Was ist eigentlich schön an Musik?

Physik der Töne, Klänge und Harmonien

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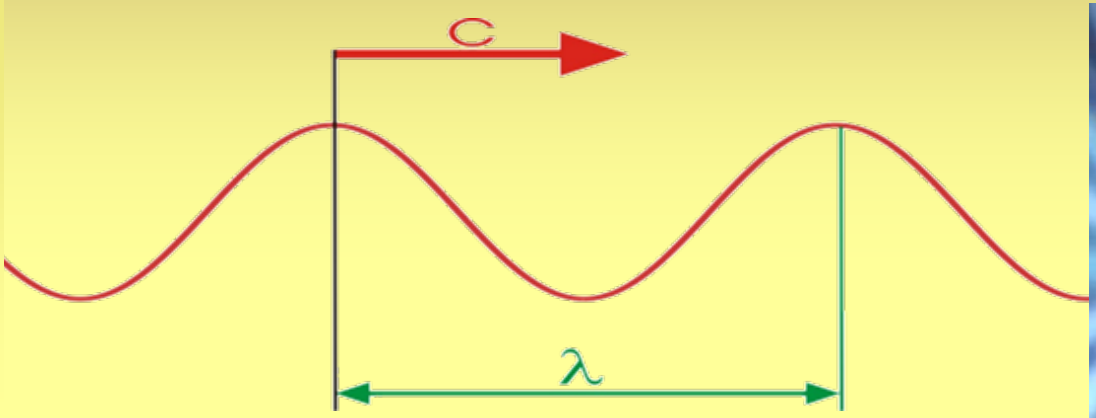
Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

Fachbereich Physik
Institut für Experimentalphysik

Physikalische Kenngrößen:



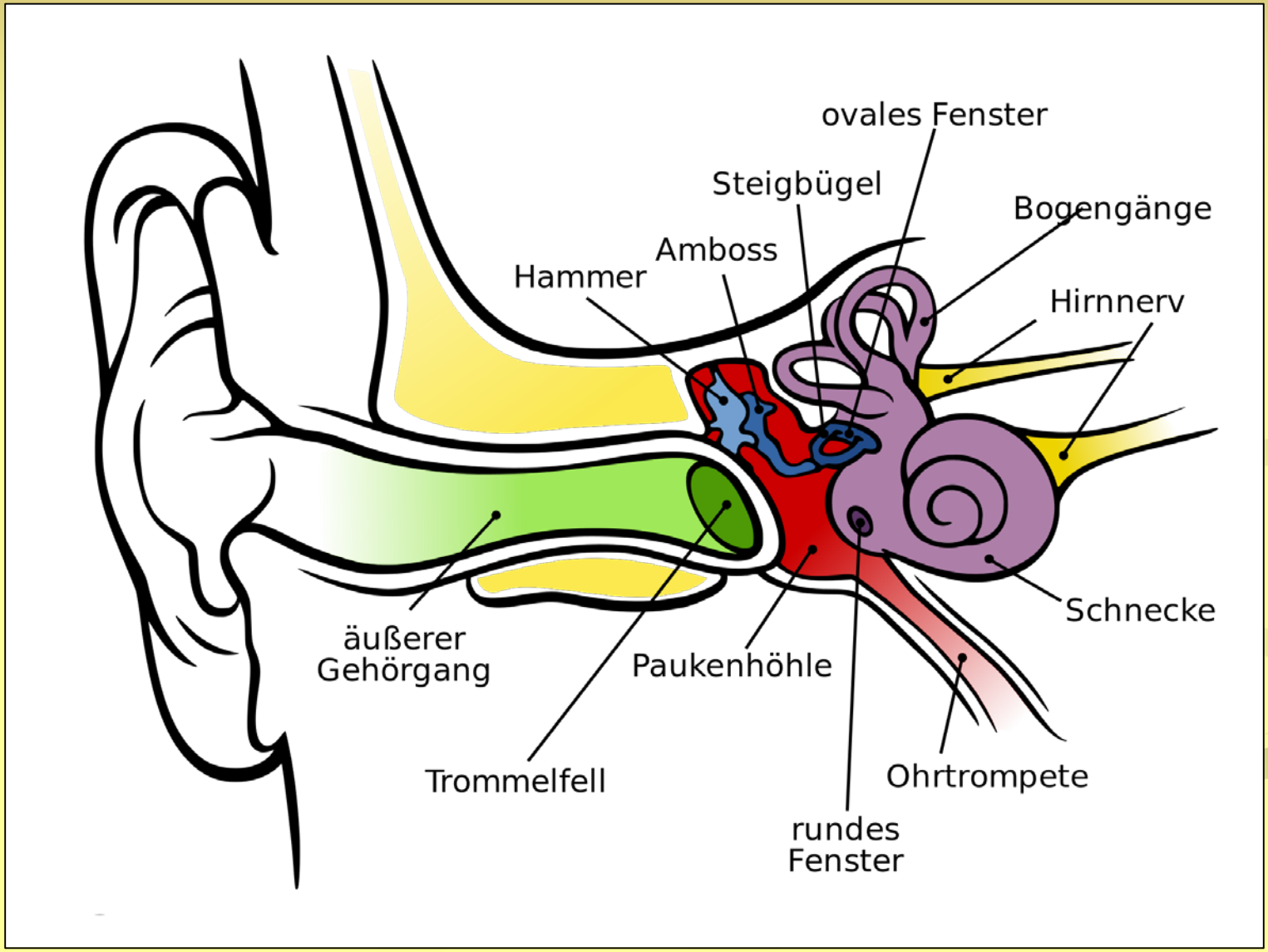
Frequenz ν: Anzahl der Schwingungen pro Sekunde

Wellenlänge λ: Abstand zweier Schwingungsbäuche

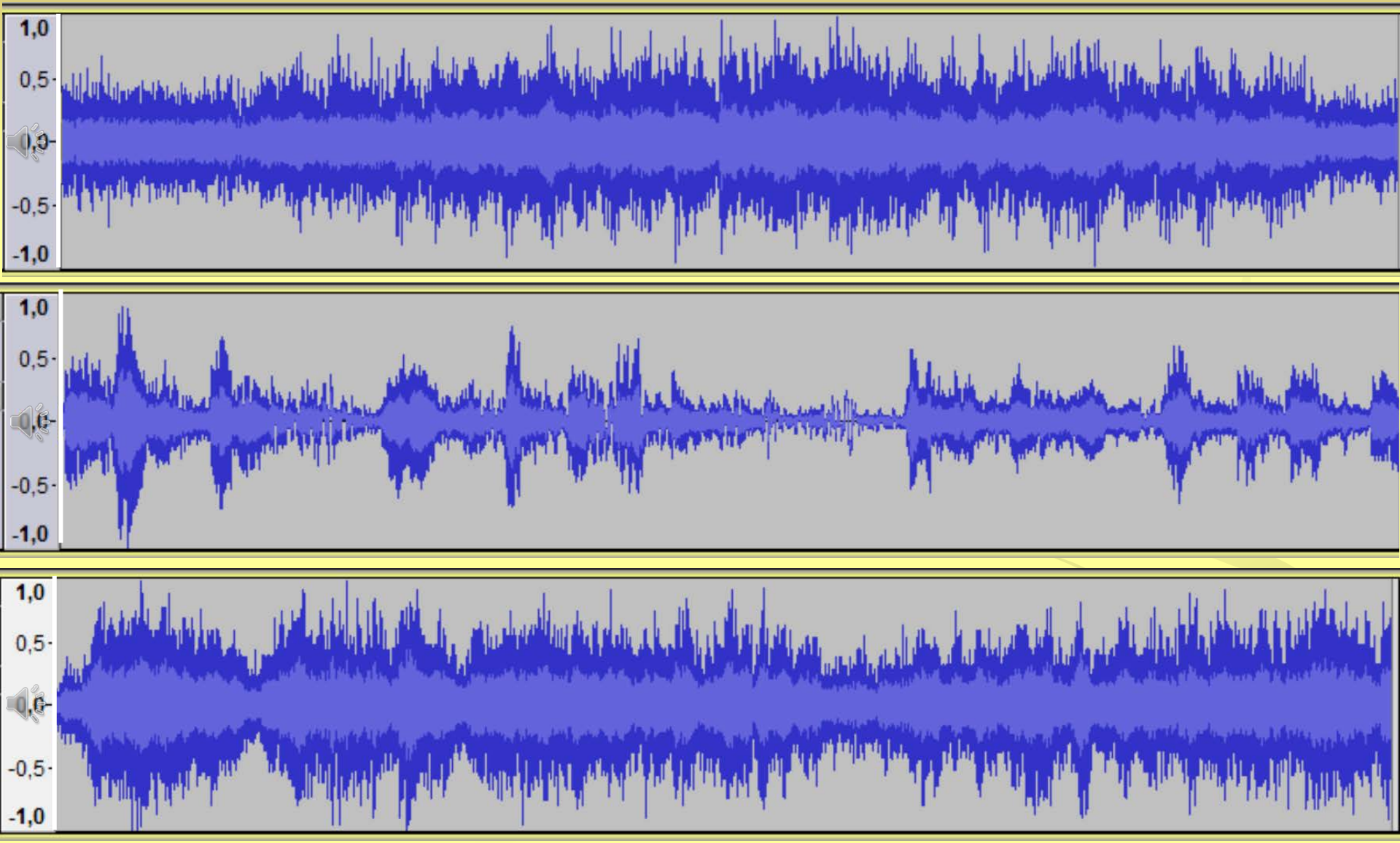
Schallgeschwindigkeit c: Ausbreitungsgeschwindigkeit

$$c = \nu \cdot \lambda$$

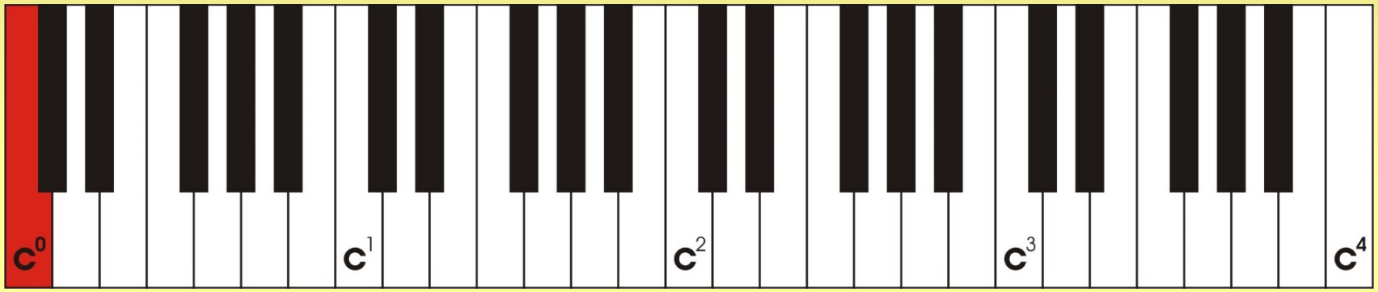
Aufbau des Ohres



Audio-Beispiele

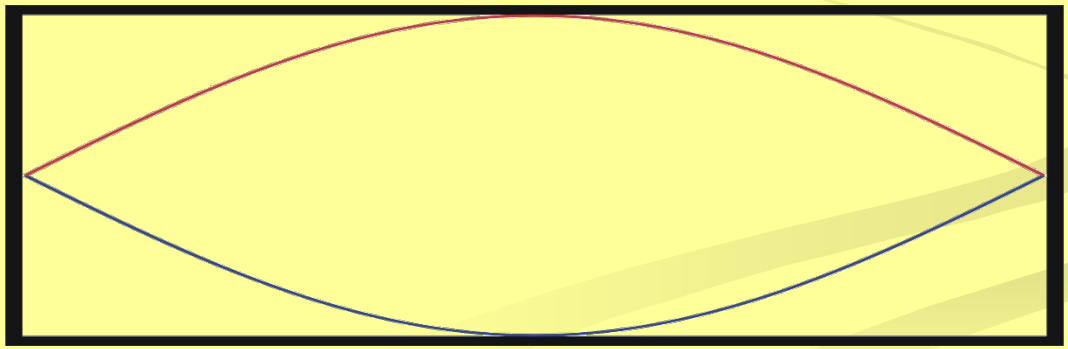


Obertonreihe:



Grundschwingung

Intervall: Prime



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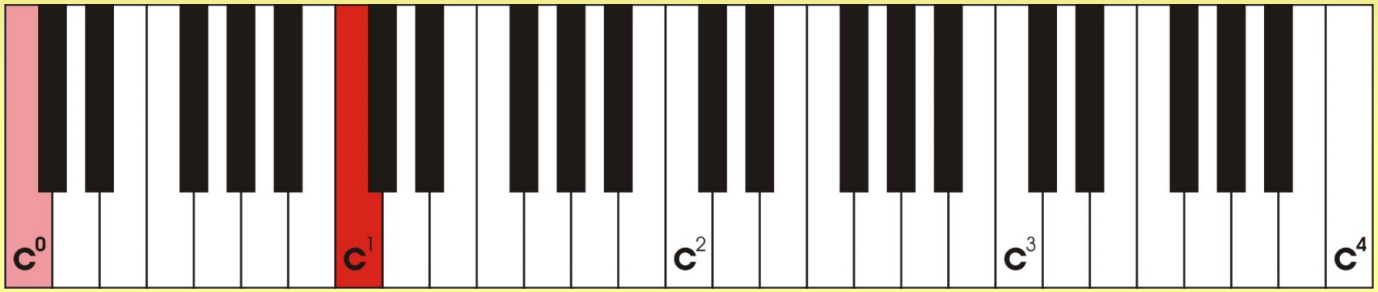
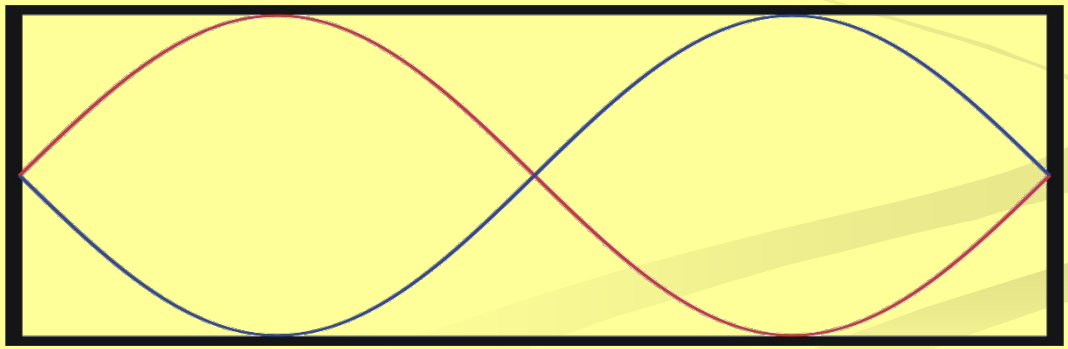
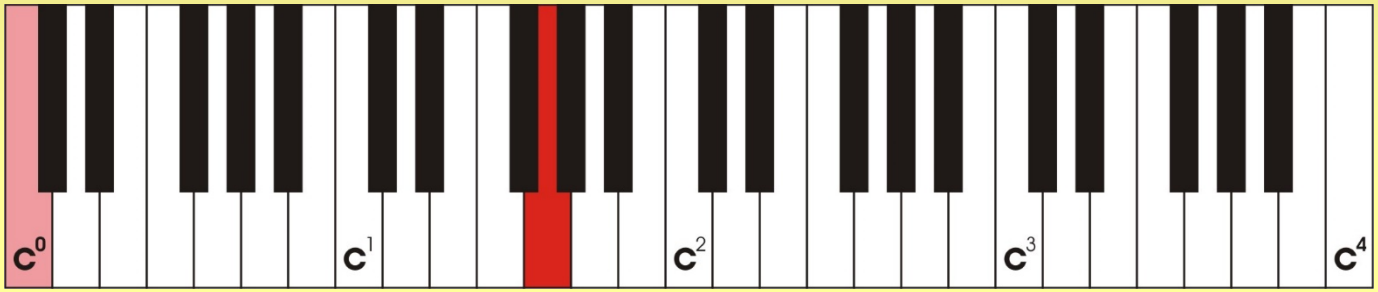


