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| Arts | | | Create works of art of aesthetic value for self-expression, enjoyment and entertainment | | Performing arts: music, theatre, dance, mime, film  Visual arts: painting, sculpture, calligraphy, architecture, photography  Literary arts: poetry, novels, short stories, essays, plays | | |
| Science | | | Discover and understand the universe, including man and society | | Mathematics: pure maths, applied math, stats and prob  Physical sciences: physics, acoustics, astronomy, cemistry, materials science  Life sciences: botany, zoology, biochemistry, anatomy, physiology, ecology, molecular biology | | |
| Technology and Engineering | | | Shape and modify the physical universe for the benefit of human society | Civil & structural eng: design & creation of large physical structures, e.g. bridges, dams, buildings, highways  Mechanical eng: design & manufacture of machines which provide the motive force for industry  Electrical eng:harnessing of electrical energy for useful applications | | | |
| Tech (alternative) | | | In terms of functions instead of engineering branches | | Power and energy: harnessing of all natural energy sources (fossil, nuclear, solar, geothermal, wind)  Materials science: design, creation and improvement of materials for the use of man and society  Information tech: tech of information and knowledge handling, processing and communication | | |
| Aspects of Music | | | Composition, Performance on instruments (piano, string, wind, percussion, voice), Conducting (control and coordination of a body of musicians performing tgt), Teaching, Listening, Reviewing and criticism | | | | |
| Music, Science & Tech | | | Musical instruments: - Physics (sound generation and transmission), - Chemistry (materials used like violin varnish, piano soundboards), - Mechanical engineering (brass valves, piano and organ actions), - Electrical engineering (pipe organs, electronnic keyboards)  Performance: physiology, psychology  Listening: psychoacoustics, concert hall acoustics and building design | | | | |
| Pianoforte / Piano | | | Musical instrument that illustrates the r/s btw music, physics and tech  Music: what it produced when played; Physics: science of its sound production; Tech: its design, construction and production | | | | |
| Piano music | Composer creates musical score (blueprint for music) to communicate his musical thoughts  Pianist creates music by playing according to score, and adding his interpretation of the music  Listener recreates emotions and thoughts of composer by listening to music and reacting to it | | | | | | |
| Piano physics | Pianist strikes a key on keyboard key cause hammer to strike piano string strings set into vibration vibration of strings is amplified and enhance by the soundboard vibrations of the string and soundboard transmitted through the air by a sound wave Listener's eardrum caused to vibrate by sound wave at same frequency | | | | | | |
| Piano tech | Action by which key causes hammer to strike the strings  Escapement mechanism invented by Cristofori allowing strings to vibrate freely after being struck by the hammer  Cast-iron frame on which strings are strung w a total tension of 18 tons  Construction of the soundboard w laminated spruce wood for optimum resonance  Pedal mechanism enabling strings to continue vibrating even after keys have been released | | | | | | |
| Physical vs Perceived sound | | Physical sound (vibrations) are the cause of the perceived sound heard by a human ear and understood by the brain as music  For every aspect of physical sound, there is a corresponding perception by the listener  1) Frequency = rapidity of vibrations perception of sound's pitch = "highness or lowness"  2) Amplitude/power = strength of vibrations perception of sound's loudness  3) Quality/timbre of sound = shape of waveform of vibration distinguish sound is coming from which instrument (e.g. flute from trumpet) | | | | | |
| Sound & vibration | | | All musical sound is produced by vibration (repeated movement). Wave = vobration of a body of objs viewed tgt.  When struck, a physical body will vibrate when excited will eventually vibrate at its natural rapidity of vibration  Oscillation = to and fro motion. Cycle = 1 complete to and fro motion  Frequency (Hz) = num of cycles the body makes a second. Period (s) = time btw adjacent crest/through. f = 1/T  Waveform = shows graph of displacement w time of vibration. | | | | |
| Pitch, unison & octave | | | Pitch = "highness or lowness" of sound, determined by its freq  2 sounds are in unison = have same freq, hence same pitch  1 octave higher = double frequency of sound, giving us a sound that sounds like a similar pitch but higher  Humans can hear vibrations from 20 – 20,000 Hz | | |  | |
| Amplitude, power & loudness | | | Power = energy radiated by sound is dependent on the square of the amplitude, which determines how loud we perceive the sound.  Softest sound power detectable by human ear ≈ 10-16 watt  Loudest sound tolerable ≈ 10-4 watt  Sound powers within human range of hearing is very small compared to other forms (e.g. light bulb use 60 watt of electrical energy)  Range of sound powers for humans is very large. Largest sound is 1012 times the power of the softest sound | | |
| Decibel, dB scale | | | Since range of sound powers is so large, we use dB scale.  More powerful sound w power P1 and less powerful sound w power P2, then P1 is greater than P2 by dB   |  |  | | --- | --- | | Increase in power | Increase in dB | | 10 times | 10 dB | | 100 times | 20 dB | | 1,000 times | 30 dB | | 1,000,000 times | 60 dB | | 1,000,000,000,000 times | 120 dB | | | |  | |
| Limits of human hearing | | | Sounds below threshold of hearing are inaudible, while sounds above threshold of pain will cause serious damage to ear.  Note sensitivity of ear at threshold of hearing is not uniform w.r.t frequency | | | | Diagram  Description automatically generated |
| Waveform and timbre | | | Timbre/quality of sound is determined by shape of the waveform  LHS: oboe at 440 Hz. RHS: harmonica at 440 Hz | | | | Graphical user interface, chart  Description automatically generatedGraphical user interface, chart  Description automatically generated with medium confidence |

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| Elements of music | Rhythm: the time pattern made by a series of music notes | | | | pitch/melody don't matter | | | | |
| Melody: series of notes of various pitches | | | must be accompanied by rhythm, if melody contain chords, then there is harmony | | | | | |
| Chord: ≥ 2 notes of diff pitches being played at the same time | | | | | | | | |
| Harmony: series of chords | | sophistication and complexity of western classical music is built on harmonic theory & practice | | | | | | |
| Counterpoint: ≥ 2 melodies played at the same time | | | | | | | | |
| Form: structure/shape/organisation of a piece of music | | | | binary form – A : B; ternary form – A : B : A, where A and B represent diff sections of a piece of music | | | | |
| Orchestration/Instrumentation: allocation of a piece of music to 1 or more musical instruments for performance | | | | can allocate each melody/part to a diff instrument;  if there is a large num of instruments -> orchestration | | | | |
| Musical Notation | To indicate duration and pitch of musical notes. Each note represented by a small circle  Note may be white or black, or have a stem w or w/o a tail or hook of various sorts  Pitch of note is represented by its position on a set of 5 parallel horizontal lines, aka staff | | | | | | | | |
| Note durations | Longest note in common use is a semibreve/whole note  Minim/half note (white circle w tail/stem),  Crotchet/quarter note, ♩. Quaver/eighth note (black circle w stem and flag), ♪ | | | | | | If there are ≥ 2 notes w flags, can be joined/beamed, ♫  Triplet (3 notes equal in duration to 1 crotchet): | | |
| Musical staff | 5 parallel lines to indicate pitch of music  Treble clef: indicate position of G above middle C,  Bass clef: indicate position of F below middle C, Diagram  Description automatically generated  Plural of staff = staves | | | | | Grand staff: treble + bass clef, Table  Description automatically generated  Background pattern  Description automatically generatedC/alto clef | | | |
| Piano keyboard | Middle C is placed on a short extra line (aka leger line).  Octave = 8 notes up or down  Full piano keyboard has 88 black and white keys  Bösendorfer Imperial grand piano has 97 keys | | | | | A close up of a keyboard  Description automatically generated with low confidence | | | |
| Beats and Bars | Duration in music measured in terms of beats.  Music may be divided into bars/measures, with each bar always starting w a stronger beat | | | | | | | 2 beats in a bar/duple time (commonly for marches)  3 beats in a bar/triple time (commonly for waltz)  4 beats in a bar/quadruple time/common time | |
| Time/Metre signature | | Top num = num of beats in a bar  Bottom num = duration of note which is equal to 1 beat (1: semibreve, 2: minim, 4: crotchet, 8: quaver)  Most common time signatures are 2/4, 3/4, 4/4. 4/4 can also be written as 'c' (for common time) | | | | | | |  |

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| Bars | Bars/measures in a piece of music are separated by vertical lines drawn across the staff, known as bar/measure lines  RHS: grand staff has time sig of 2/4, followed by 3 bars separated by bar lines.  Final bar terminated by a double bar (indicating end of music) | |  | |
| Rests | Silence during piece of music. Semibreve rest:  Minim rest: Icon  Description automatically generated with medium confidence Crotchet rest:  Quaver rest: | | | |
| Tones and semitones | From 1 note to next higher note on piano keyboard = semitone (half a tone) = distance/interval btw any 2 adjacent notes  From 1 white key to next higher white key, | | | |
| C major scale | | C major scale: 8 white notes starting from any C to next higher C  (C is known as the "home" note for C major) | |  |
| Intervals and Ratios | Interval = dist btw any 2 notes. Each interval is characterized by a num/ratio  To move upwards from a note by a certain interval, we multiply its frequency by the interval's ratio, to get the frequency of the note above the original note by the desired interval  Impt intervals are octave, the fifth, the third, the fourth. Octave's ratio = 2 | | |
| Music Intervals | Musical intervals are named by counting num of notes in scale from lower to higher note  Note C to G is a fifth, so is D to A, so is E to B and F to C...  There is a fixed num of semitones for each type of intervals (e.g. an eighth or octave has 12 semitones btw the notes) | | |

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| Freq of vibrating str | A picture containing diagram  Description automatically generatedFreq of vibrating str depends on: 1) length measured from end to end, 2) mass, which depends on its material and thickness, 3) tension or how much slack it has or how taut it is  If mass and tension are constant, then freq is inversely proportional to length, i.e. f  A vibrating str is free to vibrate except at its ends. It will vibrate in such a way that the largest amplitude will be in the middle, tapering towards zero amplitude at the ends. The max amplitude = antinode, while the ends which do not move = nodes. The string is then said to be vibrating at its fundamental freq. |
| Harmonic of str | Diagram  Description automatically generatedIf a string fixed at both ends have middle not vibrating, effectively the string is divided into 2 equal halfs. On making this str vibrate, each half will vibrate as though it was a str half the length of the whole str -> frequency is doubled = second harmonic of str = 1 octave above fundamental freq  3rd harmonic of str = 3 times the freq of the fundamental freq = interval of the fifth + 1 octave  Diagram  Description automatically generatedThe fifth has 7 semitones = 3/2 \* fundamental freq. To go down by a fifth = divide by 3/2 OR multiply by 2/3  To go down by an octave = divide by 2  C -> G -> lower G -> D -> lower D -> A -> lower A -> E -> lower E -> B -> lower B  C -> lower F -> F |
| C Major scale | Diagram  Description automatically generated with low confidencePentatonic or 5-note scale = C, D, E, G, A  Pythagorean scale (built up starting from lower C, using only intervals of the fifth and the octave): |
| Chinese mtd | Chinese mtd started w a string of certain length, shortened it to 2/3 of original length = freq up by 3/2 = a fifth. Str then lengthened to 4/3 its new length = freq down by 3/4 = a fourth. Going down by a fourth = gg up by a fifth + gg down 1 octave  The fourth is the inversion of the fifth  By successively multiplying freq of starting note by 3/2 and 3/4 alternately, we get the 5 notes of the Chinese pentatonic scale  This up and down mtd = Guan Zi mtd  5 notes of the Chinese pentatonic scale are called Gong, Shang, Jue, Zhi, Yu (C,D,E,G,A) |

