Professor Hafter's
Auditory Perception Lab

Cochlear Implants for Profound Hearing Loss – Signal Processing Considerations

Bernhard U. Seeber
Auditory Perception Lab
UC Berkeley

1966: ***"What is the likelihood that electrical stimulation of the auditory nerve can ever provide a uniquely useful means of communication?***

The chances are small indeed, perhaps 5% or less as a laboratory exercise, certainly much smaller on a clinical scale."

Simmons, in an article on electrical stimulation

2004: ***More than 70.000 cochlear implants sold.***

Agenda

The auditory system

- Anatomy and function
- Link points for cochlear implants

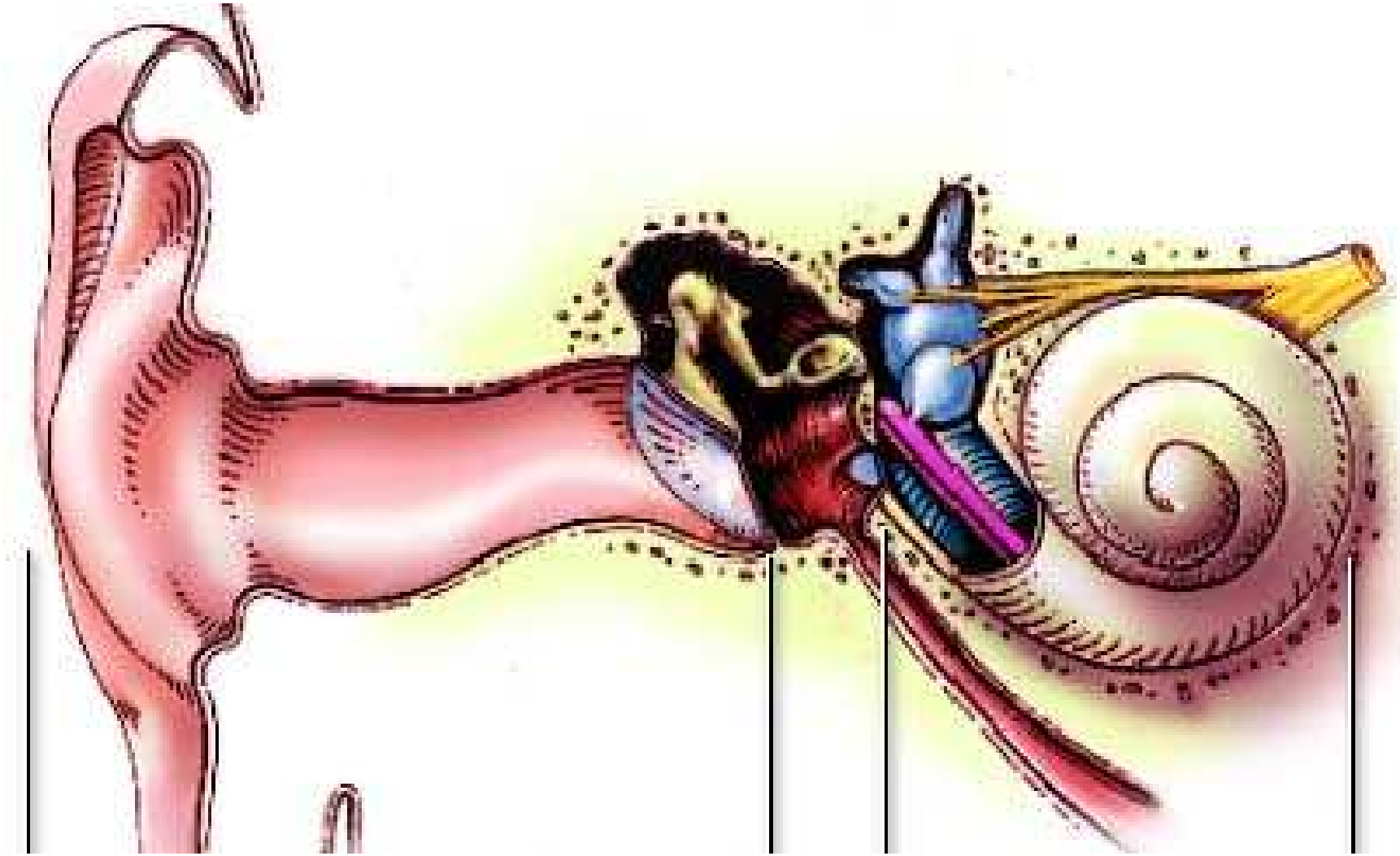
Signal processing in cochlear implants

- Single channel CIs
- Feature extraction strategies: F0/F1/F2, MPEAK
- Waveform strategies: CA, CIS, SPEAK, ACE
- A current device

