- **Resonance frequencies**
- **The glottal source**

Background reading:

- *AAP* Ch 2, sec 2.4
- *AAP* Ch 2, sec 2.1, first half

0. Today's plan

- Review/check-in
  - Standing waves
  - Resonances
  - Boundary conditions (string, tube)
  - Calculating resonance wavelengths
- Calculating resonance frequencies
- The glottal source

0. Today's plan

In the discussion this week, we will **emphasize the concepts** before introducing the formulas.

You can remember (or reinvent) the formulas more easily if you understand the concepts!

Upcoming labs will give you a chance to practice **applying** the concepts (and the formulas).

1. Review: Standing waves, resonances

- What is the connection between **standing waves** and **resonances**?

1. Review: Standing waves, resonances

- What is the connection between **standing waves** and **resonances**?
  - A wave that "fits" a particular object is called a **resonance** of that object
  - A resonance forms a **standing wave**: an oscillating pattern, stable in space over time

- Which of these settings show a standing wave? See web demo "Wave Interference 2" (Zona Land)
  - "Sinusoid 4" | "Sinusoid 5" | "Sinusoid 10"

1. Review: Standing waves, resonances

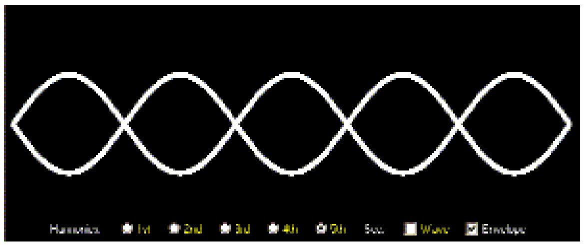
- What are the boundary conditions for…
  - The fixed end of a string
  - The free end of a string
  - The open end of a tube of vibrating air
  - The closed end of a tube of vibrating air
- **Why?**

1. Review: Standing waves, resonances

- What are the boundary conditions for…
  - The fixed end of a string | node
  - The free end of a string | antinode
  - The open end of a tube of vibrating air
    | (pressure) node / (displacement) antinode
  - The closed end of a tube of vibrating air
    | (pressure) antinode / (displacement) node
- **Why?** | physical conditions determine this!

1. Review: Standing waves, resonances

- If this is a standing wave on a string of length 10cm, what is the wavelength of the standing wave?



(from Zona Land Standing Waves demo)

  - Checking in: What are the measurement units of the wavelength, and why?
  - How can we calculate the wavelength?

1. Review: Standing waves, resonances

- We can model the **multiple modes of vibration** of a **string**, or of **air in a tube**
  - To do this, we determine the **wavelength** of each of the **resonances** of the system, based on the physical size of the system
  - Then (for air in a tube) we can calculate the **frequency** of each of the resonances

1. Review: Standing waves, resonances

- The resonances ("waves that fit") for a string or a tube are determined by
  - its **length**
  - its **boundary conditions**

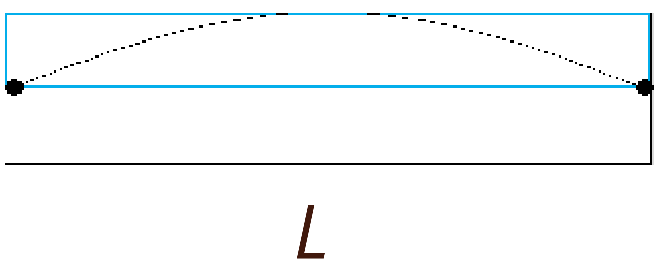
1. Review: Standing waves, resonances

- A **string**, fixed at both ends
  - What are the **boundary conditions**?
  - What does the standing-wave diagram for the first resonance look like? **Why?**

1. Review: Standing waves, resonances

- A **string**, fixed at both ends
  - What are the **boundary conditions**?

    node/node
  - What does the standing-wave diagram for the first resonance look like? **Why?**



  - What is the wavelength of this resonance, for a string of length L? **Why?**

1. Review: Standing waves, resonances

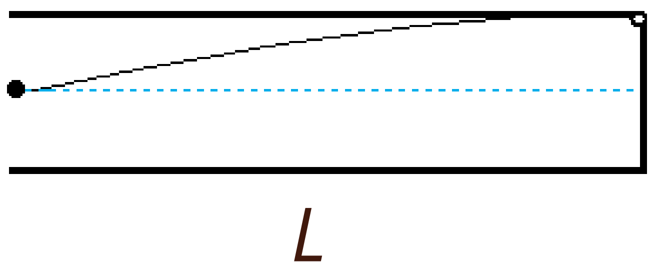
- A **tube**, open at one end and closed at the other
  - What are the **boundary conditions**?

