Getting Started in Silicon Auditory Modelling

John Lazzaro
CS Division
UC Berkeley
lazzaro@cs.berkeley.edu

This is a bibliography for researchers interested in silicon auditory models. Silicon auditory models are integrated systems that compute known or proposed representations of biological audition; representations can either be neurophysiological or psychophysical in nature.

The field started as a reaction to work in computational modeling of auditory representations. Researchers who were interested in trying out these representations in engineering applications were limited by the computational requirements of computing the models. The focus so far has been on analog, weak-inversion MOS VLSI implementation, because of the low-power and density advantages of subthreshold analog processing.

The first section of this document attempts to be a comprehensive list of all publications on implementations of auditory models in hardware; the second section of the document is a contact list of researchers who have worked in the field. The document ends with several sections of introductory readings in fields related to silicon auditory models.

Please send any updates to this document to the address above.

Silicon Model Bibliography

Here is a list, intended to be complete as of May 1996, of "Silicon Auditory Modeling" papers.

1996

Bor, J. C. and Wu, C. Y. (1996) Analog electronic cochlea design using multiplexing switched-capacitor circuits. *IEEE Transactions on Neural Networks,* **7**:1, 155-166.

Sarpeshkar, R., Lyon, R. F., and Mead, C. A. (1996). An analog VLSI cochlea with new transconductance amplifiers and nonlinear gain control. *IEEE Conference on Circuits and Systems* (in press).

Sarpeshkar, R., Lyon, R. F., and Mead, C. A. (1996). Nonvolatile correction of Q-offsets and instabilities in cochlear filters *IEEE Conference on Circuits and Systems* (in press).

1995

Firth, P. M. and Andreou, A. G. (1995). A design framework for low power analog filter banks. *IEEE Transactions on Circuits and Systems I - Fundamental Theory and Applications,* **42**:11, 966-971.

Lazzaro, J. P., Wawrzynek J. (1995). Silicon models for auditory scene analysis. In Mozer, M., Touretsky, D., and Hasselmo, M. (eds), *Advances in Neural Information Processing Systems 8.* Cambridge, MA: MIT Press.

Lazzaro, J. P. and Wawrzynek, J. (1995). A multi-sender asynchronous extension to the address-event protocol. In Dally, W. J., Poulton, J. W., Ishii, A. T. (eds), *16th Conference on Advanced Research in VLSI,* pp. 158–169.

van Schaik, A., Fragniere, E., and Vittoz, E. (1995). Improved silicon cochlea using compatible lateral bipolar transistors. In Tourestzky, D. *et al.*, (eds) *Advances in Neural Information Processing Systems 8,* Cambridge,Mass: MIT Press.

1994

Bhadkamkar, N. A. (1994). Binaural source localizer chip using subthreshold analog CMOS. *IEEE International Conference on Neural Networks,* vol 3, 1866-70.

Cornil, J. P. and Jespers, P. G. A. (1994). A micropower switched capacitor implementation of the silicon cochlea. *Twentieth European Solid-State Circuits Conference. Proceedings.*100-103.

Lazzaro, J. P., Wawrzynek, J., and Kramer, A (1994). Systems technologies for silicon auditory models. *IEEE Micro*, **14**:3, 7-15.

Lin, J. F., Ki, W. H., Edwards, T., and Shamma, S. (1994). Analog VLSI implementations of auditory wavelet transforms using switched capacitor circuits. *IEEE Transactions on Circuits and Systems I - Fundamental Theory and Applications,* **41**:9, 572-583.

Toumazou, C., Ngarmnil, J., and Lande, T. S. (1994). Micropower log-domain filter for electronic cochlea. *Electronics Letters*, **30**:22, 1839-41.

1993

Andreou, A. G. and W. Liu, W. (1993) BiCMOS circuits for silicon cochleas. In Dedieu, H. (ed), *Proceedings of the European Conference on Circuit Theory and Design (ECCDT-93),* pp.503-508, Sept. 93.