Future directions

- Stochastical nerve response
- Electro-acoustical stimulation

The Auditory System

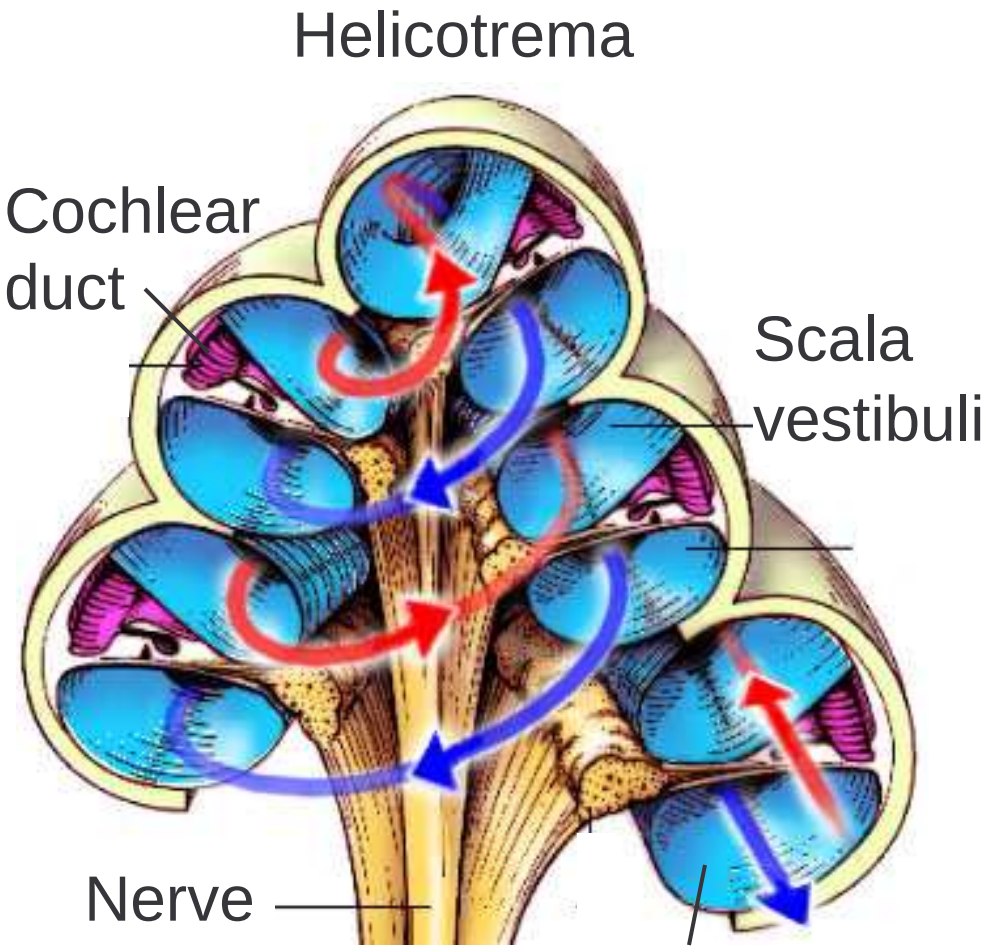


Outer Ear **Middle Ear** **Inner Ear**

Drawing w. permission from “Promenade around the cochlea”, www.cochlea.org

The Auditory System – Cochlea

Round + Oval window



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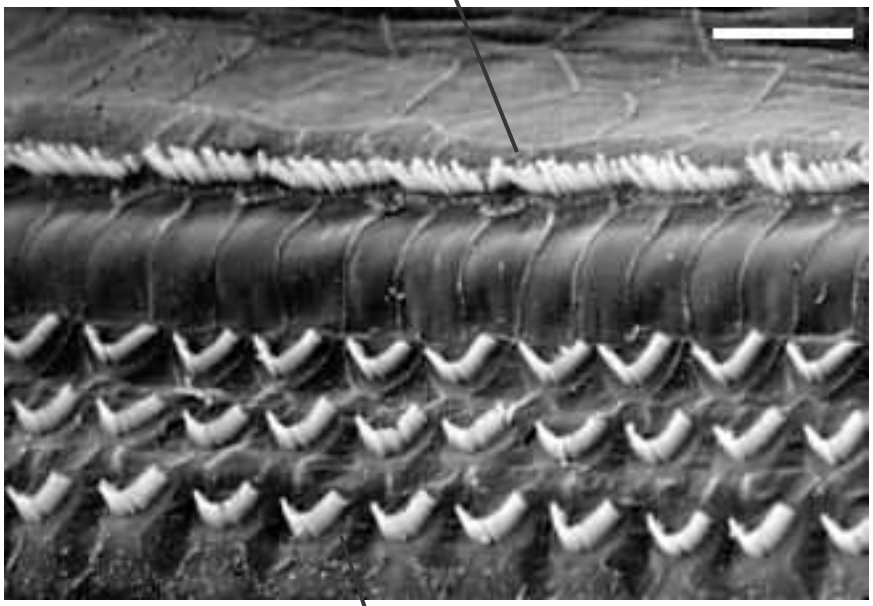
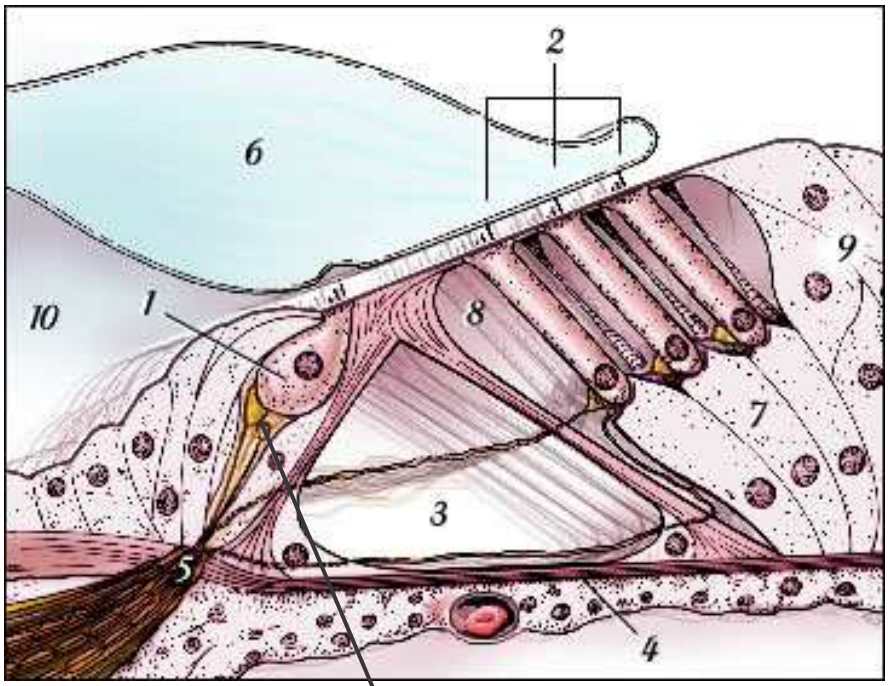
The Auditory System – Organ of Corti

Inner hair cells





Outer hair cells

Afferent pathway

Pictures w. permission from “Promenade around the cochlea”, www.cochlea.org

Candidacy for Cochlear Implantation

- **Profound hearing loss** >90 dB HL (now >70 dB HL)
  - Congenital disorders
  - Meningitis
  - Meniere's disease
  - Drug treatment, e.g. Gentamycin
- **Sentence recognition** <30% (now <60%)
- **Auditory nerve** / spiral ganglion cells intact
- **Cochlea not ossified**
- **Influential factors**
  - Duration of deafness
  - Pre/post lingual onset of deafness
  - Age at implantation

Electrical Stimulation – Historical Introduction

- **Volta, ~1780:** Discovery of electrolytic cell,
  „boom within the head“ if 50V source is connected to electrodes in ear canal
- **Brenner, 1868:** studied effects of placement of electrodes, polarity, rate and intensity of stimulus
- **Wever and Gray, 1930:** Discovery that electrical responses in nerve of cat similar in frequency and amplitude to sound
- **50s, 60s:** Serious experiments on electrical stimulation, e.g. **Simmons (1966):** in-depth studies, even multi-channel
- **Michaelson (1971), House (1976):** first implantations of electrode with implantable receiver-stimulator
  - fail due to biocompatibility, but:
- **1972 to mid 80s:** 1000 House/3M single-electrode implants were implanted (FDA approval 1984!)

House/3M Single-Channel Cochlear Implant

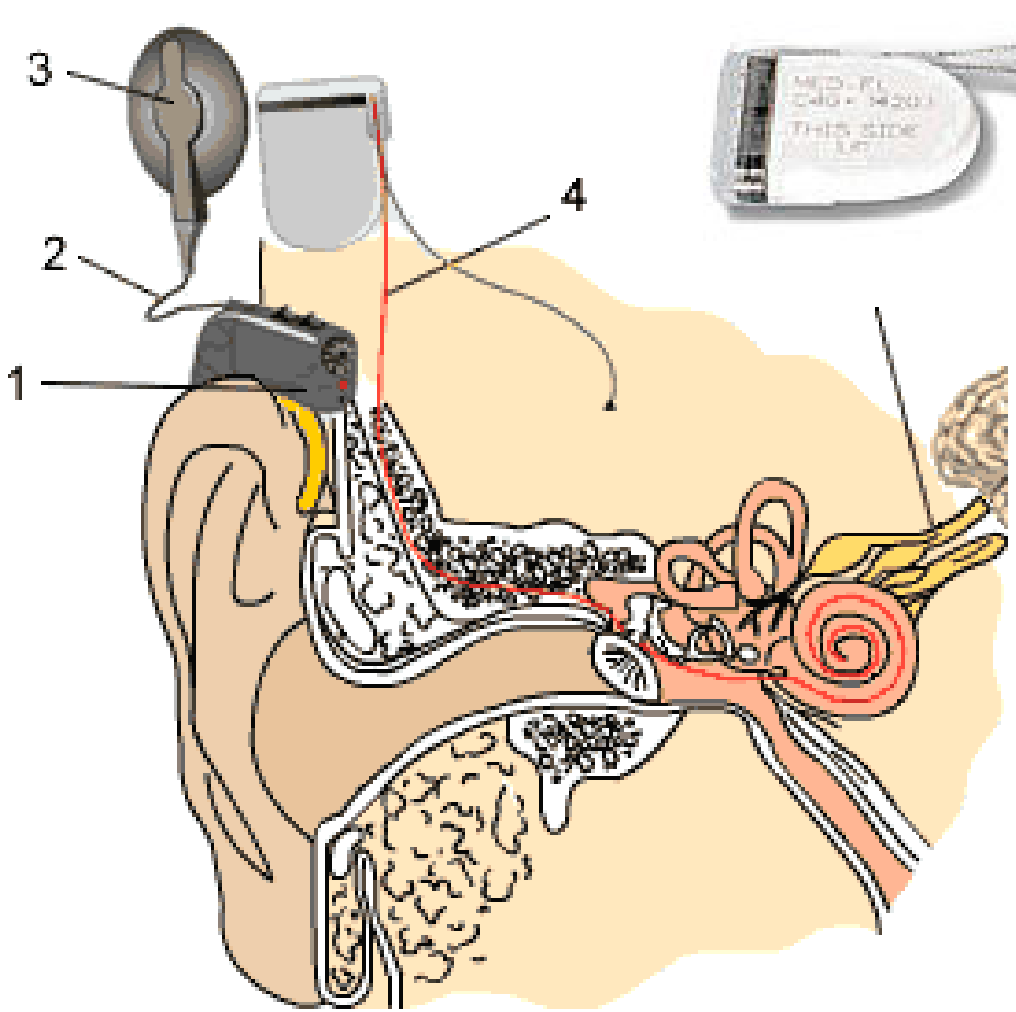
The House/3M single-channel implant

House/3M device:

- Analog stimulation includes 16 kHz carrier
- Transcutaneous link through induction coil
- Small dynamic range on nerve lets output saturate/distort
- Majority of patients did not obtain open-set speech recognition
- Exceptional patients achieved 2-4% consonant recognition

Cochlear Implants – Anatomy and Mechanics

Implant: here MED-EL Combi 40+ and Tempo+ Processor



Med-El GmbH, Innsbruck

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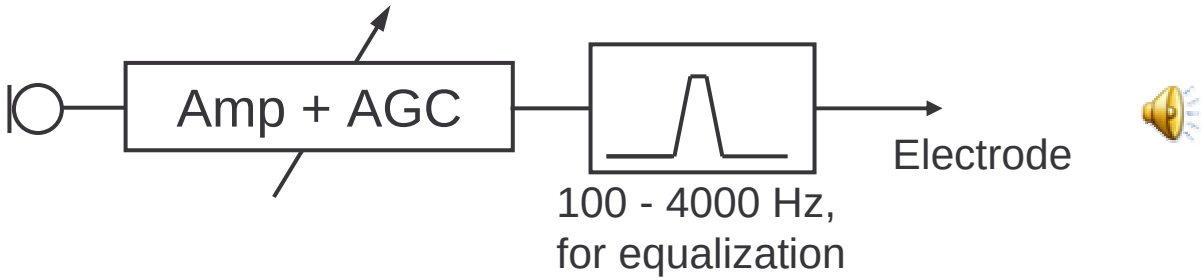
Vienna/3M Single-Channel Cochlear Implant

