Spatial computing: a unifying approach to computational materials

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Royal Society Meeting on
Heterotic Computing
November, 2013

Raytheon
BBN Technologies

Computing runs across physical space-time

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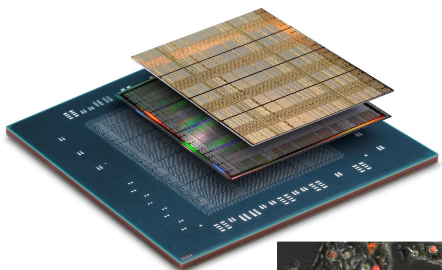
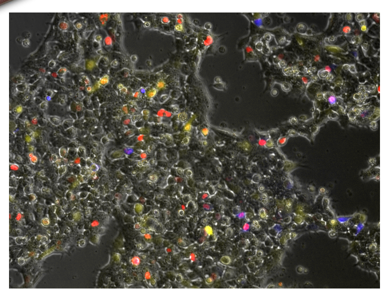
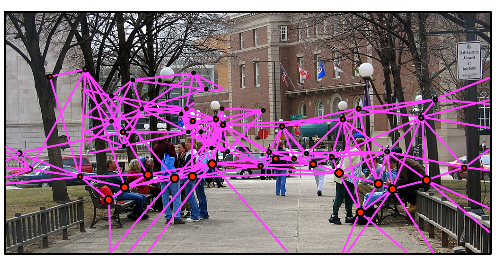
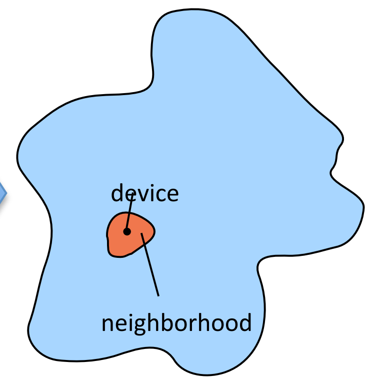
Emerging Computational Substates







Space-Time Programming Models



Multi-Substrate Computation

Outline

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- From Monolithic to Spatial Computing
- Amorphous Medium & Field Calculus
- Biological / Hybrid Computational Substrate

Traditional Monolithic Computing

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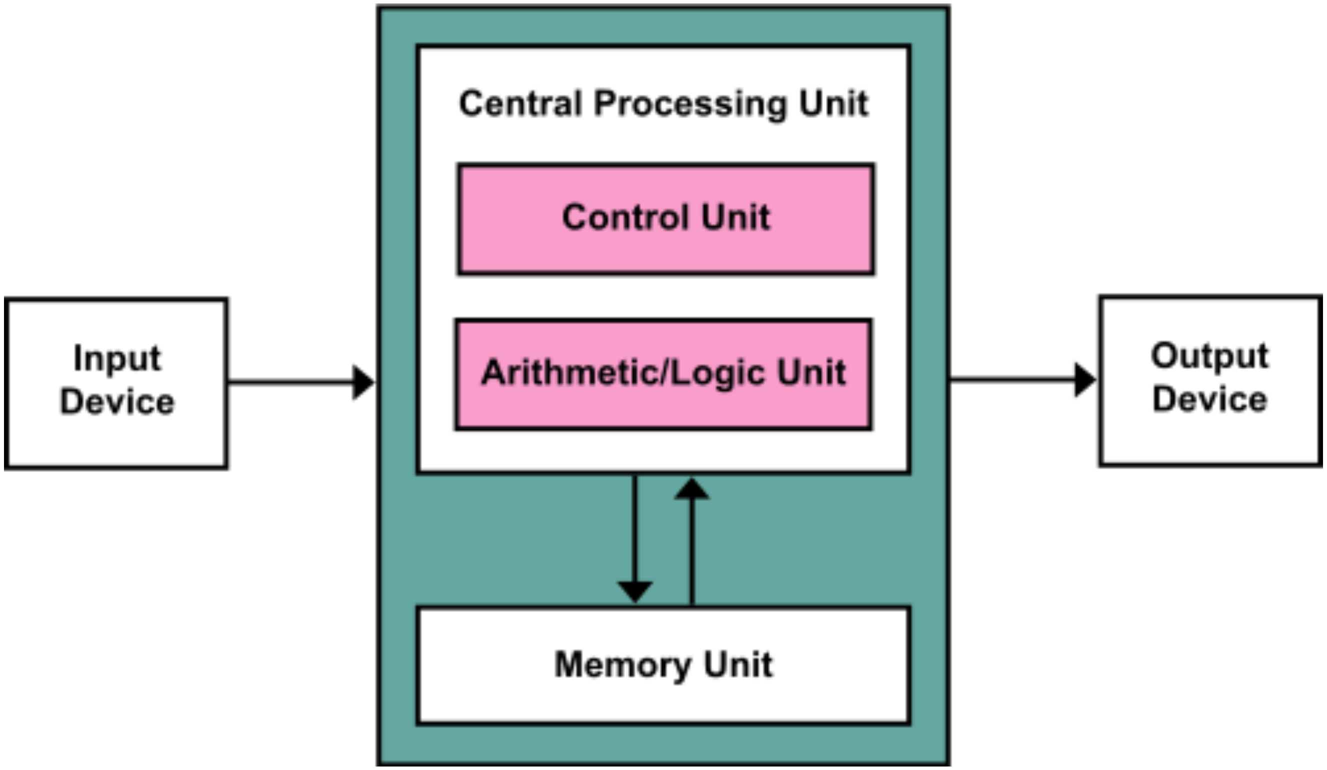

The venerable von Neumann model is breaking down in several ways…

The End of Moore's Law

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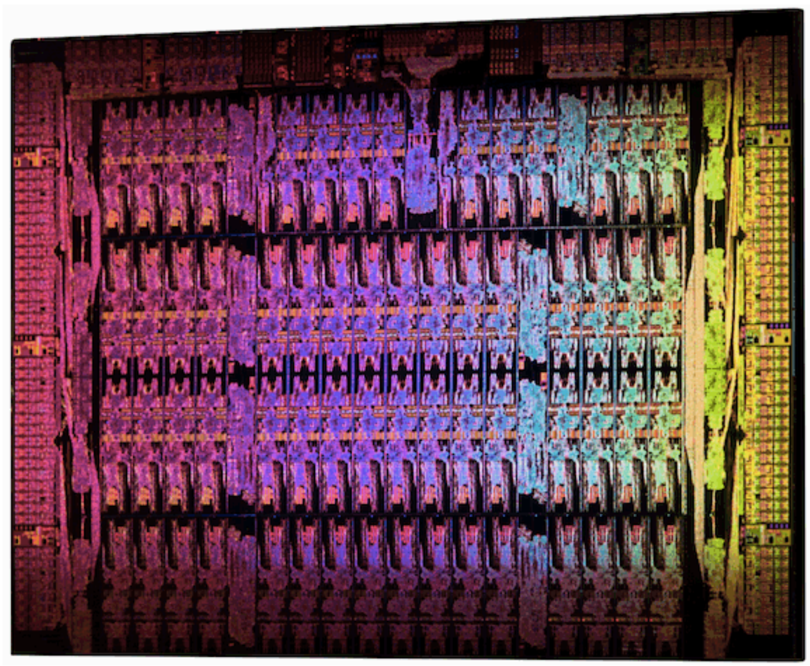
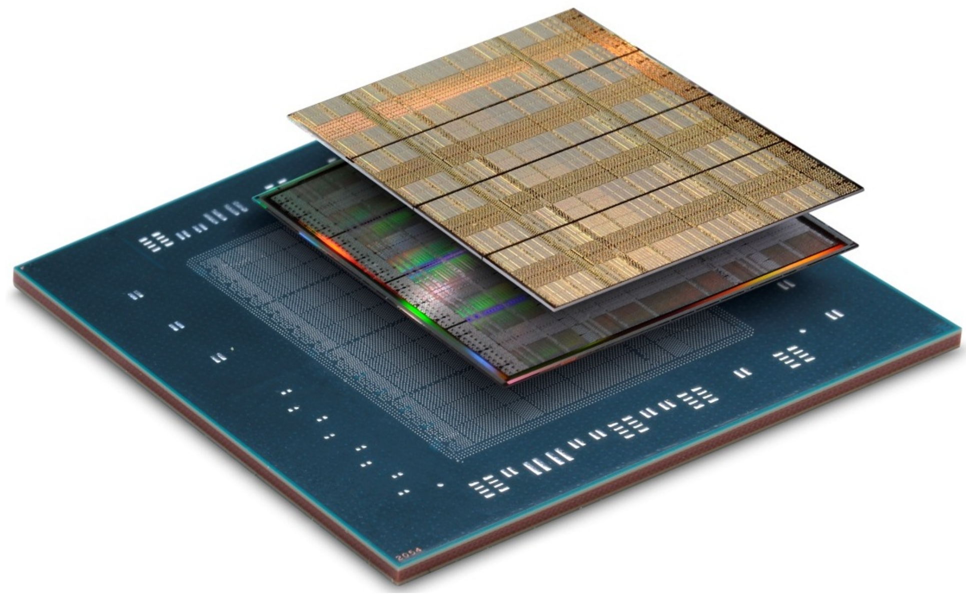