Bhadkamkar, N. (1993). A variable resolution, nonlinear silicon cochlea. Stanford University Technical Report, CSL-TR-93-558, January.

Bhadkamkar, N. and Fowler, B. (1993). A sound localization system based on biological analogy. *Proceedings of the 1993 IEEE International Conference on Neural Networks.*

Park, J. C., Abel, C., and Ismail, M. (1993). Design of a silicon cochlea using MOS switched current techniques *Proceedings of the European Conference on Circuit Theory and Design (ECCDT-93),* pp. .269-274

Lazzaro, J. P., Wawrzynek, J., Mahowald., M., Sivilotti, M., Gillespie, D. (1993). Silicon auditory processors as computer peripherals. *IEEE Journal of Neural Networks* **4**:3 523–528.

Lazzaro, J. P., Wawrzynek, J., Mahowald., M., Sivilotti, M., Gillespie, D., (1993). Silicon auditory processors as computer peripherals. In Hanson, S., Cowan, J., and Giles C., (eds), *Advances in Neural Information Processing Systems 5.* San Mateo, CA: Morgan Kaufmann Publishers.

1992

Lin, J., Wing-Hung, K., Thompson, K., Shamma, S. (1992). Realization of cochlear filters by VLT switched-capacitor biquads. *Proceedings IEEE International Conference on Acoustics, Speech, and Signal Processing*, San Francisco, II-245.

Liu, W., Andreou, A., Goldstein, M. (1992). Voiced-speech representation by an analog silicon cochlea of the auditory periphery. *IEEE Neural Networks,* **3(3):** 477–487.

Lazzaro, J. P. (1992). Temporal adaptation in a silicon auditory nerve. In Moody, J., Hanson, S., Lippmann, R. (eds), *Advances in Neural Information Processing Systems 4.* San Mateo, CA: Morgan Kaufmann Publishers.

Summerfield, C. and Lyon, R. F. (1992) ASIC implementation of the Lyon cochlea model. *Proceedings IEEE International Conference on Acoustics, Speech, and Signal Processing*, San Francisco, V-673.

Watts, L., Kerns, D. A., Lyon, R. F., Mead, C. A. (1992). Improved implementation of the silicon cochlea. *IEEE Journal Solid State Circuits,* **27:** 5, 692-700.

1991

Lazzaro, J. P. (1991). Biologically-based auditory signal processing in analog VLSI. *IEEE Asilomar Conference on Signals, Systems, and Computers*, pp. 790-795.

Lazzaro, J. P. (1991). A silicon model of an auditory neural representation of spectral shape. *IEEE Journal Solid State Circuits* **26**: 772–777.

Liu, W., Andreou, A., Goldstein, M. (1991). Analog VLSI implementation of an auditory periphery model. In *Proceedings 25th Annual Conference on Information Sciences and Systems,* Baltimore, MD.

Lyon, R. F. (1991). CCD correlators for auditory models. *IEEE Asilomar Conference on Signals, Systems, and Computers.*

Lyon, R. F. (1991). Analog implementations of auditory models. *DARPA Workshop on Speech and Natural Language,* Morgan Kaufmann Publishers, San Mateo CA.

Mead, C. A., Arreguit, X., and Lazzaro, J. P. (1991). Analog VLSI models of binaural hearing. *IEEE Journal of Neural Networks* **2**: 230–236.

Watts, L., Lyon, R. F. and Mead, C. (1991). A bidirectional analog VLSI cochlear model," *Advanced Research in VLSI, Proceedings of the 1991 Santa Cruz Conference,* C. Sequin (ed.), Cambridge, MA: MIT Press, pp. 153–163.

1990

Lazzaro, J. and Mead, C. (1990). Silicon models of auditory localization. In Zornetzer, Davis, and Lau (eds), *An Introduction to Neural and Electronic Networks.* New York: Academic Press, pp. 158–174.

Lyon, R. F. (1990). VLSI and machines that hear. In R. Suaya and G. Birtwistle, eds., *VLSI and Parallel Computation*, Morgan Kaufmann Publishers, San Mateo CA.

