C. Potel, M. Bruneau, "Acoustique générale (...)", Ed. Ellipse, collection Technosup, ISBN 2-7298-2805-2, 2006

Université du Maine

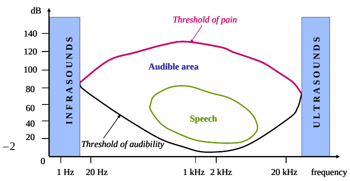
Chapter 2

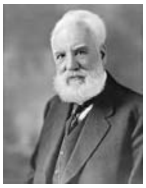
Physiological acoustics, decibel

The decibel (1/2)

- ✓ The sensitivity of human ear depends on the frequency
- ✓ The auditive sense is proportional to the ***logarithm of the acoustical intensity*** I of the wave

$L = 10 \log_{10}(I/I_s)$ *with* $I_s = 10^{-12}$ W.m^{-2}





The unit for the ***sound level*** is the ***decibel (dB)*** (one tenth of a bel), named like this in honour of the physicist Alexandre Graham Bell. This unit has the advantage of being based very well on the differential sensitivity of human ear, since 1 dB gap between two sound levels substantially corresponds to the smallest difference (in sound level) detectable by the human ear.

Alexandre Graham Bell
(1847-1922, american inventor)

http://en.wikipedia.org/wiki/Alexandre_Graham_Bell

Sound levels (1/2)

- ✓ The sensitivity of human ear depends on the frequency
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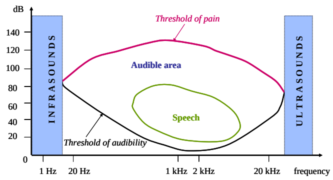
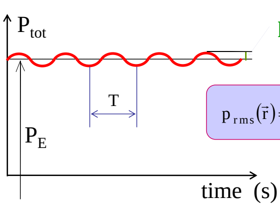


$L = 10 \log_{10}(I/I_s)$ *with* $I_s = 10^{-12}$ W.m^{-2}

$I \propto p_{rms}^2$ ⟹ $L = 20 \log_{10}(p_{rms}/p_s)$ $\quad p_s = \sqrt{\rho_0 c_0 I_s} = \sqrt{400 \cdot 10^{-12}} = 2 \cdot 10^{-5}$ Pa



averages over time, over an acoustic period T:

$\overline{p}(\vec{r}) = 0 \quad \overline{\vec{v}}(\vec{r}) = \vec{0} \quad \overline{\rho}(\vec{r}) = 0 \quad \forall \vec{r}$

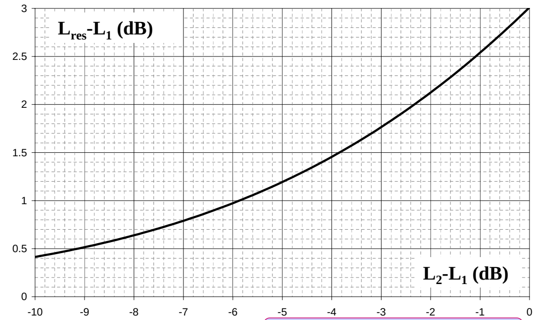
$p_{rms}(\vec{r}) = \sqrt{\overline{[p(\vec{r};t)]^2}}$ *with* $\overline{[p(\vec{r};t)]^2} = \lim_{T \to \infty} \frac{1}{T} \int_{-T/2}^{+T/2} [p(\vec{r};t)]^2 \, dt$

⚠ $\overline{[p(\vec{r};t)]^2} \neq \overline{[p(\vec{r};t)]}^2$

Sound levels (2/2)

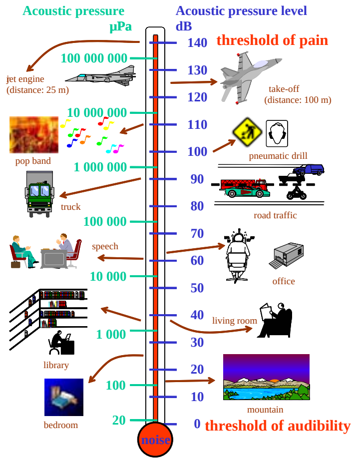
- Sound level which results from two non-correlated sources

