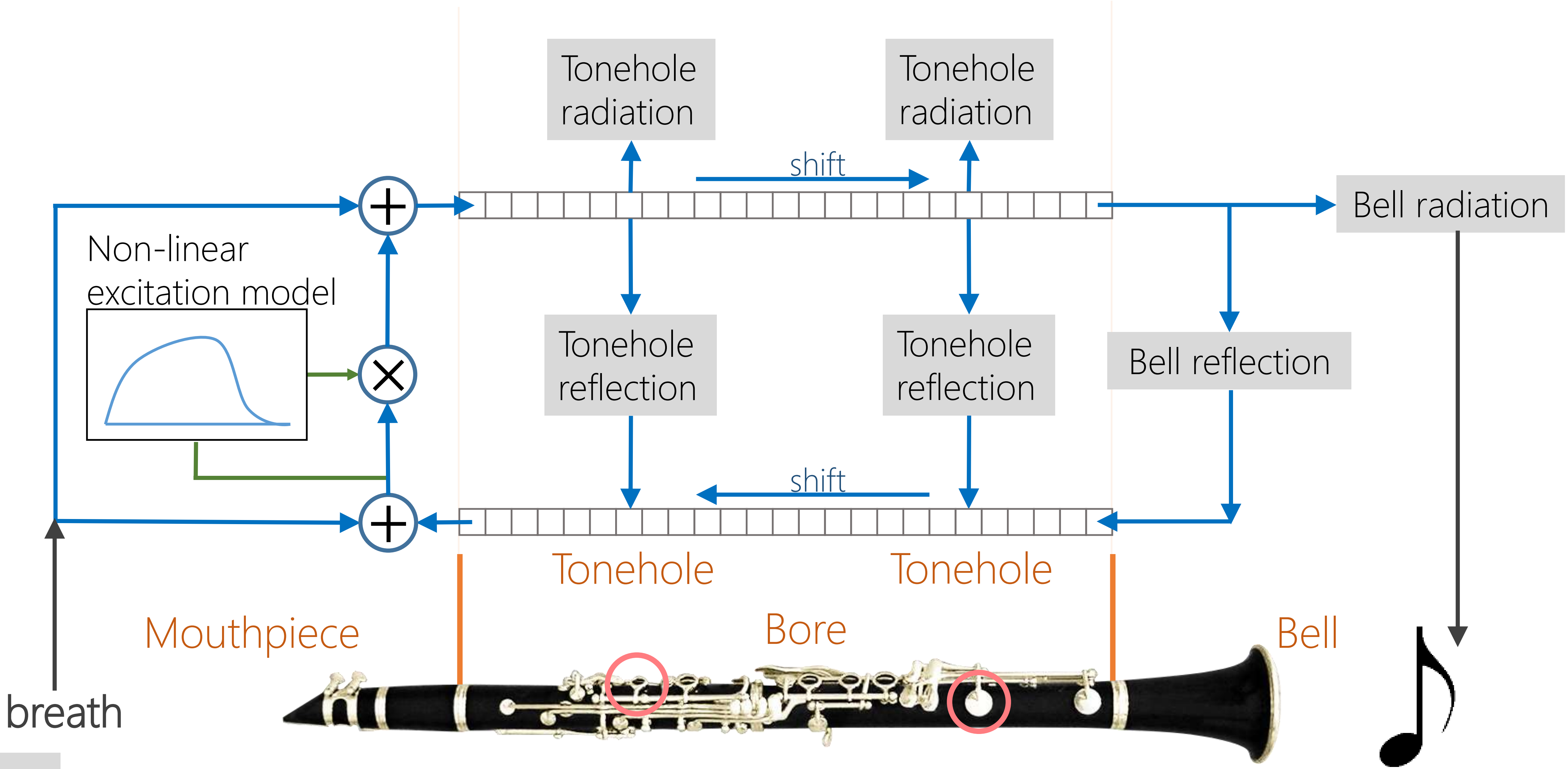


Realtime synthesis: Digital Waveguides



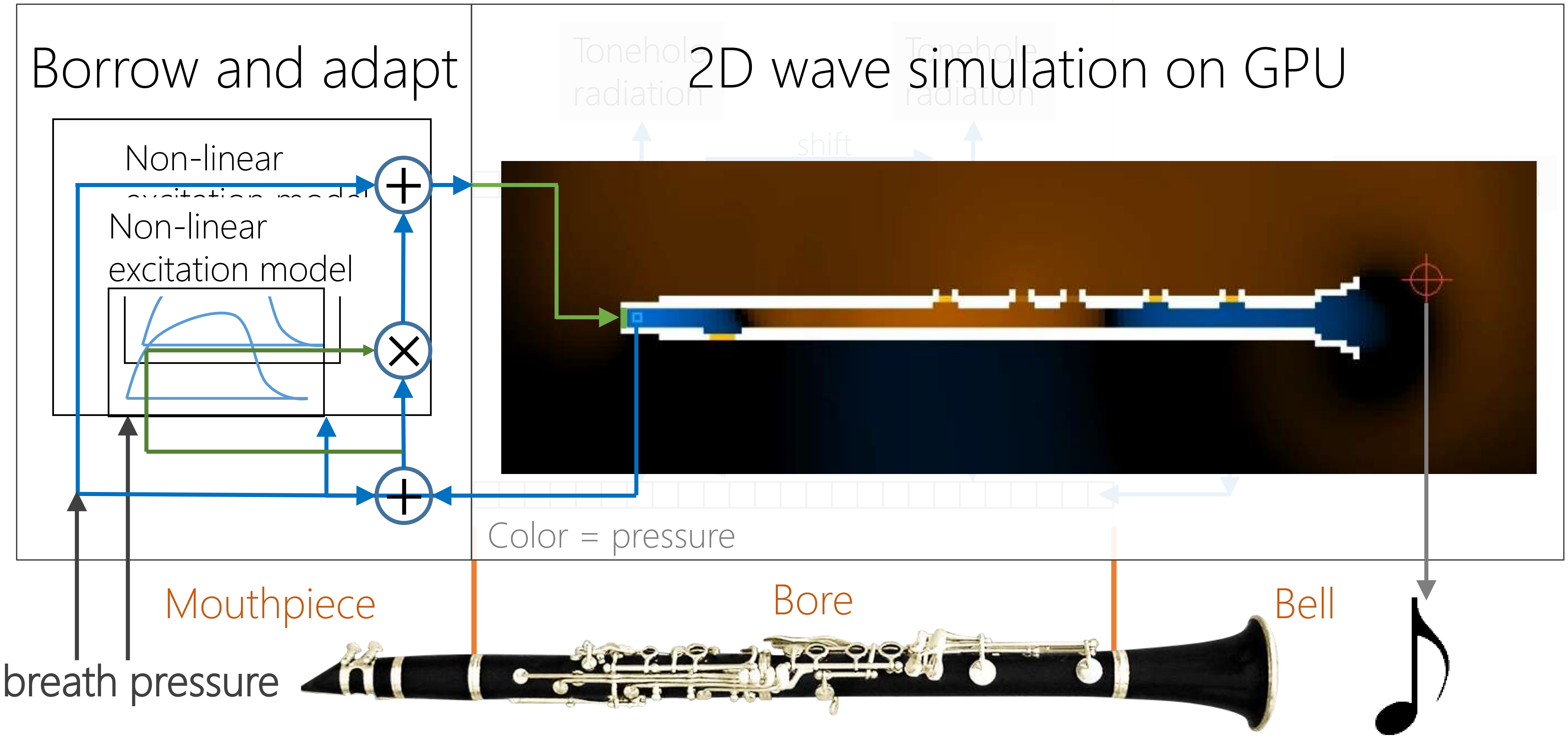
▨ = frequency-dependent filter

Realtime synthesis: Digital Waveguides



▨ = frequency-dependent filter

Our approach



Borrow and adapt

Non-linear excitation model

Non-linear excitation model

2D wave simulation on GPU

Tonehole radiation

Tonehole radiation

shift

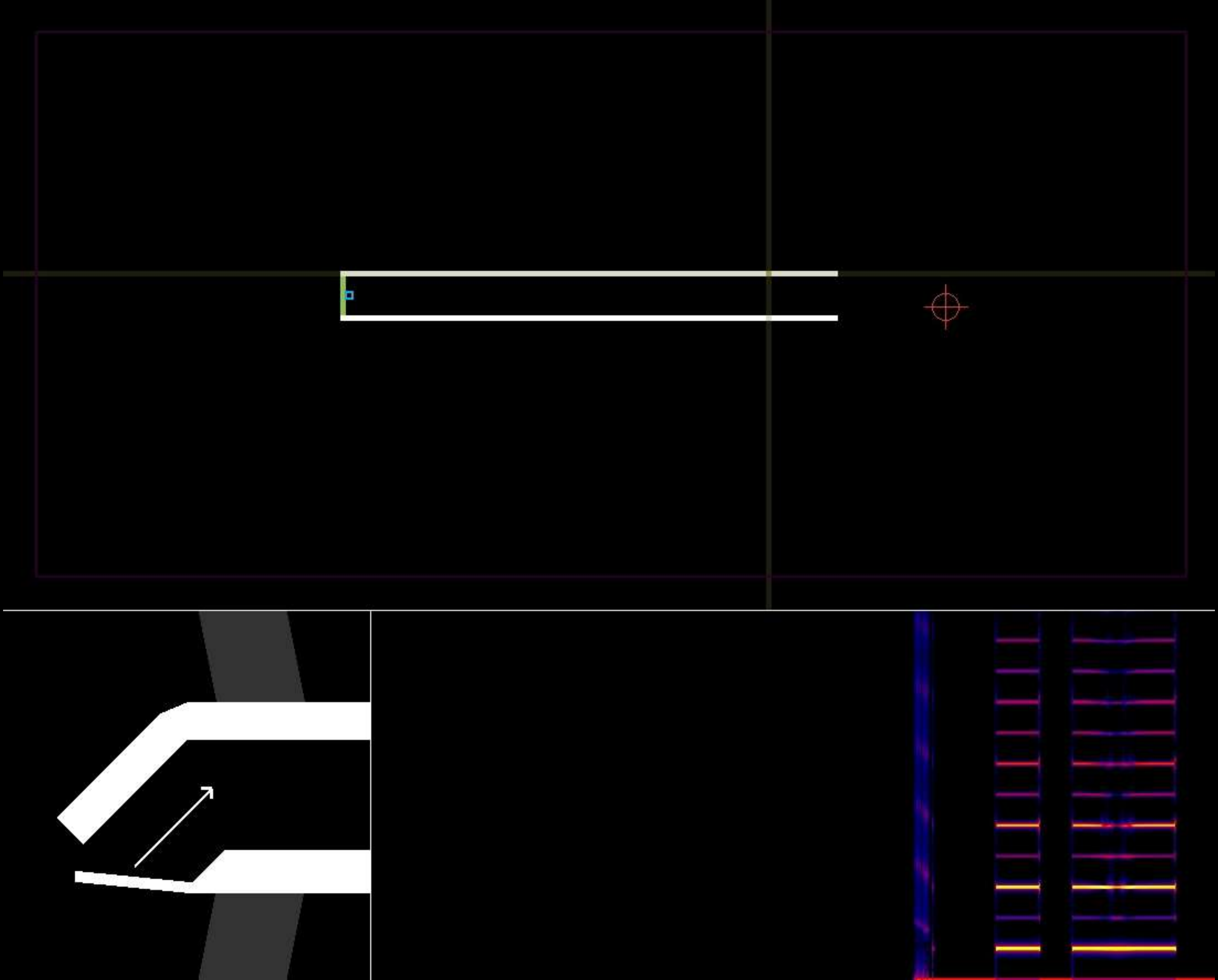
Color = pressure

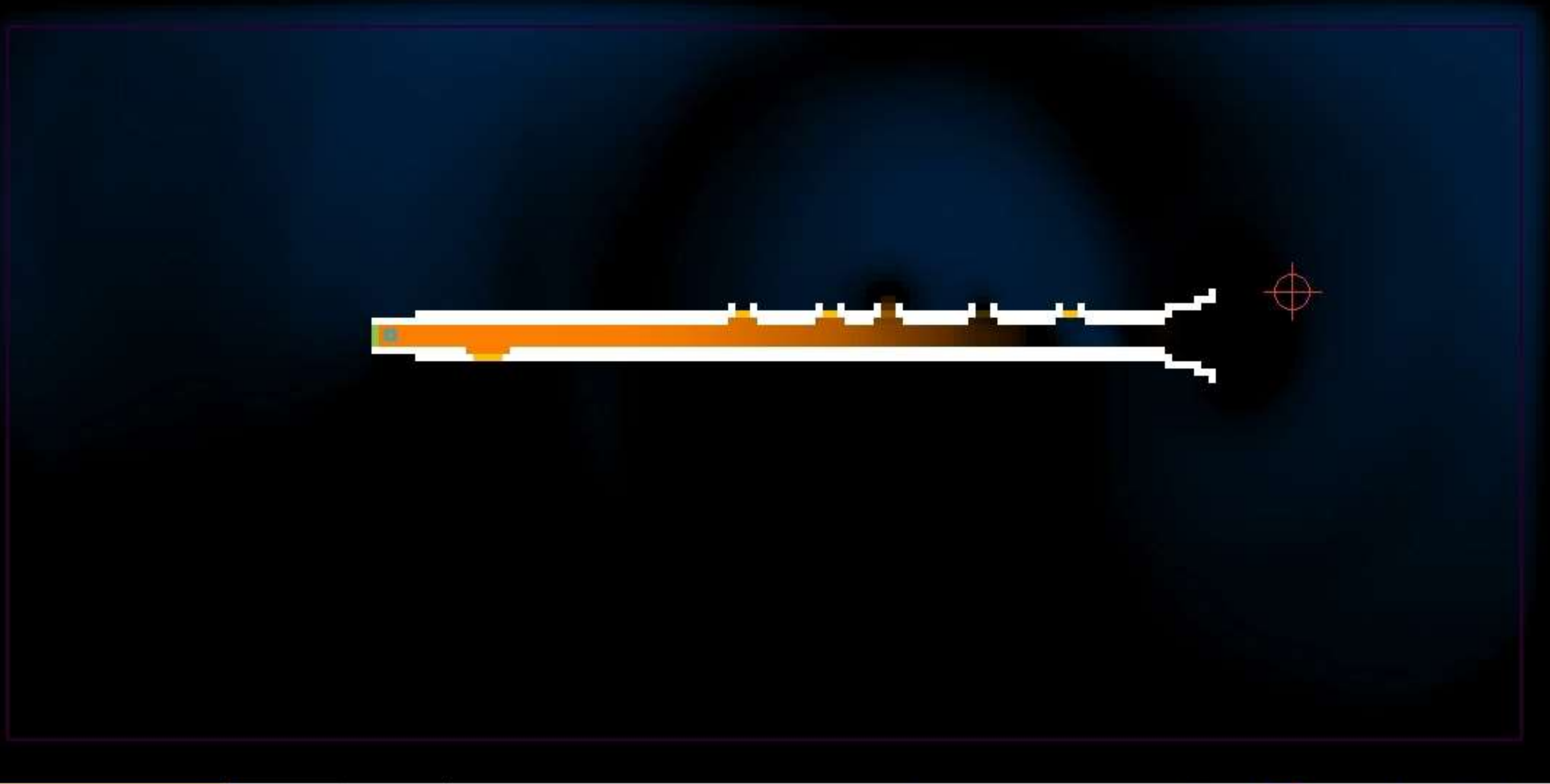
Mouthpiece

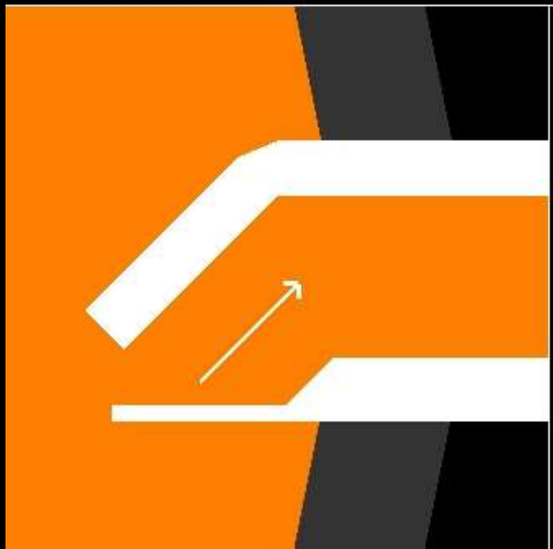
Bore

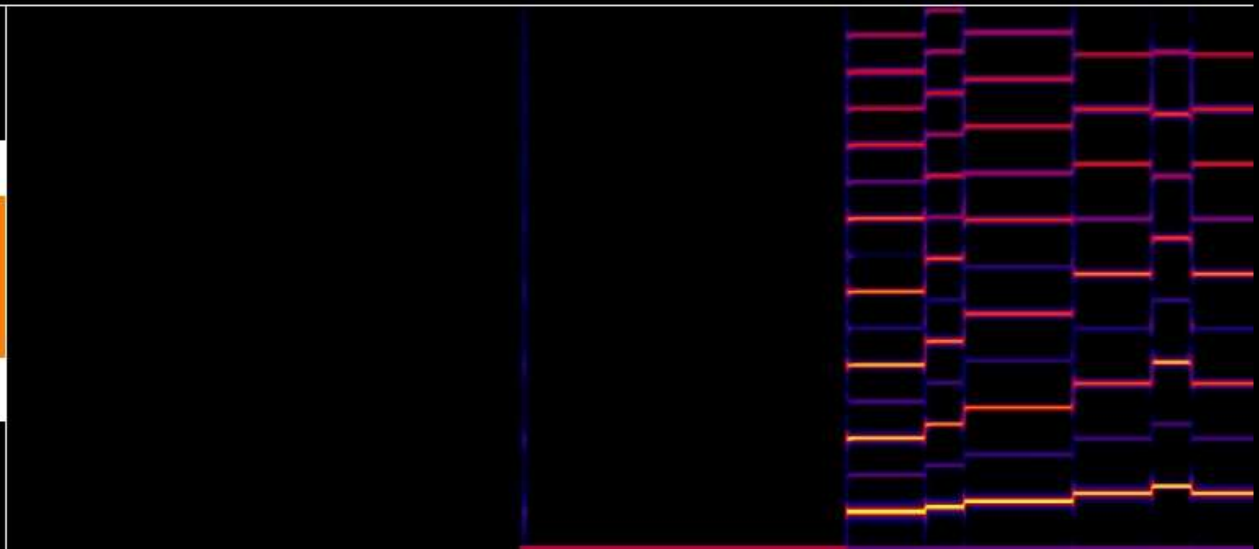
Bell

breath pressure









Advantages

- Signal processing networks require expertise to design and ensure physical plausibility.
- Geometric manipulation is intuitive.
- Guaranteed physical plausibility.
- Lower expertise bar for musical experimentation.

Challenges

- System is driven non-linearly and has perceptually salient transients (note beginnings/ends).
- Direct time-domain finite-difference solution.
- Standard finite difference generates artifacts on changing geometry.

- Need millimeter-scale resolution.