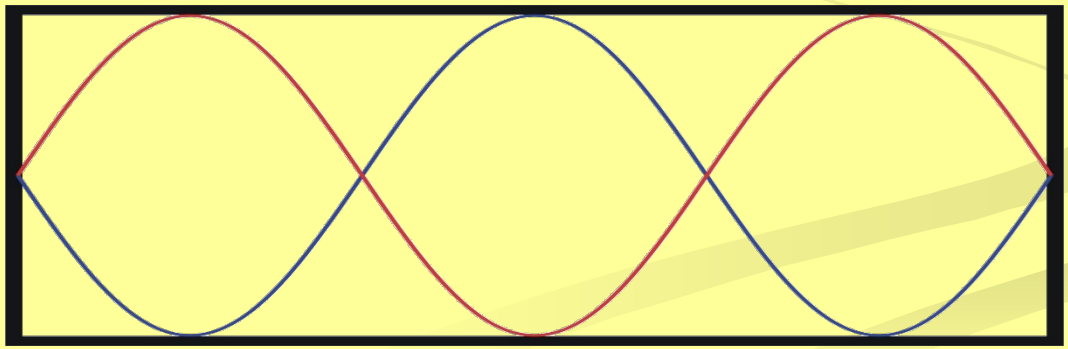
1. Oberton Intervall: Oktave



Obertonreihe:



2. Oberton **Intervall: Quinte**



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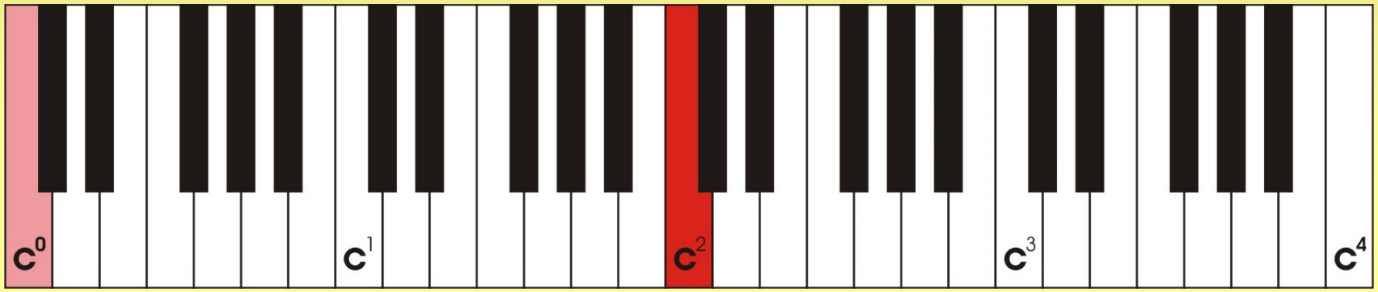
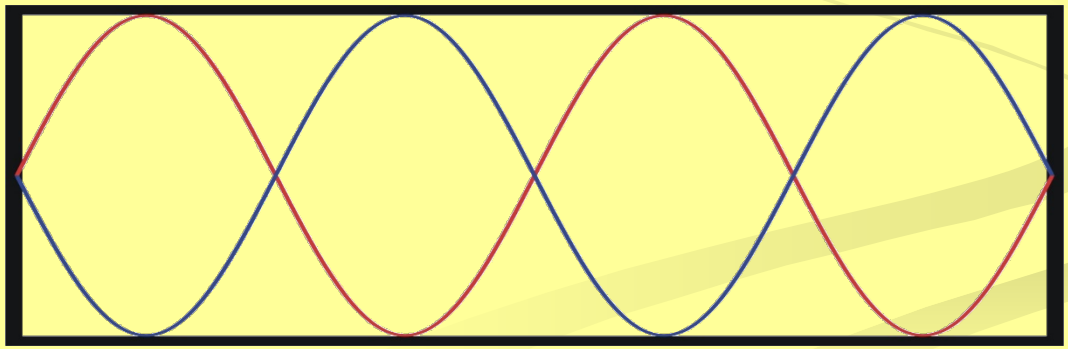


3. Oberton

Intervall: Oktave



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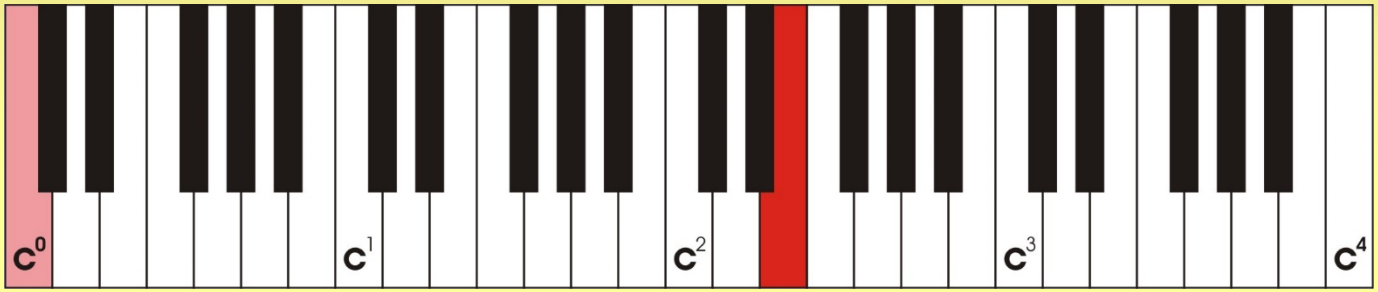
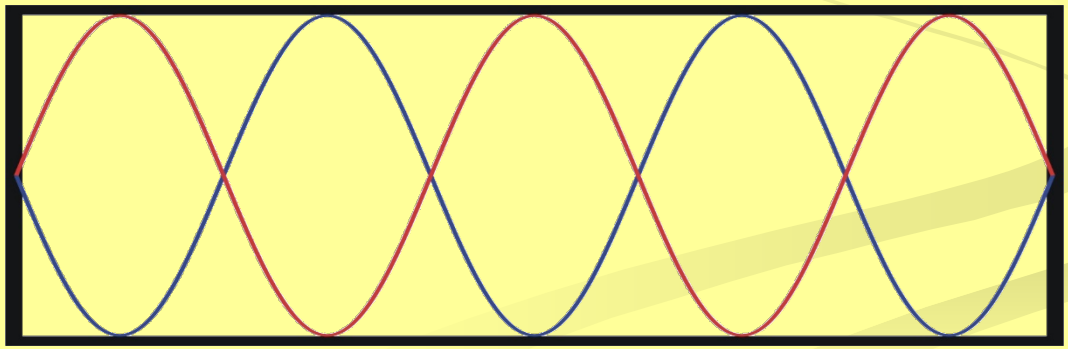
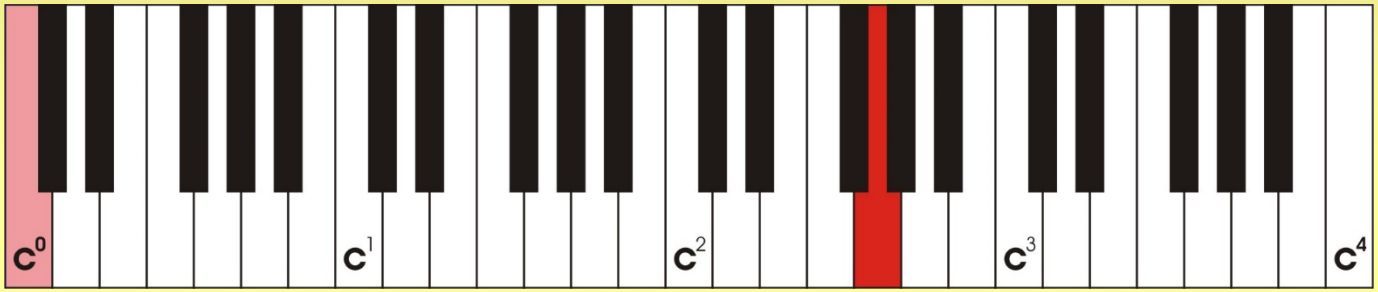


4. Oberton

Intervall: Terz

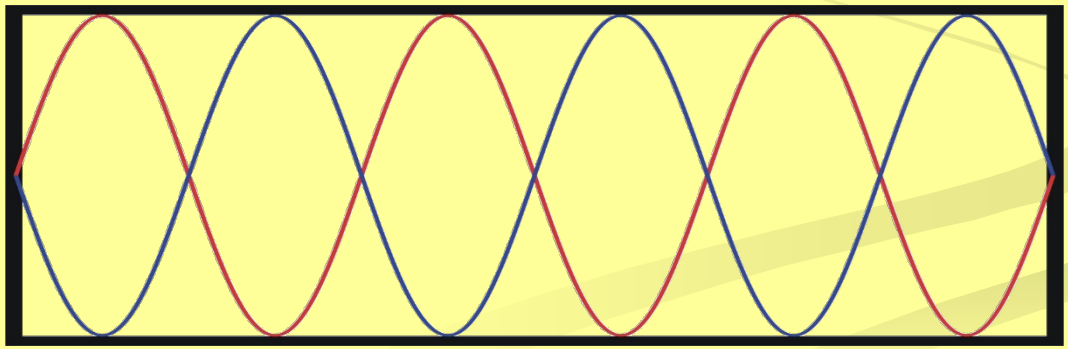


Obertonreihe:



5. Oberton

Intervall: Quinte



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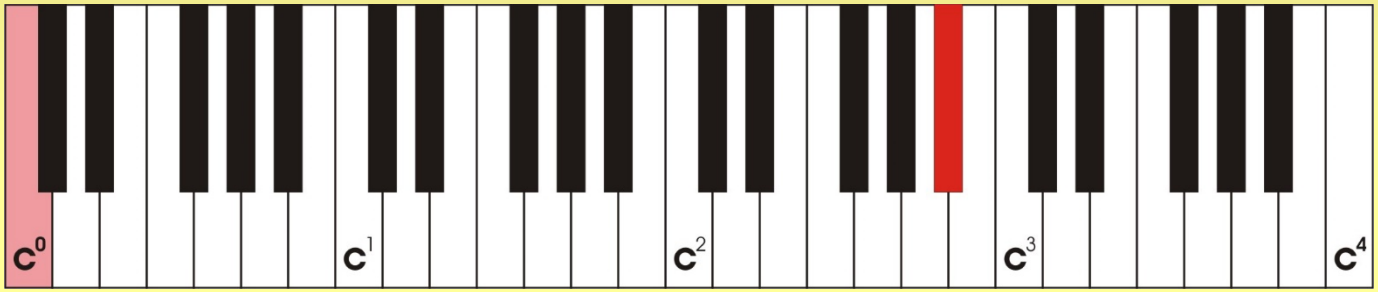
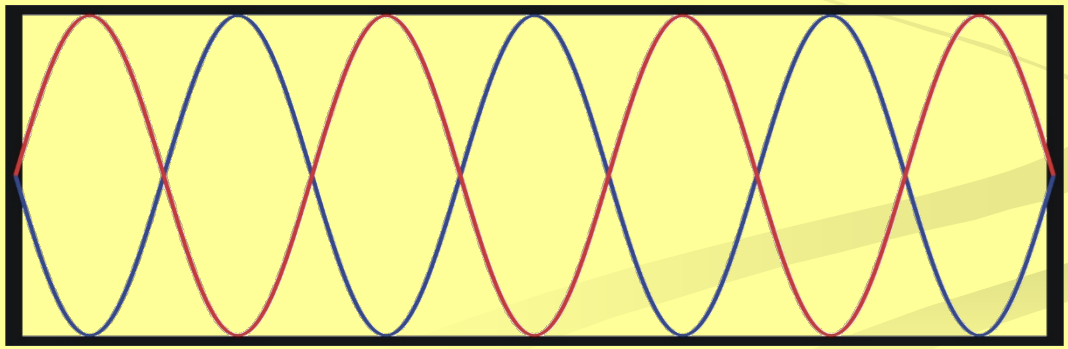
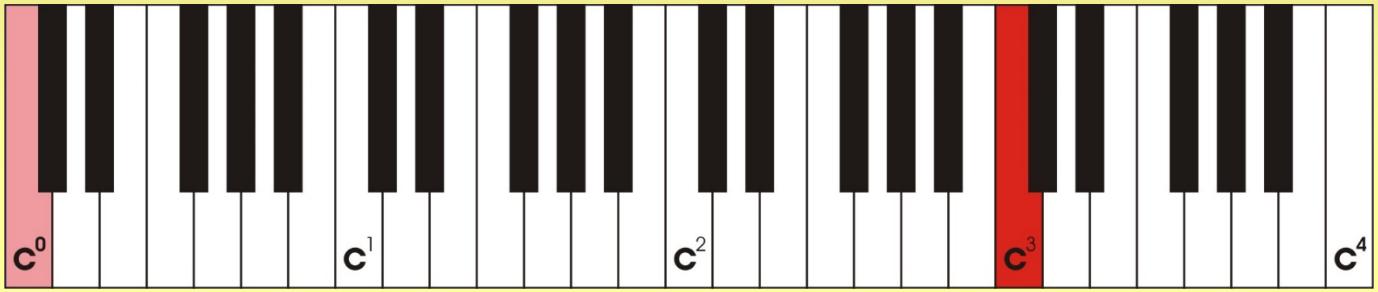


