ICAD' 01

Modeling of Psychoacoustics and Auditory Perception: How Far Can We Go?

Matti Karjalainen

Helsinki University of Technology
Laboratory of Acoustics and Audio Signal Processing
Espoo, Finland

This presentation is available in:

`www.acoustics.hut.fi/~mak/ICADkeynote.pdf`

For refs, see also: `www.acoustics.hut.fi/publications`

ICAD' 01

CONTENTS

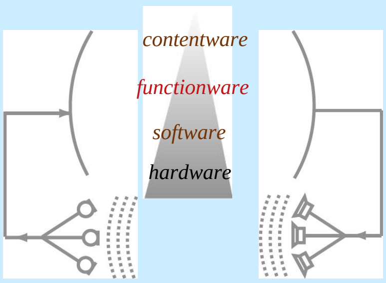
- Introduction and motivation
- Psychoacoustics and auditory functions
- Computational auditory modeling
- Modeling of basic psychoacoustic features
- Binaural modeling and spatial hearing
- Advanced modeling and CASA
- Applications of auditory modeling
- What cannot be done (yet or ever)?
- Future challenges

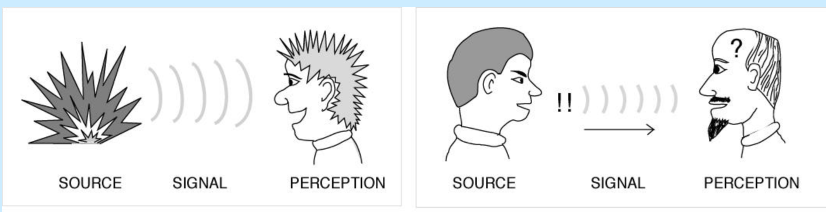
MOTIVATION

- ***Computational modeling of how we hear and perceive sounds*** is a target of active research because:
  - It adds to our knowledge on human auditory functions by enabling the testing of theories on complex auditory functions
  - It is a key enabling approach to new applications in audio, speech, and multimedia
  - Dream of advanced ”artificial listener”

FRAMEWORKS for MODELING Communication by Sound and Voice

- *Sound source modeling*
  - **physical modeling**
- *Signal modeling*
  - **channel modeling and DSP**
- *Listener modeling*
  - **auditory modeling**



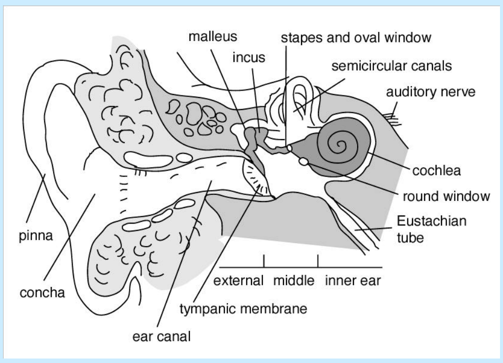


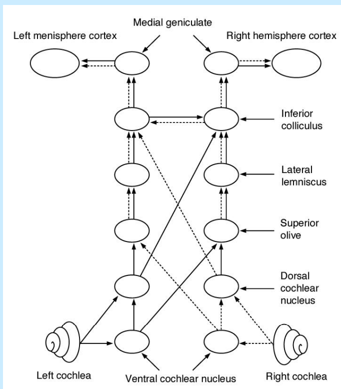
HEARING RESEARCH

- Physiology of hearing
  - *Physically/chemically measurable (objective) properties of hearing*
- Psychoacoustics (auditory psychophysics)
  - *Subjective responses to objective stimuli*
- Cognitive properties of hearing
  - *High-level functional properties of hearing*

PERIPHERAL vs. CENTRAL HEARING

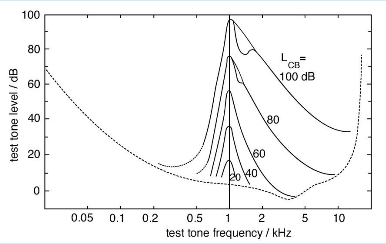
- Auditory periphery
  - *Relatively well known*
  - *Basic properties easy to model*
- Central auditory system
  - *Relatively weakly known*
  - *Difficult to model*

