# Cochlea Modelling:
# Future Directions

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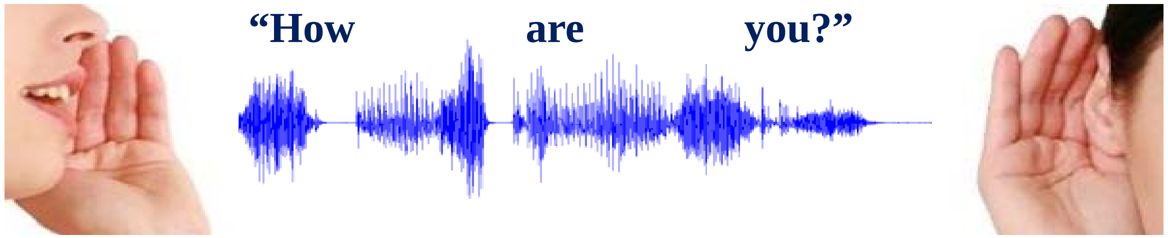
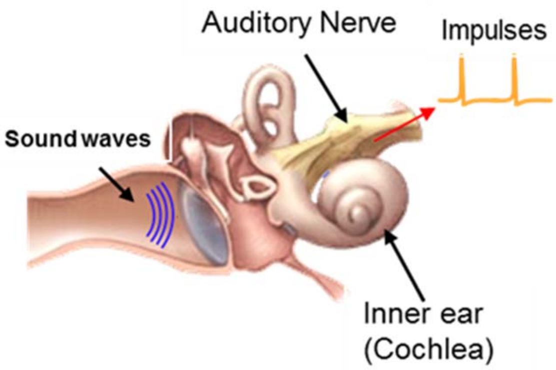
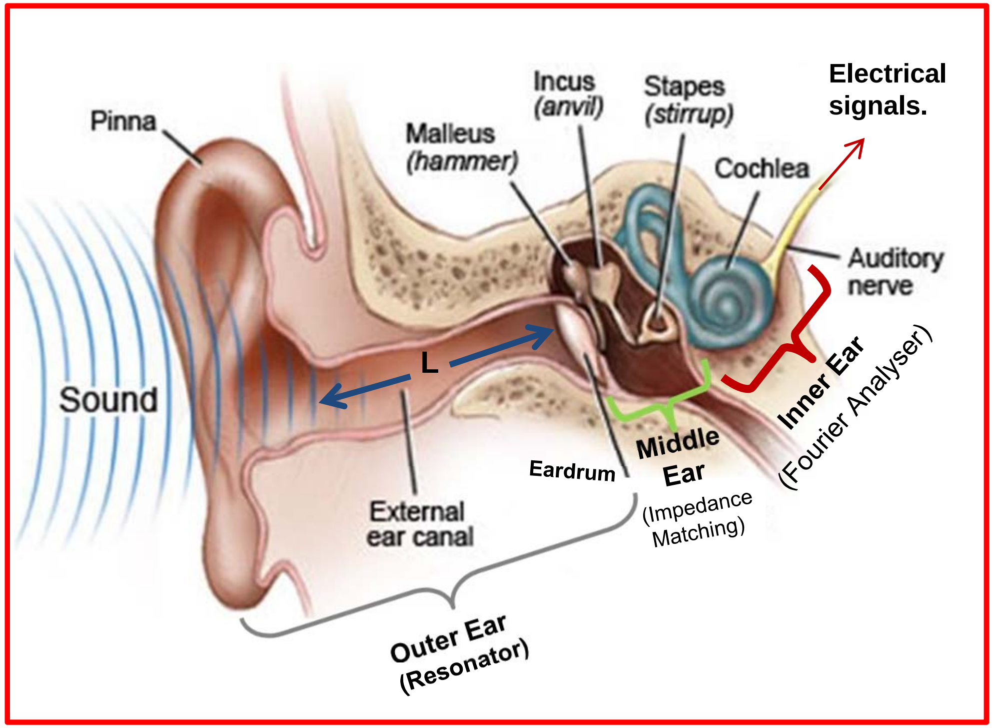


# Human Auditory System

# Introduction to the Human Auditory System

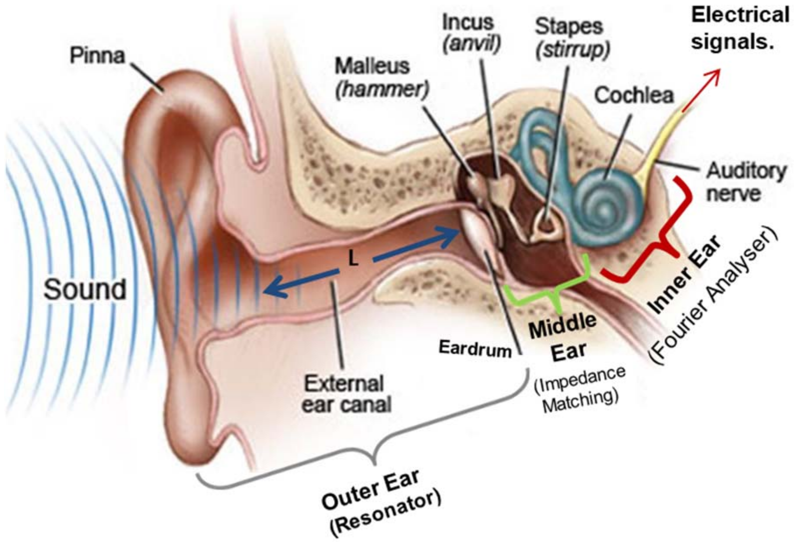
- ✓ The human auditory system is responsible for converting pressure variations caused by the sound waves that reach the ear into nerve impulses that are interpreted by the brain.
- ✓ The peripheral auditory system is divided into the Outer Ear, Middle Ear, and Inner Ear.
- ✓ The peripheral auditory system and in particular the cochlea can be viewed as a real-time spectrum analyser.
- ✓ The primary role of the cochlea is to transform the incoming complex sound wave at the ear drum into electrical signals.
- ✓ The human ear can respond to minute pressure variations in the air if they are in the audible frequency range, roughly 20 Hz - 20 kHz

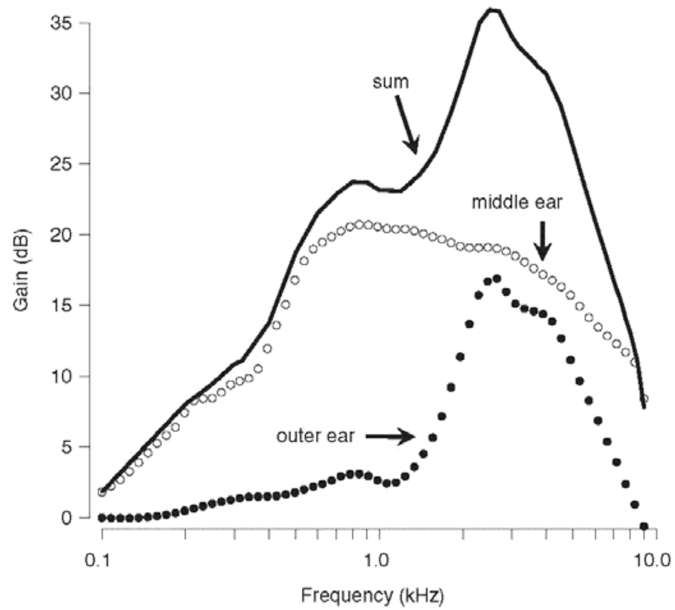



Peripheral Auditory System

# Outer and Middle Ear

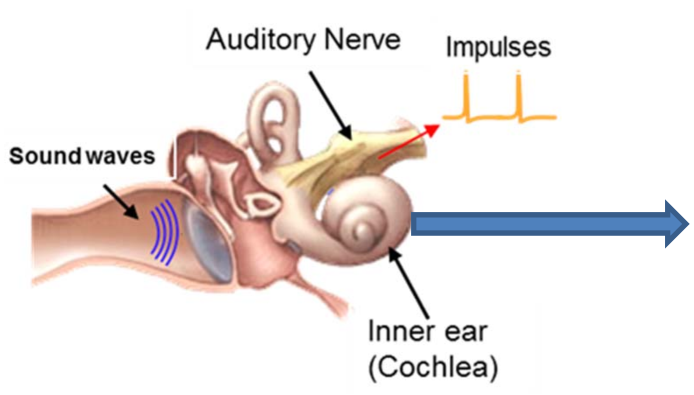
- ✓ The sound waves enter a tube-like structure called ear canal and it serves as a sound amplifier.
- ✓ The human outer ear is most sensitive at about 3kHz and provides about 20dB (decibels) of gain to the eardrum at around 3000Hz.
- ✓ Middle ear transforms the vibrating motion of the eardrum into motion of the stapes via the two tiny bones, the malleus and incus .
- ✓ The combined frequency response of the outer and middle ear is a band-pass response, with its peak dominated near 3 kHz.
- ✓ $P_{oval} = 25\, P_{drum}$ [$P$ : Pressure]



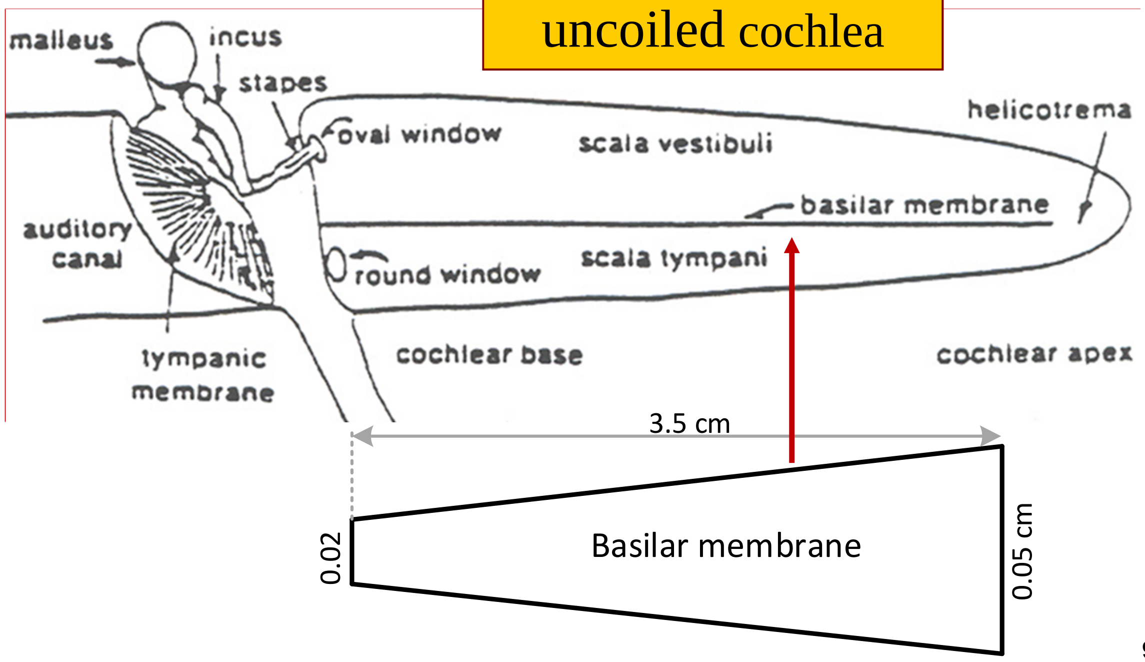



# Inner Ear

- ✓ The **inner ear** consists of the cochlea responsible for converting the vibrations of sound waves into electrochemical impulses which are passed on to the brain via the auditory nerve.
- ✓ The cochlea is divided along its length (3.5 cm) by the basilar membrane (BM) which partitions the cochlear into two fluid canals (scala vestibuli and scala tympani).
- ✓ The BM terminates just reaching the helicotrema, so there is a passage way between the scala vistibuli and the scala tymapni equalising the difference in pressure at the ends of the two scalas.




uncoiled cochlea



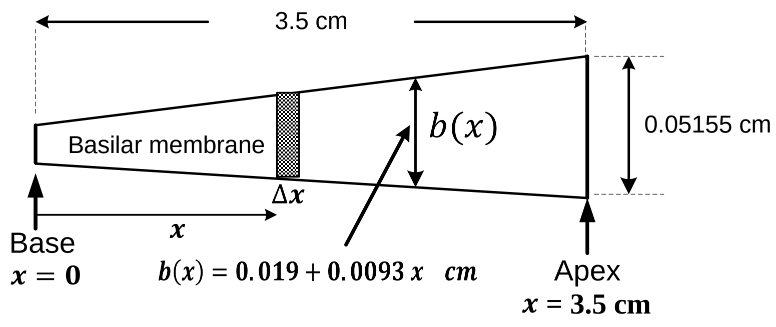
# Basilar Membrane (Hydro Dynamical process)

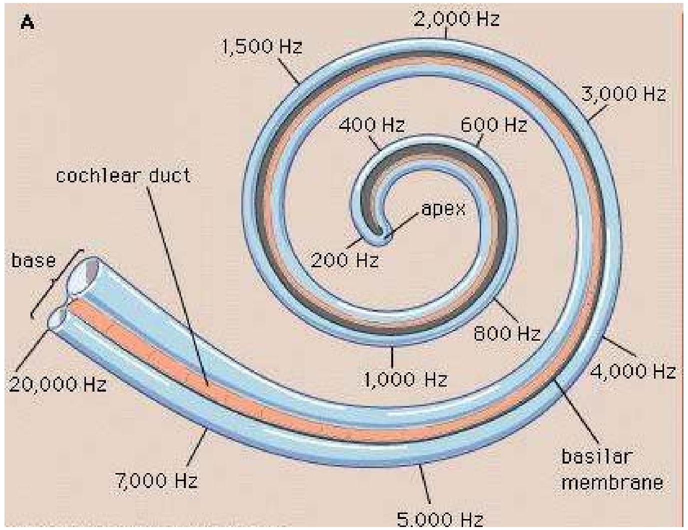
- ✓ Each point along the basilar membrane has a characteristic frequency, $f_p(x)$, to which it is most responsive.

