Cochlea Modelling: Future Directions

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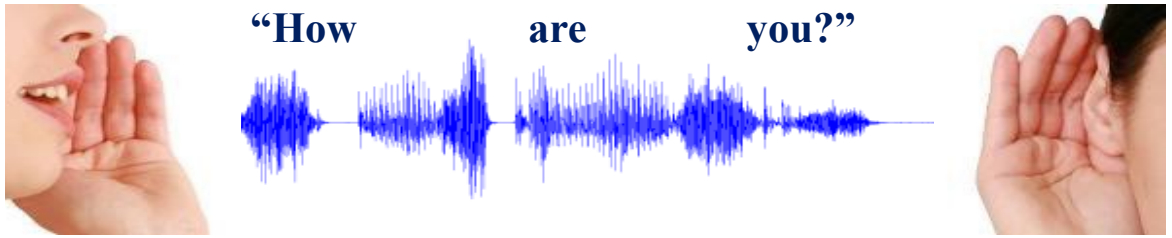
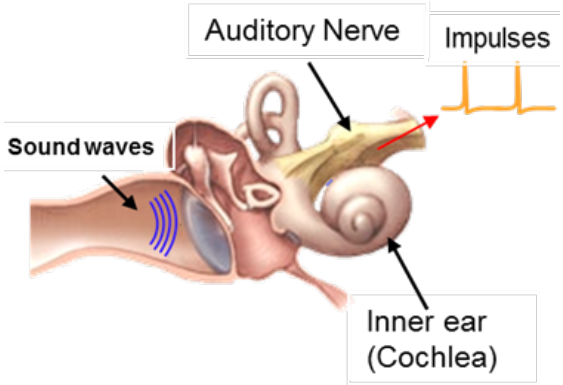
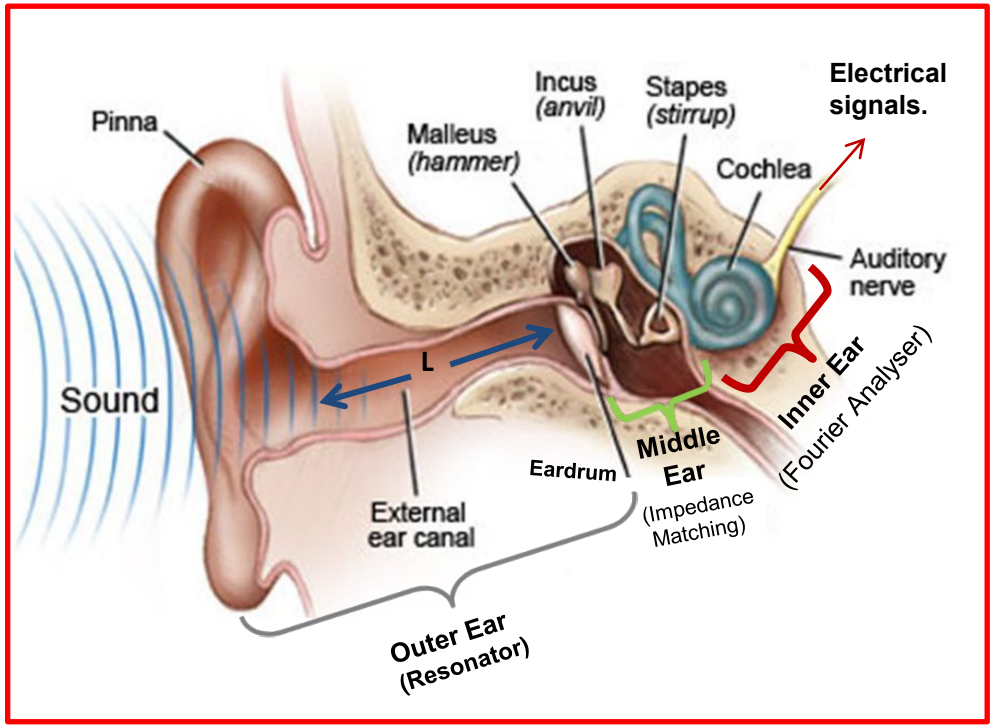




Human Auditory System

Introduction to the Human Auditory System

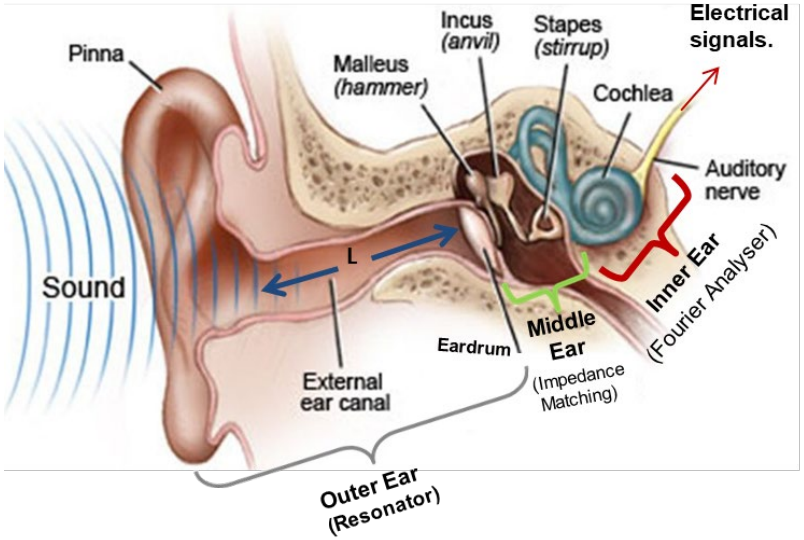
- ✓ The human auditory system is responsible for converting pressure variations caused by the sound waves that reach the ear into nerve impulses that are interpreted by the brain.
- ✓ The peripheral auditory system is divided into the Outer Ear, Middle Ear, and Inner Ear.
- ✓ The peripheral auditory 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

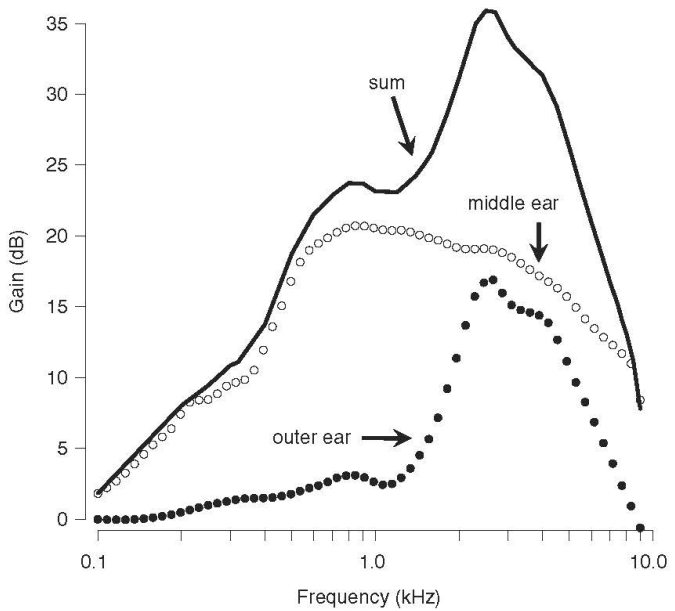


Peripheral Auditory System

Outer and Middle Ear

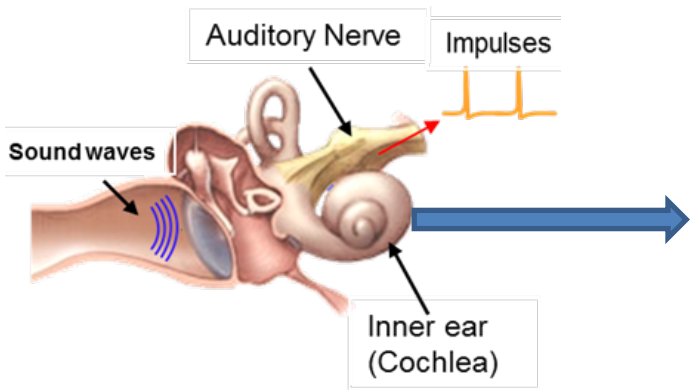
- ✓ The sound waves enter a tube-like structure called ear canal and it serves as a sound amplifier.
- ✓ The human outer ear is most sensitive at about 3kHz and provides about 20dB (decibels) of gain to the eardrum at around 3000Hz.
- ✓ Middle ear transforms the vibrating motion of the eardrum into motion 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]

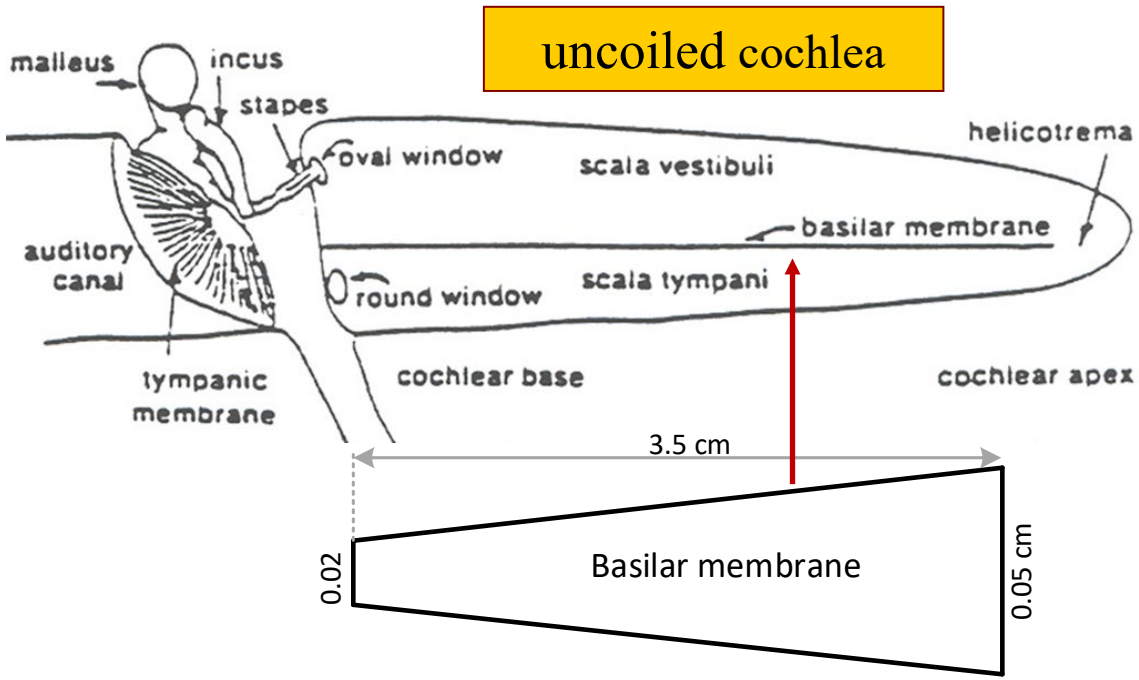




Inner Ear

- ✓ 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.



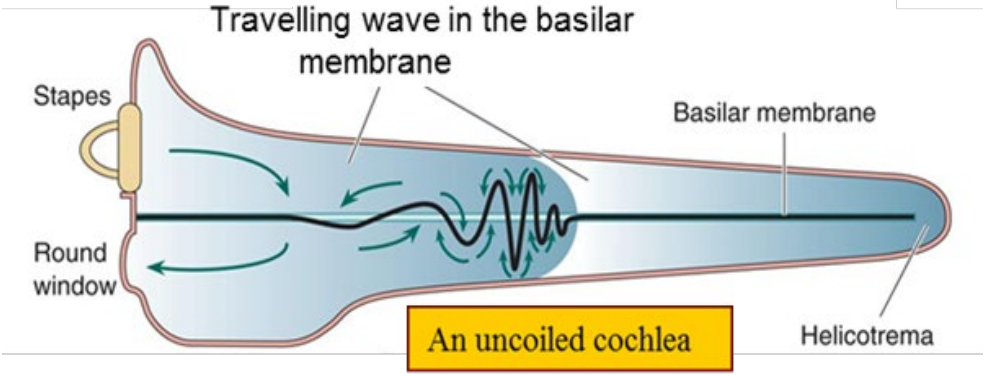


Basilar Membrane (Hydro Dynamical process)

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

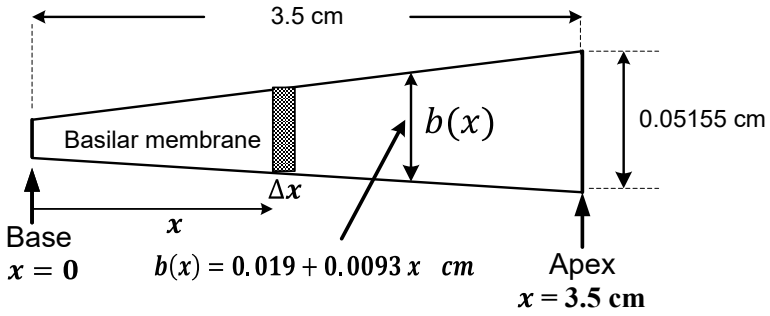
$$f_p(x) = (20000.0)\ 10^{-0.667\,x}\ Hz$$

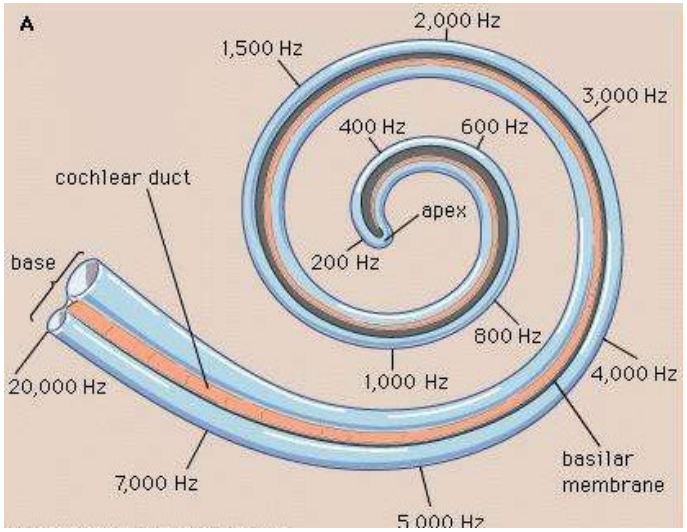
- ✓ When the vibrations of the eardrum are transmitted by the middle ear into movement of the stapes, the resulting pressure differences between the cochlear fluid chambers, generate a travelling wave that propagates down the cochlea.
- ✓ The wave reaches maximum amplitude of displacement on the basilar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