Intel Xeon Phi: 61 cores



Xilinx Virtex-7: 2M Logic cells

High-performance computing = mesh

Everything is a wireless computer

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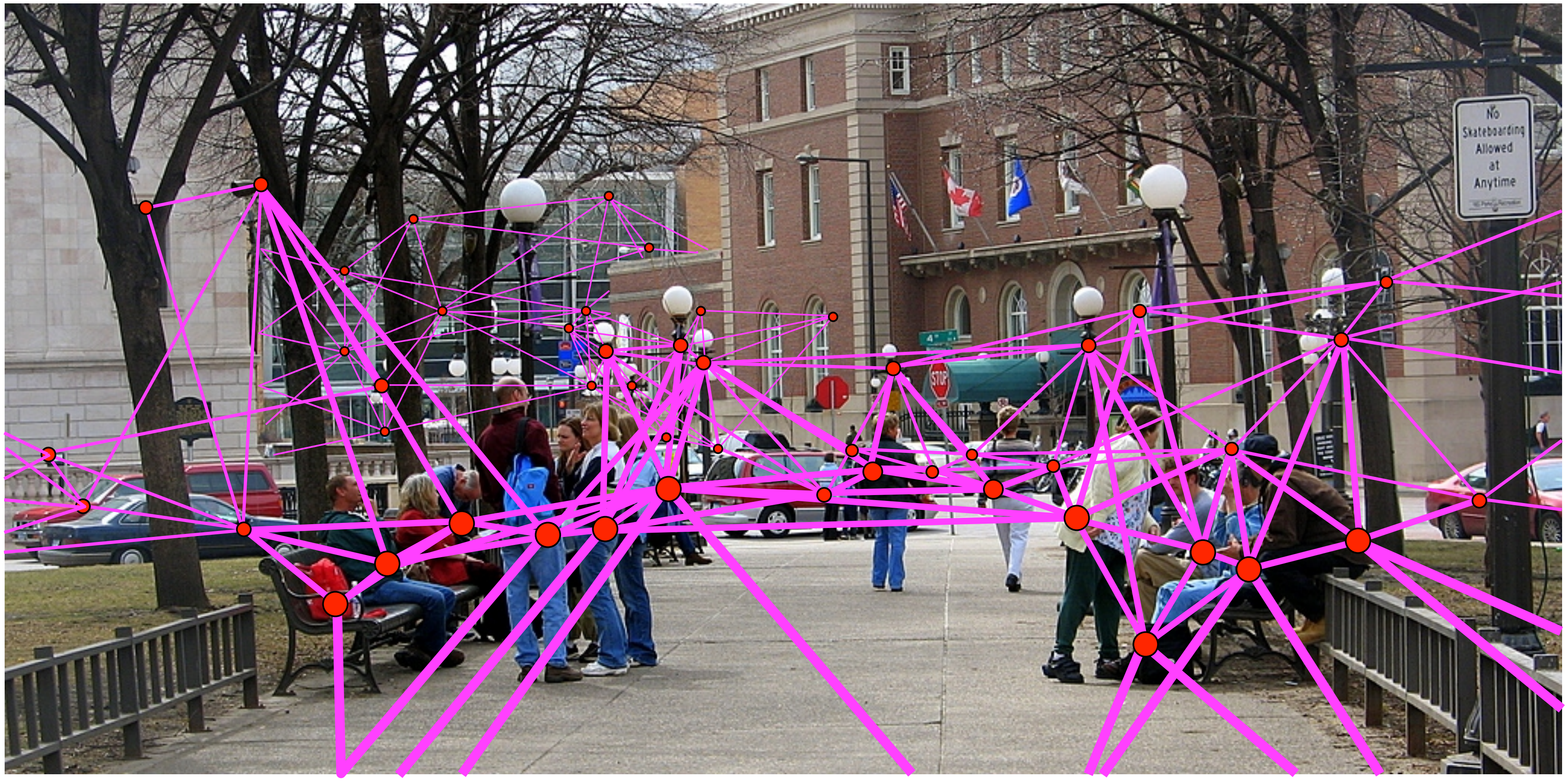

New Computational Materials

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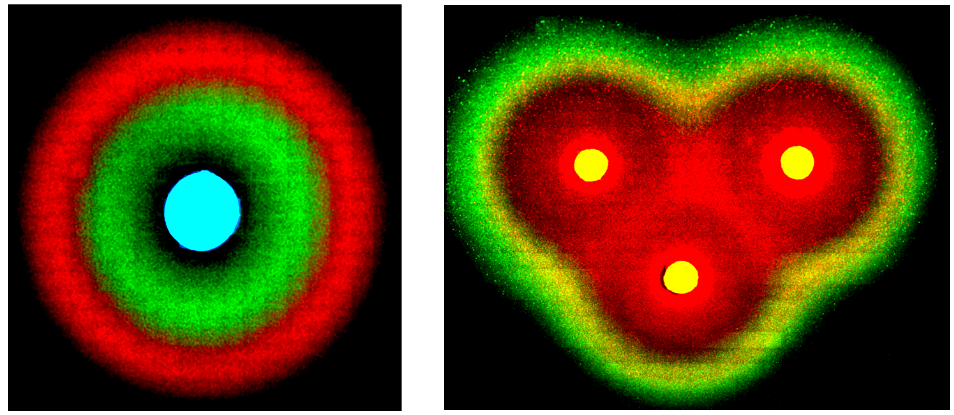
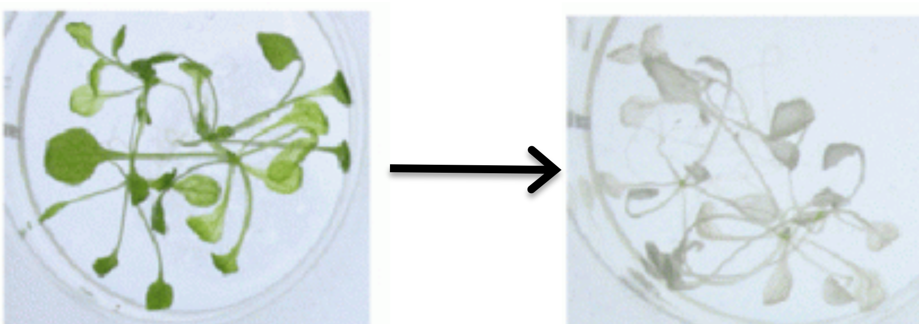
- Synthetic Biology:

[Levskaya]



[Weiss]



[Medford]

[Hasty]

Other emerging areas too, including nanoassembly, active materials…

Fundamentally different models

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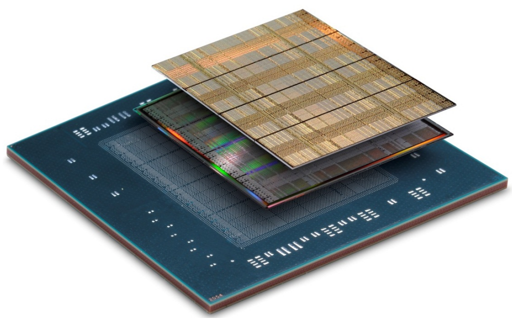

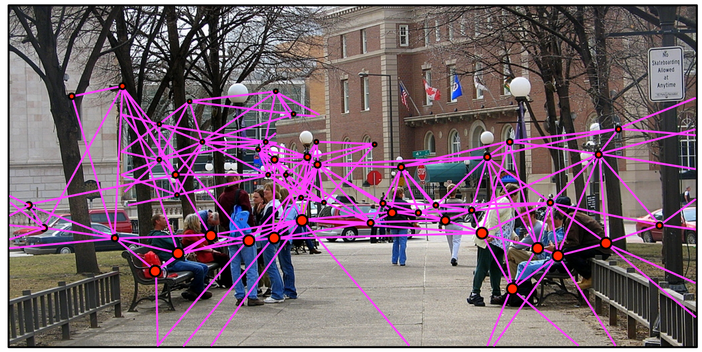

Isolate Systems
Extremely High FLOPs

High Dispersion
Moderate FLOPs

High Resolution Sense/Act
Abysmal FLOPs

How can we program aggregates adaptively & efficiently?

Can mixed systems exploit platform complementarity?

Spatial Computers

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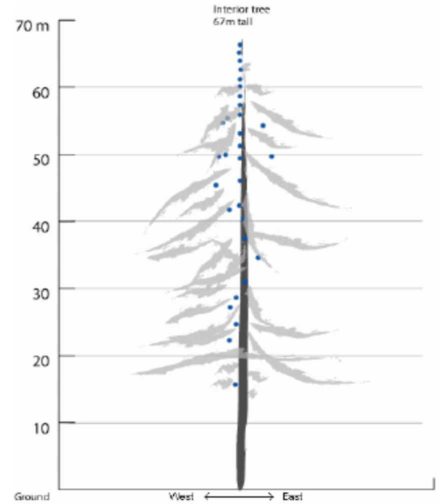
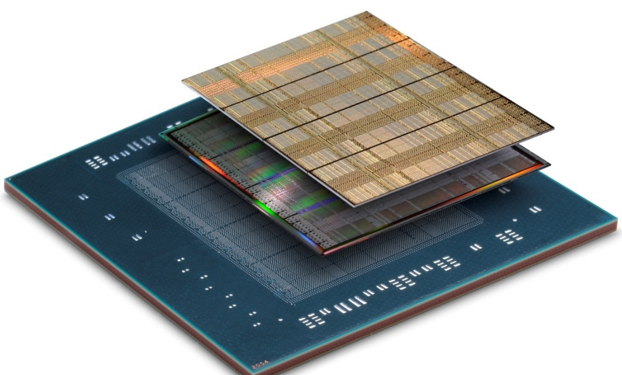
Robot Swarms

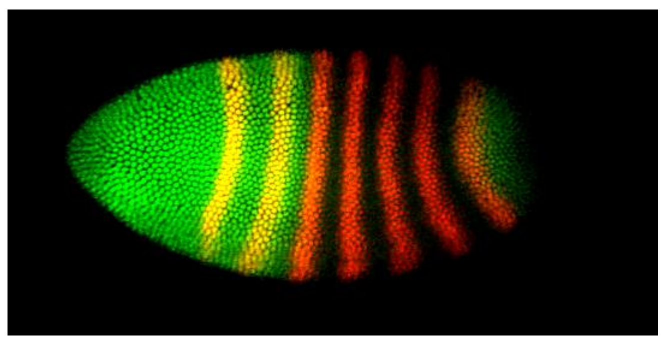
Biological Computing



Sensor Networks



Reconfigurable Computing



Cells during Morphogenesis

Modular Robotics

More formally...

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- A spatial computer is a collection of computational devices distributed through a physical space in which:
  - the difficulty of moving information between any two devices is strongly dependent on the distance between them, and
  - the “functional goals” of the system are generally defined in terms of the system's spatial structure

Outline

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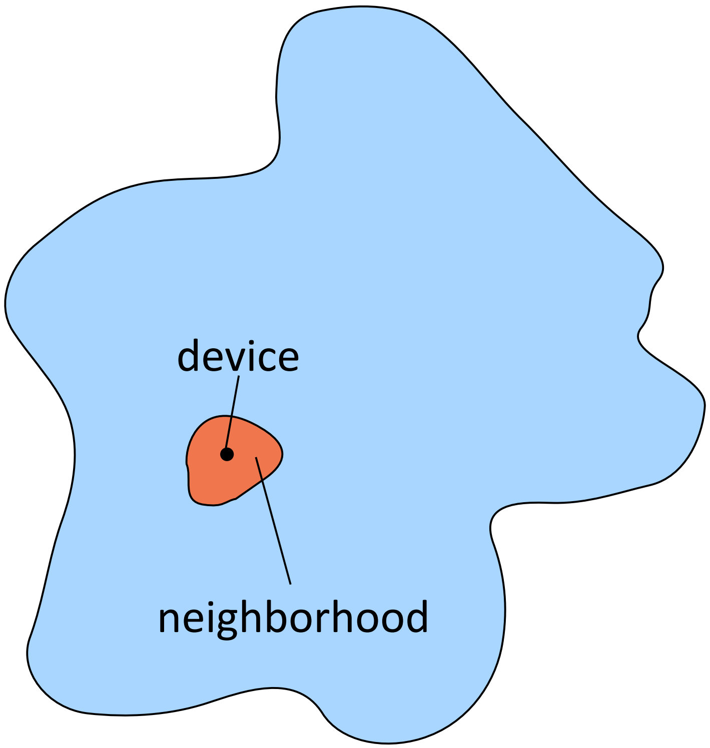
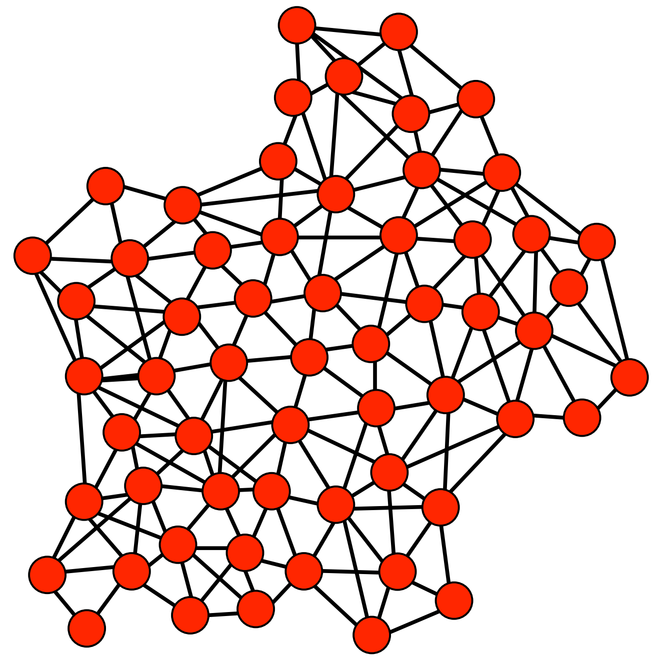
- From Monolithic to Spatial Computing
- **Amorphous Medium & Field Calculus**
- Biological / Hybrid Computational Substrate