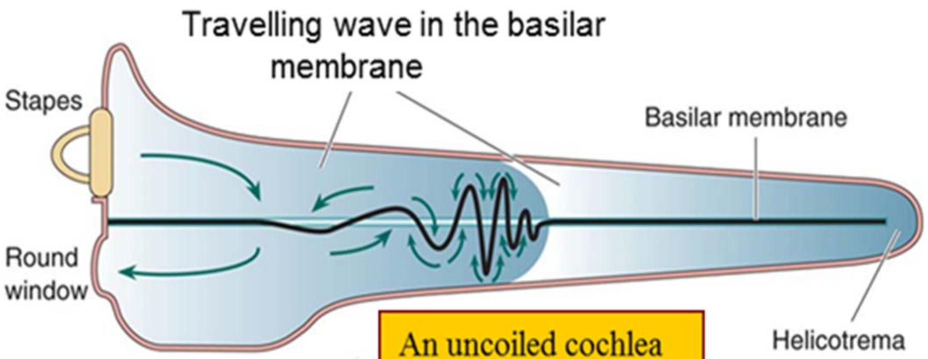
$$f_p(x) = (20000.0)\ 10^{-0.667\,x}\ Hz$$

- ✓ When the vibrations of the eardrum are transmitted by the middle ear into movement of the stapes, the resulting pressure differences between the cochlear fluid chambers, generate a travelling wave that propagates down the cochlea.
- ✓ The wave reaches maximum amplitude of displacement on the basilar membrane at a particular point before slowing down and decaying rapidly

Unrolled basilar membrane

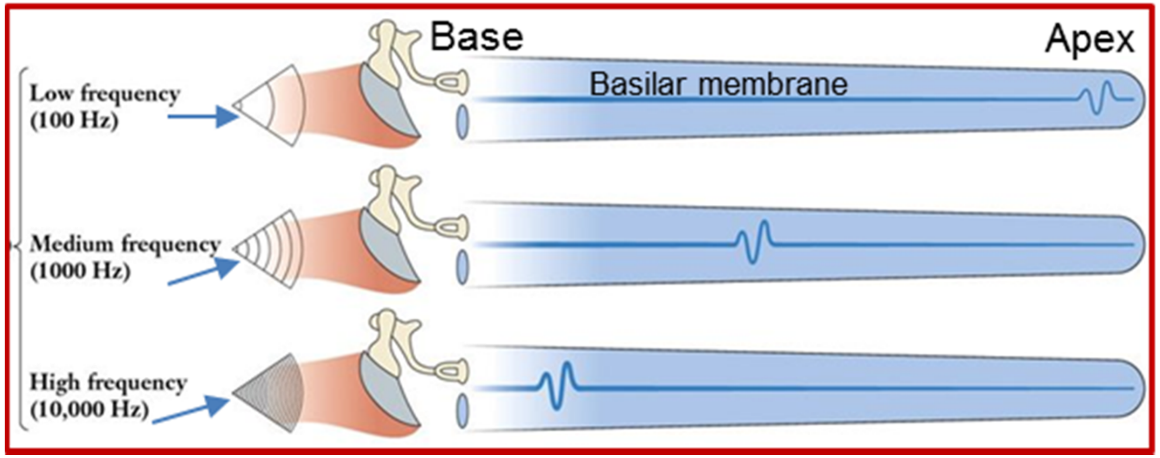


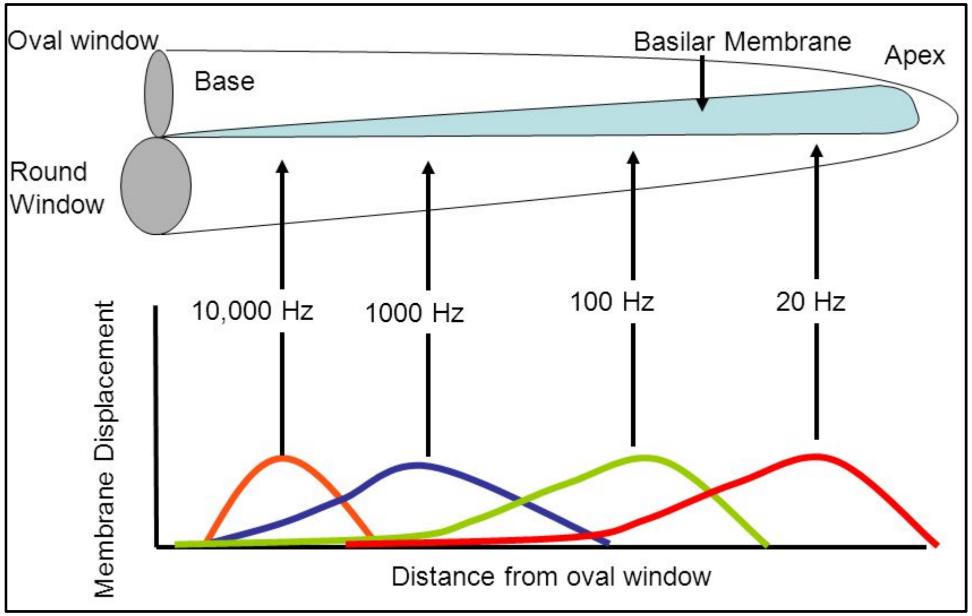




An uncoiled cochlea

# Basilar Membrane as a Filterbank




- ✓ Different frequencies stimulate different areas of the basilar membrane.
- ✓ There will be one place where the resonant frequency of the membrane matches the stimulus frequency and this place will show the maximum amount of vibration



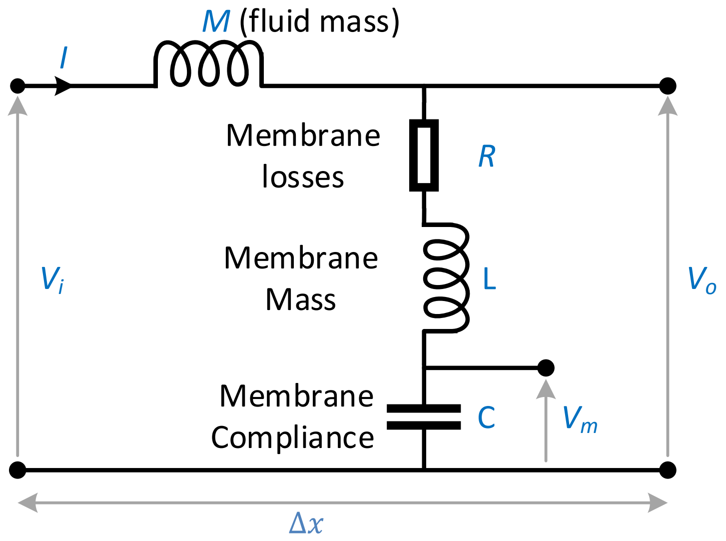

- ✓ The essential function of the basilar membrane is to act as a frequency analyser (a set of band-pass filters each responding to a different frequency region) resolving an input sound at the eardrum into its constituent frequencies

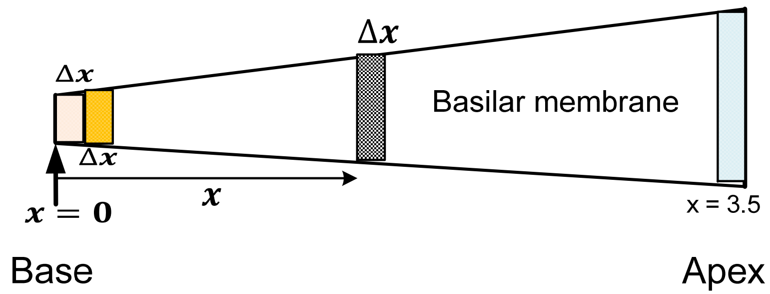
# Cochlear Animation

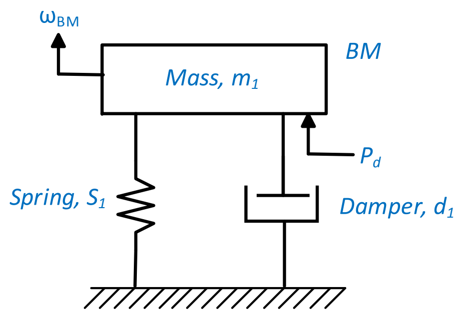
# Models of the Cochlea

# Cochlear Modelling

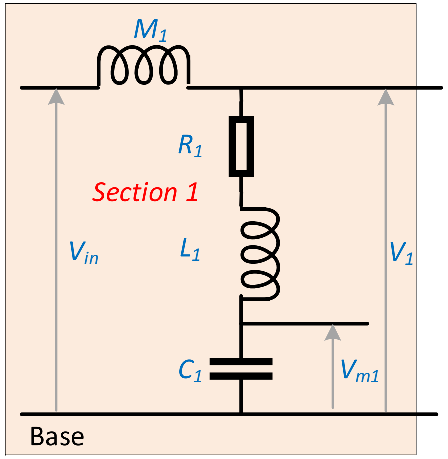
✓ A simple electrical model of a section ($\Delta x$) of the Basilar Membrane




✓ A Transmission Line Model of the Basilar Membrane



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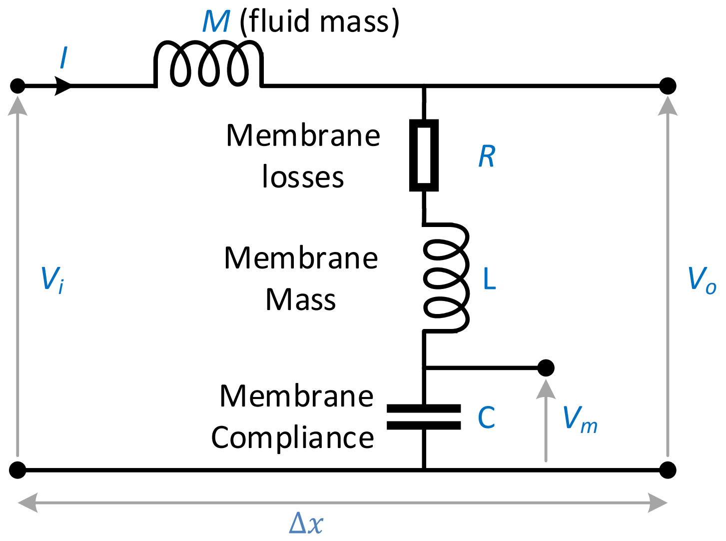


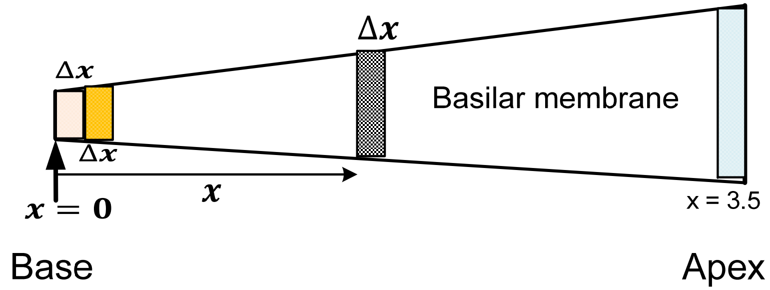


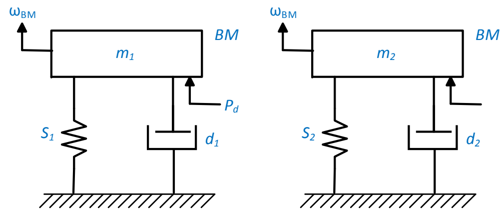


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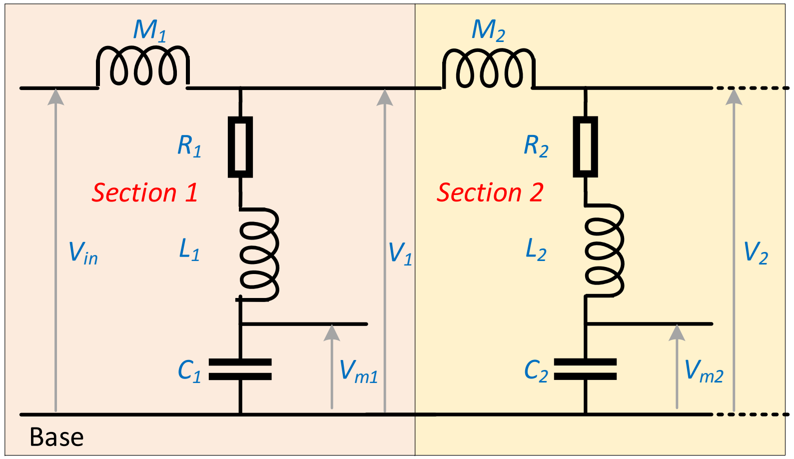

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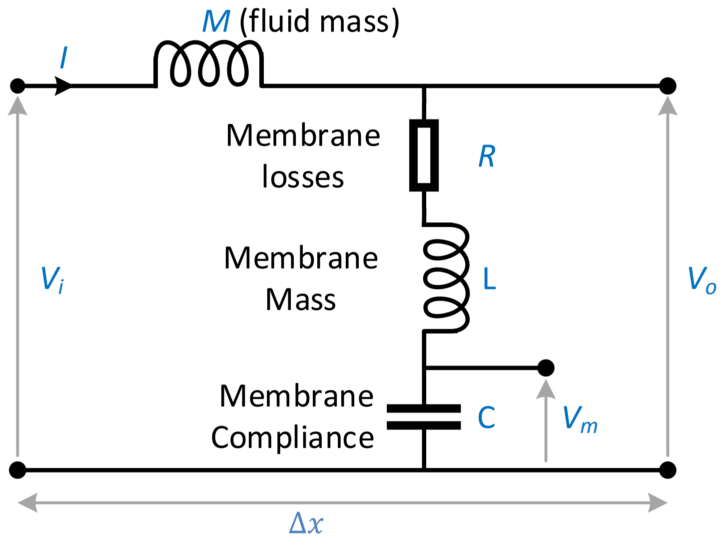


