Introduction to Spatial Computing

Jacob Beal
April, 2009

BBN TECHNOLOGIES

Agenda

- Spatial Computing
- Survey of Existing Approaches
- Proto & Amorphous Medium

From one robot, to many

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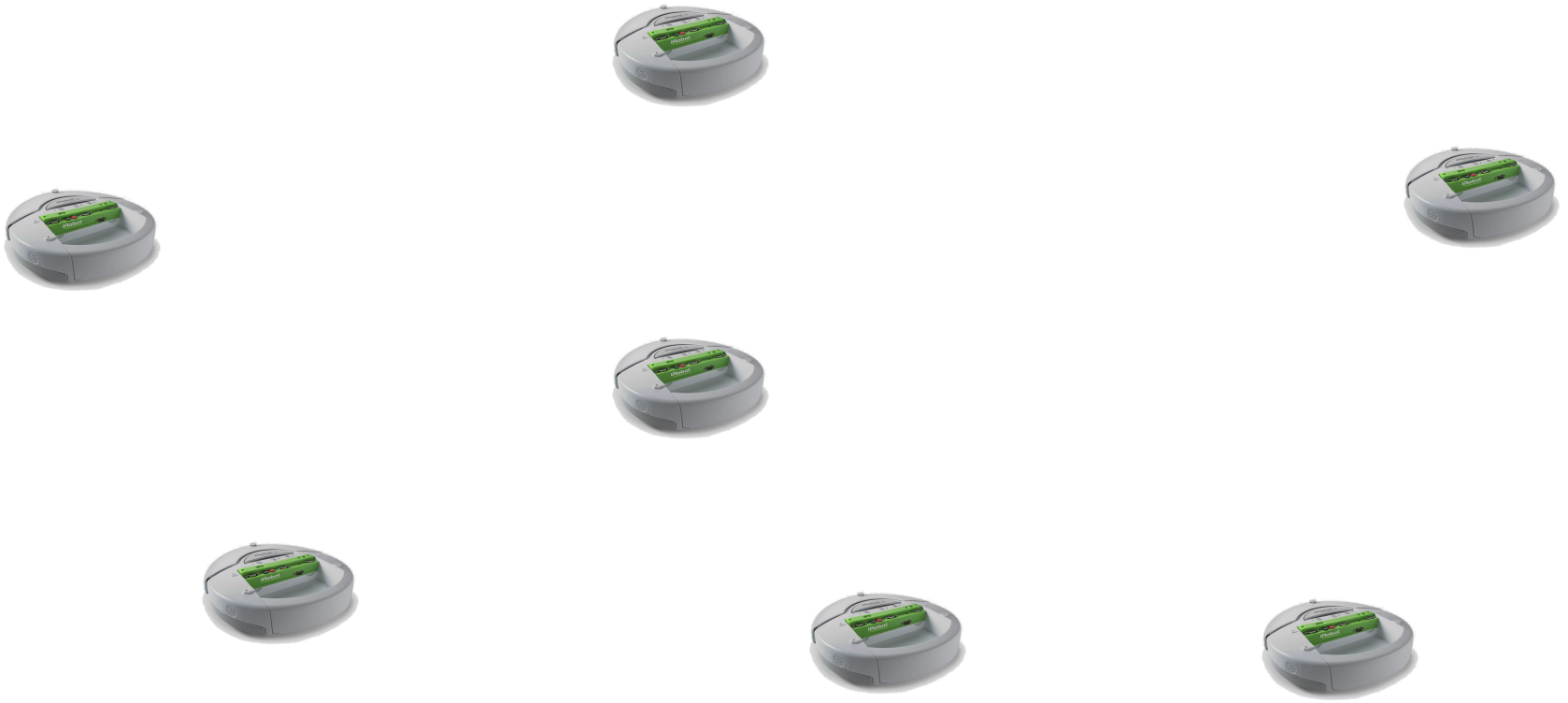

From one robot, to many

Robotic density is currently very low, but...

Networked devices are **filling** our environment...

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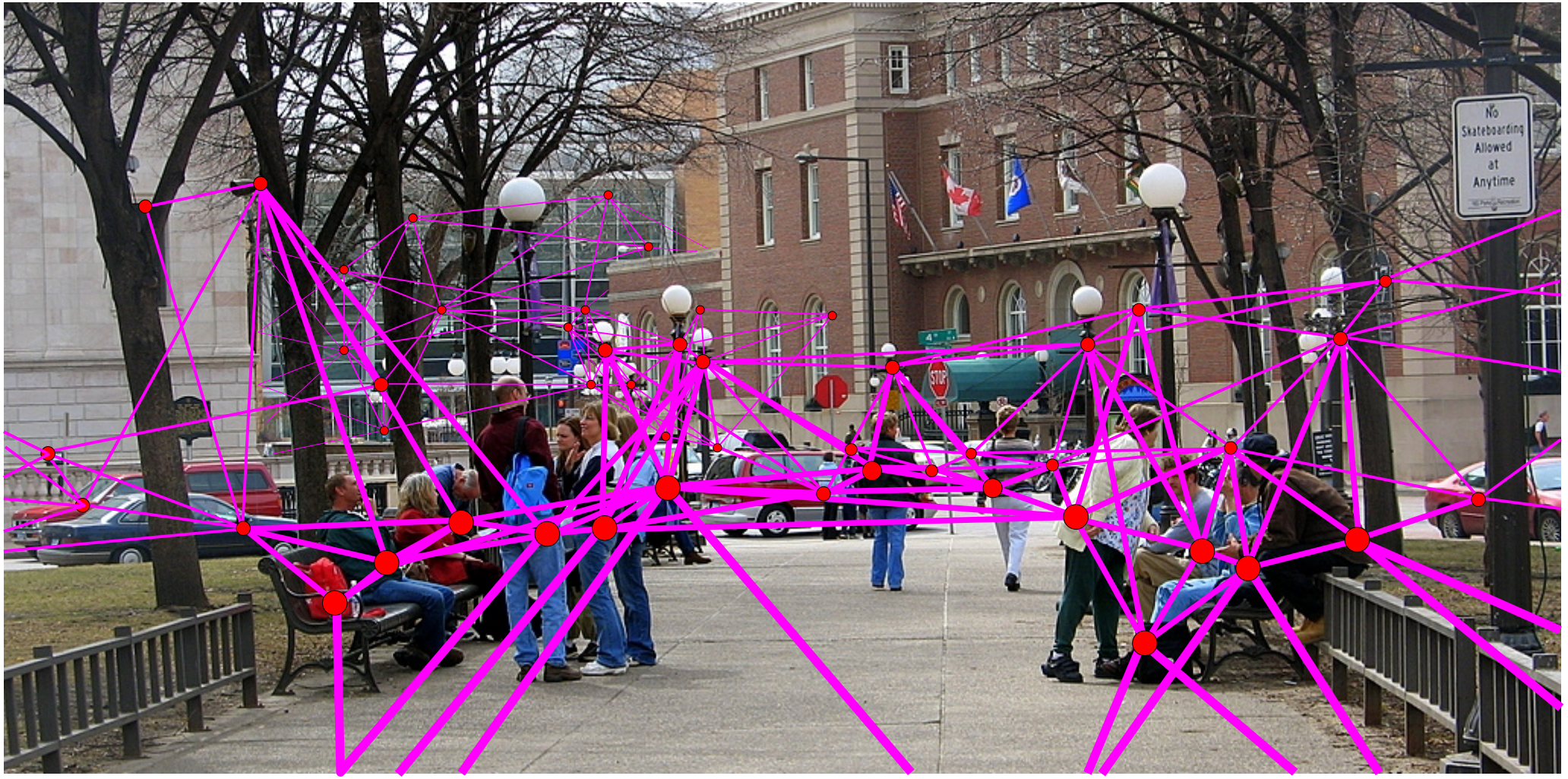


How do we program aggregates robustly?

