ACOUSTICS

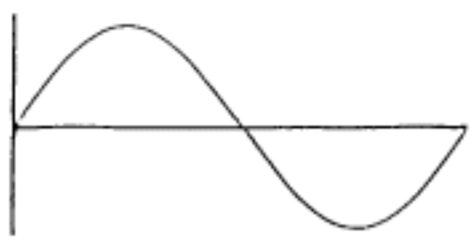
1. VIBRATIONS

Sounds are vibrations in the air, extremely small and fast fluctuations of airpressure.

These vibrations are generated from sounds sources and travel like waves in the water; sound waves however spread themselves in all directions like a steadily growing ball.
The speed of these sound waves is c.340 meters per second.

Regular vibrations are experienced as tones, irregular ones as noise (percussion instruments in music, consonants in language); sounds that are so short that it is impossible to hear a pitch, we call pulses.

Vibrationtime is the time it takes for one complete wave. The vibrating object moves first in one direction until a certain extreme, changes direction, passes the starting position until the opposite extreme point is reached, then returns again to the starting point. Drawn on a horizontal axis:



The distance between the starting point and the extreme point, the "width" of the wave is called the amplitude.

This determines the strength of the sound: the wider the amplitude, the louder the sound. Volume is measured in decibels (dB): a scientific measurement where the amplitude itself is not measured, but the energy associated with a particular amplitude.

The pitch of a tone is determined by the total amount of complete vibrations per second (so actually by the vibrationtime). The total amount of vibrations per second is the frequency and is measured in Hertz (Hz).
Naturally, in connection with large sound sources (long strings or streams of air) the vibrationtimeis longer and the frequency therefore lower in pitch than small sound sources (small strings or streams of air).

A_ (the a from a tuning fork) has according to international standards a frequency of 440Hz; 1000Hz is then named a Kilohertz (kHz).
Young, healthy people hear sounds between 16 Hz and 20 kHz. Sounds below 16 Hz are experienced as rattling, whilst sounds above 20 kHz are inaudible. (As one gets older, a decrease to c.9kHz is normal.)

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2. INTERVALS

The pure interval between two tones is determined by the ratio of their frequencies: irrespective of the range in which a particular interval sounds, the frequencies of two tones should always have the same ratio.
The more simple the ratio, the more consonant the interval will sound.

The most basic interval known - the fundamental - has a frequency ratio 1:1; both tones sound at the same pitch.

The octave has a frequency ratio of 1:2. So the octave above a tone of 200Hz will have a frequency of 400 Hz; the a from a tuning fork (=a_) as already mentioned, is 440Hz hence a" will have a frequency of 880Hz, and the a an octave lower will have a frequency of 220Hz.
Two tones forming a pure fifth have a frequency ratio of 2:3. The fifth above a tone with 200Hz therefore has 300Hz (2/3 x 600 = 400). So, the fifth below a tone with 600 Hz has 400 Hz (2/3 x 600 = 400) The fifth above a_ (440Hz), e" is therefore 660Hz.

Other intervals in their purest forms have the following ratios:

pure fourth	3 : 4	e.g. 30 and 400 Hz
major third	4 : 5	e.g. 300 and 375 Hz
minor third	5 : 6	e.g. 300 and 360 Hz
minor sixth	5 : 8	e.g. 300 and 480 Hz
major sixth	3 : 5	e.g. 300 and 500 Hz
major second	8 : 9	e.g. 300 and 337.5 Hz
minor second	15 : 16	e.g. 300 and 320 Hz

These ratios can also be seen in the playing of a stringed instrument. When you press exactly on the middle point of a string, an octave is produced. By removing a third of the string, therefore only using two thirds of the original length, a fifth will be produced. In order to make the tone a major second higher the string has to be shortened by 8/9 etc.

