Predictable Self-Organization with Computational Fields

Jacob Beal, Mirko Viroli

Tutorial at 8th IEEE SASO
Imperial College London
September 2014

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Aggregate Programming: The Big Picture

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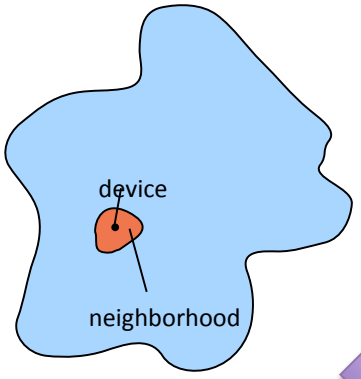
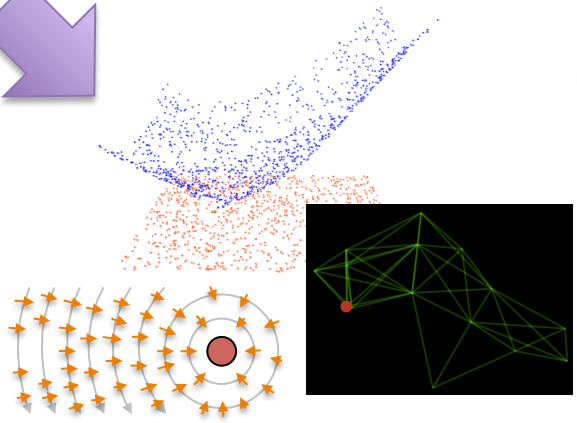


Field-Based Computing Models



Self-Organization Building Blocks

Lots of distributed applications!

Our Promises to You

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By the end of this tutorial you will…

- know about aggregate programming, field calculus, and continuous space-time abstractions
- be able to write programs in Proto
- understand how field computation can support predictable engineering of complex adaptive systems
- understand how to build complex self-organizing systems by composing building-block algorithms

Schedule:

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14:00 – 14:30	Aggregate Programming & Spatial Computing	*Jake*
14:30 – 15:30	Field Calculus	*Mirko*
	Coffee Break	
16:00 – 16:20	Ensuring Self-stabilisation	*Mirko*
16:20 – 17:20	Building Blocks & Consistency	*Jake*
17:20 – 17:30	Summary and Open Problems	*Jake*

Aggregate Programming and Spatial Computing

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Don’t micromanage your networks!

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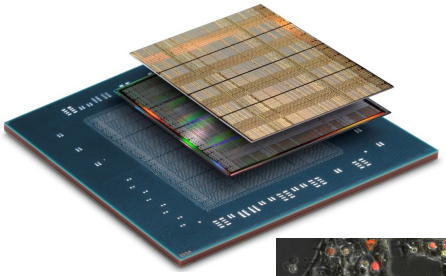
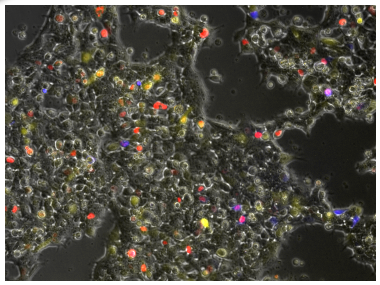
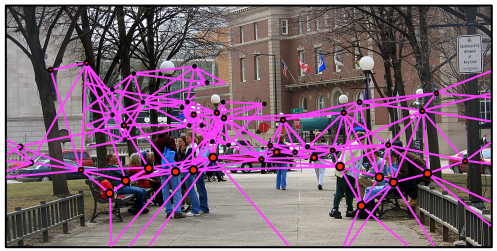
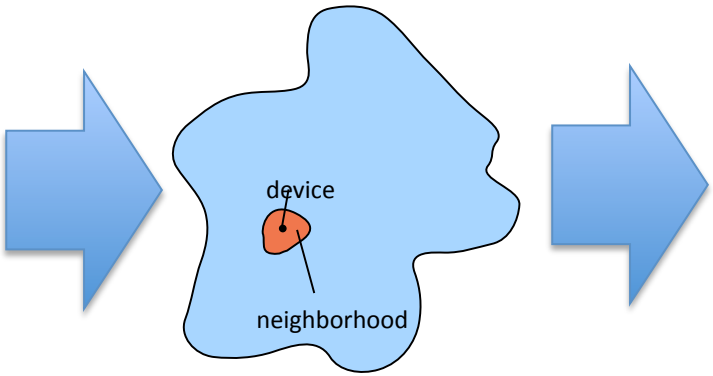
Emerging Computational Platforms







Computational Field Programming Models



Inherently Resilient Distributed Systems

Pay a little efficiency, get a lot of programmability and resilience

Traditional Monolithic Computing

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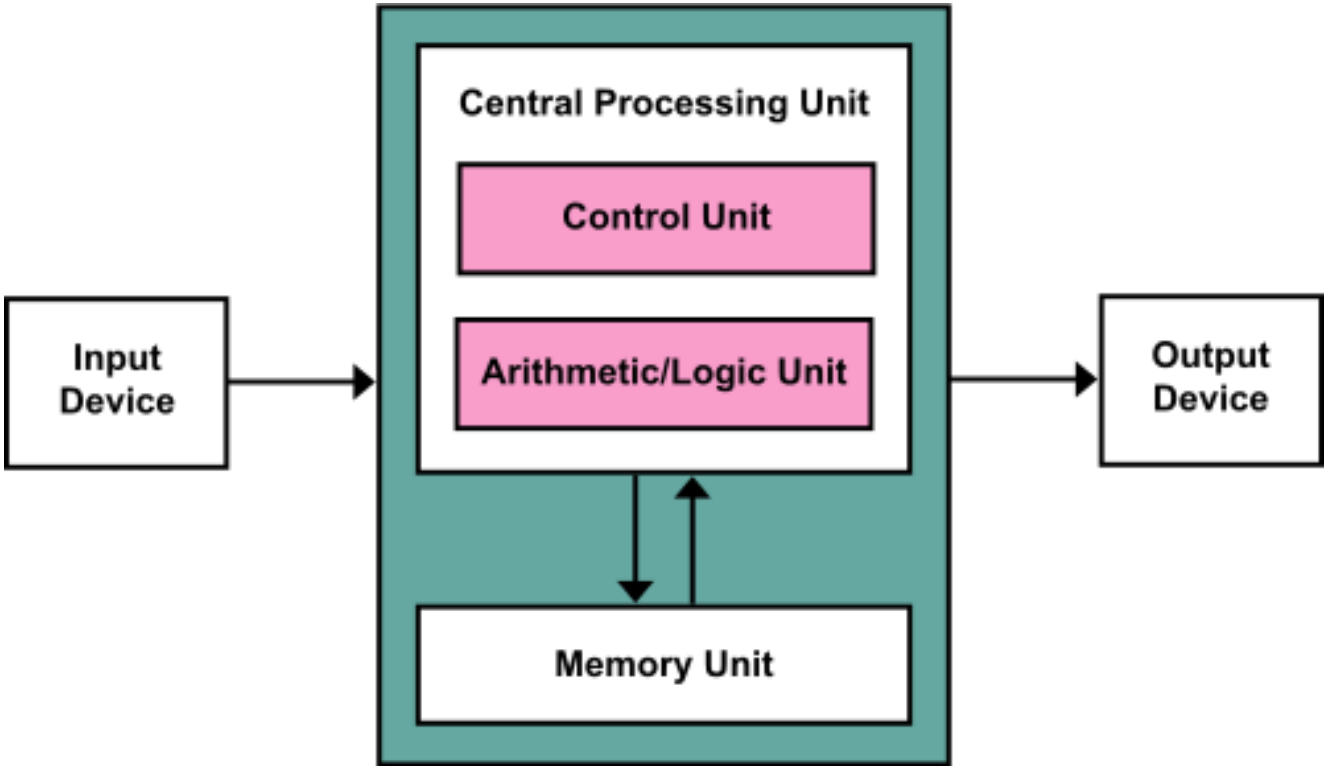

