SIGGRAPH2015

Xroads of Discovery

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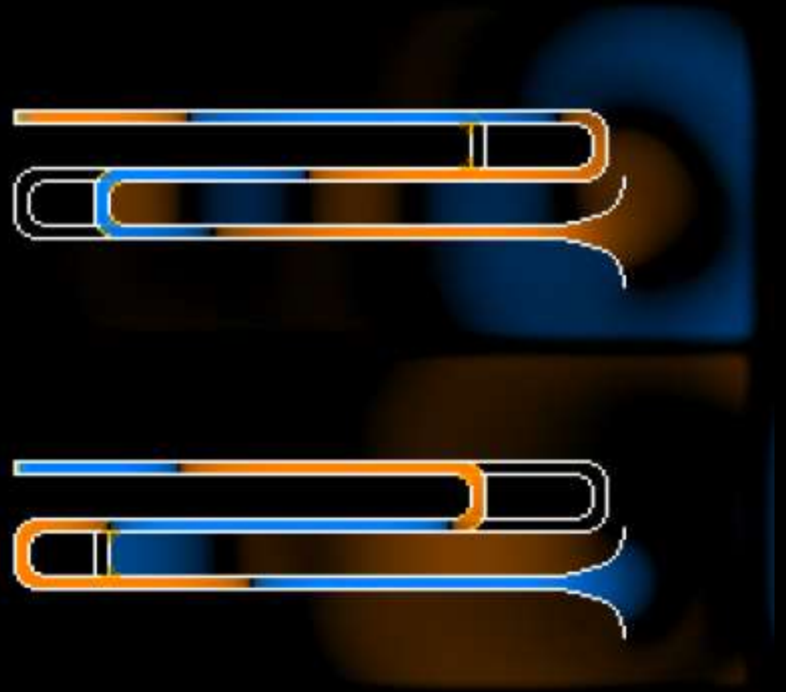
The 42nd International Conference and Exhibition
on Computer Graphics and Interactive Techniques

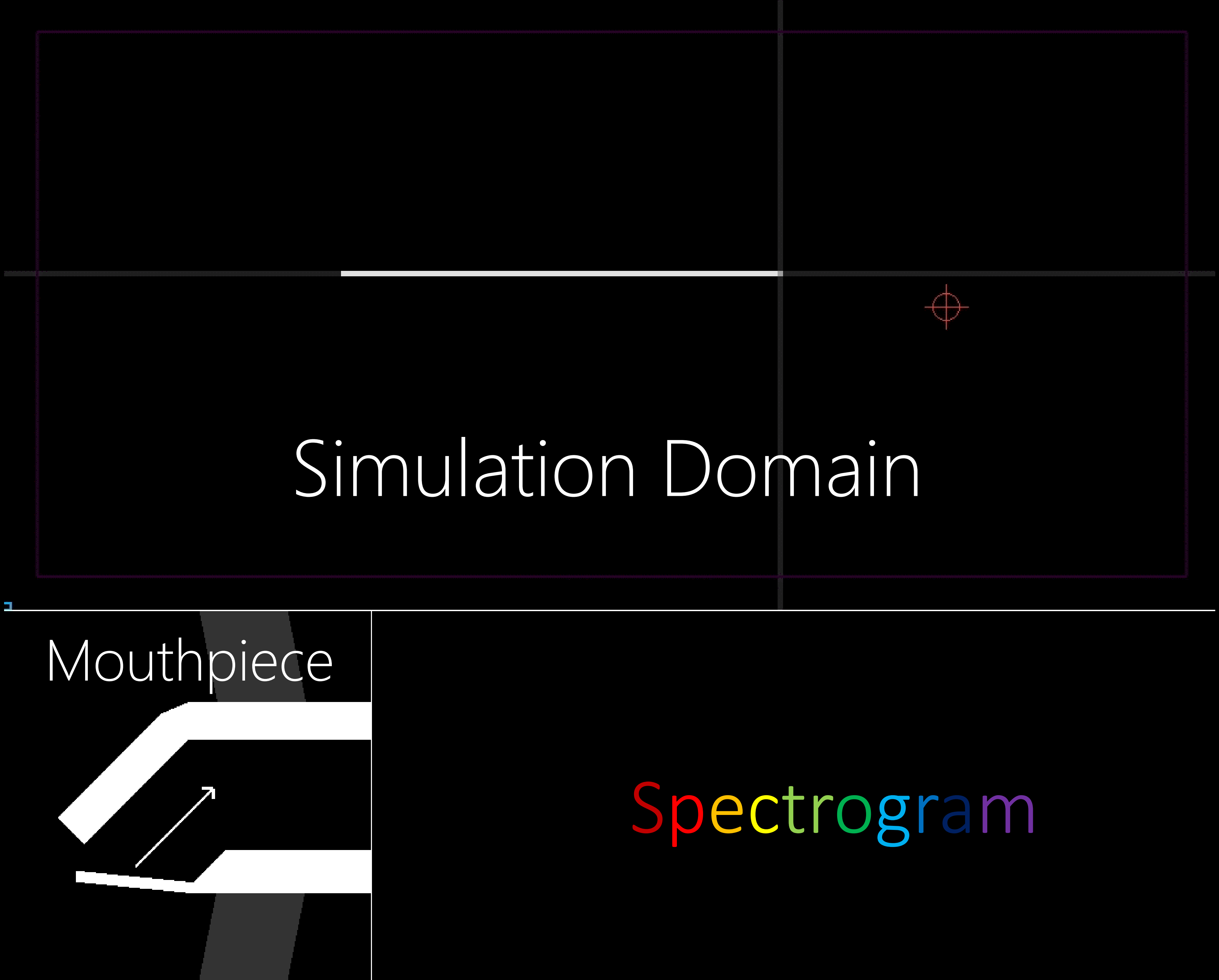


Microsoft® Research

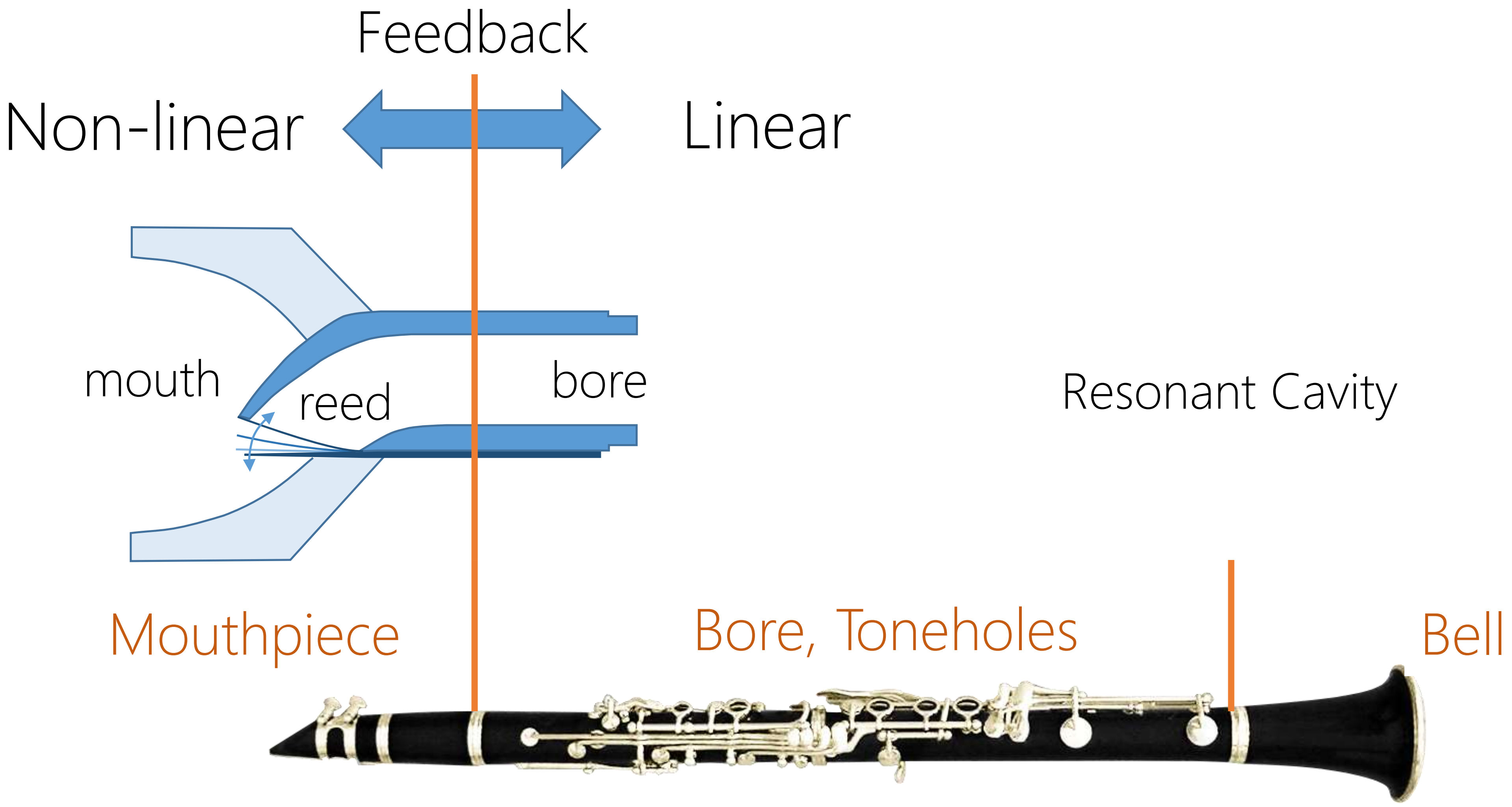
Aerophones in Flatland

Interactive Wave Simulation of Wind Instruments

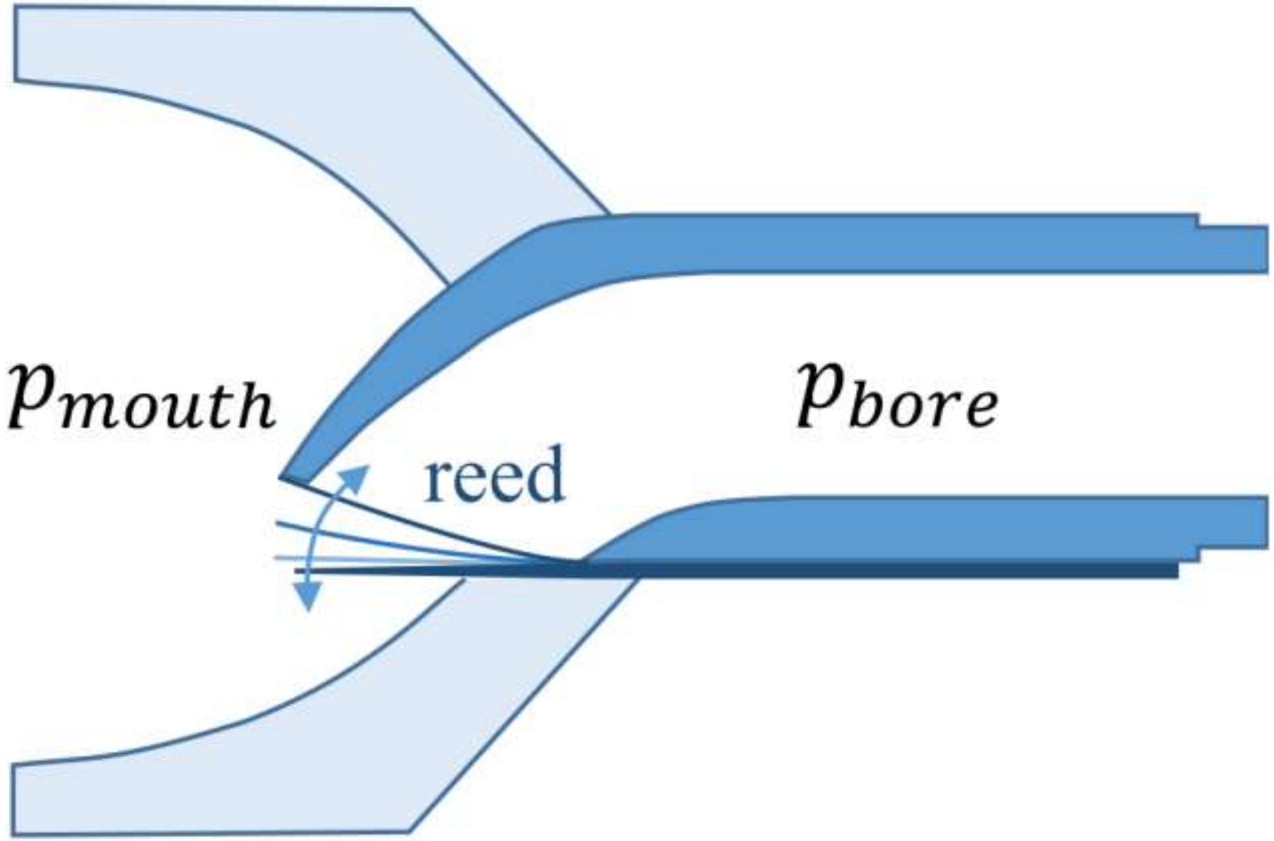
Andrew Allen
Nikunj Raghuvanshi


Simulation Domain
Mouthpiece
Spectrogram

Wind Instruments

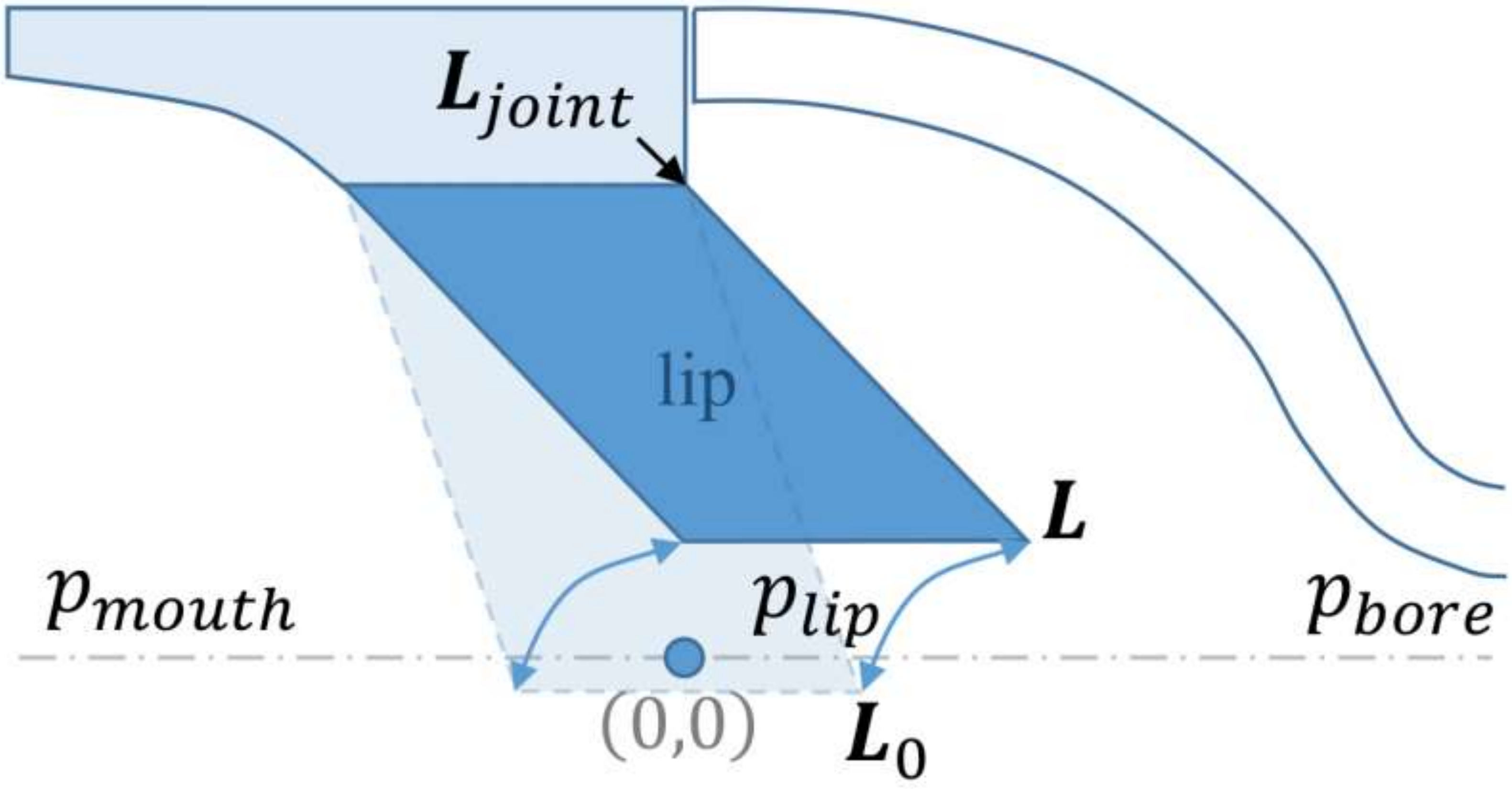


Excitation models: Single Reed (Clarinet)