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| Complete Pythagorean C major scale | | |  |  |  |  |  |  |  |  | | --- | --- | --- | --- | --- | --- | --- | --- | | Note | C | D | E | F | G | A | B | | Mult/div C by | \* 1 | \* (3/2)2 | \* (3/2)4 | / (3/2) | \* (3/2) | \* (3/2)3 | \* (3/2)5 | | Ratio relative to C | 1 | 9/4 | 81/16 | 2/3 | 3/2 | 27/8 | 243/32 | | Mult/div to bring to same octave as C by | / 1 | / 2 | / 4 | \* 2 | / 1 | / 2 | / 4 | | Pythagorean ratio | 1 | 9/8 | 81/64 | 4/3 | 3/2 | 27/16 | 243/128 | |
| Notes in diff Octave | | 1. CC to BB, C to B, c to b, c' to b', c'' to b'', c'' ' to b'' ' and c'' '' to b'' ''  2. C1 to B1, C2 to B2, C3 to B3, C4 to B4, C5 to B5, C6 to B6, C7 to B7 |
| Tones & Semitones in Pythagorean scale | | Considering the intervals btw adjacent notes in Pythagorean scale, the whole tones have ratio of 9/8 and semitones have ratio of 256/243. But 256/243 ≠ 1/2 the ratio of the whole tone, since (256/243)2 ≠ 9/8 |
| 1st 5 harmonics of a vibrating str | | |  |  |  |  |  | | --- | --- | --- | --- | --- | | Harmonic | n | frequency | 264 Hz fundamental | note | | Fundamental | 1 | f | 264 Hz | C4 | | Second | 2 | 2f | 528 Hz | C5 | | Third | 3 | 3f | 792 Hz | G5 | | Fourth | 4 | 4f | 1056 Hz | C6 | | Fifth | 5 | 5f | 1320 Hz | E6 |   If vibrating str have (fundamental) freq of f Hz, it can have higher harmonics, w nth harmonic having freq of nf Hz  If we touch a vibrating str at a pt one-fifth from 1 end, the str effectively vibrate in 5 equal sections, each one-fifth the length of the whole str. Each section and hence the entire str, will vibrate at a freq 5 times the original freq before it was touched. => 5th harmonic |
| Just third | | 5th harmonic give 1320 Hz. If we divide this freq by 4, we obtain a note which is 5/4 times of 264 Hz, i.e. 330 Hz. The Pythagorean third has ratio 81/64 and gives a note w freq 334.125Hz. Thus 330 Hz is an alternative E, and the interval w a ratio of 5/4 = a Just third |
| Just scale | | A picture containing text, clock, watch  Description automatically generatedThe true third is considered to be derived from the fifth harmonic, and has ratio 5/4.  Scale built using fifths and true thirds = Just scale  We can also start from F and G and multiply their freq by 5/4 to generate A and B (which are a third above F and G respectively) |
| Just Intonation | | C major scale derived from middle C by multiplying w simple ratios = Just scale (using intervals of octave, just third and the fifth)  Instruments tuned to this scale are said to be in Just intonation  All 3 intervals are derived from physical properties of a vibrating str, and so both the just and Pythagorean scales are firmly grounded in physics. The Greek scientist Ptolemy considered the Just scale to be a pure scale due to the simple ratios of all its intervals |
| Problems w Just intonation | D is 9/8 times middle C, A is 5/3 times. Hence, ratio from D to A is (5/3)/(9/8) = 40/27 ≈ 1.48 < 1.5 = 3/2. Thus D to A is appreciably less than a fifth should be, and tgt sound less harmonious than a fifth  2 kinds of whole tone: Whole tone from C to D has ratio 9/8 but whole tone from D to E has 10/9 ratio. Btw E and F, B and C, semitone is 16/15   |  |  |  | | --- | --- | --- | |  | Ratios | Whole tones | | Just | perfect fifth (3/2) and thirds (5/4) | 9/8 & 10/9 | | Py | accurate fifths (3/2) but imperfect thirds & sixths | 9/8 |   Freq of notes in Just scale are whole nums. Using A = 440Hz as the standard reference point,   |  |  |  |  |  |  |  |  |  | | --- | --- | --- | --- | --- | --- | --- | --- | --- | | freq\Note | C | D | E | F | G | A | B | C | | Just scale | 264 | 297 | 330 | 352 | 396 | 440 | 495 | 528 | | Pythagorean | 260.740.. | 293.333... | 330 | 347.651.. | 391.111. | 440 | 495 | 521.481.. | | |
| Fifths & Thirds in Pythagorean scale | | In Pythagorean scale, all fifths have exactly desired ratio of 3/2. However, thirds are somewhat larger than they should be, due to the way the scale is built up only from fifths. E.g. from C to D w ratio 81/64 (from C to D and from D to E, so (9/8)2 = 81/64)  In Just scale, the interval from C to E is (9/8)(10/9) = 5/4.  Diff btw 81/64 and 5/4 = (81/64)/(5/4) = 81/80 = syntonic comma  Roots of 9/8 and 10/9 (√(9/8) and √(10/9)) are approximately 1.06066 and 1.05409, neither of which is = Just semitone of 16/15 ≈ 1.06666 or Pythagorean semitone of 256/243 ≈ 1.05349 |
| Reducing the Pythagorean third | | Pythagorean third has the ratio 81/64 which is obtained from C by 4 successive upward fifths (3/2)4, then divide by 2 octaves (/ 22) to get E  We can force the high E to generate a Just third by setting its ratio to 5, which is that of a fifth harmonic. Can then split the 5 into 4 intervals to get new ratio for G, D and A (i.e. C to G, G to D, D to A and A to E: multiply by ratio ), then divide by 2 octaves |
| Fourth as inversion of Fifth | | C to G has ratio 3/2 (Just fifth). G to higher C has ratio 4/3 (Just fourth).  C to 1 octave above has ratio 2  Just fifth and Just fourth tgt exactly make up an octave, and we say the Just fourth is the inversion of the Just fifth |
| Major third & Minor third | | Interval from C to G in Just scale of C is a Just/Pythagorean fifth, w ratio 3/2  Interval from C to E is a Just third, w ratio 5/4. This is called a major third  Interval from E to G is also a third, w ratio (3/2) / (5/4) = 6/5. This is called a minor third |
| Triad chord | | Triad = chord made of three notes – a foundation note known as a root and 2 other notes, 1 a third higher and another a fifth higher.  A triad in scale of C w C as root is made of C, E, G.  This triad based on the 1st note of the scale, consists of the first, third and fifth notes of a scale and is the triad chord of 1  On a Just scale, the triad of 1 has ratio btw first and third note as 5/4, ratio btw third and fifth note is 6/5.  Hence, freq of C: freq of E: freq of G = 4:5:6 |

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| Circle of fifths | If we start from lowest C on piano and take successive perfect fifths (3/2) upwards, we obtain C, G, D, A, E and B of the Pythagorean scale.  Continuing on, after 12 fifths, we obtain a B sharp = highest C. So we return to C after 12 fifths.  Circle of fifths = seq of 12 fifths starting and ending with C   |  |  |  |  |  |  |  |  | | --- | --- | --- | --- | --- | --- | --- | --- | | Note | C | B | F# | C# | G# | D# | A# | | Ratio | 1 |  |  |  |  |  |  | |
| Pythagorean 12 note scale | This scale is similar to the piano one as it has 5 sharps corresponding to the 5 black notes in an octave. This 12 note scale is constructed using purely Pythagorean principles using only intervals of fifth (3/2) and octave (2). However, Pythagorean 12 note scale ≠ piano scale, as it has 2 types of semitones – a major semitone w ratio of and a minor semitone of . But on piano, all semitones are equal.  Diff btw the 2 semitones = = Pythagorean comma |
| Circle of fifths downwards | Diagram, schematic  Description automatically generatedStarting at uppermost C, we go downwards by a fifth = divide by 3/2 = multiply by 2/3. After 12 fifths, we get D double flat = C.  In circle of fifths upwards, F sharp is 6 fifths above C and ratio above lowest C  Likewise in circle of fiths downwards, G flat is 6 fifths below highest C, ratio below highest C. As highest C is 7 octaves, 27 = 128 above lowest C, G flat = above lowest C  Diff btw F sharp and G flat = = Pythagorean comma = diff btw major and minor semitone  Can see that flats & sharps are diff notes in Pythagorean scale (and also Just scale), meaning piano keyboard would need more notes.  Also can see that highest C is 7 octaves = 12 fifths above lowest C |
| Pythagorean Comma | To verify whether 12 fifths = 7 octaves: ­≠ 27 = 128. Diff btw 2 = / 128 = ≈ 1.01364 = Pythagorean comma  Thus on piano, have to adjust either fifths or octaves to make 12 fifths = 7 octaves  We can reduce 12 fifths by ≈ 1.01364. Since 12 fifths are multiplied tgt, each fifth shld be reduced by the 12 root of 1.01364 = ≈ 1.00113, i.e. each fifth shld be 1.5/1.00113 ≈ 1.4983 instead of 1.5 (3/2)  Using modified value for fifth (1.4983), we adjust the values of freq of notes of the C major scale. i.e. C to G shld be 1.4983, G to D shld be 1.4983, ... E to B shld be 1.4983. (C to G reduced once, C to D twice, C to A thrice, C to E four times, C to B 5 times)  For circle of fifths downwards: change fifth to 1.4983, i.e. from C to F, divide freq of C by 1.4983, and F is raised accordingly |
| Using reduced / tempered fifths | Notes of the C Major scale can be obtained from the circle of fifths in the same way as was done for the Pythagorean scale, but using reduced fifths instead of Just fifth of 3/2. (Reduced fifth)12 = 27. Reduced fifth = 27/12 = ≈ 1.4983   |  |  |  |  |  |  |  | | --- | --- | --- | --- | --- | --- | --- | | Note | D | E | F | G | A | B | | mult/div C by | \* | \* | / | \* | \* | \* | | Mult/div by | / 2 | / 4 | \* 2 | / 1 | / 2 | / 4 | | Temp ratio |  |  |  |  |  |  | | Pyth ratio | 9/8 | 81/64 | 4/3 | 3/2 | 27/16 | 243/128 |   Ratio for each notes in the tempered c major scale are all powers of ≈ 1.059463094. Tones are all and semitones are which is exactly half of a tone (i.e. semitone2 = tone) |
| Comparison | In Just scale, ratios are perfect, but fifth from D to A is too small (40/27 ≈ 1.48).  In Pythagorean scale, all fifths are perfect (3/2), but thirds are too large (81/64 ≈ 1.266 vs 5/4 = 1.25).  In Equal-tempered scale, fifths are almost perfect (1.49830), and thirds are better than Pythagorean scale (1.2599)   |  |  |  |  |  |  |  |  |  | | --- | --- | --- | --- | --- | --- | --- | --- | --- | | freq\Note | C | D | E | F | G | A | B | C | | Just | 264 | 297 | 330 | 352 | 396 | 440 | 495 | 528 | | Pyth | 260.7 | 293.3 | 330 | 347.6 | 391.1 | 440 | 495 | 521.5 | | Equal | 261.6 | 293.7 | 329.6 | 349.2 | 392 | 440 | 493.9 | 523.2 | |