6. Oberton

Intervall: Septime

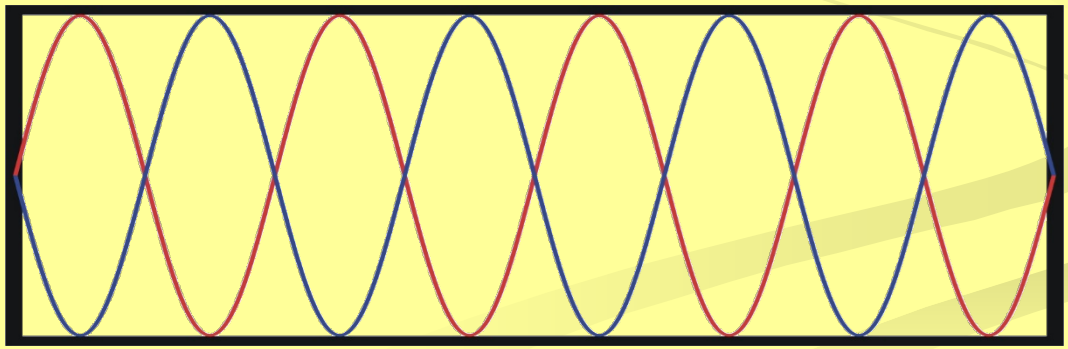


Obertonreihe:

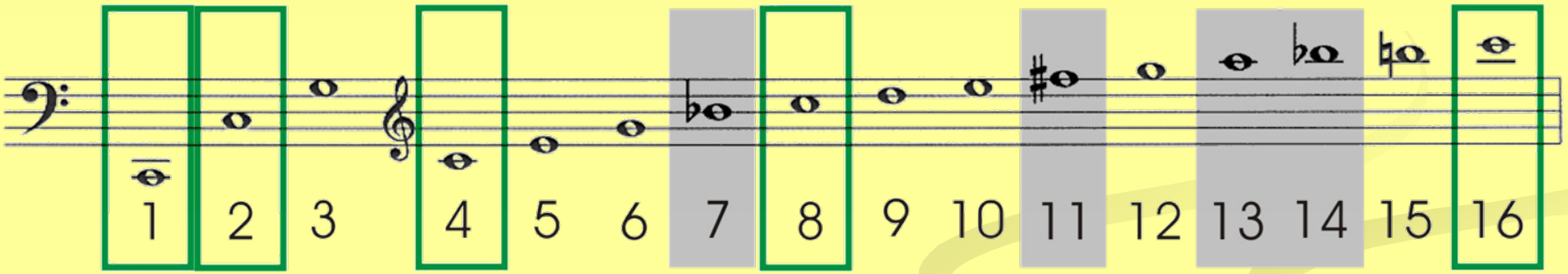


7. Oberton

Intervall: Oktave



Obertonreihe:

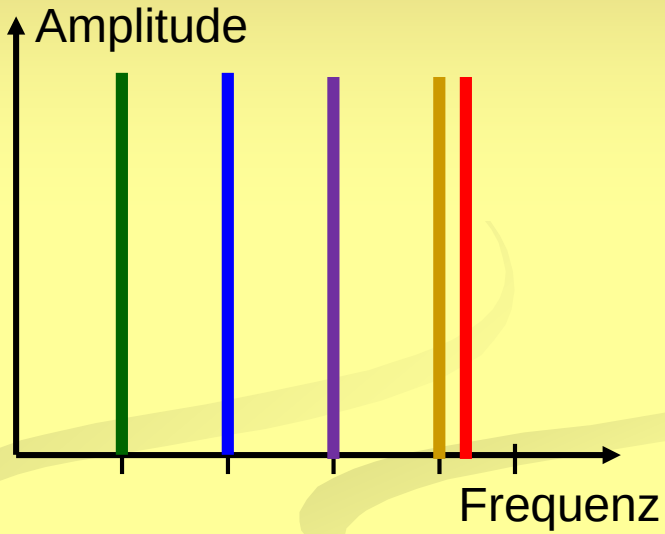


(Erste 16 Partialtöne)

Additive Synthese

Überlagerung von Harmonischen

- Grundschwingung $f = 200$ Hz
- 1. Oberton $f = 400$ Hz
- 2. Oberton $f = 600$ Hz
- 3. Oberton $f = 800$ Hz
- „falscher“ Oberton $f = 850$ Hz

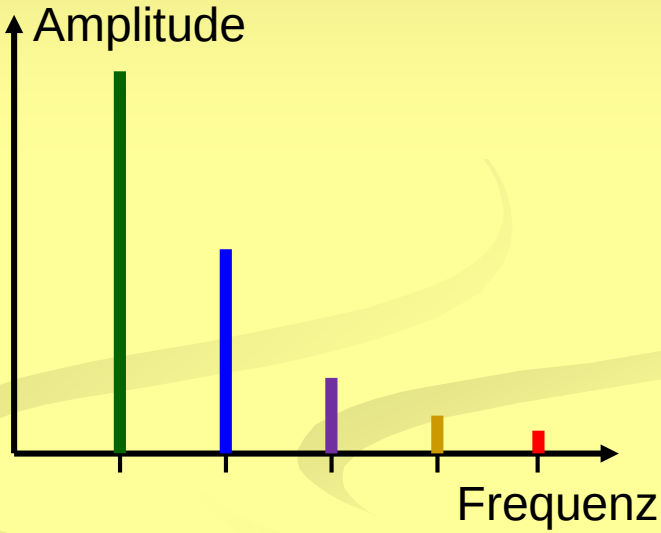


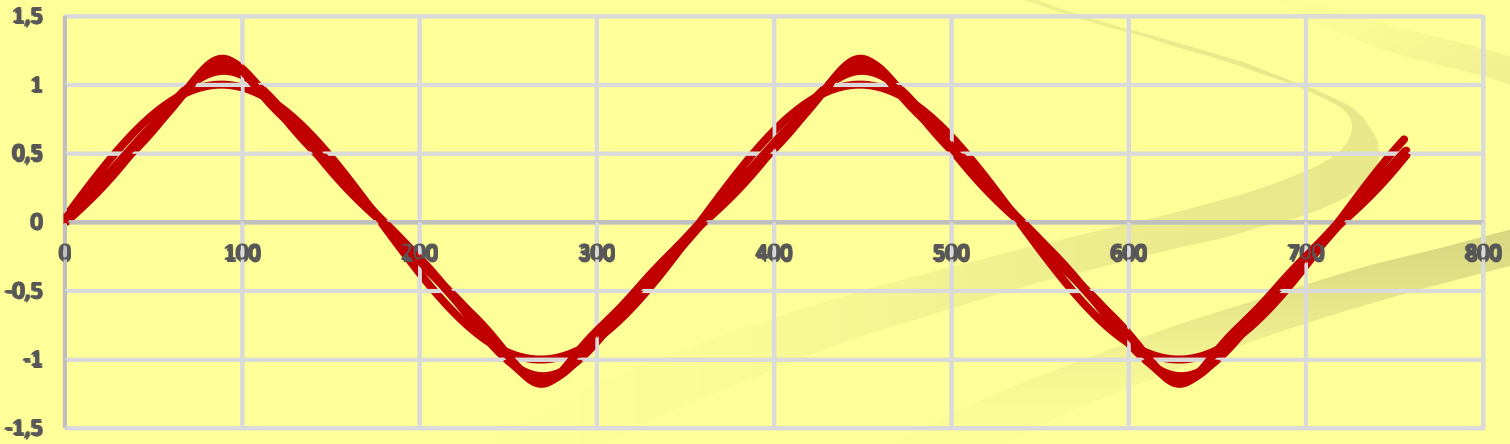
→ Audition

Analyse von Wellenformen

Zusammensetzung der Dreiecksschwingung

- Grundschwingung $f = 100$ Hz, $A = 1$
- 1. Oberschwingung $f = 300$ Hz, $A = -1/3^2$
- 2. Oberschwingung $f = 500$ Hz, $A = 1/5^2$
- 3. Oberschwingung $f = 700$ Hz, $A = -1/7^2$
- 5. Oberschwingung $f = 900$ Hz, $A = 1/9^2$





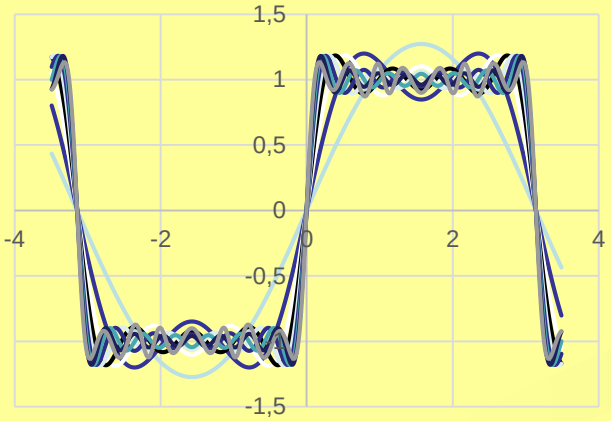
→ Audition

Phasenlage

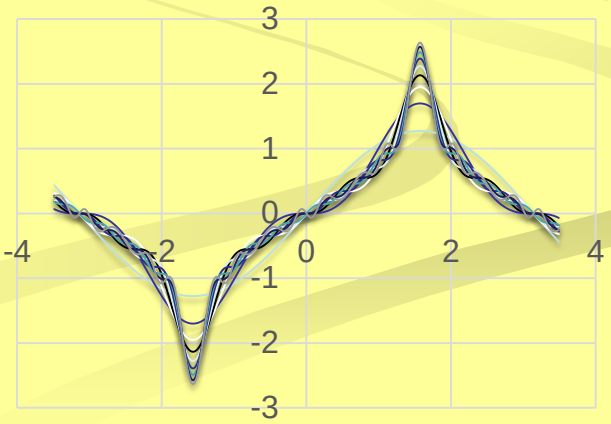
Fourier-Synthese der Rechteckschwingung

• Grundschwingung	f = 200 Hz,	A= 1	(+90°)
• 2. Teilton	f = 600 Hz,	A=1/3	(-90°)
• 3. Teilton	f = 1000 Hz,	A=1/5	(+90°)
• 4. Teilton	f = 1400 Hz,	A=1/7	(-90°)
• 5. Teilton	f = 1800 Hz,	A=1/9	(+90°)
• 6. Teilton	f = 2200 Hz,	A=1/11	(-90°)
• 7. Teilton	f = 2600 Hz,	A=1/13	(+90°)
• 8. Teilton	f = 3000 Hz,	A=1/15	(-90°)
• 9. Teilton	f = 3400 Hz,	A=1/17	(+90°)

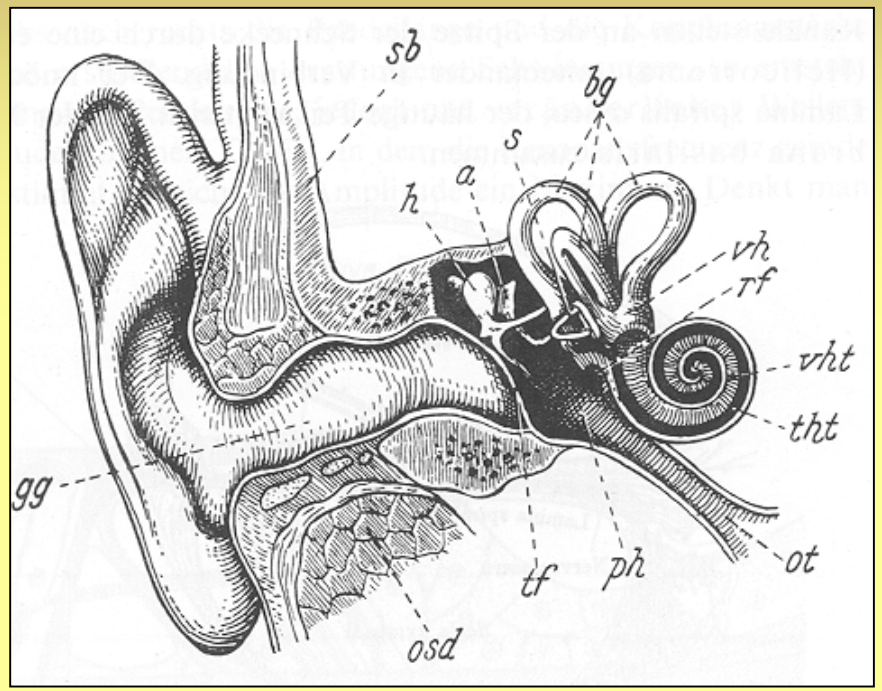
Gleiche Phase



Alternierende Phase ±90°

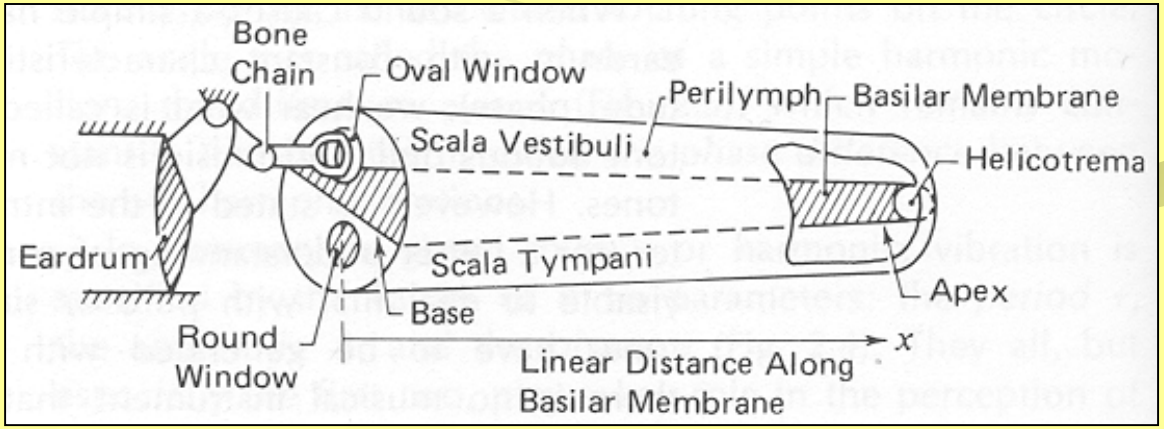


Das menschliche Ohr:

