

# Software Techniques for Analog Hardware

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Sara Achour

# Computing Today

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

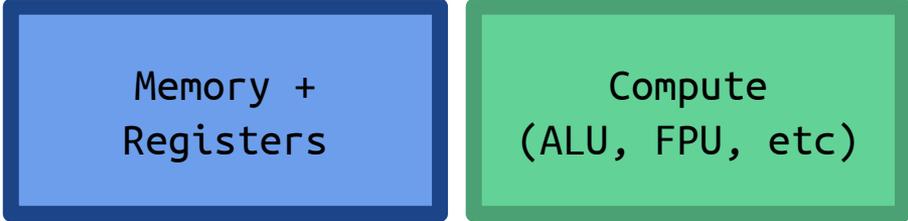
Compute  
(ALU, FPU, etc)

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Digital Computation

# Computing Today

Computation state stored as  
digital bits

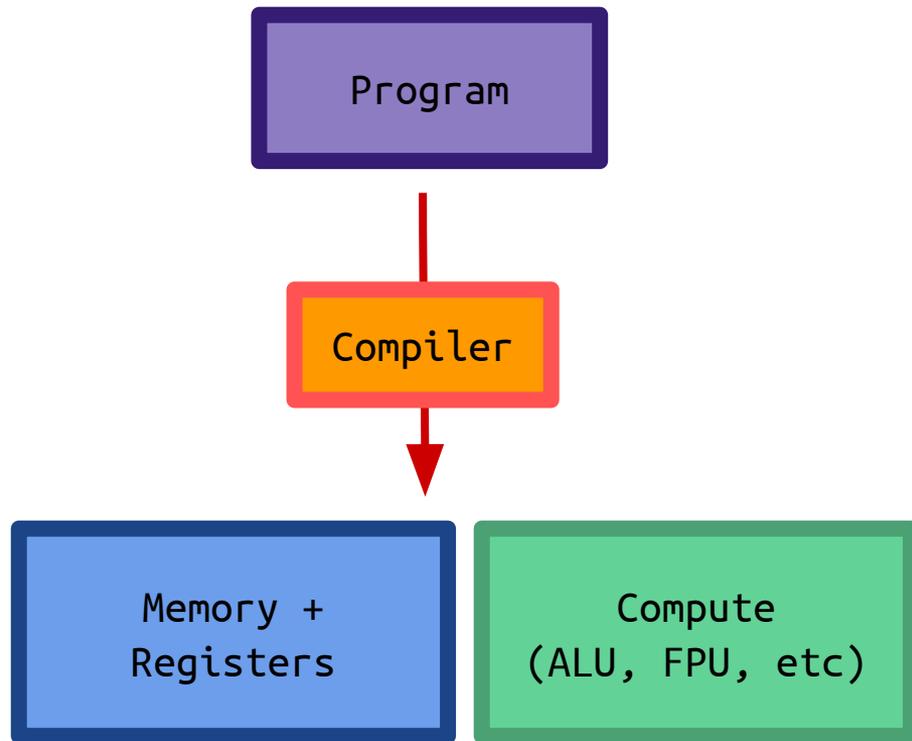


Memory +  
Registers

Compute  
(ALU, FPU, etc)

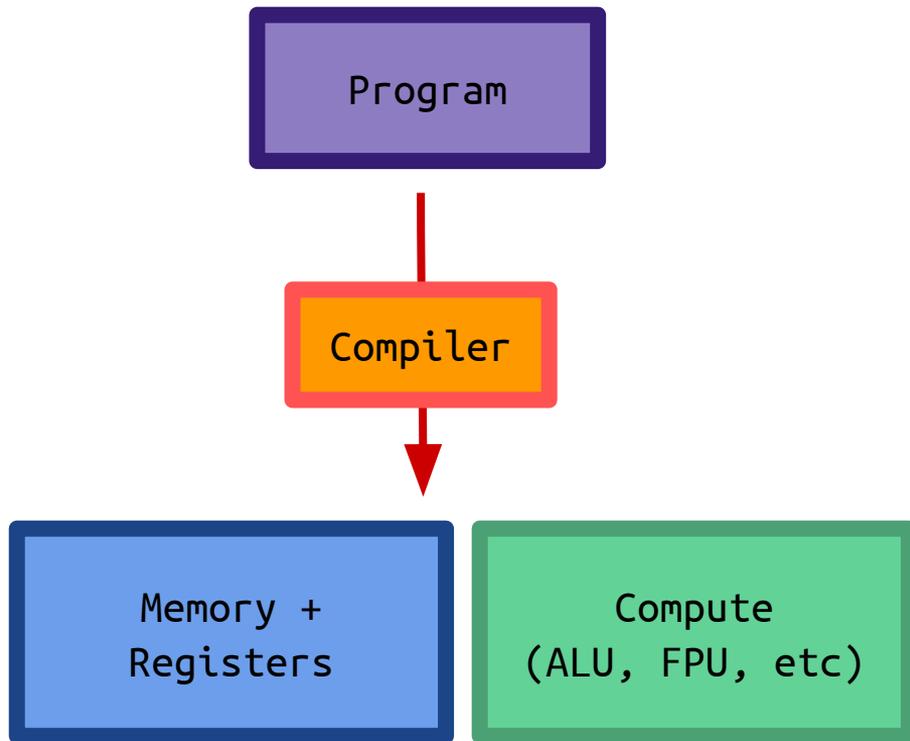
# Computing Today

Compiler automatically maps  
target program to digital  
computing platform.



# Computing Today

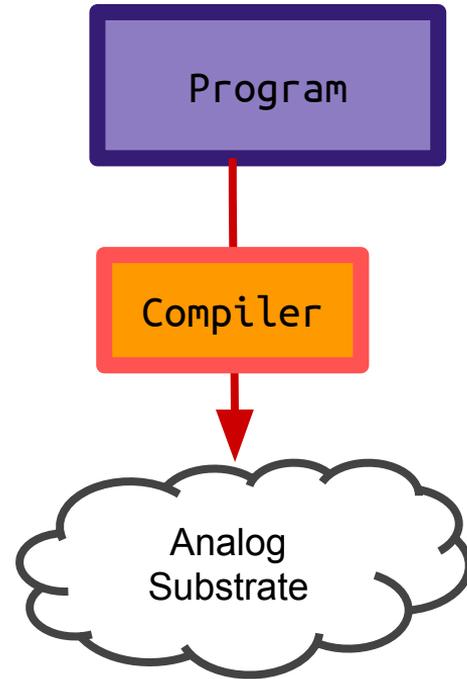
Compiler automatically maps target program to digital computing platform.



**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.

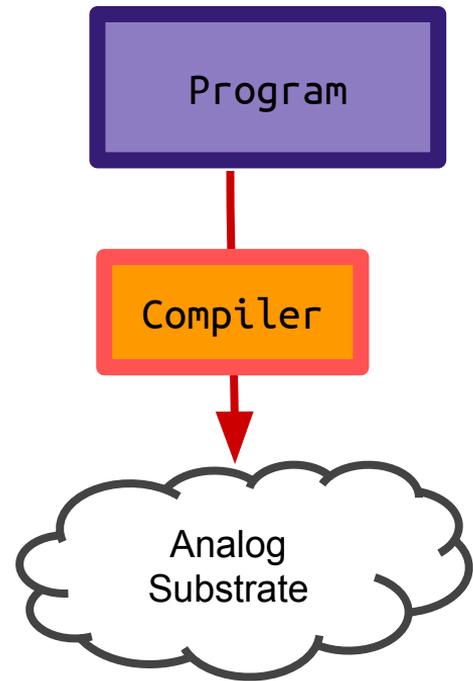


# A different computing paradigm

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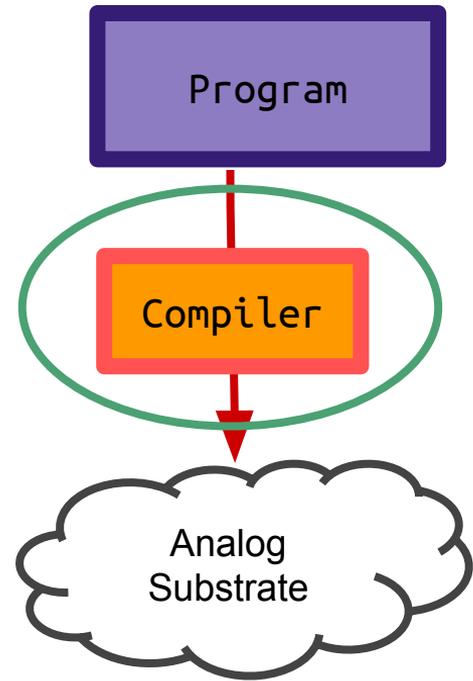
Analog Computation



**Analog Computing**

# A different computing paradigm

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



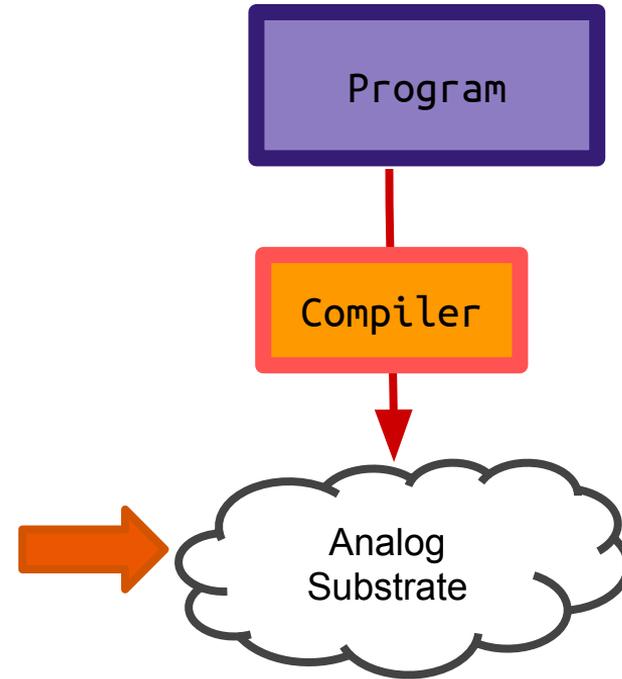
**Analog Computing**

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Analog Computation

# A different computing paradigm

What is the analog substrate?