$L_{res} = 10 \log_{10}\left(\frac{I_1 + I_2}{I_s}\right) = 10 \log_{10}\left(10^{L_1/10} + 10^{L_2/10}\right)$

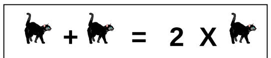


$L_{res} = (L_{res} - L_1) + L_1$ *with* $L_{res} - L_1 = 10 \log_{10}\left(1 + 10^{(L_2 - L_1)/10}\right)$

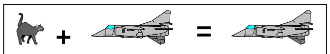
The decibel



Pa	dB
200	140
20	120
2	100
0,2	80
0,02	60
0,002	40
0,0002	**20**
0,00002	0

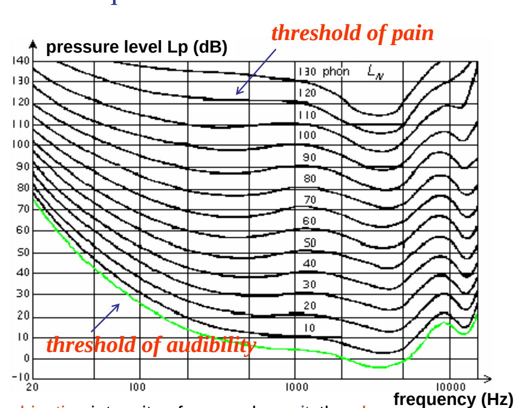


40 dB and 40 dB = 43 dB



40 dB and 140 dB = 140 dB

Equal loudness contours



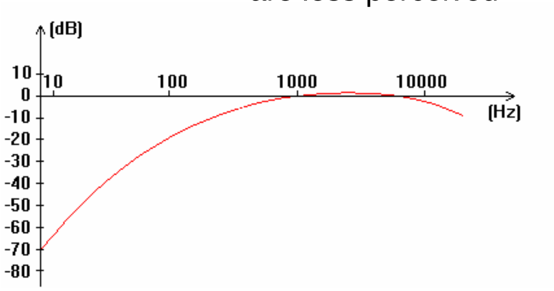
loudness: subjective intensity of a sound; *unit*: the phon

Example: A 70 phons sound provokes the same auditive perception than a 1000 Hz sound, the physical level of which is 70 dB

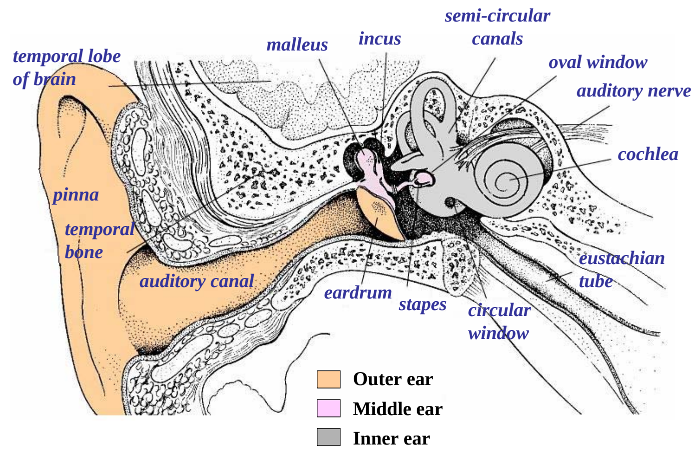
A weighting curves: dB(A)