Early 80s: Vienna/3M single-channel implant



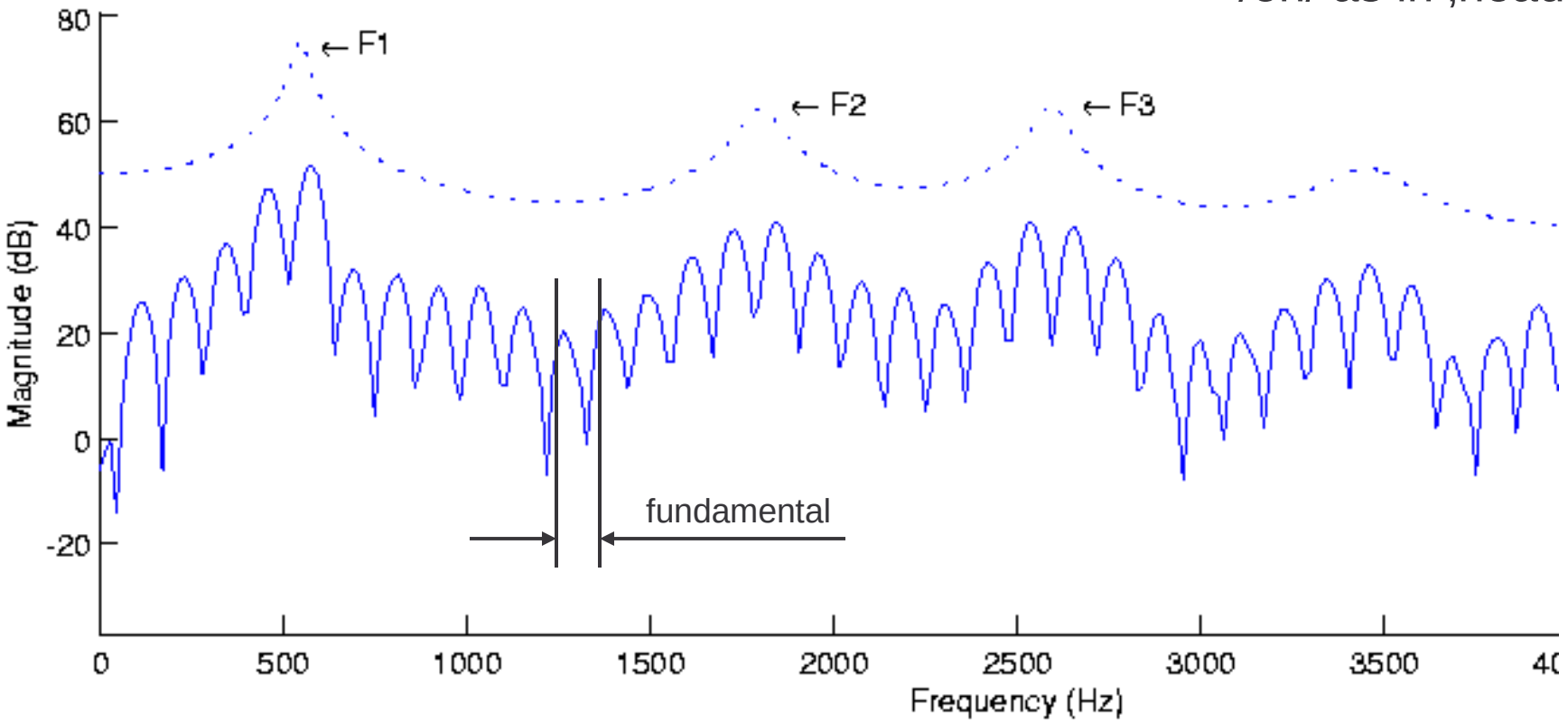
Vienna/3M device:

- AGC: Better adaptation to small dynamic range on nerve
- EQ-filter: sinusoids 0.1 – 4 kHz adjusted to equal loudness
- Transcutaneous radio-frequency link, demodulated
- Some fine temporal information transmitted
- 15-85% word identification possible (Tyler, 1988)

Single-Channel Limitations

- Temporal coding in nerve fibers limited to <1 kHz
- Speech spectrum has fundamental frequency and formats:

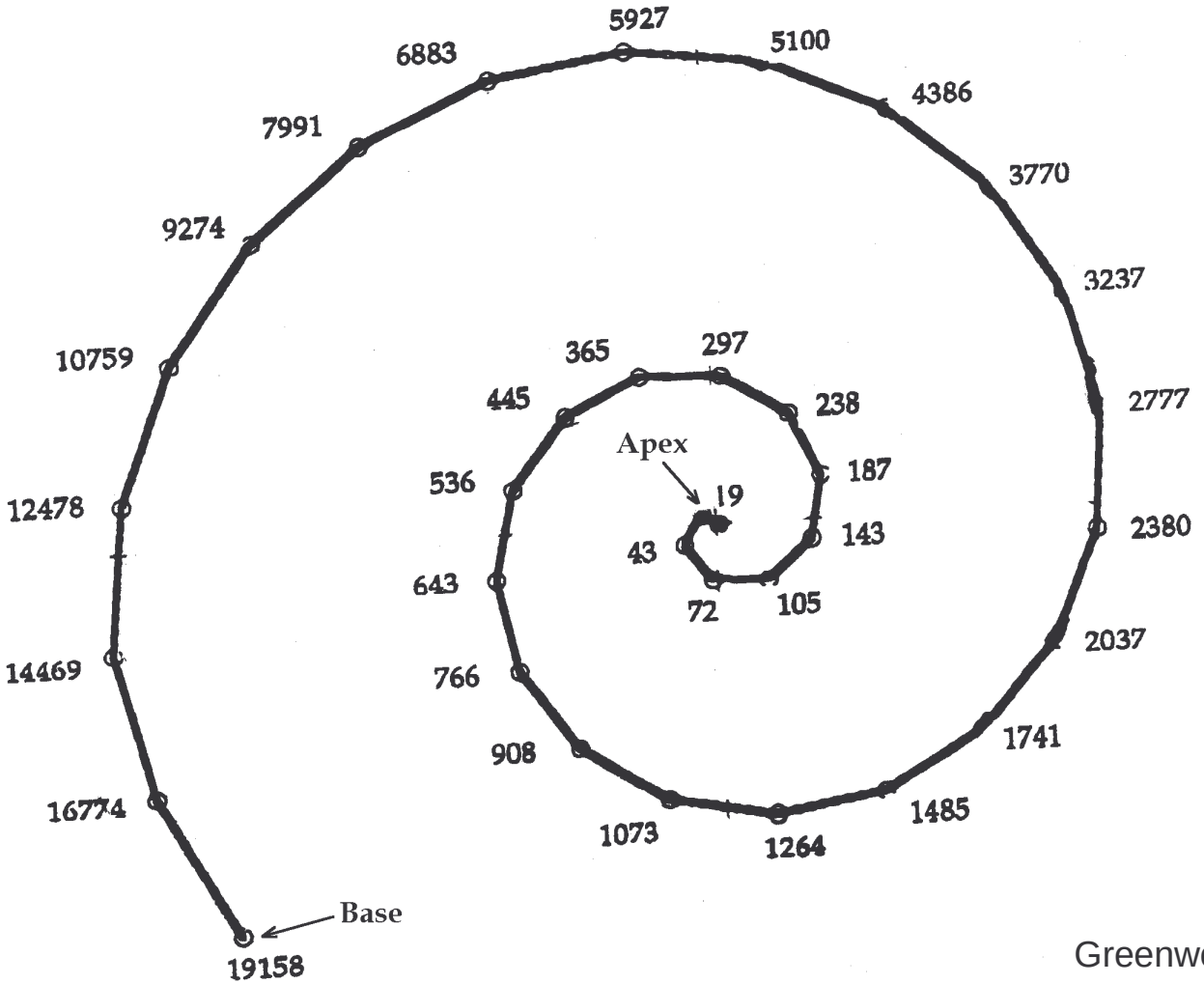
/eh/ as in ‚head‘



Loizou, 1998

Frequency – to – Place Transformation in Cochlea

Mimick Processing of Cochlea:



Greenwood, 1961

Multi-Channel Cochlear Implants

- Cochlea: Frequency to place transformation
- Speech spectrum has fundamental frequency and formats

→ **1984:** First multi-channel implant (Nucleus)

Multi-Channel Approaches

Waveform Strategies

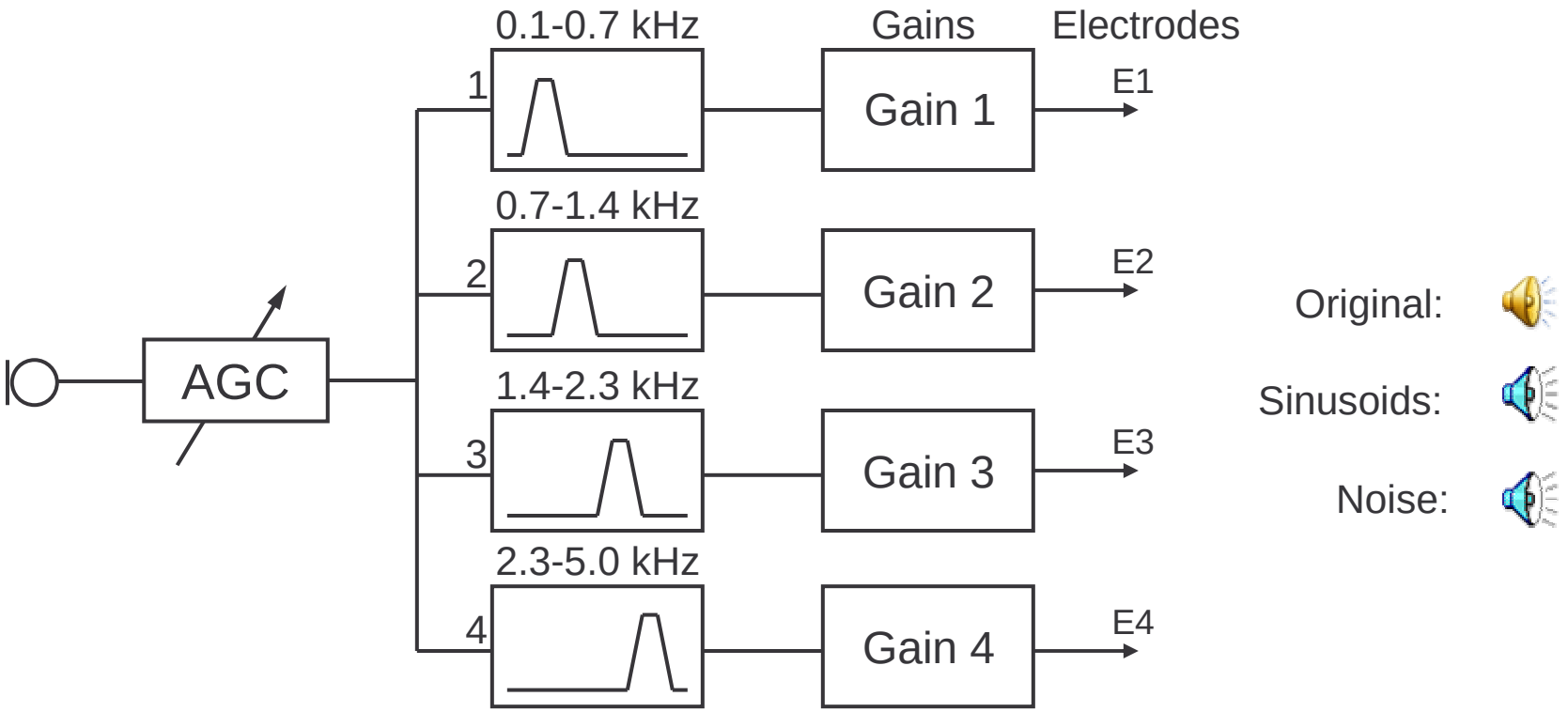
- Compressed Analog
- Continuous Interleaved Sampling