- Numerical stability requires small time-steps for wave equation.
- ~3.8mm resolution at **128,000Hz on the GPU**.

Linear Wave Equation

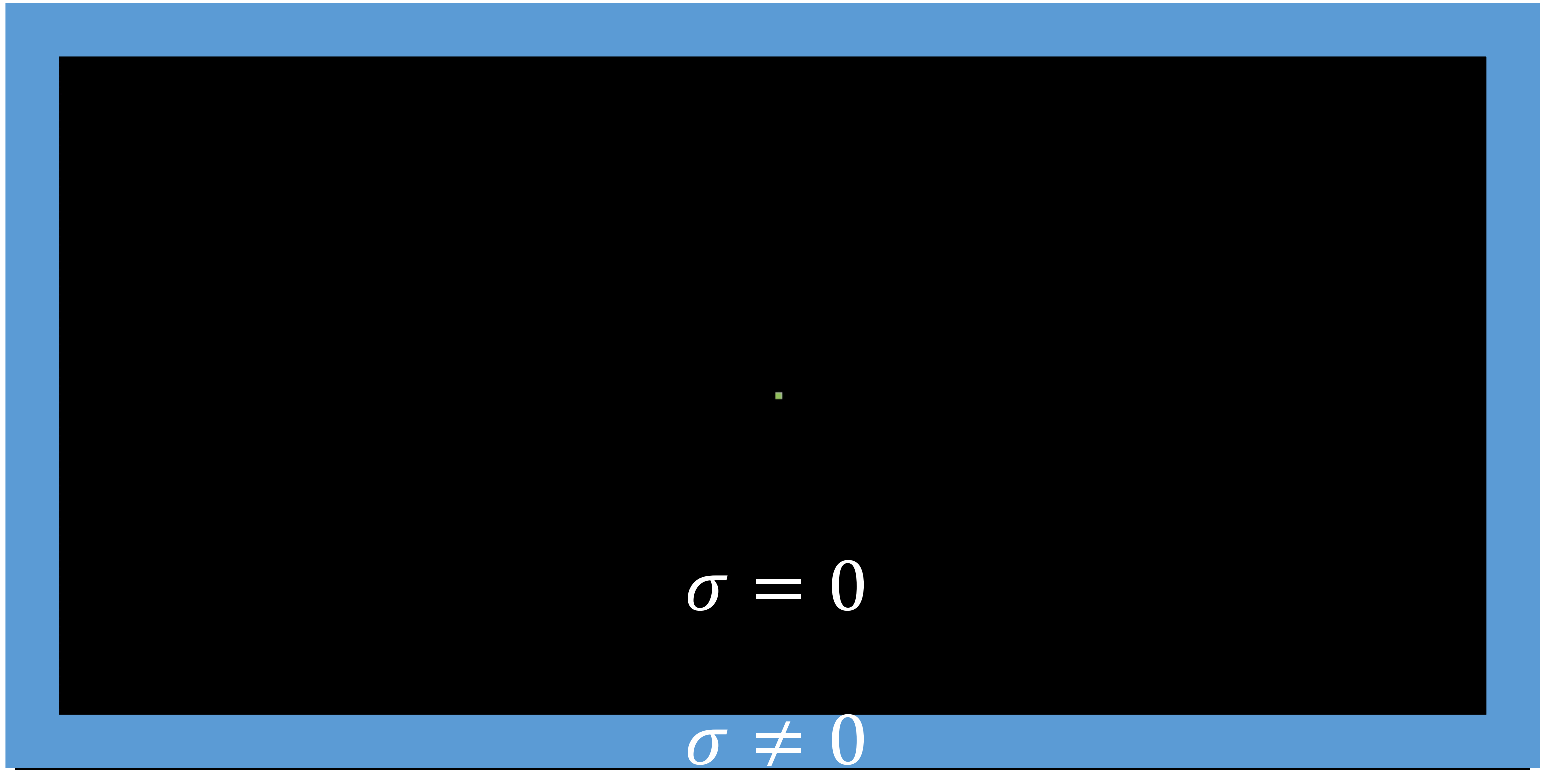
$$\frac{\partial p}{\partial t} = -\rho c^2 \nabla \cdot \mathbf{v}$$

$$\frac{\partial \mathbf{v}}{\partial t} = \frac{-\nabla p}{\rho}$$

Perfectly matched layer (PML)

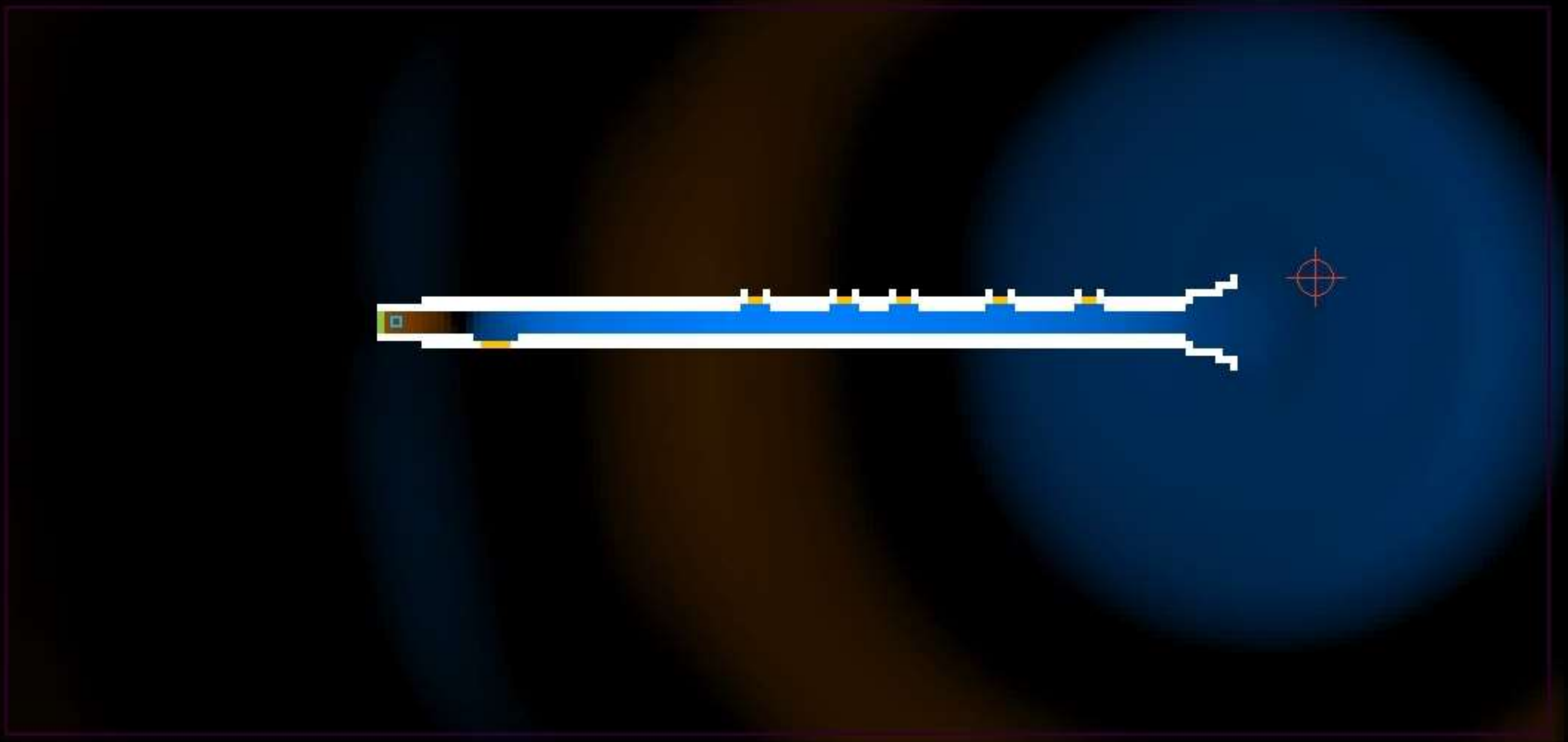
$$\frac{\partial p}{\partial t} + \sigma\, p = -\rho c^2 \nabla \cdot \mathbf{v}$$

$$\frac{\partial \mathbf{v}}{\partial t} + \sigma\, \mathbf{v} = \frac{-\nabla p}{\rho}$$



Dynamic Geometry

Tone Holes, Valves, Slides, Mutes



Abrupt geometric changes: clicks

Our formulation (time-varying PML)

$$\begin{aligned} \frac{\partial p}{\partial t} + (1-\beta+\sigma)p &= -\rho c^2 \nabla \cdot \mathbf{v} \\ \beta \frac{\partial \mathbf{v}}{\partial t} + (1-\beta+\sigma)\mathbf{v} &= \beta^2 \frac{-\nabla p}{\rho} + (1-\beta+\sigma)\mathbf{v}_b \end{aligned}$$

- $\beta(\boldsymbol{x}, t) \in [0,1]$ introduces smoothly-varying dynamic geometry.
- $\mathbf{v}_b$ enforces boundary conditions and input flow from mouthpiece.
- Handles all phenomena we model.