Amorphous Medium



- Continuous space & time
- Infinite number of devices
- See neighbors' past state

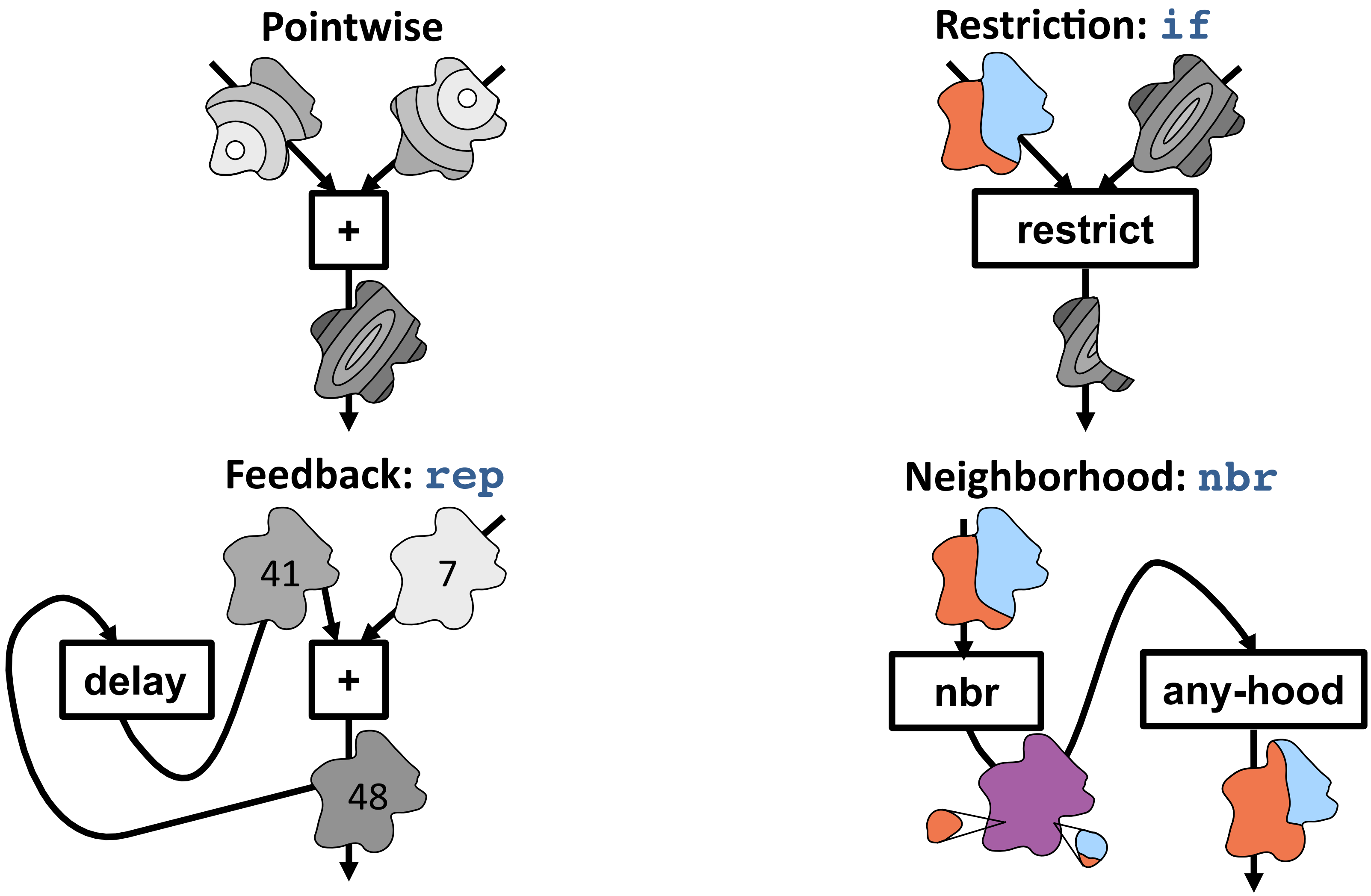


Approximate with:

- Discrete network of devices
- Signals transmit state

[Beal, '04]

Field Calculus:

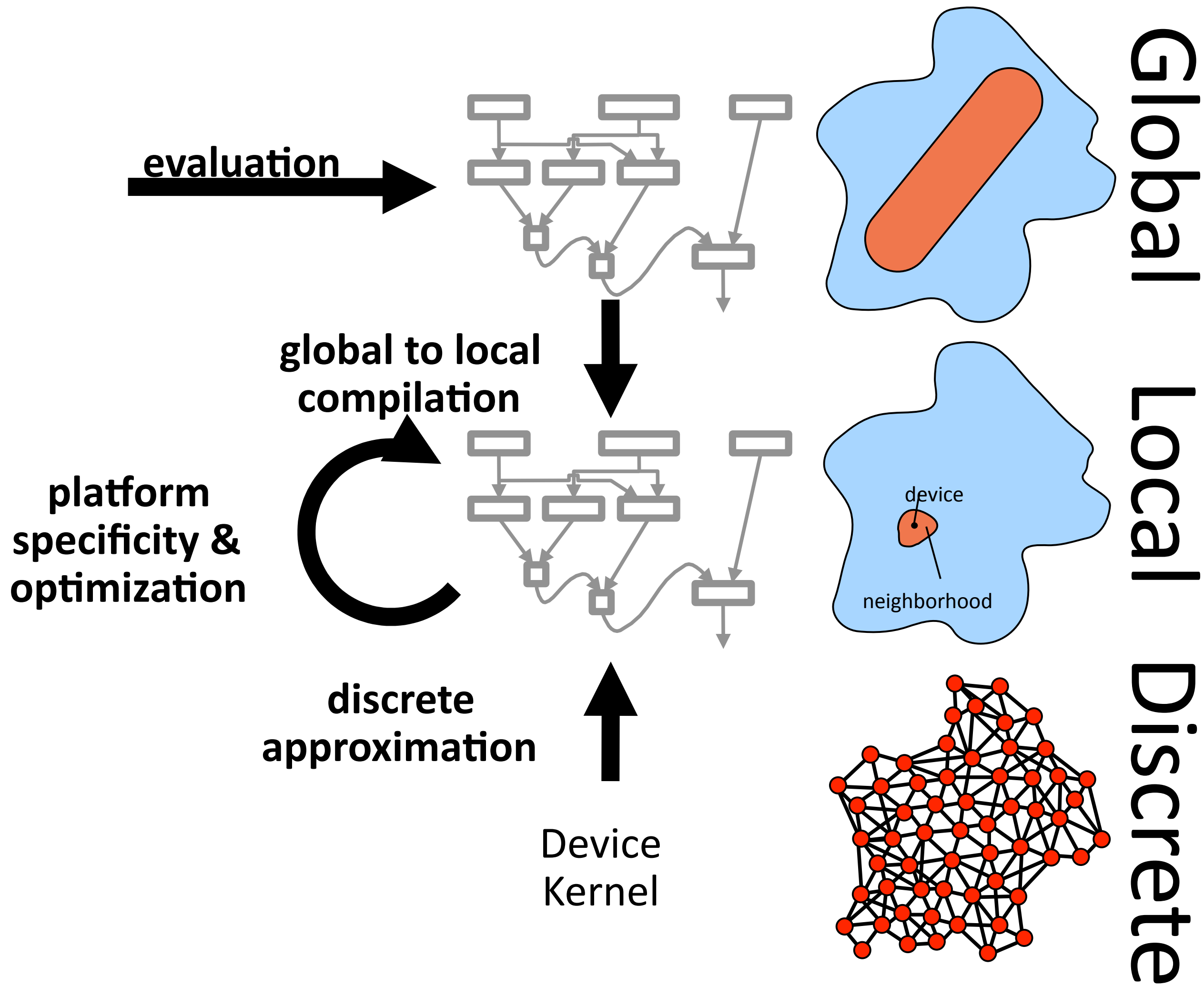


With appropriate pointwise measurements, operations are space-time universal

[Viroli et al., '13]

Implementation: Proto

```
(def gradient (src) ...)
(def distance (src dst) ...)
(def dilate (src n)
  (<= (gradient src) n))
(def channel (src dst width)
  (let* ((d (distance src dst))
         (trail (<= (+ (gradient src)
                       (gradient dst))
                    d)))
    (dilate trail width)))
```



[Beal & Bachrach, '06]

