HSI2013 Cheatsheet Guide

Science of Music (National University of Singapore)

GEH1030 Helpsheet

Types of Sound:

1) **Physical Sound** – Vibrations produced by a musical instrument
2) **Perceived Sound** – Sound as heard by the human ear and understood by the brain as music

Vibration:

Property	Physical Sound	Perceived Sound
Rapidity	Frequency - Number of cycles per second - Measured in Hertz (Hz) Period - Time taken for one cycle -	Pitch - Highness/Lowness - Two sounds with the same pitch are said to be in *unison* - Human hearing: 20 Hz to 20,000 Hz (20 kHz)
Strength	Amplitude/Power - Energy radiated by a sound - Measured in Watts - Human Hearing: watt to watt	Loudness/Volume - Measured using the decibel (dB) scale (Always used to compare 2 powers) - increase in power increase in dB - As pitch falls, it's perceived as softer too
Shape	Shape of waveform	Quality/Timbre - Differentiates sounds of instruments

Frequency of a Vibrating String:

Depends on 3 things

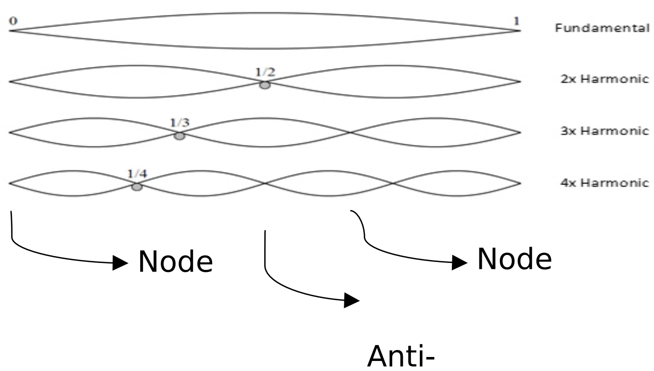
1) Length
2) Mass (Depends on Material, Thickness)
3) Tension

Assuming **Mass and Tension are equal** for 2 strings of **different length =** , , or

Harmonics of String:

Number	Frequency	Nodes	Antinodes
1^{st}			
n^{th}			

*Including the ends

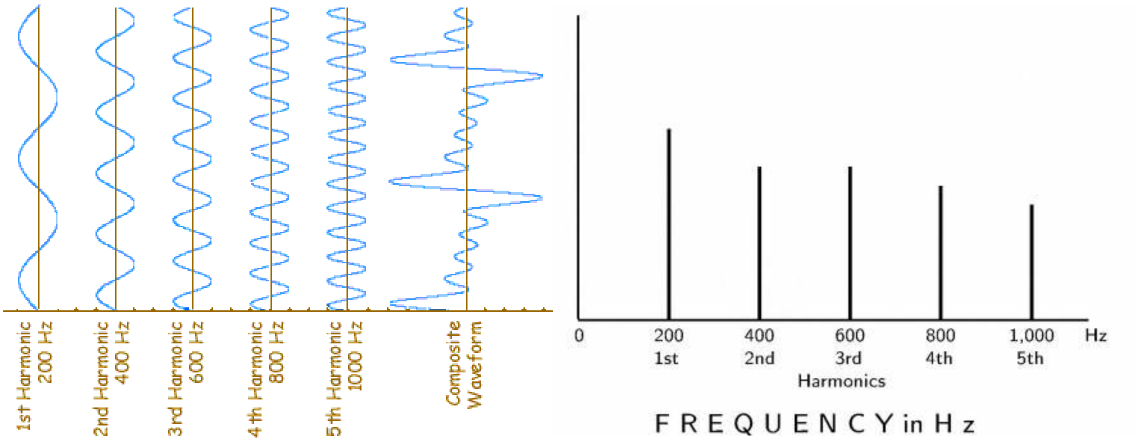


Combing Harmonics:

- A string (or any vibrating body) vibrates as a combination of its fundamental and **some** of its harmonics simultaneously when it is vibrating freely
- The **type of harmonics present**, and **their strengths** determine the timbre of the sound. Not all harmonics are always present.

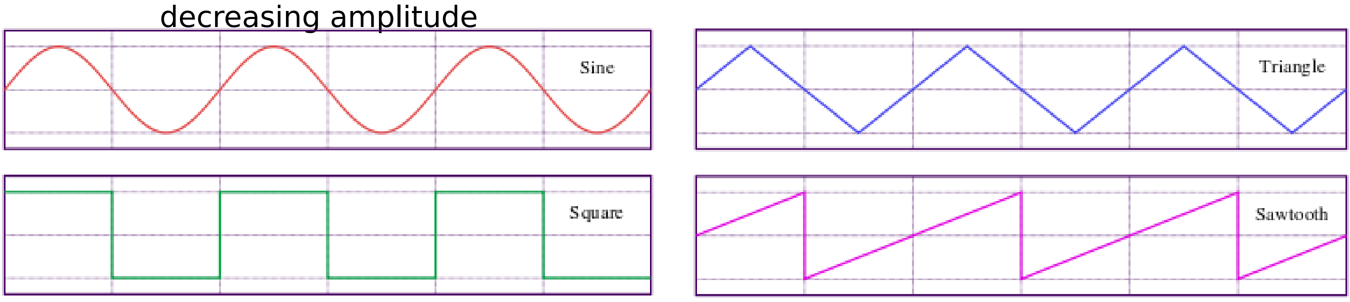
Frequency Spectrum:

- Represents the **harmonics present** and their **amplitudes** of a waveform using **vertical lines of different lengths** along an axis
- For example, this waveform with the following 5 harmonics has this spectrum
- The gap between **doubled frequencies** is usually represented with the **same gap** using a logarithmic scale to acknowledge the **doubling** of a **frequency** is an **octave**
- Measured using a spectrum analyser



Types of Waveform:

1) Sine
    - Pure wave
    - The **fundamental** and **individual harmonics** of a waveform has this shape
2) Sawtooth
    - Combined waveform, made up the **fundamental** and **all the harmonics**, of decreasing amplitude
3) Square
    - Combined waveform, made up of only the **fundamental** and **odd harmonics**, of decreasing amplitude



Waveform VS Vibrations VS Wave:

- Vibration is the **movement** of a **single object**, while a waveform/wave is the **signature of the vibration**, and is made up of the **vibration of many particles**
- A single particle alone can vibrate but cannot make up a wave
- A wave is associated with several particles or bodies, each vibrating to give the **overall wave**

Characteristics of Waves:

- Wave occupies space, and exists in an extended object or medium (e.g. the air, a string)
- Consists of the vibrations of many objects or particles
- Can result in the motion of one or more wave disturbances travelling across the particles which make up the wave. Particles themselves do not travel with the disturbance
- The wave disturbances which travel can carry energy with them

Ways to categorise waves:

1) Movement of Particles
   a) Standing Wave
      - The different parts of the string all **move up/down at the same time**
      - **Nodes** and **antinodes** remain at the **same place**
      - Examples are the fundamental and Harmonic Modes of a vibrating strings
   b) Travelling Wave
      - The **different** parts of the string **move up/down out of phase** (not at the same time) with one another
      - The individual parts are only moving up and down actually, but wave looks like its travelling left to right

2) Direction of Particle Movement
   a) Transverse Waves
      - **Particles** moving in a **direction perpendicular/transverse** to the **direction** of **wave travel**
      - Results in **peaks** and **troughs**
   b) Longitudinal Waves
      - **Particles** moving the **direction parallel** to the **direction** of **wave travel**
      - Has **compressions** and **rarefactions** instead
      - Examples are sound waves in the air, where the compressions and rarefactions are changes in air pressures

Examples of Waves	**Transverse**	**Longitudinal**
Standing	Fundamental Frequency or harmonic of a **vibrating string**	Fundamental Frequency or harmonic in a **pipe** (e.g. wind instrument)
Travelling	Kallang Wave, water waves, waves from shaking a rope up and down	Sound wave travelling from a musical instrument to a listener

Measurements of Travelling Waves:

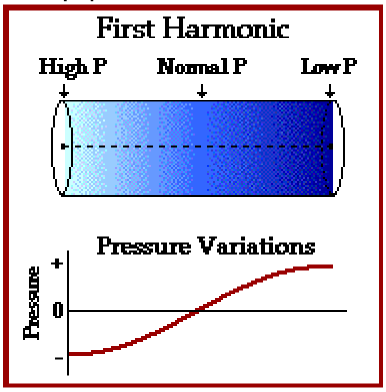
Property	**Meaning**
Wavelength	- Length of a complete wave measured from crest to crest, i.e., the **length of one cycle** - Usually denoted by
Frequency	- Number of complete wavelengths in a second - Complete to and fro motions of the particle
Wave Velocity	- Velocity = Wave length x Number of Cycles per second - Constant regardless of wavelength or frequency is constant - Thus, ,

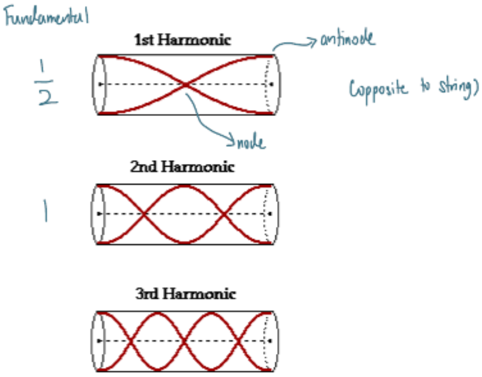
Wavelengths

- One complete wavelength of a standing wave can be measured from any point in the wave to the next corresponding point (e.g. crest to crest)
- The fundamental frequency of a string has nodes on either end, and an antinode on the middle. From one node to the next, it is half the wavelength of the standing wave, and hence, the fundamental frequency of a string has a standing wave half a wavelength along the length of the string.
- Higher harmonics has shorter wavelengths, and hence, higher frequencies
- Standing wave on a string is due to two travelling waves on the string travelling in opposite directions and are repeatedly reflected from the two ends.
- One note to the next note is half a wavelength

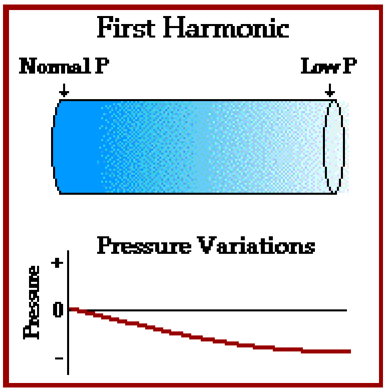
Pipes: A wind instrument may be classified as either one of 2 types of pipes

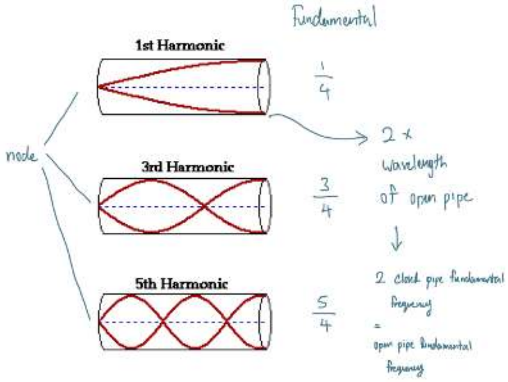
1) Open Pipe
   - Open at both ends, each end has an antinode of the standing wave, as air molecules can vibrate most freely there
   - The fundamental has a standing wave with one node in the middle, and the second harmonic has two nodes, so it is like two shorter pipes half the length of the pipe, with double the frequency.