Feature-Extraction Strategies

- F0/F2
- F0/F1/F2
- MPEAK

Compressed Analog Approach – Ineraid

- Ineraid device by Symbion, Inc., Utah (1980)
- UC San Francisco / Stortz device (1984)
- Advanced Bionics HiRes 90k Bionic Ear Implant (current)

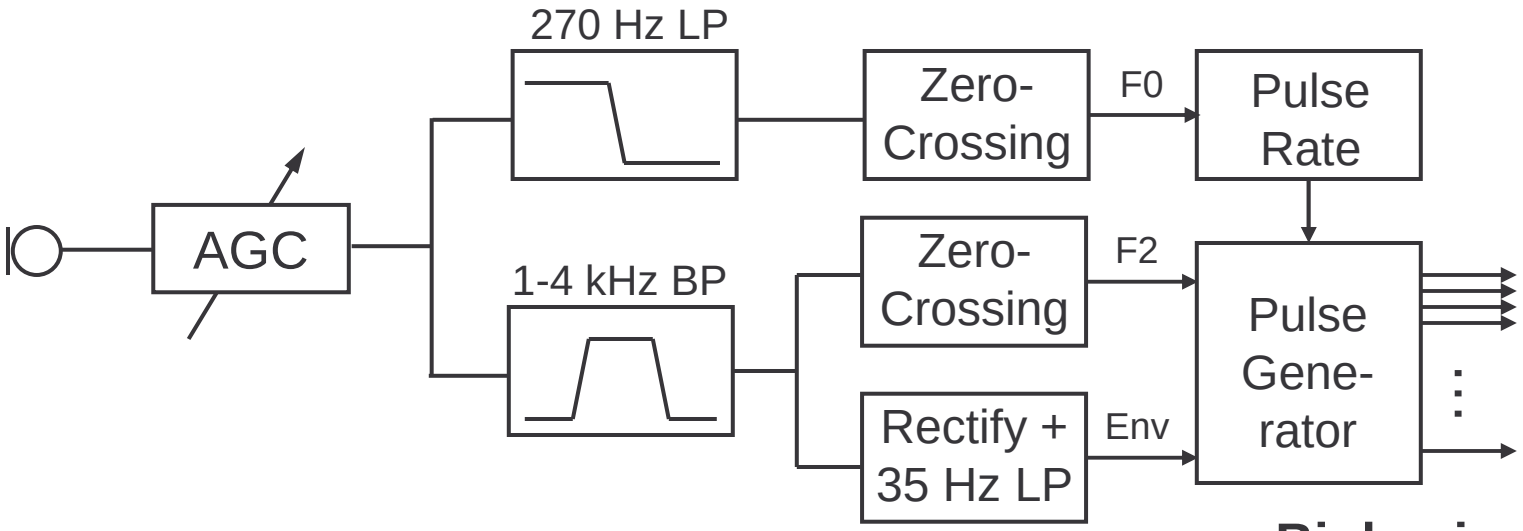


Problem: Channel overlap – current spread in cochlea

Feature-Extraction Strategies: F0/F2

1984: First multi-channel CI uses F0/F2 strategy (Nucleus)

- 22 electrode array, only 1 electrode stimulated
- F0 coded in rate and formant F2 in place and amplitude
- Unvoiced intervals: quasi-random stimulation 100 pulses/s



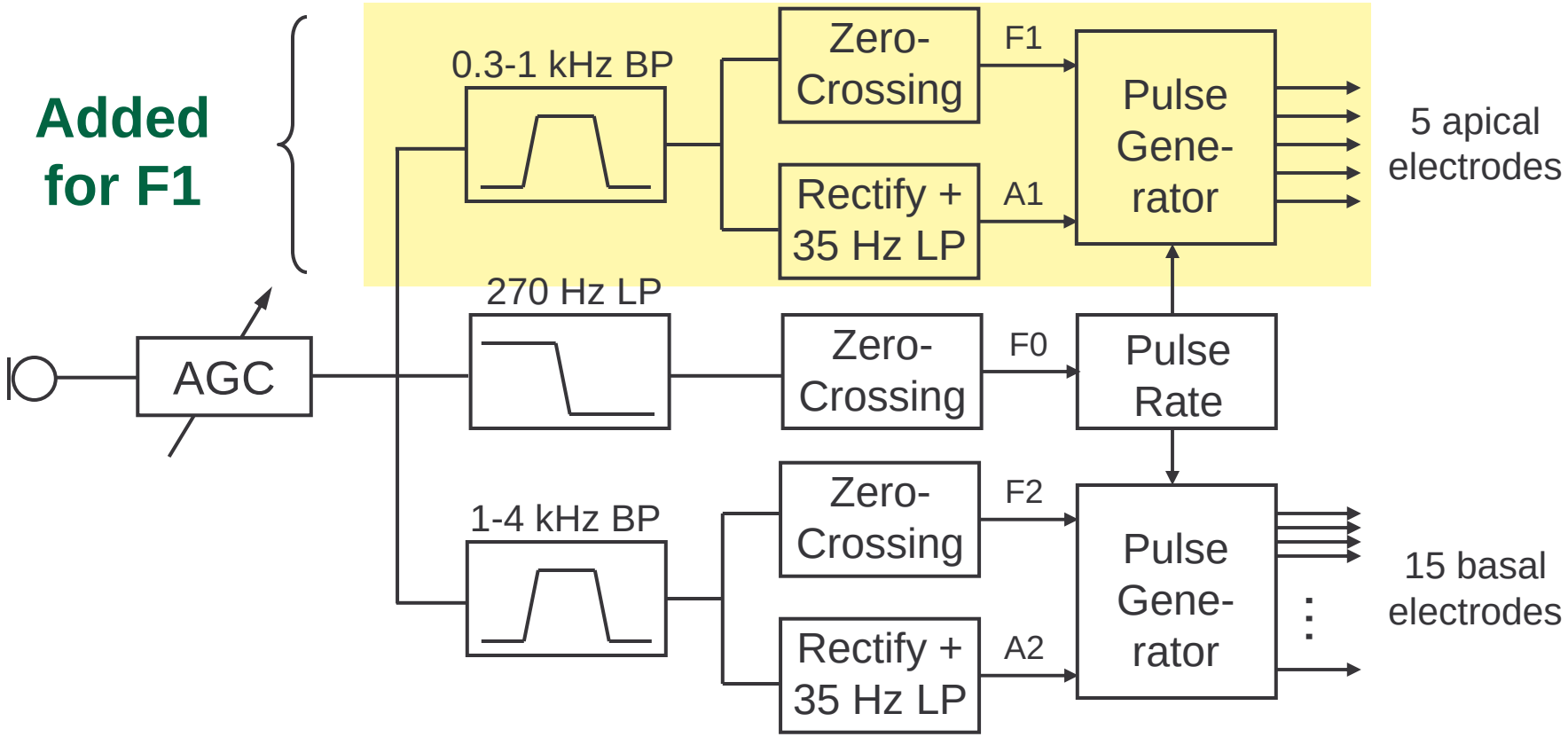
Biphasic pulses!