  - What does the standing-wave diagram for the first resonance look like? **Why?**

1. Review: Standing waves, resonances

- A **tube**, open at one end and closed at the other
  - What are the **boundary conditions**?

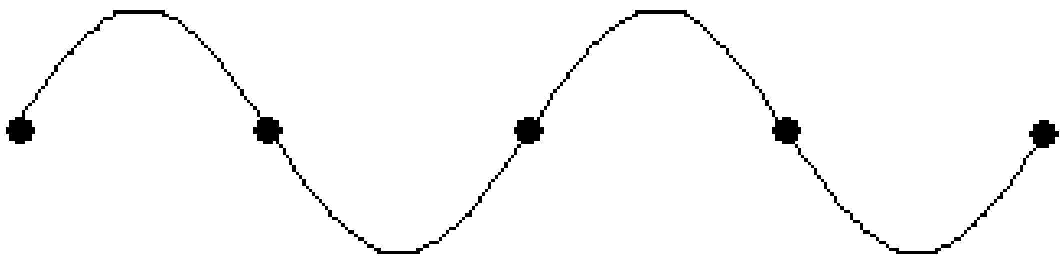
    (pressure) node/antinode | (displacement) A/N
  - What does the standing-wave diagram for the first resonance look like? **Why?**

    (pressure wave)
  - What is the wavelength of this resonance, for a tube of length L? **Why?**

1. Review: Standing waves, resonances

- A **string**, fixed at both ends: **Node/node system**
- What are the **first four** resonances?
  - Hint: Think about the boundary conditions



1. Review: Standing waves, resonances

- A **string**, fixed at both ends: **Node/node system**
- What are the **first four** resonances?
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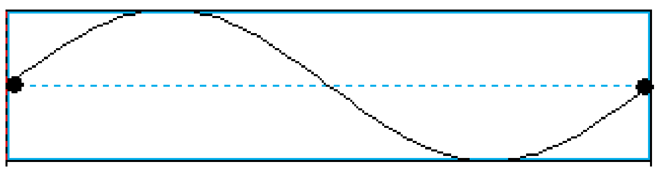
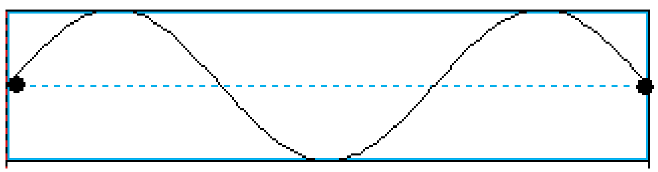
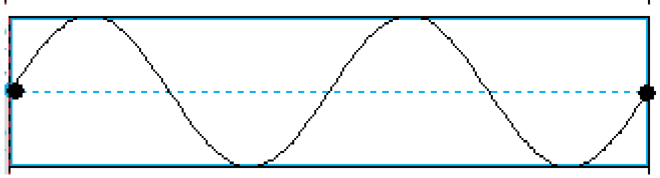
1st  → *½ cycle* of the wave "fits"

2nd  → *1 cycle* of the wave "fits"

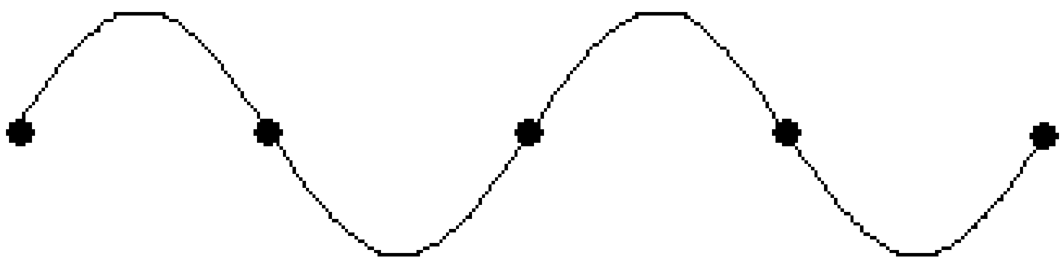
3rd  → 1½ *cycles* of the wave "fit"

4th  → *2 cycles* of the wave "fit"

- Why is this called a **half-wavelength system**?