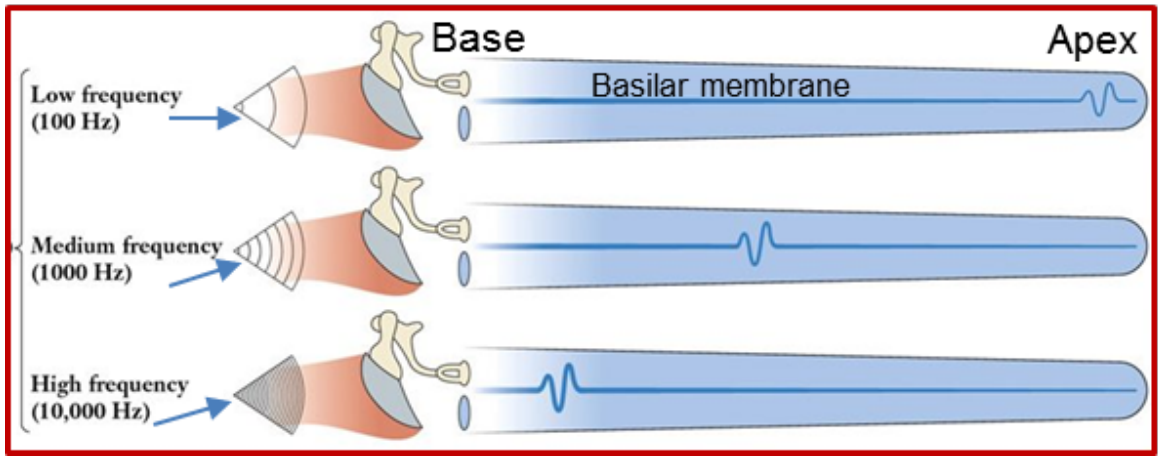
An uncoiled cochlea

Unrolled basilar membrane

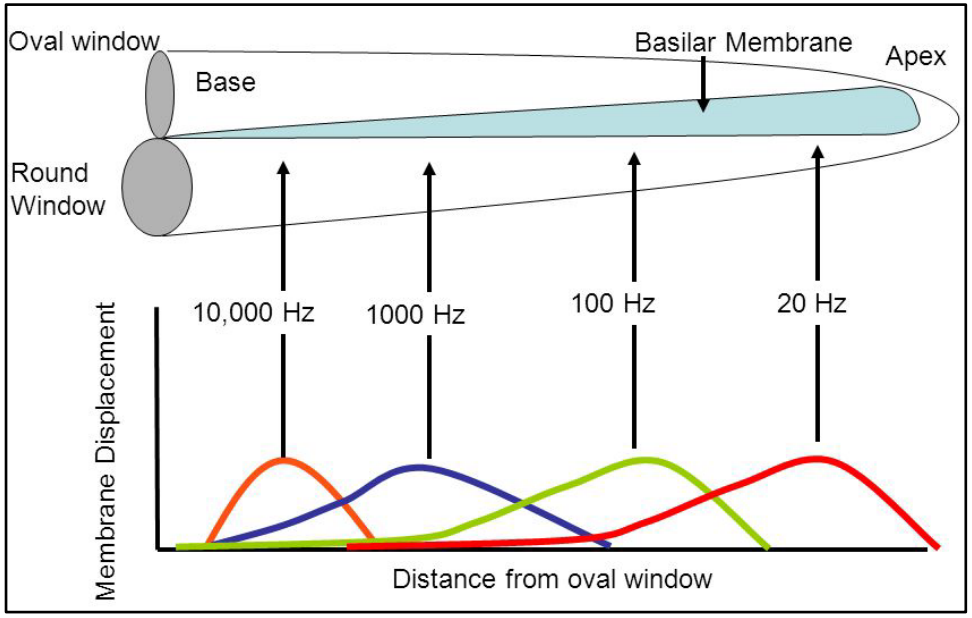




Basilar Membrane as a Filterbank

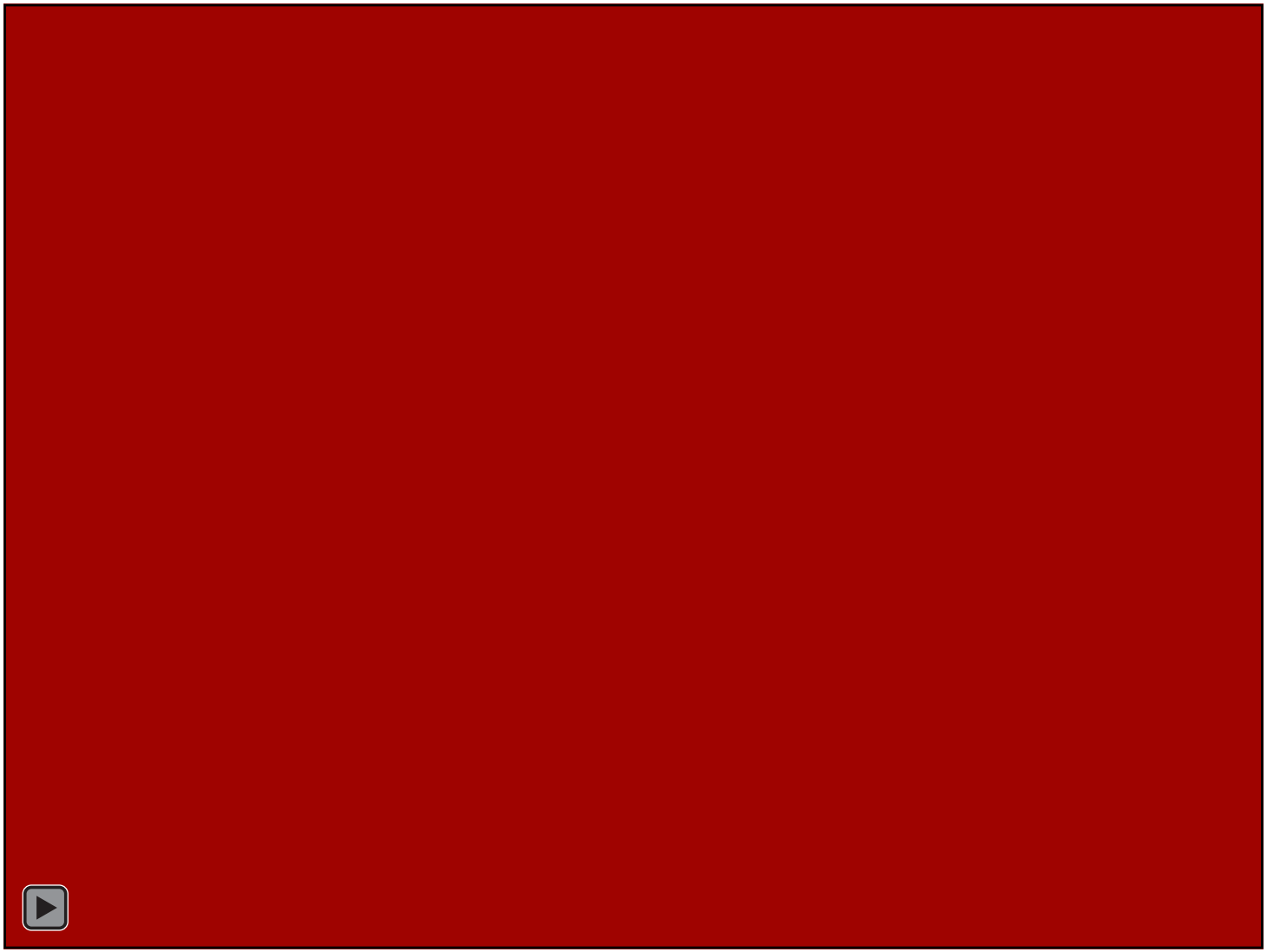


- ✓ Different frequencies stimulate different areas of the basilar membrane.
- ✓ There will be one place where the resonant frequency of the membrane matches the stimulus frequency and this place will show the maximum amount of vibration



- ✓ 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

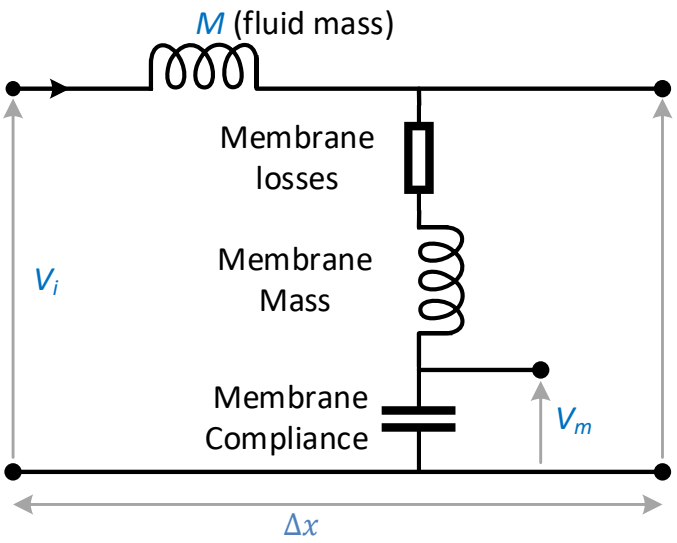
Cochlear Animation

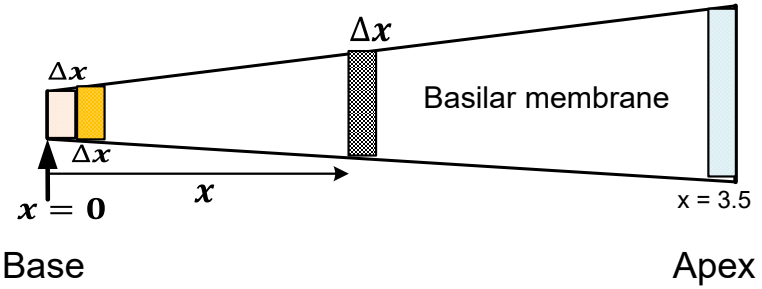


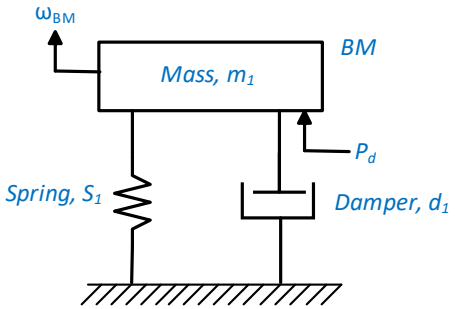
Models of the Cochlea

Cochlear Modelling

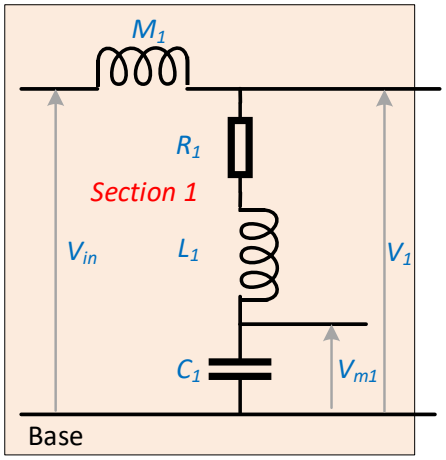
✓ A simple electrical model of a section (Δx) of the Basilar Membrane







✓ A Transmission Line Model of the Basilar Membrane



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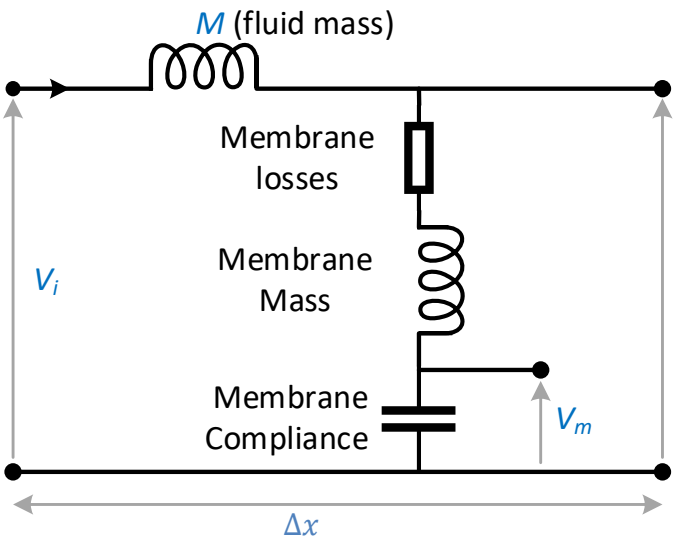

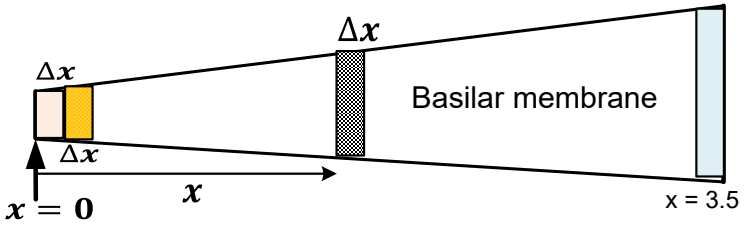

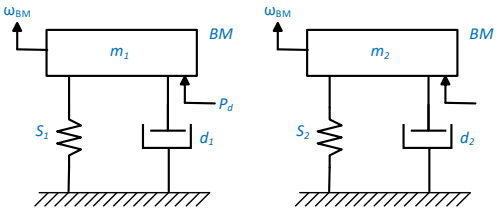

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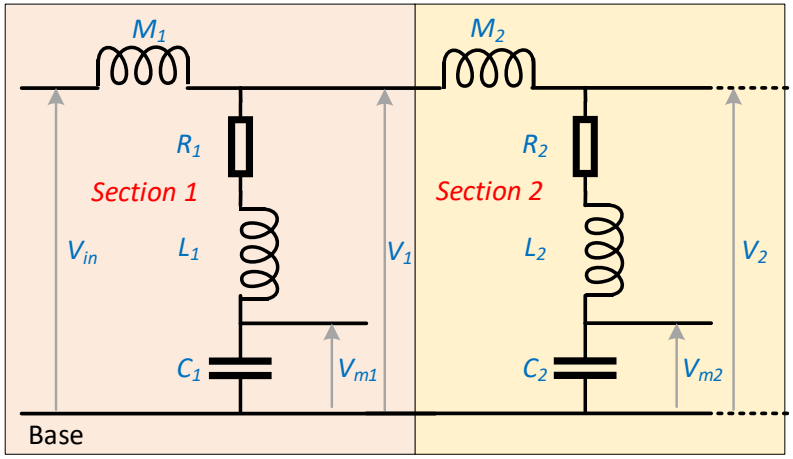

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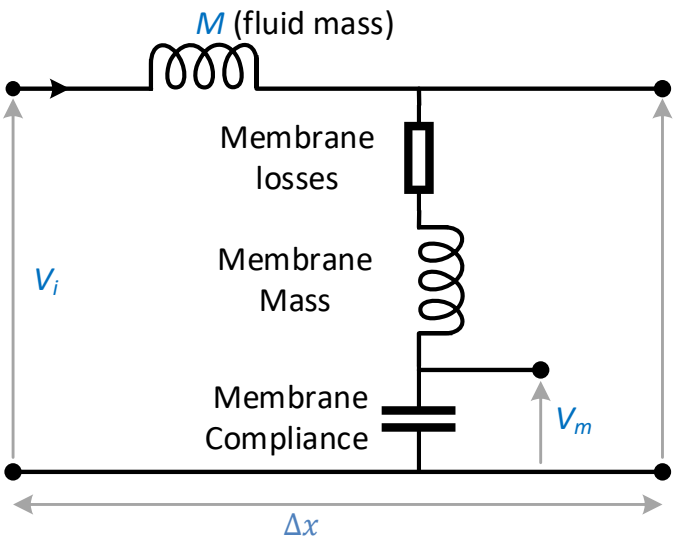

