Engineering Hope with Biomimetic Systems

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NSF Biomimetic MicroElectronics Systems Engineering Research Center
(A Partnership of UCSC, USC, Caltech)

SRC BioElectronics Round Table (BERT)
11/4/2008
Outline of Presentation

- Introduction
- Biomimetic Systems
- Enabling Technology for Biomimetic Systems
- Concluding Remarks
The work reported here receives funding from National Science Foundation, Department of Energy, DARPA, Department of VA, UC MICRO, Department of Defense, Semiconductor Research Corp, National Chiao-Tung University (Taiwan)

Faculty

- Mark Humayun, MD, PhD
- Gene de Juan, MD
- Robert Greenberg, MD, PhD
- James Weiland, PhD
- Harvey Fishman, MD, PhD
- Kimberly Cocherham, MD
- Yu-lung Hsin, MD
- J. C. Chiou, PhD
- NSF ERC-BMES/DOE Artificial Retina Team

Graduate Students: more than 20 graduate students
1864 - Maxwell’s *Dynamical Theory of the Electromagnetic Field*
   Wait 40 years: wireless telegraph, early radio invented
   Wait 40 more years: television is dominant medium

1913 - Bohr Model of Atom
   Wait 40 years: transistor invented
   Wait 40 more years: electronics dominates

1953 - Watson & Crick describe structure of DNA
   Wait 40 years: human genome sequenced
   Wait 40 more years: biotechnology dominates

(by Professor Bruce Wheeler of UIUC)
Biotechnology

- Pharmaceutics and Bio-Pharmaceutics
  - $350B

- Biomedical Engineering
  - Biomedical devices and Instruments
  - Diagnostic tools
  - $300B at present and $1,800B at 2020 (Academia Sinica)

- Healthcare Cost – 16% of GDP in USA
NeuroTechnology

- Opportunity and Challenges in Emerging New Industry: Neurotechnology for neural disorders (Revenue of $120.5B in 2006, growing rate > 10%)
  - Neuro-Pharmaceutics ($101B)
  - Neuro-Engineering
    - Biomedical devices ($4.5B)
      - Prosthetics
      - Neural/muscle stimulation
      - Neuro-surgical
    - Diagnostic tools ($15B)
      - Bio-imaging
      - Bio-informatics
      - Neuroscience/cognition tools
Brain - Source of Neural Disorders

- 100 billion neurons (grey matter)
- 100 trillion inter-neural connections (white matter)
- A synaptic gap: 20-30 nm
- Power: 20-30 watts
Brain-related illnesses afflict more than two billion people worldwide, 100 million in USA

The worldwide economic burden of this problem has reached more than $2 trillion per year; more than $1 trillion in the U.S. alone

http://www.neuroinsights.com

A new NASDAQ Index (NERV) was created for neurotechnology

Worldwide government research, private funding and public investment trends
We believe the largest markets in healthcare will be solved with biomimetic devices.

Biomimetic Devices will significantly change lifestyles in the 21st century.

Disorders Treated by Biomimetic Systems:

- **Vision**
  - Blindness – retinal prosthetics
  - Denervated eye-lid (Bell Palsy)
  - Presbyopia – Lens implantation for 50+
- **Neural Disorders and DBS**
  - Epilepsy, Parkinson, Compulsory, Alzheimer's
  - Prostate Cancer and Impotence
  - Stroke and Dementia
- **Spinal Cord Injury** – stand and walk; bladder control
- **Pain Relief** – invasive or non-invasive devices
- **Anti-depression**
- **Obesity**
  - Diabetes – Implantable drug pumps
  - Heart Disease
- **Intelligent Artificial Upper or Lower Limbs**
- **Deaf** – Cochlear implant
- **Musculoskeletal** - Orthopedic Implants for Osteoarthritis
- **Defense** – Technologies to Improve Warfare
- **Implantable Renewable Energy**
  - Powers implantable devices
  - Metabolic fuel cell that runs on glucose
Biomimetic Systems

- Treatment of neurological disorders
- Restoration and repair of biological subsystems
- Performance Enhancement (Super-man/woman)
The overwhelming diversity of the research areas in Biomedical Engineering is rapidly fueled by

- “Clinical Pull” that identifies more medical problems to be solved
- “Technology Push” that invents new tools and techniques to advance the state-of-the-art
Microelectronics