The venerable von Neumann model is breaking down in several ways…

The End of Moore's Law

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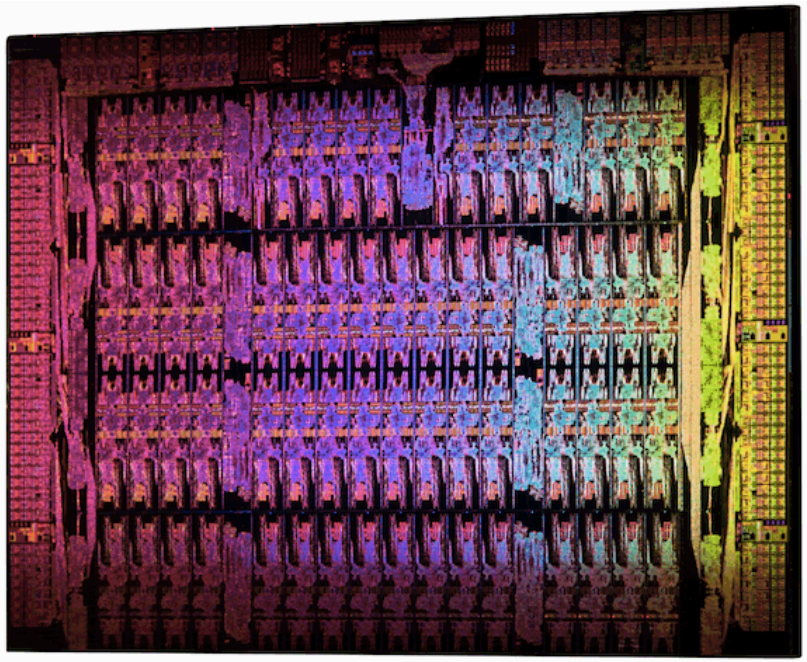
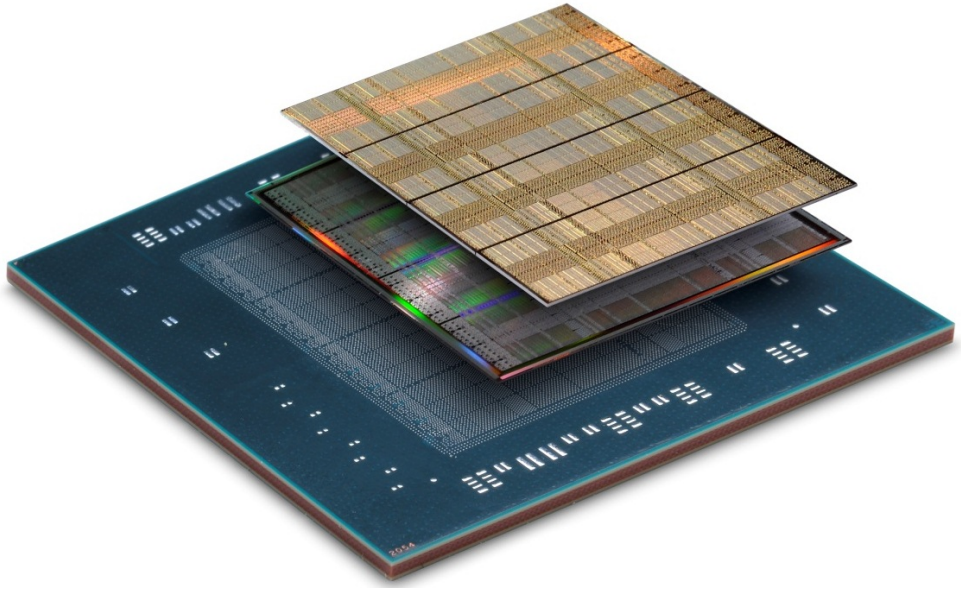


Intel Xeon Phi: 61 cores



Xilinx Virtex-7: 2M Logic cells

High-performance computing = mesh

Everything is a wireless computer

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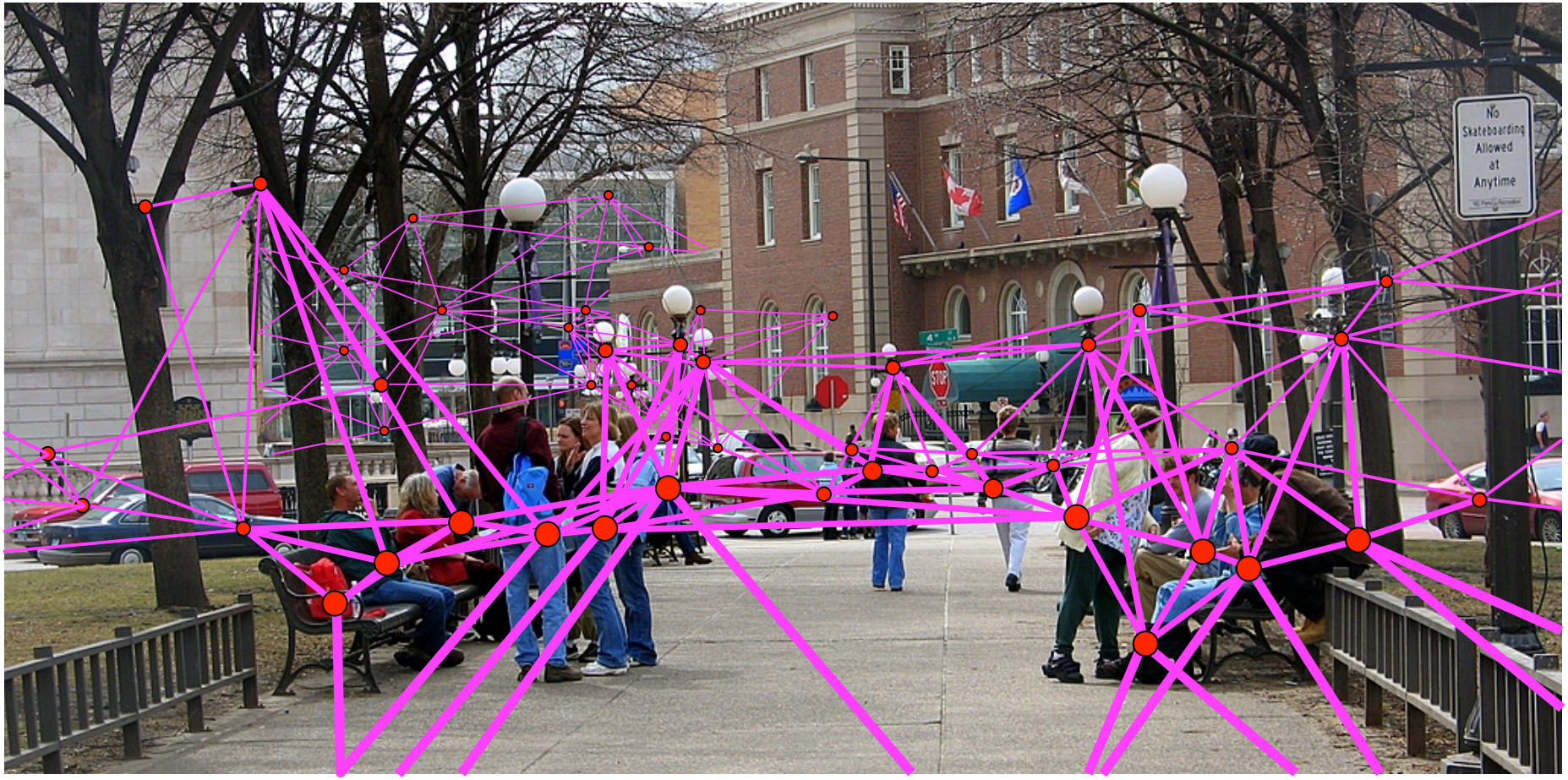

