樂器 **Musical Instrument**
設計比賽 **Design Competition**

http://i.cs.hku.hk/~music/

Sound, Music and Science
聲與樂的科學

Dr. YIP Chi Lap [Beta]
Faculty of Engineering, HKU
香港大學工程學院 葉志立博士

主辦 **Organizers**

Faculty of Engineering
THE UNIVERSITY OF HONG KONG

ATE 藝術與科技教育中心
Arts & Technology Education Centre

支持單位 **Supporting Organizations**

香港電腦教育學會
The Hong Kong Association for Computer Education

香港教育城 HKedCity

資助 **Funding Support**

The University of Hong Kong
Knowledge Exchange

Music is arts, and also...
音樂是藝術，同時……

✦ Music is also physics!
音樂亦是物理！

✦ Music is also mathematics!
音樂亦是數學！

Sound: longitudinal wave
聲音：縱波

✦ A sound source generates energy that is propagated to the receiver as longitudinal acoustic waves.
音源產生能量，以縱波的形式傳到接收者。

✦ Sound sources are often modelled as a point.
音源常以一點來表達。

✦ The receiver is often modelled as two points on two sides of a sphere representing ears.
接收者則以一球體對面之兩點來代表雙耳。

Vibration of air molecules
# 空氣分子的振動
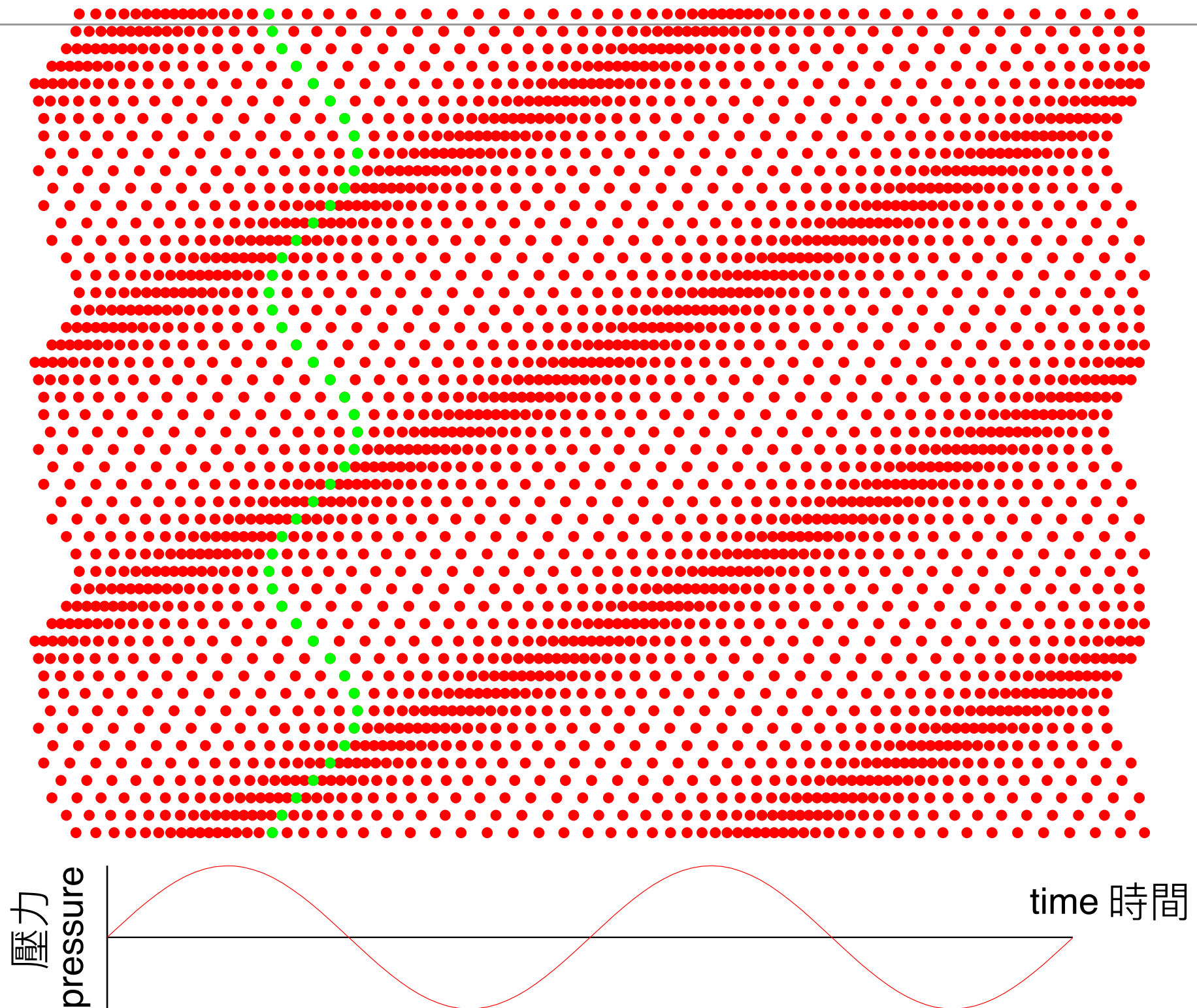
Making sound: open pipe
製造聲音：兩面開口的管