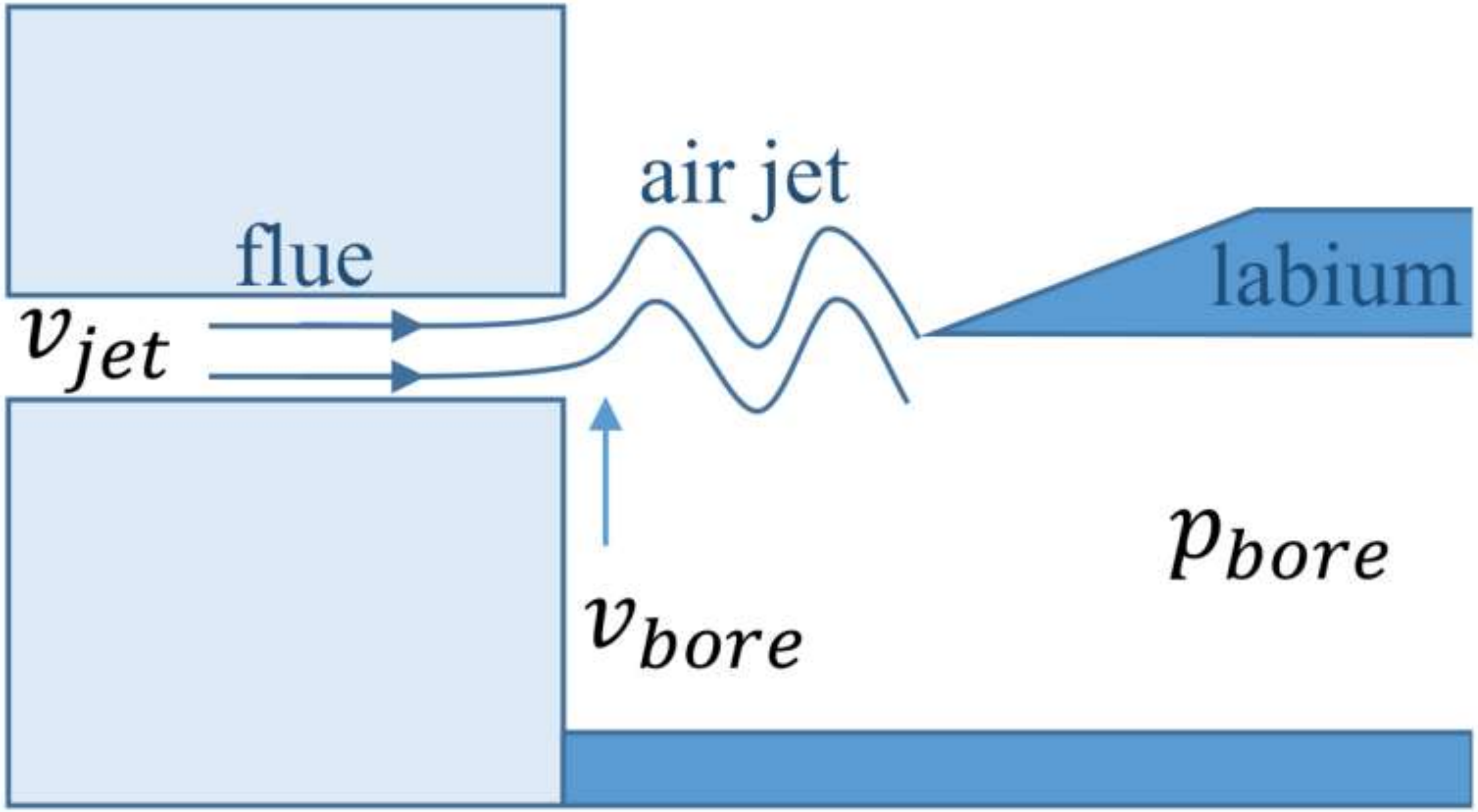
Dalmont, J.P., Gilbert J., and Ollivier, S. 2003.

Excitation models: Lips (Trumpet)



Adachi and Sato. 1996.

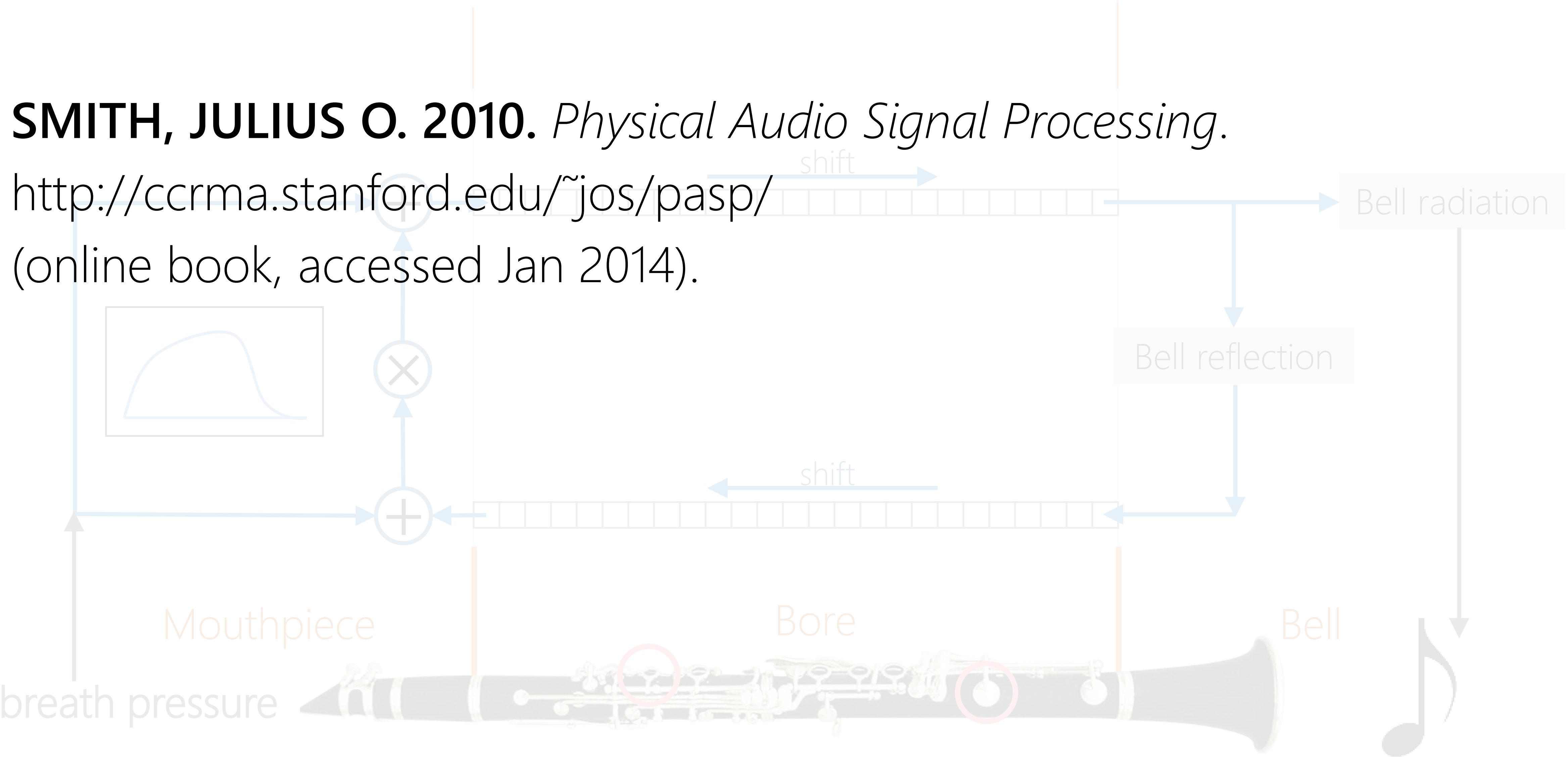
Excitation models: Air Jet (Flute)



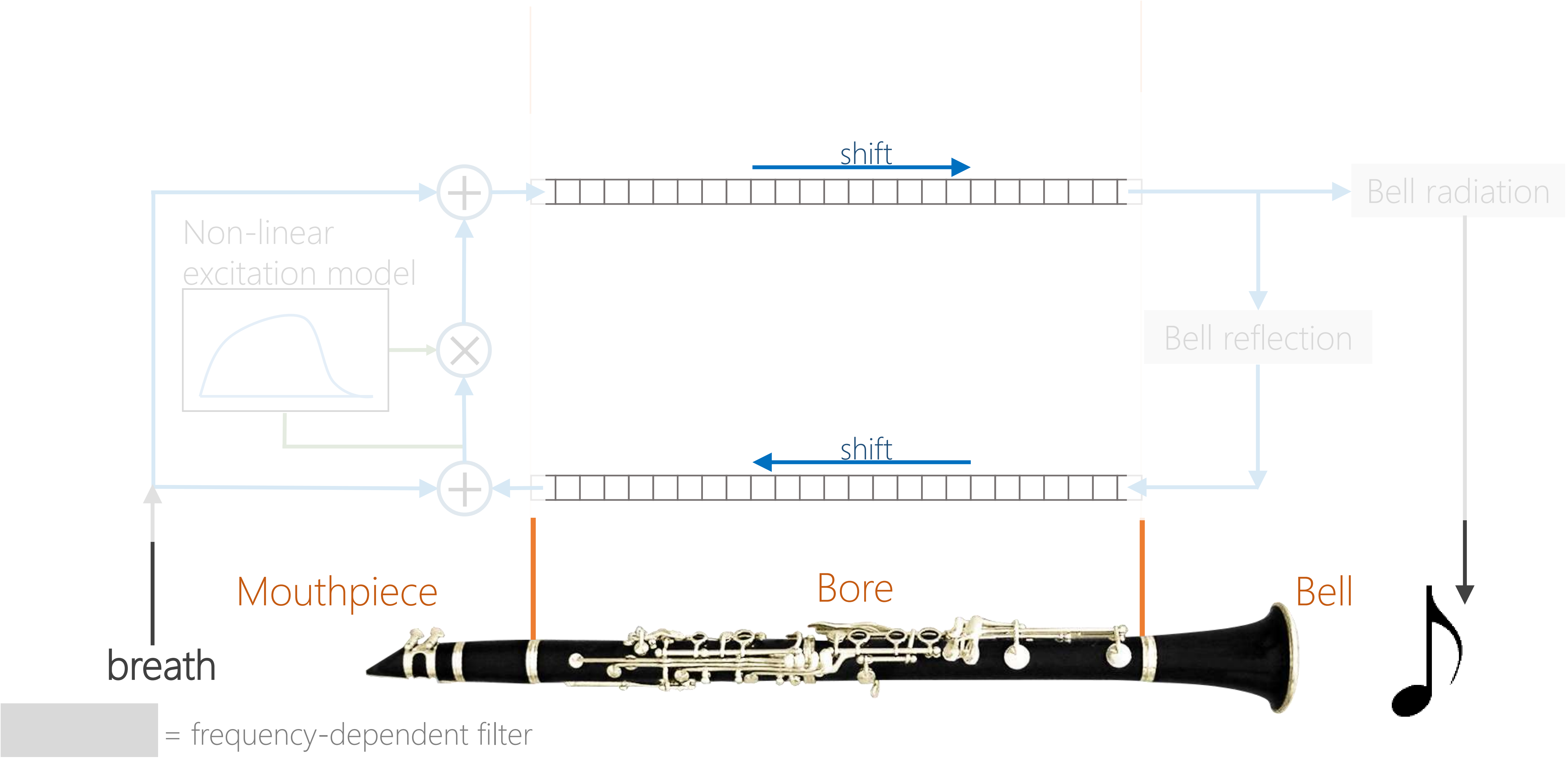
de La Cuadra. 2006.

Realtime synthesis: Digital Waveguides

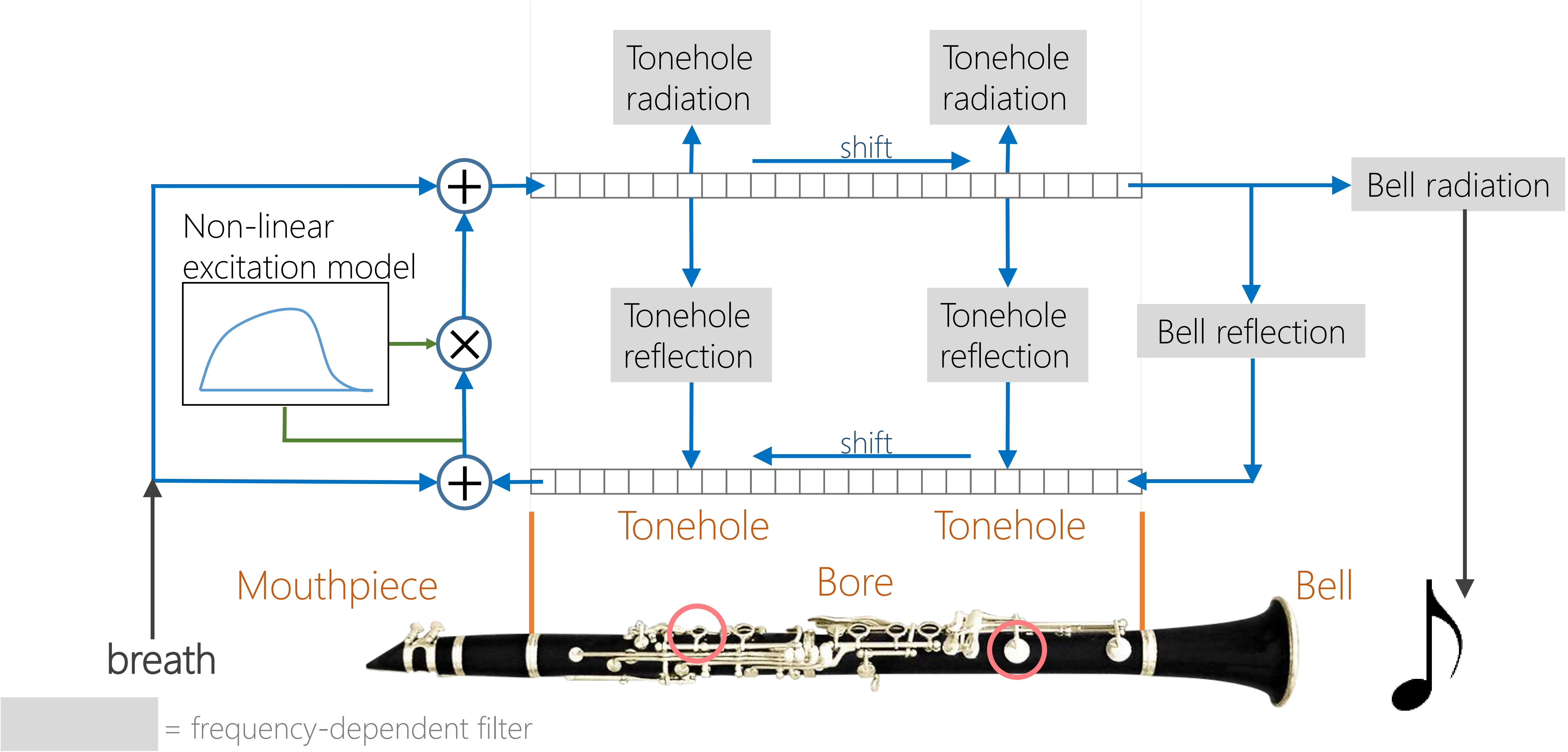
SMITH, JULIUS O. 2010. *Physical Audio Signal Processing*.
http://ccrma.stanford.edu/~jos/pasp/
(online book, accessed Jan 2014).