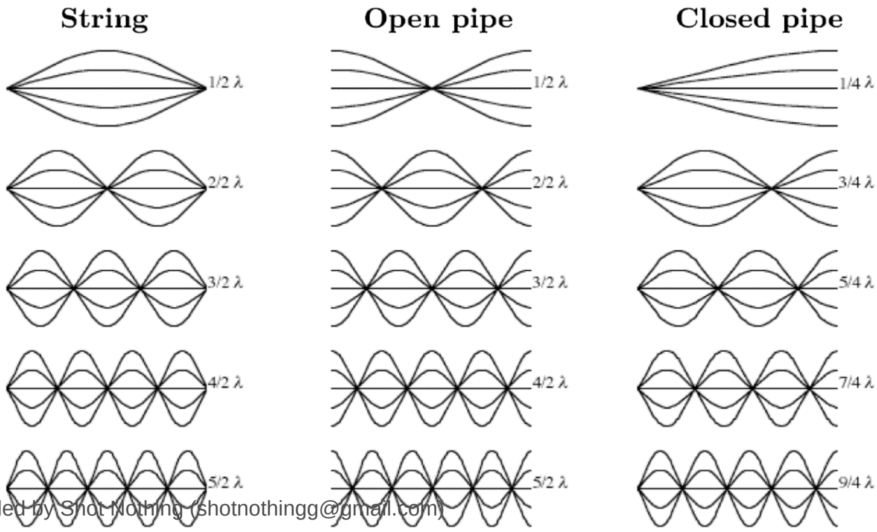
2) Closed Pipe
   - Node at the closed end and antinode at the open end
   - Half the standing wave pattern of the open pipe, and double the wavelength of an open pipe
   - Only odd harmonics (3,5,7,...) can be formed in such a pipe





* Harmonics in Strings and Pipes

- String and open pipe have fundamentals with half a wavelength (wavelength is double length of string/pipe)
- Closed pipe has a quarter wa
- Wavelength of fundamental f
  length, and hence,
- Fundamental frequency of clo



Type	Harmonic	Nodes	Antinodes
Closed			
Open			

*Including the ends

*

Elements of Music:

1) **Rhythm** – Time pattern of music notes
2) **Melody** – Series of notes of various pitches
3) **Chord** – 2 or more notes played together
4) **Harmony** – Series of Chords
5) **Counterpoint** – 2 or more different melodies played at the same time
6) **Form** – Structure or shape of music
    - Binary Form – A:B
    - Ternary Form – A:B:A
7) **Orchestration/Instrumentation** – Allocation of music to 1 or more musical instruments for a performance

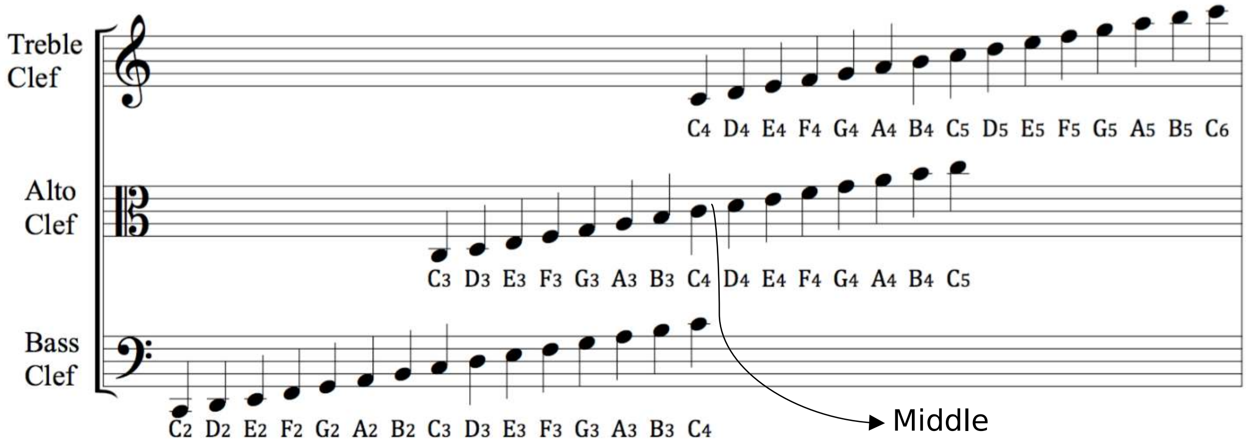
Musical Notation:

1) Notes

Name	Beat s	Note	Rest	Dotted (Add Half)	Beat s	Note	Rest
Semibreve Whole Note		w	W	**Dotted Semibreve**		R	
Minim Half Note		h	H	**Dotted Minim**		d	D
Crotchet Quarter Note		q	Q	**Dotted Crotchet**		j	J
Quaver Eighth Note		e	E	**Dotted Quaver**		i	I
Semiquaver 16th Note		s	S	**Dotted Semiquaver**			
Demisemiquaver 32nd Note				**Dotted Demisemiquaver**		You know how it looks like	

A triplet t is the duration of one crotchet

2) Clefs and Staff



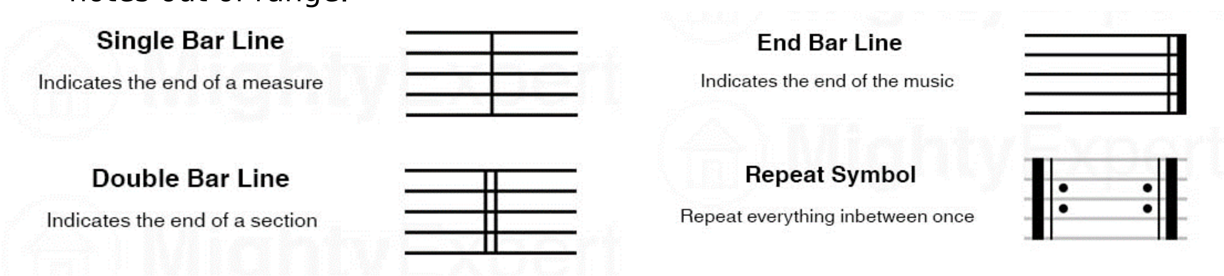
3) Time Signature and Beats (Come after Key Signatures)

(→ Number of beats in a bar, 2 = duple time, 3 = triple time, 4 =
→ Duration of a beat

% means crotchet (quarter) beats in a bar/measure

$		c ,	@		C

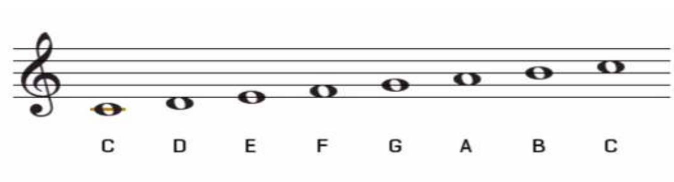
4) Staves
   - Made up of 5 horizontal lines. Additional lines called ledger lines are added for notes out of range.



<u>Key Signature and Scales:</u>

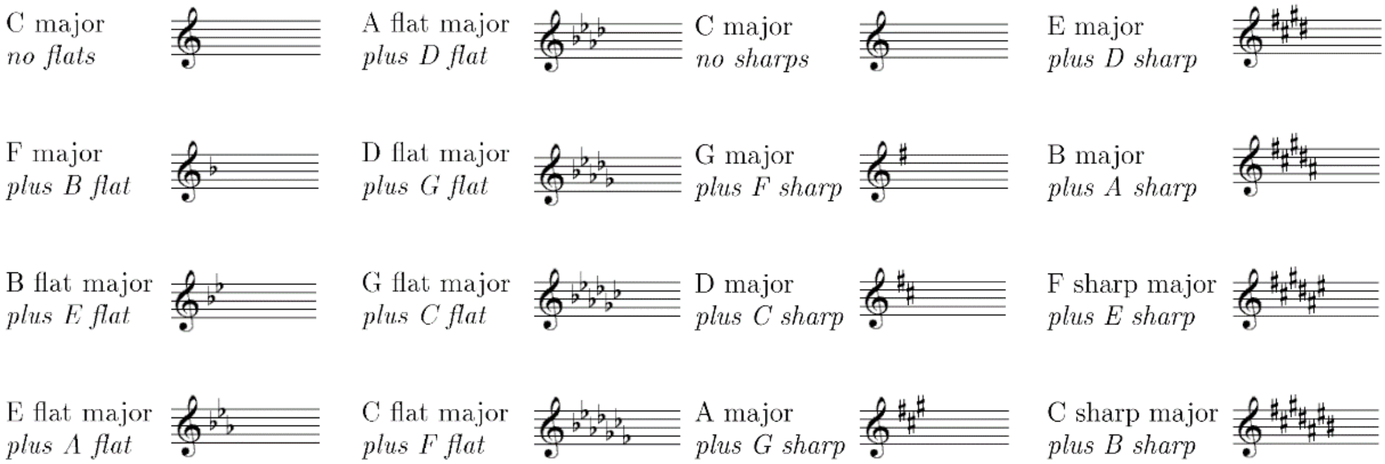
A major scale can be broken into 2 parts, with a Tone-Semitone pattern characteristic of major scales (TTSTTTS)

Lower Upper



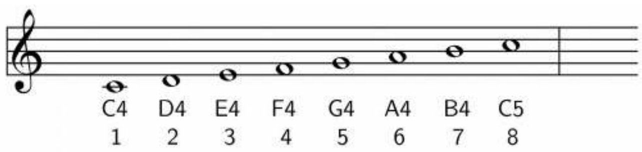
Ton Ton Semito Ton Ton Ton Semito

Modulation is possible using the Equal-tempered scale. By shifting the Upper Tetrachord down to the Lower Tetrachord over and over, and using Equal-tempered intonation to add sharps or flats, we can get any major scale

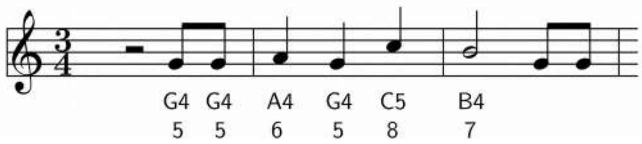


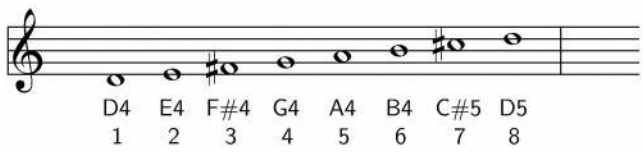
<u>Melodies as a Sequence of Intervals</u>

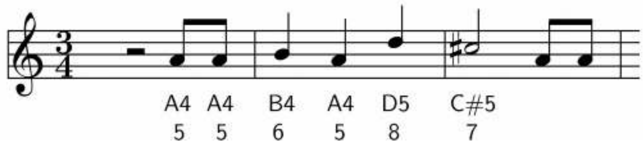
The notes of all melodies can be written as positions of notes in a certain scale. By using the same position of notes of a different scale, and thereby using the same sequence of tones and semitones, we can get the same melody in a different key.