1989

Lazzaro, J. and Mead, C. (1989). A silicon model of auditory localization. *Neural Computation* **1**: 41–70.

Lazzaro, J. and Mead, C. (1989). Silicon modeling of pitch perception. *Proceedings National Academy of Sciences* **86**: 9597–9601.

Lazzaro, J. and Mead, C. (1989). Circuit models of sensory transduction in the cochlea. In Mead, C. and Ismail, M. (eds), *Analog VLSI Implementations of Neural Networks.* Norwell, MA: Kluwer Academic Publishers, pp. 85-101.

Lyon, R. F., and Mead, C. (1989). Electronic cochlea. Ch. 16, in C. Mead, *Analog VLSI and Neural Systems.* Reading, MA: Addison-Wesley.

1988 and earlier

Lyon, R. F. and Carver A. Mead, C. A. (1988). A CMOS VLSI cochlea. *Proceedings IEEE International Conference on Acoustics, Speech, and Signal Processing,* New York.

Lyon, R. F. (1988). Analog VLSI hearing systems. In Brodersen, R. W., and Moscovitz, H. S. (eds), *VLSI Signal Processing III (workshop proceedings),* IEEE Press, Nov., 1988.

Lyon, R. F., and Mead, C. (1988). An analog electronic cochlea. *IEEE Trans. Acoust., Speech, Signal Processing* vol. 36, pp. 1119–1134.

Mueller, P. and Lazzaro J. (1986). A machine for neural computation of acoustical patterns with applications to real-time speech recognition. In Denker, J. (ed), *Neural Networks for Computing (Snowbird, Utah).* American Institute of Physics Conference Proceeding 151, pp. 321-327.

Contact List

This section is a list of active researchers doing implementations of silicon auditory models. If you'd like to be included, please send me your contact information and I'll add you to the list!

Andreas G. Andreou
andreou@olympus.ece.jhu.edu
http://olympus.ece.jhu.edu/ andreou/andreou.html

Neal A. Bhadkamkar
neal@interval.com

Thomas G. Edwards
tedwards@src.umd.edu

Michael Godfrey
godfrey@isl.stanford.edu
http://www-isl.stanford.edu/people/godfrey/analog-lab.shtml

Doug Kerns
kernsdoug@aol.com

Tor Sverre Lande
bassen@ifi.uio.no
http://www.ifi.uio.no/ vlsi/eindex.html

John Lazzaro
lazzaro@cs.berkeley.edu
http://www.cs.berkeley.edu/ lazzaro

Richard Lyon
lyon@apple.com
http://www.pcmp.caltech.edu/ dick/

G. Machado
g.machado@imperial.ac.uk

Gillian Marshall
marshall@signal.dra.hmg.gb

Paul Mueller
mueller@hodgkin.med.upenn.edu

Rahul Sarpeshkar
rahul@hobiecat.pcmp.caltech.edu
http://www.pcmp.caltech.edu/ rahul/

Andre van Schaik
vschaik@di.epfl.ch
http://diwww.epfl.ch/w3lami/team/vschaik/

Chris Toumazou
c.toumazou@ic.ac.uk
http://www.ee.ic.ac.uk/hp/staff/ctoumazou.html

Steve Watkins
stevew@pcsi.com

Introductory Reading Lists

The following sections are good introductory reading lists for many of the disciplines somehow connected to implementing auditory models in hardware. The following topics are covered

- Auditory Modeling
- Auditory Neurophysiology
- Auditory Psychophysics
- Cochlear Implants
- Cochlear Mechanics
- Entrepreneurship
- Pitch Perception
- Phonology
- Speech Processing by Engineers
- VLSI and Computer Architecture

Suggestions for additional readings are always welcome!

