Filling up a bottle

Name: **Timo Huber**
From **Berlin**
Team: Wir hätten lieber ausgeschlafen

„When a vertical water jet enters a bottle, sound may be produced, and, as the bottle is filled up, the properties of the sound change.

Investigate how *relevant parameters of the system* such as *speed* and *dimension*s of the jet, *size* and *shape* of the bottle or *water temperature* affect the sound."

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relevant parameters

↓

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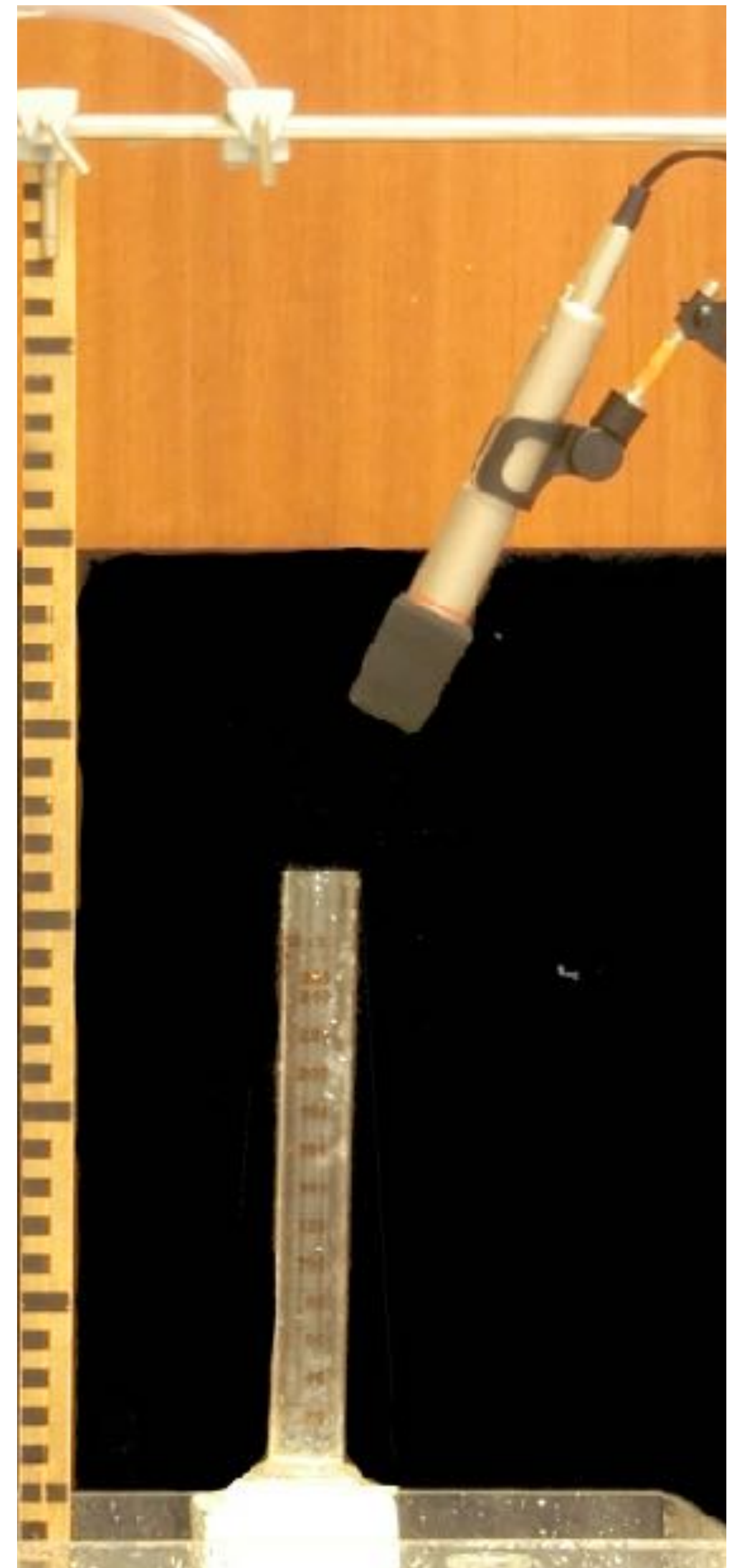
Demonstration

Experimental Setup

Water pumped from overflowing container



Linear measuring **microphone**

Audiointerface

Audio-analysis program

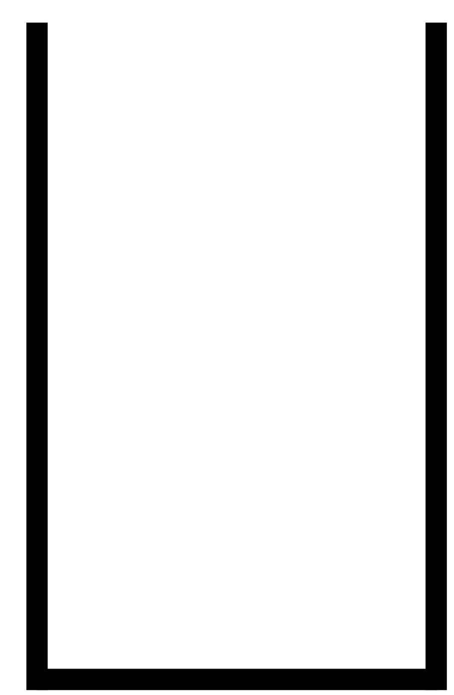
Audacity

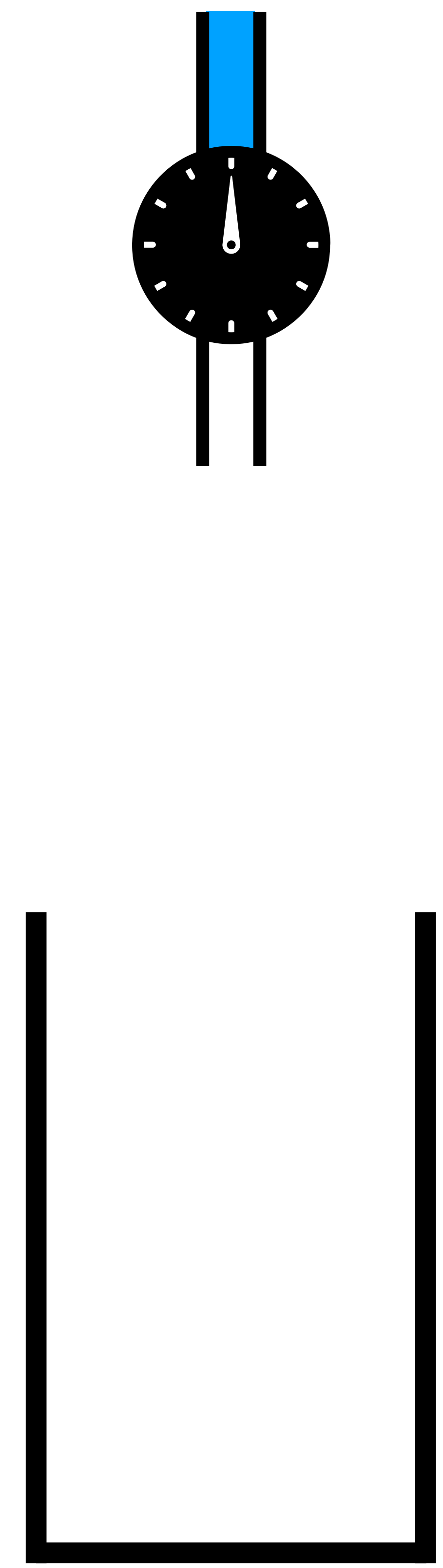
VoceVista Video Pro

Camera films from >5m with a telephoto lens

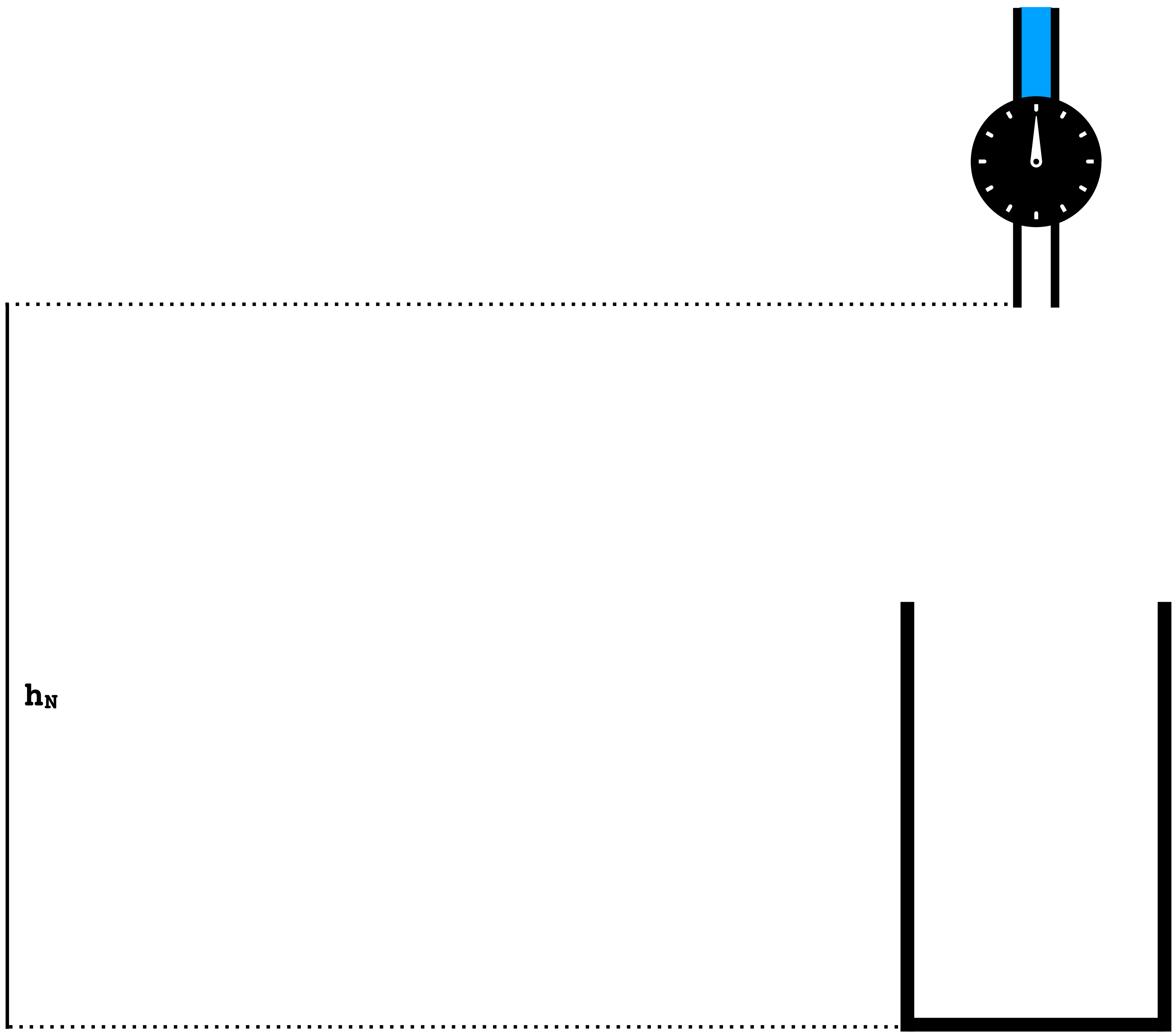
Video-analysis program

VianaNET





h_N: Nozzle height over container ground



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h_B: Container-/ bottle-height
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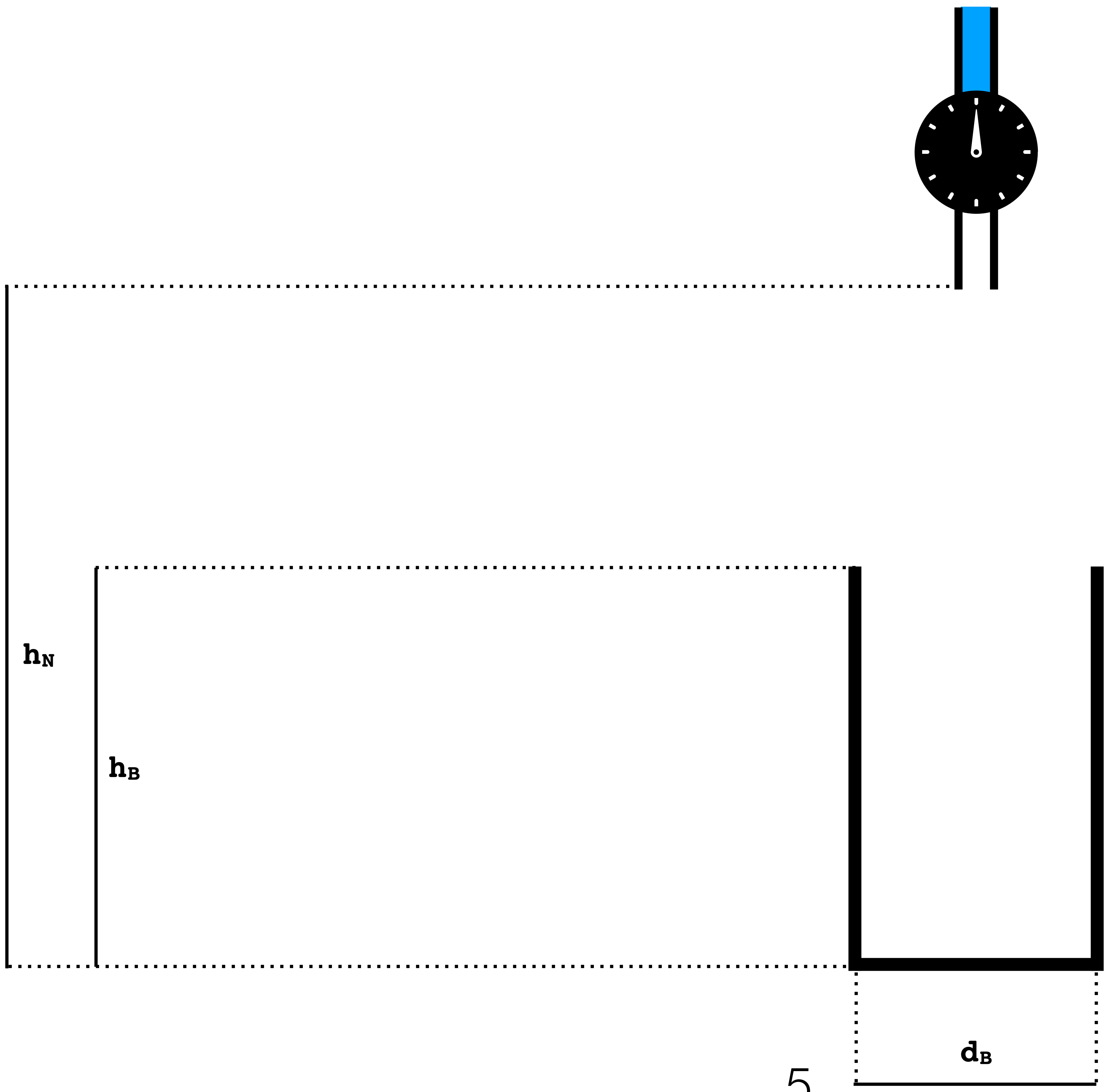

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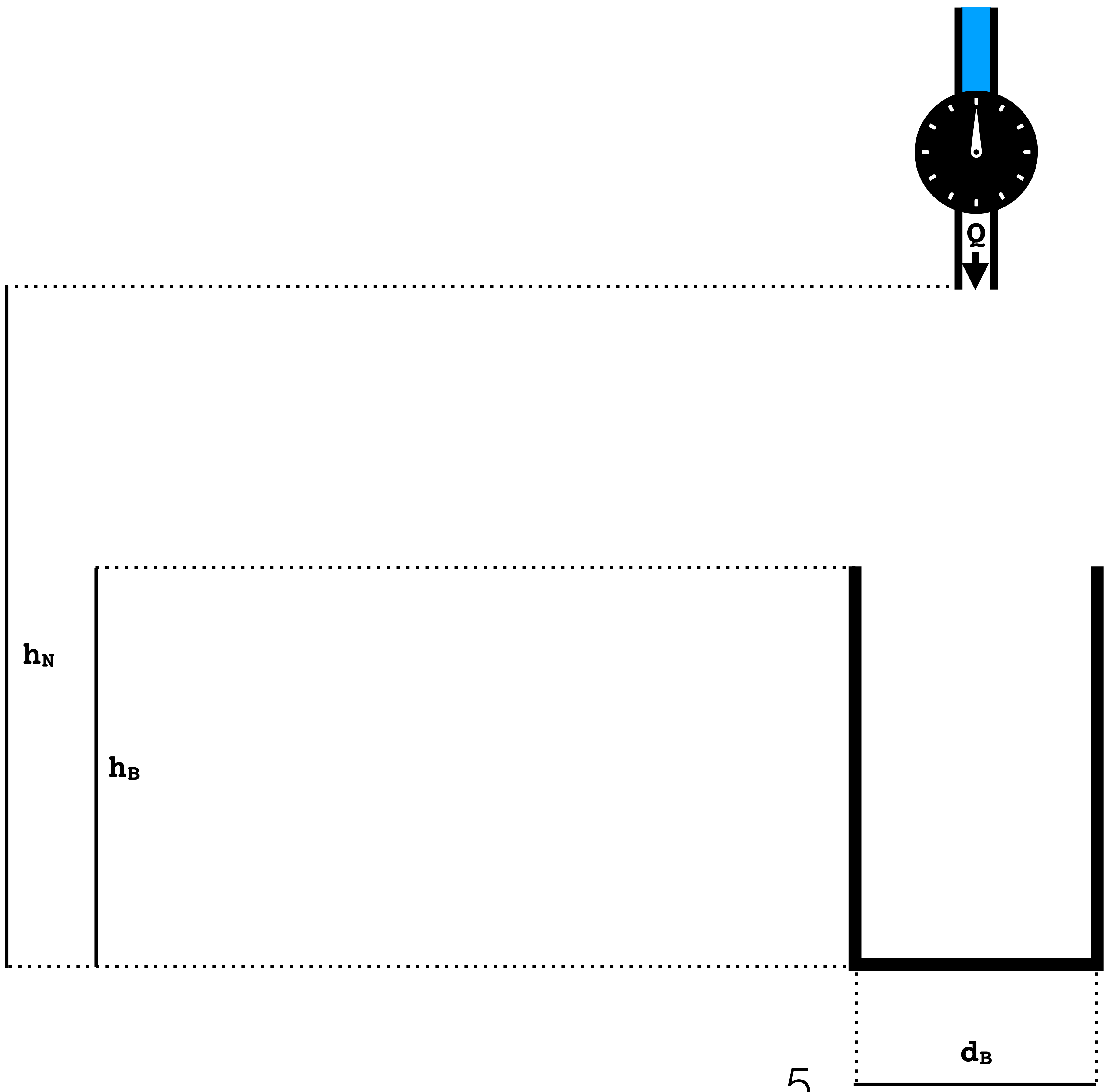

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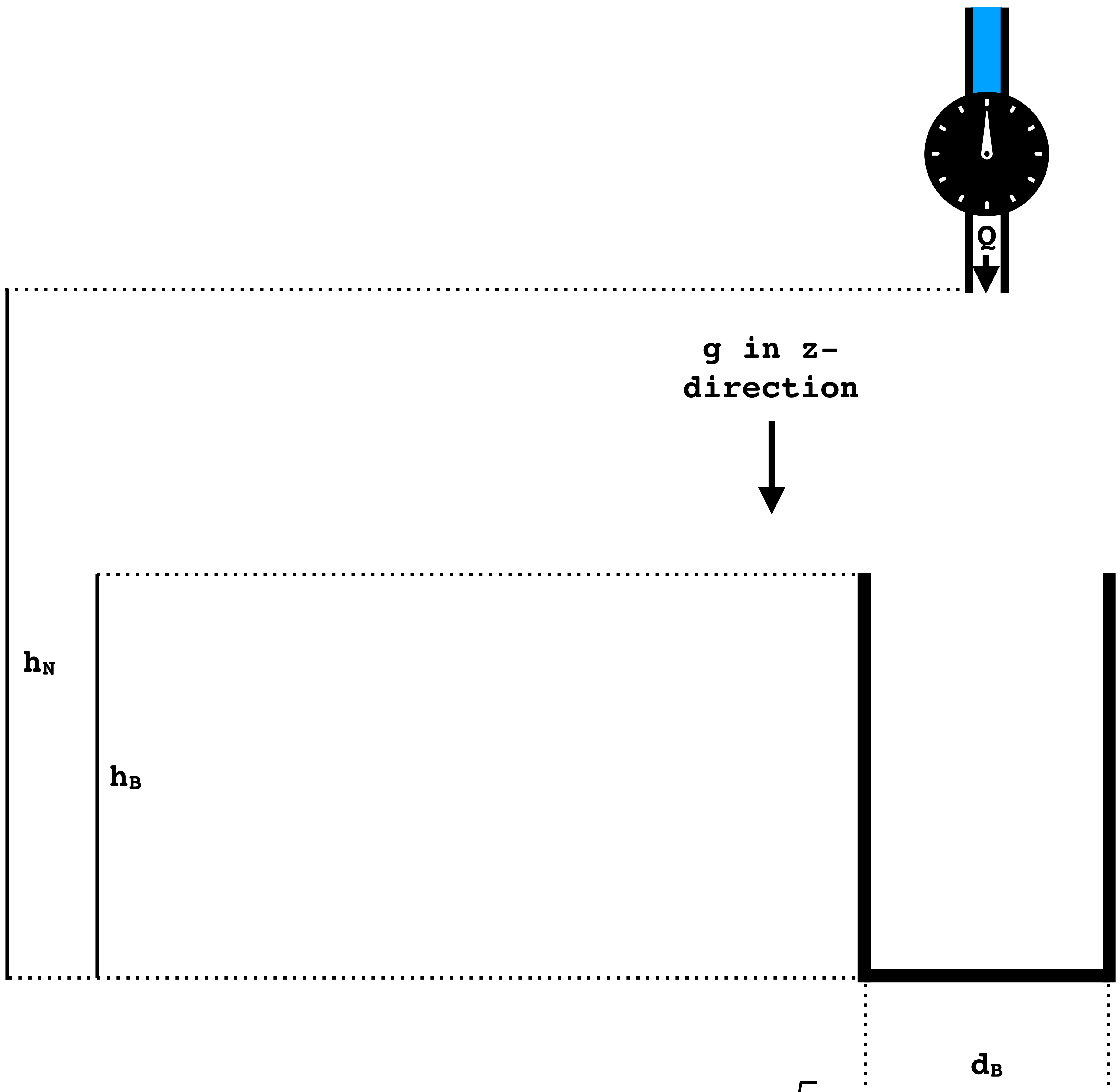

h_N: Nozzle height over container ground
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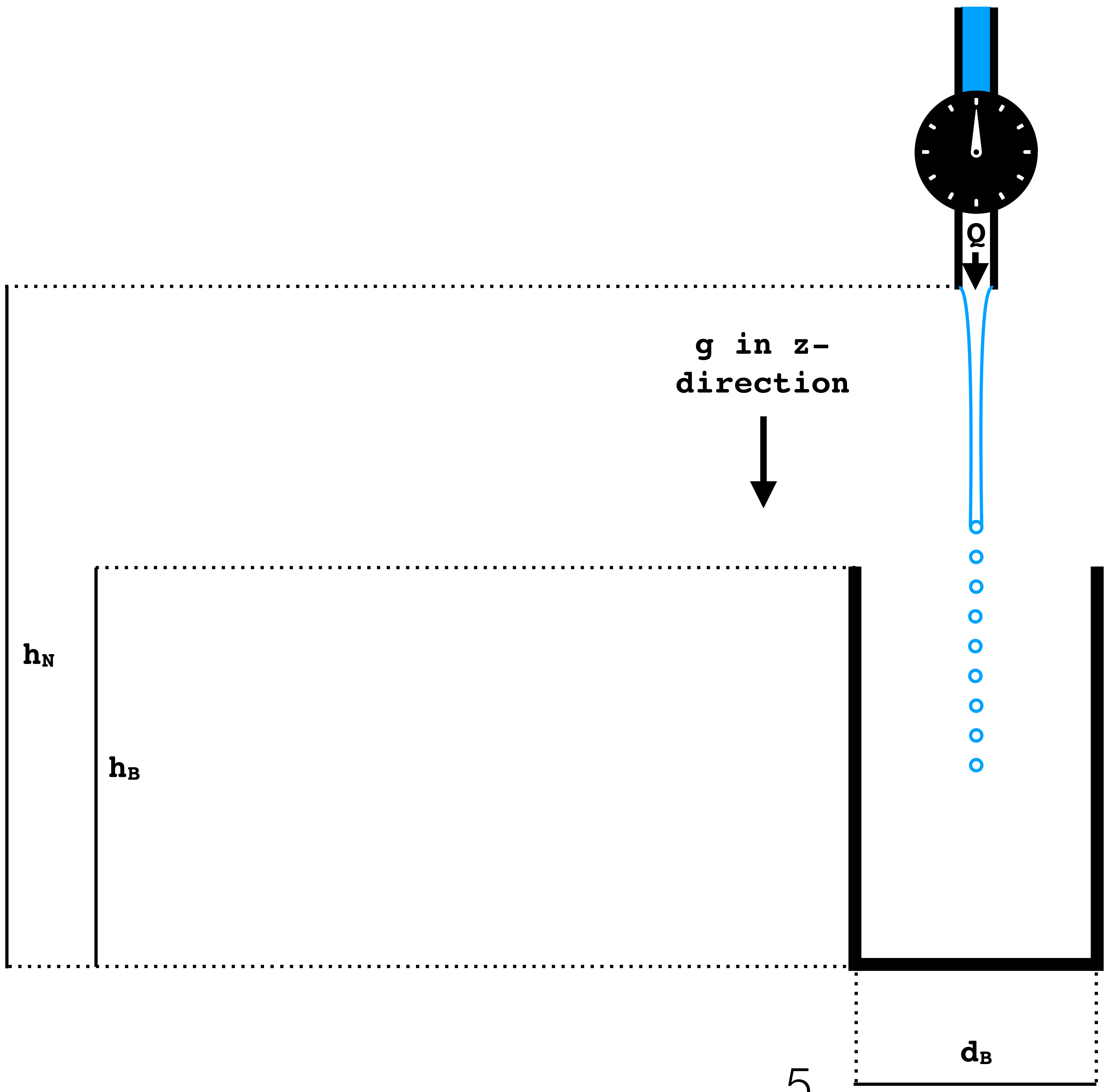
Properties of the jet:
Q: Flow rate
r_o: Nozzle radius
U_o: Speed at the nozzle



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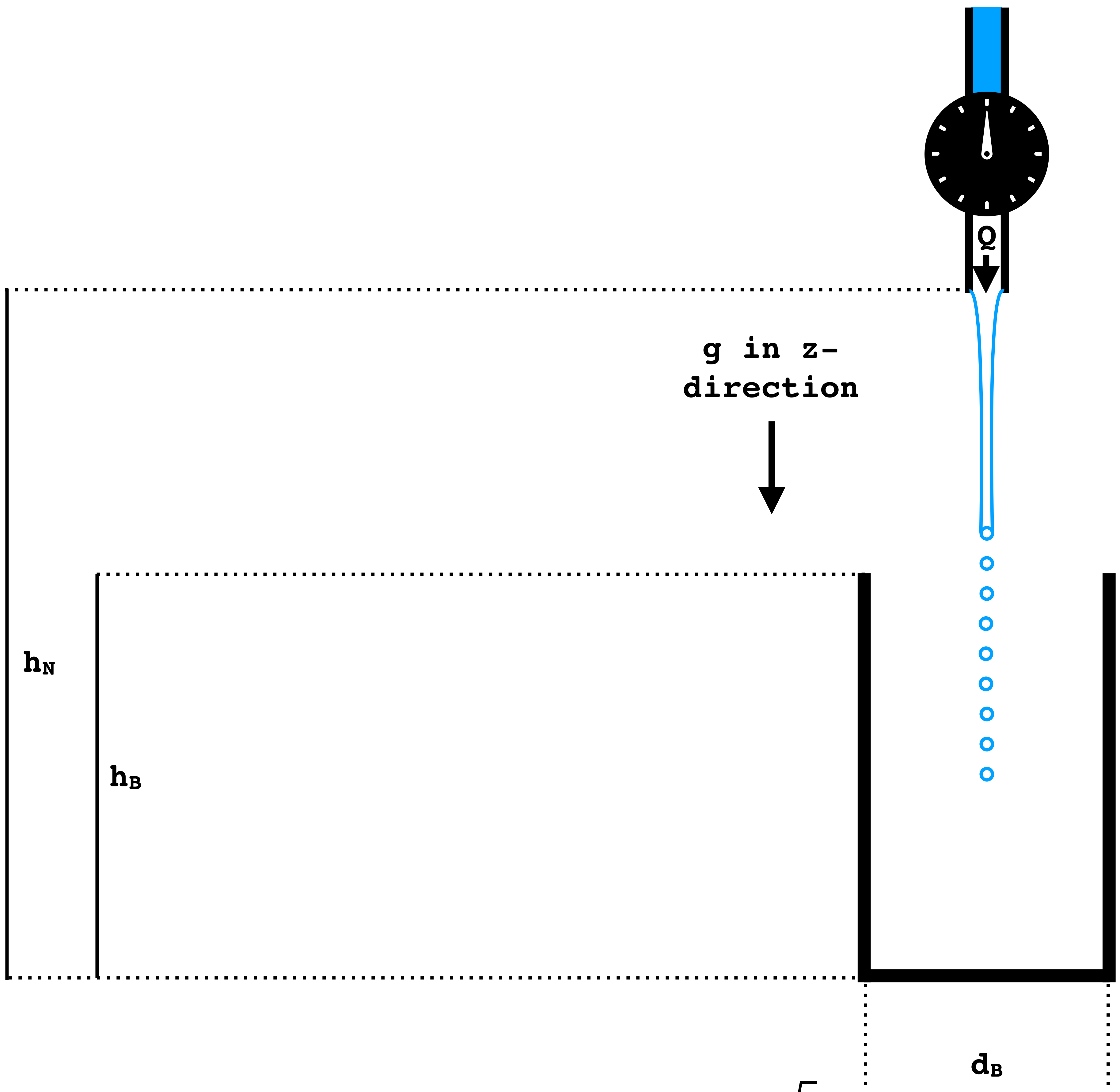

Properties of water:
ρ: Density
σ: Surface tension
η: dynamic viscosity
T_W: Water temperature (influences ρ,σ,η)

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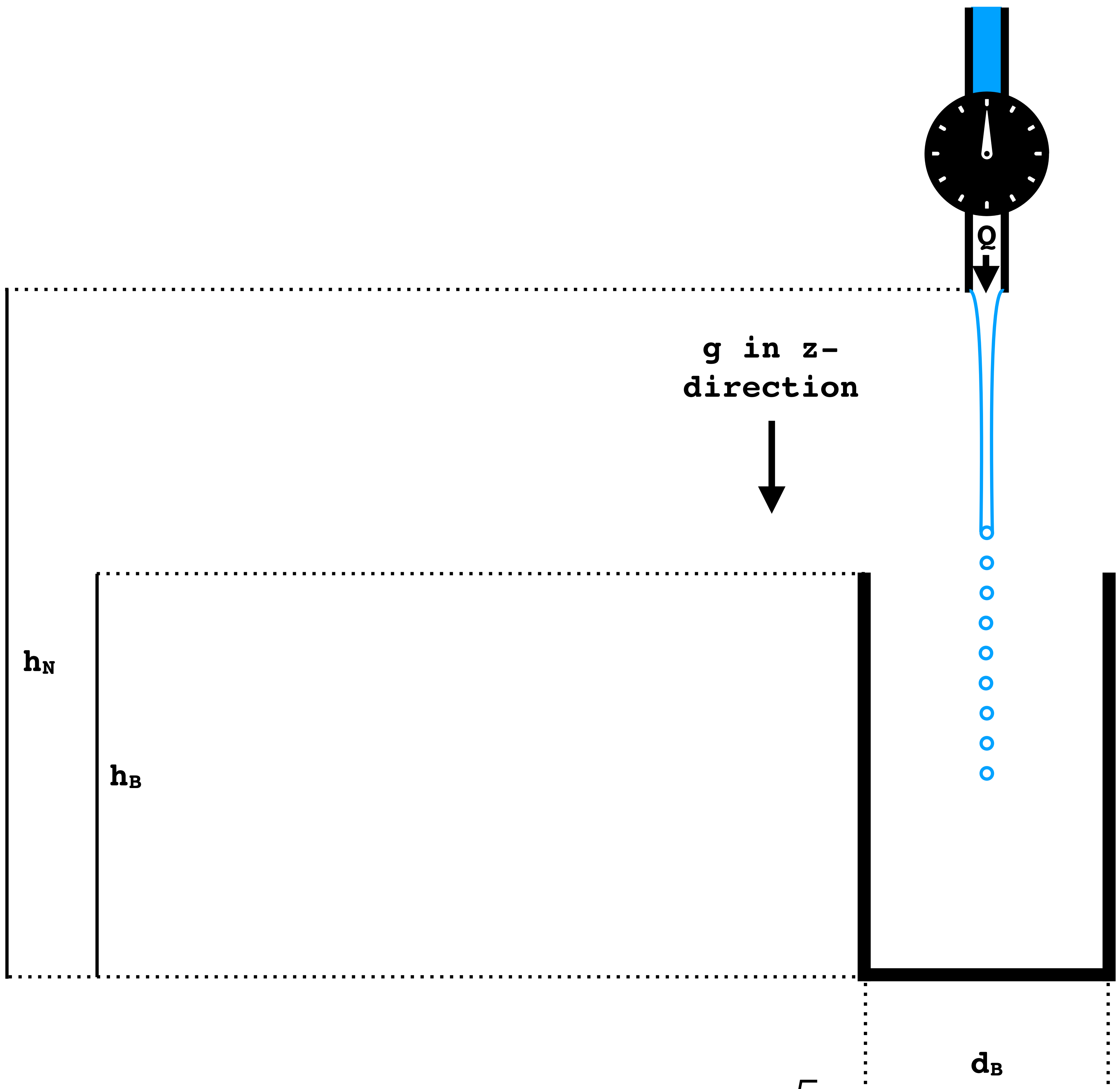

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Properties of air:

p_o: Pressure
γ: Adiabatic coefficient
c: Speed of sound
T_A: Air temperature (influences p_o, c)

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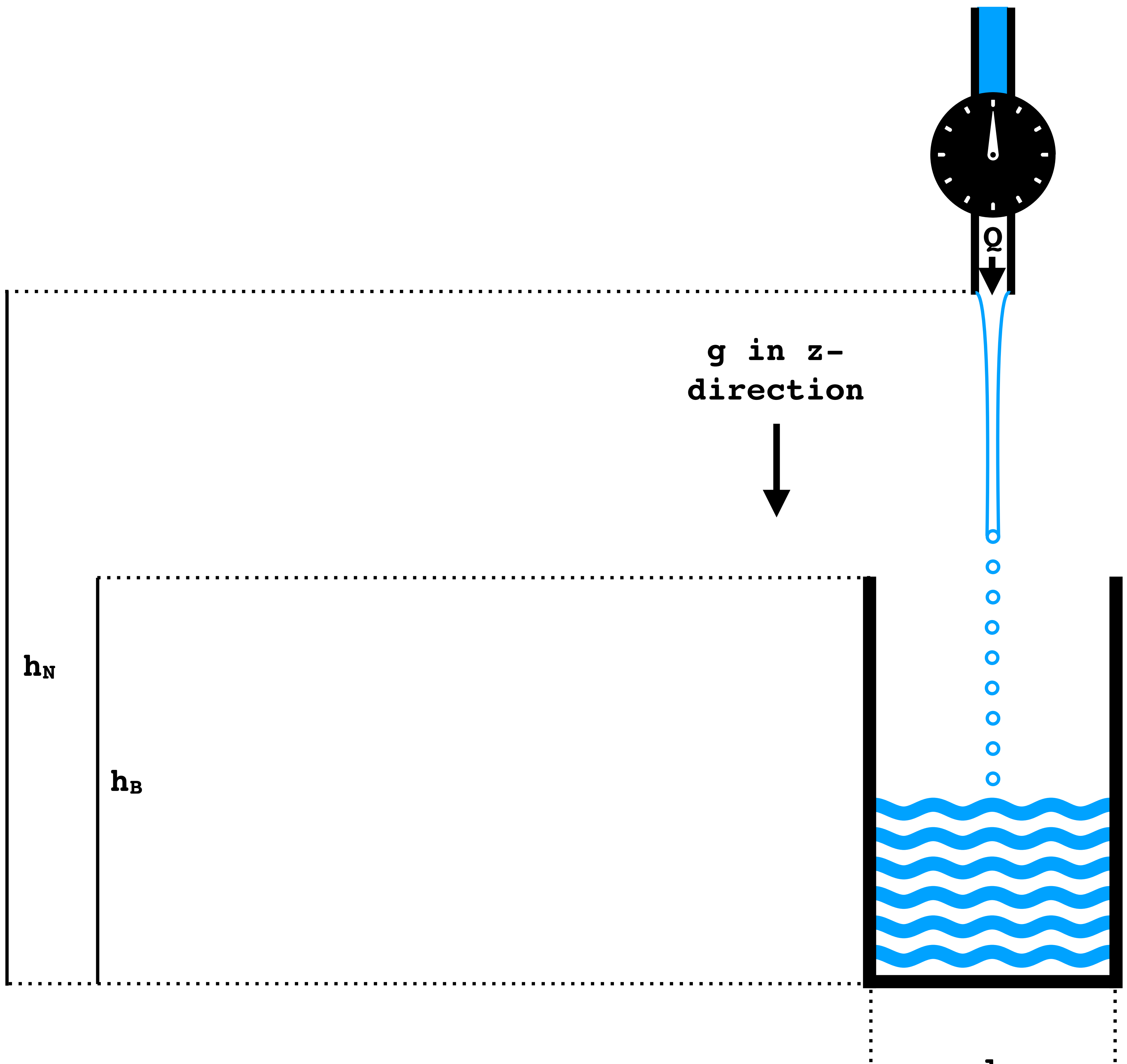

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h_W: Water height
h_C: Cavity height

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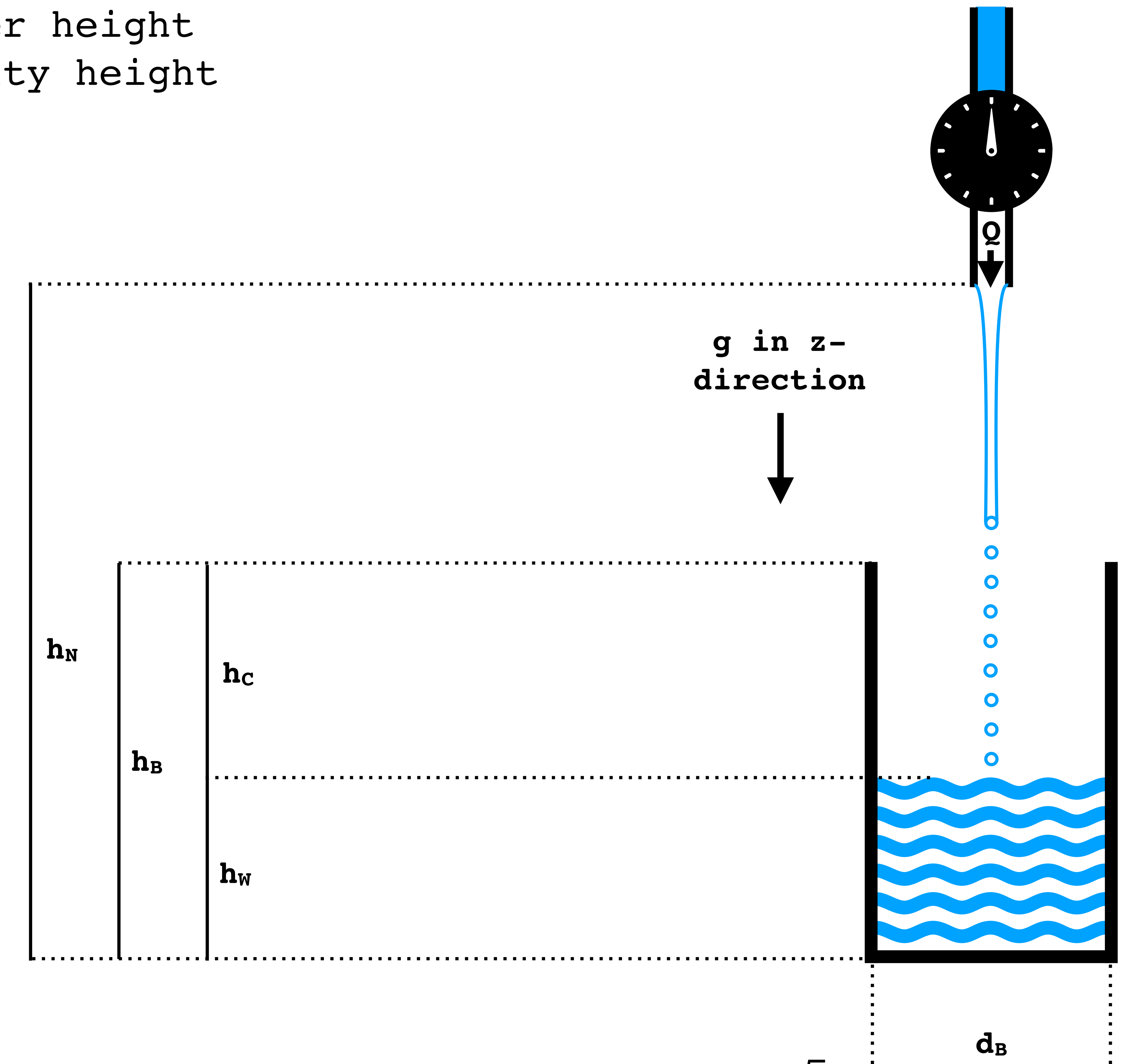

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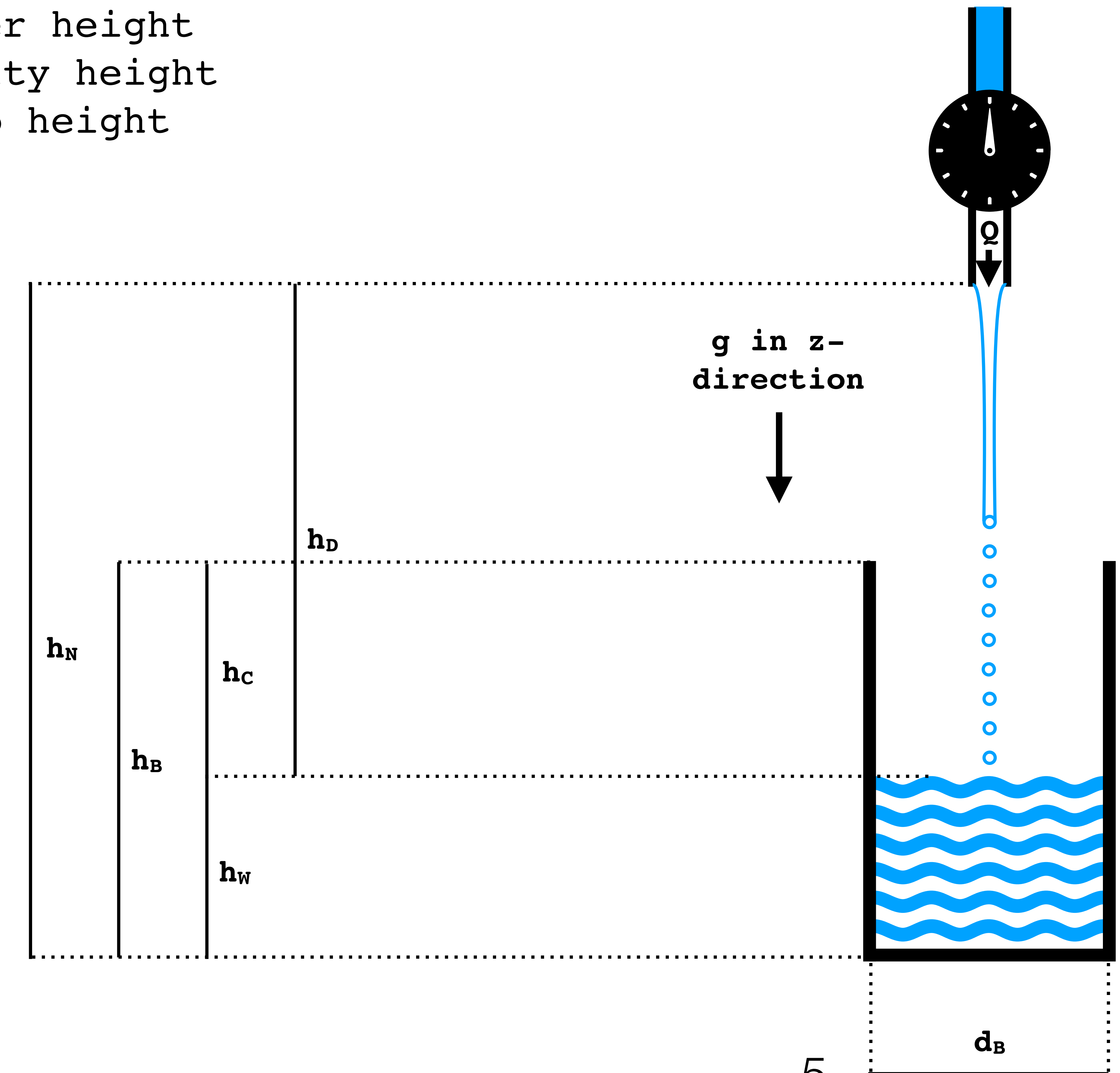
h_C: Cavity height
h_D: Drop height



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Standing waves

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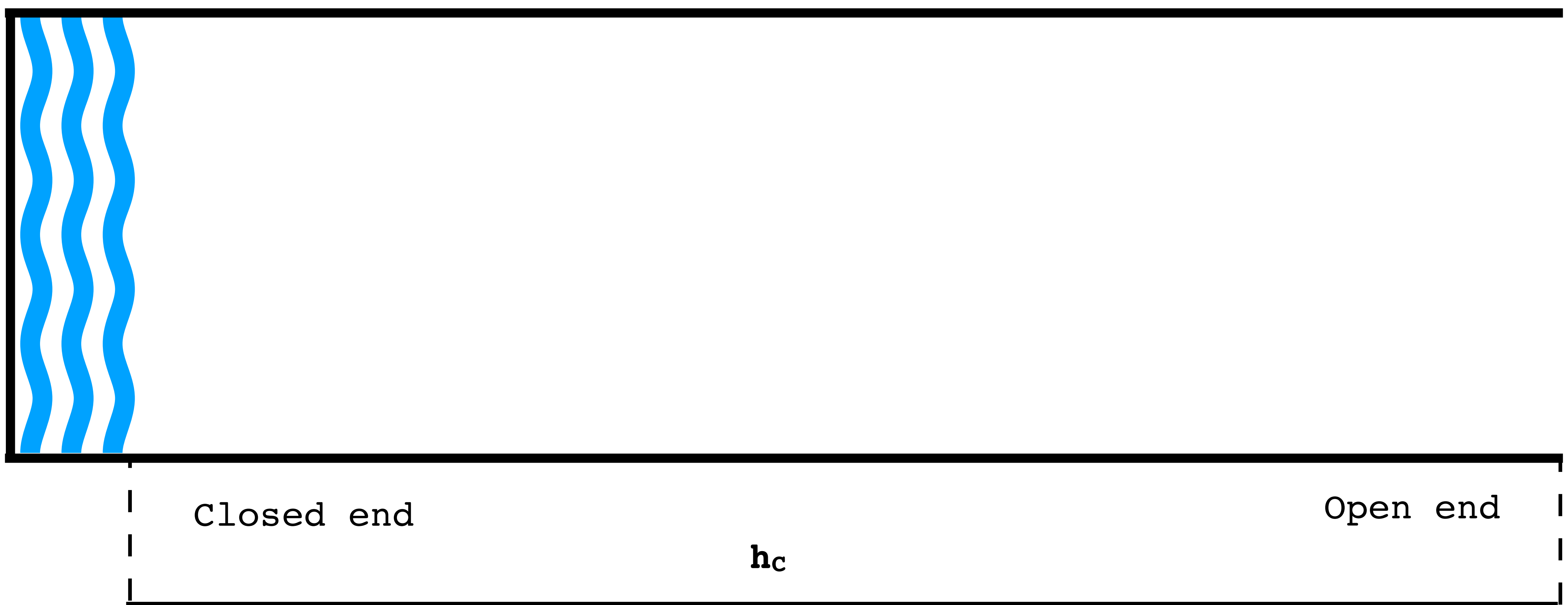

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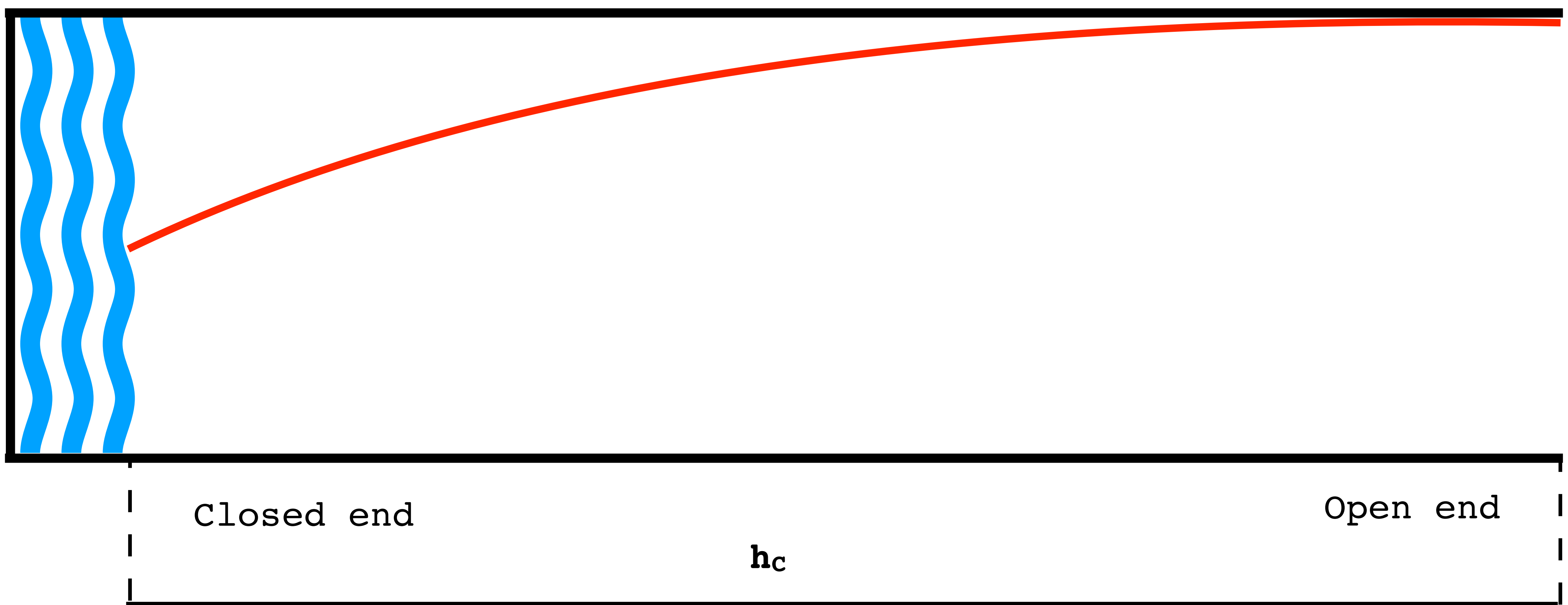

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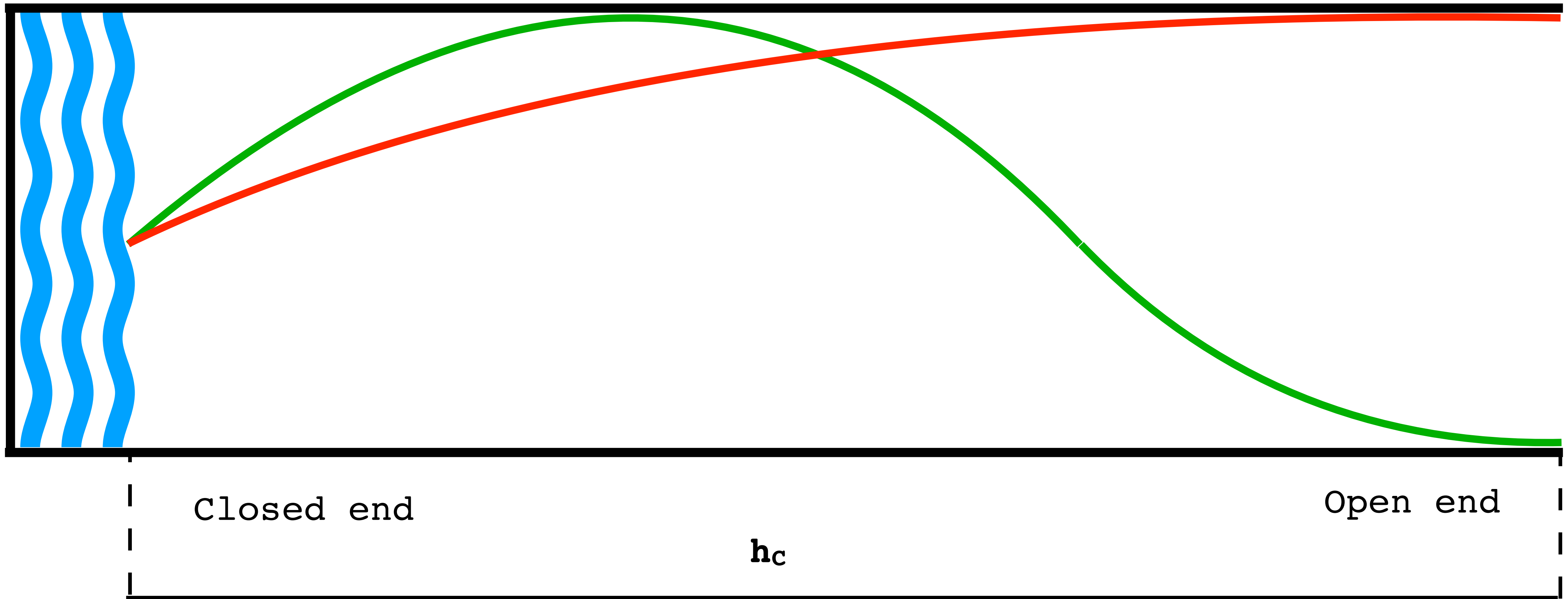

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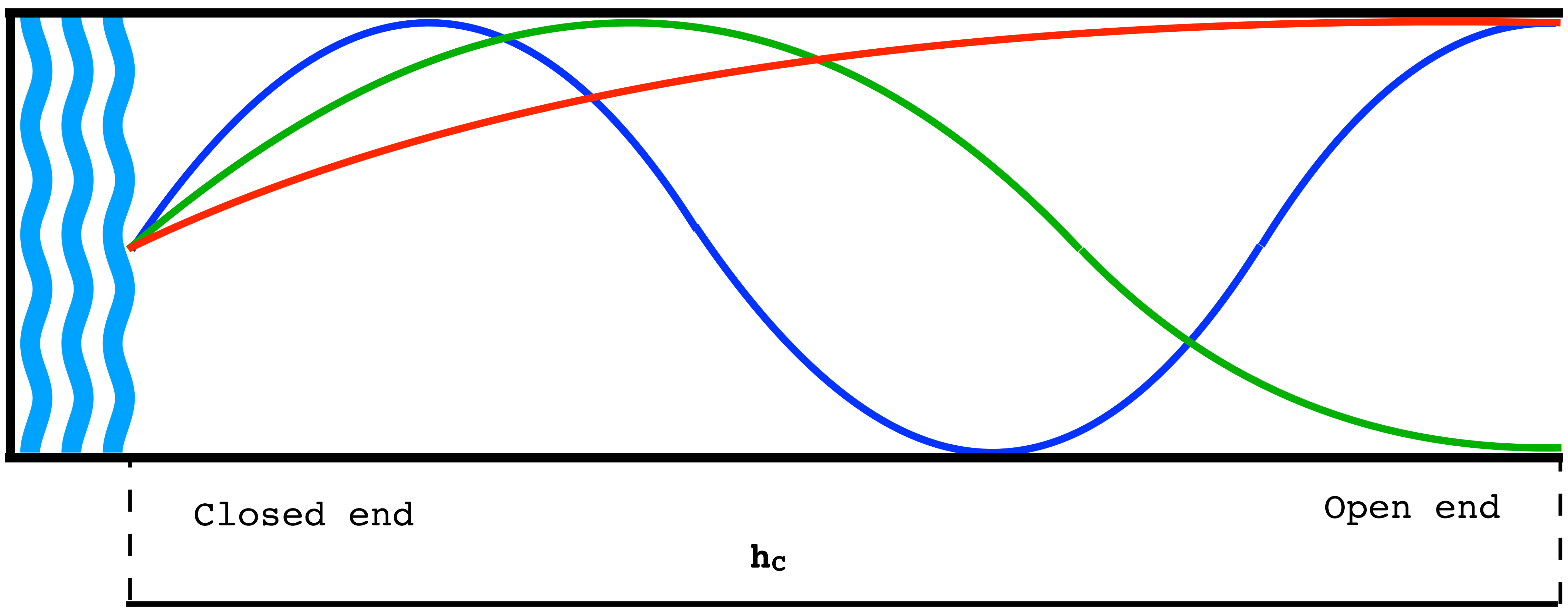