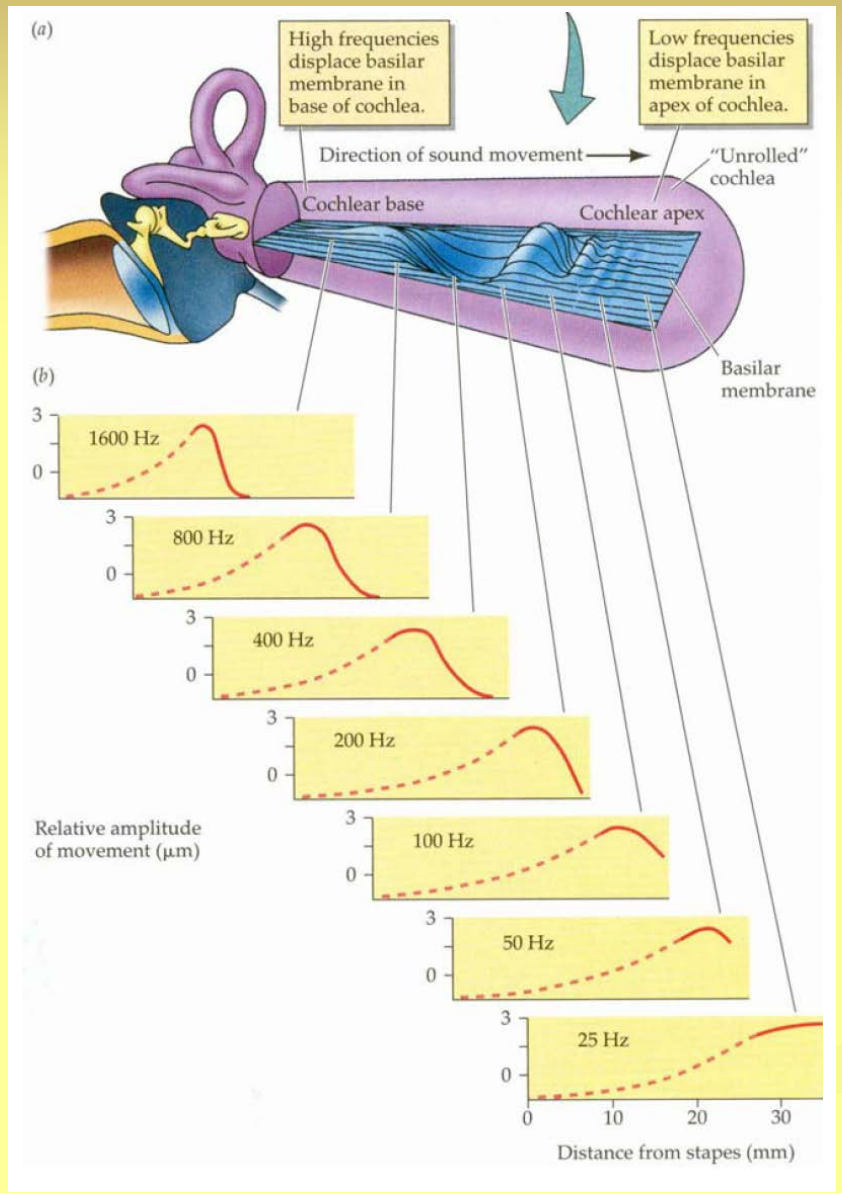


Querschnitt durch das Ohr

Cochlea
(vereinfachte Darstellung)

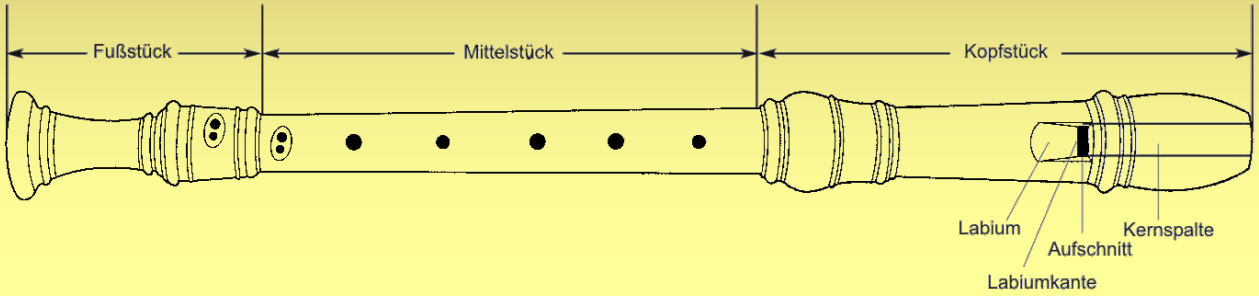


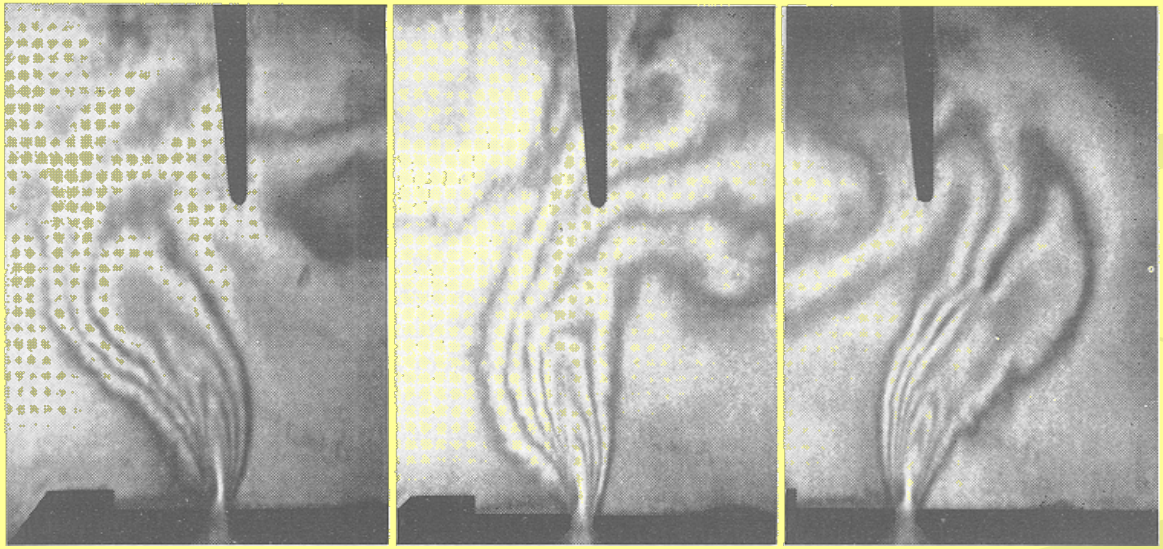
Frequenzwahrnehmung



Das Ohr ist sensitiv auf das Frequenzspektrum, nicht auf die Wellenform

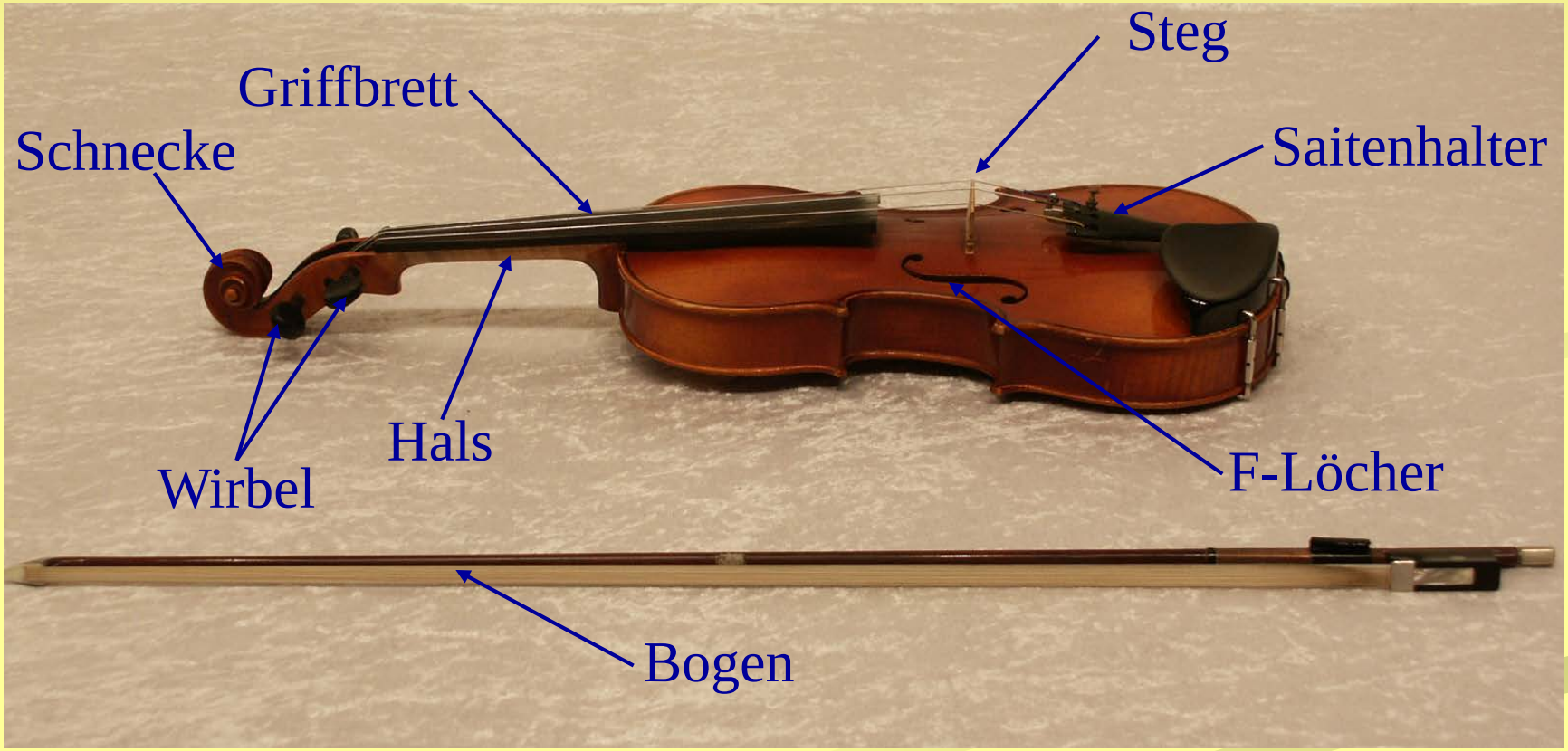
Die Blockflöte





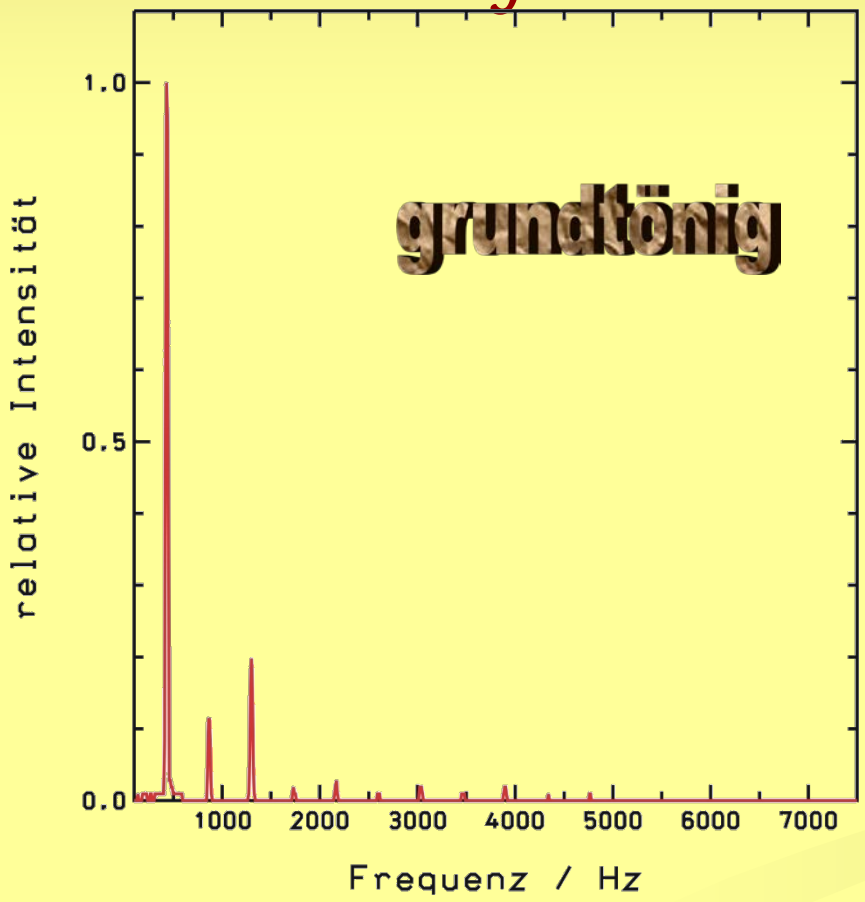
Der Resonator zwingt dem Luftstrom seine Eigenschwingung auf

Die Geige (Violine)