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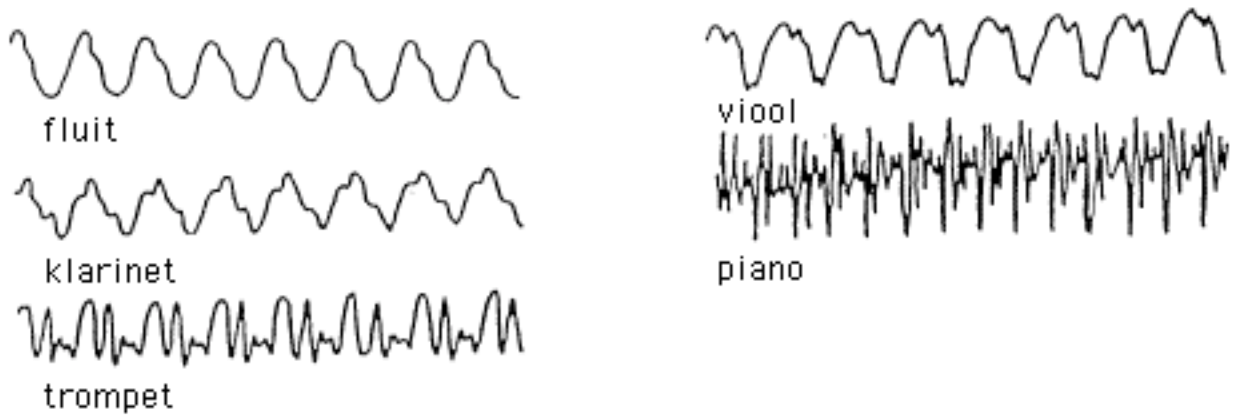
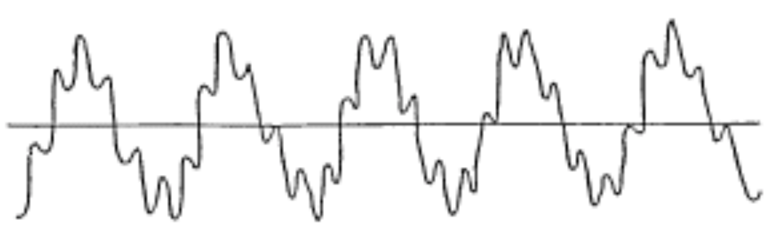
3. OVERTONES

The timbre or tone colour of a tone is determined by the way the vibration takes place. The following graphics represent tones that are high and loud (having the same frequency and amplitude), but with clear differences in timbre:

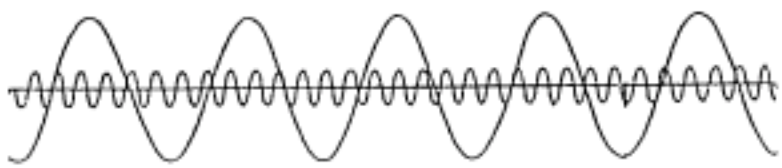


A perfectly regular and uniform oscillating vibration is never found in nature and can only be generated electronically. A similar tone is called a sine and is perfectly _colourless_. (A tuning fork still gives the best approximation). Graphically:

Now it is clearly proven that all regular vibrations can be analysed as a collection of or _additon_ of sine waves. A hypothetical wave could look like this for example:



analysed as a combination of 2 sine tones.



In our hearing system, every vibration is analysed in this way. The lowest tone from the whole (= the vibration with the largest wave) we recognise as the *pitch* of the tone, the other components of the sound we call the overtones.
The ratio of frequency and strength between the _fundamental tone_ and the overtone determines the way in which the wave travels, and consequently the timbre or tone colour of a tone.

The frequencies of the overtones are multipels of the frequencies of their fundamental tone, and are always the same 1:2:3:4:5: etc.; in other words fundamental and overtones combined, always form the same intervals.
Fundamental tones and overtones are called natural tones.