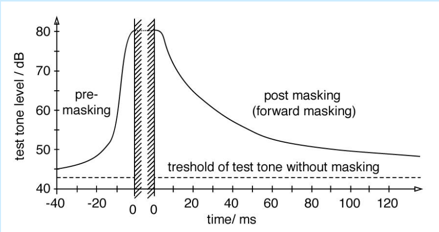




Psychoacoustics Concepts: MASKING

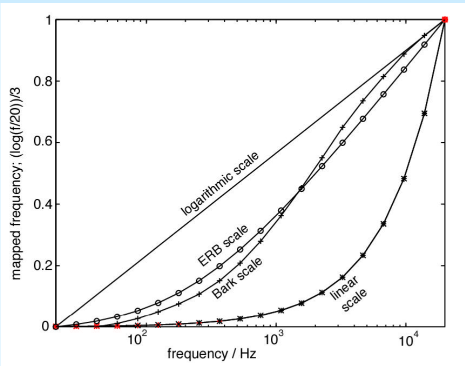
- Frequency masking
  - *Spreading of masking effect of a sound component in the frequency domain*
  - *More prominent upwards in frequency*
- Temporal masking
  - *Spreading of masking in the time domain*
  - *More prominent forward in time (lasts up to 200 ms)*





Psychoacoustics Concepts: PITCH

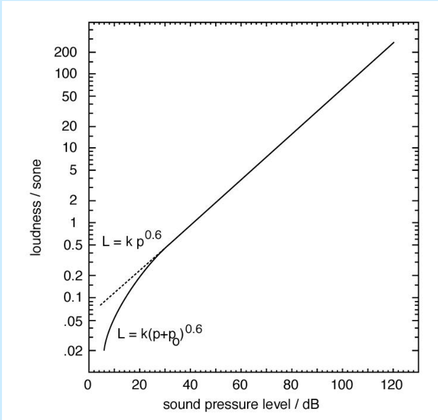
- **Pitch** = subjective sensation of sound on low/high scale
  - *Relation to frequency not linear, rather logarithmic-like*
  - ***ERB** (Equivalent Rectangular Bandwidth) scale theoretically best motivated*
  - ***Bark** scale technically most frequently used*



ICAD' 01

Psychoacoustics Concepts: LOUDNESS

- Loudness
  - Unit: 1 sone
  - 1 sone = 40 dB sine at 1 kHz
- Loudness level
  - Logarithmic measure
  - Unit: 1 phone
- Wideband loudness
  - Each critical band contributes equally to total loudness



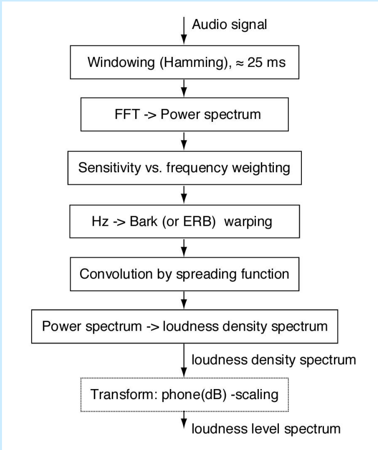
ICAD' 01

COMPUTATIONAL AUDITORY MODELING

- **Physiological models**
  - Goal: accurate simulation of physiological details
- **Psychoacoustical (perceptual) models**
  - Modeling of results of psychoacoustical facts and theories
- **Functional (hypothetical) higher level models**
  - Any potentially useful algorithms simulating auditory functions
- **Cognitive models**
  - Modeling cognitive processes in auditory perception
- **Simplified models for technical applications**
  - Mixtures of auditory, signal, and source modeling

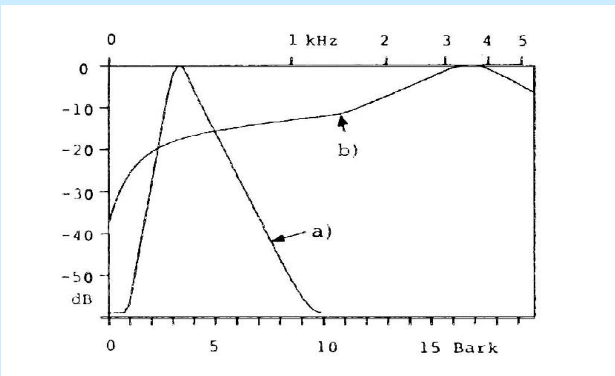
AUDITORY SPECTRUM THROUGH FFT

- A typical frequency-domain auditory spectrum computation principle
  - Frequency domain properties (particularly steady-state loudness) can fairly easily be modeled accurately
  - Zwicker’s model
  - Moore’s model
  - Problem: temporal properties not easily modeled accurately