New Computational Materials

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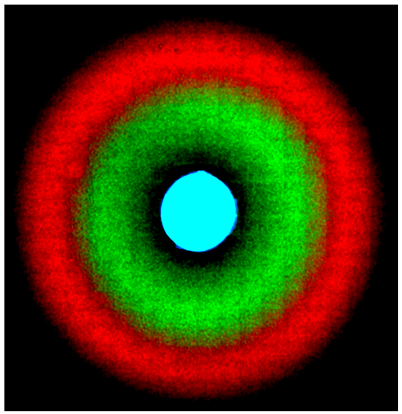
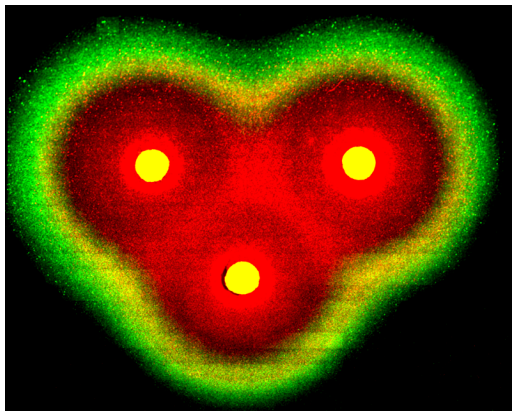
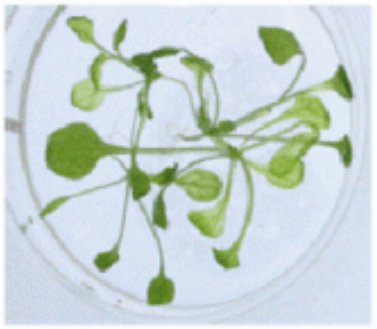
- Synthetic Biology:

[Levskaya]

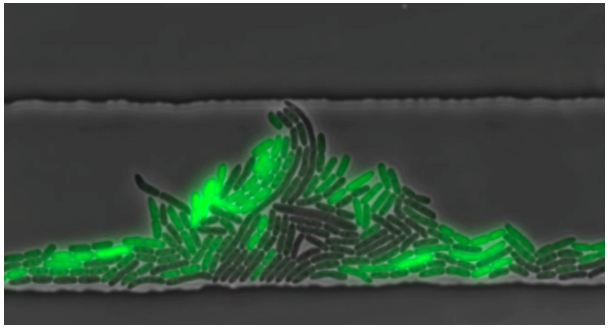




[Weiss]



[Medford]



[Hasty]

Other emerging areas too, including nanoassembly, active materials…

Fundamentally different models

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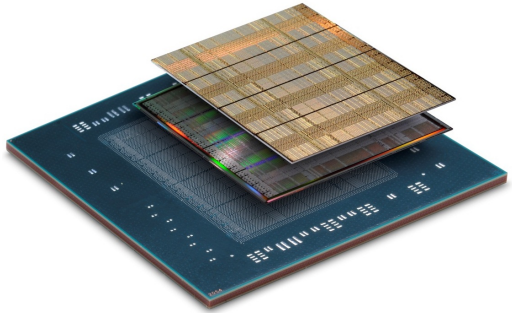
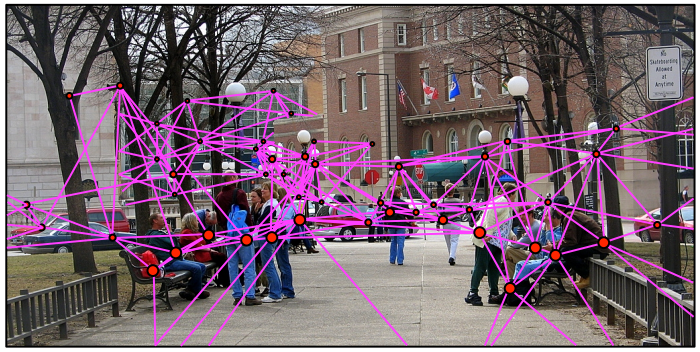


Isolate Systems
Extremely High FLOPs



High Dispersion
Moderate FLOPs

High Resolution Sense/Act
Abysmal FLOPs

How can we program aggregates adaptively & efficiently?

Are there commonalities that cross substrates?

Device-Centric Programming

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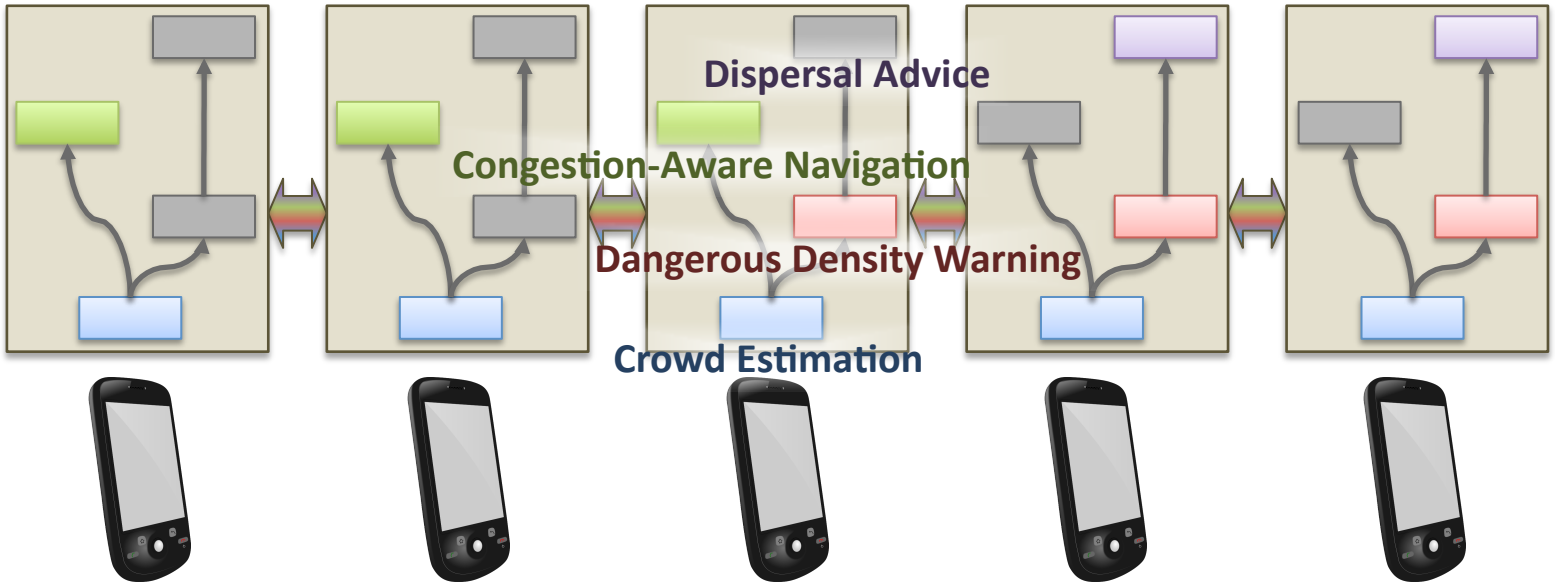

- Explicit design of adaptation and communication
- Complex per-device multi-service application
- Intractable to ensure correct behavior