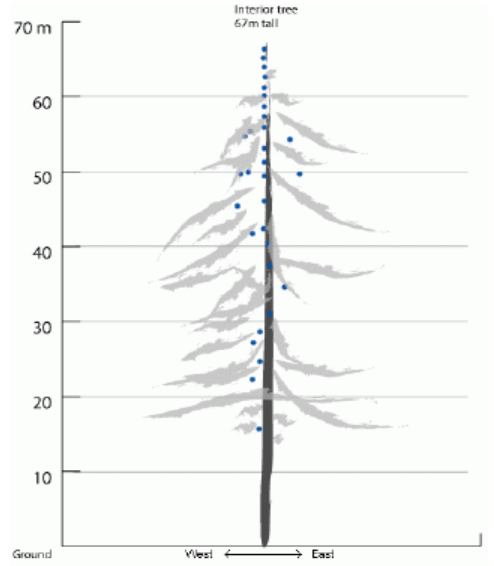
Wireless-enabled Embedded Systems

- >3.3B cell phones vs. 600M Internet-connected PC's in 2007
  - >600M cell phones with Internet capability, rising rapidly
- New cars come equipped with navigation systems and will soon have wireless interfaces (WiFi/DSRC, cellular, WiMax)
- Sensor deployment just starting, but some estimates ~5-10B units by 2015
- Military/emergency response wireless robots, unmanned vehicles, unmanned aircraft

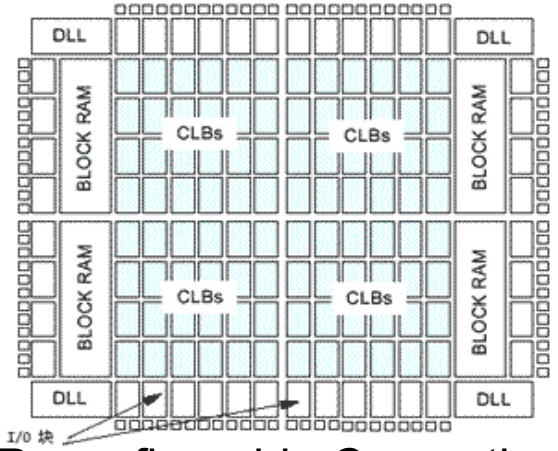
Spatial Computers

Robot Swarms

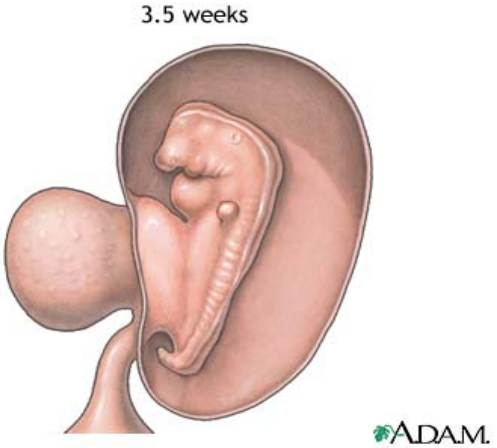
Biological Computing



Sensor Networks



Reconfigurable Computing



Cells during Morphogenesis

Modular Robotics

More formally...