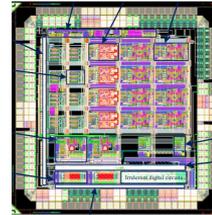
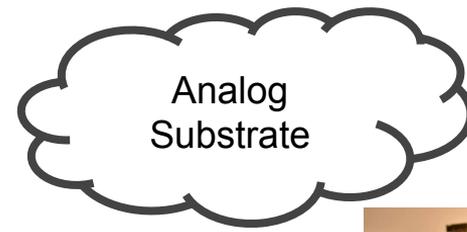


# A different computing paradigm

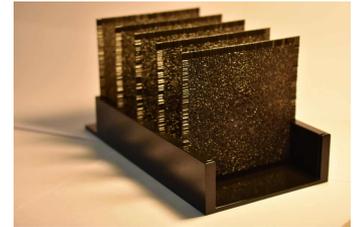
What is the analog substrate?

Anything with interesting physical behavior.

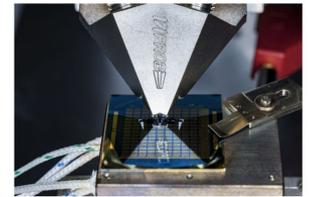
Analog Computation



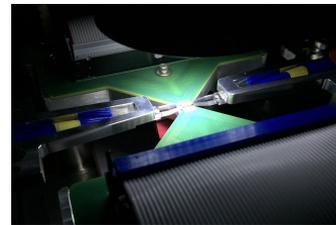
Electrical Analog Circuits



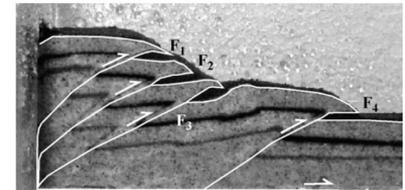
Diffractive glass



Resistive Ram



Analog Photonic Circuits

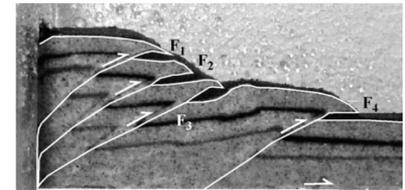
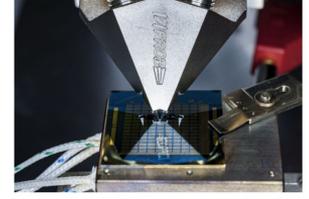
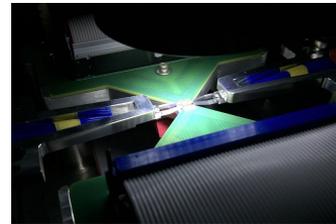
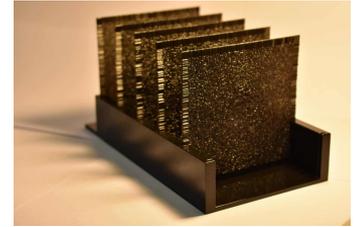
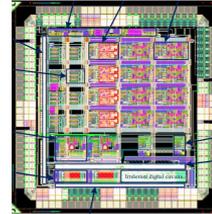
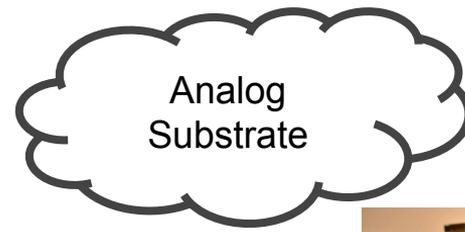


Honey and sand

# A different computing paradigm

How is data represented in the analog substrate?

Analog Computation

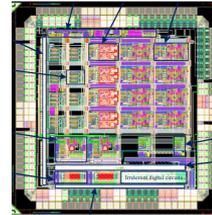
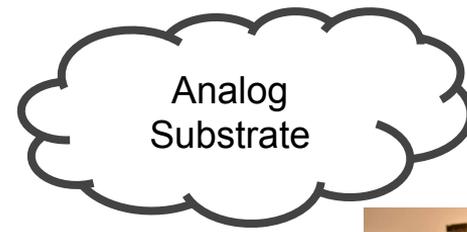


# A different computing paradigm

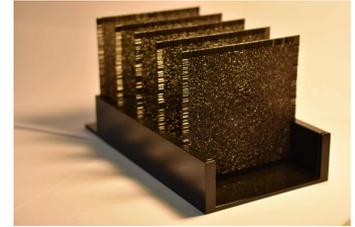
How is data represented in the analog substrate?

Depends on the analog substrate

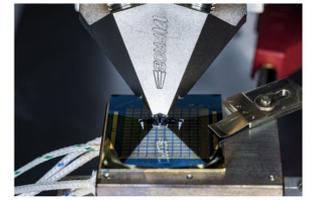
Analog Computation



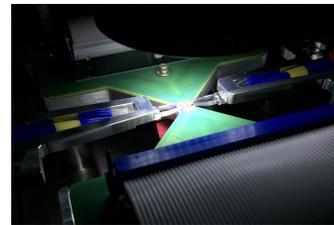
Analog currents and voltages



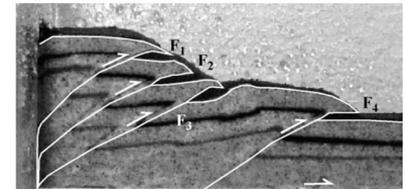
Photon Phases



Resistances



Photon Phases



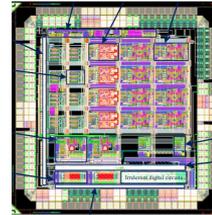
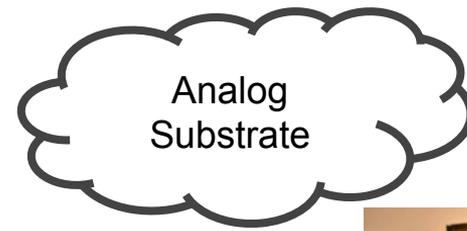
Position of Honey+Sand

# A different computing paradigm

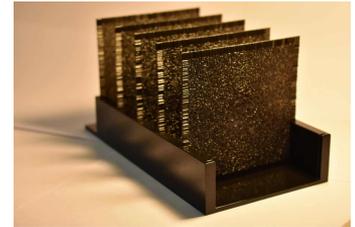
How is data represented in the analog substrate?

The compiler maps program values / variables to the appropriate analog data representation.

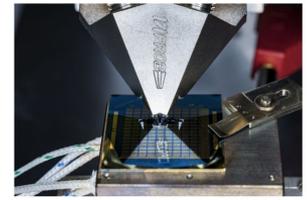
Analog Computation



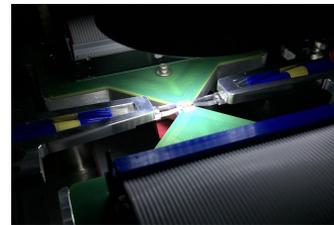
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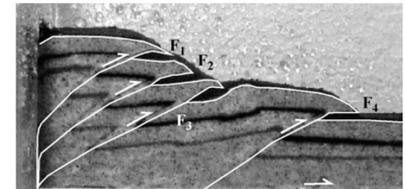
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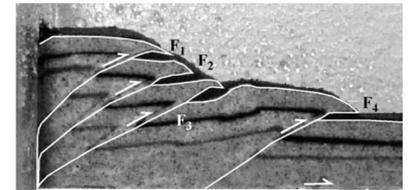
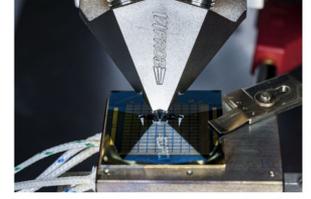
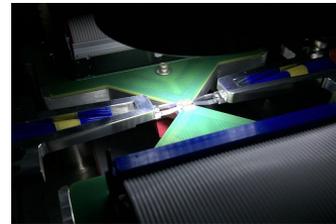
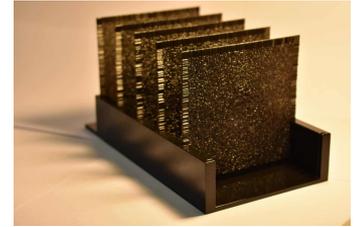
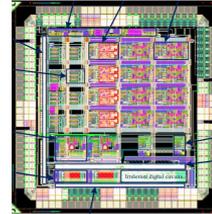
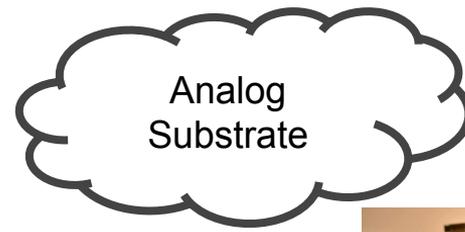


Position of Honey+Sand

# A different computing paradigm

How is computation done in the analog substrate?

Analog Computation

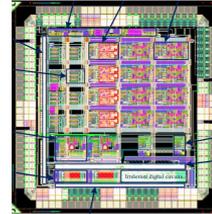
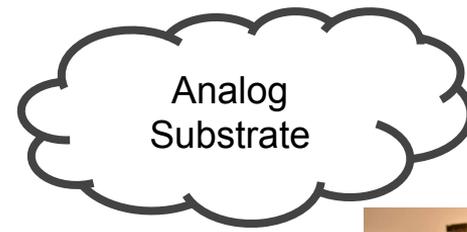


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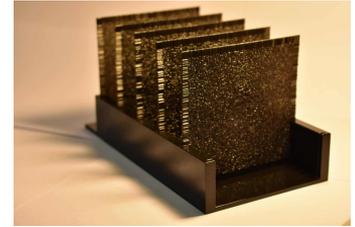
How is computation done in the analog substrate?