1. Review: Standing waves, resonances

- A **tube**, open at one end: **Node/antinode system**
- What are the **first four** resonances?
  - Hint: Think about the boundary conditions



1. Review: Standing waves, resonances

- A **tube**, open at one end: **Node/antinode system**
- What are the **first four** resonances?
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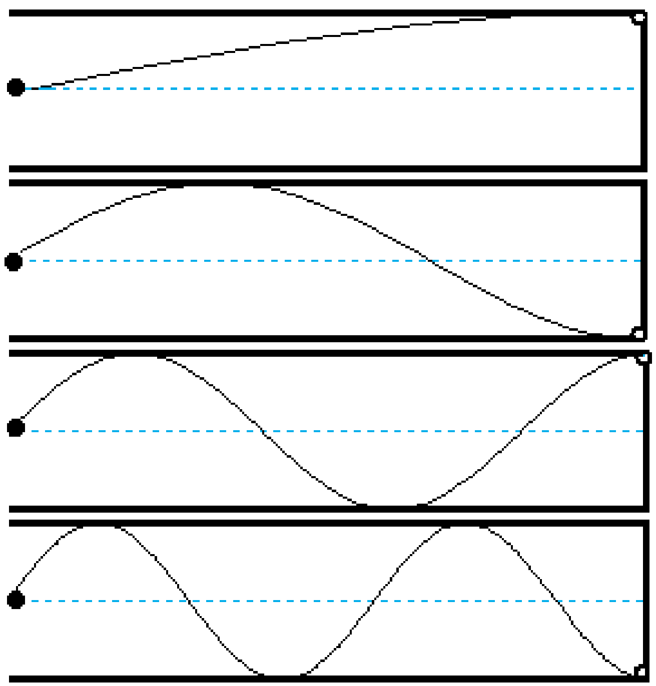


1st → *¼ cycle* of the wave "fits"

2nd → *¾ cycle* of the wave "fits"

3rd → *1¼ cycles* of the wave "fit"

4th → *1¾ cycles* of the wave "fit"

- Why is this called a **quarter-wavelength system**?

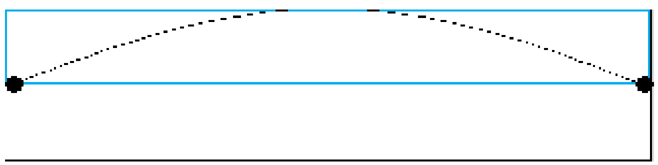
2. Calculating resonance wavelengths

- If we know
  - the **length** of the string or tube (***L***)
  - **“how much wave” fits** on the string or tube for the ***n*th resonance**

- We can calculate the **wavelength λ_n** for the ***n*th resonance**

2. Calculating resonance wavelengths

- Consider the **first resonance** of a **node/node** (half-wavelength) system

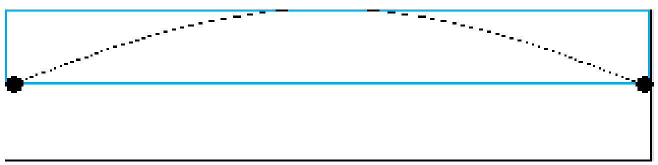


→ ½ *cycle* of the wave "fits"

- If the string or tube is length *L*,
  what is the **wavelength** of the first resonance (λ_1)?

2. Calculating resonance wavelengths

- Consider the **first resonance** of a **node/node** (half-wavelength) system



→ ½ *cycle* of the wave "fits"

- If the string or tube is length *L*, what is the **wavelength** of the first resonance (λ_1)?