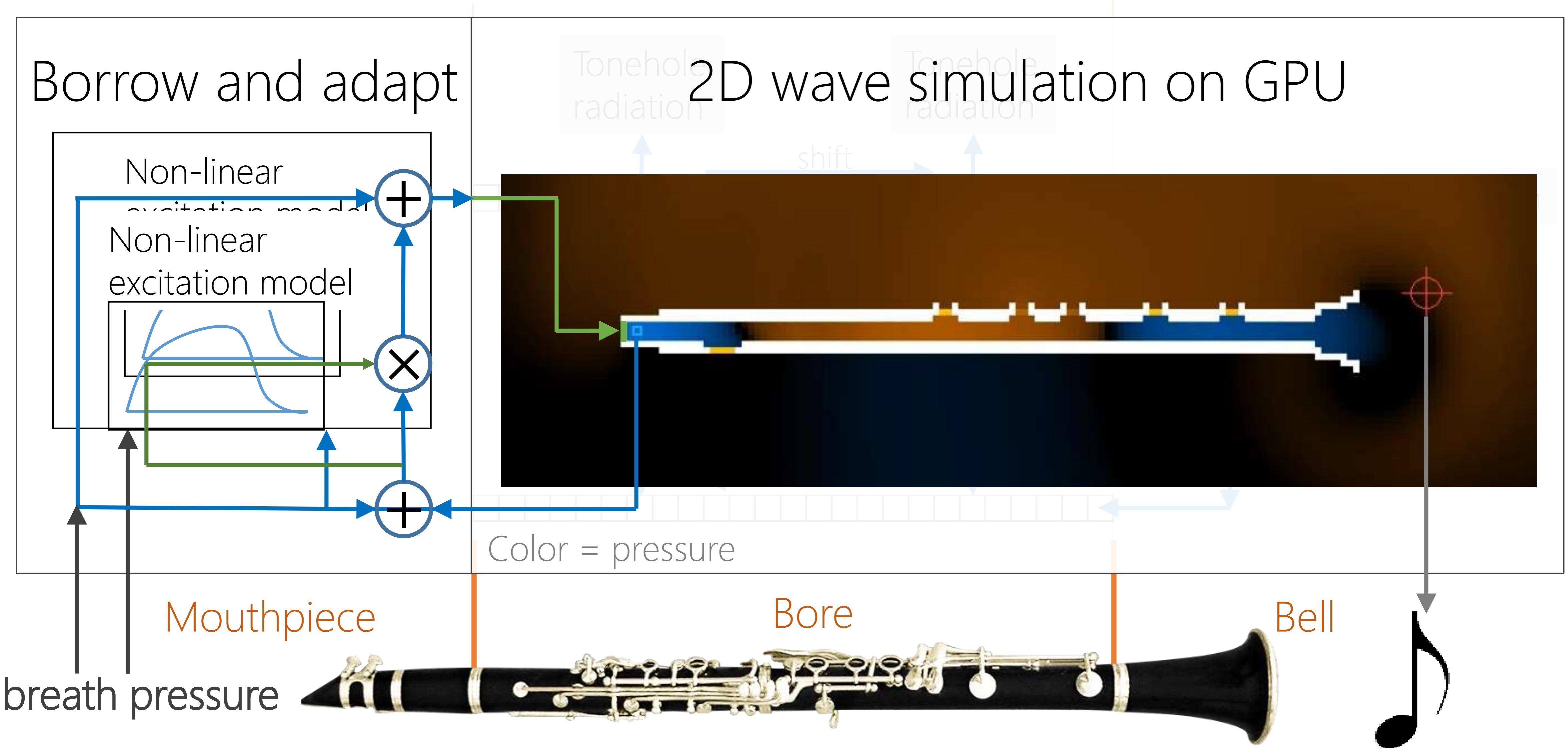
Realtime synthesis: Digital Waveguides

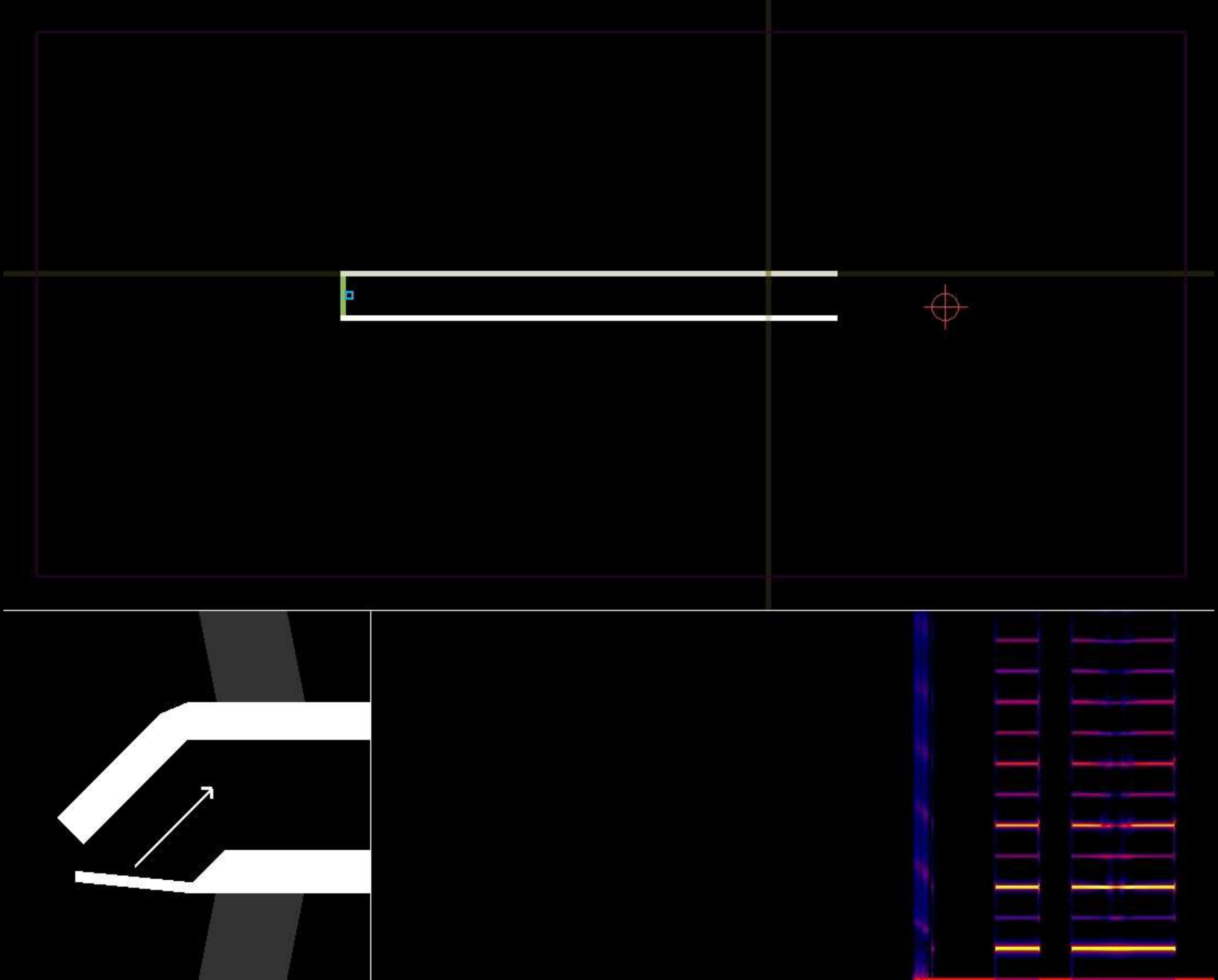


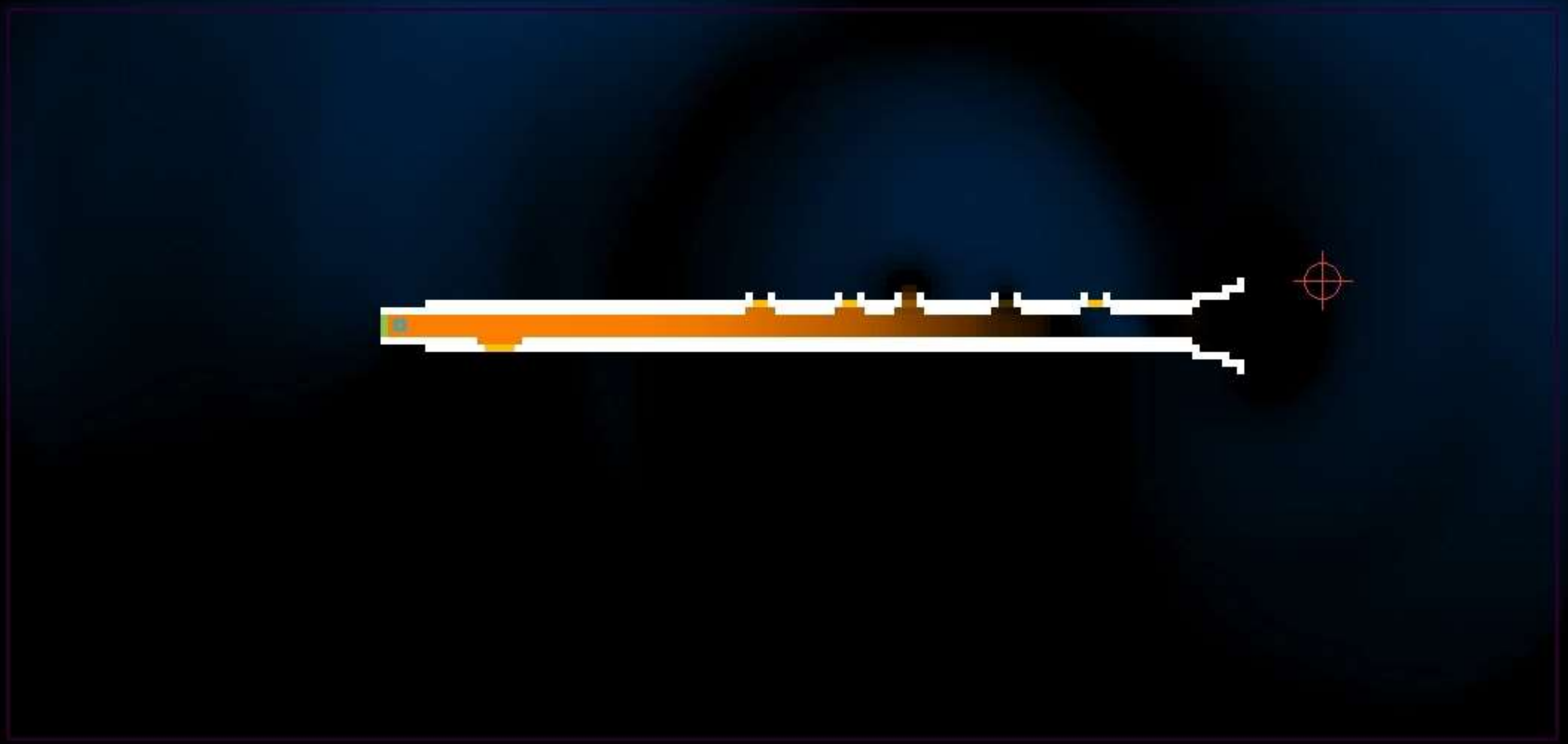
Realtime synthesis: Digital Waveguides

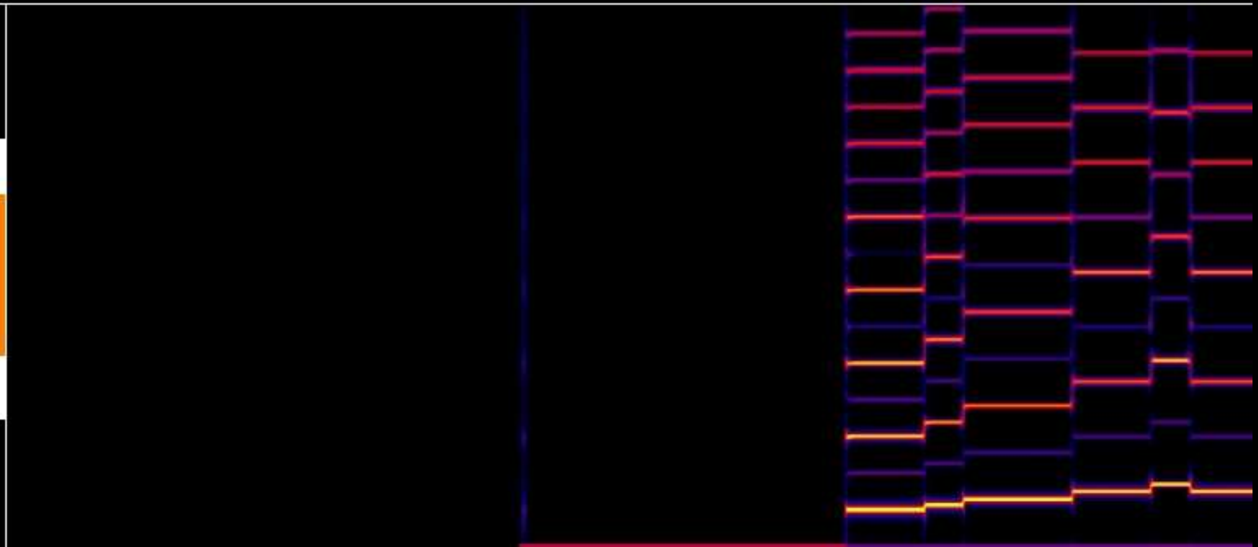


Our approach









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

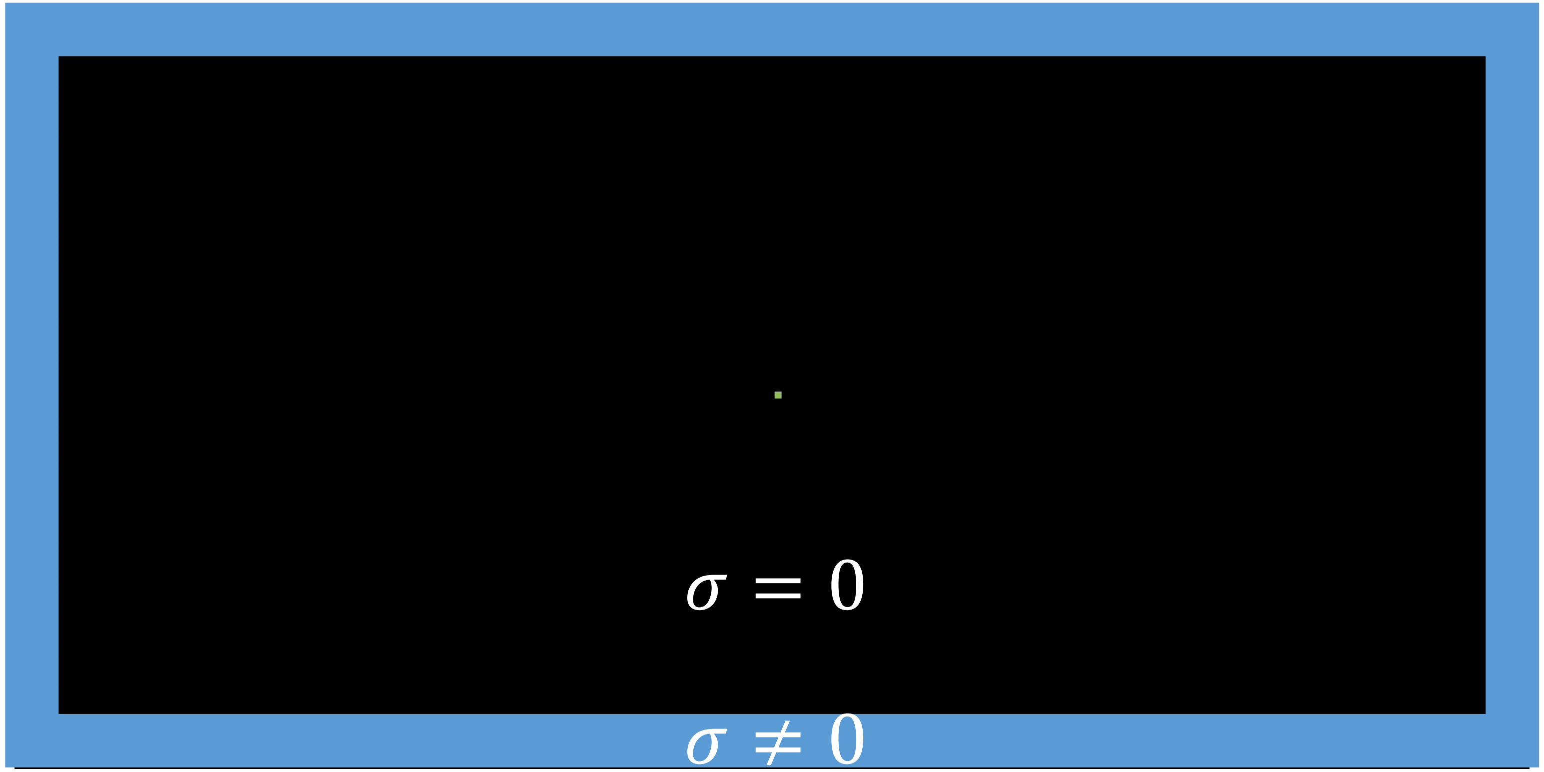
$$\frac{\partial p}{\partial t} = -\rho c^2 \nabla \cdot \mathbf{v}$$

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

Perfectly matched layer (PML)