✦ Try blowing into a drinking straw!
試吹飲管，製造聲音！

✦ Vibration of air at the ends of the pipe are free.
管道兩端空氣分子可自由振動。

✦ Different environment inside and outside the pipe cause some waves to be reflected.
管內外環境不同，有些聲音會被反射。

✦ Interference between incident and reflected waves cause stationary waves are set up in the pipe.
入射波和反射波互相干擾，駐波因而產生。

Music is physics! 音樂是物理！

✦ Why are holes on a flute arranged in a particular way? 為甚麼長笛的孔要這樣開？

✦ Why are the bars on a guitar arranged in a particular way? 為甚麼結他的琴衍要這樣排列？
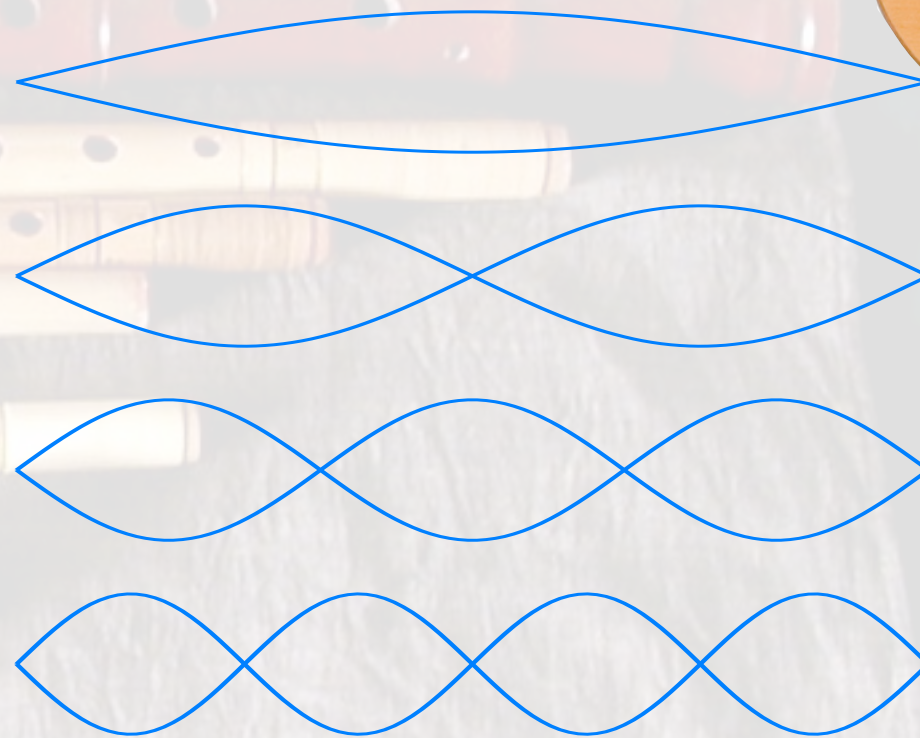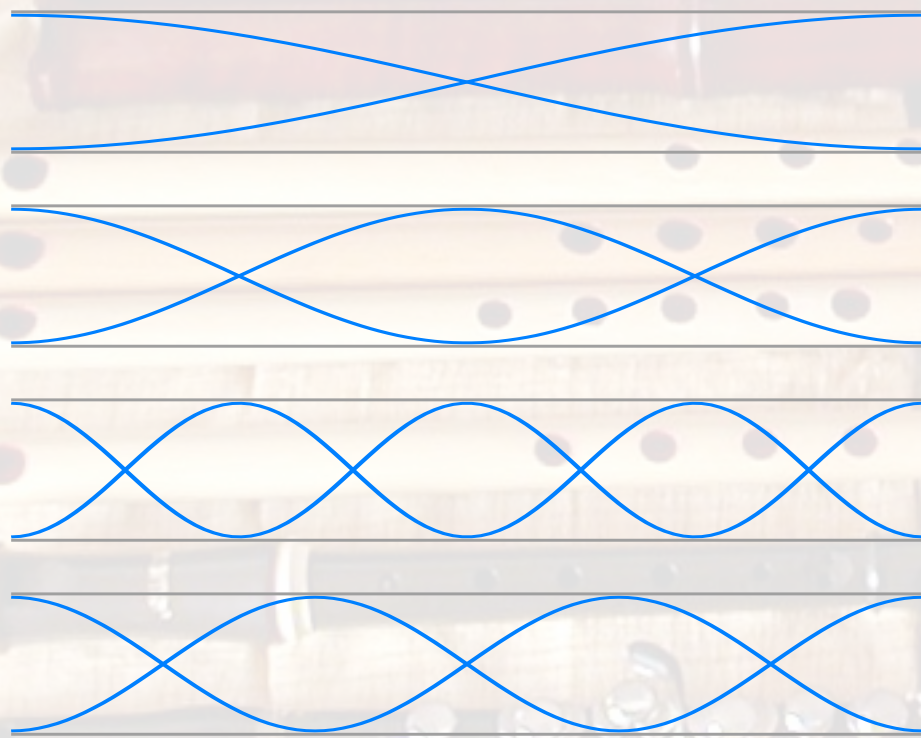
Making sound: open pipe
製造聲音：兩面開口的管