EXAMPLES OF SIMPLE AUDITORY SPECTRA

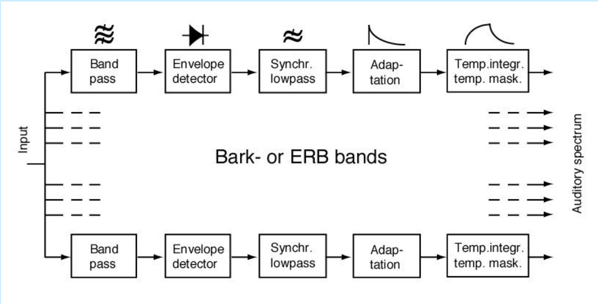
- Sine wave (a)
  - *Shows the spreading of excitation pattern for sine wave of 400 Hz*
- White noise (b)
  - *Shows the frequency sensitivity curve of the auditory system*



ICAD' 01

FILTERBANK-BASED AUDITORY MODELS

- Filterbank models of peripheral hearing
  - Bandpass filters simulate the frequency selectivity (critical bands) of the inner ear (basilar membrane and hair cells)
  - Half-wave rectification in each channel by hair cell neural firings
  - Neural firings (statistically) sychronized up to about 1-3 kHz
  - Adaptation of firing rate after onset
  - Temporal integration (lowpass filtering) in loudness formation and temporal masking

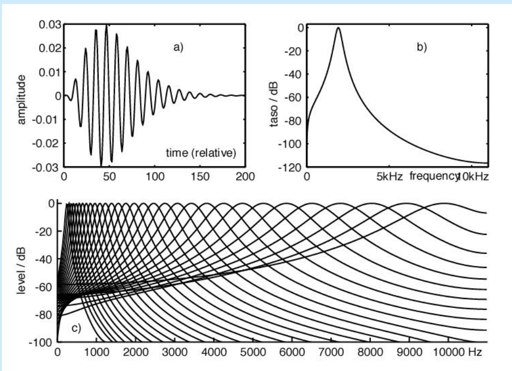


ICAD' 01

GAMMATONE FILTERBANKS

Temporal and magnitude response of a filterbank channel

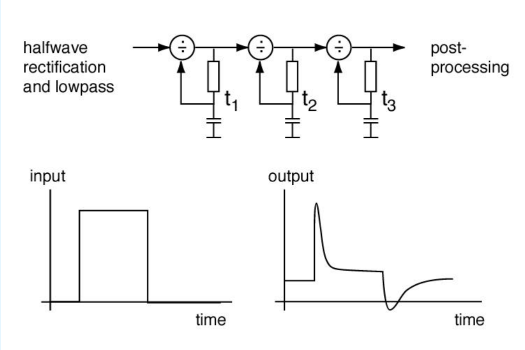
$$g(t) = a\, t^{n-1} e^{-2\pi\, b(f_c)\, t} \cos(2\pi f_c t + \phi)$$



ICAD' 01

NEURAL ADAPTATION

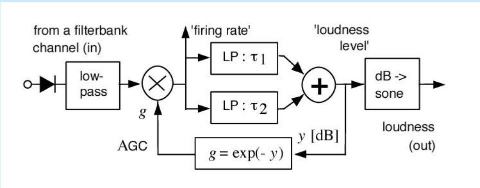
Neural adaptation model by Dau et al
Automatic gain control feedbacks used

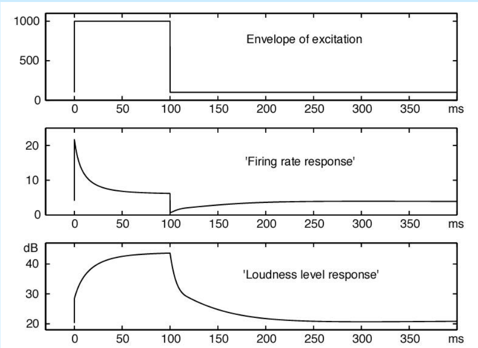


ICAD' 01

EXAMPLE OF TEMPORAL PROCESSOR

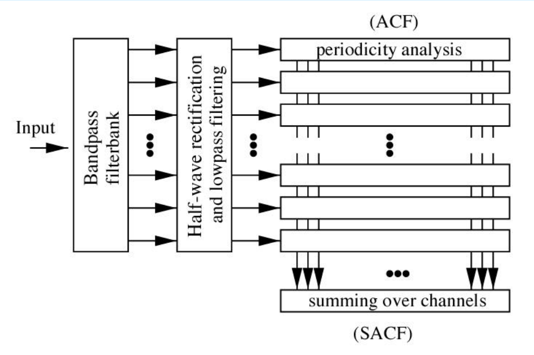
- Neural adaptation, temporal integration, and temporal masking model (Karjalainen 1996):
  - Neural feedback model
  - Adaptation (AGC) in firing rate simulation
  - Loudness (level) computation
  - Teporal masking effect
  - Temporal integration and firing rate adaptation shown to be complementary functions