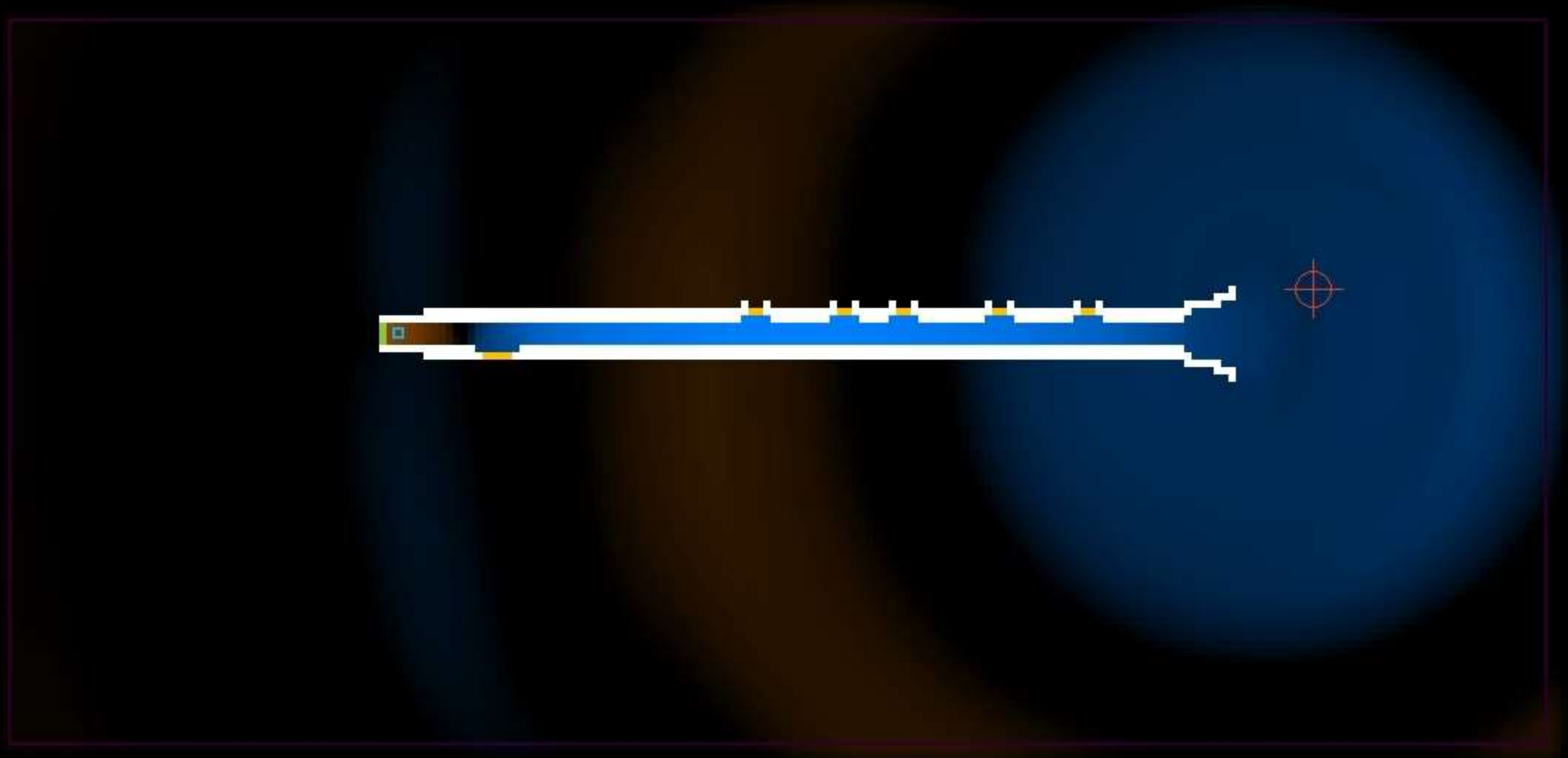
$$\frac{\partial p}{\partial t} + \sigma \, p = -\rho c^2 \nabla \cdot \mathbf{v}$$

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



Dynamic Geometry

Tone Holes, Valves, Slides, Mutes



Abrupt geometric changes: clicks

Our formulation (time-varying PML)

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

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

- $\beta(\boldsymbol{x}, t) \in [0,1]$ 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)

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

($\sigma = 0$ inside domain)

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

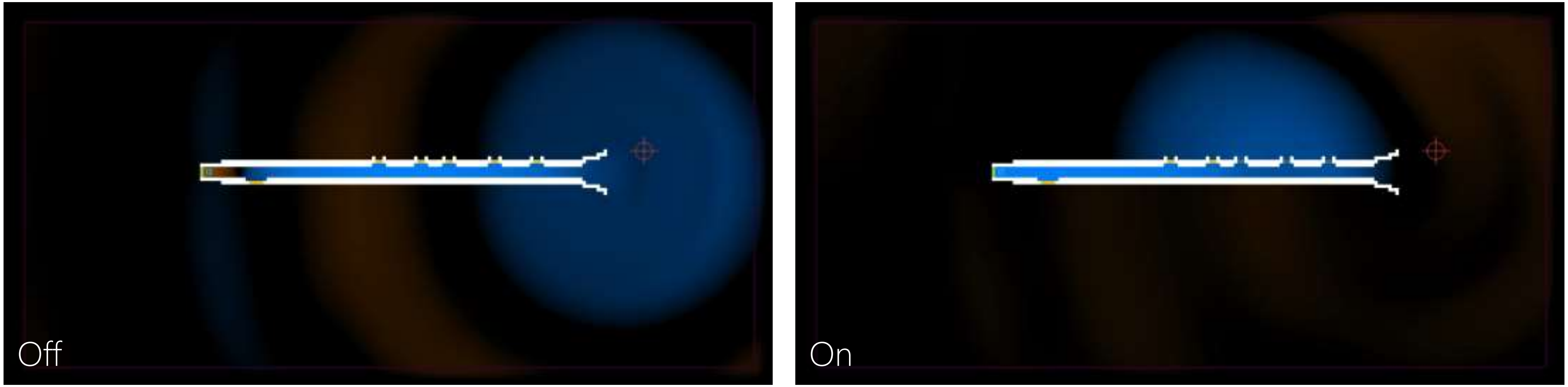
$\beta = 0$: Boundary

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

$\beta = 1$: Air

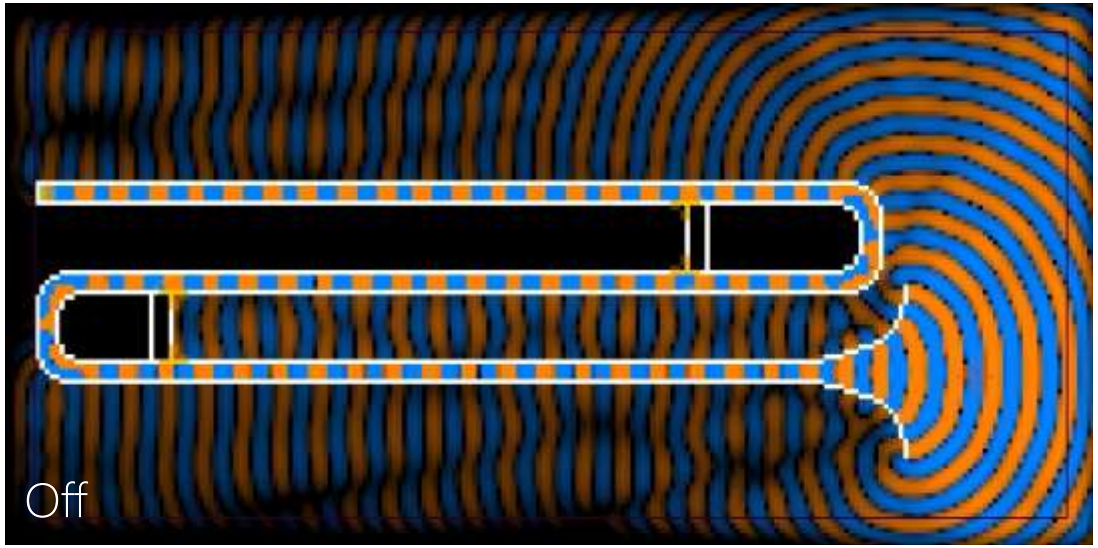
$$\frac{\partial \mathbf{v}}{\partial t} = \frac{-\nabla p}{\rho}$$

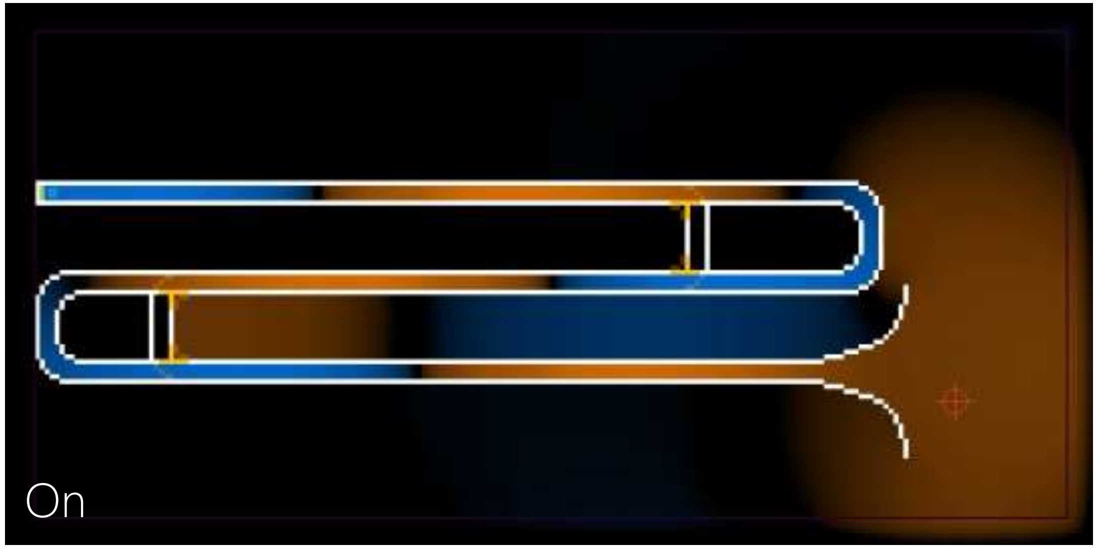
Our formulation: natural transients



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

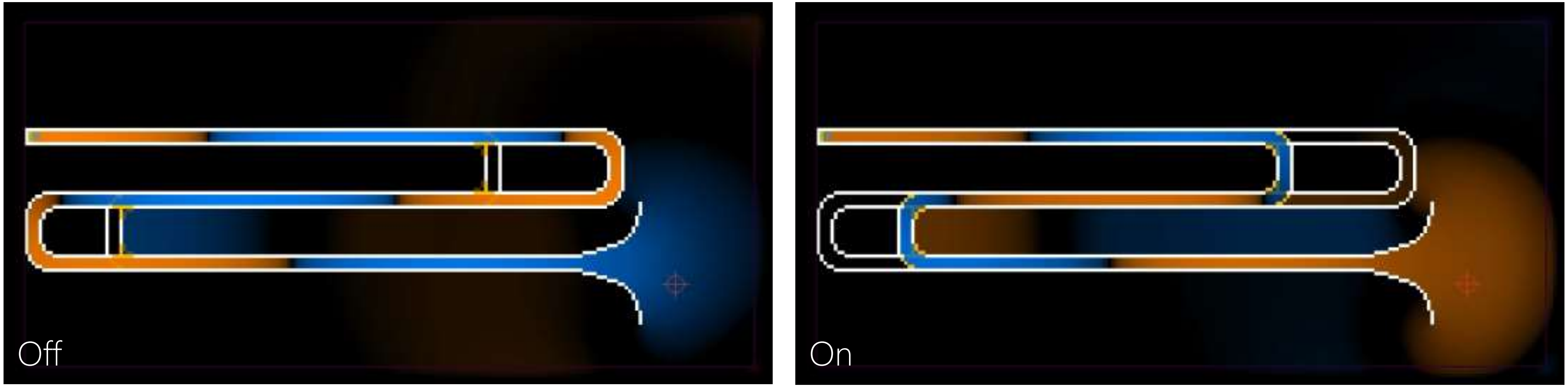
Wall losses





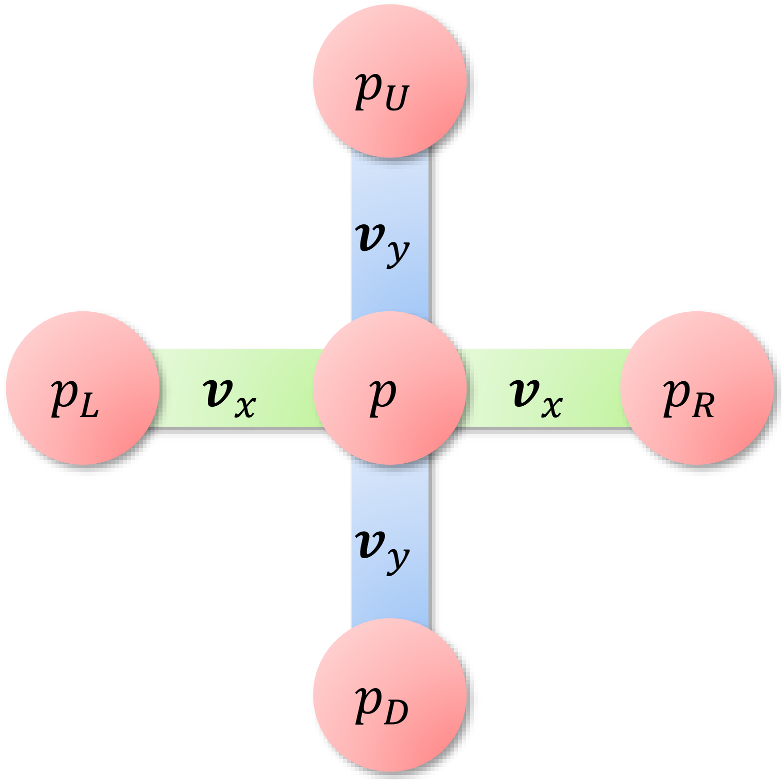
- 2D simulations support transverse resonances
- Wall loss modeling is required (unlike 1D models)

High-amplitude non-linearity



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

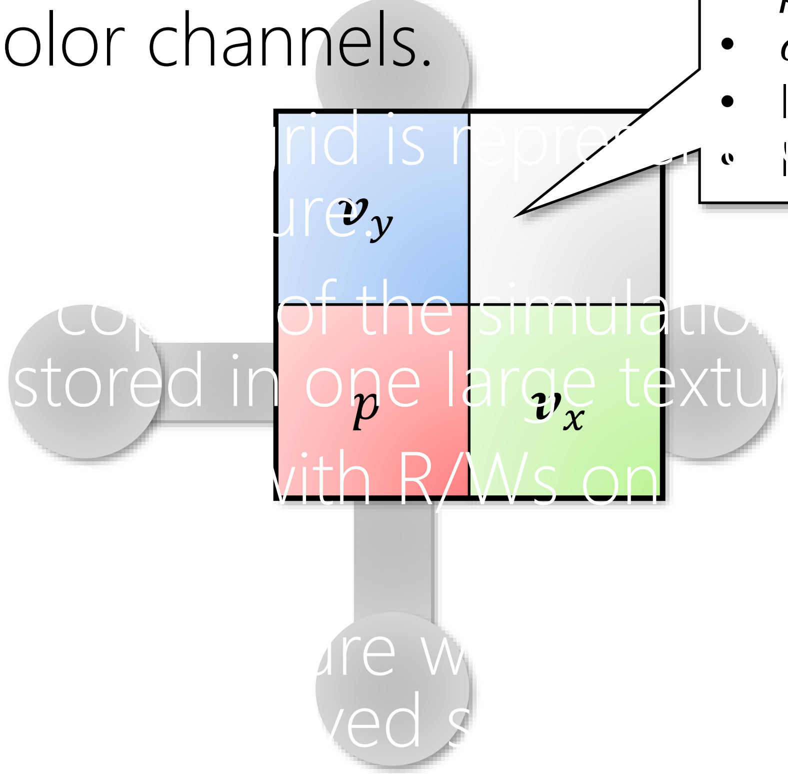
GPU Implementation



- 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:

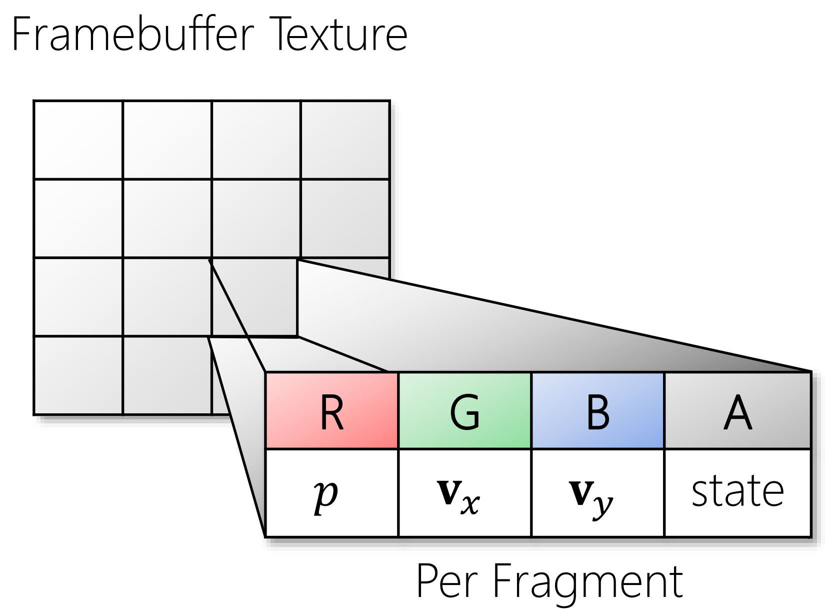
- β value (boundary-ness)
- σ value (PML)
- Is Excitation?
- Is Listener?