- 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

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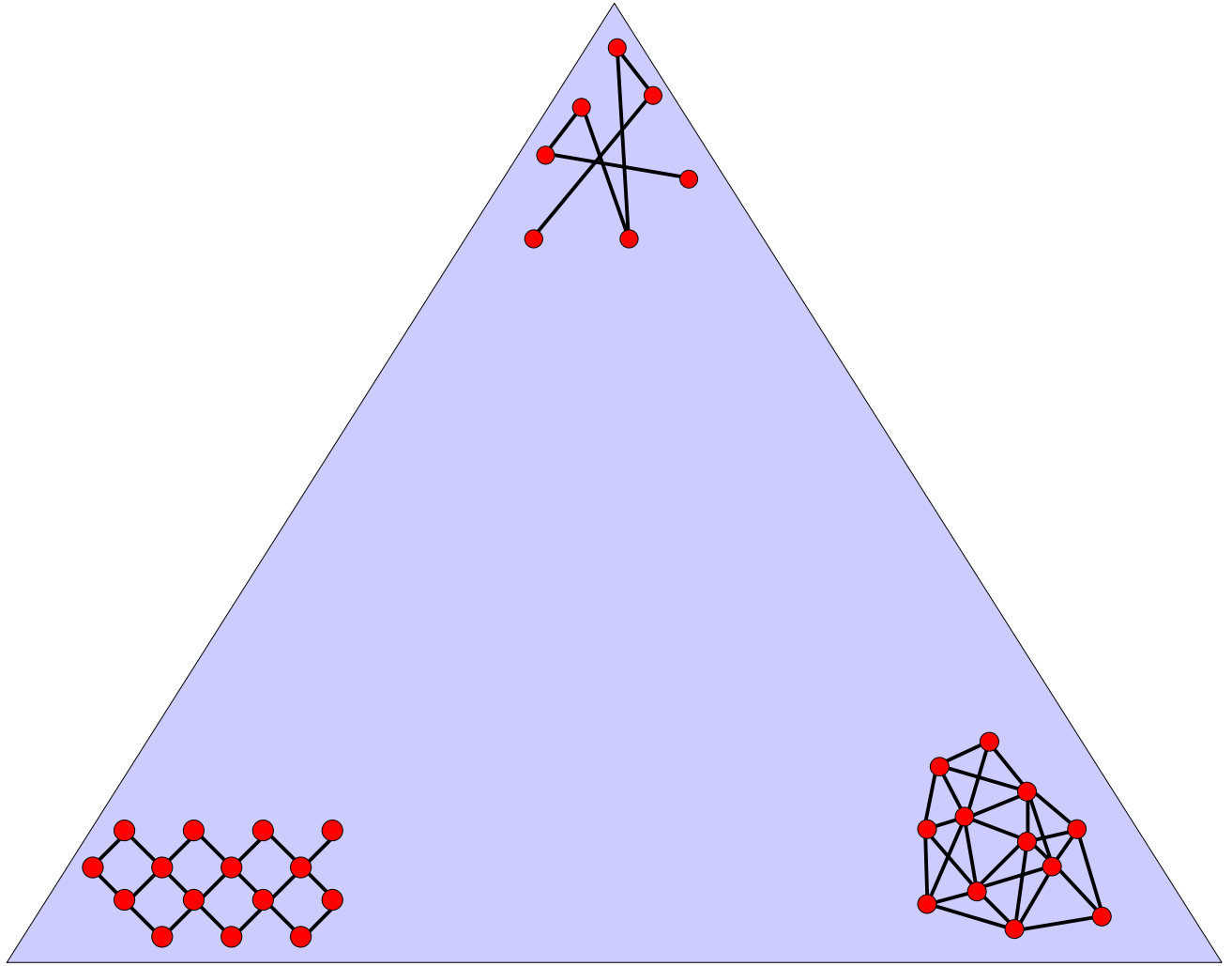
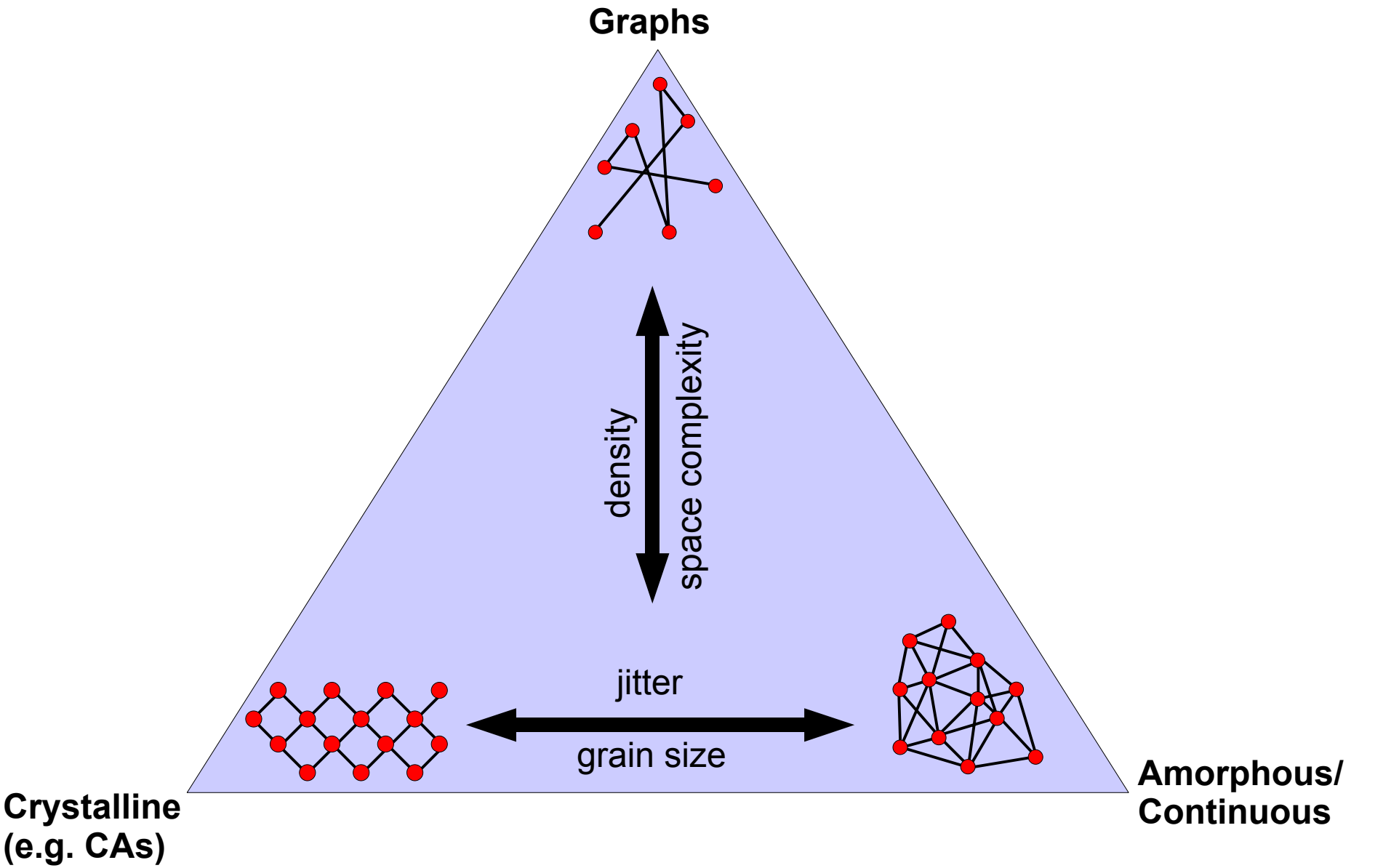
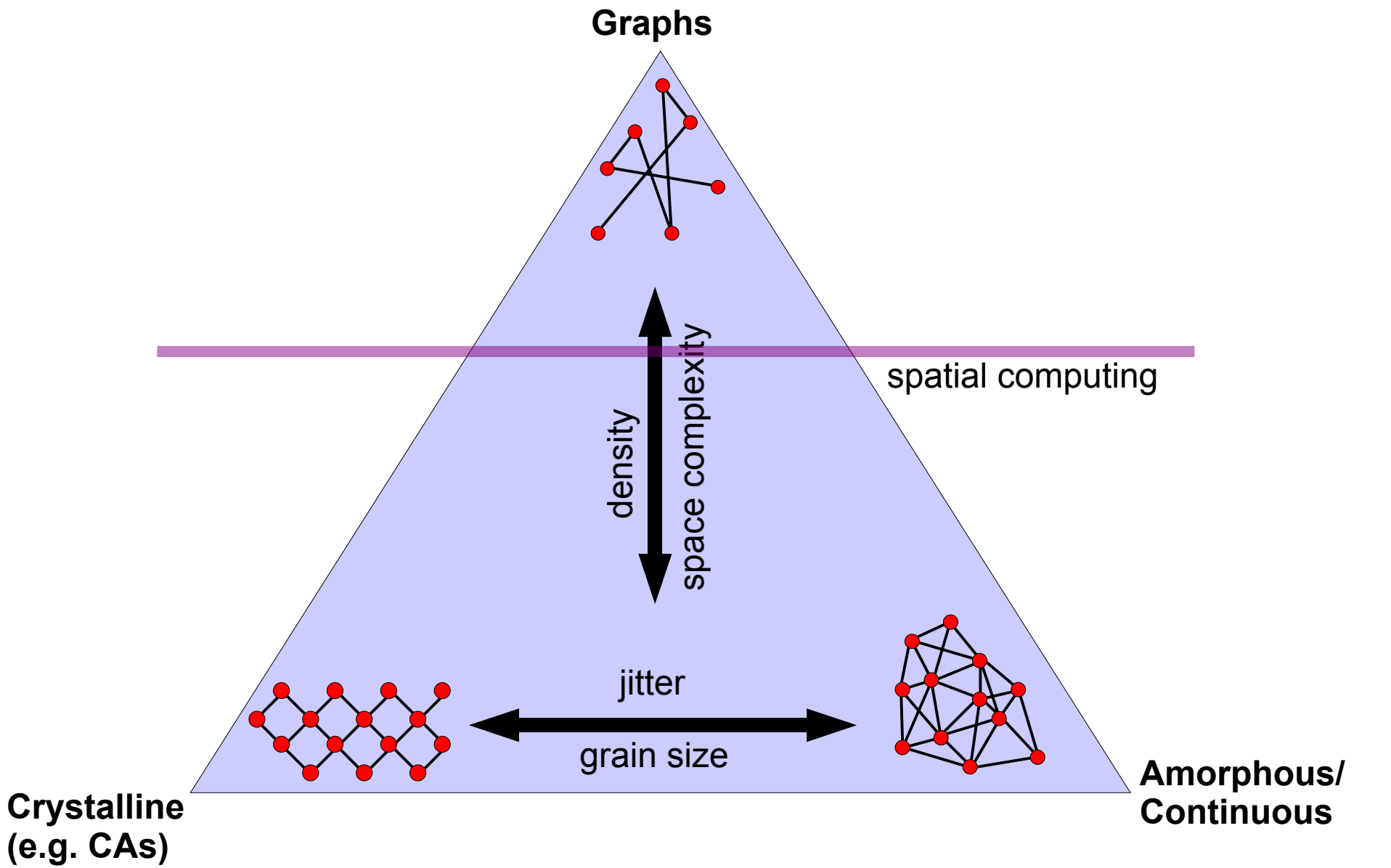
Notice the ambiguities in the definition