✦ Displacement antinodes are formed at the end of the pipe, nodes in the middle.
管道開口端空氣分子可有最大位移，而最少位移的節點在中間。

✦ Frequency of stationary wave depends on:
駐波的頻率取決於：

  ❖ Length of the pipe 管的長度

  ❖ Speed of sound in air 聲音在空氣的速度
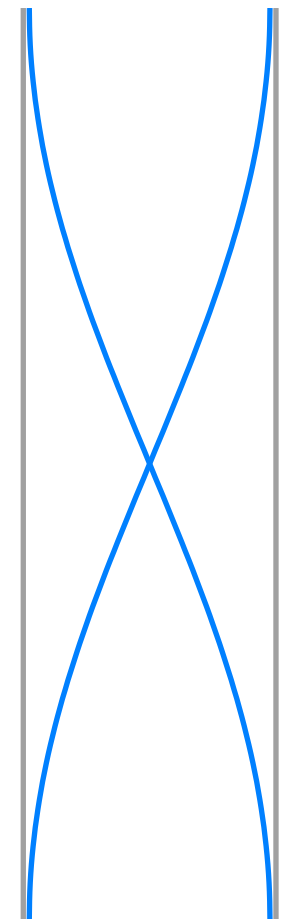
Making sound: open pipe
製造聲音：兩面開口的管

✦ Relationship between wavelength λ, sound speed v and frequency f:
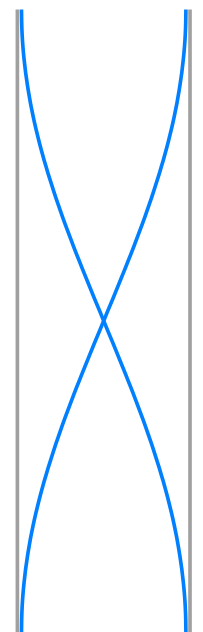波長 λ、聲音傳播速度 v 和頻率 f 的關係：
$$v = f\,\lambda$$

✦ Sound speed in air is about　聲音在空氣傳速度大概是
340ms^{-1}

✦ Example 例：tube length 管長 10cm
λ = 20cm since only half a wave is contained
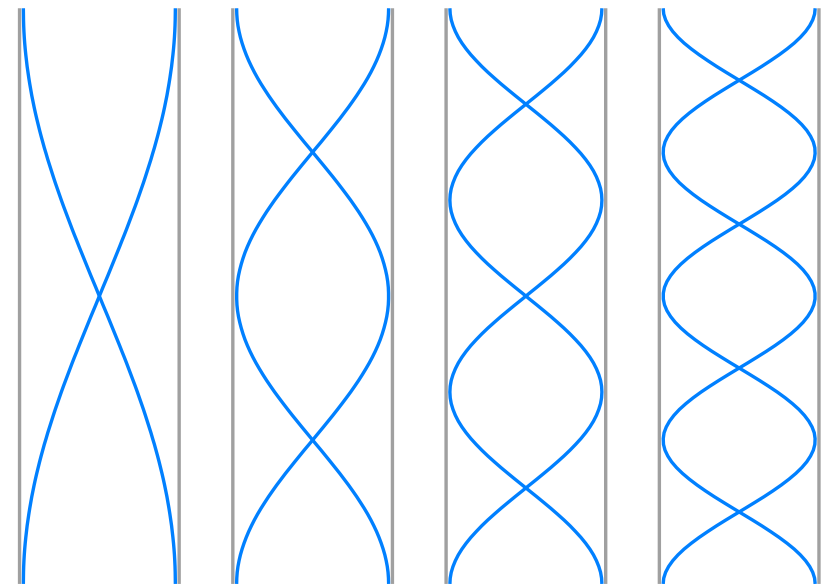   in the tube　因管只能容納半個波長
$f = v/\lambda = 340 \text{ms}^{-1} / 0.2\text{m} = 1700$ Hz

Making sound: open pipe
製造聲音：兩面開口的管

- ✦ Excitation of physical objects seldom cause only one mode of vibration.
  激發物體振動，很少只有單一振動模式。

- ✦ Simultaneous excitation of different modes of vibration makes the timbre of the instrument.
  同時激發不同振動模式，就是 樂器音色的來源。