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

Per Fragment

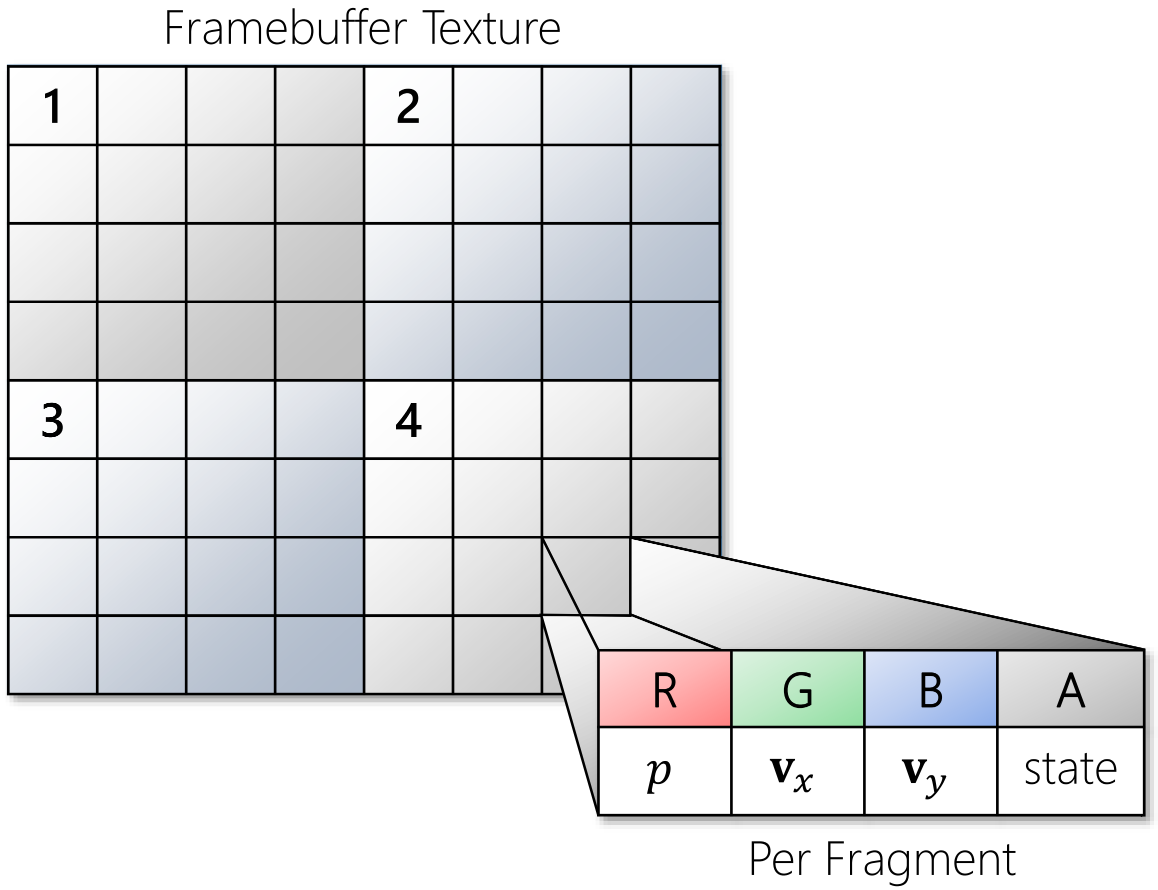
GPU Implementation

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



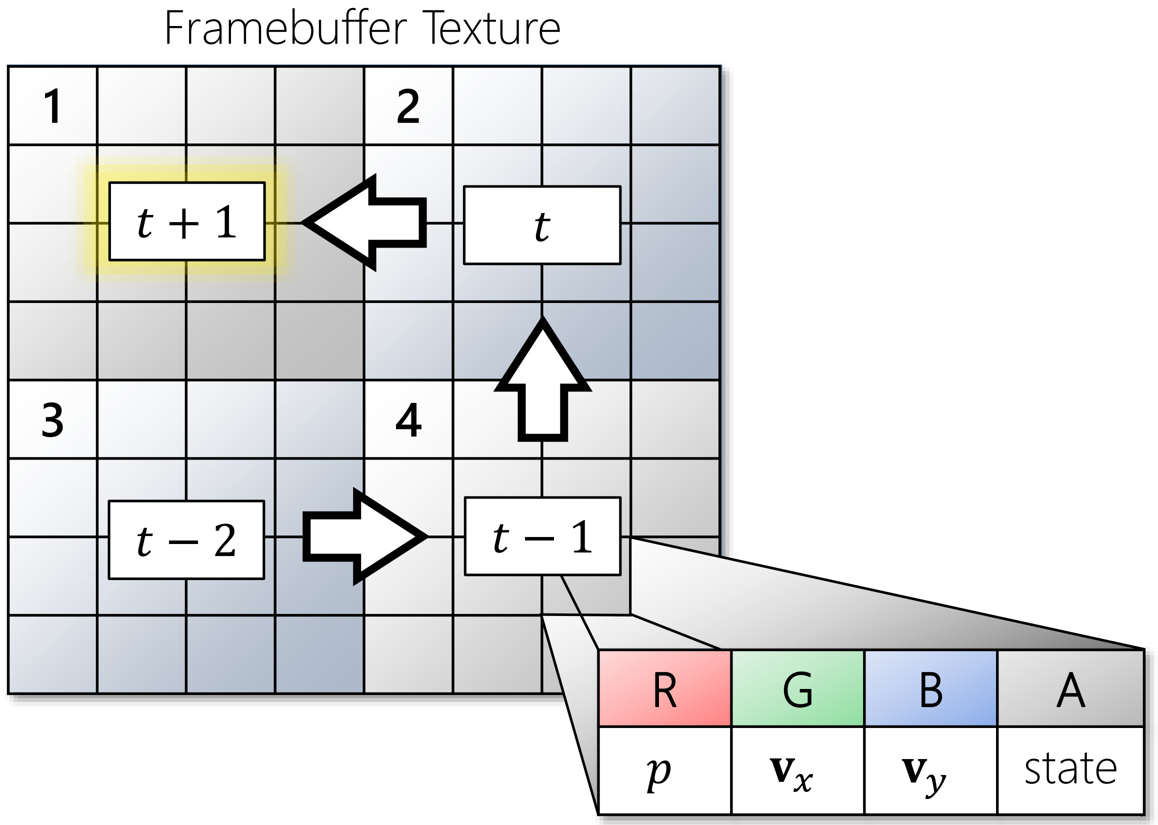
GPU Implementation

- 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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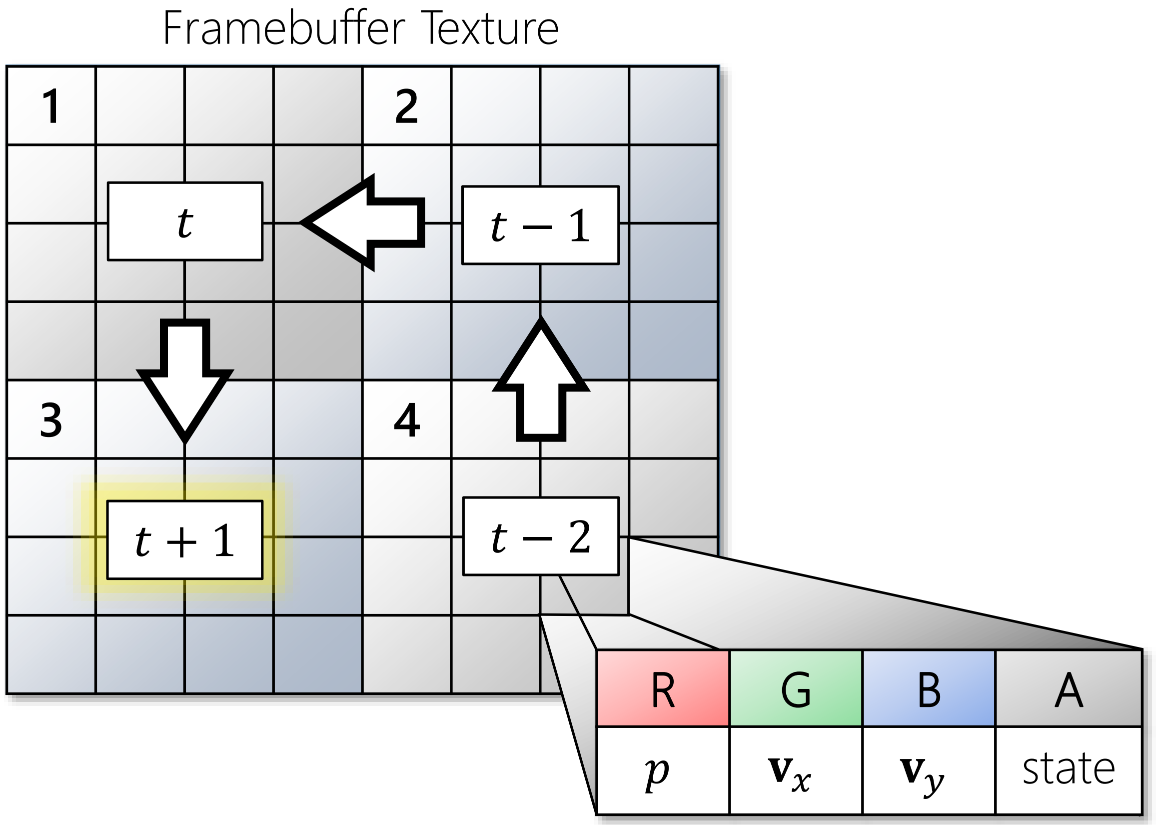

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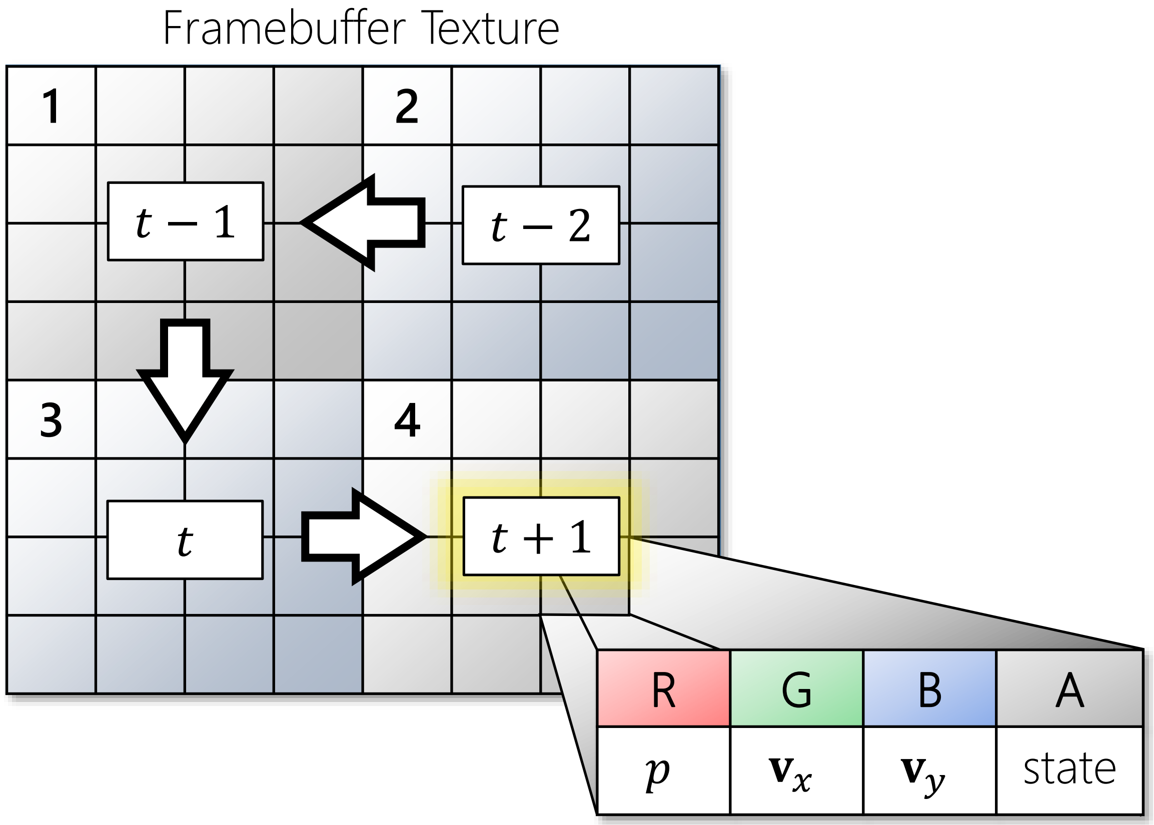

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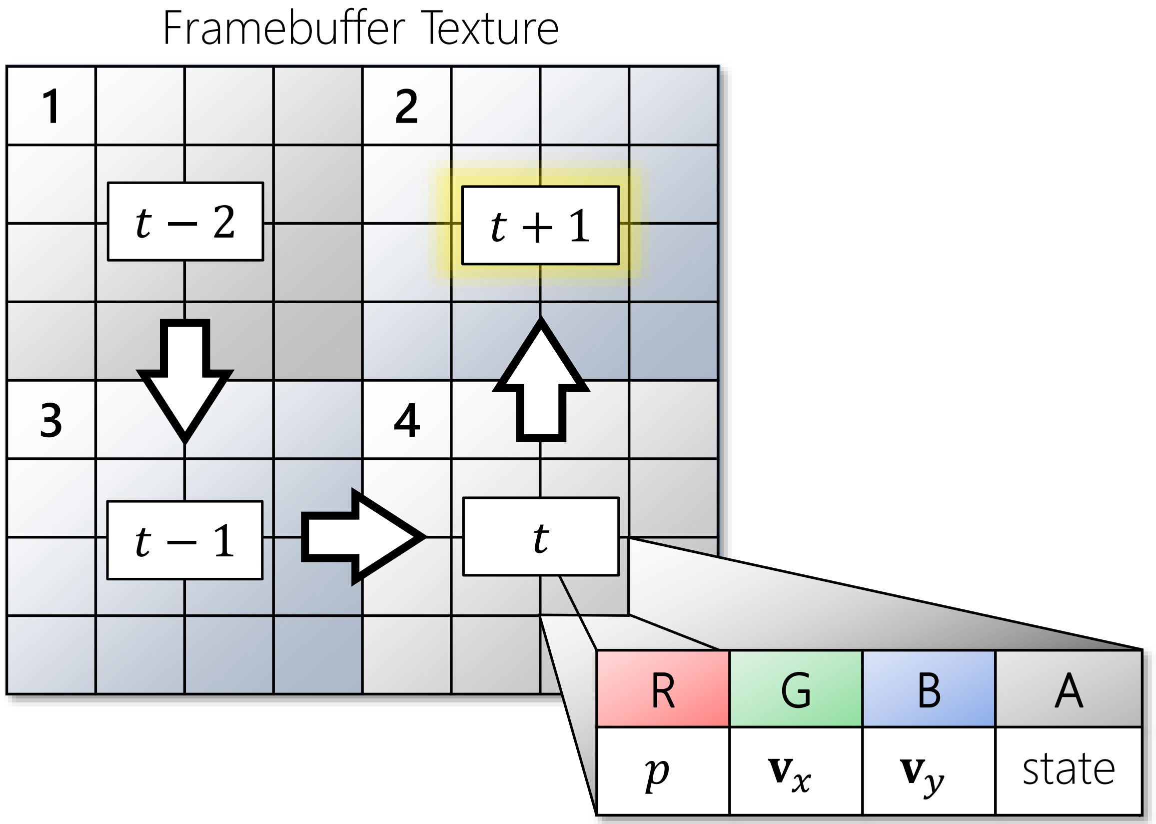