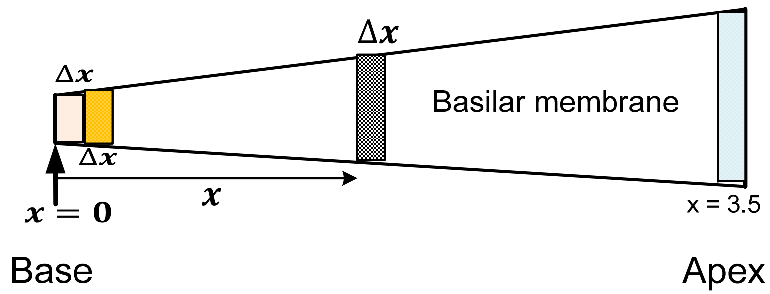


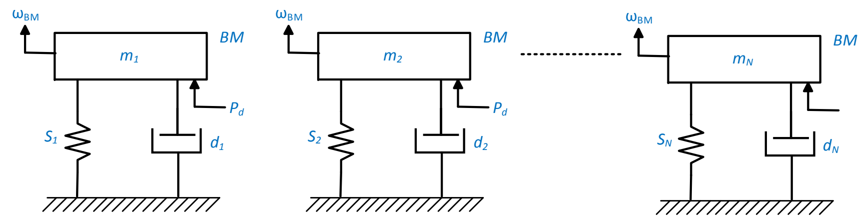


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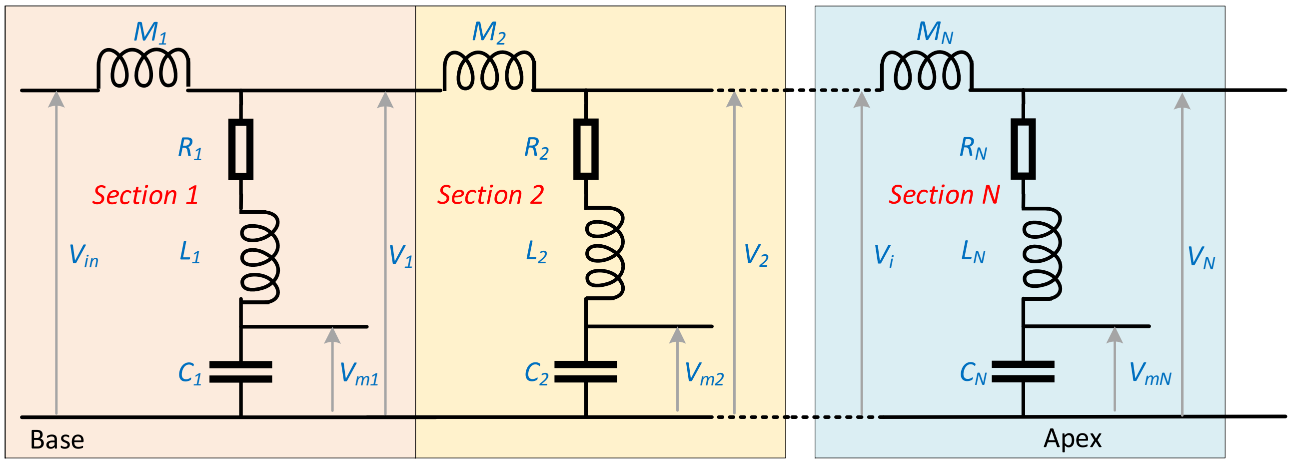
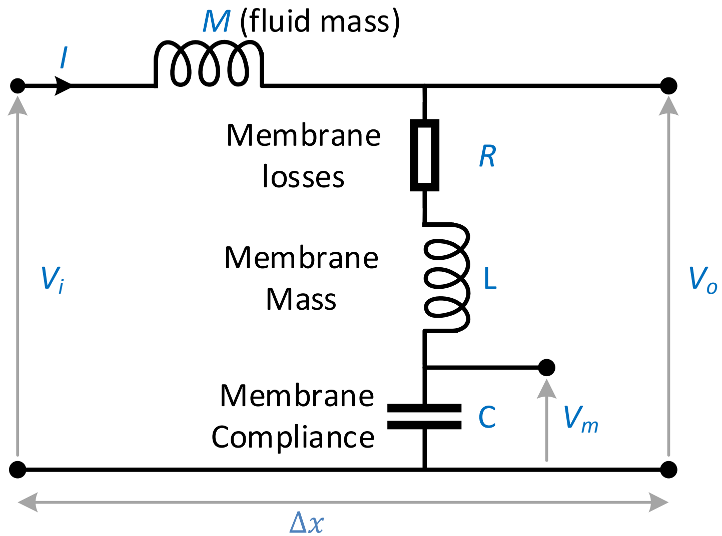
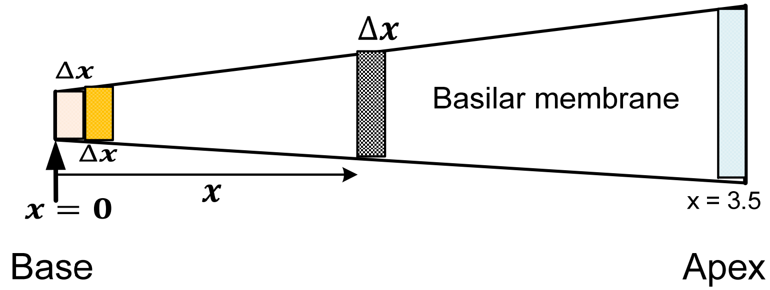
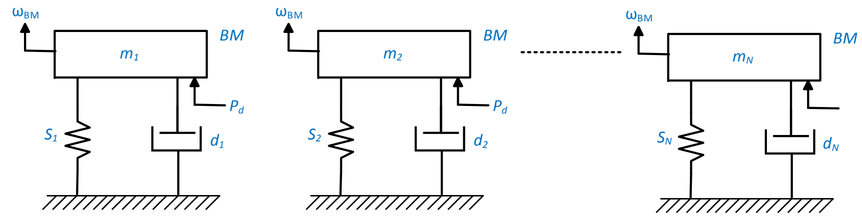


# Cochlear Modelling

✓ A simple electrical model of a section ($\Delta x$) of the Basilar Membrane

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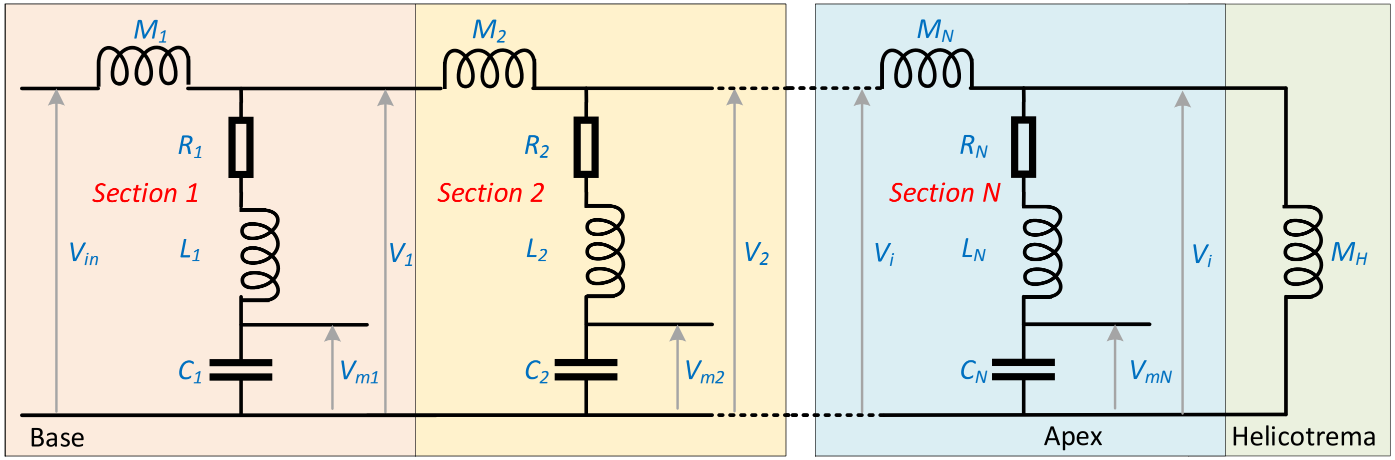
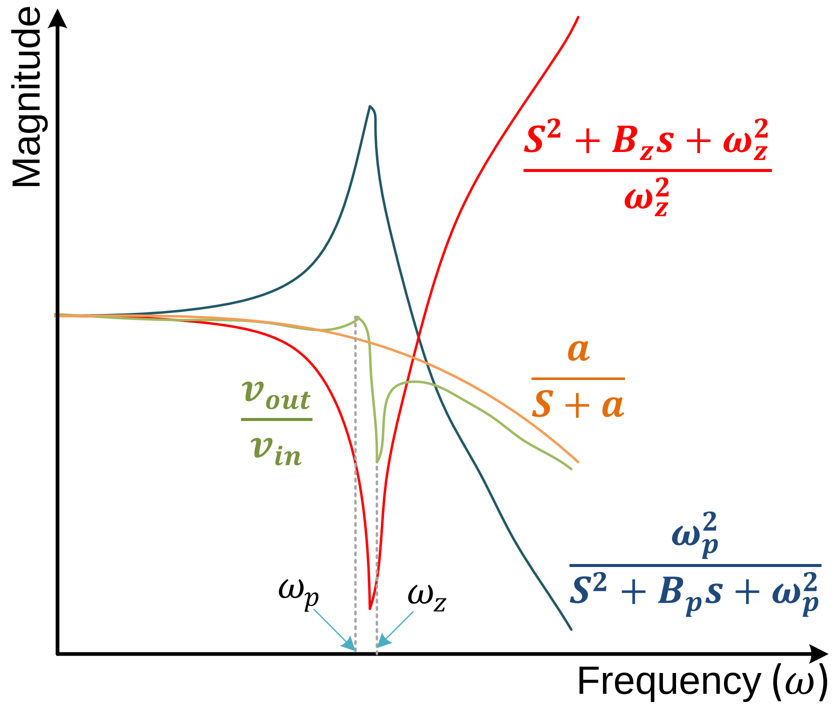


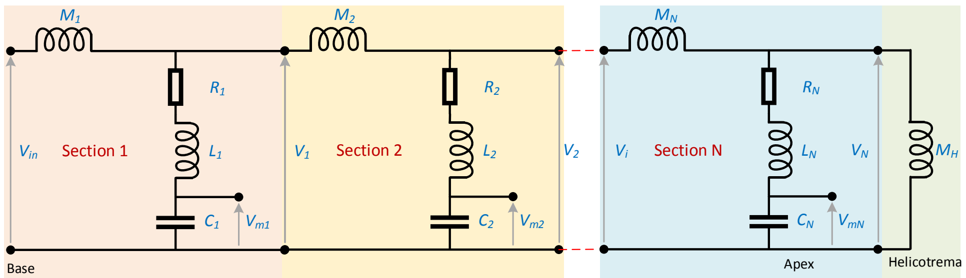
# Transmission Line Model of the Cochlea – Cascade Model

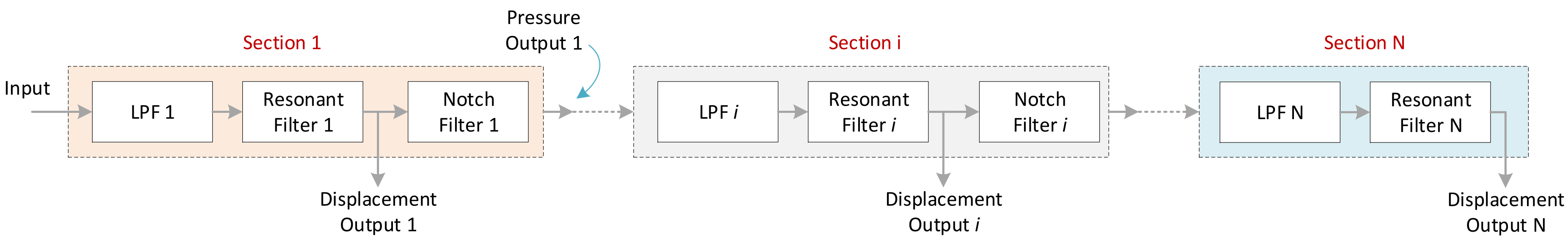
✓ The basic model of the cochlea is a transmission line model in which each section of the basilar membrane is modelled as a cascade of low pass, notch filters and resonators.

**Pressure Transfer Function**

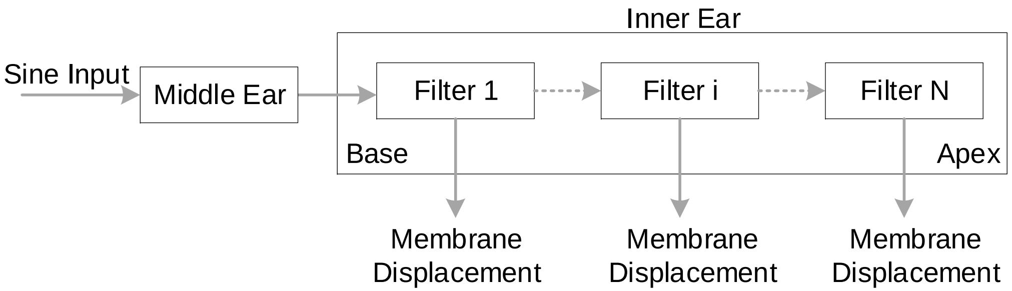
$$\frac{v_{out}(s)}{v_{in}(s)} = K \underbrace{\frac{a}{S+a}}_{\text{Low pass filter}} \underbrace{\frac{\omega_p^2}{S^2+B_p s+\omega_p^2}}_{\text{Resonant pole}} \underbrace{\frac{S^2+B_z s+\omega_z^2}{\omega_z^2}}_{\text{Resonant zero}}$$