- Clearly improved understanding of words
- Problems with consonants

Feature-Extraction Strategies: F0/F1/F2

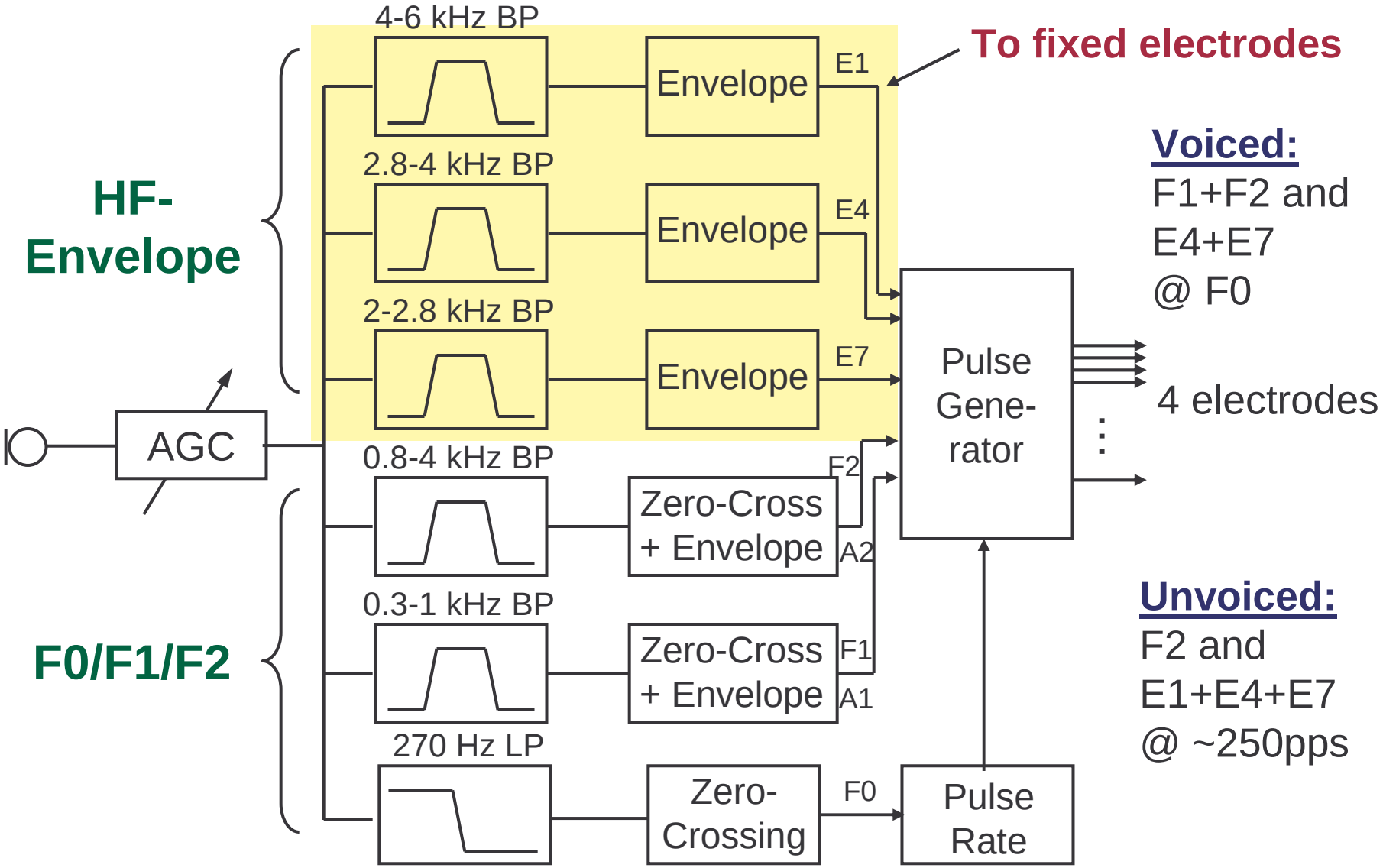
1985: Advanced to F0/F1/F2 strategy (Nucleus)

- Improvement of vowel, but not consonant recognition
- Word scores from 30% (F0/F2) to 63% (Dowell et al., 1987)

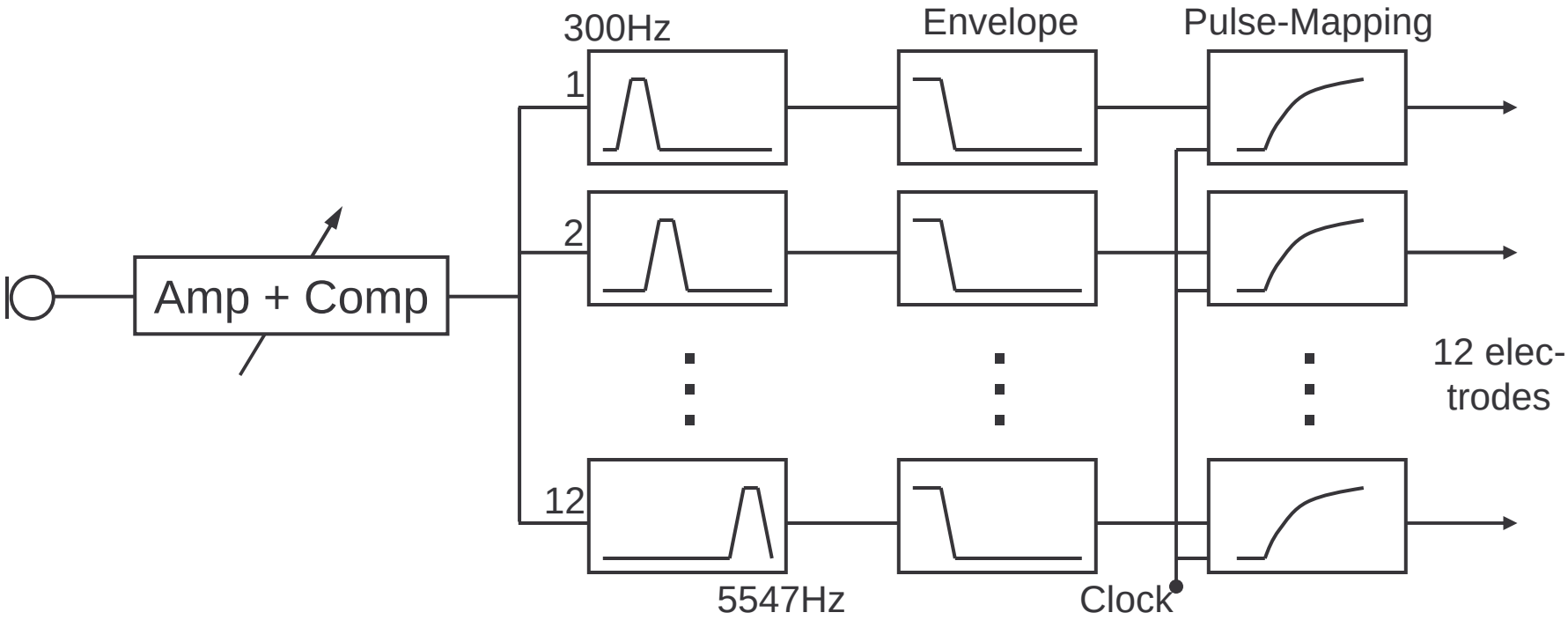


Feature-Extraction Strategies: MPEAK

~1990: MPEAK (multiple-peak) strategy (Nucleus)

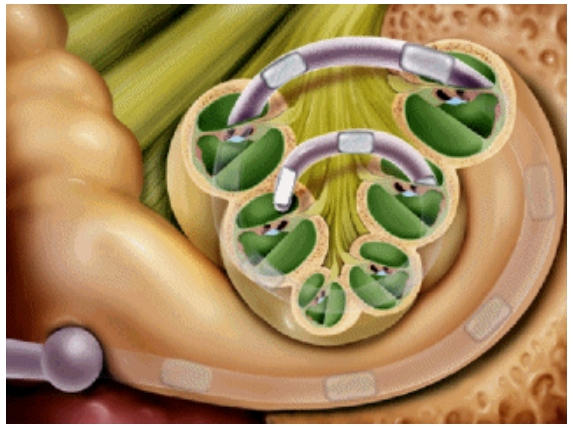


Waveform Strategies: Cont. Interleaved Sampling



1994/1995: Med-El Tempo+

- 18000 pps CIS+, interpulse interval 56 µs overall / 667 µs channel
- All channels interleaved
- Deep electrode insertion up to 30mm