GPU Implementation

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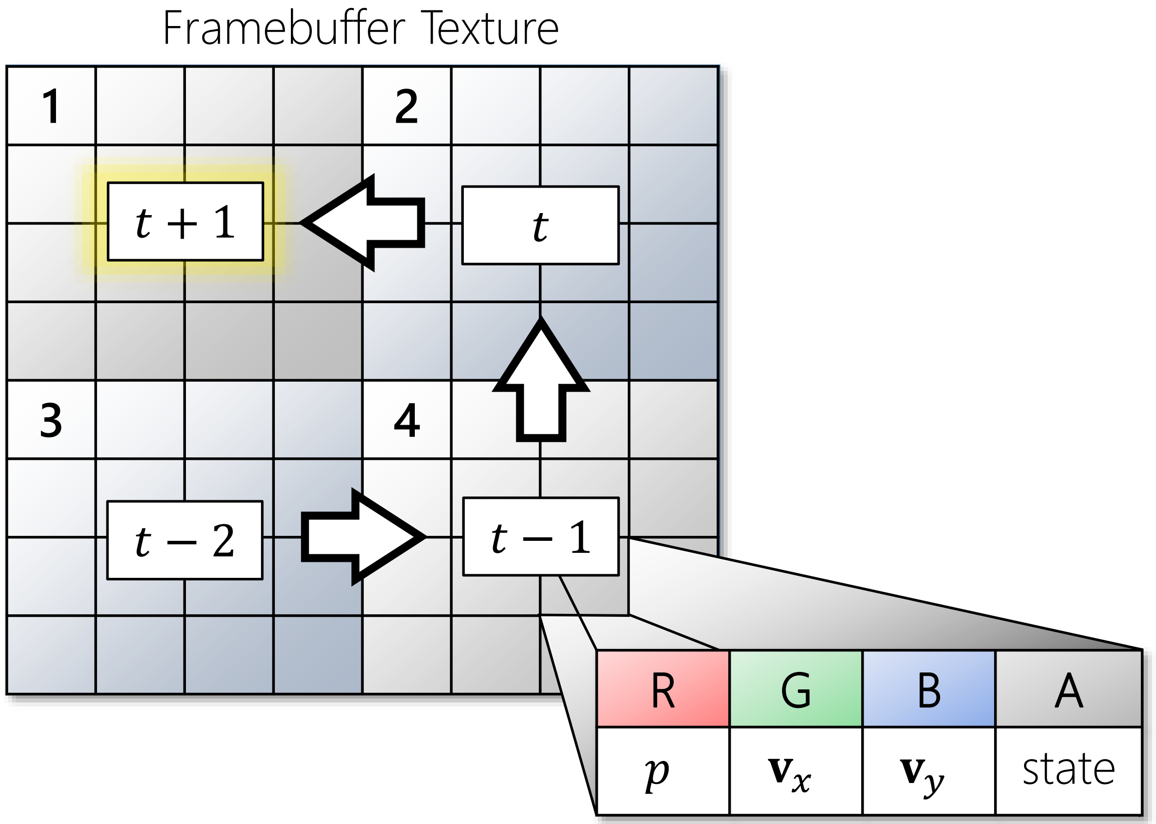
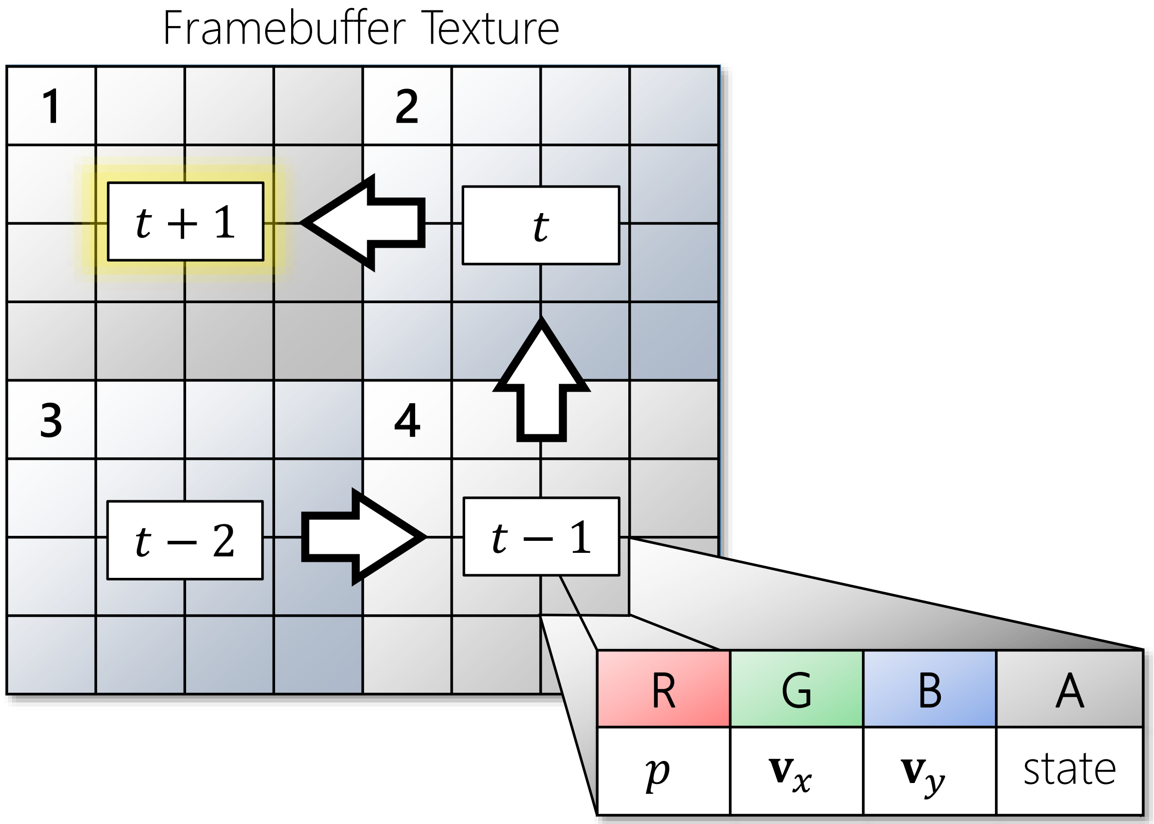
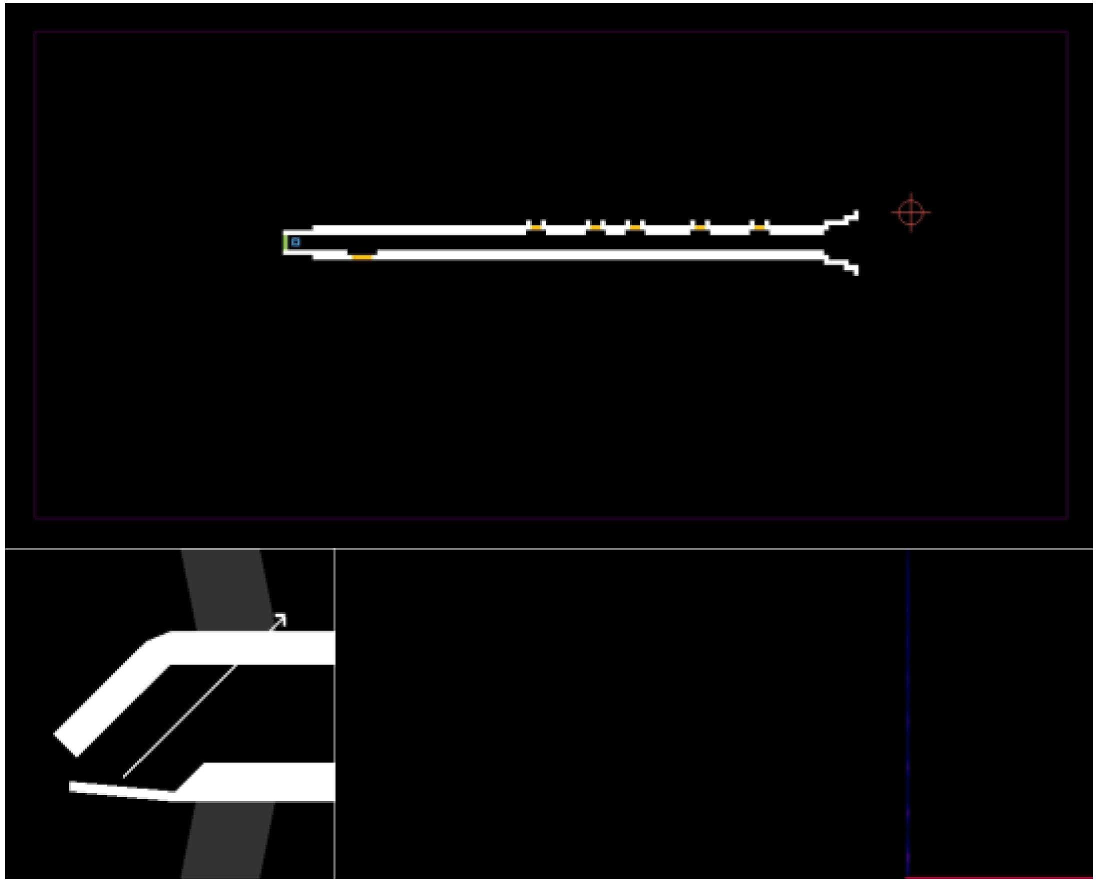


GPU Implementation

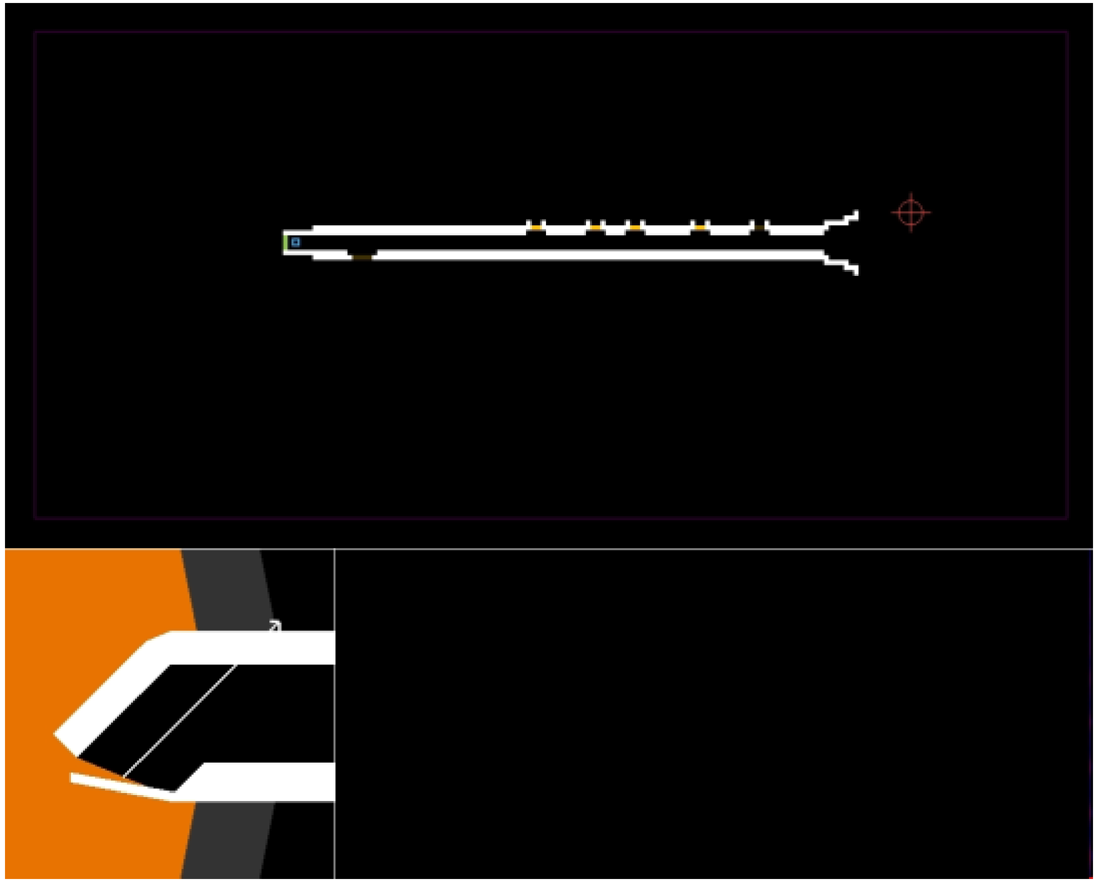
- Values for each cell are stored in color channels.
- Simulation grid is represented as a 2D texture.
- Four copies of the simulation are stored in one large texture.
- Ping-pong with R/Ws on one texture.
- Write output pressure (sound) to reserved space on the FBO.



Clarinet

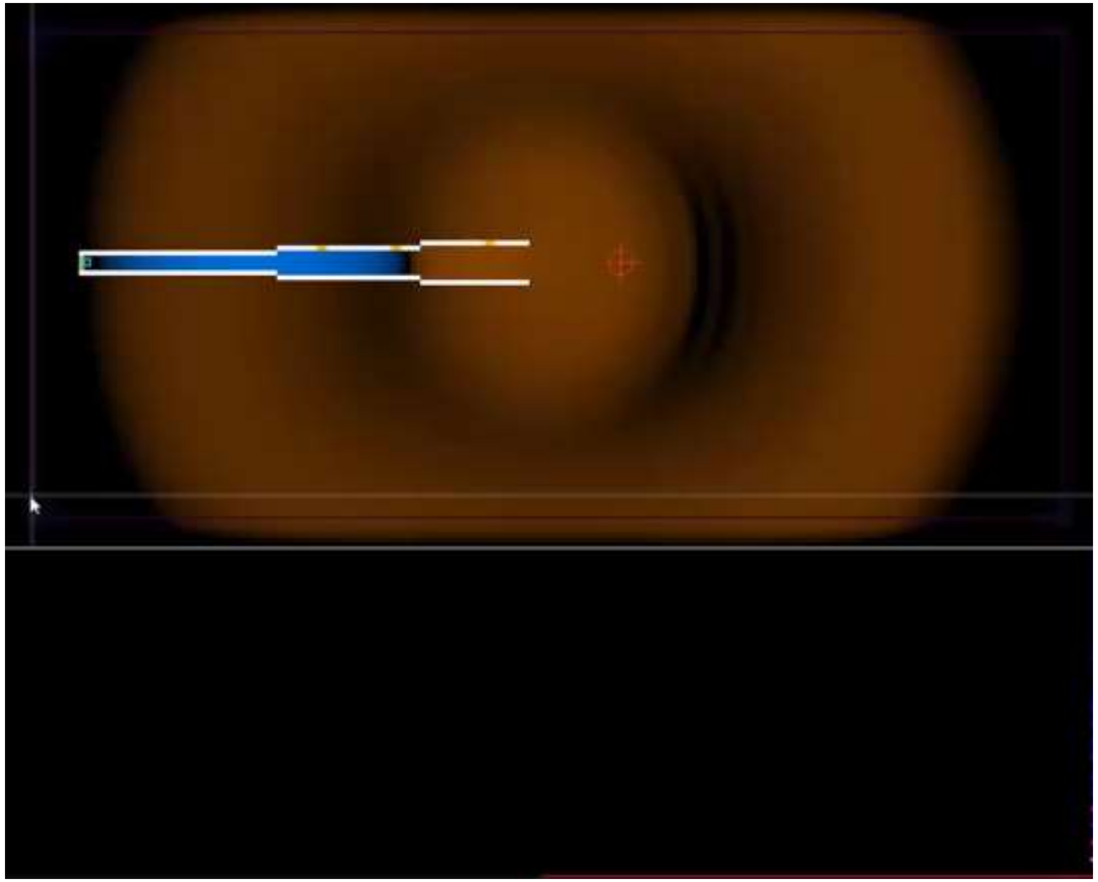


Chalumeau melody

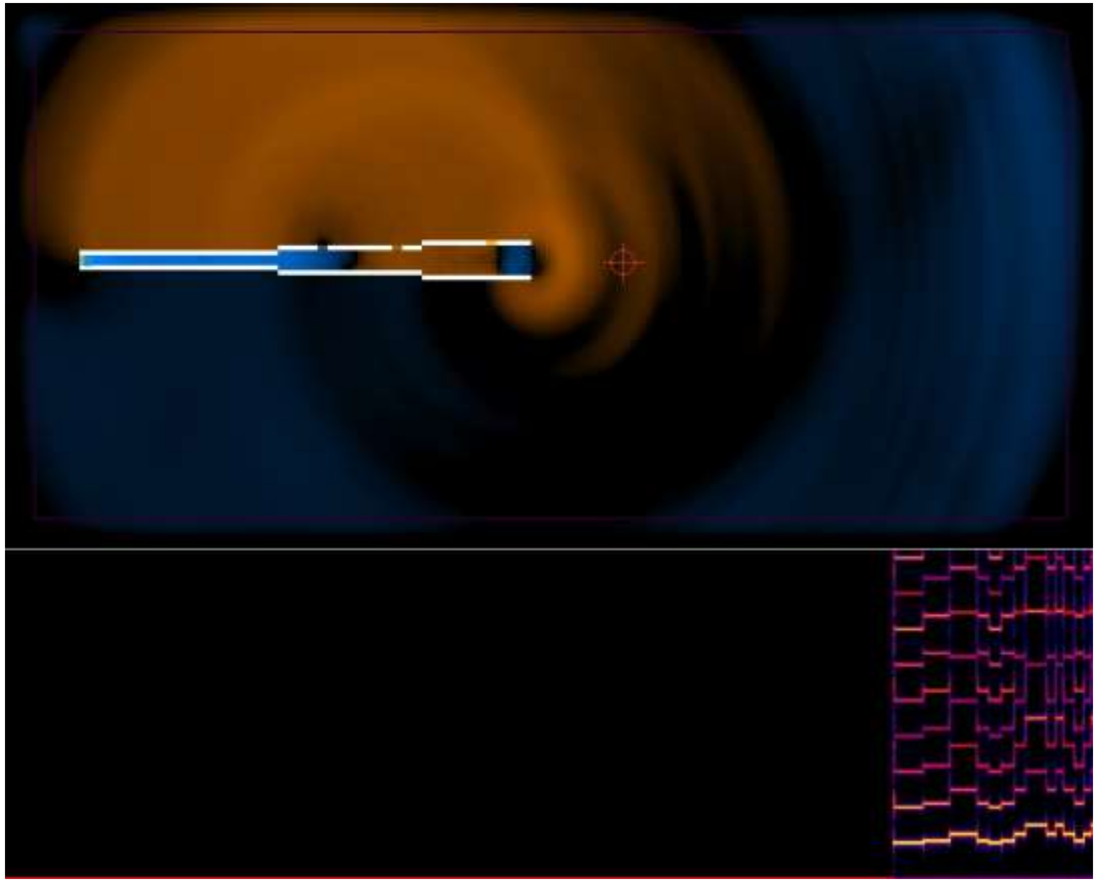


Altissimo melody (register key)