Heterogeneous Computing Materials

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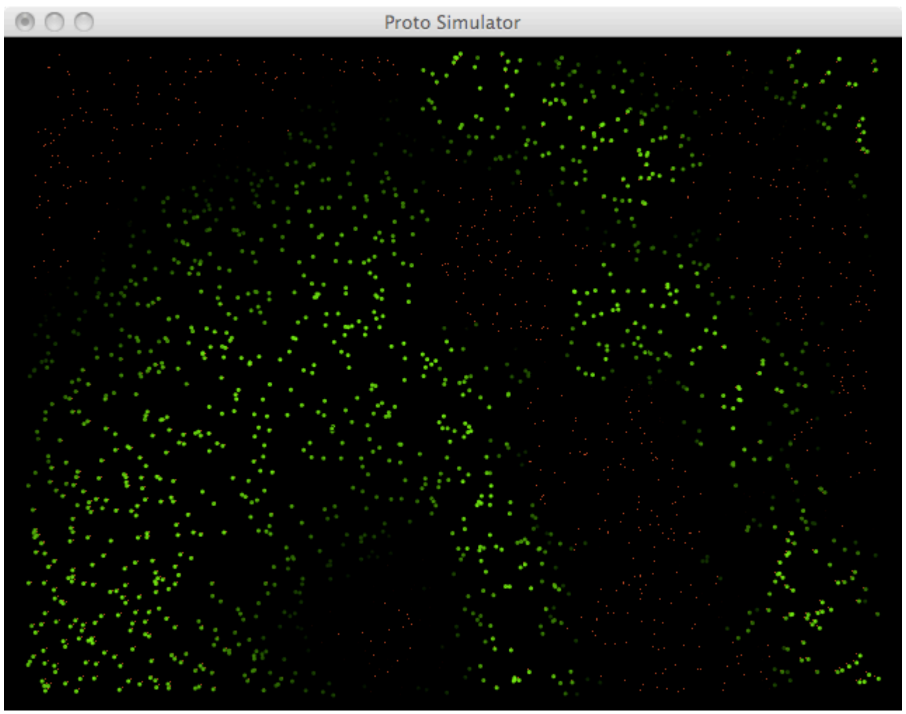
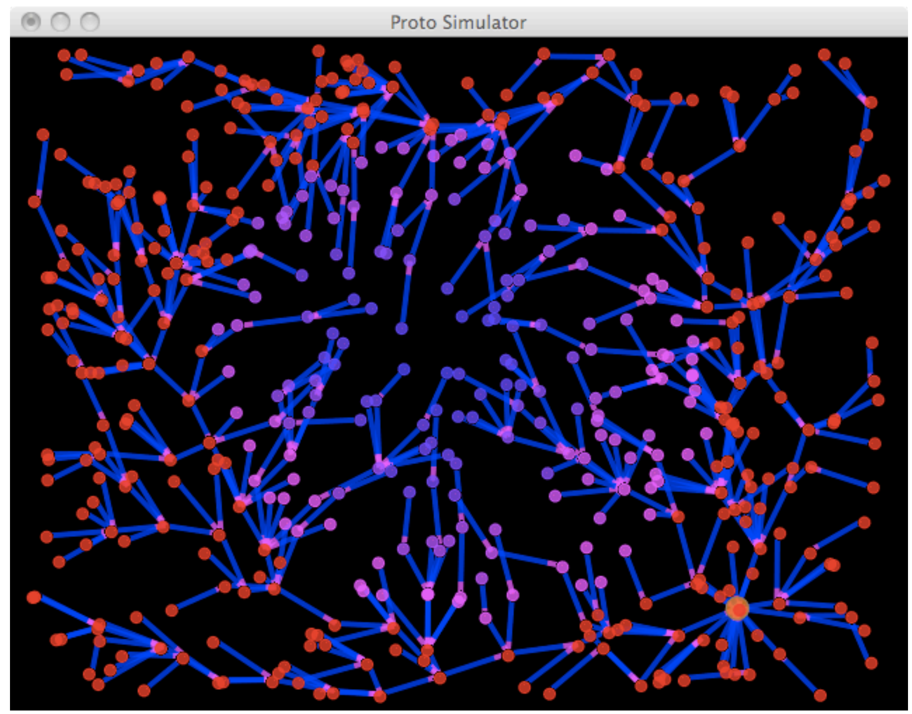
Functional "streams" integrate different time scales





Outline

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- Amorphous Medium & Field Calculus
- **Biological / Hybrid Computational Substrate**

Vision: Precision Crop Management

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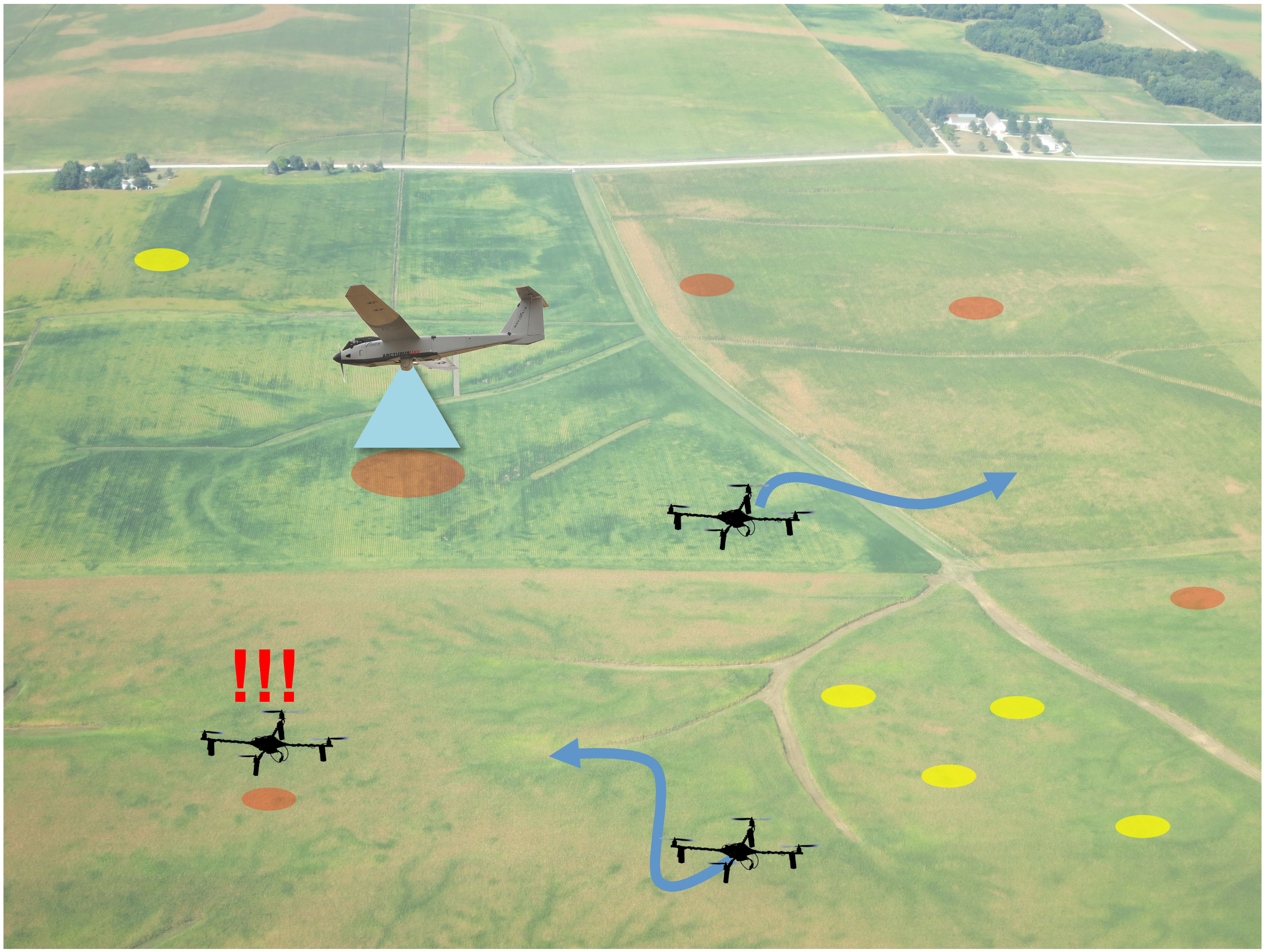

Application: Protective Biofilms

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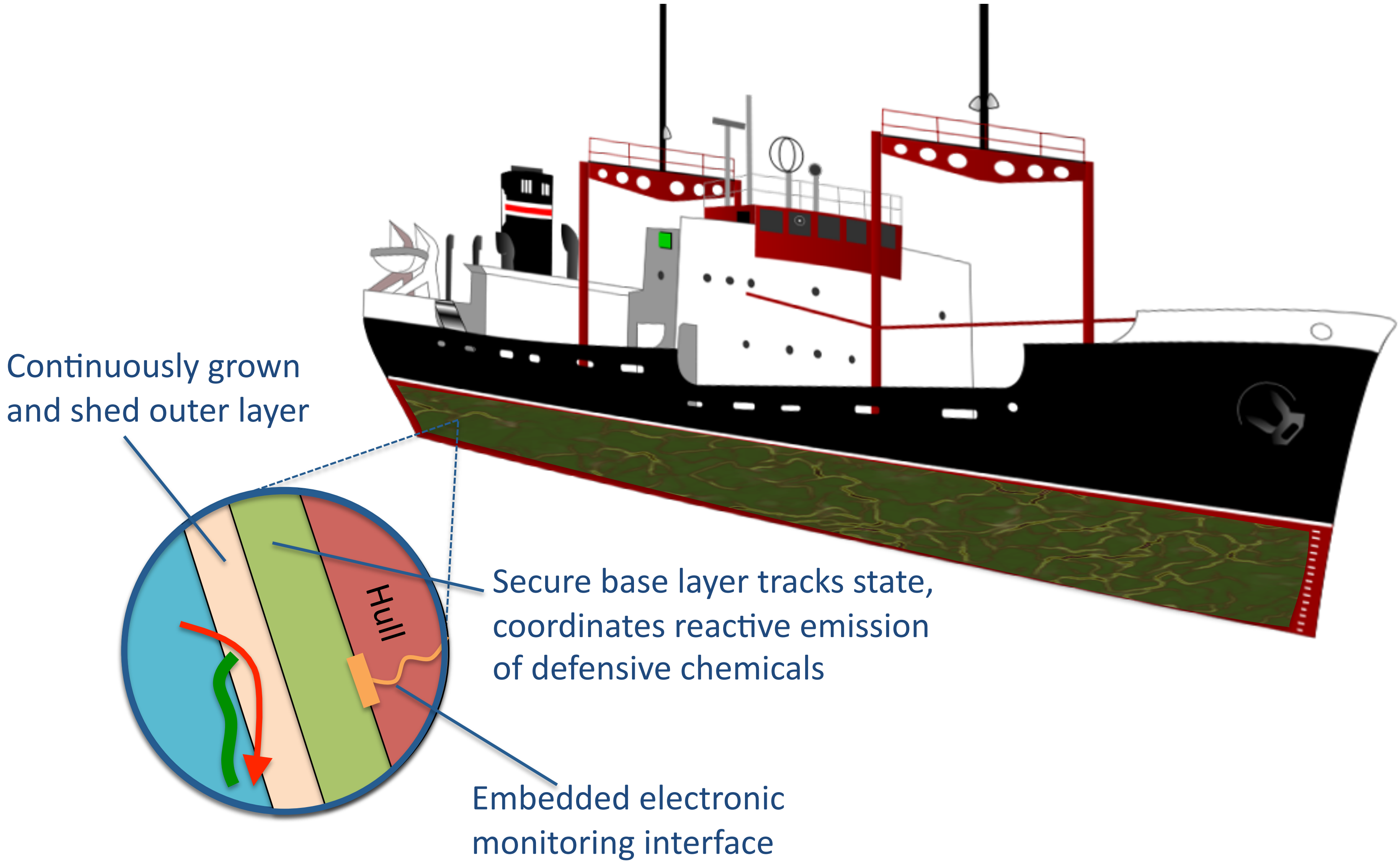
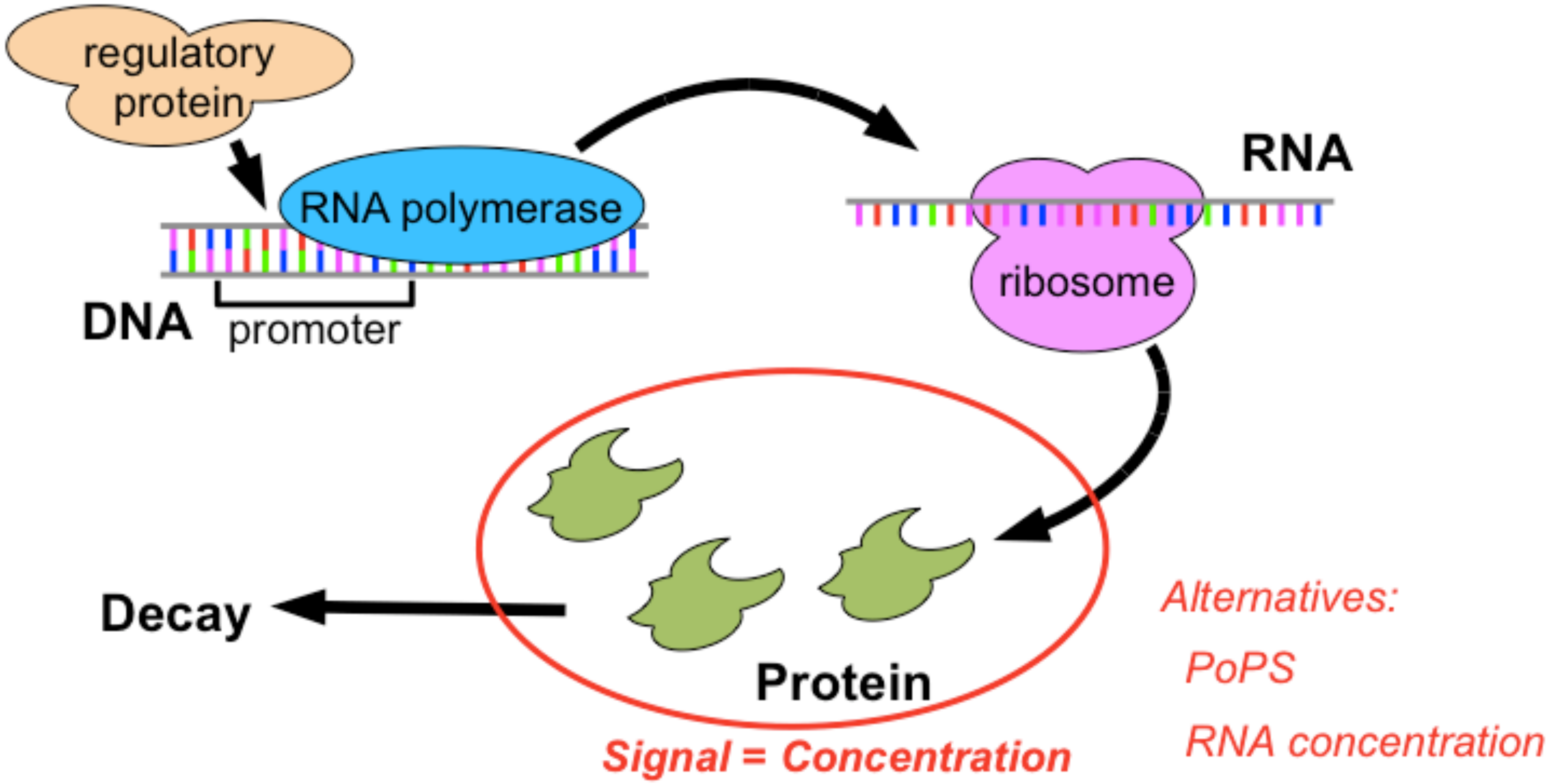