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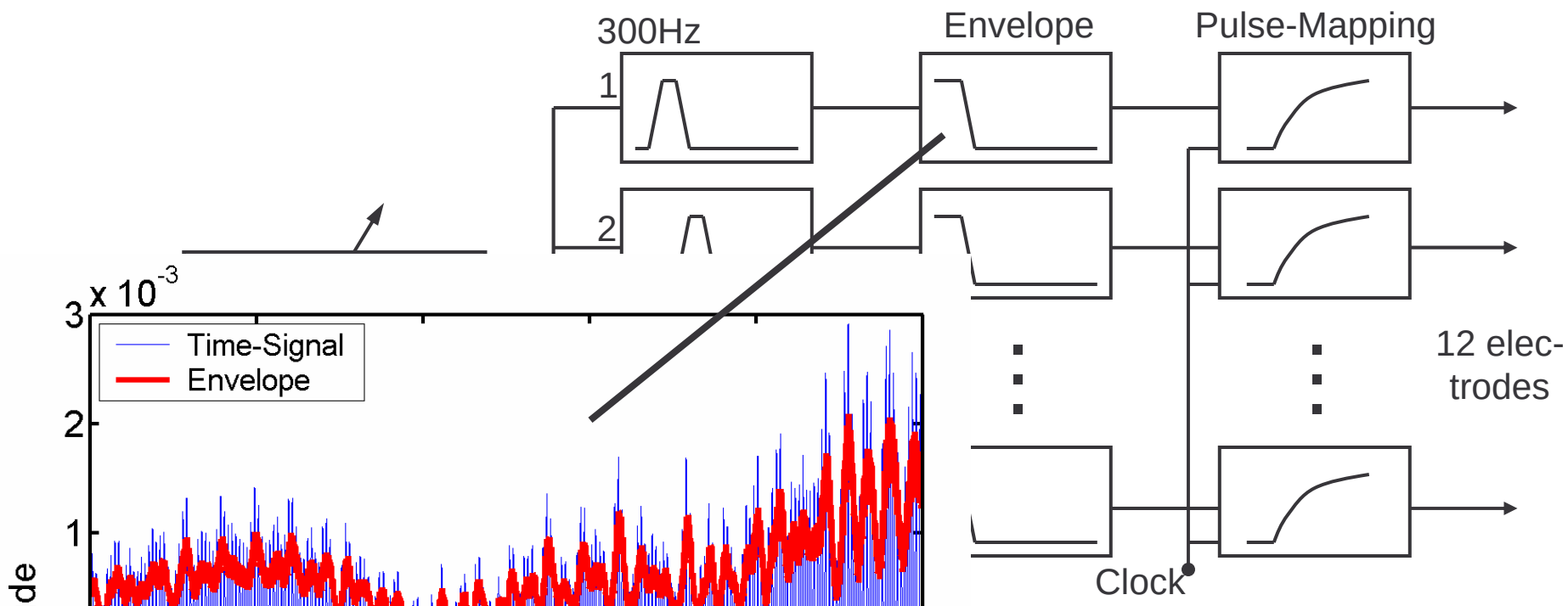
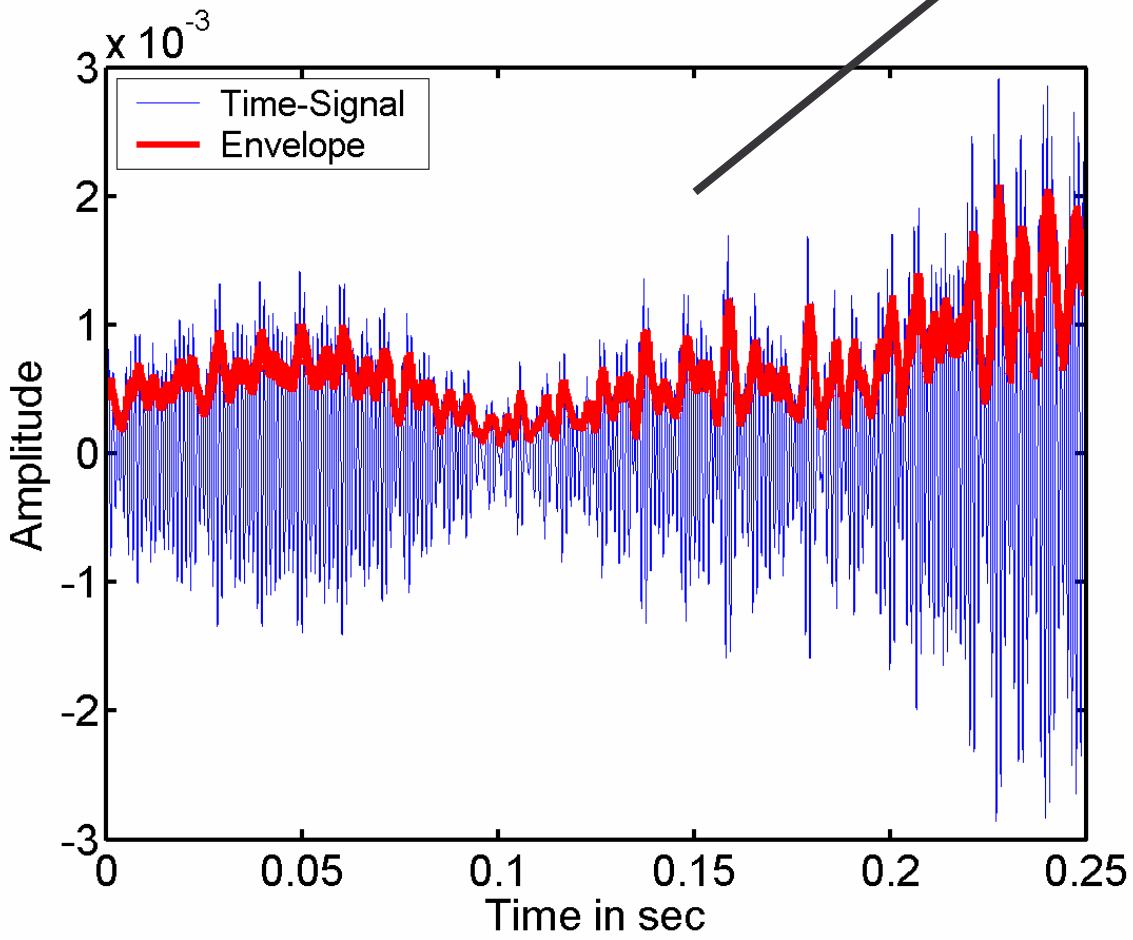
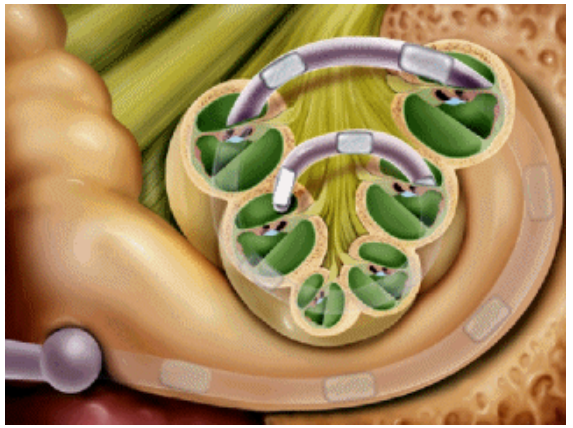
Waveform Strategies: Cont. Interleaved Sampling







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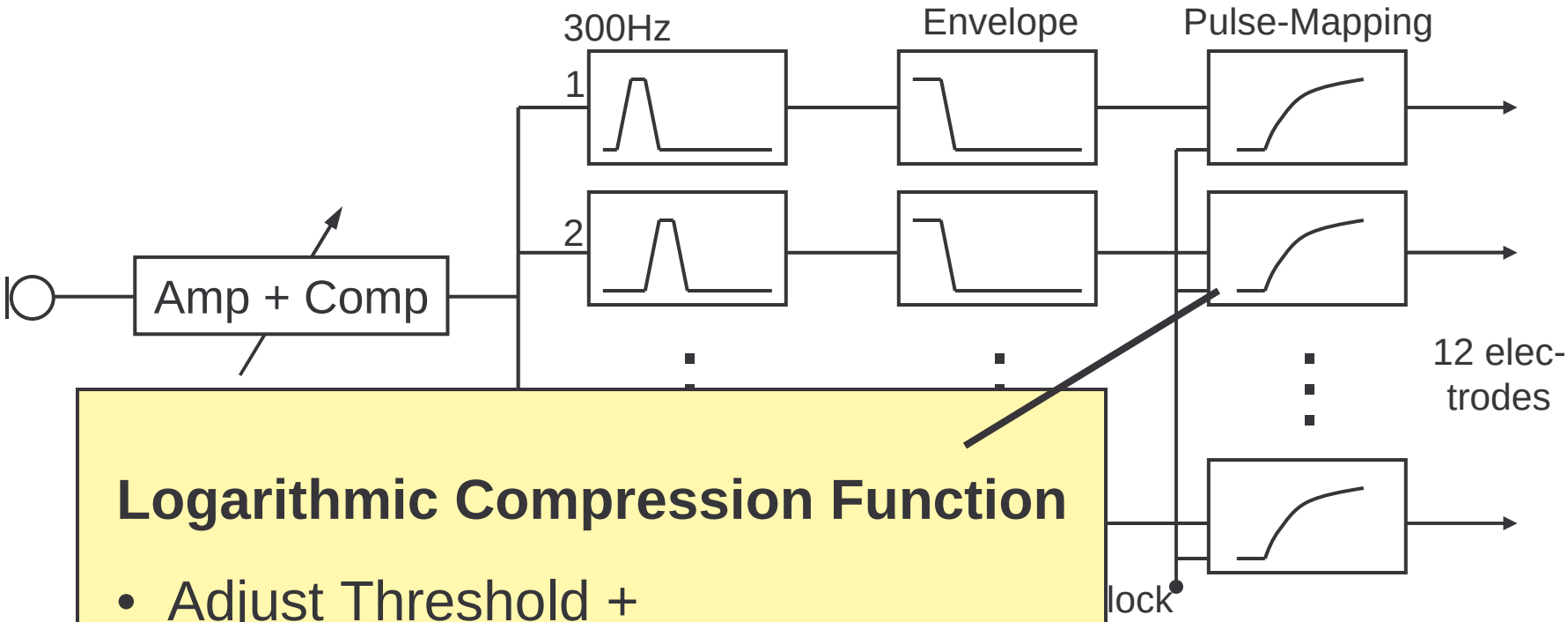
Waveform Strategies: Cont. Interleaved Sampling



Logarithmic Compression Function

- Adjust Threshold +
- Maximum Comfortable Level
- Follows loudness growth function

19

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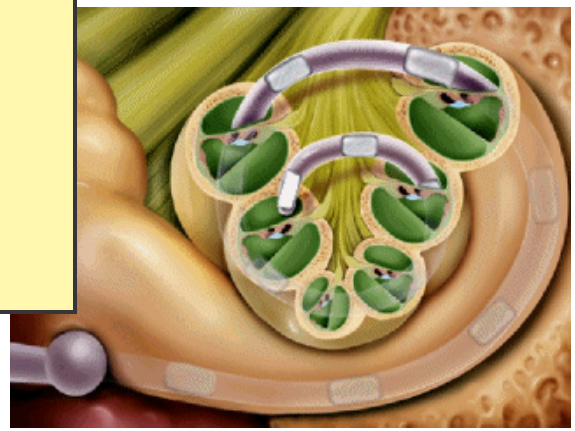
– All channels interleaved