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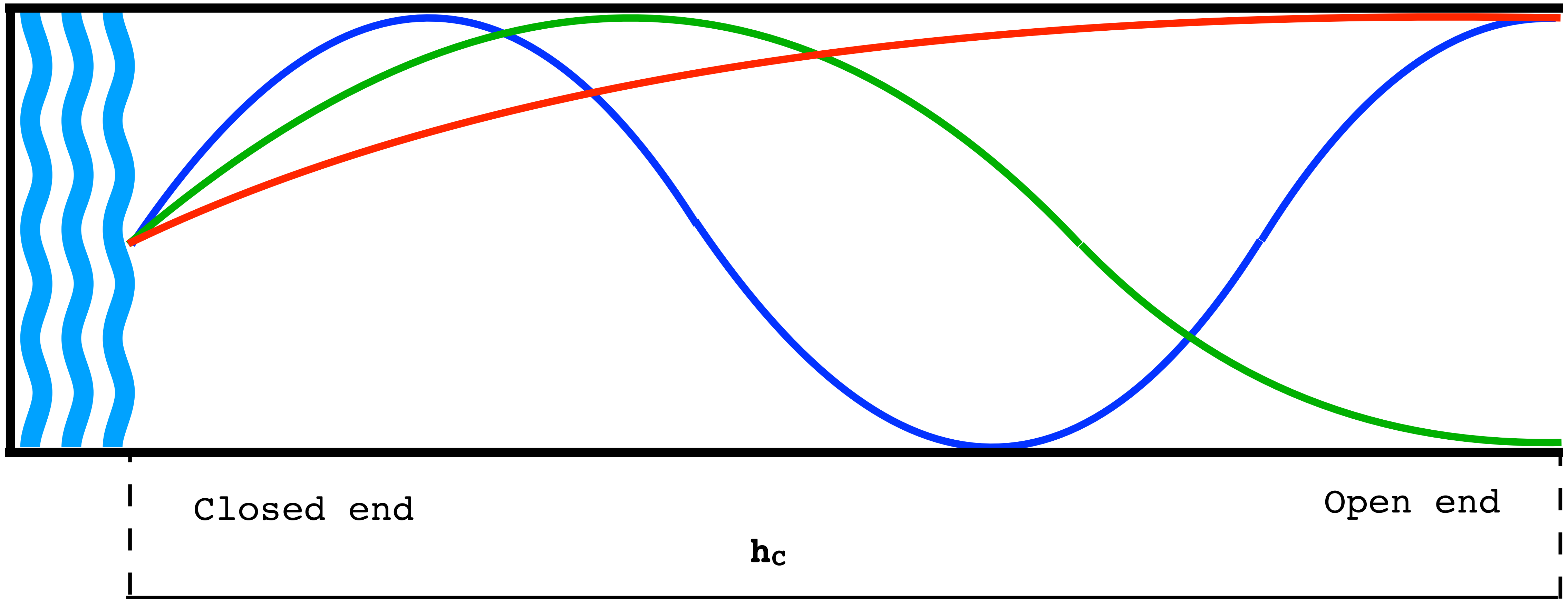


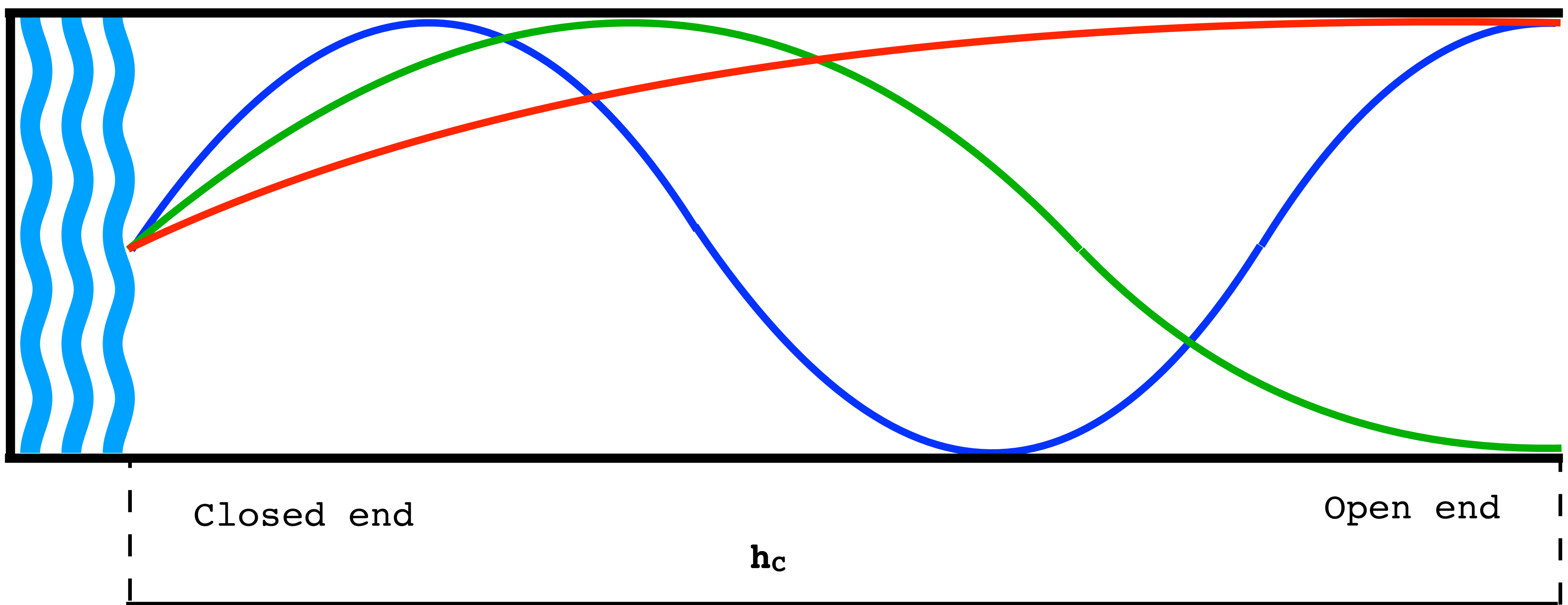
$\lambda_0 = 4h_c$

$\lambda_1 = \frac{4}{3}h_c$

$\lambda_2 = \frac{4}{5}h_c$

etc…

Standing waves



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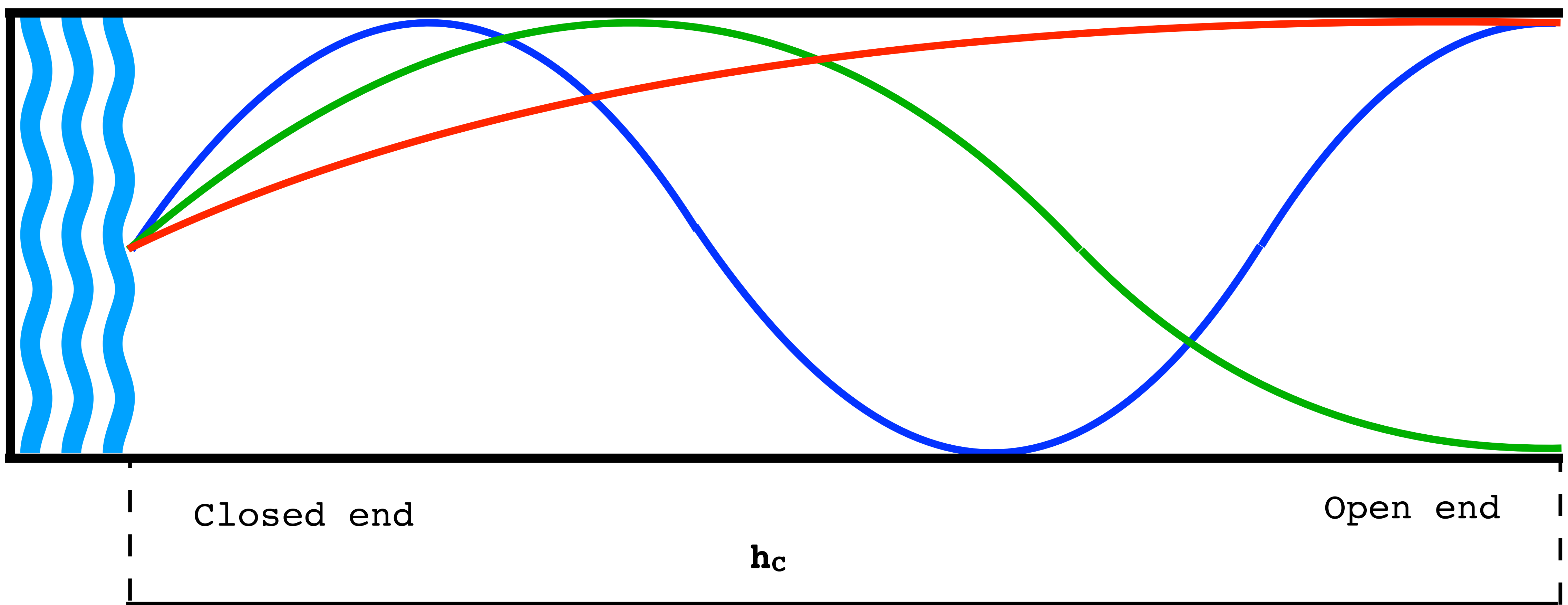
$f = \frac{c}{\lambda}$ →

Standing waves



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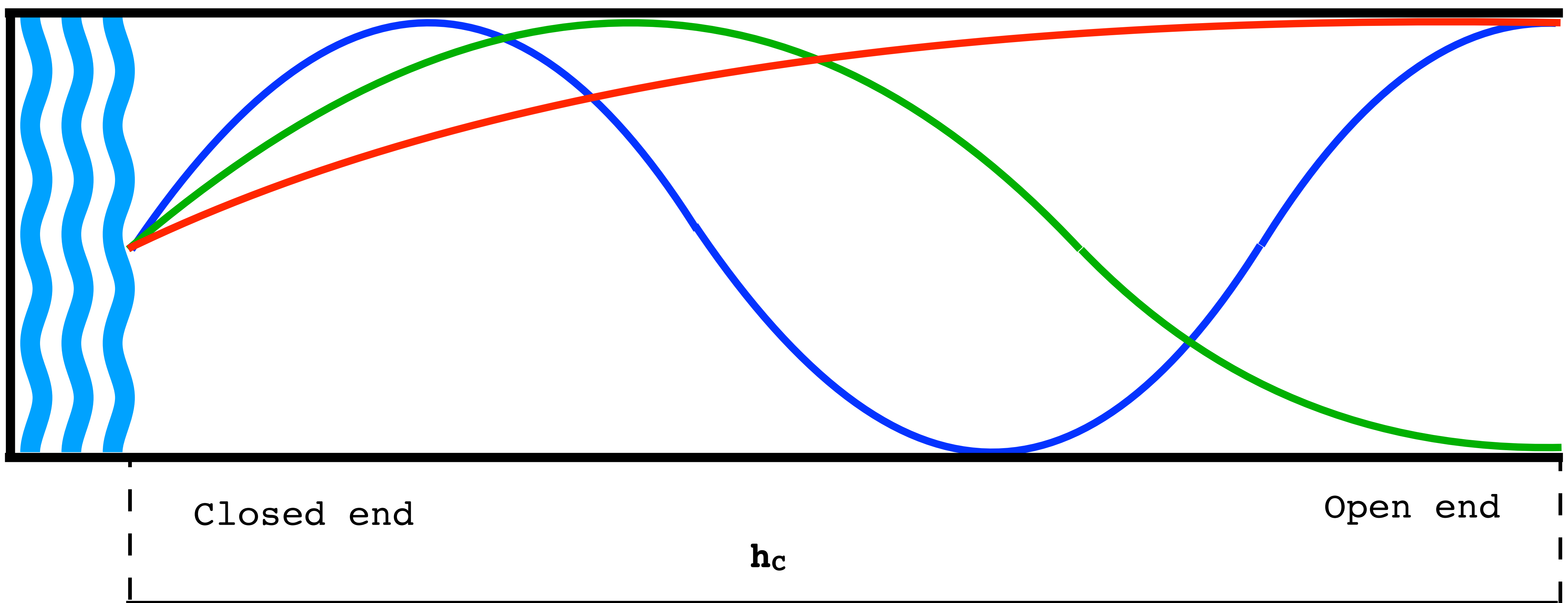
$$f = \frac{c}{\lambda} \longrightarrow$$

$f_0 = \frac{c}{4h_c}$

$f_1 = \frac{3c}{4h_c} = 3f_0$

$f_2 = \frac{5c}{4h_c} = 5f_0$

Standing waves



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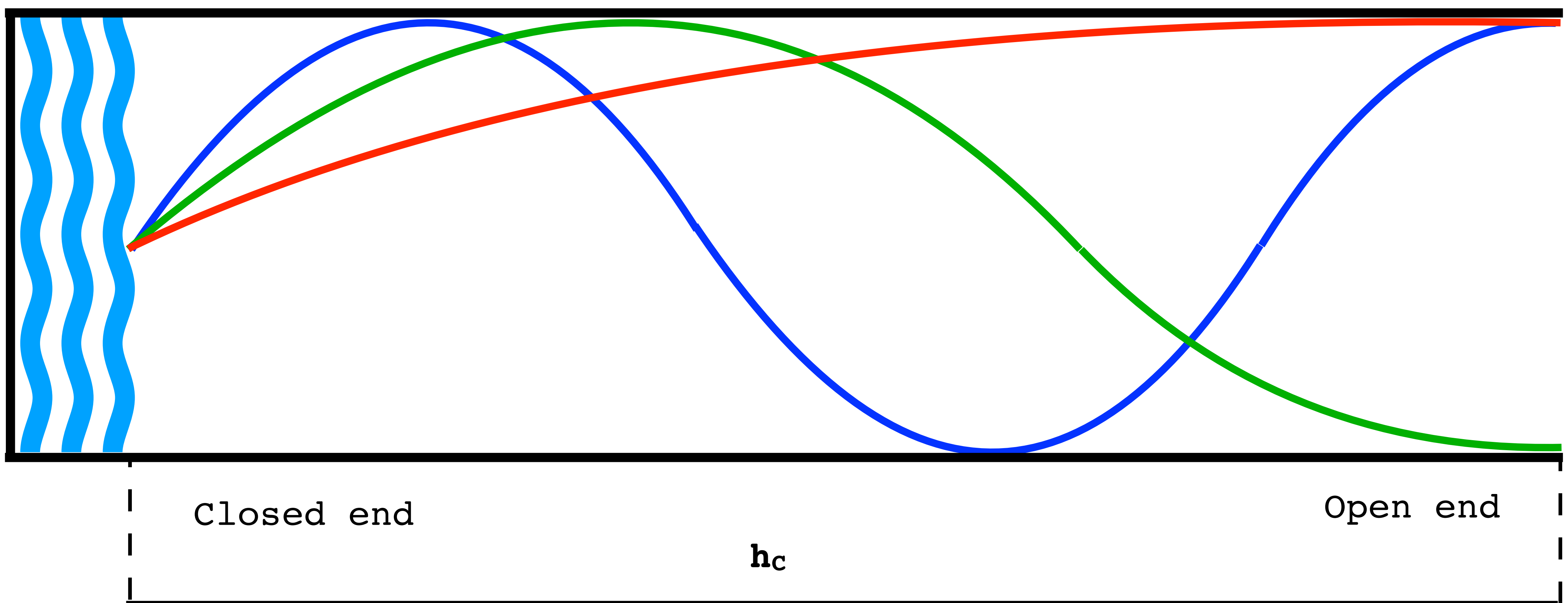
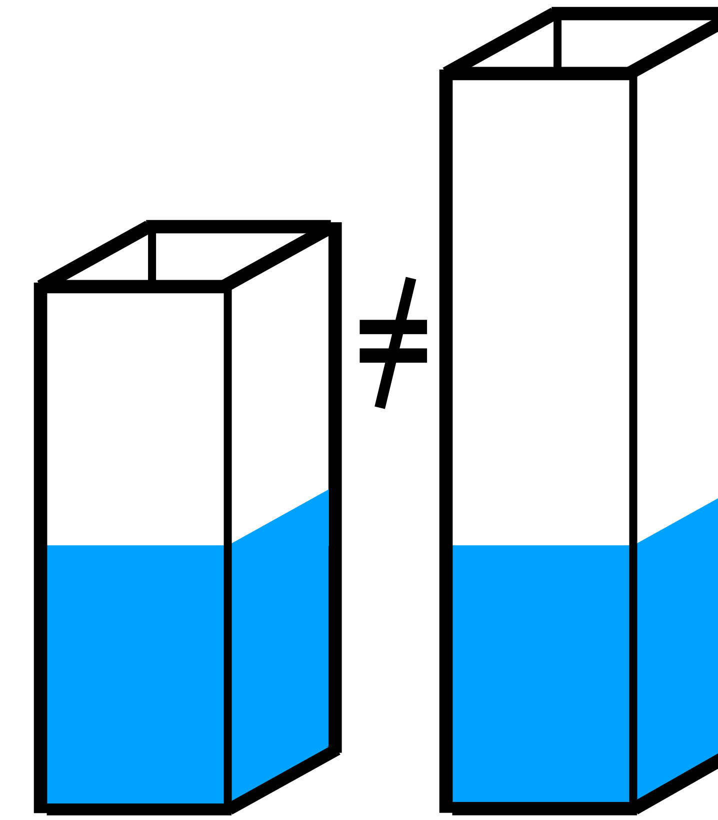
Standing waves in the cavity change their frequencies based on the changing water height.

Standing waves





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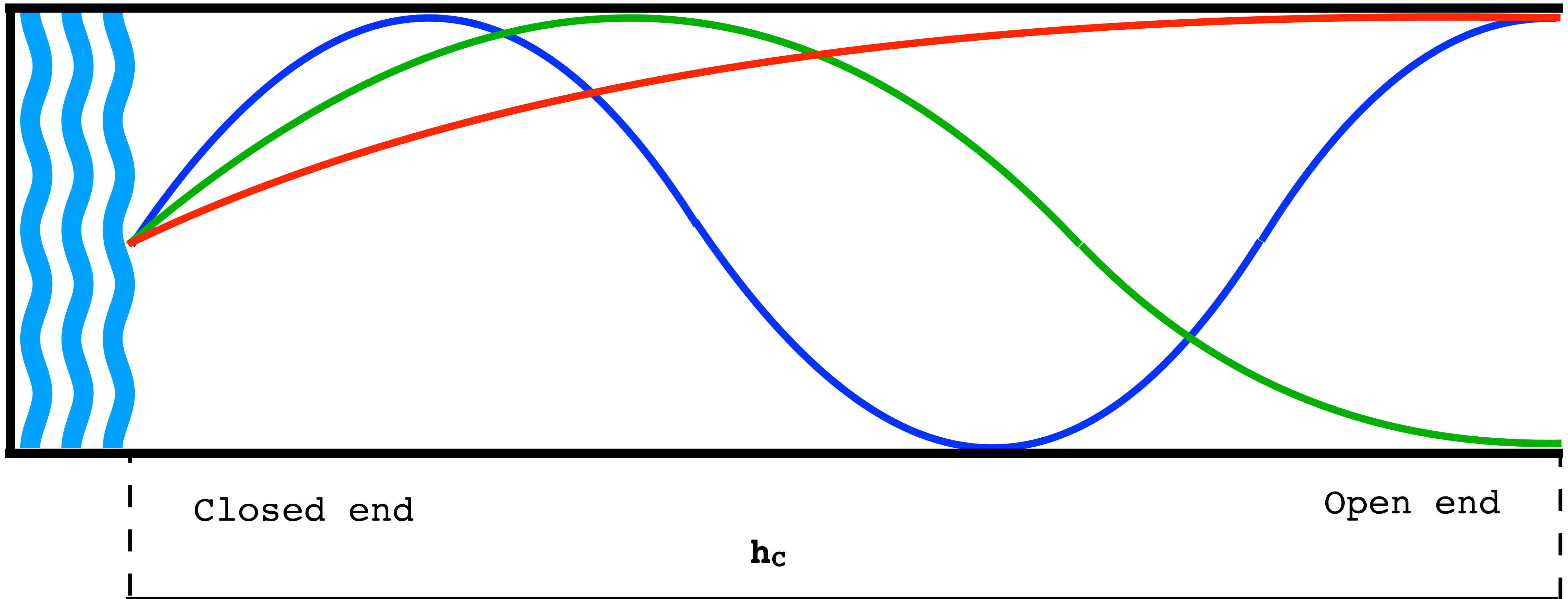

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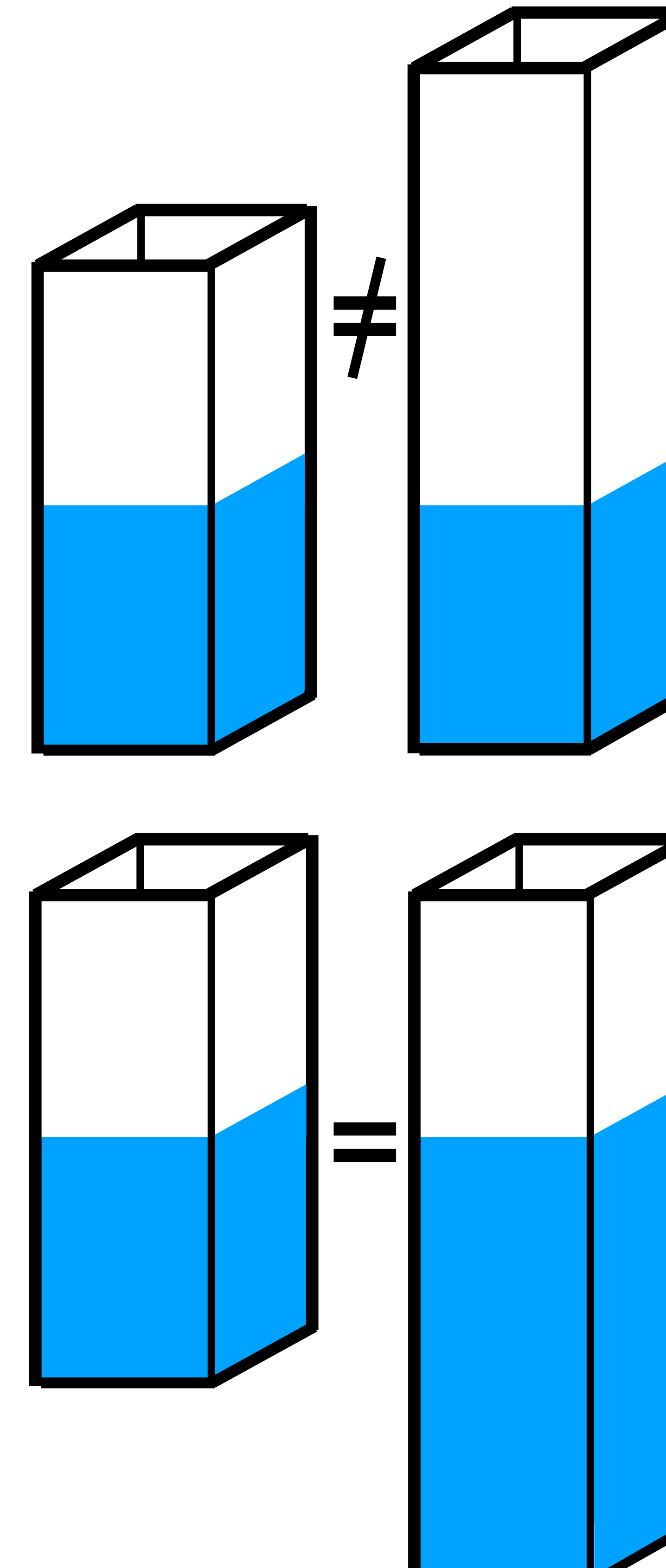
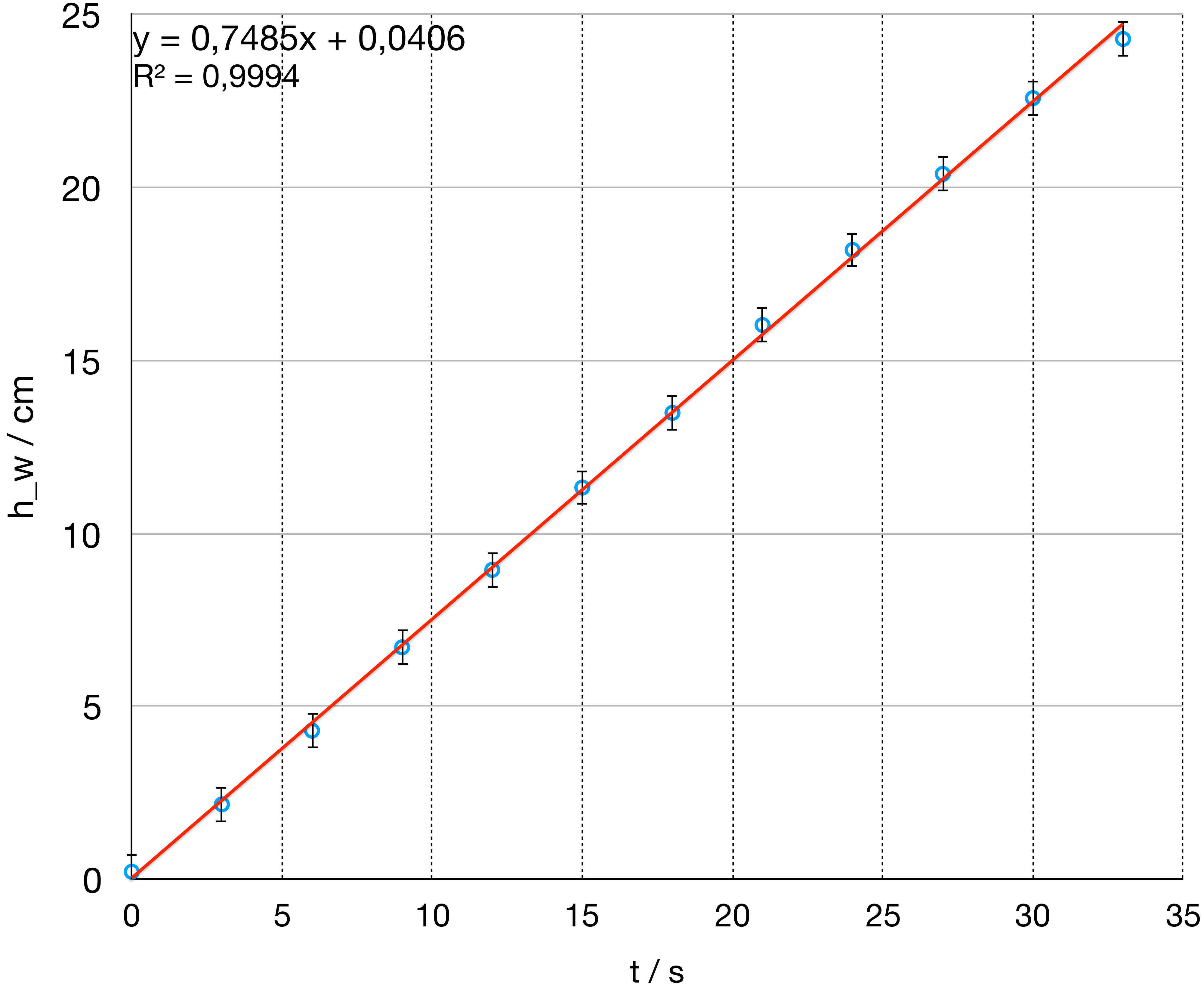
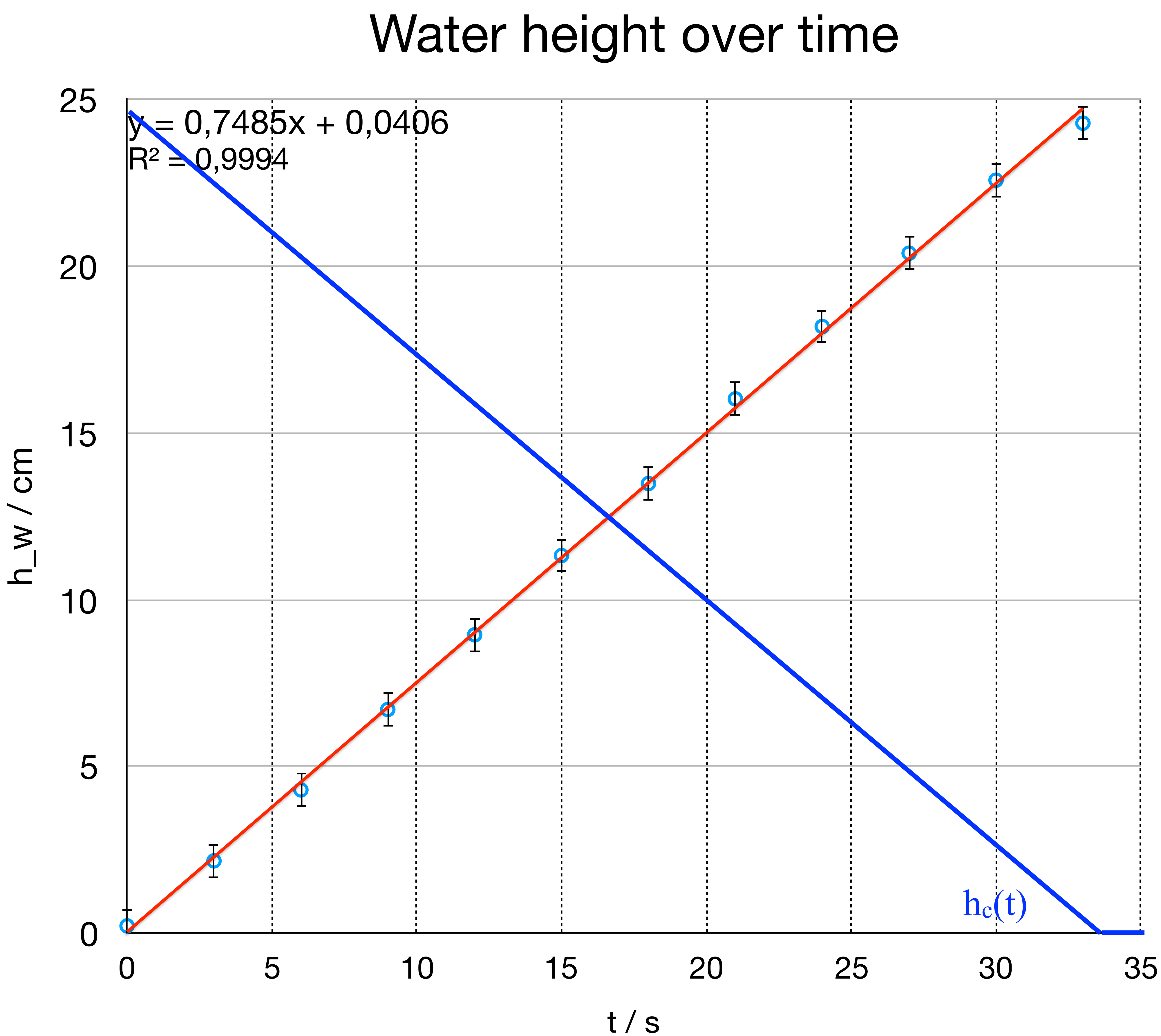


Water height over time

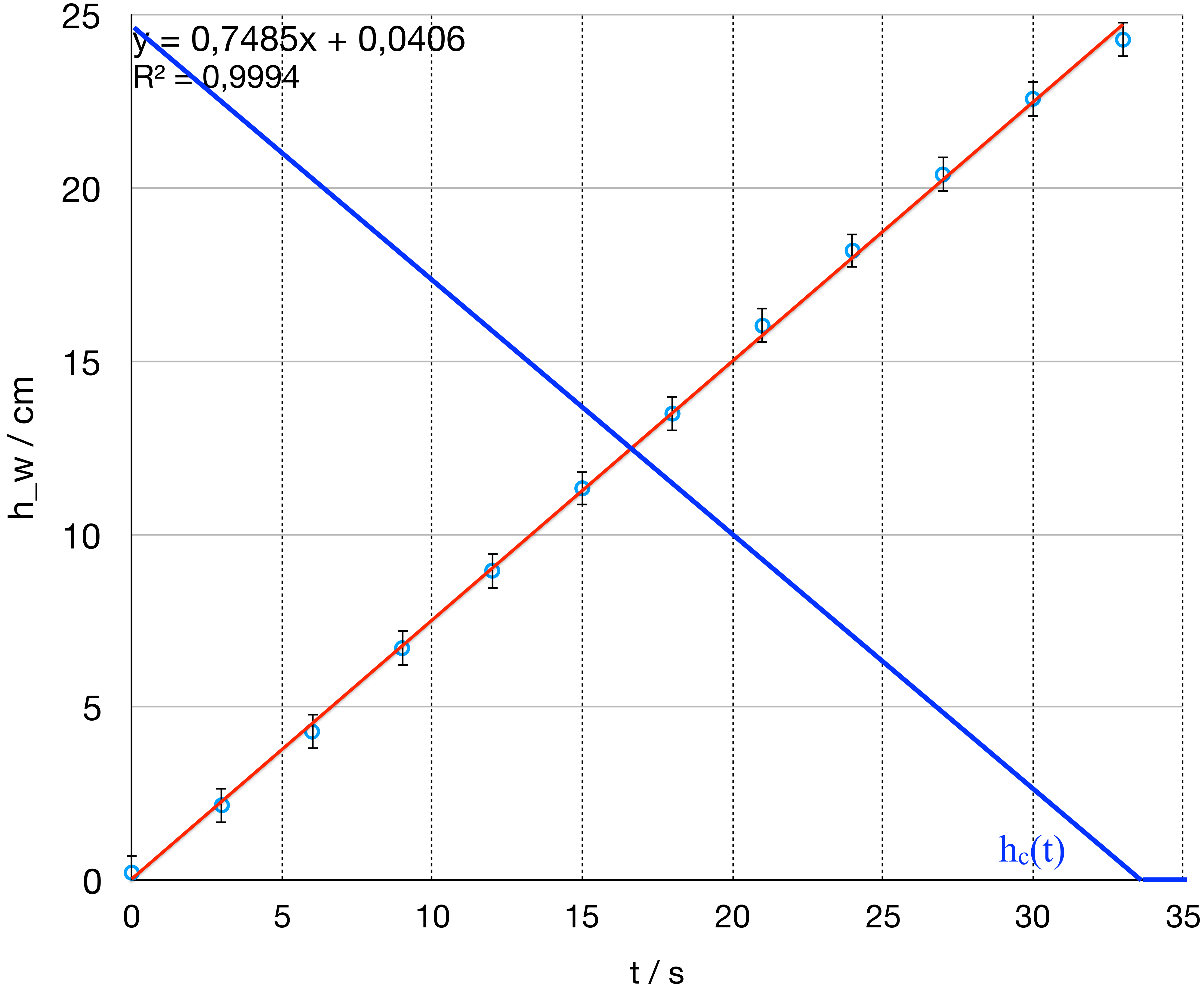



Δhw


Water height over time
y = 0,7485x + 0,0406
R² = 0,9994
h_w / cm
t / s
hc(t)
0
5
10
15
20
25
0
5
10
15
20
25
30
35

$$f = \frac{c}{\lambda}$$

Water height over time



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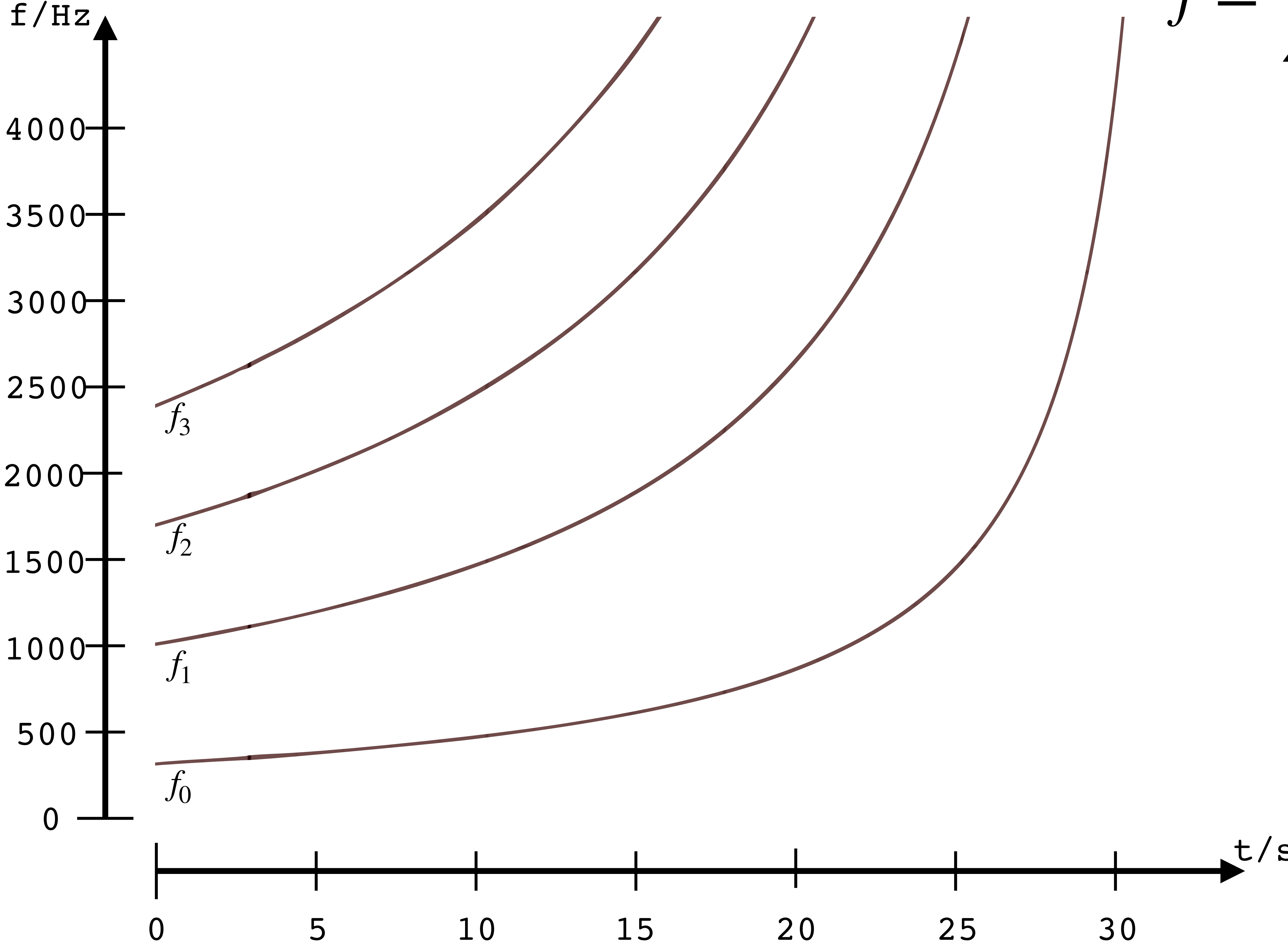
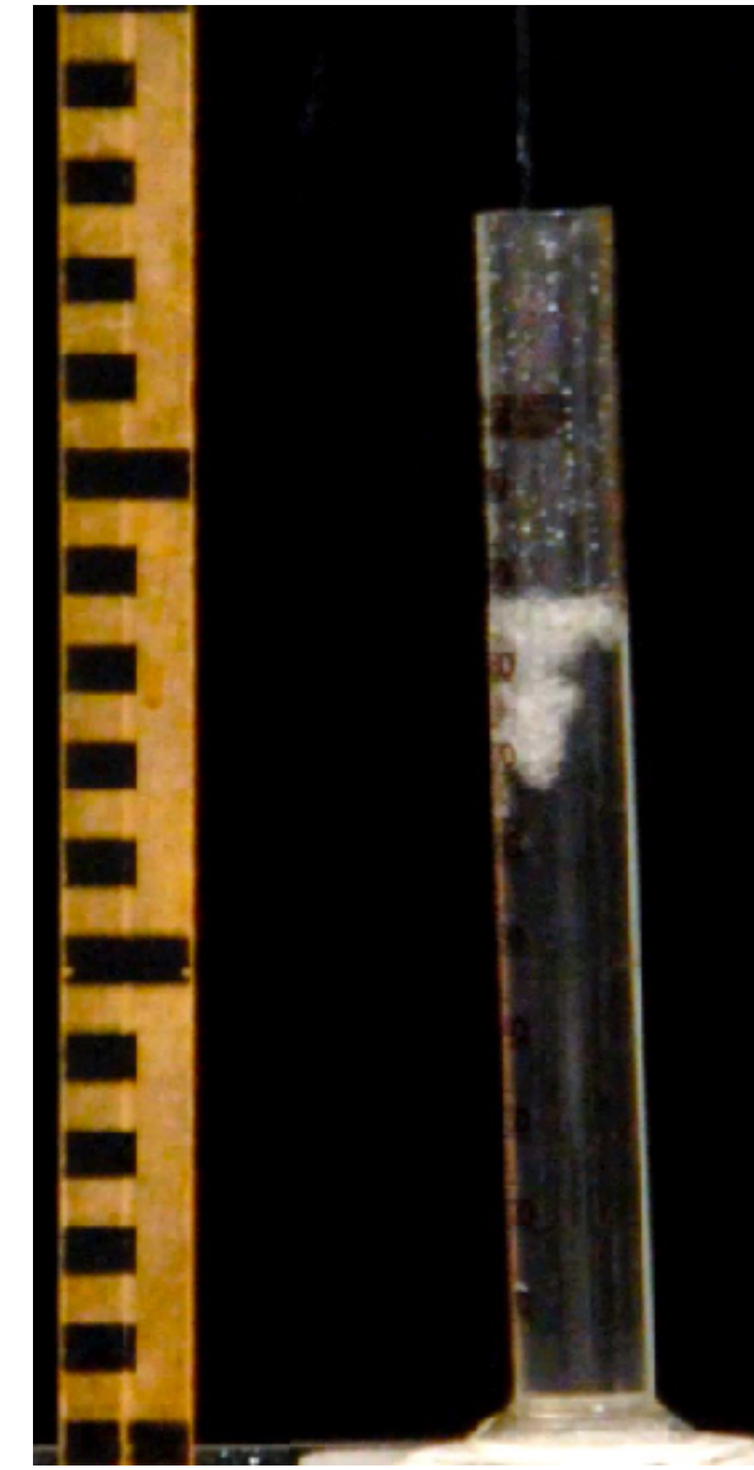
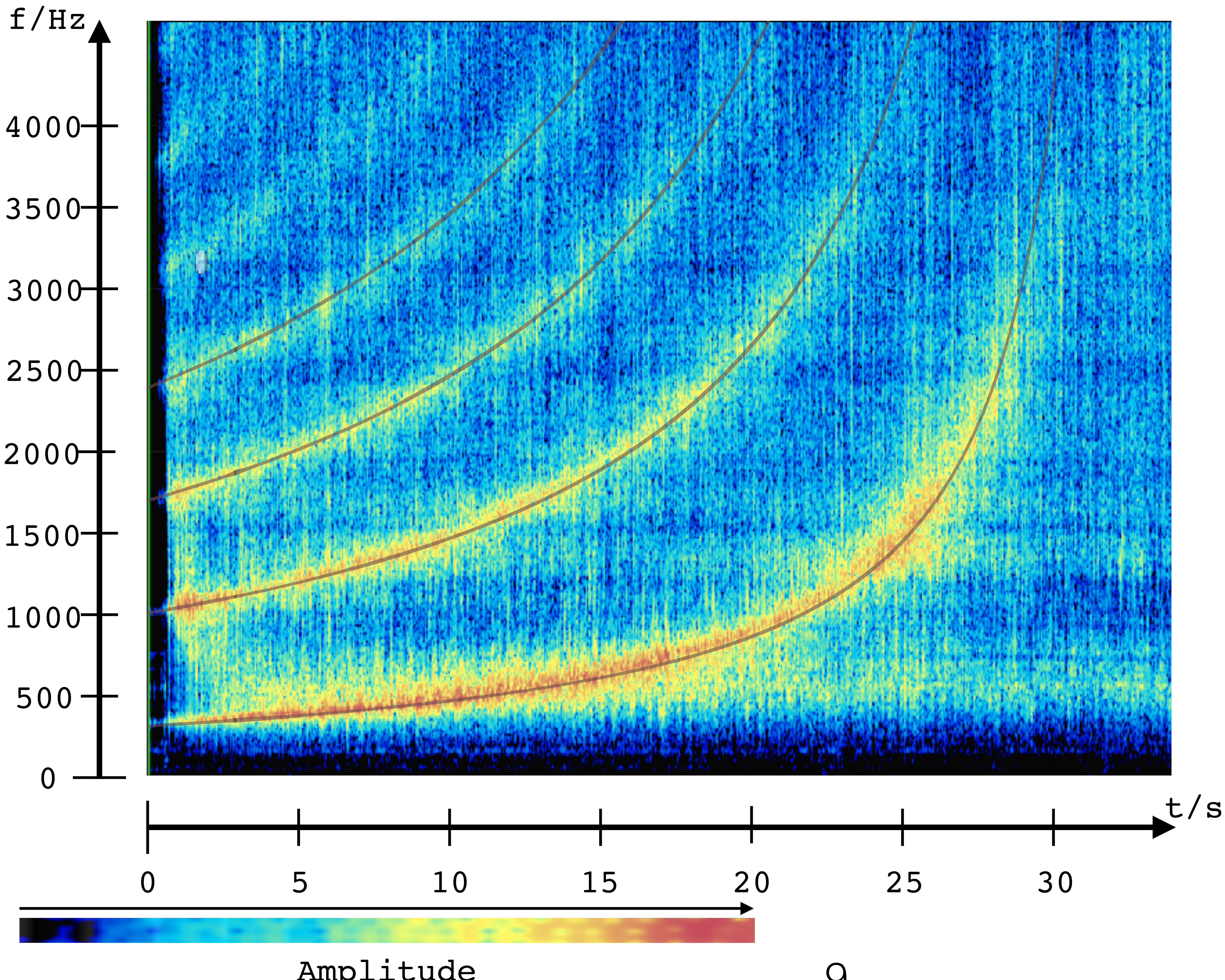
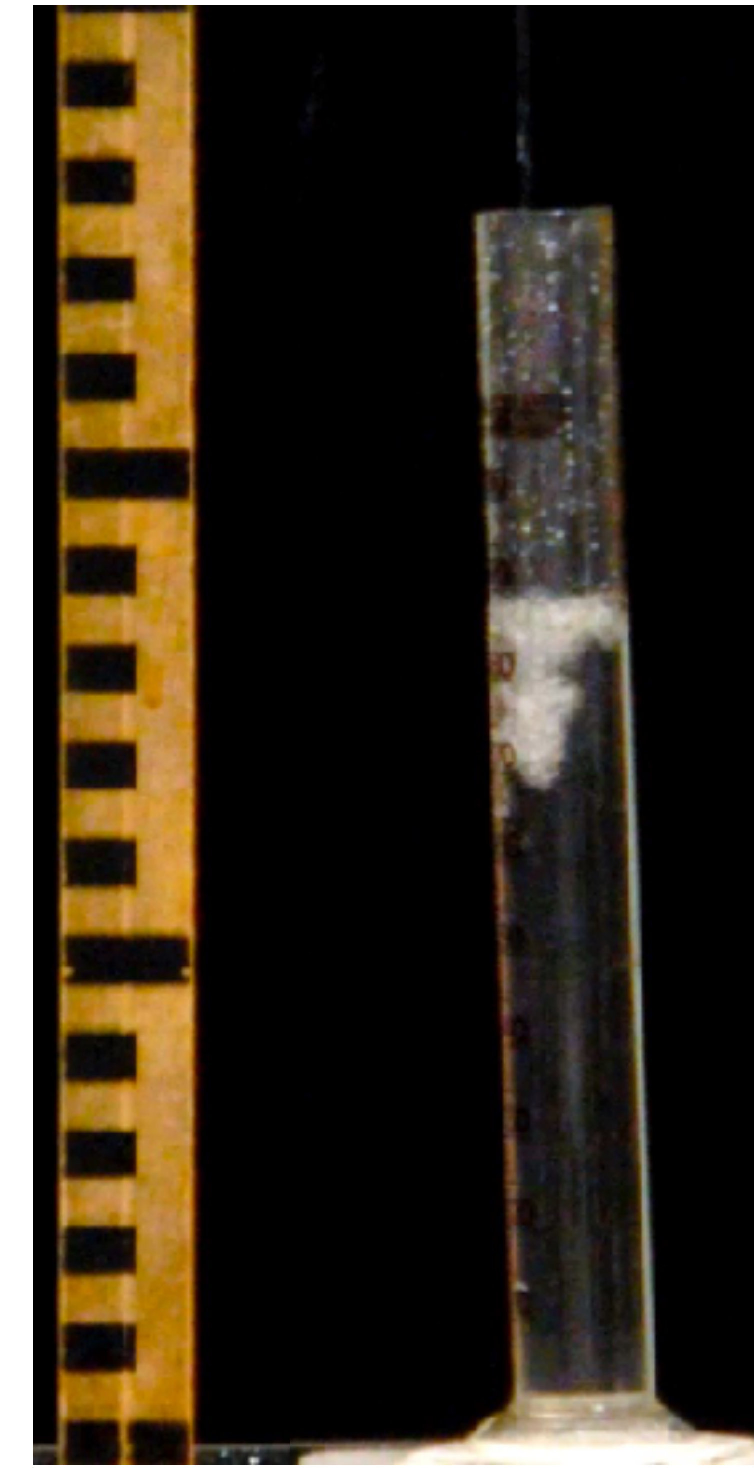




$$Q = 1.04\frac{l}{min} \pm 0.04\frac{l}{min}$$





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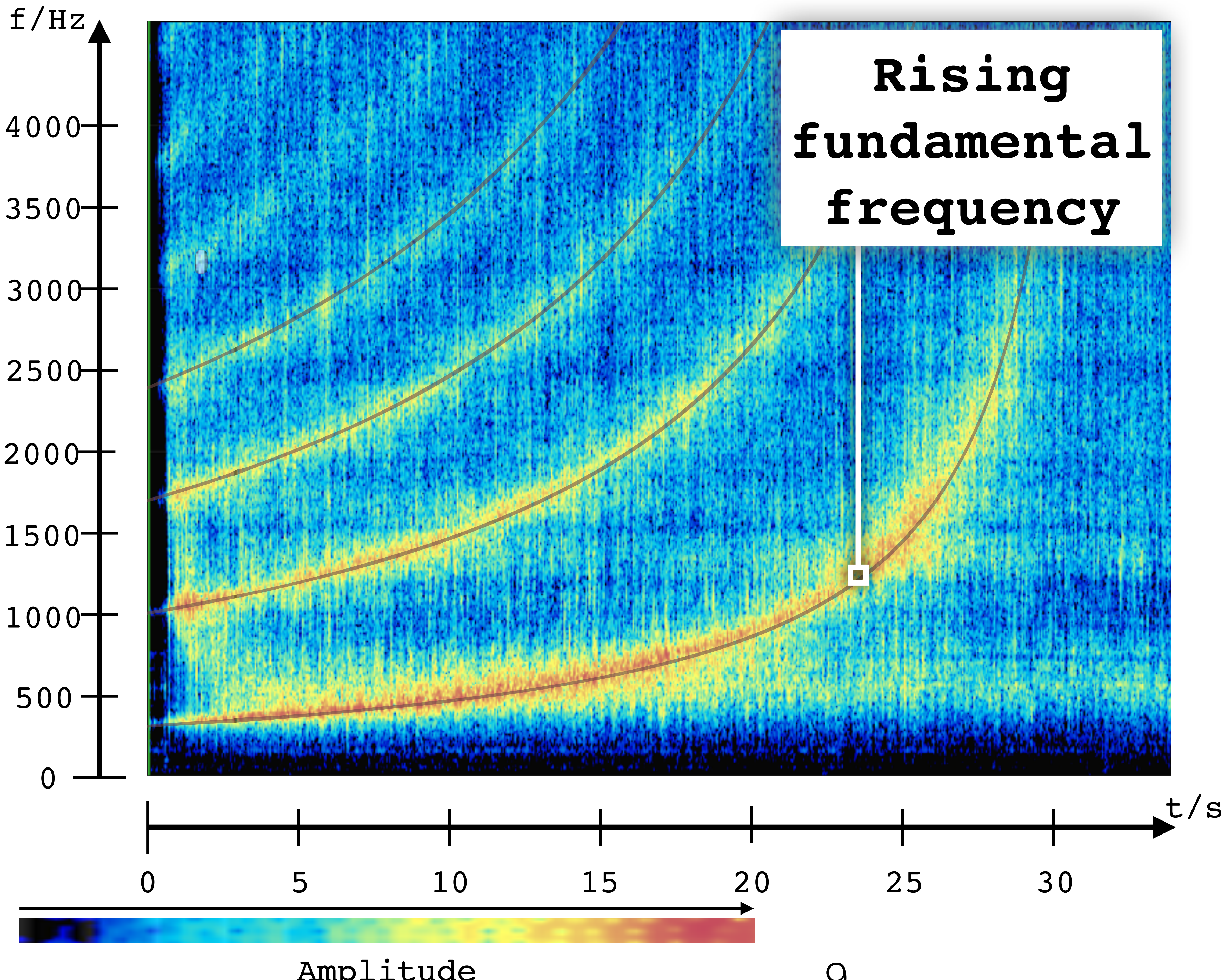

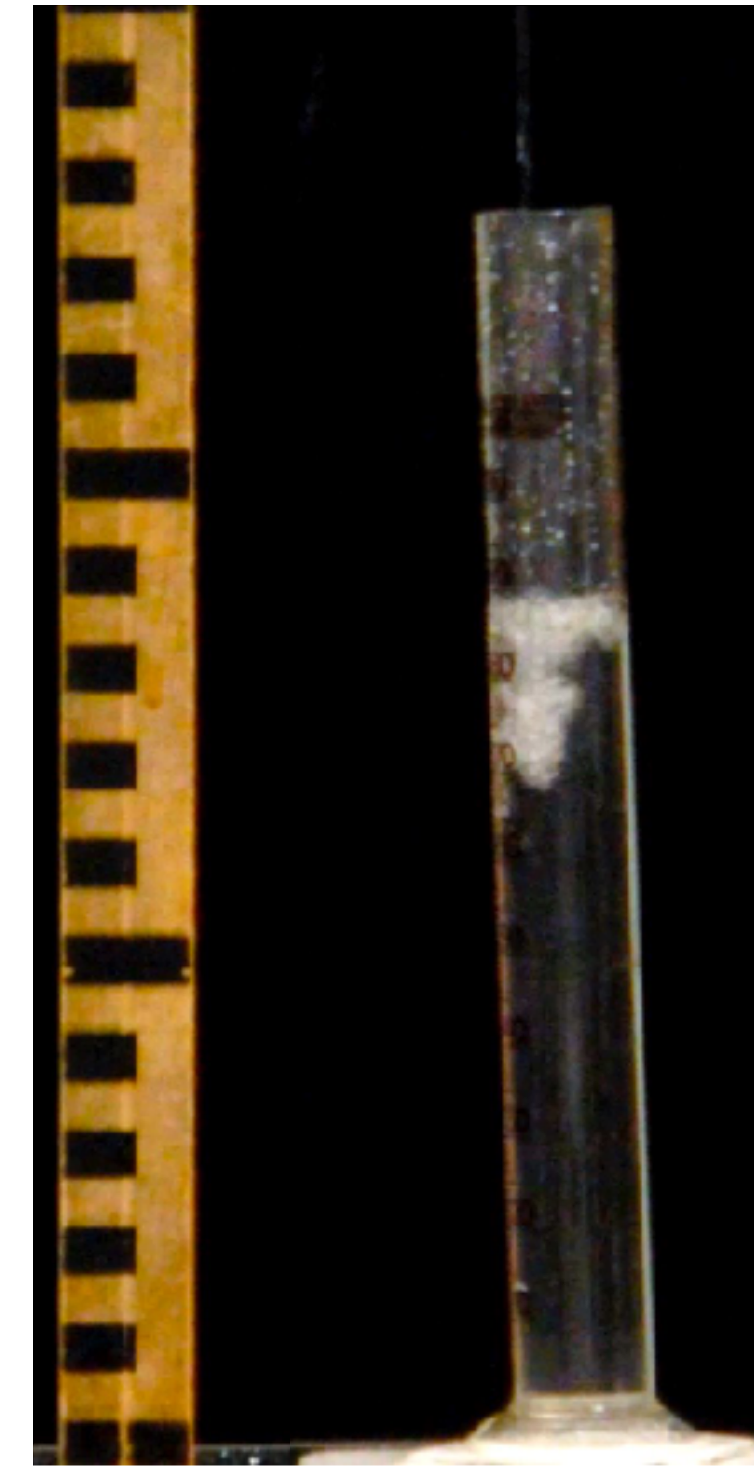

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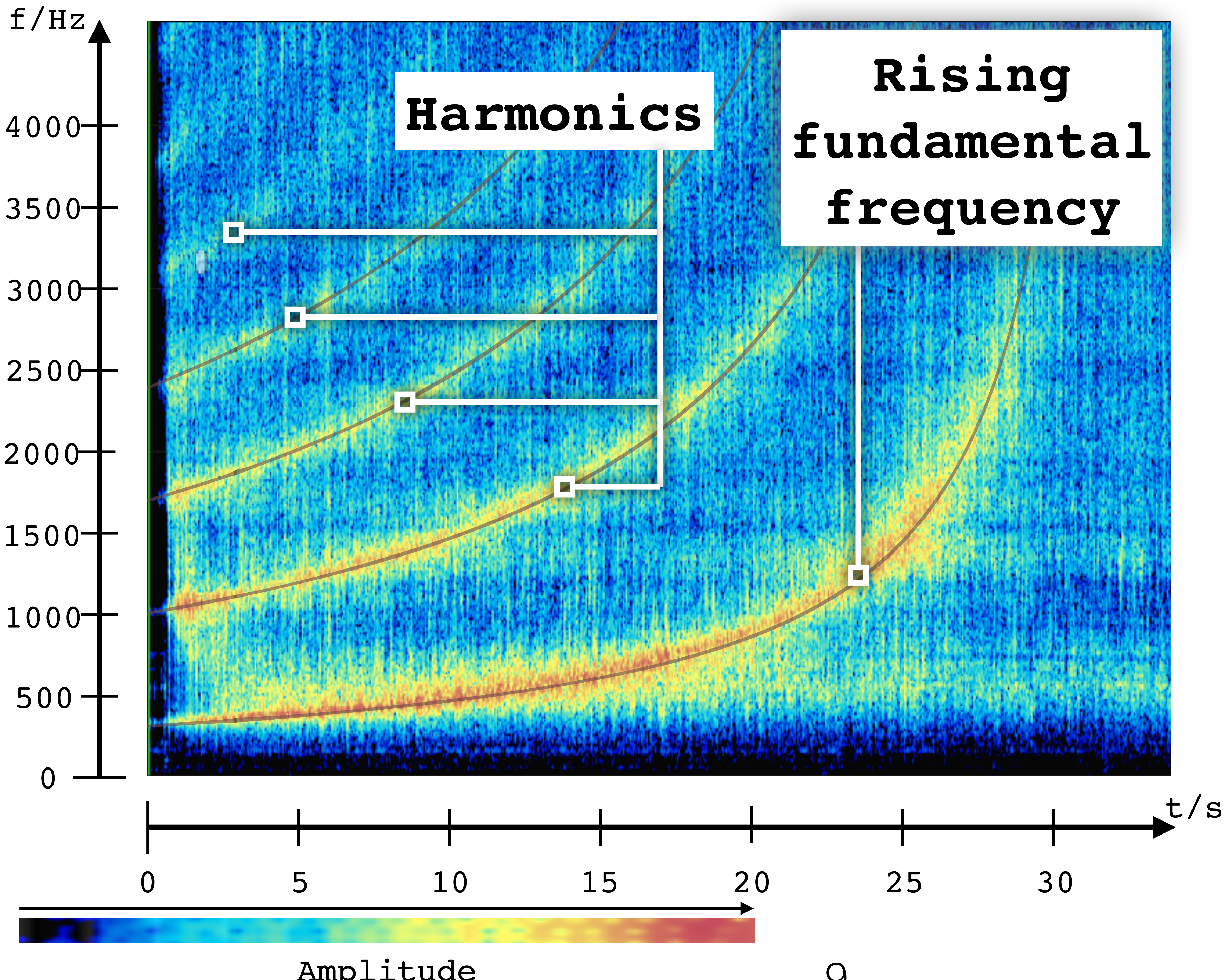