Depends on the analog substrate

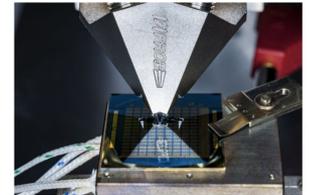
Analog Computation



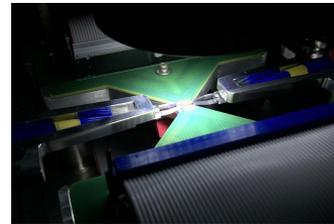
Integration +  
Analog Operations



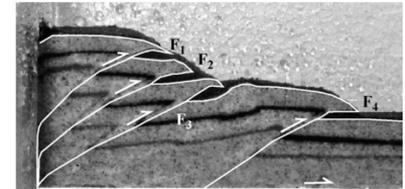
Diffraction



Ohm's / Kirchoff's Law



Interference



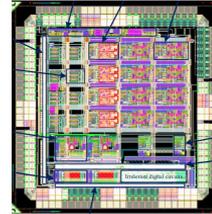
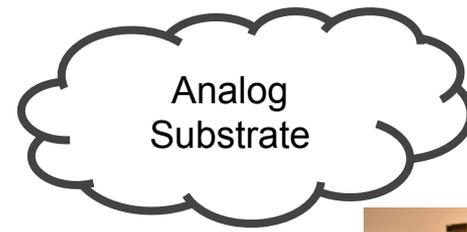
Fluid Dynamics of Honey/Sand

# A different computing paradigm

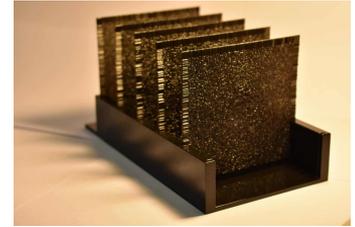
Depending on the physical medium:

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

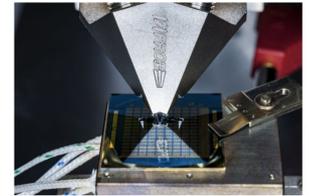
Analog Computation



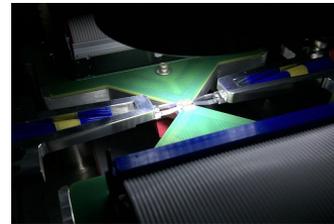
Integration +  
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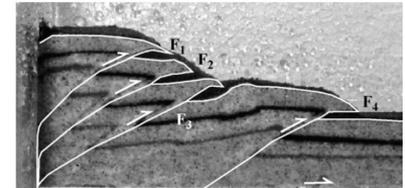
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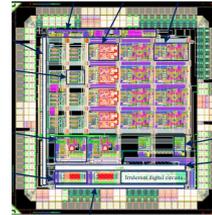
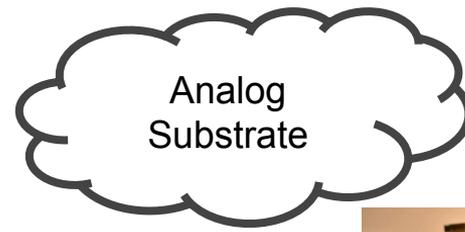
Fluid Dynamics of Honey/Sand

# A different computing paradigm

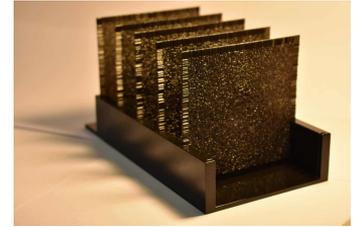
The analog substrate also has other (unwanted) analog behaviors and effects not useful to the computation.

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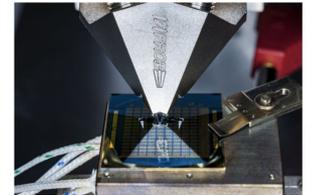
Analog Computation



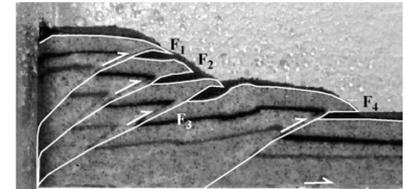
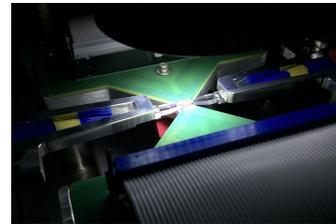
Noise, Process Variation



Fabrication error + resolution



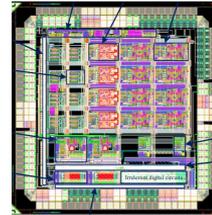
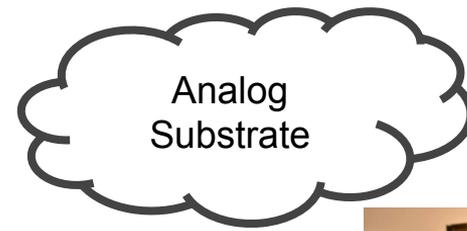
Resistance drift



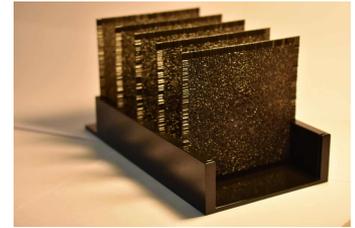
# A different computing paradigm

The compiler figures out how to implement the computation with the analog primitives available in the substrate

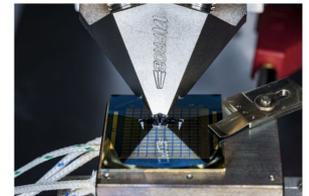
Analog Computation



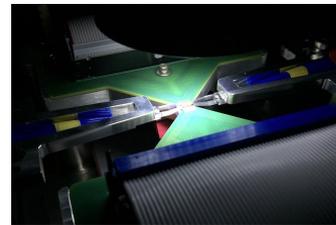
Integration +  
Analog Operations



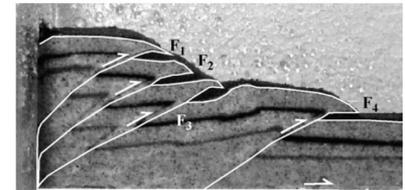
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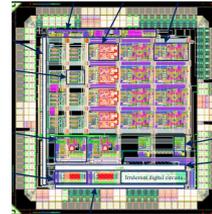
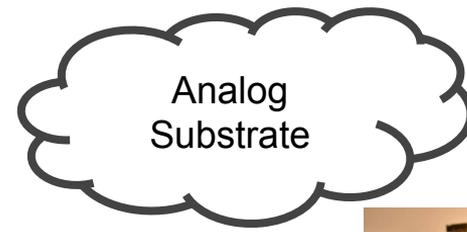


Fluid Dynamics of Honey/Sand

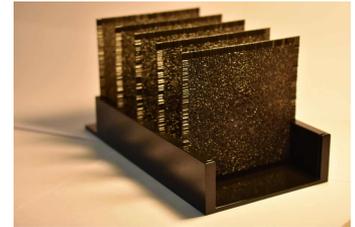
# A different computing paradigm

The compiler must also **attenuate** any unwanted analog behavior present in the analog medium.

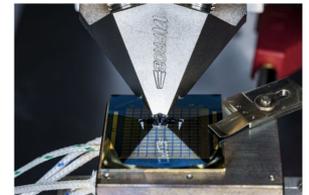
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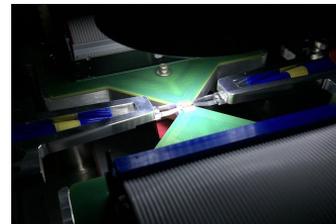
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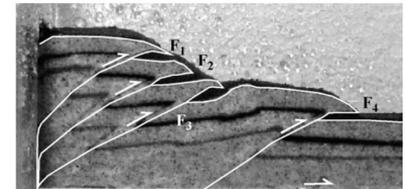
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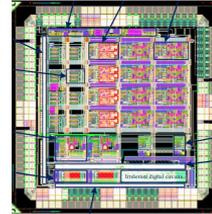
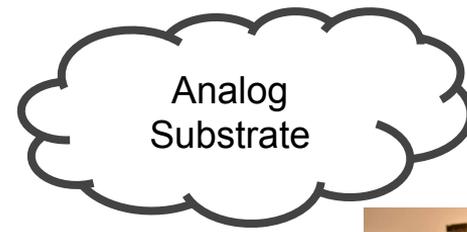


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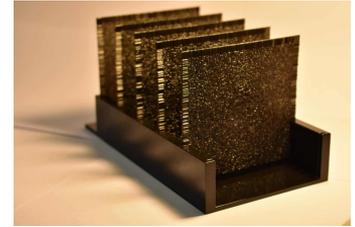
# A different computing paradigm

How do you “program” the analog substrate?

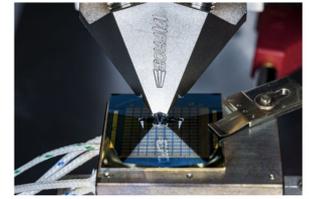
Analog Computation



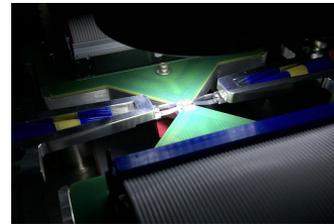
Analog currents and voltages



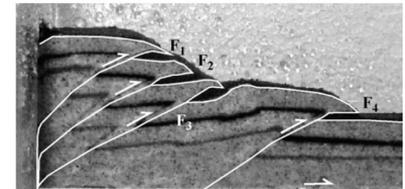
Photon Phases



Resistances



Photon Phases



Position of Honey+Sand

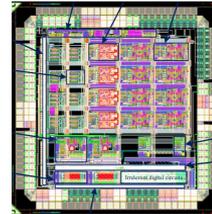
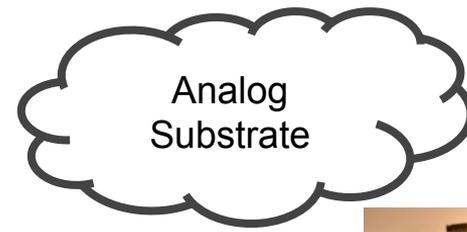
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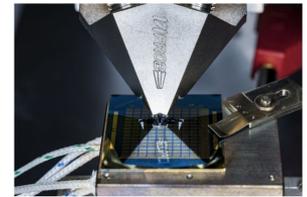
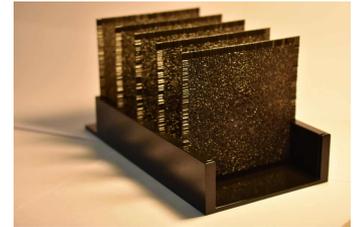
**Method 1:** Re-configure the device by tuning analog components on the fly.