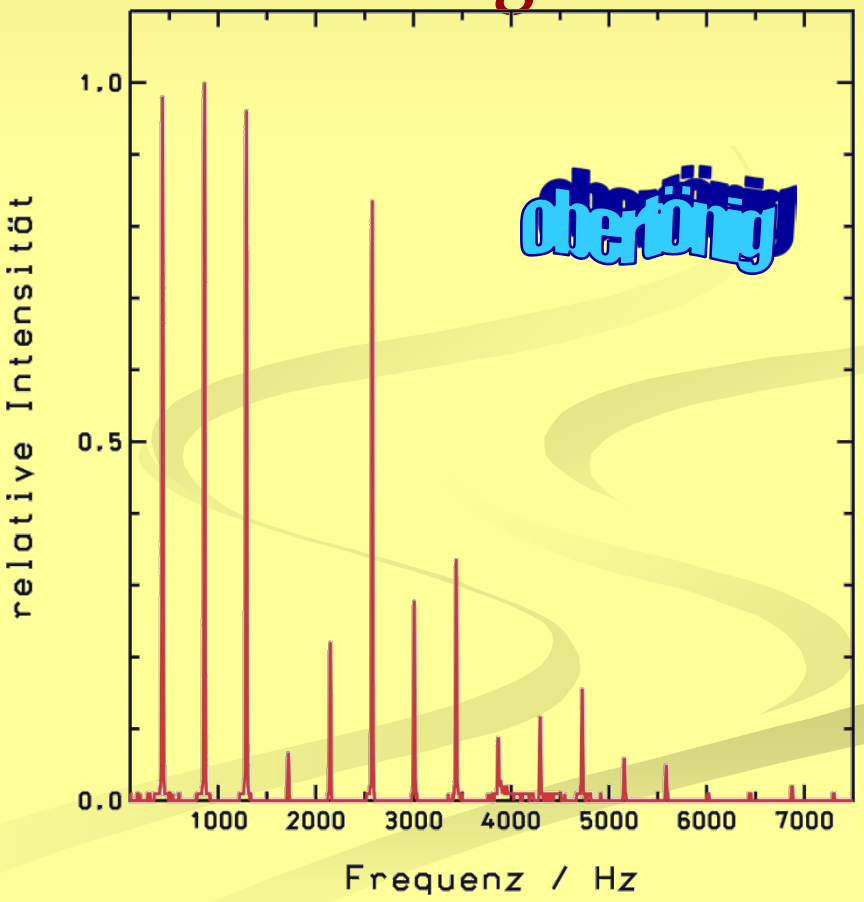


Frequenzspektren

Blockflöte

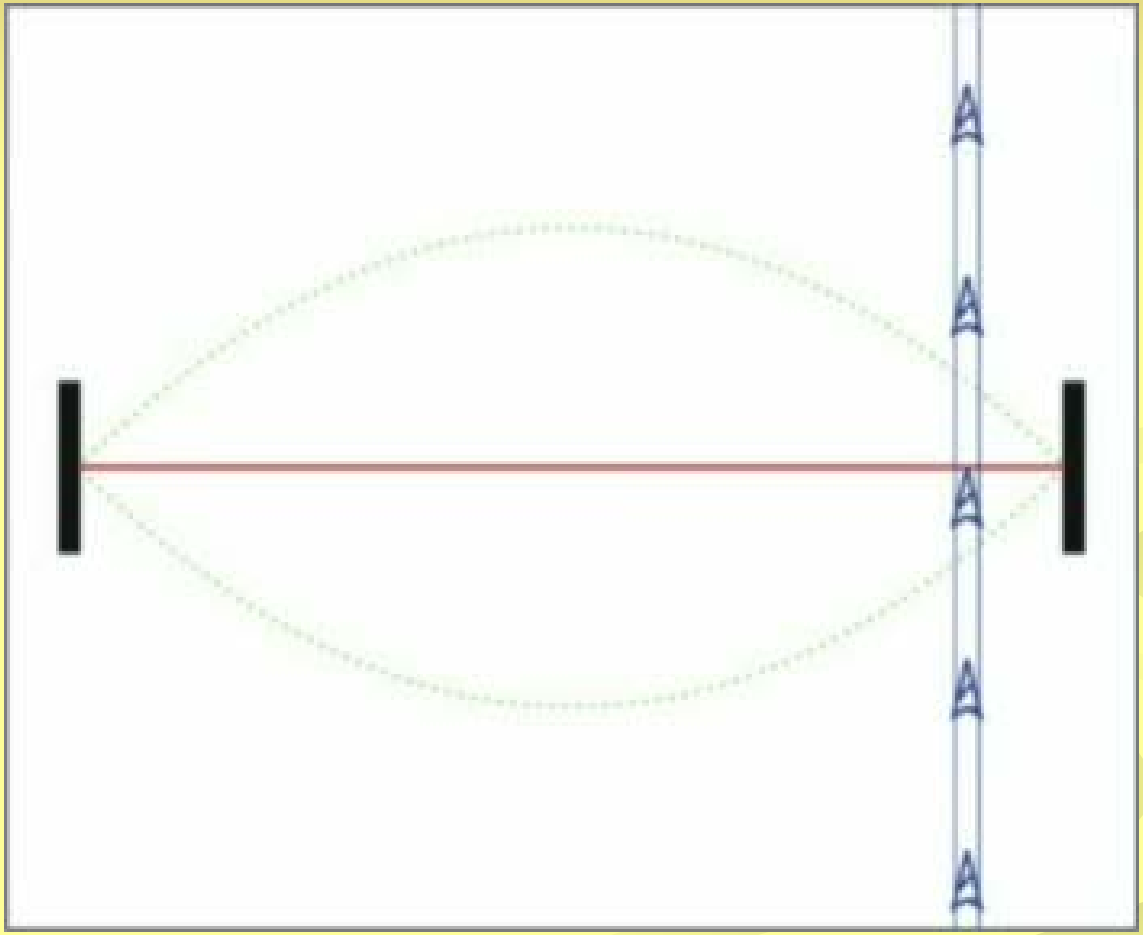


Geige



→K →S

Schwingende Saite



St. Michaelis Hauptorgel

Aufbau des Orgelklangs

	Flöten	Prinzipale	Streicher
5.Oberton	$1\frac{1}{3}'$		
4.Oberton	$1\frac{3}{5}'$		
3.Oberton	2′	2′	(2′)
2.Oberton	$2\frac{2}{3}'$	($2\frac{2}{3}'$)	
1.Oberton	4′	4′	4′
Grundton	8′	8′	8′
	(16′)	(16′)	(16′)

Disposition Hauptorgel

I Positiv C–g³

1.	Quintadena	16′
2.	Principal	8′
3.	Spitzflöte	8′
4.	Oktave	4′
5.	Rohrflöte	4′
6.	Oktave	2′
7.	Flachflöte	2′
8.	Nasat	2⅔′
9.	Mixtur VI–VIII	1⅓′
10.	Cimbel III	⅙′
11.	Fagott	16′
12.	Trompete	8′
13.	Vox humana	8′
	Tremulant	

II Hauptwerk C–g³

14.	Principal	16′
15.	Oktave	8′
16.	Oktave	4′
17.	Oktave	2′
18.	Quinte	5⅓′
19.	Quinte	2⅔′
20.	Mixtur VI–VIII	2′
21.	Scharff IV	⅔′
22.	Cornett V *(ab f)*	8′
23.	Trompete	16′
24.	Trompete	8′
25.	Trompete	4′

III Schwellwerk C–g³

26.	Bourdon	16′
27.	Principal	8′
28.	Violflöte	8′
29.	Schwebung *(ab c)*	8′
30.	Oktave	4′
31.	Flute travers	4′
32.	Oktave	2′
33.	Quinte	2⅔′
34.	Terz	1⅗′
35.	Septime	1⅐′
36.	Mixtur IV–VI	1⅓′
37.	Bombarde	16′
38.	Trompete	8′
39.	Hautbois	8′
40.	Clairon	4′
	Tremulant	

IV Kronwerk C–g³

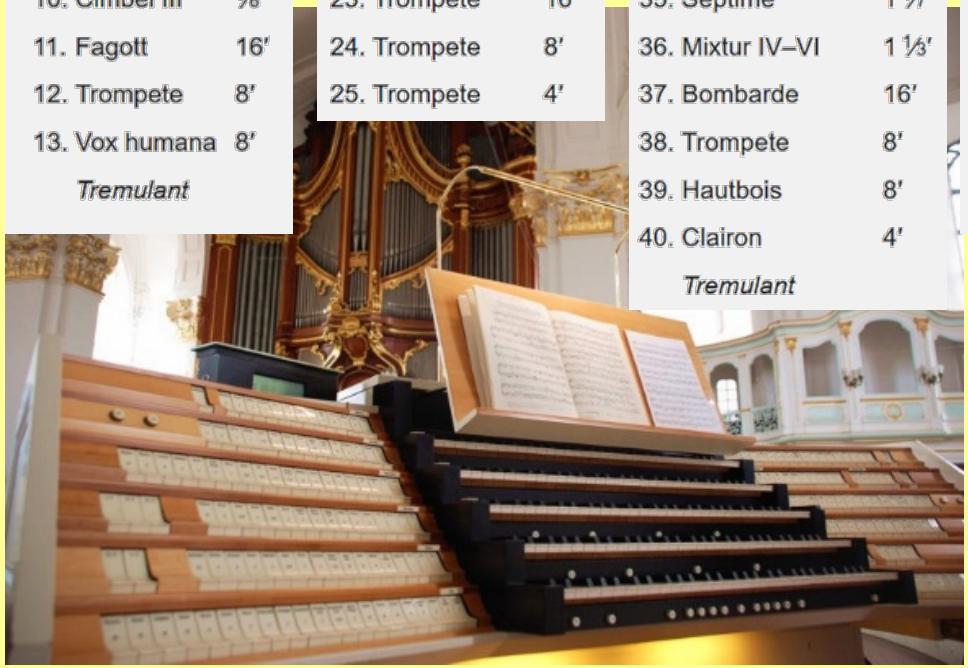
41.	Hohlflöte	8′
42.	Spitzgamba	8′
43.	Principal	4′
44.	Spitzflöte	4′
45.	Oktave	2′
46.	Gemshorn	2′
47.	Oktave	1′
48.	Nasat	2⅔′
49.	Terzian II	1⅗′
50.	Scharff VI	1′
51.	Regal	16′
52.	Krummhorn	8′
53.	Zinke	4′
	Tremulant	

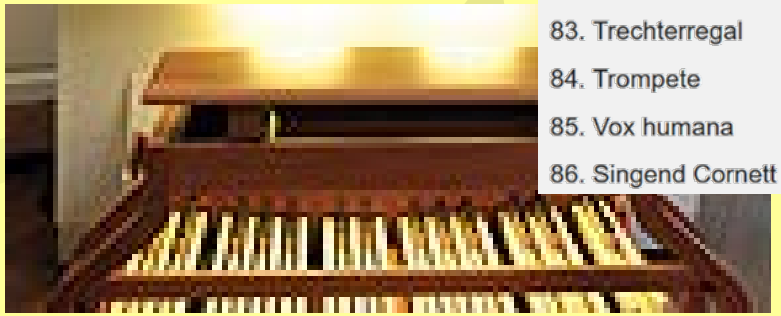
V Brustwerk C–g³

54.	Quintadena	8′
55.	Gedackt	8′
56.	Principal	4′
57.	Blockflöte	4′
58.	Oktave	2′
59.	Quinte	1⅓′
60.	Sesquialtera II	2⅔′
61.	Scharff V–VII	1′
62.	Cimbel II	⅓′
63.	Dulcian	16′
64.	Bärpfeife	8′
65.	Schalmey	4′
	Tremulant	
	Zimbelstern	

Pedal C–g¹

66.	Principal	32′
67.	Oktave	16′
68.	Gemshorn	16′
69.	Subbass (2009)	16′
70.	Oktave	8′
71.	Gedackt	8′
72.	Oktave	4′
73.	Koppelflöte	4′
74.	Nachthorn	2′
75.	Bauernflöte	1′
76.	Hintersatz V	4′
77.	Rauschpfeife III	2⅔′
78.	Mixtur VI–VIII	2′
79.	Posaune	32′
80.	Posaune	16′
81.	Dulcian	16′
82.	Trompete	8′
83.	Trechterregal	8′
84.	Trompete	4′
85.	Vox humana	4′
86.	Singend Cornett	2′

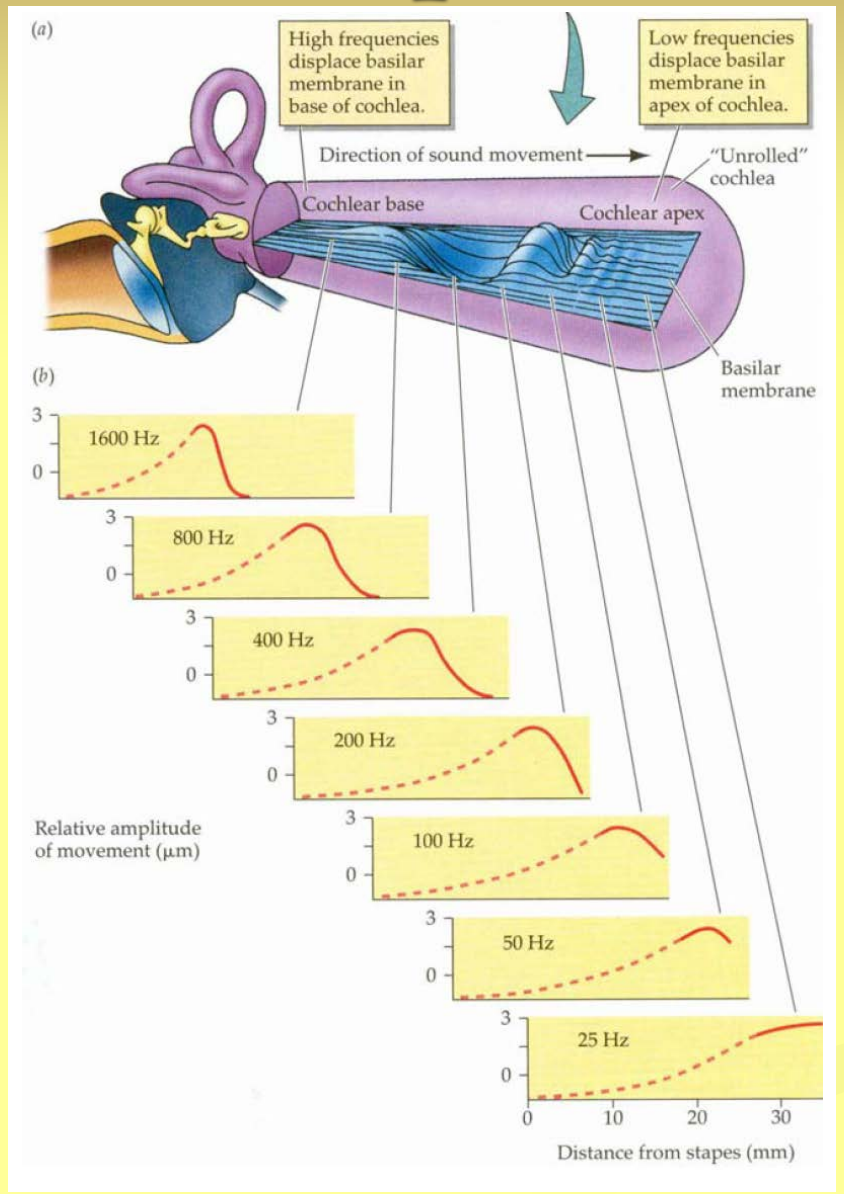




… ist es nicht erstaunlich, dass es möglich war, einen Menschen auf dem Mond zu landen, bevor man die Akustik eines traditionellen Instrumentes wie das Klavier gründlich verstanden hat!“