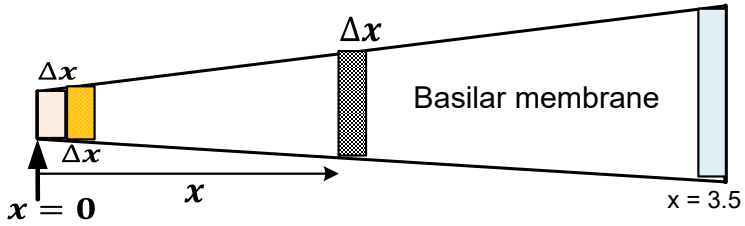

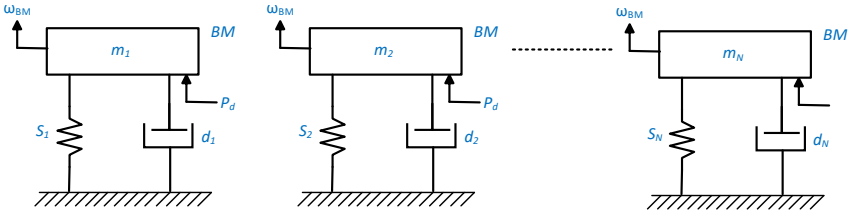

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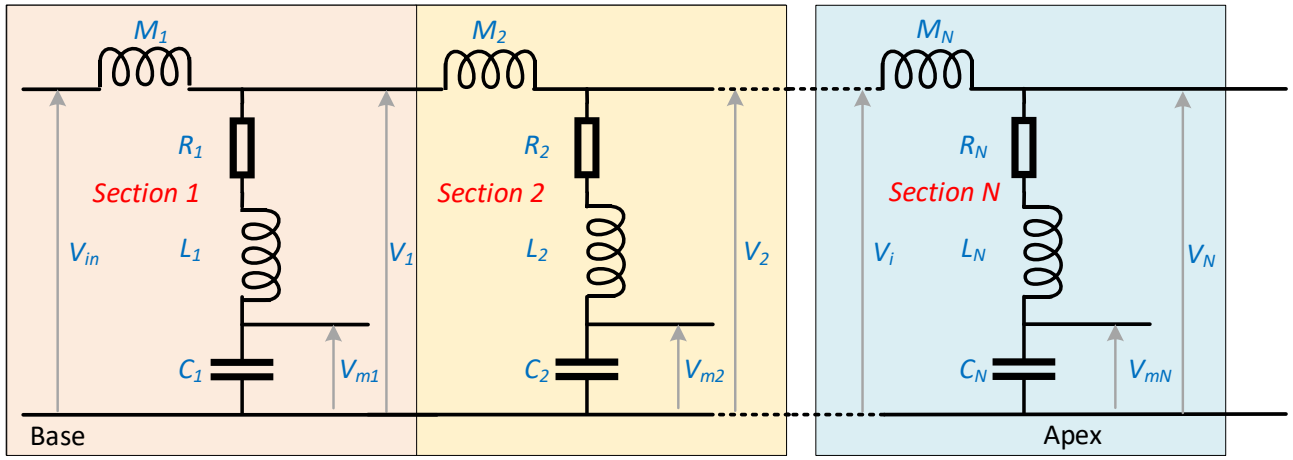

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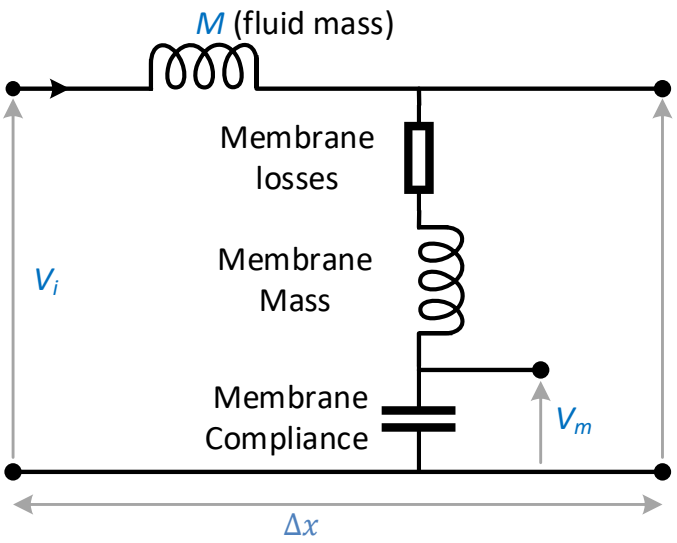

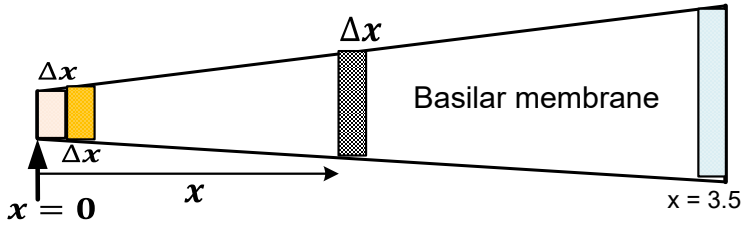

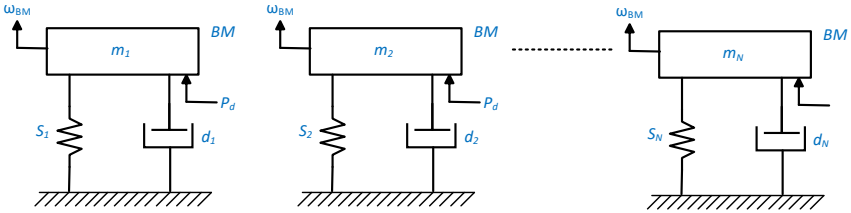

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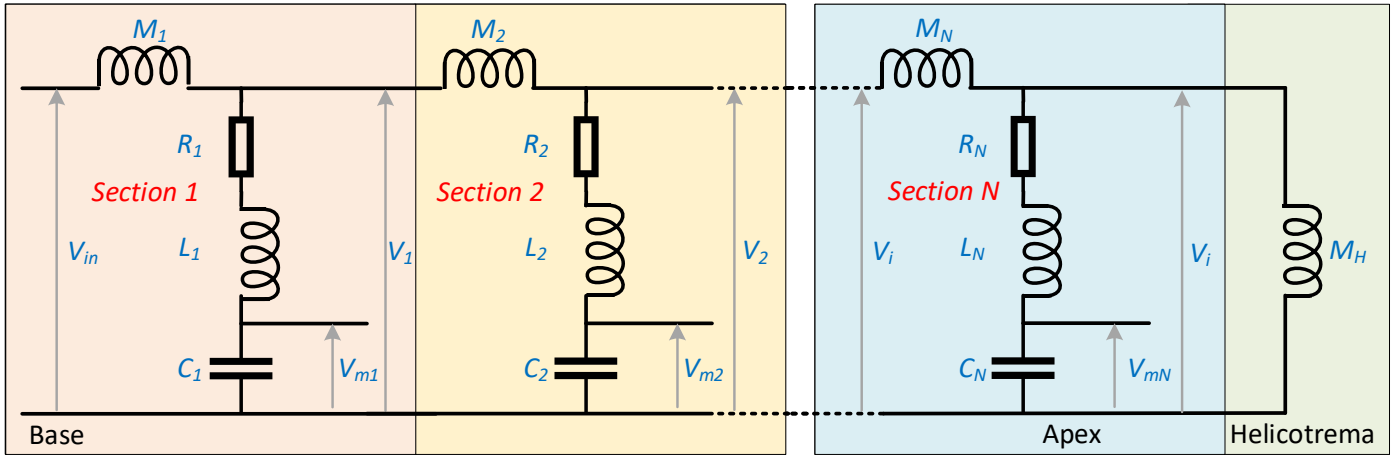


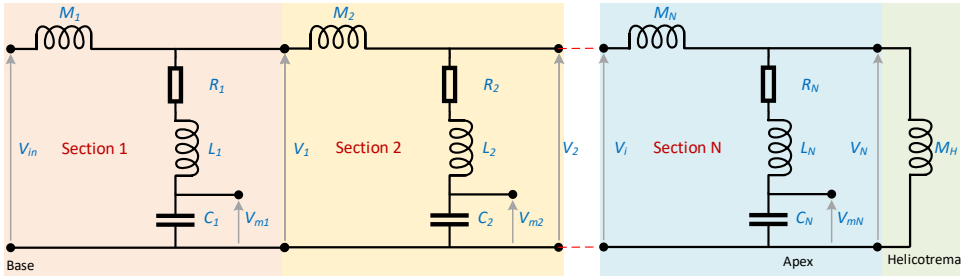
Transmission Line Model of the Cochlea – Cascade Model

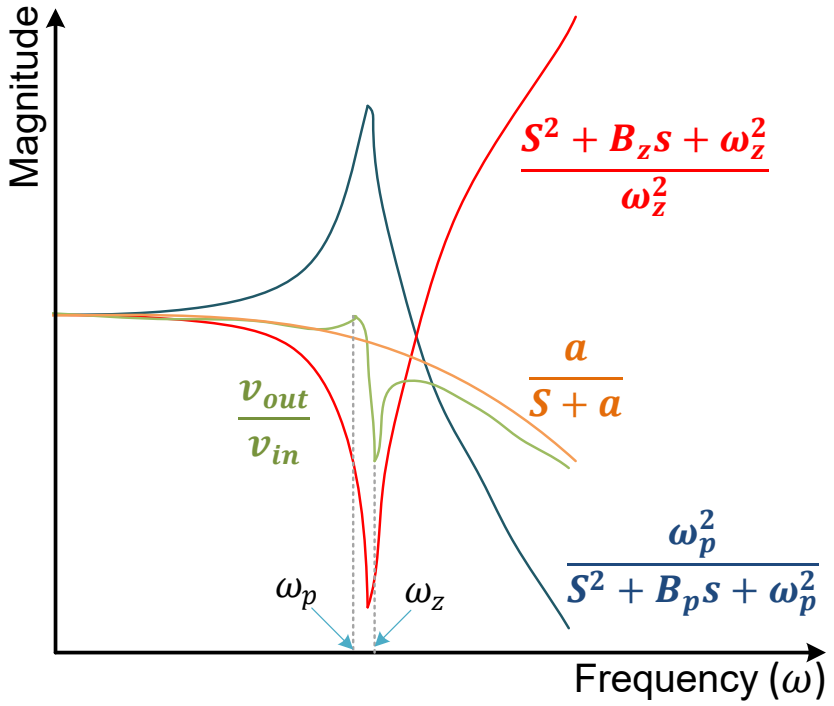
- ✓ The basic model of the cochlea is a transmission line model in which each section of the basilar membrane is modelled as a cascade of low pass, notch filters and resonators.

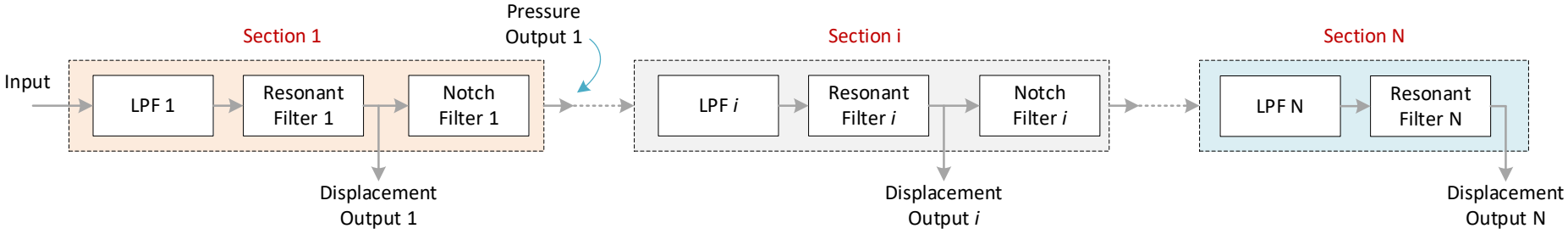
Pressure Transfer Function

$$\frac{v_{out}(s)}{v_{in}(s)} = K \frac{a}{S+a} \frac{\omega_p^2}{S^2+B_p s+\omega_p^2} \frac{S^2+B_z s+\omega_z^2}{\omega_z^2}$$

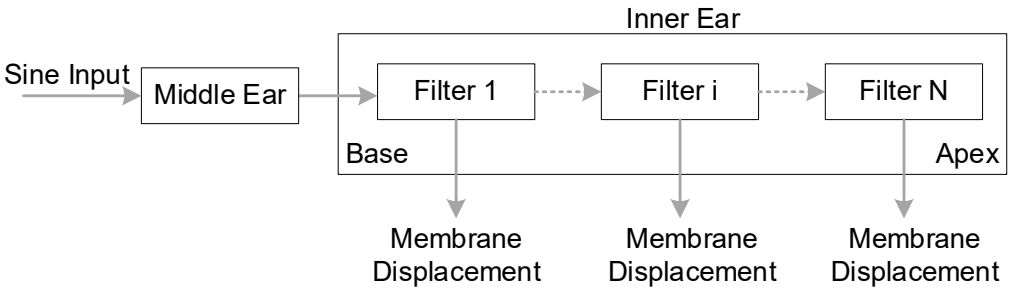
Low pass filter | **Resonant pole** | **Resonant zero**