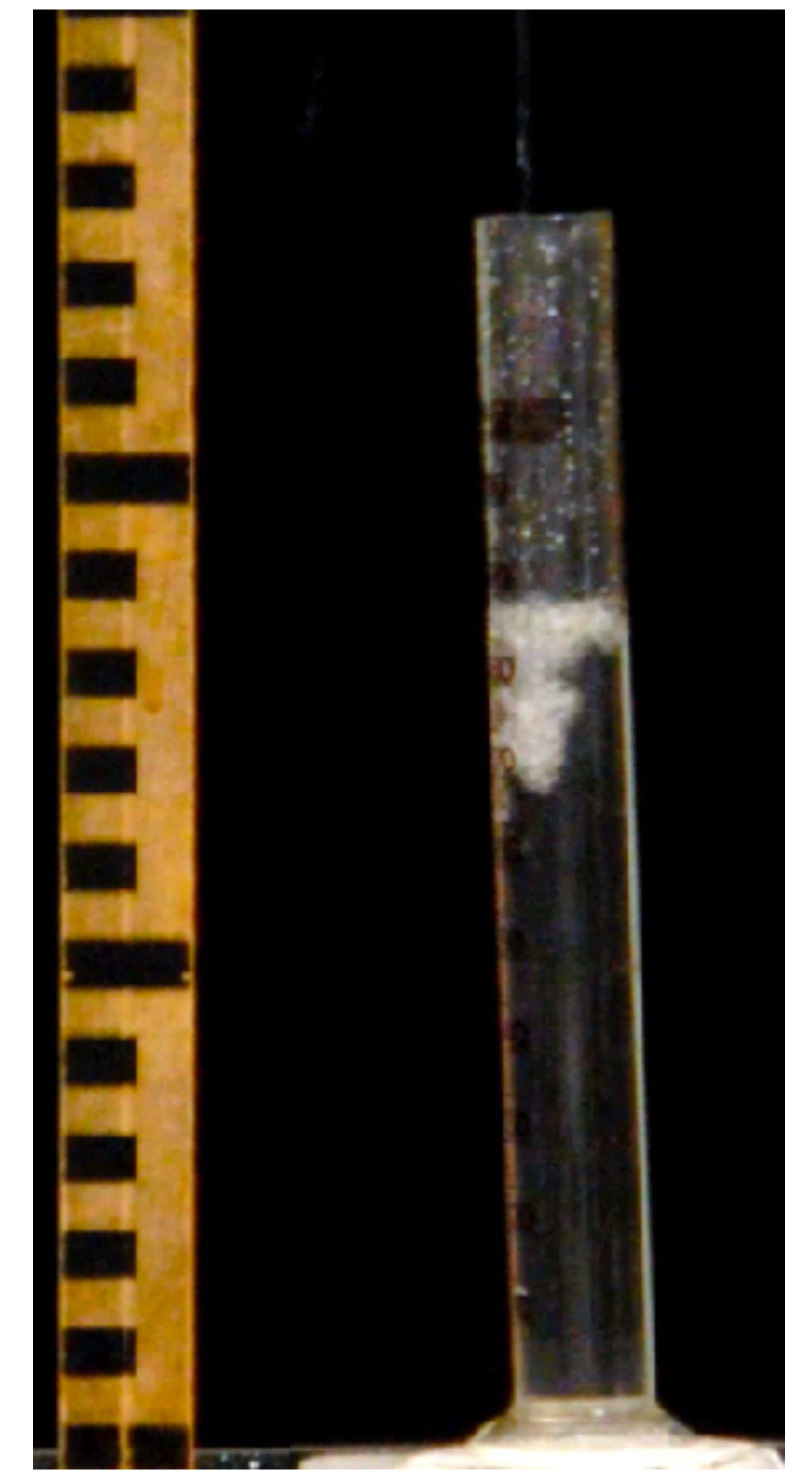

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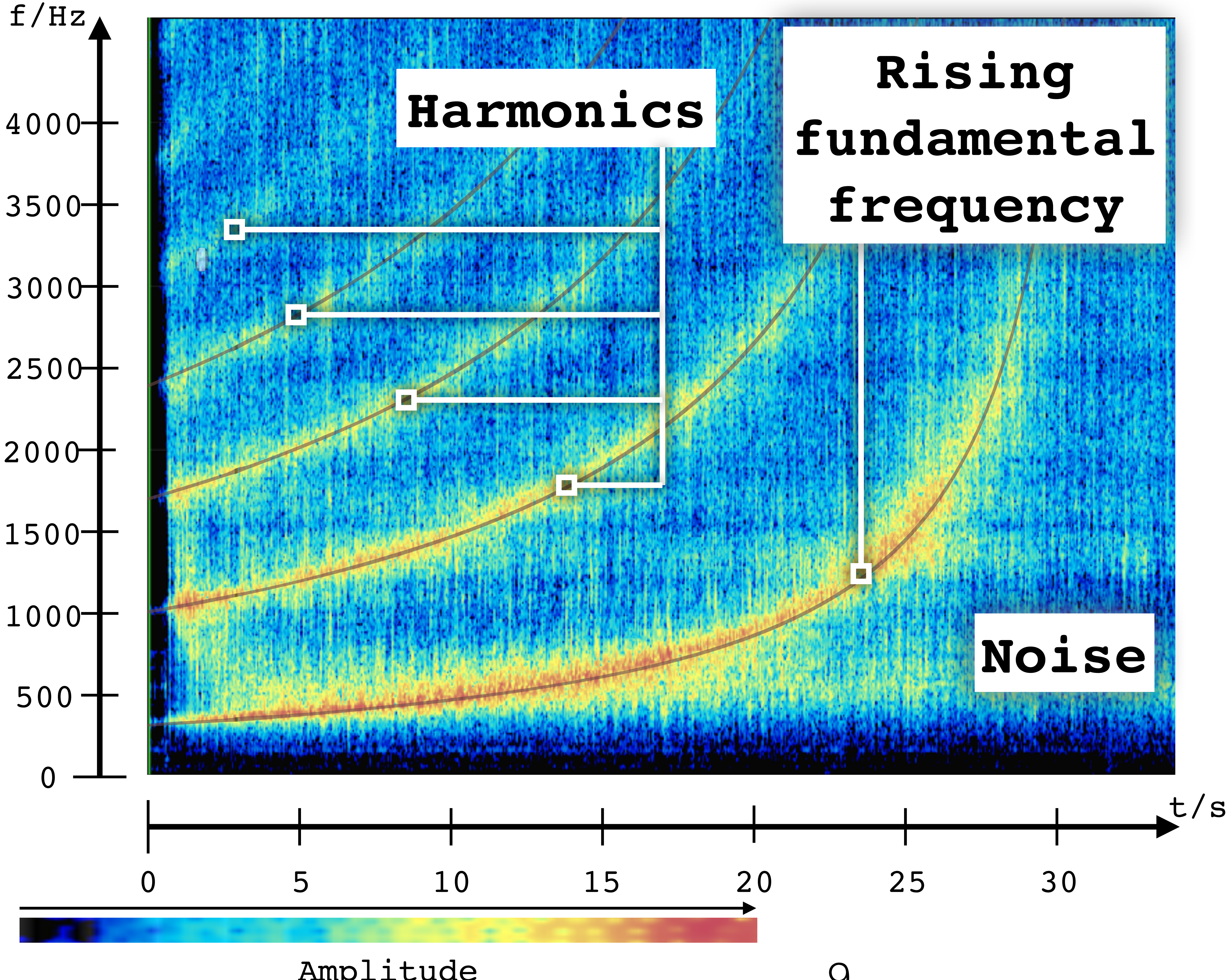

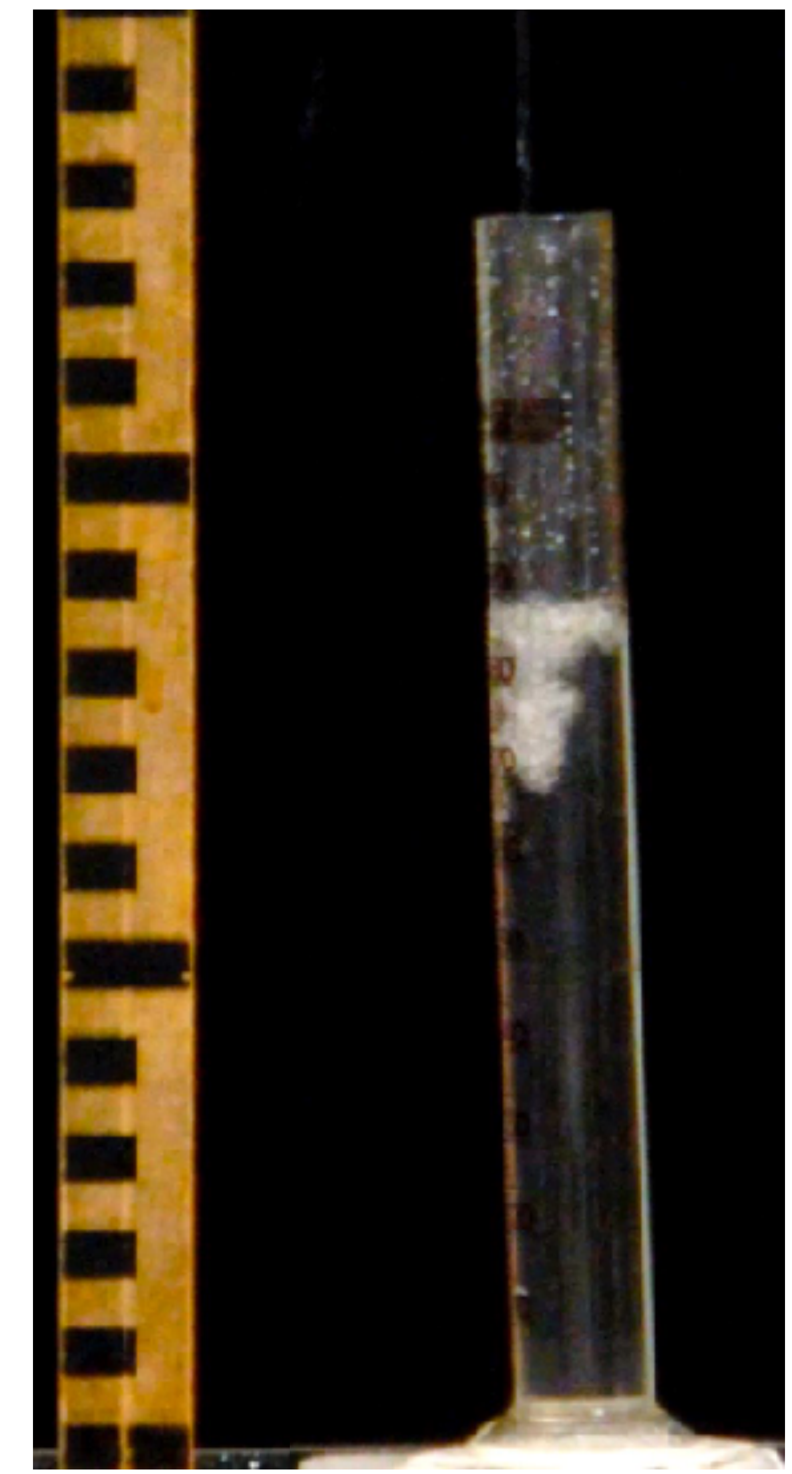

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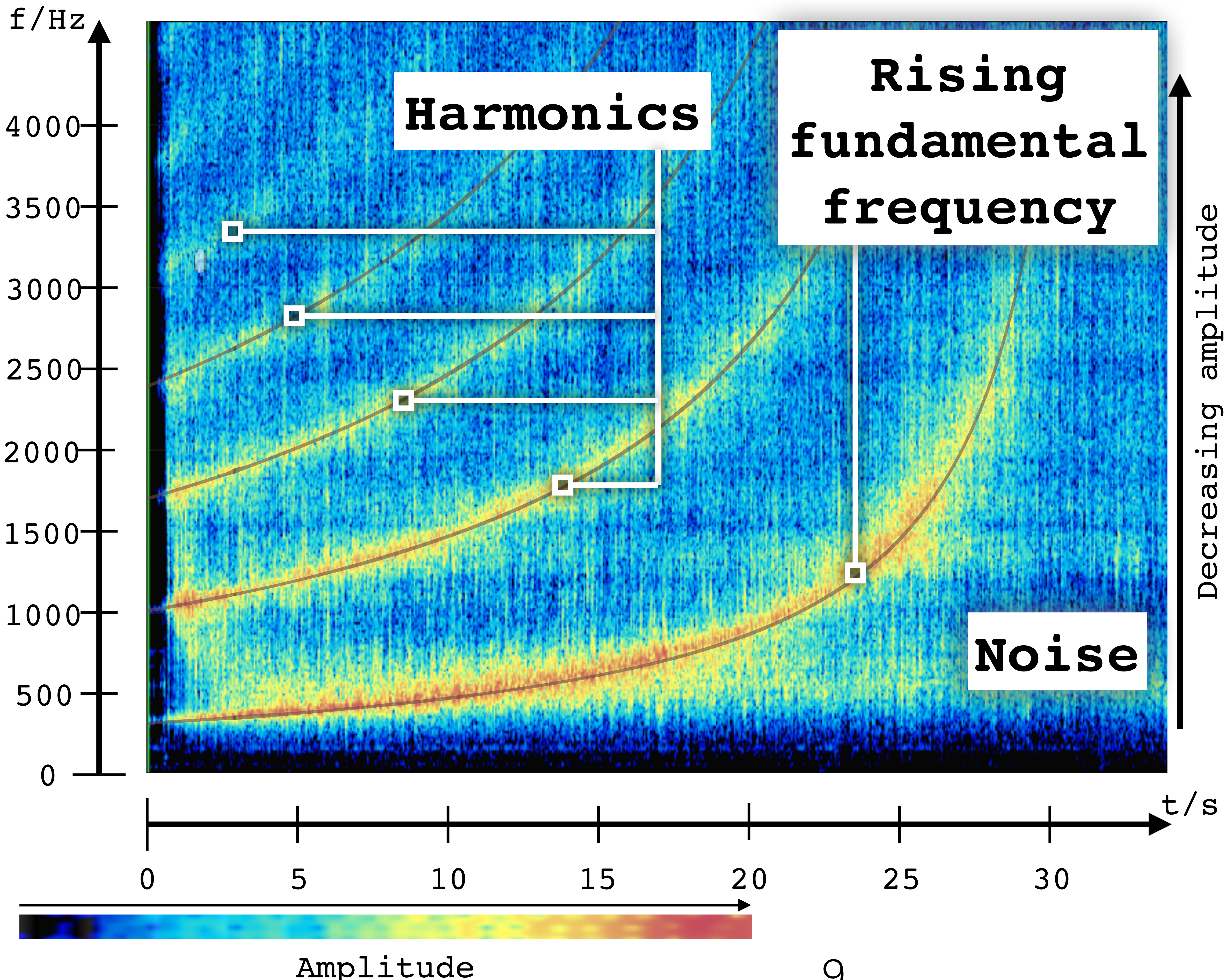

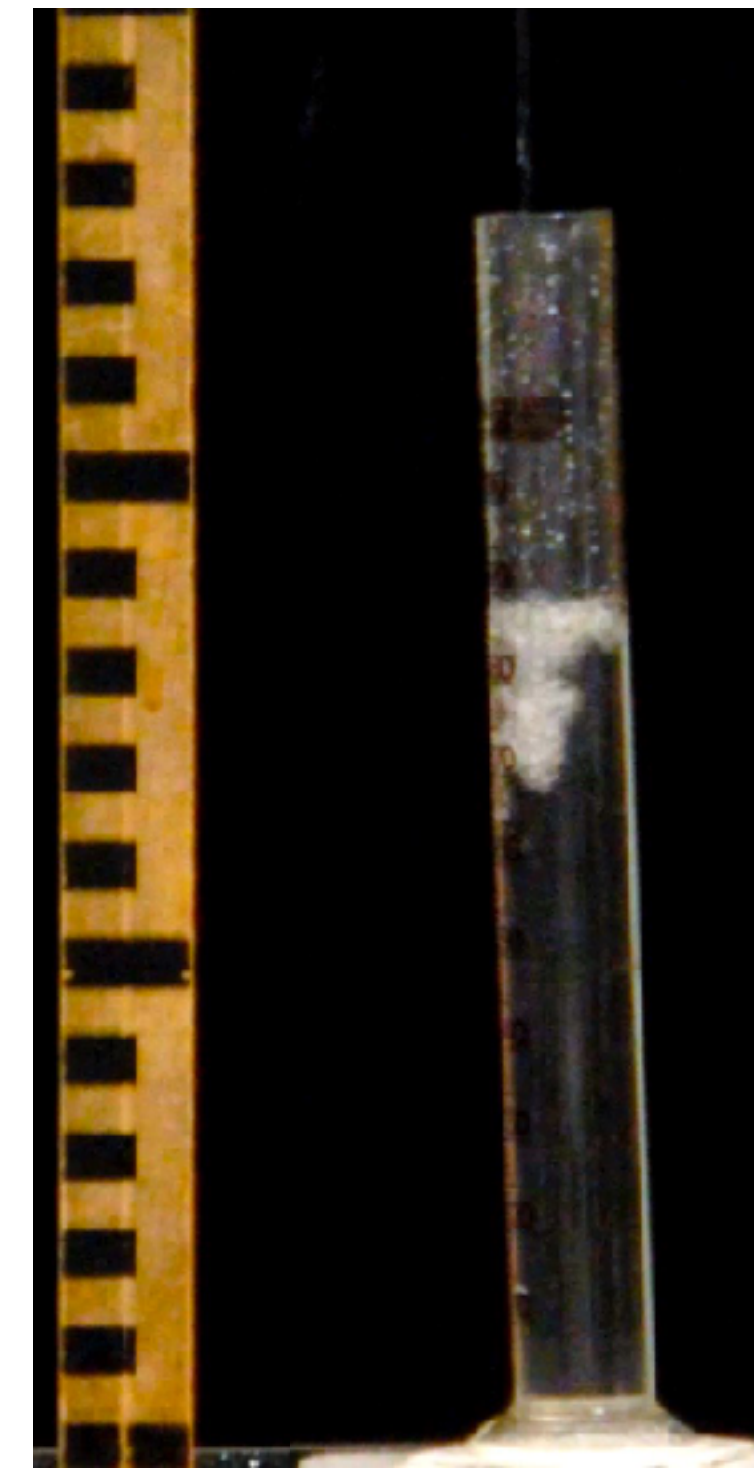

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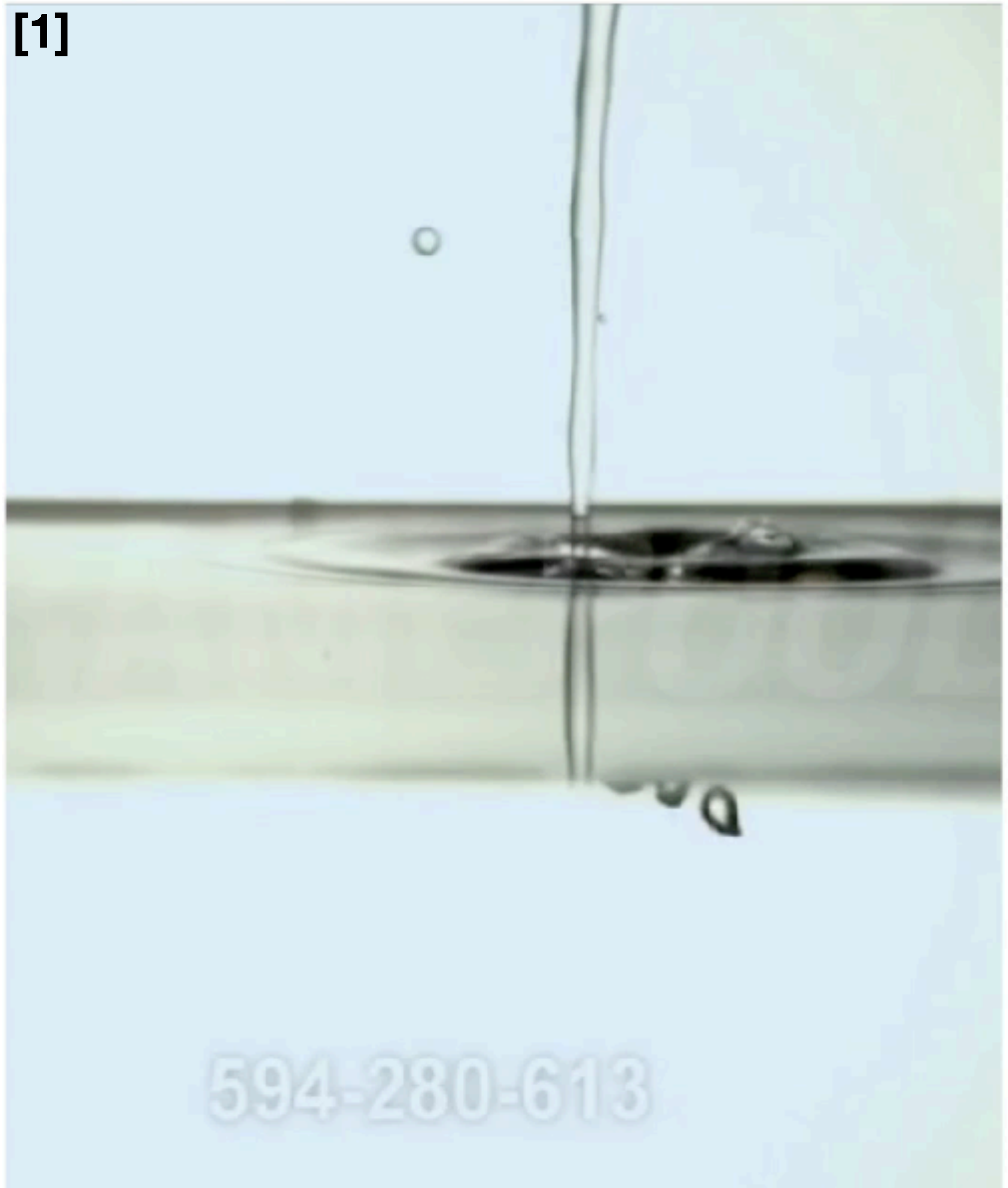
Jet-surface interactions



[1] http://footage.framepool.com/de/shot/594280613-aufprall-auftreffen-glas-behaelter-wasserbecken-luftblase

[2] http://footage.framepool.com/de/shot/202444790-aufprall-auftreffen-glas-behaelter-wasserbecken-luftblase

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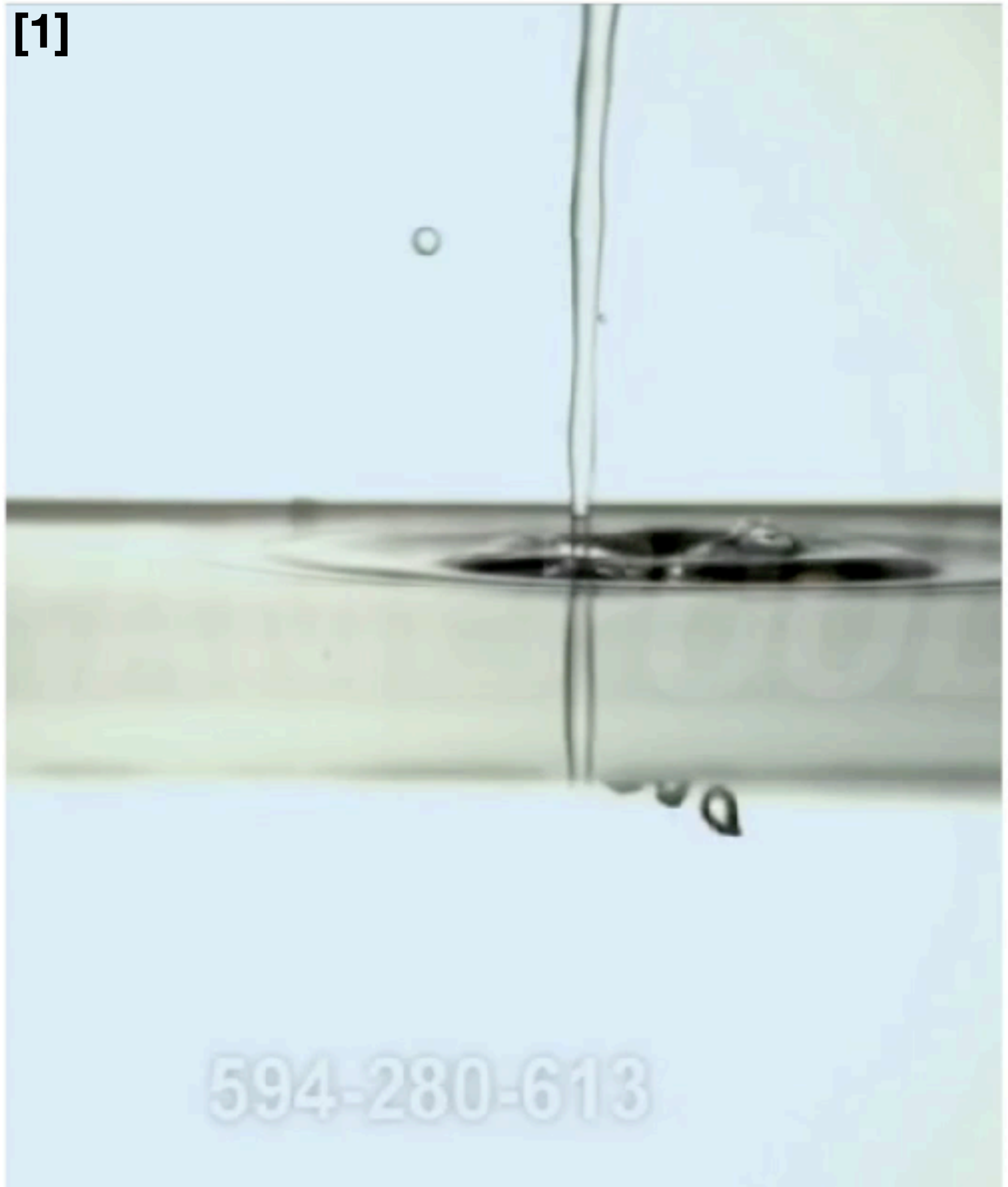

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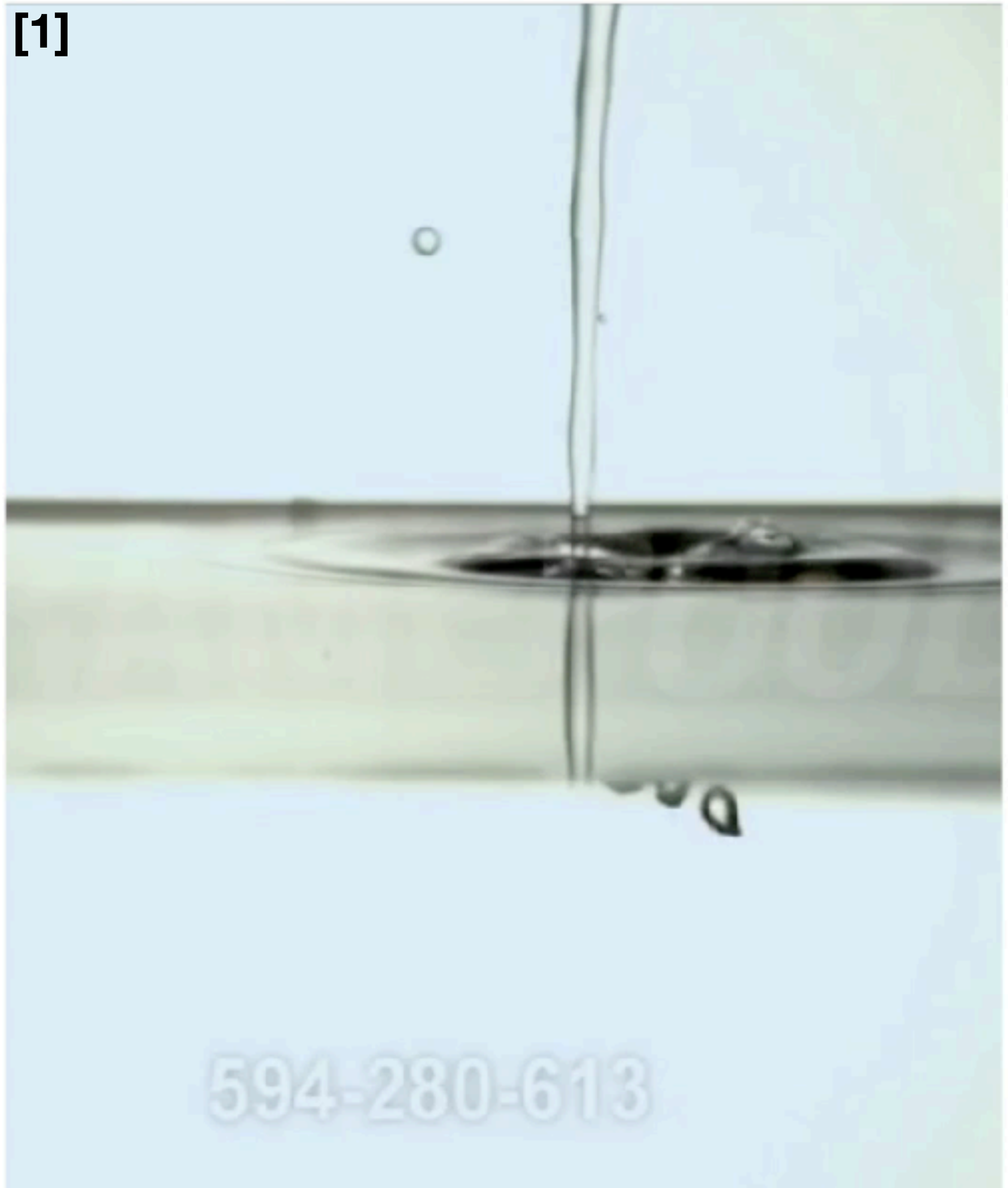

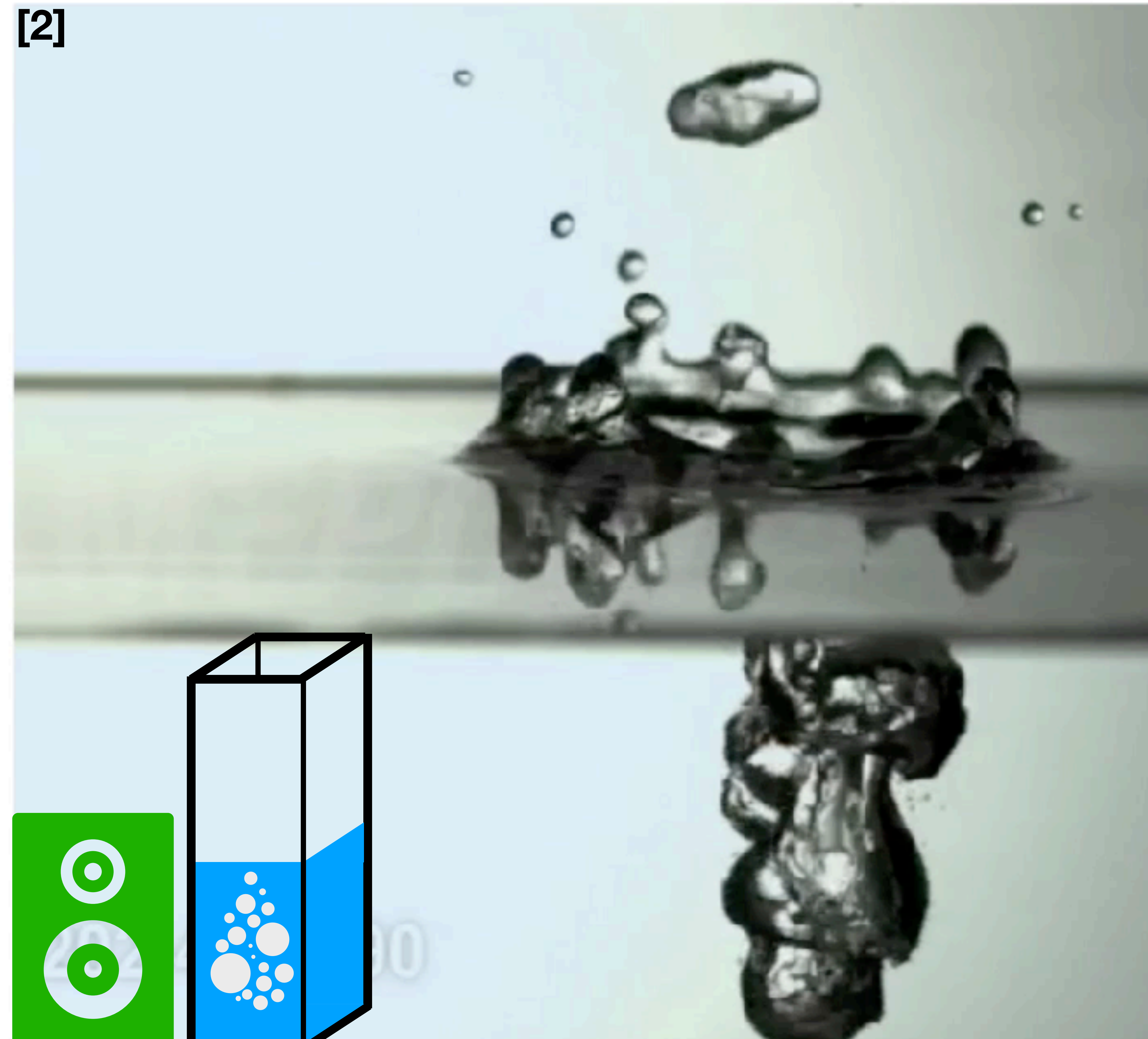

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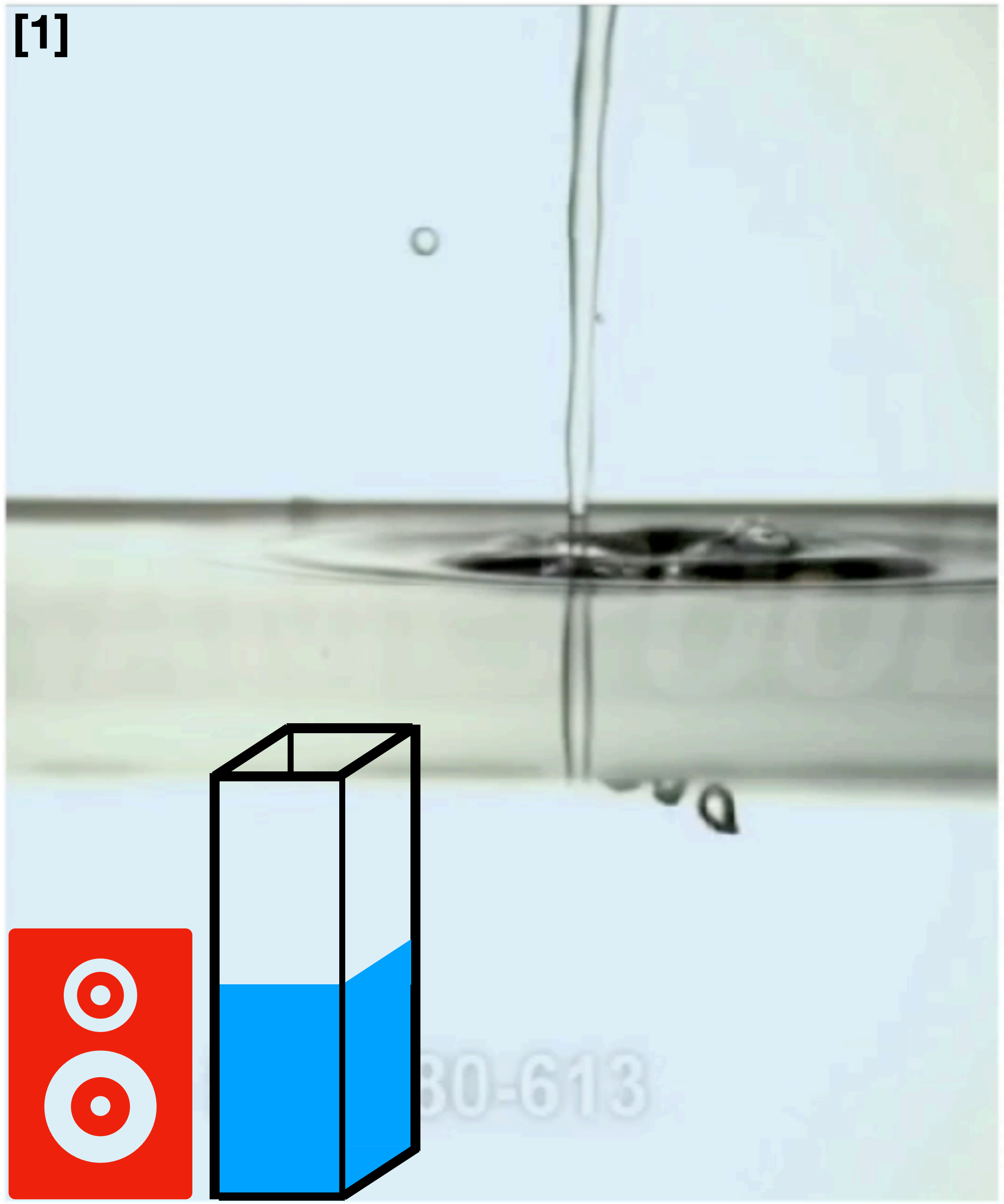

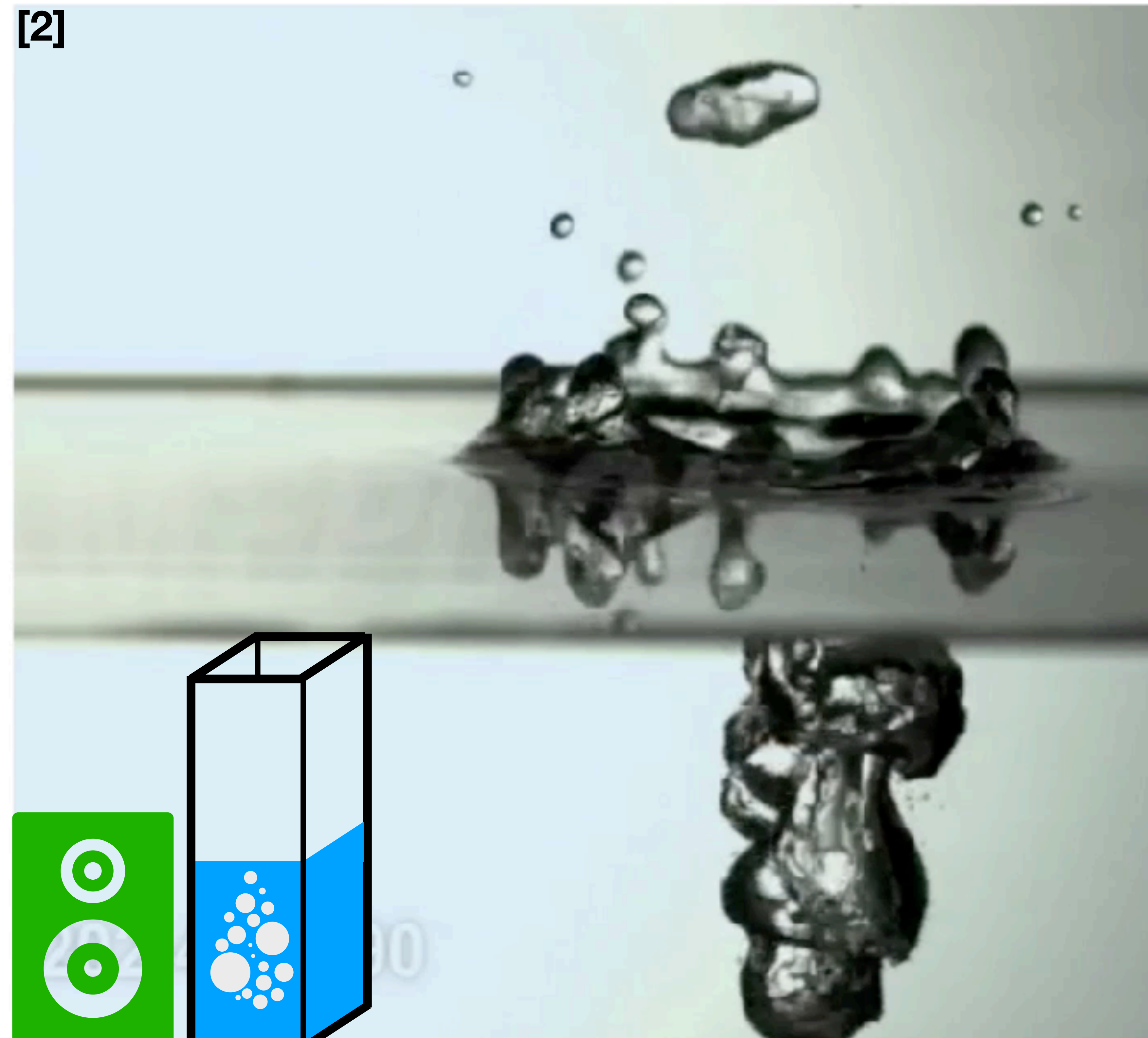

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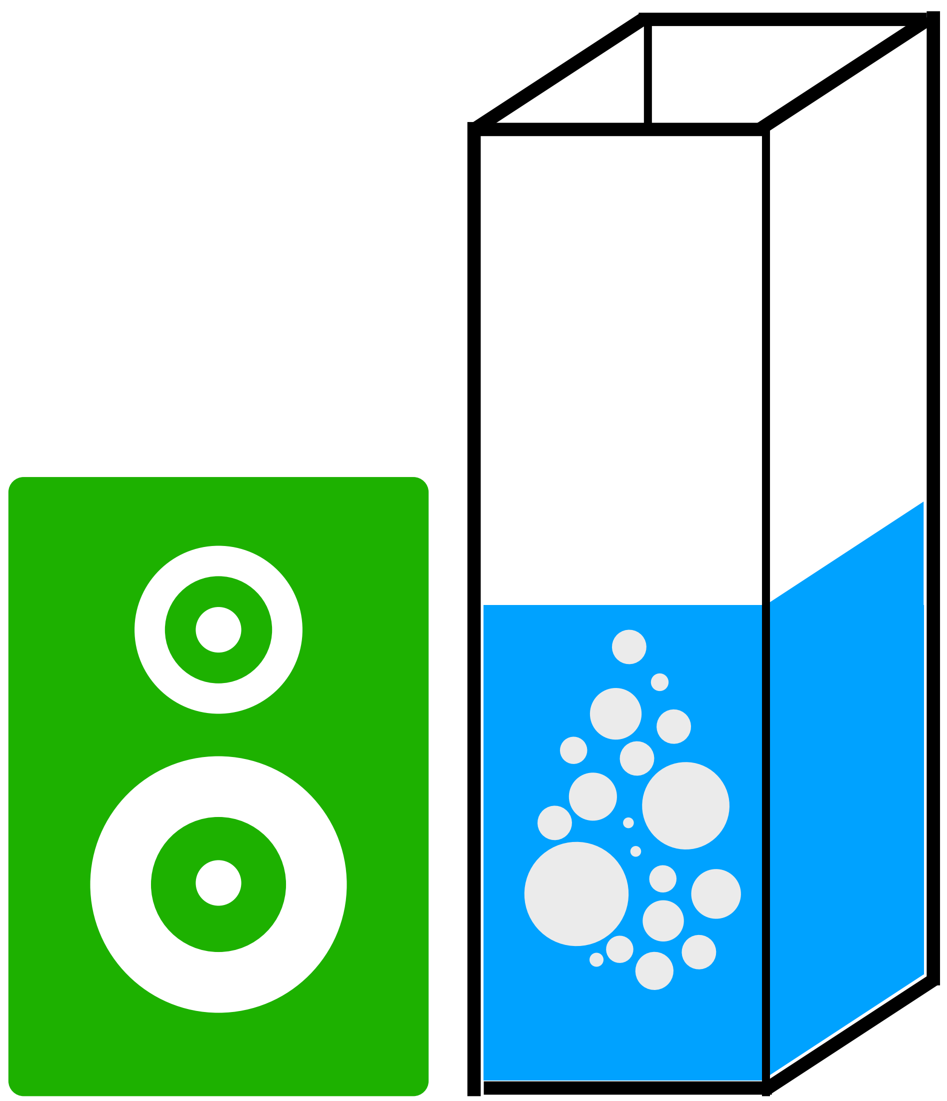
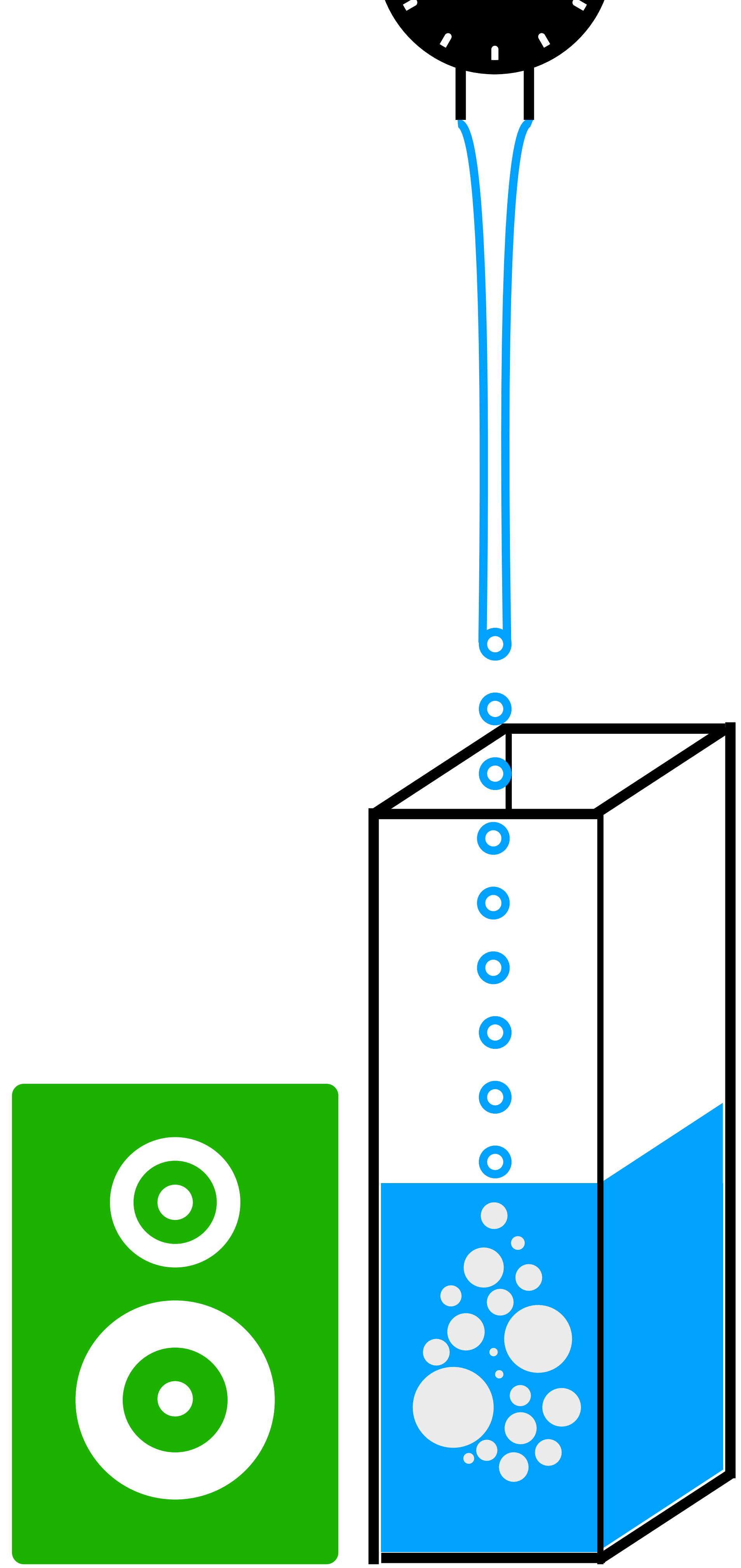
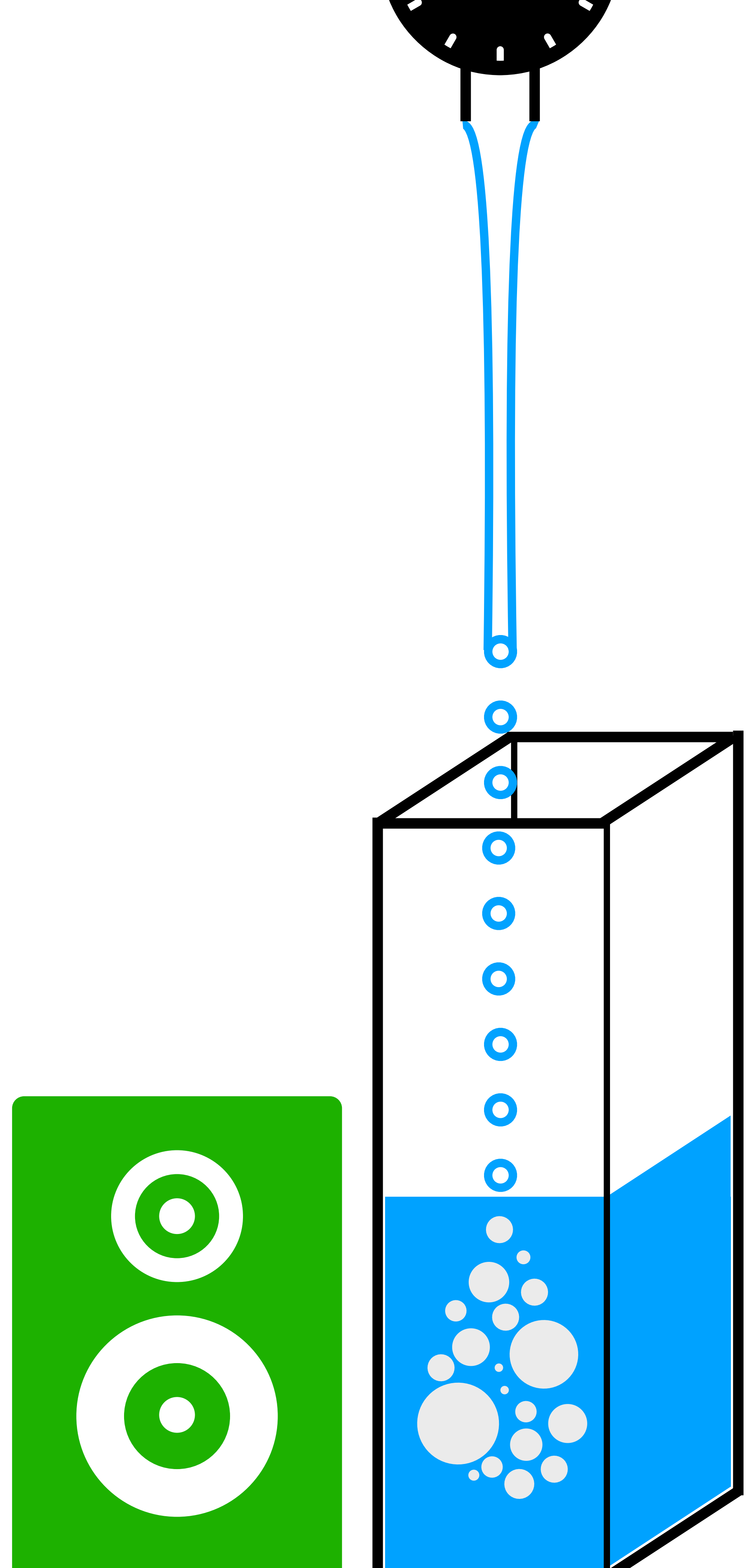
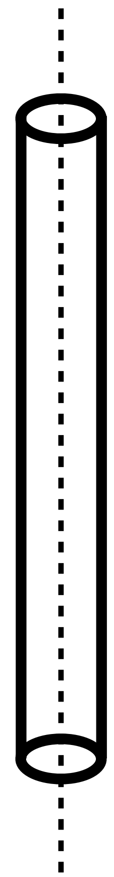