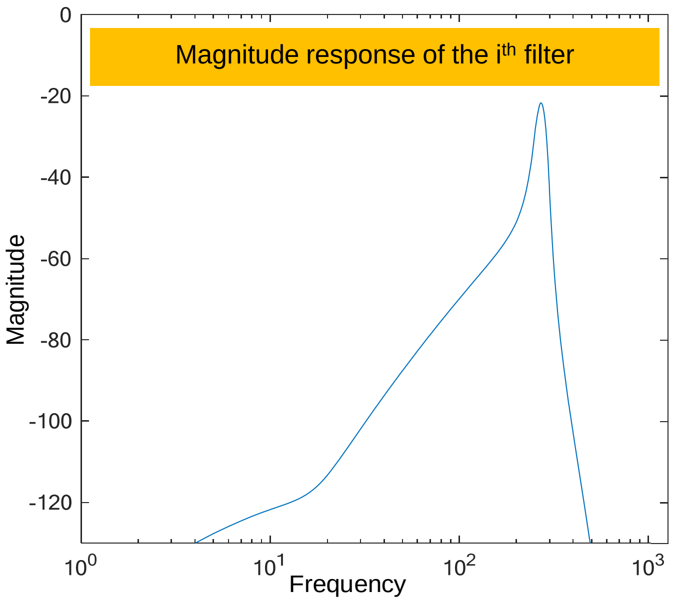


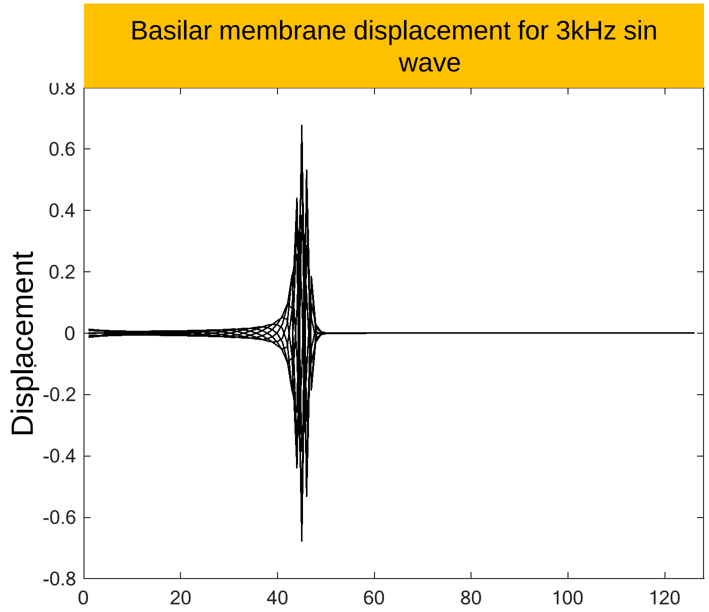



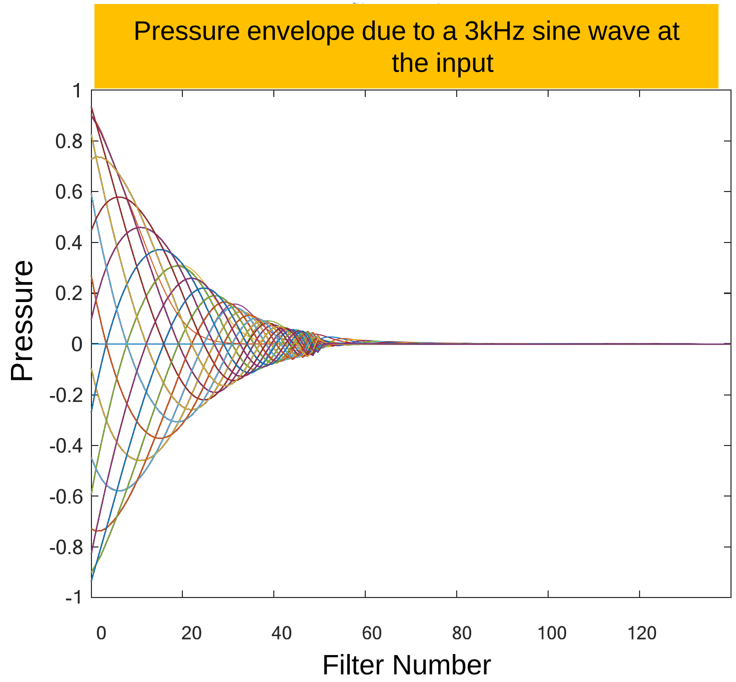



# Membrane displacement and Pressure envelope for a sinusoidal input



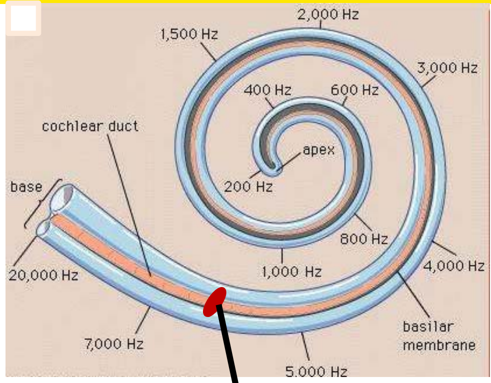



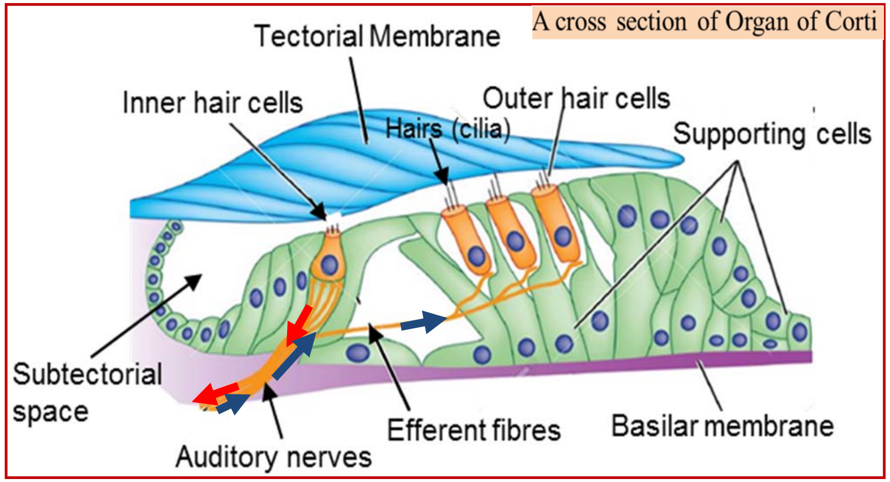

✓ Observing the envelope, the pressure is high at the basal end and decays down to zero at the resonant position.

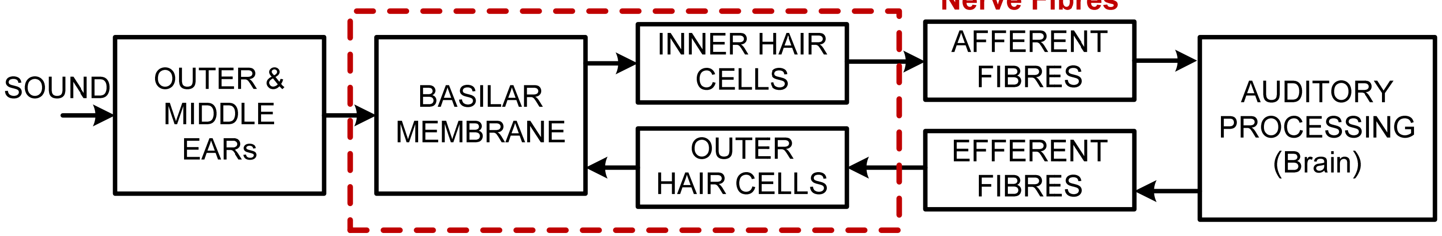
# Organ of Corti

- ✓ Attached to the basilar membrane and running its entire length is the organ of corti containing some 30,000 sensory hair cells.
- ✓ There are two types of hair cells:
  - One row of inner hair cells, which carry signals to the brain
  - Three rows of outer hair cells which receive signals from the brain
- ✓ When the basilar membrane deflects, due to pressure wave in the cochlear fluid it triggers the inner hair cells to transmit nerve impulses to brain.




Cross section

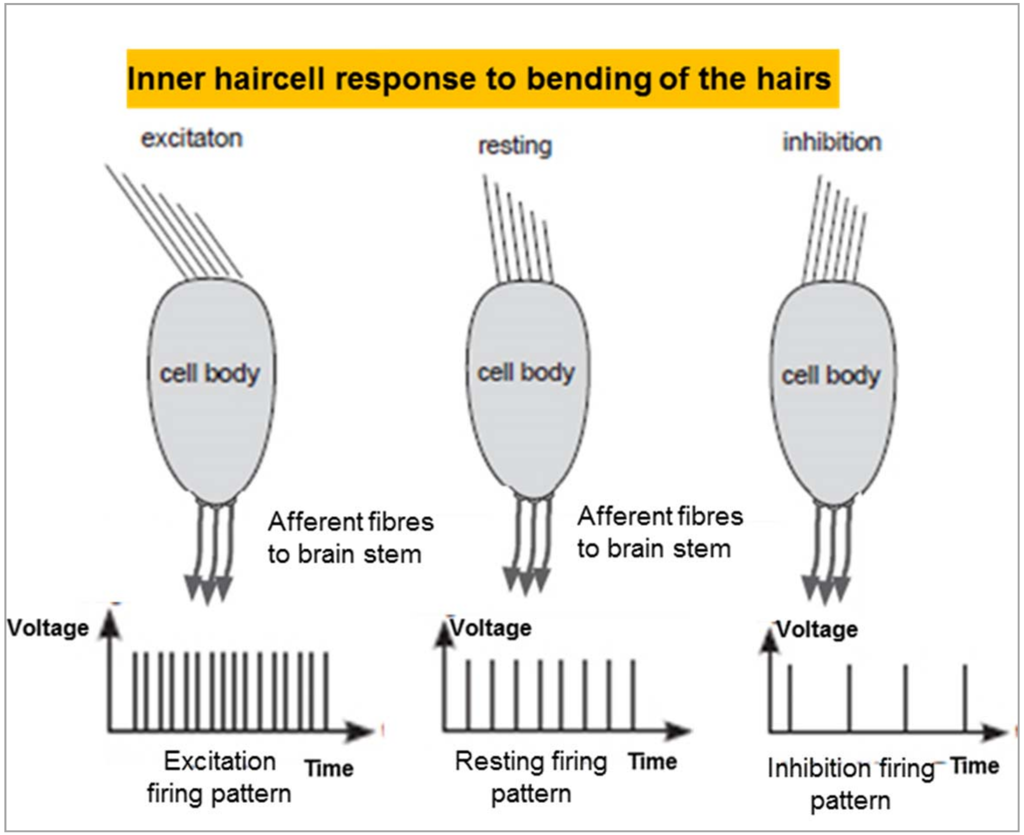


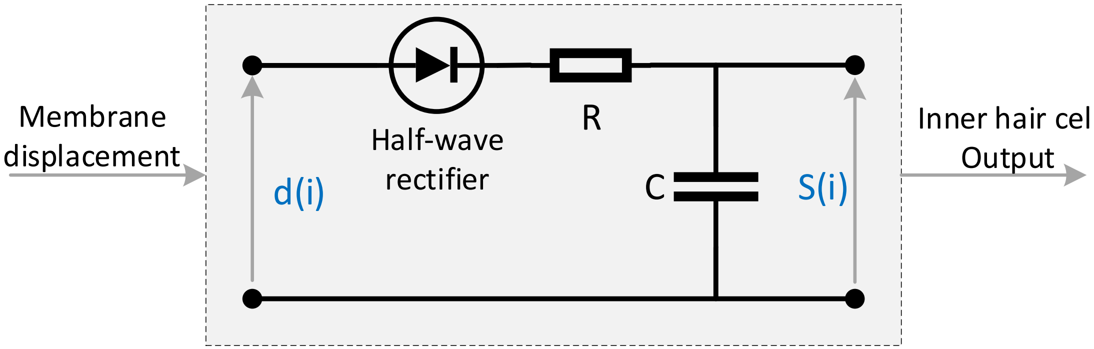

**A simplified Diagram of a Human Auditory System**

# Mechanical to Neural Transduction (Electro-Chemical)

- ✓ The mechanical displacement to electrical energy transduction process takes place in the inner hair cells
- ✓ The modulation being directly proportional to the degree of bending of the cilia and the bending of the cilia is one direction only; in effect a half wave rectification of the basilar membrane displacement takes place.