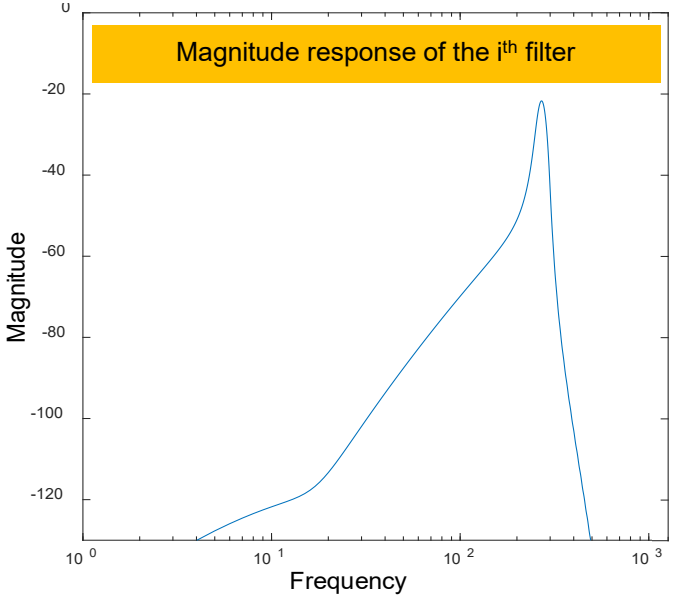


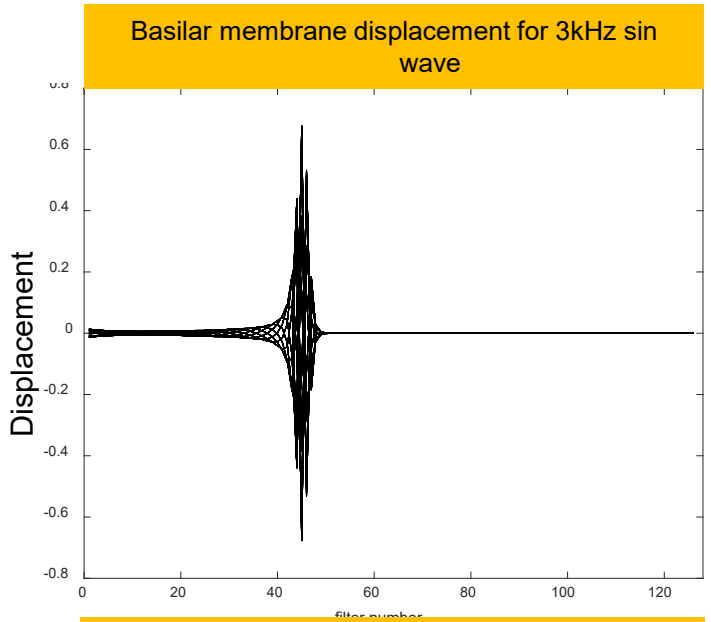


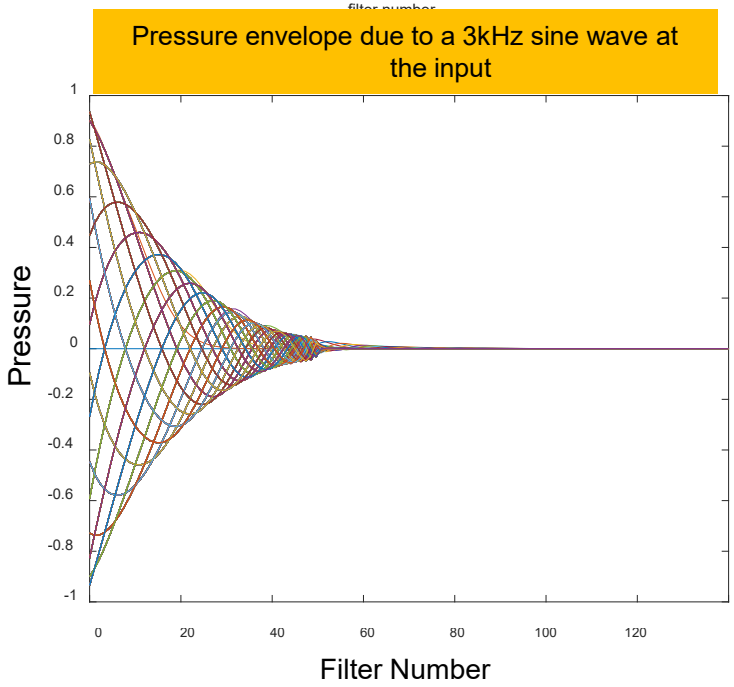


Membrane displacement and Pressure envelope for a sinusoidal input



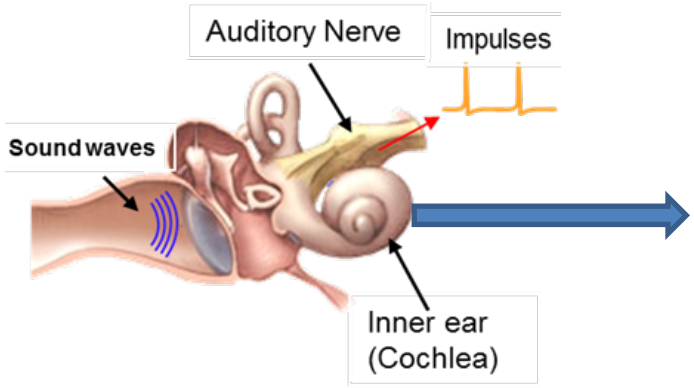


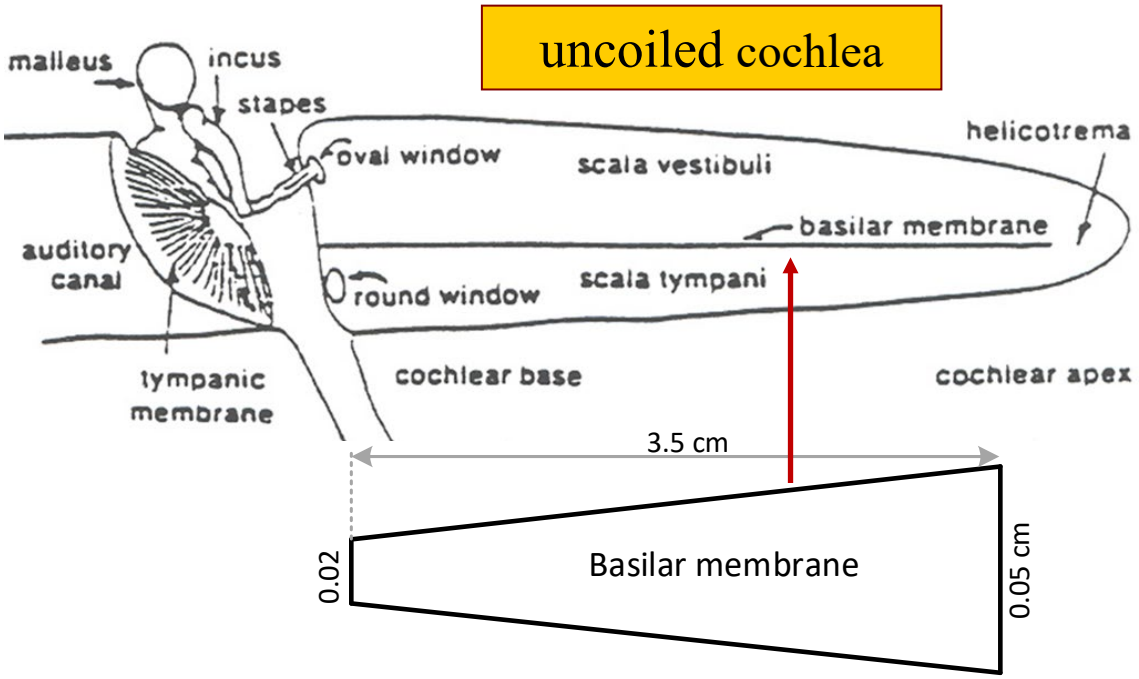


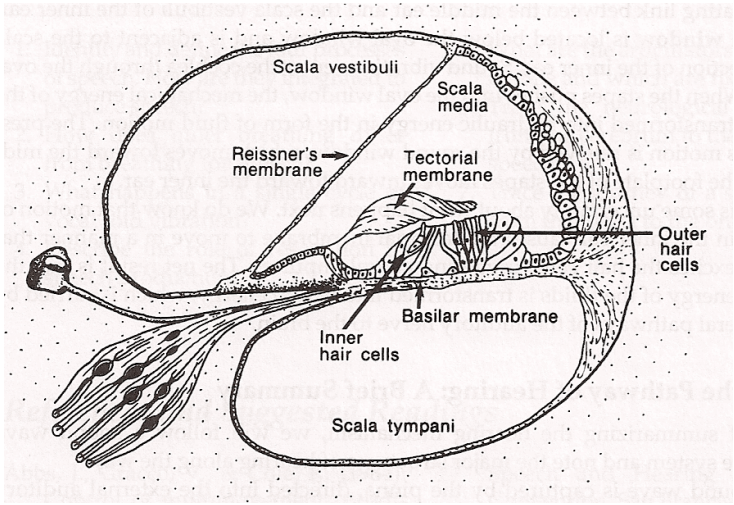


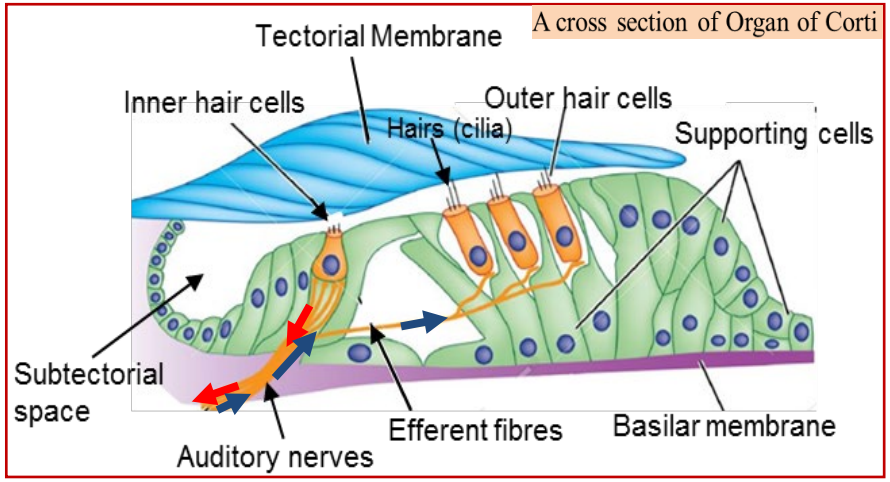
✓ Observing the envelope, the pressure is high at the basal end and decays down to zero at the resonant position.

Organ of Corti



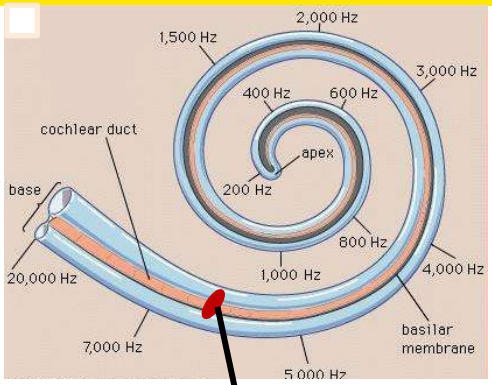




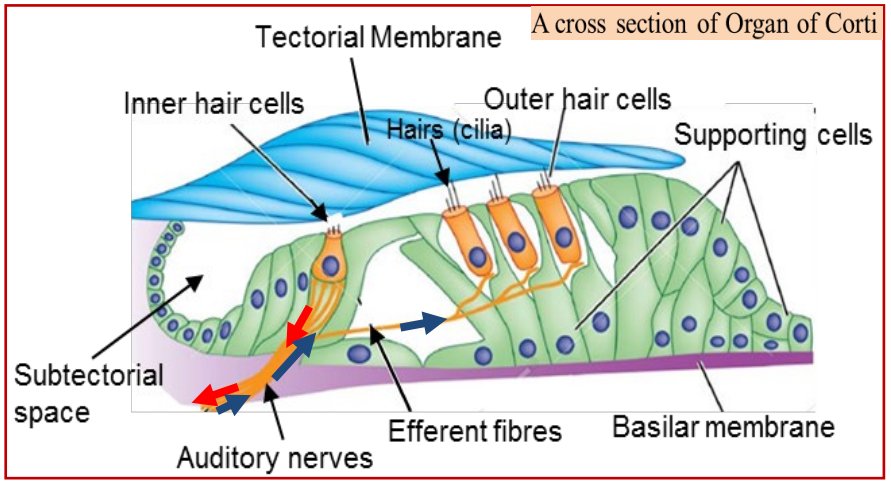


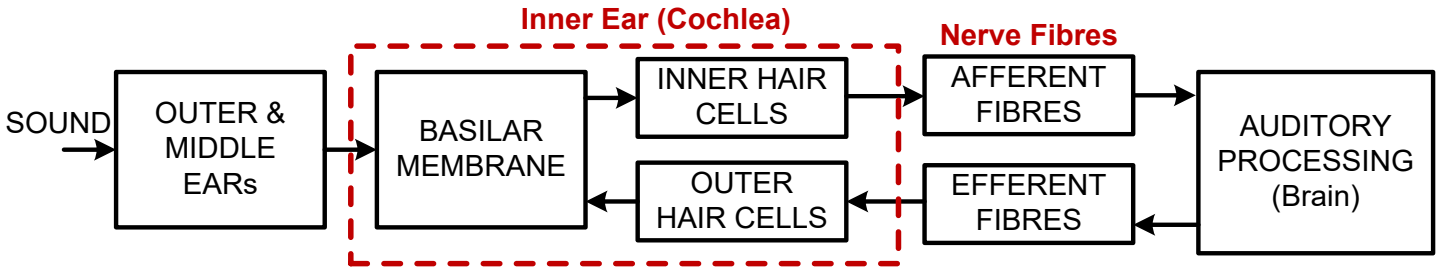
Organ of Corti

- ✓ 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

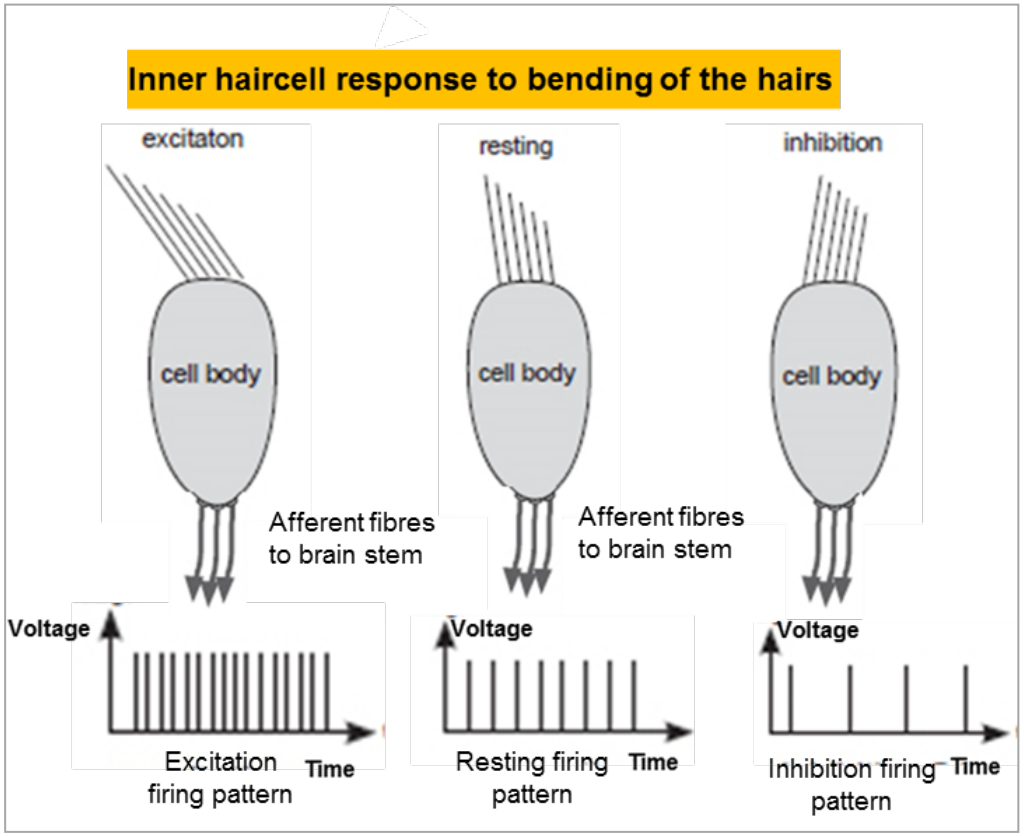


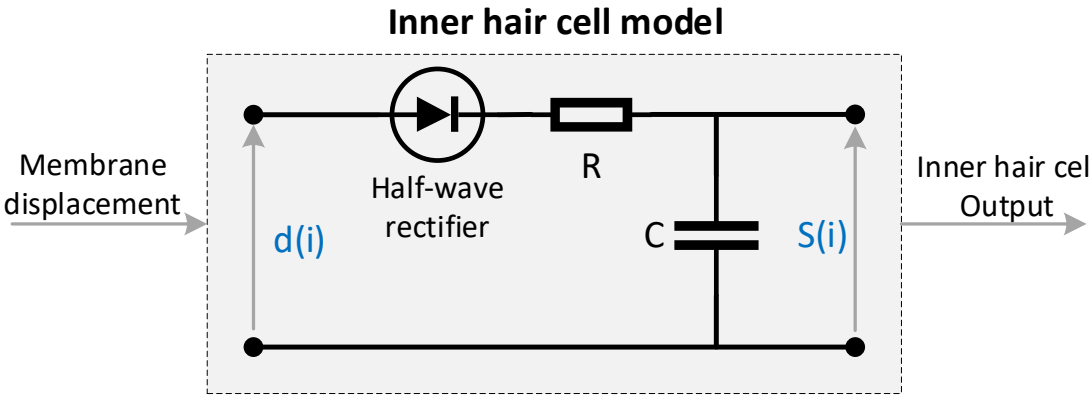


A simplified Diagram of a Human Auditory System

Mechanical to Neural Transduction (Electro-Chemical)