$z\uparrow \Rightarrow v\uparrow \Rightarrow r\downarrow$

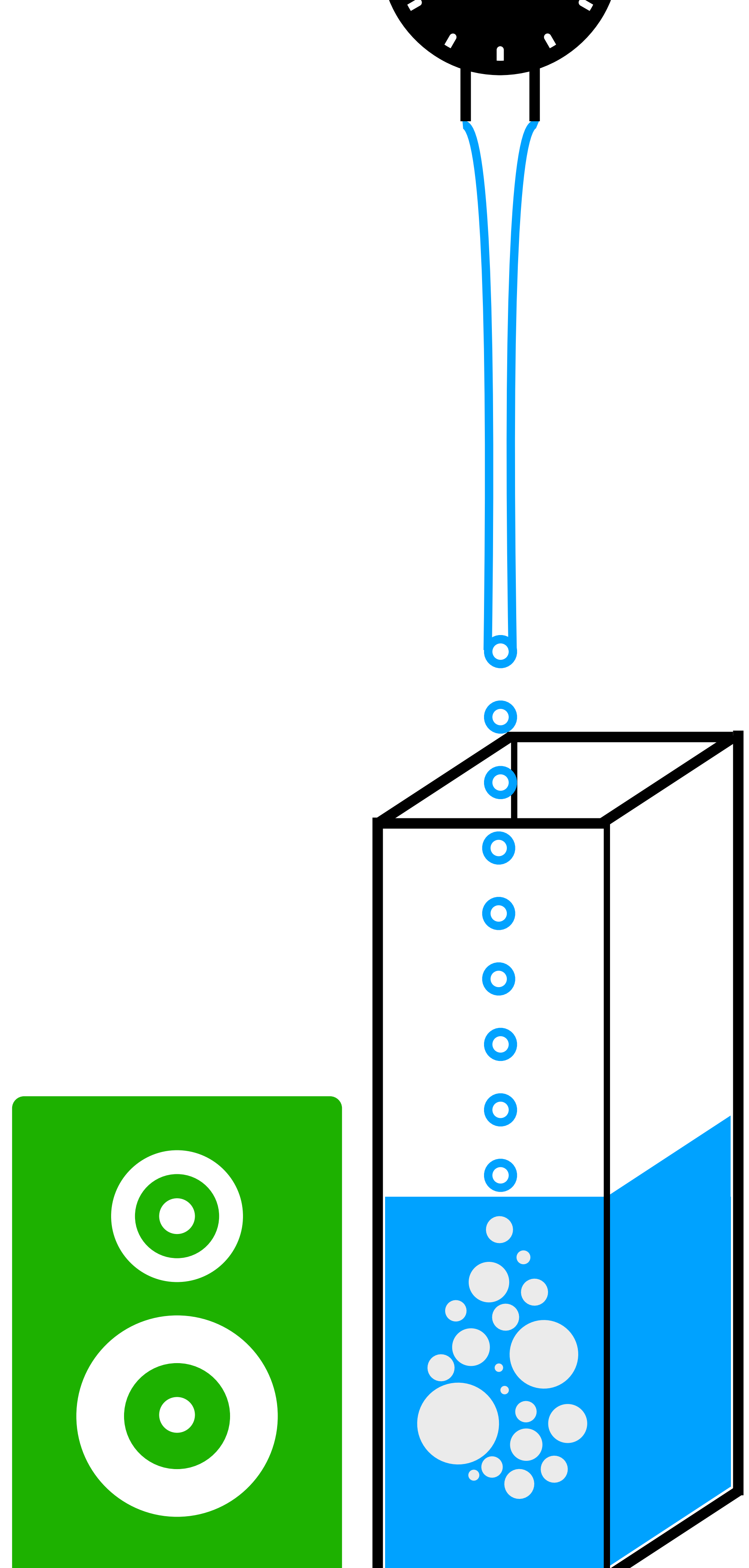
$Q = \text{const.}$





$z\uparrow \Rightarrow v\uparrow \Rightarrow r\downarrow$

$Q = \text{const.}$



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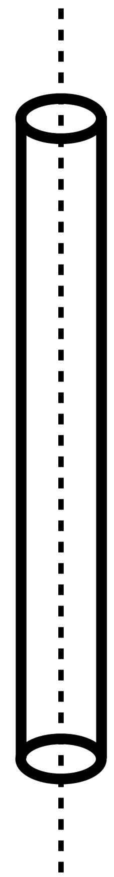
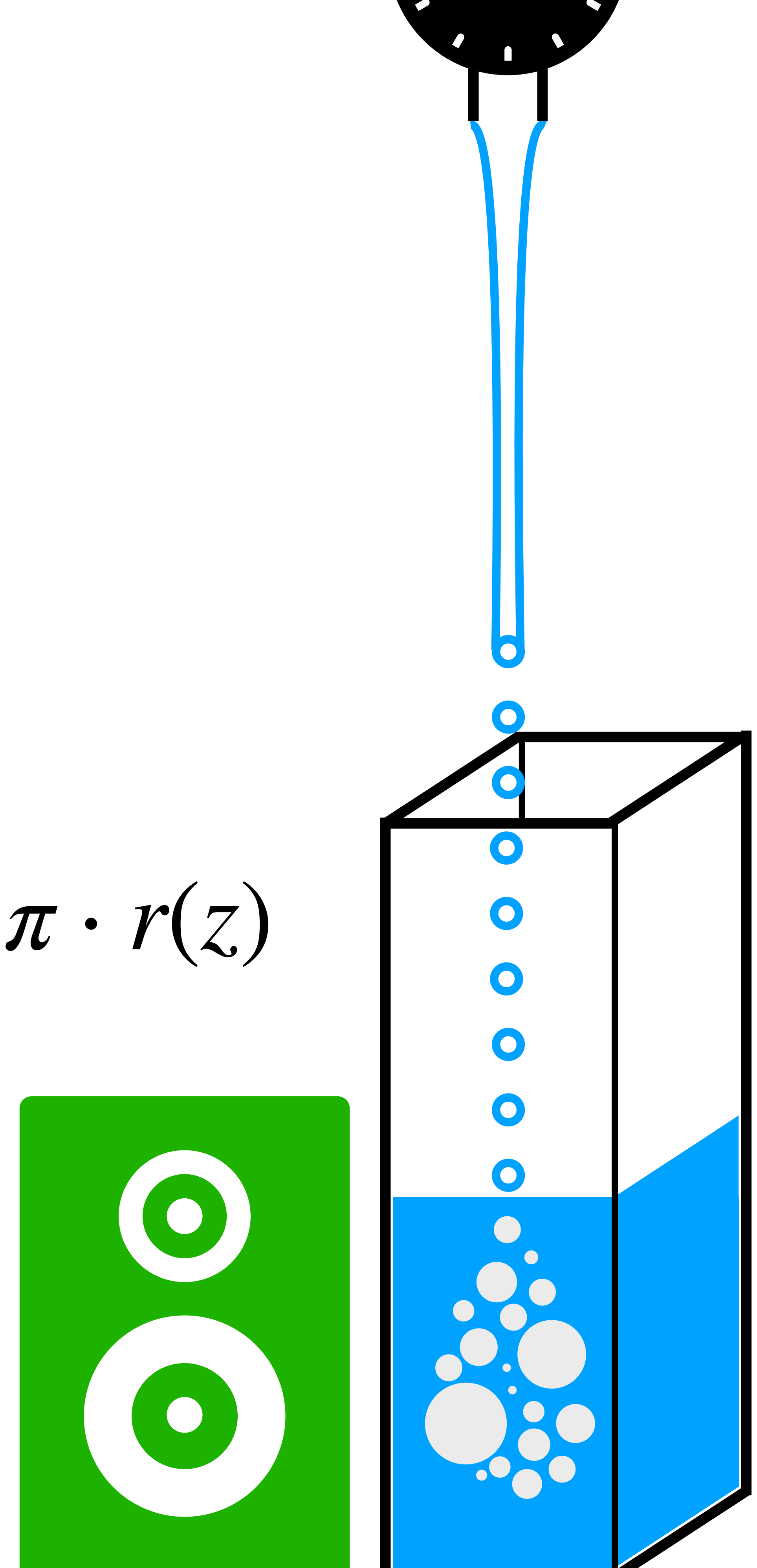


$$\lambda > \pi \cdot r(z)$$



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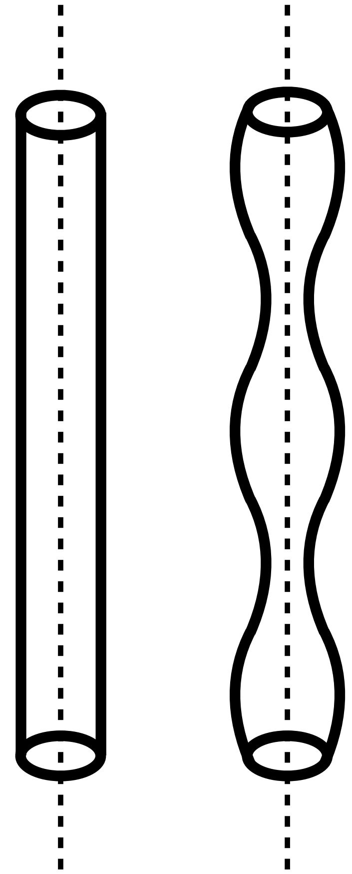

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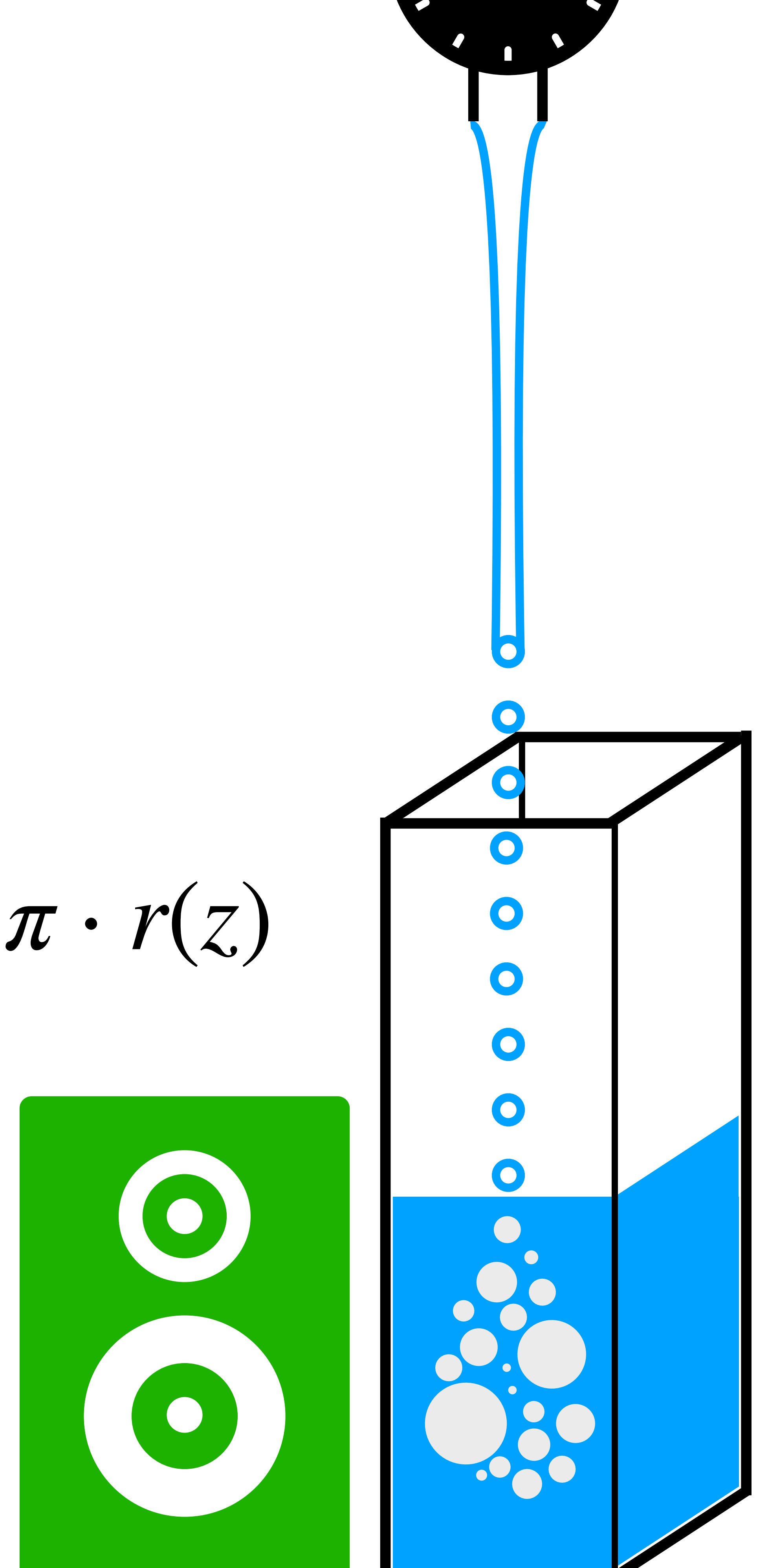

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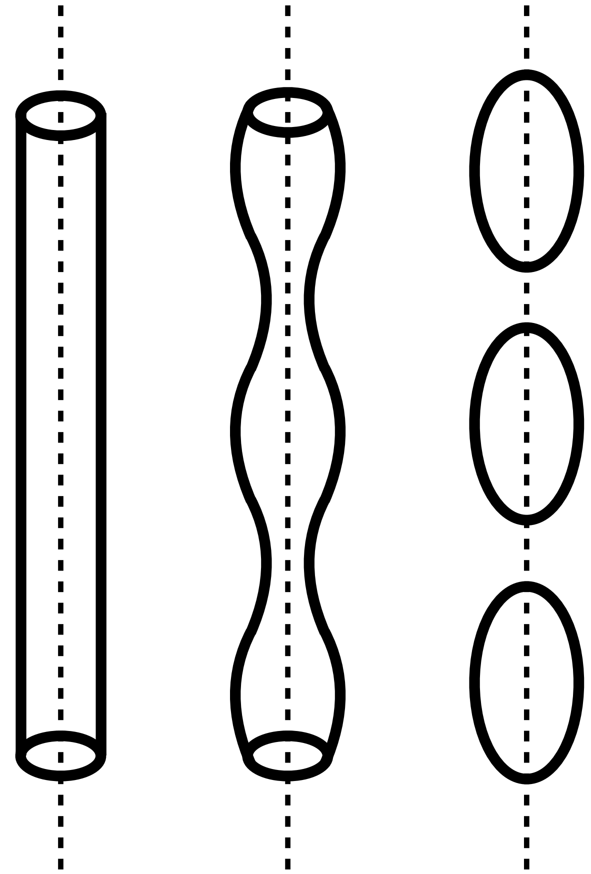

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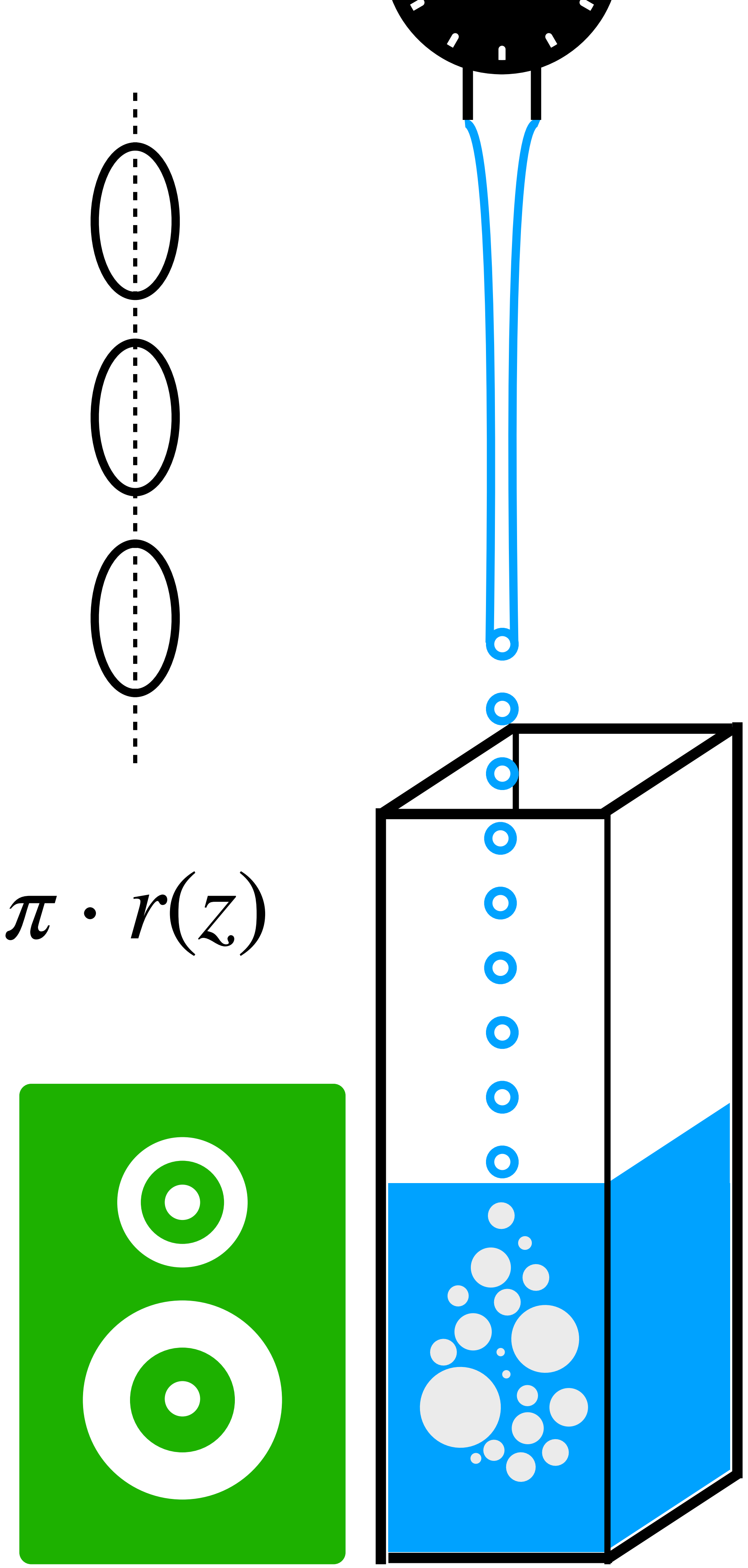

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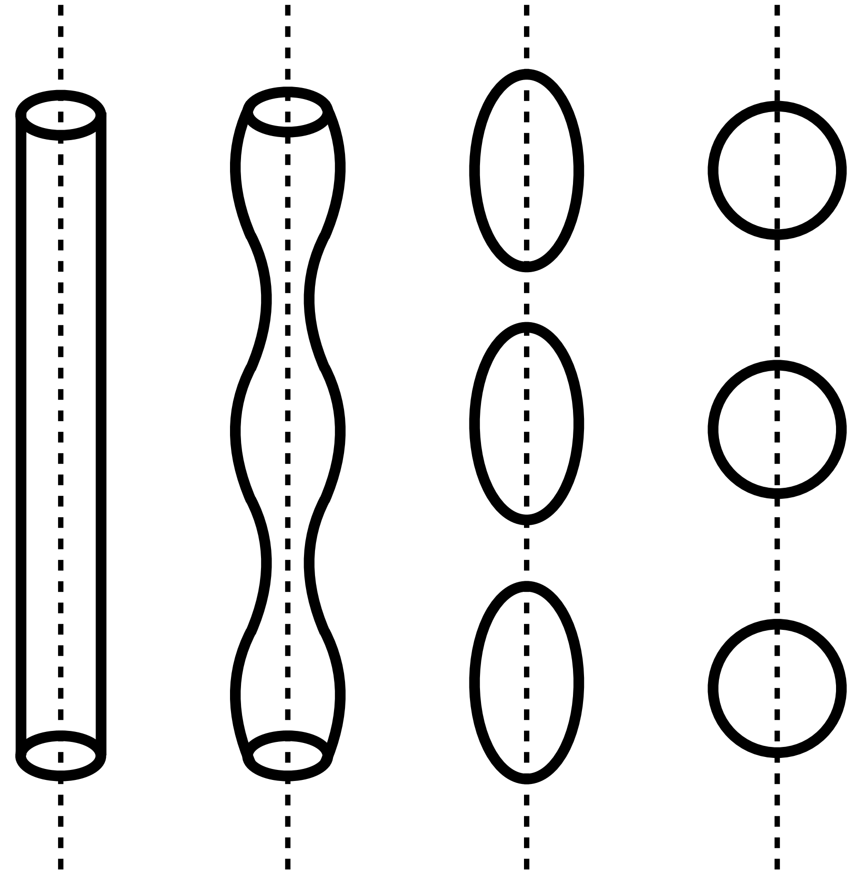

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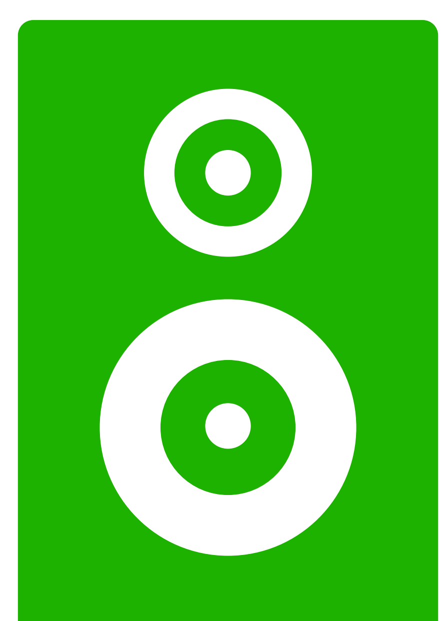

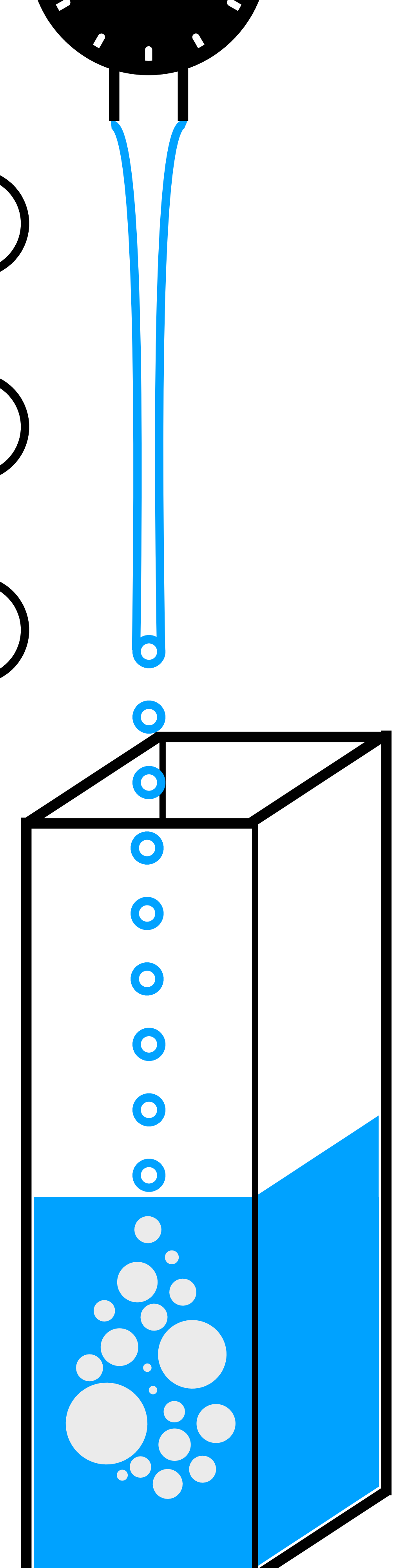

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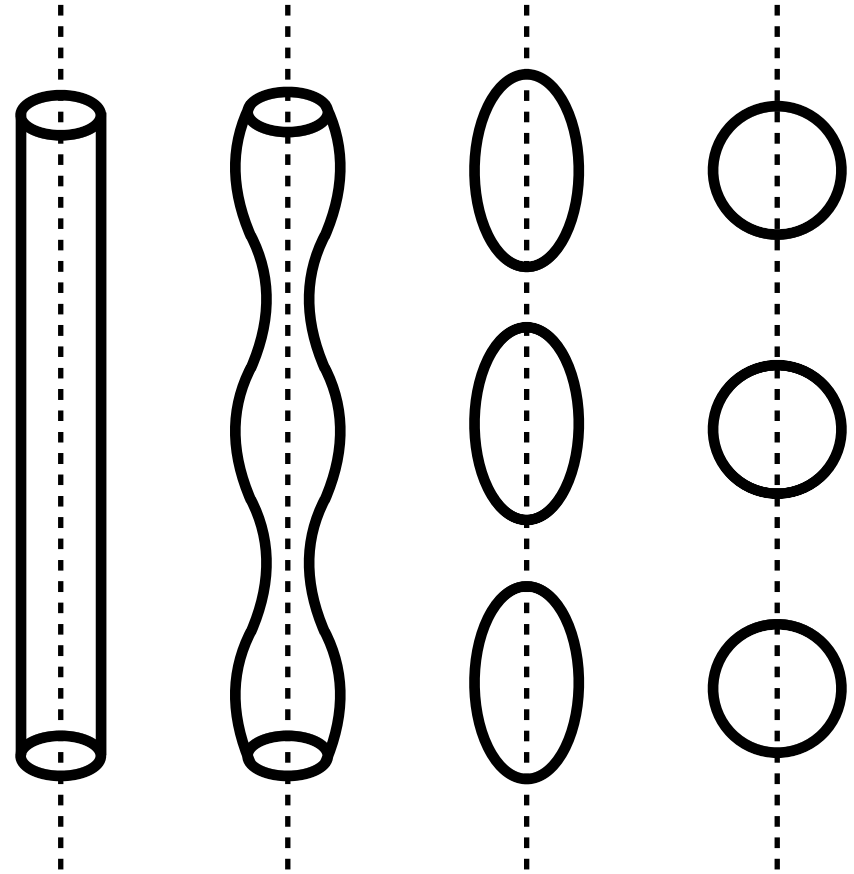

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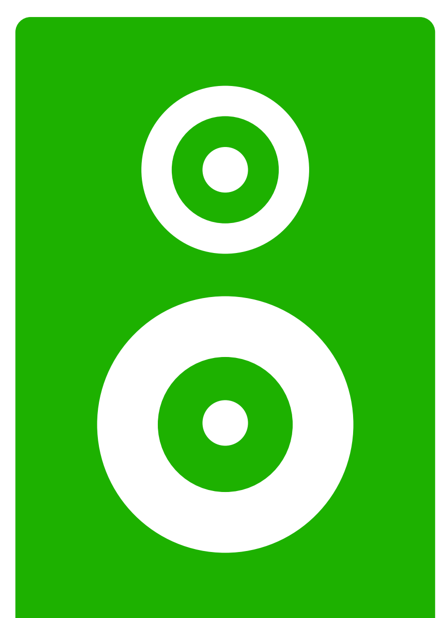

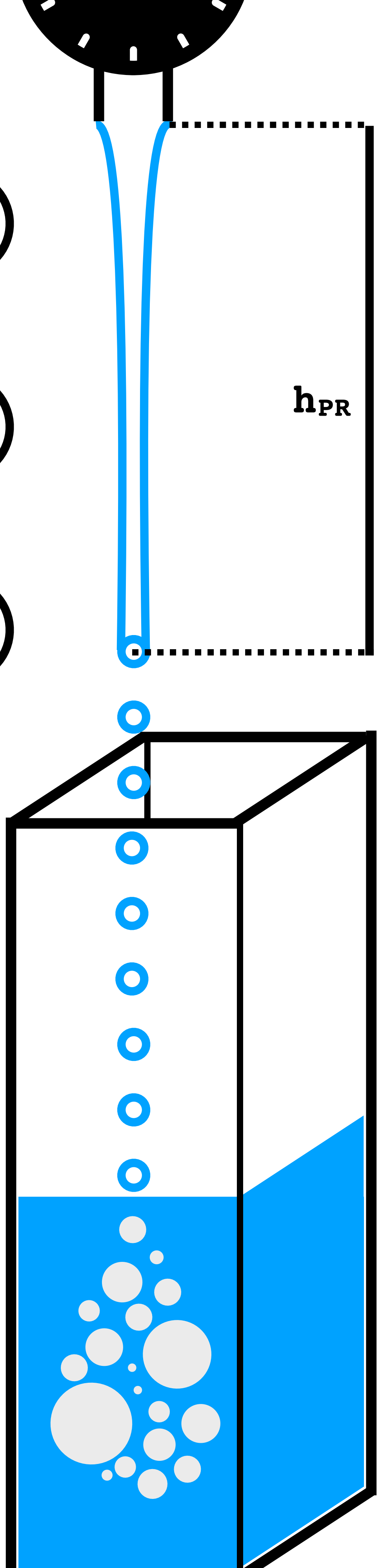

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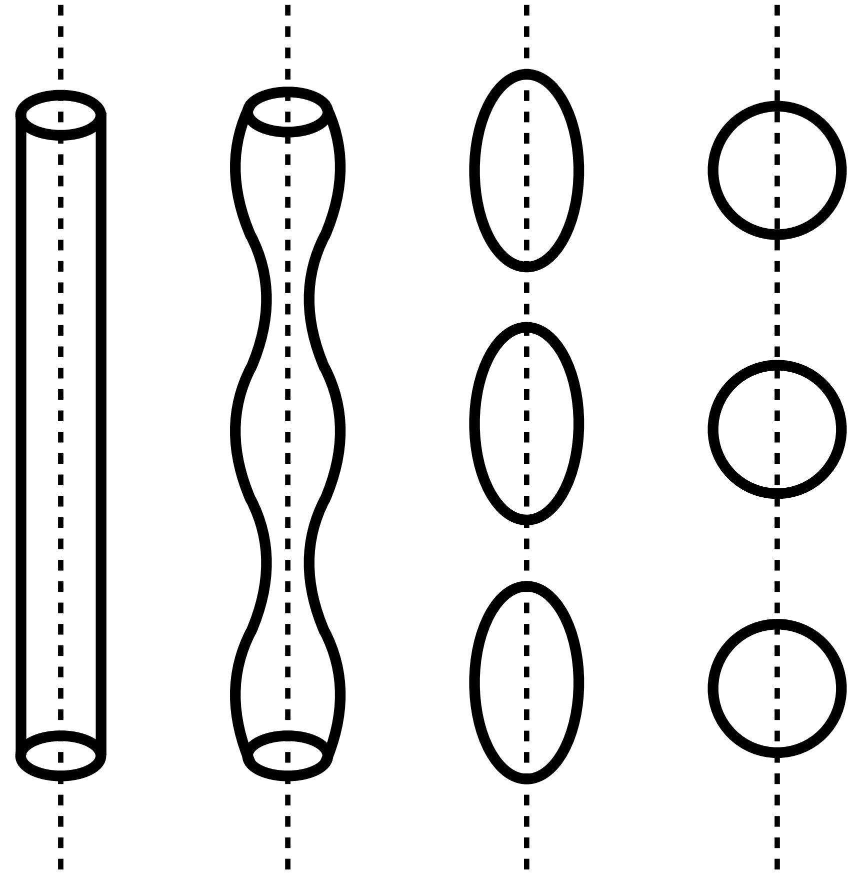

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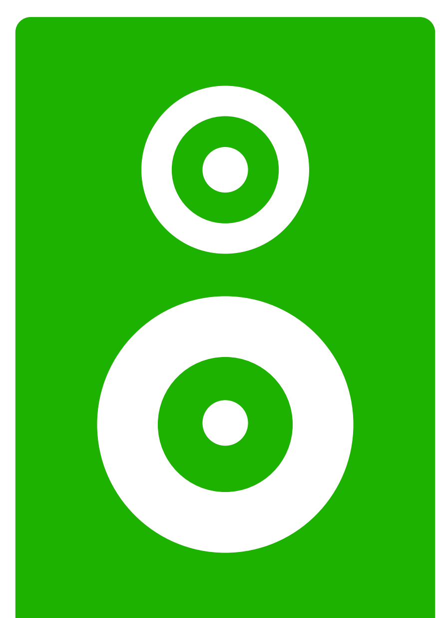

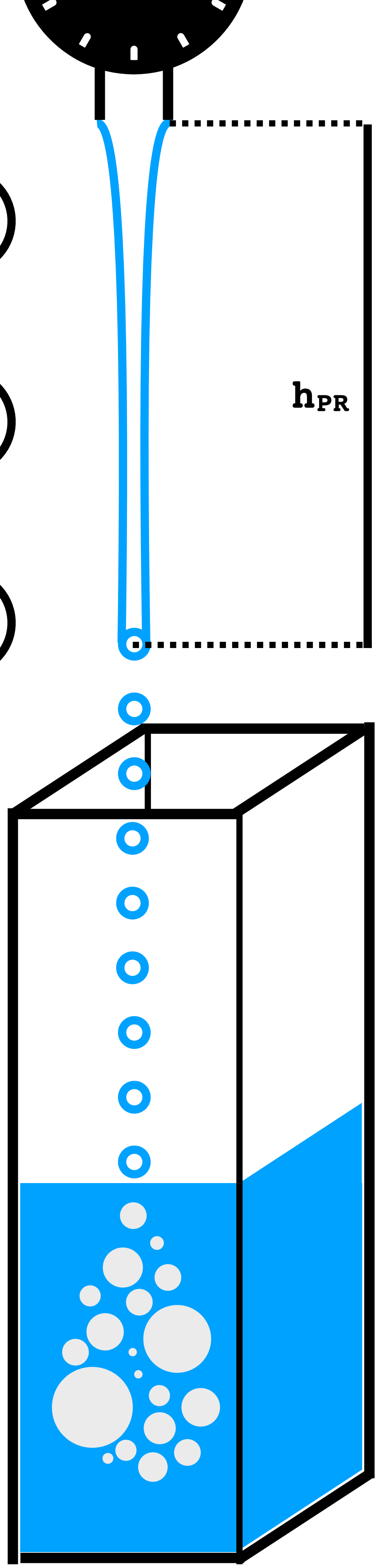

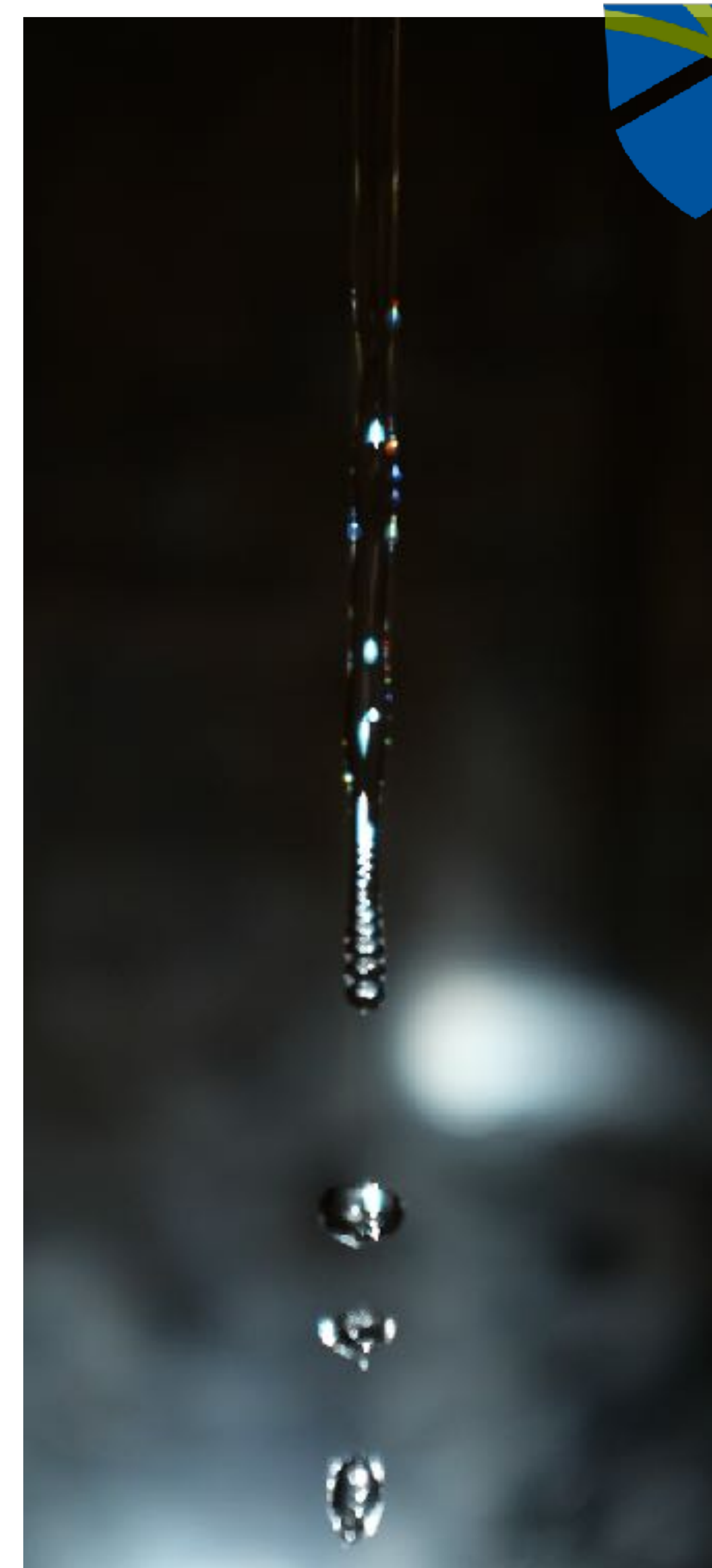

[3] **Phillips, Samuel and Agarwal, Anurag and Jordan, Peter Journal,** ***The Sound Produced by a Dripping Tap is Driven by Resonant Oscillations of an Entrapped Air Bubble.*** **Scientific Reports 2018. Vol. 8 No. 1.**

https://www.nature.com/articles/s41598-018-27913-0

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Minnaert frequency

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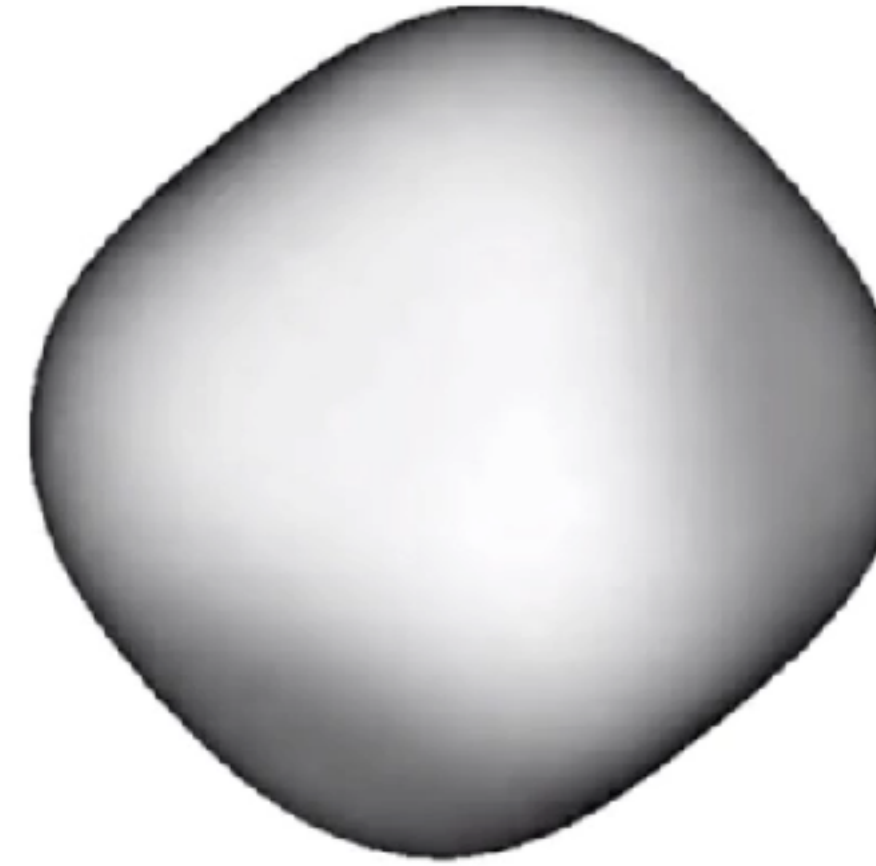

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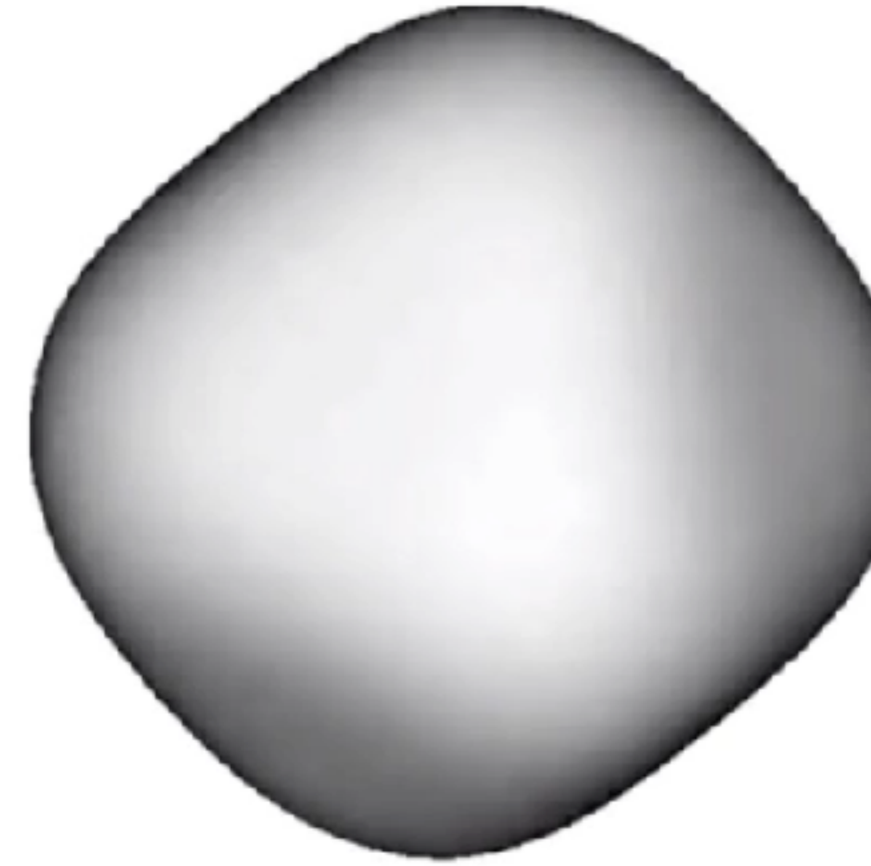
Minnaert frequency

$$f = \frac{1}{2\pi r_{bubble}} \cdot \sqrt{\frac{3\gamma p_o}{\rho_{water}}}$$



γ **Adiabatic coefficient of air**

p_o **Outer air pressure**

ρ_{water} **Density of water**

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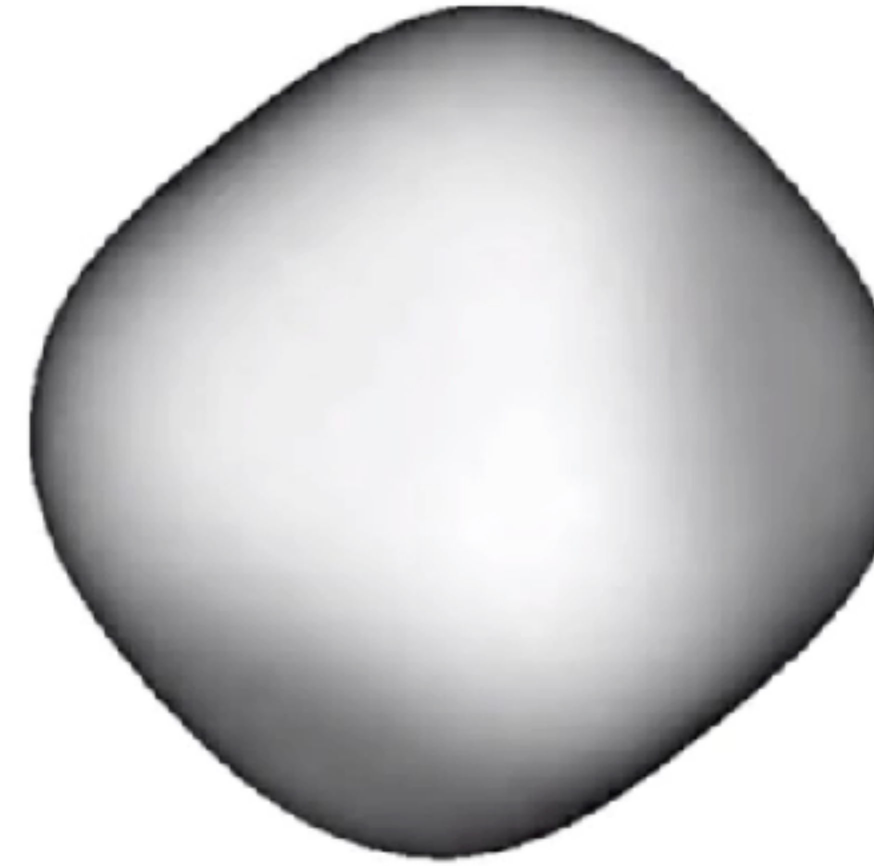

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The frequencies which occur due to Minnaert resonance can be amplified by the standing waves in the cavity.

[3] Phillips, Samuel and Agarwal, Anurag and Jordan, Peter Journal, *The Sound Produced by a Dripping Tap is Driven by Resonant Oscillations of an Entrapped Air Bubble.* Scientific Reports 2018. Vol. 8 No. 1.
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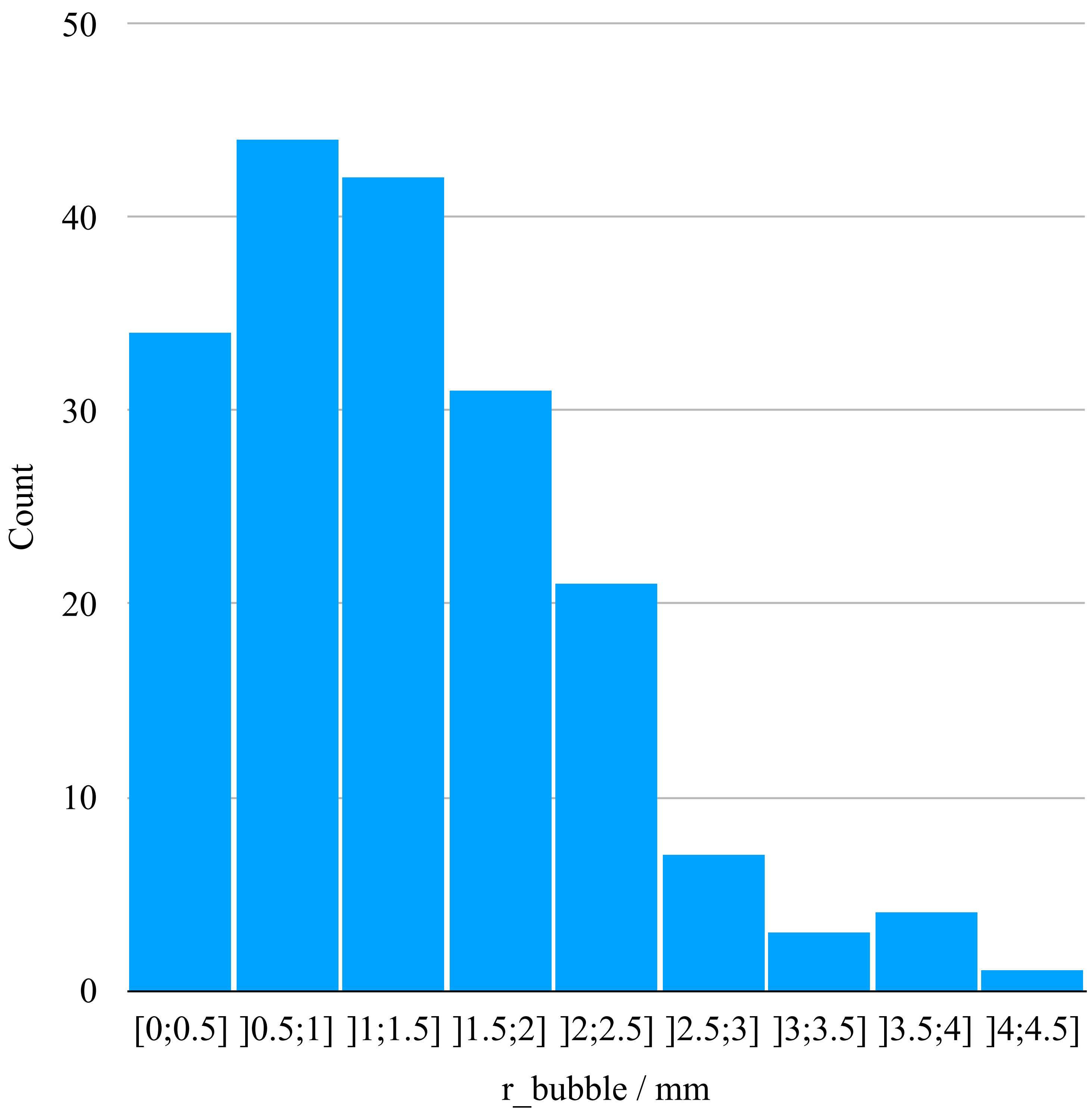
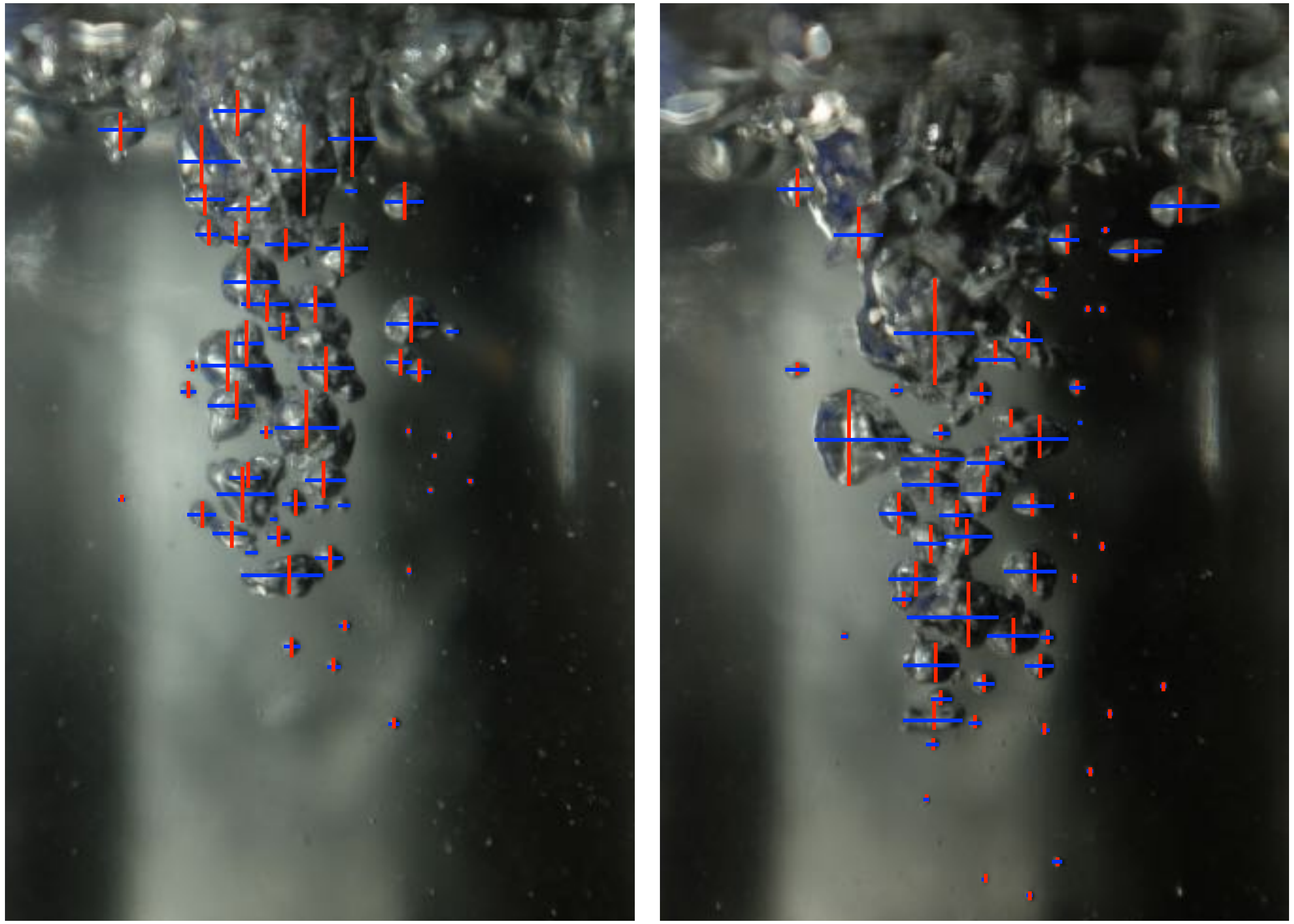
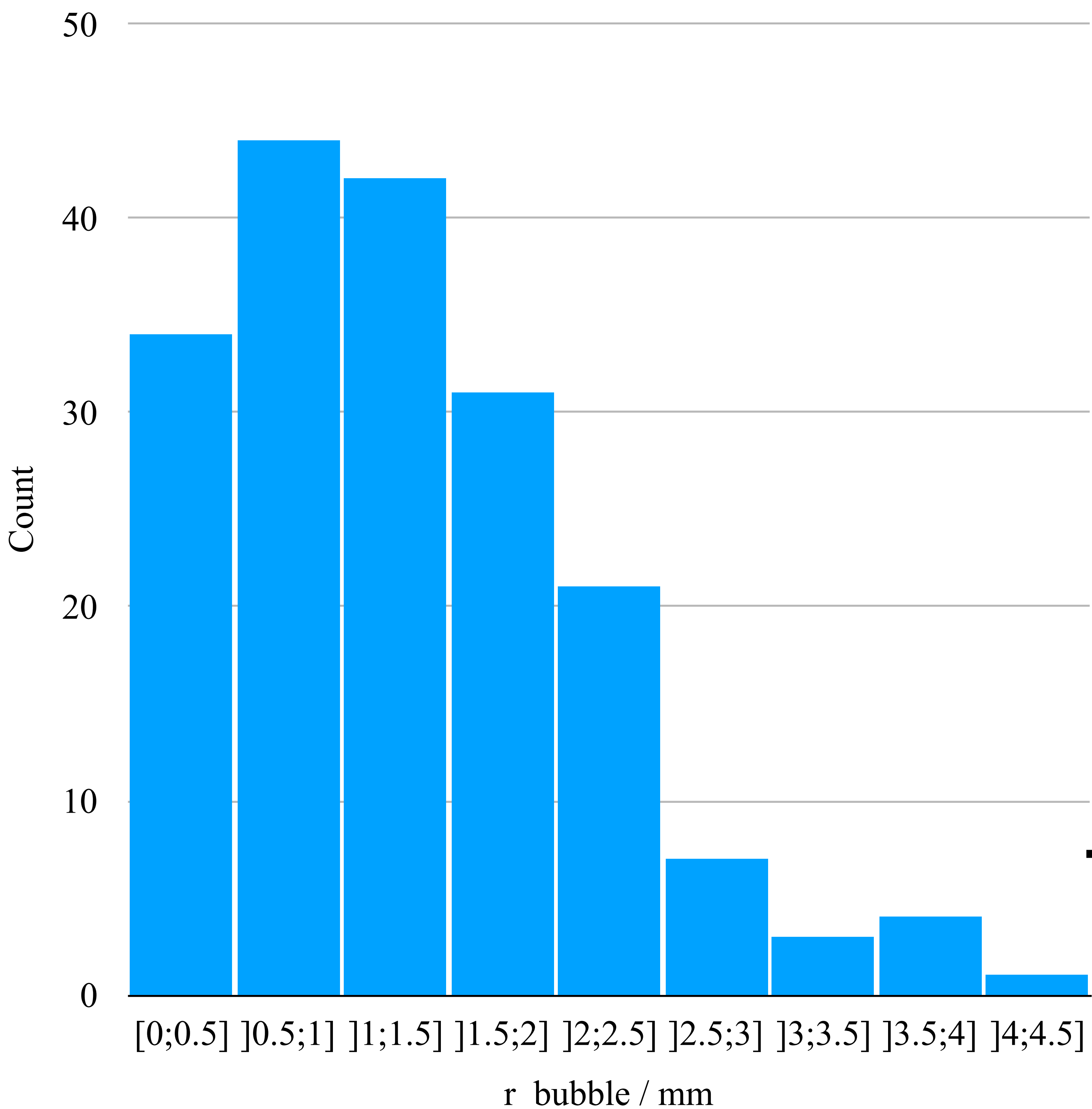
Bubble radii distribution





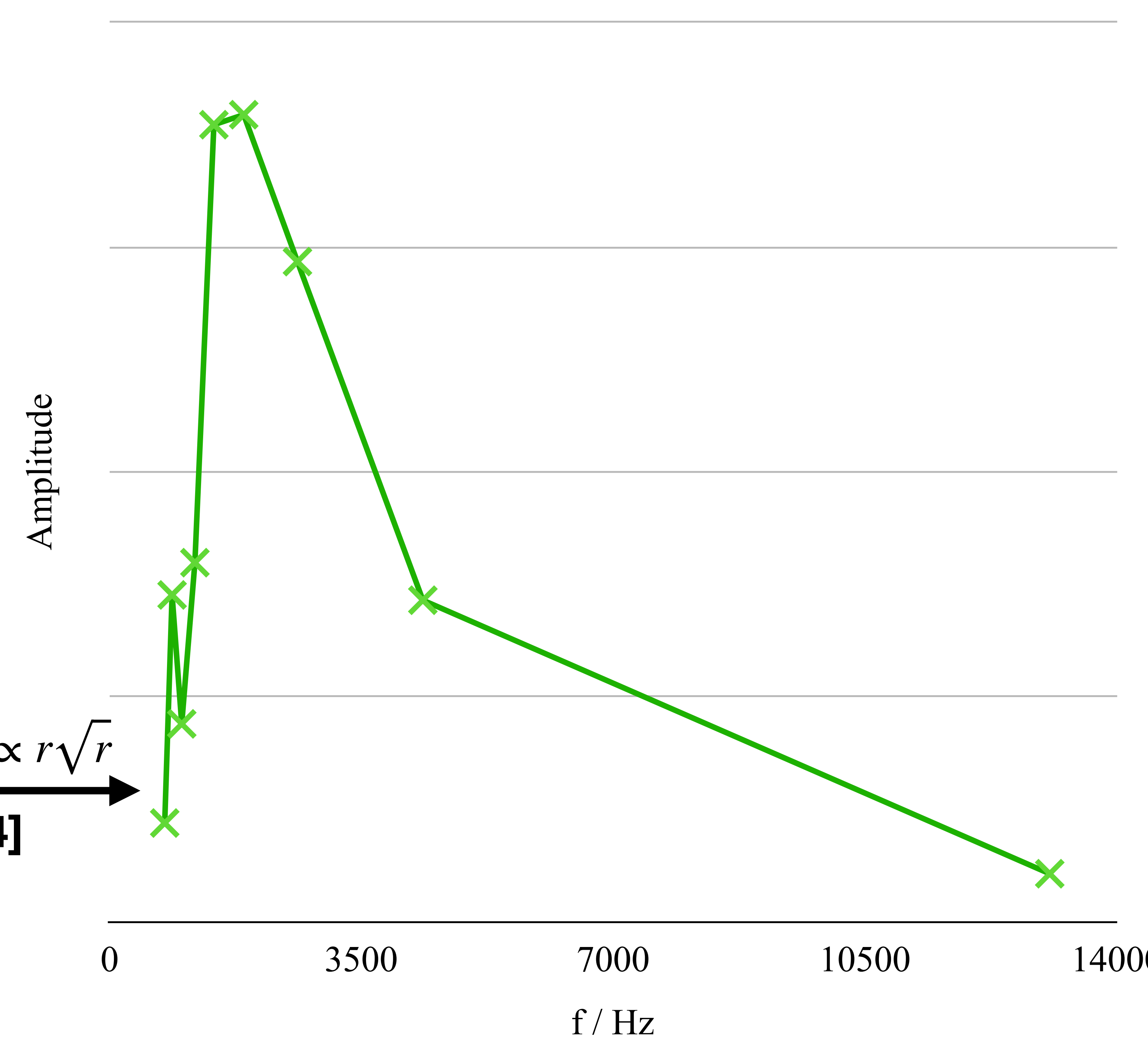
Pictures evaluated

Spectrum created (qualitative)