Our formulation (time-varying PML)

$$\beta \frac{\partial \mathbf{v}}{\partial t} + (1 - \beta + \sigma)\mathbf{v} = \beta^2 \frac{-\nabla p}{\rho} + (1 - \beta + \sigma)\mathbf{v}_b$$

($\sigma = \mathbf{0}$ inside domain)

$\beta = 0$: Boundary

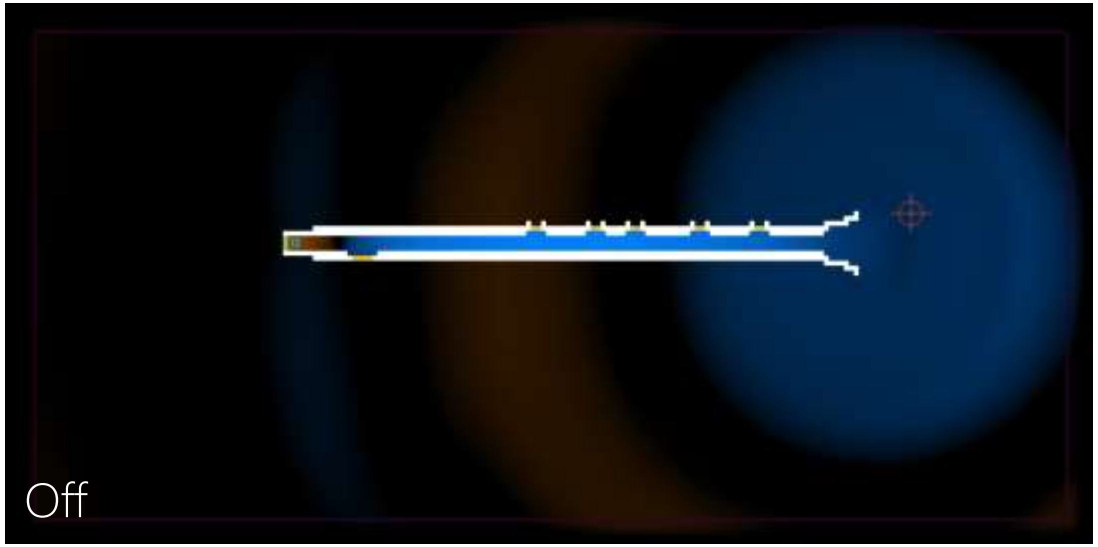
$$\mathbf{v} = \mathbf{v}_b$$

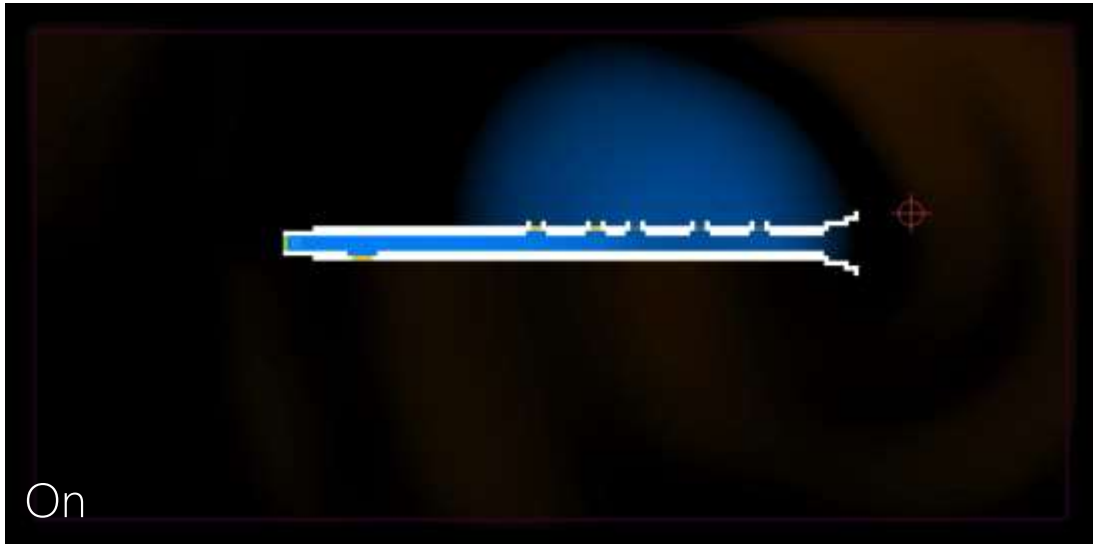
$\beta = 1$: Air

$$\frac{\partial \mathbf{v}}{\partial t} = \frac{-\nabla p}{\rho}$$

Smoothly interpolates between **Boundary** and **Air** state in every cell

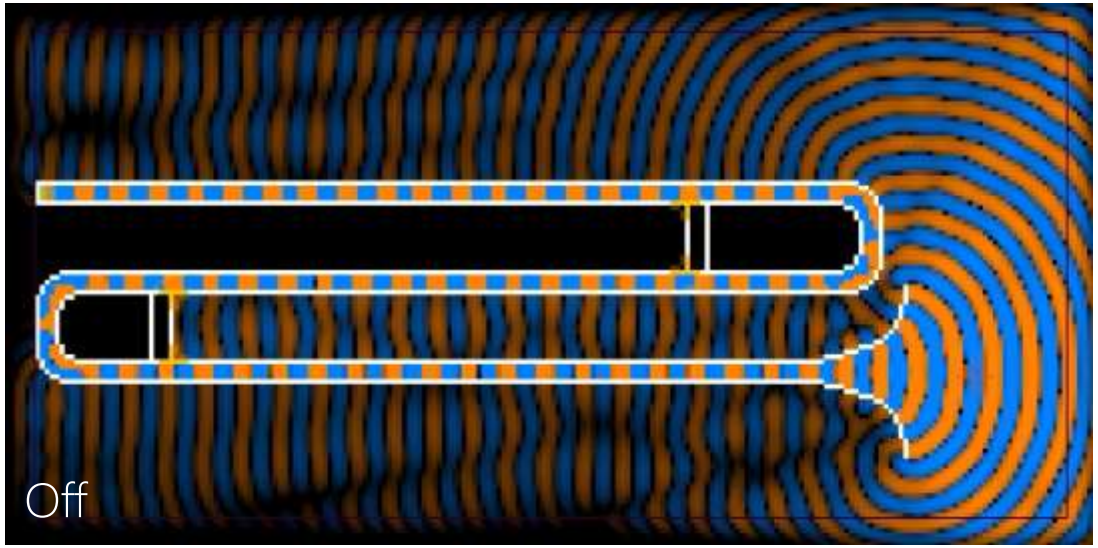
Our formulation: natural transients

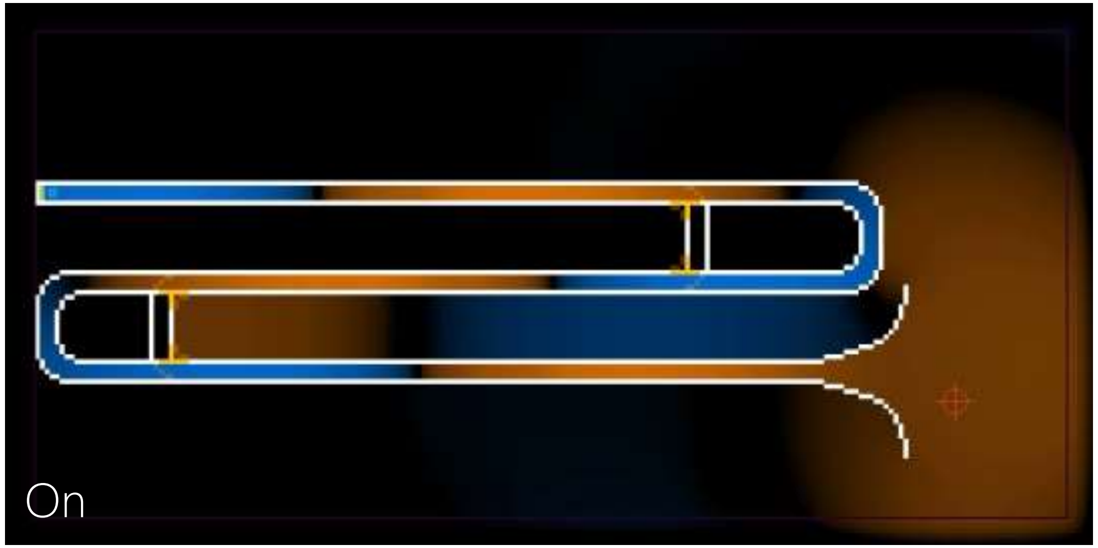




- The transition rate of β controls the smoothness of the transition.
- Results in a simple conditional-free update equation for the entire domain.

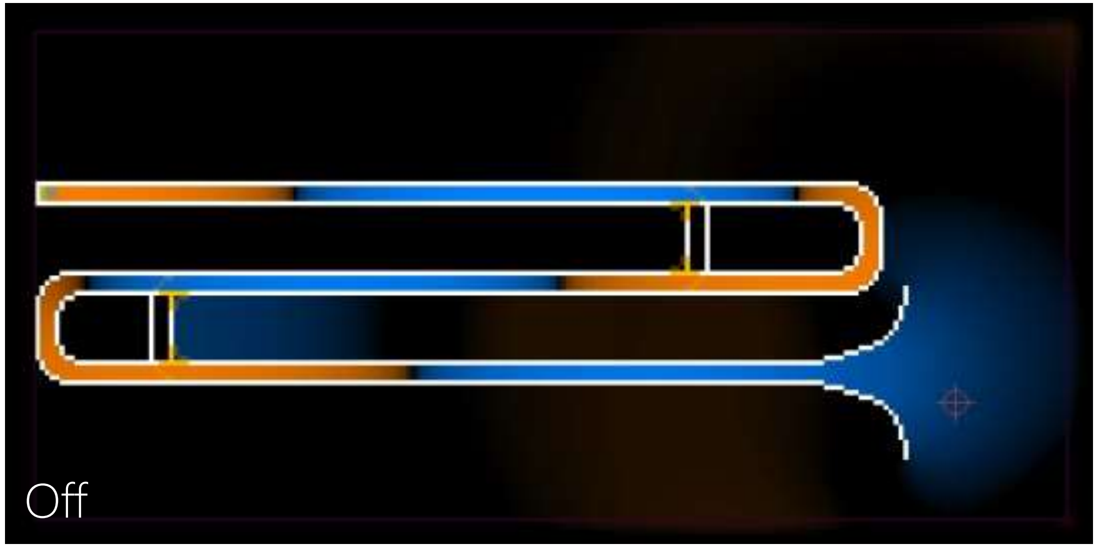
Wall losses

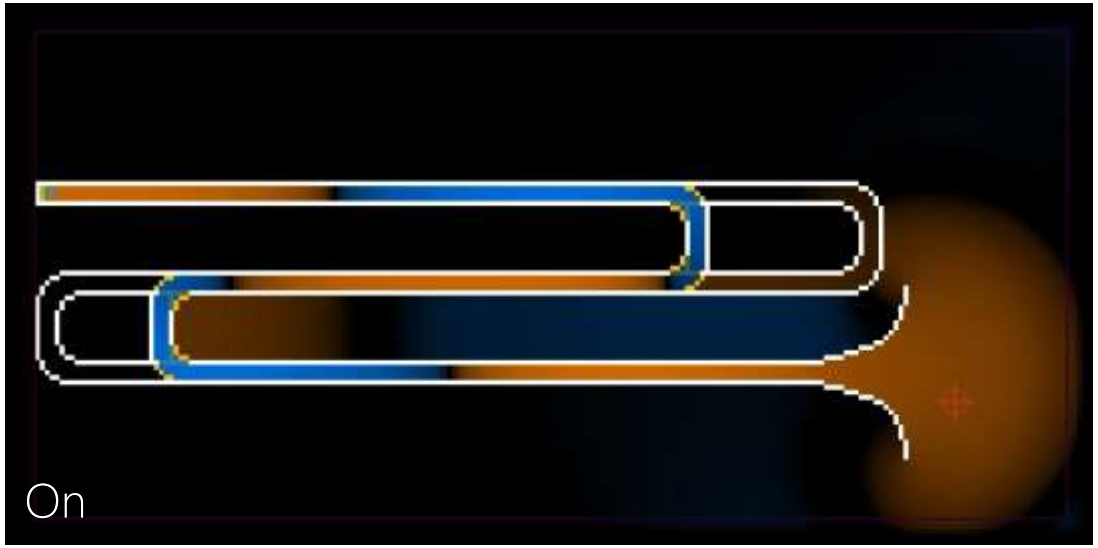




- 2D simulations support transverse resonances
- Wall loss modeling is required (unlike 1D models)

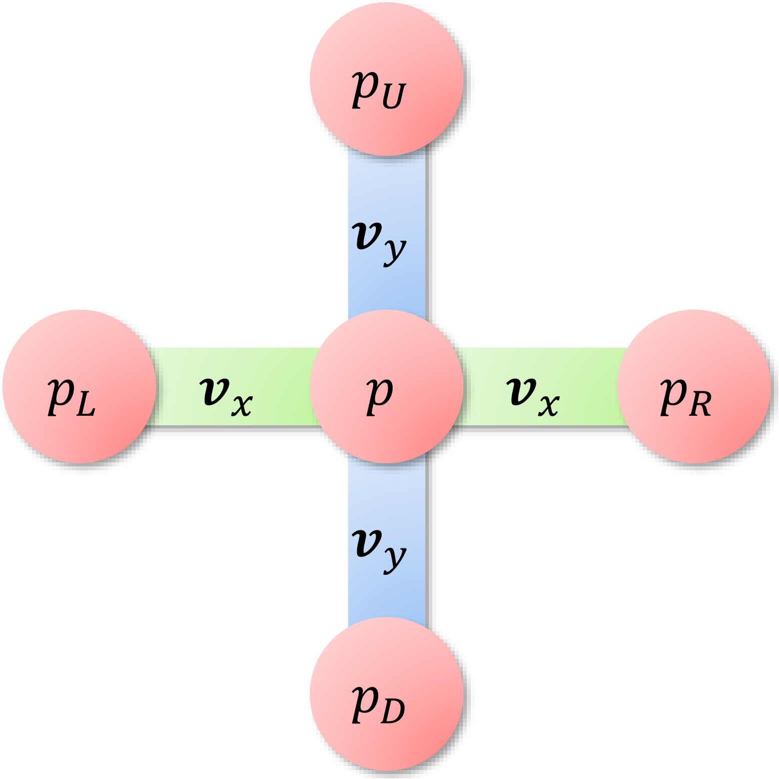
High-amplitude non-linearity





- Brass instruments have high amplitudes inside the bore.
- Makes brass sound brighter.