- ✦ Frequency ratio of the first four modes:
  首四振動模式的頻率比：
 1:2:3:4

Physics and maths time
物理和數學時間

✦ Suppose a tube with length *x* produces a frequency of *f*.
What frequency does a tube with length 2*x*/3 produce?
假設吹一長度為 *x* 的管所產生的頻率為 *f*, 吹一長度為
2*x*/3 的管所產生的頻率為何？

✦ How about one with length 4*x*/3 ？
長度為 4*x*/3 的呢？

The design matters
設計很重要

- ✦ Calculate the relative frequencies of the different modes for a pipe closed on one end.
  計算一面開口的管的各種振動模式的頻率比。

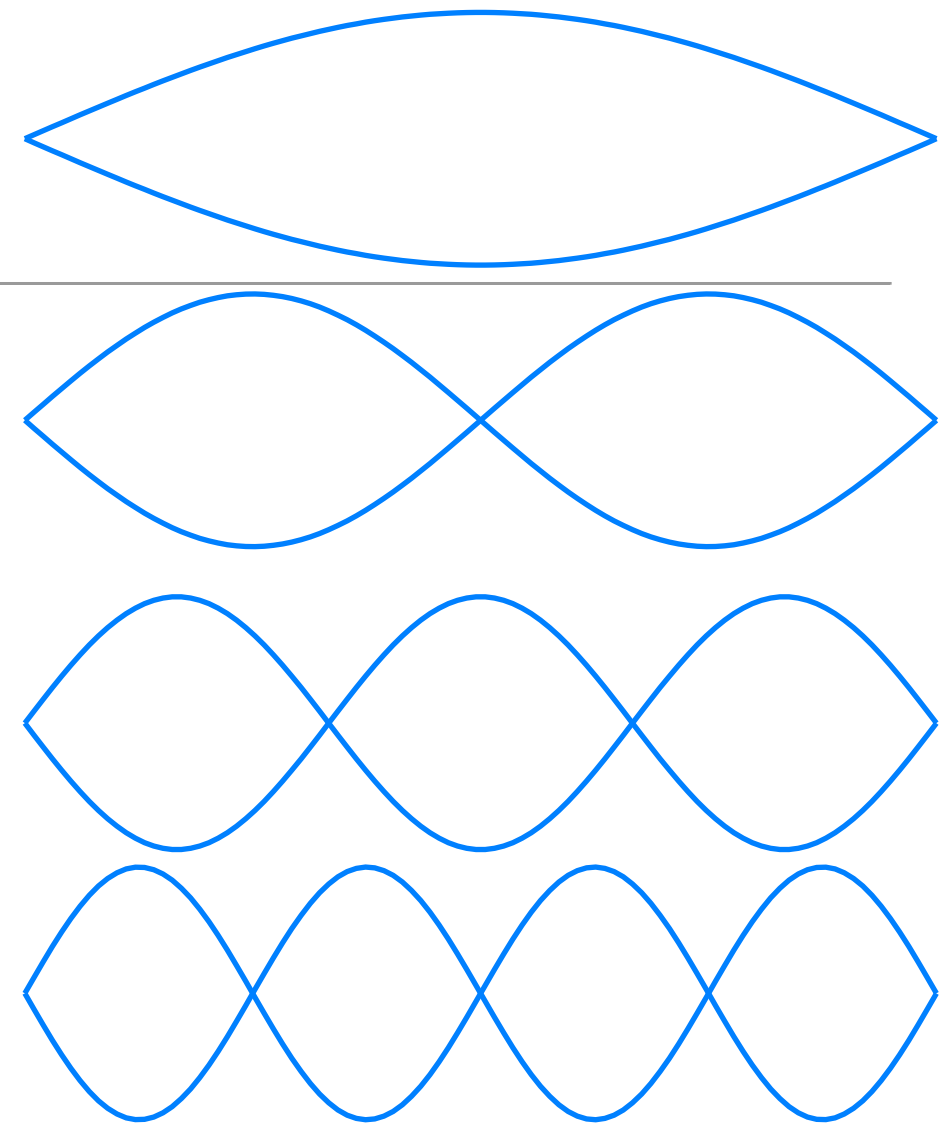- ✦ The physical design affects the timbre.
  物理設計影響音色。
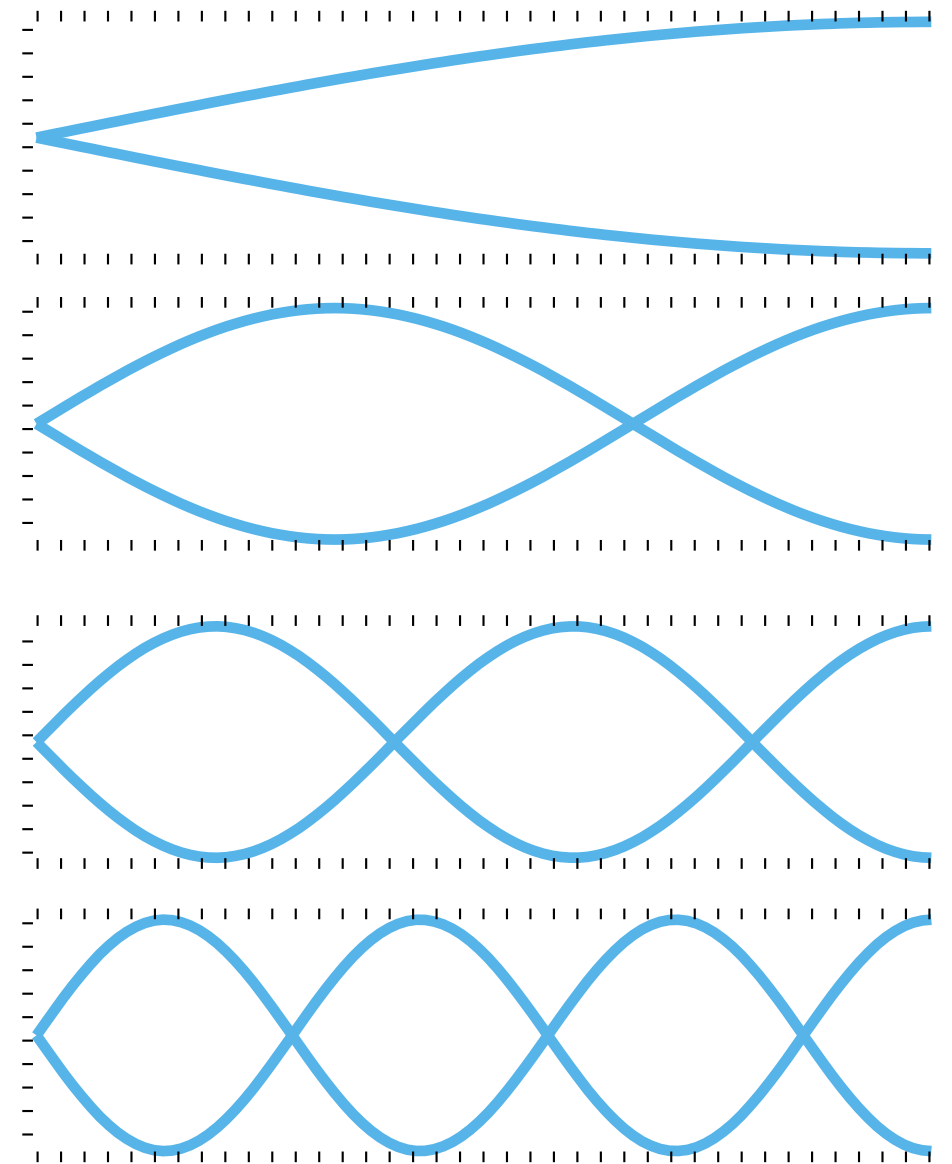
How about strings?
弦樂呢？