Saxophone

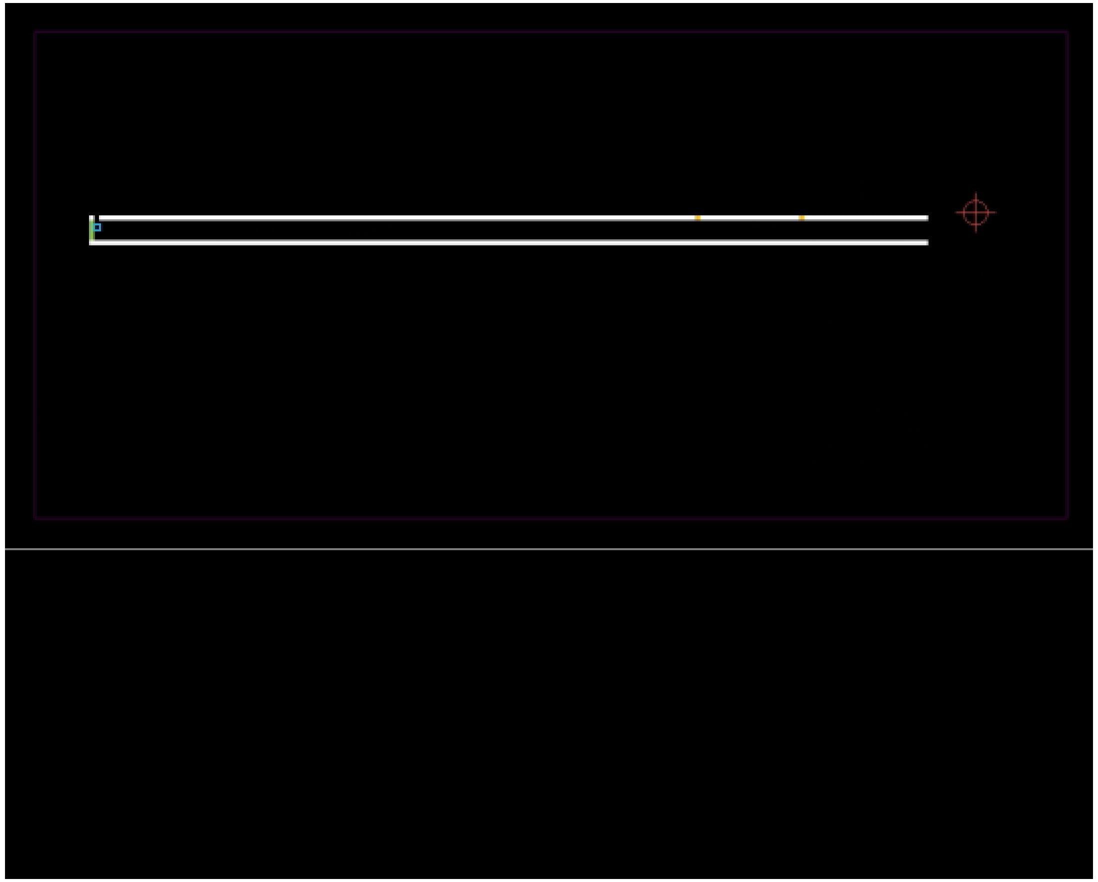


Simple melody

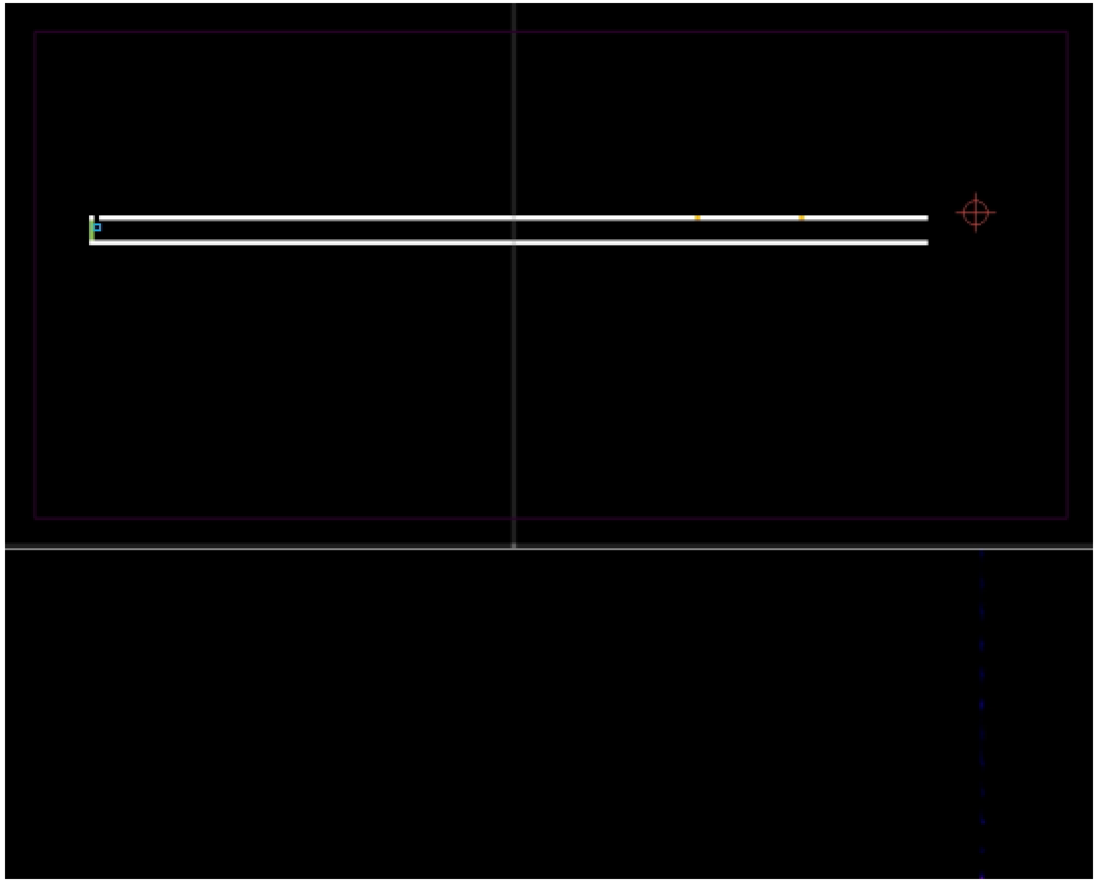


Fast Squeaks

Flute

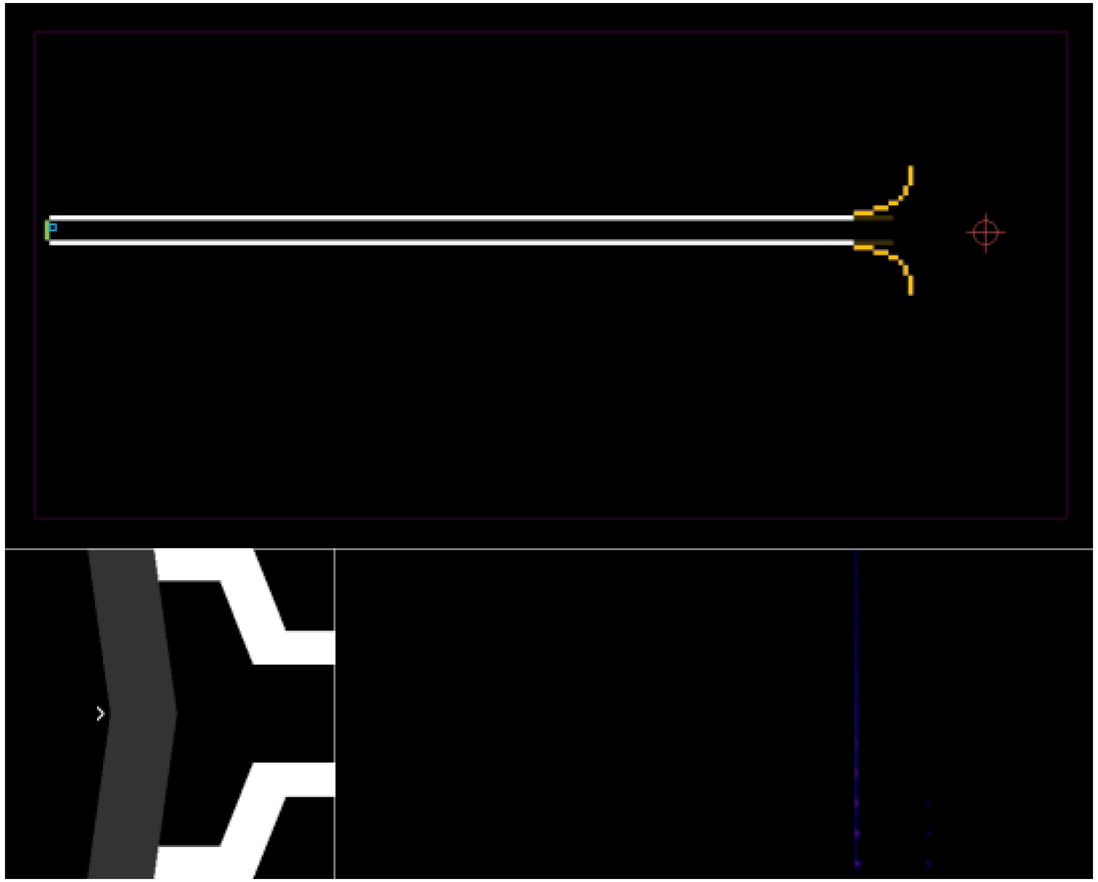


"Robot" Performer

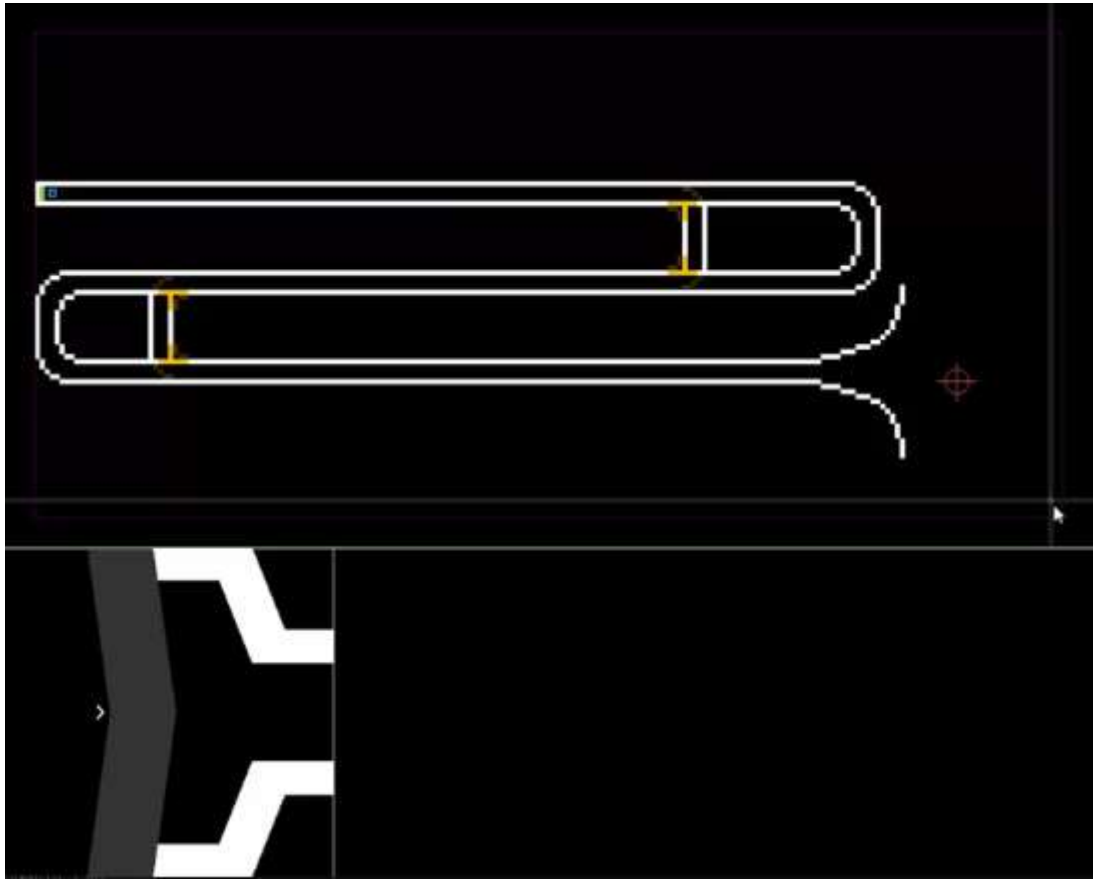


Wind Controller Interface

Bugle & Trumpet (brasses)