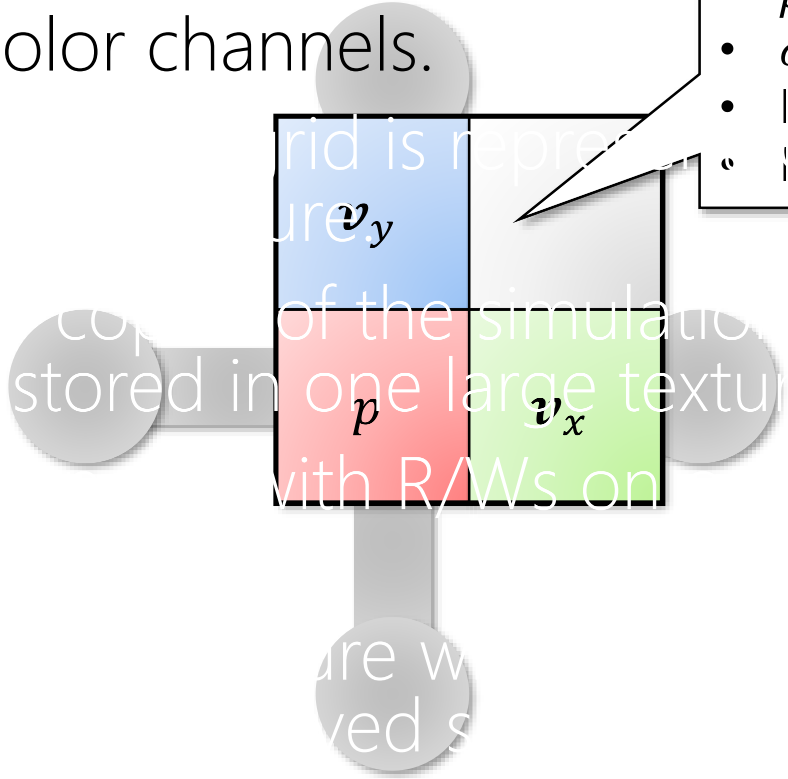
GPU Implementation



- Solving Finite Difference uses a 5-point 2D stencil.
- Neighbor pressures and velocities are used to update center pressure.

GPU Implementation

- Values for each cell are stored in color channels.



State structure stores:

- β value (boundary-ness)
- σ value (PML)
- Is Excitation?
- Is Listener?

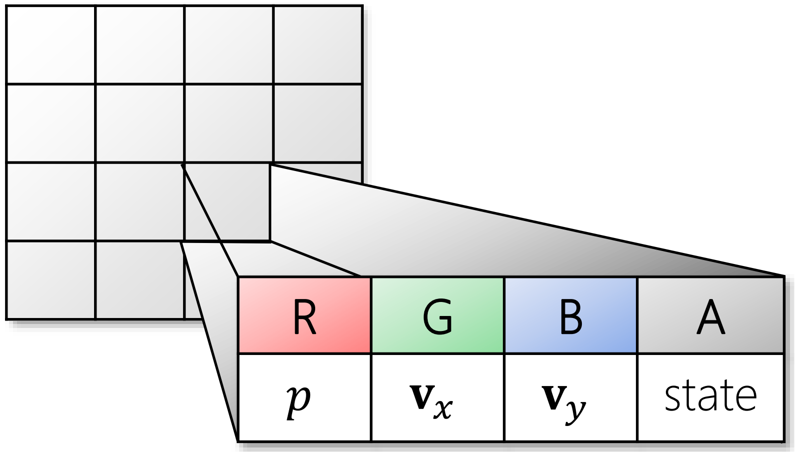
R	G	B	A
p	$\mathbf{v}_x$	$\mathbf{v}_y$	state

Per Fragment

GPU Implementation

- Values for each cell are stored in color channels.
- Simulation grid is represented as a 2D texture.

Framebuffer Texture

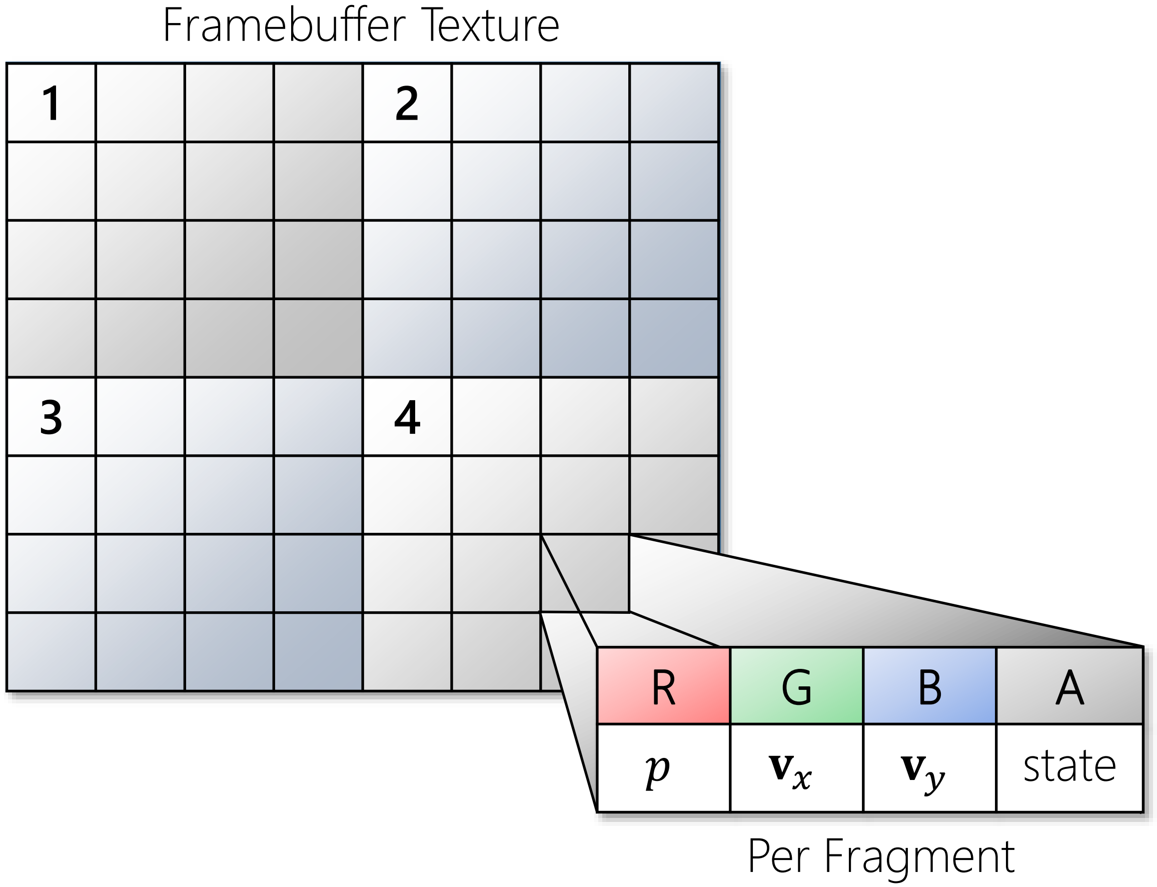


R	G	B	A
p	$\mathbf{v}_x$	$\mathbf{v}_y$	state

Per Fragment

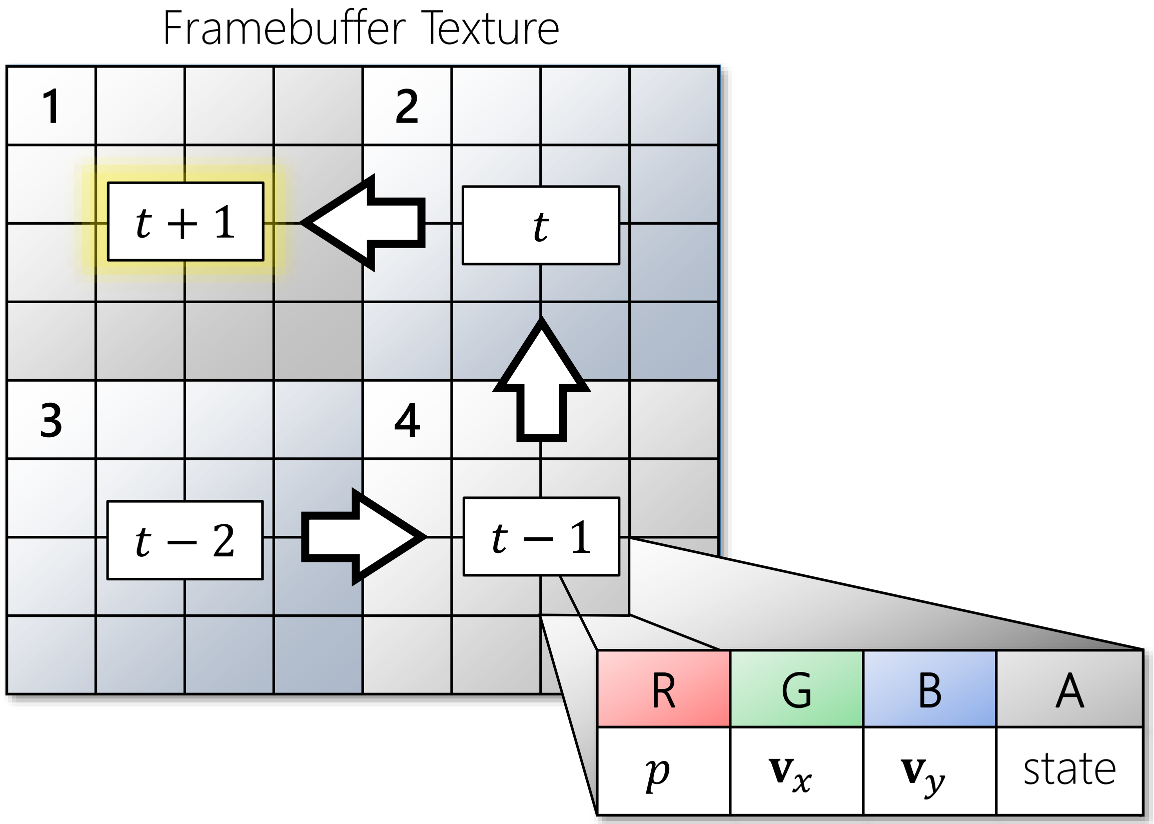
GPU Implementation

- Values for each cell are stored in color channels.
- Simulation grid is represented as a 2D texture.
- Four copies of the simulation are stored in one large texture.



GPU Implementation

- Values for each cell are stored in color channels.
- Simulation grid is represented as a 2D texture.
- Four copies of the simulation are stored in one large texture.
- Ping-pong with R/Ws on one texture.



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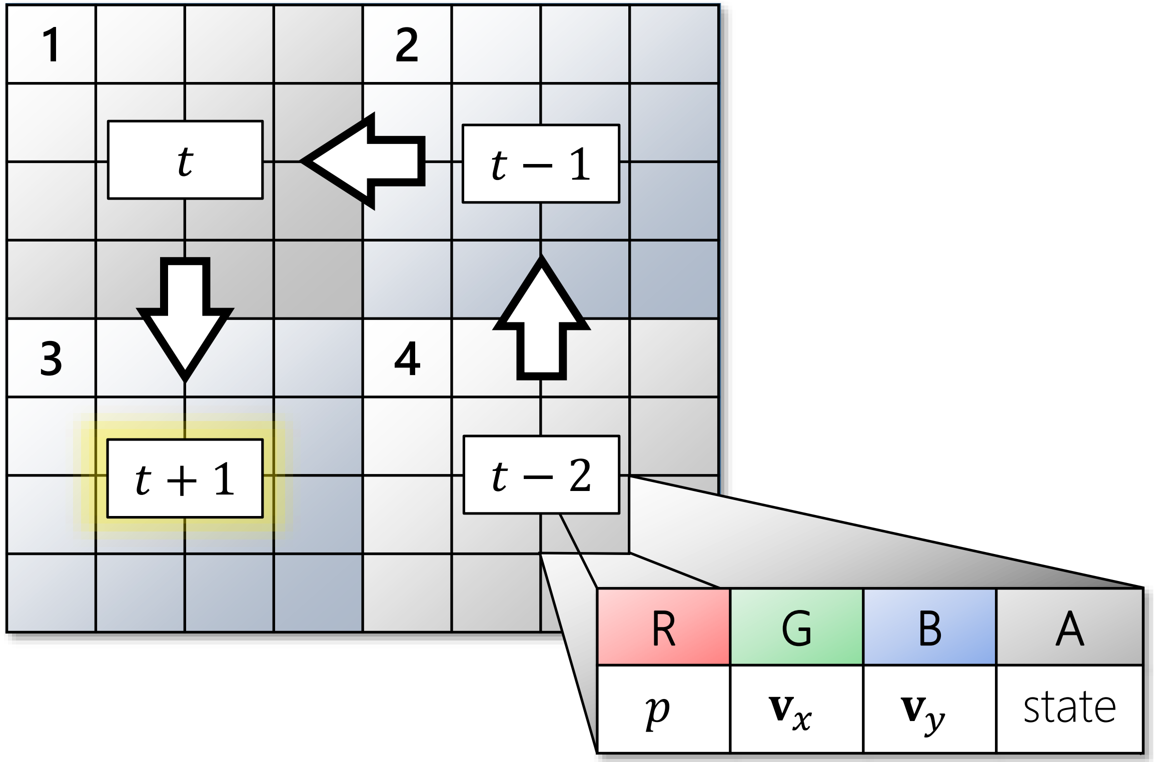

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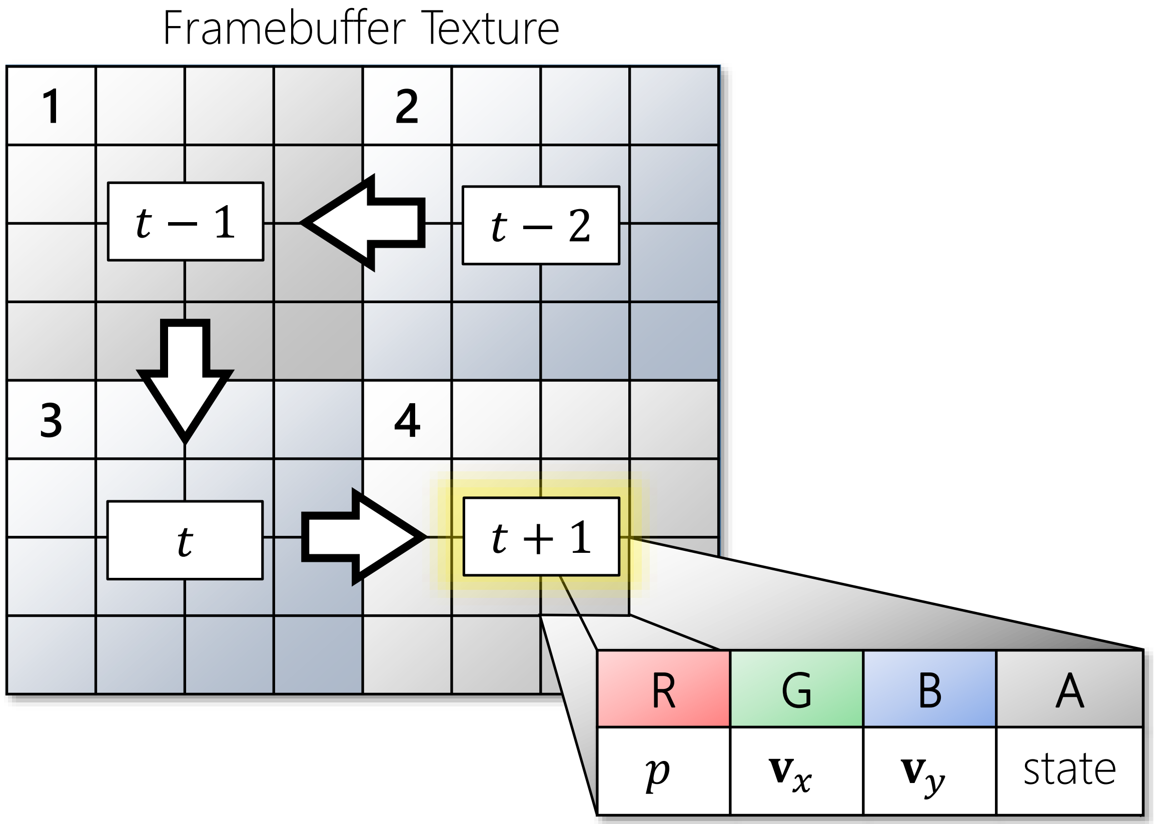

