Analog Computing

Processing the Way Nature Intended

Overview

- Why analog?
- Historical applications
- Modern applications
- Universal issues
- The analog future
- Questions

Why Analog?

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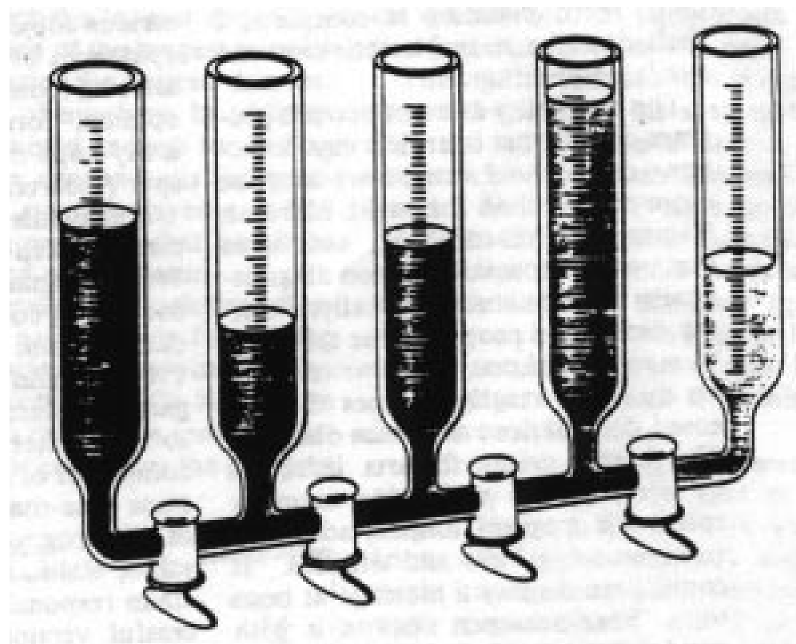
- The physical world is an amazingly accurate computational device
- We can design tools to exploit this computational power

Why “Analog”?

- Start with an abstract problem in need of solving
- Find an **analog** in the physical world
- Set up the analog as a physical experiment
- Perform the experiment and examine the results

Example: Averaging Numbers

- Avg. = $(n_1 + n_2 + n_3 + n_4 + n_5) / 5$
- Water seeks level
- Device takes 5 water "inputs"
- Produces measurable water "output"



Historical Applications

- The problem: 18.03 and 18.06
- Two general categories of device
- Mechanical
  - Thomson/Wilbur: Tilling-plate Solver
  - Bush/Hazen/Shannon: Differential Analyzer
- Electrical
  - Mallock: Electrical Calculating Machine
  - Haupt: A.C. Network Calculator
  - Soroka: Potentiometer Solver

Tilling-plate Solver

- Conceived by Thomson (later Lord Kelvin), 1878
- Improved and implemented by Wilbur at MIT, 1936
- Plates till at a particular angle based on applied forces of pulleys
- 18.06 device

Tilling-plate Solver

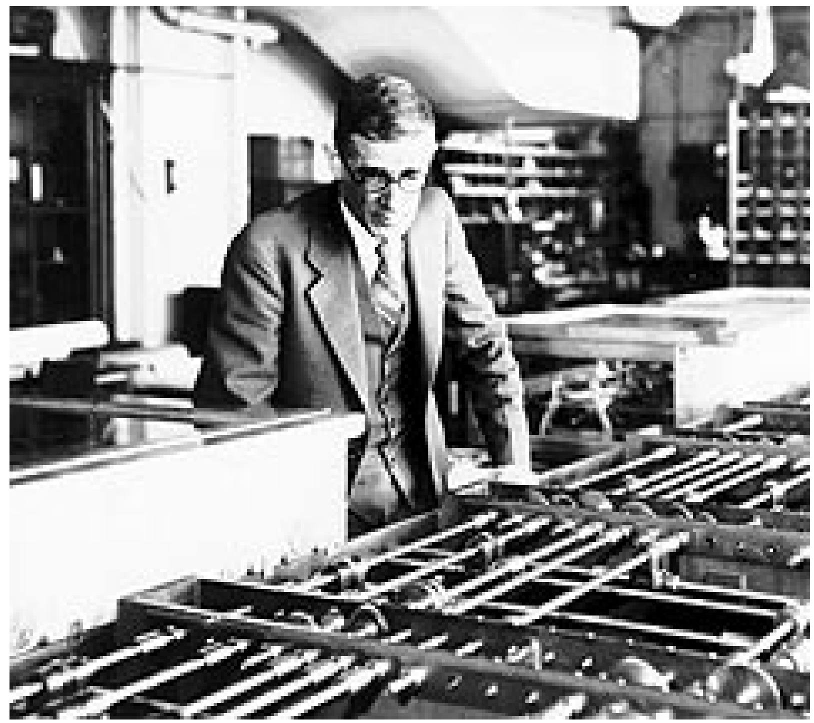
- Advantages
  - Straightforward design: build it if you get stuck on a deserted island
  - Similar calculations require proportionally smaller changes in machine settings
  - Works for negative and positive values
  - “Pushable”: changing the output changes the input