The first phrase of “Happy Birthday” in the key of C consists of the notes G4, G4, A4, G4, C5 and B4 from the scale of C, which are notes numbered 5, 5, 6, 5, 8 and 7 in the scale of C



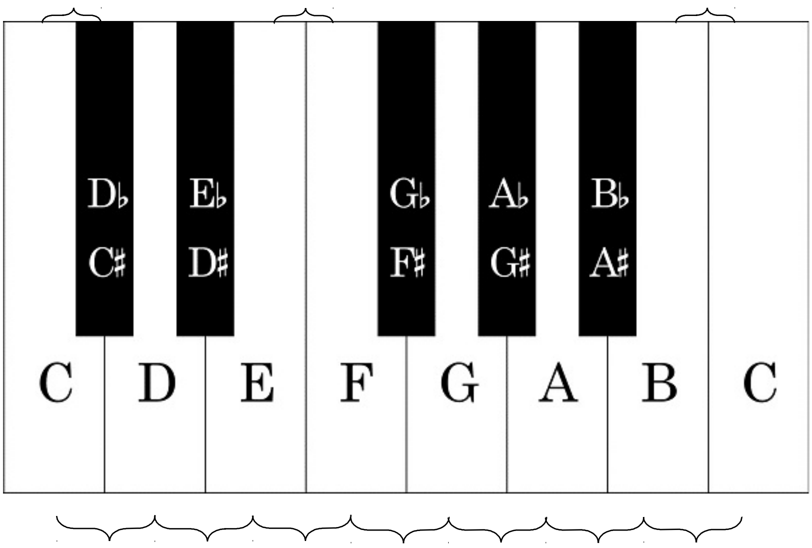


The first phrase of “Happy Birthday” in the key of D consists of the notes A4, A4, B4, A4, D5 and Csharp5 from the scale of D, which are also numbered 5, 5, 6, 5, 8 and 7 in the scale of C

<u>Other Types of Scales</u>

1) Indian Scales
   - Octave divided into 22 notes
2) Indonesian Gamelan Scales
   - 2 Types: Balinese and Javanese
   - Balinese use a seven-note scale called *Pelog* while the Javanese use a five-note scale called the *Slendro*
   - Slendro is like the common Pentatonic Scale while the Modern Pelog usually uses 5 of the 7 notes, namely **C, D Flat, E Flat, G, and A Flat**

<u>The Piano Keyboard:</u>

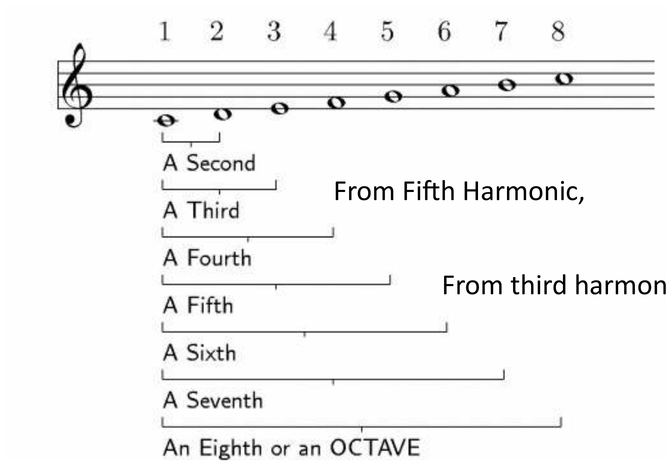
Semitone Semito Semitone (½ Tone = **Square Root** of



Ton Ton **Semito** Ton Ton Ton **Semito** **12 semitones =

<u>Intervals and Ratios:</u>

A musical interval is the **ratio of the frequency** of a **higher** note to a **lower** note



From Fifth Harmonic,

From third harmonic,

The **name** of the intervals **applies** for **any two notes**, but the **numerical ratios** between two different intervals of the same name may be different depending on the scale used.

By using only Fifths staring at C, we can obtain the pentatonic Scale – C, D, E, G, A, B

3 Types of Scales:

1) Pythagorean Scale
   - Built on only 2 intervals: Octave and Fifth - Same ratios using Guan Zi (next page)

Note	C	D	E	F	G	A	B
Mult/Div C by							
Ratio Relative to C							
Bring to same octave							
Pythagorean Ratio							

2) Just Scale
   - Built on 3 Intervals: Octave, Third, and Fifth (E, A, B Changes)

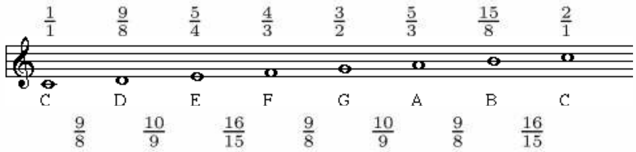
Note	C	D	E	F	G	A	B
Mult/Div C by							
Ratio Relative to C							
Bring to same octave							
Just Ratio							

3) Equal-Tempered Scale
   - Built on only 2 intervals: Octave and **Reduced** Fifth

Note	C	D	E	F	G	A	B
Mult/Div C by							
Ratio Relative to C							
Bring to same octave							
Tempered Ratio							

Comparison of Scales:

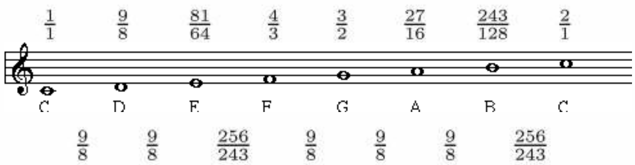
In the Just scale the intervals are perfect, but the fifth from D to A is too small.



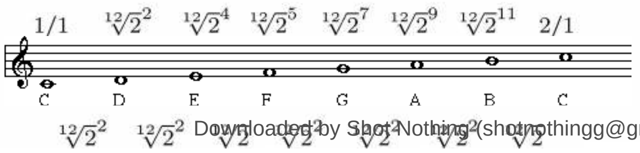
2 Types of Tones - VS

Semitone not half of tone

In the Pythagorean scale all the fifths are perfect, but the thirds are too large.



Semitone not half of

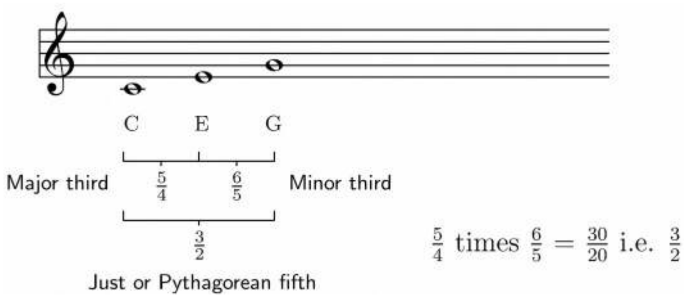
In the Equal-tempered scale the fifths are almost perfect, and the thirds are better than the Pythagorean scale.

Semitone half of

Types of Commas:

1) Syntonic Comma
    - Difference Between **The Thirds** in the Pythagorean (obtained using Fifths) and Just scale
    - Can be avoided through **reducing** the **Pythagorean Third** by using as the Fifths' ratio instead of
    -
2) Pythagorean Comma
    - 12 Fifths up should give 7 octaves, but 12 Fifths are bigger than 7 Octaves
    -

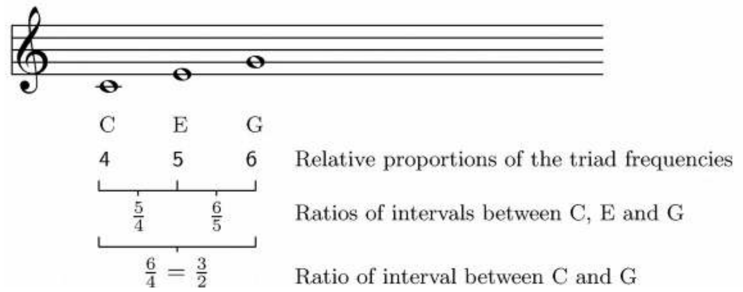
Major and Minor Thirds:

- A Fifth is made up of 2 Thirds
- But these 2 Thirds have different ratios due to the uneven spacing in the **Just Scale**



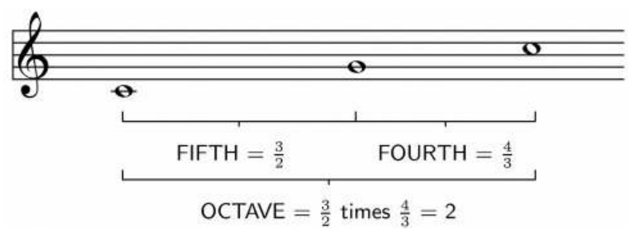
The Triad Chord:

- A chord made up of 3 notes, commonly a **Root**, its **Third**, and its **Fifth**
- The C Major Triad has a 4:5:6 Ratio in the **Just Scale**



The Fourth as the Inversion of the Fifth:

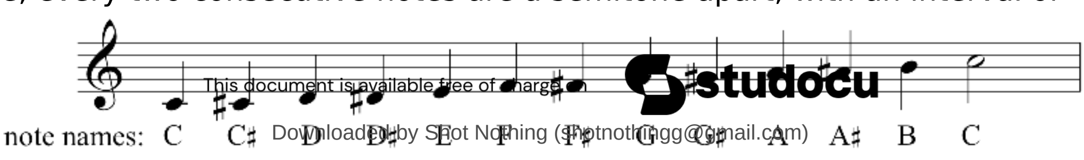
- Going up by A Fifth and then up by A Fourth make an octave
-



- Using the Chinese Up and Down (Guan Zi) Method, the Pythagorean Scale can be obtained from C by going up by a fifth , and then down by a fourth to get G, D, A, and E, making up the Chinese Pentatonic Scale
- Zhu Zaiyu used a similar method, but with more accurate ratios for Fifths and Fourths for more accurate intervals, and obtained the closest to the 12-tone Equal-tempered Scale back then

12-tone Equal-tempered Scale:

In this scale, every two consecutive notes are a semitone apart, with an interval of

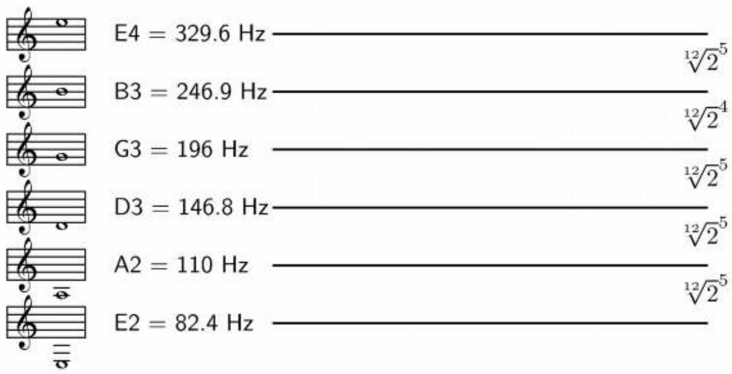


Tuning of Different Instruments:

1) Piano
   - Each key is tuned to the 12-tone equal-tempered scale as above

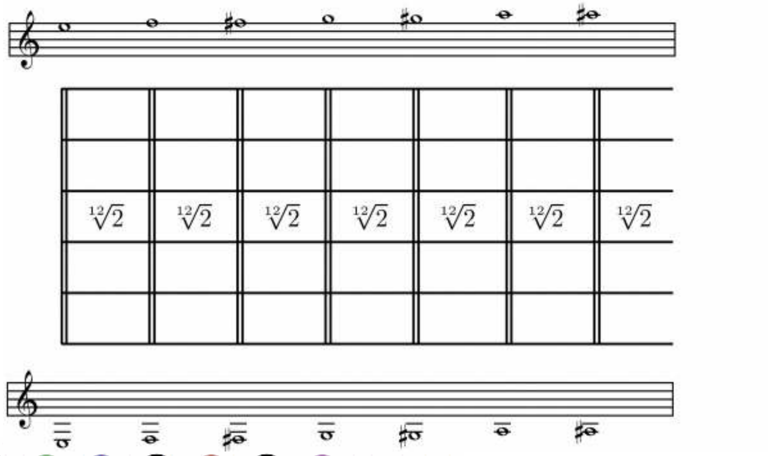
2) Guitar
   - A guitar has 6 strings, and used equal-tempered tuning