✦ Guitars, violins, guqin, yangqin,...
   結他、小提琴、古琴、揚琴⋯⋯

✦ Fixed ends has to be nodes.
   弦線兩端固定，必為節點。

✦ Waves propagate much faster in solids than in air, and depends on tension of the string.
   聲波在固體傳送速度比在空氣快得多，並受弦線鬆緊影響。

How about drums and cymbals?
鼓和鈸呢？

- ✦ The vibration modes of the skin of an ideal drum or the body of a cymbal is more complicated.
  鼓皮或鈸身的振動模式比較複雜。

- ✦ Two classes of vibration modes 有兩類振動模式:

  - ❖ Diametric mode: vibration nodes coincide with a diameter of the drum.
    直徑模式：振動節點與鼓皮的直徑一致。

  - ❖ Circular mode: vibration nodes are arranged as a circle with the same centre of the drum or cymbal.
   圓形模式：振動節點鼓邊或鈸邊的圓同心。

How about drums and cymbals?
鼓和鈸呢？

- ✦ The numbers in the parentheses indicate (diametric mode, circular mode) of vibration.
  括號內的數字顯示 (直徑, 圓形) 振動模式。

- ✦ Solid lines indicate vibration node, dashed lines antinode.
  實線表示振動節點，虛線表示振動反節點。