(w. Dan Yamins)


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

(w. Dan Yamins)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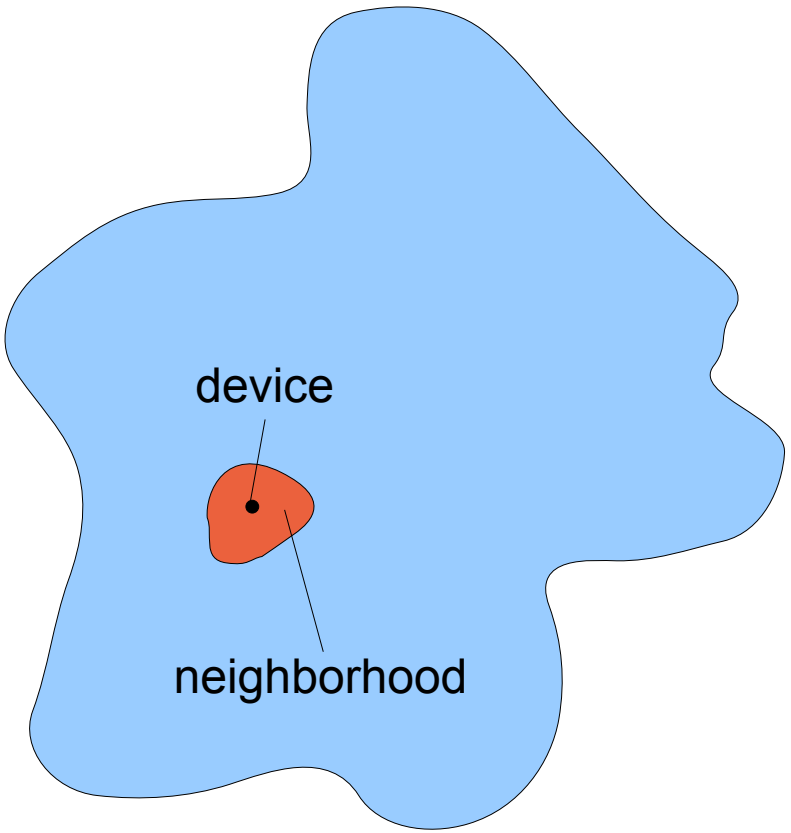
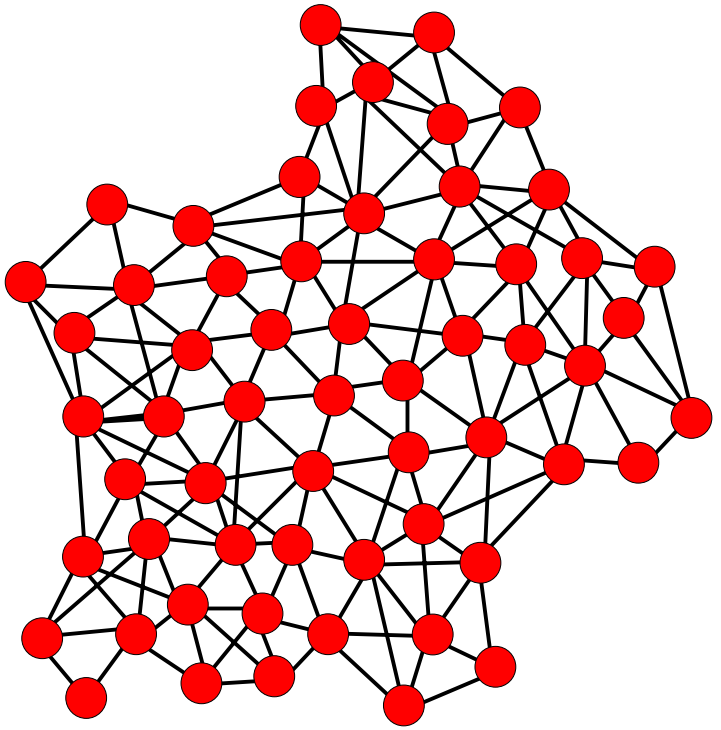
Space/Network Duality





Example: Target Tracking

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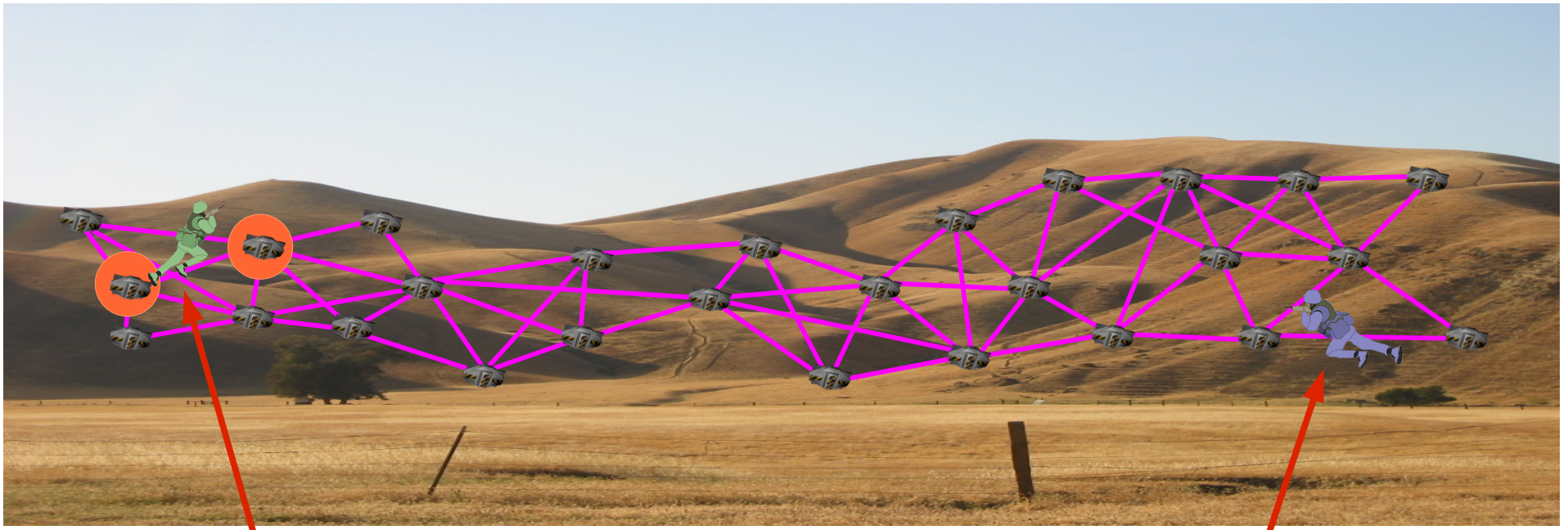