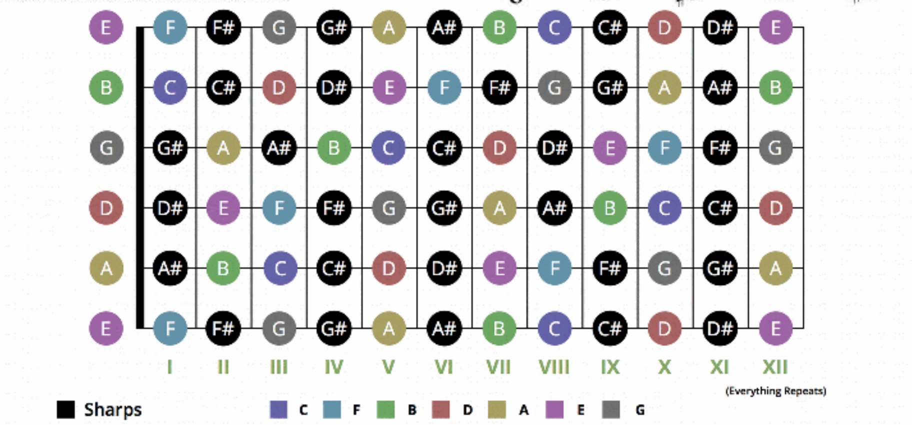
The guitar has six strings tuned to E2, A2, D3, G3, B3 and E4. The notation is an octave higher than the actual pitch.



Between each adjacent pair of strings is an Equal-tempered fourth, except for an Equal Tempered third between G3 and B3.

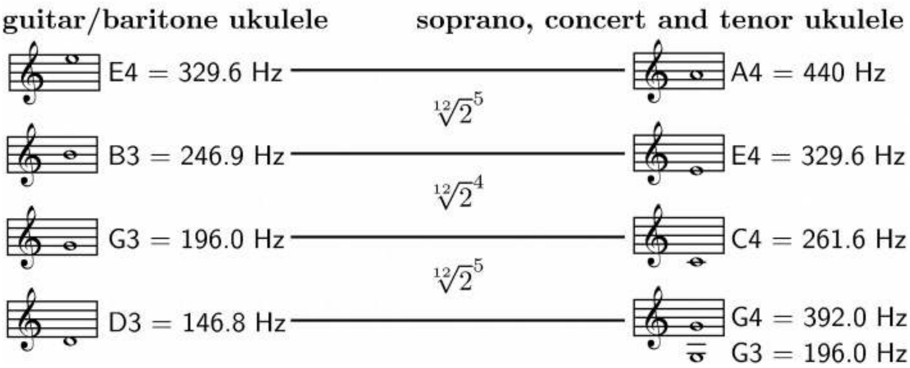
Each successive fret of the guitar raises the pitch of the string by one Equal-tempered semitone.





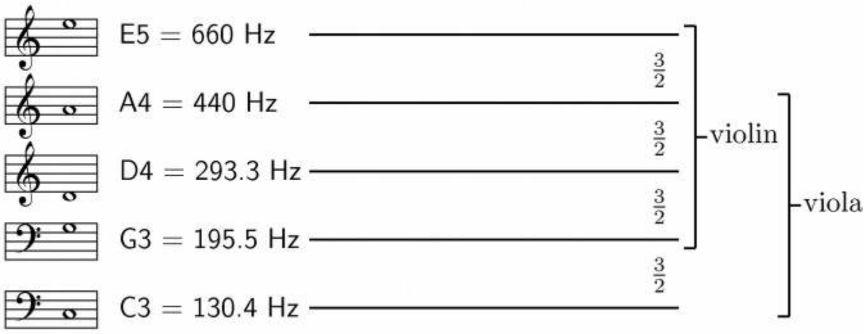
3) The Ukulele Family

Move the four highest guitar strings i.e. D3, G3, B3 and E4 up a fourth and you obtain the notes G3, C4, E4 and A4, the notes of the four strings of the soprano, concert and tenor ukulele. However, the lowest ukulele string is commonly tuned (particularly for the soprano and concert) one octave higher to G4, so that the 4 strings are G4, C4, E4 and A4. The baritone ukulele is tuned the same as the four top strings of the guitar.



4) Violin, Viola, Cello

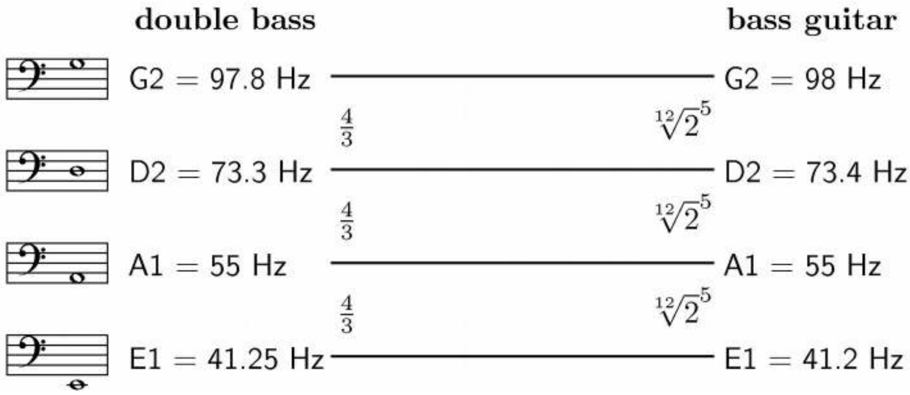
The violin has four strings tuned in perfect Pythagorean fifths with a ratio of $\frac{3}{2}$ to G3, D4, A4 and E5. The viola also has four strings tuned in perfect Pythagorean fifths but to C3, G3, D4 and A4.



Between each adjacent pair of strings is a Pythagorean or Just fifth. The violoncello or 'cello has 4 strings which are tuned one octave lower than those of the viola.

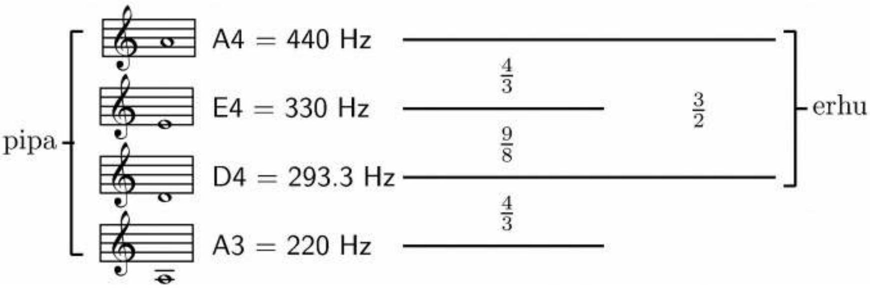
5) Double Bass and Bass Guitar

The double bass has four strings tuned in perfect Pythagorean fourths with a ratio of $\frac{4}{3}$ to E1, A1, D2 and G2. The bass guitar also has four strings, tuned to the same notes, but in Equal Tempered fourths with a ratio of $\sqrt[12]{2}^5$, one octave below the four lowest strings of the guitar. The double bass and bass guitar strings thus have slightly different frequencies. (The notation is an octave above the actual pitch.)



6) Erhu and Pipa

The erhu (二胡) and the pipa (琵琶) are tned to the Chinese pentatonic scale. The erhu has two strings which are tuned to the interval of a Just or Pythagorean fifth with a ratio of $\frac{3}{2}$, to D4 and A4, (These are the same frequencies as the two middle strings of the violin.). The pipa has four strings which are tuned to A3, D4, E4 and A4. The intervals between these four strngs are thus a Just or Pythagorean fourth with a ratio of $\frac{4}{3}$, a Just or Pythagorean second with a ratio of $\frac{9}{8}$, and a Just or Pythagorean fourth with a ratios of $\frac{4}{3}$.

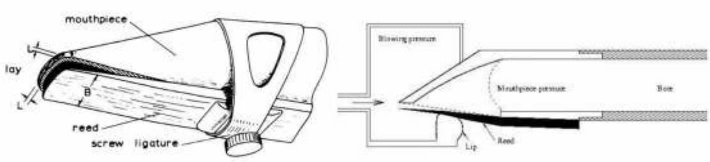


Setting off Vibrations in Different Instruments:

1) String
    - Beaten or Hammered
    - Plucked
    - Stroked or Bowed
    - Blown
2) Reed and Pipe (requires a physical body to vibrate at one end of the pipe)
    - Stream of air striking a sharp edge
    - Air stream between single reed and mouthpiece
    - Air stream between double reeds
    - Player's lips vibrating into pipe
3) Free reed
    - Free reed blown by mouth
    - Free reed blown by hand/foot-operated bellows
    - Free reed blown by mechanically cranked bellows

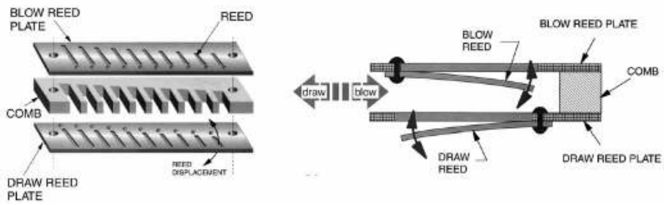
Clarinet reed

The clarinet reed is a single reed which is fixed to the solid mouthpiece by the ligature. The reed is able to vibrate towards and away from the mouthpiece. The player forces a thin stream of air between the reed and the mouthpiece, creating a lower pessure region between the reed and the mouthpiece. The reed is forced to move towards the mouthpiece and shuts off the air flow into the pipe. The reed is elastic and springs back to allow the air flow to resume. Hence a regularly interrupted airflow enters the pipe, causing a longitudinal standing wave to form. The frequency of this standing wave is determined by the pipe length, and the reed will vibrate at this frequency too.



The harmonica

The harmonica is a mouth blown free reed instrument. The instrument presents a horizontal row of holes for the player's mouth. The holes are part of the main body of the harmonica called the *comb*. Two reed plates each carrying one reed for each hole are mounted on the top and bottom of the comb. The player blows into or draws (sucks) from a hole. The blow reed on the top reed plate will vibrate when the player blows, and the reed on the bottom plate vibrates when the player draws. In this way, each hole can produce two different pitches. The vibrating reed is closely coupled to the mouth cavity, so the player can alter the frequency by changing the mouth cavity volume.



Interference and Beats

When two waveforms which have frequencies close to each other are sounded together, the combined waveform will vary in amplitude at a regular rate. The rate of variation will be the differences of the two frequencies
If and are two frequencies, then the beat frequency is

*In a spectrum where the fundamental is weak or missing, the beats from the 2^{nd} and 3^{rd} harmonic combining can form the fundamental to replace it.

Beats below Hz can be heard as individual beats while beats between Hz are perceived as unpleasant noises called Wolf Tones.