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| Equal-tempered scale | | Distance from one note to the next is exactly . This 12 note scale = 12-tone Equal-tempered scale. The 5 notes in the middle of the whole tones = black keys on piano. Each black note represents both the flat and sharp btw the 2 white notes. |
| Zhu Zaiyu's 749 mtd | | Chart  Description automatically generated with low confidenceZhu Zaiyu 1st person to divide octave into 12 equal semitones. In his book Lu Xue Xin Shuo in 1584, he use a mtd to generate note with freq closer to Equal temperament than had ever been achieved, with accuracy of 9 figures. Used the traditional up and down mtd but with ratio 749/500 and 1000/749  Table  Description automatically generated with low confidenceRefine ratio to 749.15 instead of 749 to get Equal-tempered semitone of 1.0594  Further refine ratio to 749.153583 and starting w a str of 10 inches, to get 12 notes of Equal-tempered scale accurate to 9 digits, and value for Equal-tempered semitone of 1.059463094, correct to 9dp, far more accurate that was to be achieved in Europe for over a hundread years. |
| Equal-tempered guitar | | Table  Description automatically generatedGuitar notation is an octave higher than the actual pitch.  Btw each adjacent pair of strings is an Equal-tempered fourth (i.e. 5 semitones), except for an Equal Tempered third btw G3 and B3 (i.e. 4 semitones)  Each successive fret raises the pitch of the str by 1 equal-tempered semitone (i.e. from 1 col to next) |
| Violin, viola, cello | | A picture containing chart  Description automatically generatedStrings tuned in perfect Pythagorean fifths (3/2). Btw each adjacent pair of strings is a Pythagorean/Just fifth.  Violoncello or 'cello has 4 strings which are tuned one octave lower than those of viola. |
| Double bass, bass guitar | | Table  Description automatically generatedDouble bass has 4 strings tuned in perfect Pythagorean fourths (4/3)  Bass guitar also has 4 strings tuned in Equal Tempered fourths (), and is 1 octave below the 4 lowest string of the guitar.  Notation here is an octave above the actual pitch |
| Ukulele family | | Table  Description automatically generatedMove 4 highest guitar strings up a fourth to get notes of 4 strings of the soprano, concert and tenor ukulele. However, the lowest ukulele string is commonly tuned (particularly for soprano and concert) one octave higher to G4, so 4 strings are G5, C4, E4 and A4  Baritone ukulele is tuned the same as four top strings of guitar. |
| Erhu and pipa | | Erhu and pipa are tuned to the Chinese Pentatonic scale  Erhu has 2 strings which are tuned to Just/Pythagorean fifth (3/2) to D4 and A4 (same as 2 middle strings of violin)  Pipa has 4 strings tuned to A3, D4, E4 and A4 with intervals of Just/Pythagorean fourth (4/3), and Just/Pythagorean second (9/8) |
| Tetrachords | | Diagram, schematic  Description automatically generatedC major scale and its tetrachords  Each tetrachords has 4 notes  2 tetrachords are separated by a tone |
| Modulation in Equal-tempered scale | | By adopting the Equal-tempered scale or equal temperament for the piano keyboard, changing from 1 key to another in the same piece (aka modulation) is made possible. By considering a major scale to be made up of 2 tetrachords, we can build up new scales starting on notes other than C  Since interval from one note to adjacent note is always 1 semitone (), we can assume tone, tone, semitone pattern of a tetrachord is preserved no matter what starting note we use. (Not possible with Just or Pythagorean temperament, as semitones not exactly half the whole tone. In Just scale, there are even 2 types of whole tones) |
| Major scales and sharps | Diagram  Description automatically generatedTaking upper tetrachord of C major as lower tetrachord of G major, we get Major scale starting with G. (G, A, B, C, D, E, F#, G)  Diagram  Description automatically generated with medium confidenceD major (D, E, F#, G, A, B, C#, D)  A major (A, B, C#, D, E, F#, G#, A)  E major (E, F#, G#, A, B, C#, D#, E)...Continuing process...  We get B sharp major scale C major | |
| Major scale and flats | | Diagram  Description automatically generatedBy taking lower tetrachord of C major as upper tetrachord of F major, we get F major scale (F, G, A, B flat, C, D, E, F)  B flat major (B flat, C, D, E flat, F, G, A, B flat)  E flat major (E flat, F, G, A flat, B flat, C, D, E flat)  A flat major (A flat, B flat, C, D flat, E flat, F, G, A flat) |
| Scales and keys | | Diagram, schematic  Description automatically generatedEach of the scale defines a key. When a piece of music is a certain key, it means: - 1st note of the scale (aka tonic) is the home note of the key, i.e. appears to be the most impt note of the key, and music in the key often (but not always) ends with the tonic  - Music uses only notes of the corrseponding scale (but may use them up or down 1 or more octaves)  - Notes of the scale to be sharpened or flattened are indicated by the key signature  Key signature means that all notes with same letter names, irrespective of octaves are to be sharpened/flattened  Diagram  Description automatically generated with medium confidenceB major (F#, C#, G#, D#, A#), F# major (F#, C#, G#, D#, A#, E#), C# major (F#, C#, G#, D#, A#, E#, B#)  A picture containing antenna  Description automatically generatedD flat major (B flat, E flat, A flat, D flat, G flat), G flat major (B flat, E flat, A flat, D flat, G flat, C flat), C flat major (B flat, E flat, A flat, D flat, G flat, C flat, F flat) |
| Melody | | A picture containing table  Description automatically generatedMelody as series of notes of a scale: Position of note in scale numbered  Chart, box and whisker chart  Description automatically generatedThen Happy Birthday = G, G, A, G, C, B can be expressed as 5, 5, 6, 5, 8, 7  Melody as series of intervals: Notes expressed in terms of semitone compared to adjacent note  0, up by 2, down by 2, up by 5, down by 1 |
| Same melody in diff key | | In D major, notes can also be numbered but with D as 1  Then Happy Birthday = 5, 5, 6, 5, 8, 7 (but represent diff notes)  Intervals also remain the same in diff key (happy bd: 0, 2, 2, 5, 1, but start with A4) |
| Other systems | | Other systems of tuning were dominant untl the Equal-tempered scale was established as the definitive scale for the piano in the 20th century. In the Just scale, the Just third (5/4) is amde up of 2 diff types of whole tones: 9/8 and 10/9.  In Mean-tone tuning, a whole tone which is the mean of 9/8 and 10/9 is used, i.e.  In J.S. Bach's time, there were various systems in which the 12 fifths were not uniformly reduced. In Well-tempered tuning, each key may thus have its own special "flavour". Bach may have written his "Well-tempered Klavier" to exploit the special "flavour" of each key, something which is lost with Equal temperament. |
| Indian scales | | Indian scales utilise Just intonation, dividing the octave into 22 divisions called srutis.  The basic 7 note scale in Just intonation is 1 of the basic scales in Indian music. |
| Balinese scales | | Balinese gamelan is 1 of the 2 main types of gamelan in Indonesia, other being Javanese gamelan.  Javanese gamelan uses a 5 note scale known as Slendro, while Balinese uses 7 note scale known as Pelog.  Diagram, schematic  Description automatically generatedSlendro is similar to common Pentatonic scale. Pelog scale of the modern Balinese gamelan or Gong Kebyar ofter omits 2 notes. The remaining 5 note scale is not the same as the common Pentatonic scale, but consists (in C) of C, D flat, E flat, G and A flat |

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| Waveforms and harmonics | String vibrating freely w antinode in middle and node at each end = fundamental freq  If string is touched at certain points, such as in the middle, on third or one quarter from one end, it will vibrate as though it were a string of half, one third, one quarter of its length.  String is thus able to vibrate with frequencies which are multiples of its fundamental freq = harmonics/harmonic frequencies  The more sections/divisions the string has, the higher the harmonic and hence the higher the freq with which it will vibrate  Diagram  Description automatically generated  In reality, a vibrating string when freely vibrating actually vibrates with a combination of its fundamental and some of its harmonics simultaneously  Chart, line chart  Description automatically generatedkth harmonic has k \* fundamental freq as it freq  A vibrating string which vibrates w both its fundamental and its harmonics will have a waveform which is the sum of its harmonics (vs sine wave of individual harmonic)  Note sine wave has odd symmetric (rotate 180)  Not all harmonics may be present in any vibration, and strength of those present will vary from one vibration to another, which then determines shape of resultant waveform and hence the timbre or quality of the sound. |
| Frequency spectrum | Chart, histogram  Description automatically generatedA complex waveform may be decomposed into its components – fundamental and harmonics, each of various amplitudes. These components make up the freq spectrum of the waveform (amplitudes vs freq)  Amplitude of each harmonic is indicated by the length of the vertical line representing that harmonic  A pure sine wave will have only 1 component (i.e. its fundamental)  The spectrum of a musical sound shows the amplitudes of its fundamental freq and harmonics. The number above each harmonic shows its order.  The freq axis is often shown on a log scale, in which doubling of frequencies are shown as equal lengths. This acknowledges that each doubling is equivalent ot an octave interval, which is perceived by the human ear as the same interval no matter from which freq we start. |
| Waveform shape and spectrum | In general, the shape of the waveform and timbre of its sound is dependent on its harmonics and its spectrum |
| Diagram  Description automatically generated with medium confidenceSquare wave is made up of only its odd harmonics which gives its waveform its particular shape. As order increases, amplitude decreases  Odd harmonics only  (Waveform graph, freq spectrum graph) |
| Diagram  Description automatically generated with medium confidenceSawtooth wave is made up of a series of harmonics with diminishing amplitudes as order of harmonic increases.  Odd and Even harmonics |
| Spectra of musical instruments | Quality/timbre of diff musical instruments is determined by its harmonics and spectra.  Difference in spectra allows us to distinguish btw their sounds  We can measure spectrum using a spectrum analyzer. |