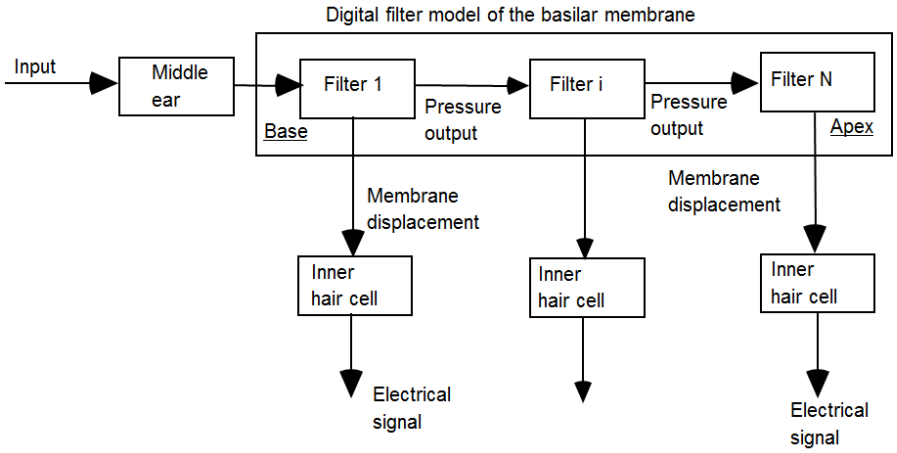
- ✓ The mechanical displacement to electrical energy transduction process takes place in the inner hair cells
- ✓ The modulation being directly proportional to the degree of bending of the cilia and the bending of the cilia is one direction only; in effect a half wave rectification of the basilar membrane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



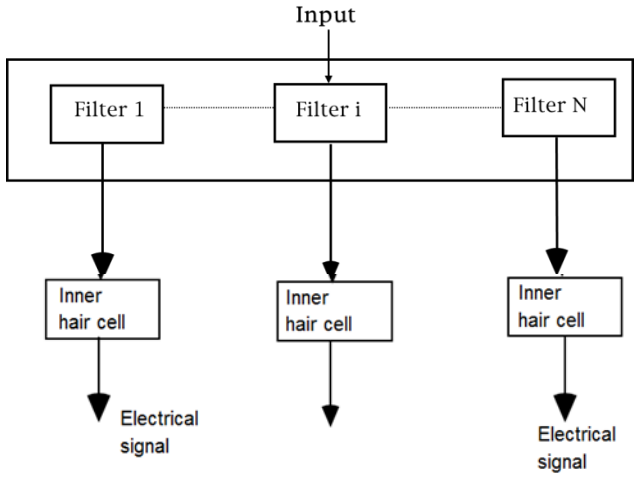


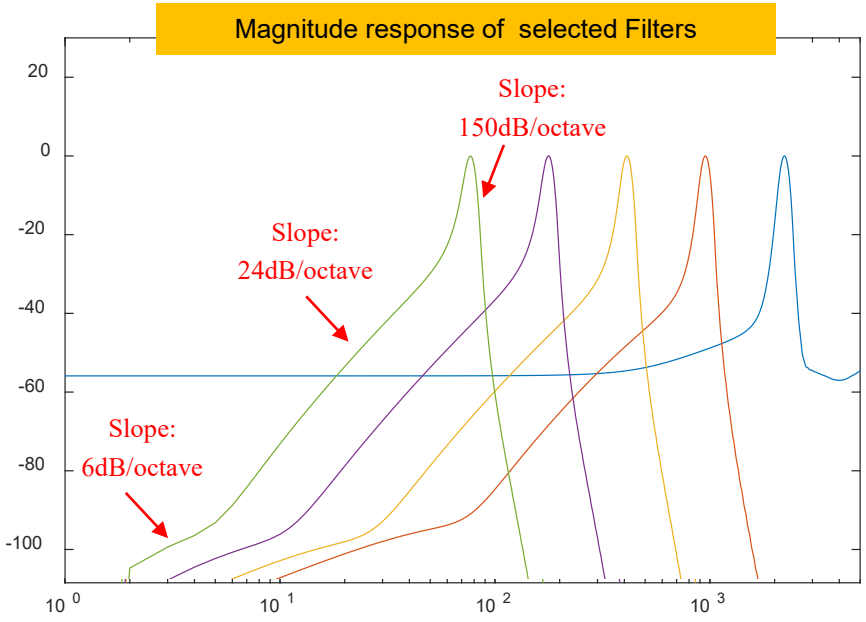
Cochlear Models

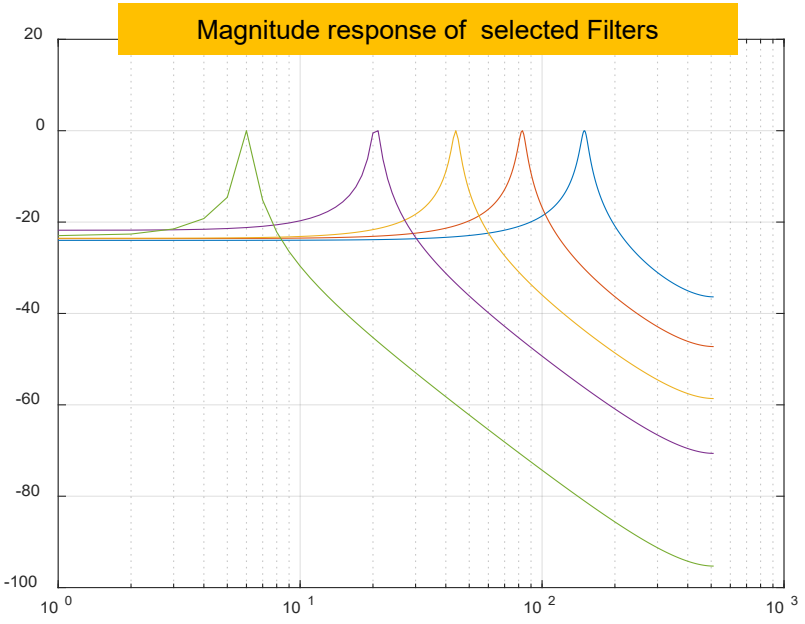
Transmission Line Model



Parallel Filter Bank Model

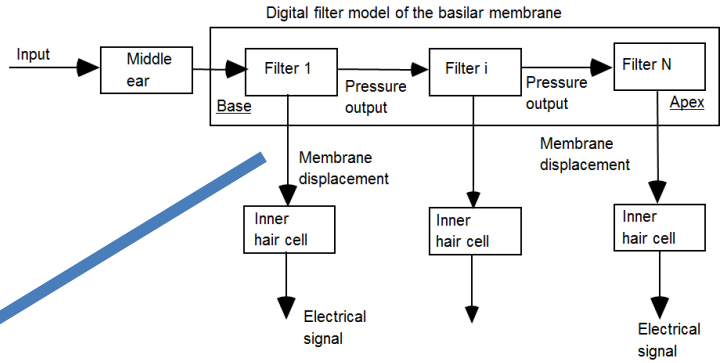


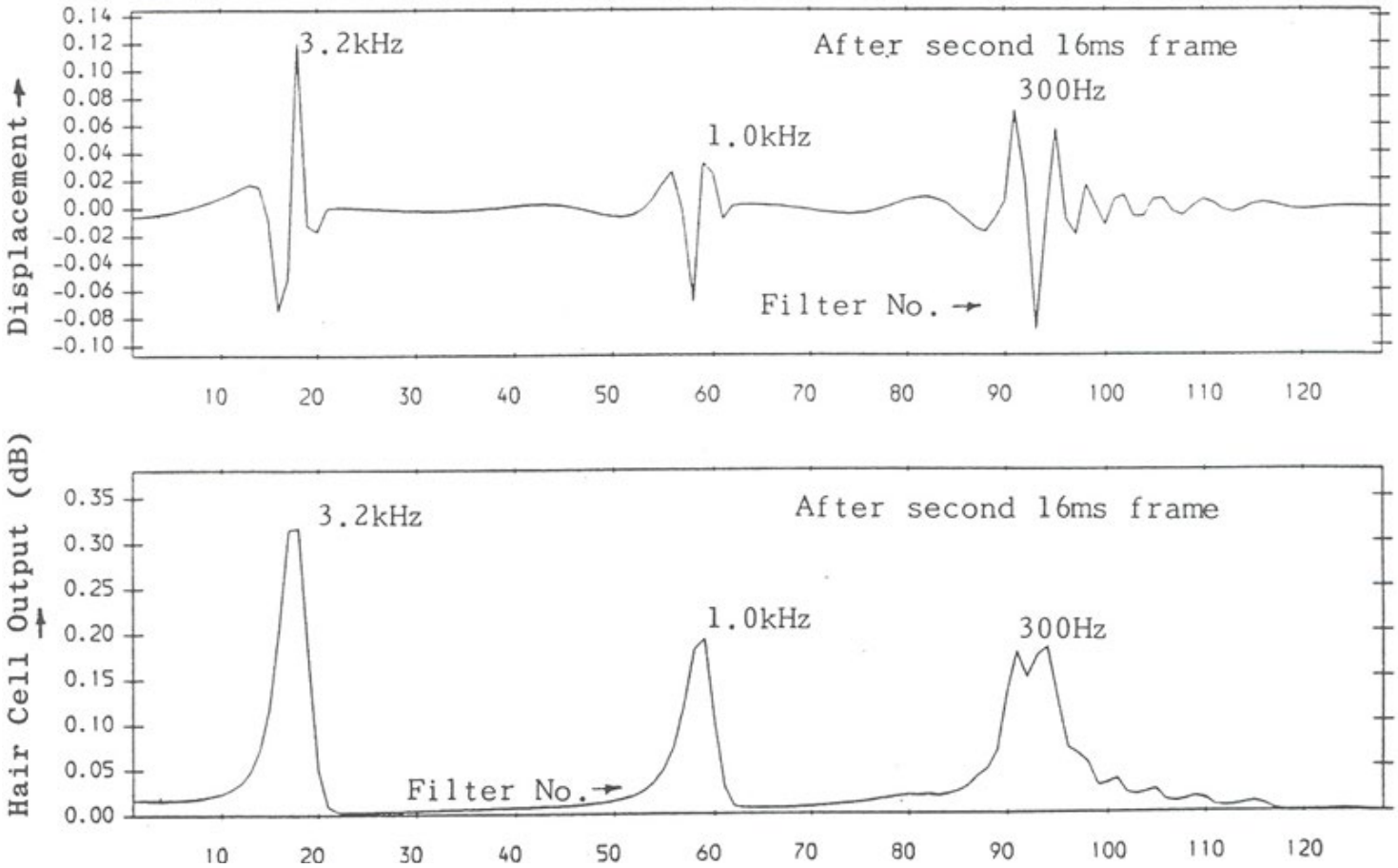




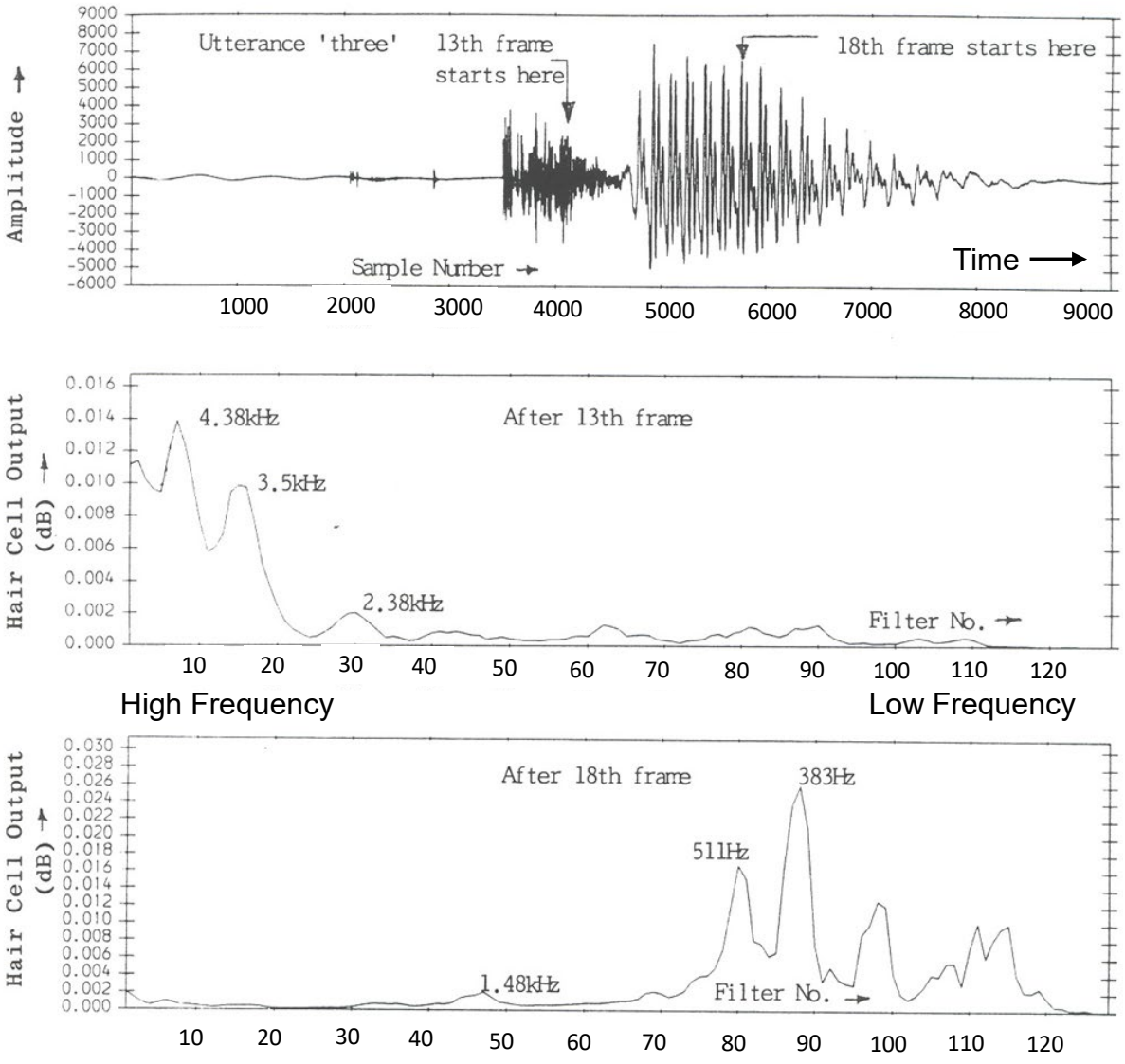
Sinusoidal components at the input

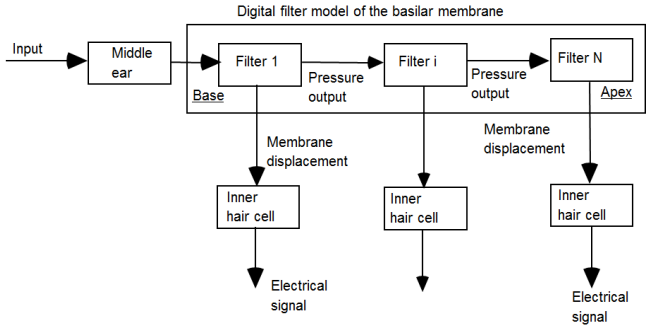
- ✓ The basilar membrane displacement and the corresponding inner hair cell output in response to a sum of three sinusoidal components applied at the input (3.2kHz, 1kHz and 300 Hz).
- ✓ The inner hair cell model output shows the spectral components in the input signal.