Synthetic Biology: Transcriptional Logic



Stablizes at *decay* = *production*

Genetic Regulatory Networks

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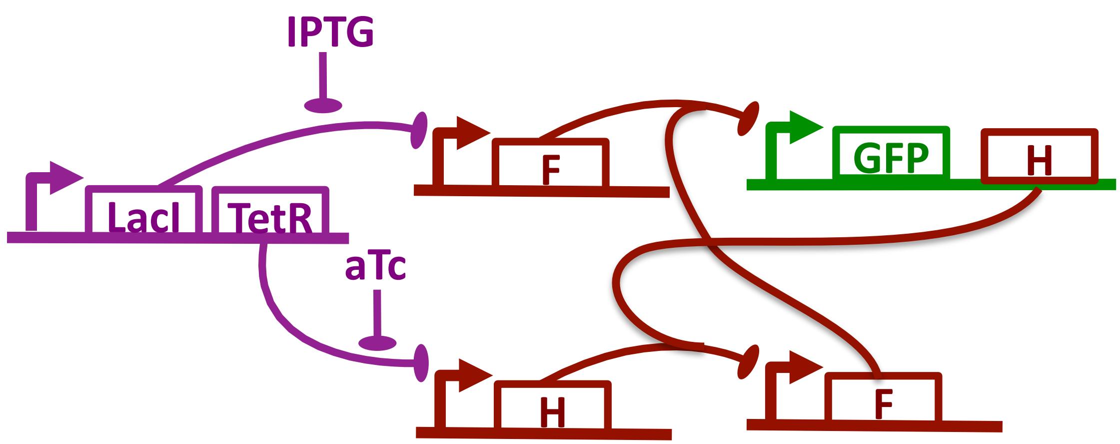
- Parallel dataflow computation
- Continuous time evolution, feedback loops

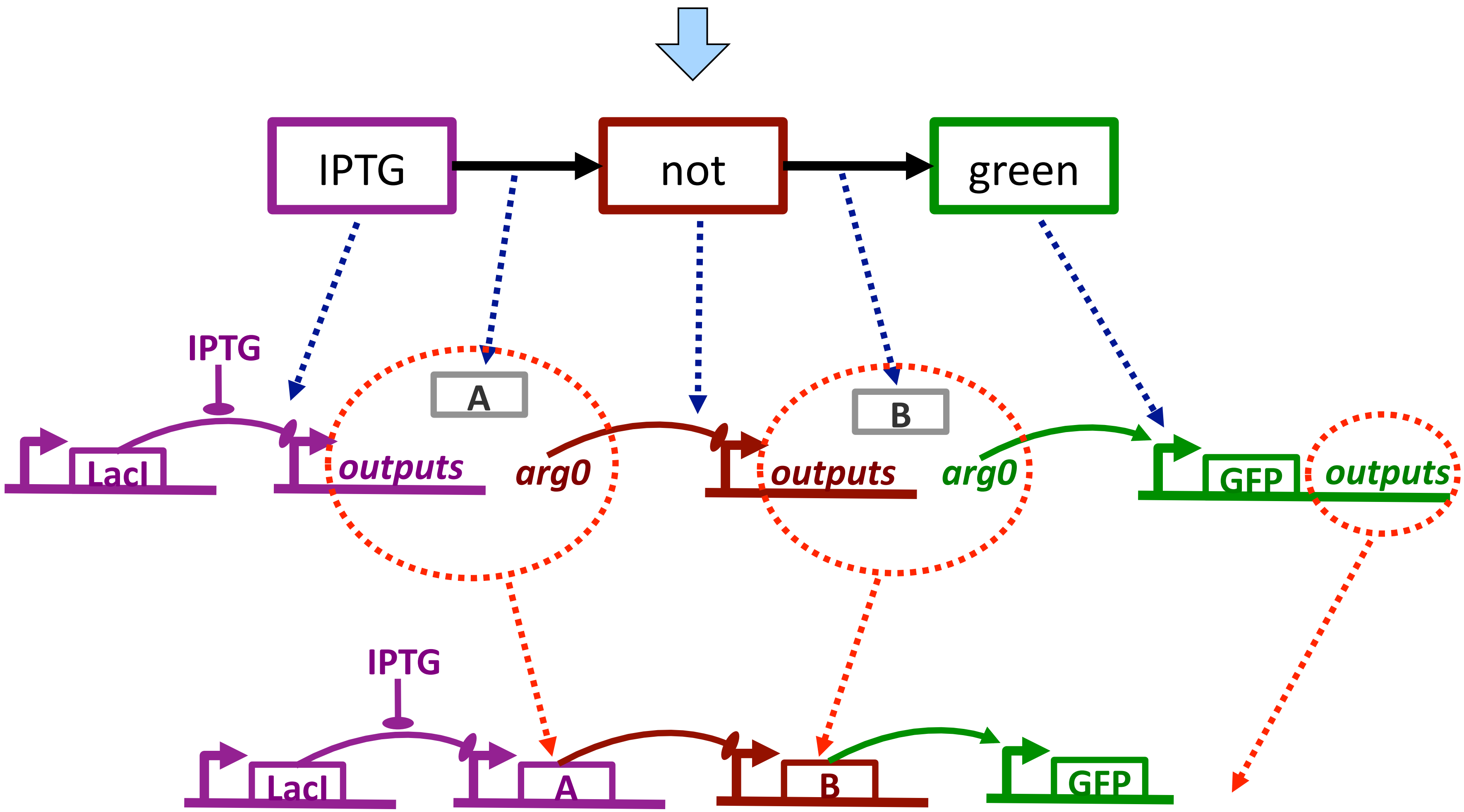
Example: SR-Latch



- Spatial patterning via intercellular signaling, adhesion, cell morphology, …

BioCompiler: Proto → GRN


```
(green (not (IPTG)))
```



[Beal, Lu & Weiss, '11]