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| Waves & Vibrations | Vibration = repetitive movement which a single object (a compact mass / particle), can undergo on its own.  Waveform/vibrationform = "signature" of the vibration, giving us all the information we need to know about it.  Wave = phenomenon which is made up of the vibrations of many particles or objects.  • A single vibrating particle cannot form a wave on its own.  • A wave is a phenomenon which occupies space, and exists in an extended object/medium (e.g. atmosphere/string).  • A wave consists of many objects or particles, which are vibrating tgt in a coordinated fashion (e.g. ppl in a Mexican wave, or the making up a vibrating string).  • A wave can result in the motion of one or more wave "disturbances" travelling across the particles which make up the wave. The particles themselves do not travel with the disturbance.  • The wave "disturbances" which travel can carry energy along with them.  • The nodes and antinodes of diff harmonics of a vibrating string remain at fixed position along the string | |
| Vibrating String | 1) Standing wave: wave which vibrate in fixed/standing position (e.g. fundamental and harmonics of a vibrating str)  Diff parts of the str (red and blue points) all move up and down at the same time, which is why nodes and anitnodes remain at the same place  2) Travelling wave = made up of vibrations of parts of the string, but moving up and down a little later or earlier than its neighbours. The resultant wave seems to move along the string, hence the name.  Though the wave seems to move along, the individual parts of the string (red and blue dots) do not actually move, but stay in the same place vibrating up and down, though a little out of phase with its neighbours. | |
| v = f | The travelling wave has a wavelength which is simply the length of a complete wave measured from crest to crest or from trough to trough.  Frequency = num of complete wavelengths passing us in one second, for that is also the number of complete to and fro movements made by the particle in front of us.  If freq = f f waves pass us in 1 sec. If wavelength = total length of wave passing us in 1 sec = f = v  Sound waves have v ≈ 340m/s. When v is constant, f | |
| Transverse wave | | Transverse wave = wave where particles vibrate/move in a dirn perpendicular/transverse to the dirn in which the wave travels (e.g. travelling wave on a vibrating str)  Usually: wave travel from left to right, while particles move up and down but just slightly out of phase |
| Longitudinal wave | | Chart  Description automatically generatedLongitudinal wave = particles making up the wave vibrate in a dirn parallel to the dirn in which the wave is travelling. Usually: the particles vibrating to left and right, while the wave is travelling from left to right.  Instead of peaks/crests and troughs in a transverse waves, the longitudinal wave has compressions (portions where particles are closer tgt), and rarefactions (portions where the particles are further apart) |
| Sound waves in air | | Diagram  Description automatically generatedSound waves travelling in air carry sounds from sound sources such as musical instruments to our ears.  Sound waves in air are longitudinal waves, and the compressions and rarefactions are actually changes in air pressure which travel along or are propagated with the wave |
| Transverse vs Longitudinal | | Diagram  Description automatically generatedCompare by using a spring:  Transverse wave generated by moving spring up and down to make a wave which moves from left to right.  Longitudinal wave generated by pushing and pulling the end of the spring back and forth |
| Types of wave motion | 1) Transverse Standing wave: e.g. fundamental freq, 2nd harmonic ... of a vibrating string (e.g. in string instrument like violin, piano, guitar)  2) Transverse Travelling wave: e.g. Mexican wave in a stadium water waves on sea surface, waves formed by shaking rope up and down  3) Longitudinal Standing wave: e.g. fundamental freq, 2nd harmonic ... in a pipe (e.g. wind instrument like flute, clarinet, trumpet)  4) Longitudinal Travelling wave: e.g. sound wave in air travelling from a musical instrument to a listener | |
| Standing waves in wind instrument | | Wind instruments such as clarinet and trumpet do not have strings, but use a column of air instead.  Text, icon  Description automatically generatedThe column of air is in the tube which is the main part of such a wind instrument  The standing wave in such a tube is similar to a standing wave on a string, but is longitudinal and not transverse, as it is made of air molecules |
| Closed and open pipes | Table  Description automatically generated with medium confidenceWind instruments may be classified as closed pipes or open pipes.  Closed pipe is closed at one end and open at the other end  Open pipe is open at both ends  When air vibrates in pipe to create a standing wave, the air can vibrate most at open end, but cannot vibrate at all at the closed end  Hence, open end will have an antinode, and closed end will have a node, for the standing waves in the pipes | |
| Open Pipe | Chart, line chart, scatter chart  Description automatically generatedA picture containing diagram  Description automatically generatedOpen pipe is open at both ends. Each ends mush each have an antinode of the standing wave, as air molecules can vibrate most freely there.  Fundamental has standing wave with 1 node in the middle  2nd harmonic has 2 nodes, so it is like 2 shorter pipes half the length of the pipe. Its freq is thus double the fundamental freq  (pressure label in top half should be opp) | |
| Closed Pipe | A picture containing application  Description automatically generatedA picture containing text, sport  Description automatically generatedClosed pipe must have node at closed end and antinode at open end  It thus has only half of the standing wave pattern of the open pipe, and has a wavelength double that of the open pipe of the same length. Thus, it behaves like an open pipe double the length of the original open pipe.  Its fundamental freq is thus half that of a open pipe of the same length.  Only odd harmonics (3rd, 5th, 7th...) can be formed in a closed pipe.  For fundamental freq, wavelength = 4 times the length of the pipe. | |

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| Vibrations, waveforms and waves | | A single body/particle may undergo a vibration, and this vibration can have a waveform which carries information about the vibration, such as what harmonics are in the vibration  A wave must always be associated with several particles or bodes, and each of these bodies are vibrating to give the overall wave.  1 complete wavelength of a standing wave can be measured from 1 crest of the wave to the adjacent crest. (or any point of wave to next corresponding point). The standing wave of the fundamental freq of a string has nodes at either end, and an antinode in the middle. From the node at one end to the node at the other end = half a wavelength. Hence fundamental freq of a string has a standing wave which has half a wavelength along the length of the string. | | |
| Wavelength | | Chart, line chart  Description automatically generatedA picture containing chart  Description automatically generatedDiagram  Description automatically generated with low confidenceFundamental freq 1 complete wavelength = 2 \* length of string  2nd harmonic 1 complete wavelength = length of string  3rd harmonic 1 complete wavelength = 2/3 \* length of string  So 2nd harmonic has 2/1 = 2 times the freq of fundamental  3rd harmonic has 2/(2/3) = 3 times the freq of fundamental  (since freq is inversely proportional to wavelength) | | |
|  | | The standing wave on a string is due to 2 travelling waves on the string which are travelling in opp dirn and are repeatedly reflected from the 2 ends. In the resultant standing/stationary wave pattern, from 1 node/antinode to the next node/antinode is half a wavelength. | | |
| Harmonics in strings and pipes | | Diagram  Description automatically generatedDiagram  Description automatically generatedDiagram  Description automatically generatedString and open pipe have fundamentals w half a wavelength (i.e. complete wavelength = 2 \* length of string or pipe)  Closed pipe has fundamental w a quarter wavelength.  Wavelength of the fundamental freq of a closed pipe is = 2 \* that of an open pipe of the same length closed pipe fundamental freq = 1/2 that of an open pipe of the same length | | |
| Setting strings & pipes into vibration | Musical notes are generated by vibrating strings and pipes whne a string or column of air in a pipe is set into vibration. When string or air column is vibrating at its fundamental freq, there will be a standing wave on the string or column of air.  For a string, energy has to be supplied to the string so that the standing wave is created. This can be done by:   |  |  |  |  | | --- | --- | --- | --- | | Beaten/hammered | Plucked | Stroked/bowed | Blown | | Piano, dulcimer, cimbalon, yangqin | Guitar, harp, harpsichord, pipa, guzheng | Violin, wiola, cello, double bass, erhu | Aeolian harp | | | | |
| Reeds and pipes | A vibrating standing wave cannot be set up in a column of air in a pipe just by blowing through the pipe, as the moving air would just flow through the pipe. A standing wave in a pipe is usually set up by getting a physical body of some sort to vibrate at one end of the pipe, thus setting the air column into longitudinal vibrations.  The flute just has a hole with a sharp edge, while brass instruments depend on the vibration of the player's lips.  Reed instruments use a thin flexible strip (aka reed) vibrating against a solid mouthpiece (clarinet) or another reed (oboe)  - Stream of air striking a sharp edge: flute, recorder, dizi  - Air stream btw single reed and mouthpiece: clarinet, saxaphone  - Air stream btw double reeds: oboe, bassonn, suona  - Player's lips vibrating into pipe: trumpet, trombone, tuba, cornet, saxhorn, baritone, euphonium and all brass instruments | | | |
| Clarinet reed | Diagram  Description automatically generatedThe 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 pressure region btw the reed and the mouthpiece.  Diagram  Description automatically generatedThe reed is foced to move towards the mouthpiece and shouts 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 freq too. | | | |
| Free reed instruments | | The reeds in the clarinet and oboe do not vibrate freely but beat against a mouthpiece or another reed. Their vibrating freq is determing by the pipe to which they are closely coupled.  Free reeds are reeds which freely vibrate w/o hitting somthing else. In free reed instruments, the free reeds are mounted on a solid frame which does not obstruct the reeds.  A free reed is made to vibarte by an air stream along the reed, and is generally free to vibrate at its own resonant freq. As each reed vibrates up and down, it crosses the frame at its side and forms puffs of air, thus creating a longitudinal sound wave  Free reed blown by the mouth: harmonica, sheng. Free reed blown by hand operated bellows: accordion, concertina, indian harmonium  Free reed blown by foot operated bellows: harmonium. Free reed blown by mechanically cranked bellows: barrel organ, orchestrion | | |
| Harmonica | | Diagram, engineering drawing  Description automatically generatedThe harmonica is a mouth blwon free reed instrumeng.  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  2 reed plates each carrying 1 reed for each hole are mounted on the top and bottom of the comb  The players 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 2 diff pitches.  Diagram  Description automatically generatedThe vibrating reed is closely coupled to the mouth cavity, so the player can alter the freq by changing the mouth cavity volume | | |
| Wind instruments | | Diagram  Description automatically generatedWind instruments are of 2 types: woodwind instruments (clarinet) and brass instruments (trumpet). The part they have in common are the mouthpiece, the bore and the bell | | Woodwind family |
| Brass family | | |
| Free reed instruments | |  | | |
| Guitars |  | | | |
| Ukueleles | |  | | |
| Strings | |  | | |
| Percussion | | Timpani, Snare Drum, Xylophone | | |
| Interference and beats | | When 2 waveforms which has freq close to each other are sounded tgt, the combined waveform will vary in amplitude at a regular rate.  The rate of variation will be the diff in in the 2 freq  If f1 and f2 are the 2 freq, then the beat freq is f1 - f2 | | |
| Beats in piano tuning | | Beats are used in tuning musical instruments such as the piano. If the piano tuner has a reference tone which is the correct freq, he can adjust the tension of a string to get it to be close to this frequency by listening for beats btw the two tones. As he adjusts the freq of the string, the beats btw the two tones will be slower as the two freq become more similar.  Lengthen string -> freq incr -> beats decrease if lower than reference / increase if higher than reference  Loosen string -> tension decr -> freq decrease -> beats increase if lower than reference / decrease if higher than reference | | |
| Beats & missing fundamentals | | | |  |  |  | | --- | --- | --- | | Harmonic | Frequency (Hz) | Amplitude | | Fundamental/1st | 100 | 0 | | 2nd harmonic | 200 | 7 | | 3rd | 300 | 9 | | 4th | 400 | 6 | | 5th | 500 | 5 |   Beats = |f1 - f2|. Sounds can combine/interfere to produce beats.  In spectrum of a musical instrument in which the fundamental is very weak or missing altogether, it will still be possible to hear the fundamental because of beats.  In this spectrum, the fundamental is missing, but the 2nd and 3rd harmonic will combine to form a 100 Hz beat to replace the fundamental. | |