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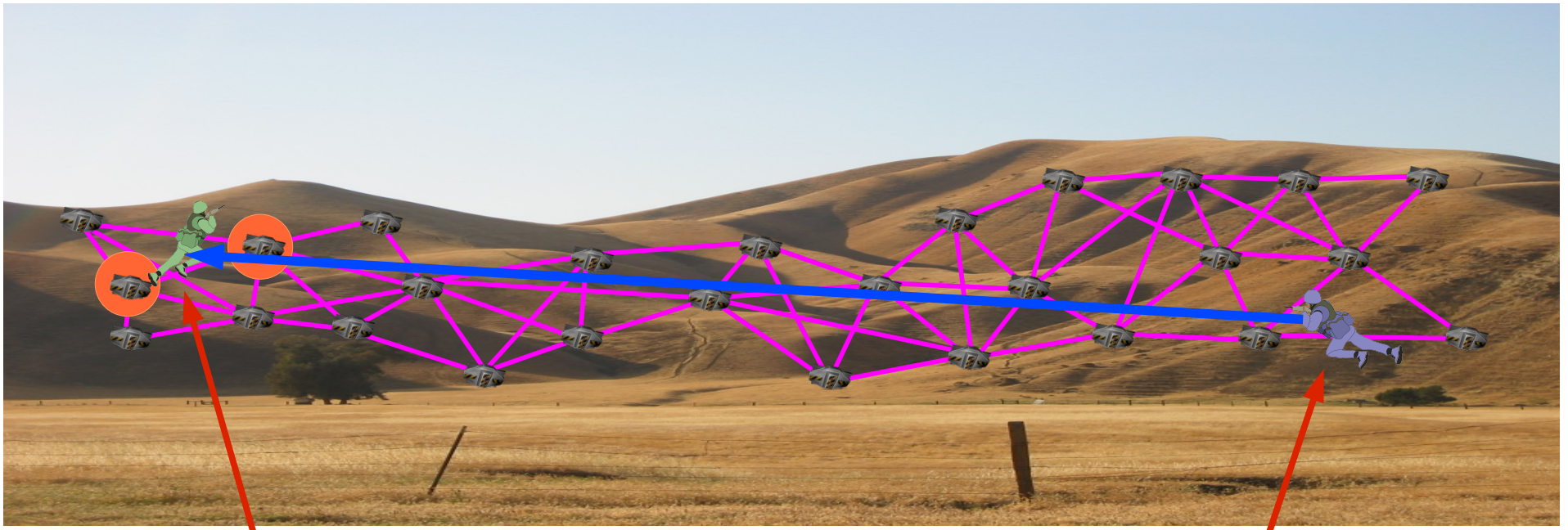
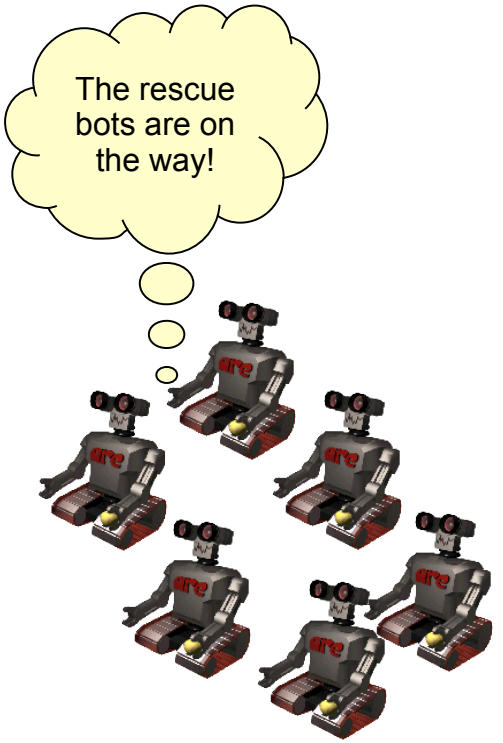


Example: Search & Rescue



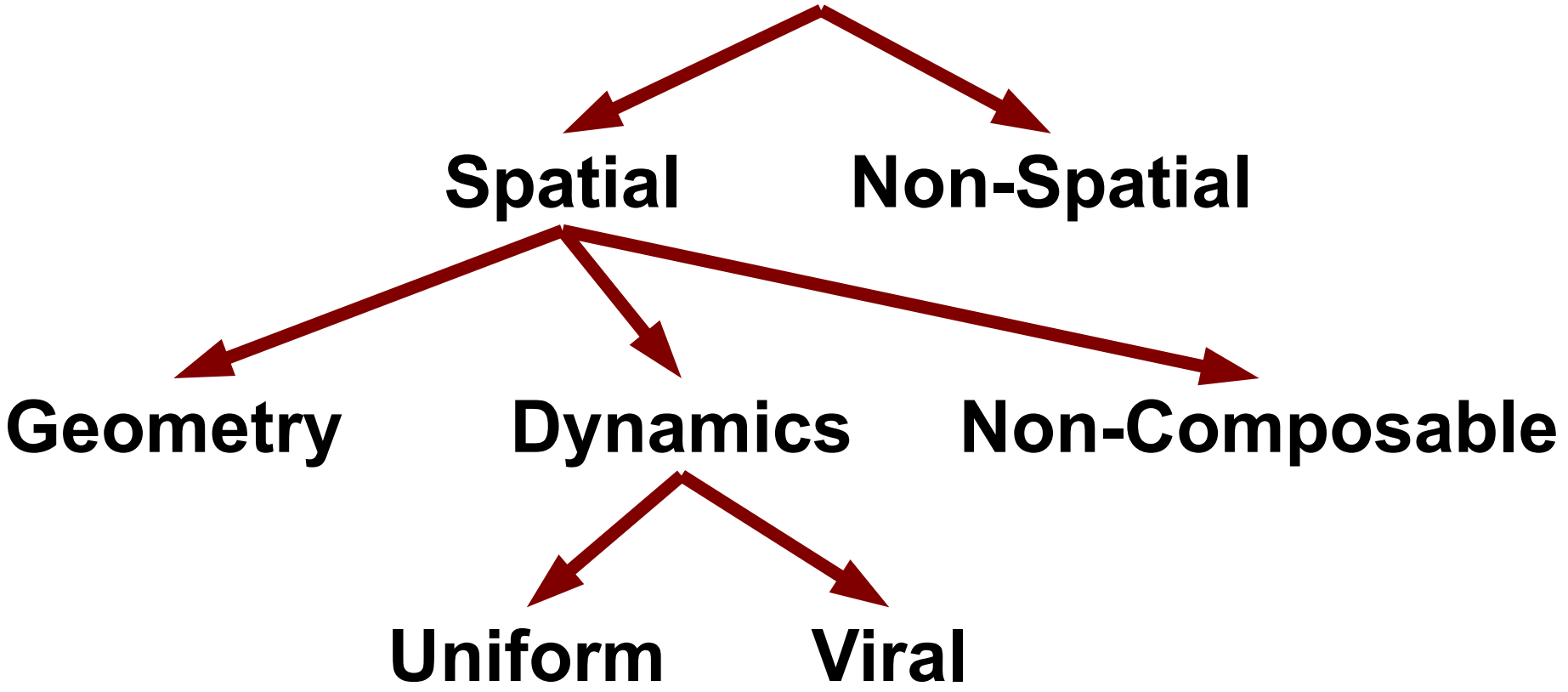
How can we program these?