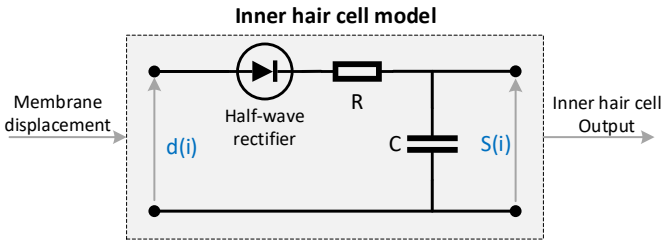




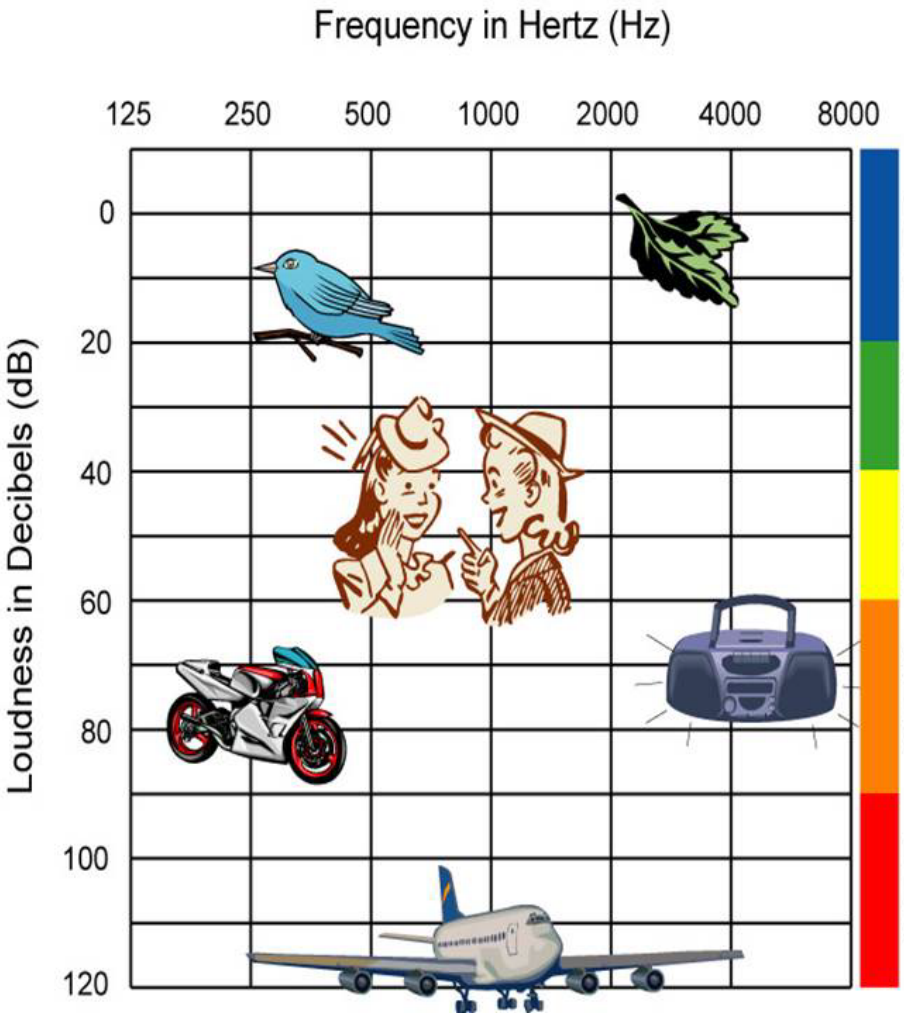
Inner hair cell output for the speech utterance "three"







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) 110dB (Concerts, car horns)
Uncomfortable	120dB (jet planes during take off)
Painful and dangerous	130dB(Jackhammers) 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

Prof. E. Ambikairajah (UNSW), Prof. J. Epps (UNSW), Dr V. Sethu (UNSW)
and
Prof. Li Haizhou (NUS)

Research Project funded by

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Australian Research Council

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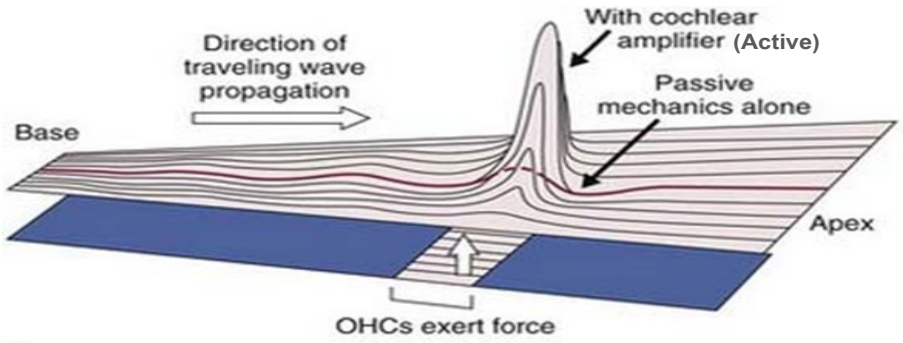
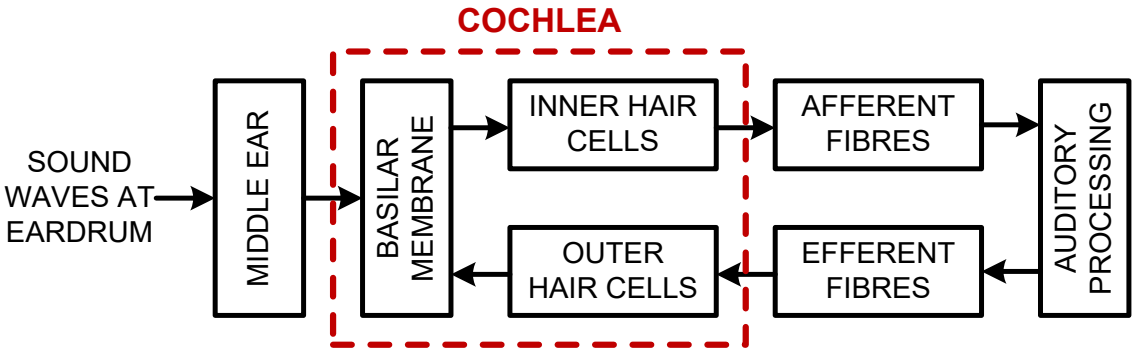
Cochlear Response with Active Gain

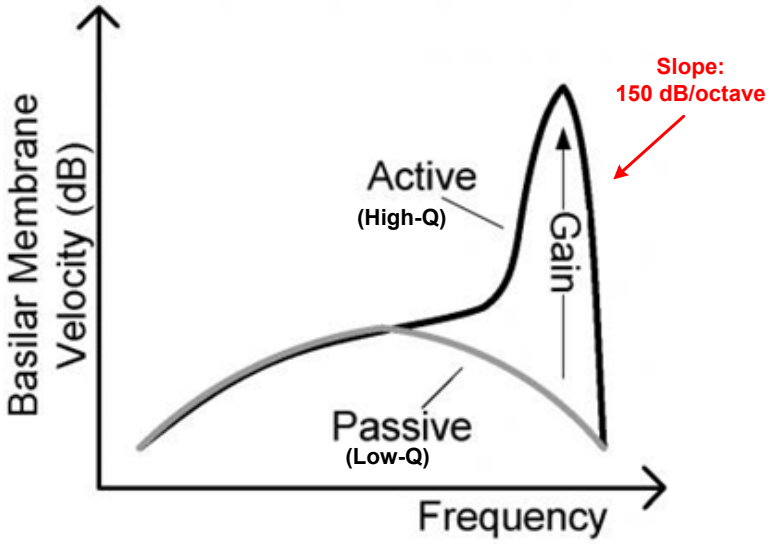
- ✓ Human auditory system can process a vast range of sounds spanning some twelve orders of magnitude of input pressure intensity
- ✓ In order to achieve this, the cochlea makes use of both passive and active systems
- ✓ The outer hair cells (OHC) provide this active mechanism - they amplify the motion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

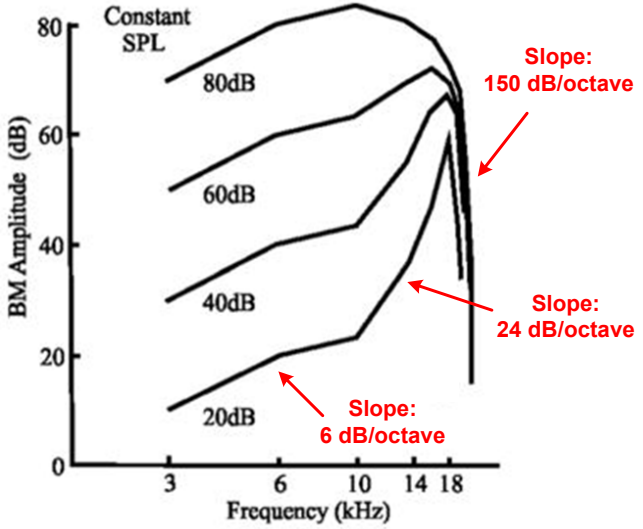




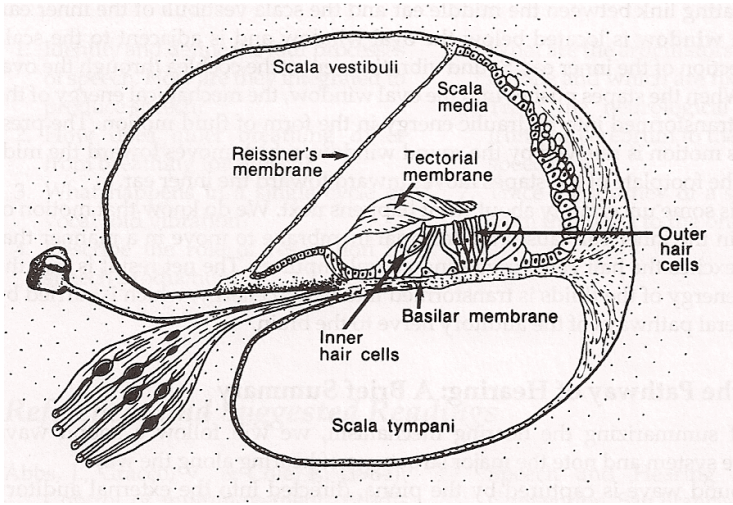
Transmission Line Model with Feedback

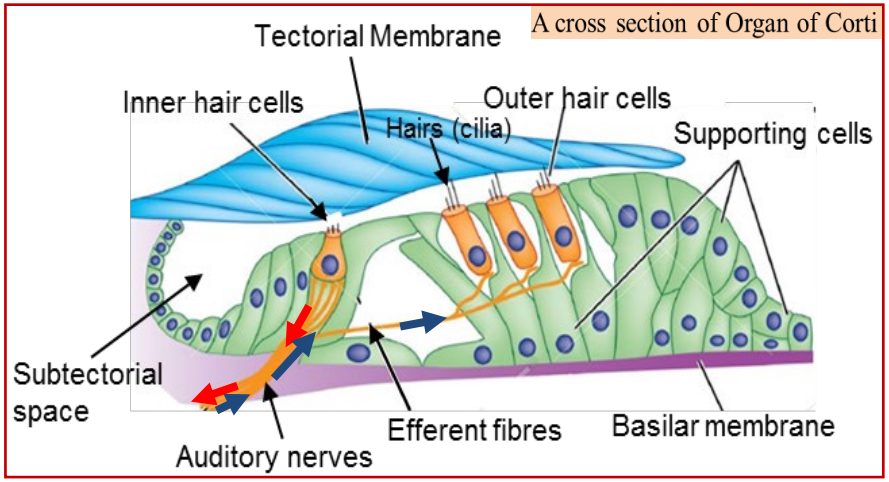
- ✓ The basilar membrane within the cochlea is normally in a passive state.
- ✓ Upon stimulation by a frequency of low amplitude, the section of the basilar membrane corresponding to that frequency transitions to an active state (adaptively higher-Q spectral decomposition).
- ✓ It is surprising how this 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.