high pitch and low pitch sounds

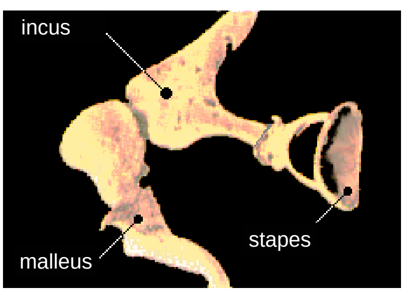
are less perceived



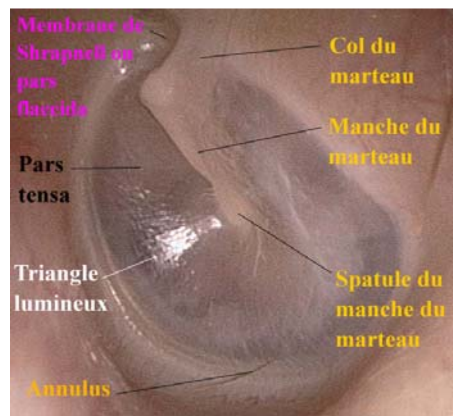
Structure of human ear



Ossicles

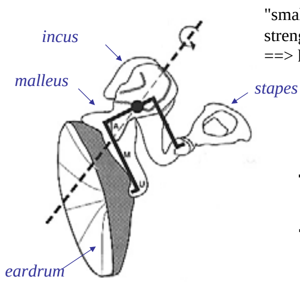


The tympanic membrane (eardrum)

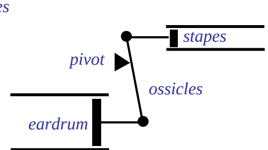


From Robier

Transfer of acoustic pressures (sonic waves) from air medium to fluid media and to inner ear structures (cochlea)



"small" displacement (not very compressible liquid)
strength "higher" and S smaller
==> higher pressure

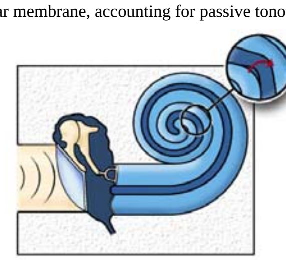


"large" displacement (compressible gas)
"less large" strength and greater S
==> smaller pressure

Transfer of acoustic pressures (sonic waves) from air medium to fluid media and to inner ear structures (cochlea) - animation

The sound wave moves the eardrum and attached ossicular chain. The stapes footplate, in the oval window, transfers the vibrations to the perilymphatic compartment (scala vestibuli) and to the inner ear structures. Depending on the frequency, the vibration has a maximum effect (resonance) at a different point along the basilar membrane, accounting for passive tonotopy.

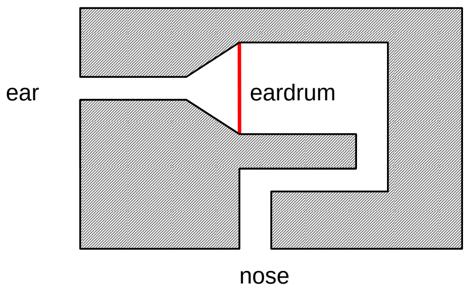
a high frequency sound affects a basal portion of the cochlea



a low frequency sound affects a more apical part of the cochlea

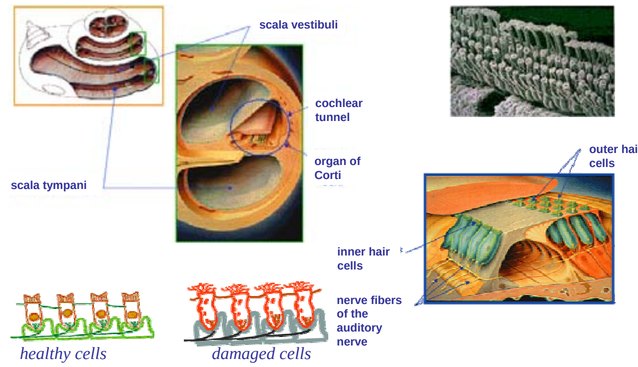
Text and images from website "Promenade 'round the cochlea" (http://www.cochlee.info) by R Pujol et al., Université Montpellier 1 et INSERM - France
http://www.iurc.montp.inserm.fr/cric51/audition/fran%E7ais/ear/fear.htm

