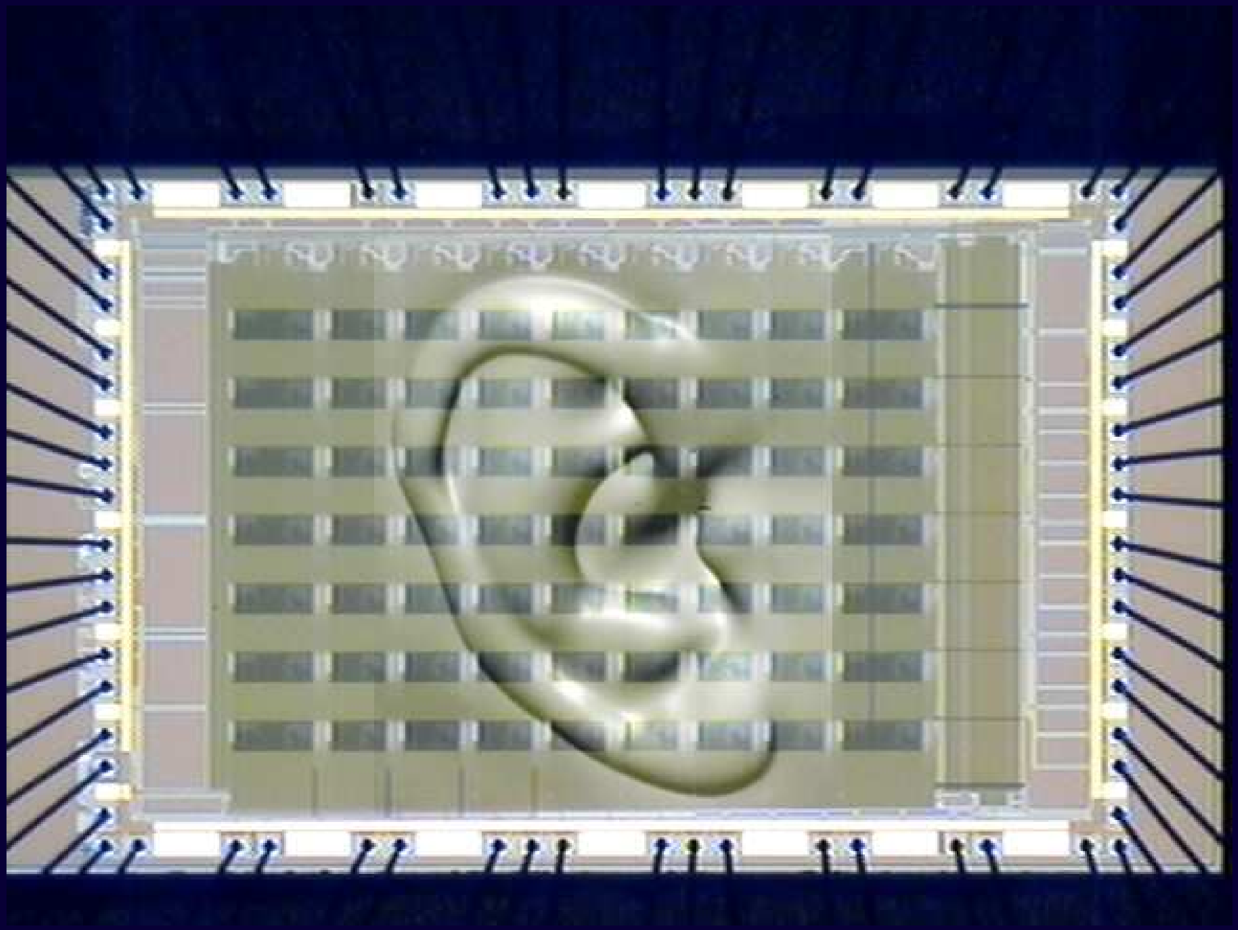
Neuromorphic Analog VLSI



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Neuromorphic Analog VLSI

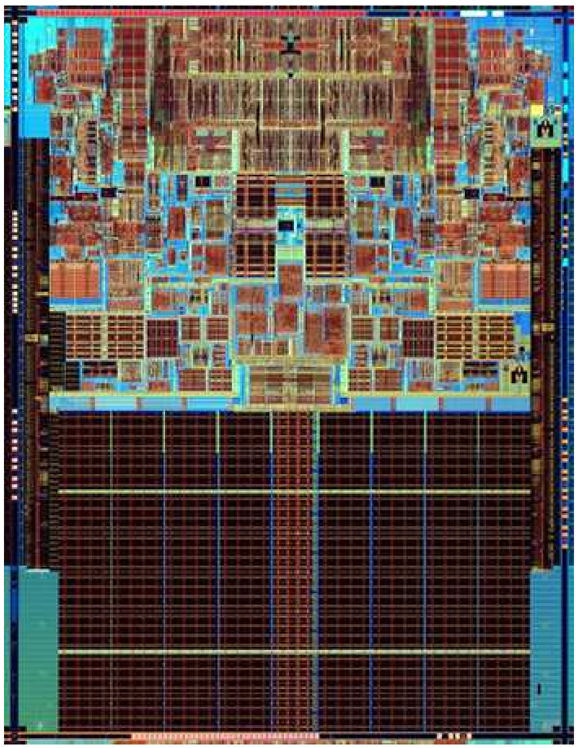
Each word has meaning

- Neuromorphic
- Analog
- VLSI

Engineering Versus Biology

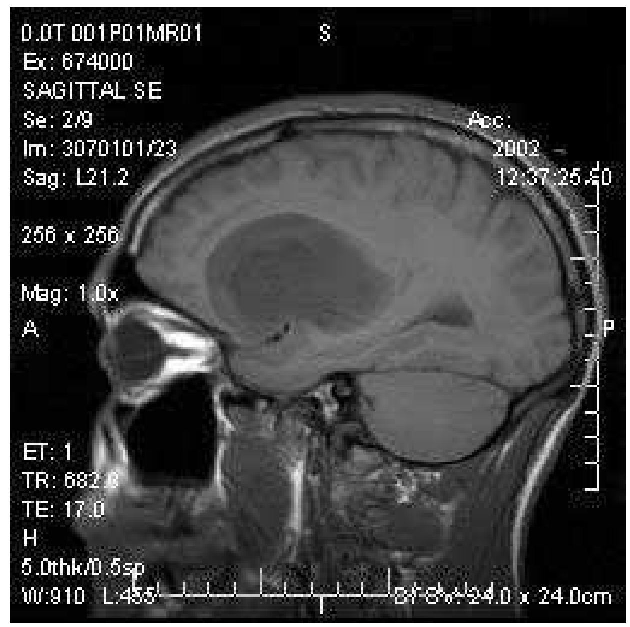
Core 2 Duo

- 65 watts
- 291 million transistors
- >200nW/transistor



Brain

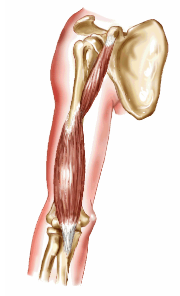
- 10 watts
- >100 billion neurons
- ~100pW/neuron



Neuromorphic/Bio-Mimetic Engineering

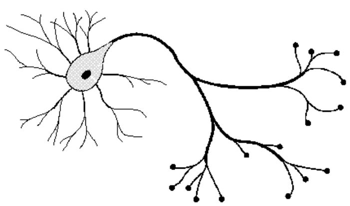
Neuromorphic/Bio-Mimetic Engineering – Using biology to inspire better engineering