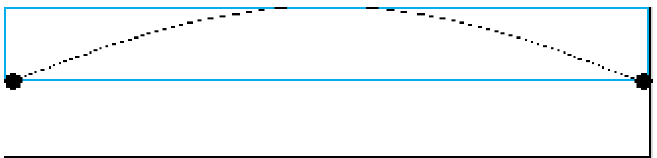
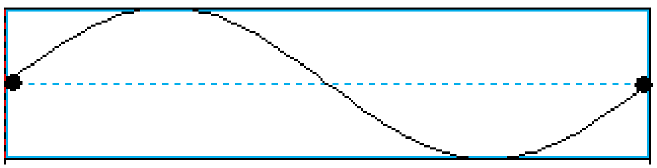
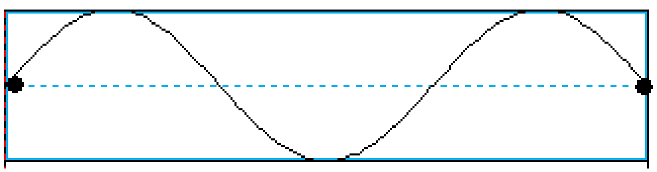
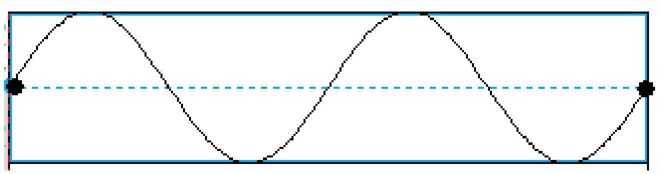
L fits half of the wave

L is half as long as λ_1

$\boldsymbol{\lambda_1 = 2L}$

2. Calculating resonance wavelengths

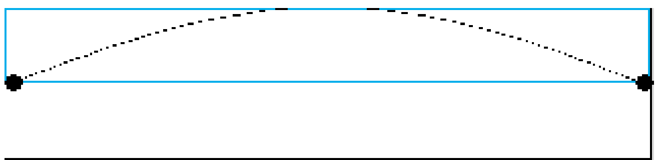
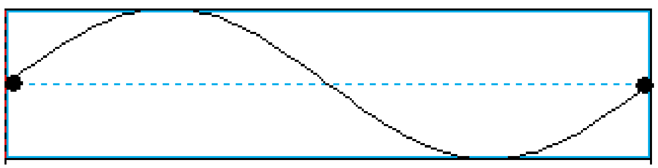
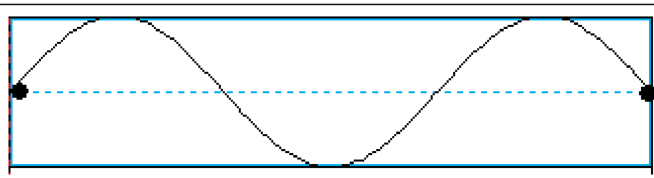
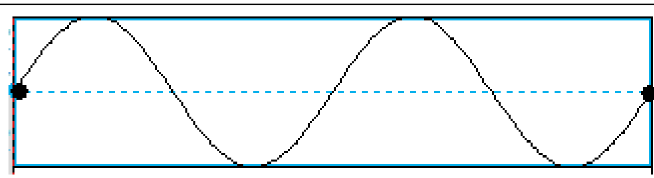
- **Node/node** (half-wavelength) system
  Tube or string of length *L*

	$L = \frac{1}{2} \cdot \lambda_1$	$\lambda_1 = 2\,L$	$\lambda_1 = (2/1) \cdot L$
	$L = 1 \cdot \lambda_2$	$\lambda_2 = L$	$\lambda_2 = (2/2) \cdot L$
	$L = 1\frac{1}{2} \cdot \lambda_3$	$\lambda_3 = \frac{2}{3}\,L$	$\lambda_3 = (2/3) \cdot L$
	$L = 2 \cdot \lambda_4$	$\lambda_4 = \frac{1}{2}\,L$	$\lambda_4 = (2/4) \cdot L$