- ✦ Different ways of playing excites different modes of vibration differently.
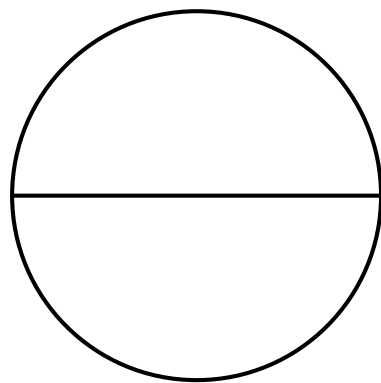 不同奏法令不同振動模式激發度不同。
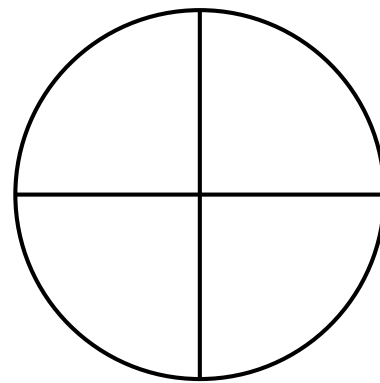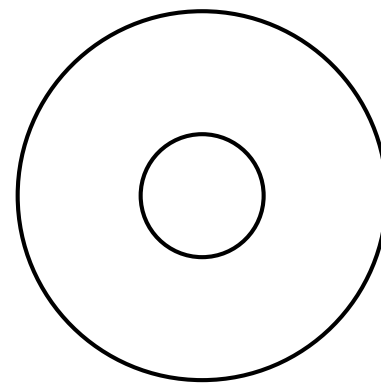
How about drums and cymbals?
鼓和鈸呢？

Drum 鼓
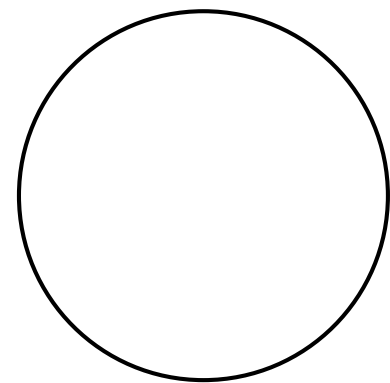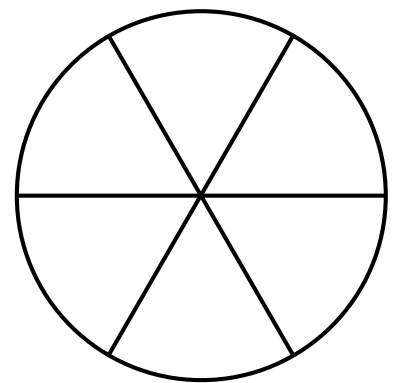
| (0,1) | (1,1) | (2,1) | (0,2) | (3,1) |

Cymbal 鈸
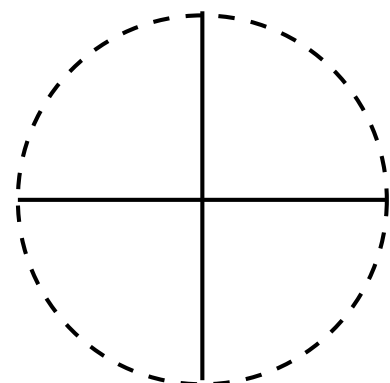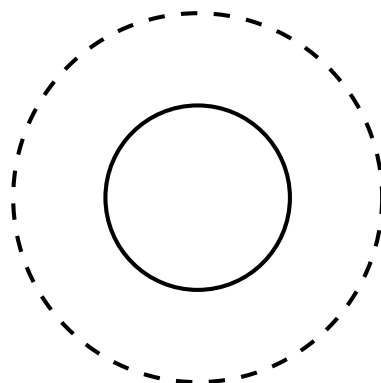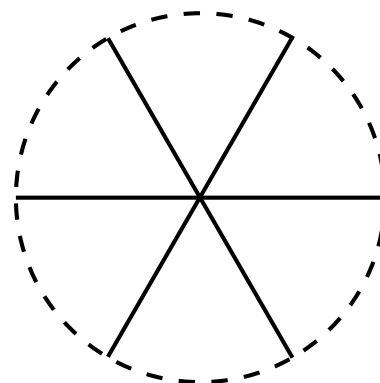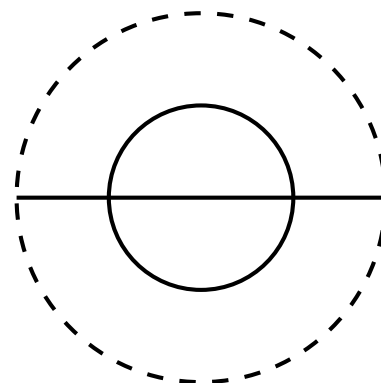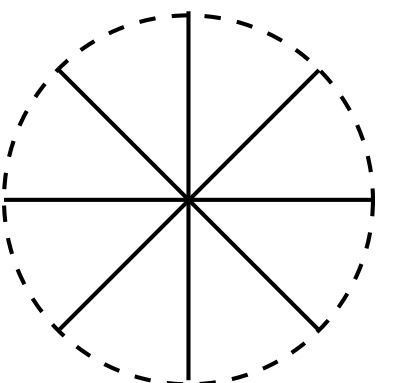
| (2,0) | (0,1) | (3,0) | (1,1) | (4,0) |

References
參考書

✦ Acoustics and Psychoacoustics
David M. Howard and James Angus
Focal Press, 1996, ISBN 0-240-51428-9

  ❖ Introductory and easy to read.

✦ Introduction to the Physics and Psychophysics of Music
second edition
Juan G. Roederer
Heidelberg science library, 1975.