- High-quality processing
- Low power consumption



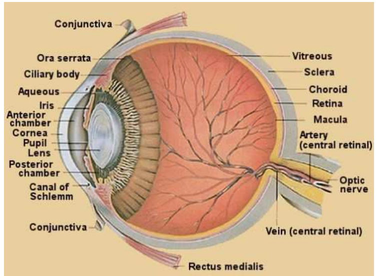
Sensorimotor Systems

- Intelligent robotics
- Intelligent controls
- Locomotive systems



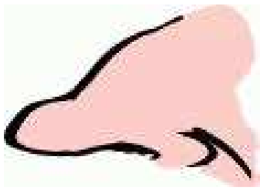
Neurons

- Systems that learn
- Systems that adapt
- Neural networks
- Understanding biology



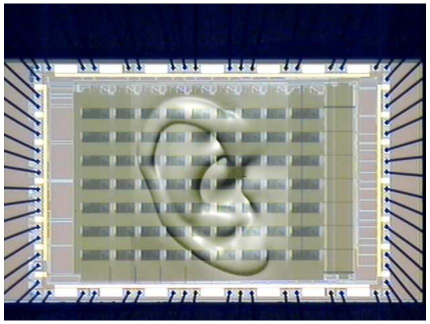
Silicon Retina

- CMOS imagers
- Intelligent imagers
- Retinal implants



Electronic Nose

- "Sniff out" odors
- Chemical sensors
- Drug traffic control
- Bio terror detection



Audio Systems

- Audio front ends
- Signal processing systems
- Hearing aids
- Cochlear implants

Why Neuromorphic Engineering?