Retinal Prosthesis to Restore Vision in Blind Patients

Scientists are also working on an artificial retina to help many blind people to see.... President Clinton in his 2000 State of the Union Address

Successful implants in six patients through Stimulation of Retina

Artificial Synapse Chip for Denervated Muscles

Modeling muscle stimulation and design of electronics

Prosthesis to Restore Mobility in SCI Patients

Stand/Walk/Sit

MicroSurgery for Axon Repair

Modeling dielectrophoresis, electrofusion and design of electronics

Epilepsy Implant

Neural Signal Recording

Neural Signal Processing

Brain-Machine Interface

Neural Signal Recording

Neural Signal Processing

Neuron-Chip Interface

Use nanotechnology to interface living tissue and electronic chips resulting in novel applications

25+ years microchip design experience

Prof. Wentai Liu, Campus Director of NSF Biomimetic Microelectronics Systems Engineering Research Center
Current In-Vitro/In-Vivo Experiments in IBR Lab

- 20 member talented and active research group conducting interdisciplinary research with $1,000,000 annual funding
- All systems are tested “beyond the bench” in vitro and in vivo

- Retinal implants – human trials already underway
  - USC, Second Sight, USA and Europe (2008)
- Epilepsy Implant
  - Nat’l Chiao Tung University and Tsu-Chi Medical Center (Taiwan)
- Bladder and bowel control for SCI
  - Huntington Medical Research Institutes
- Eyelid implants (closure)
  - Stanford University and VA-Palo Alto
- Eyelid implants (opening)
  - Smith Kettlewell Eye Research Institute
- Brain Machine Interface
  - CalTech
- Muscle limb implants
  - Long Beach VA and Cleveland Clinics
- Cortical implants for cognition and motor control
  - Arizona State University
- In-Vitro and Ex-Vivo validation for dynamic membrane modeling
  - UCSC
Neuron Stimulation and Signal Recording

- **Action Potential:** 100Hz-10kHz (energy dominate around 1kHz), [10μV, 500μV]
- **Local Field Potential:** 1Hz-100Hz, 5mV, the composite extracellular potential field from several hundreds of neurons around the electrode tip.

**Recording:**
- Action Potential (intracellular)
- 1st derivative
- 2nd derivative

![Neuron diagram](attachment:image.png)
Muscle Stimulation - Contraction and Expansion

- Action potential propagates to the end plates at the buttons
- The action potential then propagates along the muscle fibers
Two major functions are **recording** and **stimulation**.

- Integrated/Miniaturized Low Power Stimulator/Recorder
- High Energy Efficiency Wireless Power Transmission
- Wireless Bi-directional Communication
- Closed-loop system
Professor Wentai Liu Group’s Chip Gallery

- Forward data detection analog front-end
- Back data detection analog part
- Class-E loop control circuits
- Comparators for clock recovery
Intraocular Retinal Prosthesis

Retinal Prosthesis Project
Retinal Prosthesis

➢ To Bring Back Sight for the Blind with Retina Disease

- Stem cell approach
- Gene therapy approach
- Growth factor approach
- Transplantation approach
- Micro/nano-electronics approach - Prosthesis

- Retinitis Pigmentosa (RP - genetic) - 1 in 4000 incidence and 200,000 in USA, 12 millions worldwide
- Age-related Macular Degeneration (AMD) – 6 millions of Americans (dried AMD)
Retinal Prosthesis - A Neural Implant to Restore Vision

- Restore useful vision to the blind using microelectronics
  - First, restore vision that will enable unaided mobility for the totally blind
  - Second, restore reading and face recognition to the functionally/legally blind
- Project initiated in 1988 by Dr. Mark Humayun (medicine) and Dr. Wentai Liu (engineering)
- Now a multi-disciplinary multi-institutional project with over five million dollars annual funding and commercial company for product manufacturing
**Dual Band Power and Data Telemetry**

- **Dual Band Telemetry**
- **Power Carrier: 2 MHz**
- **Data Carrier: 22 MHz**
- **Hybrid Telemetry Link achieves both**
  - High Power Transmission Efficiency
  - High Forward Data Rate