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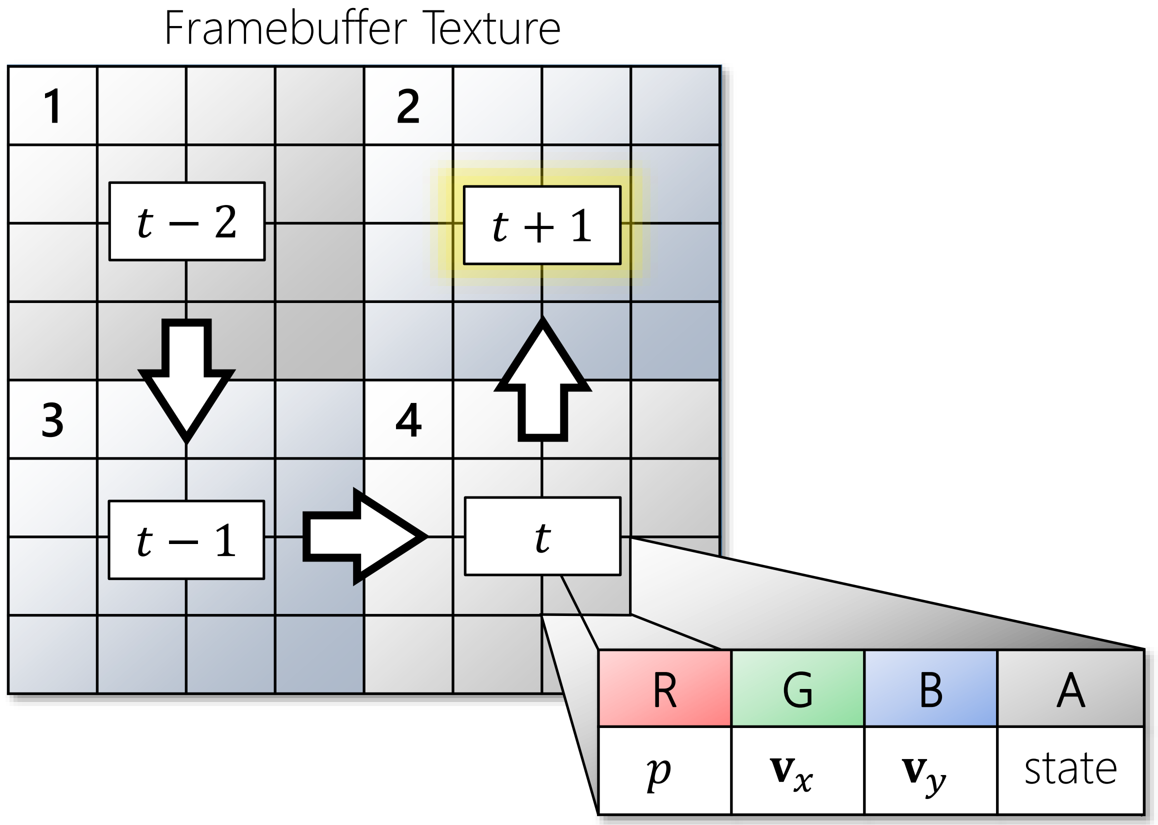

GPU Implementation

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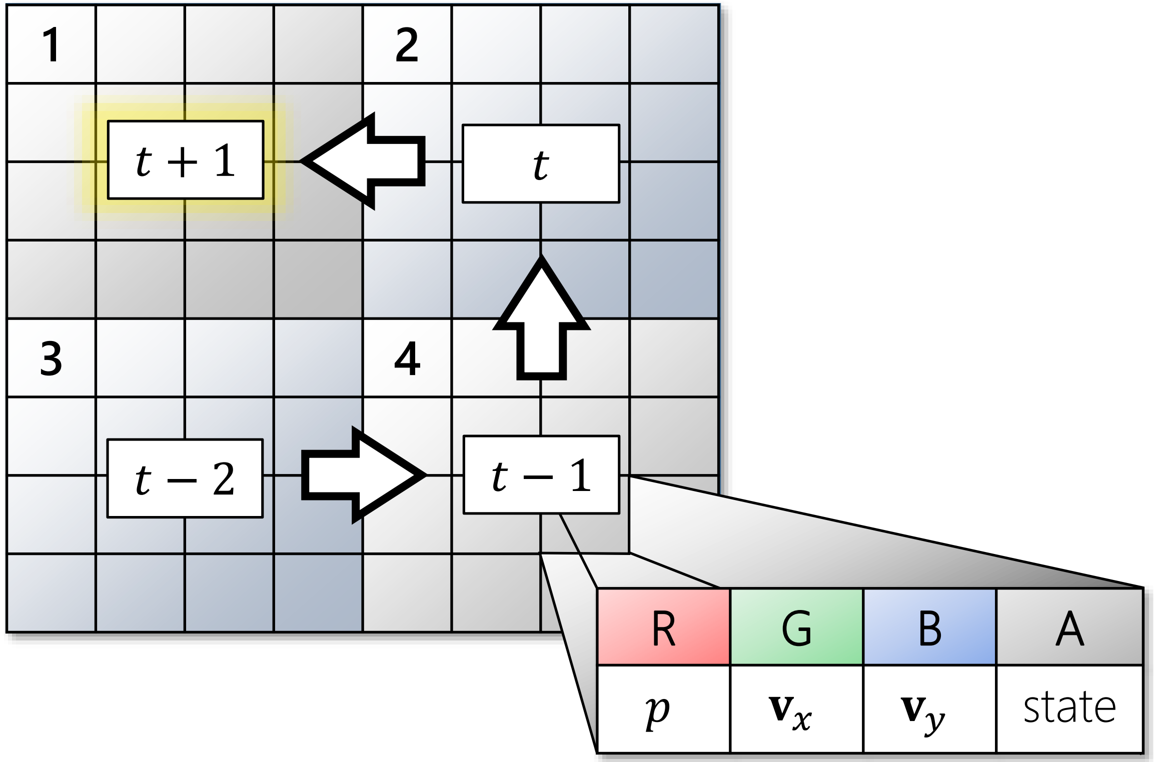
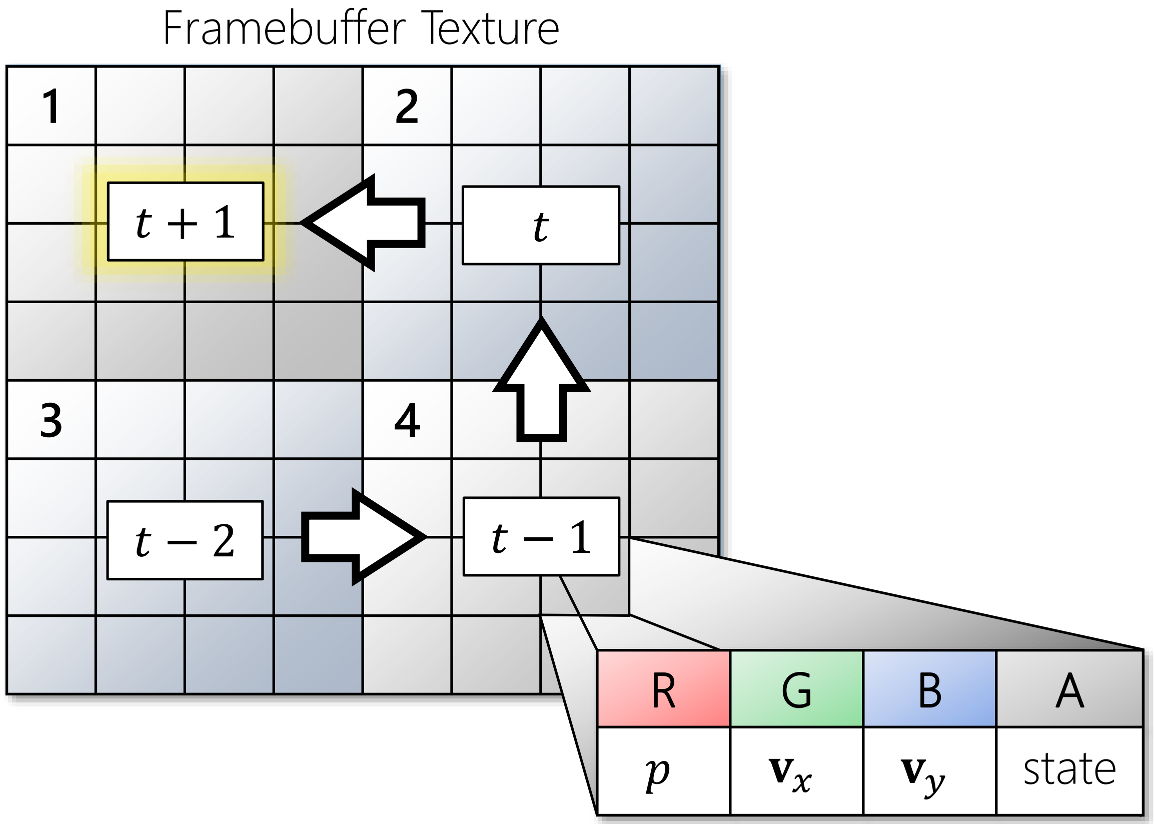
Framebuffer Texture

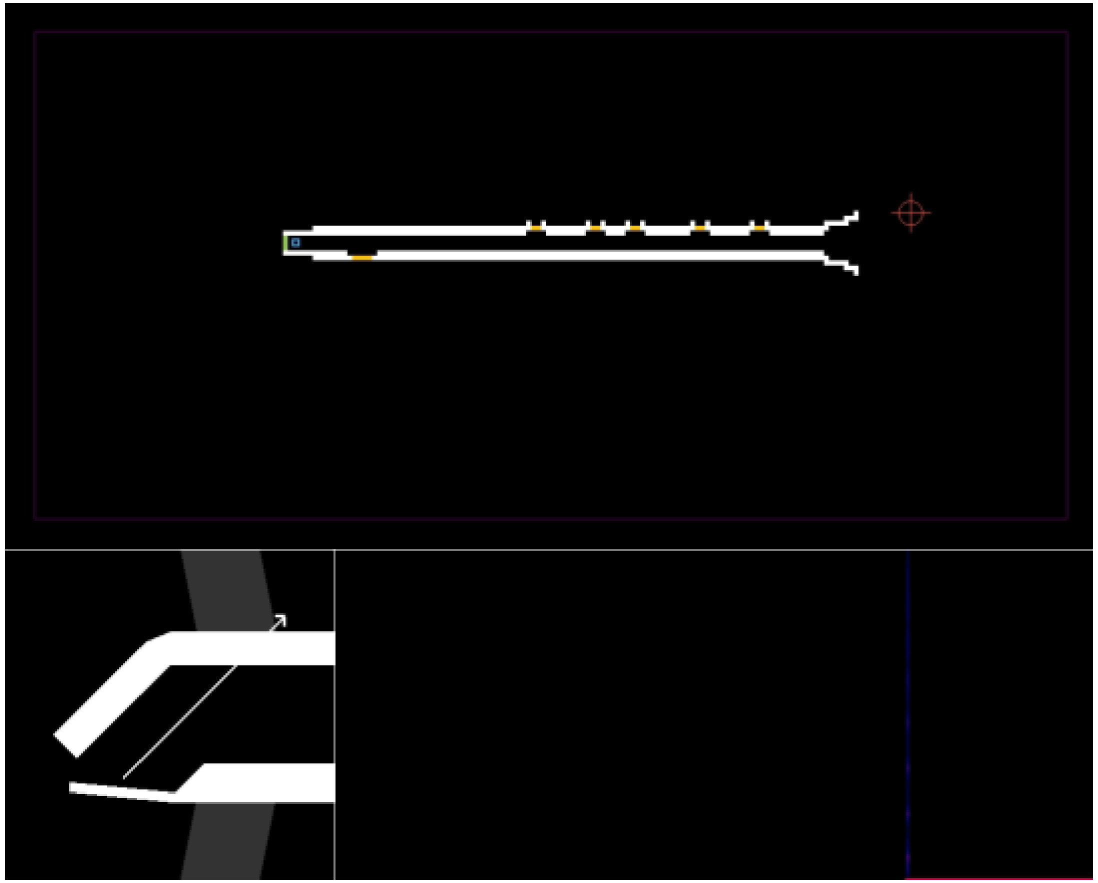


GPU Implementation

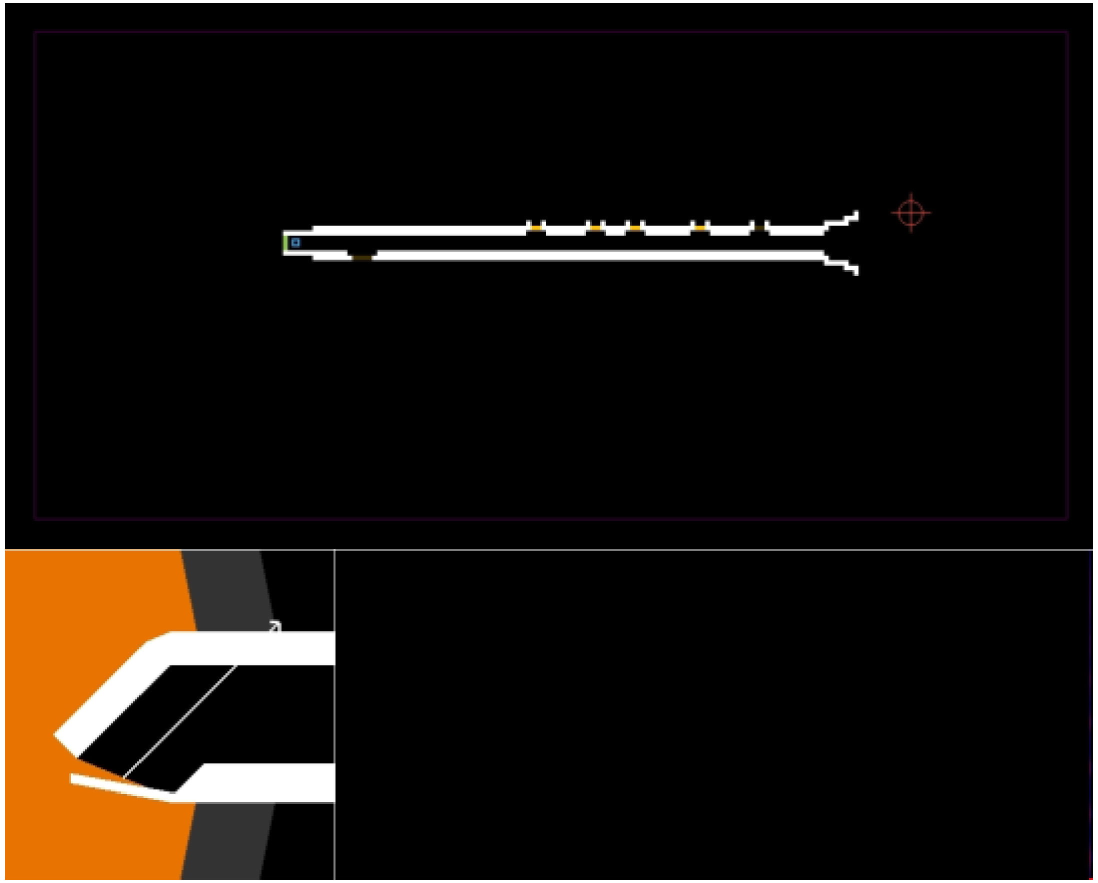
- Values for each cell are stored in color channels.
- Simulation grid is represented as a 2D texture.
- Four copies of the simulation are stored in one large texture.
- Ping-pong with R/Ws on one texture.
- Write output pressure (sound) to reserved space on the FBO.