Schematic functioning of the eardrum



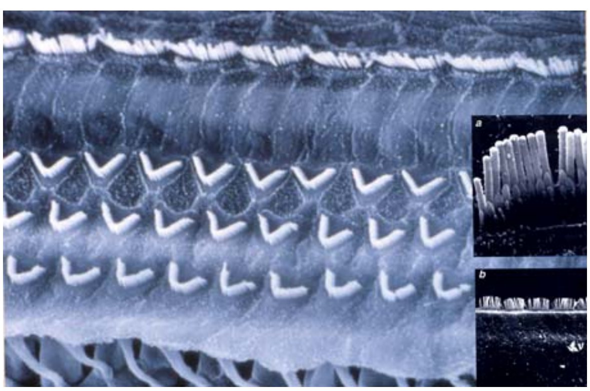
equilibrium of pressures

Cochlea - Organ of Corti - Hair cells

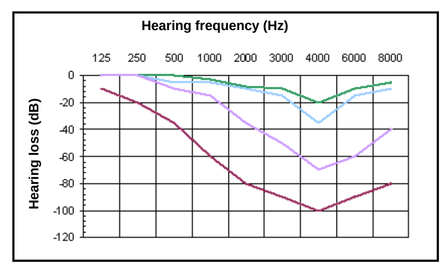


http://ile-de-france.sante.gouv.fr/santenv/bruit/notions/celcil.htm
http://ile-de-france.sante.gouv.fr/santenv/bruit/notions/corti.htm

Hair cells



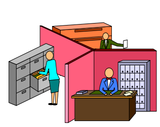
Audiograms



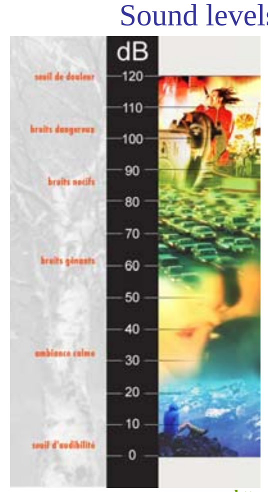
- normal hearing
- hearing loss reaches 2000 Hz
- hearing loss at 4000 Hz
- important or irreversible deafness

Too much silence?

- Danger
  - ✓ at work (wearing of hard hat)
  - ✓ in the streets (noiseless vehicles)
- Deprivation of sound information
  - ✓ noise of an engine
  - ✓ functioning of a machine
  - ✓ lack of pleasantness (the good noise!)
- Discomfort
  - ✓ public transports (train)
  - ✓ open-plan offices



Sound levels - Noise annoyance



The audible sounds range from 0 dB (threshold of hearing) and 140 dB. The threshold of pain is around 120 dB. Annoyance, which is a subjective concept, is felt with a great variability from one person to another.

Consequently, no objective noise level can give an absolute indication of the annoyance.

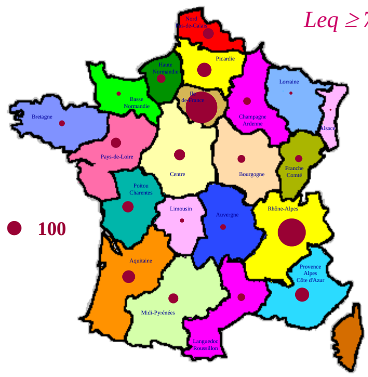
http://www.acnusa.fr/bruit_et_mesure/bruit_et_mes_echelle.asp