- 5x5 photo sensor and signal driver
- 1:5 multiplexing, 4bit resolution 100 channel output stimulator using single current mirror for each channel
- ASK demodulator with hysteresis for reliable data recovery. Achieving data rates of up to 250kb/s
- 64 channel stimulator with two independent DACs per each channel creating independent anodic and cathodic pulses (A-60 core)
- Advanced stimulator with multi bias DAC technique reducing 8-bit DAC area to 52% allowing more spatial resolution
- 1:8 demux driver with variable gain and current limiting charge cancellation
- Wireless power transmitter circuits and reverse data demodulator
- Wireless power regulation and reverse data transmitter
- 8-channel driver with 6-bit DAC with variable full scale and current limiting charge cancellation
- 64-channel driver with 4-bit DAC with variable full scale in 5V sub-micron CMOS

1 Mbps dual band telemetry data demodulator in 5V sub-micron CMOS

Test chip with 12-channel stimulator, CUP output pad, regulator in 32V deep sub-micron CMOS

2 Mbps fully integrated dual band telemetry data demodulator in 5V sub-micron CMOS

High voltage deep sub-micron CMOS process for the first time to meet the stimulation requirements of 1000+ channels
First in Sight (Reading)
(First Chronic Implant in Feb. 2002)
Epilepsy Implant – Prediction, Detection, and Intervention

Collaborators:
• Yu-Lung Hsin (MD), Tsu-Chi Medical Center, Taiwan
• Biomimetic System Research Center, Nat’l Chiao-Tung University, Taiwan
Epilepsy is one of the most common neurological disorder and has no age, racial, social, sexual or geographical boundaries.

Up to 5% of people in the world may have at least one seizure in their lives.

At any one point in time, 50 million people have epilepsy, especially in childhood, adolescence and old age.

Epilepsy can have profound social, physical and psychological consequences.

http://www.who.int/mediacentre/factsheets/fs165/en/
Biomimetic System for Epilepsy

Collaborated with Tsu Chi Medical Center (Hualien, Taiwan)
Eyelid Reanimation: A Hybrid Muscle Implantable System

Collaborators:
- Kim Cocheram (MD), VA Palo Alto
- Juan Sandiego, Stanford University
Electrochemical Stimulation Experiment

Automatic experimental environment is developed

- All experimental equipments are controlled by PC in a pre-programmed sequence
  - A National Instrument device is used as interface among PC and all equipments
  - A high speed camera is used to capture eyelid closure at 200 frame/sec

- Advantages:
  - All experiment equipments are synchronized, so the eyelid response time can be precisely measured
  - Reduce error introduced from human intervention
  - Highly improve experiment efficiency

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![Diagram of Blink Analysis Software and Programmable, Automatic, and Synchronized Experiment Platform](image-url)
Prosthesis for Spinal Cord Injury

Lower Limb Control
Bladder/Vowel control
Prosthesis for Spinal Cord Injury

Lower Limb Control
Bladder/Vowel control
Wireless neural recording technology to sense signals from the brain

Restoring functions in patients with spinal cord injury, and other neural disorders (arguably the biggest challenge in field of neural prosthesis)

Enable sophisticated experiments in free running animals in natural environment without wires and boxes (current systems limit animal movement and number of channels)
Signal from brain do not reach spinal cord after injury

Intraspinal Microstimulation (ISMS) selectively stimulates spinal neurons for bladder control and voiding

Pikov et al., Journal of Neural Engineering, 2007

Technology needed:
- Penetrating microelectrodes
- High density stimulator
Brain-Machine Interface:

Shark Head Implant
Enabling Technology

Smart Electrode
Electrode/electronics/sensor
Signal processing
Abiotic interface
Power source
Packaging
Wireless technology
Enabling Technology

- Miniaturization and Integration (wishful list, but some have already happened)
  - Smart 3D electrode with navigation and self-tune
  - Better Packaging
  - Better power source
  - Hybrid sensor – electrical/biochemical/optical
  - Sophisticated signal processing
  - Closed loop hybrid system
  - Access of a single cell in-vitro and in-vivo
  - Magnetic stimulation
  - BioSpice project
Closed Loop System: (Brain Controlled Limb)

- **Cortical Motor Plan (Detection)**
- **Spinal-like Regulator**
- **Musculoskeletal System**
- **Preflexes**
- **Visual feedback**