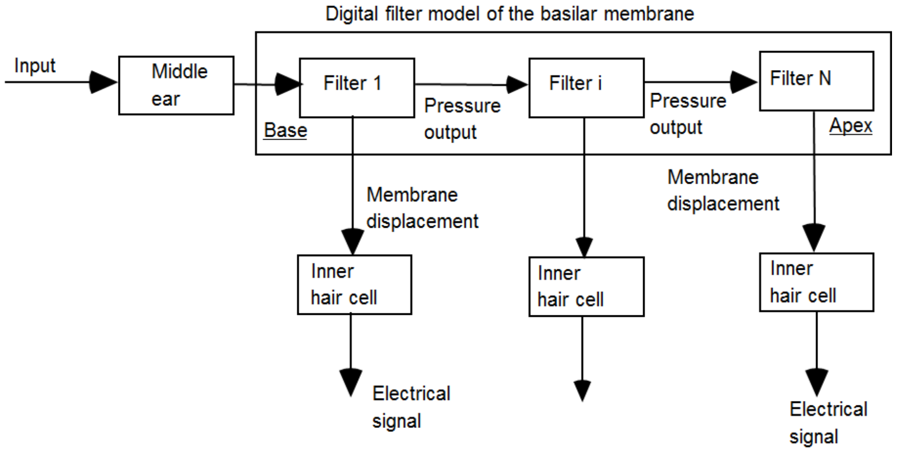


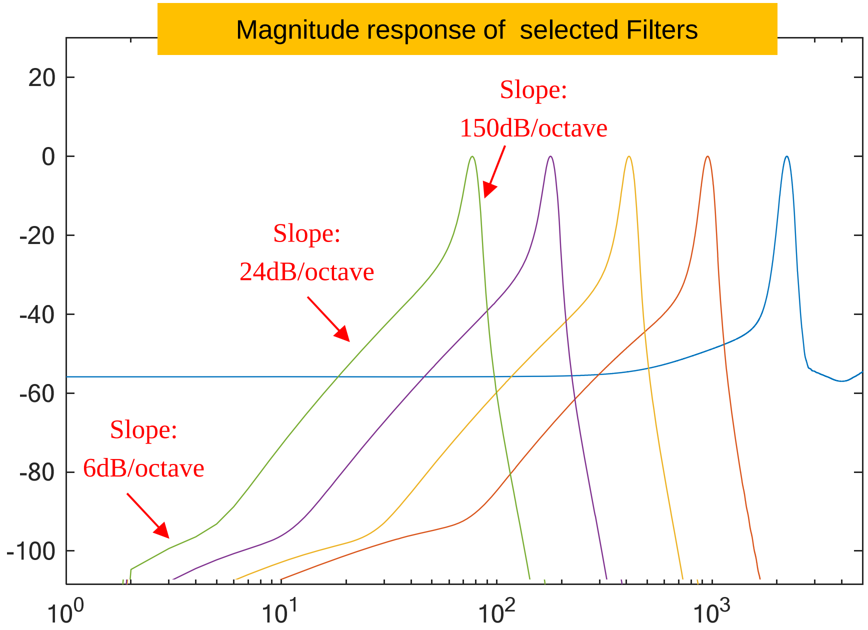

Inner hair cell model



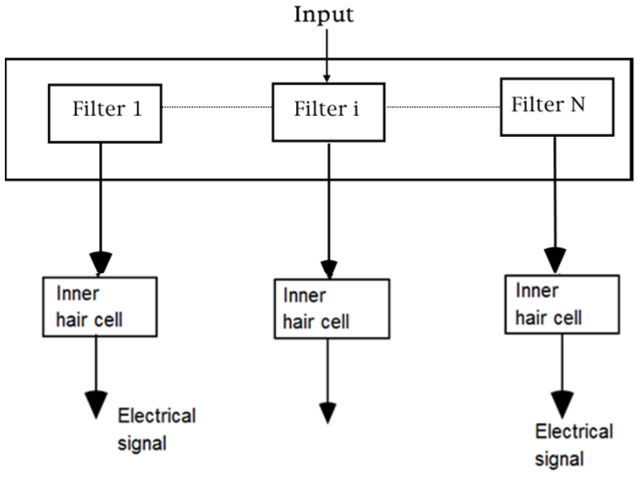
# Cochlear Models

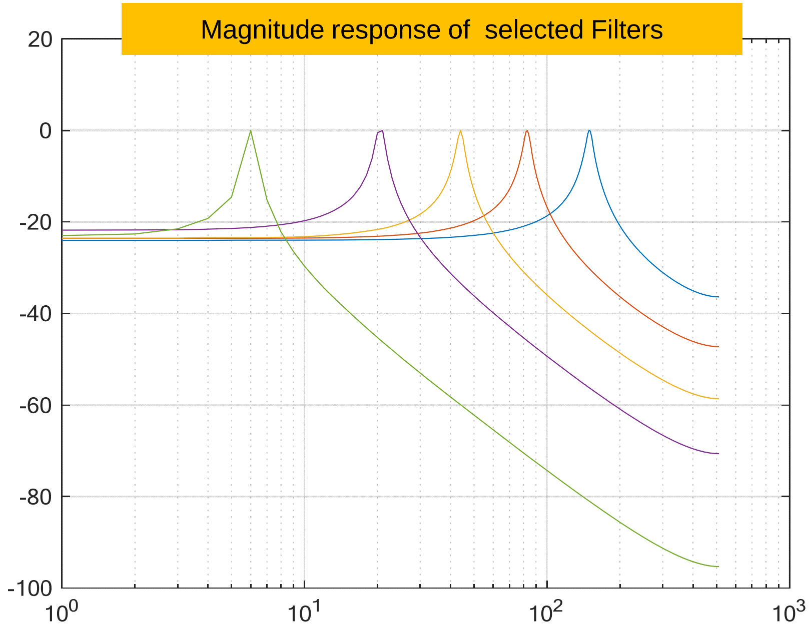
## Transmission Line Model



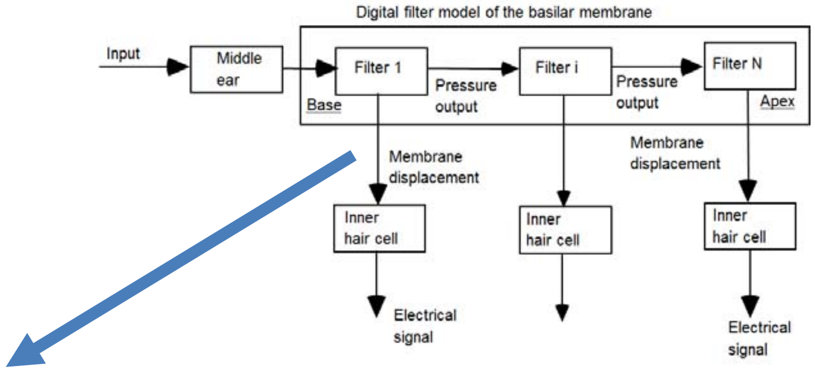

## Parallel Filter Bank Model

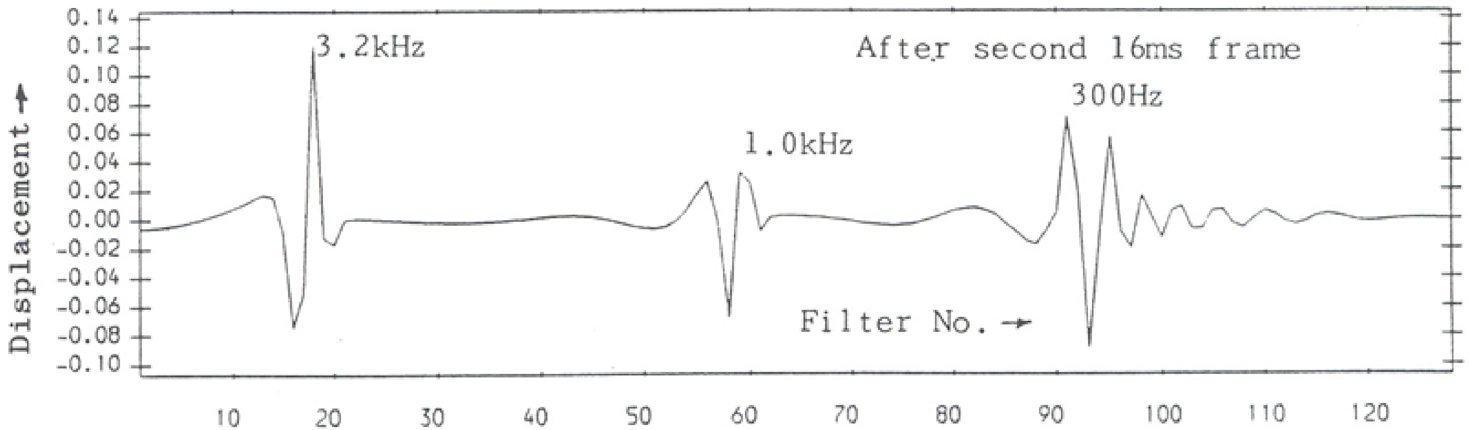


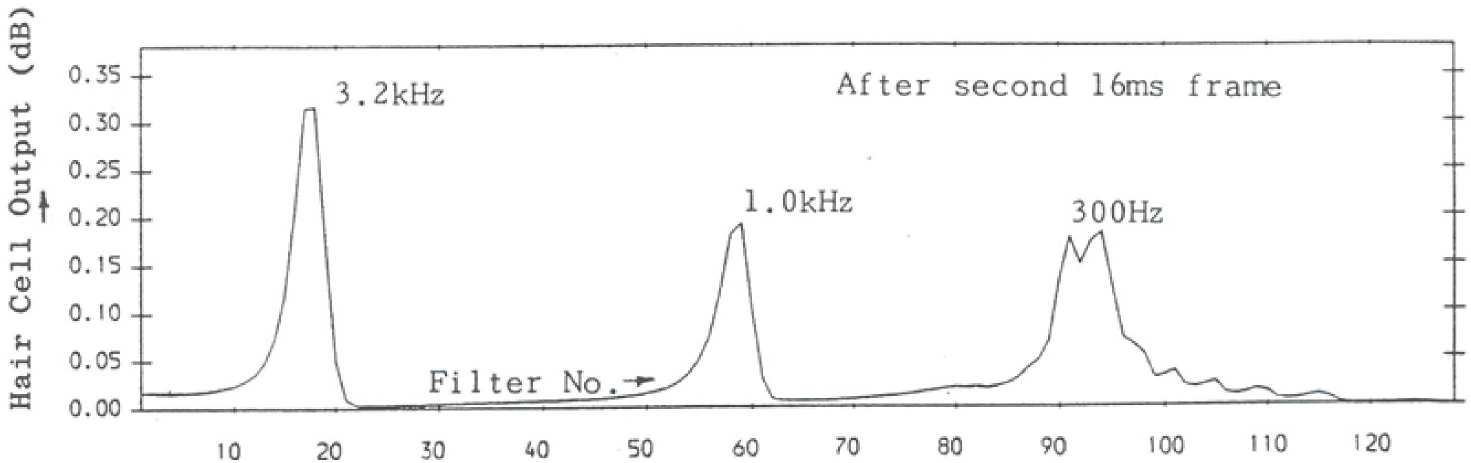



# Sinusoidal components at the input

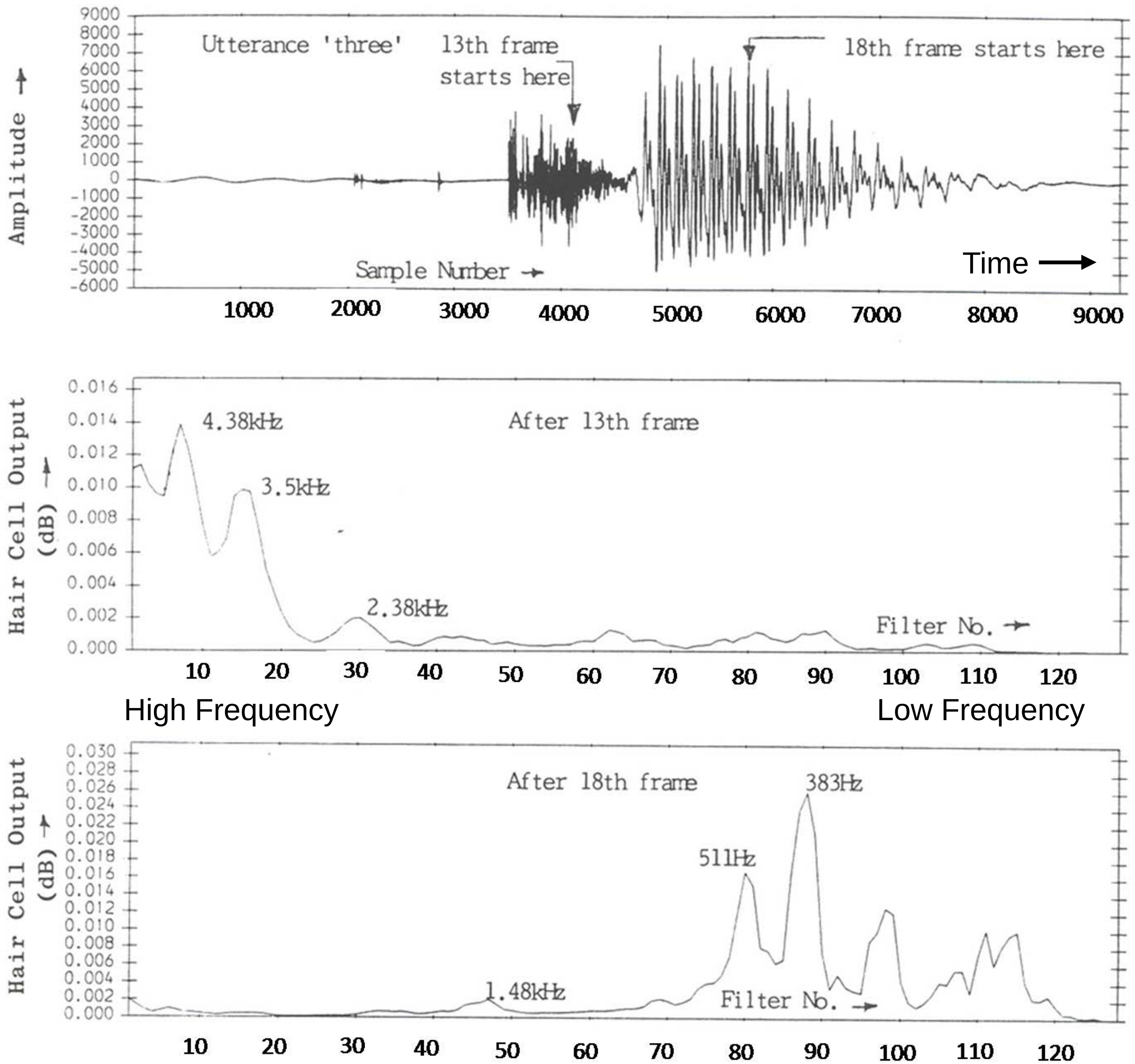
- ✓ The basilar membrane displacement and the corresponding inner hair cell output in response to a sum of three sinusoidal components applied at the input (3.2kHz, 1kHz and 300 Hz).
- ✓ The inner hair cell model output shows the spectral components in the input signal.