Aggregate Programming

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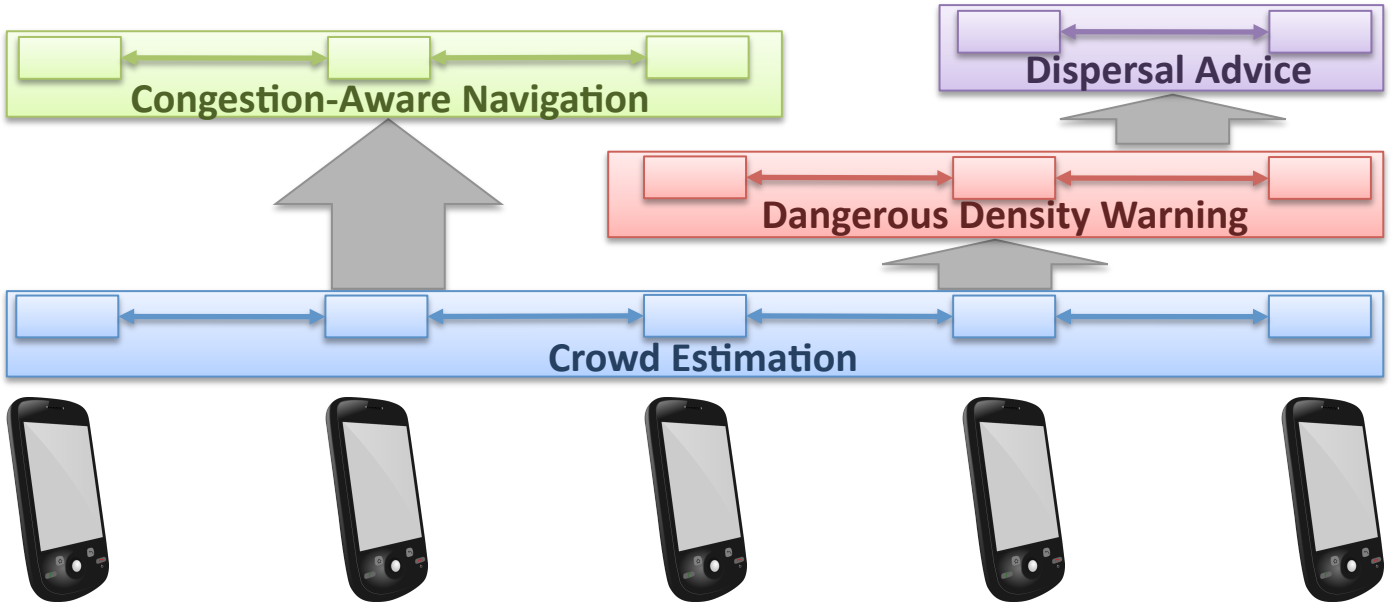

- Implicit adaptation and communication
- Code each collective service independently
- Compose via scope and information flow

Spatial Computers

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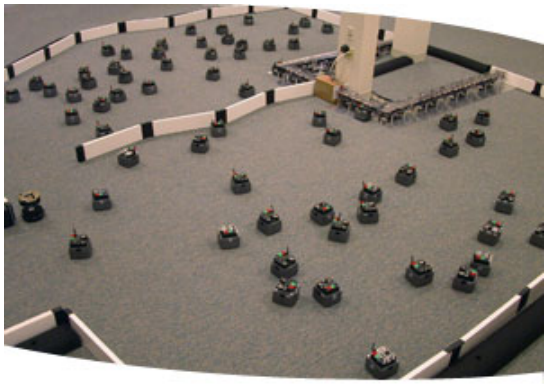
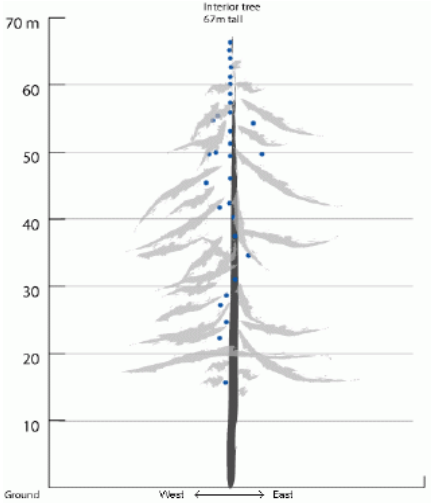
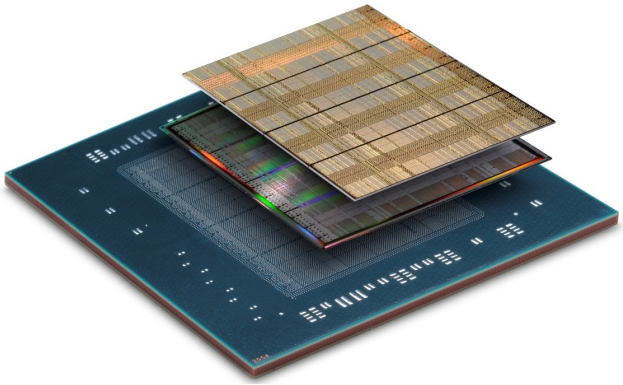


Robot Swarms

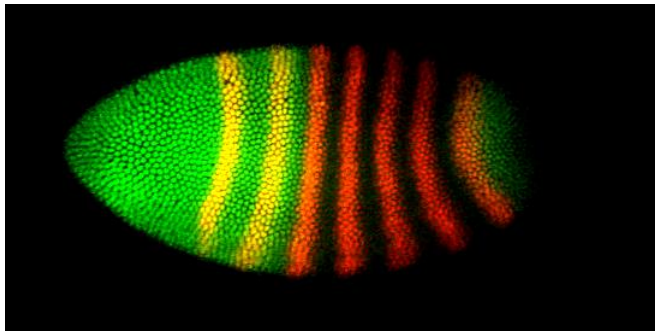
Biological Computing



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

More formally...