C. Potel, M. Bruneau, "Acoustique générale (...)", Ed. Ellipse, collection Technosup, ISBN 2-7298-2805-2, 2006

Terrestrian transports

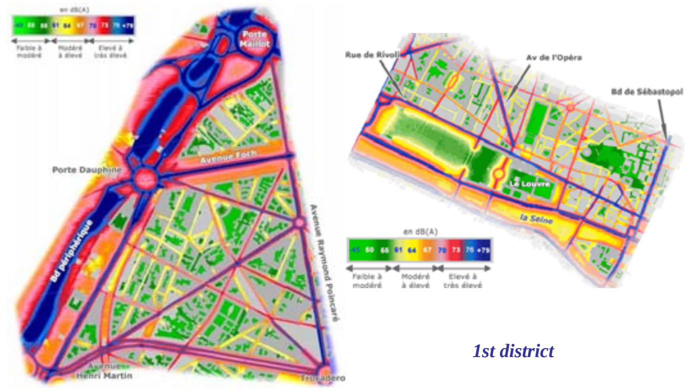
Exposure of population to roadway noise: number of road black points

Leq ≥ 70 dB(A) between 8 h -20 h



From data bank of LRPC Strasbourg - France (results 1998)

Noise contour maps (Paris - France)



1st district

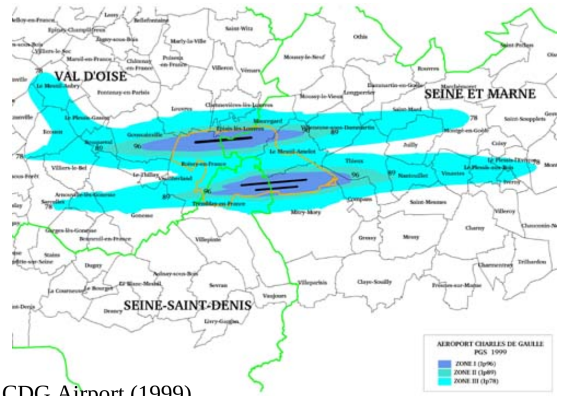
16th district

www.paris.fr/FR/Environnement/bruit/carto_bruit/default.ASP

French noise annoying plan (plan de gène sonore - PGS in french)

Document provided by French law 92-1444 of 31 December 1992 (Article 19) which permits to define the areas in which residents are eligible for assistance for soundproofing.

French noise annoying plan (plan de gène sonore - PGS in french)



Roissy CDG Airport (1999)

http://www.adp.fr/labo/web/surenv/bruit/index.html

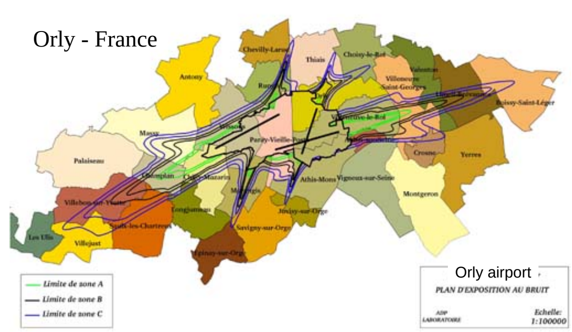
French noise exposure plan (plan d'exposition au bruit - PEB in french)

Document provided by the French law 85-696 of 11th July 1985 which regulates urbanism near airports so as not to expose new populations to noise annoyance. Specific measures can take into account the specificities of the pre-existing context.

→ Precautionary principle

French noise exposure plan (plan d'exposition au bruit - PEB in french)

Orly - France



http://www.adp.fr/labo/web/surenv/bruit/index.html

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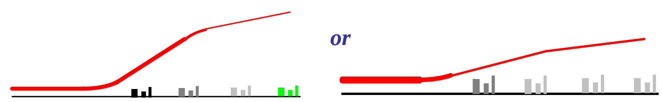
PEB - PGS: merger?

An french interministerial working group studied the question of bringing together the procedures relating to the noise exposure and noise annoying plans in France. A report released in December 2007 weighs the advantages and disavantages of a merger of the two zonings, and makes proposals.