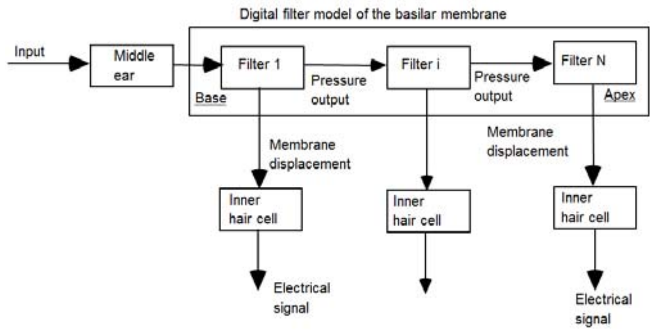


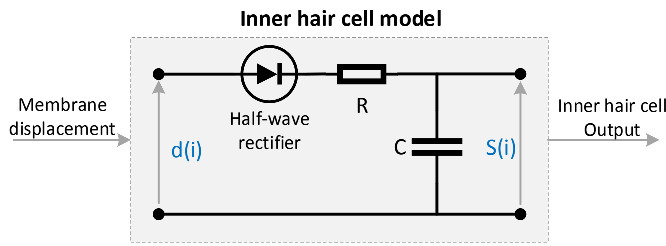



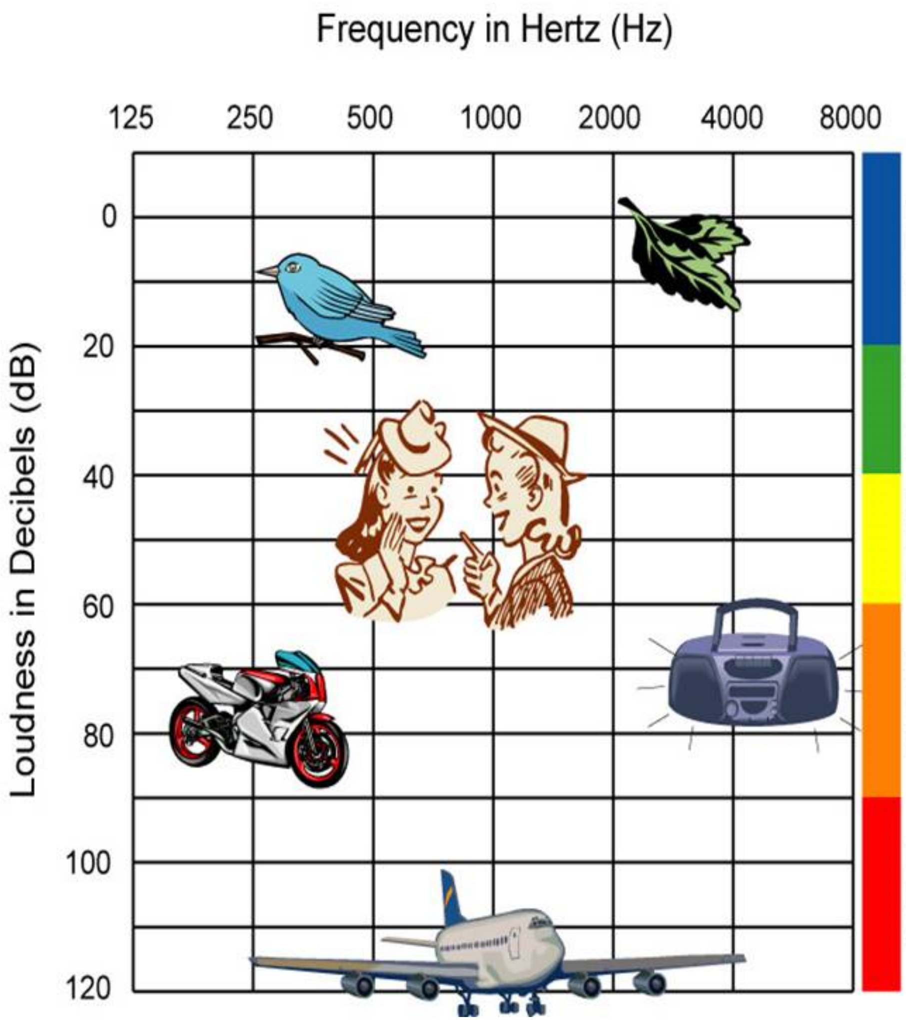
# Inner hair cell output for the speech utterance “three”



# Typical Sound Levels




| Sounds | Level |
|---|---|
| Faint | 20dB (A faint Whisper is 30dB) |
| Soft (Quiet) | 40dB |
| Moderate | 60dB (normal conversation) |
| Loud | 80dB (alarm clocks, vacuum cleaners) |
| Very Loud | 90dB(Blenders)<br>110dB (Concerts, car horns) |
| Uncomfortable | 120dB (jet planes during take off) |
| Painful and dangerous | 130dB(Jackhammers)<br>140dB(Gunshots) |

- ✓ Over 85 dB for extended periods can cause permanent hearing loss
- ✓ Zero decibels (0 dB) represent the absolute threshold of human hearing, below which we cannot hear a sound.

# Adaptive Models of Cochlea

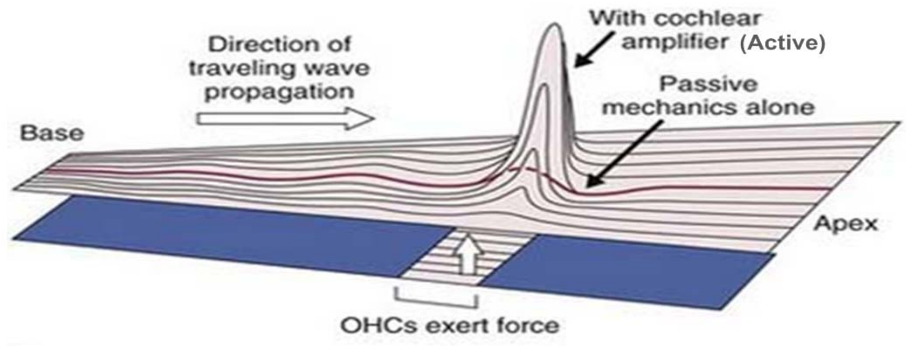
**Research Project funded by**

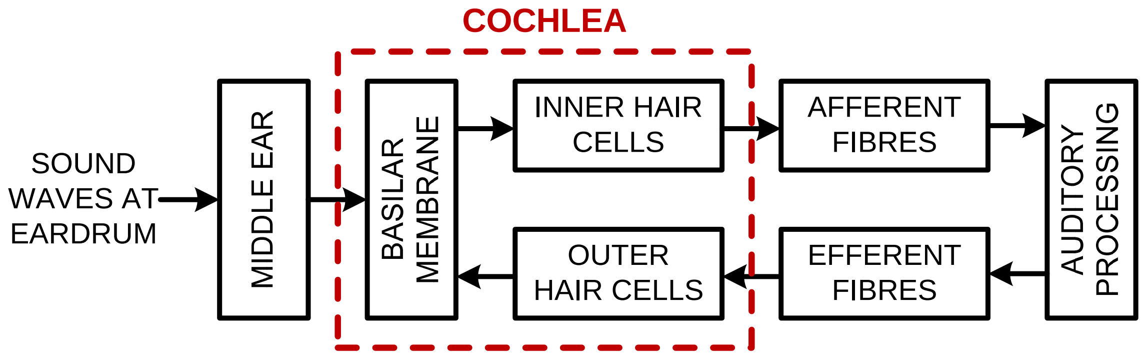
Australian Government

Australian Research Council

# Cochlear Response with Active Gain

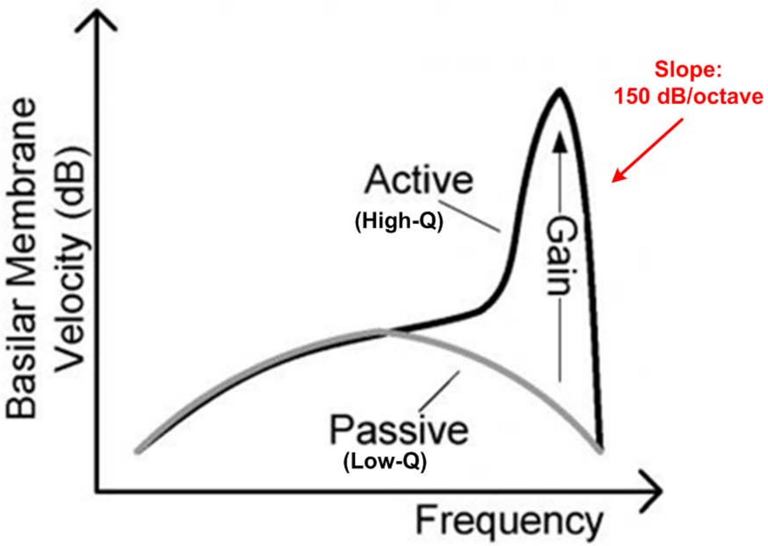
- ✓ Human auditory system can process a vast range of sounds spanning some twelve orders of magnitude of input pressure intensity
- ✓ In order to achieve this, the cochlea makes use of both passive and active systems
- ✓ The outer hair cells (OHC) provide this active mechanism - they amplify the motion picked up by the IHC at low input sound levels at that frequency

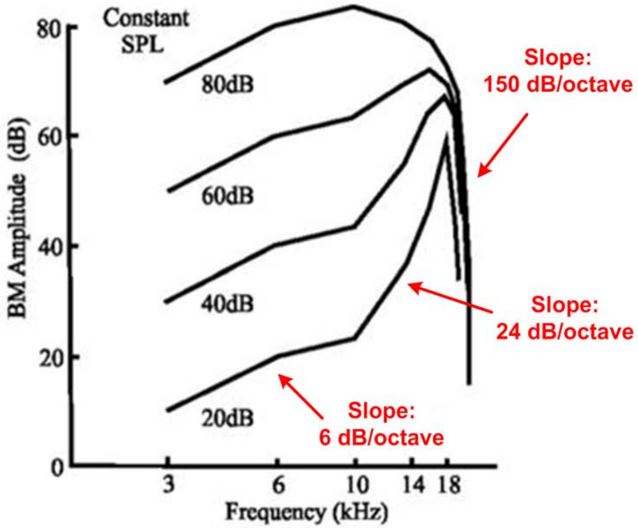


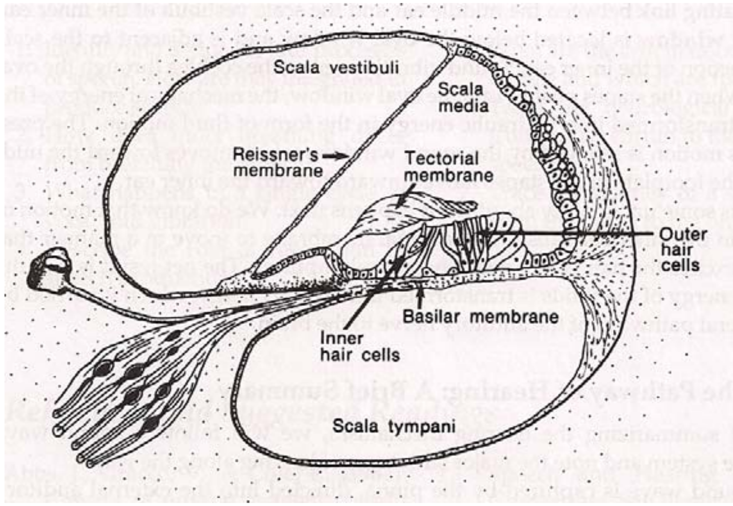
# Transmission Line Model with Feedback

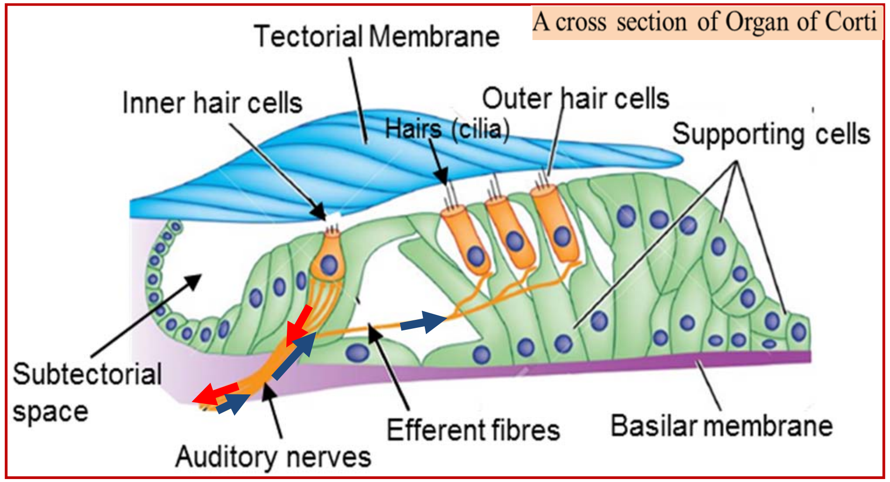
- ✓ The basilar membrane within the cochlea is normally in a passive state.
- ✓ Upon stimulation by a frequency of low amplitude, the section of the basilar membrane corresponding to that frequency transitions to an active state (adaptively higher-Q spectral decomposition).
- ✓ It is surprising how this large number of locally acting feedback loops can act together to give a large and uniform amplification of the global response of the BM.
- ✓ It would be desirable to have an active model of the cochlea that incorporates the level-dependent adaptive gain and adaptive frequency selectivity properties.