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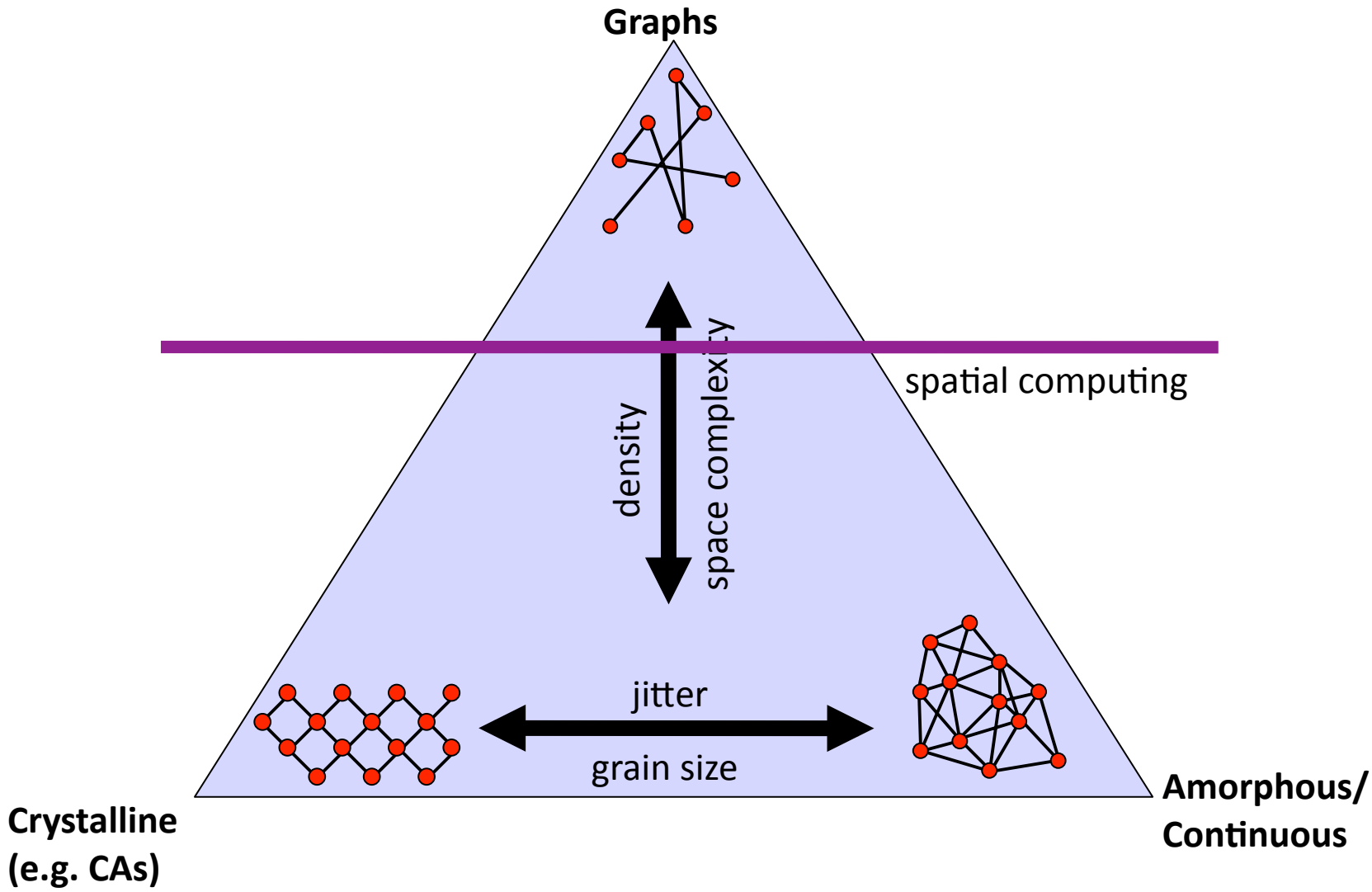
- A spatial computer is a collection of computational devices distributed through a physical space in which:
  - the difficulty of moving information between any two devices is strongly dependent on the distance between them, and
  - the “functional goals” of the system are generally defined in terms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

Notice the ambiguities in the definition


Graphs
spatial computing
density
space complexity
jitter
grain size
Crystalline
(e.g. CAs)
Amorphous/
Continuous

(w. Dan Yamins)

Example: Services for Mass Events

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Example: Managing Crowd Danger

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Example: Agent-Based Simulations

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[Beal et al., 2012]

Example: Cellular Oscillator

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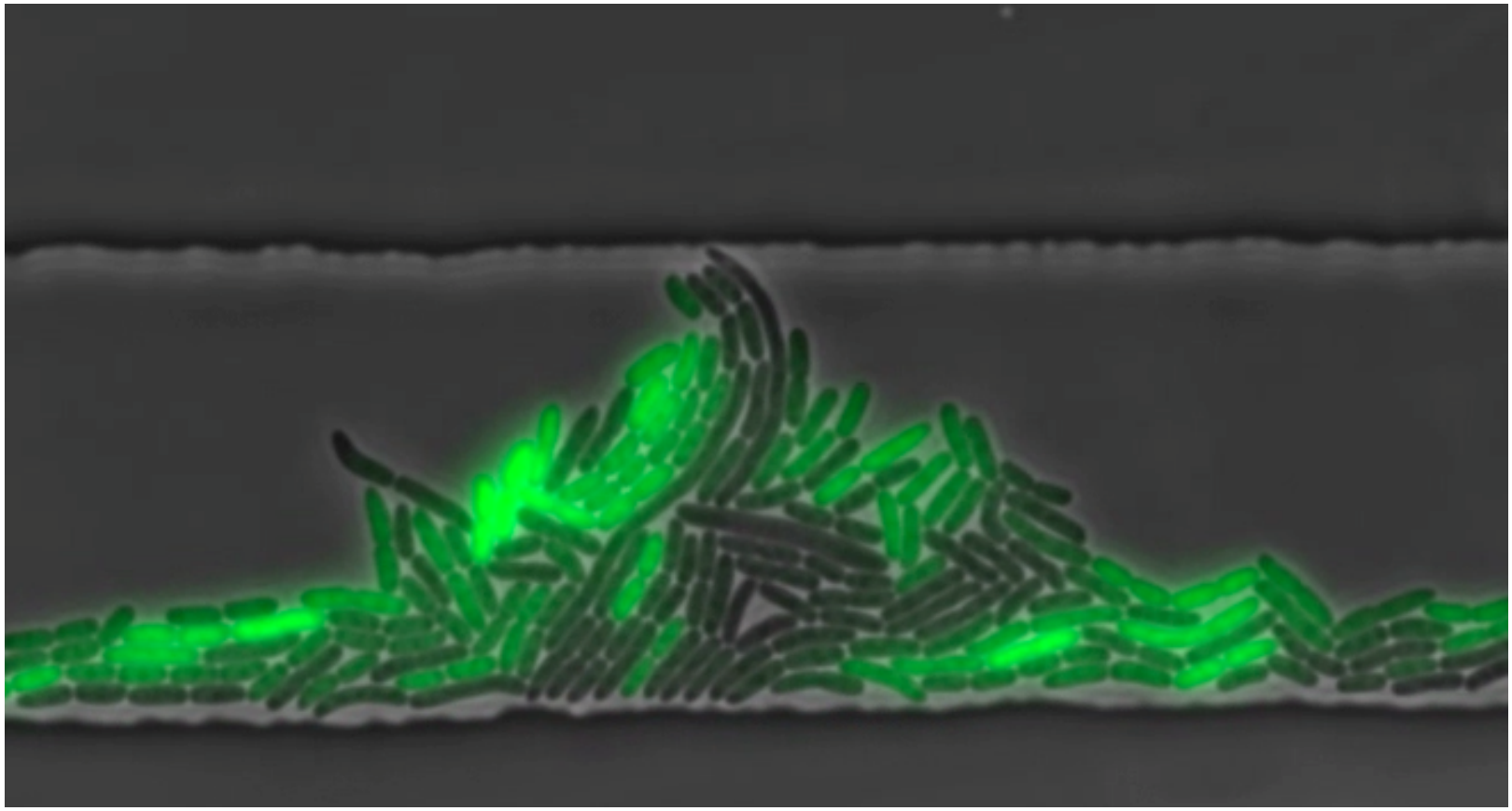

[Danino et al., 2010]

How can we program these?

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- Desiderata for approaches:
  - Simple, easy to understand code
  - Robust to errors, adapt to changing environment
  - Scalable to potentially vast numbers of devices
  - Take advantage of spatial nature of problems

Myriad proposed approaches

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A small sample…

Many Domains: Sensor Networks, Agent systems, Biological Modeling, Synthetic Biology, Pervasive Computing, Amorphous, Swarm/Modular Robotics, High-Peformance Computing, Reconfigurable Computing, …

How do we understand and synthesize them all?