- 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

Agenda

- Spatial Computing
- **Survey of Existing Approaches**
- Proto & Amorphous Medium

A Taxonomy of Approaches



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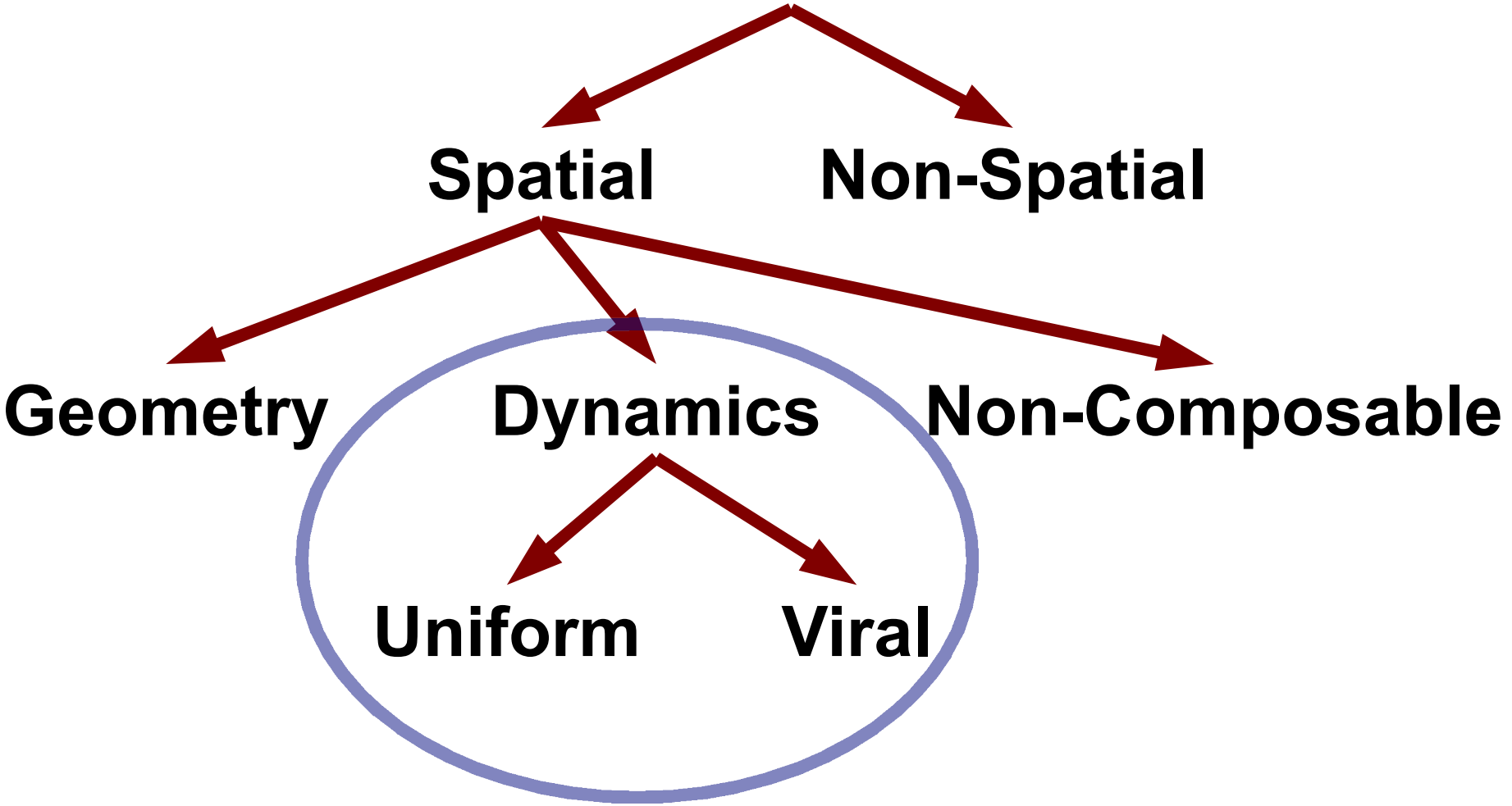

Approaches from Local Dynamics

Primitives describe only actions between devices and the neighbors they communicate with.

- Advantages: coherent and correct semantics
- Disadvantages: programmer must figure out how to marshal local dynamics to produce coherent large-area programs