Optimization of Complex Designs

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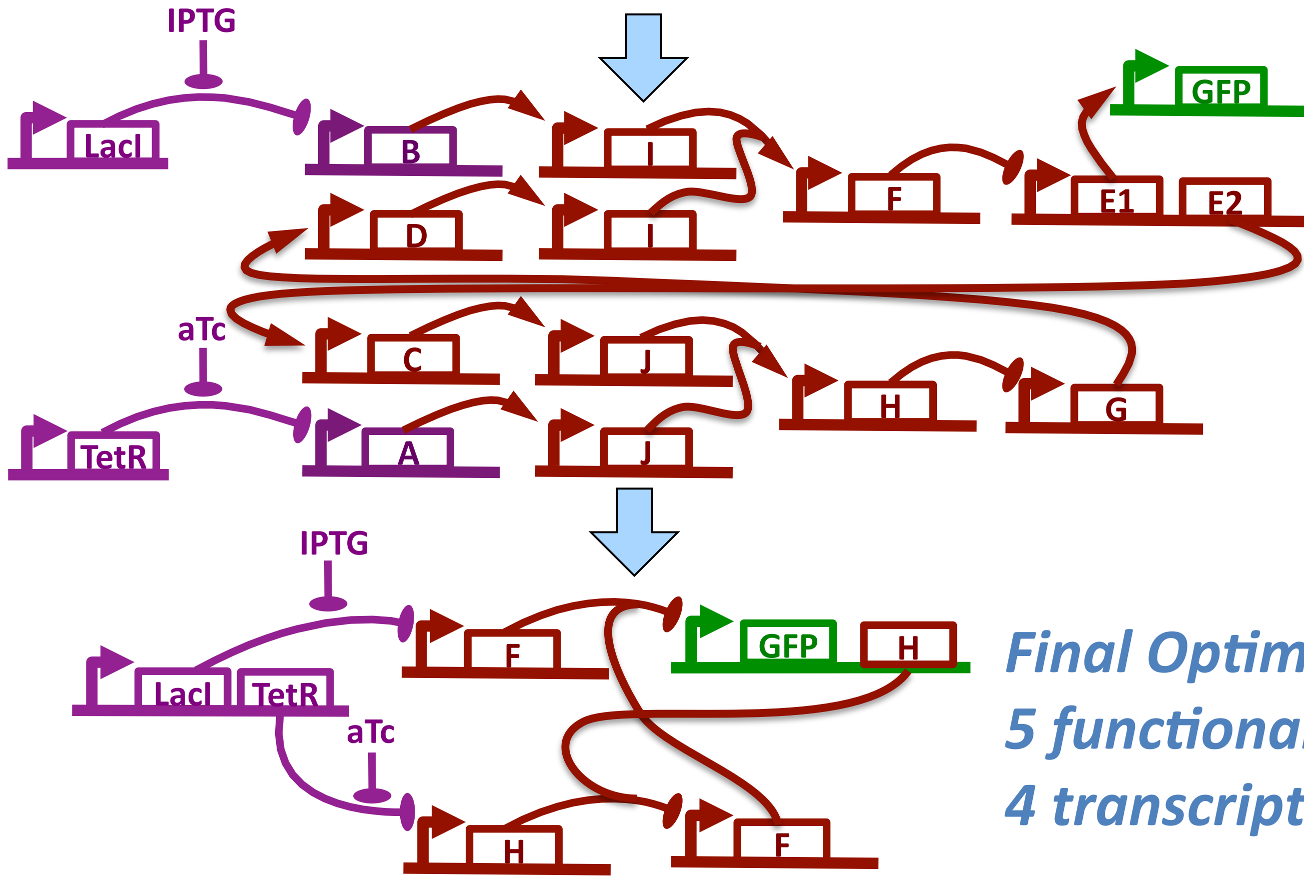
```
(def sr-latch (s r)
  (letfed+ ((o boolean (not (or r o-bar)))
            (o-bar boolean (not (or s o))))
    o))

(green (sr-latch (aTc) (IPTG)))
```



Final Optimized:
5 functional units
4 transcription factors

Unoptimized: 15 functional units, 13 transcription factors

TASBE Tool-Chain

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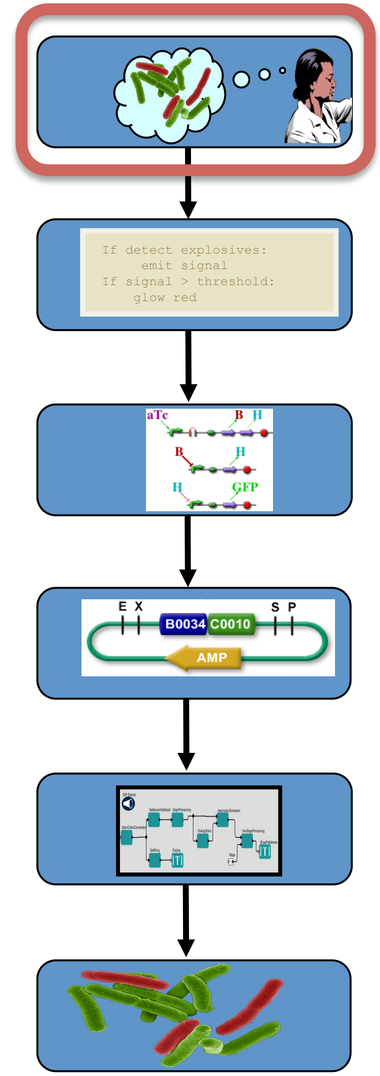
A high-level program of a system that reacts depending on sensor output

```
(def simple-sensor-actuator ()
  (let ((x (test-sensor)))
    (debug-1 x)
    (debug-2 (not x))))
```

Mammalian Target

E. coli Target



[Beal et al., 2012]

TASBE Tool-Chain

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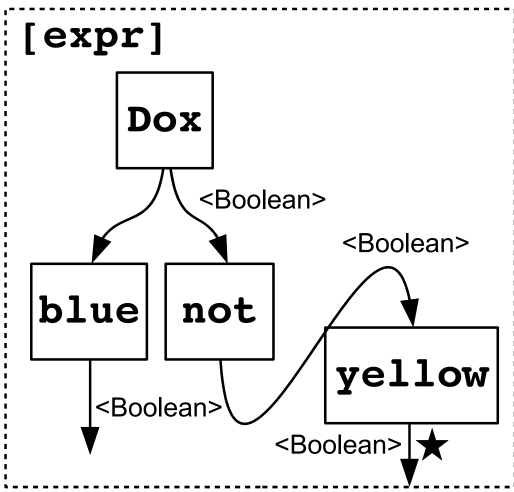
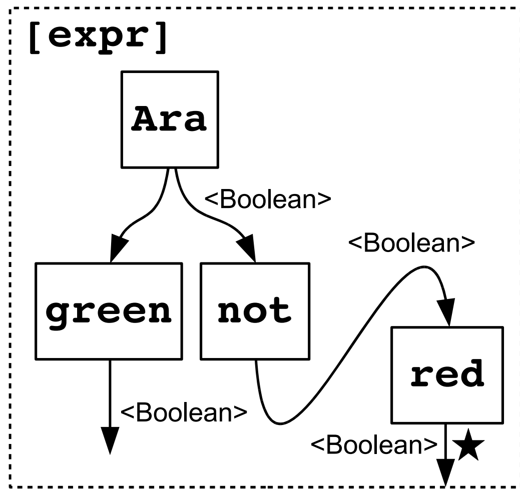
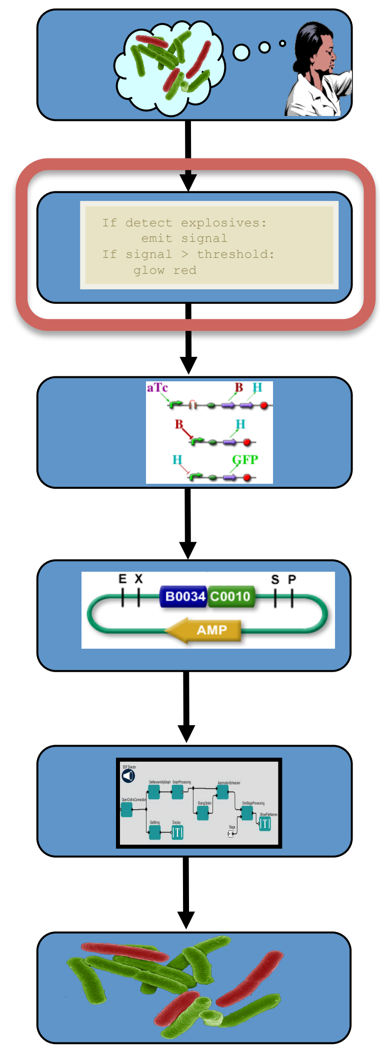
Program instantiated for two target platforms



Mammalian Target



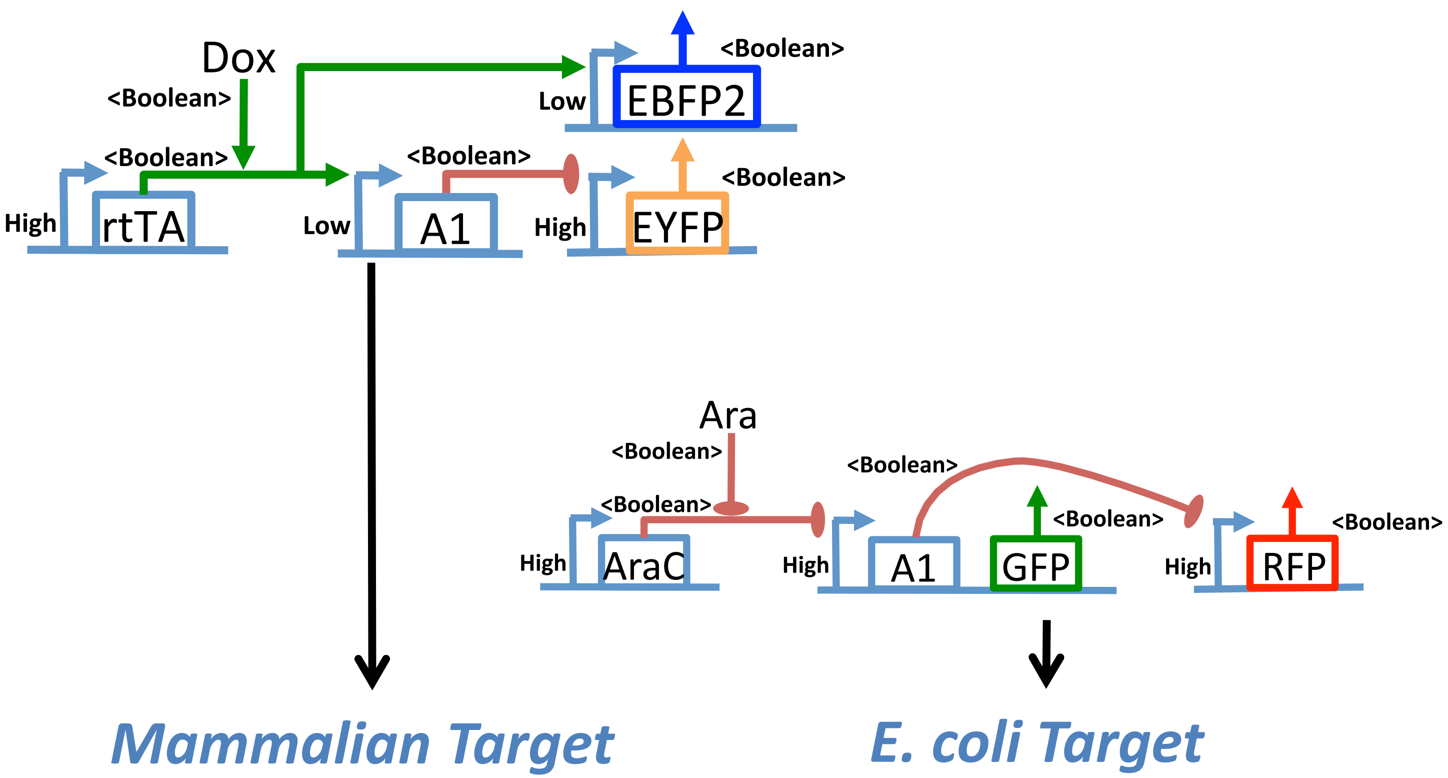
E. coli Target

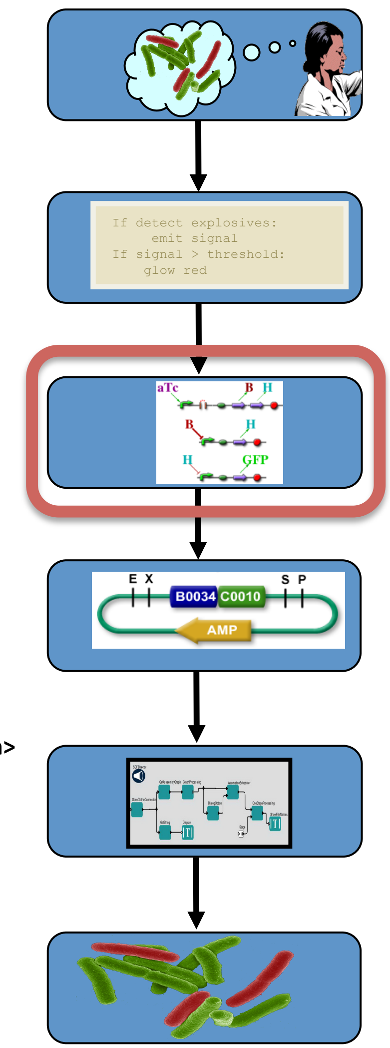


[Beal et al., 2012]