Auditory Modeling

Computational models of auditory perception are often present as a component of auditory neurophysiology and auditory psychophysics; in this context the modeling has the primary goal of accurately modeling the scientific data. Other modelers aim at a more abstract level of detail. One recent collection of model papers that tend towards the abstract is

Cooke, M., Beet, S., Crawford, M (1993). *Visual representations of speech signals,* New York: John Wiley and Sons.

An earlier collection of auditory modeling papers appeared as a special issue of the Journal of Phonetics:

Greenberg, S. (special issue editor) (1988). *The Journal of Phonetics*, Vol 16.

Auditory Neurophysiology

The following two publications were written as general introductions to auditory neurophysiology; these books are aimed at both clinical and academic audiences, so readers from a wide variety of backgrounds should feel comfortable with the material. For readers interested in a longer treatment of the material:

J. O. Pickles, *An introduction to the physiology of hearing,* San Diego, CA: Academic Press, 1992.

and for readers interested in a shorter treatment:

Evans, E. F. (1982). Functional anatomy of the auditory system. In Barlow, H. B. and Mollon, J. D. (eds), *The Senses.* Cambridge, England: Cambridge University Press, p. 251.

These books will provide you with a good conceptual grounding of the broad framework of biological audition. If you want to go further, I would suggest the following collection of papers:

G. M. Edelman, G. M., Gall, W. E., and W. M. Cowan, W. M. (1988) *Auditory Function* New York: Wiley.

For further reading, two journals, The Journal of the Acoustical Society of America and Hearing Research, are the major specialty journals in the field. Several other archival journals, such as the Journal of Neuroscience and the Journal of Neurophysiology, are also major sources of information; in addition, major advances are sometimes presented in Nature and Science.

Auditory Psychophysics

A good introduction to auditory psychophysics is the book

Moore, B. C. J., *An Introduction to the Psychology of Hearing,* Academic Press, London, 1989.

Traditional psychophysics is a very quantitative field, concerned with the limits of perception. The following books take a more qualitative approach, focusing on the human ability to listen to many sounds concurrently in a natural environment:

Bregman, A. S. (1990) *Auditory scene analysis,* Cambridge, Mass: MIT Press.

Handel, Stephen (1989) *Listening : an introduction to the perception of auditory events,* Cambridge, Mass: MIT Press.

Hearing Research and The Journal of the Acoustical Society of America both include psychophysical papers. Musically-oriented papers can be found in the The Computer Music Journal and Music Perception.

Cochlear Implants

Readers with interest in biomedical issues in auditory physiology, and in particular cochlear implants, should start with the following review articles:

Watson, C.S. (1991) Speech-perception aids for hearing-impaired people - current status and needed research, *Journal of the Acoustical Society of America,* Vol 90, No. 2, 637-685.

Feigenbaum, E. (1987) Cochlear implant devices for the profoundly hearing-impaired. *IEEE Engineering in Medicine and Biology Magazine,* Vol 6(2):10-21.

Wilson, B.S. et al (1991) Better speech recognition with cochlear implants. *Nature,* Vol. 352, No. 6332:236-238.

For further reading on biomedical issues, the following books are also recommended:

Haggard, M. P. and Evans, E. F. (eds) (1987), *Hearing,* British Medical Bulletin, Vol 43, No 4, October, Published for the British Council by Churchill Livingstone.

G. M. Clark, Y. C. Tong, and J. F. Patrick (eds) (1990) *Cochlear Prosthesis,* Edinborough:Churchill Livingstone.

Cochlear Mechanics

Understanding the electromechanical natural of the inner ear in mathematical terms is a subject with a long and fascinating history; researchers interested in designing better silicon cochleas have much to learn by understanding the field in a scholarly way. A series of three review papers by deBoer serve as a good introduction to the field; the most recent paper, that contains references to the earlier reviews, is:

deBoer, E. (1991). Auditory Physics - Physical Principals in Hearing Theory. *Physics Reports - Review Section of Physics Letters,* **203:3,** pp. 125-231.

An alternative introduction to cochlear mechanics appears in the following technical report:

Lyon, R. F. and Mead, C. (1989). Cochlear Hydrodynamics Demystified. *Caltech Computer Science Technical Report,* Caltech-CS-TR-88-4.