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| Consonance & Dissonance | | Consonance: when 2 notes sound very pleasant together . Dissonance: when 2 notes sound unpleasant tgt |
| Consonance & Harmonics | Table  Description automatically generatedWhen 2 musical sounds or tones are sounded tgt, their fundamentals and harmonics are heard. The more harmonics of the 2 notes w the same freq, the more they are in consonance.  2 tones/sounds are in unison: the harmonics of 2 tones w the same freq will match exactly, hence both are in complete consonance.  If 2 tones are an octave apart, the harmonics of the higher tone will all coincide w the even harmonics of the lower tone. Thus the octave has a very high degree of consonance, even though not all harmonics coincide.  Not as many harmonics of 2 tones a fifth apart will coincide, compared with the octave. But still have some, so fifth is a highly consonant interval (freq shown on right)  The third (5/4) is also considered a consonant interval (125Hz, 250, 375, 500, 625, 750, 875, 1000) | |
| Dissonance of semitone | The Pythagorean semitone (256/243 ≈ 1.0534979) is considered a highly dissonant interval. The lowest harmonic of the upper note which coincides w a harmonic of a the lower note is the 243th harmonic  The equal-tempered semitone () will have no harmonics coinciding at all, as cannot be expressed as a ratio of 2 integers. | |
| Beats, Roughness & Dissonance | Beats slow enough to be individually discerned are generally tolerable. The human ear can perceive individual beats when the beat freq is < about 10 Hz  Above a beat freq of about 10Hz, the individual beats are too fast to be discerned. However, the beats cannot be perceived as a sound since their freq is < 20 Hz (lowest freq which can be perceived by human ear)  When beat freq is too high for beats to be discerned individually, but too low for them to be perceived as audible sound, the beats will be perceived as an unpleasant "roughness" | |
| Wolf Tones & Dissonance | Table  Description automatically generatedWhen 2 notes are played simultaneously have harmonics which can combine to produce beats, w a beat freq too high for the beats to be individually perceived, but too low to create audible sound, the beats produce a perceived "roughness" which add to the perception of dissonance btw the 2 notes  Conside the Just C major scale. The 3rd harmonic of D (297 Hz) and 2nd harmonic of A (440 Hz), will combine to give beats of 891-880 = 11Hz  The 11Hz beat is perceived as an unpleasant roughness, known as wolf tone | |
| Consonance / dissonance from unison to octave | Chart, line chart, histogram  Description automatically generatedGraph of perceived dissonance for a cts range of intervals, starting from unison to octave.  This is done by sounding 2 notes in unison, e.g. C, and then increasing freq of 1 note smoothly until it reaches the C 1 octave above.  In graph, can see "valleys" of consonance at impt intervals such as octave, fifth and the third.  The dissonance is highest at freq diff btw the 2 notes at which their harmonics combine to form beats which are perceived as most rough  m3 = minor third? | |

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| Clavichord | | | Most impt keyboard instruments using strings before piano was invented was the clavichord and harpsichord  Clavichord has the simplest possible action, w its key pivoting to strike the string w a tangent.  Diagram, engineering drawing  Description automatically generatedThe other end of a clavichord key has a metal piece called a tangent which remains in contact w the string after striking it so that the player can actually affect the tone of the str w the pressure on the key while the str is vibrating. While this gives the clavichord great powers of expression not available even w the piano, the sound of the clavichord is weak and soft as the tangent cannot strike the str strongly |
| Harpsichord | | | Chart  Description automatically generatedThe harpsichord jack is lifted up when the key is struck, so that the quill plucks the str. When the quill goes down, it is pushed out of the way by the tongue so that the str is not plucked. The tongue is then pulled back to its normal position by a spring. This action is called an escapement  Diagram  Description automatically generated |
| Harpsichord action is similar but plucks the string w a plectrum mounted on a jack insteadDiagram, engineering drawing  Description automatically generated.  Harpsichord key plucks the str w a plectrum such as a quill mounted on a jack. The quill is fitted on a tongue which can pivot backwards. The quill is able to impart stronger vibrations to the str than the clavichord tangent. However, the quill will pluck the str w the same speed no matter how the key is struck, giving the same loudness no matter how the key is pressed. |
| Dulcimer | | A picture containing chart  Description automatically generatedThe Dulcimer is an ancient instrument consisting of several strings streched over a wooden framework. The instrument is played by hammering thes trings w 2 hammers held by the performer. The dulcimer is thus an ancestor of the piano. In fact, the piano is just a large dulcimer whose hammers are operated w a keyboard. Variants of the dulcimer are the cimbalom/tsimbaly of Central Europe, and the yang jin of China.  The dulcimer player is able to hit a str w a hammer and rebound the hammer manually, so that the str can vibrate freely, and the hammer can hit the str again.  The clavichord tangent hits the str and stays there as long as the str is depressed, as the hammer cannot rebound. For the dulcimer action to be imitated by a mechanical hammer activated by a keyboard, there has to be a way for the hammer to hit the str and then rebound off the str  Hence, we need a mechanism more complex than the simple clavichord action, which would allow a key to cause a hammer to strike a string and rebound after striking | |
| Cristofori's piano | | | Diagram  Description automatically generatedAround 1700, the Italian harpsichord maker, Bartolomeo Cristofori, invented a harpsichord w "piano e forte" (soft & loud), which had an action enabling the keyboard to strike the strings w hammers which could rebound, w a variable force and loudness (unlike harpsichord)  The action of the Cristofori piano is basically a series of levers which converts the downwards movement of the 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, which is in turn determined by the key velocity. |
| Piano action | Diagram  Description automatically generatedThe key is itself a lever w the effort (E) applied to the key at 1 end and the jack at the other end as the load. The pivot around which the key moves is the fulcrum of the lever. The key is thus a class 1 lever, w mechanical advantage (M.A.) of about 1, and the jack rises about as fast as the key is depressed.  The jack supplies the effort for the intermediate lever, whose pivot is at 1 end and load is at the other. The intermediate lever is a class 3 lever, whose M.A is ≈ 0.5 (< 1 as load moves faster than effort). The free end of the intermediate lever thus rises about twice as fast as the jack  The free end of the intermediate lever supplies the effort for the hammer at a pt on its shank near its fulcrum. The hammer is another class 3 lever w an M.A of 1/4, and the hammer thus rises 4 times faster than the free end of the intermediate lever. The hammer thus moves 8 times faster than the key moves down. When hammer gains this velocity, it is thrown up into flight and hits the string. Once it is in flight, the player has no more influence on the hammer. | | |
| Escapement | | | Diagram  Description automatically generatedThe jack in the Cristofori action has a notch which is an essential part of the action's escapement mechanism. When key is depressed, the action throw the hammer upwards to hit the string. The notch in the jack enables it to get out of the way or escape, enabling the hammer to rebound and fall back even when 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 this free flight is, the more control the player has over the loudness. A spring brings the jack back to its original position when the key is released. |
| Fortepiano | | | After Cristofori's invention, other alternative actions were invented and refined as improvements on Cristofori's action. These early pianos are known as fortepianos to distinguish them from today's modern pianofortes  The main diff btw a fortepiano and a modern piano is its more delicate/refined sound, mainly due to the fact that its strings are strung over a wooden frame, and hence have a lower tension than a modern piano. Some purists insist that all piano music up to the middle or late nineteenth century should be performed on a fortepiano and not modern piano. |

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| Piano developments | | - Double escapement to enable rapid repitition of notes  - Cast iron frame enabling string tension to incr, hence allowing hammer to strike strings w greater force and produce greater loudness  - Overstringing of lower strings over the upper strings in the frame of the grand piano, so as to reduce the overall length of the piano  - Invention of the upright piano (w springs replacing gravity in pulling back the hammers from the strings), making possible a compact piano for domestic use |
| Modern grand piano | 0199work1[1]The modern grand piano is a more powerful and complex instrument compared to Cristofori's piano. However, in its basic action, i.e. using its action to amplify the velocity of the key to throw the hammer towards the string is similar to Cristofori's piano. The modern piano has a cast iron frame which enables it to be louder than fortepianos w their wooden frames.  Diagram  Description automatically generatedModern grand piano also has double escapement mechanism, allowing pianist to play a repeated note without having to lift the finger off the key completely, thus making rapid repetition of notes possible (as in many pieces by Chopin and Liszt)  Modern grand piano action is very similar to Cristofori's action. Major diff is that the jack is not directly activating the hammer, but through a roller, and the addition of a repetition lever. | |
| Repetition lever | Diagram  Description automatically generatedThe repetition lever enables the hammer to be struck again a second time before the actual escapement mechanism can complete its action thus enabling repeated notes to be played faster than would be allowed by the escapement alone. The jack actually protrudes through a groove in the repetition lever to contact the knuckle or roller. | |
| Grand piano action | Diagram, schematic  Description automatically generatedDiagram, schematic  Description automatically generatedDiagram  Description automatically generatedDiagram  Description automatically generated | |
| Repetition lever | The hammer rebounds and the knuckle lands on the repetition lever, compressing its spring. The repetition lever tries to lift the hammer, but the hammer tail is stopped by the back check as long as the key is depressed. If the key is fully released, the jack will go back to its original rest position. If the key had to be releaded fully for the next note to be played, rapid repetition of notes would not be possible.  However, if the key is only partly released, for about one-third of its travel, then the hammer will be released from the back check. The repetition lever will lift the hammer and move the knuckle up, allowing the jack to slip back under it. Thus the jack will be in position to enable the hammer to strike the string again, if the key is depressed another time. Notes can hence be repeated w/o the key having to be fully released | |
| Main parts of a piano | p2[1]- Cast-iron frame/plate: invented by Alpheus Babcock in 1825, enables strings to carry tension of up to 18 tons  - Soundboard: amplifies sound produced by strings, normally made of spruce (a dense wood)  - Bridge: transfers sound from strings to the soundboard  - Pinblock: hold the tuning pins around which the strings are wound  - Action: responsible for activating hammers from keyboard  - Keyboard: interface w the player  - Pedals: allows player to control sustaining of string vibrations  - Case: protective and decorative outer covering | |
| Piano string and soundboard | 0199work2[1]p171[1]A piano string is strung btw the tuning pin and the hitch pin  The actual vibrating part of the string or its speaking length is btw the Capo d'astro bar (cap of the star) or Capo tasto (cap of the key) and the bridge | |
| Overstringing | | pint[1]Overstringing first used by Steinway, strings the lower strings of the piano over the middle strings, thus shortening the length of the grand piano (or height of the upright piano)   |  |  |  | | --- | --- | --- | | Type | Length | Yamaha | | Petite/apartment grand | under 5' |  | | Baby grand | 5'1'' – 5'3'' | C1 | | Parlour grand | 5'4'' – 5'9'' | C2 | | Living room grand | 5'10'' – 6'3'' | C3, C5 | | Semi-concert grand | 6'10'' – 7'5'' | C6 | | Full-size concert grand | 7'6'' – 9'6'' | C7, CFIIIS |   Grand piano size are measured iin lengths from outer edge of keyboard to end of lid |