TASBE Tool-Chain

Abstract genetic regulatory networks

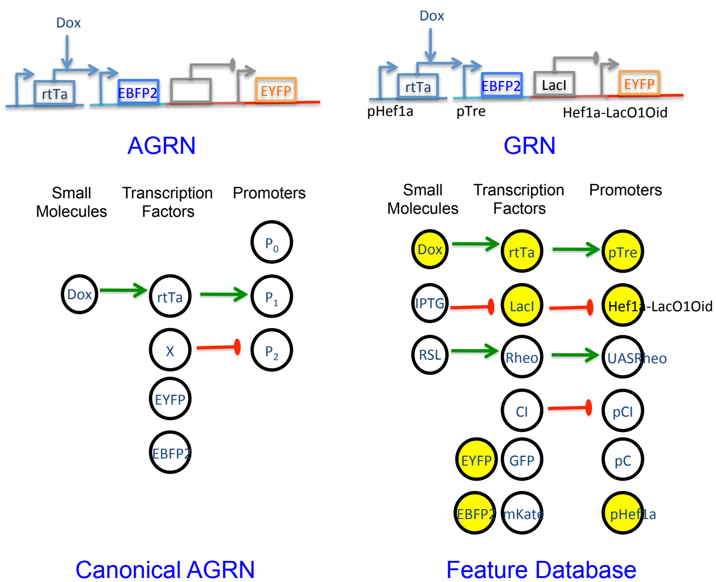




[Beal et al., 2012]

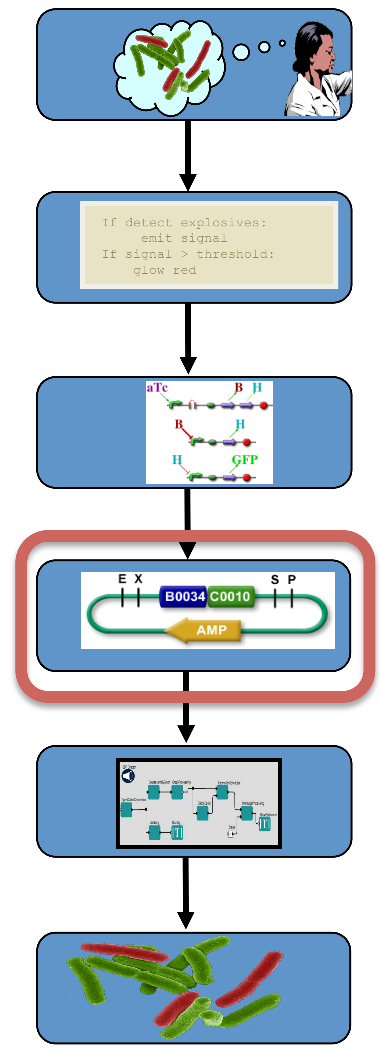
TASBE Tool-Chain

Automated part selection using database of known part behaviors



Mammalian Target

E. coli Target



[Beal et al., 2012]

TASBE Tool-Chain

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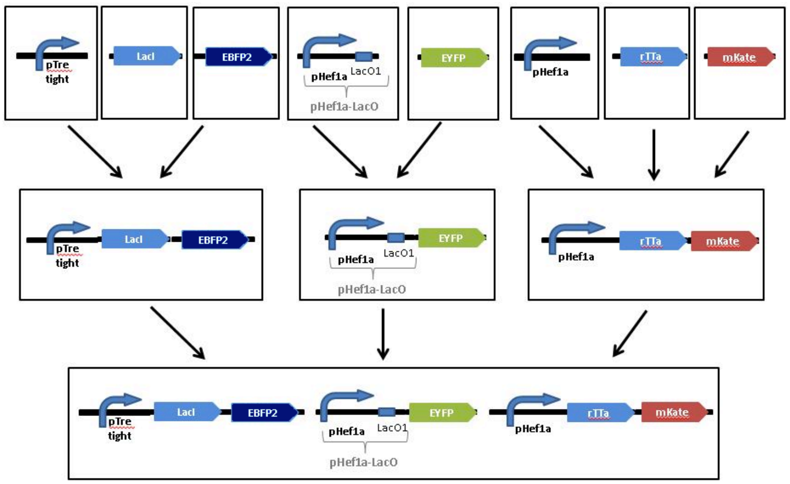
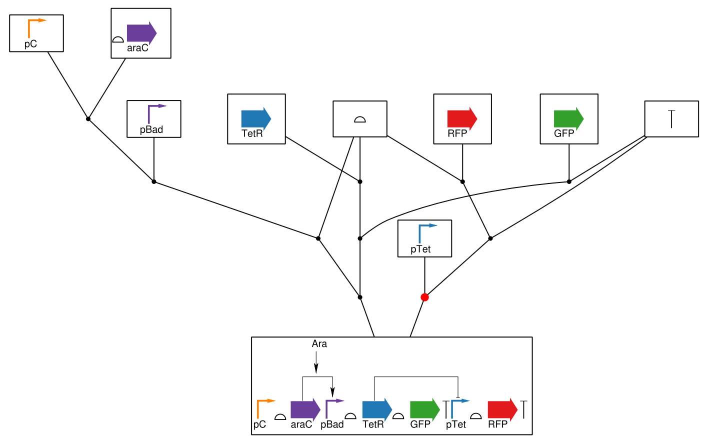
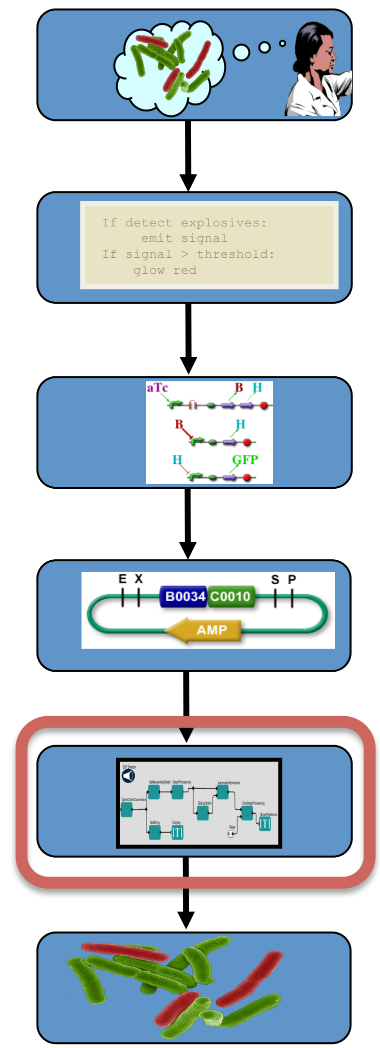
Automated assembly step selection for two different platform-specific assembly protocols





Mammalian Target

E. coli Target



[Beal et al., 2012]

TASBE Tool-Chain

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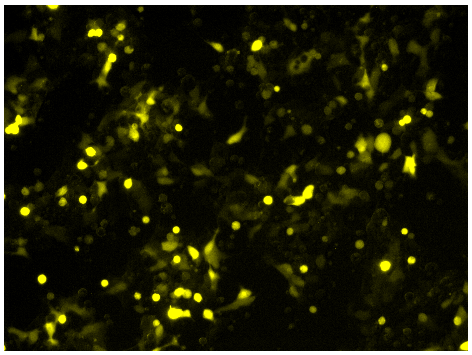
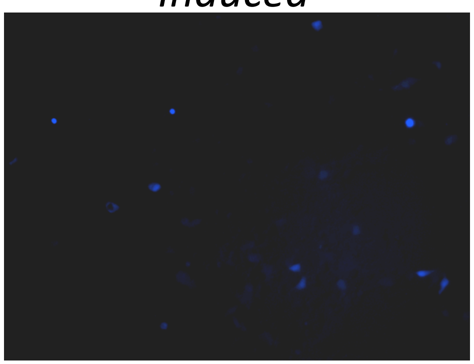
Resulting cells demonstrating expected behavior

Uninduced

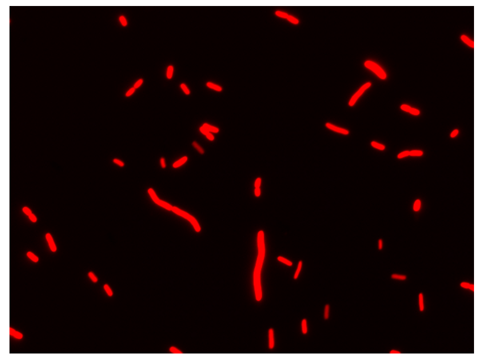


Induced

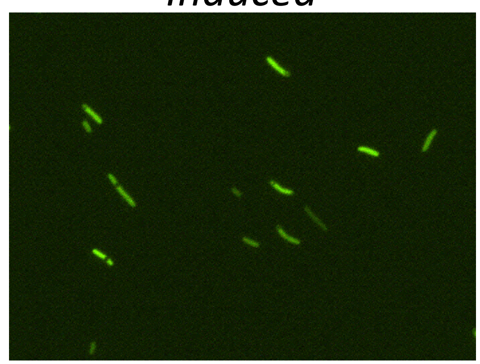


Mammalian Target

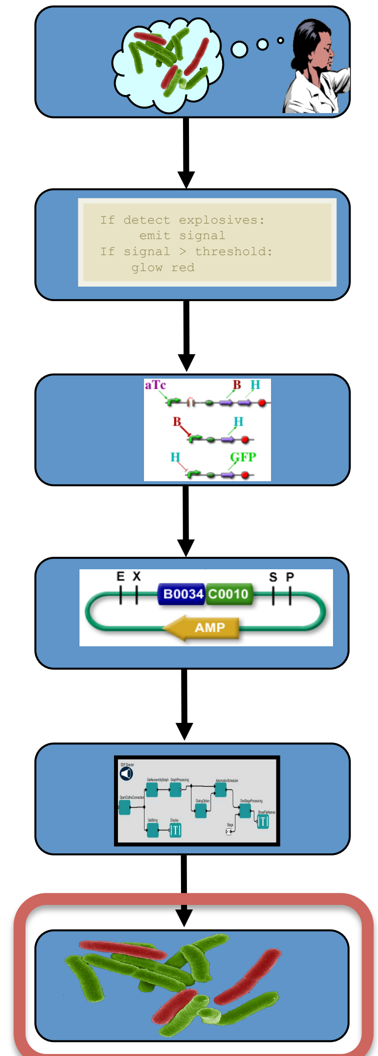
Uninduced



Induced



E. coli Target



[Beal et al., 2012]