- ***General formula:***

2. Calculating resonance wavelengths

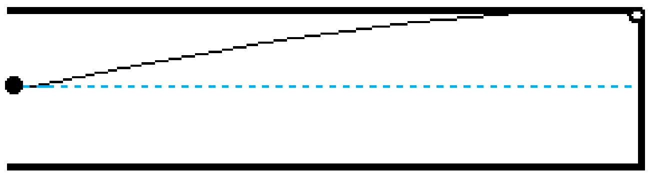
- **Node/node** (half-wavelength) system
  Tube or string of length L

	$L = ½ \cdot \lambda_1$	$\lambda_1 = 2\,L$	$\lambda_1 = (2/1) \cdot L$
	$L = 1 \cdot \lambda_2$	$\lambda_2 = L$	$\lambda_2 = (2/2) \cdot L$
	$L = 1½ \cdot \lambda_3$	$\lambda_3 = ⅔\,L$	$\lambda_3 = (2/3) \cdot L$
	$L = 2 \cdot \lambda_4$	$\lambda_4 = ½\,L$	$\lambda_4 = (2/4) \cdot L$

- ***General formula:*** $\lambda_n = (2/n)\,L$ or $\lambda_n = 2L/n$

2. Calculating resonance wavelengths

- Consider the **first resonance** of a **node/antinode** (quarter-wavelength) system

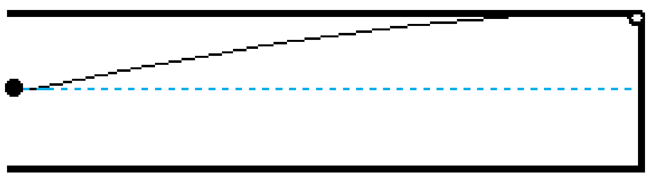


→ ¼ *cycle* of the wave "fits"

- If the tube is length *L*, what is the **wavelength** of the first resonance (λ_1)?

2. Calculating resonance wavelengths

- Consider the **first resonance** of a **node/antinode** (quarter-wavelength) system



→ ¼ *cycle* of the wave "fits"

- If the tube is length *L*,
  what is the **wavelength** of the first resonance (λ_1)?

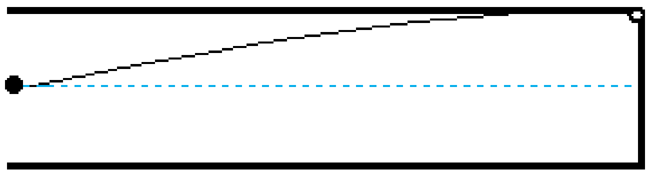
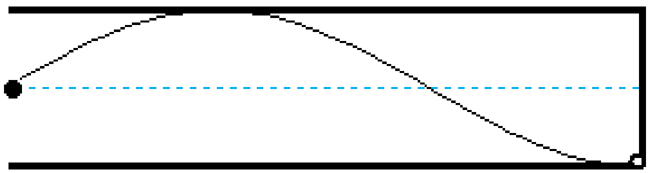
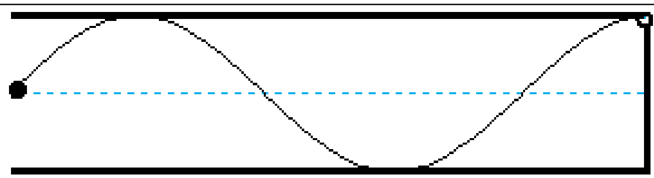
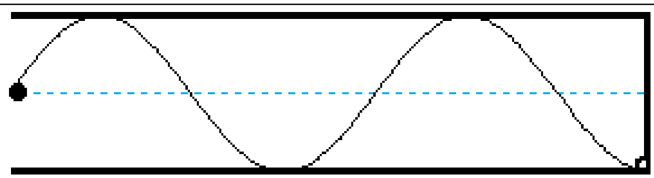
  L fits one quarter of the wave