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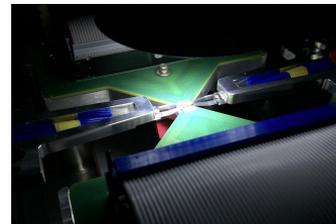
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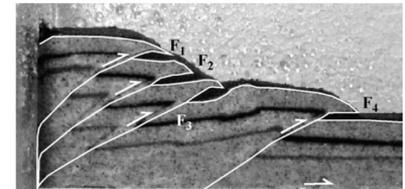
Programmable Bits



Voltage Pulses



Tunable Interferometers

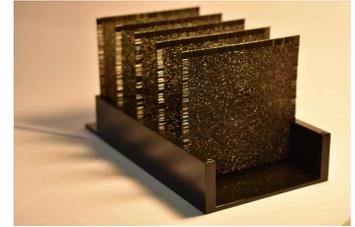
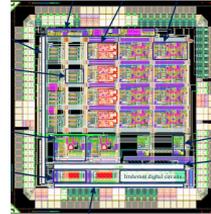
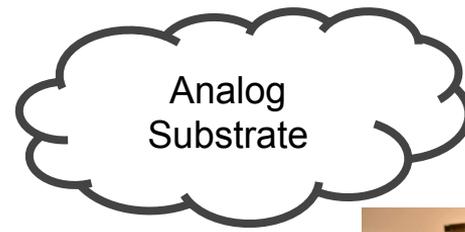


# A different computing paradigm

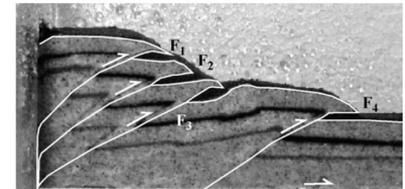
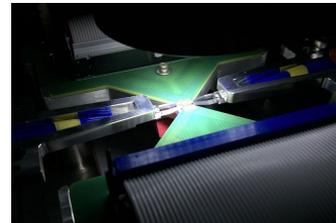
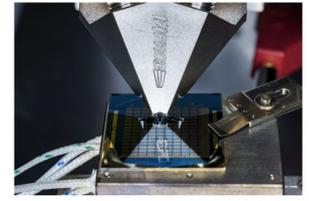
How do you “program” the analog substrate?

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

Analog Computation



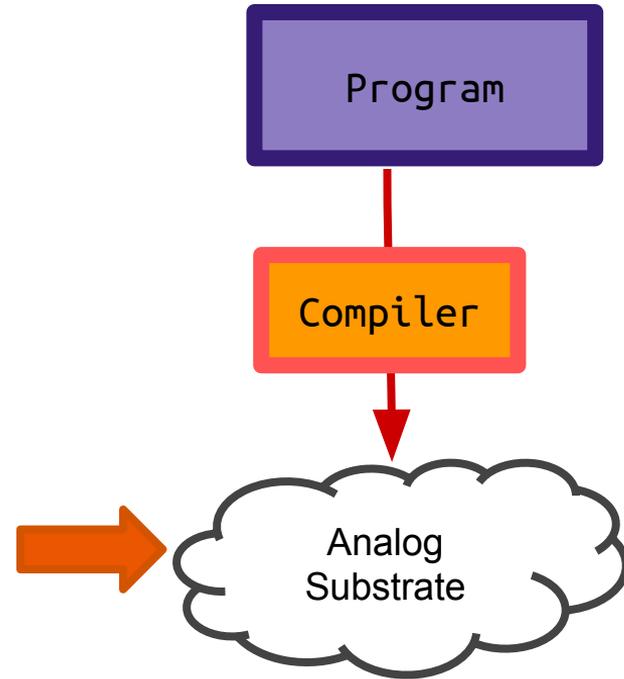
Photon Phases



Position of Honey+Sand

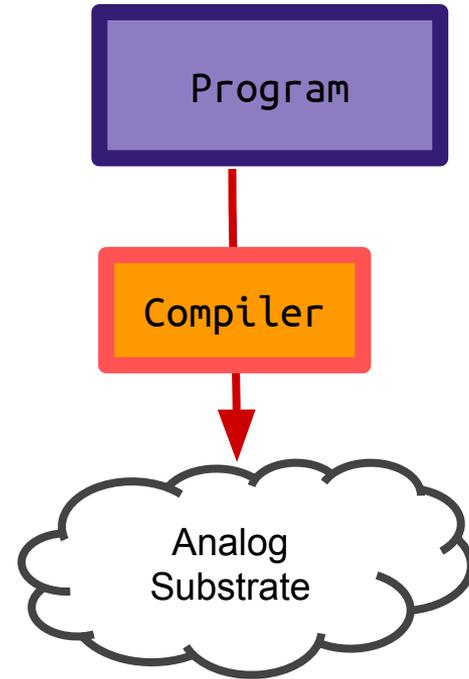
# A different computing paradigm

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



# A different computing paradigm

Analog computing is a useful computational model.

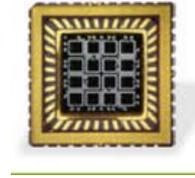


When does analog computing  
make sense?

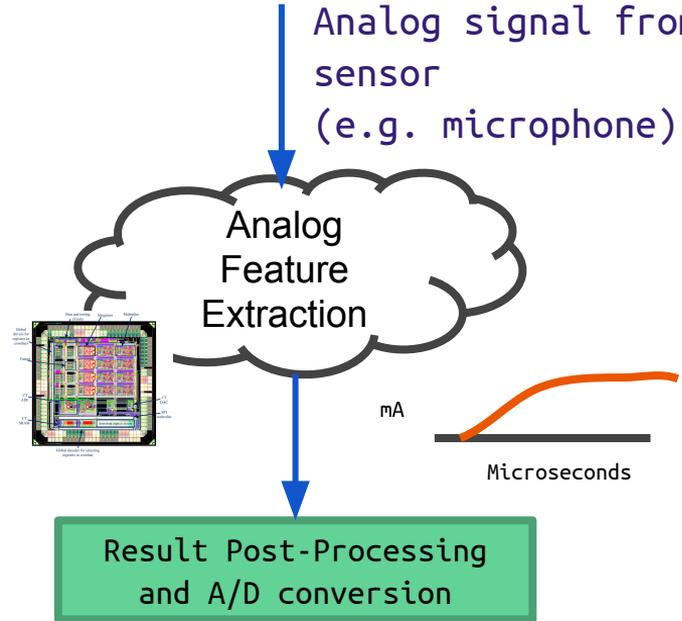
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# Analog Computing

At the analog interface

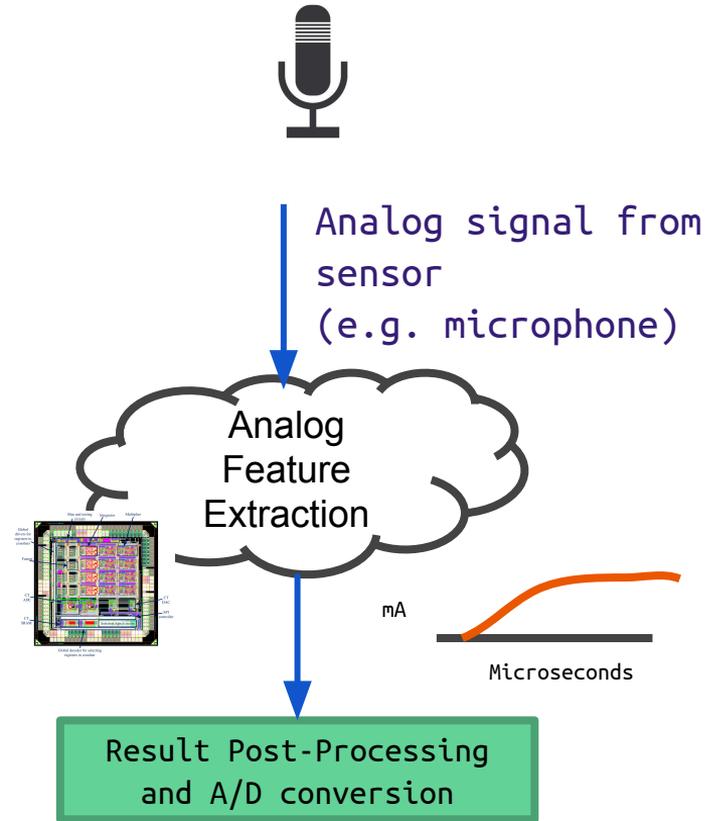


Analog signal from sensor  
(e.g. microphone)



# Analog Computing

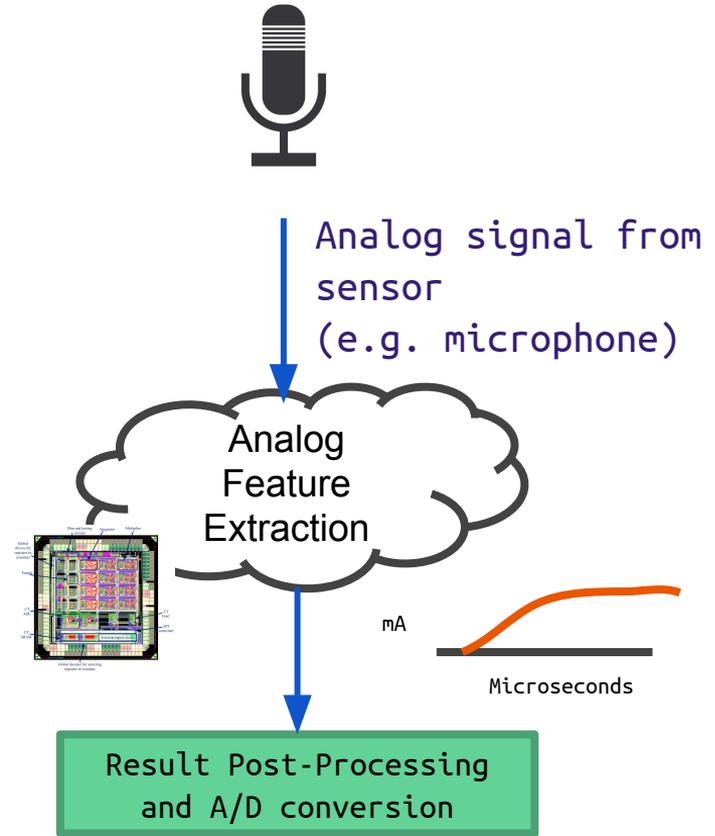
Can potentially process analog signals (from sensors, for example) in the analog domain before converting it to a digital signal.