And finally, for a description of cochlear mechanics that trades lengthy mathematical derivations for circuit analogs:

Allen, J. B. (1985) Cochlear Modeling. *IEEE ASSP Magazine,* January, pp. 3–29.

Entrepreneurship

Silicon audition might well find its way into practical applications in the next decade, and small companies often launch nascent technologies into the marketplace. I recommend these two books for good introductions to the product marketing and company formation aspects of entrepreneurship.

Moore, G. A. (1991). *Crossing the chasm : marketing and selling technology products to mainstream customers.* New York : HarperBusiness.

Nesheim, J. L (1992). *High tech startup : the complete how-to handbook for creating successful new high tech companies.* Saratoga, CA : Electronic Trends.

Pitch Perception

This section derived from Malcolm Slaney's contribution to the comp.dsp Frequently-Asked-Questions list on Usenet.

Human pitch perception is a long-studied field in psychoacoustics, and there is much data on human performance in controlled experiments. Pitch is officially defined as "That attribute of auditory sensation in terms of which sounds may be ordered on a musical scale." Several good examples illustrating the subtleties of pitch perception are included in the "Auditory Demonstrations CD" which is available from the Acoustical Society of America, Woodbury, NY 10797 for $20.

There have been many algorithms proposed for pitch perception for engineering applications. An algorithm implementation that matches a large body of psychoacoustical work, but which is computationally very intensive, is presented in the paper:

Slaney, M. and Lyon, R. F. (1990). A Perceptual Pitch Detector. *Proceedings of the International Conference of Acoustics, Speech, and Signal Processing,* Albuquerque, New Mexico.

The definitive papers describing the use of such a perceptual pitch detector as applied to the classical pitch literature is in:

Meddis, R. and Hewitt, M. J. (1991) Virtual pitch and phase sensitivity of a computer model of the auditory periphery. I. Pitch identification. *Journal of the Acoustical Society of America* Vol 89 No 6 : pp. 2866-2682.

Meddis, R. and Hewitt, M. J. (1991) Virtual pitch and phase sensitivity of a computer model of the auditory periphery. II. Phase sensitivity. *Journal of the Acoustical Society of America* Vol 89 No 6 : pp. 2883-2894.

Both of the papers above model pitch using a spatial-temporal model of the cochlea. This is a matter of some debate within the auditory community and most of the current work that argues for a pure spectral method start with the work of Goldstein:

Goldstein, J. (1973). An optimum processor theory for the central formation of the pitch of complex tones. *Journal of the Acoustical Society of America* Vol 54, 1496-1516.

See the comp.dsp frequently-asked questions (FAQ) list for more information on pitch, specifically engineering approaches to pitch tracking.

Phonology

Phonology is focused on understanding the speech signal itself, its acoustic origins and the resulting waveforms. If you're sending speech sounds through auditory chips and interpreting the results visually, such knowledge is invaluable. A classical reference is:

Potter, R. K., Kopp, G. A., Green, H. C. (1966) *Visible Speech,* New York: Dover Publications

A modern version of this book is also highly recommended.

Edwards, H. T. (1992) *Applied Phonetics: The Sounds of American English,* San Diego: Singular Publishing.

Speech Processing by Engineers

In the context of telephony, communications, and speech recognition, engineers have made many contributions to audition. An enjoyable and easy to read introduction to the full span of this contribution can be found in this book:

Pelton, G. E. (1993). *Voice processing.* New York : McGraw-Hill.

For further readings into speech recognition, three recommended books are:

Rabiner, L. and Juang, B. (1993) *Fundamentals of Speech Recognition,* Englewood Cliffs: Prentice Hall.

Waibel, A. and Lee, K-F (eds) (1990). *Readings in Speech Recognition.* San Mateo: Morgan Kaufmann Publishers.

Bourlard, H. and Morgan, N. (1994) *Connectionist speech recognition: a hybrid approach,* Boston: Kluwer Academic Publishers.