Here are the first 16 overtones from the fundamental tone C:

1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16

The series of overtones is in principal unlimited. The overtones that have an influence on the tone colour can have much higher numbers, until the limits of hearing.
Some tones do not fit into our tonal system i.e. the numbers 7, 11, 13 and 14 (the octave for No. 7). The minus sign above the note indicates that the natural tone is somewhat lower than the corresponding tone in our tonal system.

The structure of the harmonic series is perhaps easier to remember or reconstruct if one thinks:

- the octave from every natural tone is produced when the number is multiplied by 2. The second natural tone (= the first overtone) is an octave from the 1st, the 4th from the 2nd, the 8th from the 4th, the 16th from the 8th etc. The 3rd, 6th, and 12th also make octaves etc.
- the first 6 natural tones are made up of tones from a major triad, afterwards one can _count through_ 7, 9 11, 13, chords
- the numbers from two tones give the ratio of the interval that make:

numbers 1 and 2 form an octave octave ratio = 1:2
numbers 2 and 3 form a fifth fifth ratio = 2:3
numbers 3 and 4 form a fourth fourth ratio = 3:4
etc. but also:
numbers 3 and 5 form a major sixth major sixth ratio = 3:5
etc.

- a 3-fold forms a fifth with a 2-fold: number 9 (3x3) creates a fifth with number 6(2x3), number15 (3x5) creates a fifth with number 10 (2x5), etc.
- the intervals become smaller as they ascend. This can not be accurately notated because intervals, which are not customary, are produced.

Numbers 4 and 5 form a normal major third, 5 and 6 create a normal minor third but
because 7 is lower in our tonal system, 6 and 7 form a third which is smaller than the standard minor third, and 7 and 8 from a major second which is slightly wider than the usual major second. This only occurred between 8 and 9.
Between 10 and 11 we find a major second that is _too small_, between 11 and 12 minor second that is _too small_. Between 12 and 14 we have to notate one of the intervals as a major second although it is smaller than the _too large_ minor second between 11 and 12.

When sound vibrations reach an object that is sensitive to their frequency, that object vibrates with it. This phenomenon is called resonance.
Resonance is of great importance for nearly all musical instruments. They consist of one or more sound sources (e.g. strings), a resonator (e.g. the resonance box on a violin, the sound board of a piano).
Since every resonator prefers a specific frequency range, particular frequencies will resonate much more than others. This also determines which overtones will sound strong(er) and the overtones that will sound weak(er).
In other words: the resonator determines, for the most part, the tone colour of an instrument (and the volume). Therefore, everything is important: the type of wood, the thickness of the material, total layers of varnish, and the type of varnish.
These resonance-area's are also called formants, often compared with vowels in speech. When the mouth takes in a certain position)a soundbody) a vowelsound can be produced: ii, ee, aa, oh, oo, oe, uu. Instruments also have a certain vowelsound: e.g. a violin 'ii' and a cello more of an 'oh' sound.

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4. KEYS and TUNING

Based on the harmonic series let us clarify the measurement of consonance and dissonance in intervals: intervals sound more consonant if they have more common overtones and the unrelated tones have a _higher_ position. They sound more dissonant if they have fewer common overtones and the unrelated ones are in a _lower_ position.

At the same time, to explain the phenomenon of the harmonic series, low consonant intervals still do not sound more consonant and high dissonant intervals actually no more dissonant: the high, unrelated overtones from a consonant interval occur with a low position still within our hearing, and from a high positioned dissonant interval, most of the overtones are outside of our hearing range.

In the tuning of instruments _ usually done in fifths or fourths _ overtones also play a role: the beats that you hear is the difference between the first common overtone from both tones. The interval is only pure when these common tones are exactly the same pitch and the beats disappear.

With tuning there is more taking place than expected. There are two important problems:

Problem No. 1

Firstly, for example, to tune an ascending fifth from c_ (ratio 2:3) and then again a descending fourth (ratio 4:3) one creates a major second c_- d_. The frequency of d_ is then 3/4 x 3/2 = 9/8, which of course is the same ratio that we see with

the major second in the harmonic series. (Although: naturally?).
If you stack major seconds on top of each other, the frequency of each new second is 9/8 of the previous one. By staking 6 major seconds on top of each other - or alternating 6 x a fifth higher and a fourth lower - one makes an octave: c_- d - e_ - f sharp_- g sharp, a sharp_- b sharp_, b sharp_ being the enharmonic of c".