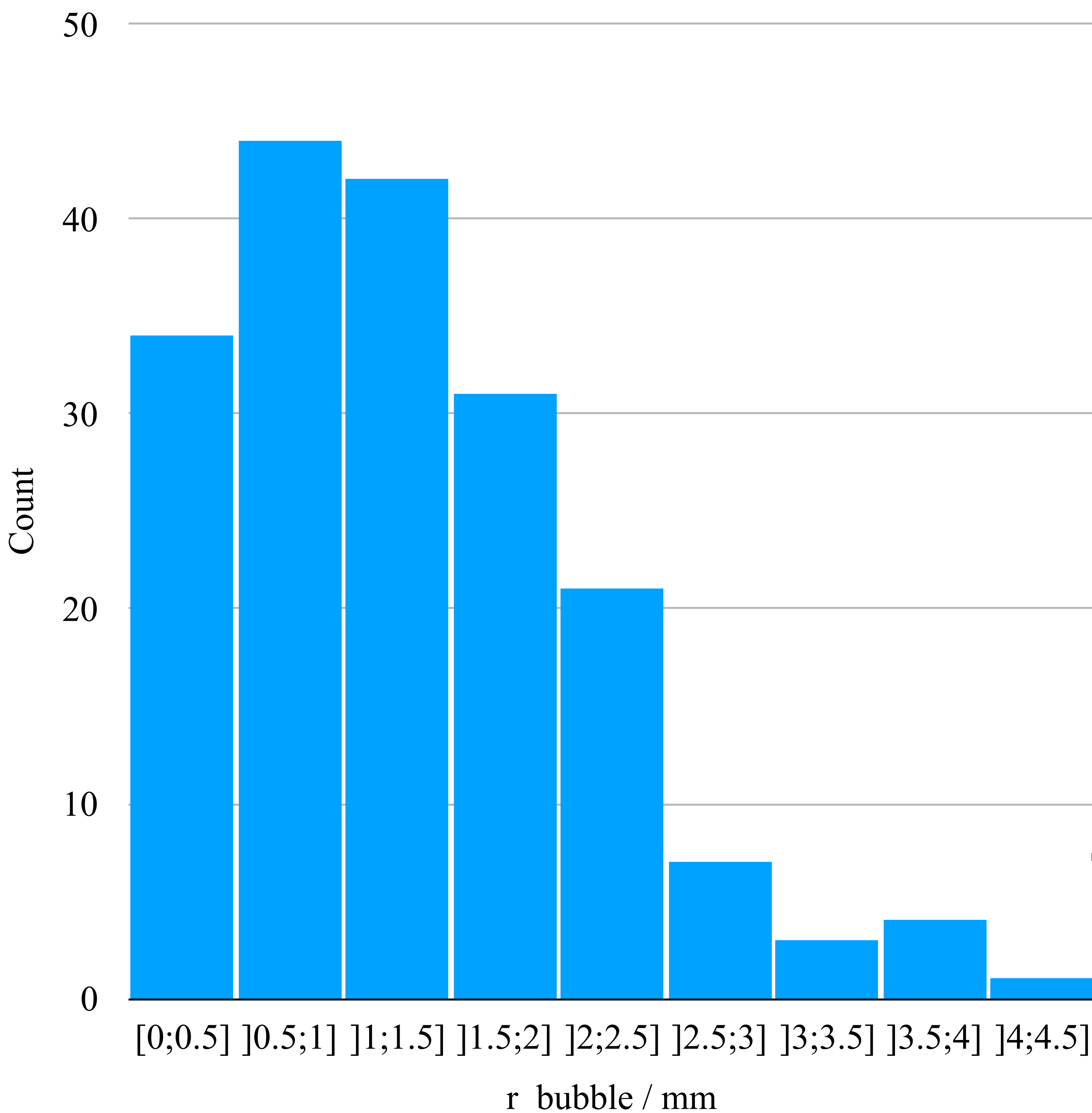
$Amp \propto r\sqrt{r}$

[4]



[4] Doel, Kees van den. "Physically based models for liquid sounds." (2004)

Spectrum created (qualitative)



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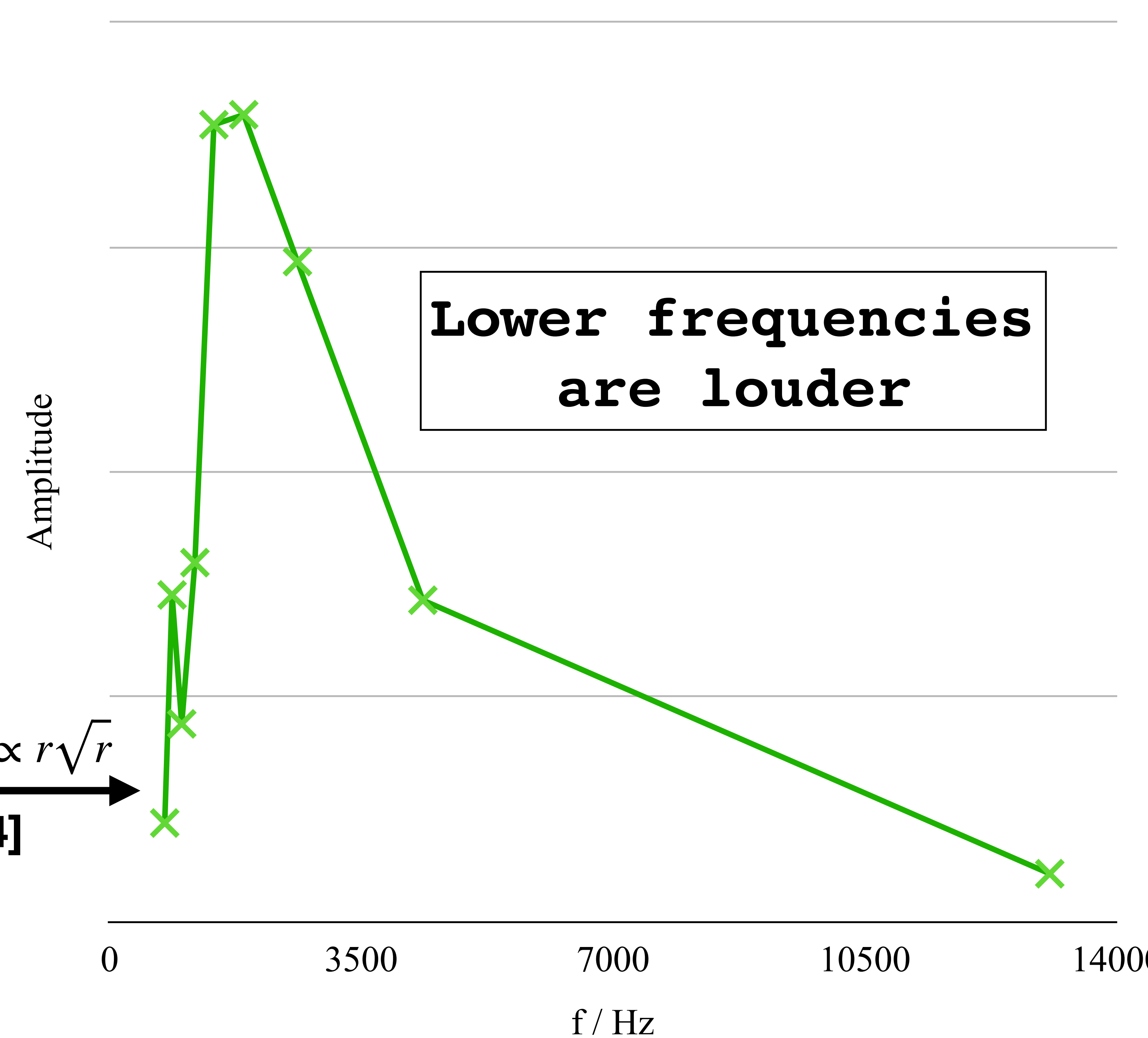

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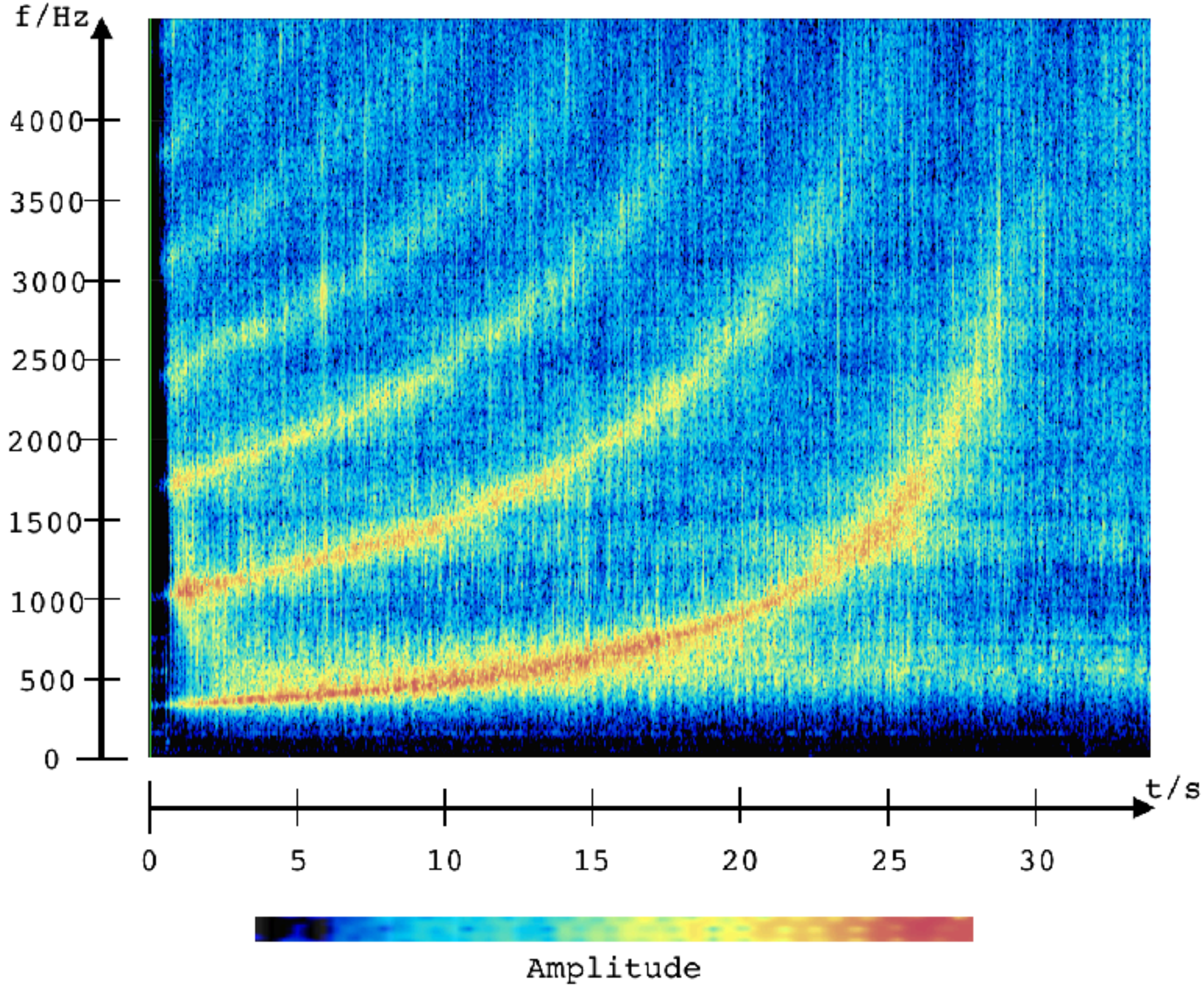
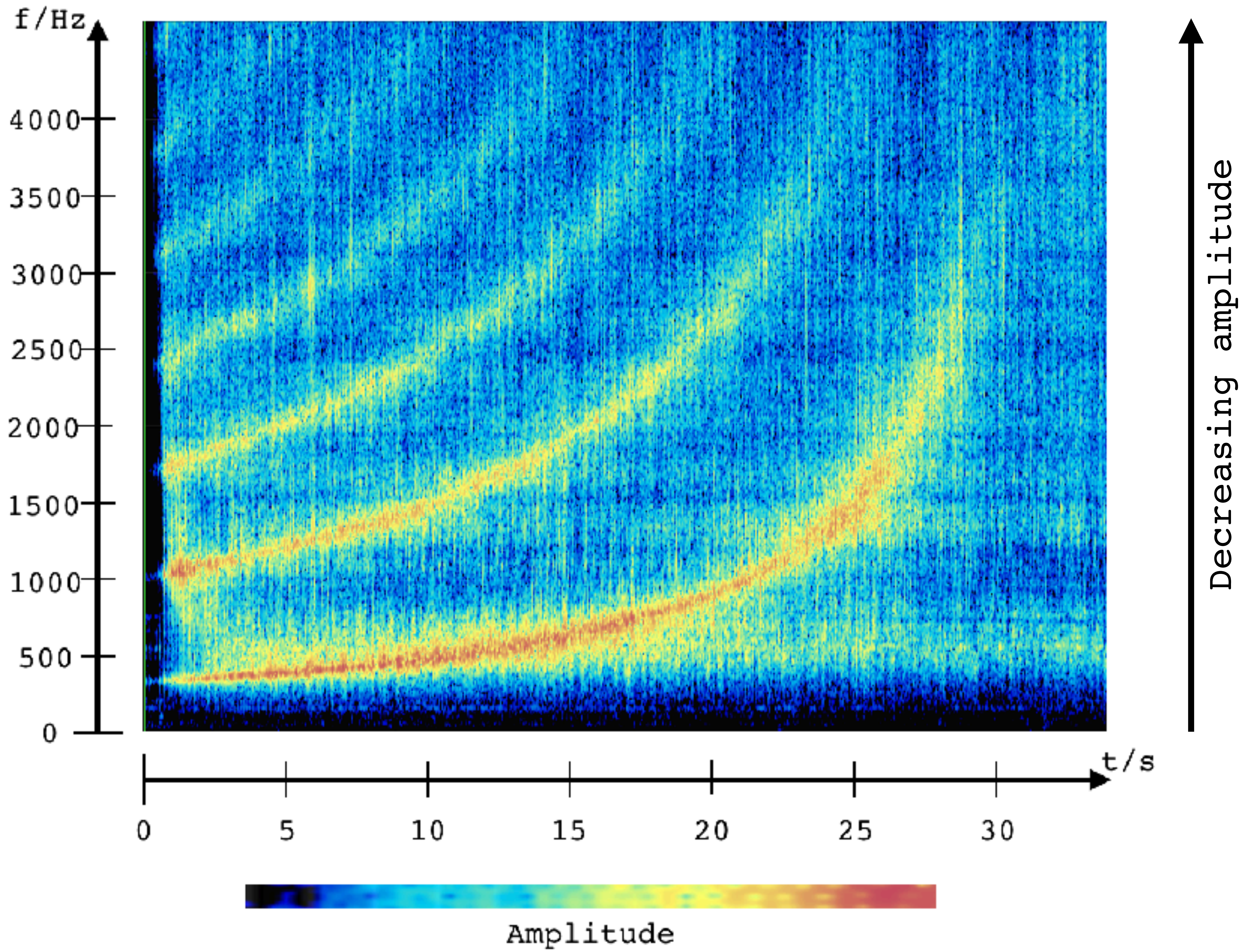
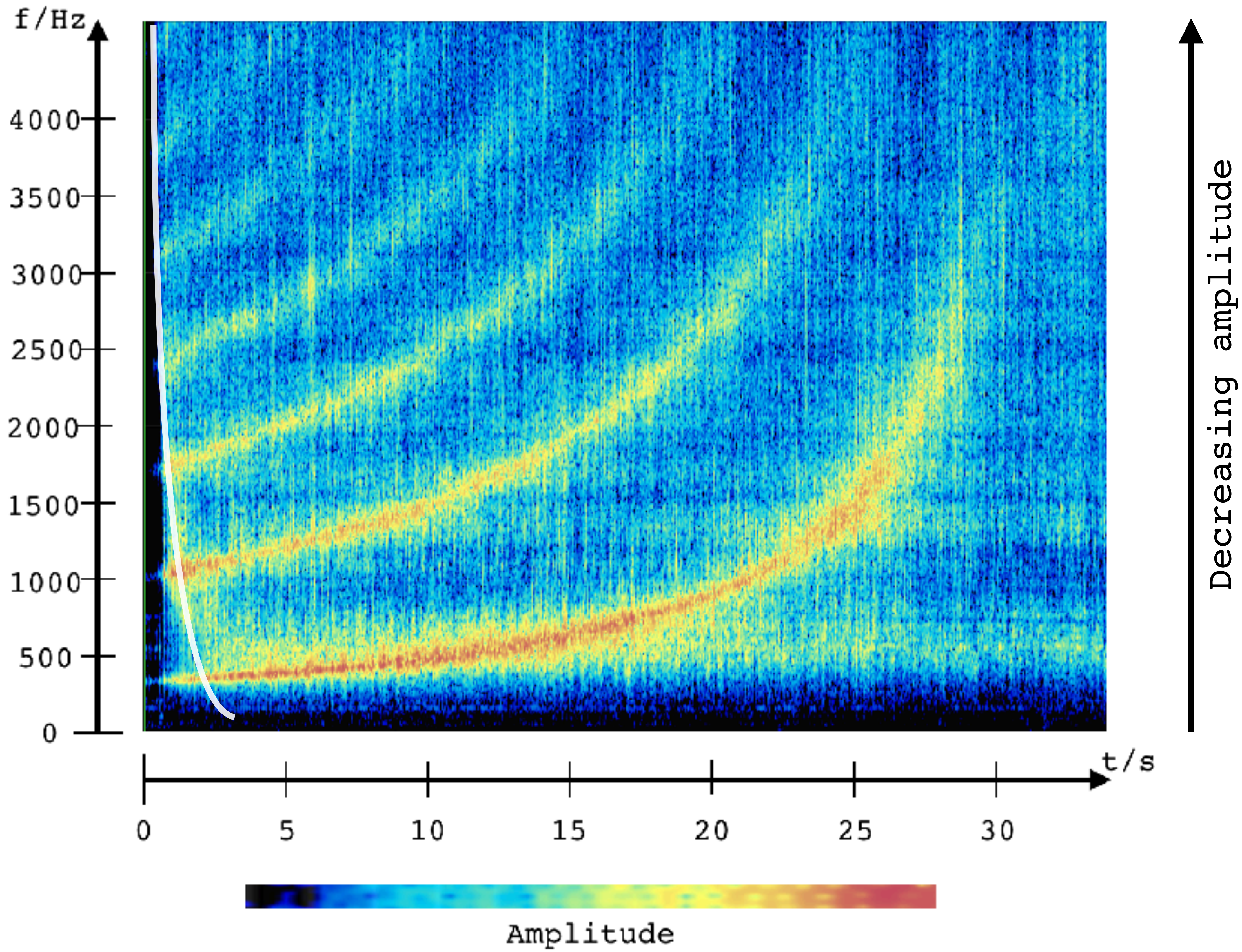
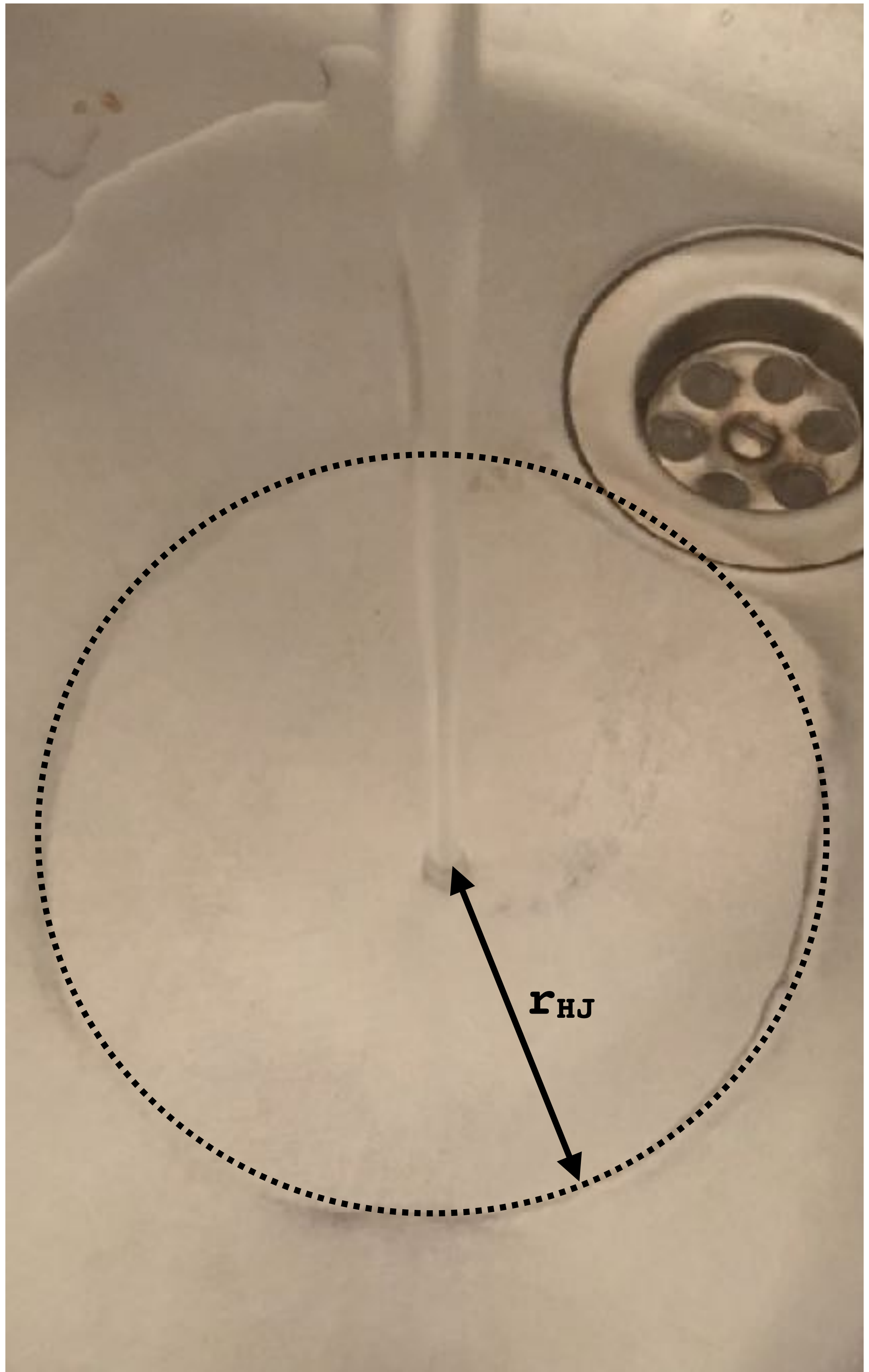
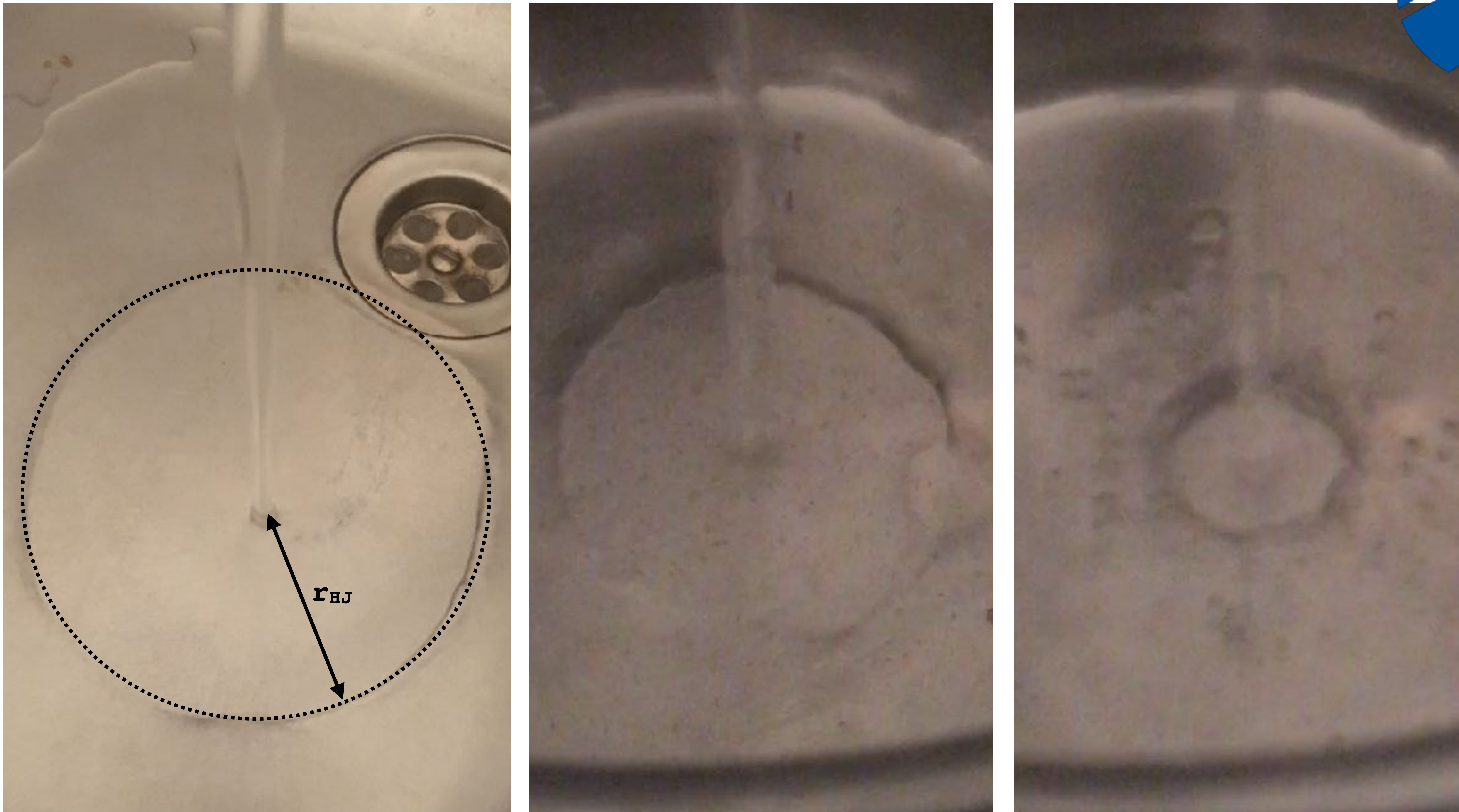


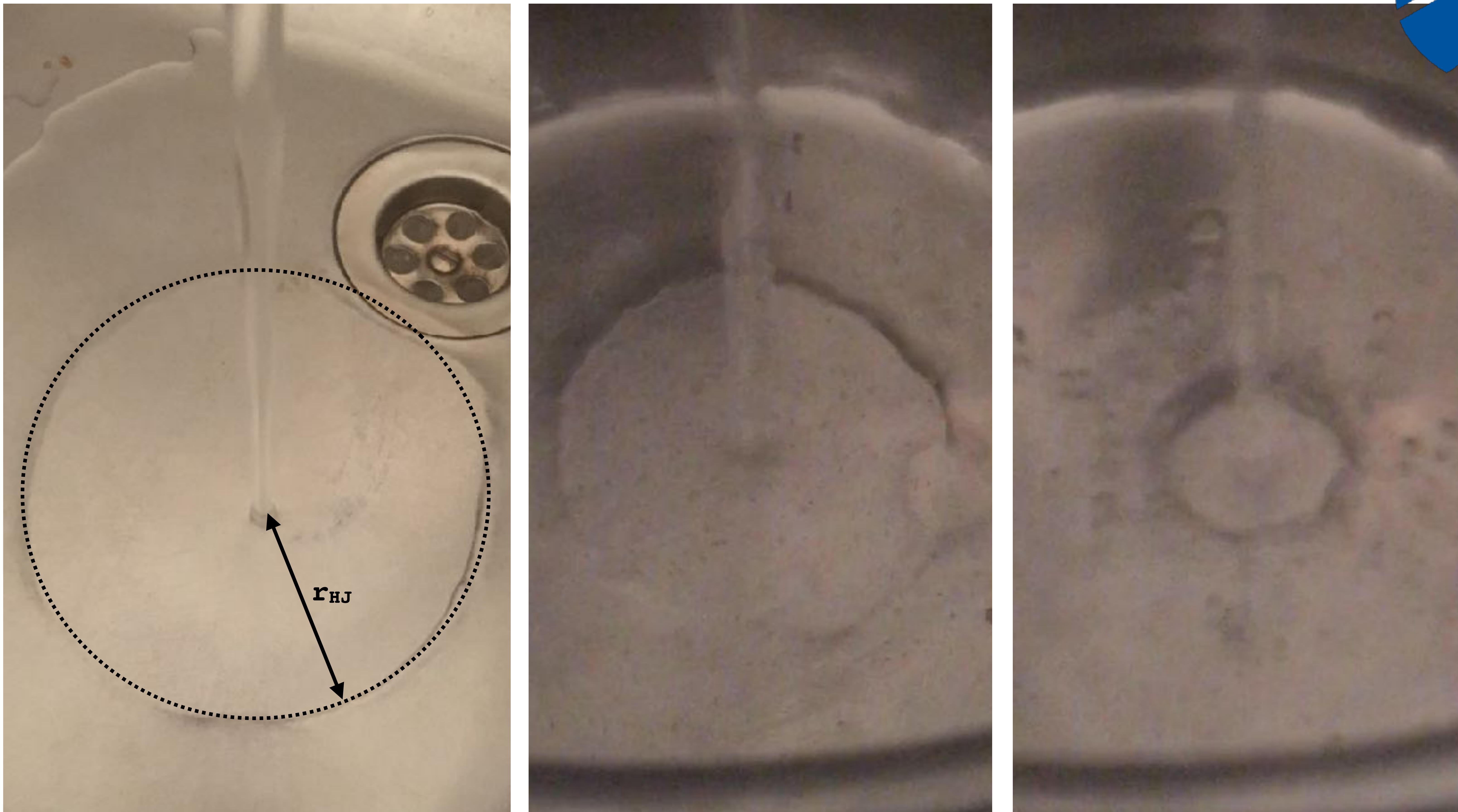
f/Hz
4000
3500
3000
2500
2000
1500
1000
500
0
t/s
0
5
10
15
20
25
30
Amplitude


f/Hz
4000
3500
3000
2500
2000
1500
1000
500
0
t/s
0
5
10
15
20
25
30
Decreasing amplitude
Amplitude


f/Hz
4000
3500
3000
2500
2000
1500
1000
500
0
t/s
0
5
10
15
20
25
30
Amplitude
Decreasing amplitude


r_HJ

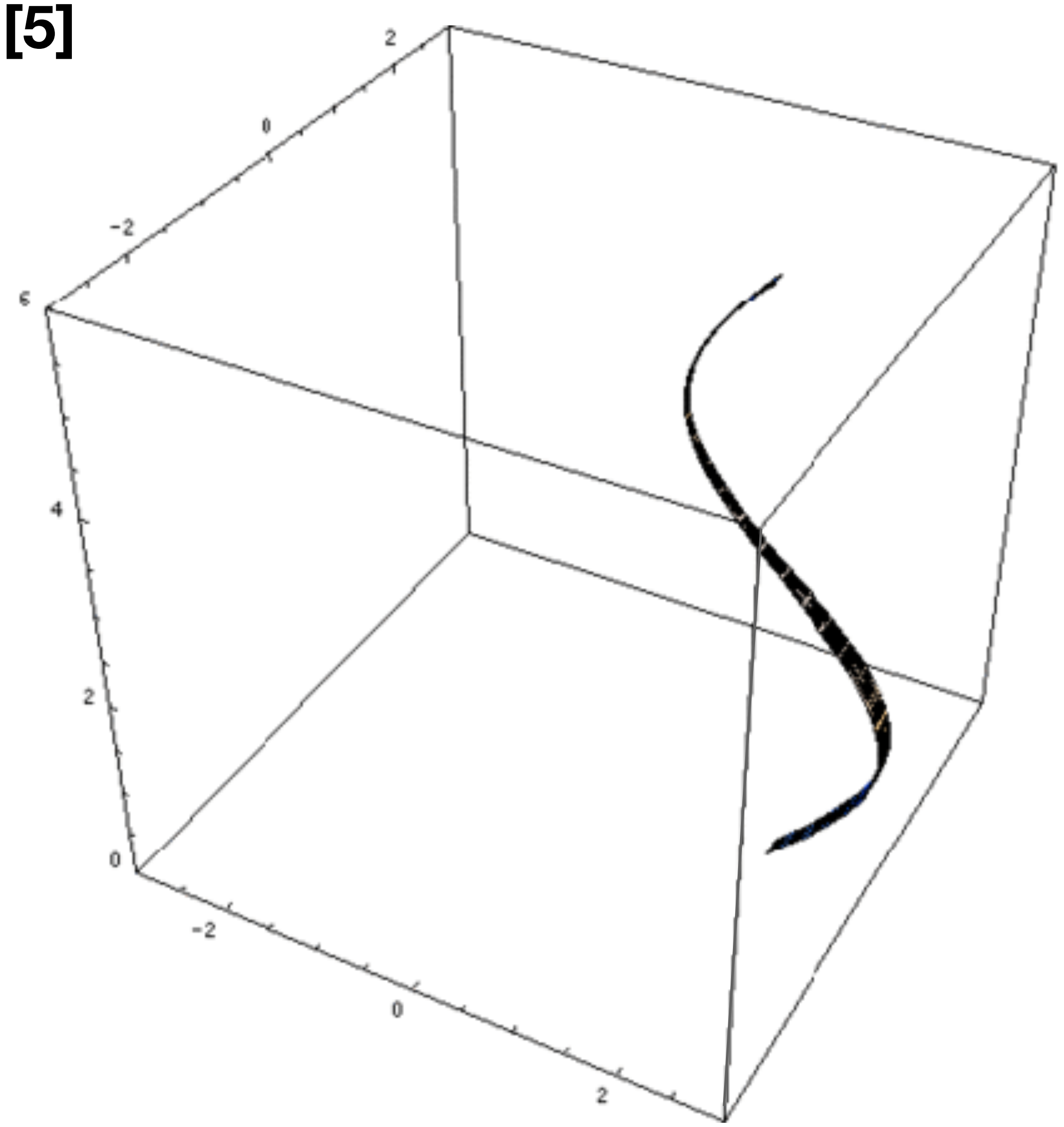

r_{HJ}



r_{HJ} decreases with increasing h_W

Modeling all possible bottles: Change of h_c

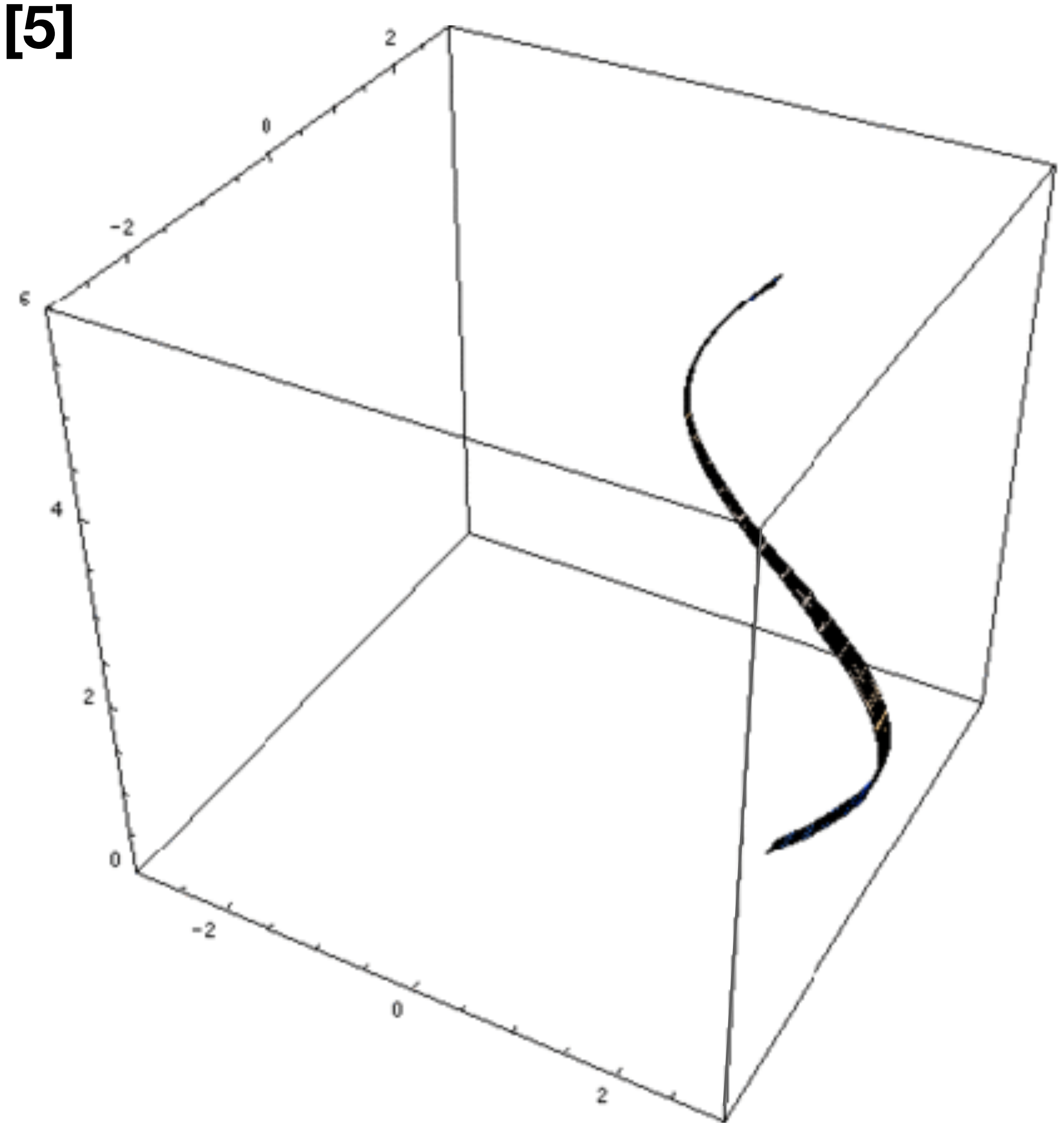
[5]



[5] https://commons.wikimedia.org/wiki/File:Rotationskoerper_animation.gif

Modeling all possible bottles: Change of h_c

[5]



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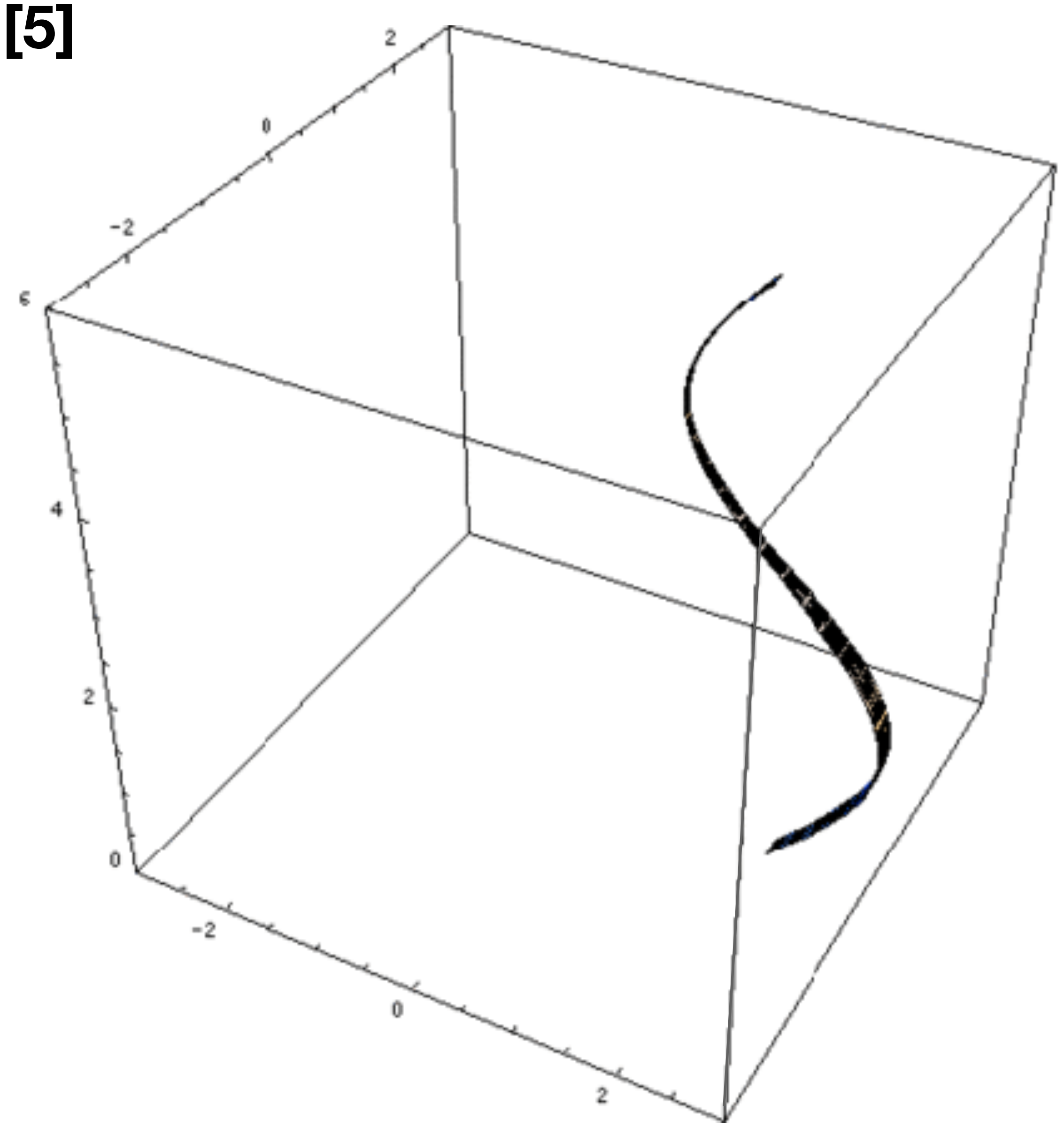

The changing rate of the water height in the container depends on the cross-sectional area at this height.

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Modeling all possible bottles: Change of h_c

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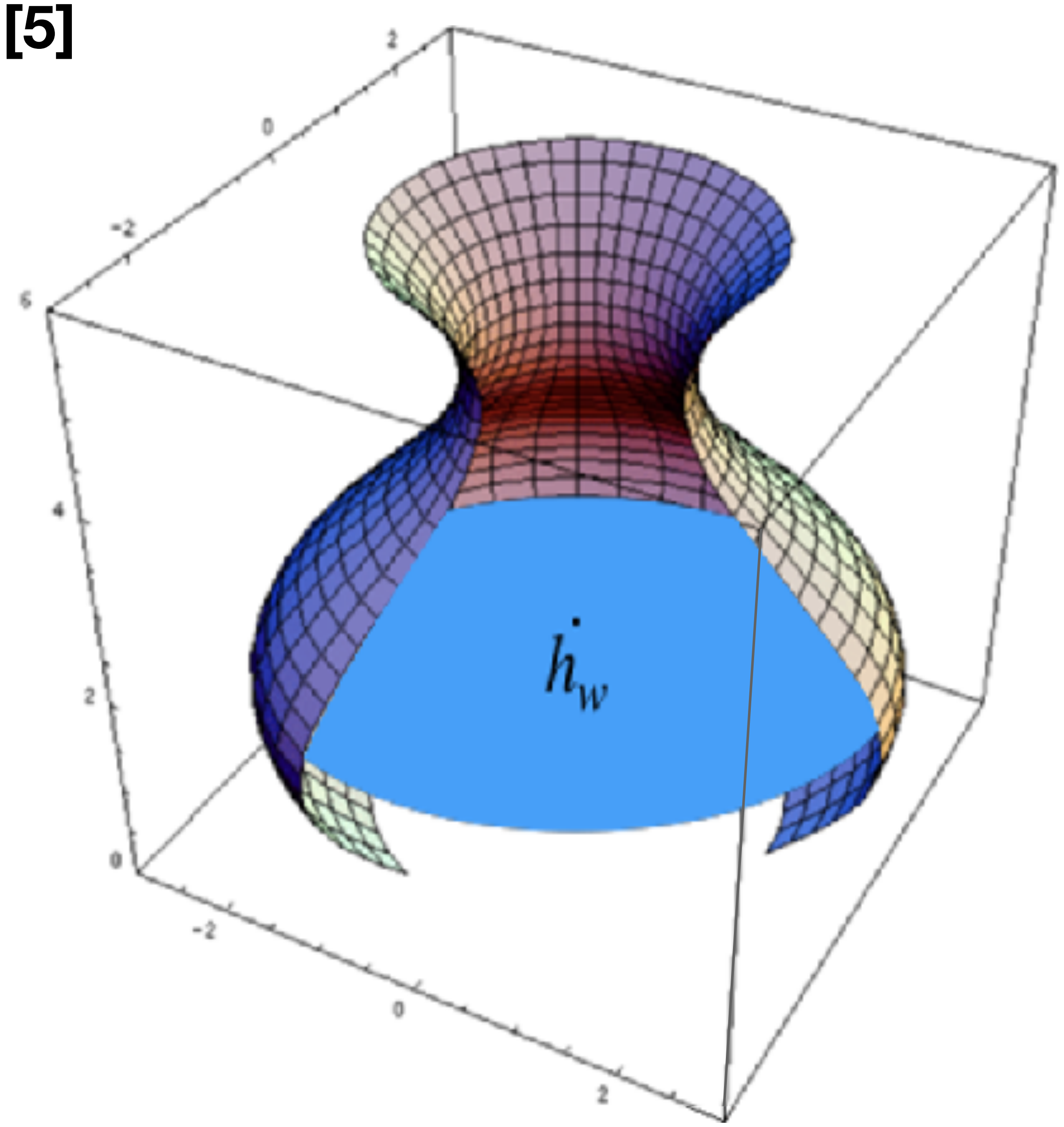

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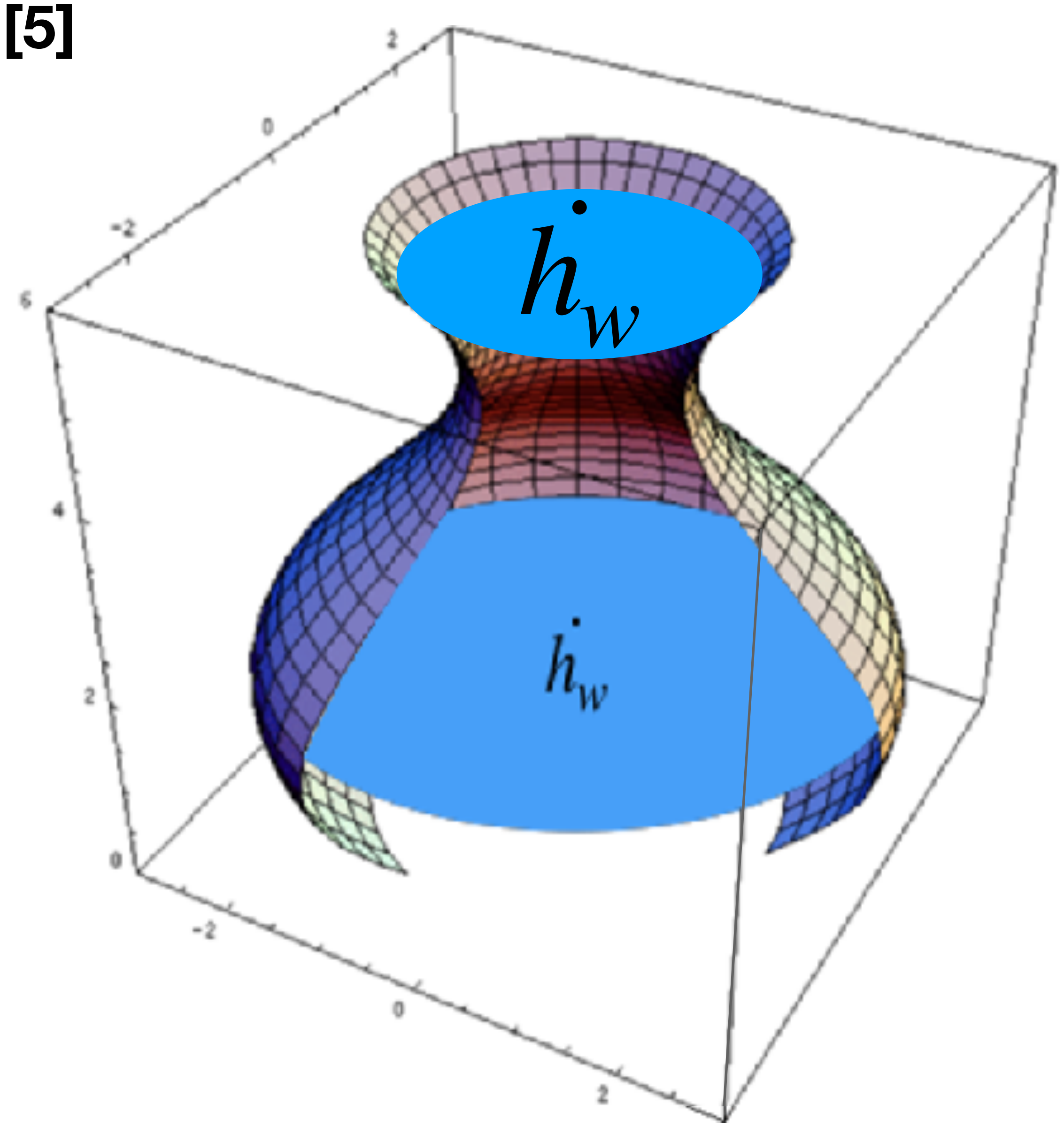

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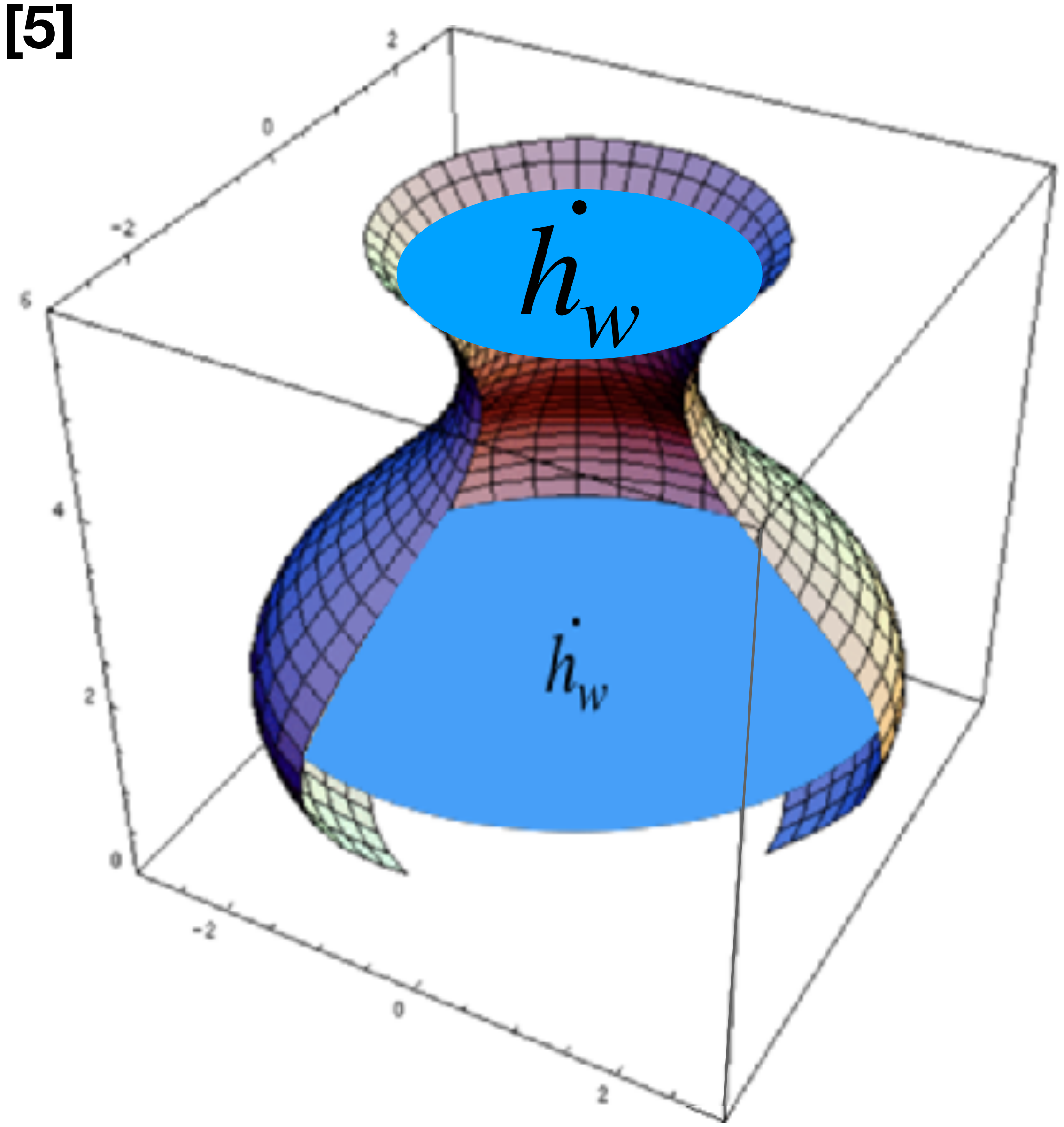

The changing rate of the water height in the container depends on the cross-sectional area at this height.

$$h_c(t) = h_B - h_w(t)$$

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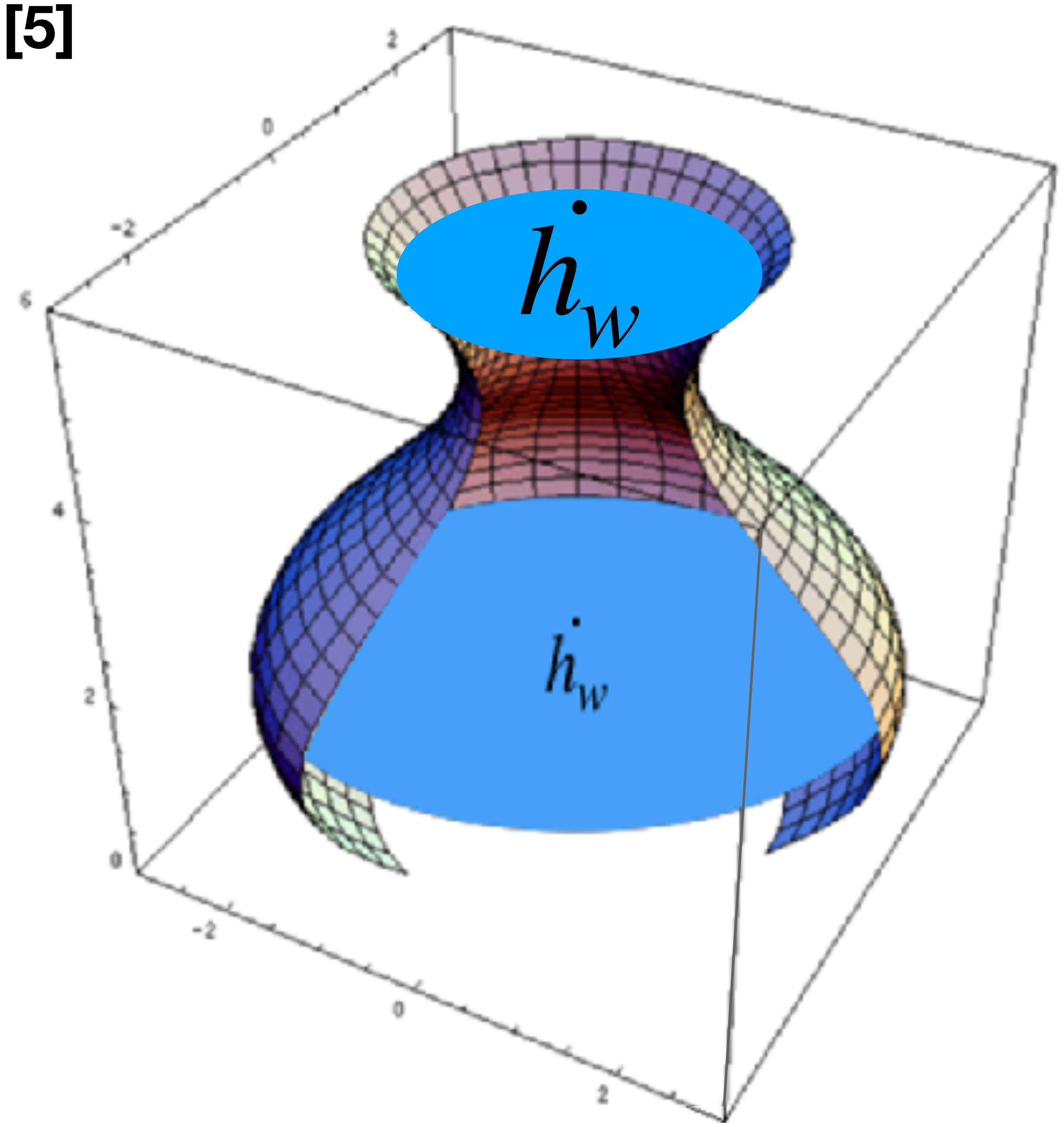
Modeling all possible bottles: Change of h_c

[5]



The changing rate of the water height in the container depends on the cross-sectional area at this height.

$$h_c(t) = h_B - h_w(t)$$

The height of the cavity can be calculated for every container for every given moment in time.