  ❖ Goes deep into the physics.

How to map note to frequency?

如何找出音的頻率？

Have you been in a concert?
有去過音樂會嗎？

✦ Orchestra Tuning / Warm Up - Clean Sound.
  Urb Mak. YouTube. 2011-04-08.
  https://www.youtube.com/watch?v=KfSH1ezevjM

✦ Which note is that at the beginning?
  開始的是哪粒音？

✦ What is its frequency?
  這粒音頻率是多少？

An experiment
做實驗

✦ Generate and listen tones of these frequencies:
產生並聆聽以下頻率的音調：
440Hz, 220Hz, 330Hz, 495Hz, 247.5Hz, 371.25Hz, 556.875Hz, 278.4375Hz, 417.65625Hz, 626.484375Hz, 313.2421875Hz

✦ What's your observation? 觀察到甚麼？

✦ What's the pattern? 有甚麼模式？

Music quiz! 音樂測驗！
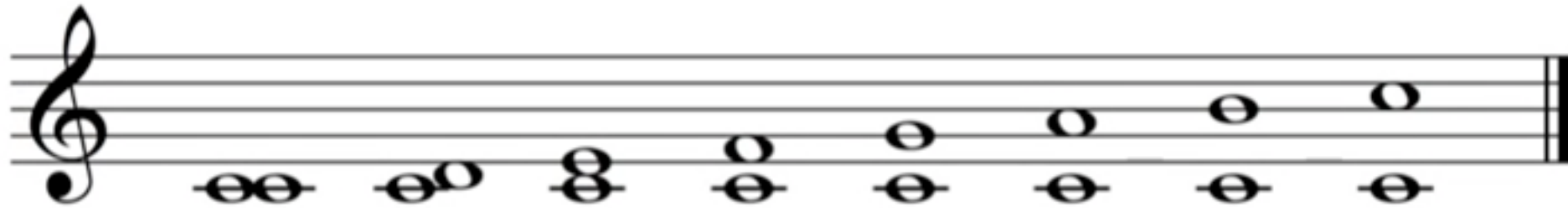
✦ What is an octave?
甚麼是完全八度？

✦ What is a perfect fifth?
甚麼是完全五度？

✦ What is a perfect fourth?
甚麼是完全四度？

✦ What is a major third?
甚麼是大三度？

✦ What is a minor third?
甚麼是小三度？

About intervals 關於音程

✦ 八分鐘以內，一次搞懂音程名稱！
　NiceChord (好和弦)
　YouTube 2015-01-24
　https://www.youtube.com/watch?v=QLDktqMxgmY

Musical intervals 音程

✦ Listen first 先聽聽

Interval 音程	Frequency ratio 頻率比	Bottom note 底音	Top note 頂音
Octave 全八度	2:1	220 Hz	440 Hz
Perfect fifth 全五度	3:2	220 Hz	330 Hz
Perfect fourth 全四度	4:3	220 Hz	293.3̇ Hz
Major third 大三度	5:4	220 Hz	275 Hz
Minor third 小三度	6:5	220 Hz	264 Hz
Major sixth 大六度	5:3	220 Hz	366.6̇ Hz
Minor sixth 小六度	8:5	220 Hz	352 Hz

✦ This is Just intonation 這是純律

✦ There is also Pythagorean tuning 還有畢達哥拉斯律式，又叫五度相生律。

Calculate the frequencies!
計頻率！

✦ Can you find out the frequencies of the top notes?
你能計出頂音的頻率嗎？

Interval 音程	Frequency ratio 頻率比	Bottom note 底音	Top note 頂音
Major second 大二度	9:8	220 Hz	
Minor second 小二度	16:15	220 Hz	
Augmented fourth 增四度	45:32	220 Hz	
Diminished fifth 減五度	64:45	220 Hz	
Major seventh 大七度	15:8	220 Hz	
Minor seventh 小七度	16:9	220 Hz	

Can you give names
to the notes in the tables earlier?
你可以給之前兩表內的音命名嗎？

e.g., A4=440

Listen again. Is it a bit strange?

再聽。怪怪的？

聽過這首歌嗎？
Do you know this song?

✦ 許冠傑演唱會2016 尾場 -滄海一聲笑 (何傲兒古箏伴奏)
  wpw star. 4:38. YouTube. 2016-10-29.
  https://www.youtube.com/watch?v=8bli46moVug
  Start from 86s 由86秒開始：
  https://www.youtube.com/watch?v=8bli46moVug&t=86s

✦ 笑傲江湖 Swordsman - 黃霑的專訪
  CosmosEarthManWater. 8:35. YouTube. 2014-08-21.
  https://www.youtube.com/watch?v=SNYh9YfKjTo

Tuning systems 律式

✦ Mapping between note name and frequency is related to tuning systems.
音名到頻率的對應與律式（調音系統）有關。