– Deep electrode insertion up to 30mm



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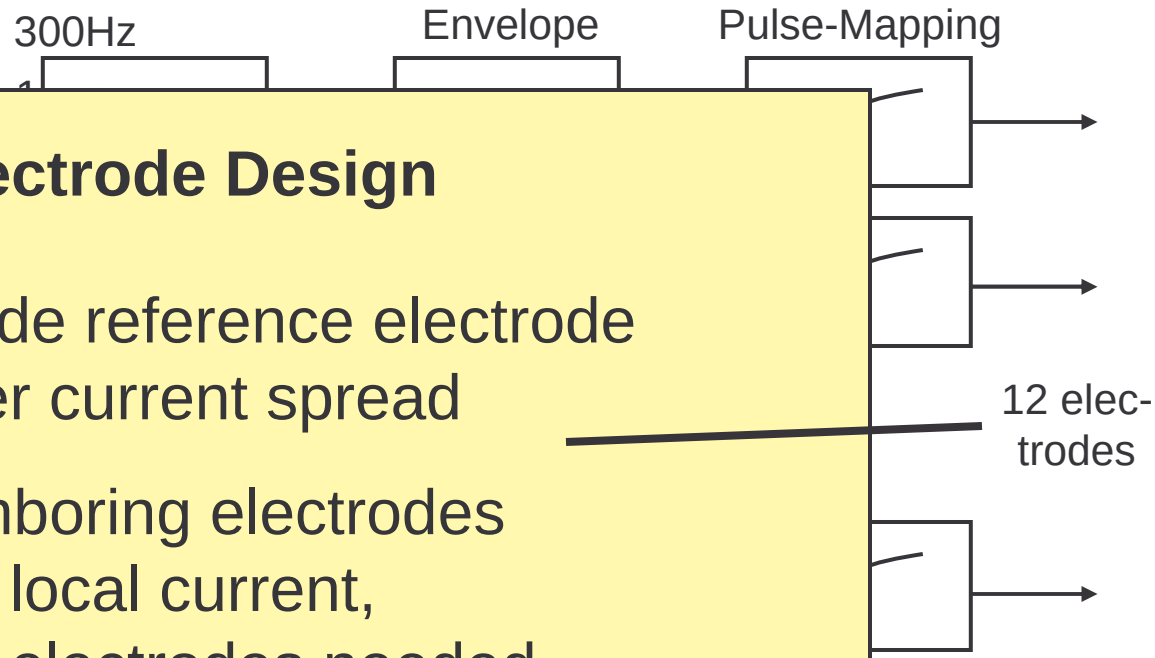
Waveform Strategies: Cont. Interleaved Sampling



Electrode Design

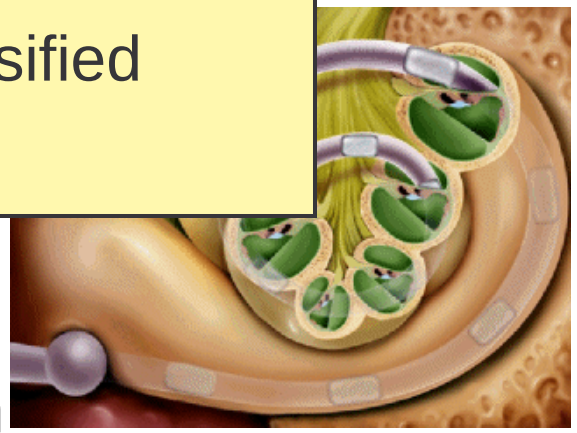
Monopolar: Outside reference electrode
Larger current spread

Bipolar: Neighboring electrodes
More local current,
more electrodes needed

Electrodes for specific applications: ossified cochlea, electro-acoustic stimulation…

56 µs overall / 667 µs channel

– All channels interleaved
– **Deep electrode insertion** up to 30mm



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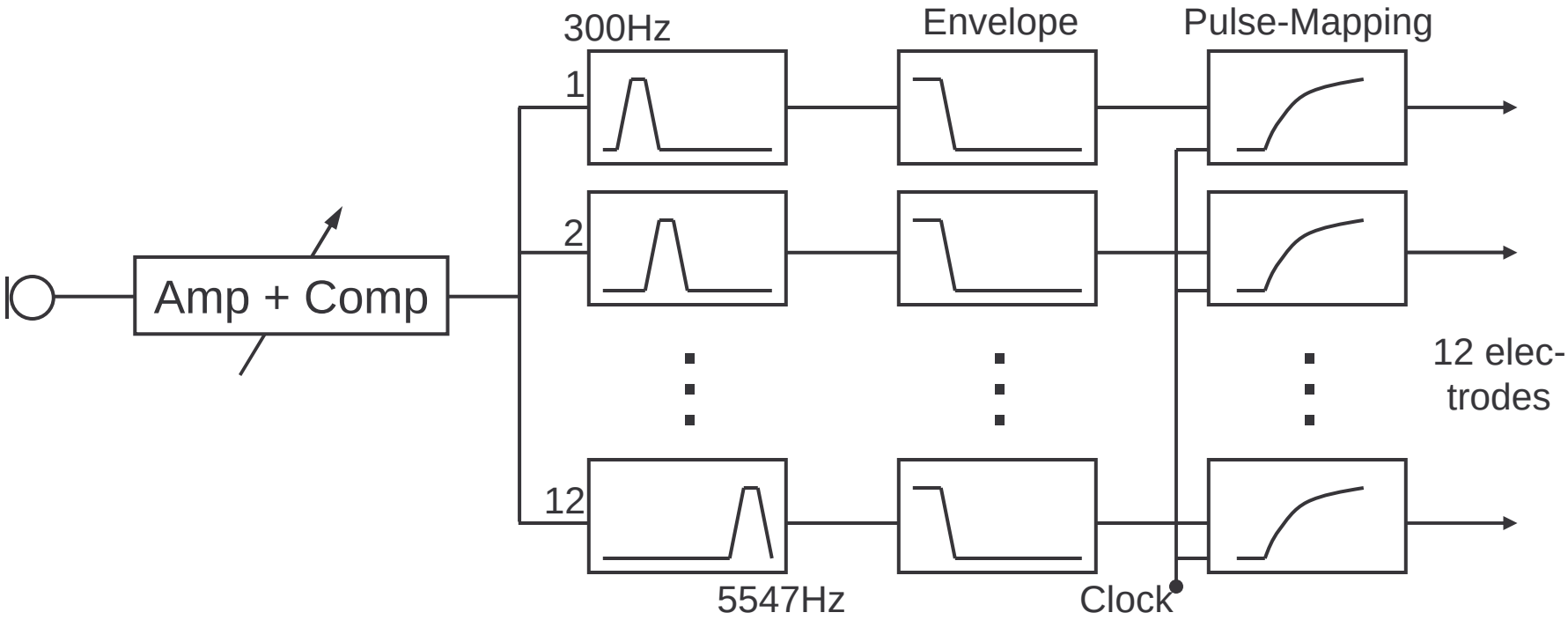
Waveform Strategies: Cont. Interleaved Sampling



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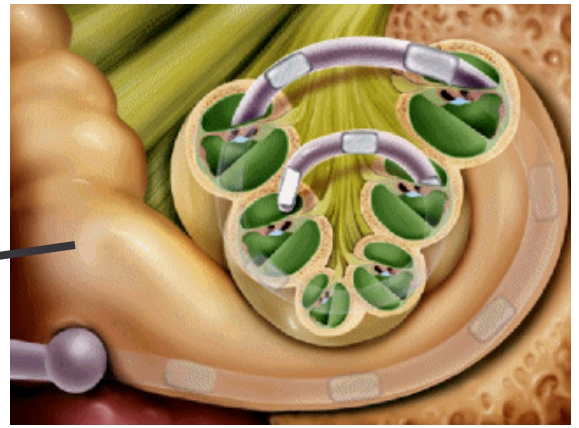