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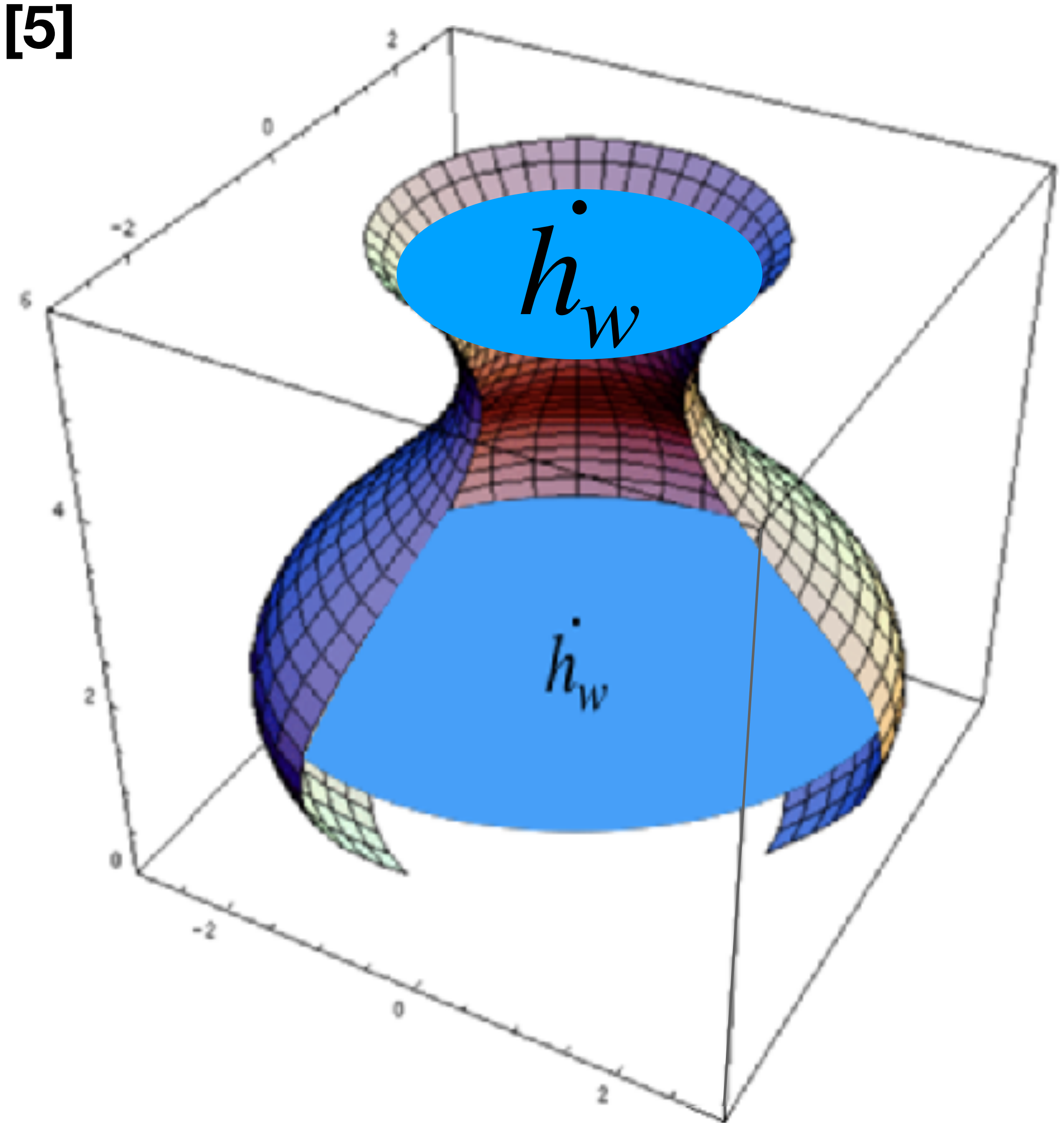
Modeling all possible bottles: Change of h_c

[5]



The changing rate of the water height in the container depends on the cross-sectional area at this height.

$$h_c(t) = h_B - h_w(t)$$

The height of the cavity can be calculated for every container for every given moment in time.

$$f_0 = \frac{c}{4h_c(t)}$$

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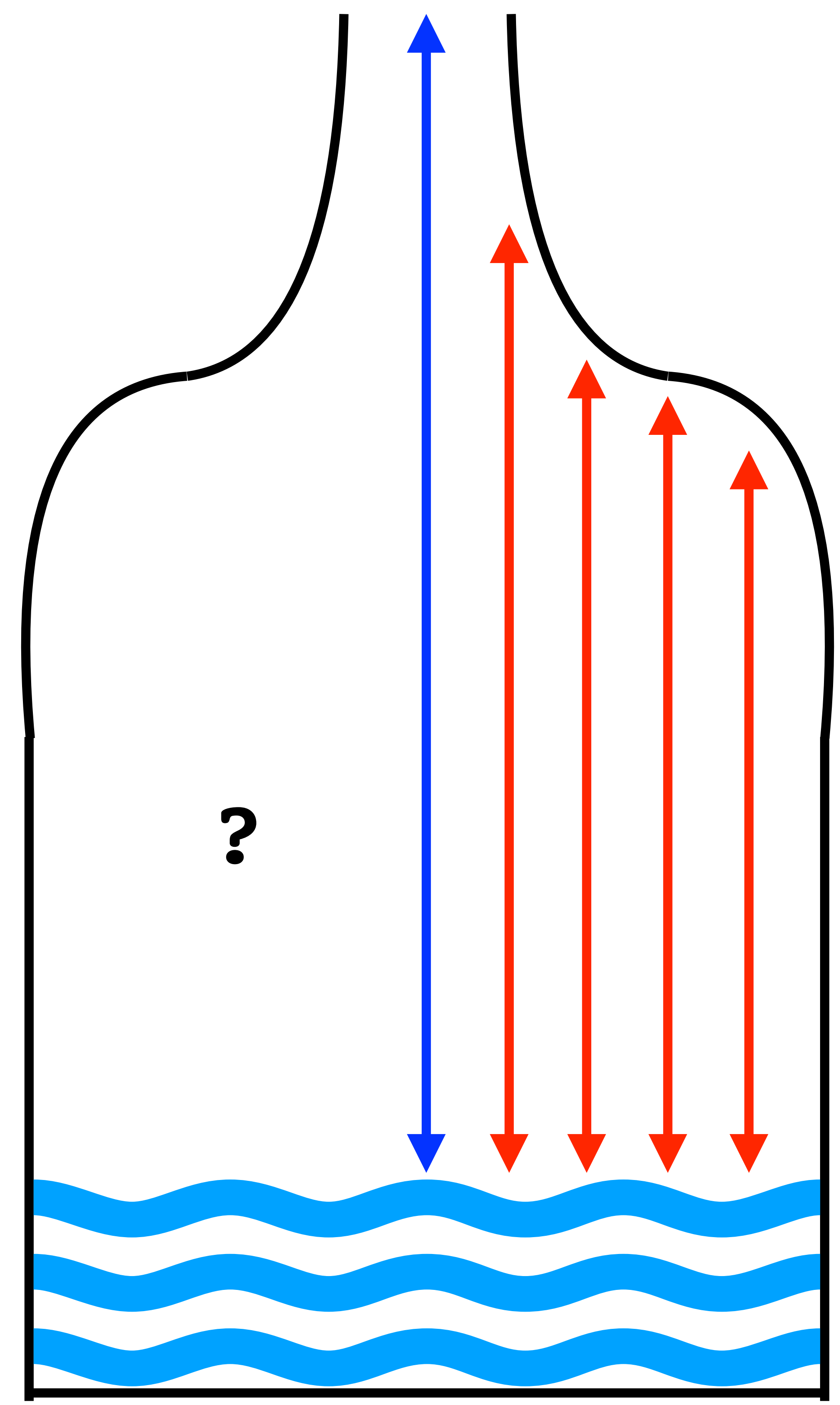
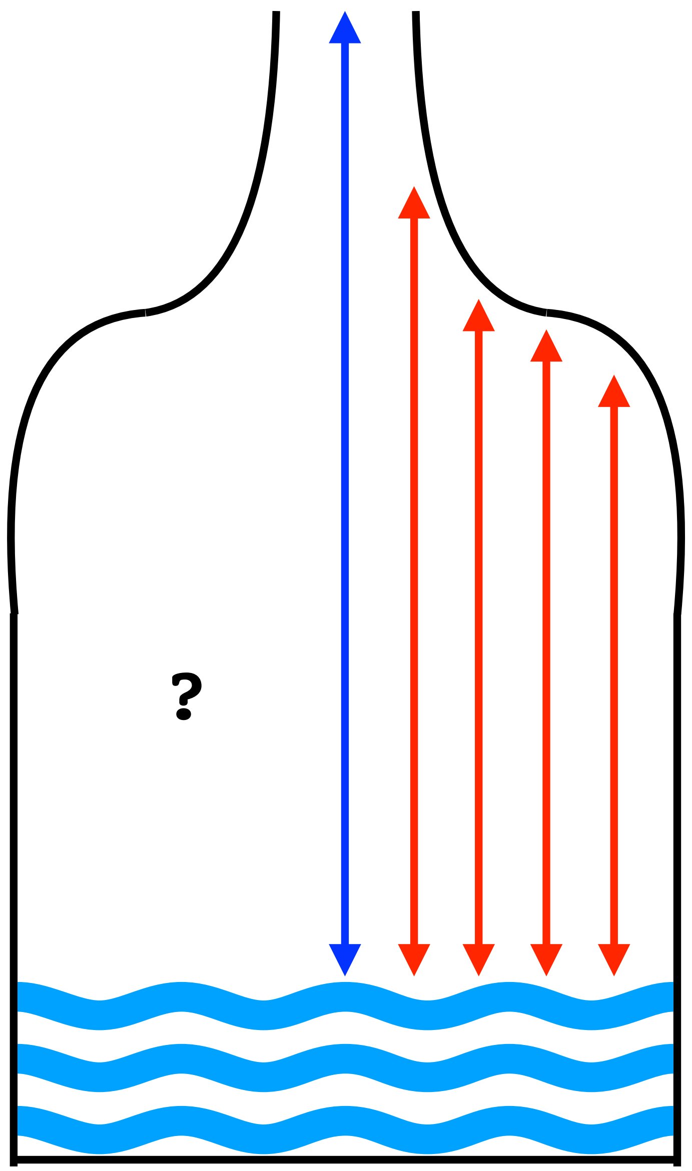
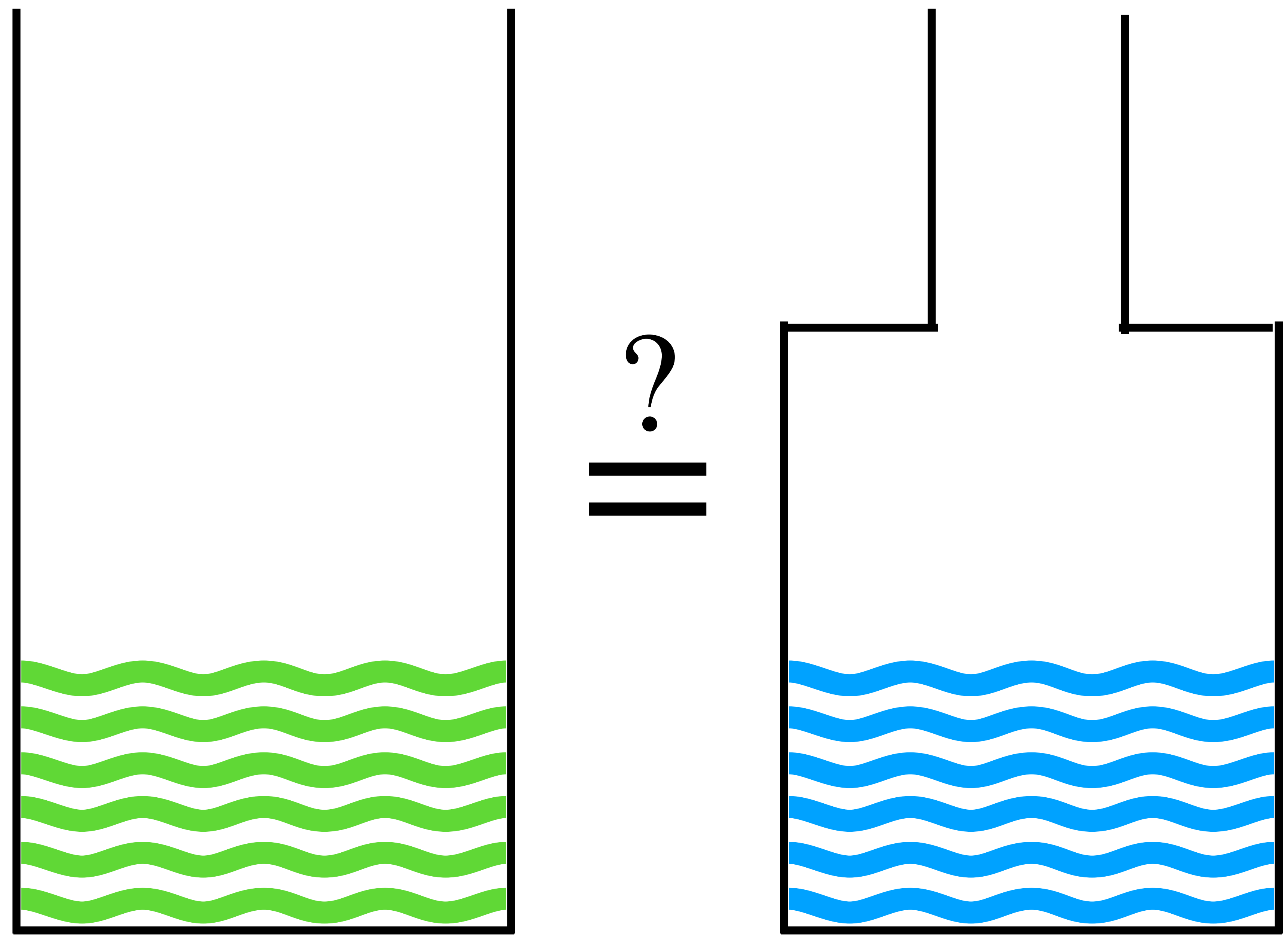
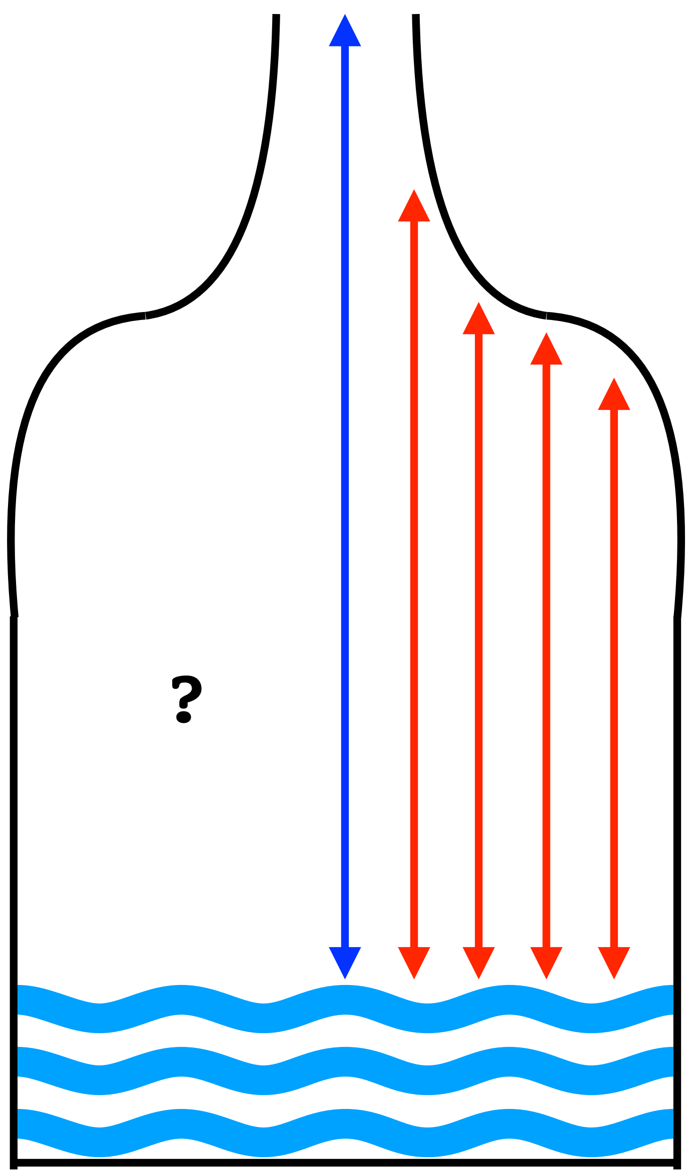
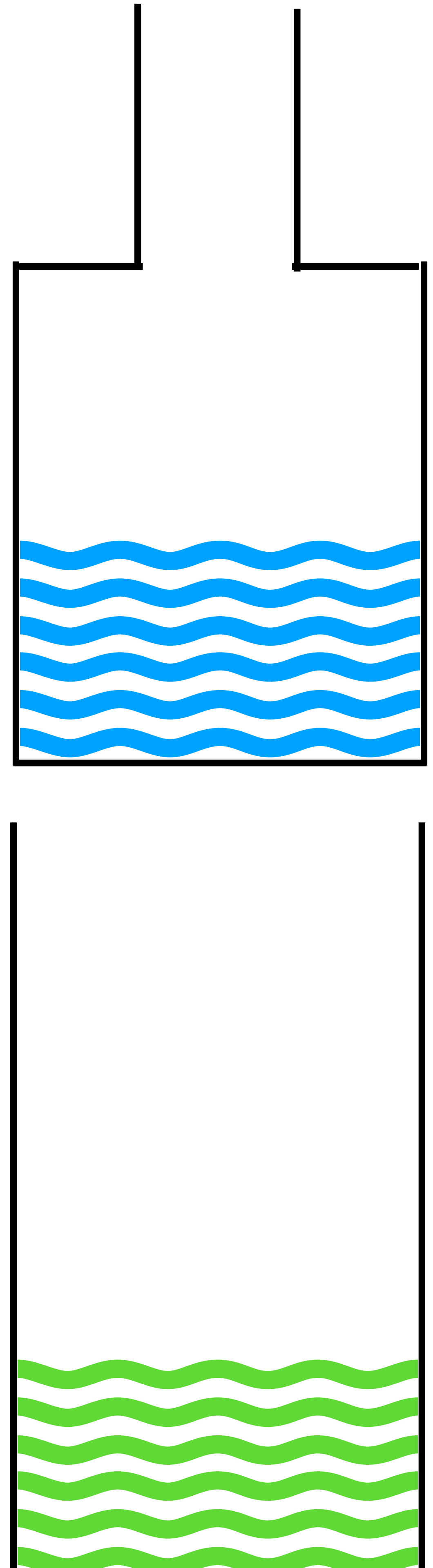
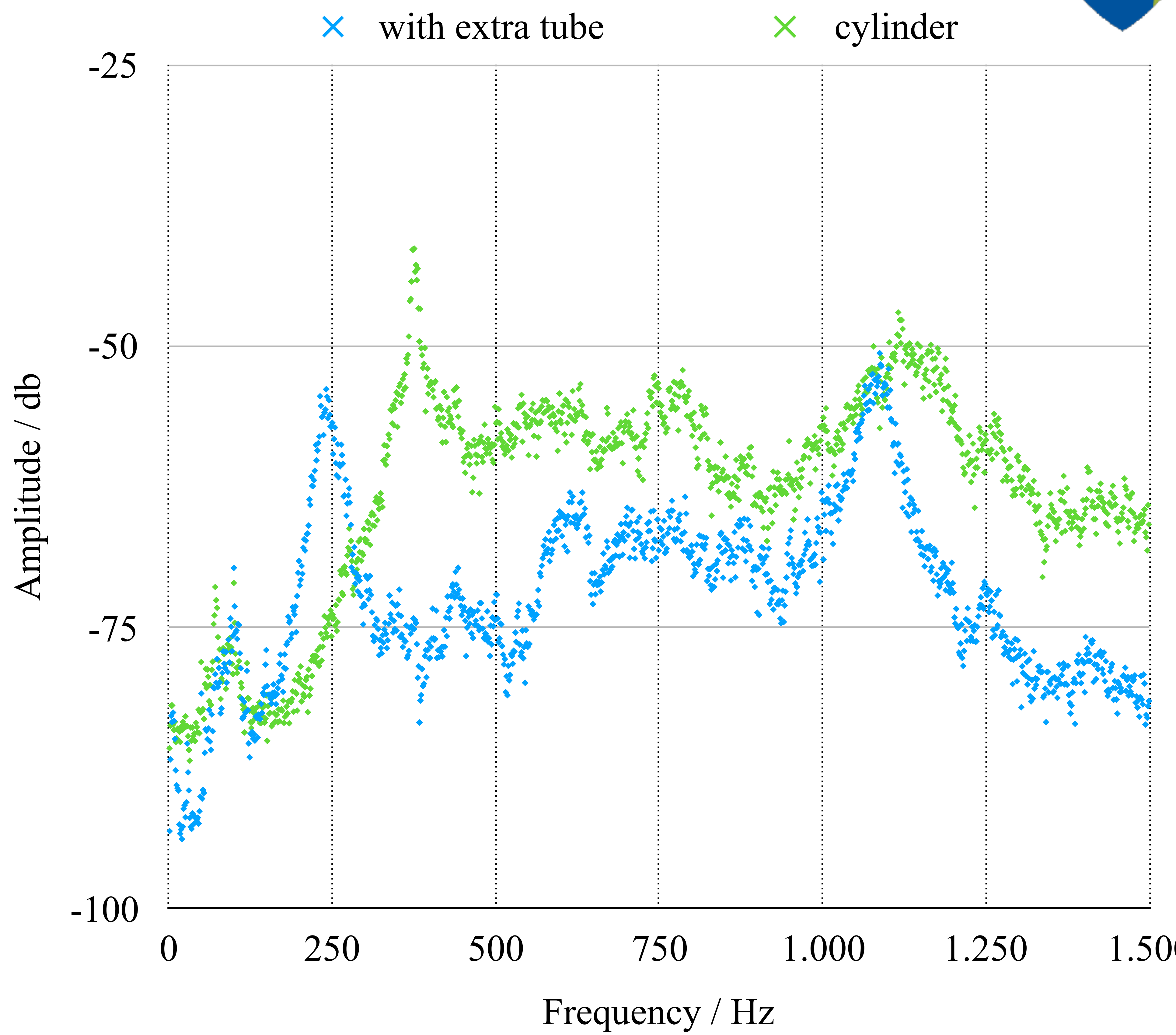


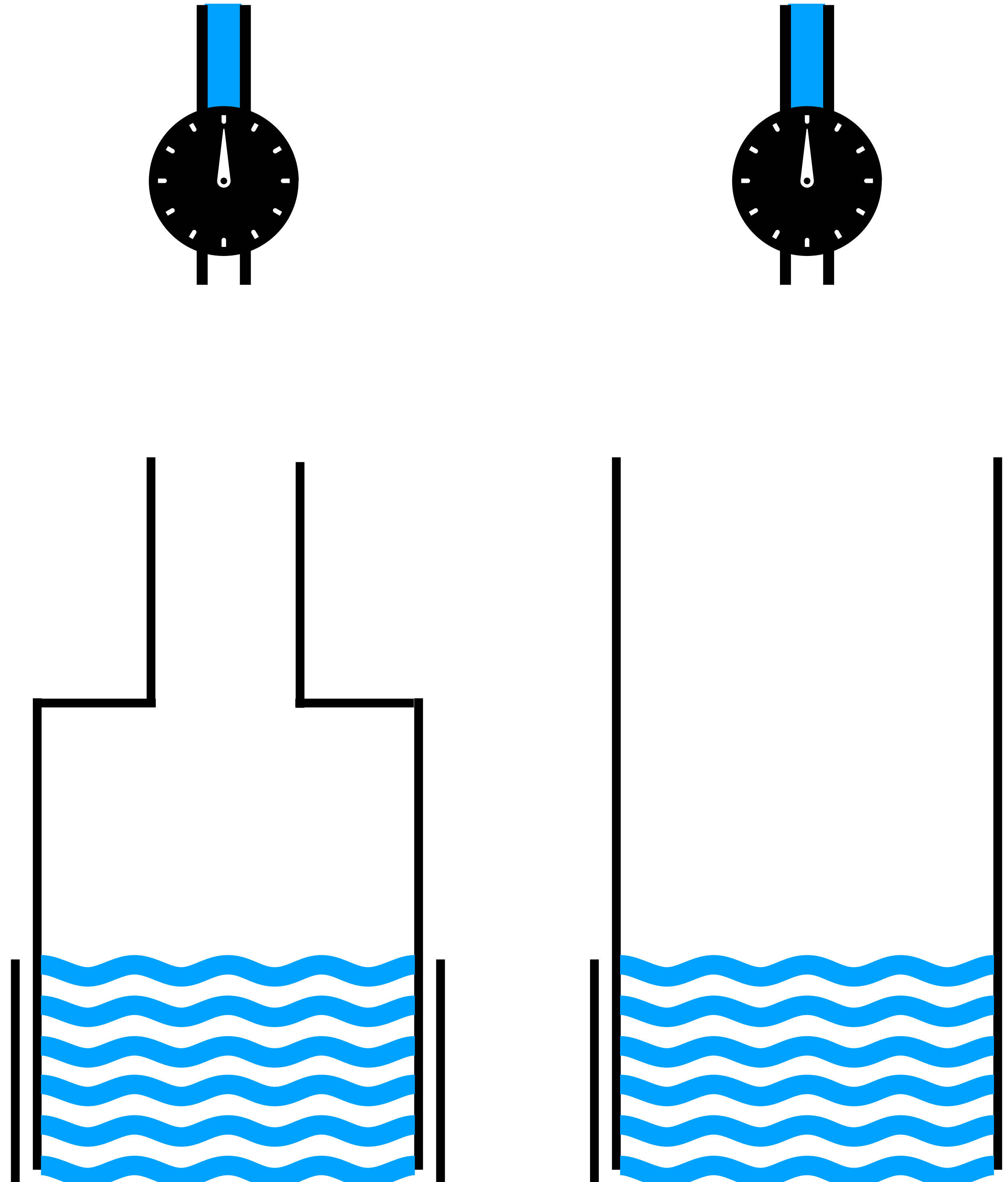


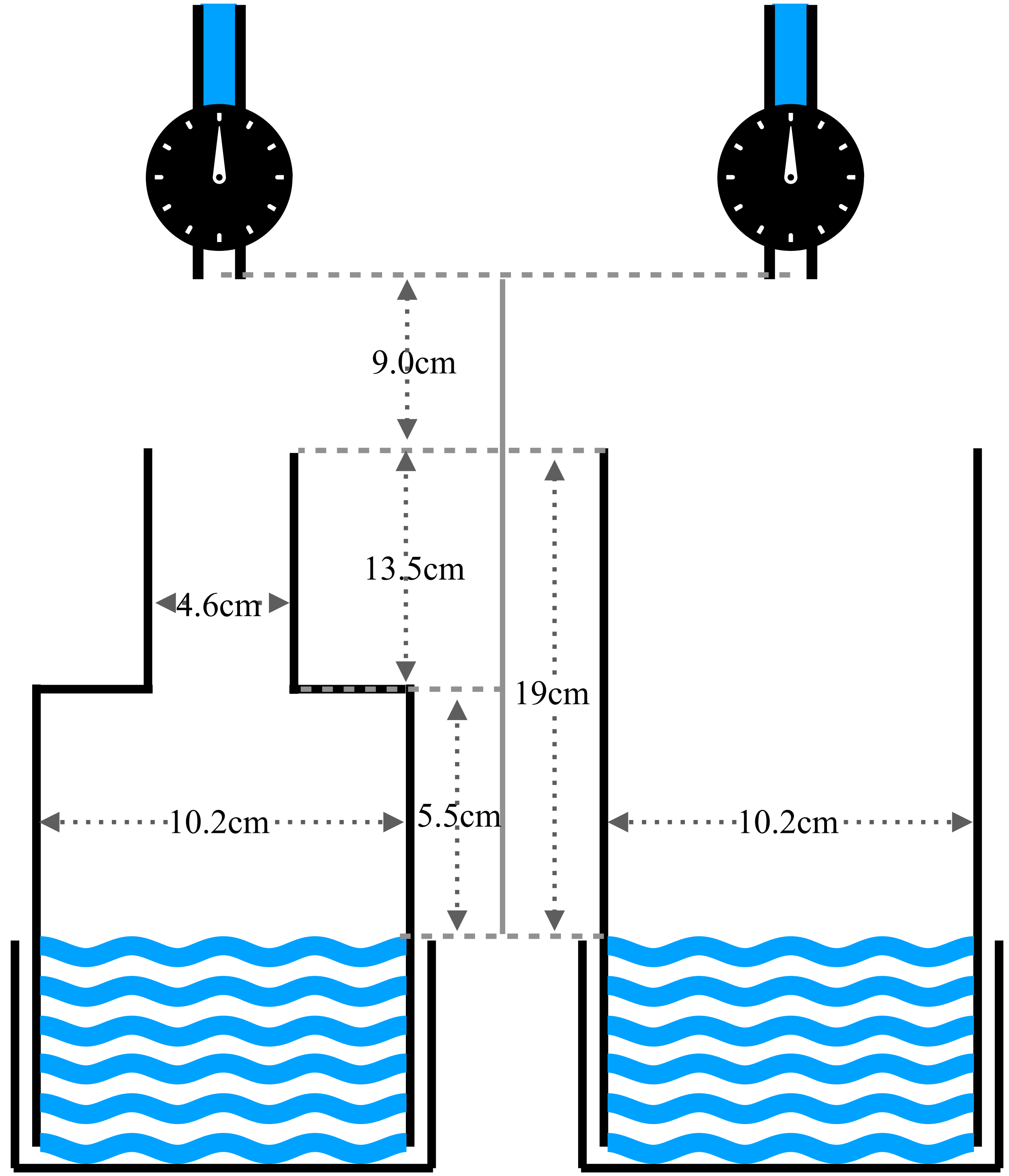



?

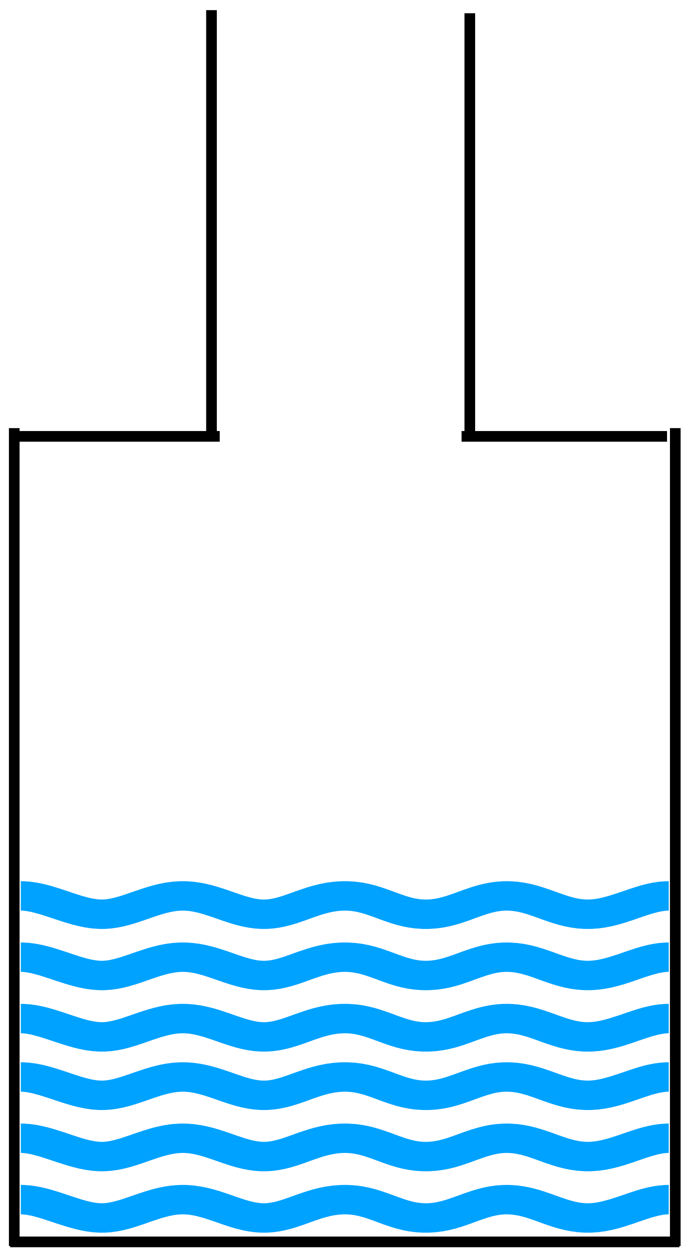



with extra tube
cylinder
-25
-50
-75
-100
Amplitude / db
0
250
500
750
1.000
1.250
1.500
Frequency / Hz

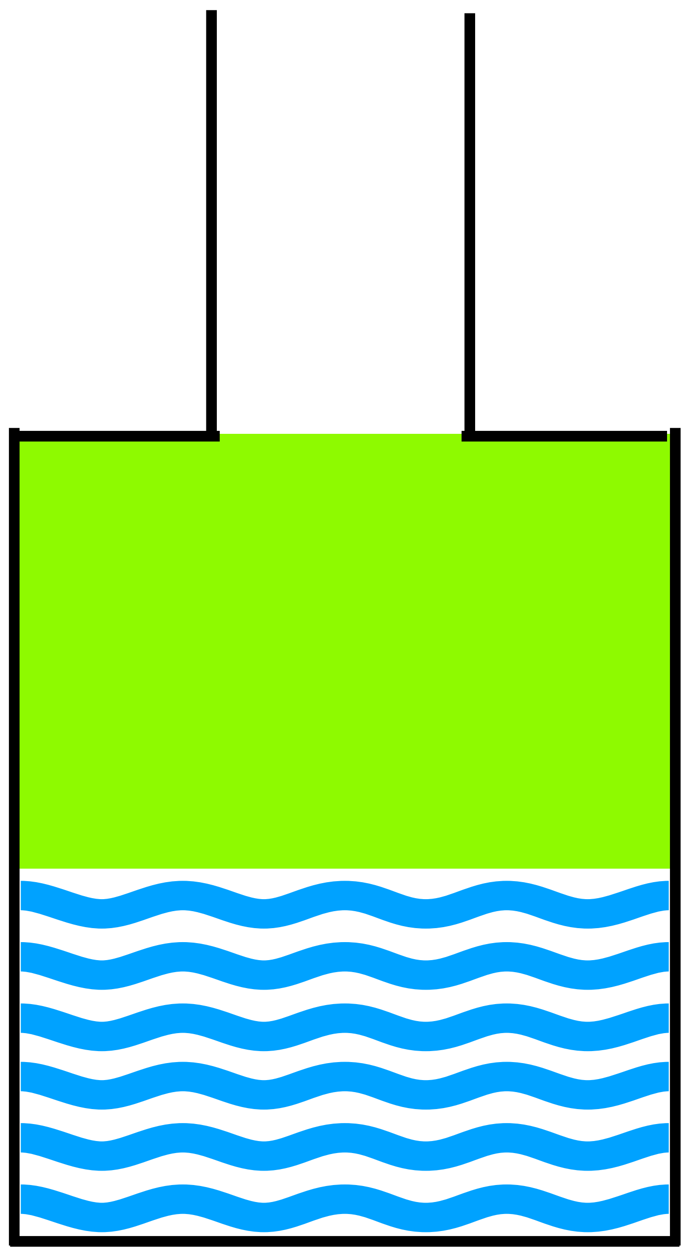



9.0cm
13.5cm
4.6cm
19cm
10.2cm
5.5cm
10.2cm

Helmholtz resonance



Helmholtz resonance



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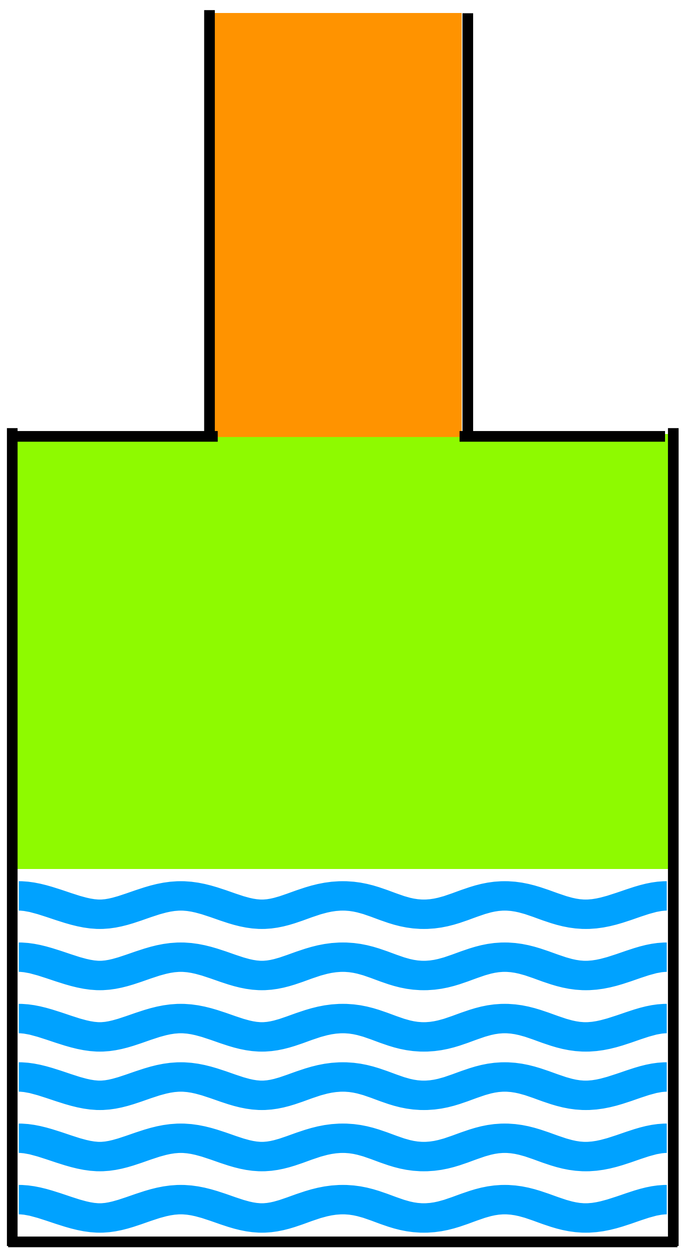
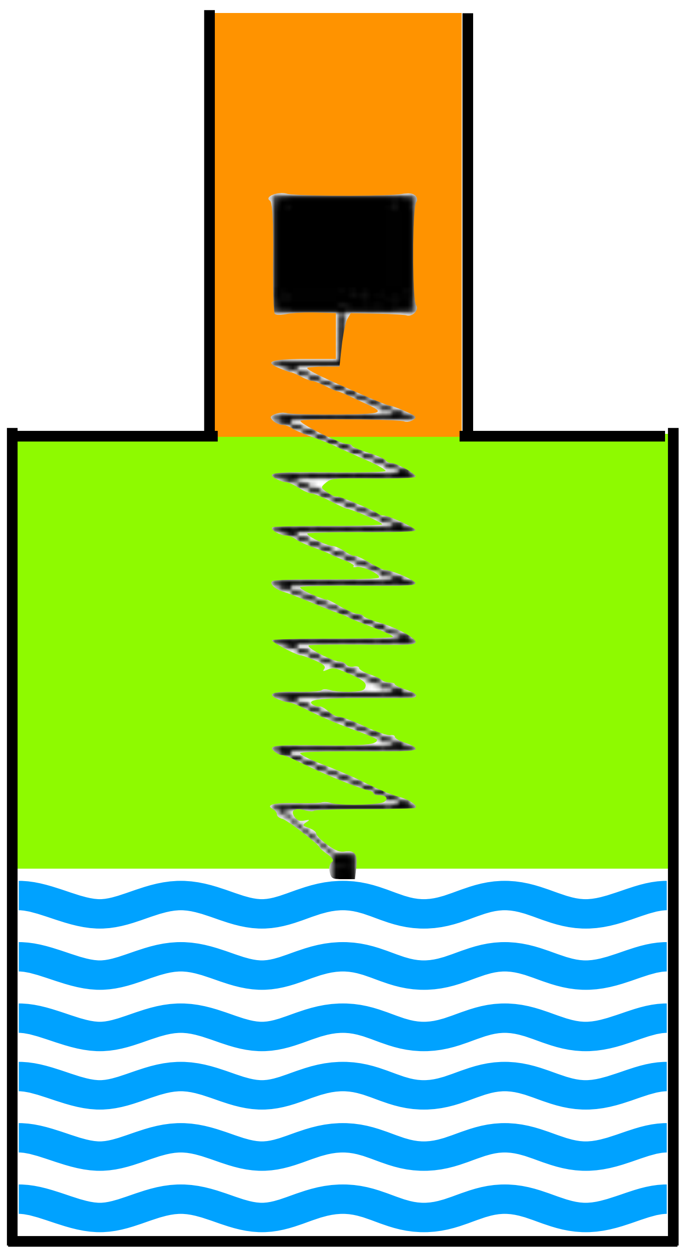


Helmholtz resonance



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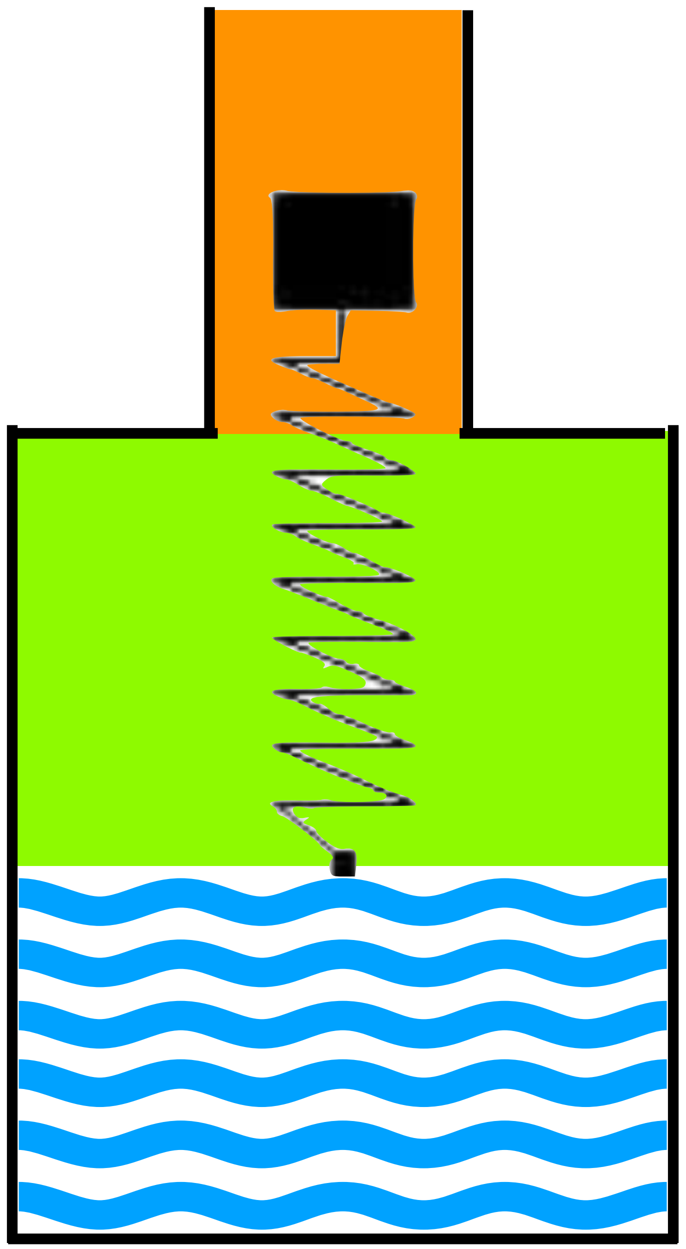


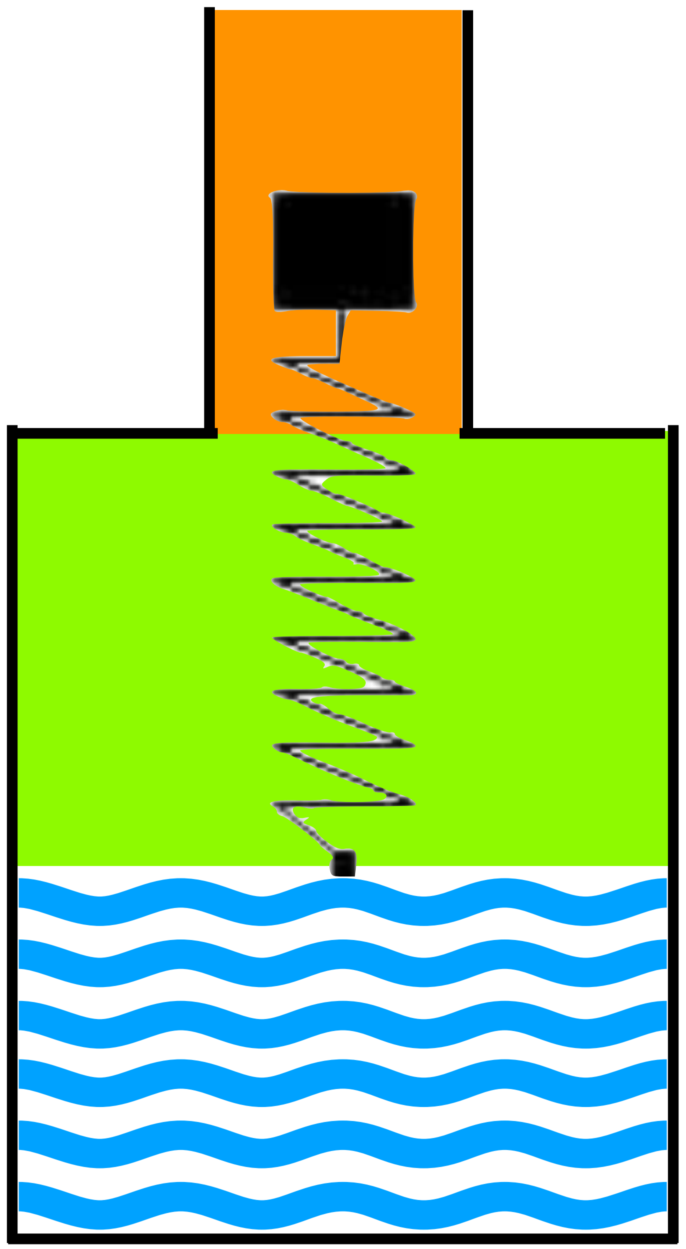
$$f_0 = \frac{c}{2\pi} \cdot \sqrt{\frac{A_{opening}}{V_{air} \cdot l_{neck}}}$$

$A_{opening}$ - Area of the opening

V_{air} - Volume of the air in the container

l_{neck} - Length of the neck

Helmholtz resonance



$$f_0 = \frac{343\frac{m}{s}}{2\pi} \cdot \sqrt{\frac{0.00166m^2}{0.0449m^3 \cdot 0.135m}}$$

$$\approx 26.8Hz$$

$$f_1 = 3 \cdot f_0 = 80.4Hz$$

$$f_2 = 5 \cdot f_0 = 134.0Hz$$

$$f_3 = 7 \cdot f_0 = 187.6Hz$$

$$f_4 = 9 \cdot f_0 = 241.2Hz$$

$$\dots$$

$$f_0 = \frac{c}{2\pi} \cdot \sqrt{\frac{A_{opening}}{V_{air} \cdot l_{neck}}}$$

$A_{opening}$ - Area of the opening

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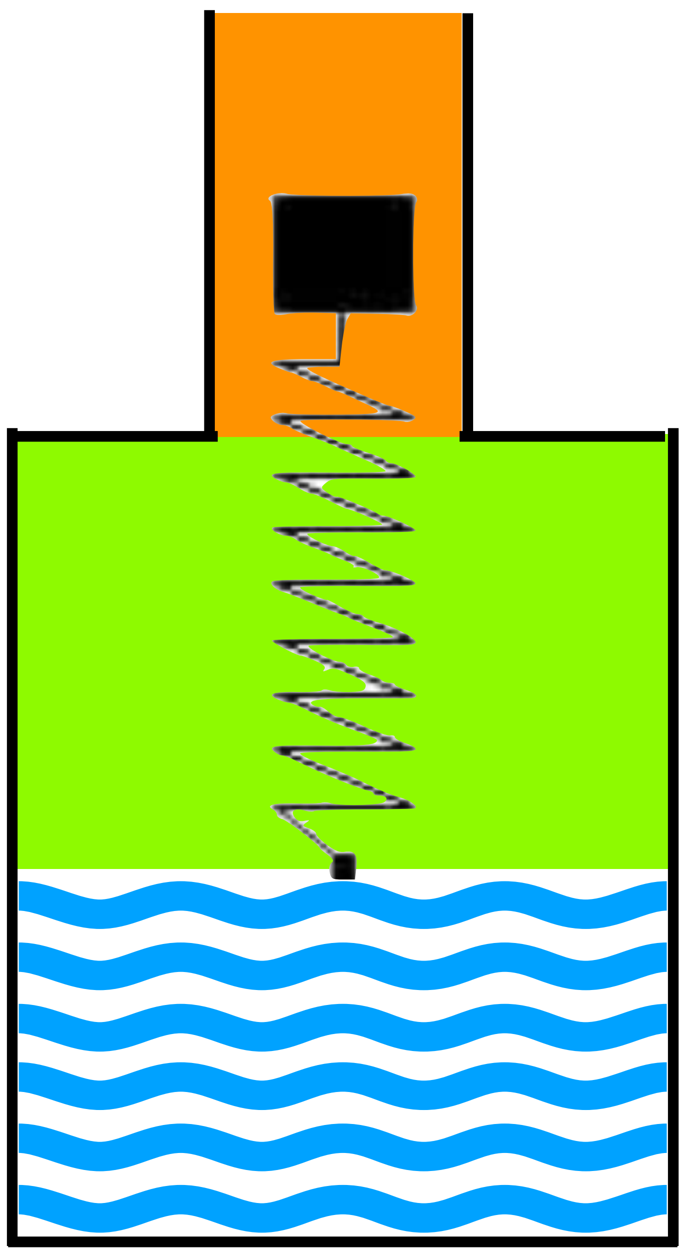
l_{neck} - Length of the neck