Interest in exploring neuroscience ⟷ Interest in building neurally inspired systems

Key Advantages

- The dynamics is the system
- What if our primitive gates were a neuron computation? a synapse computation? a piece of dendritic cable?
- Efficient implementations compute *in* their memory elements – more efficient than directly reading all the coefficients
- Precise systems out of imprecise parts

Biology and Silicon Devices

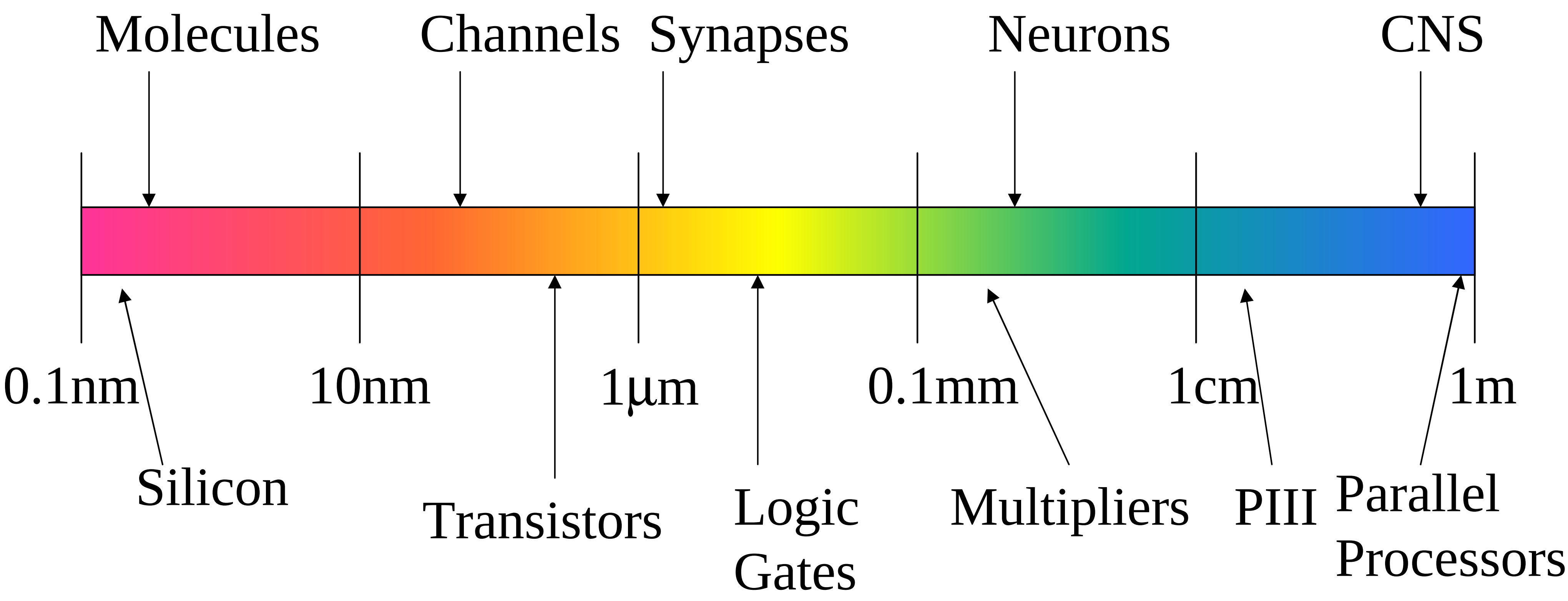
Similar physics of biological channels and p-n junctions

- Drift and Diffusion equations form a built-in Barrier
  (V_{bi} versus Nernst Potential)

- Exponential distribution of particles
  (Ions in biology and electrons/holes in silicon)

Both biological channels and transistors have a gating mechanism that modulates a channel.