# Analog Computing

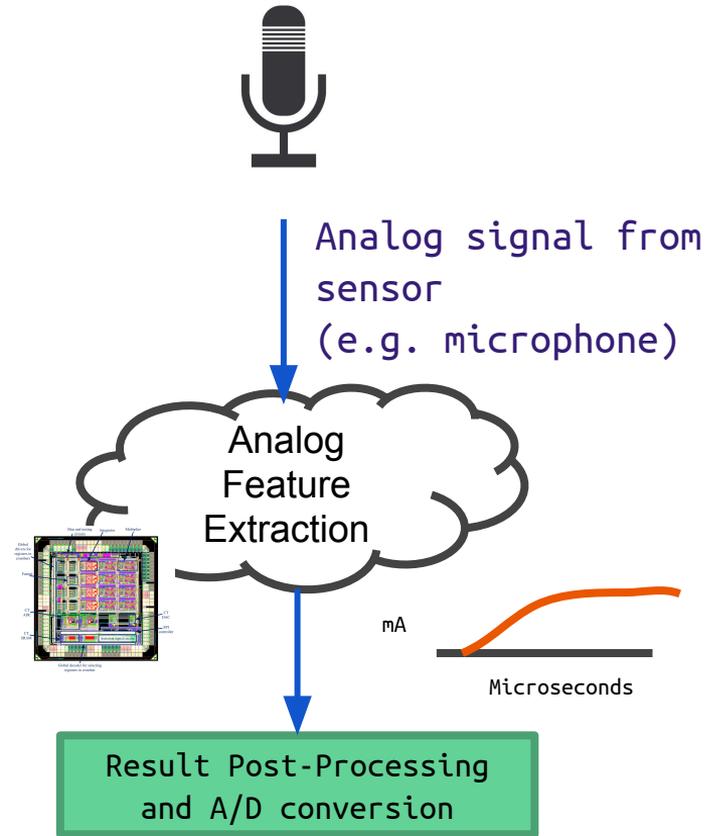
Reduce the complexity of the A/D interface.

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



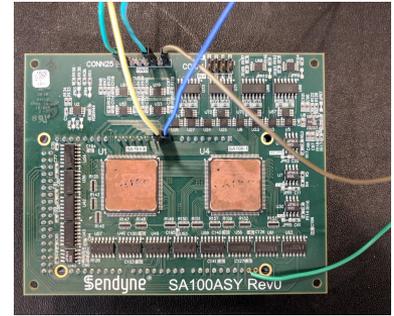
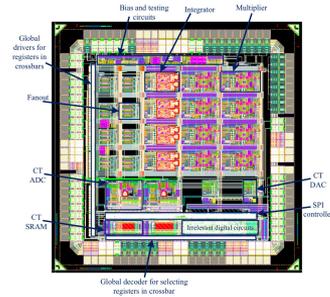
# Analog Computing

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



# Analog Computing

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

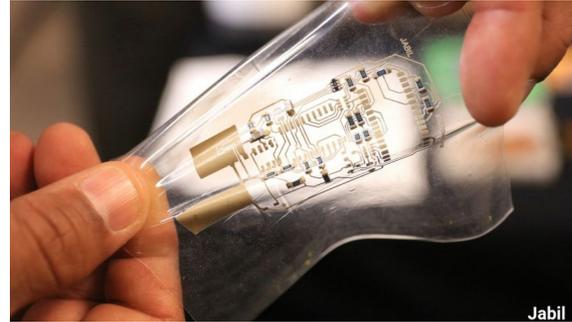


## Analog CMOS ICs

- + 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.

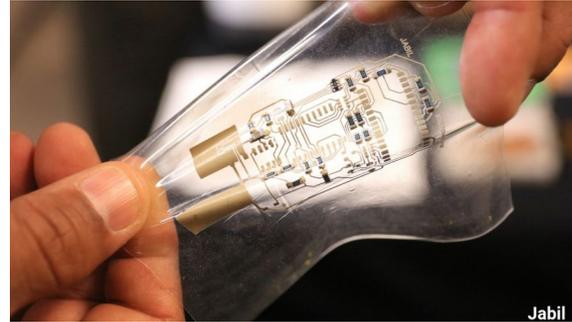


## Flexible and Organic ICs

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

# Analog Computing

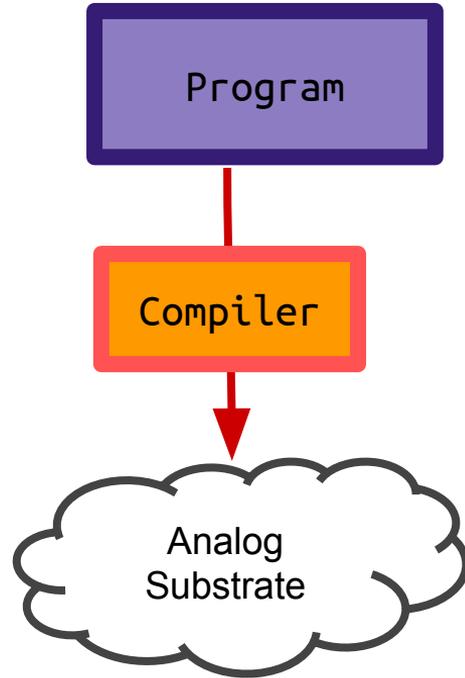
With analog computing, we can potentially get some near-term benefits without necessarily requiring fabrication processes to improve significantly.



## Flexible and Organic ICs

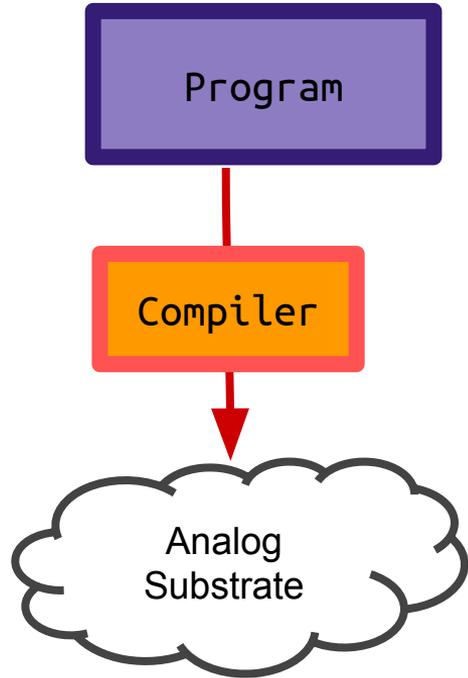
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# Analog Computing



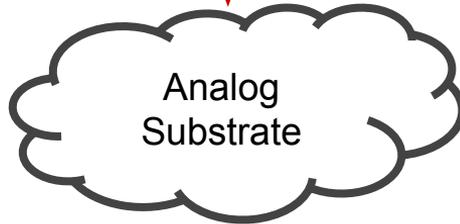
Analog behavior is desirable  
and leveraged to perform  
computation.

# Analog Computing



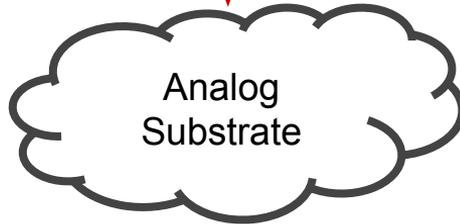
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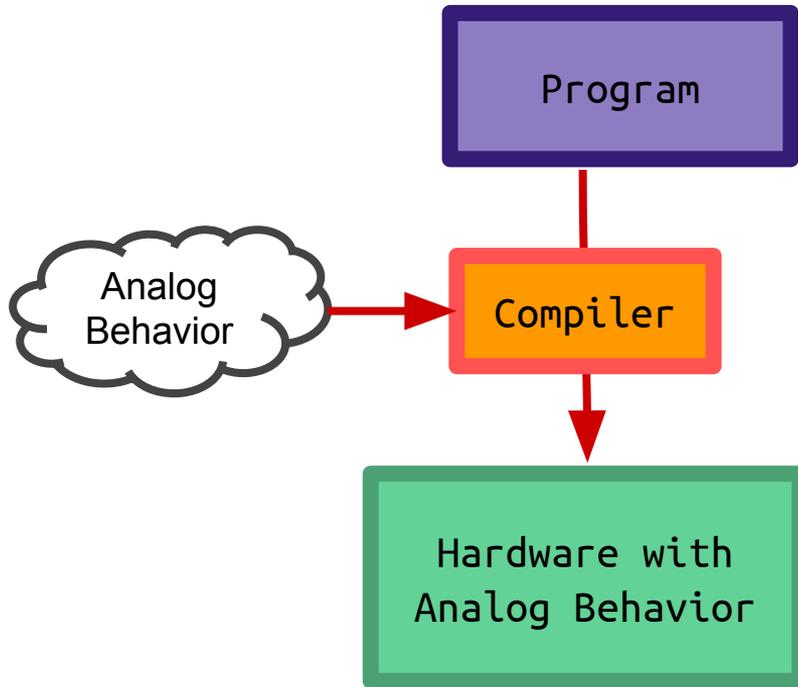
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# Analog Computing