**Task**

- **Prosthetic Limb**
- **FES Limb**
- **Actuators**

**Perception**

**Intent**

**State**

**Feedback**

**Control**
Electrode: Self-Navigation (Fine GPS)
Enabling Technology – Wireless Recording

- Develop an effective and efficient neural recording/stimulation system
  - Real time (throughput and latency)
  - Robust Detection and Classification (noise and movement)
  - Wireless Telemetry (power and data)
  - Miniaturized Integrated Circuits (power and size)

- Enable complex experiments and study of new cognitive phenomena through sophisticated tools with advanced capabilities beyond existing recording systems
  - Unrestrained Behaving Animals in Natural Environment
  - Multiple Channels ranging from 10’s to 100’s
  - Miniaturized Wearable or Implantable Device
Chip Architecture (NEUREC4.0)
Chip Specs

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
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<tbody>
<tr>
<td>Number of channels</td>
<td>128</td>
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<tr>
<td>Signal gain of the preamp</td>
<td>40dB</td>
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<tr>
<td>Input impedance (at 1KHz)</td>
<td>8MΩ</td>
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<tr>
<td>Input referred noise</td>
<td>4.9μVrms</td>
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<tr>
<td>CMRR of the preamp</td>
<td>90dB</td>
</tr>
<tr>
<td>PSRR of the preamp</td>
<td>80dB</td>
</tr>
<tr>
<td>LF roll-off of the preamp</td>
<td>0.1Hz ~ 200Hz *</td>
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<tr>
<td>HF roll-off of the preamp</td>
<td>2KHz ~ 20KHz *</td>
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<tr>
<td>Signal gain of the 2nd amp</td>
<td>17dB ~ 20dB *</td>
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<tr>
<td>ADC resolution</td>
<td>6 ~ 9 bits *</td>
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<tr>
<td>ADC sampling rate</td>
<td>640Ksample/sec</td>
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<tr>
<td>Power dissipated by DSP</td>
<td>0.1mW</td>
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<tr>
<td>Maximum UWB data rate</td>
<td>150Mbps</td>
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<tr>
<td>Power dissipated by UWB</td>
<td>1.6mW</td>
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<tr>
<td>Power supply level</td>
<td>± 1.65V</td>
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<tr>
<td>Total chip power dissipation</td>
<td>6.0mW</td>
</tr>
<tr>
<td>Technology</td>
<td>0.35μm 4M2P CMOS</td>
</tr>
<tr>
<td>Total chip area</td>
<td>8.8mm× 7.2mm</td>
</tr>
</tbody>
</table>

* specification is programmable through external controls
Ex-Vivo Experiments

Amplifier output

DSPA output

UWB transmitter output

Serialized 9-bit sampled data

Redundant data

PSD at UWB Tx

FCC emission mask

Low pass filter & FPGA output

X: [10msec/div] Y: [100mV/div]

X: [30nsec/div] Y: [50mV/div]

X: [200nsec/div] Y: [200mV/div]
Sophisticated Signal Processing: Spike Sorting

Cat

Monkey

Snail

Human
Spike Sorting: Detection and Classification

- In neural recording, an electrode may be surrounded by multiple firing neurons, and it is necessary to resolve spikes into individual neuronal sources.
Feature Extraction Algorithm

- Spike Height and Width - *Simon, 1965*
- Principal Components Analysis (PCA) - *Zumsteg ZS, 2005, Thakur, 2007*
- Wavelets - *Quian Quiroga, 2004*
- Template Matching - *Lewicki, 1994, Zhang, 2004*
- Independent Component Analysis (ICA) - *Sakurai, 2006*

- **Deficiency for spike sorting**
  - Require long/frequent training for spike sorting
  - No on-chip implementation of classifier

- Looking for On-the-Flying or Minimal Training Sorting Algorithm which is possibly miniaturized

Derivative or Sample Selection based followed by Evolving Mean Shift (EMS) Classifier – *Z. Yang and W. Liu 2008*
Noise Spectrum Shaping using Derivative Waveform peaks + noise shaping filter implementation

- Neural Signal
- Energy-filter-based Spike Detection
- Channel-specified Noise Shaping Filter
- Feature Extractor With Maximum-minimum Detector
- Mean-shift Classification

Training Phase Required

Sorting Result

(a) Noise Power Spectrum
(b) Noise Power Spectrum of Waveform Derivative
(c) Noise Power Spectrum
(d) Noise Power Spectrum of Waveform Derivative
Different sample points contain different amounts of information.