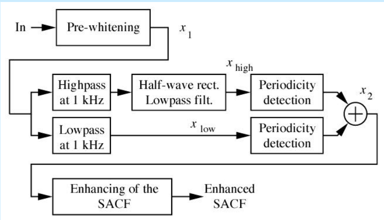
PERIODICITY (PITCH) ANALYSIS

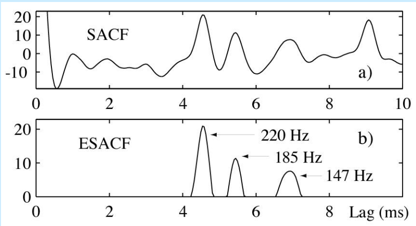
- Periodicity analysis model (Meddis)
  - *Bandpass filterbank + half-wave rectification + lowpass*
  - *Periodicity analysis in each critical band by autocorrelation*
  - *Summary autocorrelation function (SACF) a good periodicity indicator in many cases*
  - *Valid only at low frequencies (< 1kHz)*



MULTIPITCH ANALYSIS

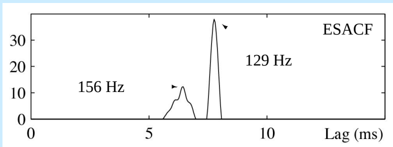
- **Enhanced SACF in two channels** (Tolonen & Karjalainen 2000)
  - *Only two channels used in SACF computation (below and above 1 kHz)*
  - *Enhanced SACF (= ESACF) for better resolving multiple pitches by removing periodic and negative peaks in autocorrelation function*
  - *Can resolve up to 3-5 simultaneous harmonic sounds*
  - *ESACF example mixture of 3 harmonic sounds (a musical chord):*

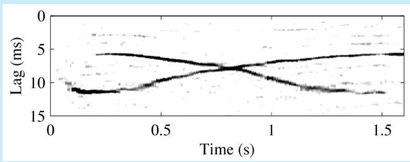


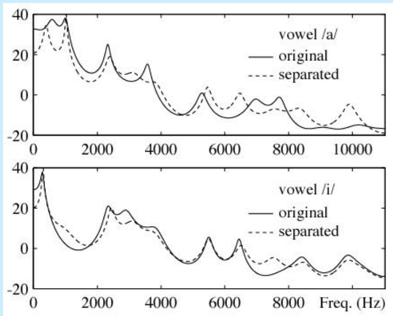


SOURCE SEPARATION (example)

- **Separation of simultaneous vowels** (Karjalainen & Tolonen 2000)
  - *– Multipitch analysis applied to find pitch values of two or more vowels*
  - *– Iterative technique can be used to improve multipitch analysis*
    - *Pitches are removed one by one from the mixture*
  - *– Separated vowel spectra estimated (for 2 vowels)*







ICAD' 01

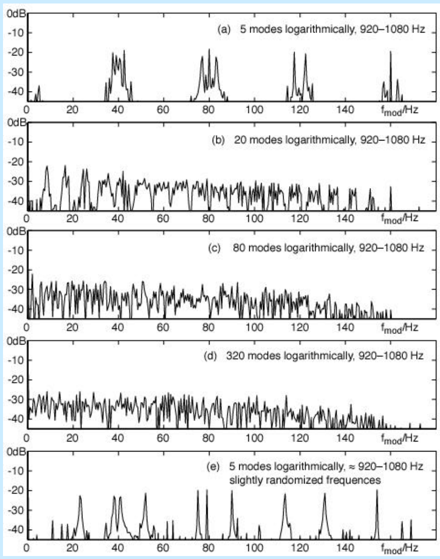
REVERBERATION VS. AUDITORY MODELING

Quality of late reverberation vs. modal density (Karjalainen & Järveläinen 2001)

• How many modes per critical band needed for perfect reverberation (or random noise)?

• How the auditory system resolves or analyzes a mixture of modes?