Comparison of scales

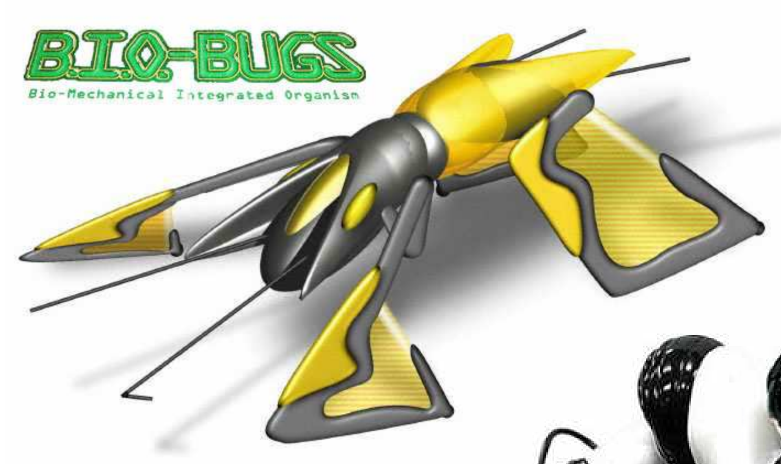


Neuromorphic Products

Neuromorphic Engineering is a relatively young field. However, it is already producing some very popular products.

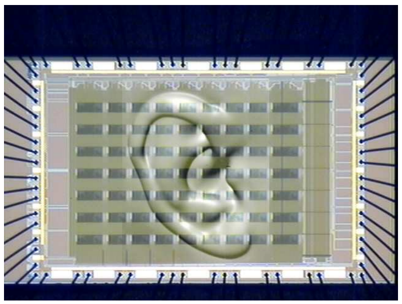
- Logitech Trackball
- B.I.O.-Bugs and Robosapien

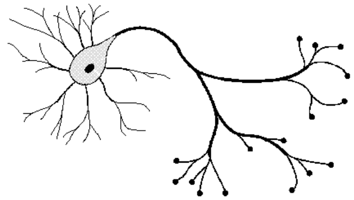
Neuromorphic Engineering is also helping to advance the field of neuroscience.

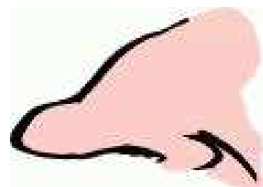


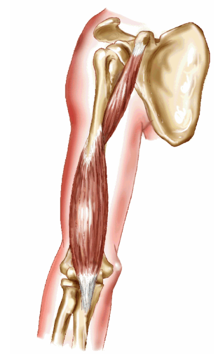
Where Can We Go?

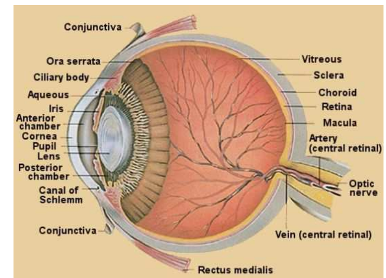
Bio-Inspired Systems





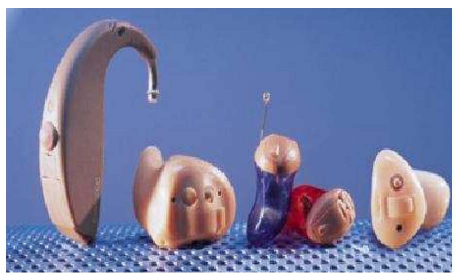


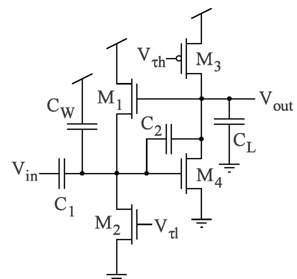




Smart Embedded Sensors

- Hearing Aids
- Cochlear Implants

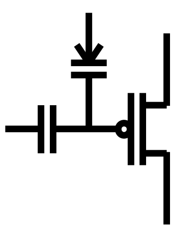




Low-Power Analog

- Consumer Electronics
- Implantable Devices
- Subthreshold Design

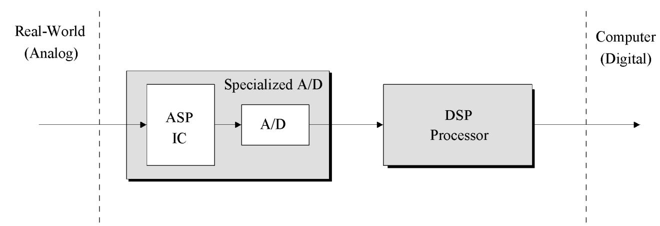
Analog Programmability



Provides digital features to the analog domain

- Programmability
- Accuracy
- Reconfigurability
- "Silicon Simulation"