Report of the working group « Rapprochement des procédures PEB et PGS » - report n°004577-01 - june 2007 (format pdf - 784,9 Ko) - Authors : Gilles Rouques (CGPC) and Annick Helias (IGE)
http://publications.ecologie.gouv.fr/publications/IMG/pdf/Rapport_GT_Rapprochement_PEB_et_PGS.pdf

Example of solution: traffic management (noise mitigation)

- Maximum number aircrafts movements
  (Orly airport : 200.000 per year)
- Time of day restrictions (Orly airport : 7 am to 11 pm)
- Choice of air lanes
- Departure flight path and slope



Perception and room acoustics (1/10)

- Sounds

➡ ✓ noise (annoyance, alert function)
✓ speech (intelligibility)
✓ music (esthetic)

↳ organization of sounds
- time (rythm, melody)
- spatial (fill the space)

↳ space { - visually / - auditively } perceived

➡ ✓ spectrum
✓ intensity
✓ duration

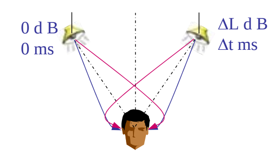
Perception and room acoustics (2/10)

- Perception

➡ ✓ Location: comparison by the brain of
- intensities
- times of arrival

} to the two ears

✓ Attributes:
- monaural hearing ➡ loundness, pitch, timbre
- binaural hearing ➡ (timbre), soundscape

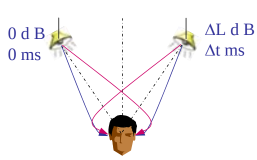


➡ ✓ Continuous: formants for the voice
✓ Transient: consonants, musical attack

Perception and room acoustics (3/10)

- The sound space

➡ ✓ Location of one source
- binaural
- pinna
- scattering



✓ Location of two sources
- coherent sources: impossible
- non coherent sources: distinct

✓ Delay between two coherent sources
- summation effect (~ 1ms)
- precedence effect (loudness + space effect)
- space effect (3D)

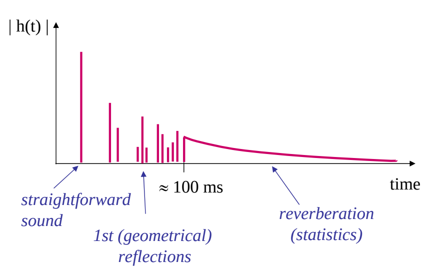
➡ ✓ These three effects can be simultaneously perceived (reflections in a room)
✓ Large number of reflections, late effects: reverberation

Perception and room acoustics (4/10)

- Soundscape: intelligibility and noise

➡ ✓ Noise masking speech
- Example: pernicious effect of reverberation

✓ Reverberation which permits to the speaker to hear himself
✓ Too high reverberation: tiredness



C. Potel, M. Bruneau, "Acoustique générale (...)", Ed. Ellipse, collection Technosup, ISBN 2-7298-2805-2, 2006

Perception and room acoustics (5/10)

- Soundscape, room acoustics (1/6)
  - Expectation of the listener ➡ blooming, esthetic pleasure
  - Expectation of the performer ➡ interpretation of music

➡ The listener try to:
- ✓ benefit from a sonorous sound (avoid tiredness)
- ✓ make the most of his two ears (space effect)
- ✓ well understand music (but small "fuzziness")
- ✓ have a good adjustment of tones (instrumental equilibrium, tonal equilibrium, …)

➡ Moreover, the musician try to:
- ✓ well listen what he is playing
- ✓ have a good contact with other musicians

Perception and room acoustics (6/10)

- Soundscape, room acoustics (2/6)
  - Listeners

➡ Sonorous sound

Orchestra: 10 to 100 W (in facts < 110 dB)
- ✓ good distribution of sound energy
- ✓ increase the number of reflections
  - ↳ increase the volume of the room (6 to 11 m^3 per listener)

➡ Use of the two ears
- ✓ initial side reflections (close to the listener)
  - ↳ improve the clarity

➡ Good understanding
- ✓ limited reverberation (compromise with sonorousness)
  - ↳ favor the small "fuzziness"

➡ Good adjustement of tones (delicate)
- ✓ avoid front reflectors (above and behind the orchestra), ➡ coloration
  - ↳ if the reflector are present, split them