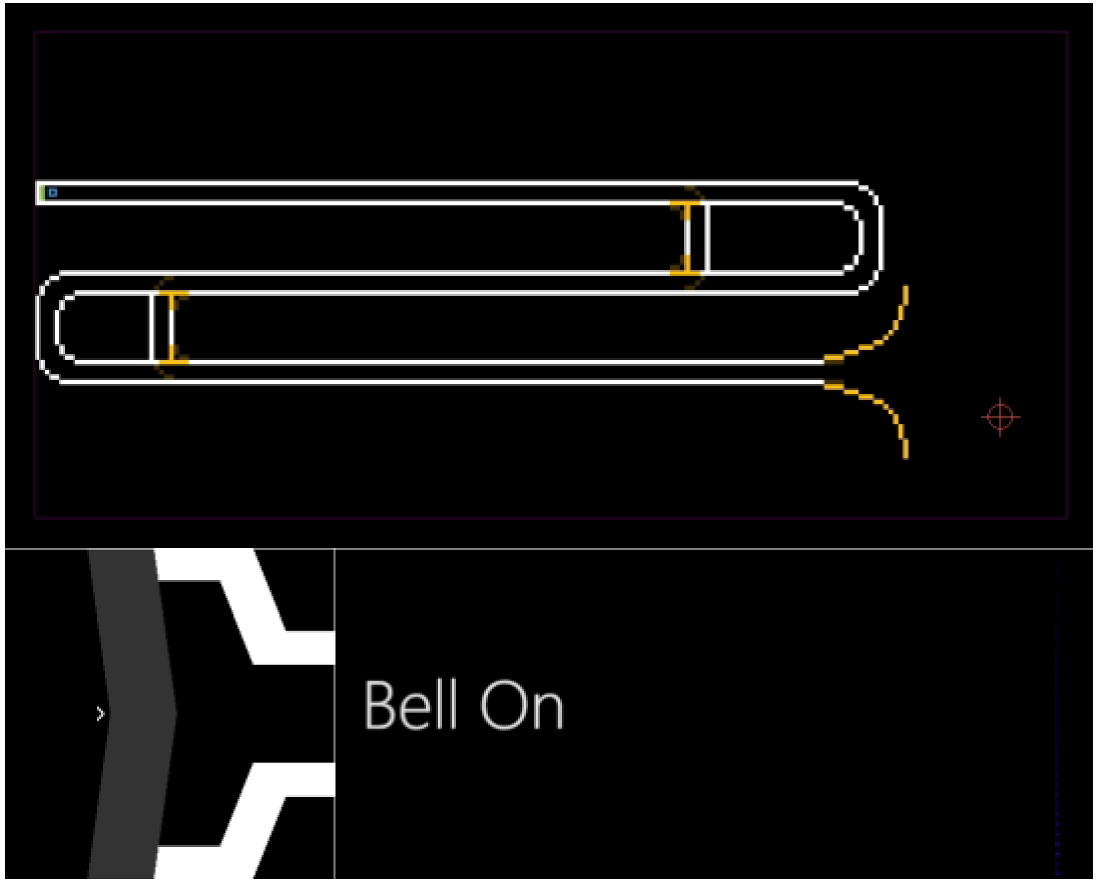


Lips Overblowing

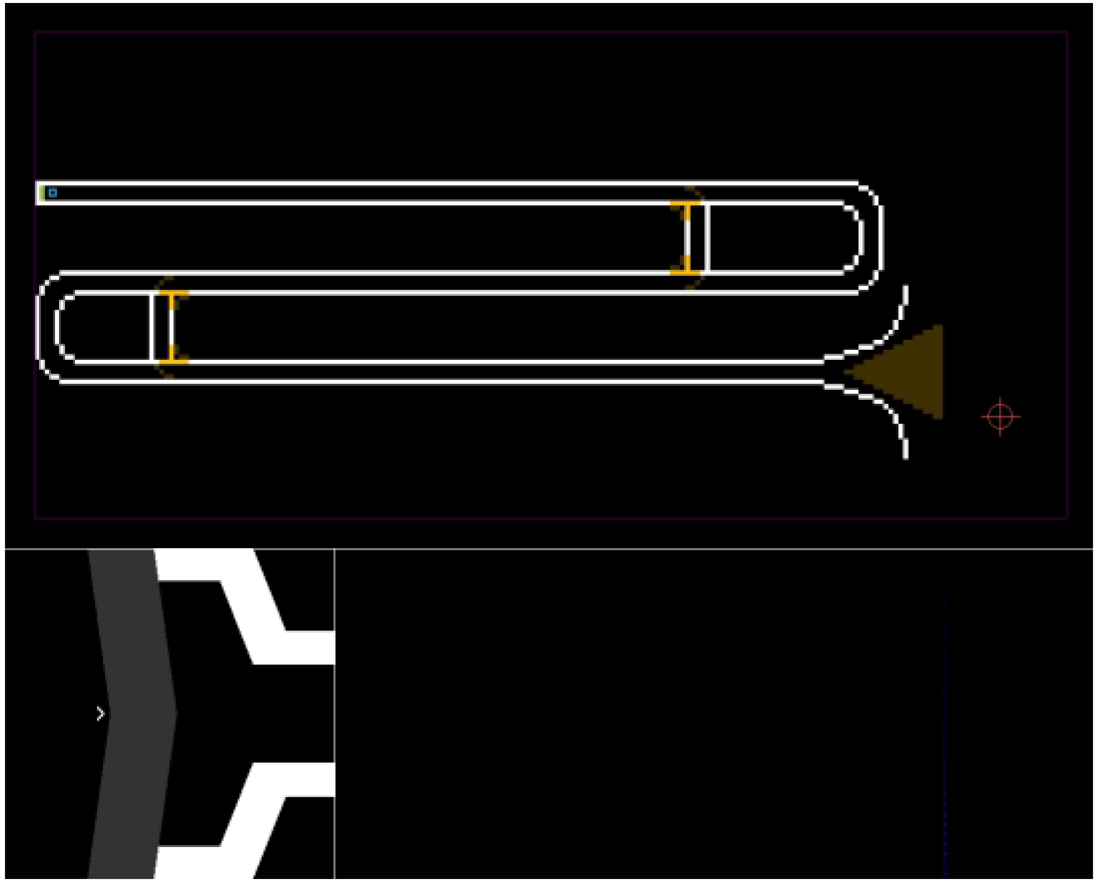


Valve System

Trumpet w/o Bell and w/ Mutes

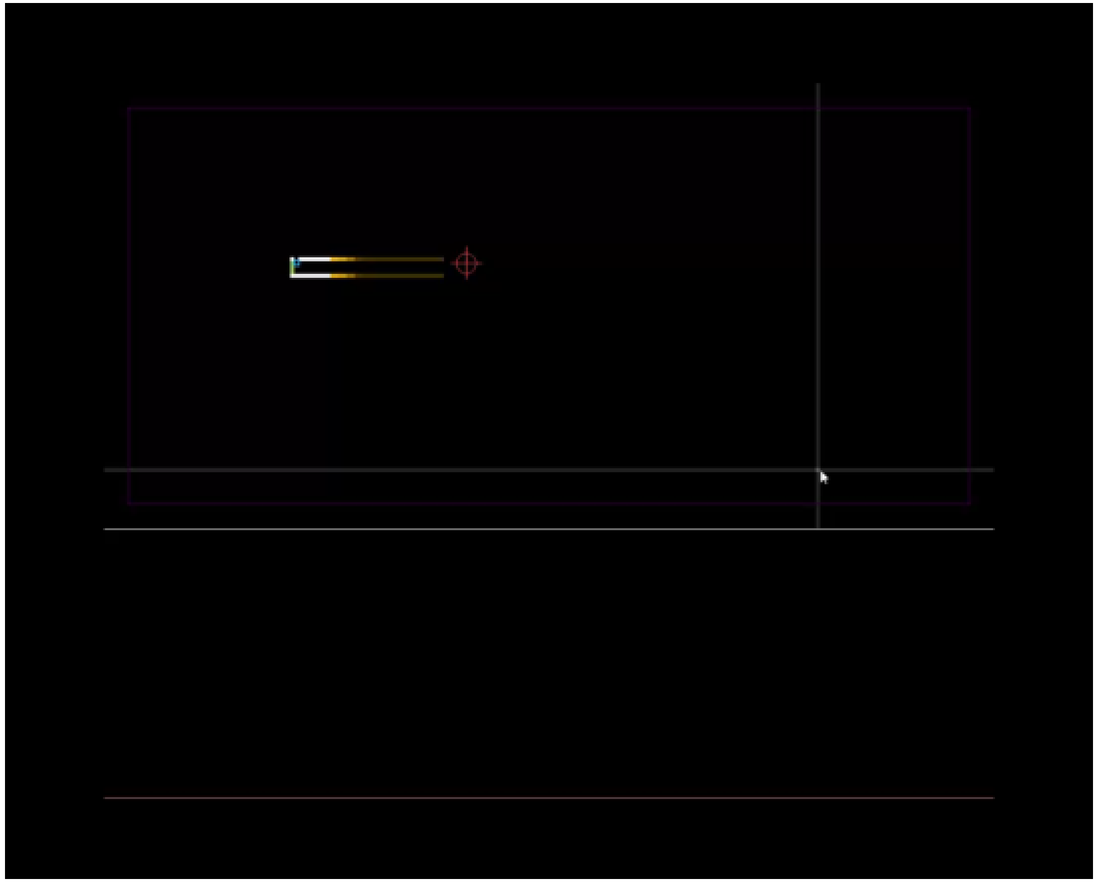


Bell On/Off

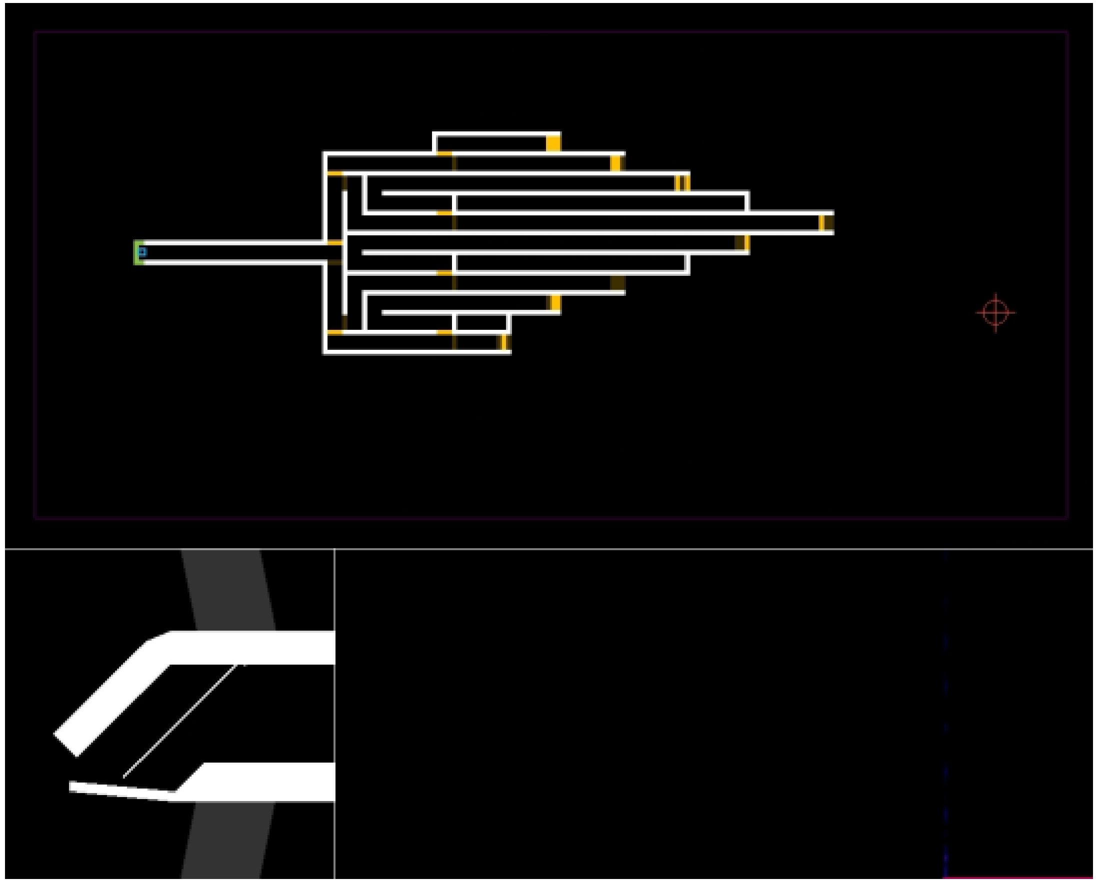


Straight, Cup and Harmon Mute

“Slide Whistle” and “Menorah”

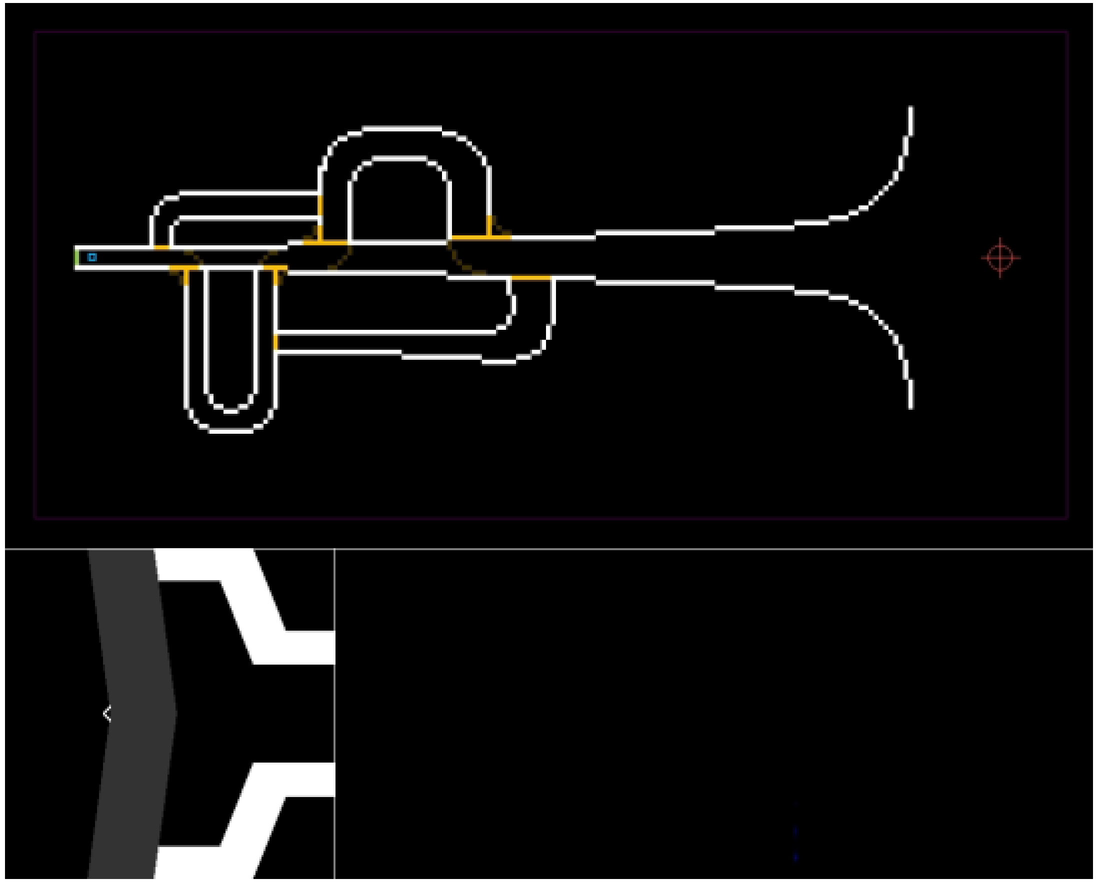


Dynamic Bore Geometry

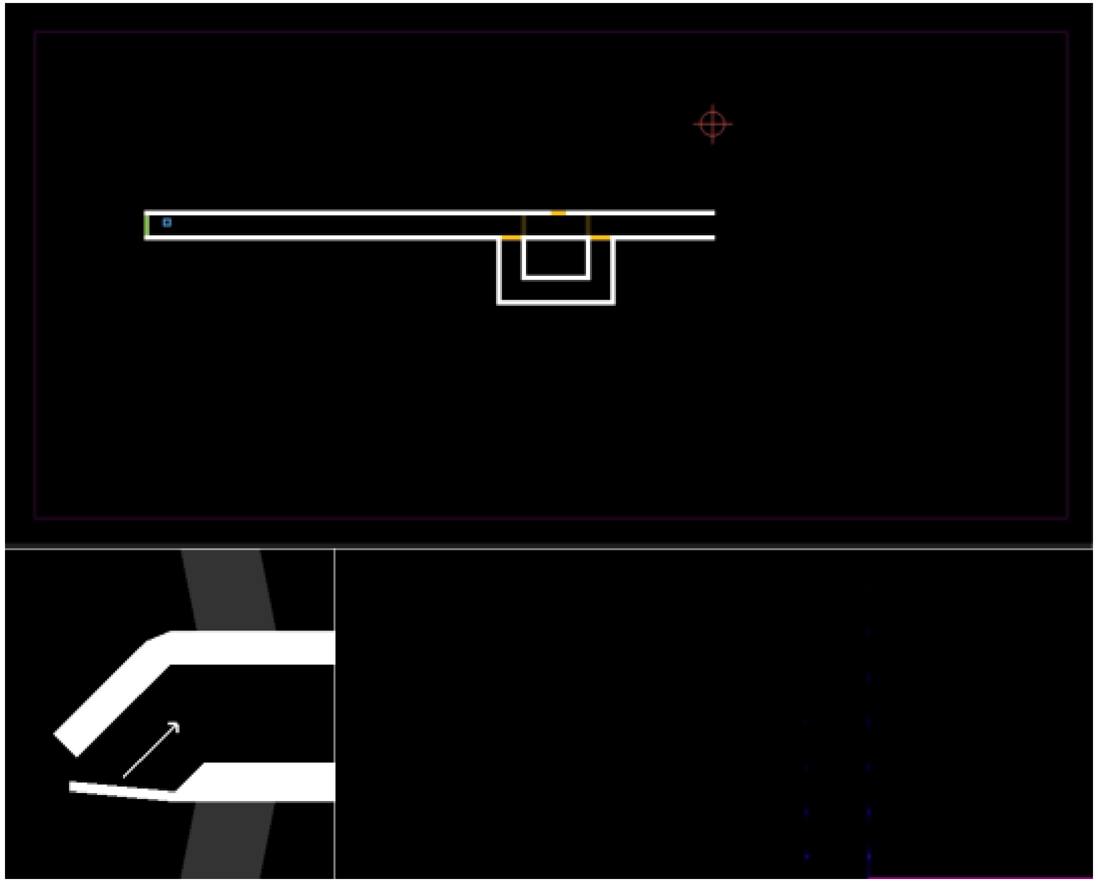


Interlocking Valve System

“Tuba?” and “Hybrid”

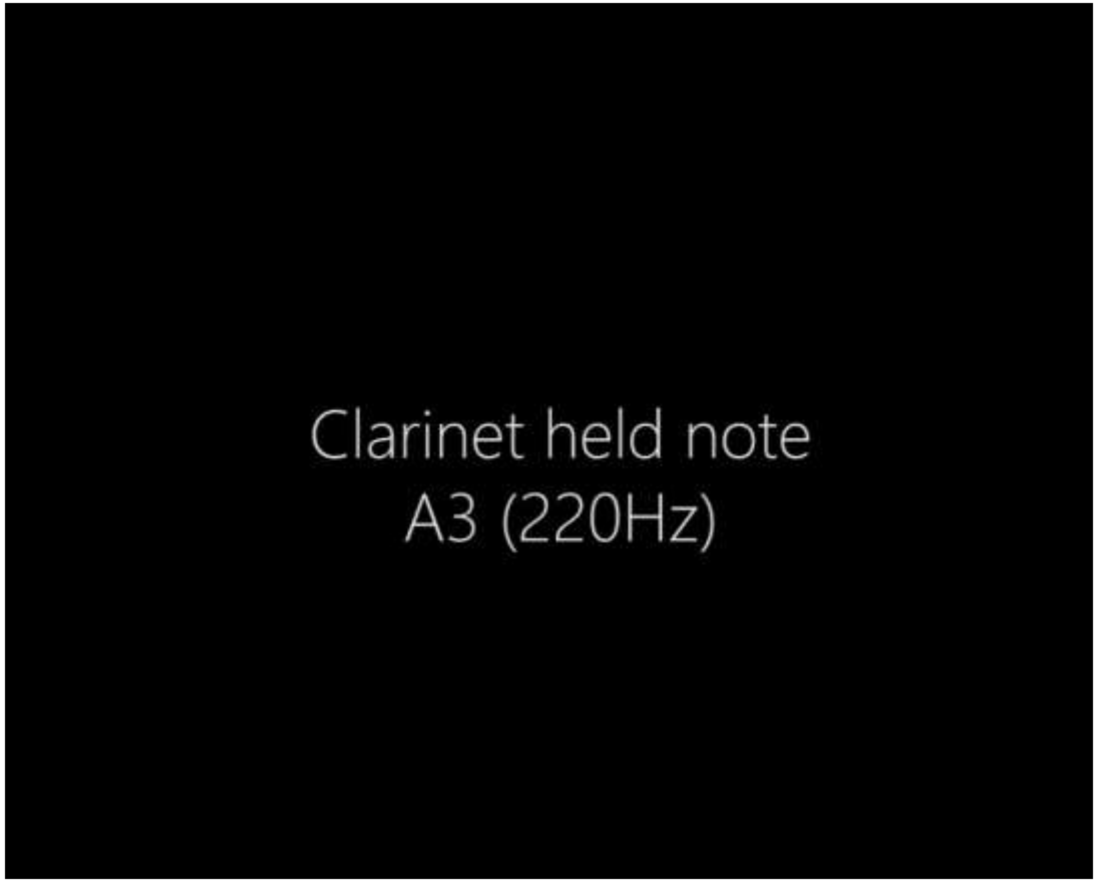


Implausible-to-construct Instrument



Reed, Lips, Valve, Tonehole, Bell

Comparisons to STK (Digital Waveguides)



Low note

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