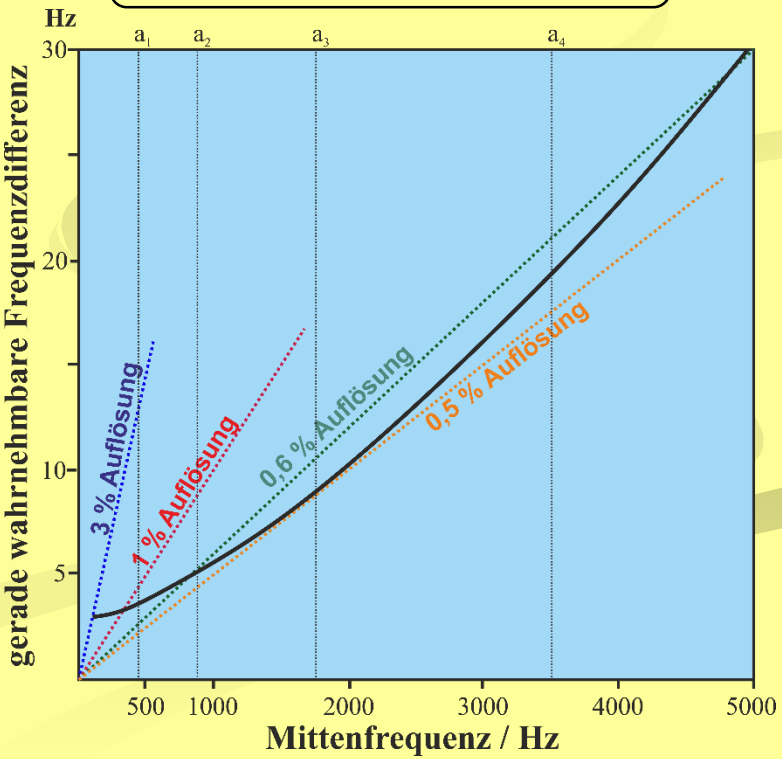
A. Askenfelt in „*The Acoustics of the Piano*“,
Königlich Schwedische Akademie für Musik, 1990

Frequenzwahrnehmung

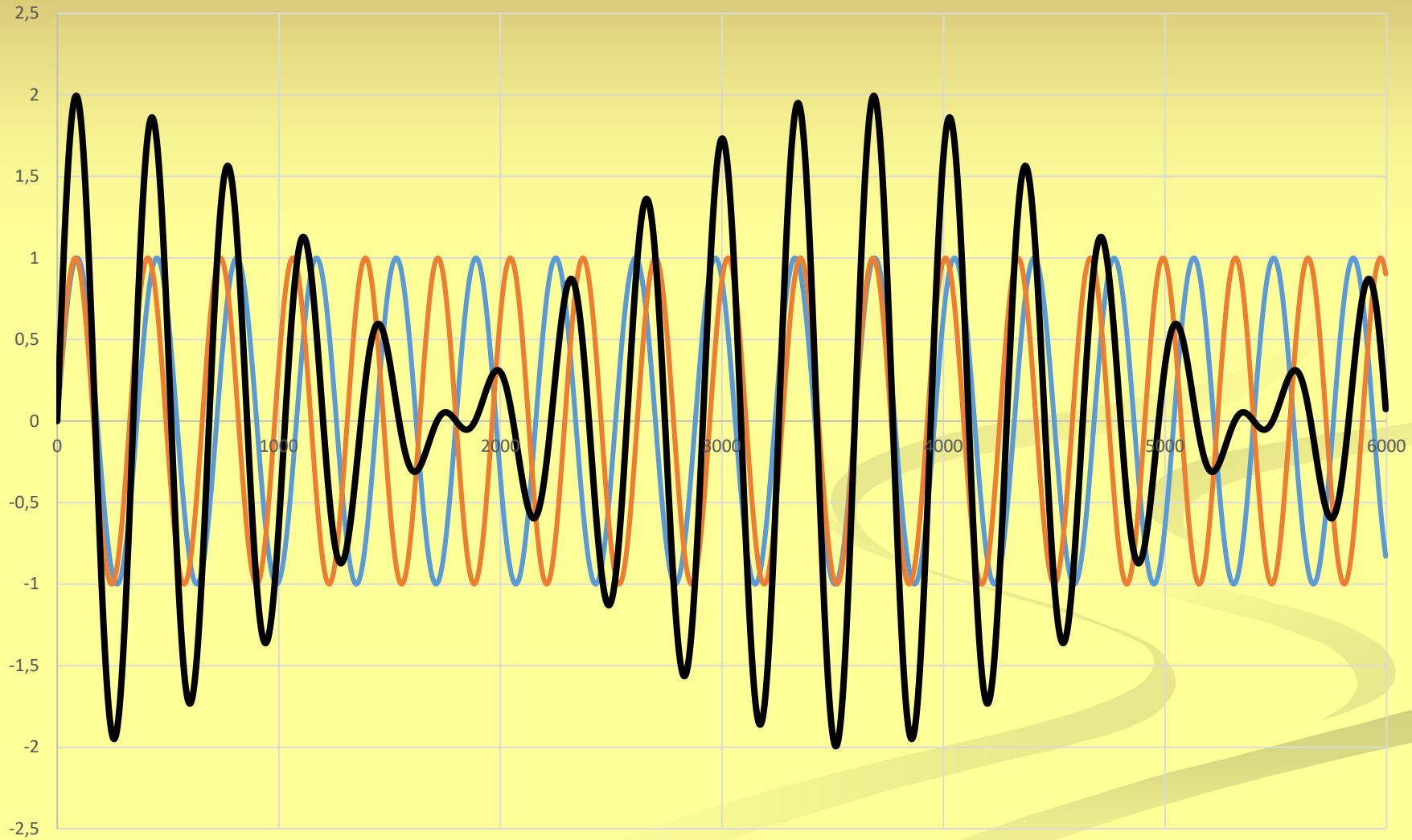


Grundfrequenz 440Hz (a)

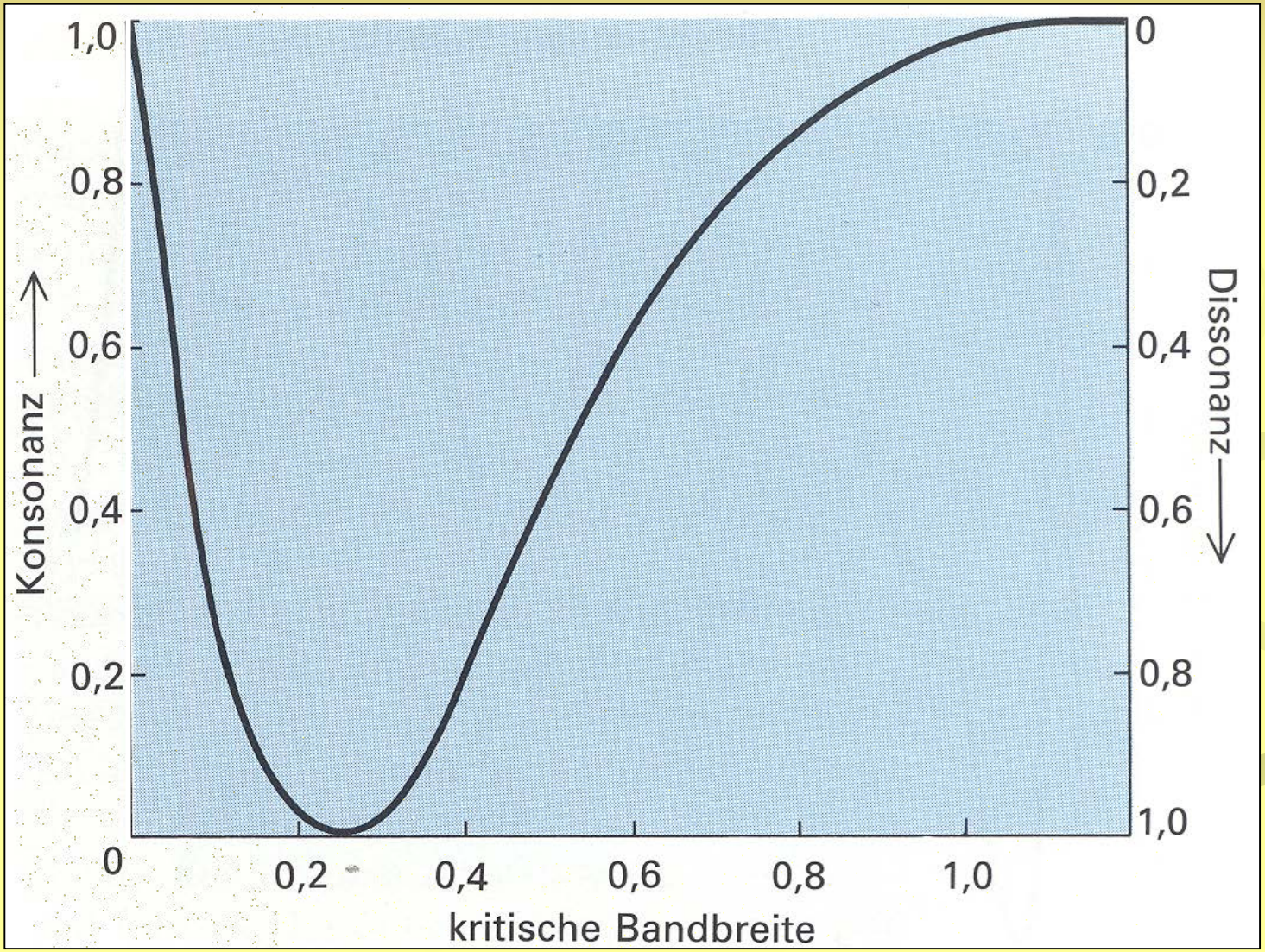
- 3% Auflösung
- 2% Auflösung
- 1% Auflösung
- ½% Auflösung

