Software Techniques for Analog Hardware

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When we think about a computer, we usually think about some sort of silicon chip that implements digital logic.
Computing Today

Computation with digital logic

Compute (ALU, FPU, etc)
Computing Today

Computation state stored as digital bits

Digital Computation

- Memory + Registers
- Compute (ALU, FPU, etc)
Computing Today

Compiler automatically maps target program to digital computing platform.
Computing Today

Compiler automatically maps target program to digital computing platform.

What if we adopt a different computing paradigm?
A different computing paradigm

Let’s map the program to an analog substrate and use the **physics of the substrate** to compute the program results.
A different computing paradigm

Let’s map the program to an analog substrate and use the physics of the substrate to compute the program results.
A different computing paradigm

In this context, the compiler automatically maps the high-level computation to the analog substrate.
A different computing paradigm

What is the analog substrate?
A different computing paradigm

What is the analog substrate?

Anything with interesting physical behavior.

Analog Computation
A different computing paradigm

How is data represented in the analog substrate?
A different computing paradigm

How is data represented in the analog substrate?

Depends on the analog substrate
A different computing paradigm

How is data represented in the analog substrate?

The compiler maps program values / variables to the appropriate analog data representation.
A different computing paradigm

How is computation done in the analog substrate?

Analog Computation
A different computing paradigm

How is computation done in the analog substrate?

Depends on the analog substrate

Analog Computation
A different computing paradigm

Depending on the physical medium:

- Some computations are easy to implement.
- Some computations are difficult to implement.

Analog Computation

Analog Substrate

Diffraction

Integration + Analog Operations

Ohm’s / Kirchoff’s Law

Interference

Fluid Dynamics of Honey/Sand
A different computing paradigm

The analog substrate also has other (unwanted) analog behaviors and effects not useful to the computation.
A different computing paradigm

The compiler figures out how to implement the computation with the analog primitives available in the substrate.
A different computing paradigm

The compiler must also **attenuate** any unwanted analog behavior present in the analog medium.
A different computing paradigm

How do you “program” the analog substrate?
A different computing paradigm

How do you “program” the analog substrate?

**Method 1:** Re-configure the device by tuning analog components on the fly.
A different computing paradigm

How do you “program” the analog substrate?

**Method 2:** Fabricate a fresh instance of the substrate that implements the desired computation.
A different computing paradigm

Analog computing substrates have a lot of unusual properties that make compilation interesting.
A different computing paradigm

Analog computing is a useful computational model.
When does analog computing make sense?
Analog Computing

At the analog interface

Analog signal from sensor (e.g. microphone)

Analog Feature Extraction

Result Post-Processing and A/D conversion

mA

Microseconds
Analog Computing

Can potentially process analog signals (from sensors, for example) in the analog domain before converting it to a digital signal.
Analog Computing

Reduce the complexity of the A/D interface.

“complexity” : sampling rate, number of analog-to-digital converters, sampling fidelity.

Analog signal from sensor (e.g. microphone)

Analog Feature Extraction

Result Post-Processing and A/D conversion
Analog Computing

In some sensing interfaces, analog signal processing is done to ‘clean up’ the signal.

Analog signal from sensor (e.g. microphone)

Analog Feature Extraction

Result Post-Processing and A/D conversion

Microseconds

mA
Analog Computing

Can potentially get better power/performance characteristics with existing fabrication technologies.

Analog CMOS ICs

+ Low power
+ Program runtime computable at compile-time.
- difficult to miniaturize, large feature sizes.
- operates at very low frequencies.
Analog Computing

The analog computing paradigm is potentially useful for non-CMOS technologies that confer other benefits, but face significant fabrication limitations.

Flexible and Organic ICs

+ relatively cheap to produce custom designs.
+ Can be made biodegradable*
  - difficult to miniaturize, large feature sizes.
- operates at very low frequencies.
Analog Computing

With analog computing, we can potentially get some near-term benefits without necessarily requiring fabrication processes to improve significantly.

Flexible and Organic ICs

+ relatively cheap to produce custom designs.
+ Can be made biodegradable*
  - difficult to miniaturize, large feature sizes.
  - operates at very low frequencies.

*Note: The term "biodegradable" is marked with an asterisk, indicating a special condition or limitation.
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Compiler must reason about analog behavior to effectively map computation.

Computing in the Presence of Analog Behavior
Computing in the Presence of Analog Behavior

Does this happen in practice?
Computing in the Presence of Analog Behavior

Program

Compiler

Computer with Analog Behavior

Analog Behavior

Resistance drift, Thermal effects, Process variation

Emerging Memory Technologies
Computing in the Presence of Analog Behavior

Program

Compiler

Computer with Analog Behavior

Analog Behavior

Thermal gradients, non-idealities related to emerging fabrication processes.

Monolithic 3D ICs
Computing *in the Presence of Analog Behavior*

- **Program**
- **Compiler**
- **Computer with Analog Behavior**
- **Quantum Computers**

**Analog Behavior**
- Crosstalk, Noise, Qubit Variations
Computing in the Presence of Analog Behavior

Program

Compiler

Computer with Analog Behavior

Other emerging technologies
Analog behavior is undesirable and should be eliminated from the computation.
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Why reason about any of this in software? What are the alternatives?

Alternative 1: Wait for the device technologies to improve.

**Cons:** High investment cost, low yield, interest may ‘cool off’ if technology doesn’t improve fast enough.
Analog behavior is undesirable and should be eliminated from the computation.

**Alternative 2:** Mitigate behavior in hardware (calibration, self-test)

Great as complementary technique, cannot aggressively perform whole-program optimizations.

Why reason about any of this in software? What are the alternatives?
Computing in the Presence of Analog Behavior

Why reason about any of this in software? What are the alternatives?

Compiler can aggressively optimize program to improve fidelity in the presence of analog behavior.

Alternative 2: Mitigate behavior in hardware (calibration, self-test)

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Computing in the Presence of Analog Behavior

We can design programming languages and language constructs that enable efficient optimization of programs for target hardware.

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Net effect: Push emerging technologies to its limits and fully vet the capabilities of emerging technologies.
Computing in the Presence of Analog Behavior

- Program
- Compiler
- Data representation
- Error Models
- Optimization Criteria
- Performance/Fidelity
- Storage optimization (e.g., level allocation)
- Analog Behavioral Models
- Characterization Data

- Architecture-level characteristics
  - Sense amplifier thresholds, read/write tolerances
- Device-level characteristics
  - Process variation, thermal drift, relaxation

Analog Behavior
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Analog behavior is undesirable and should be eliminated from the computation.