\[ \text{info}_j = - \sum_{p_q > p_0} p_q \ln(p_q) \]
Prototype with Customized Sorting Chip

Waveform peaks + noise shaping filter implementation

Energy-filter based Spike Detection

Channel-specified Noise Shaping filter

Feature Extractor With Maximum-minimum Detector

Mean-shift Classification

Training Phase Required

Sorting Result

Custom software

NI card Custom IC

(a) (b) (c) (d) (e) (f) (g) (h) (i) (j) (k) (l) (m) (n) (o) (p)
## Performance Comparison

### Sample Selection + Derivative

- Waveform peaks
- Waveform peaks and width

### Performance Metrics

<table>
<thead>
<tr>
<th>Sequence Number</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
</tr>
</thead>
<tbody>
<tr>
<td>Informative Samples + Derivative Peaks</td>
<td>98%</td>
<td>98%</td>
<td>98%</td>
<td>97%</td>
<td>98%</td>
<td>99%</td>
<td>97%</td>
<td>92%</td>
<td>95%</td>
</tr>
<tr>
<td>PCA</td>
<td>98%</td>
<td>89%</td>
<td>60%</td>
<td>55%</td>
<td>98%</td>
<td>78%</td>
<td>80%</td>
<td>69%</td>
<td>55%</td>
</tr>
<tr>
<td>Wavelets</td>
<td>92%</td>
<td>91%</td>
<td>82%</td>
<td>57%</td>
<td>97%</td>
<td>68%</td>
<td>51%</td>
<td>49%</td>
<td>40%</td>
</tr>
<tr>
<td>Spike Peaks</td>
<td>34%</td>
<td>34%</td>
<td>35%</td>
<td>34%</td>
<td>36%</td>
<td>37%</td>
<td>36%</td>
<td>36%</td>
<td>35%</td>
</tr>
</tbody>
</table>
Evolving Mean Shift Classifier
Integration of Neural Signal Processor and Stimulator

Fully Integrated Platform IC

Programmable, Automatic, and Synchronized Experiment Platform

Under construction

Images for Post-experiment Analysis

Chemical Drug

Electrical Biphasic Current Waveform

a

b

c

d

Harvard Syringe Pump

Programmable Muscle Stimulator

National Instruments Data Acquisition Device

PC with LabView and Matlab Software
Understanding of an Ion Channel

From R. MacKinnon (Nobel Laureate)
Intracellular Recordings

- Extracellular microelectrodes generally record superimposed neural responses from multiple neurons.

- Intracellular recordings provide very localized membrane responses.

- Essential to quantify individual neuron’s response to specific stimulus.
Patch Clamp Recording

- Individual channel’s response are stochastic in nature.


Ion Channel Markov Model

Model work at Liu’s Lab

\[
\frac{dy}{dt} = -(R_{yz}(V_m, t) + R_{yz}(V_m, t))y + R_{yz}(V_m, t)z
\]

\[
\frac{dz}{dt} = -R_{yz}(V_m, t)z + R_{yz}(V_m, t)y + R_{qz}(V_m, t)q
\]

\[
\frac{dq}{dt} = R_{qz}(V_m, t)y - R_{qz}(V_m, t)q = -\frac{dy}{dt} - \frac{dz}{dt}
\]

\(y\): the number of sodium channels in activation state
\(z\): the number of sodium channels in rest state
\(q\): the number of sodium channels in inactivation state

\(R_{yz}\): transferring rate from activation to rest
\(R_{yz}\): transferring rate from activation to inactivation
\(R_{yz}\): transferring rate from rest to activation
\(R_{yz}\): transferring rate from inactivation to rest

\[
t_{\text{peak}} = (\ln \tau_2 - \ln \tau_1) / (\tau_1^{-1} - \tau_2^{-1});
\]

\[
\tau_{1,2}^{-1} = \frac{(R_{yz} + R_{yz} + R_{yz}) \mp \sqrt{\Delta}}{2},
\]

\[
\Delta = (R_{yz} + R_{yz} + R_{yz})^2 - 4R_{yz}R_{yz}.
\]

Experimental Results

Moran, O. and Conti, F. “Sodium ionic and gating currents in mammalian cells” European Biophysics Journal, 1990
Transmembrane Gating Current


Transmembrane Current Components?