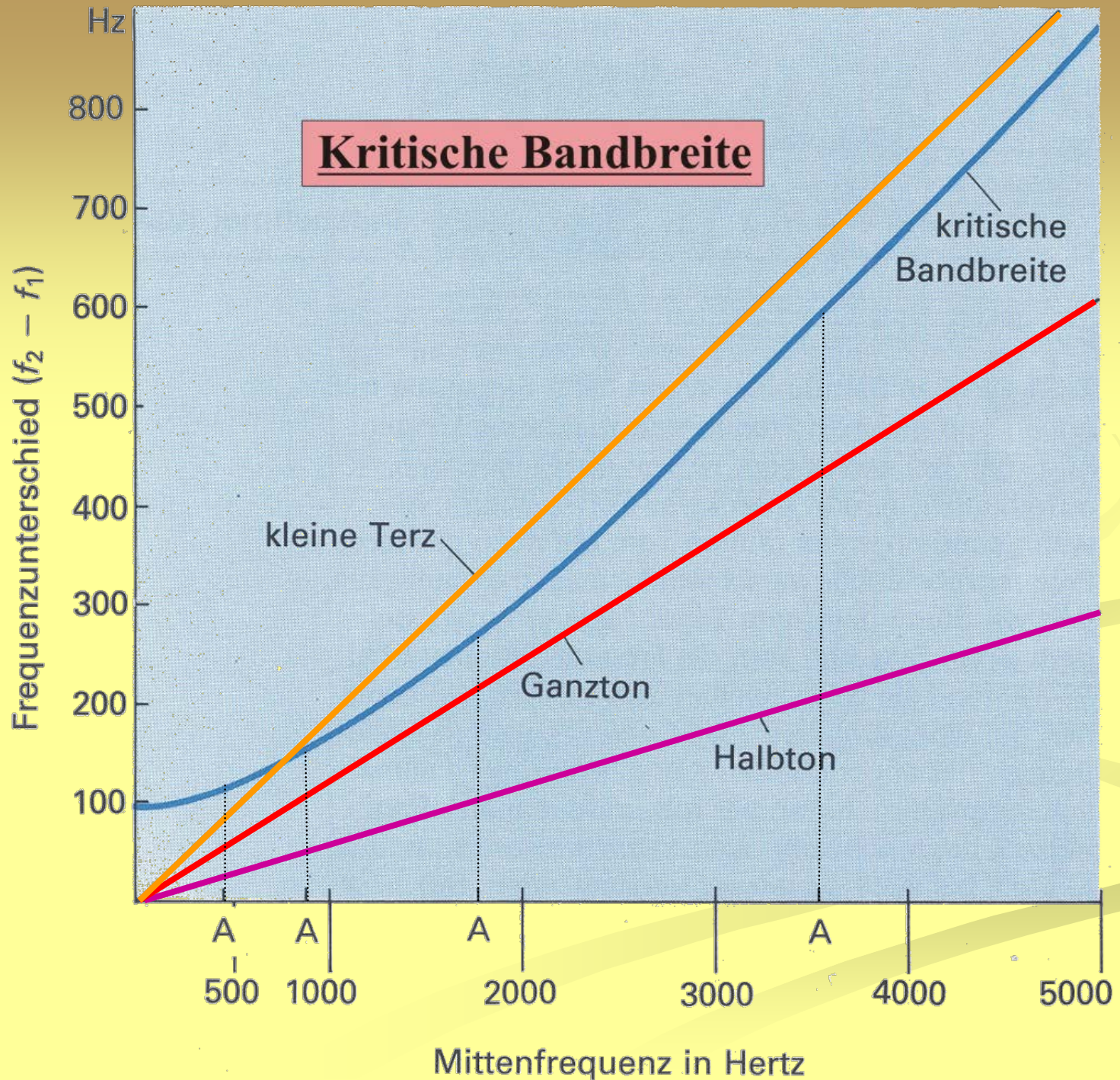


Schwebung



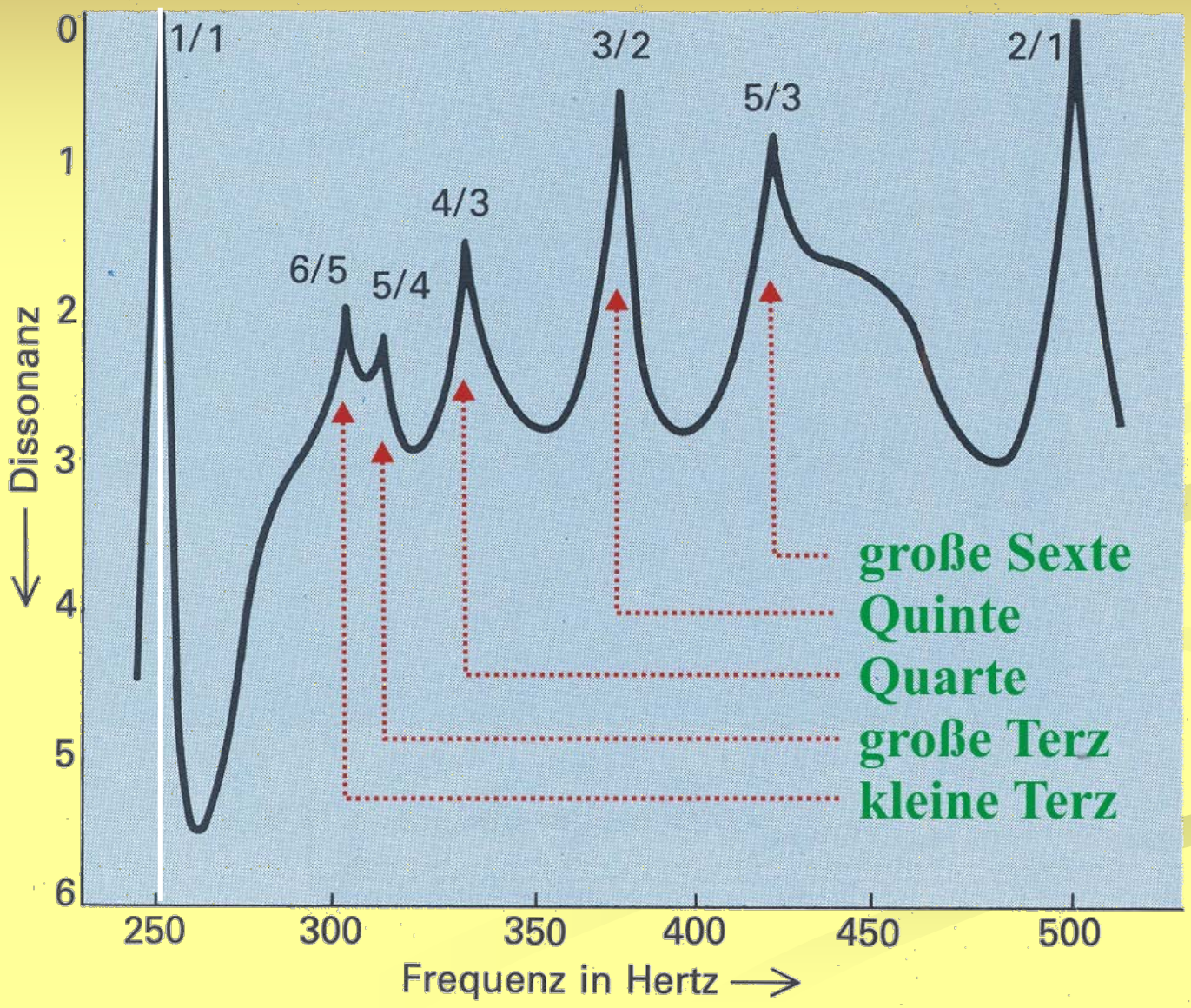
Konsonanz zweier Sinustöne




Kritische Bandbreite
Hz
800
700
600
500
400
300
200
100
Frequenzunterschied ($f_2 - f_1$)
kritische Bandbreite
kleine Terz
Ganzton
Halbton
A
A
A
A
500
1000
2000
3000
4000
5000
Mittenfrequenz in Hertz

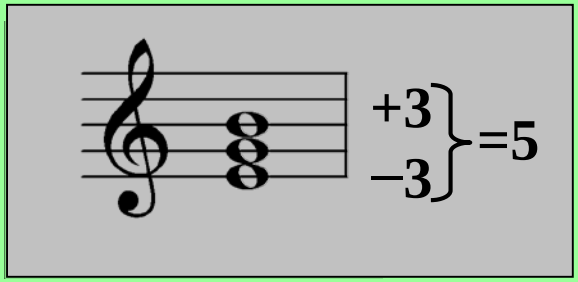
Konsonanzkurve

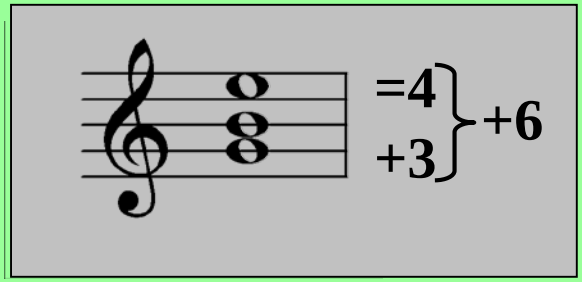
2 Töne aus je 6 Harmonischen

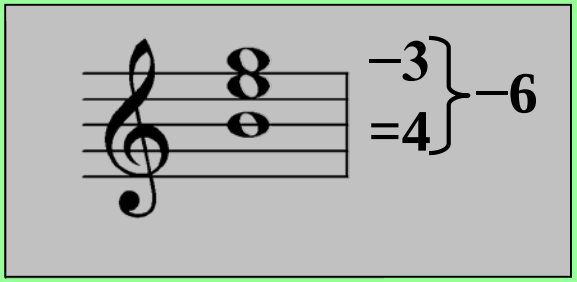


Natürliches Tonsystem

Moll – Dreiklänge:



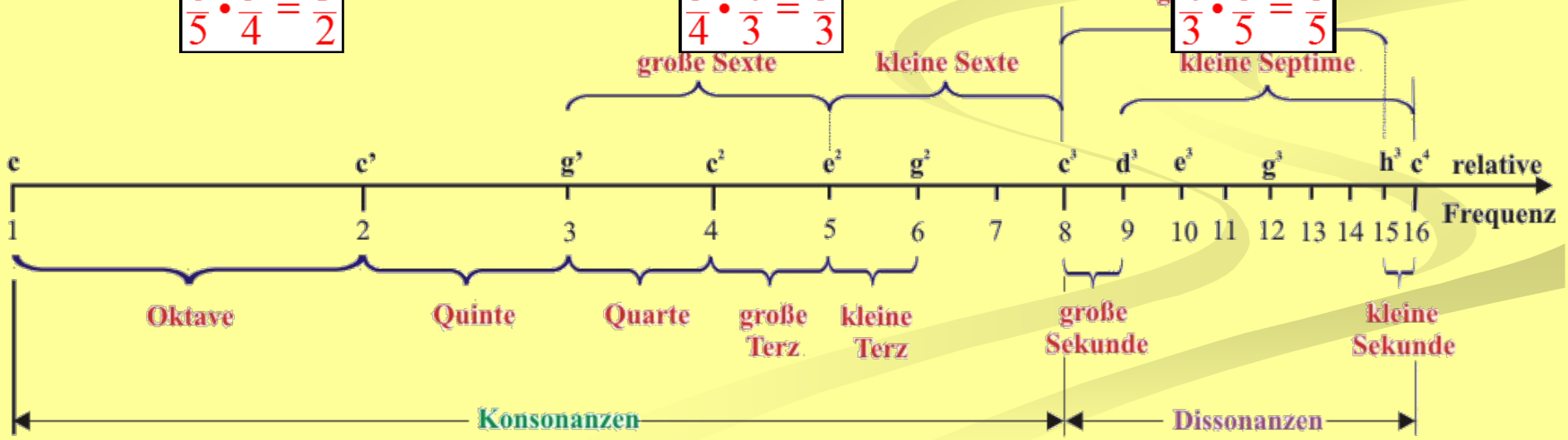




$\frac{6}{5} \cdot \frac{5}{4} = \frac{3}{2}$

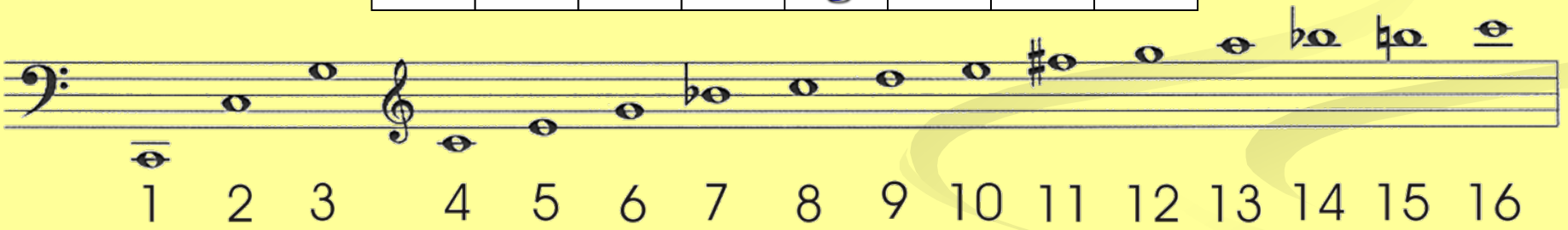
$\frac{5}{4} \cdot \frac{4}{3} = \frac{5}{3}$

$\frac{4}{3} \cdot \frac{6}{5} = \frac{8}{5}$



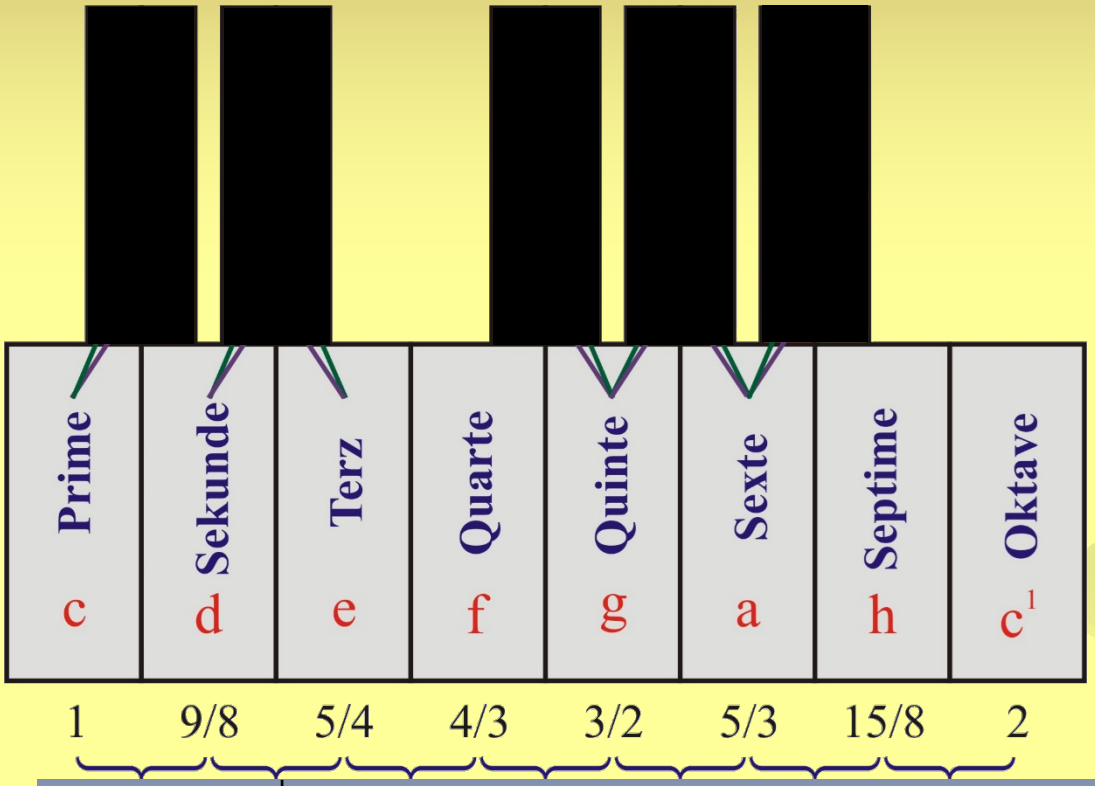
Die Tonleiter

1/1	16/15	9/8	6/5	5/4	4/3	45/32	3/2	8/5	5/3	16/9	15/8	2/1
Prime	♭d	Sekunde	♭e	Terz	Quarte	#f	Quinte	♭a	Sexte	b	Septime	Oktave
c		d		e	f		g		a		h	c’



Prime	Oktave	Quinte	Quarte	große Sexte	große Terz	kleine Terz	kleine Sexte	kleine Septime	große Sekunde	große Septime	kleine Sekunde
1 : 1	2 : 1	3 : 2	4 : 3	5 : 3	5 : 4	6 : 5	8 : 5	16 : 9	9 : 8	15 : 8	16 : 15
c – c	c – c^1	c^1 – g^1	g^1 – c^2	g^1 – e^2	c^2 – e^2	e^2 – g^2	e^2 – c^3	d^3 – c^4	c^3 – d^3	c^3 – h^3	h^3 – c^4
⟵ zunehmend konsonant								⟶ zunehmend dissonant			