  L is one quarter as long as λ_1

  $\boldsymbol{\lambda_1 = 4L}$

2. Calculating resonance wavelengths

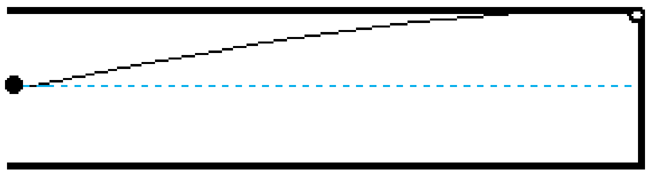
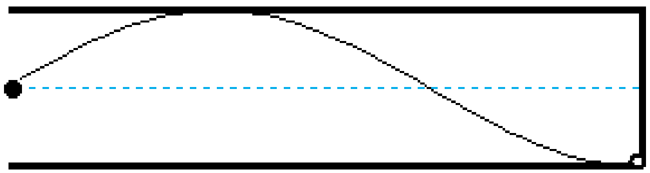
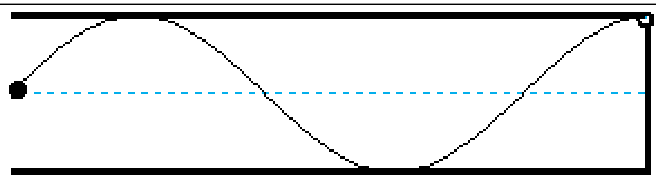
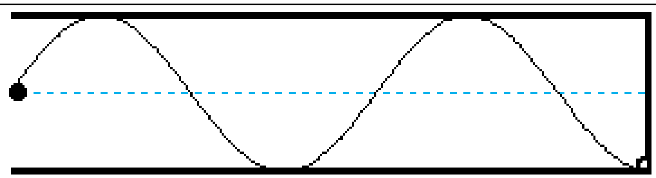
- **Node/antinode** (quarter-wavelength) system
  Tube of length L

	$L = \frac{1}{4} \cdot \lambda_1$	$\lambda_1 = 4\,L$	$\lambda_1 = (4/\mathbf{1}) \cdot L$
	$L = \frac{3}{4} \cdot \lambda_2$	$\lambda_2 = 4/3\,L$	$\lambda_2 = (4/\mathbf{3}) \cdot L$
	$L = 1\frac{1}{4} \cdot \lambda_3$	$\lambda_3 = 4/5\,L$	$\lambda_3 = (4/\mathbf{5}) \cdot L$
	$L = 1\frac{3}{4} \cdot \lambda_4$	$\lambda_4 = 4/7\,L$	$\lambda_4 = (4/\mathbf{7}) \cdot L$

- ***General formula:***

2. Calculating resonance wavelengths

- **Node/antinode** (quarter-wavelength) system
  Tube of length *L*

	$L = \frac{1}{4} \cdot \lambda_1$	$\lambda_1 = 4\,L$	$\lambda_1 = (4/\mathbf{1}) \cdot L$
	$L = \frac{3}{4} \cdot \lambda_2$	$\lambda_2 = 4/3\,L$	$\lambda_2 = (4/\mathbf{3}) \cdot L$
	$L = 1\frac{1}{4} \cdot \lambda_3$	$\lambda_3 = 4/5\,L$	$\lambda_3 = (4/\mathbf{5}) \cdot L$
	$L = 1\frac{3}{4} \cdot \lambda_4$	$\lambda_4 = 4/7\,L$	$\lambda_4 = (4/\mathbf{7}) \cdot L$

- ***General formula:*** $\boldsymbol{\lambda_n = (4/(2n-1)) \cdot L}$ or $\boldsymbol{\lambda_n = 4L / (2n-1)}$

3. Calculating resonance frequencies

- Finally!—the **frequencies** of the resonances are what we really want to know
  - Knowing the resonance frequencies of a tube of air (in the vocal tract) helps us **model the acoustics of speech sounds**
- *Example:* Soon we will learn about the **source-filter model** of speech acoustics as applied to **vowels**
  - The **source** is the glottal-source wave
  - The **filter** is determined by the **resonance frequencies of the vocal tract**

3. Calculating resonance frequencies

- **Wavelength (λ)** and **frequency (*f*)** are related:

$$c=\lambda f$$

  - where ***c*** is the speed of the wave (about **350 m/s** for sound in air, according to *AAP*)

- Wavelength and frequency are ***inversely*** related
  - **Long** wavelength means **low** frequency
  - **Short** wavelength means **high** frequency

Imagine traffic moving by at a steady 35 mph. Many VW bugs (short) would go by in 1 minute (higher frequency), but few buses (long) would go by in 1 minute (lower frequency).