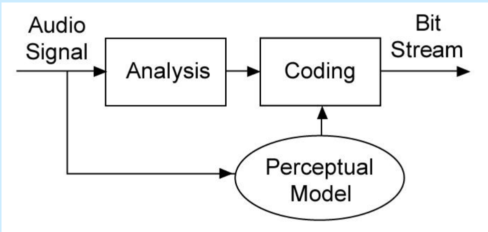
• Any perceivable periodicity higher in level than about -30 dB in a critical band envelope signal may degrade or color reverberation



ICAD' 01

Applications: AUDIO CODING

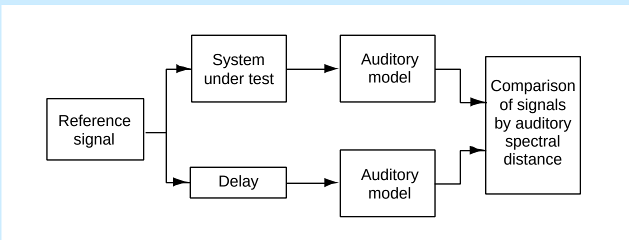
- Audio coding (such as MPEG-nn) is
  - probably the most important application so far utilizing auditory (perceptual) models
  - based on coding only auditorily relevant and non-redundant information of audio signals: data rate reduction about 10:1



ICAD' 01

Applications: SOUND QUALITY ESTIMATION

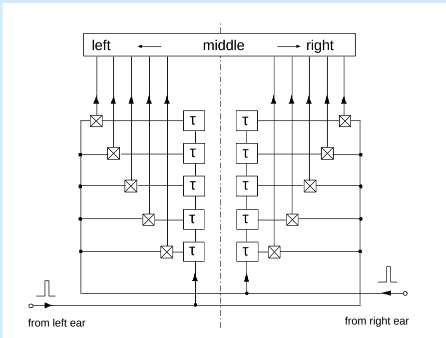
- Objective sound quality measures to correspond subjective perception must be based on auditory (perceptual) models
- Perceptual sound quality models can be applied to many problems, (although quite differently):
  - *Quality of audio and speech systems*
  - *Sound quality of performing spaces, musical instruments, etc.*
  - *Noise quality (annoyance, disturbance), product sound quality*
- Example: auditory principle for audio sound quality (Karjalainen 1981-85)



ICAD' 01

BINAURAL AUDITORY MODELING

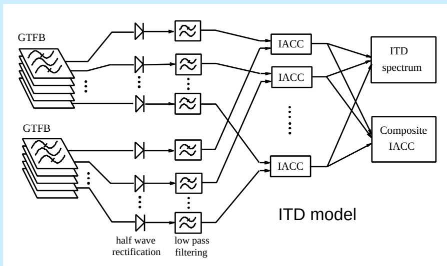
- In binaural (two-ear) listening, modeling of:
  - Sound source direction
  - Sound source distance
  - Binaural loudness, timbre, etc.
- Perceived direction is based primarily on:
  - Interaural time difference (ITD)
  - Interaural level difference (ILD)
  - Spectral cues
- Binaural auditory modeling less developed than modeling of monaural properties, although basic ideas have existed since 1940's (Jeffress)

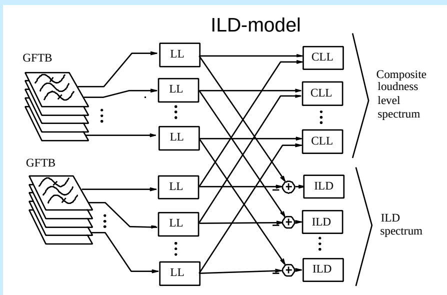


ICAD' 01

BINAURAL AUDITORY MODEL (Example)

- Computational modeling of binaural hearing has turned out to be successful, e.g., in amplitude-panned sound reproduction (Pulkki et al)
- ITD estimated from auditory interaural cross-correlations
- ILD estimated left-right ear signal levels in critical bands
- ITD and ILD features can be combined to perceived direction by various ways (table lookup, neural nets)
- These simple models are successful as far as the precedence effect does not have to be taken into account



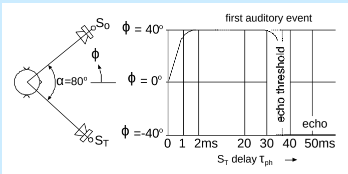


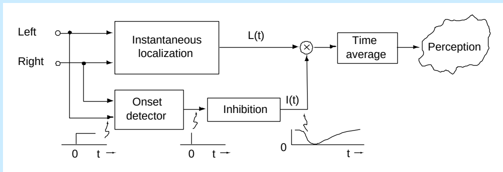
ICAD' 01

PRECEDENCE EFFECT MODELING

- Precedence effect
  - Repetitions of a sound within 1 – 30 ms after initial version don't affect perceived source direction (dominance of first wavefront)
  - No essential precedence effect found for example for timbre
  - Precedence effect is probably a mixture of high- and low-level processes