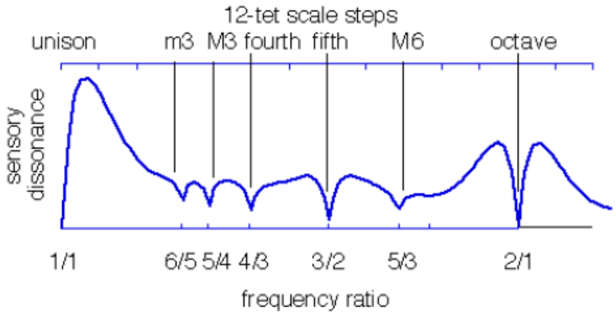
Consonance and Dissonance

When two notes are sounded together, they may sound pleasant (consonance) or unpleasant (dissonance) together. The degree of consonance or dissonance depends on how many harmonics they share.

To find the number of shared harmonics in the first harmonics of a note and another note that differs by a ratio of , then the number of shared harmonics is

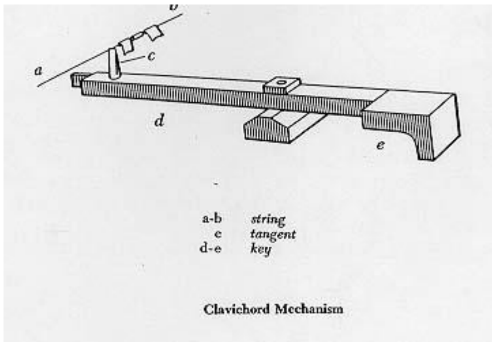
Consonance/dissonance from unison to octave

We can plot the graph of perceived dissonance for a *continuous* range of intervals, starting from unison to an octave. This is done by sounding two notes in unison, say C, and then increasing the frequency of one note smoothly until it reaches the C one octave above. In this graph, we can see "valleys" of consonance at the important intervals such as the octave, the fifth and the third. The dissonance is the highest at the frequency differences between the two notes at which their harmonics combine to form beats which are perceived as most rough.



<u>History of Piano</u>

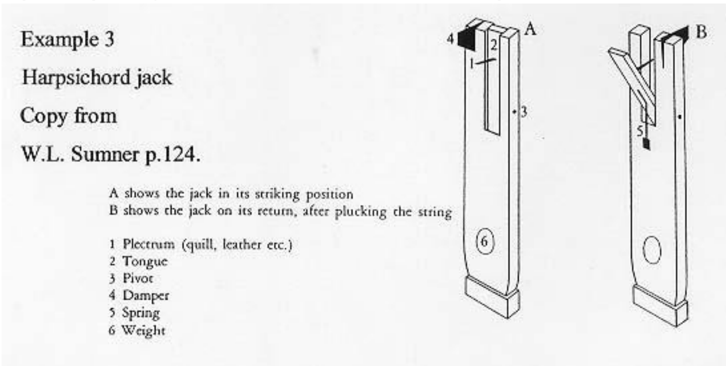
1) Clavichord

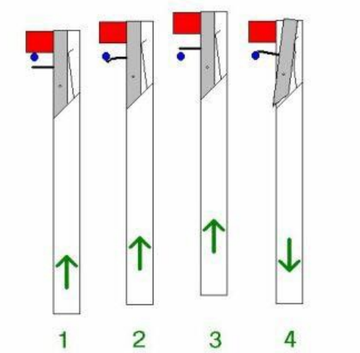


- One end of the clavichord key has a meal piece called a tangent which remains in contact with the string after striking it
- Player can affect tone of string with the pressure on the key while the string is vibrating – giving it great powers of expression not available even with the piano
- However, this makes the sound weak as the tangent cannot strike the string strongly

2) Harpsichord

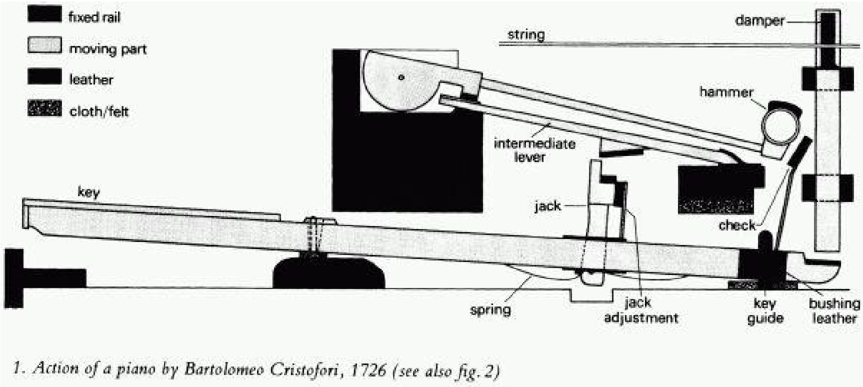
- Harpsichord key plucks the string with a plectrum such as a quill, mounted on a jack. The quill is fitted on a tongue which can pivot backwards.
- The quill can impart stronger vibrations to the string than the clavichord tangent.
- The quill will pluck the string with the same speed no matter how the key is struck, giving the same loudness no matter how the key is pressed
- The harpsichord jack is lifted when the key is struck, so that the quill plucks the string. When the quill goes down, it is pushed out of the way by the tongue so that the string is not plucked, and the tongue is pulled back to its normal position by a spring. This is called an escapement.





3) Cristofori Piano

- Converts downwards movement of key when it is depressed to a much faster upward movement of the hammer. The hammer is thus flung upwards freely like a projectile to hit the string
- The loudness of the note produced is determined by the velocity of the hammer, and the key velocity
- The jack has a notch that enables it to get out of the way or escape, enabling the hammer to rebound and fall back even while the player is still depressing the key.
- The fall-back distance of the rebound is thus longer than the free flight before striking. The shorter the free flight the more control the player has over the loudness.
- A spring brings the jack back to its original position when the key is released.



1. *Action of a piano by Bartolomeo Cristofori, 1726 (see also fig. 2)*

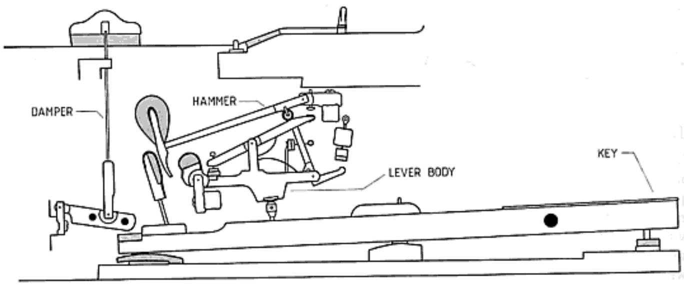
4) Dulcimer
   - Ancient instrument consisting of several strings stretched over a wooden framework. The instrument is played by hammering the strings with two hammers held by the performer

<u>Modern Grand Piano</u>

- Main Parts of a Piano
  - Cast-iron frame/plate: Enable strings to carry tension up
  - Soundboard – Amplifies sound produced by strings
  - Bridge – Transfers sound from strings to soundboard
  - Pinblock – Holds tuning pins around which strings are wo
  - Action – Responsible for activating hammers from keyboa
  - Keyboard – Interface with player
  - Pedals – Allows plater to control sustaining of string vibra
  - Case – Protective and decorative outer coating

- Important Developments:
  - Double Escapement: Rapid repetition of notes
  - Cast Iron Frame: Increased string tensions, and allow hammers to strike the strings with greater force and produce greater loudness
  - Overstringing: Overstring lower strings over upper strings to reduce overall length
  - Upright Piano: Compact piano for domestic use

- Repetition lever
  - Enables hammer to be struck again before the actual escapement mechanism can complete its action
  - Enables repeated notes to be played faster than allowed by escapement
  - Jack protrudes through a groove in the repetition lever to contact the knuckle or roller
  - If key is partly released, hammer will be released from the back check. The repetition lever lifts the hammer and moves the knuckle up, allowing the jack to slip back under it. It will be in position to enable the hammer to strike the string again if the key is depressed another time.



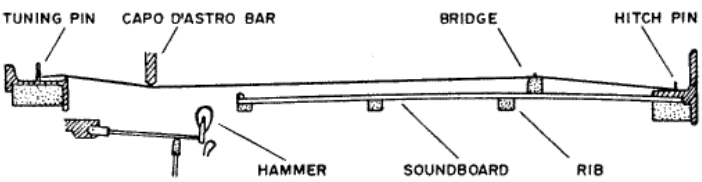


Fig. 17.1.

- Piano String and Soundboard
    - String between tuning pin and hitch pin. Vibrates between Capo d'astro and Bridge.

Upright VS Grand

- Upright action is more complex and less responsive
- Upright's strings, frame, and soundboard are vertical. Key activates the action through a vertical level (sticker)
- Hammers hit strings horizontally in the upright, but vertically in the grand
- Hammers are pulled back by bridle tape in the upright, but by gravity in the grand
- Jack provides an escapement like the Grand, and the jack spring returns under the butt of the hammer for the next note
- In the upright, the soft pedal works by placing hammers closer to the strings, but in the grand the hammers shift to strike only one string
- The upright occupies a smaller floor area than the grand

In-depth of parts of piano

1) Hammers and Voicing
   - Piano hammers are made of wood, with a covering of wool felt which is compressed on the inside and highly stretched on the outside. This makes the hammer compress and bounce well.
   - As the hammer hits the string over a long period, its contact point with the string becomes flatter, and the may have to be reshaped.
   - Contact point may become more compressed and harder, and tone is harder. To counter this, the hammer may be pierced with needles around the contact point to soften the surface (voicing)

2) Piano Strings
   - Made of steel wire of different thickness. Bass strings wound with copper wire.
   - Shortest are 2 inches and longest are 84 inches

Notes	Lowest 10-15	Next 20 or so	Remaining
Strings	One string of very thick steel wrapped with two layers of copper winding	2 strings each, smaller in thickness, with one thinner copper winding	3 steel strings with no copper winding.
Decreasing thickness or gauge			

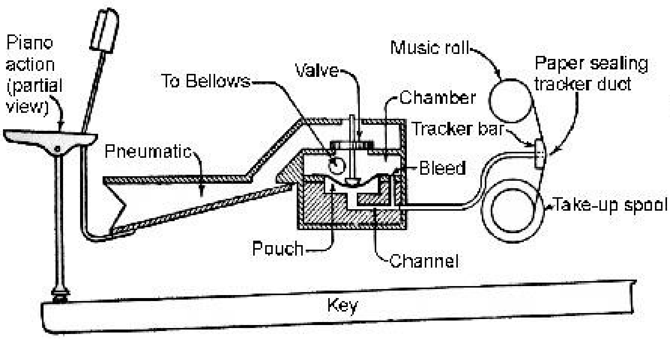
3) Piano Pedals
   - Every string has a damper which normally is in contact with the string but is lifted to allow it to vibrate as along as the key is depressed.
   - From left to right, the keys are:
     - **Soft Pedal**: Shifts the hammers so that they strike only one string
     - **Sostenuto Pedal**: When one or more notes are played, and this pedal is then depressed, only these notes will be sustained (have their dampers off)
     - **Sustain Pedal**: Lifts all the dampers to let all the strings freely vibrate
   - To use middle/Sostenuto pedal:
     - Play a note
     - While keeping key pressed, press pedal to lift dampers
     - Release keys, notes still sustained