These papers provide a good introduction to auditory modeling from an engineering perspective:

Lyon, R. F. (1982). A computational model of filtering, detection, and compression in the cochlea. *Proceedings of the International Conference on Acoustics Speech and Signal Processing,* pp. 1282-1285.

Lyon, R. F. (1984). Computational models of neural auditory processing. *Proceedings of the International Conference on Acoustics Speech and Signal Processing.*

The IEEE Journal of Acoustics, Speech, and Signal Processing is an excellent primary source for engineering work in speech; it has been recently divided into two journals, one of which focuses on speech work. In addition, the journal Computers, Speech, and Language is another good primary source, as is the yearly conference proceedings of the International Conference on Acoustics Speech and Signal Processing (ICASSP).

VLSI and Computer Architecture

The style of analog VLSI design used by many of the current researchers in silicon modeling is best described in the book and review paper:

C. A. Mead (1989). *Analog VLSI and neural systems.* Reading, MA: Addison-Wesley.

Andreou, A.G., Boahen K. A., and Pouliquen, P. O. (1991). Current-mode subthreshold MOS circuits for analog VLSI neural systems, *IEEE Transactions on Neural Networks,* **2**:2, p. 205.

Several good analog introductory textbooks are:

Gray, P. R. and Meyer, R. G. (1993). *Analysis and design of analog integrated circuits.* New York : Wiley.

Grebene, A. B. (1984). *Bipolar and MOS analog integrated circuit design,* New York: Wiley.

Gregorian, R. and Temes, G. C. (1986). *Analog MOS integrated circuits for signal processing.* New York: Wiley.

Ismail, M. and Fiez, T. (1994). *Analog VLSI : signal and information processing.* New York: McGraw Hill.

Laker, K. R. and Sansen, W. M. C. (1994). *Design of analog integrated circuits and systems.* New York: McGraw Hill.

Toumazou, C., Hughes, J. B., and Battersby, N. C. (1993). *Switched-currents: an analogue technique for digital technology,* IEE (Peregrinus): London.

Trontelj, J., Trontelj, L., Shenton, G. (1989). *Analog digital ASIC design,* London: McGraw-Hill.

For digital design, good introductions to computer architecture and VLSI issues are, respectively:

Patterson, D. A. and Hennessy, J. L. (1996) *Computer architecture: a quantitative approach (2nd edition).* San Mateo : Morgan Kauffman.

Weste, N. H. E. and Eshraghian, K. (1993) *Principles of CMOS VLSI design : a systems perspective.* Reading, Mass. : Addison-Wesley.

The IEEE Journal of Solid State Circuits and is a good primary source for analog VLSI research; silicon models of biology are also frequently found in IEEE Transactions on Circuits and Systems I and II, the Kluwer journal Analog Integrated Circuits and Signal Processing, and IEEE Journal of Neural Networks. The Neural Information Processing Systems conference books are another good source of information, as are proceedings of the International Conference on Microelectronics for Neural Networks (a European conference) and the IEEE Conference on Circuits and Systems.

Electronic Resources

In addition to the documents mentioned above, the Internet has several resources of interest. The Usenet groups comp.arch (computer architecture), comp.lsi (lsi design), comp.lsi.cad (lsi cad tools), comp.speech (speech processing), and comp.dsp (dsp processing) have good signal-to-noise ratios and are worth reading. In particular, the Frequently-Asked-Questions (FAQ) list for comp.lsi.cad is an excellent source of information on free and commercial CAD tools, and the comp.dsp FAQ is a good resource as well. For Web sites, a good place to start are the Web pointers in the "Contact List" section of this document.

Acknowledgments

Thanks to Andreas Andreou, Neal Bhadkamkar, Elizabeth Corey, Micheal Godfrey, Doug Kerns, Richard Lyon, Gerson Machado, Rahul Sarpeshkar, and Malcolm Slaney for suggestions and additions to this bibliography.