3. Calculating resonance frequencies

- If we know wavelength, we can **solve for frequency**

  $c = \lambda f$

  $\boldsymbol{f = c/\lambda}$

- Find the **frequency** of the ***n*th resonance** (***f_n***):
  - Reminder: What is *c*?
  - Plug the wavelength λ_n into the formula
  - Solve for f_n

3. Calculating resonance frequencies

- For a **node/node** system with tube of length L

$\lambda_n = 2L/n$	relates wavelength to tube length
$f_n = c/\lambda_n$	relates frequency to wavelength
$f_n = c\ /\ (2L/n)$	relates frequency to tube length
$\boldsymbol{f_n = n \cdot c/2L}$	

- **Shortcut!** Once you know the **1st resonance f_1** :

$f_n =$ ______

3. Calculating resonance frequencies

- For a **node/node** system with tube of length L

$\lambda_n = 2L/n$ | relates wavelength to tube length

$f_n = c/\lambda_n$ | relates frequency to wavelength

$f_n = c\ /\ (2L/n)$ | relates frequency to tube length

$\boldsymbol{f_n = n \cdot c\ /\ 2L}$

- **Shortcut!** Once you know the **1st resonance** $\boldsymbol{f_1}$:

$\boldsymbol{f_n = n \cdot f_1}$ | because $\boldsymbol{f_1} = 1 \cdot c\ /\ 2L = c\ /\ 2L$

→ The resonance frequencies in a **node/node** system are **whole-number multiples** of f_1

3. Calculating resonance frequencies

- For a **node/antinode** system with tube of length *L*

$\lambda_n = 4L / (2n-1)$	relates wavelength to tube length
$f_n = c/\lambda_n$	relates frequency to wavelength
$f_n = c / (4L / (2n-1))$	relates frequency to tube length
$\boldsymbol{f_n = (2n-1) \cdot c / 4L}$	

- **Shortcut!** Once you know the **1st resonance f_1** :

f_n = ____________

3. Calculating resonance frequencies

- For a **node/antinode** system with tube of length *L*

  $\lambda_n = 4L / (2n-1)$ | relates wavelength to tube length

  $f_n = c/\lambda_n$ | relates frequency to wavelength

  $f_n = c / (4L / (2n-1))$ | relates frequency to tube length

  $\boldsymbol{f_n = (2n-1) \cdot c / 4L}$

- **Shortcut!** Once you know the **1st resonance f_1** :

  $\boldsymbol{f_n = (2n-1) \cdot f_1}$ | because $f_1 = 1 \cdot c / 4L = c / 4L$

→ The resonance frequencies in a **node/antinode** system are **odd-numbered multiples** of f_1

3. Calculating resonance frequencies

- What is the **relationship** between f_1 (the **first resonance** frequency) and f_0 (the **fundamental frequency** of the complex wave itself) for...
  - a **node/node** system?
  - a **node/antinode** system?

3. Calculating resonance frequencies

- What is the **relationship** between $\boldsymbol{f_1}$ (the **first resonance** frequency) and $\boldsymbol{f_0}$ (the **fundamental frequency** of the complex wave itself) for...
  - a **node/node** system?
    - Resonance *f*s = whole-number multiples of f_1
      What does this tell us?
  - a **node/antinode** system?
    - Resonance *f*s = odd-numbered multiples of f_1
      What does this tell us?

4. The glottal source wave

- What is the **glottal source wave**?
  - Also called the **voicing wave**(form) in *AAP* Ch 2

  → The sound wave produced by ______

4. The glottal source wave

- What is the **glottal source wave**?
  - Also called the **voicing wave**(form) in *AAP* Ch 2

  → The sound wave produced by the vibration of the vocal folds

- To actually hear this sound wave, you would have to put a microphone right above the glottis
  - The sound waves of any speech we normally hear are **further modified** by passing through the vocal tract
    - This is the content of the rest of the course!

4. The glottal source wave

- The glottal source wave is a complex wave with the following property:
  - All of the components of this complex wave have frequencies that are **whole-number multiples** of the lowest-component frequency

- How does the fundamental frequency of the glottal source wave **relate** to the frequency of its lowest component?