Tilling-plate Solver

- Disadvantages
  - Slow: hours to set up, still faster than manual calculation
  - Big: room-size, not desk-size
  - Specific: solves just one kind of (admittedly useful) problem

Differential Analyzer

- Designed by Bush and Hazen and built at MIT in 1931
- Composed of integrators, adders, gearboxes and input tables
- 18.03 machine: solved up to 6^{th} order differential equations



Differential Analyzer

- Advantages
  - General: Shannon demonstrates it can solve a wide range of problems
  - Programmable: use the same machine to solve different kinds of problem
  - Looks and sounds very cool

Differential Analyzer

- Disadvantages
  - Long setup time
  - Mechanically intricate: hard to build and maintain
  - Big: the next-generation “Rockefeller” machine weighed 100 tons for one order of magnitude improvement in accuracy

Electrical Calculating Machine

- Designed and built by Mallock, 1931
- Used switches to create variable coil loop transformers
- 18.06 machine: solved up to 10 simultaneous linear equations

Electrical Calculating Machine

- Advantages
  - Fast: low setup time, quick output response
  - Small: desk-size, not room-size
  - Simple: wiring is straightforward
  - Durable: only moving parts are switches
  - Auto-correcting

Electrical Calculating Machine

- Disadvantages
  - Single-purpose
  - Works only for positive coefficients
  - EMF

A.C. Network Calculator

- Described by Haupt paper
- Uses resistors and inductors in variable configurations – Kirchoff law equations
- Solves 18.06 and 18.03 problems

A.C. Network Calculator

- Advantages
  - Small
  - Flexible architecture: solves linear and non-linear equations
  - Durable: no moving parts
  - Handles negative coefficients

A.C. Network Calculator

- Disadvantages
  - Long setup time
  - Susceptible to “personal errors”

Potentiometer Solver

- Described by Soroka chapter alongside other examples
- Potentiometers allow for configurable resistor networks
- Solves 18.06 problems
- Network adjusted until solution found
- Hand-adjusted or auto-adjusted with op amps

Potentiometer Solver

- Advantages
  - Small
  - Durable
  - Straight-forward implementation

Potentiometer Solver

- Disadvantages
  - Single-purpose
  - Hand-adjusting is involved and time-consuming
  - Auto-adjusting requires good op amps

Modern Applications

- Generally electronic
- Take advantage of advances in component integration – VLSI
- Same problems, different applications
  – Robot dynamics
  – Machine vision
  – Neural networks

Robot Dynamics

- Sturges paper
- 18.06 problem
- Tradeoff between calculation speed and accuracy
- Stability concerns

Machine Vision

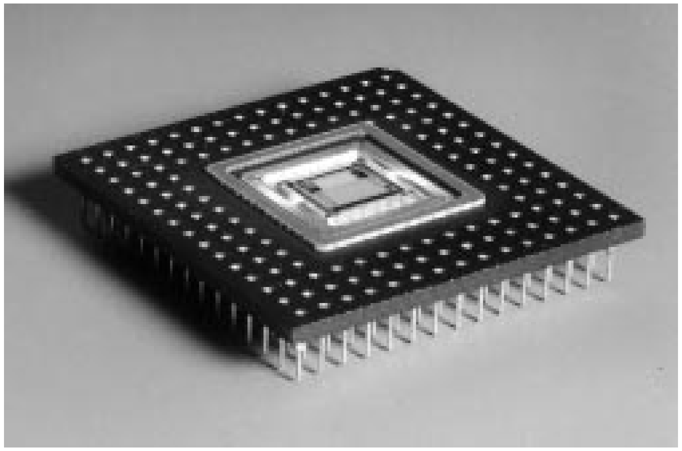
- Harris/Koch/Luo paper
- VLSI resistive network
- Analog design allows processing in real-time
- Extremely high degree of parallelism
- Scalable with fabrication technology