Helmholtz resonance



$$f_0 = \frac{343\frac{m}{s}}{2\pi} \cdot \sqrt{\frac{0.00166m^2}{0.0449m^3 \cdot 0.135m}}$$

$$\approx 26.8Hz$$

$$f_1 = 3 \cdot f_0 = 80.4Hz$$

$$f_2 = 5 \cdot f_0 = 134.0Hz$$

$$f_3 = 7 \cdot f_0 = 187.6Hz$$

$$f_4 = 9 \cdot f_0 = 241.2Hz$$

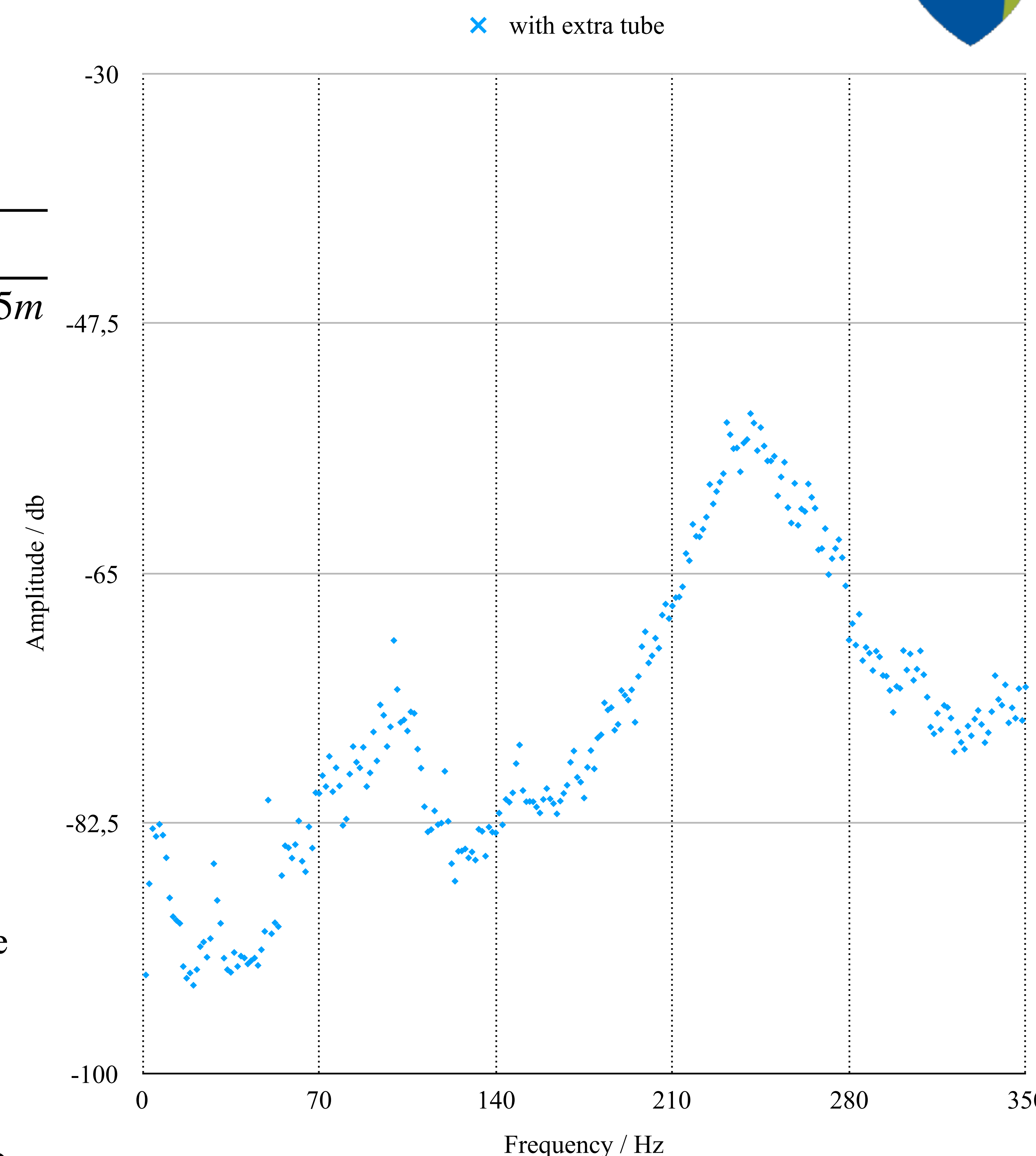
$$\ldots$$

$$f_0 = \frac{c}{2\pi} \cdot \sqrt{\frac{A_{opening}}{V_{air} \cdot l_{neck}}}$$

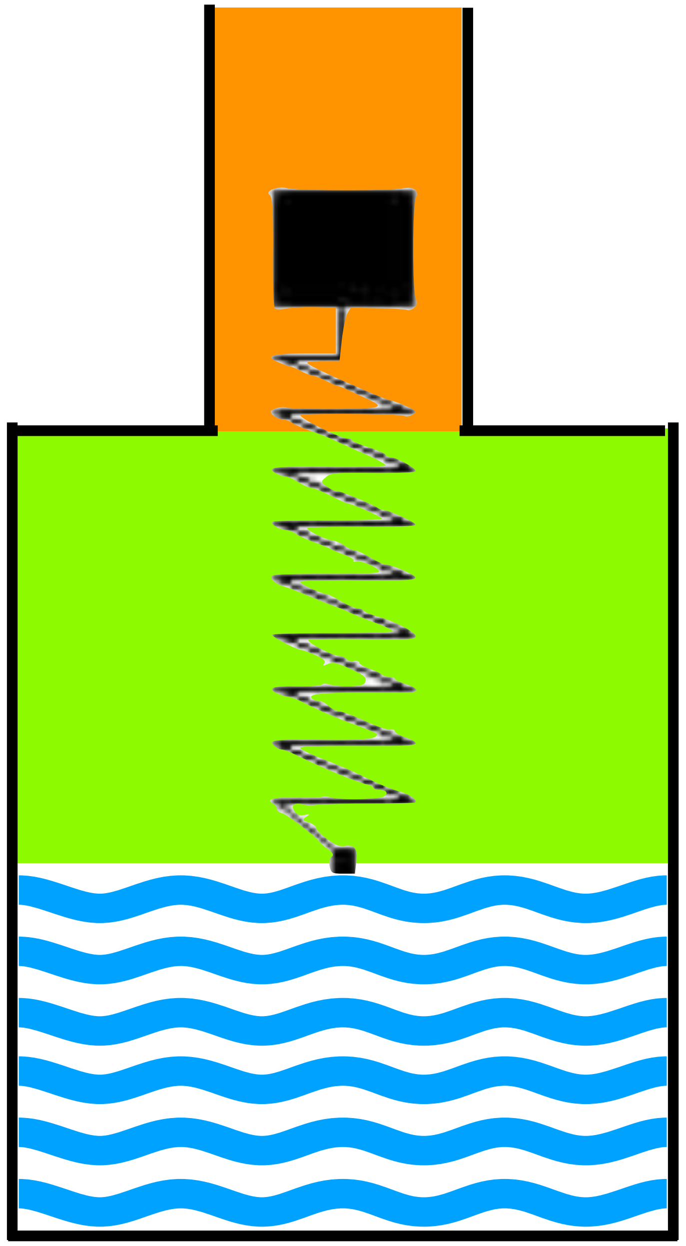
$A_{opening}$ - Area of the opening

V_{air} - Volume of the air in the container

l_{neck} - Length of the neck



Helmholtz resonance



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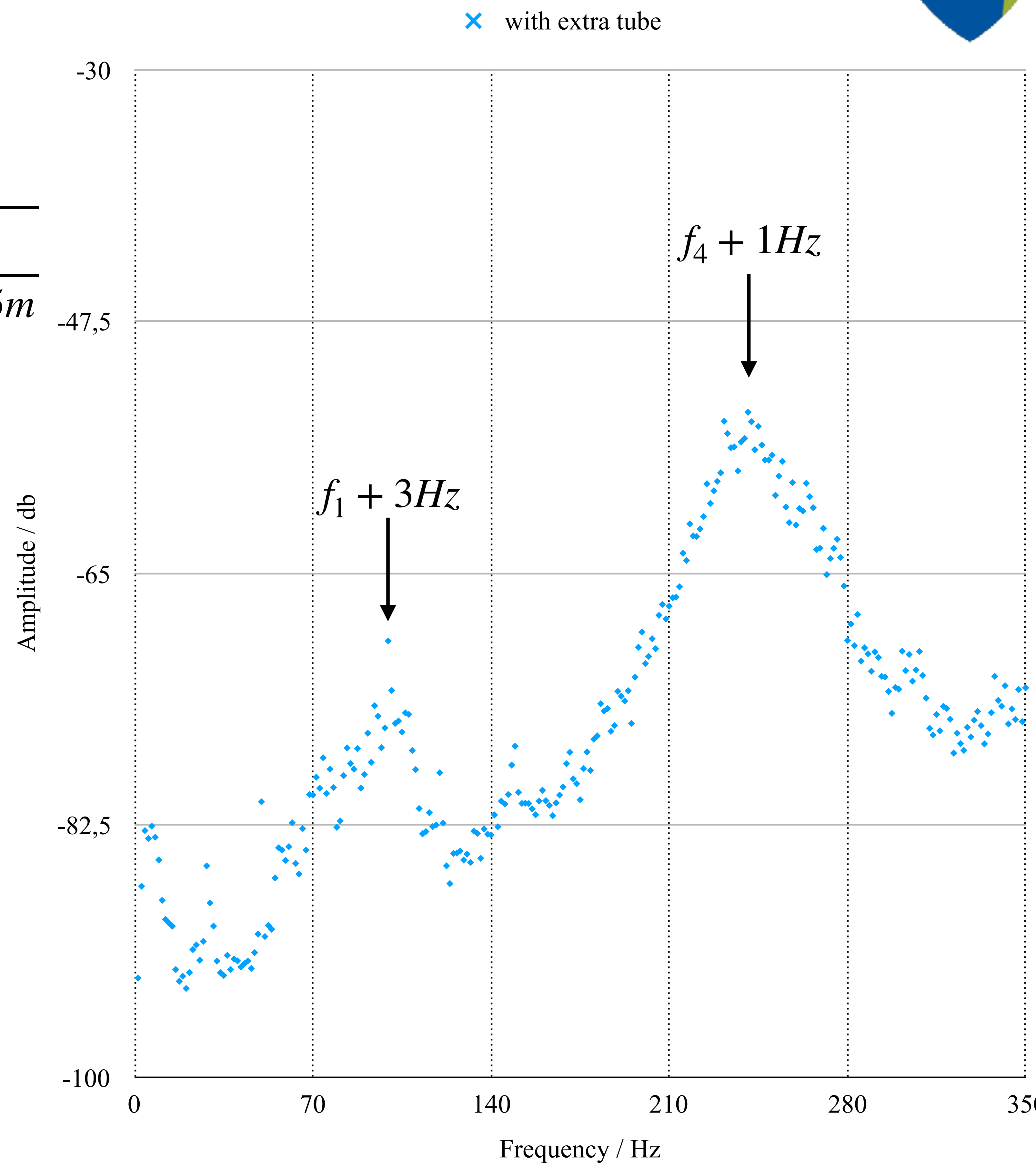
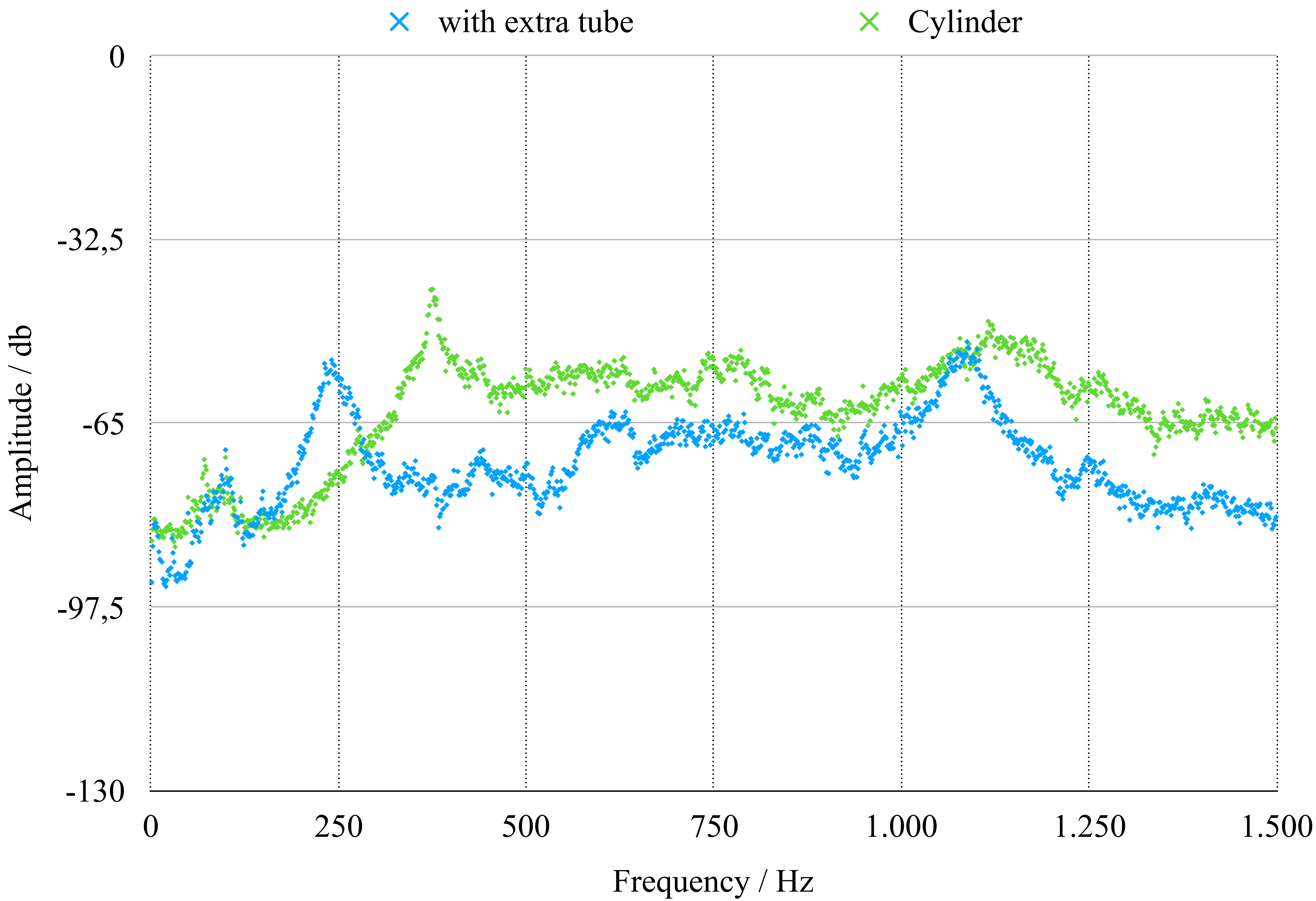
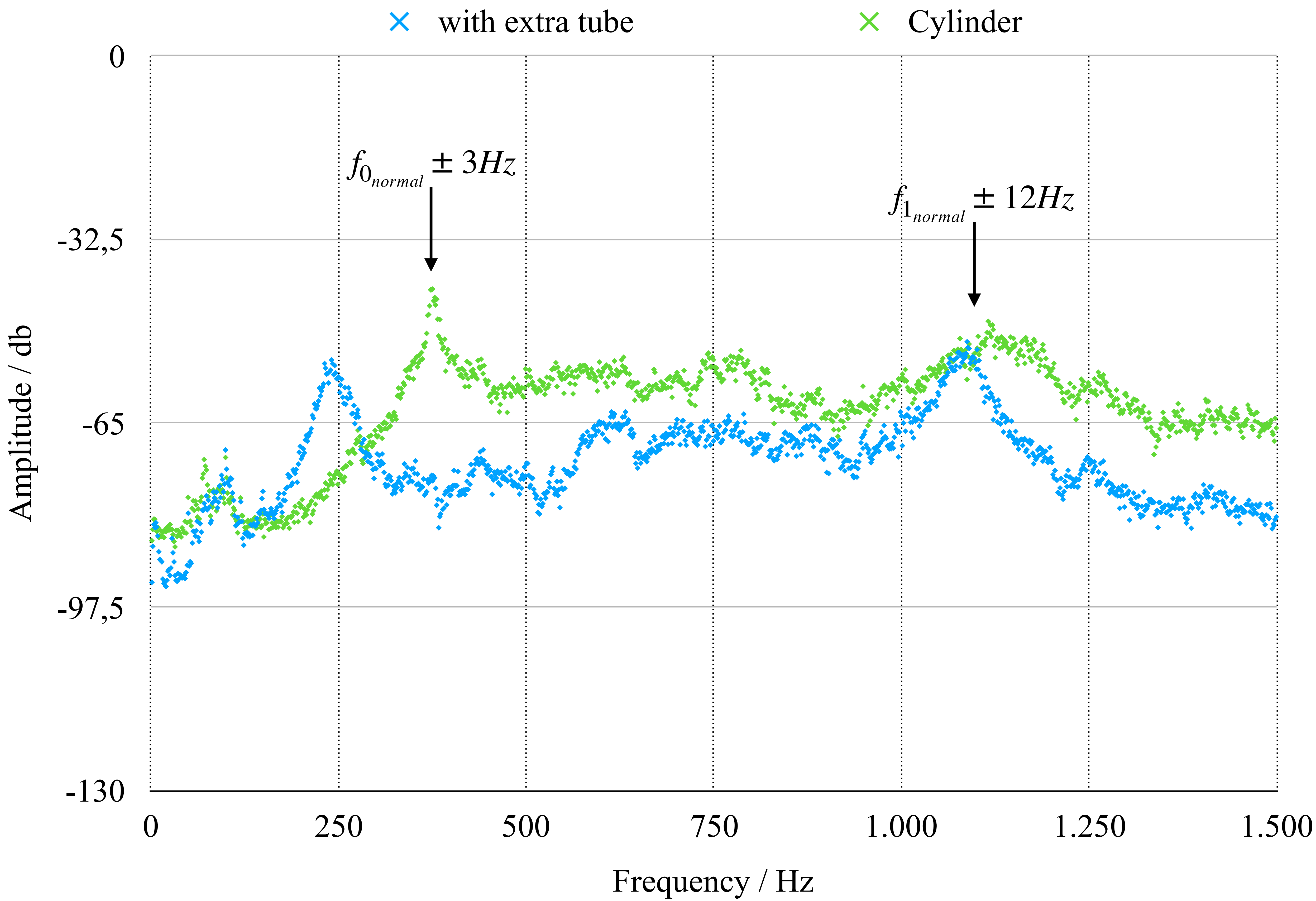
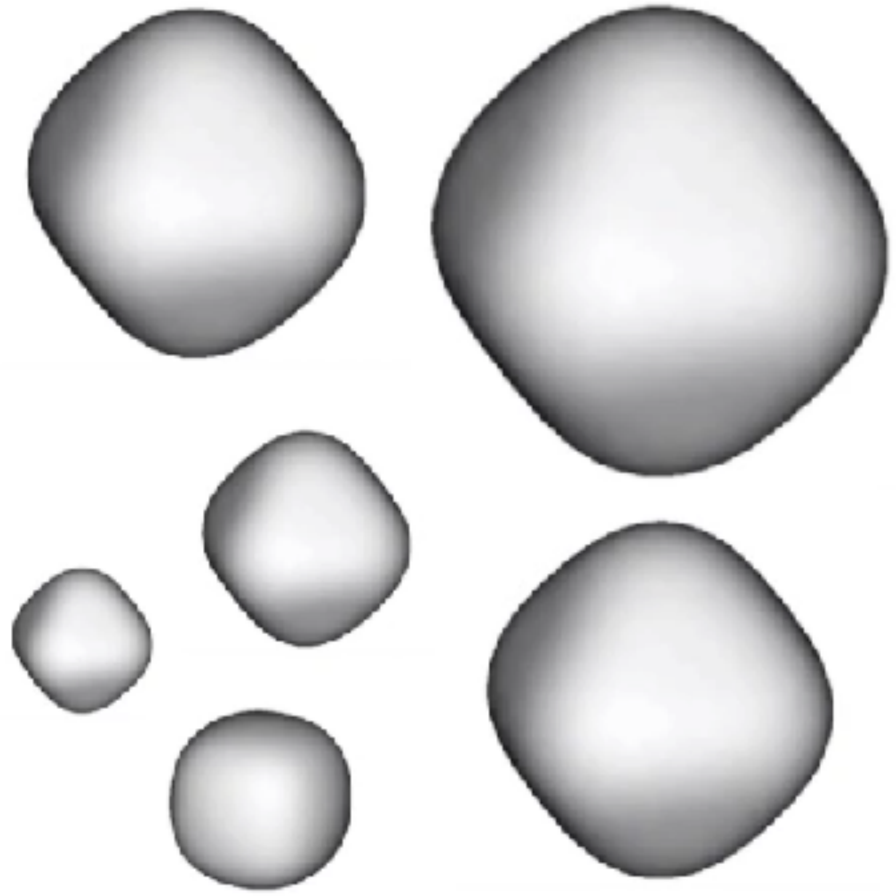
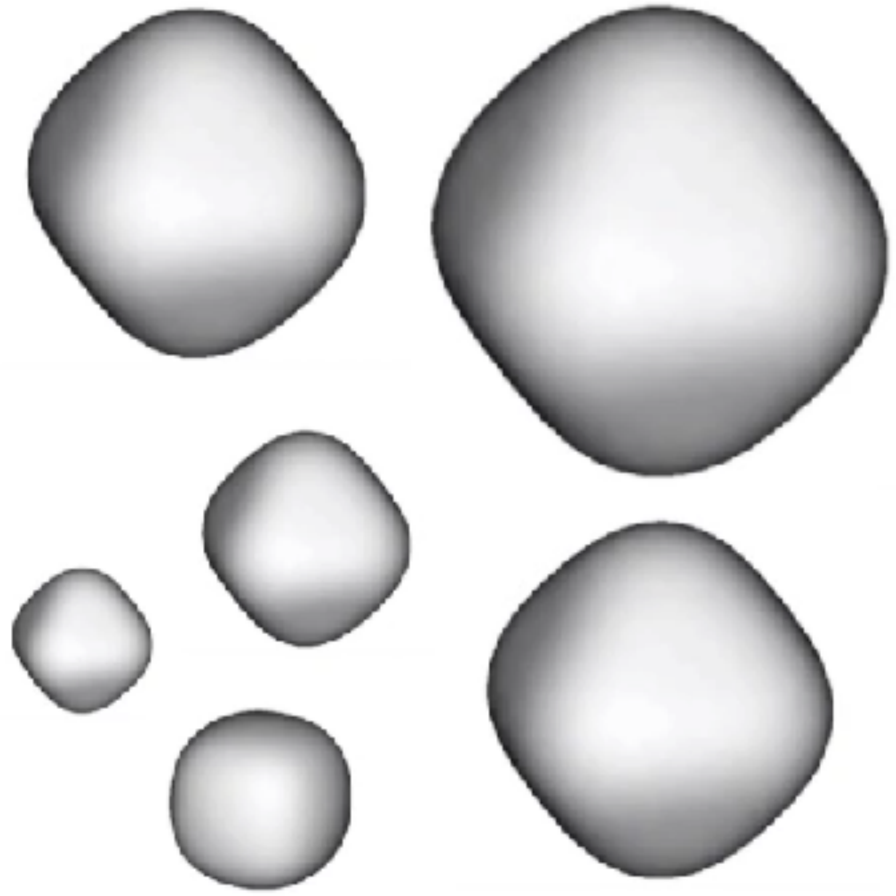



with extra tube
Cylinder
Amplitude / db
0
-32,5
-65
-97,5
-130
0
250
500
750
1.000
1.250
1.500
Frequency / Hz

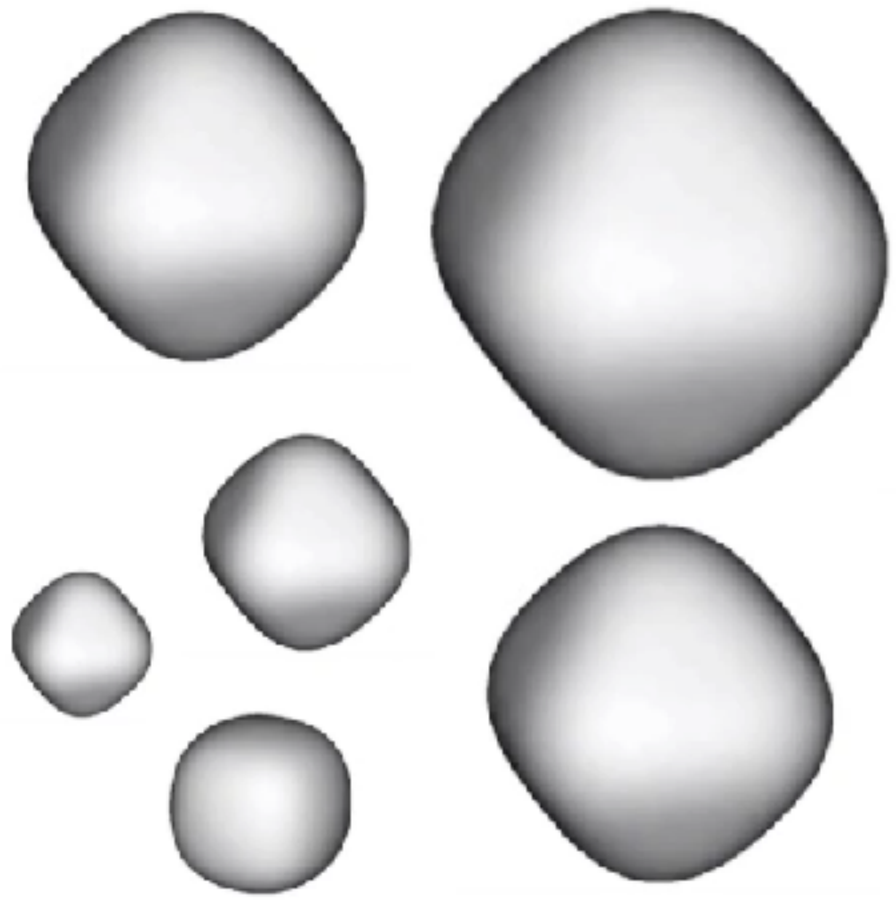

with extra tube
Cylinder
0
-32,5
-65
-97,5
-130
$f_{0_{normal}} \pm 3Hz$
$f_{1_{normal}} \pm 12Hz$
Amplitude / db
0
250
500
750
1.000
1.250
1.500
Frequency / Hz



Conclusion

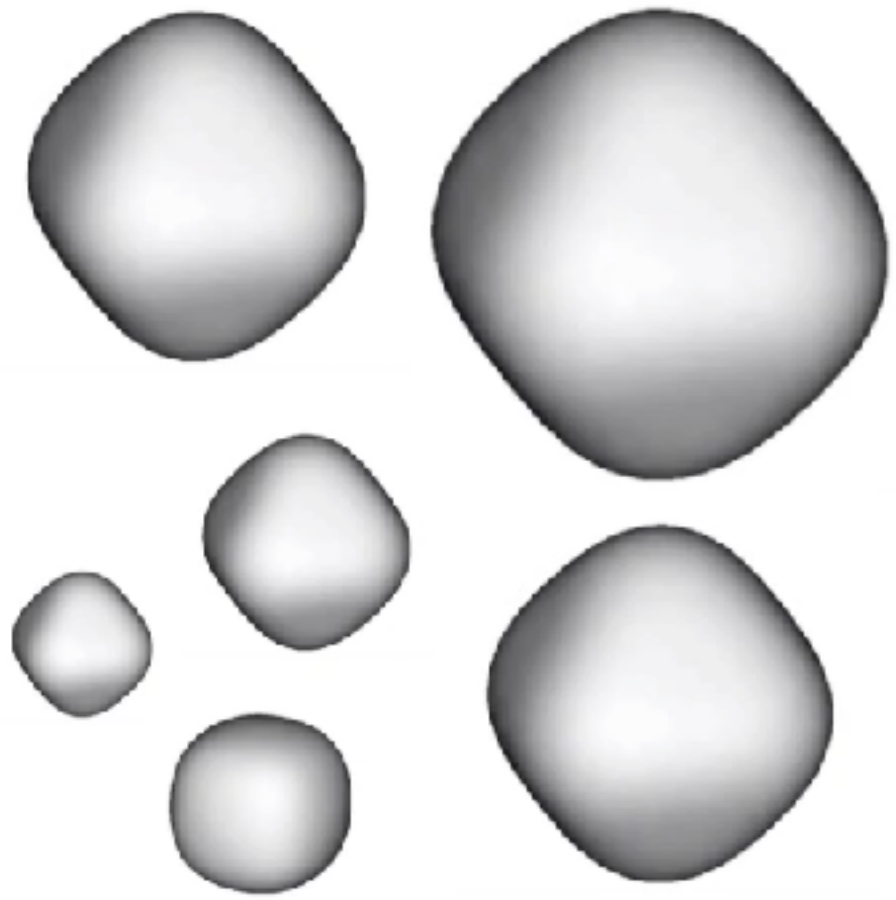


Conclusion



Bubbles with different radii oscillate with different frequencies

Conclusion

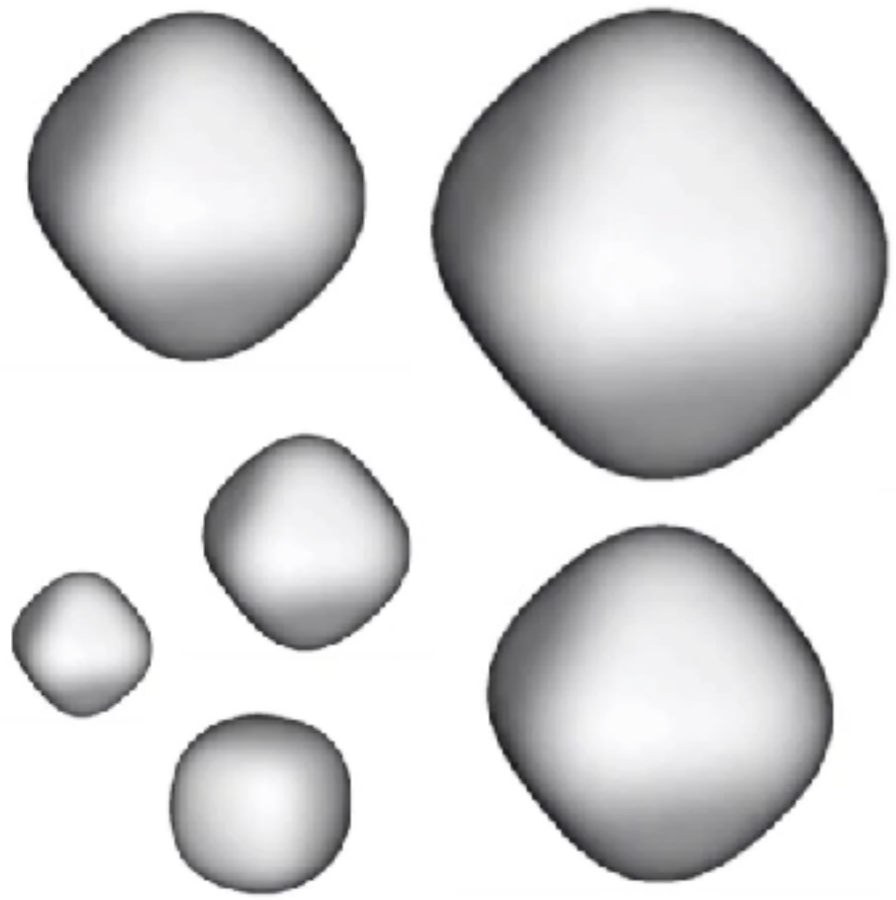


Conclusion

Bubbles with different radii oscillate with different frequencies

Larger bubbles oscillate with lower frequencies, which are louder

Conclusion



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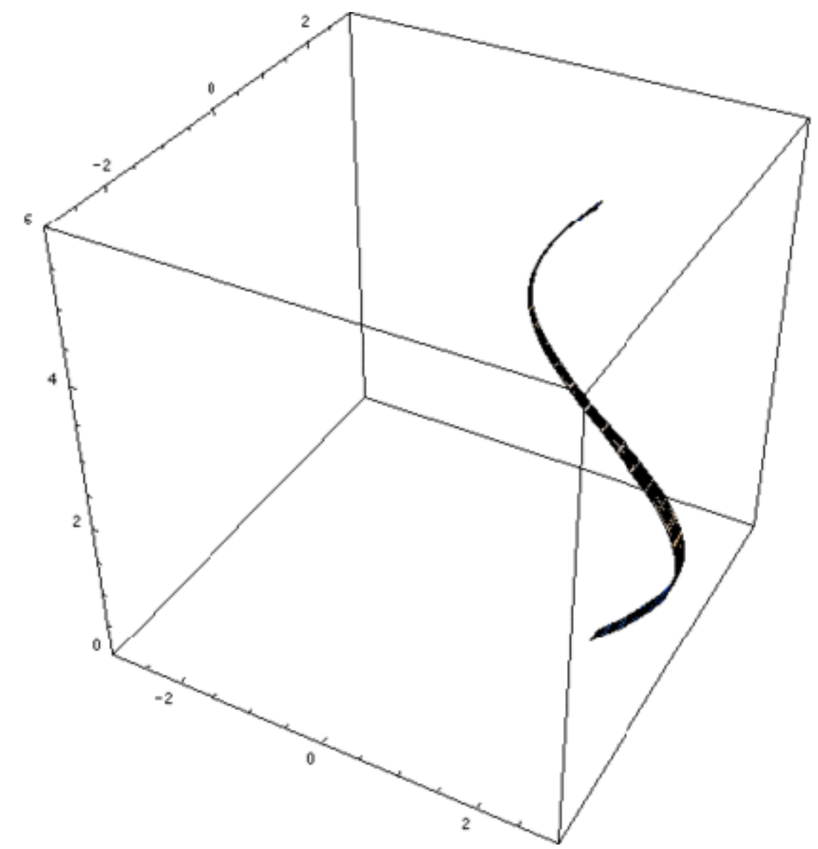
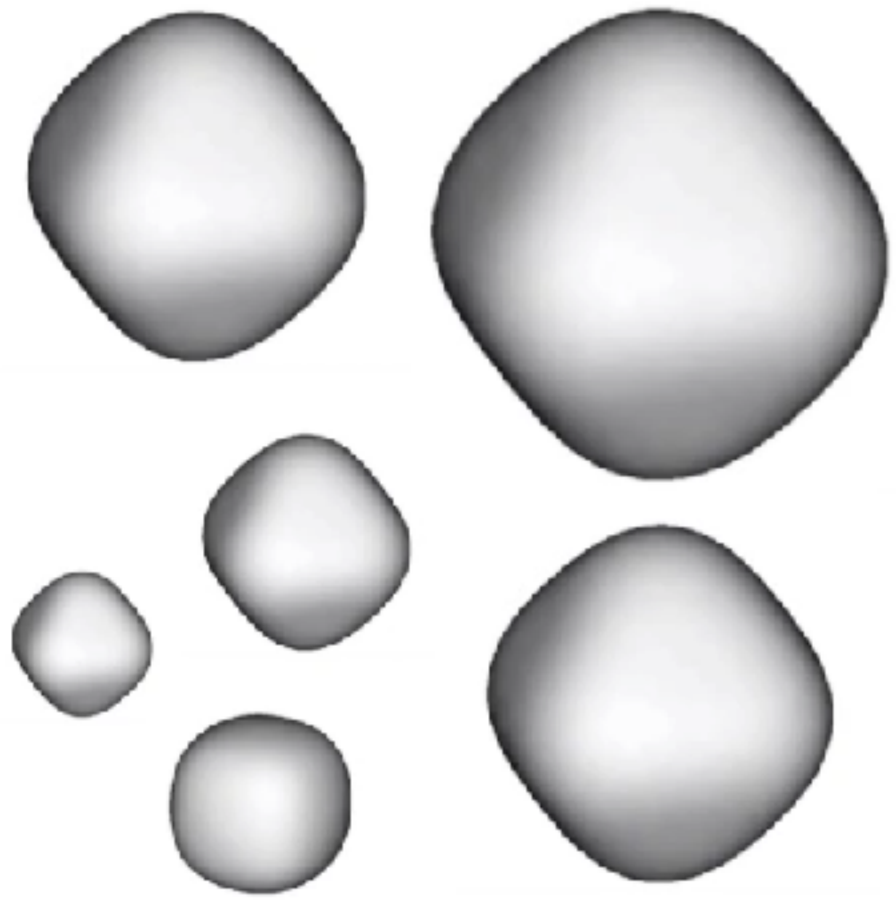
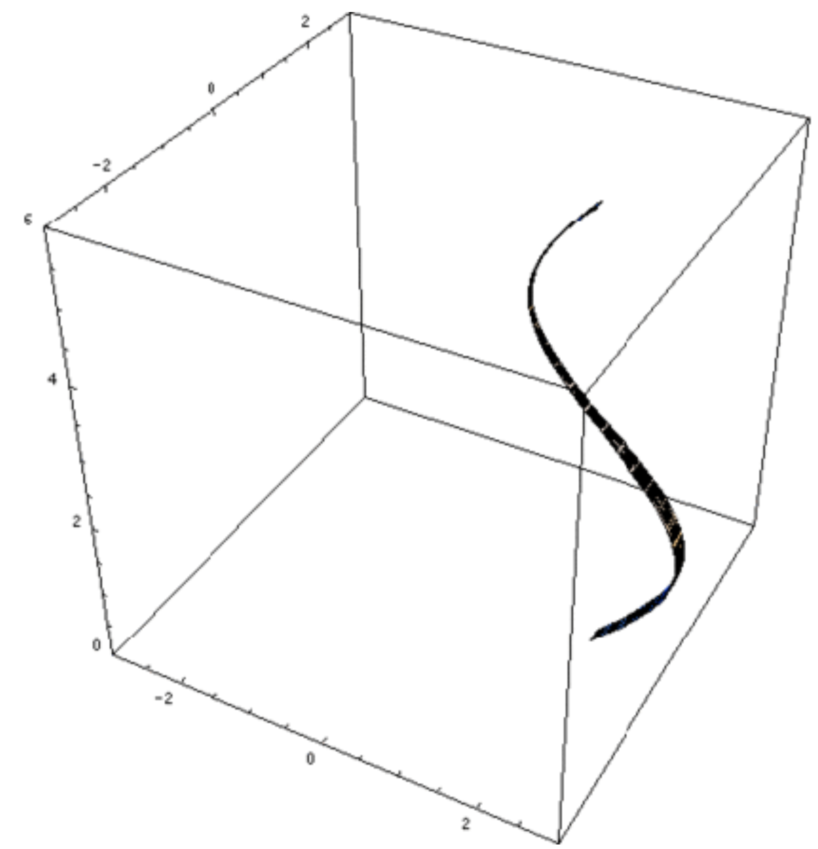




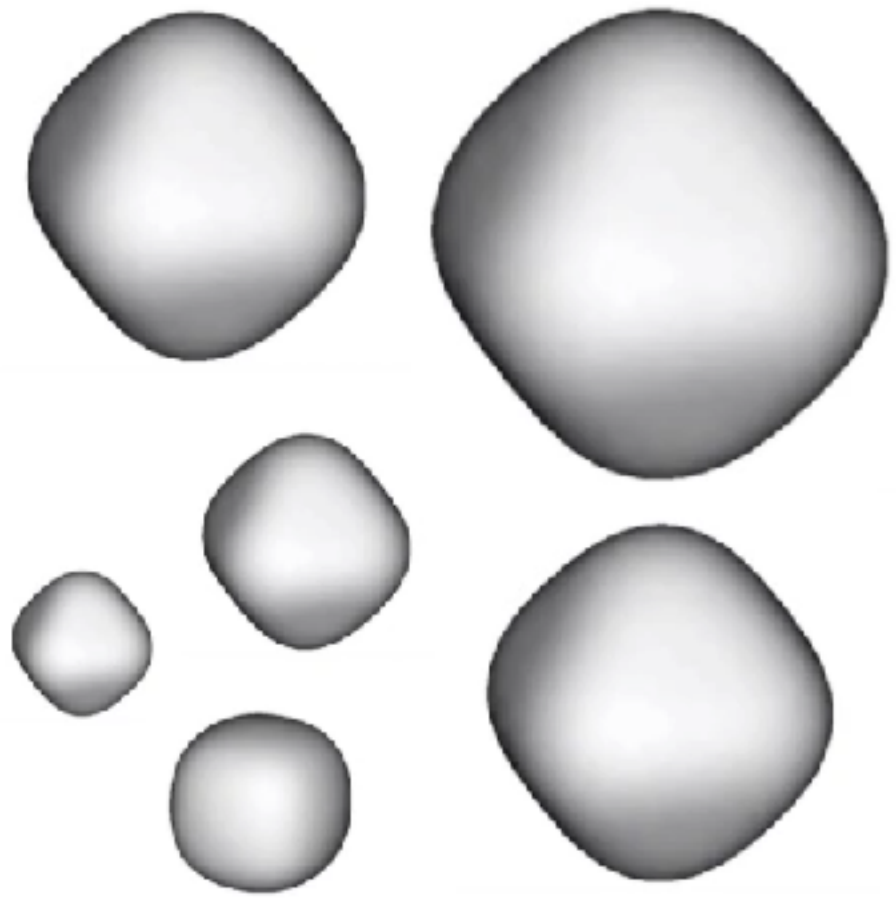
Conclusion



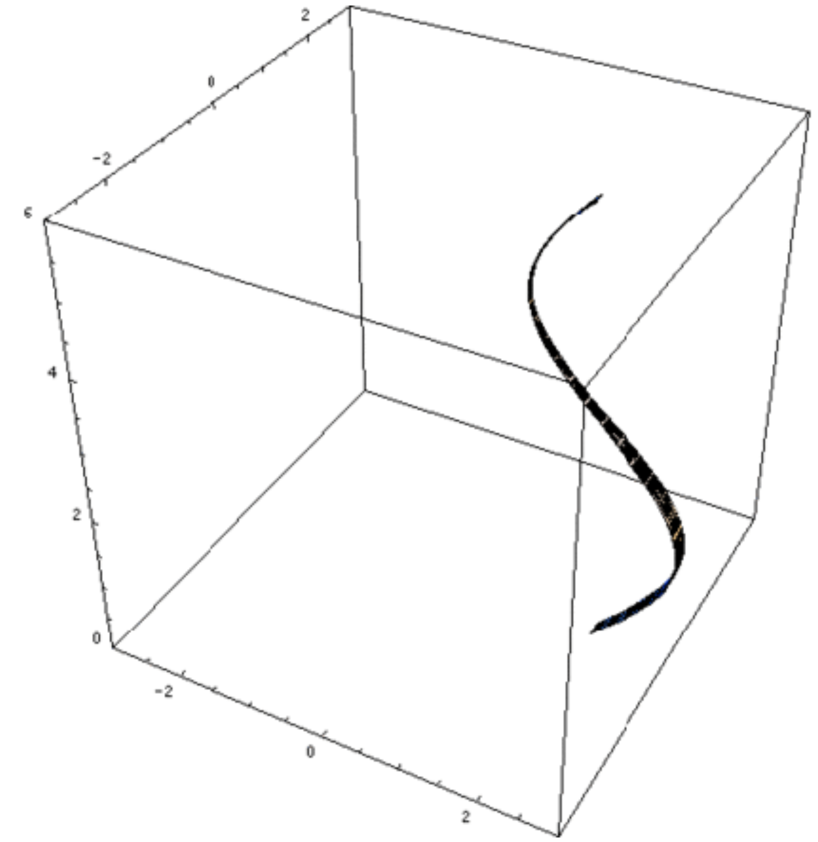
Bubbles with different radii oscillate with different frequencies

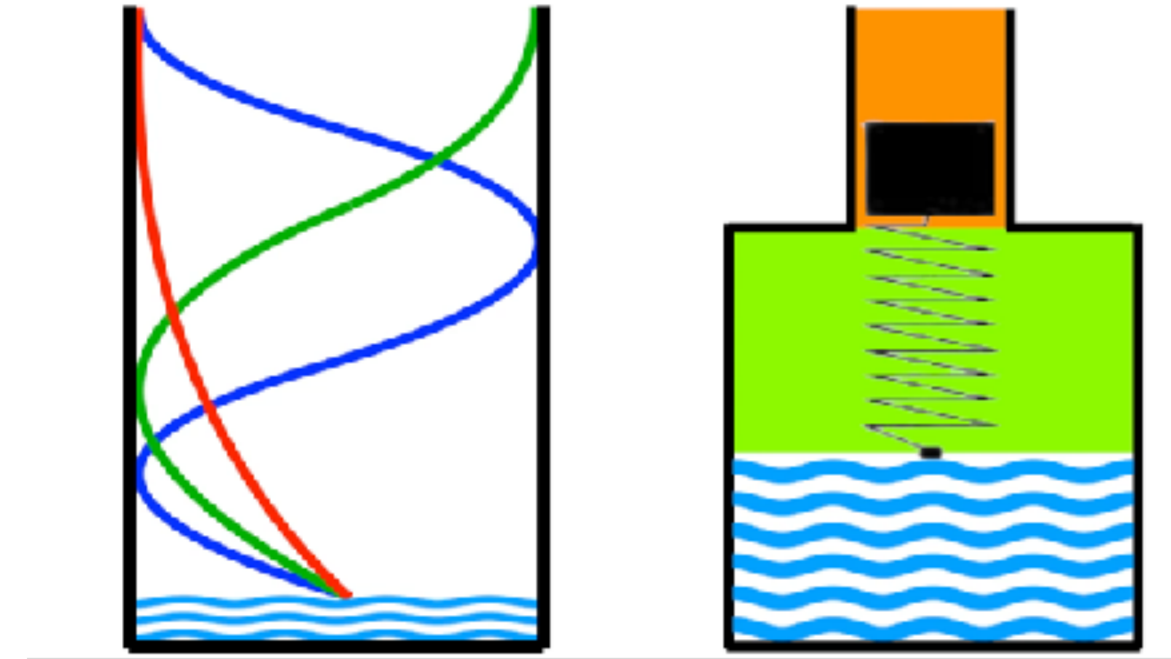
Larger bubbles oscillate with lower frequencies, which are louder

For every bottle a prediction for the cavity at any given moment can be calculated by the shape of the bottle



Conclusion





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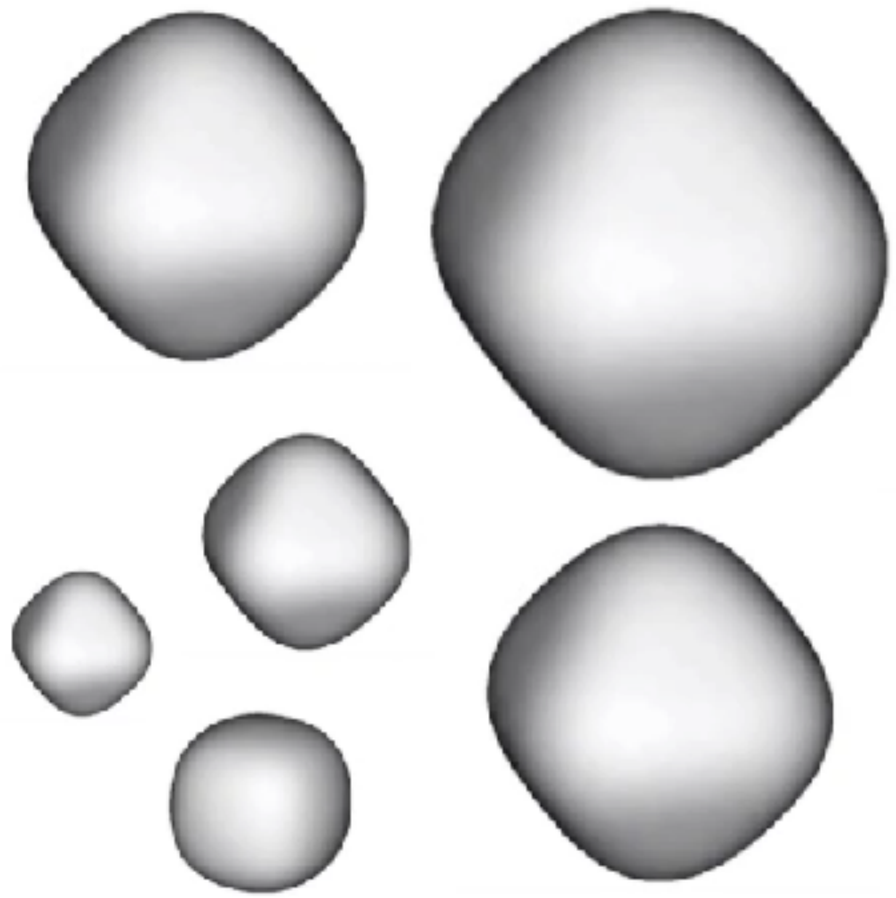

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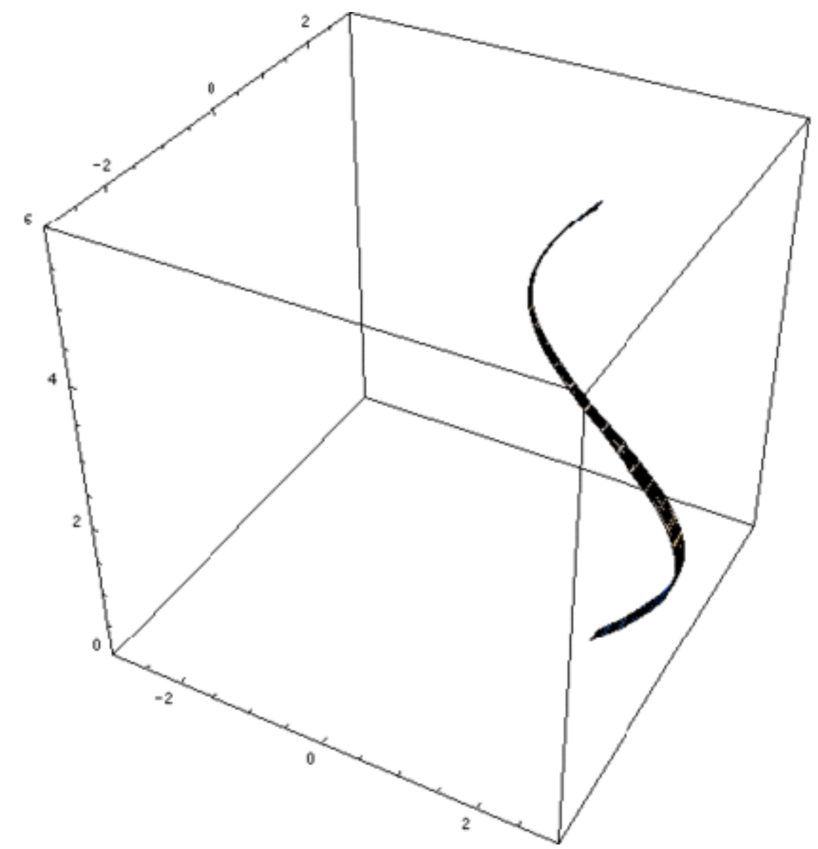

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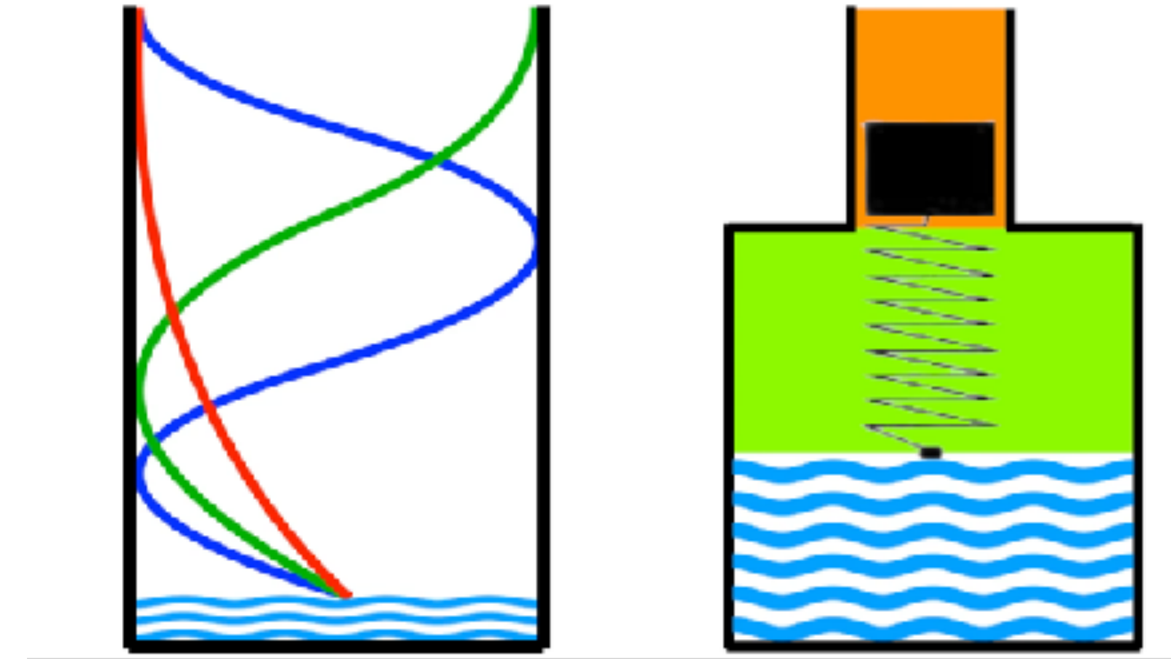
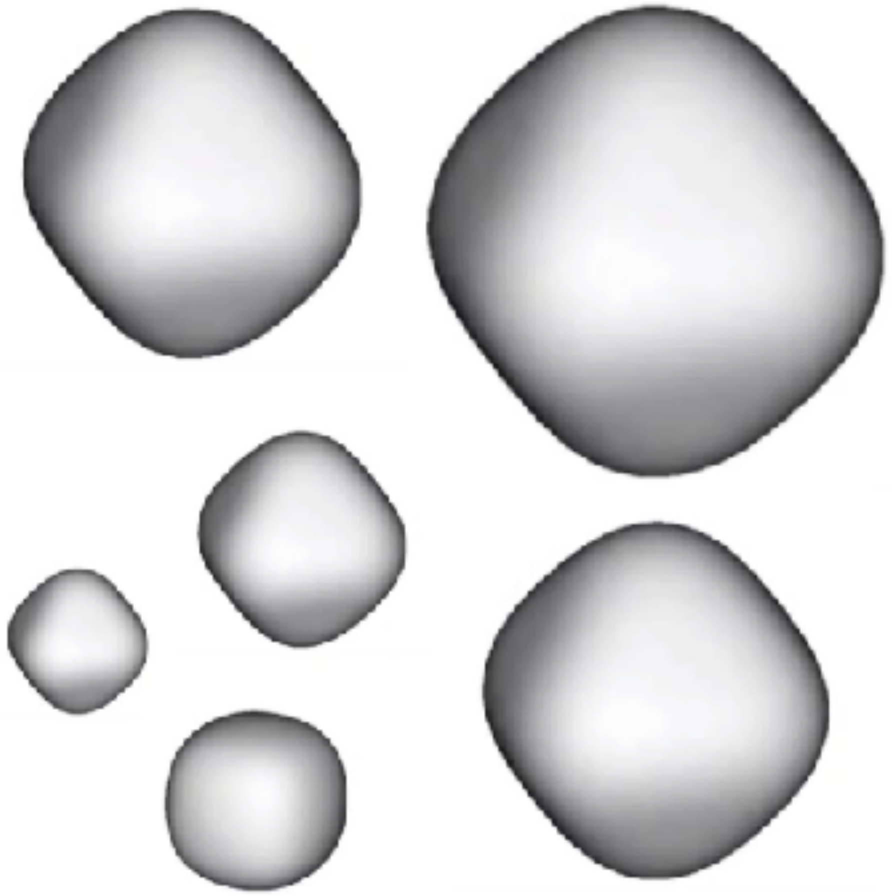


Standing waves inside the cavity amplify certain frequencies

Conclusion



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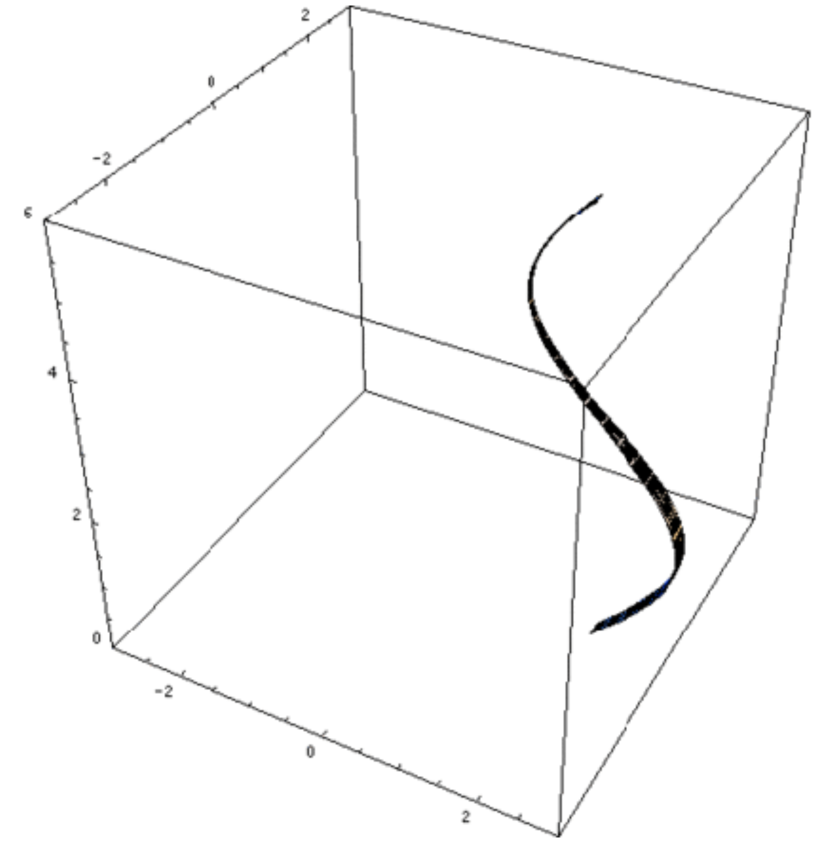

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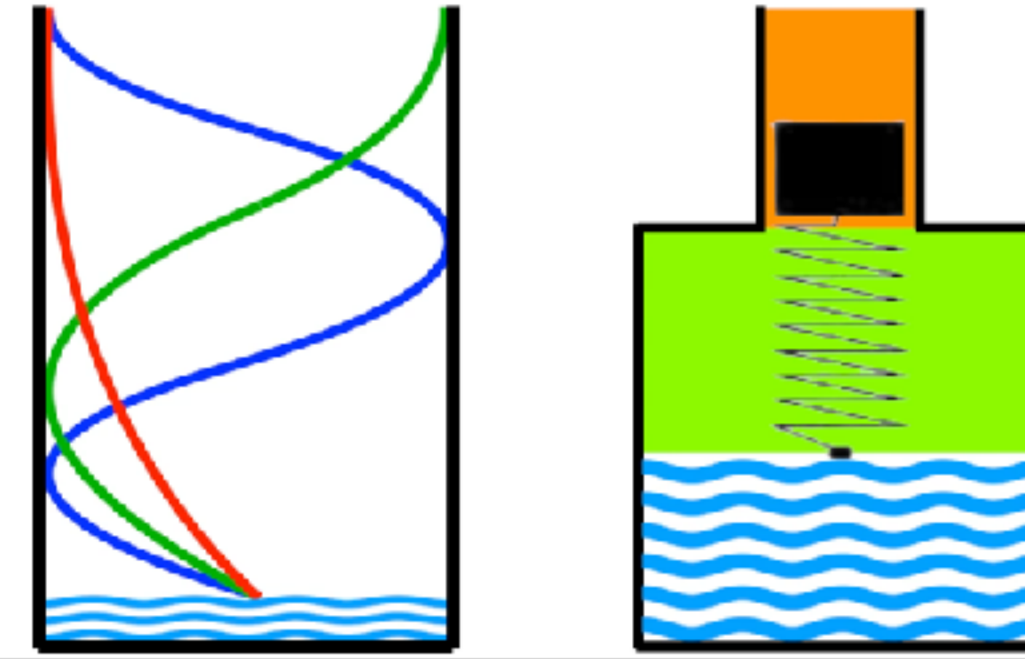

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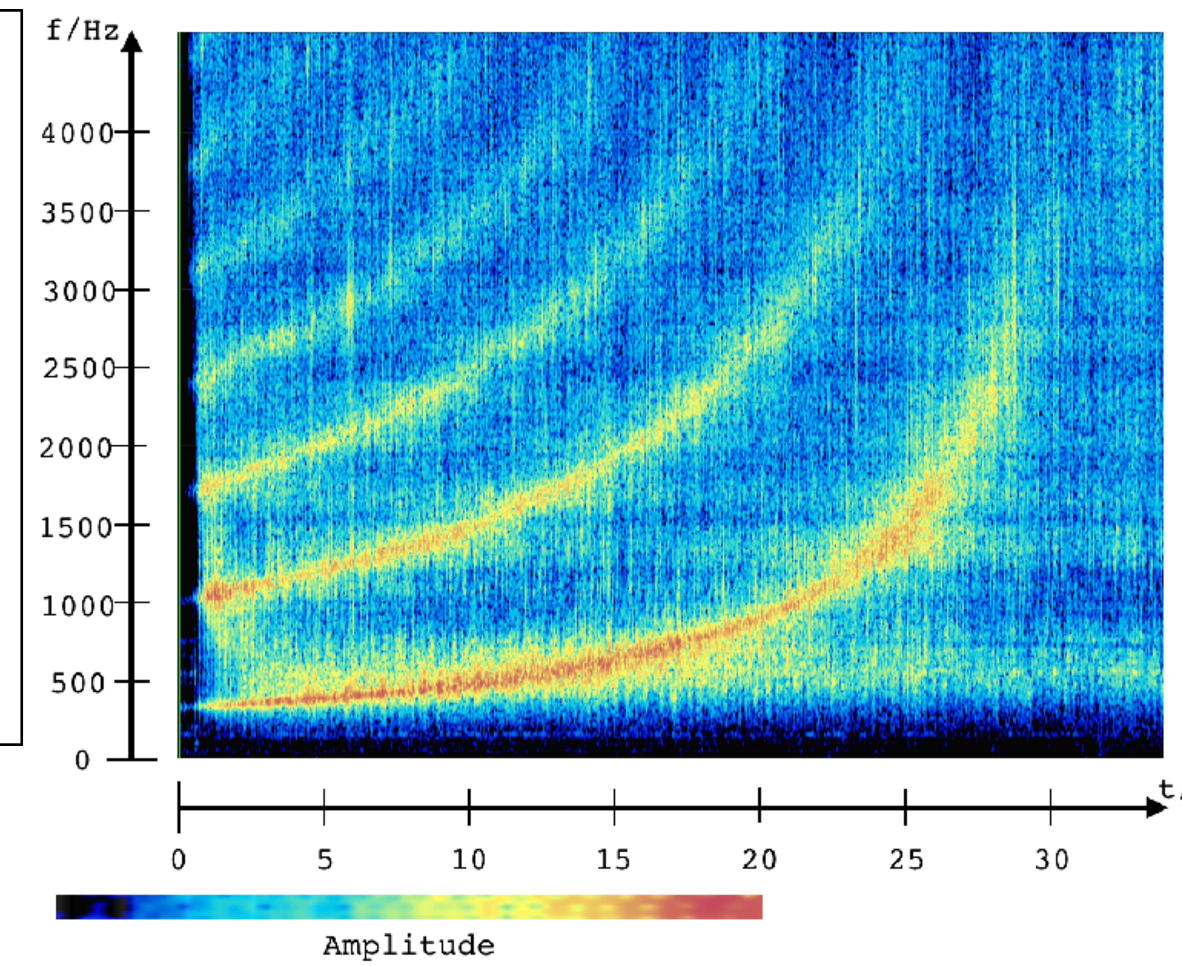

Thank you for your attention.

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Yves Brechet and Zoltan Neda. On the circular hydraulic jump (1999)

$h_w(t)$

Mass conservation says that the rate of mass accumulated in the tank equals the mass flow rate $\dot{m}_{in}$ into the tank:

$$\frac{dM_{tank}}{dt} = \dot{m}_{in}$$

where the mass in the tank at time t is given by

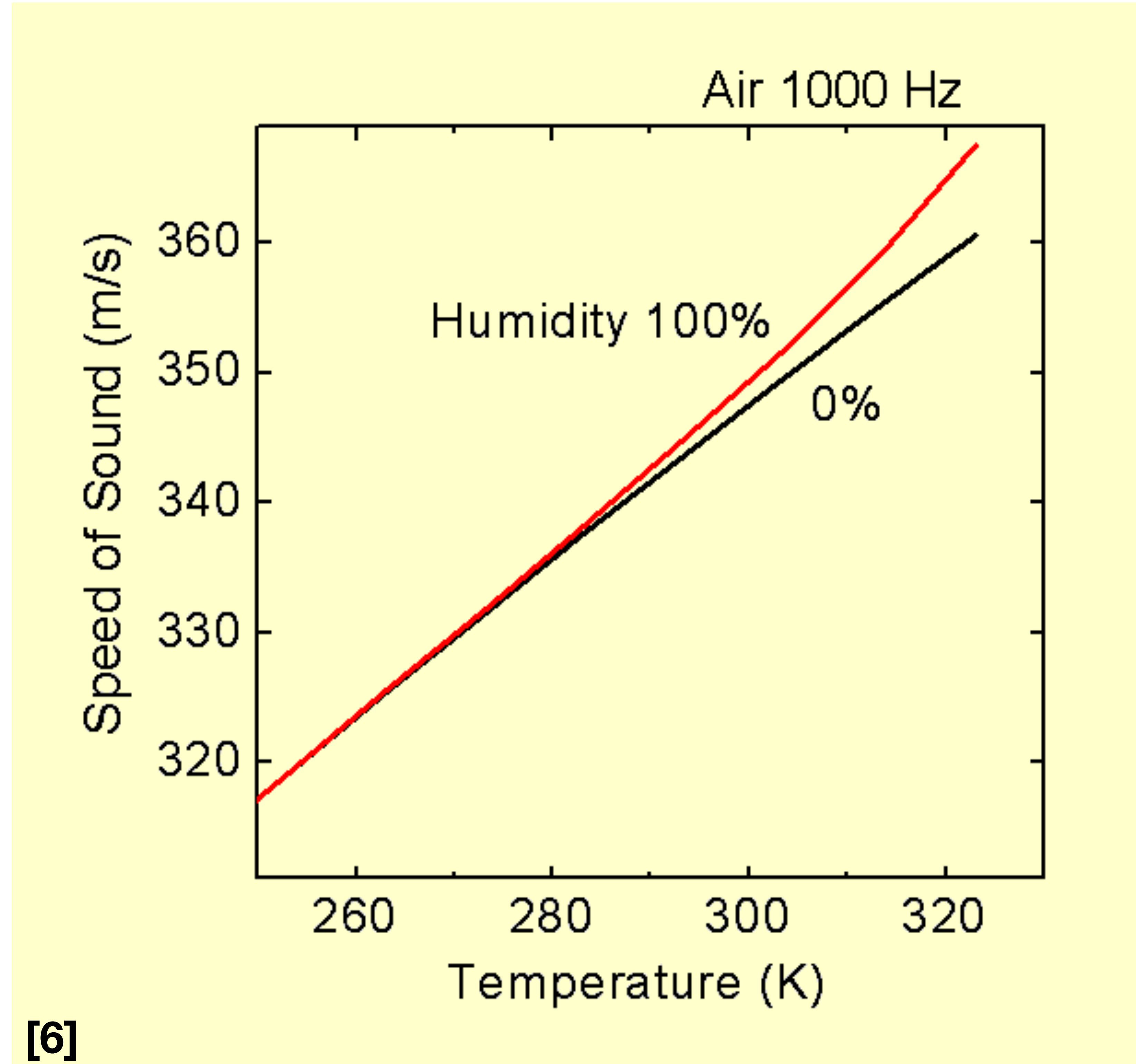
$$M_{tank} = \rho\pi \int_0^{h_w(t)} r^2(z)dz$$

and $r(z)$ is the radius of the solid of tank shape as a function of height z, is the height $h(t)$ of the fluid.