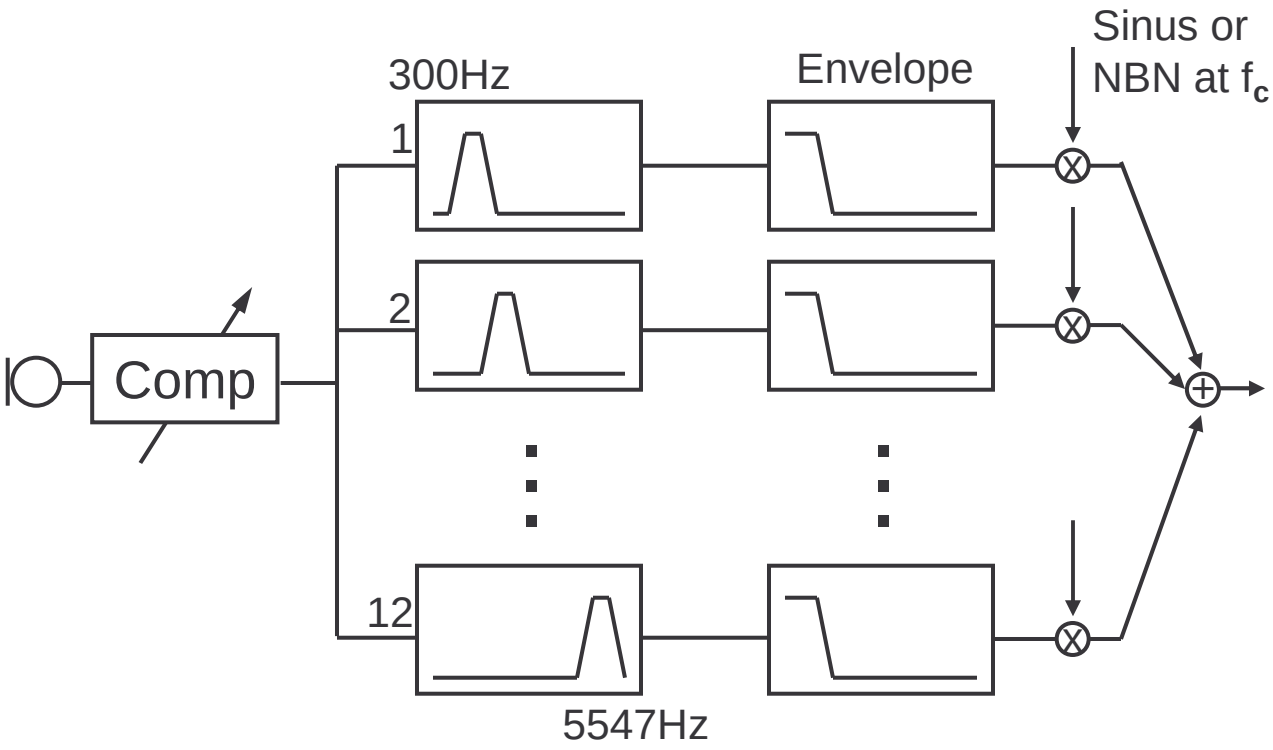
Med-El GmbH, Innsbruck

Multi-Channel CIs – Auditory Simulation

Test speech reception with different pre-processing

Modulation of sinusoids or narrow-band noise

Original

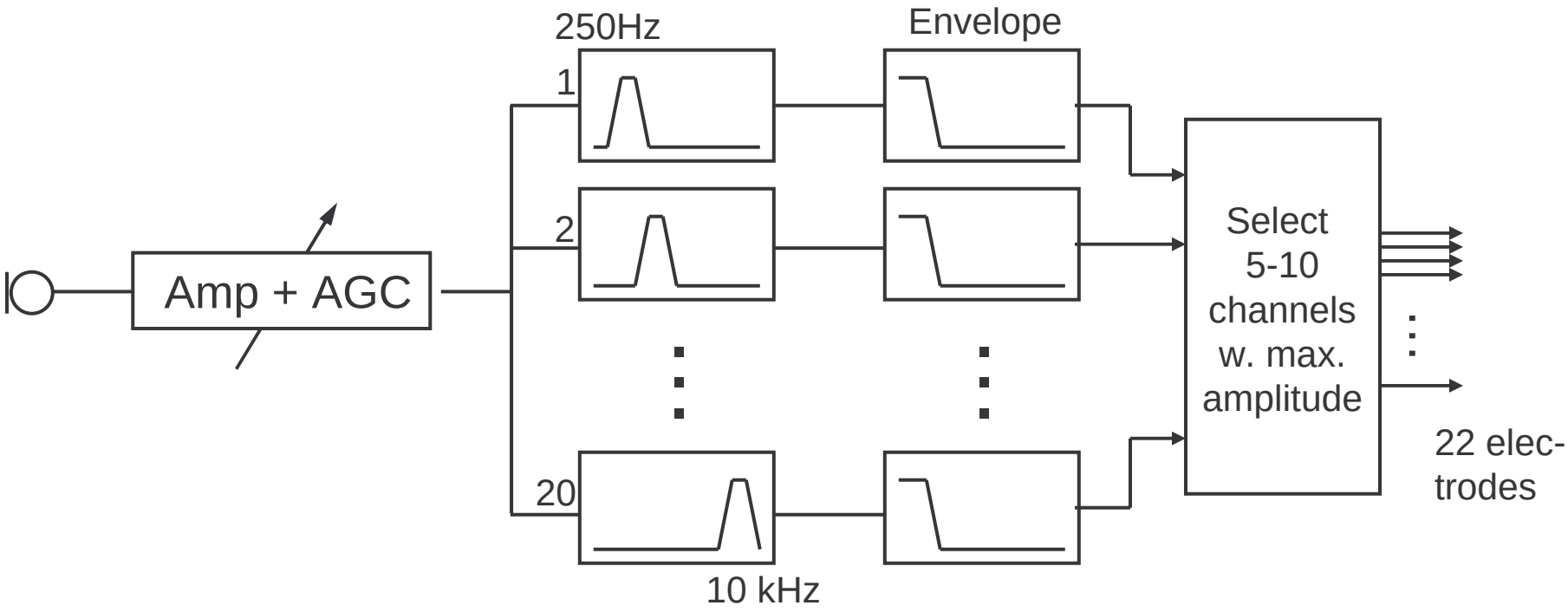


Ch	Sinus	Noise
3		
5		
9		
3+5		
9+11		
3+7+11		
1-6		
7-12		

All channels, sinusoids: (12-ch CIS)

All channels, noise: (12-ch CIS)

Waveform Strategies: SPEAK (n of m)



1995: Nucleus CI24M implant – SPEAK:

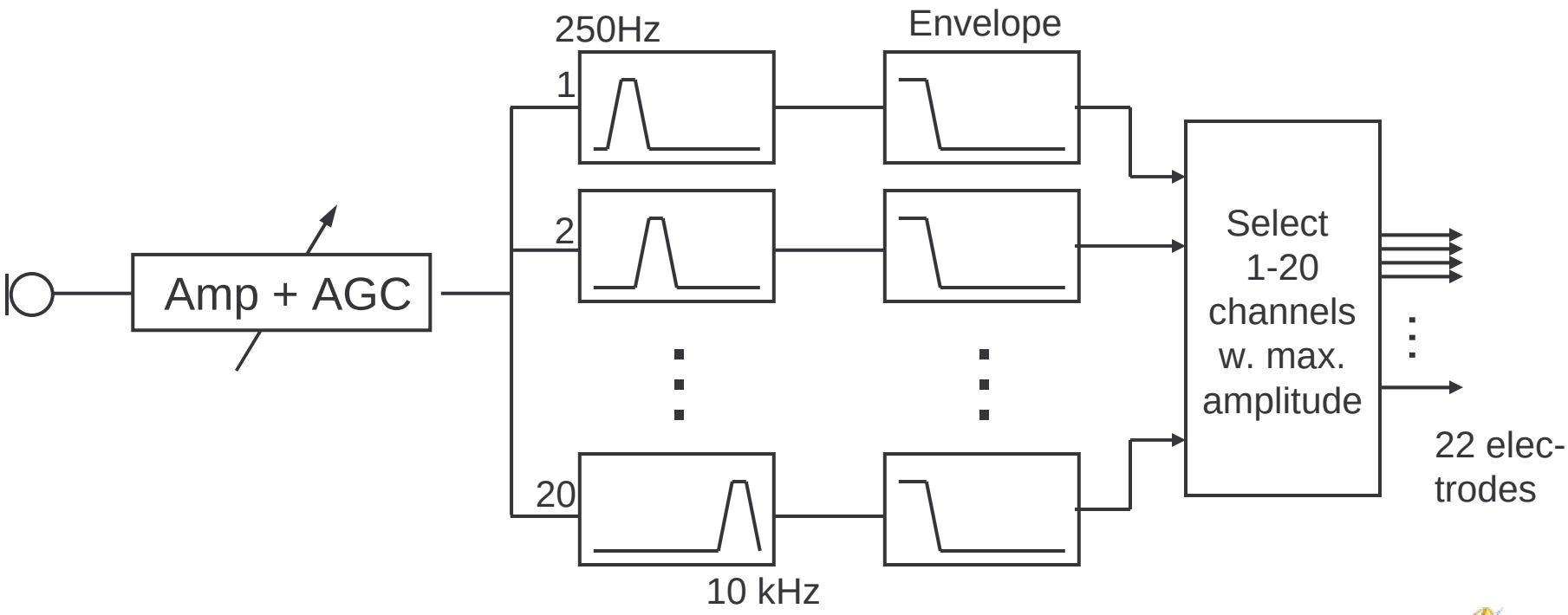
- Blockwise channel picking strategy
- Adaptive stimulation rate 180-300 pps/ch
- Behind-the-ear device available
- Better performance than MPEAK (feature extraction)

Original:

6 ch, sinusoids:

6 ch, noise:

Waveform Strategies: From SPEAK to ACE



2000: From SPEAK to **ACE:**

- Up to 2400 pps/ch and 14400 pps overall
- 8-16 ch used in clinical setting
- Subjective preference: 60% ACE, 23% SPEAK
- CUNY sentences in noise: 63% SPEAK, 71% ACE (Skinner, 2002)

Original:

12 ch, sinusoids:

12 ch, noise:

Cochlear Implants – Current and Future

Manufacturers:

- Nucleus/Cochlear Corp., Lane Cove, Australia
- MedEl GmbH., Innsbruck, Austria
- Advanced Bionics/Clarion, Valencia, CA, USA:

HiRes 90K Implant:

- Higher stimulation rates: 83.000 pps
- Achieve natural, stochastical nerve response
- 16 channels, simultaneous, partially simultaneous and non-simultaneous operation: channel overlap
- Pulsatile or analog
- Monopolar, bipolar, or multi-polar
- Telemetry possibilities, MRI compatibility

Adv. Bionics

Cochlear Implants – Future Outlook

- **Channel interaction – electrode design**
  - limit current spread: perimodiolar electrode placement
  - high-rate stimulation seems to allow better preservation of temporal information in nerve
- **Speech and music perception** – new algorithms
  - base on cochlea-preprocessing + compression
  - achieve natural, stochastical nerve response
- **Improve listening in noise**
  - Noise reduction algorithms
  - Directional microphones
- **Restoration of binaural abilities**
  - Improves speech perception especially in noise
  - Localization of sound sources

Simulation

Original

Cochlear Implants – Future Outlook

- **Electro-acoustic stimulation**
  - Preserve low-frequency hearing during surgery
  - Find CI-algorithms that add on to acoustic information
- **Reduce variability between subjects**
  - Find factors: channel interaction, age, time of implantation, training, …
  - Modeling, Prediction from psychophysics
- **Pre-surgery prediction**
- **Fitting parameters for the audiologist**
  - Efficient and accurate individual adjustments
  - Reduction of number of parameters

Summary

- **History** of electrical stimulation
- **Single-channel cochlear implants**
  - stimulate with analog, band-passed signal
- **Multi-channel cochlear implants**
  - Feature extraction strategies
    - F0/F2, F0/F1/F2, MPEAK
    - Features of speech coded
  - Waveform strategies:
    - CIS, SPEAK, ACE
    - Cochlear preprocessing mimicked by filterbank
- **Outlook:** Achieve natural response on nerve


Thank you!
Questions?