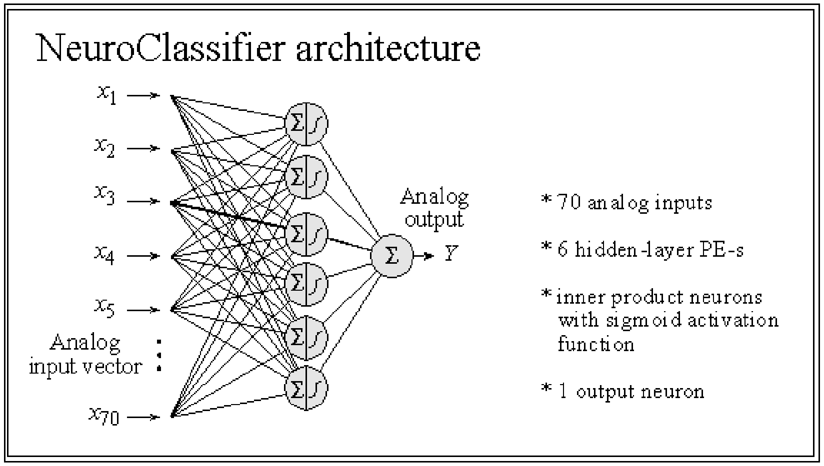
Neural Networks

- Need to perform huge number of multiplies and adds in parallel
- Can sacrifice accuracy for speed, make up for it in parallelism
- Analog multipliers much cheaper than digital ones—two orders of magnitude in some cases

NeuroClassifier

- Developed by Péter Masa, 1994
- Designed for high-speed pattern classification
- 20ns propagation delay
- 425 5-bit multiplies and 6 non-linear transformations per "cycle"
- 20 *billion* operations/second
- 1.5 micron process
- 0.6W power dissipation





Universal Issues

- Precision doesn't scale
- Setup time vs. execution time
- Storing results
- Error handling

Universal Issues

- Precision doesn't scale
  - Need more precision in the Pentium FPU? Just add bits
  - Not so easy with analog devices: you need more physical precision
  - "Duron Rod"

Universal Issues

- Setup time vs. execution time
  - Analog execution is about as fast as you can get
  - Setup can be a lot slower, complicated
  - Tradeoff: general purpose & longer setup vs. single-use & shorter setup
  - Complement with easily programmable digital logic?

Universal Issues

- Storing results
  - “Results” are really just one way of looking at the state of the device
  - No (easy) way to pause execution
  - Massive potential bandwidth could overwhelm digital storage devices
  - NeuroClassifier uses on-chip SRAM

Universal Issues

- Error handling
  - Errors can be hard to detect
  - Stability issues
  - Calibration
  - Some applications have tolerance for errors
  - Compensate with (cheap) parallelism

The Analog Future

- Nick Negroponte not withstanding, the world will always be an analog place
- Computation is moving into areas where analog data is the norm:
  - Audio/video processing (compression!)
  - Speech recognition
  - Natural language analysis
- These applications require speed, not accuracy

The Analog Future

- Special purpose devices, ASICs
- VLSI advances help analog as well as digital components
- Simple parallelism
- Mass-produced computing
- “Clockless” logic – asynchronous processing

Questions

- Can analog machines solve NP complete problems in polynomial time?
  - Yes, but you need non-polynomial resources
  - Ken Steiglitz ran a course like 6.911 at Princeton:
    - http://www.cs.princeton.edu/courses/archive/spring98/cs598c/
  - Check out "The Complexity of Analog Computation" under Links

Questions

- Can we solve the slow-setup problem?
  - We want configurable devices that are programmable like digital ones, but fast and cheap like analog ones
  - Some analog/digital integration could obviously be beneficial
  - Are FPGAs the answer?

Questions

- Fast Analog Solutions
  - http://www.fas.co.uk/
- TRAC: Totally Reconfigurable Analog Circuit
- “World’s First” FPAD: Field Programmable Analog Device
- Individually programmable “cells”
- Log, Antilog, Add, Rectify, Differentiate, Integrate functions available