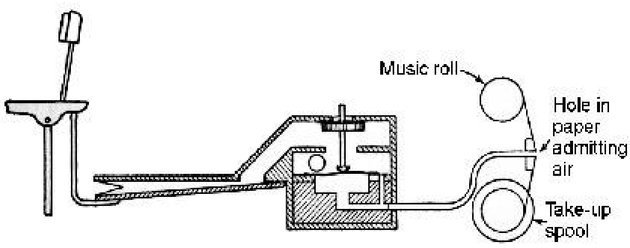
Automated Pianos

- Mechanical Pianos: Pianola, Player Piano, Reproducing Piano
- Modern Electronic Pianos: Disklavier, Pianodisc, Pianomation

1) Pianola
   - The first mechanism for playing a piano automatically
   - Driven by air pumped food pedal, a paper roll with perforations controlling felt-covered wooden “fingers” depressing the keys on a separate and normal piano

2) Player Piano
   - Incorporated Pianola mechanism in a normal piano. Hammers are activated by a change in air pressure delivered by a bellows operated by pedals
   - Loudness controlled by how vigorously the pedals are operated to increase and decrease air pressure
   - Notes selected are determined by a paper roll with perforations, like the Pianola, through which air can pass through to control a valve
   - The valve when open allows the air pressure from the bellows to active the hammer,
   - Tempo controlled by human pedal operator with tempo control
   - Sustain, bass soft, treble soft, and tempo controls are controlled through a lever





3) Reproducing Pianos
   - Introduced electric air pump to assure consistency of air pressure, and a paper roll which included extra tracks to control parameters such as pressure of air operating the hammers
   - This varies the tempo and loudness as required, allowing the reproducing piano to more successfully imitate a human player and record performances of human pianists

Paper Rolls

Channel (track)	88-key player piano	Reproducing Piano
2		Full vacuum
3	sustain	Sustain
4		Express softer
5		Express louder
6	A0	Rewind
7	$A^{\#}0$	Shut off
8	B0	B0
9 – 92	C1 to B7	C1 to B7
93	C8	C8
94		Bass Hammer Rail
95		Treble Hammer

} 88 keys

Originally paper rolls only had 58 or 65 tracks, and not all notes of 88 key piano could be played.

		Rail
96		Accent
97		Play

MIDI

- Standard General MIDI (GM1) calls for at least 24 simultaneous voices
- Modern equivalent of the perforated paper roll
- Standard method of controlling electronic musical instruments so that they will play music according to the information contained in a MIDI file
- The information includes
    - Turning notes on and off
    - Expressing loudness of each note
    - Sending program changes
    - Use of sustain pedal and other controllers, such as pitch bend or modulation wheel
    - Timing relationships of all MIDI notes and events
    - Other types of control data
- MIDI timing clock controls tempo, measured in terms of fractions of a crochet

MIDI Interface

- Any instrument with MIDI interface must have either a **MIDI IN** or **MIDI OUT** and may have a **MIDI THRU**
- **MIDI OUT** can be used to send signals from a computer, sequencer, or another instrument to control another instrument/synthesiser connected to it by its **MIDI IN**
- These ports allow for Daisy chaining of many synthesisers to control more than one at a time if a **MIDI THRU** socket is available to pass on the signal

Standard MIDI Files

- MIDI Sequence consists of a stream of MIDI messages, a stream of bytes that make up MIDI messages telling a MIDI instrument which notes to play, and how to play with the required volume, tempo, etc.
- Standard MIDI files provide a common file format used by most musical software and hardware devices to store song information including the title, track names, and what instruments to use as well as the MIDI sequence of musical events
- Standard MIDI file format allows a computer music program to create and save files that can be later loaded and edited by a different computer program.

MIDI in Mobile Phones

- Mobile phones with polyphonic ring tones generally use MIDI (a reduced form) to play them
    - GM Lite: Requires only 16 voices to be used at any one time, instead of 24 voices of GM1
    - Scalable Polyphony (SP-MIDI): Vary voices used (5 to 24), depending on capabilities of sound generator or mobile phone. Composer must specify how the voices are substituted when number is reduced
- There are also other variants such as Roland’s GS and Yamaha’s XG, which expand the instrument sets and MIDI messages to increase the variety of sounds and the expressivity of MIDI performances

MIDI Channel Voice Messages (in Decimal)

	Status Byte		Data Byte 1	Data Byte 2
	0 to 15 (4 bits)	0 to 15 (4 bits)	0 to 255	0 to 255
	Message	Channel No. (Track)	Data	Data
Note Off	8	x	Note (Key) No.	Note off Velocity
Note On	9	x	Note (Key) No.	Note on Velocity
Key Pressure	10	x	Note (Key) No.	Pressure Amount

* Although a byte (8 bits) can take decimal values 0 to 255, for Data Byte 2, values only range from 0 (lowest) to 127 (highest).
* Velocity-sensitive keyboard use note on velocity to determine loudness of the note played.

	C	**C#\Db**	**D**	**D#\Eb**	**E**	**F**	**F#\Gb**	**G**	**G#\Ab**	**A**	**A#\Bb**	**B**
0	12	13	14	15	16	17	18	19	20	21	22	23
1	24	25	26	27	28	29	30	31	32	33	34	35
2	36	37	38	39	40	41	42	43	44	45	46	47
3	48	49	50	51	52	53	54	55	56	57	58	59
4	60	61	62	63	64	65	66	67	68	69	70	71
5	72	73	74	75	76	77	78	79	80	81	82	83
6	84	85	86	87	88	89	90	91	92	93	94	95
7	96	97	98	99	100	101	102	103	104	105	106	107
8	108	109	110	111	112	113	114	115	116	117	118	119

MIDI Channel Mode and System Messages (in Decimal)

	Status Byte		Data Byte 1	Data Byte 2
	0 to 15 (4 bits)	0 to 15 (4 bits)	0 to 255	0 to 255
	Message	Channel No. (Track)	Data	Data
Reset all controllers	11	x	121	nil
Local Control	11	x	122	0 = off; 127 = on
All notes off	11	x	123	nil

MIDI system messages carry information that is not channel specific, such as timing signal for synchronisation, position information in pre-recoded MIDI sequences, and detailed setup information for the destination device.

- Real time messages, E.g. timing clock which has only a Status Bye value 248
- Common and Exclusive Messages

Using MIDI Signals to play music

When playing any piece of music using MIDI, there are steps to be taken.

- Step 1: Program Change
  First assign a program (Instrument) to a channel.

	Status Byte		Data Byte 1
	0 to 15 (4 bits)	0 to 15 (4 bits)	0 to 255
	Message	Channel No. (Track)	Data
Program Change	12	x	0 to 127, Program Number

* Can be used in the middle to change instruments as well. Most synthesisers are multi-timbral, which means that they can generate more than one type of instrument sound at any one time.

- Step 2: Turn on a note

*Multiple notes cannot be played simultaneously as only one message can be sent at one time. But MIDI messages are transmitted at 31,250 bits/s which means that one “Note On” message will take about 1 millisecond. This essentially means the notes sound like they are played together.

- Step 3: Turn off a note

For each of the channels 0 to 15 (except Channel 10), the instrument (programs) are as follows

PC #	Instrument Name	PC #	Instrument Name	PC #	Instrument Name	PC #	Instrument Name
1.	Acoustic Grand Piano	33.	Acoustic Bass	65.	Soprano Sax	97.	FX 1 (rain)
2.	Bright Acoustic Piano	34.	Electric Bass (finger)	66.	Alto Sax	98.	FX 2 (soundtrack)
3.	Electric Grand Piano	35.	Electric Bass (pick)	67.	Tenor Sax	99.	FX 3 (crystal)
4.	Honky-tonk Piano	36.	Fretless Bass	68.	Baritone Sax	100.	FX 4 (atmosphere)
5.	Electric Piano 1	37.	Slap Bass 1	69.	Oboe	101.	FX 5 (brightness)
6.	Electric Piano 2	38.	Slap Bass 2	70.	English Horn	102.	FX 6 (goblins)
7.	Harpsichord	39.	Synth Bass 1	71.	Bassoon	103.	FX 7 (echoes)
8.	Clavi	40.	Synth Bass 2	72.	Clarinet	104.	FX 8 (sci-fi)
9.	Celesta	41.	Violin	73.	Piccolo	105.	Sitar
10.	Glockenspiel	42.	Viola	74.	Flute	106.	Banjo
11.	Music Box	43.	Cello	75.	Recorder	107.	Shamisen
12.	Vibraphone	44.	Contrabass	76.	Pan Flute	108.	Koto
13.	Marimba	45.	Tremolo Strings	77.	Blown Bottle	109.	Kalimba
14.	Xylophone	46.	Pizzicato Strings	78.	Shakuhachi	110.	Bag pipe
15.	Tubular Bells	47.	Orchestral Harp	79.	Whistle	111.	Fiddle
16.	Dulcimer	48.	Timpani	80.	Ocarina	112.	Shanai
17.	Drawbar Organ	49.	String Ensemble 1	81.	Lead 1 (square)	113.	Tinkle Bell
18.	Percussive Organ	50.	String Ensemble 2	82.	Lead 2 (sawtooth)	114.	Agogo
19.	Rock Organ	51.	Synth Strings 1	83.	Lead 3 (calliope)	115.	Steel Drums
20.	Church Organ	52.	Synth Strings 2	84.	Lead 4 (chiff)	116.	Woodblock
21.	Reed Organ	53.	Choir Aahs	85.	Lead 5 (charang)	117.	Taiko Drum
22.	Accordion	54.	Voice Oohs	86.	Lead 6 (voice)	118.	Melodic Tom
23.	Harmonica	55.	Synth Voice	87.	Lead 7 (fifths)	119.	Synth Drum

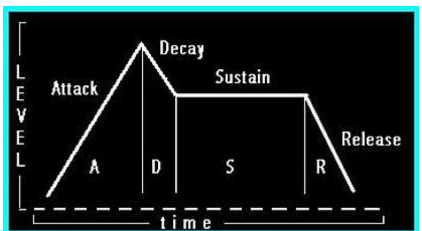
24.	Tango Accordion	56.	Orchestra Hit	88.	Lead 8 (bass + lead)	120.	Reverse Cymbal
25.	Acoustic Guitar (nylon)	57.	Trumpet	89.	Pad 1 (new age)	121.	Guitar Fret Noise
26.	Acoustic Guitar (steel)	58.	Trombone	90.	Pad 2 (warm)	122.	Breath Noise
27.	Electric Guitar (jazz)	59.	Tuba	91.	Pad 3 (polysynth)	123.	Seashore
28.	Electric Guitar (clean)	60.	Muted Trumpet	92.	Pad 4 (choir)	124.	Bird Tweet
29.	Electric Guitar (muted)	61.	French Horn	93.	Pad 5 (bowed)	125.	Telephone Ring
30.	Overdriven Guitar	62.	Brass Section	94.	Pad 6 (metallic)	126.	Helicopter
31.	Distortion Guitar	63.	SynthBrass 1	95.	Pad 7 (halo)	127.	Applause
32.	Guitar harmonics	64.	SynthBrass 2	96.	Pad 8 (sweep)	128.	Gunshot

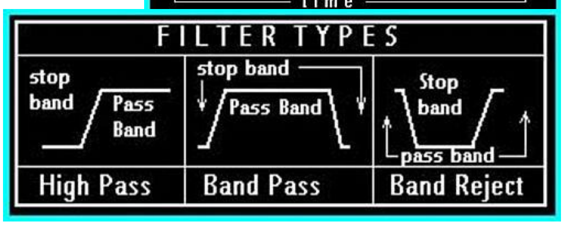
Channel 10 (Out of the 16 Channels 0 to 15) is reserved for percussion, and the instruments are as follows