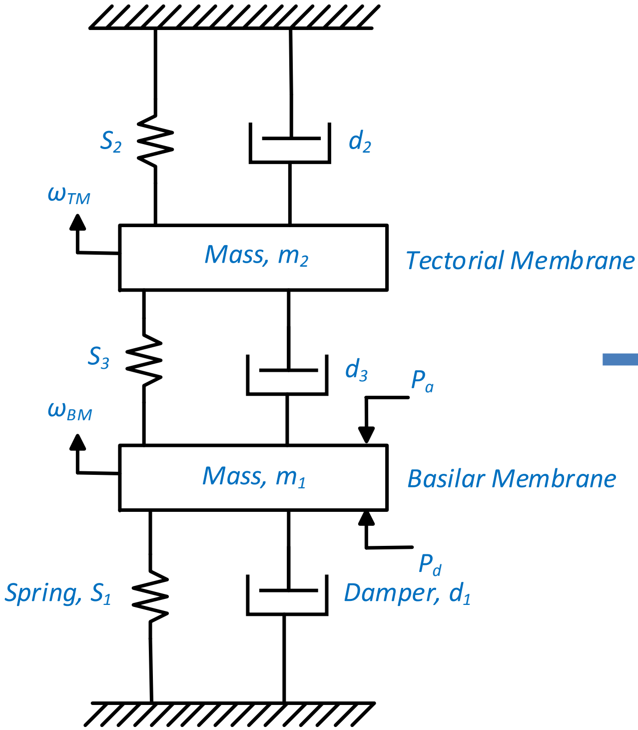


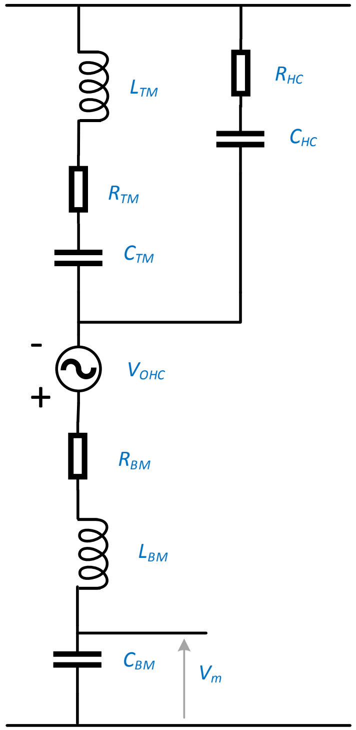



# Active Cochlear Modelling

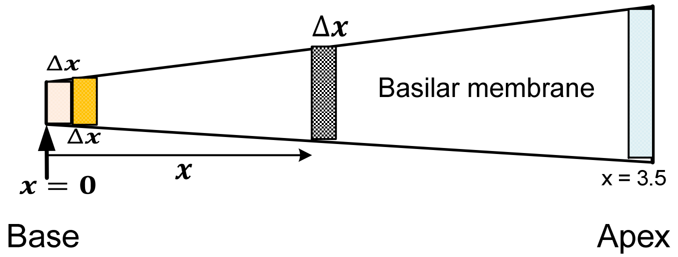


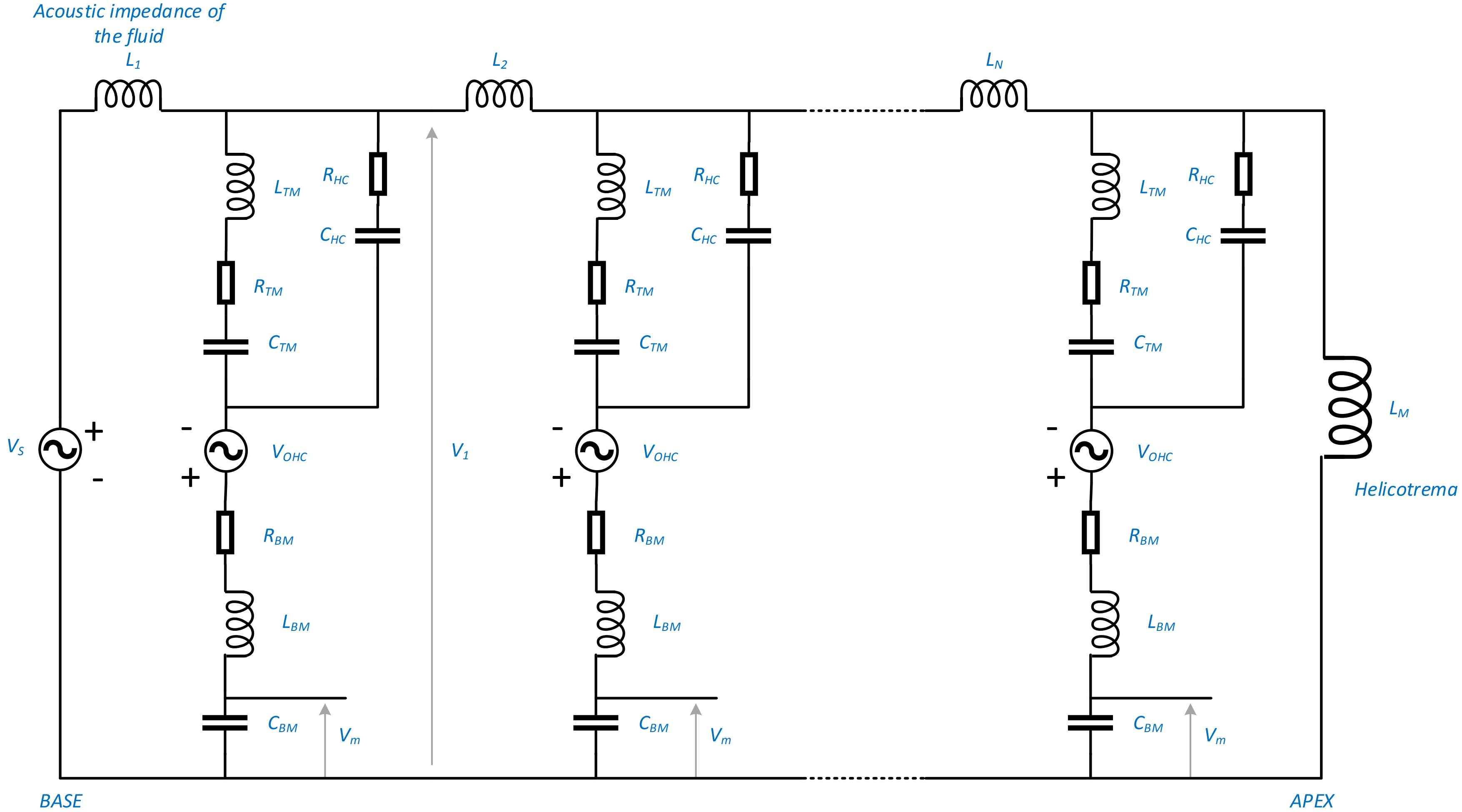



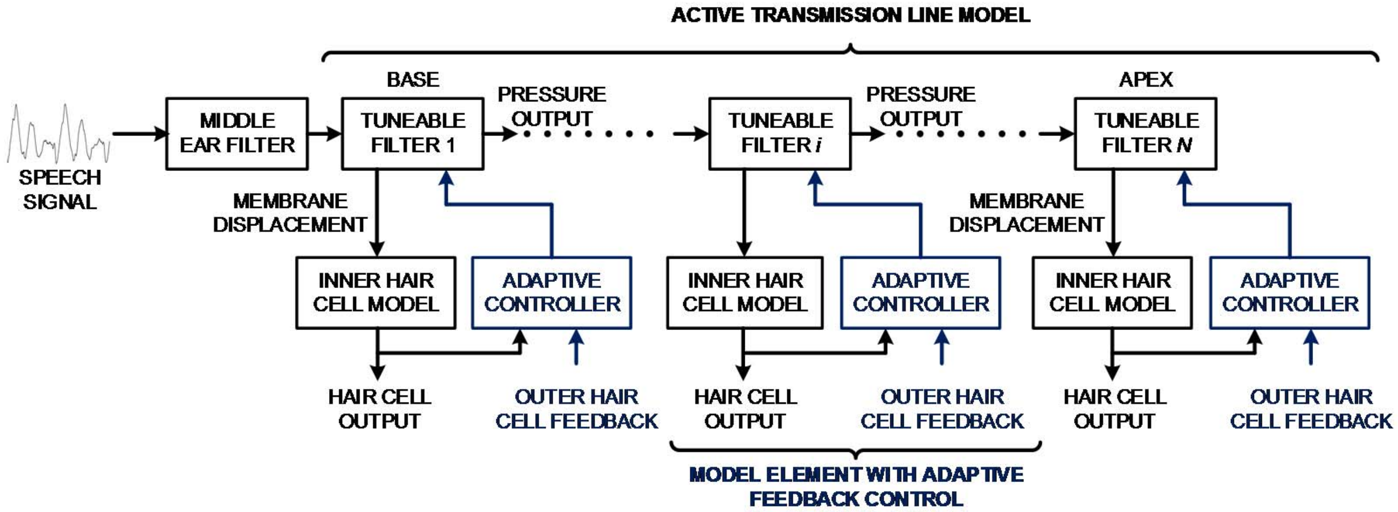



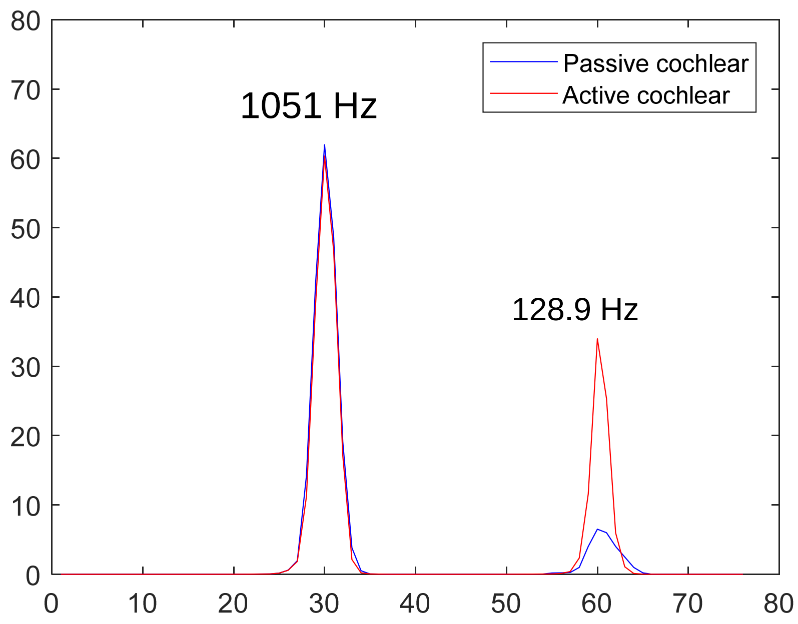
# Active Cochlear Modelling



# Active Transmission Line Model



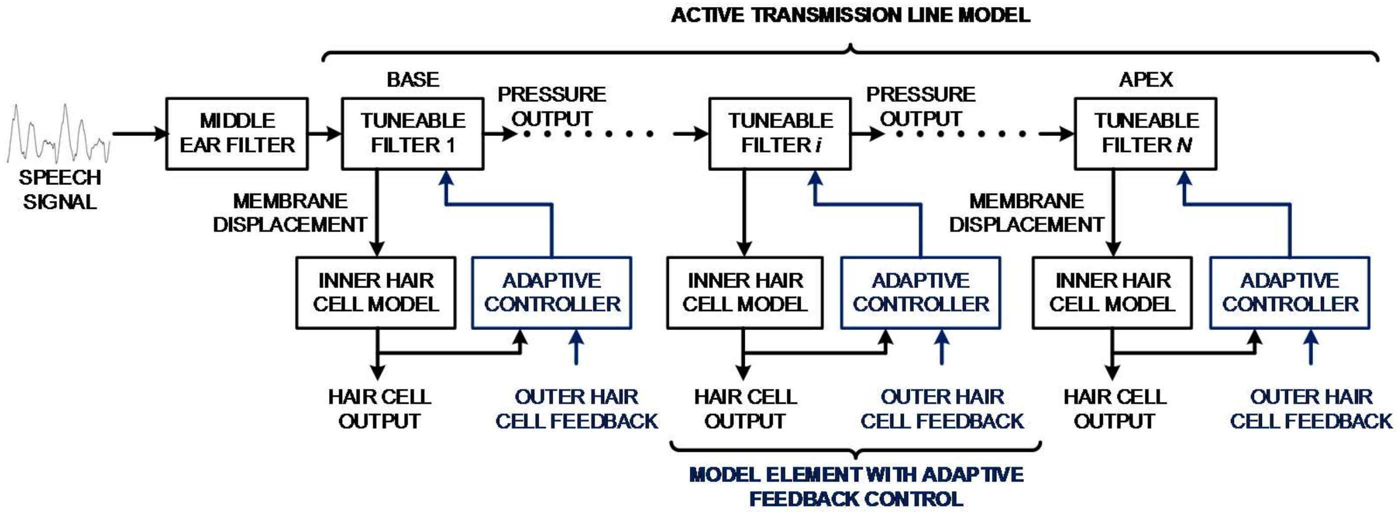



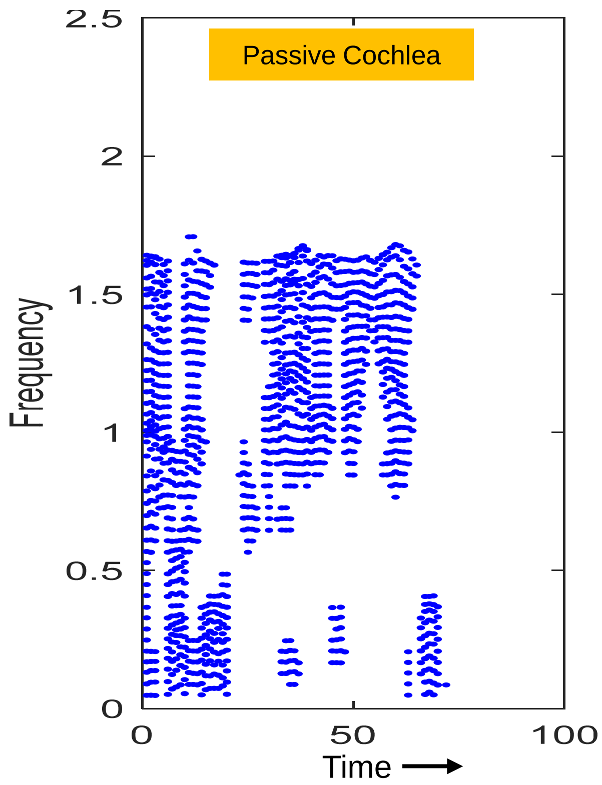

Ideally, models of the cochlea should exhibit

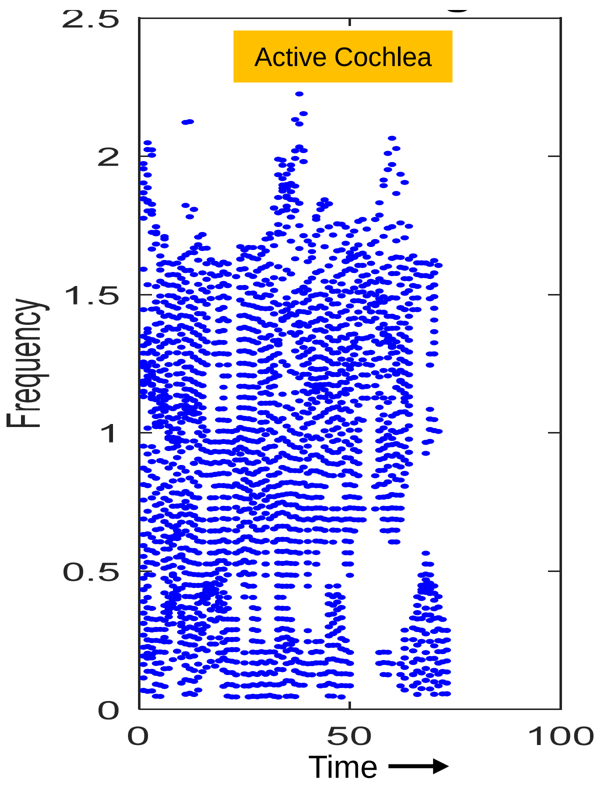
- level-dependence
- sharp auditory tuning curves
- fast adaptation