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| Upright piano action | Diagram  Description automatically generatedThe upright piano is really a grand piano with the strings in a vertical instead of horizontal position, to minimise its footprint. The keyboard remains in a horizontal position, and the action is modified to allow the hammer to strike the strings from the front. The hammer's rebound and fall back is aided by a bridle tape. The jack provides an escapement in a similar way to the grand, and the jack spring returns it under the butt of the hammer for the next note.  Diagram  Description automatically generatedFull-size upright (47 – 60 in) - full-size action, extended direct blow type  Diagram  Description automatically generatedDiagram  Description automatically generatedStudio (43 – 47 in) - full size action, direct blow type  A picture containing text  Description automatically generatedConsole (40 – 43 in) - compressed action, direct blow type  Spinet (36 – 39 in) - full size action, indirect blow type  - Upright action is more complex and less responsive than grand  - Upright's strings, frame and soundboard are vertical, not horizontal  - In upright, key activates action through a vertical lever called a sticker  - Hammers hit strings horizontally in upright, not vertically as in the grand  - Hammers are pulled back by a bridle tape in upright, not by gravity as in grand  - In upright, soft pedal works by placing hammers closer to strings, in grand by shifting hammers to strike only one string | | |
| Hammers and voicing | Piano hammers are made of wood, w a covering of wool felt which is compressed on the inside and highly stretched on the outside which makes the hammer compress and bounce well. As a hammer hits the string over a long period, its contact point w the string becomes more and more flat and the hammer may have to be reshaped. Also, the contact point may become more compressed and harder, and the tone becomes correspondingly harder. To counteract this, the hammer may be pierced w needles around the contact point to soften the surface there. This process is known as voicing | | |
| Piano strings | Piano strings are made of steel wire of diff thicknesses, and the bass strings are wound with copper wire. The shortest strings are about 2 inches, and longest strings about 84 inches long. Although most pianos have 88 notes, there are btw 220 to 240 strings in all.  The lowest 10 to 15 notes have one string each, made up of a very thick steel wire wrapped with two layers of copper winding. The next 20 or so notes have two strings each, smaller in thicknesses with one thinner copper winding. Each of the remaining two-thirds of the notes has three steel strings w no copper winding. Throughout the entire piano, the gauge or thickness of the steel wire is decreased every few notes. | | |
| Piano pedals | Every string has a damper which normally is in contact w the string, but is lifted to allow it to vibrate as long as the key is depressed.  Grand piano pedals are: Left: soft pedal – shifts the hammer so that they strike only 1 string (una corda).  Middle: sostenuto pedal – when 1 or more notes are played, and this pedal then depressed, only these notes will be sustained, i.e. have their dampers off  Right: sustain pedal – lifts all dampers to let all strings freely vibrate  Upright piano pedals are: Left: soft pedal – shifts hammers closer to strings  Middle: "sostenuto" pedal – on some uprights it raises the dampers from E below Middle C downwards. Often a lockable soft pedal which interposes a layer of felt btw hammers and strings, for quiet practicing. No fn on some pianos  Right: sustain pedal – lifts all dampers to let all strings freely vibrate | | |
| Automated pianos | | Mechanical pianos: pianola, player piano, reproducing piano. Modern electronic pianos: disklavier, pianodisc, pianomation | |
| Pianola | First mechanism for playing a piano automatically was the pianola, invented in 1896 by Edwin Votey. This was a mechanism driven by air pumped by foot pedal, and a paper roll w perforations controlling felt-covered wooden "fingers" depressing the keys on a separate and normal piano. | | |
| Player piano | Player piano was invented by Meville Clark incorporated the pianola mechanism in a normal piano. The hammers are activated by a change in air pressure delivered by a bellows operated by pedals. The loudness was controlled by how vigorously the pedals were operated so as to incr or decr the air pressure. Which keys are selected is determined by a paper roll w perforations, as in the pianola, through whose holes air can pass through to control a valve. The valve when open allows the air pressure from the bellows to activate the hammer. (The roll perforations are too weak to control the air from the bellows directly.) The roll did not indicate the tempo, which had to be controlled by the human pedal operator with a tempo control. However, the player piano could still be played on its keys like an ordinary piano.Diagram  Description automatically generatedDiagram, engineering drawing  Description automatically generated | | |
| Typical player piano | Diagram, schematic  Description automatically generatedThe human operator of a typical player piano had to pump the foot pedals, which activated a bellows to pump air for the pneumatically-operated player piano mechanism. The pedals of a normal piano were therefore not present, and the operator could usually operate 4 manual controls: sustain lever, bass soft lever, treble soft lever, tempo lever | | |
| Reproducing pianos | The loudness of the player piano was controlled by the person operating the pedals, who also controlled the tempo manually. The reproducing piano introduced an electrical air pump to assure consistency of air pressure, and a paper roll which included extra tracks to control parameters such as the pressure of air operating the hammers, and thus varying the loudness as required, as well as the tempo. This allowed the reproducing piano to more successfully imitate a human player, and to record the performances of human pianists. | | |
| Paper rolls | |  |  |  |  |  |  |  |  |  |  |  |  |  | | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | | Channel (track) | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 – 93 | 94 | 95 | 96 | 97 | | 88-key player piano |  | sustain |  |  | A0 | A#0 | B0 | C1 – C8 |  |  |  |  | | Reproducing piano | full vacuum | sustain | express softer | express louder | rewind | shut off | B0 | C1 – C8 | bass hammer rail | treble hammer rail | accent | play |   The paper rolls in a pianola or player piano initially had a range of only 58 or 65 tracks, so that not all the notes of an 88 key piano could be activated, preventing many classical pieces from being playerd. In 1908, an 88-track paper roll was adopted which became the industry standard. This had 9 holes to the inch on an 11 wide paper roll to give a total of 99 tracks. | | |
| Typical 88-key paper roll (green line (dynamics) red line (tempo) for manual control) | | Diagram  Description automatically generated88-key paper roll w chained perforations (green line (dynamics) red line (tempo) for manual control) |

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| Modern Reproducing Pianos | | | The modern equivalent of the reproducing piano is a system such as the Yamaha Disklavier system, in which the piano action is activated electro-mechanically (not pneumatically, by air) nad controlled by a computer system. The equivalent of the paper roll in the Disklavier is a computer floppy disk | |
| MIDI | The modern equivalent of the perforated paper roll is the Musical Instrument Digital Interface (MIDI) file. MIDI is a standard mtd of controlling electronic musical instruments so that they will play music according to the info contained in a MIDI file. This info includes turning notes on and off, expressing loudness of each note, sending program changes, use of sustain pedal and other controllers such at pitch bend or modulation wheel, timing r/s of all MIDI notes and events, other types of control data | | | |
| A musical instrument which can be controlled by MIDI will have a MIDI interface, which is usually a socket which can accept a MIDI plug and cable. The socket and plug are usually a 5-pin DIN socket and plug respectively. Every instrument equipped w a MIDI interface must have either a MIDI input or MIDI output or both. When 2 instruments w MIDI interfaces are connected, a MIDI input on 1 instrument is usually connected to a MIDI output on the other instruments. Some MIDI instruments also have a MIDI thru (T) socket | | | |
| Diagram  Description automatically generatedDiagram  Description automatically generatedThe MIDI out of a synthesizer can be connected to a MIDI in of a 2nd synthesizer. The 2nd synthesize ("slave") can be played by the keyboard of the 1st synthesizer ("master") by sending MIDI data through the cable. A synthesizer can also be controlled by a sequencer which can record the seq of notes played on the keyboard of the syntehsizer (record) and playback the seq on the synthesizer  A MIDI signal can be used to control several MIDI instruments by daisy chaining the MIDI cable through the instruments using the MIDI thru socket to link the instuments as shown. This is possible as the MIDI in socket is linked to the MIDI thru socket | | | |
| MIDI channels | | Diagram  Description automatically generatedMIDI information transmitted through a MIDI cable carries data on MIDI channels. The MIDI channel is a basic stream of data which can control the performance of a musical instrument. A typical MIDI set up, with several instruments, pieces of equipment or computers linked together, will normally have 16 MIDI channels.  In diagram, the computer has one MIDI in (I) and two MIDI outs (O). It is connected via MIDI cables to a keyboard and a sound generating module.  The keyboard out goes to a computer MIDI in, while one computer MIDI out sends channels 1,2 and 3 to the keyboard MIDI in and the second computer MIDI out sends channels 4, 5, 6, 7, 8, 9 and 10 to the MIDI in of the sound module. | | |
| MIDI timing clock | | A MIDI channel consists of a series of events which control the performance of an instruments w a MIDI interface. The events in a MIDI channel are measured in terms of fractions of a crochet or quarter note. The standard unit is one twenty-fourth (1/24) of a crochet and one four hundred and eightieth (1/480) at the professional MIDI level | | |
| MIDI messages | | MIDI messages sent through a MIDI channel can be categorised into | | - channel messages: voice messages, mode messages  - system messages: real-time messages, common messages, exclusive messages |
| Structure of MIDI messages | | |  |  |  |  | | --- | --- | --- | --- | | status byte | | data byte 1 | data byte 2 | | 0 to 15 | 0 to 15 | 0 to 255 | 0 to 255 | | message | channel no. | data | data |   Each MIDI message consists of a string of one to three nums. Each num is in digital binary form and consists of one byte. A byte can take values from 0 to 255. We can subdivide a byte into two nibbles each having the value from 0 to 15. Hence a byte can be represented as:   |  |  | | --- | --- | | 0 to 15 | 0 to 15 |  |  | | --- | | 0 to 255 |   or  The 3 bytes in each message can be represented as | | |
| MIDI key num | | Each note on the piano is given a MIDI key num to identify it. The key num is used in MIDI messags which instruct a MIDI instrument to turn on/off a note etc. The MIDI key num can range from 0 to 127, with Middle C or C4 having the key num 60. Going up a semi-  tone will incr the key number by one, while going down will decr it by 1. The Cs on the piano will have the following key numbers:   |  |  |  |  |  |  |  |  |  |  | | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | | Note | C0 | C1 | C2 | C3 | C4 | C5 | C6 | C7 | C8 | | Key No | 12 | 24 | 36 | 48 | 60 | 72 | 84 | 96 | 108 | | | |
| MIDI channel voice messages | | MIDI channel voice messages are the basic messages which instruct the instruments to produce tones and include the following fns: - instruct receiving instrument to assign particular sounds to its voice, - turn notes on and off, - alter sound of currently active note or notes  Common voice messages:   |  |  |  |  |  | | --- | --- | --- | --- | --- | |  | status byte | | data byte 1 | data byte 2 | | 0 to 15 | 0 to 15 | 0 to 255 | 0 to 255 | | message | channel no. | data | data | | note off | 8 | x | key no. | notes off velocity\* | | note on | 9 | x | key no. | notes on velocity\* | | key pressure | 10 | x | key no. | amt of pressure\* |   \*For these quantities, data byte 2 takes only values 0 to 127, where 0 is lowest and 127 is highest velocity or pressure. For velocity-sensitive keyboards, note on velocity can be used to determine the volume/loudness of the note being played | | |
| MIDI channel mode messages | | MIDI channel mode messages determine how an instrument will process MIDI voice message. Common mode messages:   |  |  |  |  |  | | --- | --- | --- | --- | --- | |  | status byte | | data byte 1 | data byte 2 | | 0 to 15 | 0 to 15 | 0 to 255 | 0 to 255 | | message | channel no. | 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 message | | MIDI system messages carry info that is not channel specific, such as timing signal for synchronization, positioning info in pre-recorded MIDI sequences, and detailed setup info for destination device.  - real-time messages (timing clock which has only a status byte w value 248), - common messages - exclusive messages | | |