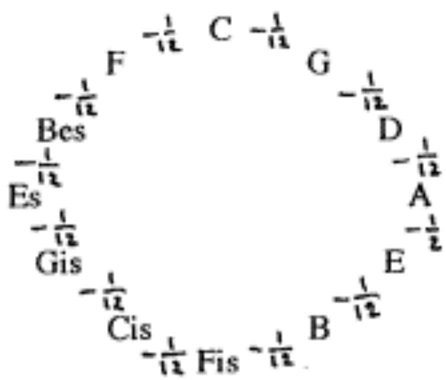
Actually: if you calculate the frequency of the octave by the six-fold multiplying method, then you do not end up with a pure octave ration of 1:2.

Namely: 9/8 x 9/8 x 9/8 x 9/8 x 9/8 x 9/8 = 531441/262144;or in other words: b sharp_ has a ratio to c_ of 531441/262144.

In making an octave from c_- c__ you get the ratio b sharp - c":531441/524288, or in other words: b sharp is higher than c. This difference is known as the Pythagorean comma.

So: if one tunes pure fourths and fifths uniformly you end up _too high_.

Since c.1800 people have tried to solve this problem by making each fifth a little smaller and each fourth a little larger so that the Pythagorean comma is divided equally between every fifth. This became known as _equal_ or _even temperament_.

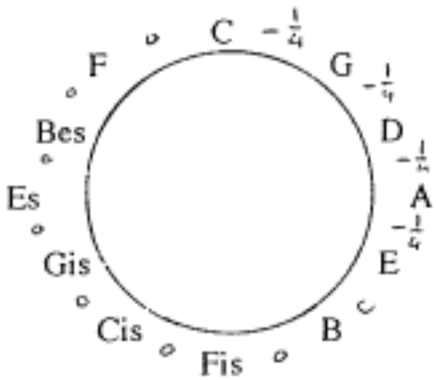


In this tuning system the impurities are so insignificant that one is not disturbed. Noticeably, the enharmonic tones are alike (b sharp = c) and all keys are playable and sound equal.

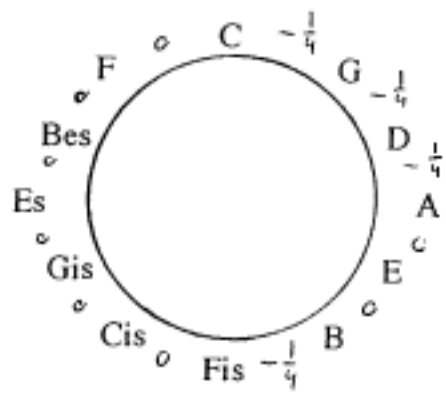
Between c.1700 and c.1800 people tried to tackle this problem in a different way: they did not divide the Pythagorean comma over all 12 (=proportional), but usually over 4, or sometimes 6, of the fifths.
Tuning of this kind was called Well Tempered, named and often attributed to the one who wrote them.

Some examples:

1. Kirnberger (1721-1783)
leerling van Bach:



2. Werckmeister (1645-1706)
organist en theoreticus:



The fact that not all the fifths/fourths, and therefore other intervals as well, are not _just as large_, each key sounds different.

In the time that this _Well Tempered_ tuning was used, the principle of 'proportional' or 'even tuning' was well known and written about (among others Werkmeister). The reason for it not being so widely used is due to the second large problem with tuning.

Problem No. 2

By tuning 2 pure descending fifths and pure ascending fourths, one creates a major third.