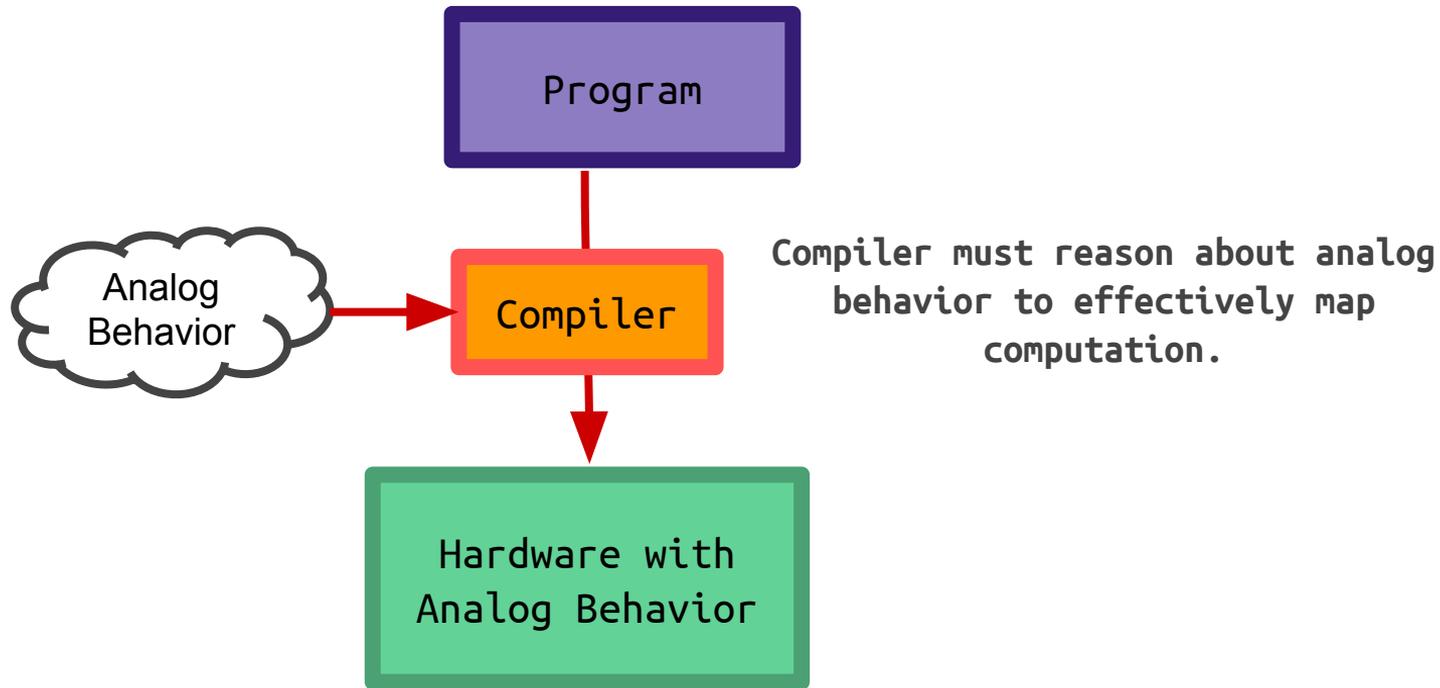
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# Computing in the Presence of Analog Behavior



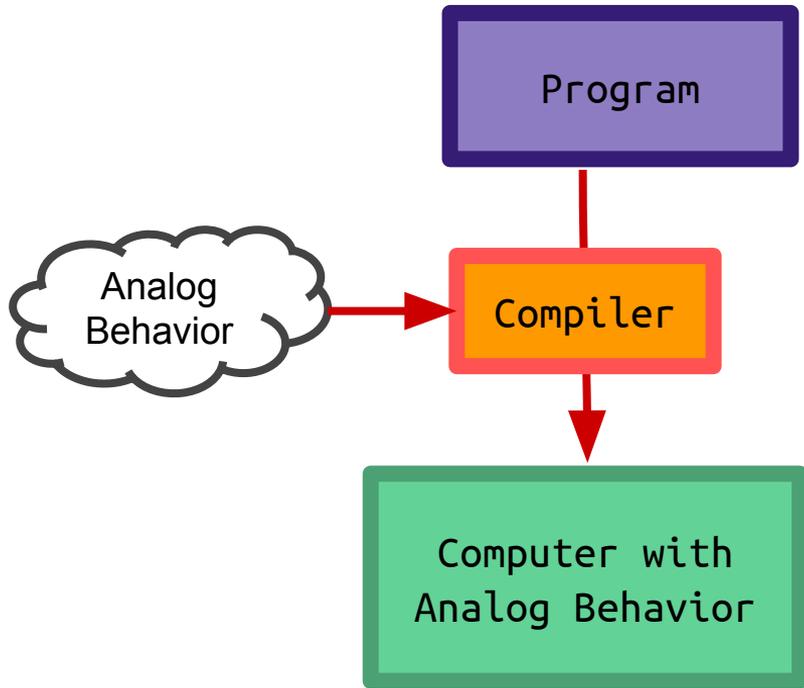
Analog behavior is undesirable and should be eliminated from the computation.

# Computing in the Presence of Analog Behavior



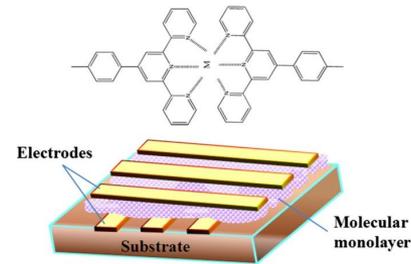
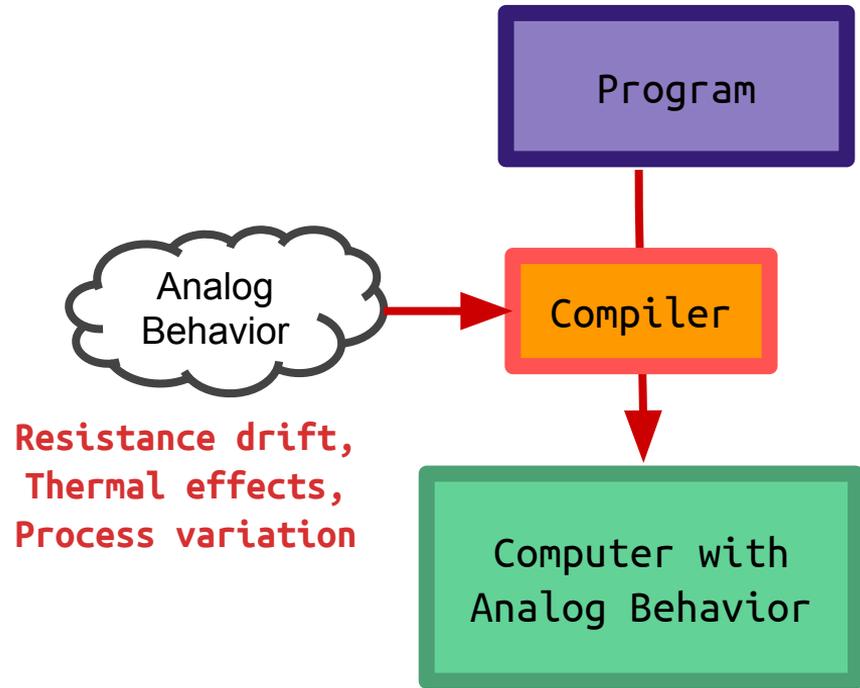
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# Computing in the Presence of Analog Behavior



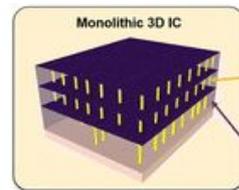
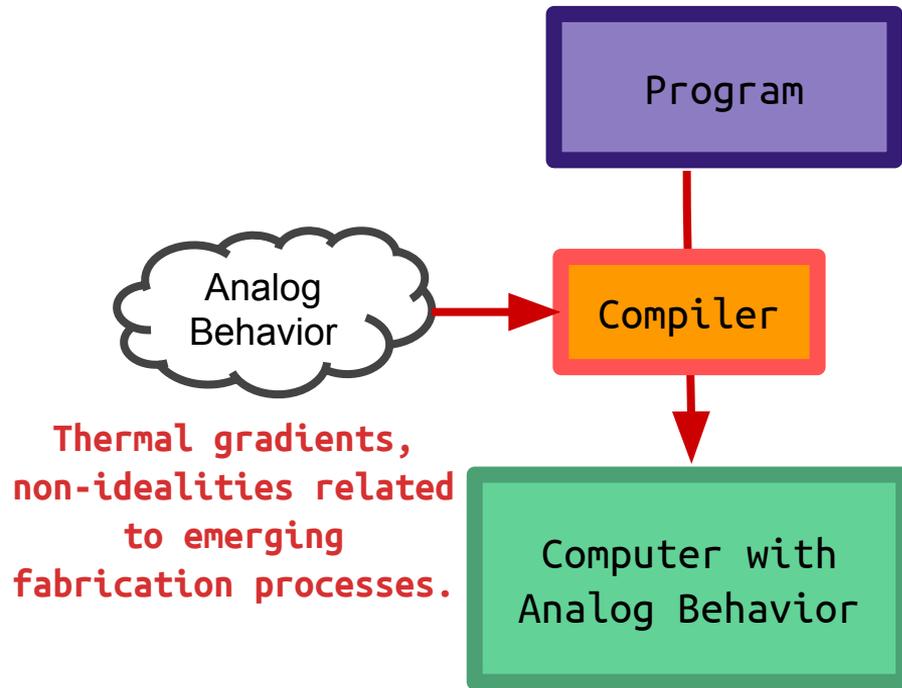
Does this happen in practice?