Clarinet

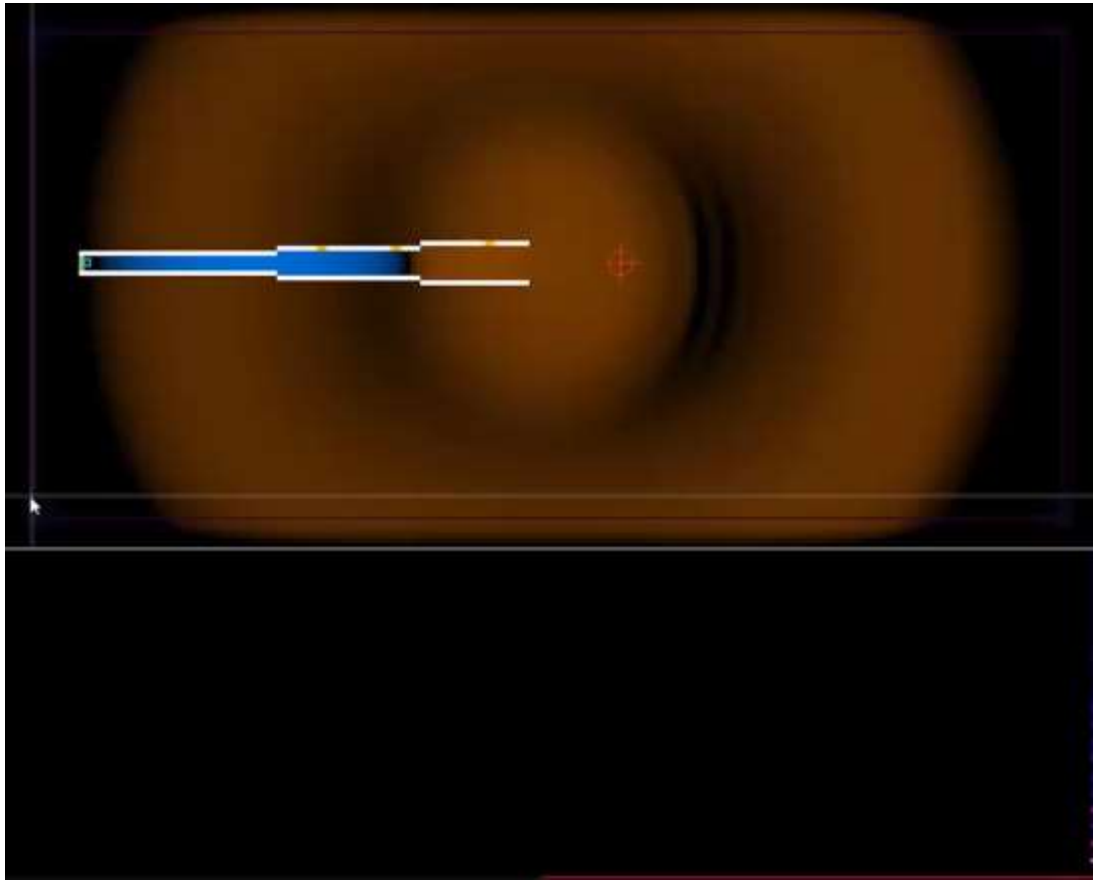


Chalumeau melody

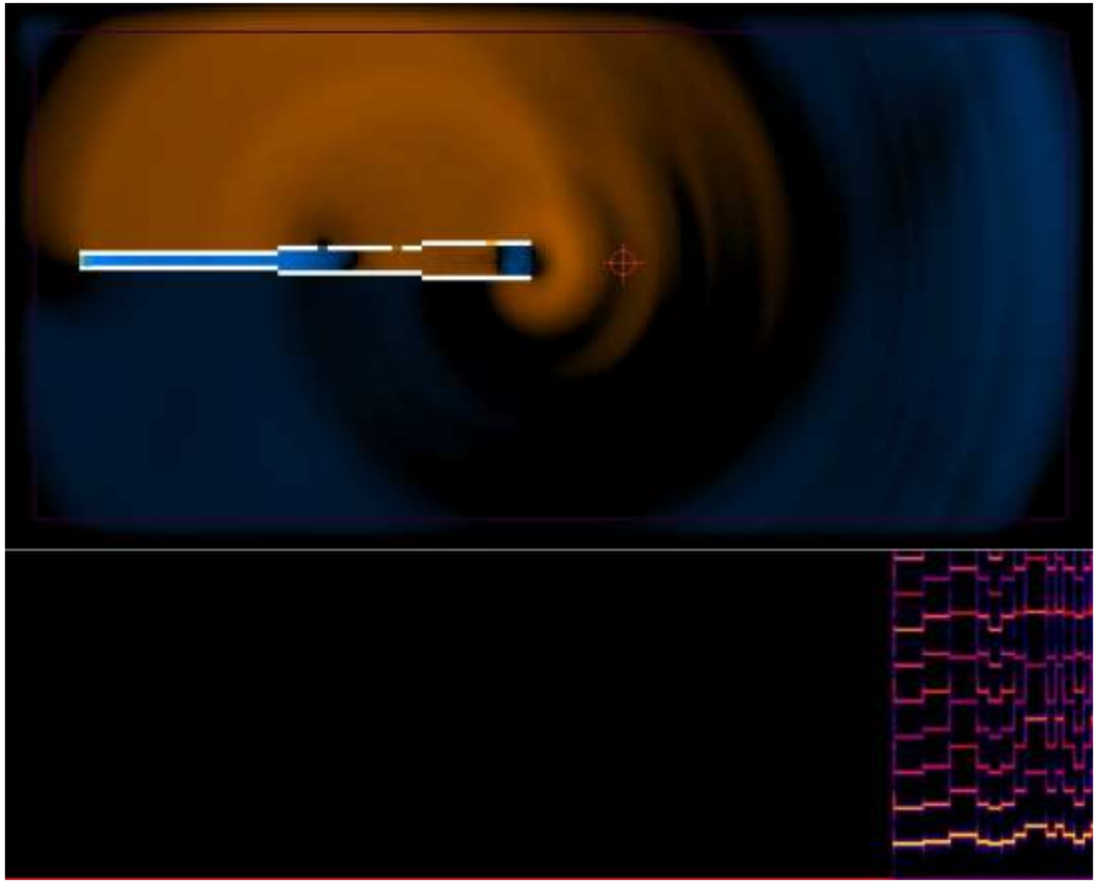


Altissimo melody (register key)