The ratio of this major third can be calculated as follows with the help of the 2:3 ratio and the 4:3 ratio of the pure fifth and pure fourth respectively:

- the frequency of d _ is 2/3 of a_
- the frequency of g _ is 4/3 of d_, therefore 4/3 x 2/3 = 8/9 of a_
- the frequency of c _ is 2/3 of g_, therefore 2/3 x 8/9 = 16/27of a_
- the frequency of f _ is 4/3 of c_, therefore 4/3 x 16/27 = 64/81 of a_

Therefore the major third is subsequently a little larger than the pure major third with the ratio of 4:5, or converted 64:80. This difference is largely known as the Syntonic comma, and is approximately 1/5 of a semitone. Since a major and minor third form a pure fifth, minor thirds are a comma too small.
All in all, a simple chord like a major triad in this tuning system was quite unpleasant, certainly when compared to the perfectly pure triad from the harmonic series.

Once more a short historical interval:
tuning in pure fifths and fourths is the oldest tuning method in Western music history. This simple system is known as Pythagorean Tuning_ named after the Greek philosopher and mathematician Pythagoras (6BC). The polyphonic music of the Middle Ages (until c.1500), that is to say the first polyphonic music, was based on this system. The most practical manner in this method of tuning is for the cycle of fifths to continue in a flat direction (therefore left) until E flat and in a sharp direction (right) until g sharp:

Once arriving at this point one realises that you do not end up in the same place. The interval g sharp - e flat is not a pure fifth or inverted, a pure fourth. (we always work from the purity of an octave). The resulting interval g sharp - e flat is a fifth which is too small and a fourth which is too large: the previously mentioned Pythagorean comma compensates for this.

Good attempt, but in practice this tuning system has quite limited use: the thirds and therefore the sixths, are very dissonant, and because of the remaining fifth/fourth g sharp - e flat it is not possible to play in all keys.
In other words: pure fifths and fourths can not be combined with pure thirds.

Back to the 'Well Tempered' system: the 'too small' fifths were therefore positioned so that the thirds in all keys with fewer accidentals were impure (more harmonious) than those keys with many accidentals. Every key therefore has its own character.
The thirds in the Equal temperament system are in general purer that those from Even Temperament: that is why people from the period between c.1700 and c.1800 gave preference to this.

Before, (from c.1500 - c.1700) the term 'Mean Tone' tuning was used: they strove for as many pure thirds as possible, by making most of the fifths a little smaller.

This is at the expense of a fifth which is far too large, whereby in this tuning only the use of a limited number of keys was possible.
(the name 'Mean Tone Tuning' indicates the d _ which in this tuning is the pure major third c - e divided exactly into two., so not into two uneven major seconds as in the harmonic series with the ratio 8:9 and 9:10)

