1 Archetypal sound objects
Mouth harp, straws, glass bottles, strings (guitar, violin), drums

2 Wave properties
- Amplitude $A$
- Frequency $f$
- Wavelength $\lambda$
- Phase $\varphi$
- Speed of sound $c = \lambda \cdot f$

3 Simple harmonic oscillators
- Mass-spring system
- Pendulum
- Solved by means of differential equations

4 Complex harmonic oscillators
4.1 Concept of harmonicity
- A sound is harmonic if its partials are multiples of a fundamental frequency
- Terminology: Fundamental vs. harmonics vs. overtones
- Periodicity in the time domain means harmonicity in the frequency domain
- Harmonicity is related to pitch perception
  - Harmonic sounds favor perception of a specific pitch
  - Inharmonic sounds are not perceived as pitch
- But harmonicity is a fluid concept (no clear-cut line between harmonic vs. inharmonic sounds)
• Demo: Pd patch
  – Harmonic sound whose partials are not perfect integer multiples
  – Still sounds pitched

4.2 Oscillation of a string
• YouTube video that goes with slides
• Bridge video (recommendation by Peter P): https://upload.wikimedia.org/wikipedia/commons/1/19/Tacoma_Narrows_Bridge_destruction.ogg
• Harmonics (cf., Farnell 2010, eq. 4.12):
  \[ f_n = \frac{n}{2l} \sqrt{\frac{T}{\mu}} \]
  – \( f_n \) ... modes (Hz)
  – \( n \) ... mode number (\( n \in \mathbb{N} = 1, 2, 3, ... \))
  – \( l \) ... string length (m)
  – \( T \) ... linear tension (N)
  – \( \mu \) ... linear density (kg m\(^{-1}\))
• Demo: Karplus-Strong plucked string synthesis implemented in Pd vanilla by Colin Barry: http://blog.loomer.co.uk/2010/02/karplus-strong-guitar-string-synthesis.html

4.3 Pipe closed on one end
• Russell animation
• Distinguish particle displacement vs. sound pressure distribution!
• Why do pressure nodes and peaks have to be distributed that way?

4.4 Pipe open on both ends
• What would we expect the distribution to look like?
• In groups of 2 or 3, derive an equation for the expected harmonics of an open pipe

4.5 Helmholtz resonator
  \[ f = \frac{c \cdot d}{4\pi} \sqrt{\frac{\pi}{V \cdot l}} \]
• \( f \) ... resonant frequency (Hz)
• \( c \) ... speed of sound in air (m s\(^{-1}\))
• \( d \) ... neck diameter (m)
• \( V \) ... resonator volume (m\(^3\))
• \( l \) ... neck length (m)
4.6 Bar clamped at one end

\[ f_1 = \frac{0.5596}{l^2} \sqrt{\frac{ER^2}{\rho}} \]

- \( f_1 \) ... fundamental frequency (Hz)
- \( l \) ... bar length (m)
- \( E \) ... Young's modulus (Pa)
- \( R \) ... radius of gyration (m)
- \( \rho \) ... material density (kg m\(^{-3}\))

<table>
<thead>
<tr>
<th>Material</th>
<th>( E ) / (10^{10})Pa</th>
<th>( \rho ) / (10^3)kg m(^{-3})</th>
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<tbody>
<tr>
<td>Aluminium</td>
<td>7.05</td>
<td>2.7</td>
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<tr>
<td>Brass</td>
<td>10.05 ( \pm ) 0.35</td>
<td>8.48</td>
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<tr>
<td>Copper</td>
<td>12.98</td>
<td>8.79</td>
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<tr>
<td>Gold</td>
<td>7.8</td>
<td>19.29</td>
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<tr>
<td>Iron</td>
<td>21.2</td>
<td>7.87</td>
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<tr>
<td>Lead</td>
<td>1.62</td>
<td>11.35</td>
</tr>
<tr>
<td>Silver</td>
<td>8.27</td>
<td>10.5</td>
</tr>
<tr>
<td>Steel</td>
<td>21.0</td>
<td>7.82</td>
</tr>
<tr>
<td>Zinc</td>
<td>9.0</td>
<td>7.12</td>
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<tr>
<td>Glass</td>
<td>6.1 ( \pm ) 1.0</td>
<td>2.6 ( \pm ) 0.2</td>
</tr>
<tr>
<td>Rosewood</td>
<td>1.4 ( \pm ) 0.2</td>
<td>0.86 ( \pm ) 0.04</td>
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Table 1. Young’s modulus \( E \) and density \( \rho \) of different materials (Benson 2008, p. 117)

5 Group work

<table>
<thead>
<tr>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
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Table 2. Student groups

5.1 Group A (glass bottle)

- Try to predict the glass bottle’s fundamental frequency
- Compare the result to reality
- How could we synthesize this in Pd?
5.2 Group B (mouth harp)
- Try to predict the mouth harp’s fundamental frequency
- Compare the result to reality

5.3 Group C (straw closed on one end)
- Cover the far end of a straw your blowing into with your hand
- What happens to the pitch?
- Derive the equations for the harmonics of the closed straw
  - Remember how sound pressure behaves at open and closed end
  - How does this change the relationship between the straw’s length $l$ and the resulting wavelengths $\lambda_n$?
  - What about the fundamental frequency?
  - Which harmonics would you actually expect to occur?
  - How would that change our perception of that sound?
- Use the equations to predict the straw’s fundamental frequency
- Compare the result to reality

5.4 Group D ( violin)
- Determine the fundamental frequency of an open A string on the violin.
- Do online research to find reasonable estimates for any missing quantities.
  - __________________________
  - __________________________
  - __________________________
- How does your result compare to reality?

6 Group discussion
- Differences between open and closed pipes?
- Is end correction relevant also for glass bottle?

References and further reading
Hardcopy and electronic resource.