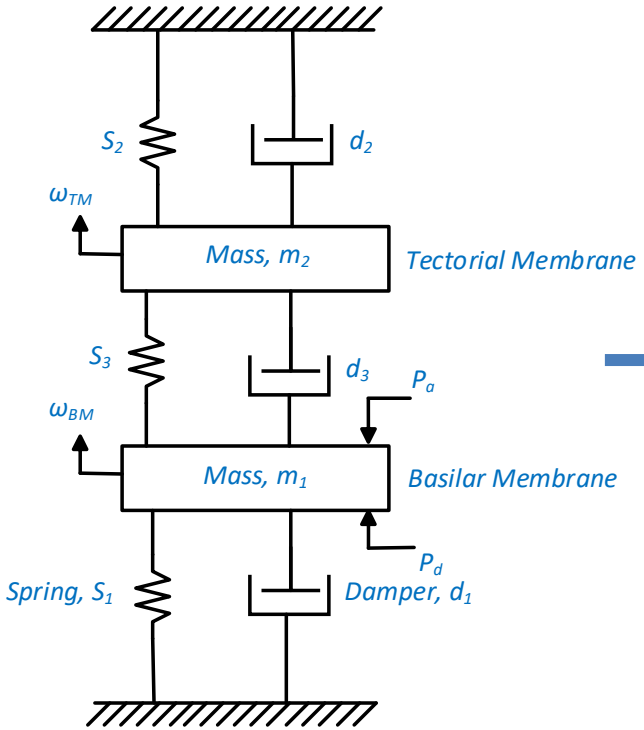


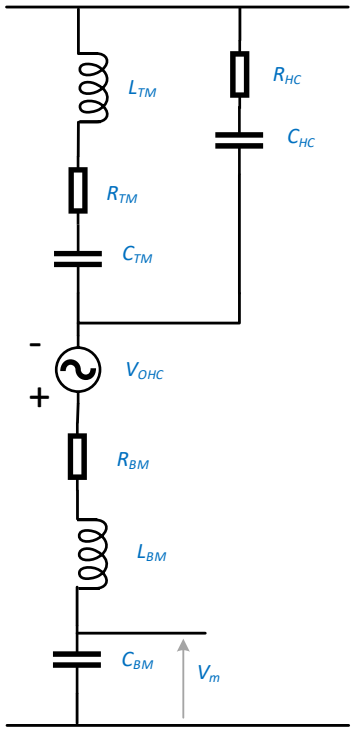


Active Cochlear Modelling

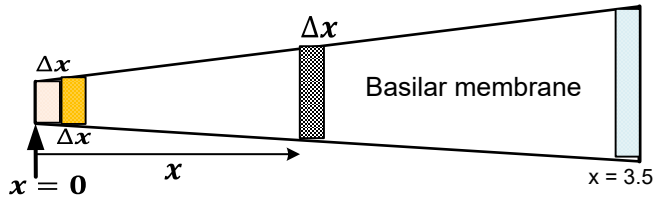


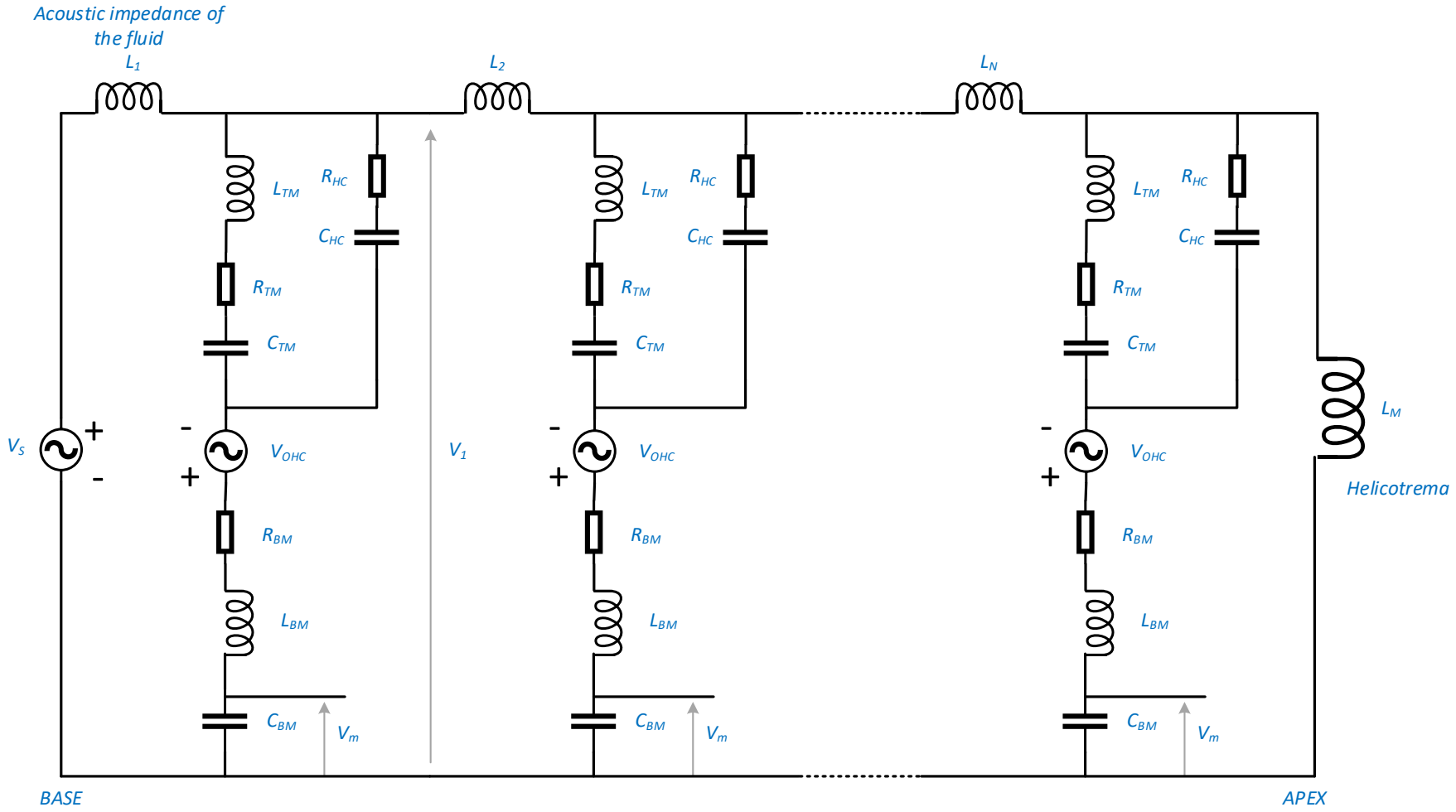




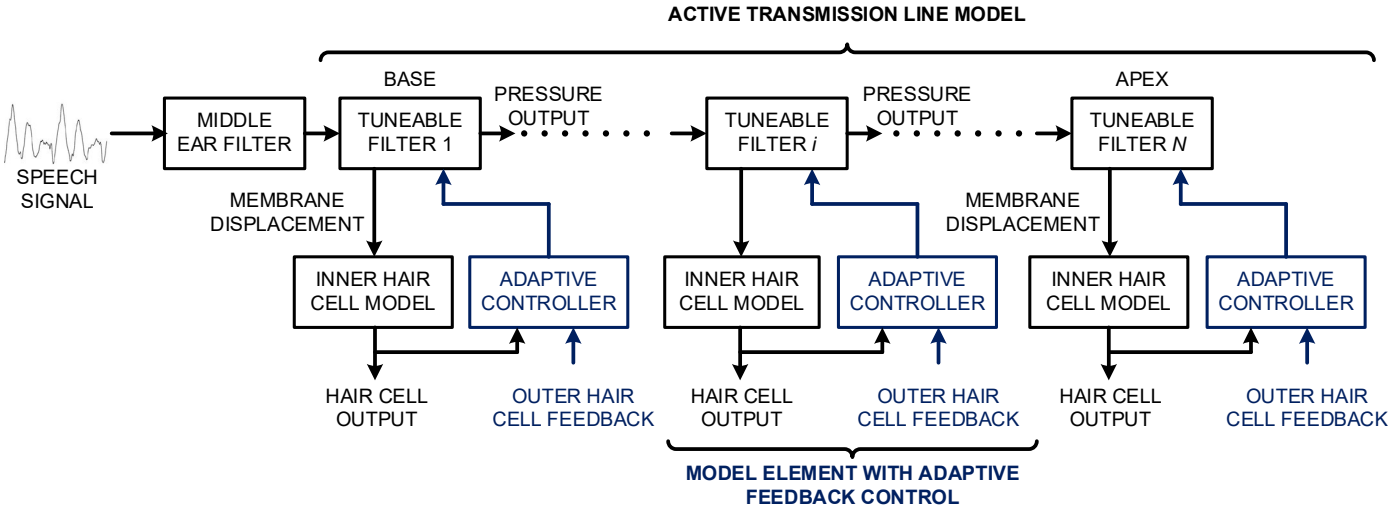


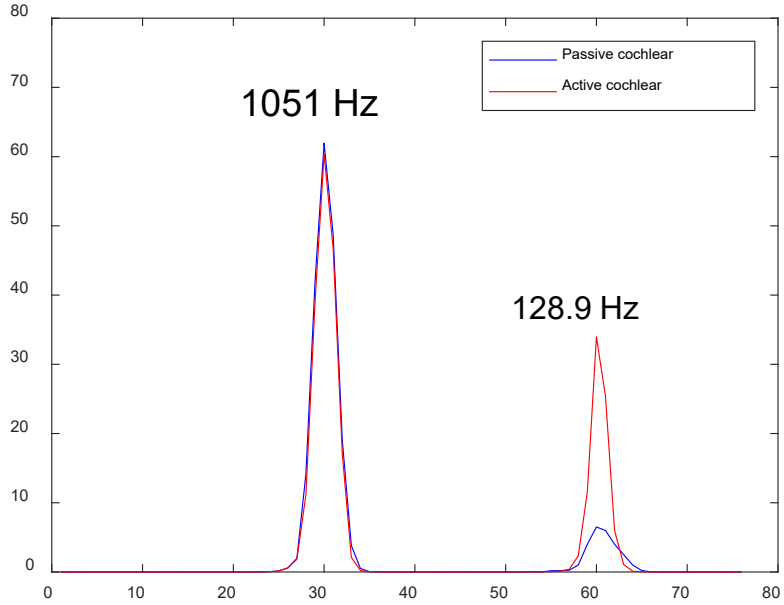
Active Cochlear Modelling





Active Transmission Line Model



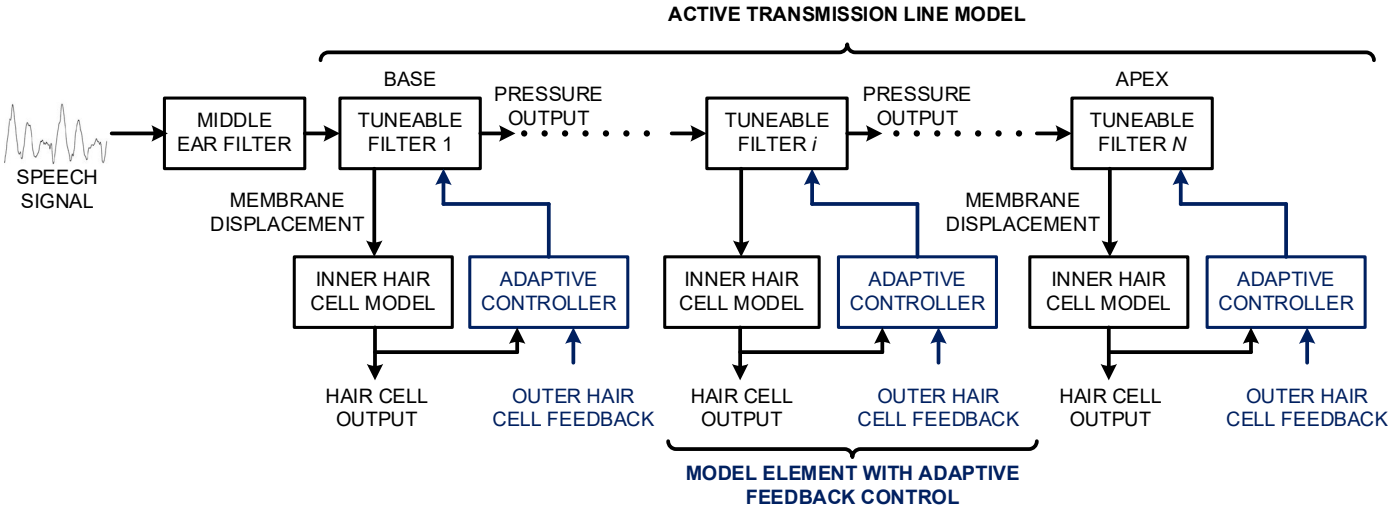


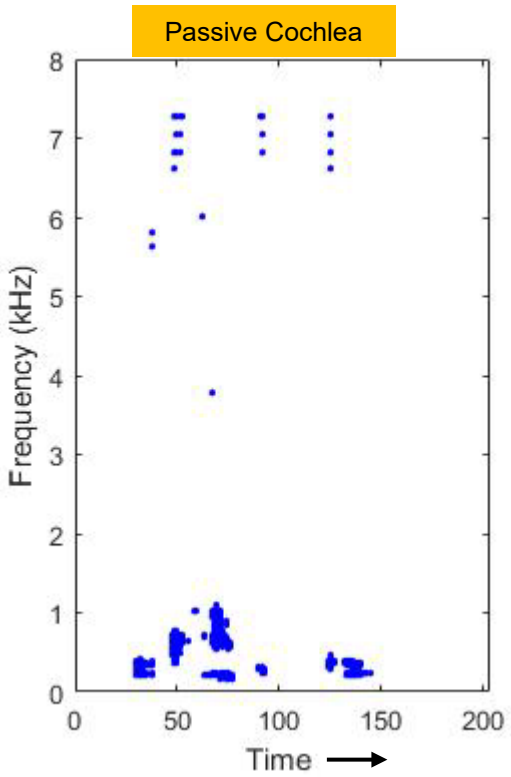
Ideally, models of the cochlea should exhibit

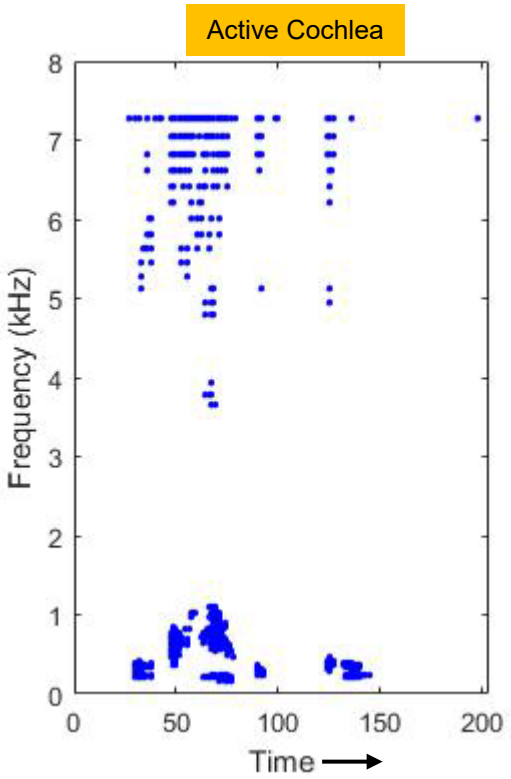
- level-dependence
- sharp auditory tuning curves
- fast adaptation