PC #	Instrument Name	PC #	Instrument Name	PC #	Instrument Name	PC #	Instrument Name
35.	Acoustic Bass Drum	47.	Low-Mid Tom	59.	Ride Cymbal 2	71.	Short Whistle
36.	Bass Drum 1	48.	Hi-Mid Tom	60.	Hi Bongo	72.	Long Whistle
37.	Side Stick	49.	Crash Cymbal 1	61.	Low Bongo	73.	Short Guiro
38.	Acoustic Snare	50.	High Tom	62.	Mute Hi Conga	74.	Long Guiro
39.	Hand Clap	51.	Ride Cymbal 1	63.	Open Hi Conga	75.	Claves
40.	Electric Snare	52.	Chinese Cymbal	64.	Low Conga	76.	Hi Wood Block
41.	Low Floor Tom	53.	Ride Bell	65.	High Timbale	77.	Low Wood Block
42.	Closed Hi Hat	54.	Tambourine	66.	Low Timbale	78.	Mute Cuica
43.	High Floor Tom	55.	Splash Cymbal	67.	High Agogo	79.	Open Cuica
44.	Pedal Hi-Hat	56.	Cowbell	68.	Low Agogo	80.	Mute Triangle
45.	Low Tom	57.	Crash Cymbal 2	69.	Cabasa	81.	Open Triangle
46.	Open Hi-Hat	58.	Vibraslap	70.	Maracas		

Synthesis of Waveforms

- In order to create (synthesise) musical sounds like original sounds of real instruments, we need to synthesise their waveforms. We can do this if we know the frequency spectrum (nature of harmonics), we can recreate the original waveform
- Synthesised sound can have an amplitude envelope superimposed on its amplitude, with 4 parts:
  - Attack: How the onset of the sound behaves
  - Decay: The decay of the onset from a peak value
  - Sustain: The steady portion of the amplitude
  - Release: The decay of the note to zero at the end
- Some techniques are:
  i. Additive Synthesis
  ii. Subtractive Synthesis
  iii. Amplitude Modulation (AM) Synthesis
  iv. Frequency Modulation (FM) Synthesis
  v. Wavetable synthesis and sampling
  vi. Physical Modelling

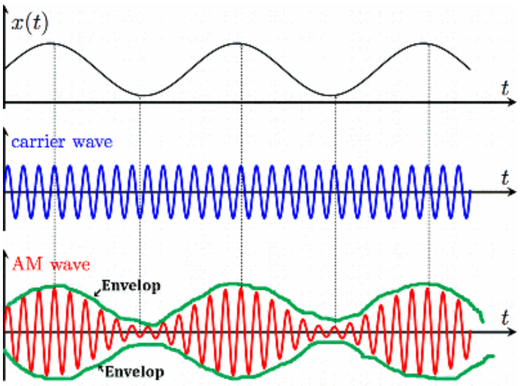




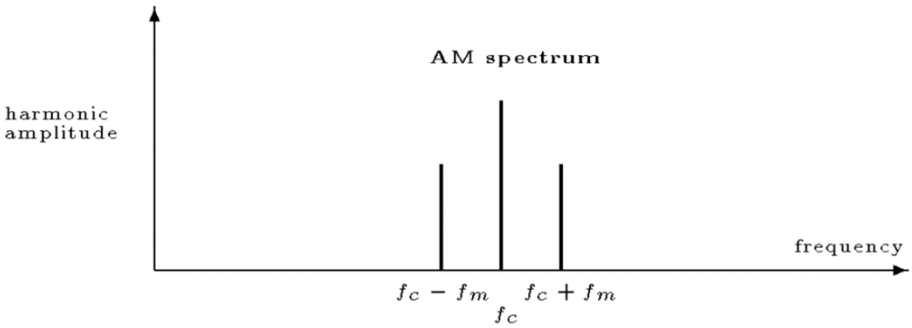
1) Additive Synthesis: Takes separate waveforms and combines them into a new waveform
   - By analysing a complex waveform, it can be broken down into several harmonics, each a simple Sine wave.
   - By using several Sine wave oscillators to generate the harmonics, we can combine them in a mixer to reproduce the original waveform

2) Subtractive Synthesis: Starts with a given waveform and subtracts its harmonics to produce a new waveform
   - By taking a waveform rich in harmonics, we can remove or reduce some so that the desired frequency spectrum is obtained.
   - This is done using subtractive filters
     - Low Pass Filter: Rejects all harmonics **above** a certain frequency
     - High Pass Filter: Rejects all harmonics **below** a certain frequency
     - Band Pass Filter: Rejects all harmonics **outside** a certain range of frequencies
     - Band Stop Filer: Rejects all harmonics **within** a certain range of frequencies

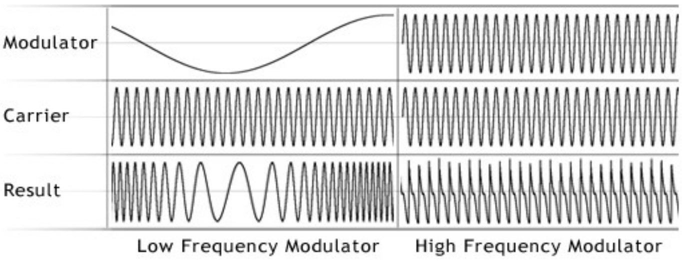
3) Amplitude Modulation Synthesis: One waveform changes the **amplitude** of the other waveform
   - A waveform of a lower frequency (modulator wave) modifies the amplitude of a waveform of higher frequency (carrier wave)
   - The amplitude of the second waveform is made to resemble the shape of the first waveform
   - If the frequency of the carrier wave is and the modulator wave is , then the spectrum of the AM carrier wave will contain the sum and the difference of and , and itself.

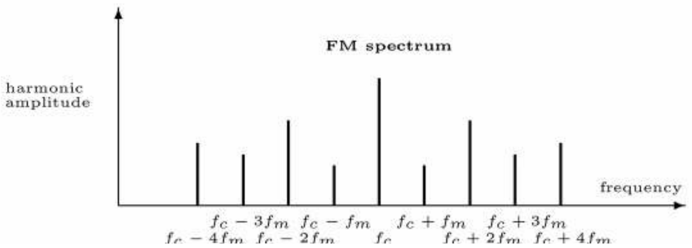


EXAMPLE OF AMPLITUDE MODULATION



4) Frequency Modulation Synthesis: One waveform changes the frequency of the other waveform
    - A carrier wave with frequency is modulated by a modulator wave with frequency (not necessarily lower) such that the carrier wave’s frequency changes according to the modulator wave’s swings.
    - This allows for more complex waveforms. The total width of the spectrum (bandwidth) depends on the modulator wave, and the shape depends on the amount by which the carrier frequency varies (modulation depth or index) and the relative values of the carrier and modulator frequencies.





    - A FM system has 2 minimum 2 waveforms, each of which is an operator: a modulator and carrier waveform. The output of an operator can become the input to another, and the outputs of 2 or more operators can be added.

5) Wavetable Synthesis and Sampling
    - Waveform is stored as a series of numerical values, obtained by sampling waveform values at regular intervals in wavetable. The waveform is generated from the values
    - We can generate the same waveform at a higher frequency by reading every 2nd or 3rd value, or lower frequency by repeating values twice or thrice.
    - Only one period of the waveform needs to be stored in memory, making it efficient in generating periodic waveforms
    - However, it can only product static spectrums, while real sounds have a dynamic spectrum
    - Keyboards and synthesisers today store sets of one-period waveforms in ROMs, and in high-end synthesisers, each of the notes of the instruments range is separately sampled

ROM Storage for Wavetable Synthesis

    - For greater realism, each note is sampled at different loudness
    - The ROM will carry all the waveforms for at least a GM set of 128 instruments stored
    - Very high-end synthesisers can accept samples of wavetables into their RAM Storage, which can be user generated or from CD-ROMs
    - Very large wavetable libraries of orchestral instrument sounds, sampled at different pitches, volumes, and articulations are available on CD-ROM for use in such systems
    - For example, the MOTU Symphonic Instrument is a library of 8GB of orchestral instrument

6) Physical Modelling
    - Physics model of the musical instrument whose sound is to be synthesised is developed
    - Must understand how the instrument produces sound from the physics/acoustics point of view
    - Physical model attempts to express in mathematical terms the behaviour of each of the components of the instrument which take part in sound production

- This method attempts to reproduce the actual physical phenomena reproducing the waveforms (no actual waveforms are stored)
- Advantage: Able to reproduce all possible changes in the waveforms corresponding to the different ways in which the sound may be produced

Electric Waves

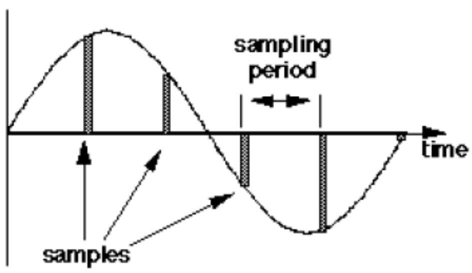
- Microphone
  - Converts vibrations of sound waves into electrical current vibrations with the same waveform
  - A thin membrane called a diaphragm is made to vibrate by the sound waves, which generates electrical waves in a wire with the same waveform as the sound waves
- Loudspeaker
  - The electrical waves generated can be carried by electrical cables in wires, radio waves in the air, or recorded on magnetic tapes
  - Using a loudspeaker, the electrical wave causes a diaphragm in it to vibrate, producing sound waves with the same waveform as the electrical wave

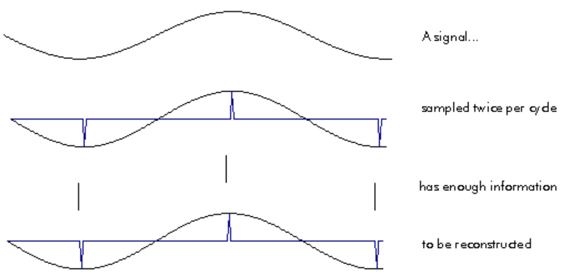
Analog and Digital Signals

- Waveforms in the real world are smooth and continuous and are **Analog.** Recordings of such waveforms on media such as cassette tape and long-playing vinyl records are also Analog.
- In computers, data is stored as numbers, each consisting of several digits. This is **Digital.**

Analog-to-Digital Conversion

- Step 1: Sampling
  - Converts waveform to a series of waveform values read at regular intervals
  - A waveform is input into an electronic circuit controlled by a clock, which commands the circuit to read the waveform at specific regular intervals (sampling period)
  - Sampling Theorem: Sine wave must be sampled at twice its frequency (Nyquist Frequency)
  - Highest frequency sampled is half of sampling frequency