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| MIDI signals | Text  Description automatically generated with medium confidenceMIDI signals normally sent by control units such as electronic keyboards and are sent to units which can generate musical sounds, such as synthesizers, sound generators or even electronically controlled musical instruments such as the Disklavier.  Diagram shows keyboard sending MIDI message to sound generator to turn on note   |  |  |  |  |  | | --- | --- | --- | --- | --- | |  | status byte | | data byte 1 | data byte 2 | | 0 to 15 | 0 to 15 | 0 to 255 | 0 to 255 | | message | channel no | data | data | | note on | 9 | x | key no. | note on velocity | | decimal num | 9 | 0 | 60 | 114 | | hexadecimal | 9 | 0 | 3C | 72 | | binary num | 1001 | 0000 | 00111100 | 01110010 | | meaning | note on | channel 1 | note = C4 | velocity = 114 | |
| MIDI signal speeds | Nums in MIDI messages transmitted in from of binary nums. Each binary digit is known as a bit. In MIDI, bits are transmitted one at a time (serially) at speed of 31,250 bits/s |
| Chords | Message to turn on a note requires 3 bytes or 24 bits (8 bits = 1 byte). As a rule of thumb, a note-on message takes about one-thousandth of a second or 1 millisecond and thus about 1000 such messages can be sent per sec  When a chord which has ≥ 2 notes is to be played using MIDI, each note of the chord have to be turned on or off individually, as only 1 MIDI message can be sent at any one time. So for a chord, the notes will first have to be turned on 1 by 1 in seq until all notes are tunred on, and then turned off in the same order. This is done so quickly that the notes appear to have been turned on/off simultaneously |
| MIDI program change and patches | |  |  |  |  | | --- | --- | --- | --- | |  | status byte | | data byte 1 | | 0 to 15 | 0 to 15 | 0 to 255 | | message | channel no | data | | program change | 12 | x | 0 to 127, program num |   A MIDI channel can order a synthesizer or sound generator to switch to a particular instrument sound by means of the program change message. Most synthesizers and sound generators today are multi-timbral = can generate more than one type of instrument sound at any one time. At the beginning of a MIDI seq, each channel will send a program change message to tell the synthesizer or sound generator which instrument sound or patch is to be used.  E.g. status byte is 12 (binary 1100) followed by 15 (binary 1111) for channel 16. Data byte is 26 (binary 00011010) to indicate sound generator should switch to program num 27 |
| General MIDI (GM) | GM is a system in which all manufactures of MIDI synthesizers and sound generators agree that the MIDI program numbers from 1to 128 will always produce the same instrumental sound. (individual instrument in GMinstr.pdf). Need change to 0 indexing   |  |  |  |  |  |  |  |  |  |  |  |  | | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | | Program num | Instrument | 17-24 | Organ | 41-48 | Strings | 65-72 | Reed | 89-96 | Synth Pad | 105-112 | Ethnic | | 1 - 8 | Piano | 25-32 | Guitar | 49-56 | Ensemble | 73-80 | Pipe | 97-104 | Synth Effects | 113-120 | Percussive | | 9 - 16 | Chromatic Percussion | 33-40 | Bass | 57-64 | Brass | 81-88 | Synth Lead |  |  | 121-128 | Sound Effects | |
| Standard MIDI files | A MIDI sequence consists of a stream of MIDI messages consisting of stream of bytes telling a MIDI instrument which notes to play and how to play the music w the required volume, tempo etc.  Standard MIDI files provide a common file format used by most musical software and hardware devices to store song info including title, track names, and what instruments to use as well as the MIDI sequence of musical events described above.  The software music sequencer is the most common type of computer software using standard MIDI files. Almost any music sequencer, whether software or hardware, is capable of creating and reading standard MIDI files. |
| MIDI sequencers | A MIDI sequencer is a device which can store a sequence of MIDI messages and output them through a MIDI out socket, in order to control a MIDI sound source such as a synthesizer or sound generator.  A MIDI sequencer may be a hardware sequencer such as the Yamaha QY100 or software sequencer (Anvil Studio, Jammin32) |

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| Synthesis of waveforms | | To create or synthesize musical sounds which are similar to original sounds from real instruments, we need to synthesize their waveforms using their freq spectrum i.e. the nature of the harmonics of the waveform, to recreate the original waveform. There are several techniques for synthesizing musical sounds by supplying the required harmonics:  1) Additive synthesis. 2) Subtractice synthesis. 3) Amplitude modulation synthesis. 4) Freq modulation (FM) synthesis. 5) Wavetable synthesis and sampling. 6) Physical modelling | | | | |
| 1) & 2) | | Additive synthesis takes a num of separate waveforms and comvines them to produce a new waveform  Subtractive synthesis starts w a given waveform and subtracts from its harmonics to produce a new waveform | | | | |
| 1) | | Analyzing a complex waveform: it can be broken down into a num of harmonics/overtones, w each as a simple sine wave  By using a num of sine wave oscallators to generate the harmonics, we can combine them in a mixer to reproduce the original waveform | | | | |
| 2) | | Take a waveform which is very rich in harmonics, and remove or reduce some of them so that the desired freq spectrum is obtained  Typical subtractive synthesis system: Oscillator (produces a starting waveform rich in harmonics) Filter (reduce or enhance spectrum as desired) Amplifier (amplifies output to desired loudness) | | | | |
| Low-pass filter: Rejects all harmonics above a certain freq  High-pass filter: Rejects all harmonics below a certain freq | Band-pass filter: Rejects all harmonics outside a certain range of freq  Band-stop filters: Rejects all harmonics within a certain range of freq | | | |
| Graphical user interface  Description automatically generated with medium confidenceThe synthesized sound can have an amplitude envelope superimposer on its amplitude. The envelope has 4 parts:  Attack: how onset of sound behaves. Decay: decay of onset from peak value. Sustain: Steady portion of amplitude. Release: Decay of note to 0 at the end | | | | |
| Modulation Synthesis | | Combine 2 or more waveforms in a non-linear way to produce harmonics which were not present in either of the starting waveforms.  1 such mtd of combining 2 waveforms is by modulation, such as 3) & 4) | | | | |
| 3) | | Chart, histogram  Description automatically generatedWaveform of lower freq (modulator wave) modifies the amplitude of a waveform of higher freq (carrier wave). Amplitude envelope of the 2nd waveform is made to resemble the shape of the 1st waveform.  If freq of carrier wave is fc and freq of modulator wave if fm. Then spectrum of amplitude modulated (AM) carrier wave will contain fc and fc ± fm  Amplitude of fc - fm = amplitude of fc + fm but both lower than fc  FM spectrum is much rich in harmonics than AM spectrum, but symmetrical in shape | | | | |
| 4) | | Diagram  Description automatically generatedA carrier wave w freq fc is modulated by a modulator wave w freq fm s.t. the carrier wave's freq changes/is modulated according to the modulator wave's swings up and down. E.g. if it swings up, fc incr, and if it swings down, fc decr  Diagram  Description automatically generated with medium confidenceFM harmonics are fm, fc ± kfm, k  Total width of spectrum/its bandwidth also depends on the modulator wave. Shape of spectrum depends on amt by which the carrier freq varies (or the modulation depth or index) and the relative values of the carrier and modulator freqs.  A minimum FM system has 2 waveforms, each of which is an operator (modulator and carrier waveform). Output of an operator can become input to another operator and outputs of 2 or more operators can be added.  Creative Soundblaster use OPL2 FM chip which has 2 operators. Yamaha DX7 synthesizer has 6 operators which could be connected in various ways to create complex waveforms. | | | | |
| 5) | | In wavetable synthesis, the waveform is stored as a series of numerical values, obtained by sampling the waveform values at regular intervals in a wavetable. The waveform is generated from the values in the wavetable. | | | |  |
| Histogram  Description automatically generatedBy reading every 2nd or 3rd value (e.g.), we can generate same waveform at higher freq | | Waveform of lower freq can be generated by repeating the values twice or three times | | |
| Only one period of the waveform needs to be stored in memory.  Good: efficient in generating periodic waveforms, as only one waveform is stored.  Bad: produces a static spectrum, while real sounds have a dynamic spectrum. | | | Keyboards and synthesizers today store sets of one-period waveforms in their ROMs.  In high end synthesizers, each of the notes of the instrument's range is separately sampled. | |
| 6) | In Physical modelling synthesis, a physics model of the musical instrument whose sound is to be synthesized is developed.  To develop such a physical model, we need to understand how the instrument produces sound from the physics/acoustics point of view.  The physical model then attempts to express in mathematical terms the behaviour of each of the components of the instrument which take part in the sound production.  E.g. for piano, we need to model the hammer, string, damper etc, and how they interact to produce a sound.  This method thus attempts to reproduce the actual physical phenomena reproducing the waveforms; no actual waveforms are stored.  Advantage: ability to reproduce all possible changes in the waveforms corresponding to the diff ways in which the sound may be produced.  Cons: computationally expensive but has been available for wind instruments, and is only now coming into the electronic piano market. | | | | | |
| ROM storage for 5) | | For even greater realism, each note is sampled at diff loudnesses.  The ROM will carry all the waveforms for at least a General Midi (GM) set of 128 intruments stored.  – Mid range keyboard - Korg TR61: 64MB ROM. – High end keyboard /synthesizer Yamaha Motif ES8: 185 MB ROM  Very high end synthesizers 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 diff pitches, volumes and articulations are available on CD-ROM for use in such systems. E.g. the MOTU Symphonic Instrument is a library of 8 GB of orchestral instrument | | | | |
| Current Practice in Music Synthesis | | 5) were not used earlier due to large memory storage required. FM and other synthesis methods flourished because of need to conserve memory. With advent of cheap memory, 5) have now largely supplanted FM methods of synthesis.  5) is not really a method of synthesis, but a reproduction of recorded sound. New methods of synthesis, such as 6) and granular synthesis, have appeared. "Holy Grail" of Synthesis is still to create realistic imitations of instruments, and new sounds in real time computation. | | | | |

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| Microphone & Electrical waves | The microphone converts the vibrations of air particles which make up sound waves into electrical current vibrations, which have the same waveform as the sound waves. A thin membrane in the mic – a diaphragm, is made to vibrate by the sound waves. The diaphragm's vibration then generates electrical waves in a wire which have the same waveform as the sound waves. | |
| Electrical waves & Loudspeakers | | The electrical waves which are generated have the same waveform as the sound waves and can be carried by an electrical cable or over the air by radio waves or recorded on magnetic tapes.  To get back the sound wave from the electrical wave, use loudspeaker which works in reverse to a microphone. The electrical waves in a wire cause a diaphragm to vibrate, which produces sound waves with the same waveform as the electrical wave, and thus identical to the original sound wave |
| Analog & Digital signals | Waveforms in the real world vary smoothly and continuously and can take a cts series of values = analog  Recordings of such waveforms on media such as cassette tape and long playing vinyl records are also analog in nature.  Compute use binary system, but humans usually use decimal system. Binary system uses only two digits - "0" and "1". We say that they are stored in digital form. | |
| Analog to digital conversion | Chart, line chart  Description automatically generatedProcess of converting an analog waveform to digital form = analog-to-digital conversion or digitisation. When an analog waveform is to be converted to a series of binary nums by analog to digital or A to D conversion, it has to undergo a two-step process:  1) sampling: converts waveform to a series of values at regular intervals  2) quantisation: converts values into series of binary nums that can be stored/processed as computer data | |
| Sampling | In sampling, value of waveform is read at regular intervals. In sampling process, a waveform is input into an electronic circuit which is controlled by a clock. The clock commands the circuit to read the waveform at specific times at regular intervals, aka sampling period. These samples of the waveform are then passed on to the next stage of the circuit to be quantised. | |
| Rate at which waveform is sampled is impt to ensure shape of waveform is preserved by the sampling process.  Table  Description automatically generatedSampling theorem: sine wave must be sampled at twice its freq for it to be adequately stored and reproduced. This is known as the Nyquist freq.  Hence, the highest freq preserved in a waveform being sampled is half of the sampling freq.  To preserve freq in waveform up to f, sampling freq must be at least 2f. In practice, sampling freq is more than twice the highest freq in waveform | |
| Quantisation | | The values of the waveform which have been obtained by sampling are converted into nums. Each num reflects the value of the waveform as sampled at a particular point in time. The values can take a cts range, but in converting the values to nums, we have to settle for a certain degree of accuracy depending on how long we want each num to be. |
| Binary system | 0 and 1 are known as binary digits or bits. 002 = 0; 012 = 1; 102 = 2; 112 = 3  00002 = 0. 00012 = 1. 00102 = 2. 00112 = 3. 01002 = 4. 01012 = 5. 01102 = 6. 01112 = 7. 10002 = 8. 10012 = 9. 10102 = 10. 10112 = 11. 11002 = 12. 11012 = 13. 11102 = 14. 11112 = 15. The audio compact disc uses 16 bit nums, which give 65,536 diff values  The longer the bit length, the more combinations of 1s and 0s possible, hence more nums can be expressed. | |
|  | Num of possible values, and hence num of quantisation levels is directly dependent on bit length. If bit length = n, num of values which binary num can represent is 2n   |  |  |  |  |  |  |  |  |  |  | | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | | Bit length n | 1 | 2 | 3 | 4 | 5 | 8 | 10 | 12 | 16 | | 2n | 21 | 22 | 23 | 24 | 25 | 28 | 210 | 212 | 216 | | Num of quantisation levels | 2 | 4 | 8 | 16 | 32 | 256 | 1,024 | 4,096 | 65,536 | | |