to changes in the input stimuli

Active Transmission Line Model



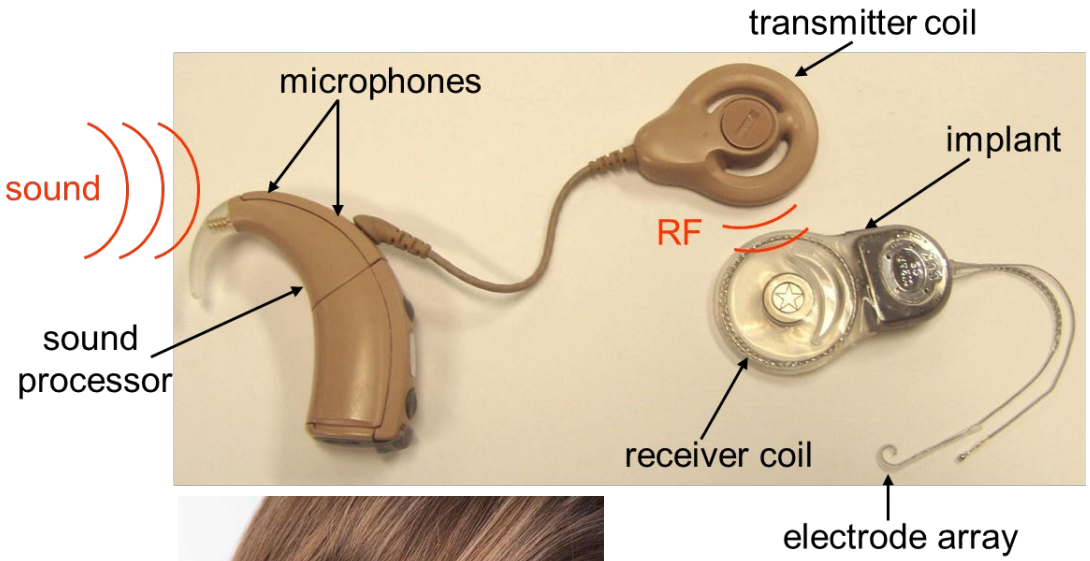


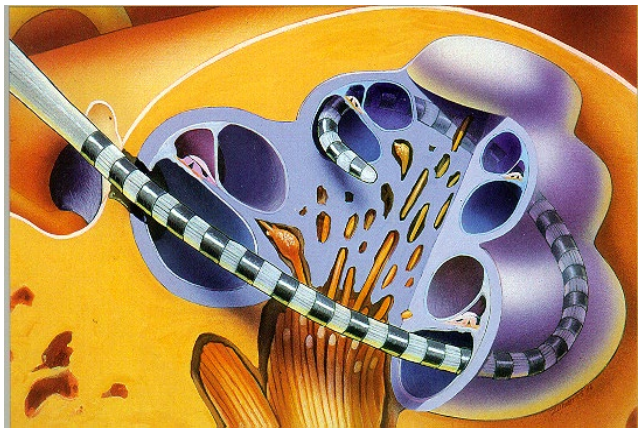


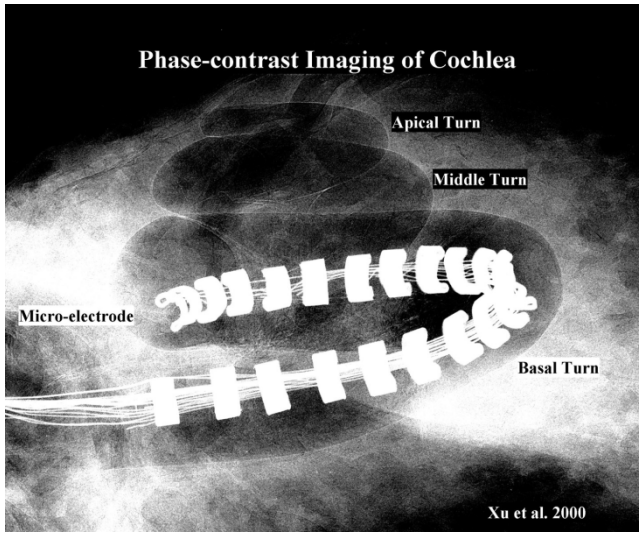
Cochlear implants

Cochlear Implant System

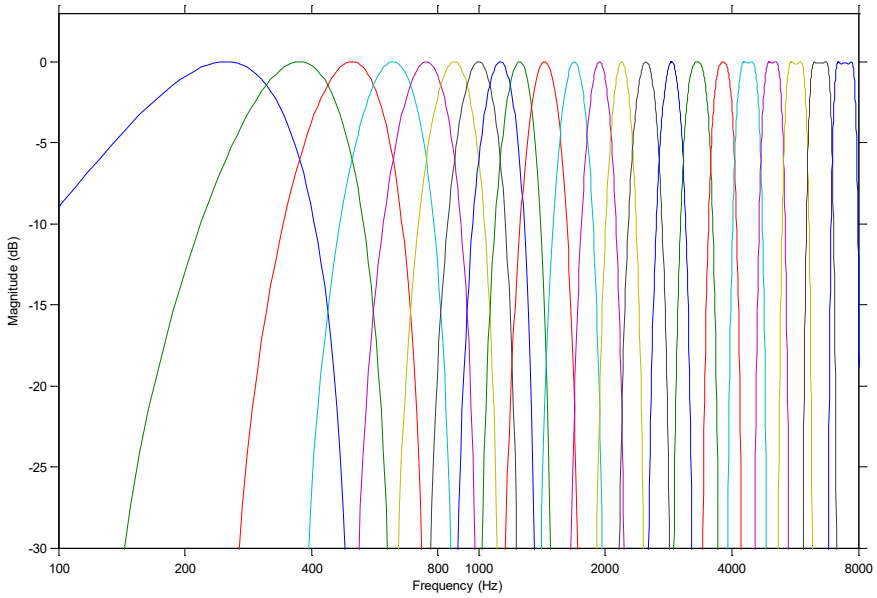
- ✓ Sounds processor is positioned behind the ear and transmits signals via RF to implant
- ✓ Implant consists of receiver coil and electrode array and is surgically inserted inside the inner ear
- ✓ Electrode array excites the auditory nerves



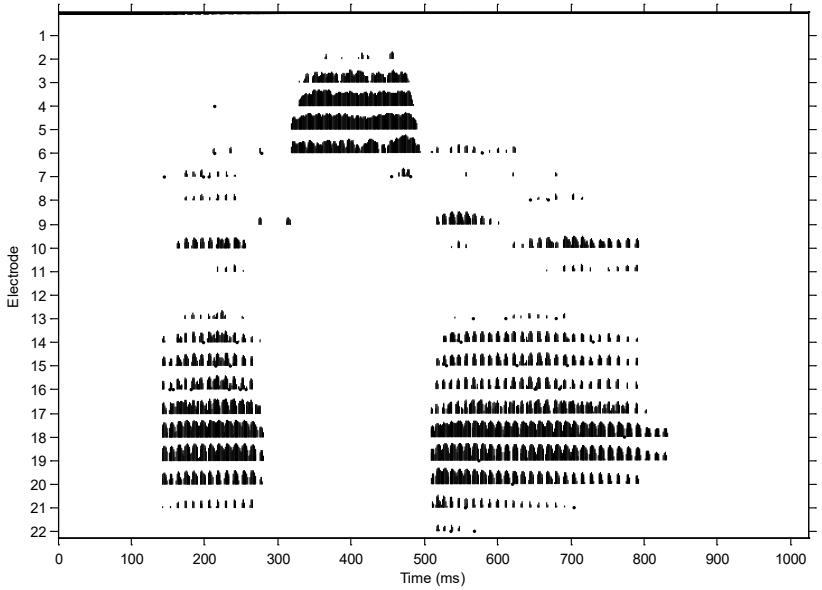




Signal Path Overview – Sound Processor



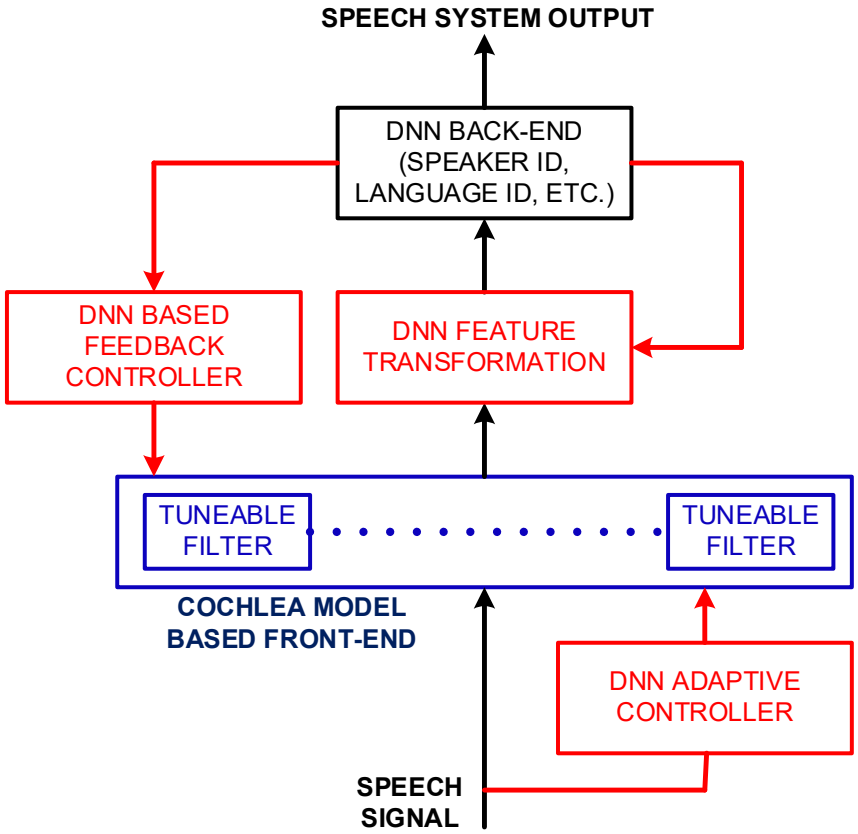
Magnitude Response of Filter-bank



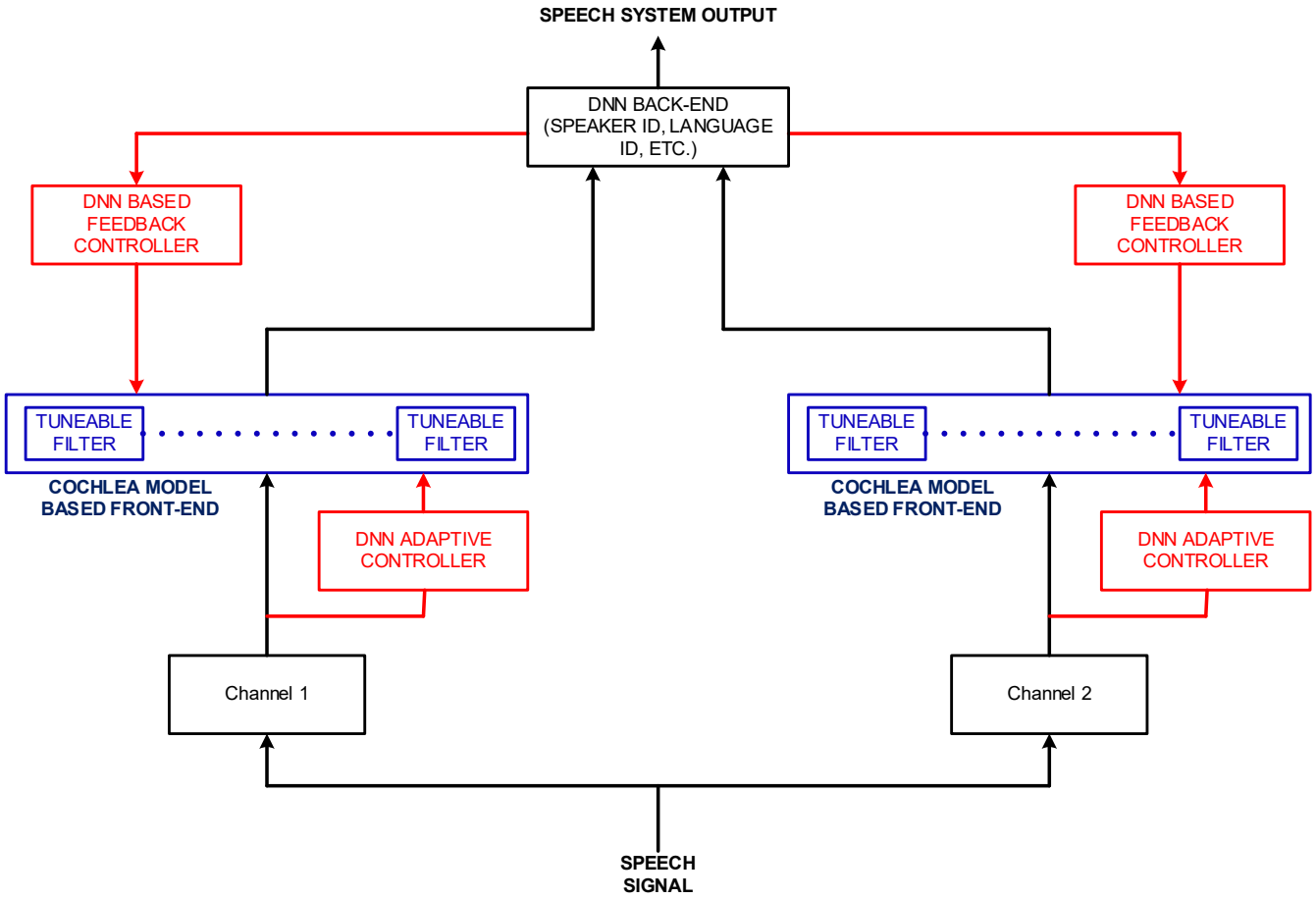
Electrode Signals

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.



Future Trends –Binaural Auditory Models for AI



- ✓ Exploit binaural variations to develop a robust cochlear front-end for future AI systems

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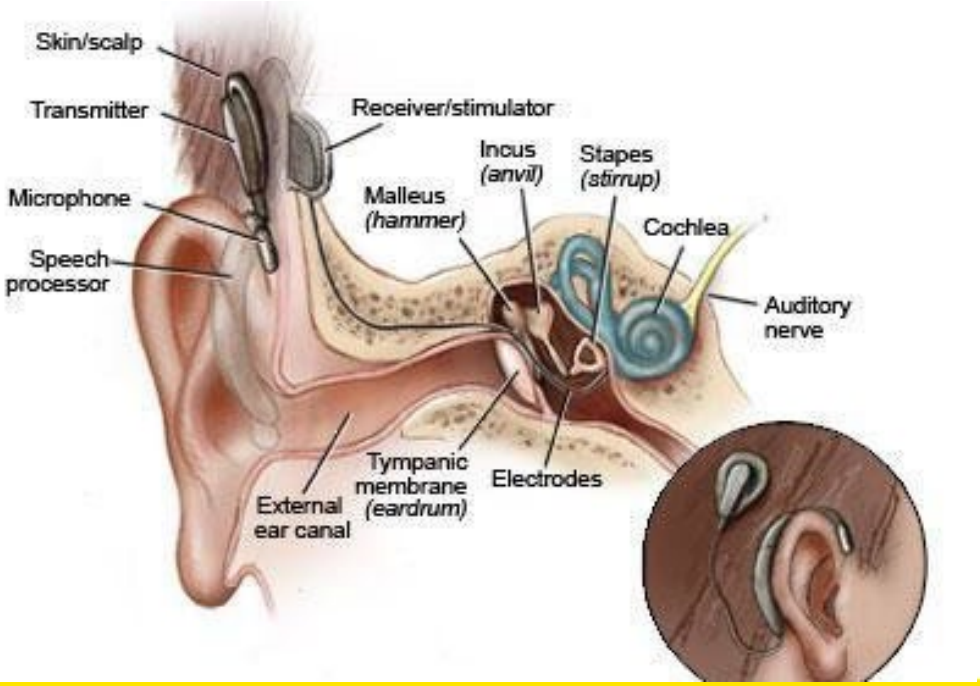
Conclusions

- ✓ 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



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Electrical Engineering @ UNSW

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- ✓ Top School for Research in Australia (Multiple University Rankings)
- ✓ Ranked 36 (QS World University Rankings, 2019)
- ✓ 5 star ERA (Excellence in Research Australia) rating – 2010, 2012, 2015 and 2018
- ✓ ~$25m research income in 2018
- ✓ ~2000 students (2019)
  - 1000 - UG; 800 - PG; 200 - PhD
- ✓ 46 Academic staff
- ✓ 30% of our staff received the top teaching awards
- ✓ $104m Refurbishment – Cutting edge lab facilities among best in the world

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Active Transmission Line Model