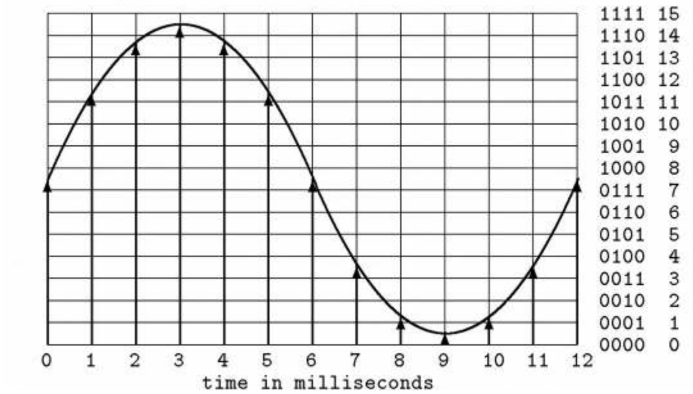


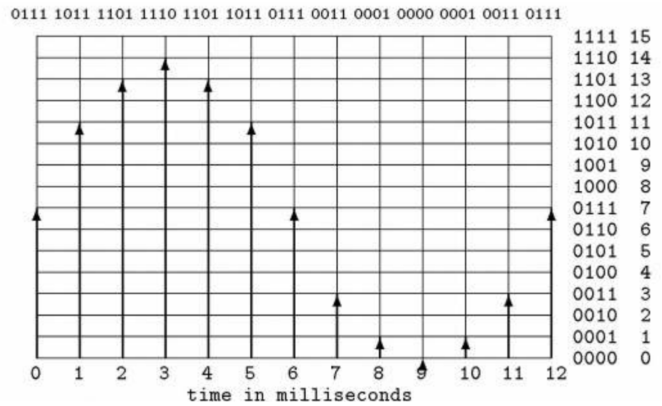


- Step 2: Quantisation
  - Converts values into a series of binary numbers that can be stored or processed as computer data
  - Each number reflects the value of the waveform as sampled at a particular point in time. The values can be continuous but to convert to numbers, we must settle of a certain degree of accuracy depending on each number's length (bit length)
  - With a bit length of , we can have quantisation levels, which is the number of values available for quantisation

Quantisation

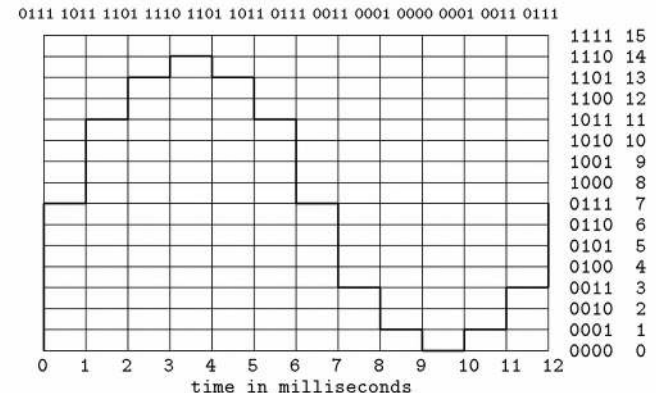
- At each sampling instant, the value of the waveform is read and measured
- There are a few ways to match the quantisation levels to transform it into a series of binary numbers
    - Round to nearest level
    - Round up
    - Round down
- Whichever method is chosen, it must be used throughout

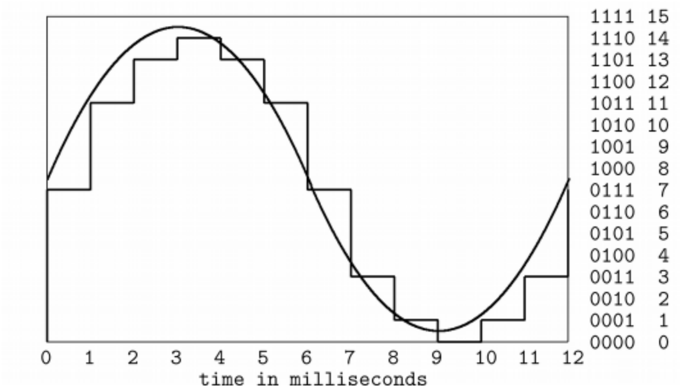




Quantisation Noise

- Quantisation noise refers to inaccuracies in preserving the waveform due to too few quantisation levels
- When reproducing the waveform, each binary number is converted back to its corresponding value at the start of each sampling interval. If the sampling rate is high enough to reproduce the frequency, quantisation noise can be kept low





S/N ratio

- The noise in a musical signal can be expressed in terms of the signal-to-noise (S/N) ratio, which compares the signal power to the noise power, measured in dB
- The maximum error for any quantisation value is 1 due to the nature of the estimation. We measure S/N ratio by comparing the segments of signal and noise.
- Power Amplitude^2

Bit Length	No. of levels	No. of segments	S/N Amplitude Ratio	S/N Power Ratio	S/N Ratio in dB

*As a rule of thumb, each bit increases S/N Ratio by 6dB for bit length , S/N Ratio will be dB

Sampling and Bit Rate

- Sampling Rate/Frequency: Measured in Hz (e.g. 1 kHZ means 1000 samples/sec or 1 sample/millisecond)

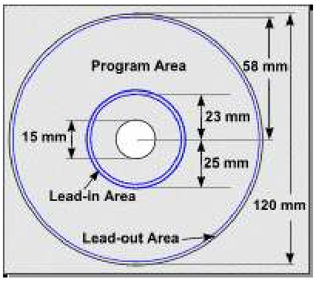
- Bit Rate: Measured in bits/second
    - Mono Bit Rate = Sampling Rate Bit length
    - Stereo Bit Rate = Sampling Rate Bit length 2

Audio Combat Disk

- Normal CD has over 700Mbytes of data of storage capacity
- Sampling Rate: 44.1 kHz, Bit Length: 16 bits, Bit Rate = 44.1*16 kilobits/second
- In 1 minute of stereo recording, there are 44.1*16*60*2 kilobits/minute = 84,672 kilobits/minute
- In 74 minutes, there are 6,265,728 kilobits, or 783,216 kilobytes (almost 800 Mbytes)

Structure of audio CD

- Audio CD is a 12 cm diameter plastic disk in which 1’s and 0’s are encoded as pits in an aluminium layer in the plastic. It can hold up to 74 mins of music encoded at 44.1 kHz and 16 bits



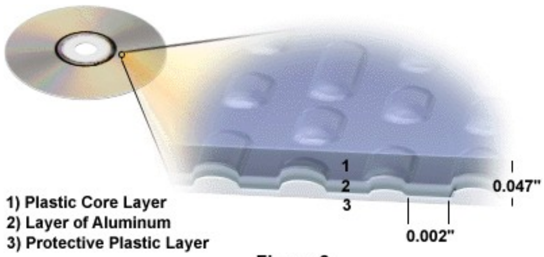
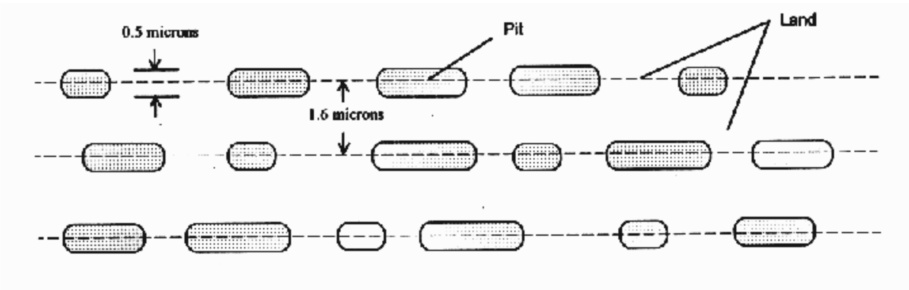


Figure 2

- The 1’s and 0’s are recorded as oval depressions (pits), with the surrounding area known as land
- The pits are 0.5 micron wide and the separation between tracks is only 1.6 micron (1 micron = meter)



- CD is read by a laser beam which is made to shine on pits. The laser beam is reflected differently according to whether there is a bit or land. Transitions between pit and land is binary 1, and no transition is 0

Digital Video Disk

- Improves over the CD by making pits smaller, having a double layer of pits, and pits on both side of the disc
- Primarily designed for the storage of movies in a higher resolution (720 x 480) than VCD (360 x 24) movies.
- DVDs may also be used be used to store audio signals at a higher quality than CDs are able to
- There are several competing formats for the storage of audio on DVD
    - DVD-audio: Can record up to 6 channels (for surround sound) at a sampling rate of 96 kHz and bit length of 24 bits
    - SACD (Super Audio CD): Sampling rate is very high – 2.8224 MHz, but bit length of 1 but

Digital Audio Compression

- By using sophisticated mathematical techniques, it is possible to store music in digital form using a much smaller number of bits for the equivalent recording, with hardly any loss in quality.
- In general, there will be some loss in quality, and the greater the compression, the greater the loss of quality.
- Some examples are:
  - DAB: Digital Audio Broadcasting
  - SONY's Minidisc: ATRAC Compression System
  - MP3: MPEG Level 3

Minidisc

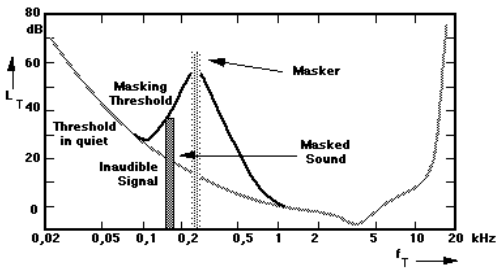
- 6.4 cm magneto-optical recordable disk enclosed in a plastic case
- The disc has magneto-optical pits which can be recorded and re-recorded many times. Hence, it is not just a compression system, but a physical standard intended to replace the cassette tape
- Uses masking effect via SONY’s ATRAC, with compression ratio of 5:1 so that the Minidisc can hold 64 minutes of music with imperceptible loss of quality.

MP3

- Offers several different levels of compression. More compression means smaller data size, but generally lower quality as well. Hence there needs to be a compromise between compression and quality.
- System of storing music digitally in a very compressed form for downloading on the internet. MP3 can store music in less than of the bits needed for an equivalent audio CD, using techniques such as:
    - Minimal Audition Threshold: leaving out sounds below the threshold of hearing
    - Masking Effect: using the psycho-acoustic masking effect to reduce information to be coded
    - Reservoir of bytes: to build up storage capacity for extra-dense signals
    - Joint Stereo: using the fact that the two stereo channels have a lot of common information which does not have to be coded twice
    - Huffman coding: a sophisticated mathematical algorithm to reduce the number of bytes further

Masking Effect

- When 2 sounds are perceived by the human ear, under certain circumstances one sound can make the other sound inaudible (masking)
- MP3 uses the masking effect to reduce the information to store by dropping the masked information



MP3 vs MIDI

MP3	MIDI
- Method of compressing digitised sound and music waveforms so that files occupy less space - Allow rapid transmission and take up less space - Original waveform (actual recording) - Bigger and slower to transmit	- Musical score or piano roll that must be performed to be heard, not actual recording - Synthesised in a sound generator, not as expressive as human performance - Smaller and quicker to transmit

Bitrate	Quality	kByte/min	mode	bandwidth	approx reduction
1411k	CD	10584	stereo	22.05 kHz	1:1
192k	perfect CD	1440	stereo	> 15 kHz	8:1
128k	excellent CD	960	stereo	> 15 kHz	11:1
96k	near CD	720	stereo	15 kHz	15:1
56k/64k	FM quality	480	stereo	11 kHz	25:1 & 22:1
32k	AM quality	240	mono	7.5 kHz	44:1
16k	shortwave	120	mono	4.5 kHz	88:1
8k	telephone	60	mono	2.5 kHz	176:1

Medium	Sampling frequency	Waveform frequency
NICAM stereo TV sound	32 kHz	16 kHz
Audio compact disc	44.1 kHz	22.05 kHz
Digital audio broadcasting (DAB)	24 kHz to 48 kHz	12 kHz to 24 kHz
Digital audio tape (DAT)	48 kHz	24 kHz
DVD audio	96 kHz	48 kHz