Saxophone

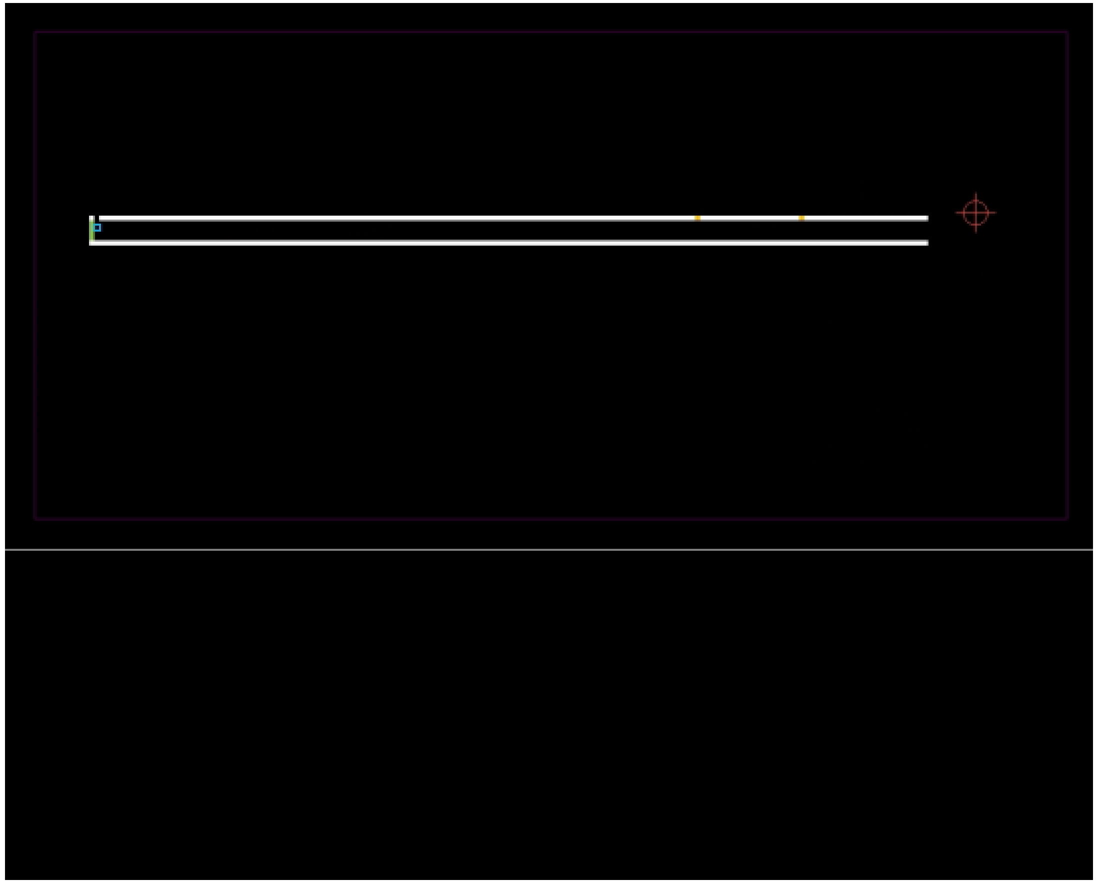


Simple melody

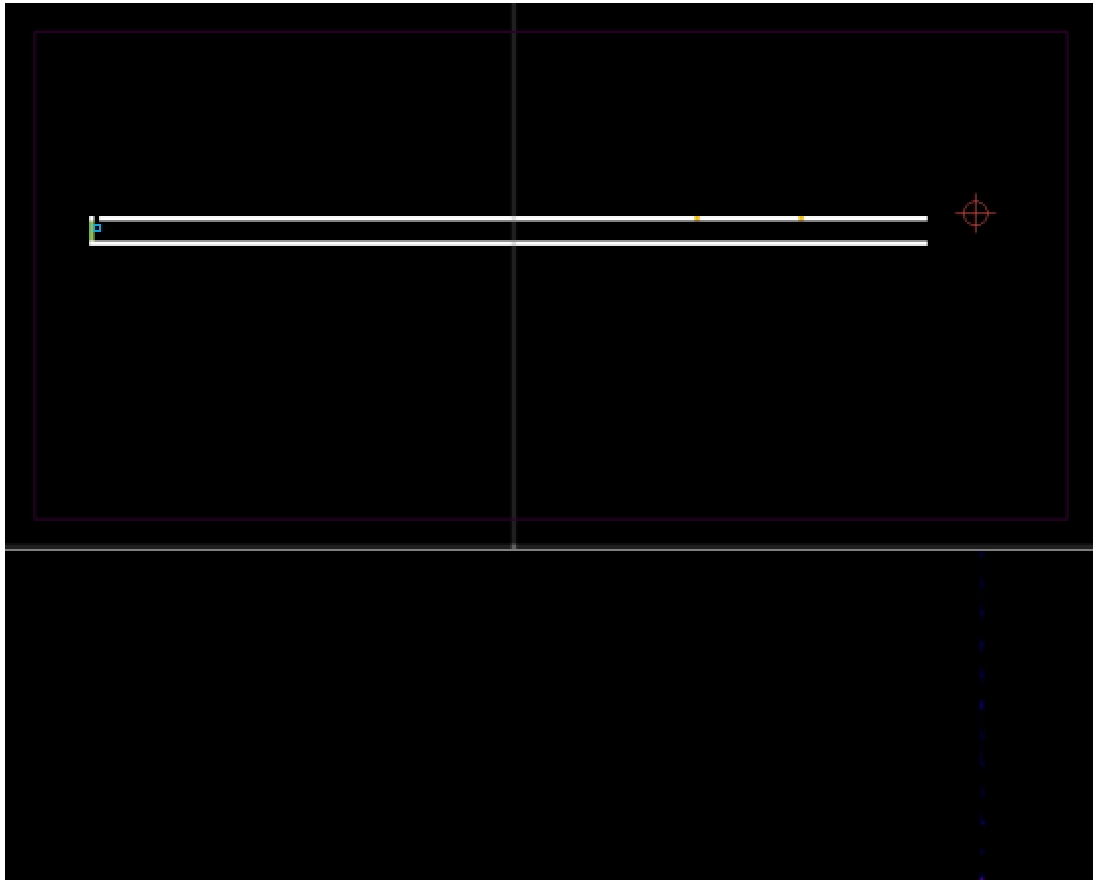


Fast Squeaks

Flute

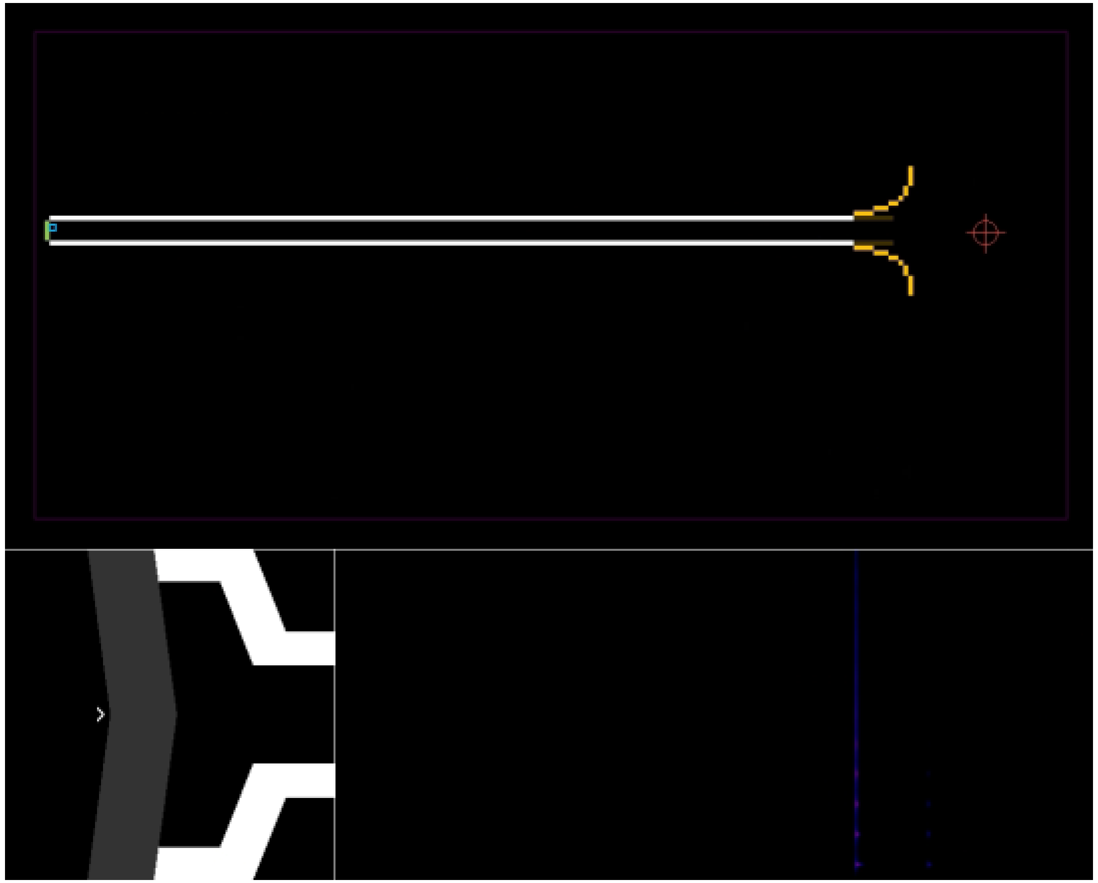


“Robot” Performer

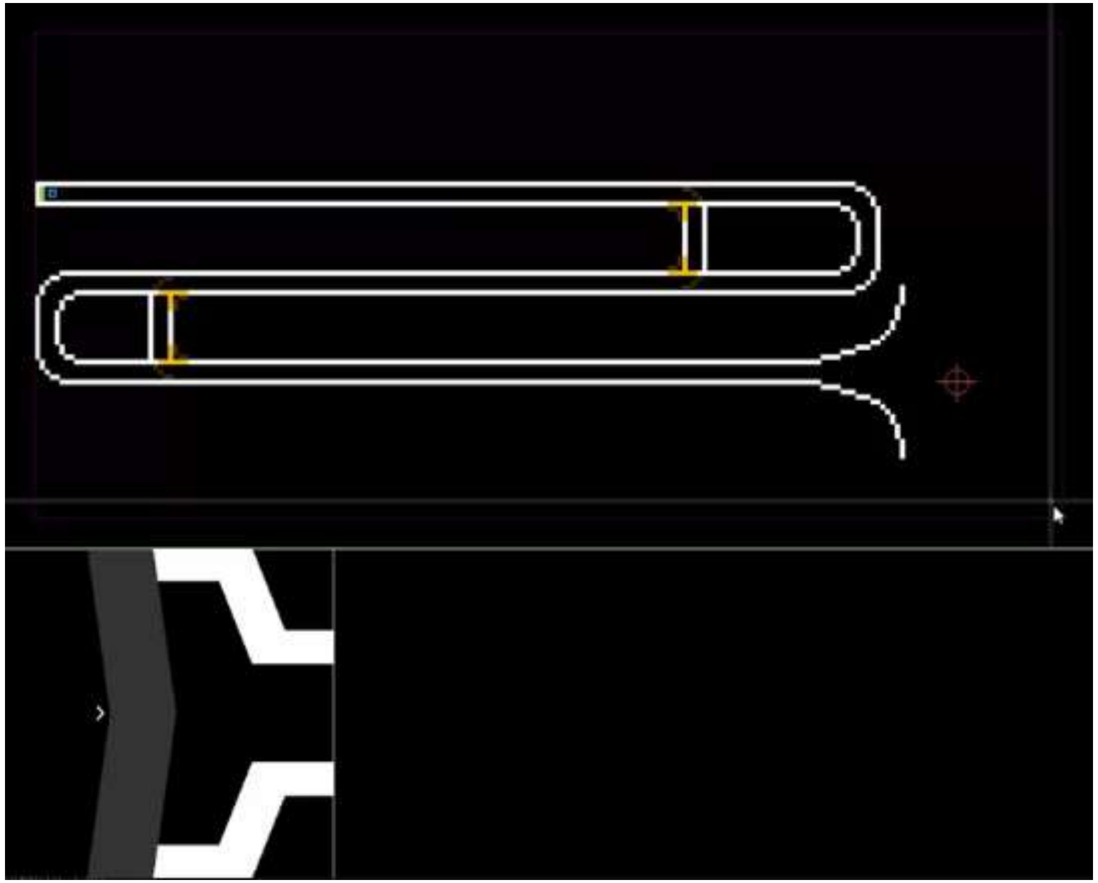


Wind Controller Interface

Bugle & Trumpet (brasses)