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| Sampling & Quantisation | | Chart, line chart  Description automatically generated Combining quantisation levels w sampling, this forms a grid which determines the pts at which the waveform is sampled, and the nearest level to which each sampled value has to be fixed  The digitisation (analog-to-digital) conversion of a waveform is thus equivalent to fitting the waveform on the grid formed by the sampling instants and quantisation levels.  At each sampling instant, value of waveform at that instant is read and measured (arrows in diagram)  Each sampled value may be quantised by matching it to 1 of the quantisation levels. (e.g. match each value to level just below it)  Binary num is then taken as the quantised value for the corresponding sample. (e.g. 0111 1011 1101 1110 ...) |
| Digitised waveform | Diagram  Description automatically generatedIn e.g., sampling freq = 1kHz and bit length of 4 bits w 16 quantisation levels. Equivalent to 4 bits per millisecond or 4000 bits or 4kHz bits per sec. Ones and zeros can be transmitted as voltage levels: | |
| Reproducing waveform & Quantisation noise | | Histogram  Description automatically generated with medium confidenceEach binary num is converted back into its corresponding value  Reproduction is accurate enough, if sampling rate is high enough to reproduce highest freq required, and bit length long enough to keep quantisation noise as low as required.  Inaccuracies in preserving waveform due to too few quantisation level result in quantisation noise  Bit length determines num of grid lines in vertical axis  Sampling freq determines num of grid lines in horizontal axis  Quantisation noise is equivalent to a noise signal equal to the diff btw successive quantisation levels. This is because the effect of quantisation is introducing errors which are as large as the diff btw successive levels. |
| S/N ratio | The noise in a musical signal is expressed in terms of signal-to-noise (S/N ratio), usually in terms of dB units.  Chart, line chart  Description automatically generatedS/N ratio gives the ratio of signal/music power compared to noise power. The noise usually manifests itselfs as a background hiss (white noise) | |
| Bit length, signal and noise | If bit length is 4 bits, there are 16 quantisation levels. S/N ratio = ratio of maximum possible size/amplitude of music signal, and noise = one-fifteenth of the maximum, since the max amplitude can be divided into 16 - 1 = 15 segments.  Inaccuracy is one-fifteenth of max level, giving the effect of noise also one-fifteenth of the signal level  Bit length = n, num of levels = 2n, num of segments = 2n - 1. n = 4, S/N ratio = 15. n = 8, S/N ratio = 255. n = 16, S/N ratio = 65,535 | |
| Power, S/N ratio, dB | 10dB = 10 times increase in music signal power compared to noise power. 40 dB = 104 = 10,000 times  For good music playback, S/N ratio should be at least 60 dB = 1,000,000 times (music power compared to noise power) | |
| Bit length & S/N ratio | Power of a signal is directly proportional to the squares of its amplitude. Units for power is watts   |  |  |  |  | | --- | --- | --- | --- | | Bit length | Ratio of amplitudes of signal to noise | Ratio of signal power to noise power | S/N ratio in dB | | 4 | 42 - 1 = 15 | 152 = 225 | 10 \* log(225) = 23.521 | | 8 | 255 | 65025 | 48.130 | | 16 | 65,535 | 4,294,836,225 | 96.329 |   For n bit quantisation, there will be 2n quantisation levels, thus 2n-1 segments, but in general, 2n 1. So num of segments can be taken as 2n. Ratio of amplitudes = 2n, and ratio of powers = (2n)2 = 22n. S/N ratio = 10 \* log (22n) = 10 \* 2n \* log(2) ≈ 6.020n dB | |
| Transmission and storage of digital signals | | Amt of numerical info to store /transmit in 1 sec thus depends on: sampling rate & bit length of each binary num  Bit rate = sampling rate/freq \* bit length = num of bits per sec   |  |  |  |  | | --- | --- | --- | --- | | Medium | Sampling freq | Bit length | Bits per sec (stereo = 2 channels) | | NICAM stereo TV sound | 32 kHz | 10 bits | 32000 \* 10 \* 2 = 640,000 | | Audio compact disc | 44.1 kHz | 16 bits | 1,411,200 | | Digital audio broadcasting (DAB) | 24 kHz – 48 kHz | 16 bits | 768,000 – 1,536,000 | | Digital audio tape (DAT) | 48 kHz | 16 bits | 1,536,000 | | DVD/Professional audio | 96 kHz | 24 bits | 4,608,000 | |

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| Audio Compact Disk (CD) | Normal audio CD has a raw digital storage capacity of over 700 Mbytes. 1 byte = 8 bits  In 1 sec, we have 44,100 samples. Each sample is 16 bits / 2 bytes. 1 sec has 88,200 bytes. 1 min has 5,292 kbytes.  For 2 stereo channels, we have 10,584 kbytes. A 74 min CD thus has 10,584 \* 74 = 783,216 kbytes or almost 800 Mbytes | | |
| Audio CD is a 12cm diameter plastic disk in which ones and zeros are encoded as pits in an aluminium layer in the plastic. Can hold up to 74 mins of music encoded at 44.1 kHz and 16 bits | | |
| Ones and zeros are recorded as oval depressions = pits, with the surrounding undepressed area = land. The pits are only 0.5 micron wide and separation btw tracks is only 1.6 micron. (1 micron = 10-6 m) | | |
| Playing an audio CD | CD is read by a laser beam which is made to shine on the pits. The laser beam is reflected differently according to whether there is a pit or land. This is detected and converted to binary digits. (Actually, transitions btw pits and land indicate a binary 1, no transition = binary 0) | | |
| Digital Video Disk (DVD) | DVD improves the capacity of CD is 3 ways: 1) make pits much smaller 2) Having a double layer of pits 3) Having pits on both sides of disc (CD only 1 sided) | | |
| DVD was designed for storage of movies in higher resolution (720 x 480) than VCD (360 x 240) movies. DVD can also be used to store audio signals at higher quality than CDs are able to. Several formats to store audio on DVD:  1) DVD-audio: record up to 6 channels (for surround sound) at sampling rate of 96 kHz and bit length of 24 bits  2) SACD (Super Audio CD): sampling rate is 2.8224 MHz, but bit length only 1 bit. The digitisation process is very diff from normal analog-to-digital process | | |
| Digital audio compres-sion | Using mathematical techniques, possible to store music in digital form using much smaller num of bits for equivalent recording, w hardly any loss in quality.  But in general, there will be some loss in quality, and the greater the compression, the greater the loss of quality. Some digital music systems which use compression in this way are: - Digital audio broadcasting (DAB), - SONY's minidisc system (uses ATRAC compression sys), - MP3 sys (MPEG Level 3) | | |
| Minidisc (MD) | Minidisc looks like a 3.5 inch floppy disk, but is actually a 6.4cm magneto-optical recordable disk enclosed in a plastic case. | | Diagram, engineering drawing  Description automatically generated |
| Minidisc sys uses a compression sys similar in principle to that of MP3 (uses masking effect to leave out sounds which are not perceived by human ear). The Sony compression sys = ATRAC (Adaptive Transform Acousitc Coding). This gives a compression ratio of 5:1, so minidisc is able to hold 74 mins of mmusic (same as CD) with unperceptible loss of quality  The sys uses 6.4cm discs ina protective plastic case. The discs have magneto-optical pits which can be recorded and re-recorded many times. Hence, the minidisc is not just a compression sys but a physical standard which is intended to replace the cassette tape | |
| MP3 | MP3 is a system of storing music digitally in a very compressed form for downloading on the internet. Can store music in less than one-tenth of the bits needed for an equivalent audio CD (44.1 kHz, 16 bits. It uses a num of diff techniques to compress data:  • Minimal audition threshold - leaving out sounds below the threshold of hearing.  • Masking effect - using the psycho-acoustic masking effect to reduce info to be coded.  • Reservoir of bytes - to build up spare storage capacity for extra- dense signals.  • Joint stereo - Using the fact that the two stereo channels have a lot of common info which does not have to be coded twice.  • Huffman coding - a sophisticated mathematical algorithm to reduce the number of bytes further. | | |
| Masking effect | In masking, when 2 sounds are perceived by the human ear, under certain circumstances, 1 sound can make the other sound inaudible. This is known as masking. MP3 makes use of masking effect to reduce amt of info it has to store, by dropping the info which is masked and hence not needed. | Diagram  Description automatically generated | |
| MP3 quality | |  |  |  |  |  |  |  |  |  | | --- | --- | --- | --- | --- | --- | --- | --- | --- | | Bitrate | 1411k | 192k | 128k | 96k | 56/64k | 32k | 16k | 8k | | Quality | CD | perfect CD | excellent CD | near CD | FM quality | AM quality | shortwave | telephone | | kByte/min | 10584 | 1440 | 960 | 720 | 480 | 240 | 120 | 60 | | mode | stereo | stereo | stereo | stereo | stereo | mono | mono | mono | | bandwidth | 22.05kHz | > 15kHz | > 15kHz | 15 kHz | 11 kHz | 7.5kHz | 4.5kHz | 2.5kHz | | approx reduction | 1:1 | 8:1 | 11:1 | 15:1 | 25:1 & 22:1 | 44:1 | 88:1 | 176:1 | | | |
| Diff btw MP3 and MIDI | • MP3 compresses sound & music waveforms which have been digitized, so that it occupy less space and hence, more rapidly transmitted or take less space to store. MP3 files are basically like the original waveforms, i.e. they are recordings of actual performances.  • MIDI files are not recordings of actual performances. A MIDI file is basically a musical score or a piano roll which has to be performed  in order to be heard. However, the performance of the MIDI file is usually done, not by live human performers, but by synthesized instruments in a sound generator. This means that the performance is not as expressive as a human performance. However, the MIDI file is much smaller and quicker to transmit than an MP3 file. | | |
| Mobile phones & MIDI | Mobile phones with "polyphonic ring tones" generally use MIDI to play the ring tones. A reduced form of General MIDI (GM) is generally  used. There are two types of reduced GM: GM Lite and SP-MIDI.  • Standard General Midi, now called GM1 by the Midi Manufacturers Association (MMA), calls for at least 24 simultaneous voices.  • GIM Lite requires only 16 voices to be used at any one time, instead of the 24 voices of GM1.  • Scalable Polyphony or SP-MIDI can vary the number of voices used, e.g. from 5 to 24, depending on the capabilities of the sound generator or mobile phone. The composer must specify how the voices are substituted when the number of voices is reduced.  There are also other variants of MIDI such as Roland's GS, and Yamaha's XG, which expand the instrument sets and MIDI messages so as to increase the variety of sounds and the expressivity of the MIDI performances. | | |