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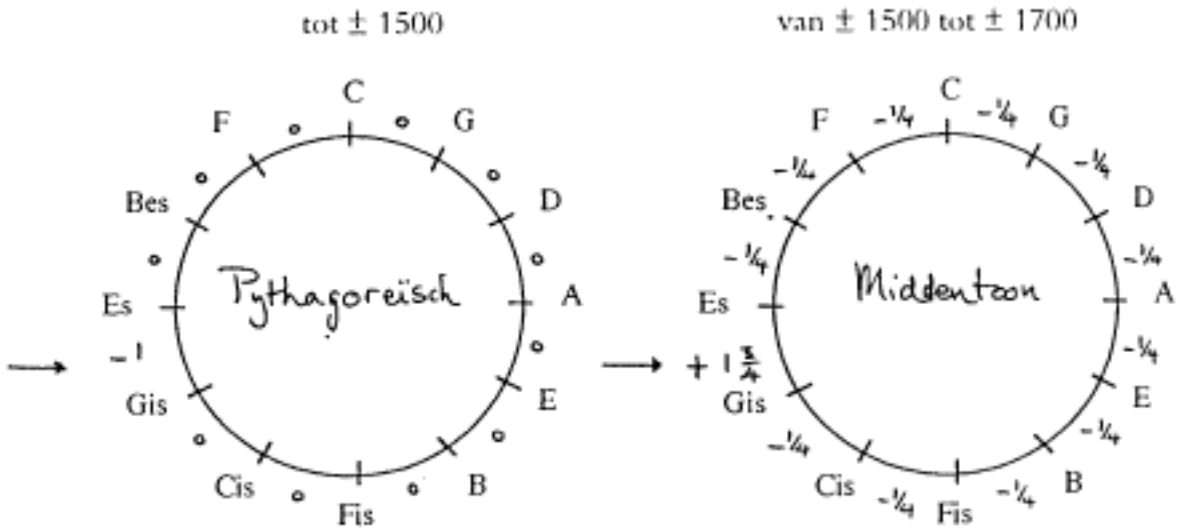
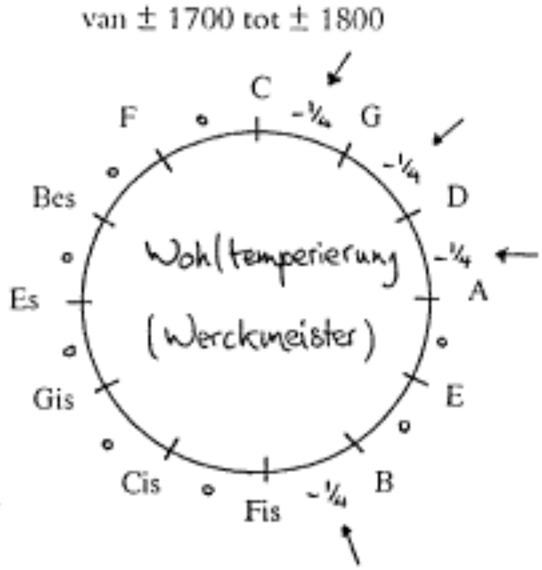
5. TUNINGS



Starting point
- All fifths are pure except one, here the Pythagorean comma is too small
Advantage
- Pure fourths and fifths
Disadvantage
- Major thirds and sixths are too large (Syntonic Comma)
Consequences
- Diatonic leading notes are tuned too high (small)
- Because of the bad fifth it is not possible to play in all keys

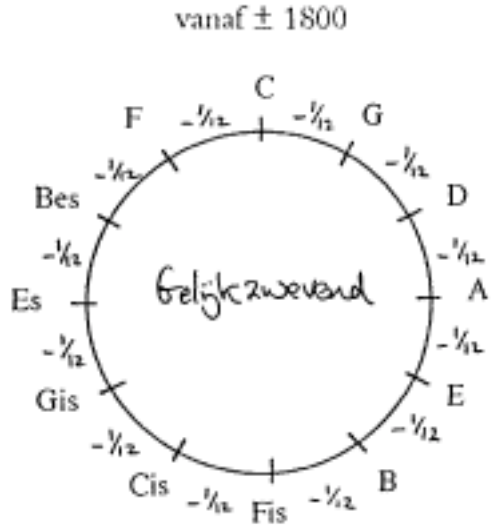
Starting point
- All fifth are 1/4 too small except one, the 'wolvesfifth' , which is far too large
Advantage
- More pure major thirds and sixths
Disadvantage
- Fifths are too small (fourths therefore too large)
- Because of the poor fifths it is not possible to play in all keys
Consequences
- Diatonic leading tones are tuned lower (large)



Starting point
- Four fifths are made 1/4 too small

Advantage
- No bad fifths, so it is possible to play in all keys
- where the fifths are too small the major thirds and sixths are purer
- the difference in purity gives every key its own character

Disadvantage
- All enharmonic tones are (on the keyboard in any case) alike (e.g. g sharp - a flat)



Starting point
- All fifths are 1/12 of a comma too small

Disadvantage
-nothings is more pure, everything is impure
All keys sound alike

Advantage
- Impurities are so slight that one is not really disturbed
- All keys are playable
- All enharmonic tones are alike (g sharp = a flat)