[Beal et al., ’12]

Space/Network Type #1: Sampling

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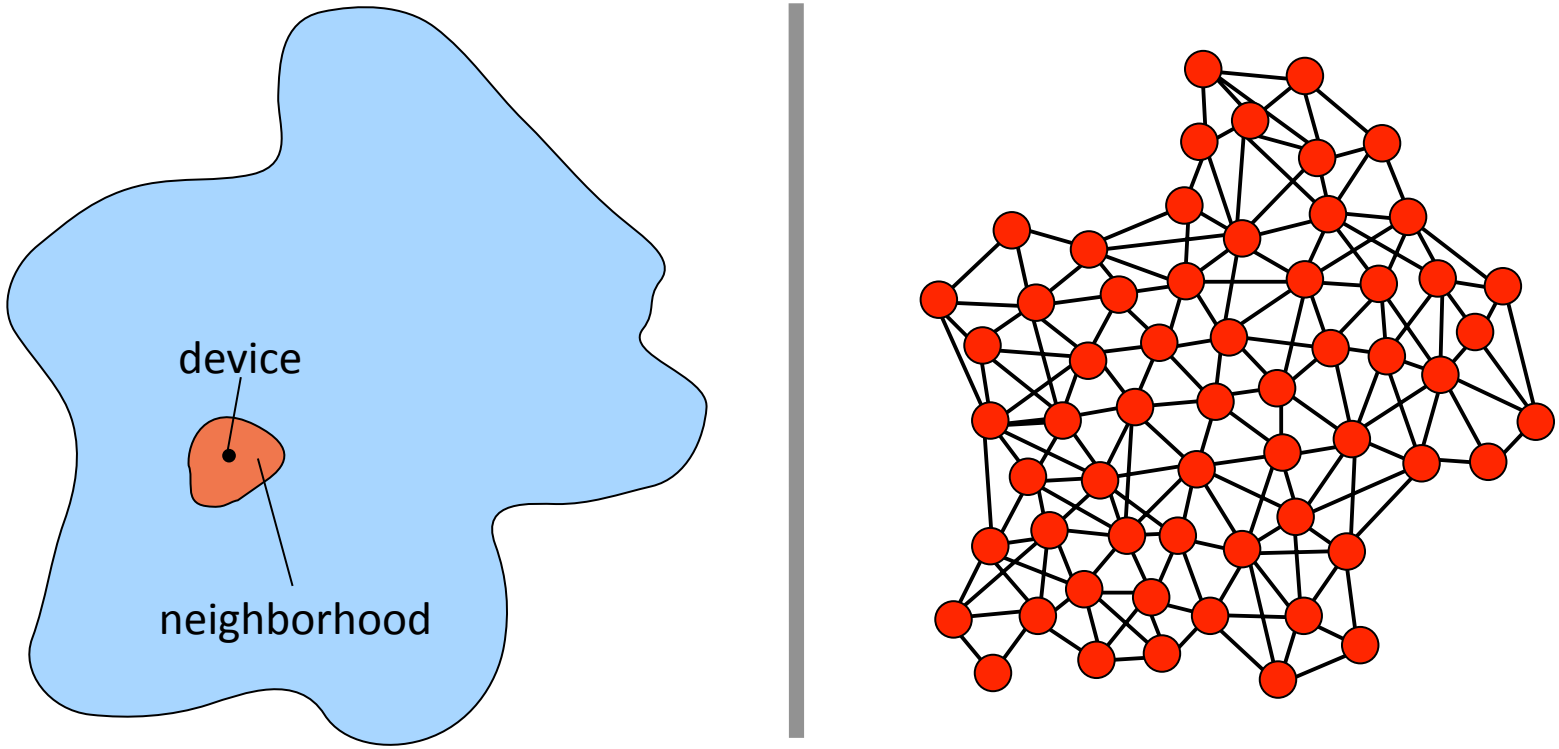

e.g. sensor nets, pervasive systems, swarm robots

Space/Network Type #2: Cellular

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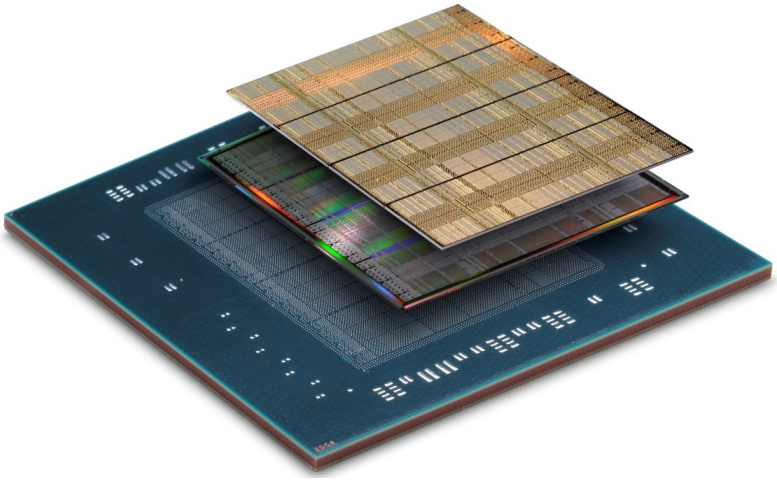
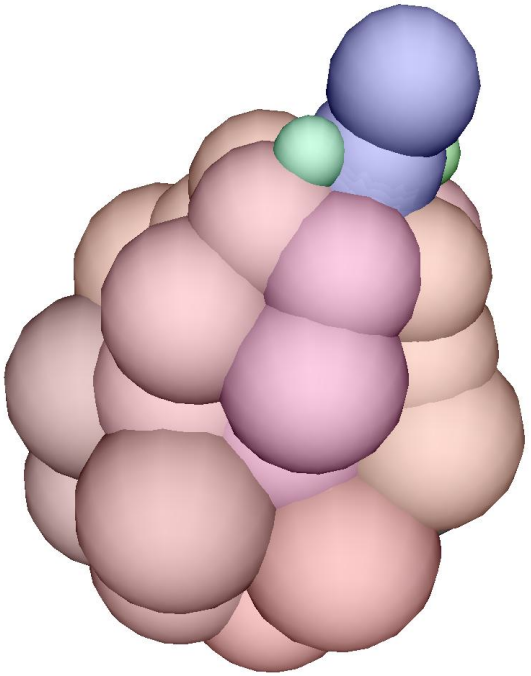