Proto: Computing with Fields

```
(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)
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                    d)))
    (dilate trail width)))
```
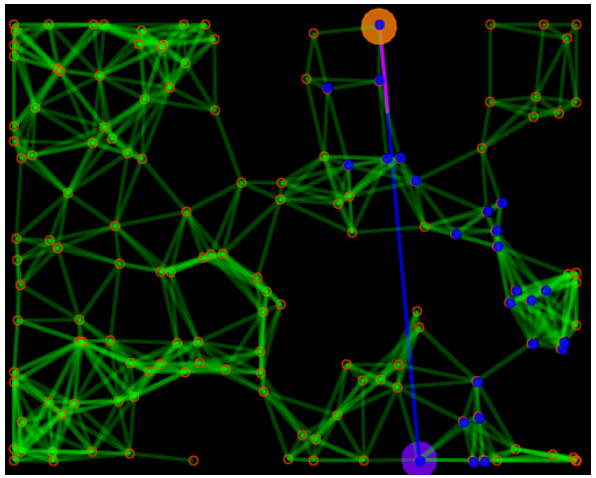
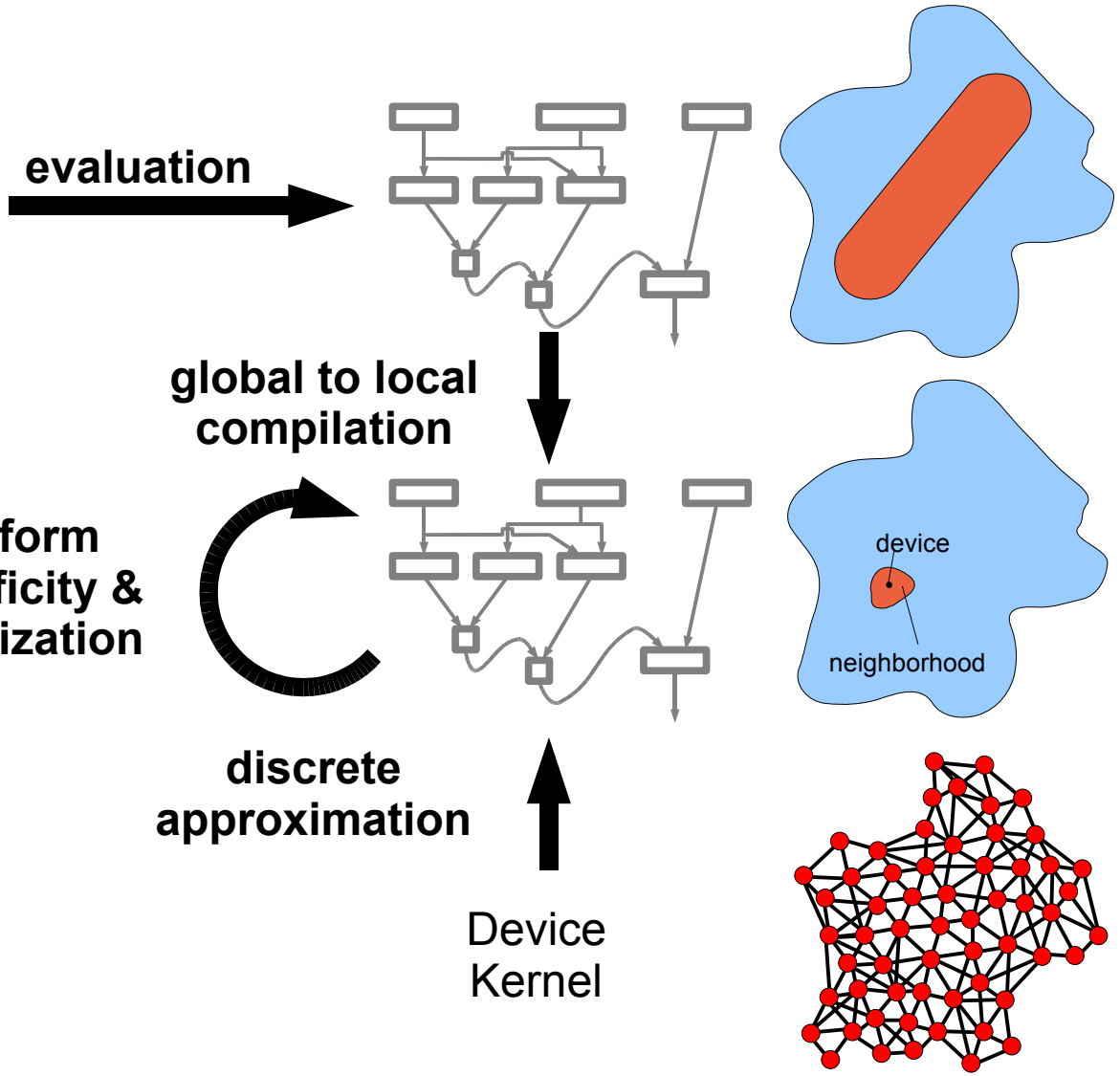



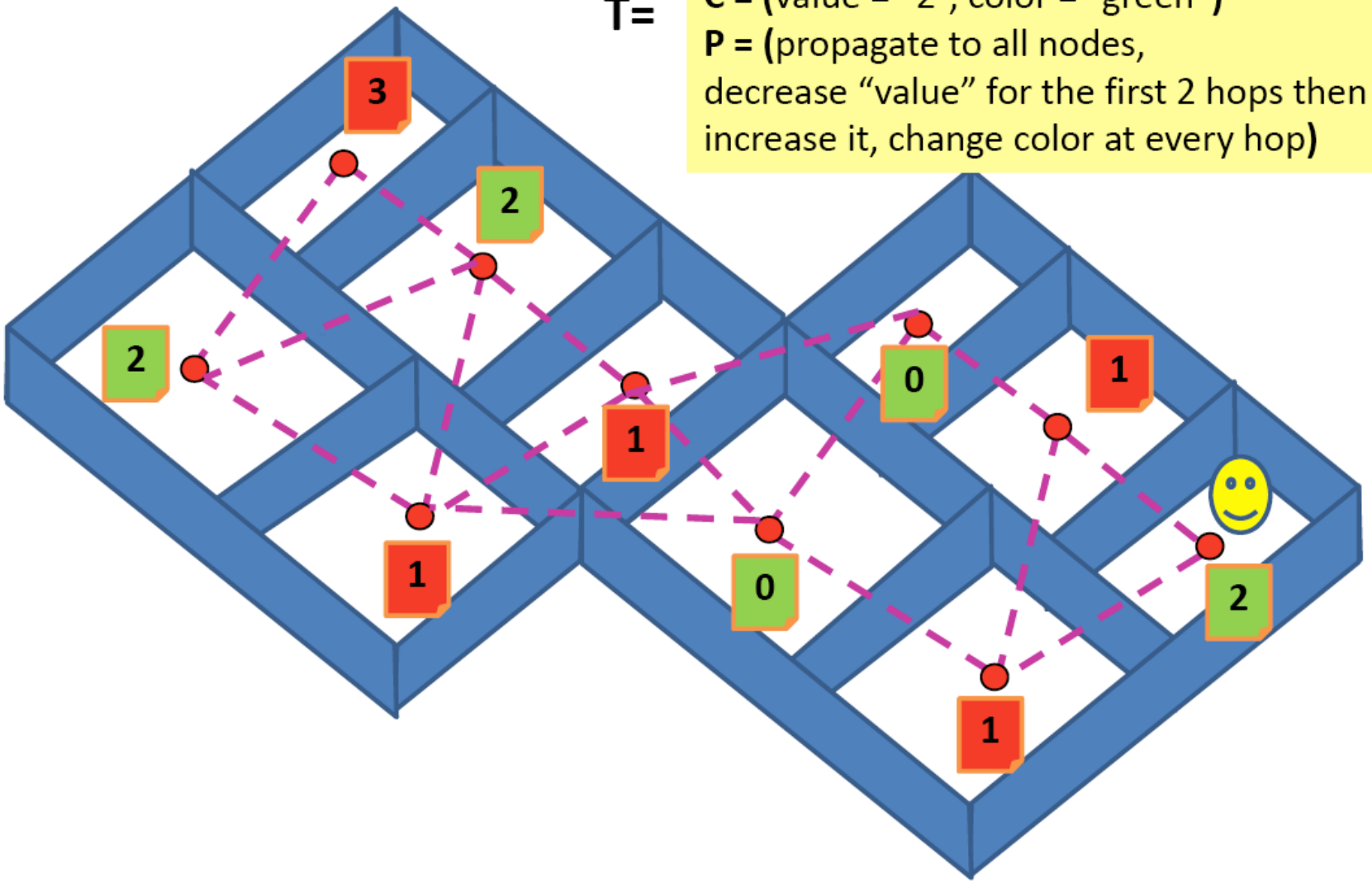


Beal & Bachrach

TOTA: Viral tuples

T=

C = (value = “2”, color = “green”**)**
P = (propagate to all nodes,
decrease “value” for the first 2 hops then
increase it, change color at every hop**)**