Perception and room acoustics (7/10)

- Soundscape, room acoustics (3/6)
  - Musicians

➡ listen what they are playing
- ✓ return of sound towards stage
- ✓ good coupling stage / room

➡ good contact between them
- ✓ reflectors above the orchestra

  - The room

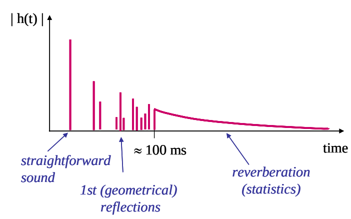
➡ Room acoustics ≡ question of geometry
- ✓ arrangement of volumes
- ✓ arrangement of walls
  - ↳ • contact listeners / musicians
  - • coupling stage / room

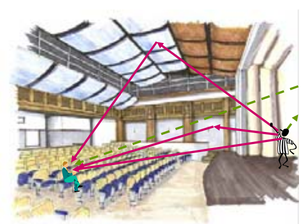
➡ Absorbant acoustical treatment does not improve anything
- ✓ (permits eventually to remove some echoes)

Perception and room acoustics (8/10)

- Soundscape, room acoustics (4/6)
  - Impulse response

$$p_r(t) = h(t) * p_{anechoic}(t)$$





Perception and room acoustics (9/10)

- Soundscape, room acoustics (5/6)
  - Subjective characterization
    - ✓ Reverberation
    - ✓ Clarity
    - ✓ Loudness
    - ✓ Intimacy
    - ✓ Uniformity
    - ✓ Diffusion
    - ✓ Envelopment
    - ✓ Performer's satisfaction
  - Questionnaire
  - Binaural hearing
    - ✓ numerical simulation, scale model

Perception and room acoustics (10/10)

- Soundscape, room acoustics (6/6)
  - Objective characterization (examples)
    - ✓ sound amplitude → $10\log_{10}\left(\int_0^\infty p^2(t)\,dt / p_{ref}^2\right)$
    - ✓ reverberation duration at -60 dB
    - ✓ early decay time (1st reflections)

$$10\log_{10}\left(\int_0^{80\ \text{ms}} p^2(t)\,dt \Big/ \int_{80}^{\infty} p^2(t)\,dt\right)$$

    - ✓ timbre

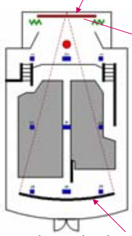
$$10\log_{10}\left[\left(\int_{500\ \text{Hz}}^{5000\ \text{Hz}} M(f)\,df \Big/ 4500\right) \Big/ \left(\int_{50\ \text{Hz}}^{500\ \text{Hz}} M(f)\,df \Big/ 450\right)\right]$$

  - Numerical simulation
  - Scale model

Example of mistakes (1/2)

large movie projection screen on a perfectly reflecting wall

McKinnon Theater, Kettering University, Flint, MI



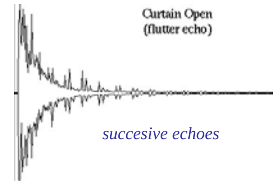
large movie projection screen on a perfectly reflecting wall

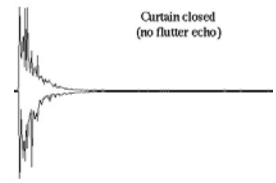
400 seats

http://www.kettering.edu/acad/scimath/physics/acoustics/McKinnon/McKinnon.html

Example of mistakes (2/2)

- **flutter echo**





McKinnon Theater, Kettering University, Flint, MI

http://www.kettering.edu/acad/scimath/physics/acoustics/McKinnon/McKinnon.html

Animation courtesy of Dr. Dan Russell, Kettering University

Slides based upon

C. POTEL, M. BRUNEAU, *Acoustique Générale - équations différentielles et intégrales, solutions en milieux fluide et solide, applications*, Ed. Ellipse collection Technosup, 352 pages, ISBN 2-7298-2805-2, 2006