Powerful Mixed-Signal Systems

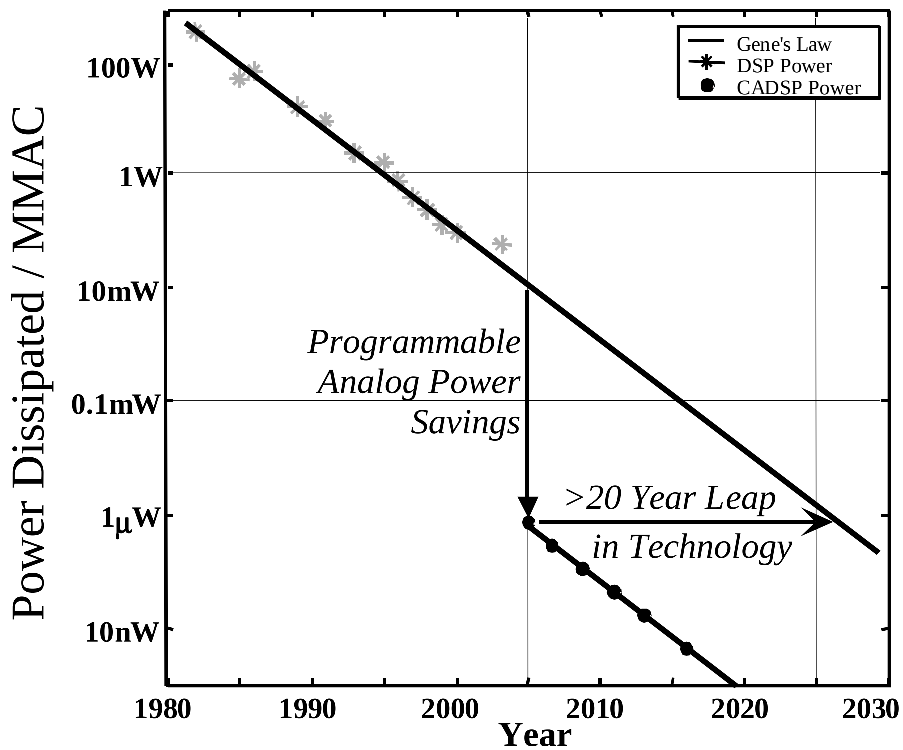


Analog alleviates the burden of the digital

Why Analog?

- Much lower power than digital
- Can perform many computations faster and more efficiently than digital
- Follows the same physical laws as biological systems

Analog Power Savings



Gene's Law

- Power consumption of integrated circuits decreases exponentially over time
- Follows Moore's Law
- Analog computation yields tremendous power savings equal to a >20 year leap in technology

FFT vs. Analog Cochlear Model

- 32 subbands at 44.1kHz
- FFT consumes ~5mW (audio-streamlined DSP)
- Analog consumes <5µW
- Analog power savings of >1000

Why VLSI?

- Cheaper (and easier to mass produce)
- Smaller
- Reduces power
- Keeps everything contained
  - Reduces noise
  - Reduces coupling from the environment
- Need a large number of transistors to perform real-world computations/tasks
- Allows a high density or circuit elements (therefore, VLSI reduces costs)

Difference Between Discrete and VLSI Design

	Analog VLSI	Discrete Analog
Device Size and Values	Relatively Small ex. Capacitors 10fF-10pF	Large ex. Capacitors 100pF-100μF
Resistors	Mostly bad Very expensive (large real estate)	Easy to Use Cheap
Inductors	Only feasible for very high frequencies Extremely expensive	Use when needed
Parasitics	Very big concern Seriously alter system performance	Exist, but rarely affect performance (Large size of devices and currents)
Matching	Difficult to deal with Major concern Stuck with whatever was fabricated ex. 50% mismatch is not uncommon	Concern Can more easily match/replace
Power	Efficient (Small currents pA-mA)	Use more power (Large currents >mA)

To Summarize …

Good Things about Analog VLSI

- Inexpensive
- Compact
- Power Efficient

Not So Good Things about Analog VLSI (not necessarily bad)

- Limited to transistors and capacitors (and sometimes resistors if a very good reason)
- Parasitics and device mismatch are big concerns
- You are stuck with what you built/fabricated (no swapping parts out)

However, Neuromorphic Analog VLSI is all about how to cope with these "problems," how to get around them, and how to use them as an advantage

Important Considerations

We will limit our discussion to CMOS technologies

- No BJTs
- Only MOSFETs

Therefore, we will discuss only silicon processes

Every story has a beginning…

- Begin at MOS device physics
- Look at circuits using the device properties
- Building small systems from circuits

Looking at connections with neurobiology