to changes in the input stimuli

# Active Transmission Line Model



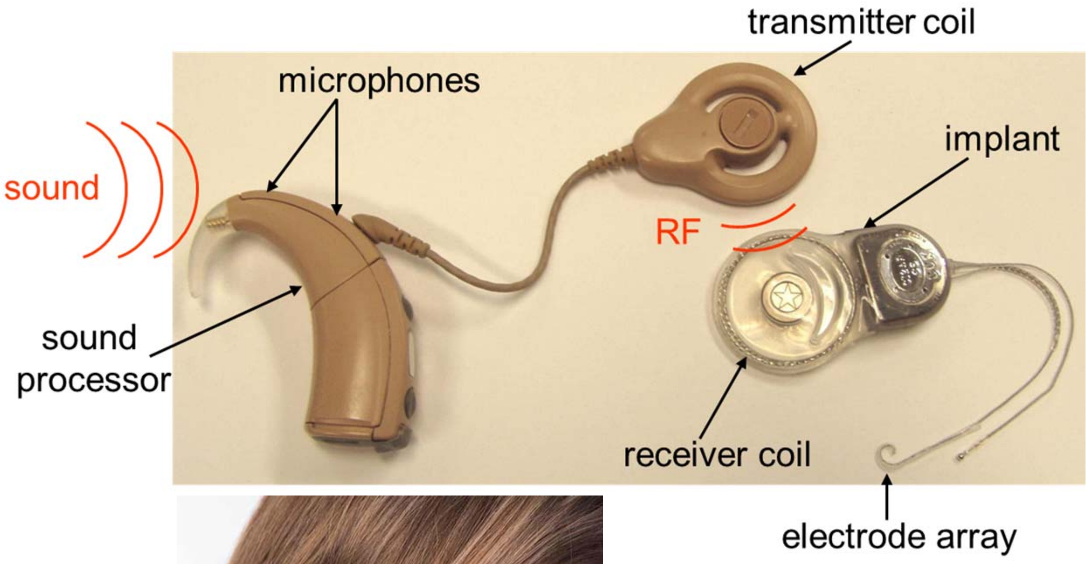



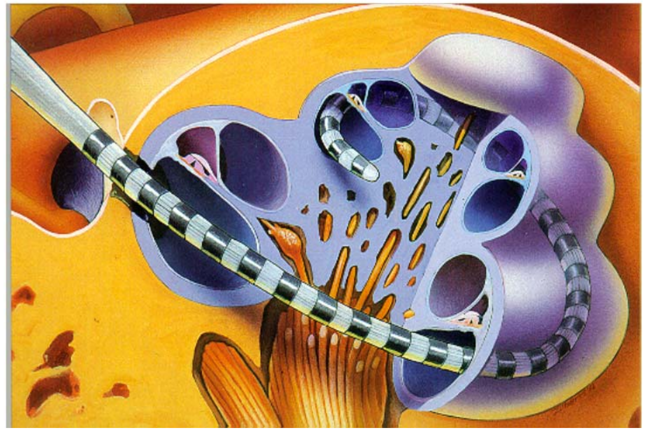



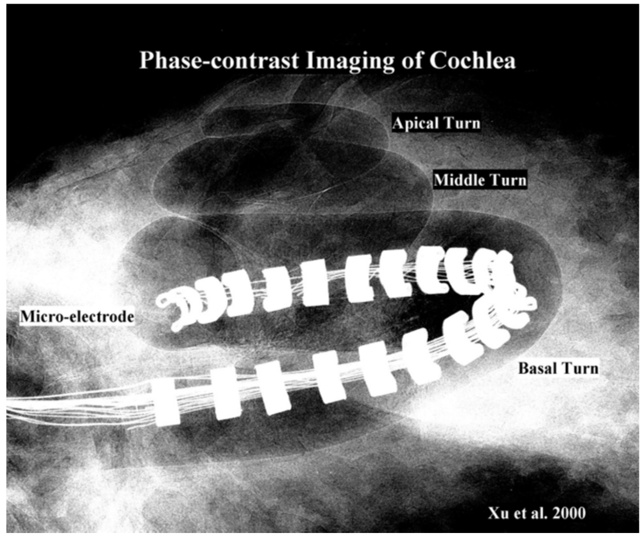
# Cochlear implants

# Cochlear Implant System

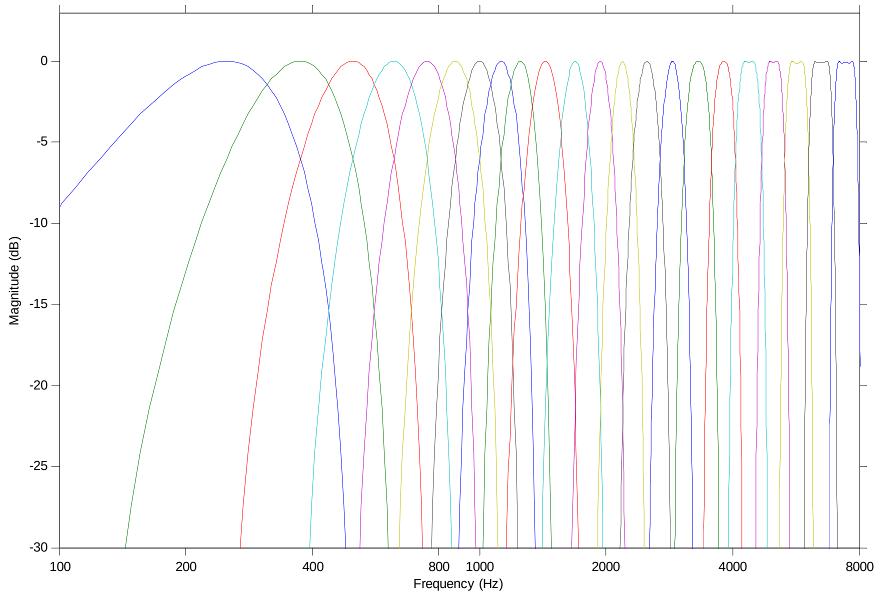
- ✓ Sounds processor is positioned behind the ear and transmits signals via RF to implant
- ✓ Implant consists of receiver coil and electrode array and is surgically inserted inside the inner ear
- ✓ Electrode array excites the auditory nerves



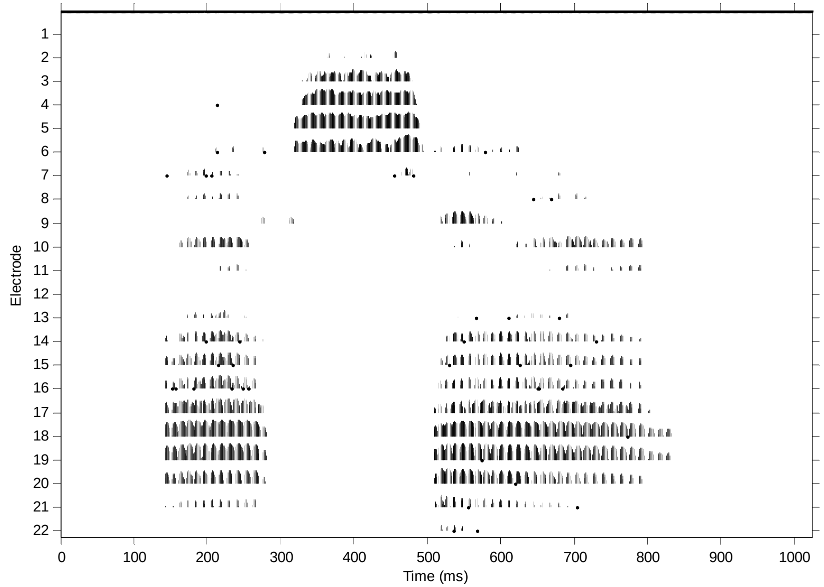





# Signal Path Overview – Sound Processor

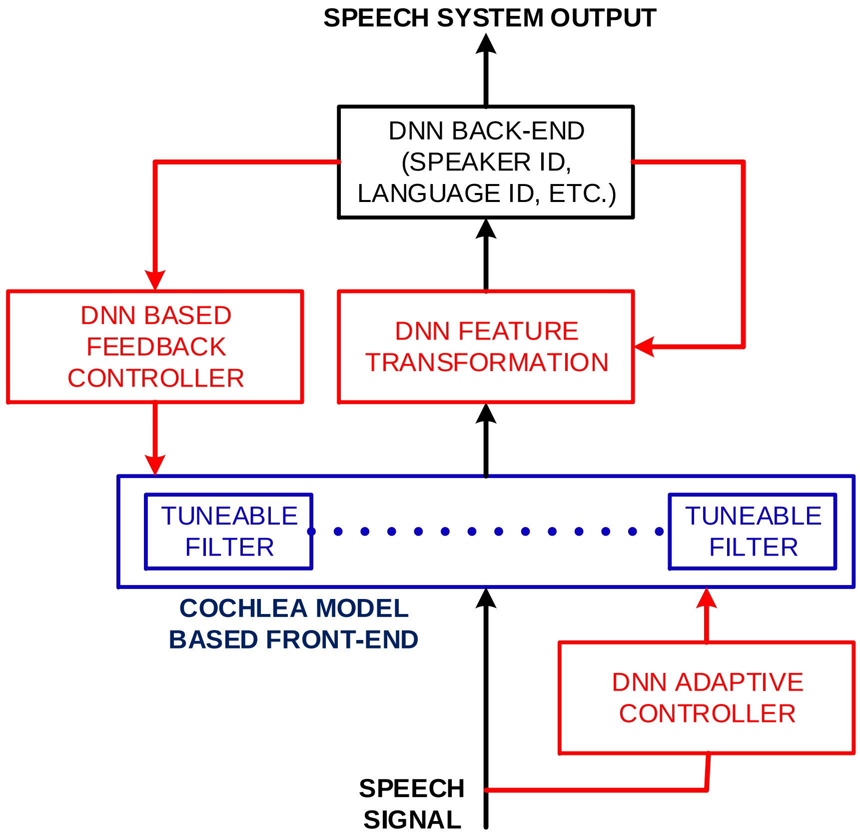

Magnitude Response of Filter-bank




Electrode Signals

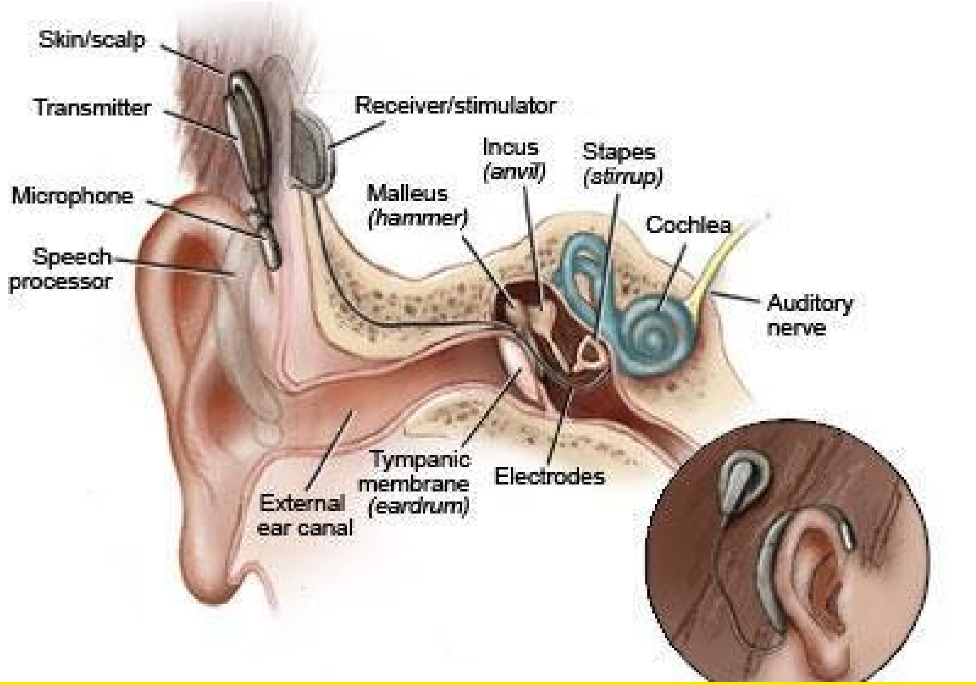
# Future Trends – Integration Auditory Models with DNN

- ✓ A feed-forward adaptive spectral decomposition model based on the cochlea;
- ✓ A back-end dependent feedback path to improve the adaptive spectral decomposition;
- ✓ Extending the end-to-end system to learn a channel-invariant speech signal representation.



# Conclusions

- ✓ Future models of cochlea will include active feedback mechanisms to improve detection of smaller signals
- ✓ Filters in the cochlear models and adaptive feedback paths both may be implemented as deep learning models thus enabling integration with state-of-the-art speech processing systems
- ✓ This could lead to benefits for cochlear implants in terms of being able to adapt to the environment as well as learning and adapting to the individual



# Prof. Eliathamby Ambikairajah

- ✓ 1974 - Graduated from University of Sri Lanka (Katubedde Campus) – BEng(Sc) Electronics and Telecommunications
- ✓ 1975 - Ceylon Institute of Scientific and Industrial Research – Scientific Officer
- ✓ 1978 - First person from Sri Lanka awarded scholarship to work at Phillips International Institute and co-inventor of automatic tuning radio
- ✓ 1982 - Graduated with Doctor of Philosophy (PhD) in electronic engineering from Keele University, UK
- ✓ 1983 - Postdoctoral fellow at Queens University Belfast, Northern Ireland
- ✓ 1984 to 1999 - Head of Department, Dean of Engineering at Athlone Institute of Technology, Ireland
- ✓ 1989 to 1999 - Invited Visiting Research Fellow at British Telecom Laboratories, Ipswich, UK
- ✓ 2000 to 2008 - Deputy Head of School of Electrical Engineering and Telecommunications at UNSW, Sydney
- ✓ 2009 to 2019 - Longest serving Head of School of Electrical Engineering and Telecommunications at UNSW, Sydney (10 years)

Awards

- ✓ IEE Younger Member Award (1982)
- ✓ Vice-Chancellor's Teaching Award (2003)
- ✓ School of EE&T Academic Management and Teaching Award (2000)
- ✓ UNSW Leadership Excellence Award (2014)
- ✓ Fellow of Engineers Australia (2002)
- ✓ Fellow of IET (1996)

These successes are the outcome of the foundational education that was received in Sri Lanka