# Computing in the Presence of Analog Behavior



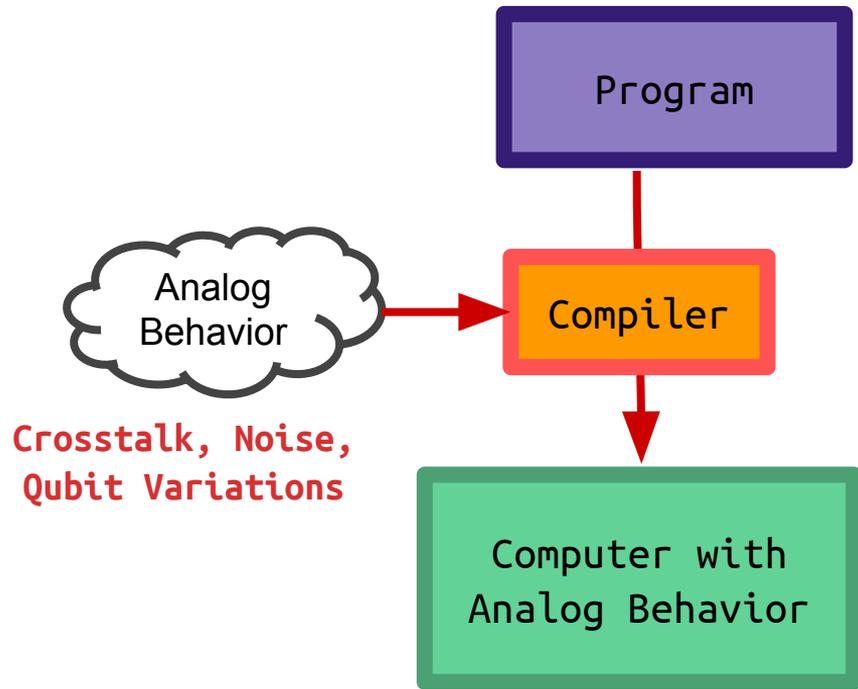
Emerging Memory Technologies

# Computing in the Presence of Analog Behavior



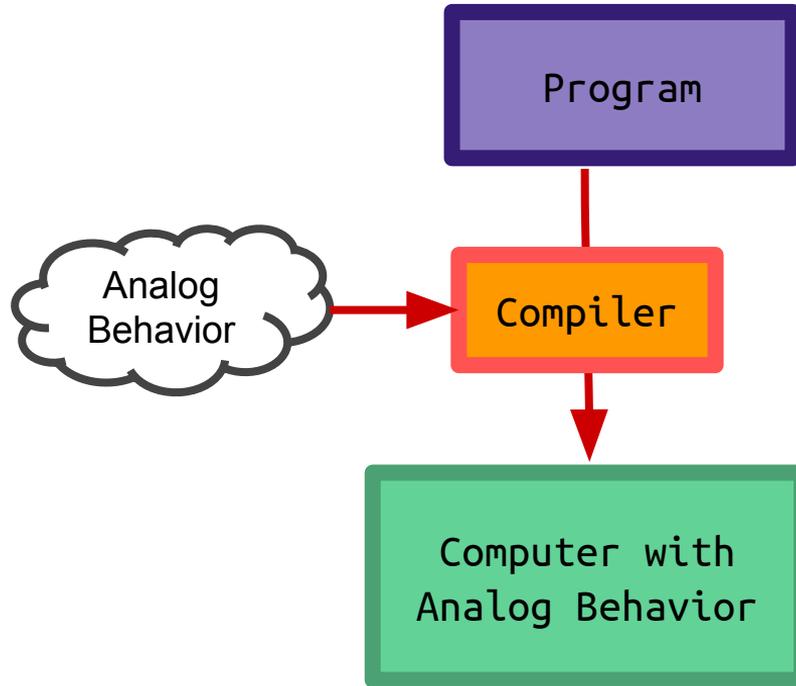
Monolithic 3D ICs

# Computing in the Presence of Analog Behavior



Quantum Computers

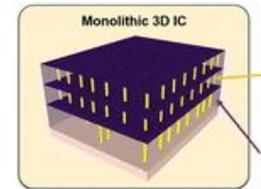
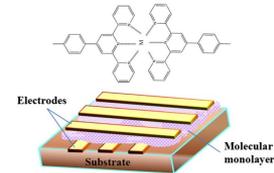
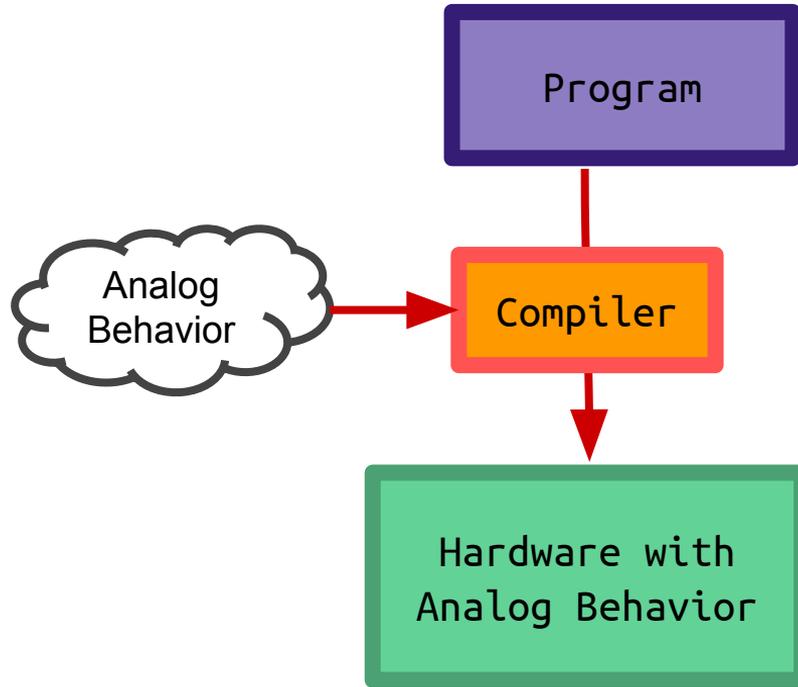
# Computing in the Presence of Analog Behavior



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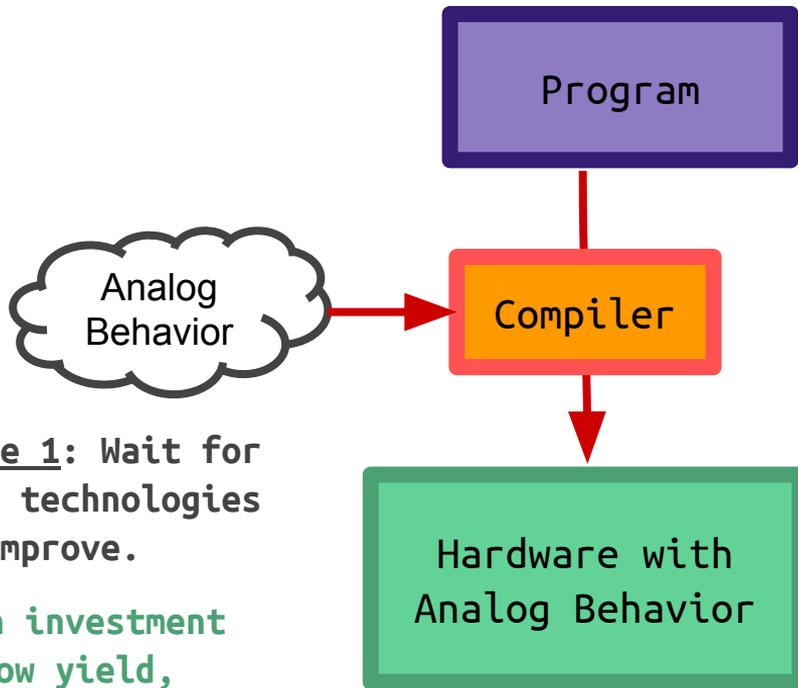
Other emerging technologies

# Computing in the Presence of Analog Behavior



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

# Computing in the Presence of Analog Behavior

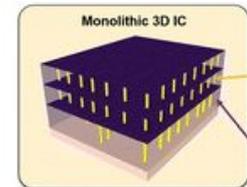
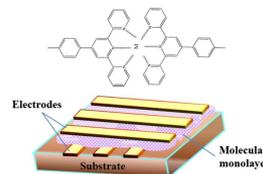


Alternative 1: Wait for the device technologies to improve.

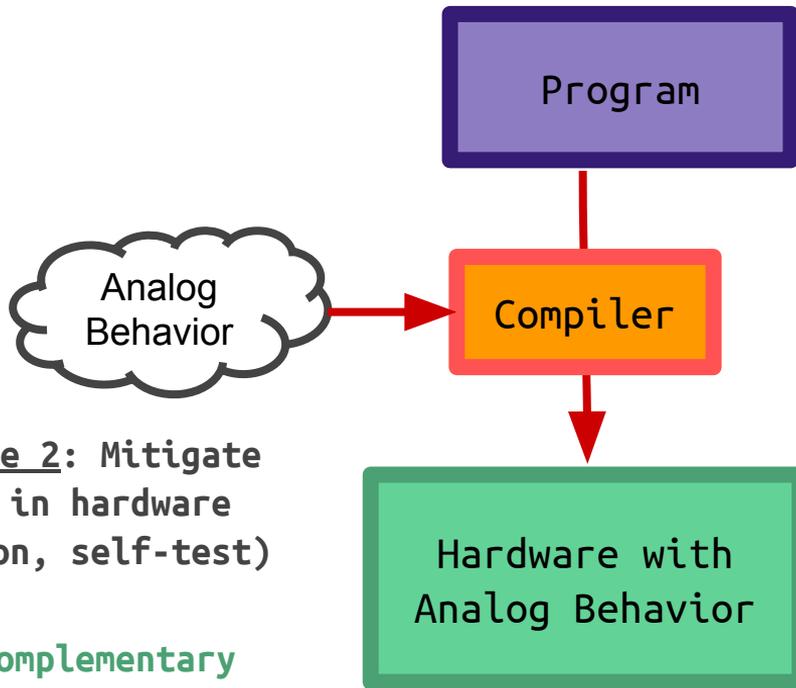
Cons: High investment cost, low yield, interest may 'cool off' if technology doesn't improve fast enough.

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

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



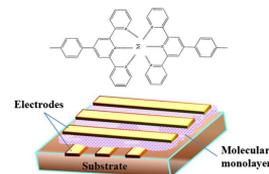
# Computing in the Presence of Analog Behavior



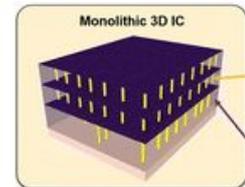
Alternative 2: Mitigate behavior in hardware (calibration, self-test)

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

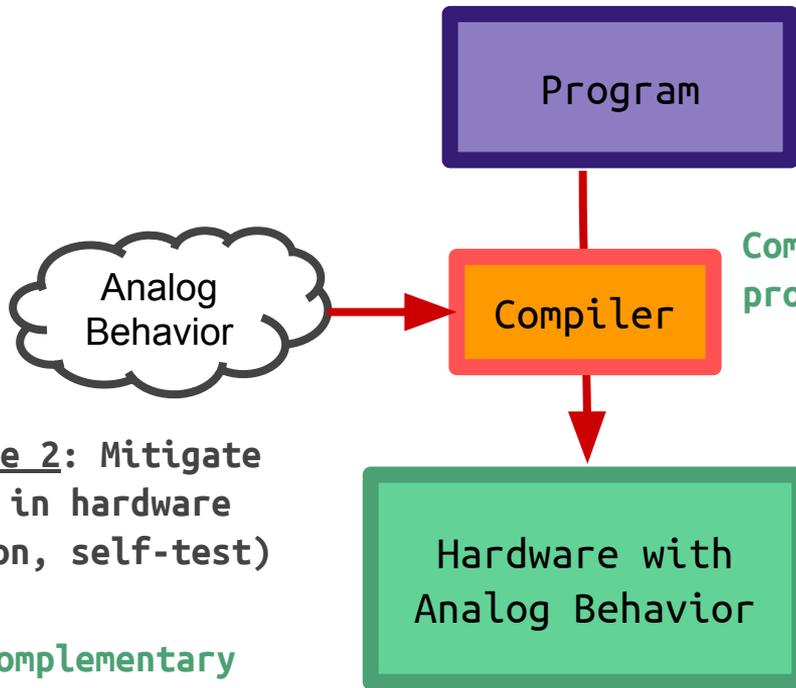
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# Computing in the Presence of Analog Behavior



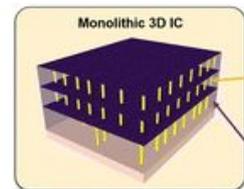
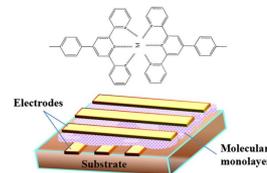
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Compiler can aggressively optimize program to improve fidelity in the presence of analog behavior.