Model proposed by Zurek

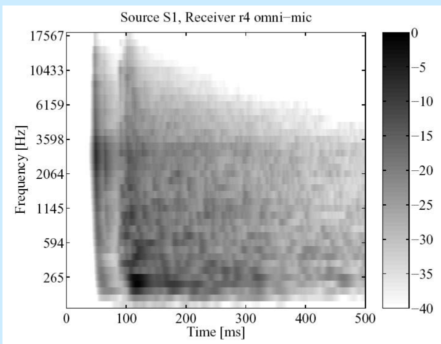


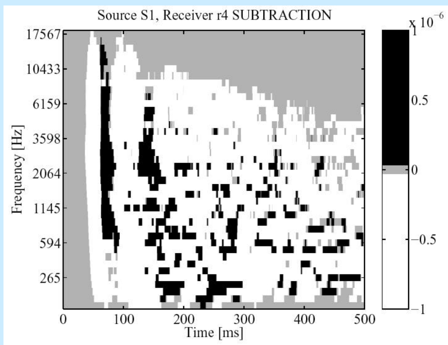


ICAD' 01

AUDITORY ANALYSIS OF SOUND FIELD

- Auditory modeling applied to room and concert hall responses (Lokki & Karjalainen 2000)
  - Auditory spectrogram (time-frequency plot) of room impulse response
  - Directional information, such as lateral or front-back 'spectrogram'

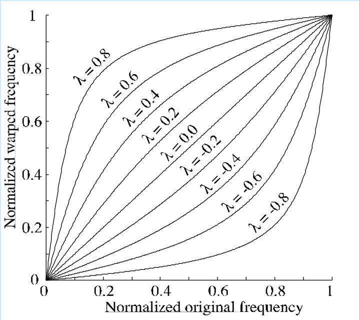


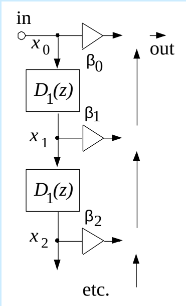


ICAD' 01

FREQUENCY-WARPED DSP vs. AUDITORY MODELING

- We have shown that frequency-warped DSP techniques are often an efficient and straightforward way of inclusing basic auditory features in traditional signal processing algorithms (Härmä et al 2000)
- Frequency warped techniques are based on replacing unit delays by first-order allpass filters.
- By proper parameters, warping makes a very good match to the Bark scale (linear Hz scale mapped to Bark scale, Smith & Abel)





ICAD' 01

AUDITORY SCENE ANALYSIS AND CASA

- ASA attempts to explain the ability of the auditory system to organize the incoming sound into separate sound objects (streams, events) and their interrelationships
- Important study: Bregman: Auditory Scene Analysis (1990)
- CASA (Computational ASA) has been developed for about 10 years based on ASA findings (Cooke, Ellis, etc.)
- Many challenging technical problems are more or less CASA type of problems:
  - Automatic transcription of music
  - Analysis of ambient and environmental sounds
  - Speech recognition in complex noisy environments
  - Audio content analysis

ICAD' 01

WHAT NEXT ?

- Development of useful models for difficult phenomena
  - *Precedence effect, separation of more complex sounds, etc.*
- More accurate time-frequency modeling
  - *Dynamic loudness, pre- and postmasking, level-dependent masking*
- Modeling of timbre perception
  - *Categorization of timbres*
- Modeling specific phenomena in music perception
  - *Consonance, dissonance, rhythm, sound textures*
- Much improved binaural auditory modeling needed
  - *Perceptual and cognitive modeling of sound environments (rooms, concert halls, etc.) including reverberant phenomena*
- Integration of existing models into large-scale models
  - *Needed for complex applications and for better overall understanding of auditory functions*
- Much work needed for high-level and cognitive modeling
- Improved computational auditory scene analysis (CASA)
- Etc, etc ....

ICAD' 01

HOW FAR CAN WE GO ?

Personal opinion:

In principle everything can be modeled computationally – (How about in practice?)

Time schedule of progress:

The most difficult (sub)problems take at least tens of years to solve even tentatively (cf., speech recognition)

Big challenge:

How to achive much improved automatic self-learning and organization principles?