Reine ↔ Temperierte Stimmung



Temperierte Stimmung:

kleiner Ganzton ≠ großer Ganzton

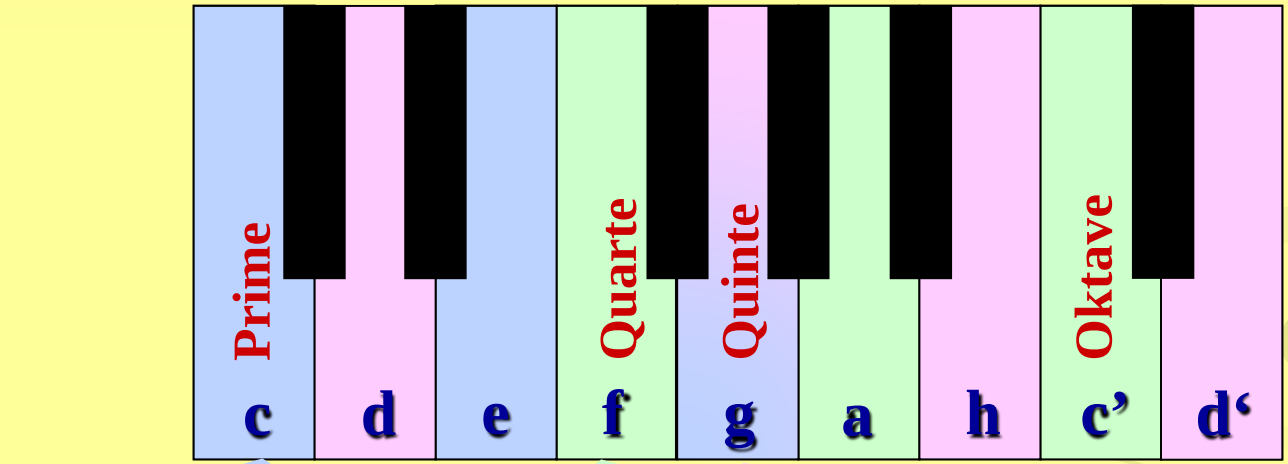
“Pythagoreisches Komma”

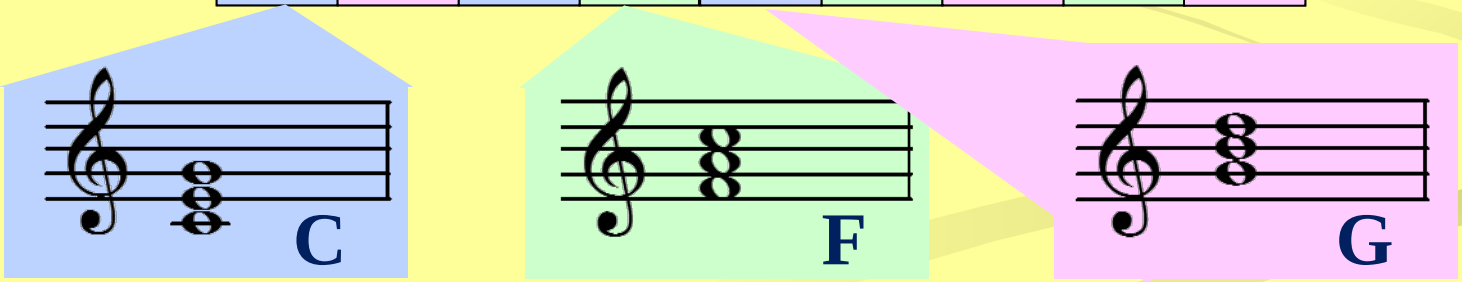
$$\left(\frac{3}{2}\right)^{12} \approx 129{,}75 > 128$$

	Sekunde	Terz	Quarte	Quinte	Sexte	Septime
rein	1,125	1,25	1,33	1,50	1,667	1,875
temp.	1,1225	1,26	1,335	1,498	1,682	1,888

Skalen und Harmonien

C-Dur Tonleiter (diatonisch)

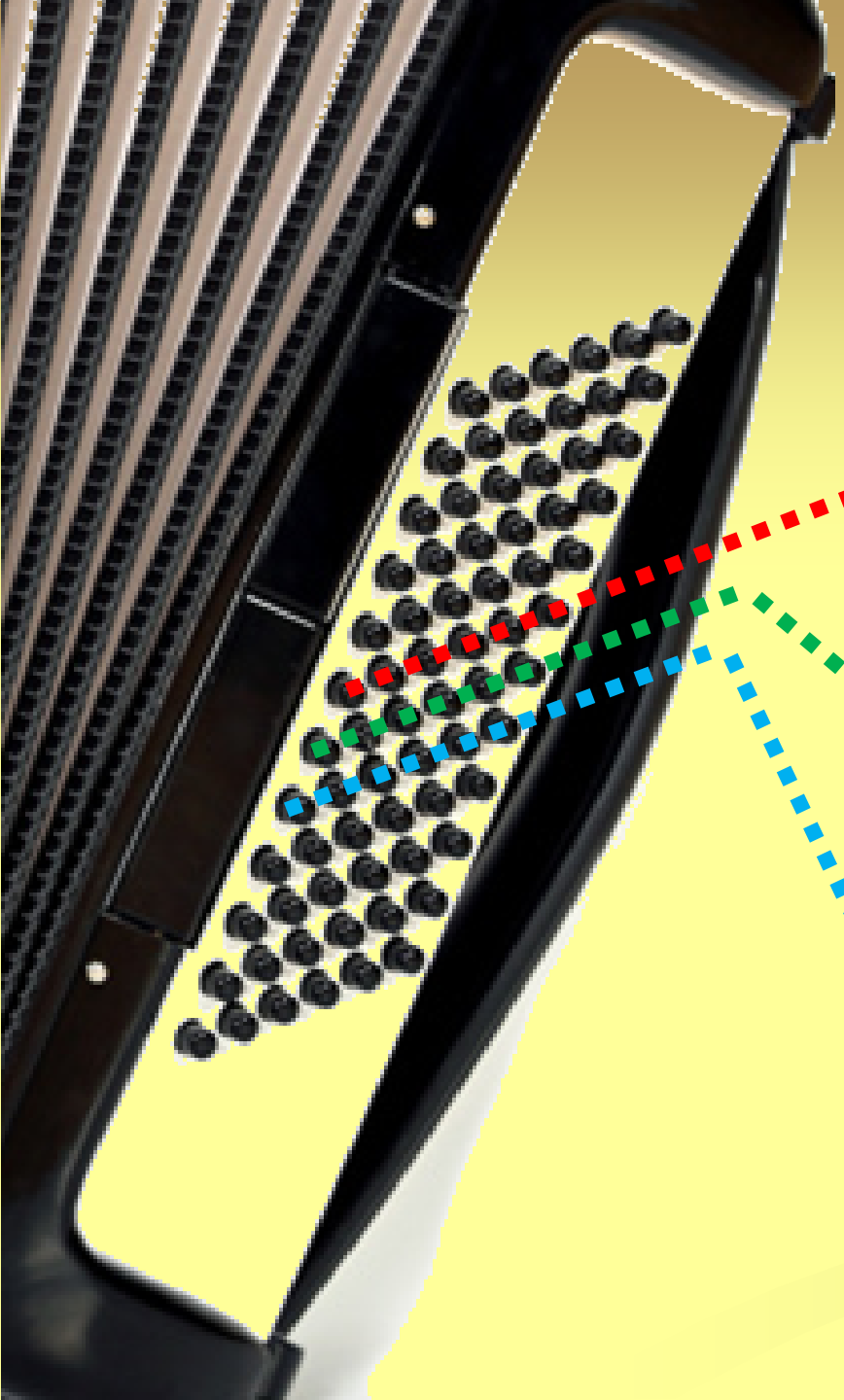


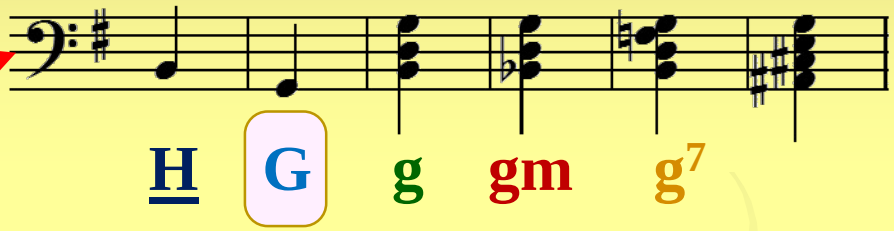


konsonante Dreiklänge

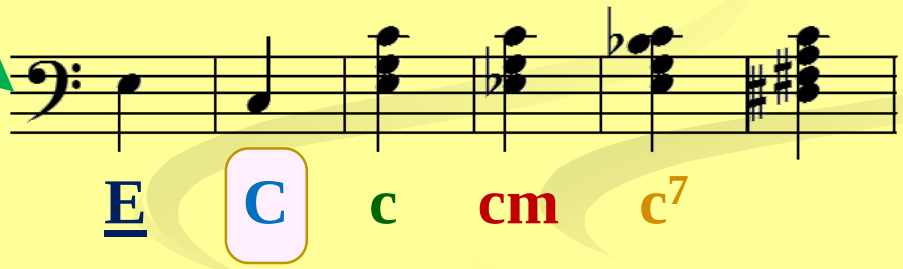
Das Akkordeon

Das Akkordeon

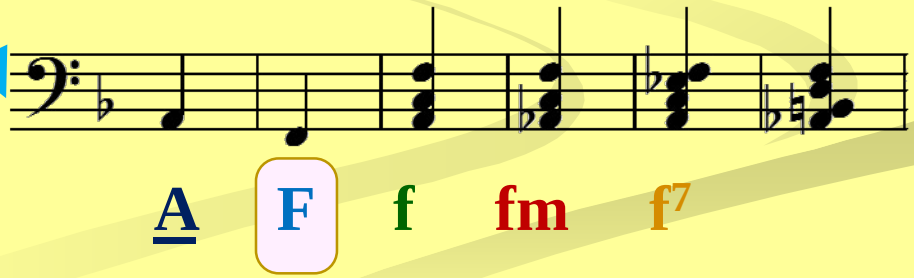




H G g gm g7



E C c cm c7



A F f fm f7



Ick hew mol en Hamborger Veermaster sehn,
to my hoodah, to my hoodah.
De Masten so scheef as den Schipper sien Been,
to my hoodah, hoodah ho.

Blow, boys, blow for Californio!
There is plenty of gold, so I am told,
on the banks of Sacramento.

Töne und Geräusche = Gemisch von Frequenzen

Zusammenfassung

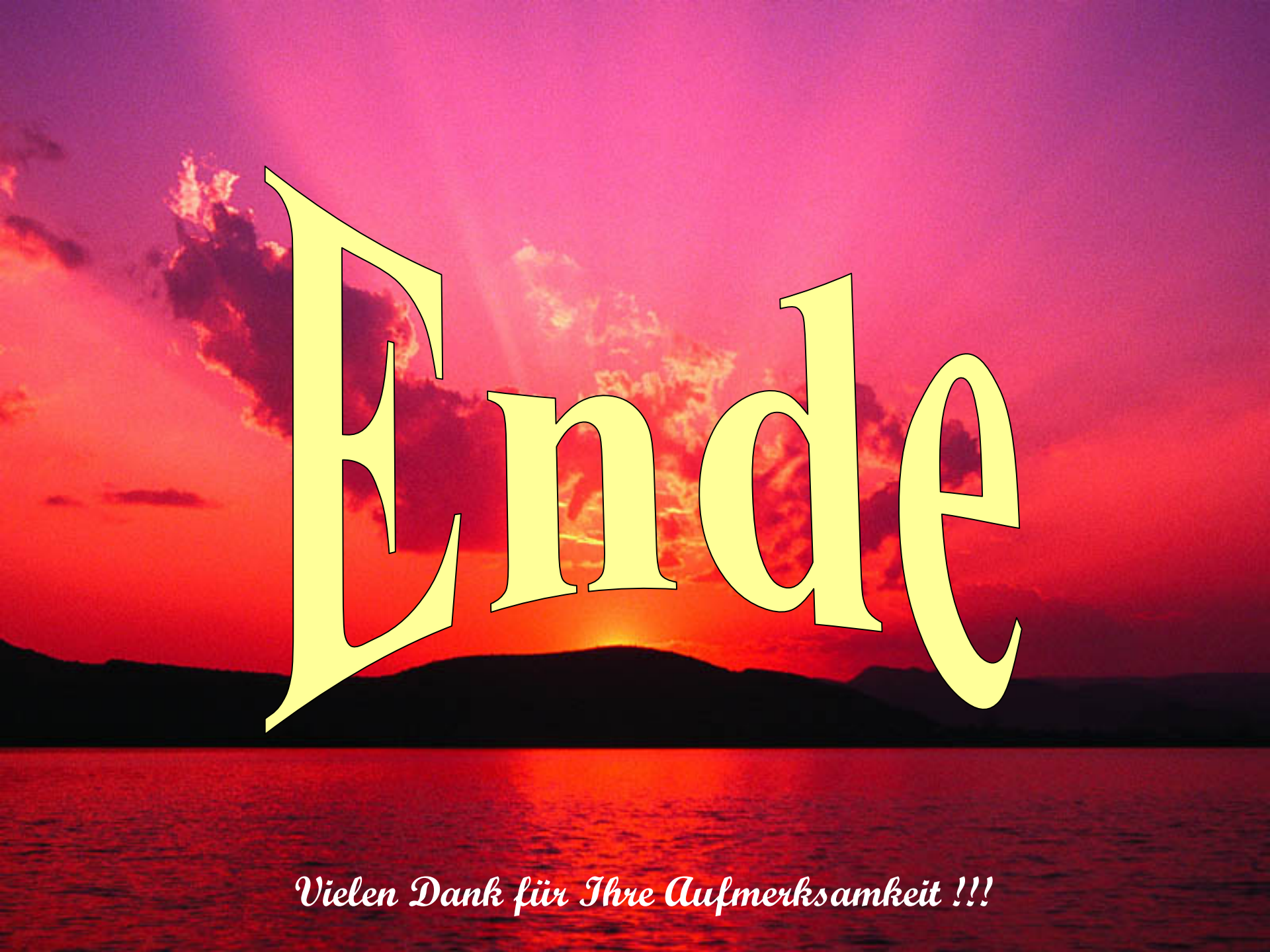
Töne bestehen aus
Grundschwingung + Oberschwingungen

Frequenz der Oberschwingungen:
ganzzahliges Vielfaches der Grundschwingung

Entscheidend für den Klang:
Anzahl und Stärke der Obertöne

diatonische Tonleiter:
Intervalle aus der Obertonreihe
Temperierte Stimmung ↔ Transponieren

Dur- und Moll-Akkorde:
Zusammensetzung „konsonanter“ Intervalle


Ende
Vielen Dank für Ihre Aufmerksamkeit !!!