Challenge: Synthetic Device Libraries

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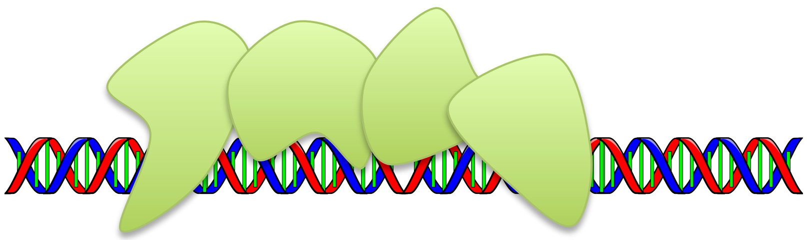
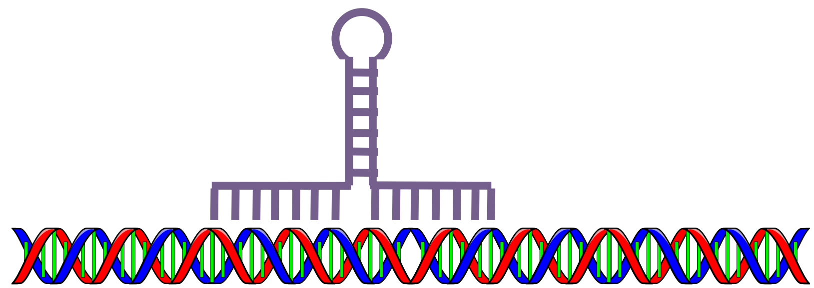
Can use a device only once/circuit

→ need lots of devices!

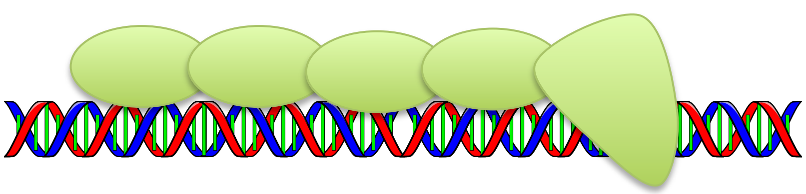
Zinc-Finger Proteins:



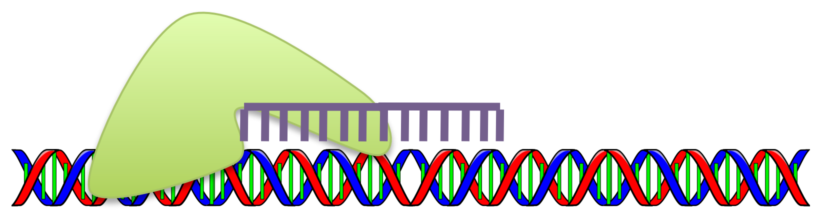
micro RNAs:



TALE Proteins:



CRISPR: CAS/gRNA:



Challenge: Predictable Composition

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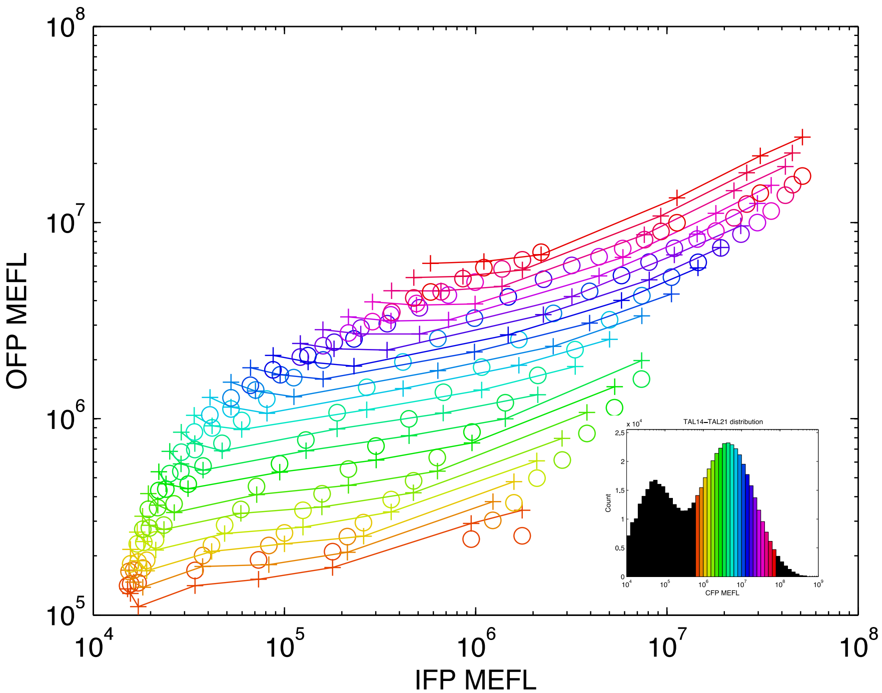
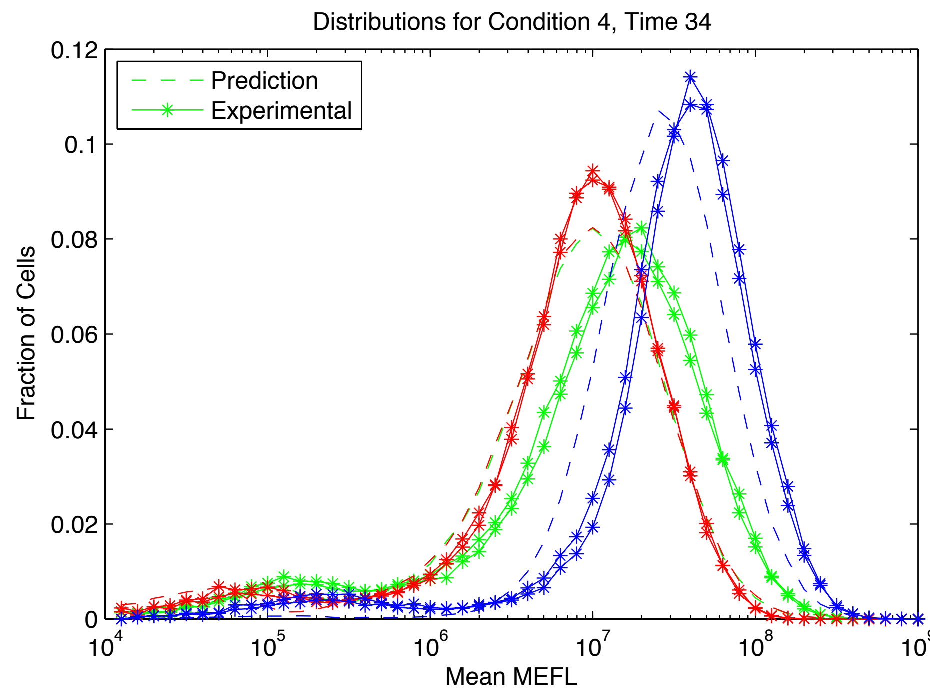
Improved models & metrology

→ high-precision circuit prediction



Two-Repressor Cascade



Three-Replicon Mixture

[Davidsohn et al., 2013]

Biological/Hybrid Substrates: where we stand

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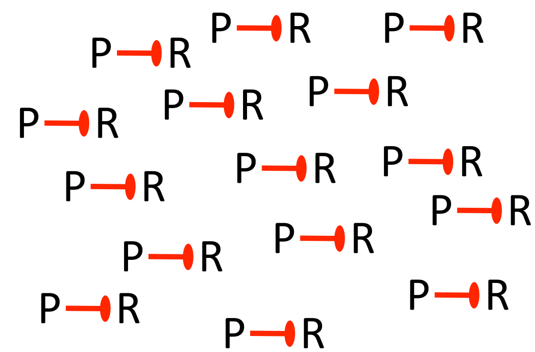
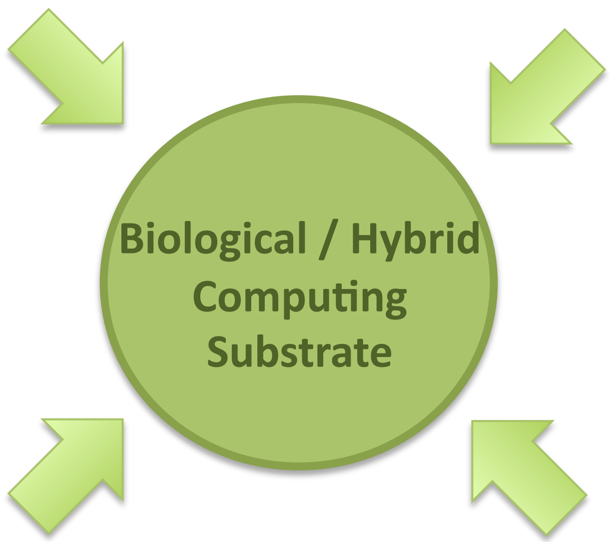
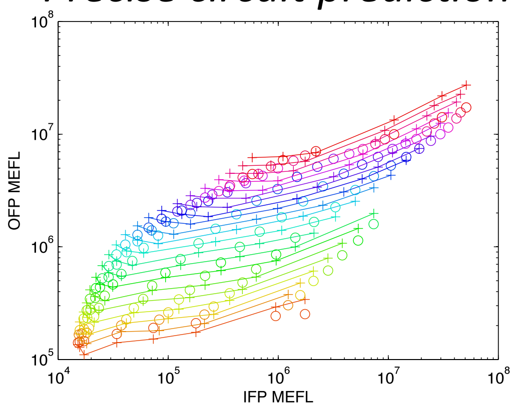
High-level specification of complex circuits



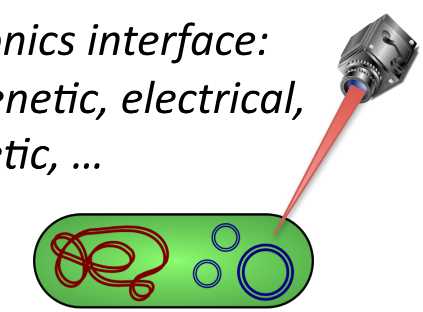
Large, well-characterized device libraries



Precise circuit prediction



Electronics interface: optogenetic, electrical, magnetic, …



Summary

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- Major technological trends are all driving towards a world filled with spatial computers
- Continuous space-time models allow effective adaptive aggregate programming.
- Mixed-material computation will enable a wide range of visionary applications.
- Rapid progress towards predictable, scalable computational control of biological organisms

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Raytheon BBN Technologies

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Chenkai Liu
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Tyler Wagner

Mirko Viroli
Matteo Cascadei

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DARPA

Tools available online!

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http://proto.bbn.com/ **http://synbiotools.bbn.com**