Therefore $h(t)$ and $\frac{dh_w}{dt}$ are calculable by solving

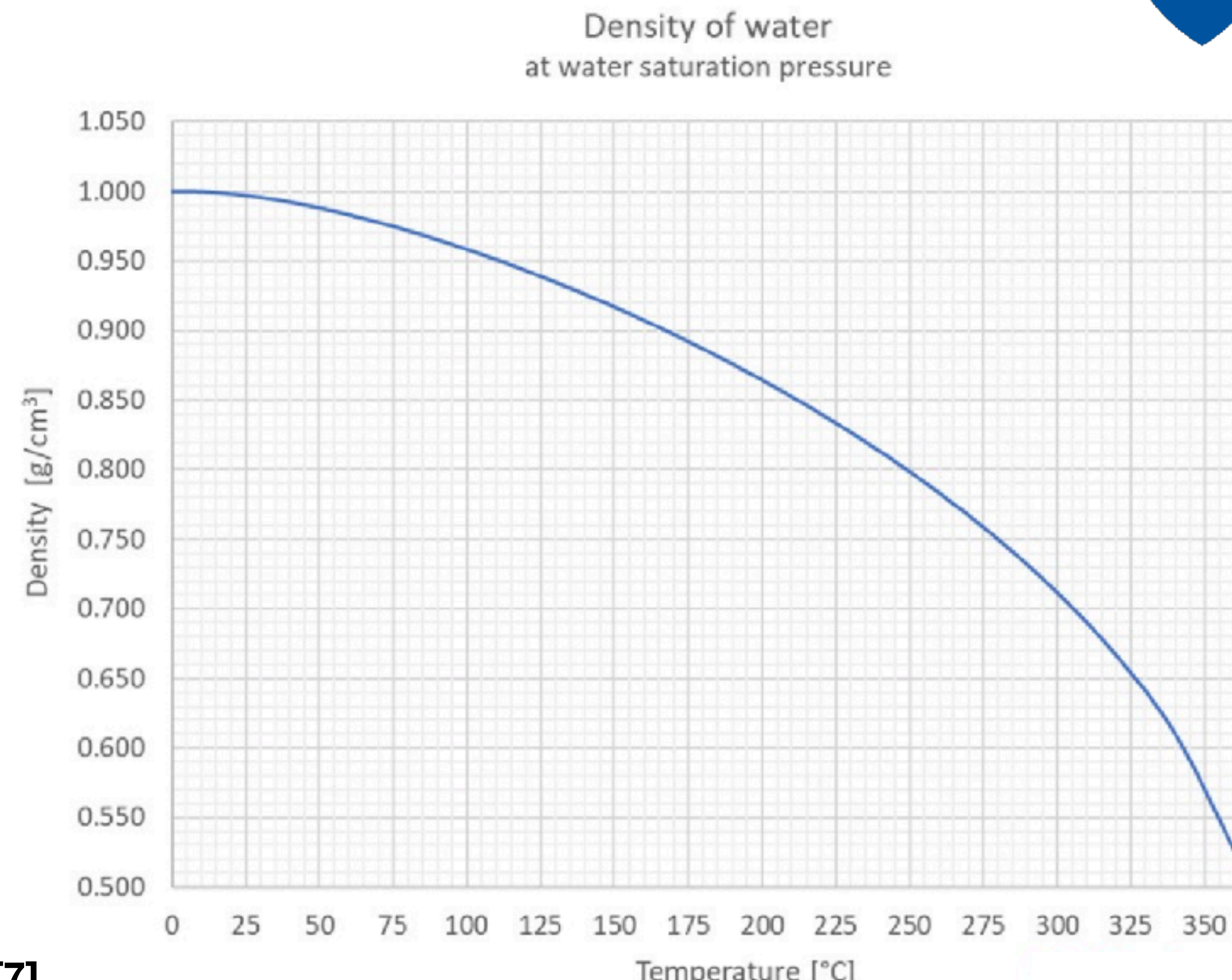
$$\rho\pi \frac{d}{dt} \int_0^{h_w(t)} r^2(z)dz = \dot{m}_{in}$$

Influence of temperature



[6] http://pages.mtu.edu/~suits/SpeedofSound.html

Influence of temperature



[7]

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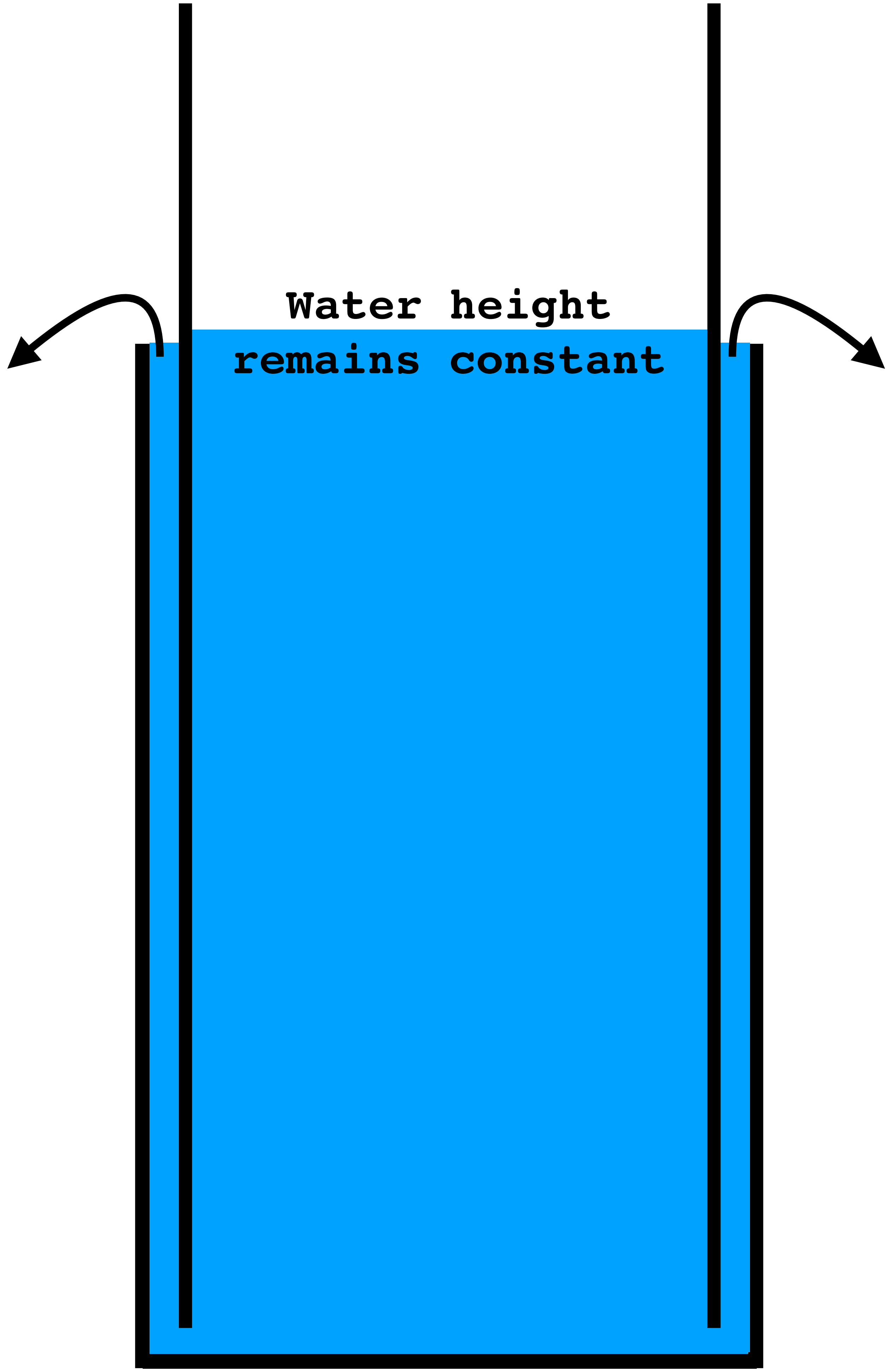
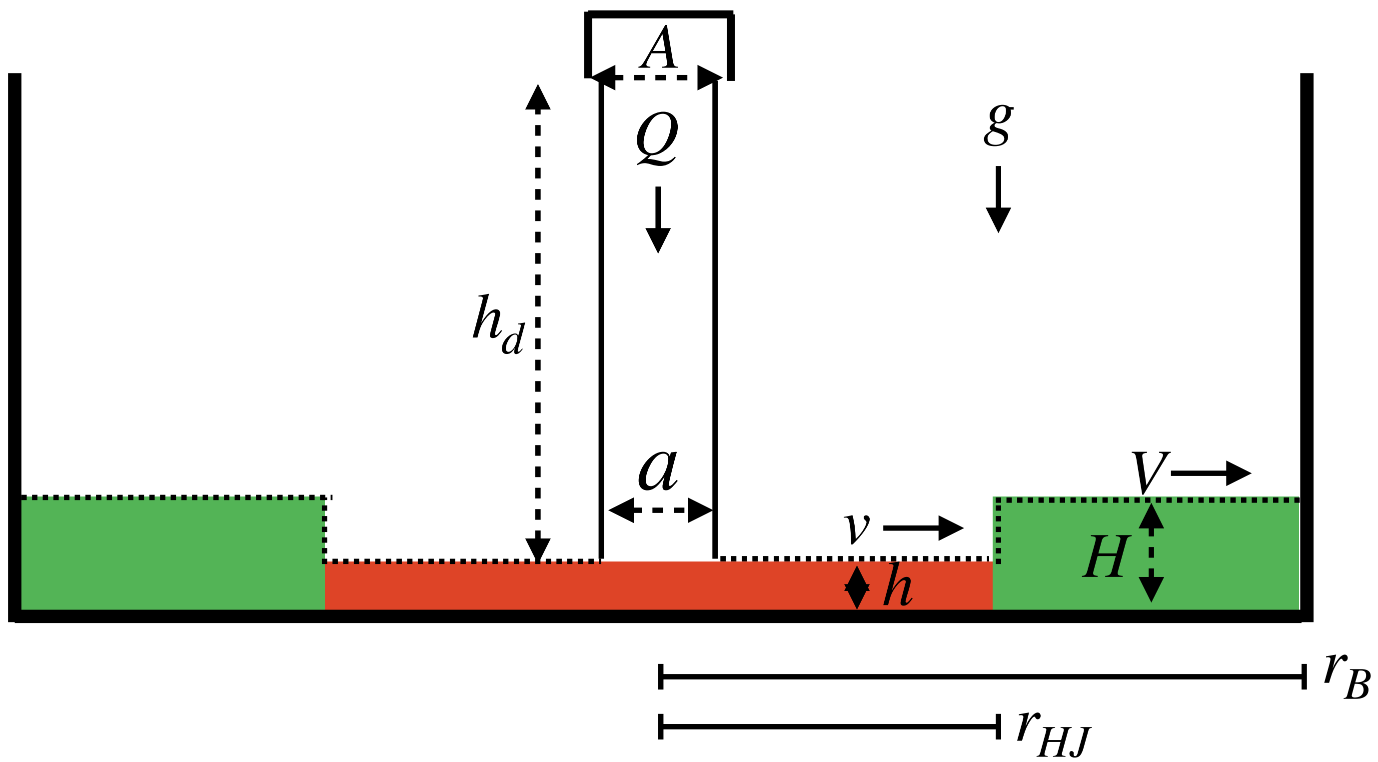
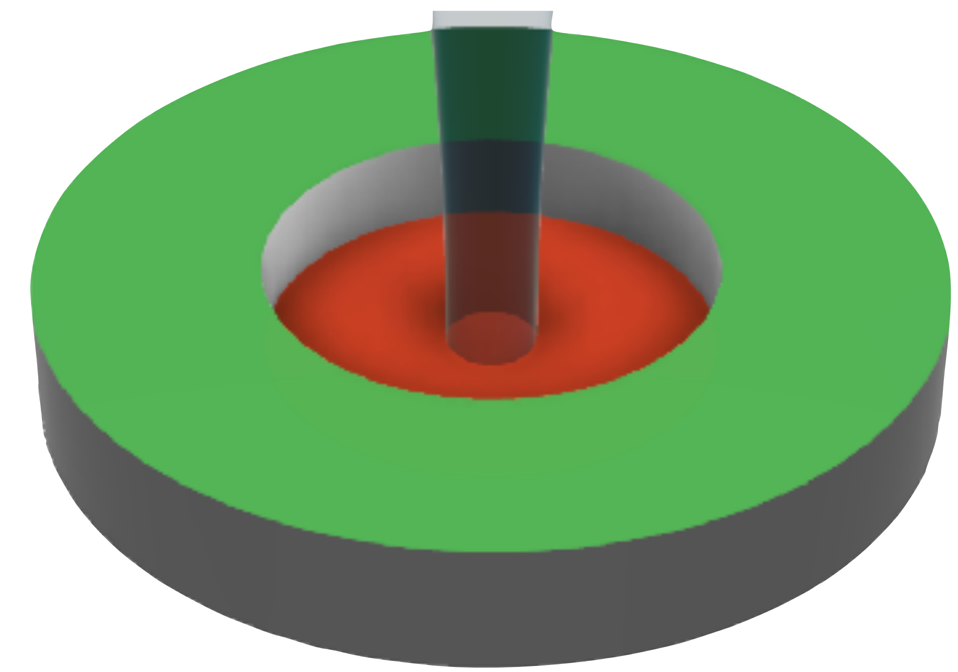

Water height
remains constant

Theoretical Approach

Hydraulic jump





$$r_{HJ} = \frac{4Q^2}{\pi^2 a^2 H^2 g}$$

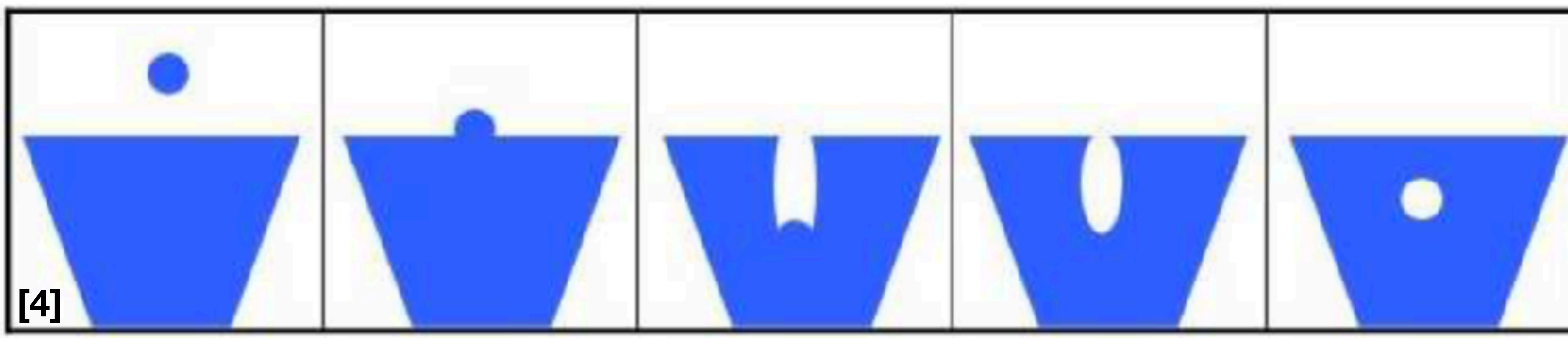
$$Qt = H \cdot r_b^2 - H \cdot r_{HJ}^2 \qquad \text{for h=0}$$

$$H = \frac{Qt}{r_b^2 - r_{HJ}^2}$$

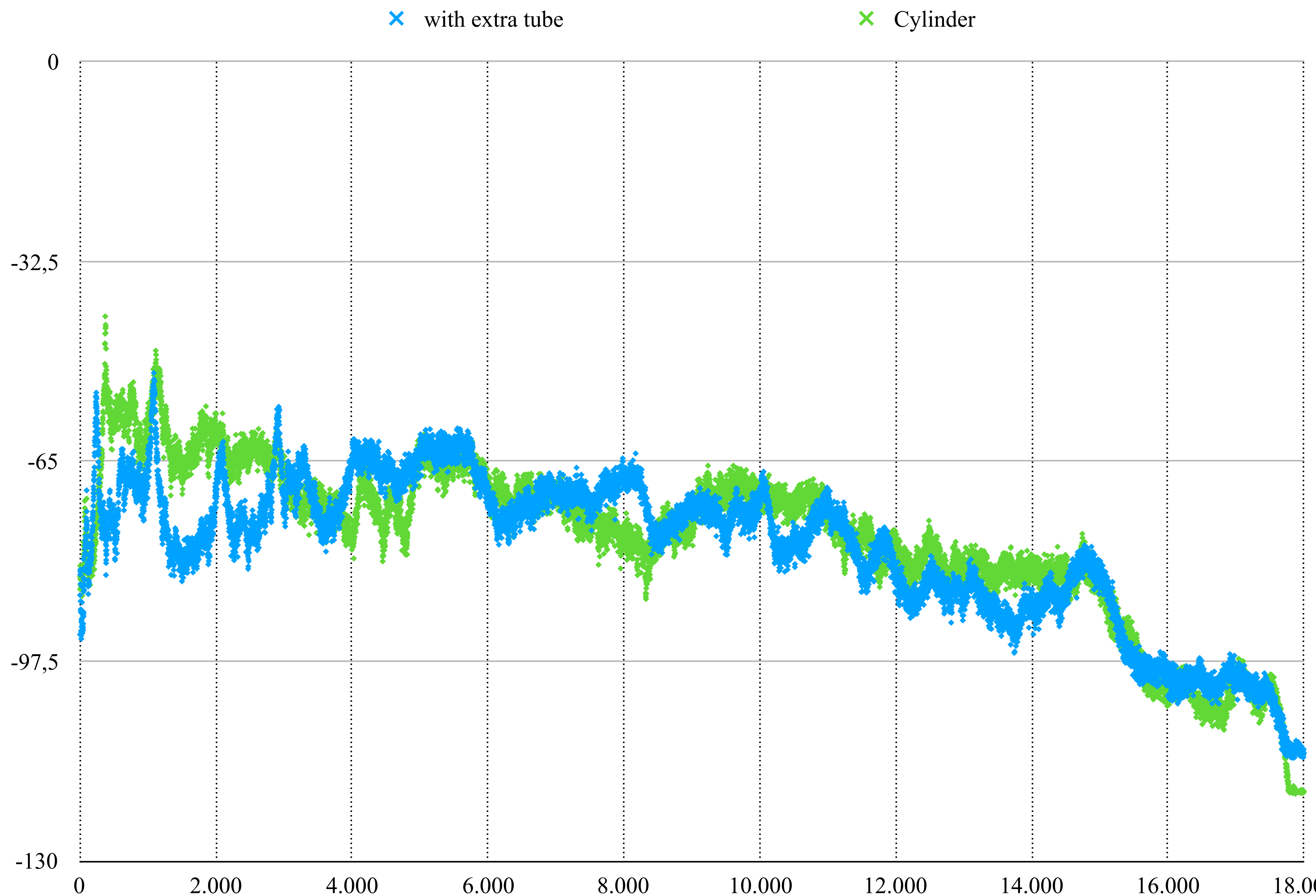
$$r_{HJ} = \frac{4r_b^4 - r_{HJ}^4}{\pi^2 a^2 t^2 g} = 0$$

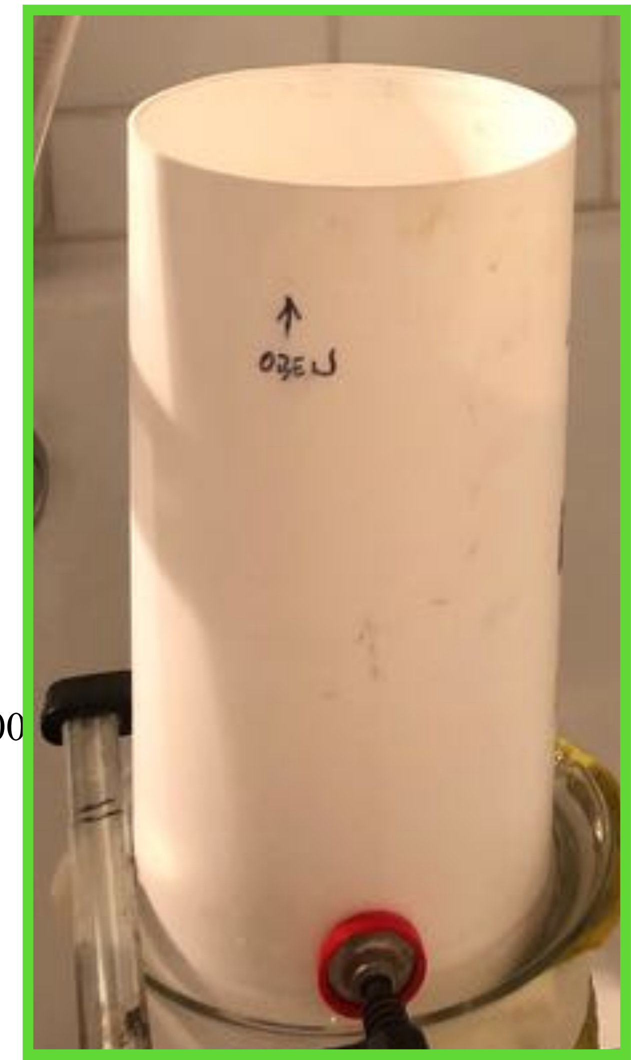
$$\sqrt{\frac{4r_b^4}{\pi^2 a^2 g}} = t = \frac{2r_b^2}{\pi a \sqrt{g}}$$

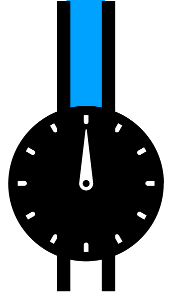
$$a = \frac{\pi^2 g h_d}{8Q^2 A^4}^{-\frac{1}{4}}$$



[4] Doel, Kees van den. "Physically based models for liquid sounds." (2004)
https://smartech.gatech.edu/bitstream/handle/1853/50904/vandenDoel2 004.pdf

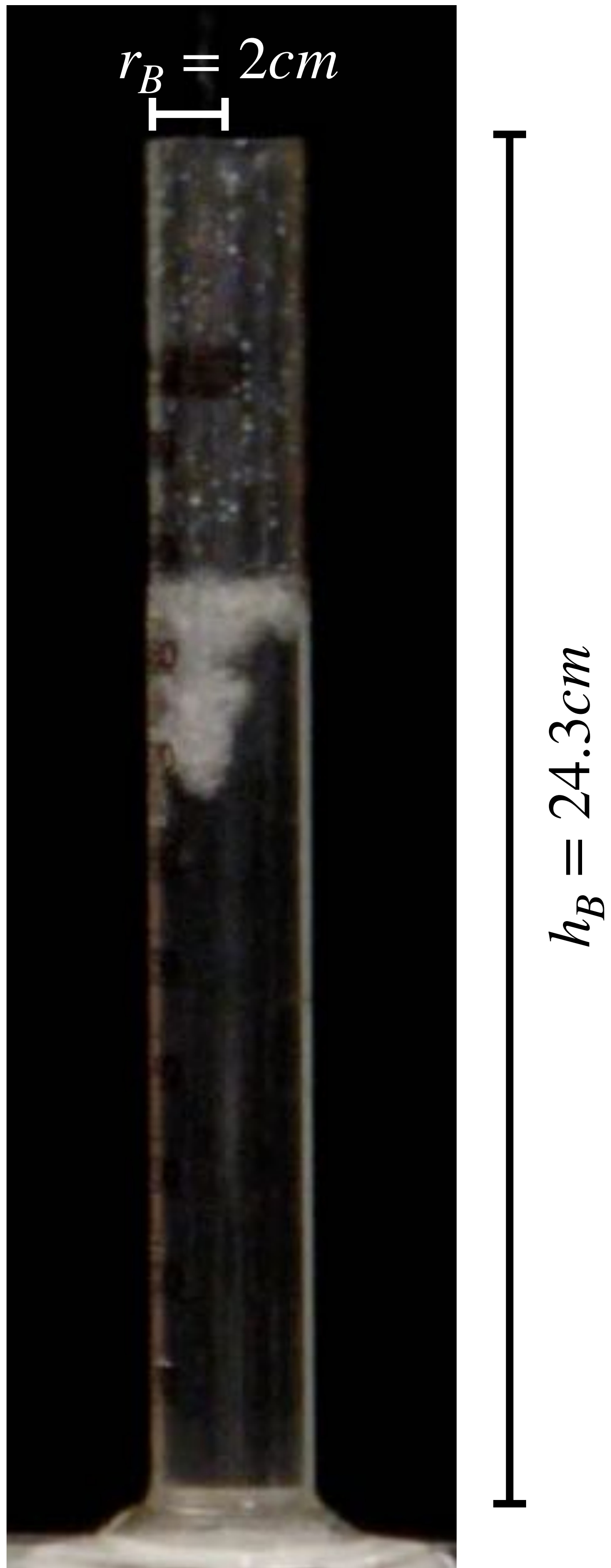

with extra tube
Cylinder
0
-32,5
-65
-97,5
-130
0
2.000
4.000
6.000
8.000
10.000
12.000
14.000
16.000
18.00

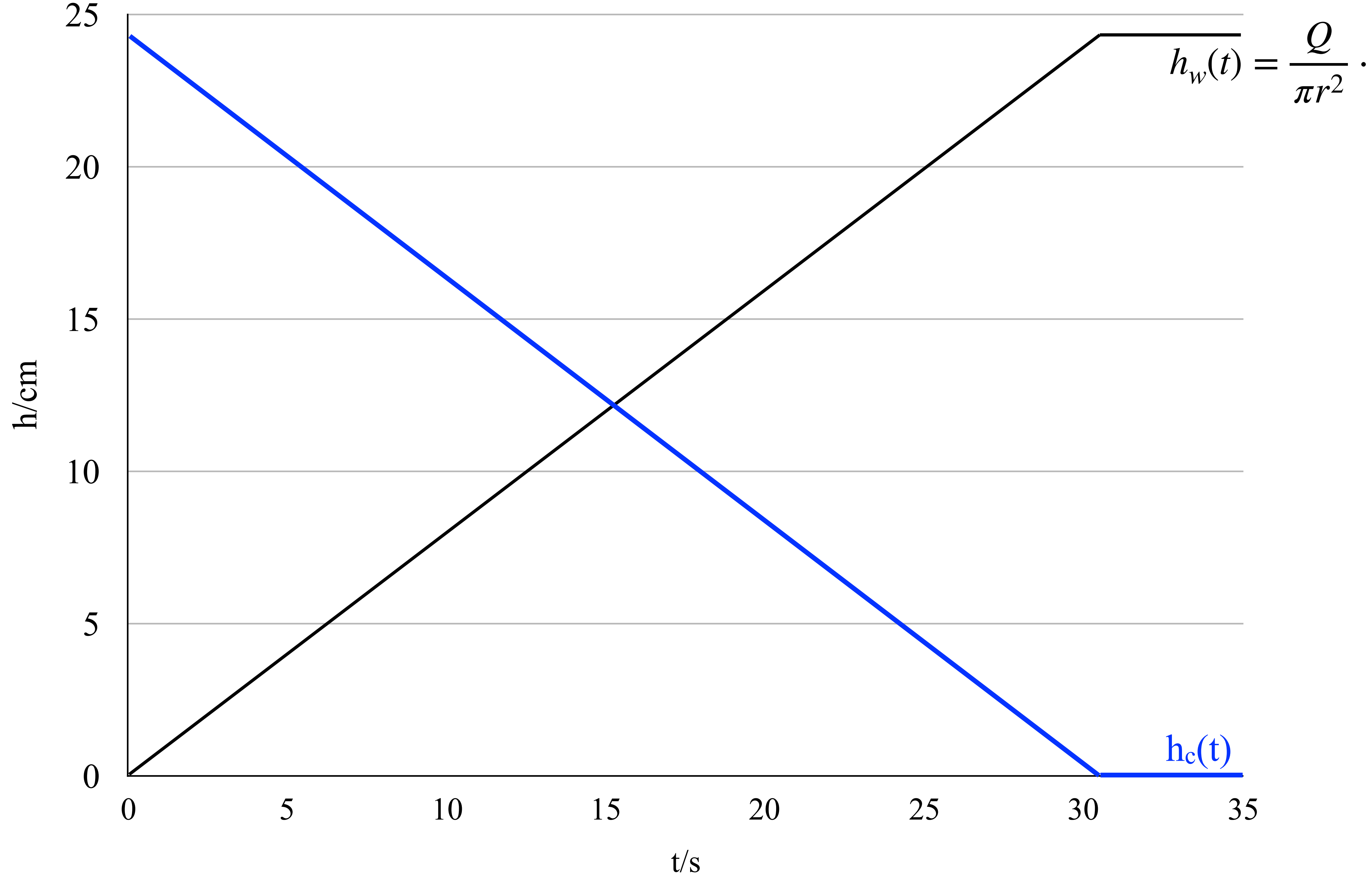


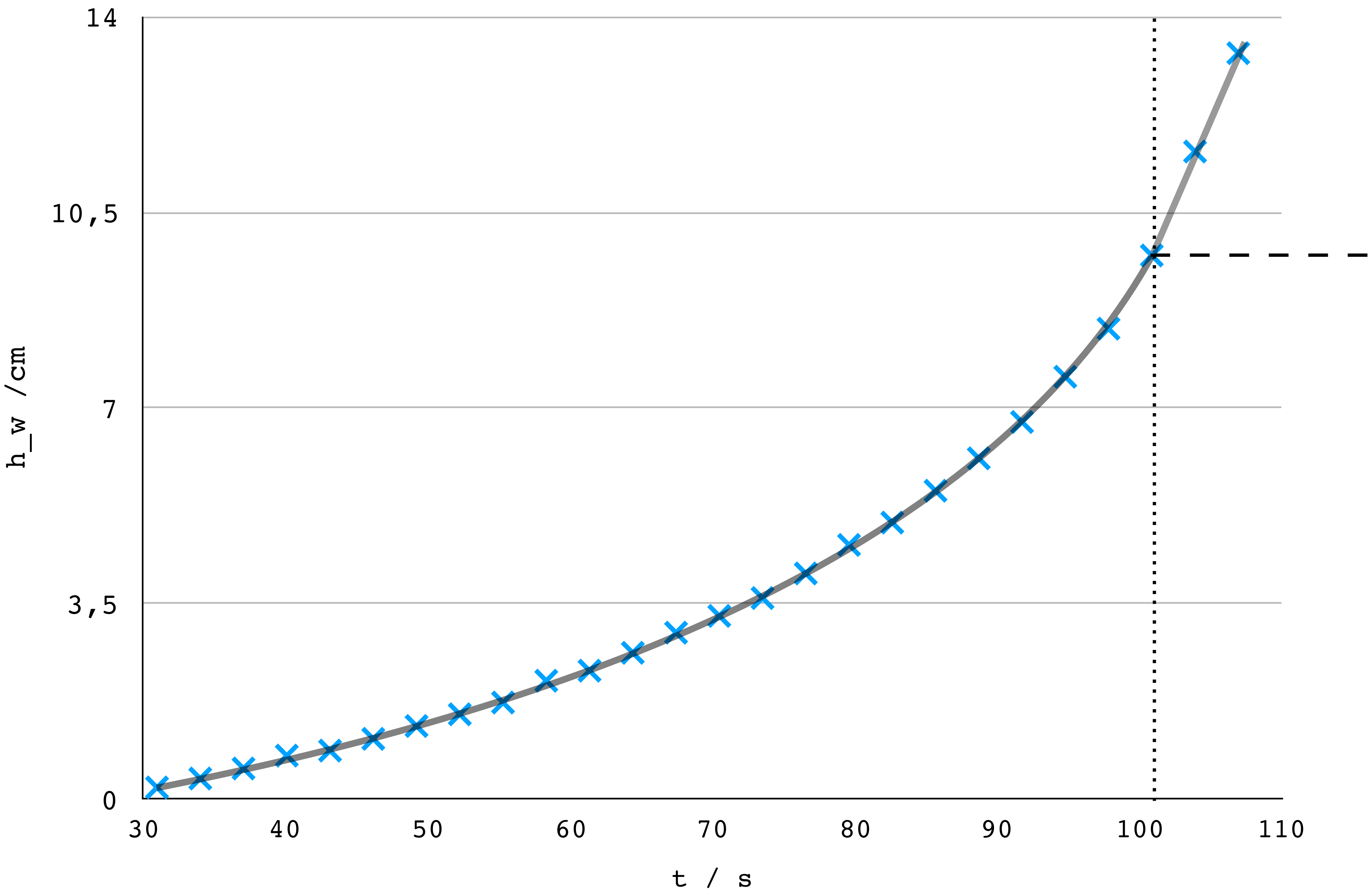


$Q = 10^{-5}\frac{m^3}{s}$

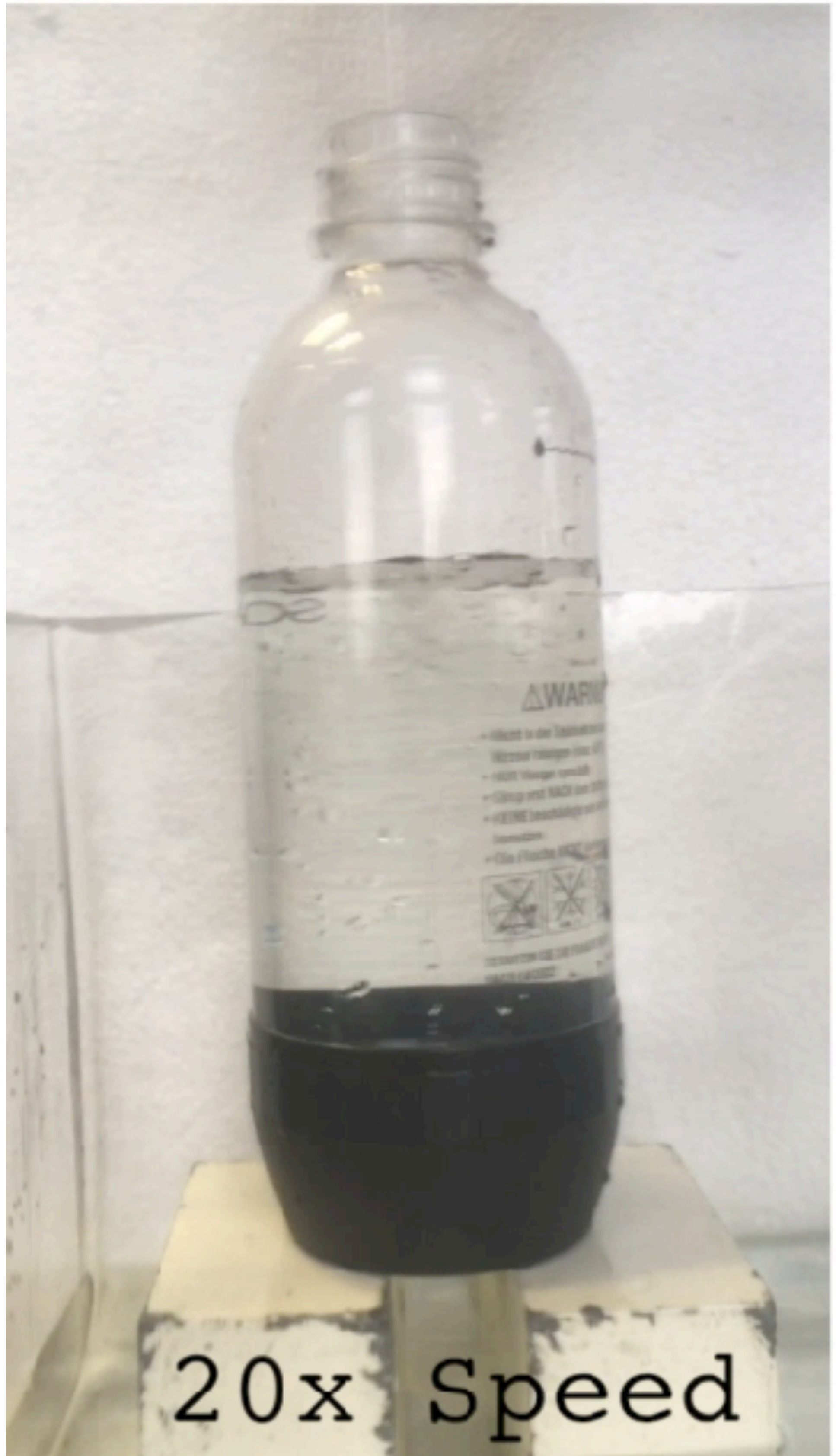
$V = \pi r_B^2 \cdot h_B = 305 \cdot 10^{-6} m^3$ $\quad t_{full} = \frac{V}{Q} = 30.5s$ $\quad f_0 = \frac{c}{4h_c(t)}$

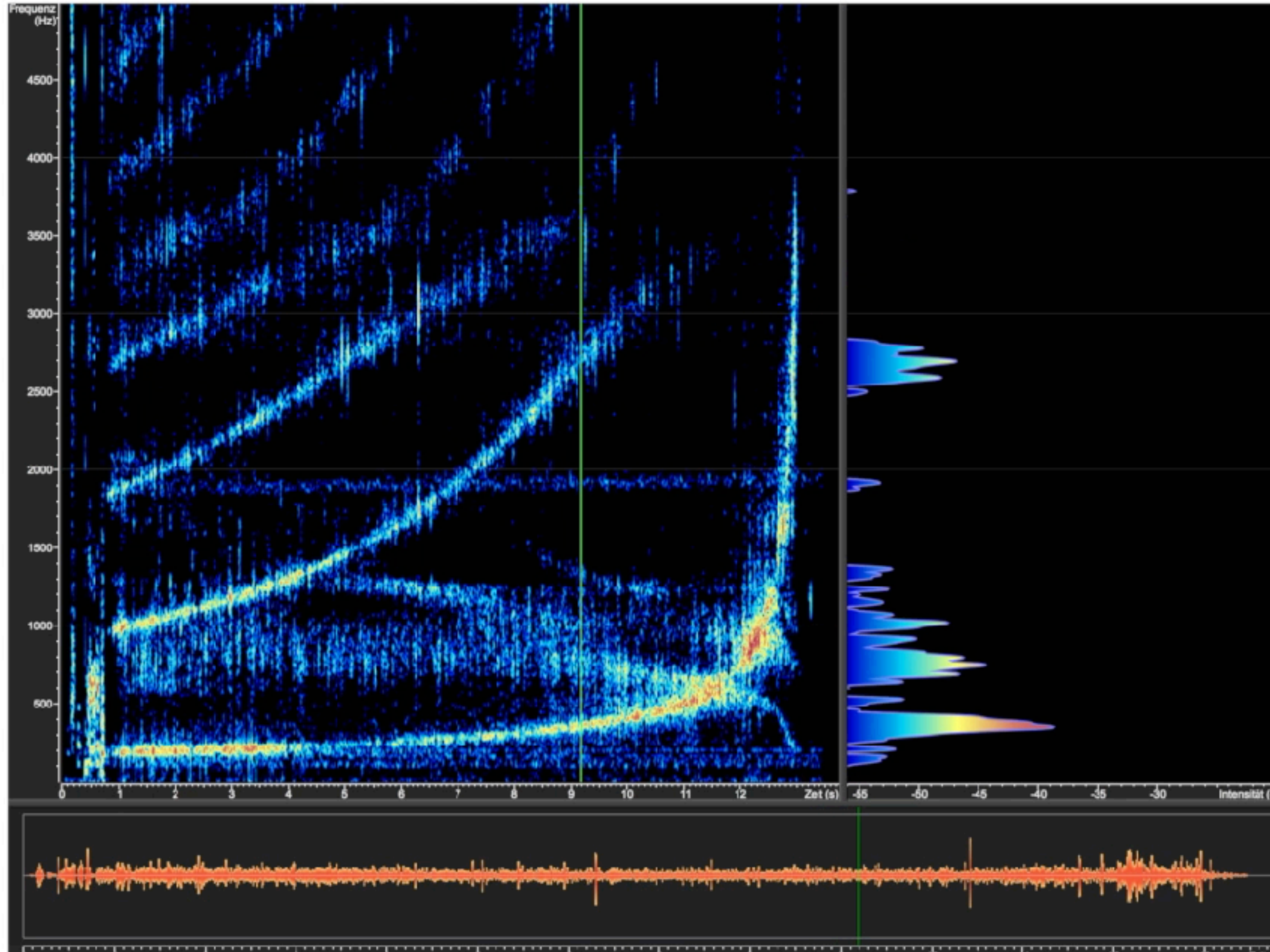


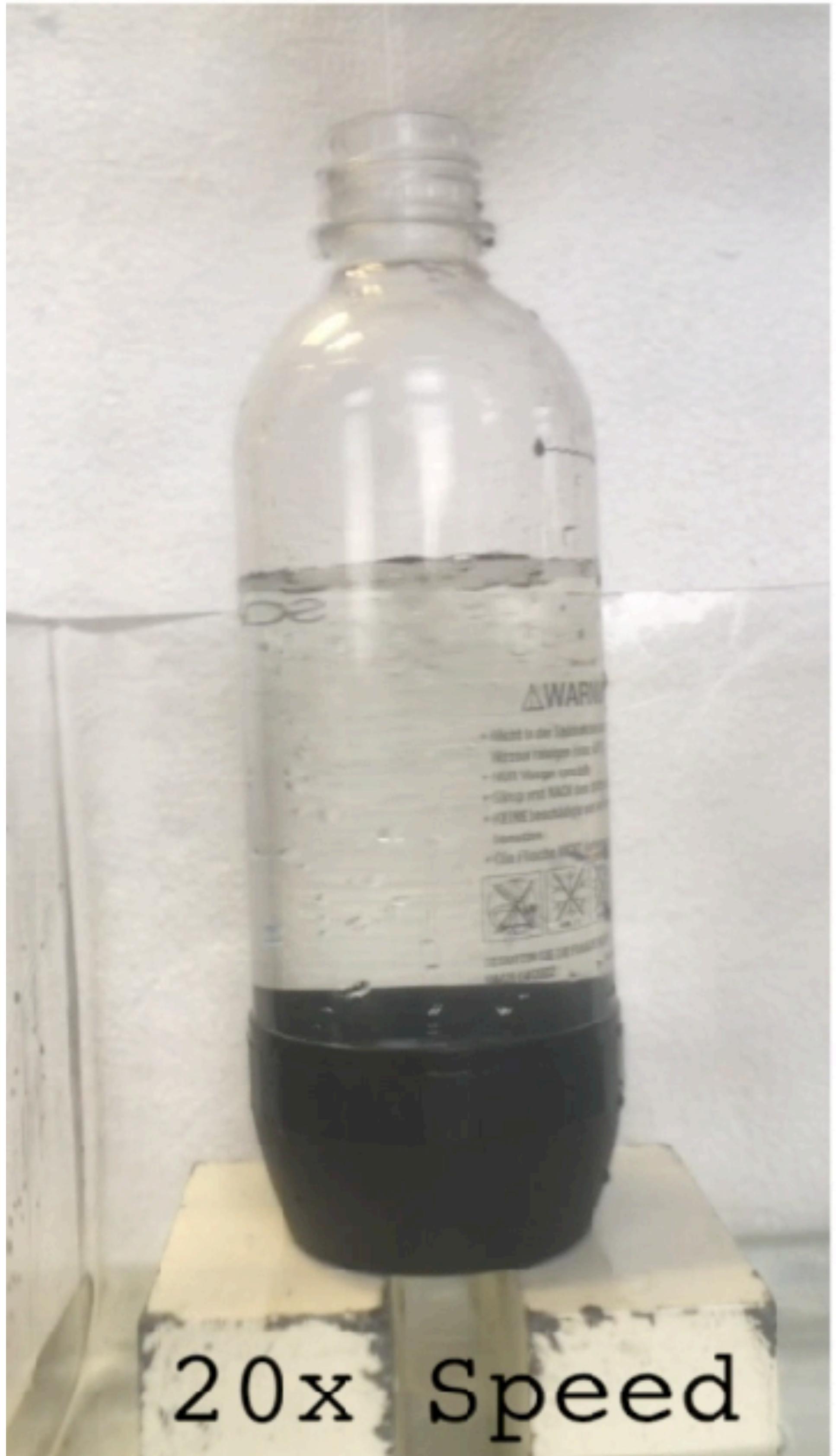


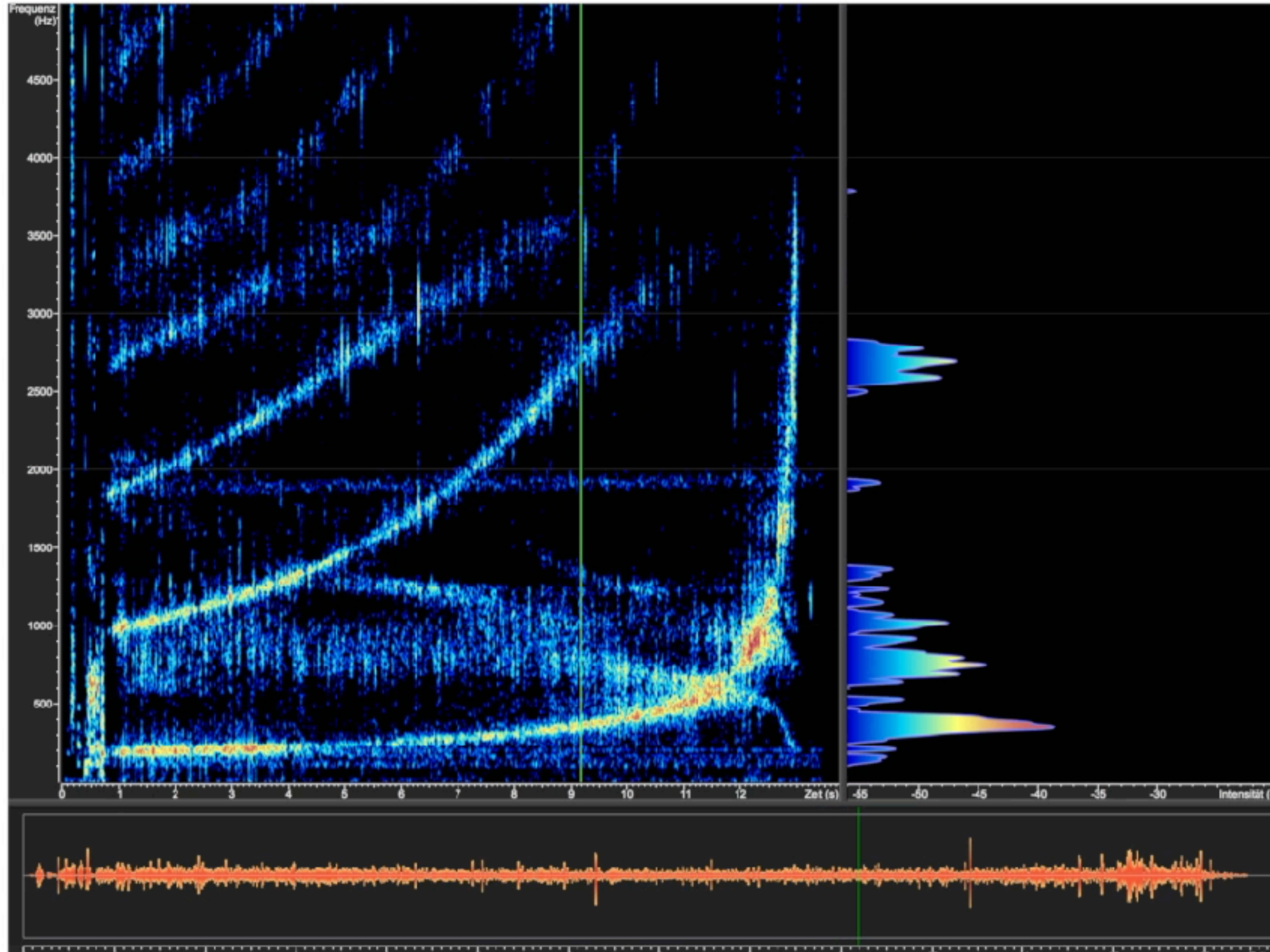


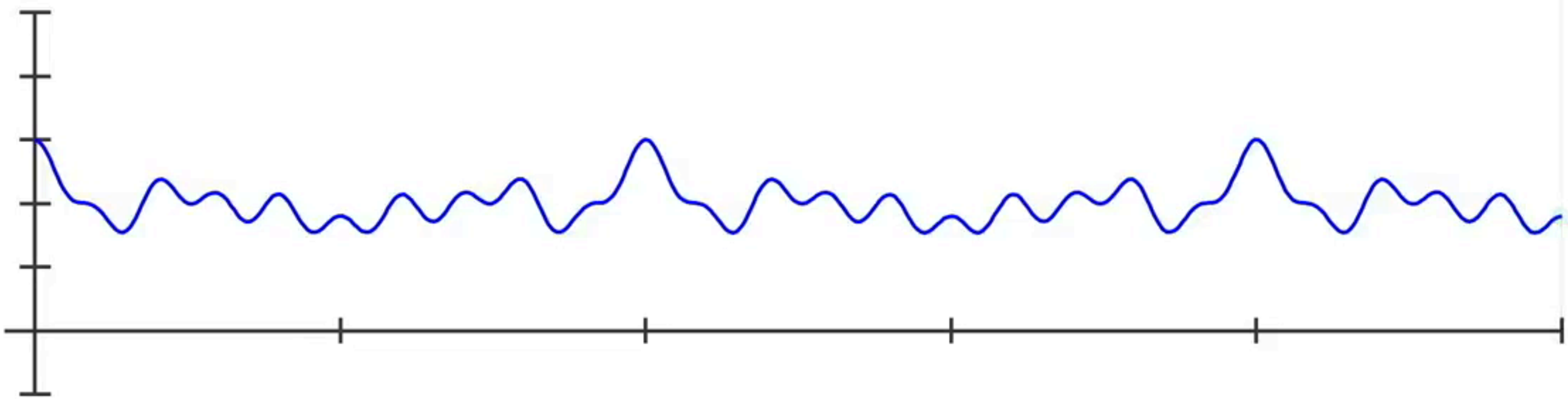
14
10,5
7
3,5
0
30
40
50
60
70
80
90
100
110
t / s
h_w /cm


20x Speed


Frequenz (Hz)
Zeit (s)
Intensität (dB)


20x Speed


Frequenz (Hz)
4500
4000
3500
3000
2500
2000
1500
1000
500
Zeit (s)
Intensität (dB)



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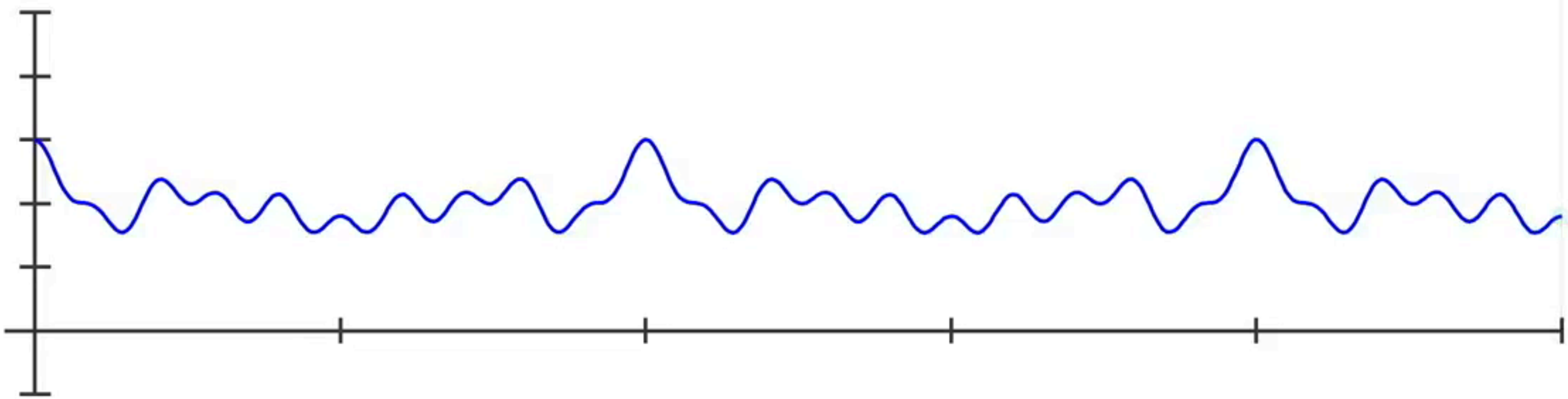

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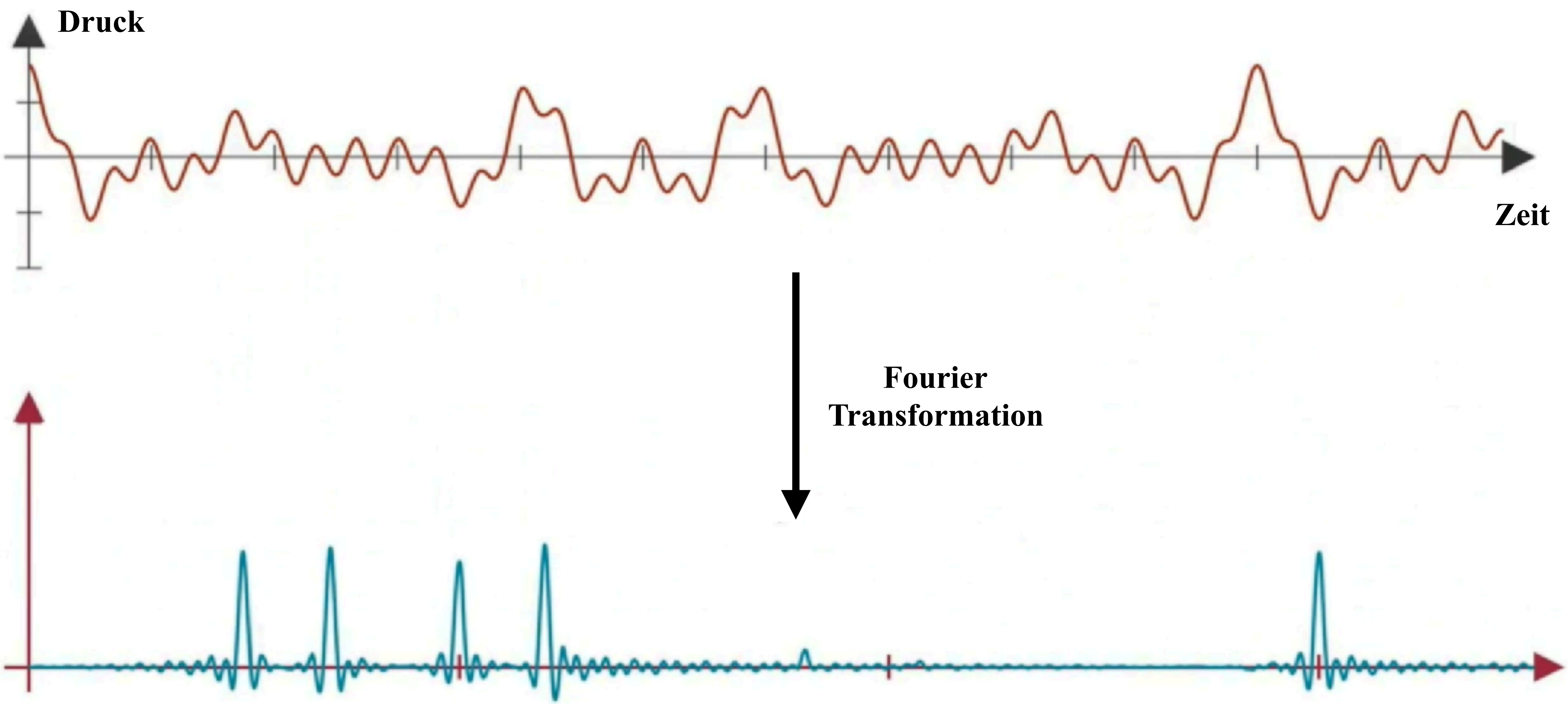

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