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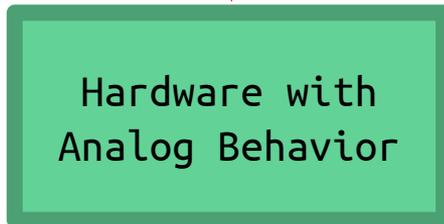
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# Computing in the Presence of Analog Behavior

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



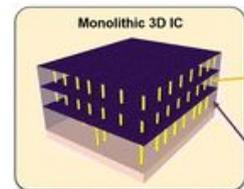
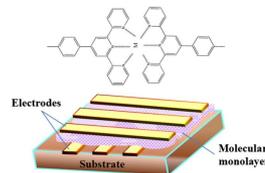
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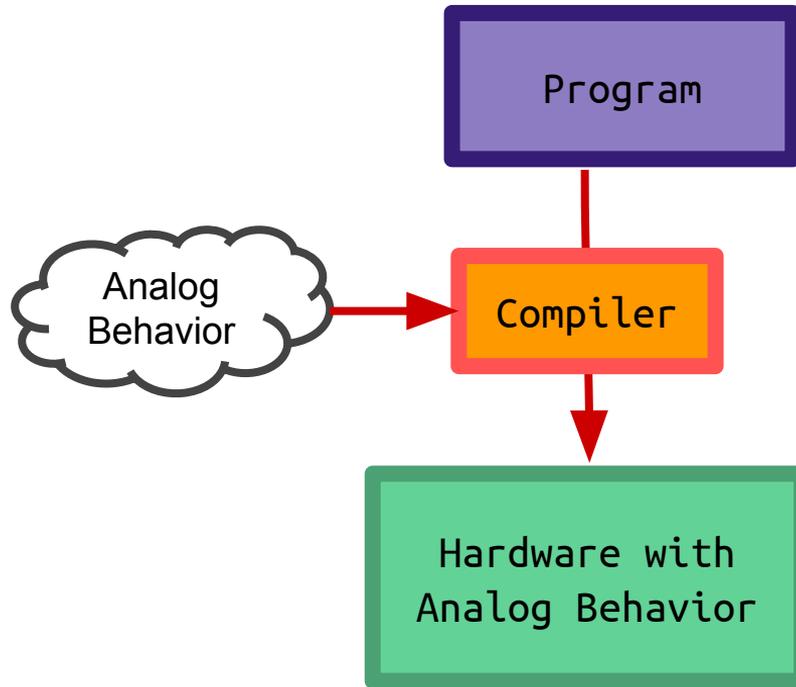
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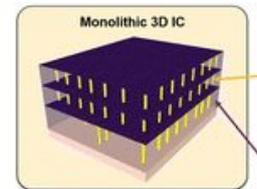
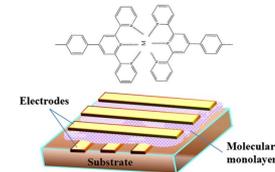


# Computing in the Presence of Analog Behavior

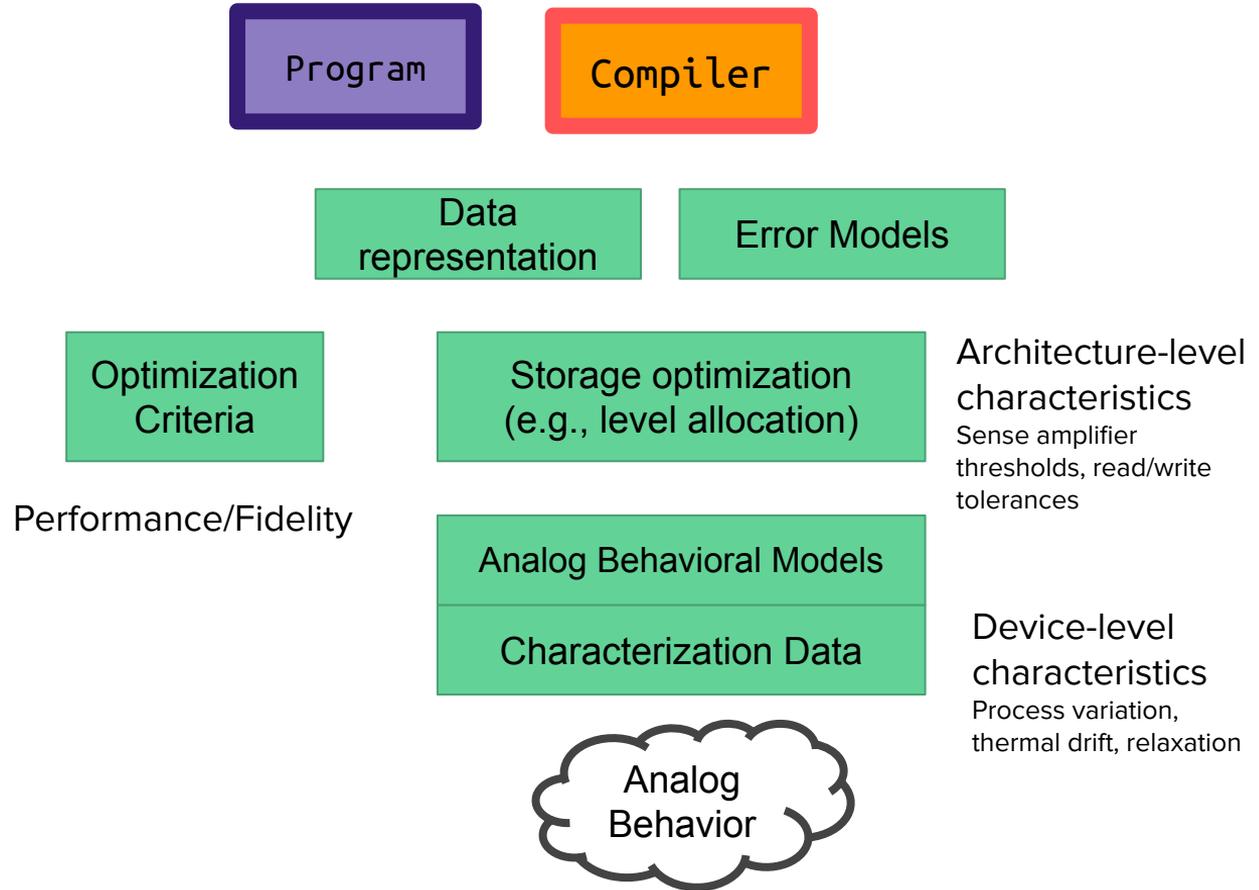


**Net effect:** Push emerging technologies to its limits and fully vet the capabilities of emerging technologies.

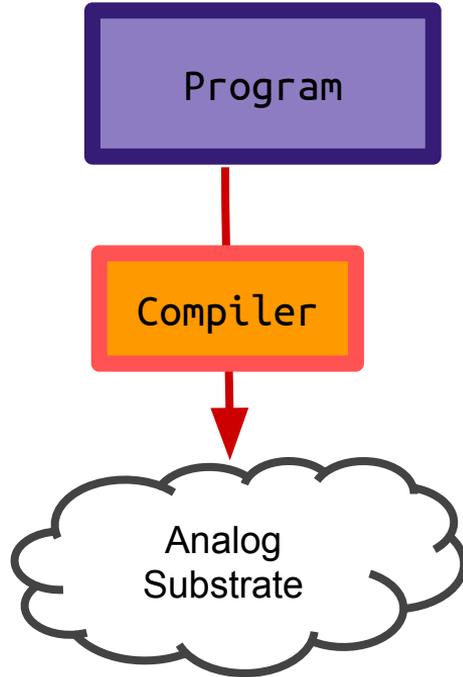
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# Computing in the Presence of Analog Behavior

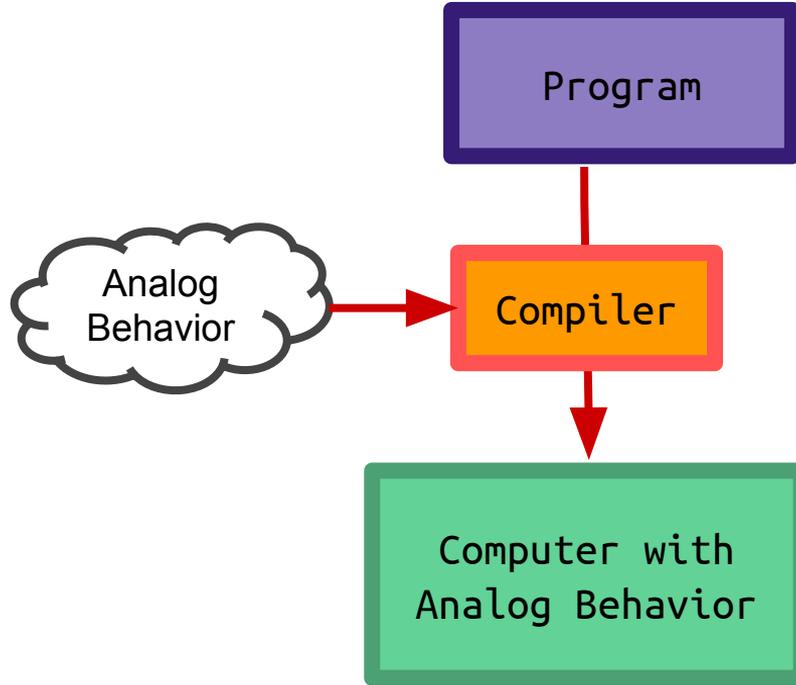


# Analog Computing



Analog behavior is desirable and leveraged to perform computation.

# Computing in the Presence of Analog Behavior



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