Crystalline



Amorphous

e.g. processing fabrics, biologicals, modular robots

Four General Language Classes

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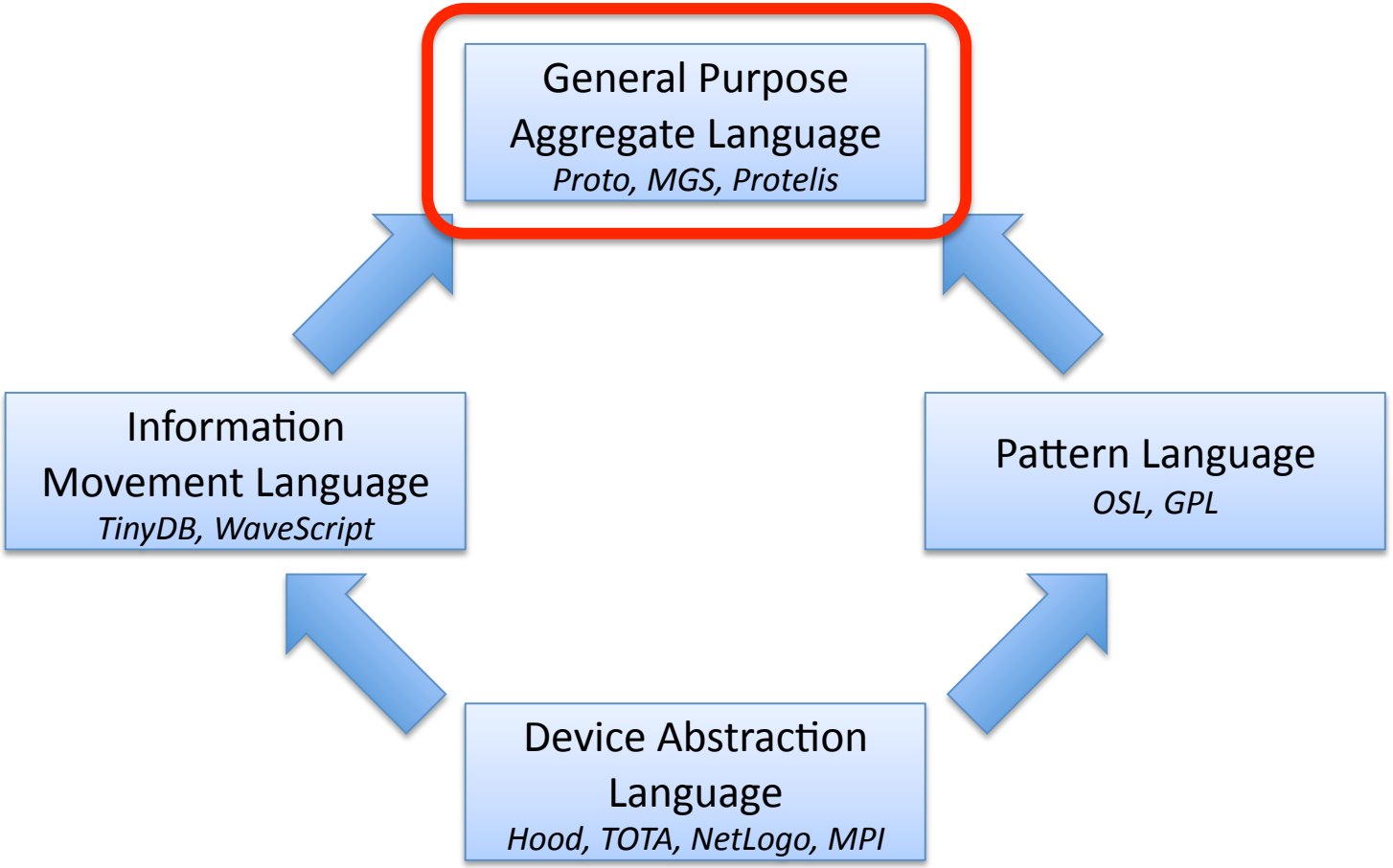

[Beal et al., '12]

Field Calculus:

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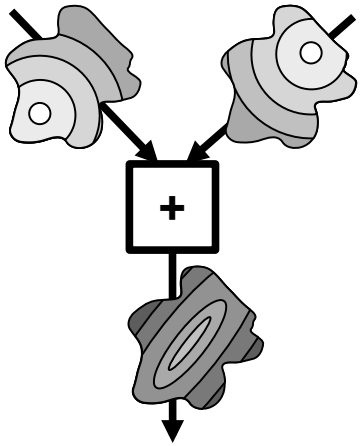
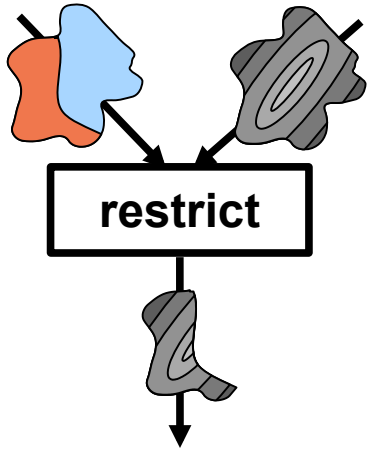
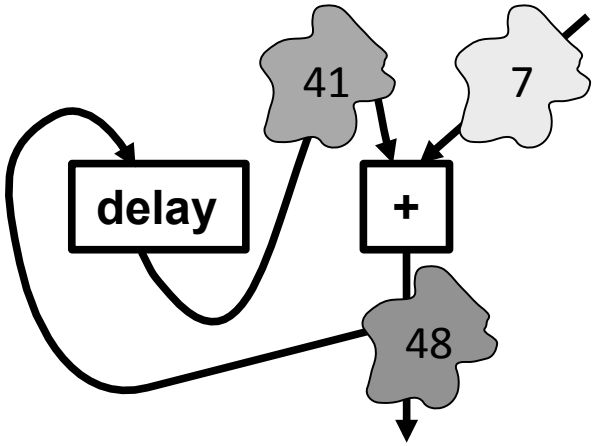
Pointwise



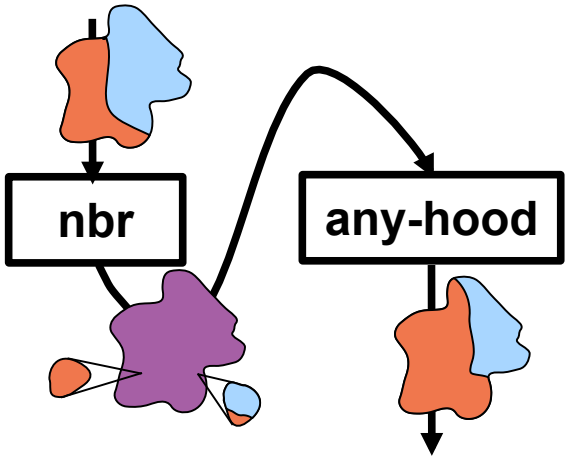
Restriction: `if`



Feedback: `rep`



Neighborhood: `nbr`



[Viroli et al., ’13]

Implementation: Proto

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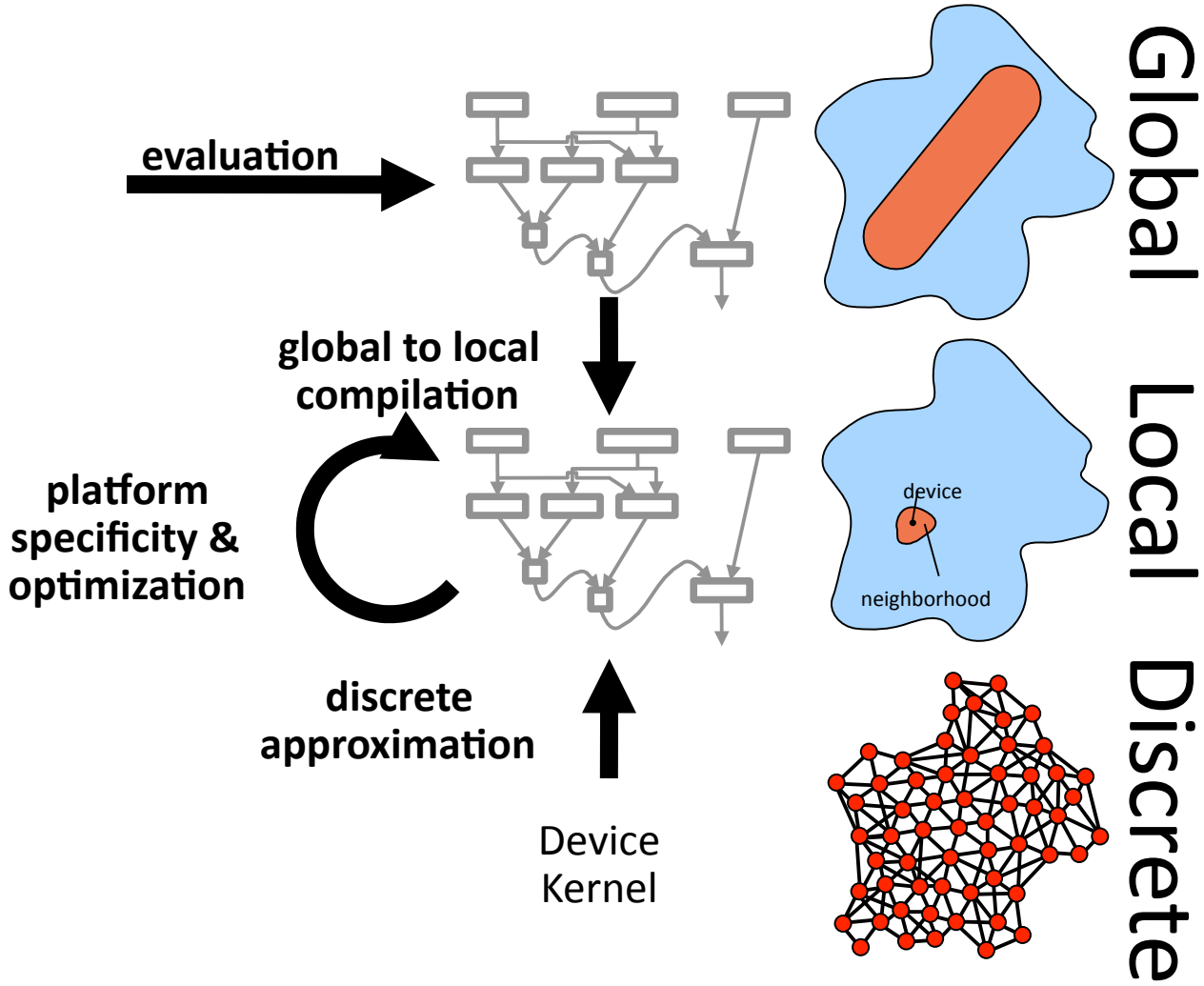
```
(def gradient (src) ...)
(def distance (src dst) ...)
(def dilate (src n)
  (<= (gradient src) n))
(def channel (src dst width)
  (let* ((d (distance src dst))
         (trail (<= (+ (gradient src)
                       (gradient dst))
                    d)))
    (dilate trail width)))
```