✦ Note with the same name can have different frequencies and thus sound
differently under different tuning systems!
同音名的音在不同的律式下，頻率可以不同，從而聽出來也不一樣。

✦ Some tuning systems: 一些律式：

❖ 三分損益法

❖ Just intonation 純律

❖ Pythagorean tuning 畢達哥拉斯律式

❖ Equal temperament tuning 十二平均律

A bit of Chinese music theory: 三分損益法

一些中國音樂理論：三分損益法

✦ 司馬遷《史記》「律書第三」：「……九九八十一以為宮。三分去一，五十四以為徵。三分益一，七十二以為商。三分去一，四十八以為羽。三分益一，六十四以為角。」（是為「三分損益法」）

✦ Take a tube with 81 units in length as producing the 宮 sound. Cut one third of it, 54 units long, 徵 sound. Add one third to its length, 72 units, 商 sound. Remove one third of it, 48 units, 羽 sound. Add one third of its length, 64 units, 角 sound.

Not only Chinese...
不止中樂……

✦ Music in many cultures use pentatonic scales.
很多地方的音樂也用五聲音階。

✦ e.g., Indonesian Gamelan, orchestra containing gongs, and metallophones.
例如印尼一種利用銅鑼和鐘的名為甘美蘭的音樂。

Indonesian Gamelan music
印尼甘美蘭音樂

✦ Javanese and Balinese gamelans have different musical styles.
爪哇和峇里的甘美蘭音樂風格不同。

✦ The notes are different from those in Chinese music.
音階亦與中國音樂的不同。

✦ The tuning can be different in different villages!
他們不同村落的律式也可以不同！

Equal temperament tuning
十二平均律

✦ Not all notes are equal for tuning systems based on one note.
以一音為本的律式，每音並非平等。

✦ Change of key requires tuning the instrument again.
轉調需再對樂器調音。

✦ Equal temperament tuning tries to make all notes equal by considering that an octave is double the frequency only.
十二平均律只用八度即兩倍頻率，以致所有音平等。

Equal temperament tuning
十二平均律

✦ Up an octave 高八度： $f \rightarrow 2f$

✦ Frequency ratio of notes the same interval apart is the same.
音程一樣的任何兩音的頻率比一樣。

✦ There are 12 semitones in an octave.
一個八度有12個半音。

✦ 半音頻率比為 $2^{1/12} \approx 1.0594630943592953$

Problem!
有問題！

- ✦ What's the frequency ratio of notes a perfect fifth apart under equal temperament tuning?
  十二平均律中，大五度的頻率比是甚麼？

- ✦ $2^{7/12} \approx 1.4983070768766815$

- ✦ A bit from the perfectly naturally consonant ratio of 1.5.
  與自然而完美的協和音程還差一點點！

- ✦ Tradeoff between easy change of keys and perfect consonance.
  轉調容易和完美協和的權衡。

Videos about tuning systems
關於律式的影片

✦ 電磁波、七色彩虹和 65 歲的早餐店老闆！
NiceChord (好和弦). 7:12. YouTube 2017-02-18
https://www.youtube.com/watch?v=mqPUfBE4UMQ

✦ 為什麼「八度」很重要，以及住在希臘的聰明男人
NiceChord (好和弦). 8:00. YouTube 2017-02-25
https://www.youtube.com/watch?v=rpZV2YO4LJA

✦ 畢達哥拉斯怎麼找到 Do Re Mi？
NiceChord (好和弦). 8:25. YouTube 2017-03-04
https://www.youtube.com/watch?v=p6f__AYhqUA

It's Bach!
巴赫！

✦ The Well Tempered Clavier. gerubach. Playlist. 1:52:34+2:26:05. YouTube. 2014-12-04. https://www.youtube.com/playlist?list=PLmCLUrrx_kSdaPkuU1XOxmWIzoKYo-j3d

❖ Shows scrolling score.

Good book
好書

✦ Gödel, Escher, Bach: An Eternal Golden Braid
Douglas R. Hofstadter
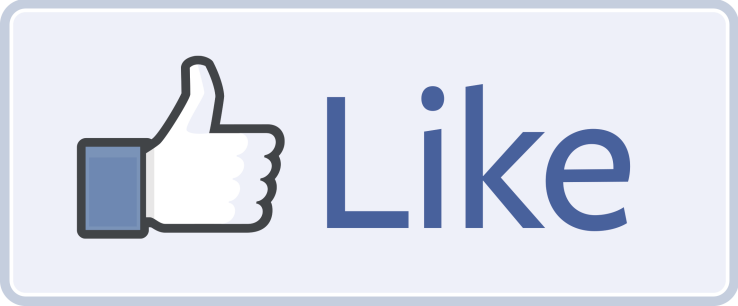Penguin Book 1979
ISBN 0140179976

Musicians' reference resources
音樂人的參考資源

✦ Grove Music Online
   http://www.oxfordmusiconline.com/grovemusic/

Got questions? 有問題？

https://www.facebook.com/HKUEnggMusic