- Ionic Current
- Displacement Current
- Gating Current

Liu’s Lab
- States diagram of the transmembrane protein currents in terms of sensor states.

- Assign the sensors with initial states, a Markov model could be used to quantify the current states of the sensors.

- Once all the sensors are in activated positions, the Na+ channel opens and ionic current appears.

- After a short period of activation, the sensors move to the inactivating state and close the channel.

- The movement of the sensors is in principle governed by thermal dynamics shown by the equations.


\[
k_f(V) = k_{eq} e^{\frac{z\beta(V_m-V_0)F}{RT}}
\]

\[
k_b(V) = k_{eq} e^{\frac{-z(1-\beta)(V_m-V_0)F}{RT}}
\]

\[
\beta \in (0.6, 0.8)
\]

\[
I_g(t) = \sum z_{ij}(k_{ij}P_i(t) - k_{ji}P_j(t))
\]
Alan Hodgkin and Andrew Huxley first predicted the existence of the transmembrane sensors and HH model was proposed accordingly. The transmembrane current is an average macro scope one. The sensors are proved to be charged proteins and responding to the transmembrane voltage changes. (Nobel Prize in Medicine, 1963)

Bert Sakmann and Erwin Neher measured an individual ionic channel current by using voltage clamp technique (Nobel Prize in Medicine, 1991)

R. MacKinnon is able to locate the protein sensors using optical measurement (Nobel Prize in Chemistry, 2003)

Challenges:

- $I_{gate}$ is a small transient current due to protein motion. To detect a single channel protein current composed of 12e charge proteins, the recording bandwidth is >1MHz with a signal amplitude of 100fA.
- The transmembrane voltage is required to be stabilized in 10us in order to filter out the effect of the displacement current.
- The membrane/circuit interface requires a custom design.
Magnetic Field Electrode and Stimulation

(No protein encapsulation problem as occurred in electrical field electrode)
- **Magnetic stimulation**
  - Noninvasive
  - Treatment for neurologic/psychiatric disorders:
    - Stroke, Parkinson's disease, dystonia, Tinnitus, depression, hallucination

- **Major challenges**
  - Large current to create magnetic field \(\sim 0.5\) tesla in the cortex; or current to create electric field \(\sim 10\)V/m or E field derivative \(\sim 10,000\)V/m\(^2\) for activating neurons in vitro
  - Coil design (appropriate geometry parameters, inductance value \(\sim\)tens uH, high Q)
  - Supporting electronics (ramp current through inductive load, up to 10,000V output, up to 10\(^8\) A/s slew rate for large coil)
  - Penetration depth (\(\sim\) coil radius)
  - Spatial selectivity

**Conceptual figure**
- Targeting cortex
- Targeting axons in vitro

**Stimulation protocols**
- No activation
- Activation

- coil current
- E field

- Poor
  - Inefficient
  - Good
Circuit & ramp current waveform
slew rate: $10^5$ A/sec
supply +/-15V
bandwidth 100KHz
only drive small coil

Quad coil setup, 20uH, R~1Ohm, coil radius ~1mm, penetrate depth ~ hundreds um

Neuron preparation:
H. Aspersa circumoesophageal ring

Magnetically triggered single action potentials using H. Aspersa neurobiological preparation (each trace represent one trail).

Magnetically triggered single action potentials using P. Clarkii neurobiological preparation.
(Basham, E., Yang, Z. and Liu, W. 08)
Access of a Single Cell
In-Vitro and In-Vivo
BioSpice Project for Neuroscience

- A Spice-like simulator consists of
  - Elements and models (type and geometry)
  - Connections and signals (mode of level and pulse)
  - Signal processing and matrix algorithms

(Figure taken from John Dowling, *The Retina*, Harvard University Press, 1987)
Concluding Remarks

- Many applications with biomimetic systems
- Enabling Technology for integrated and miniaturized biomimetic SYSTEM that can be deployed in experimental and clinical settings
  - Wireless EEG cap for epilepsy implant - a 128-channel 6-mW neural recording chip with programmable parameters, on-chip spike sorting and UWB telemetry has been designed, fabricated and tested
  - Wireless Stimulator - A 256-channel +/-12V single chip for retinal prosthesis with power receiver, data receiver, analog drivers and digital controllers has been designed and fabricated
- Many other enabling technologies are needed to develop
- However, manufacturing grade integrated hermetic packaging is the key to realize implantable systems