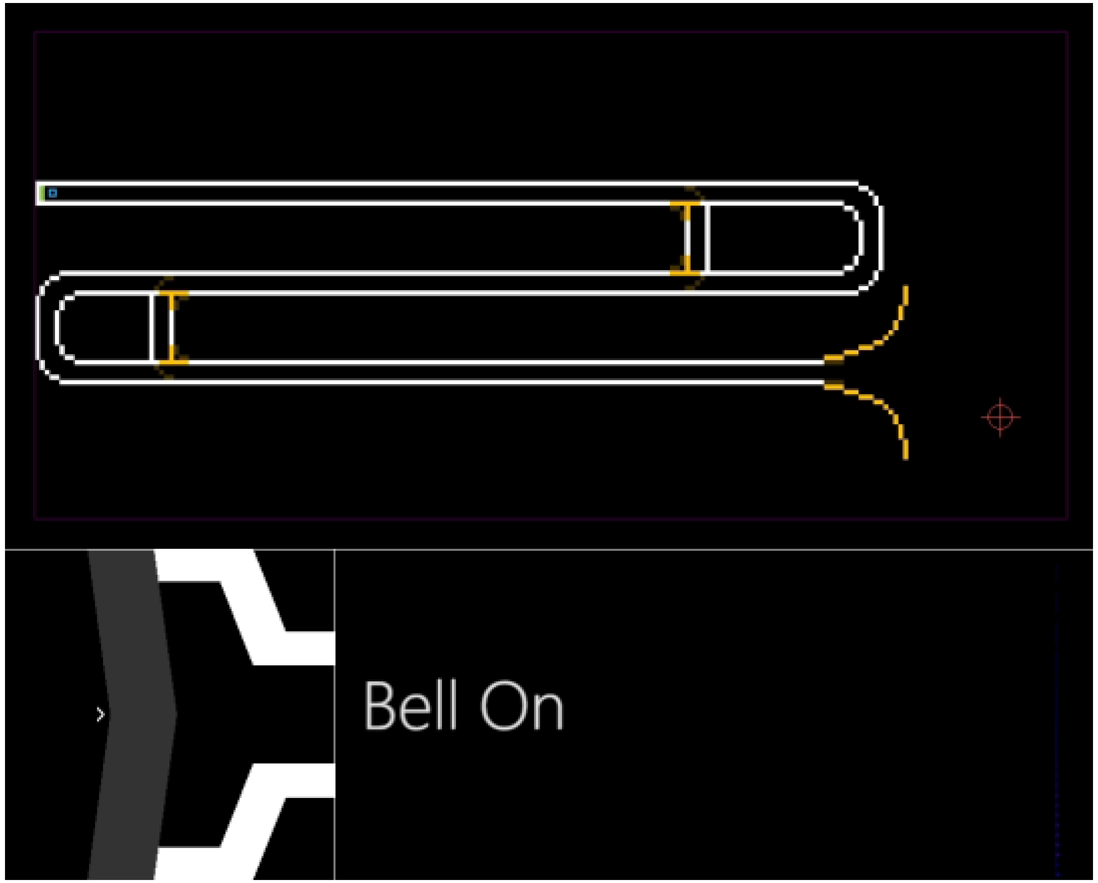


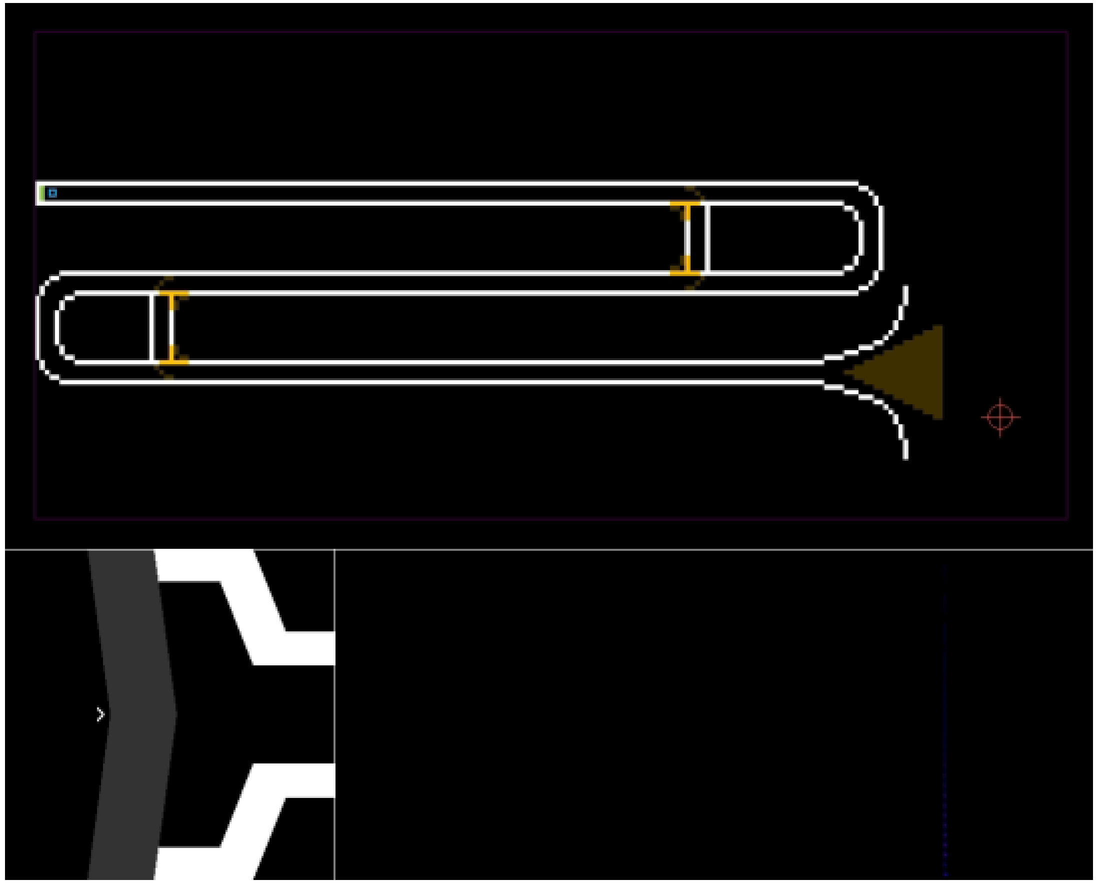
Lips Overblowing



Valve System

Trumpet w/o Bell and w/ Mutes

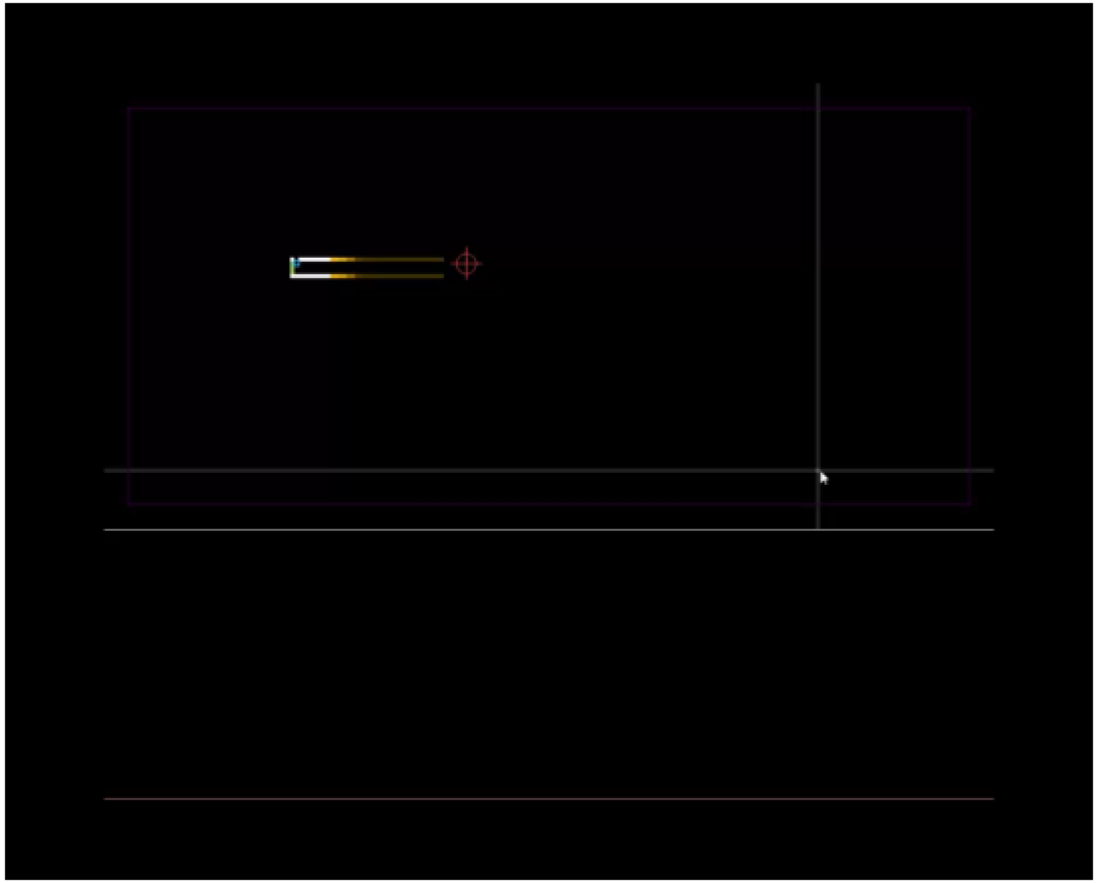




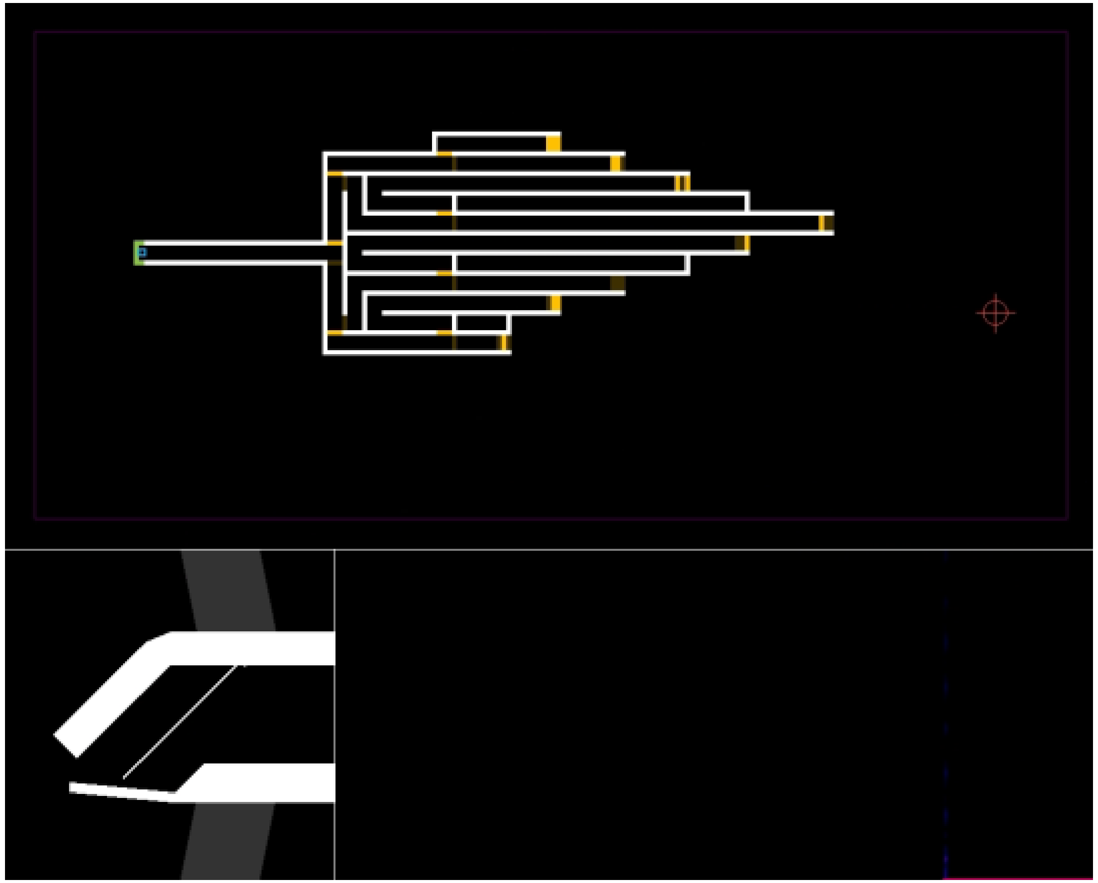
Bell On/Off

Straight, Cup and Harmon Mute

“Slide Whistle” and “Menorah”

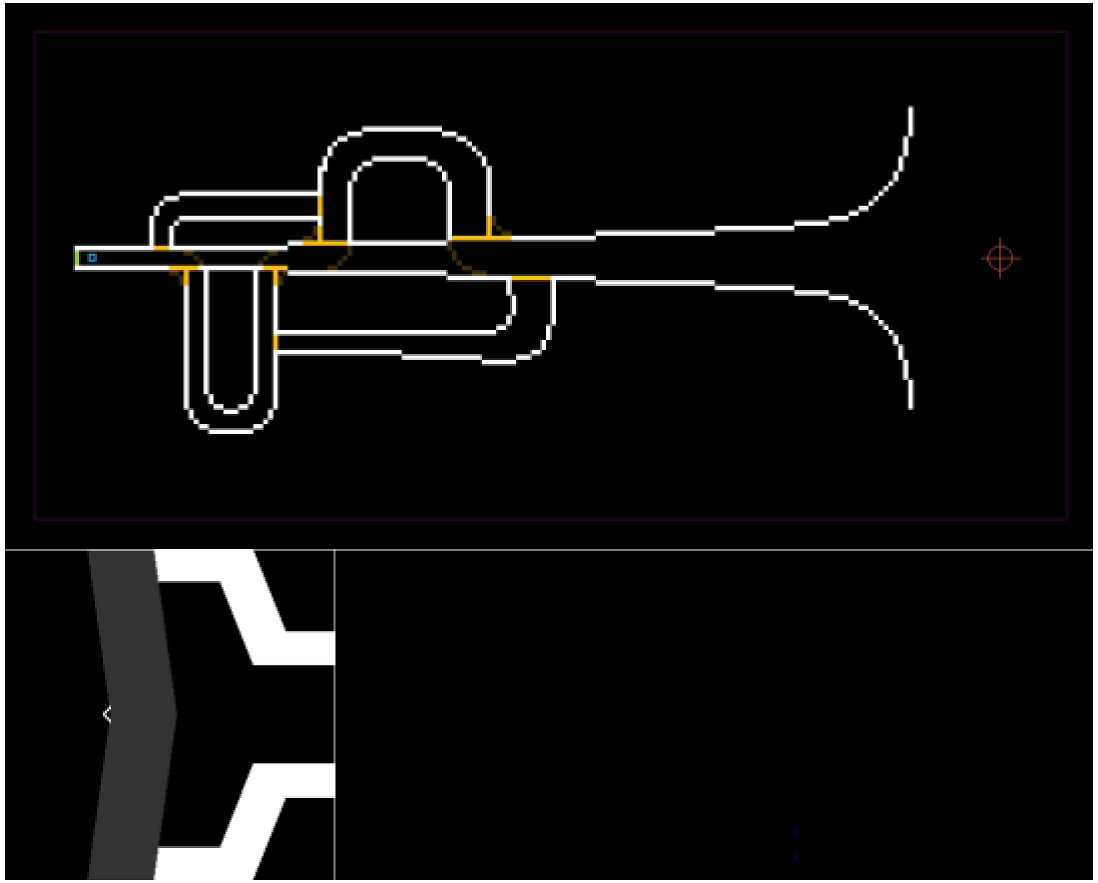


Dynamic Bore Geometry

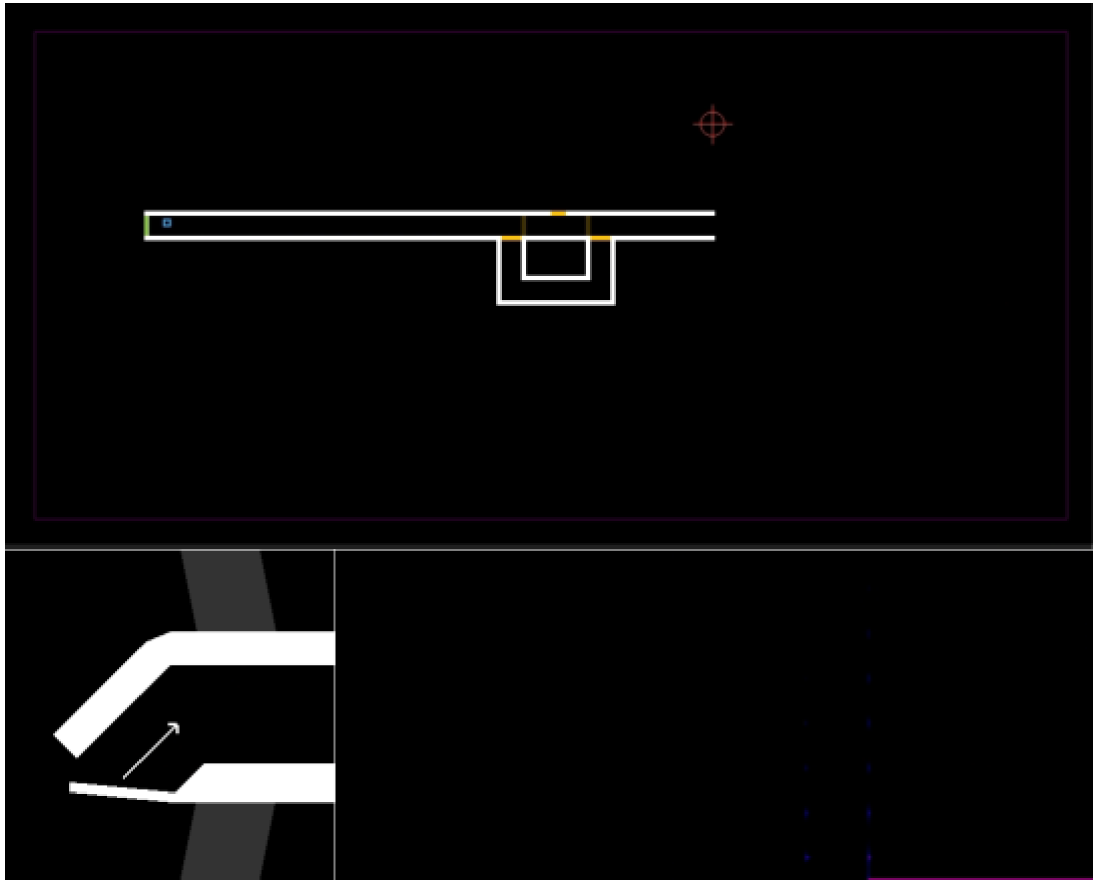


Interlocking Valve System

“Tuba?” and “Hybrid”

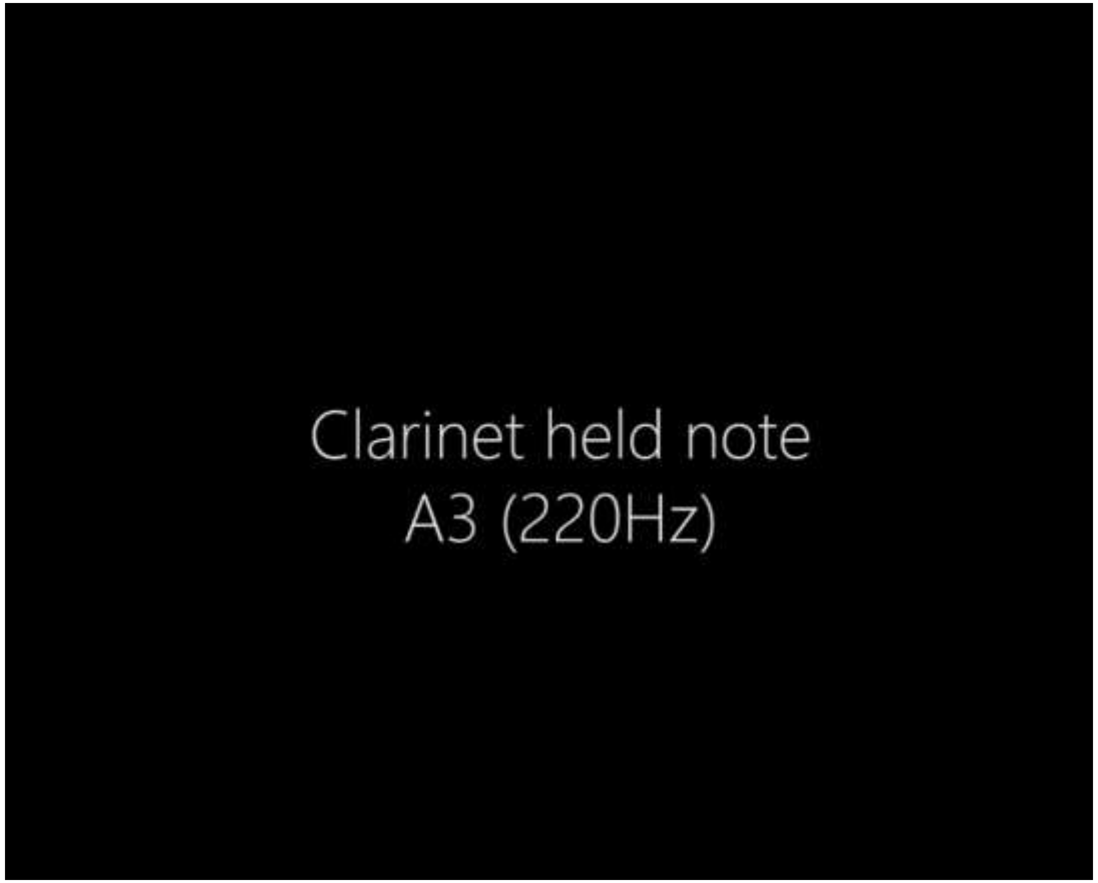


Implausible-to-construct Instrument



Reed, Lips, Valve, Tonehole, Bell

Comparisons to STK (Digital Waveguides)



Clarinet held note
A3 (220Hz)

Low note

Clarinet register key
C#6 (1109Hz)

High note

Conclusions and Future Work

- First system for real-time 2D simulation of Aerophones

- Improving the control of excitation mechanisms
- Automatic tuning of geometry
- Generalized excitation model
- Modeling of larynx/syrinx (speech synthesis/bird song)

Thank You! Questions?

Special thanks for providing performances –

- Kyle Rowan, clarinetist
- Paul Hembree, trumpeter