[Beal & Bachrach, '06]

Proto available online!

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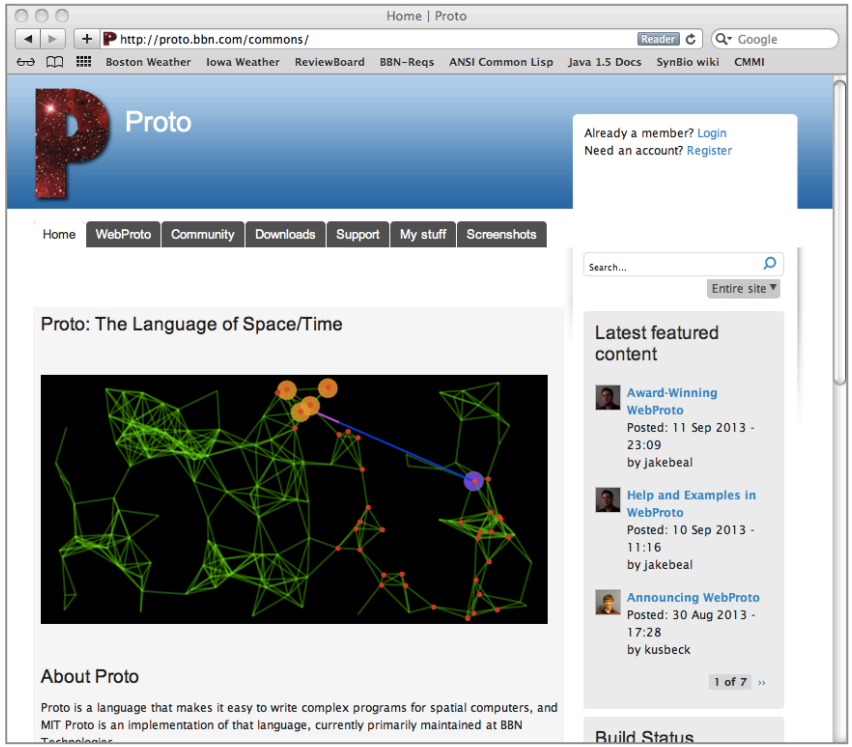
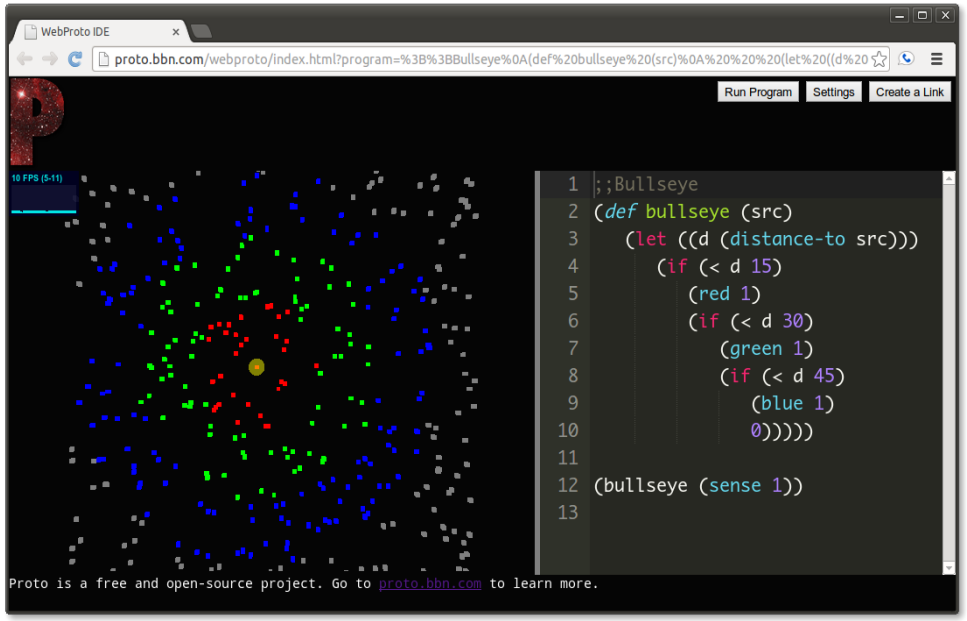
http://proto.bbn.com/

Free & Open Software



WebProto



From Principle to Practice:

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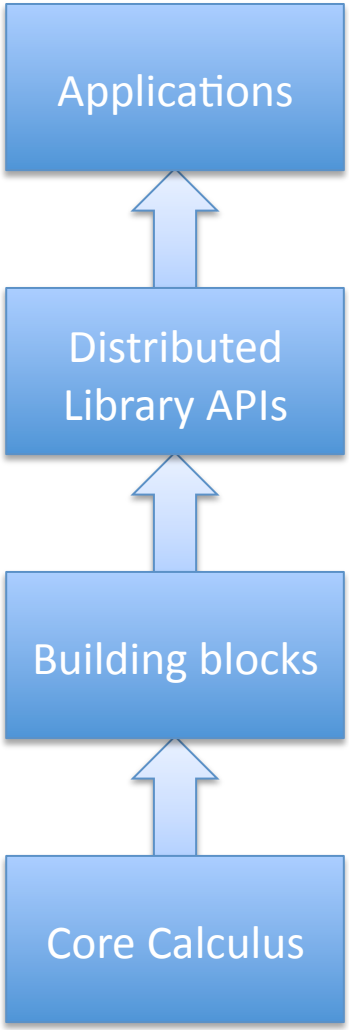
Transparent use of robust distributed algorithms

Programmer level: lots of useful, intuitive methods Domain-specific APIs

Provable robustness, scalability, composability

Provable universality, aggregate/local relation



unlimited uses

many algorithms

5-20 combinators

5 operators

Summary

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- Major technological trends are all driving towards a world filled with distributed systems
- Aggregate programming aims at rapid and reliable engineering of complex distributed systems
- Field calculus provides a solid mathematical foundation for predicting aggregate behaviors
- Aggregates are often closely tied to space, and geometry is a good source of "building blocks"
- Methods are useful for many types of application

Bibliography

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