Other Viral Approaches

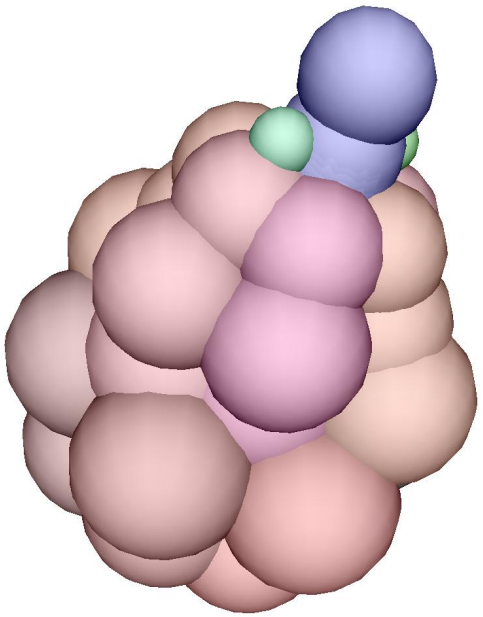
- Smart Messages (Borcea)
  - Execution migrates to nodes of interest, found via self-routing code packets
- Paintable Computing (Butera)
  - Consistent transfer, view of neighbor data
  - Code for install, de-install, transfer-granted, transfer-denied, update
- RGLL (Sutherland)
  - Code for arrival, tick, collision, departure
  - Communication via collision

Approaches from Geometry

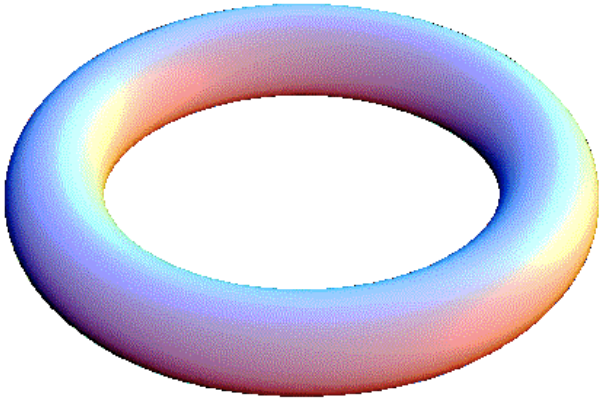
Primitives describe large-scale geometric regions (e.g. “all devices on the left hill”)

- Advantages: coherent, easy to specify large-scale programs
- Disadvantages: generally easy to accidentally specify programs that cannot be executed correctly

MGS



Meristem formation



Turing pattern on torus

Michel, Giavitto, Spicher

Regiment

- Streaming collection of data from regions
  - Spatial primitives:
    - K-hop neighborhood
    - K-nearest nodes
  - Composition:
    - Union/Intersection
    - Map/Filter
- Distributed execution as a compiler optimization

Other Geometric Approaches

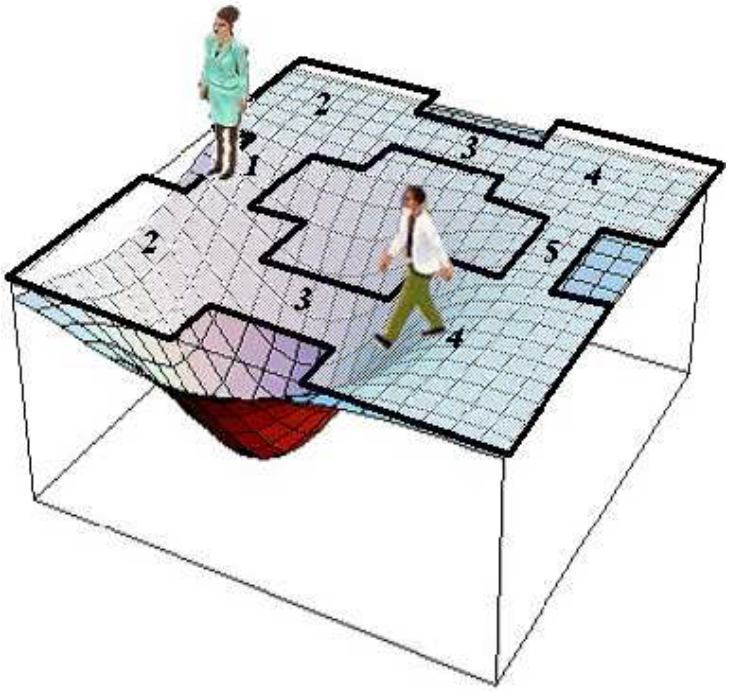
- Borcea's Spatial Programming
- EgoSpaces
- SpatialViews
- Spidey
- Abstract Regions

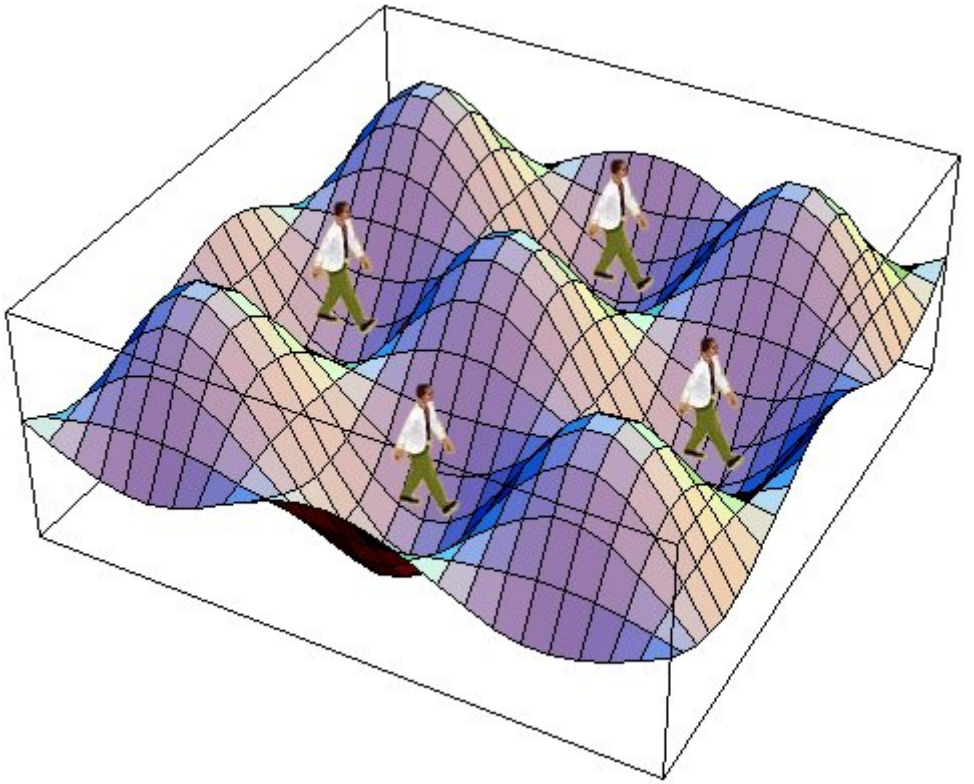
Non-Composable Approaches

Algorithms and techniques, generally based on geometry, but not part of a system of composable parts

- Advantages: powerful spatial ideas for that are good for inclusion in code libraries
- Disadvantages: developed as stand-alone ideas, and may have limited composability

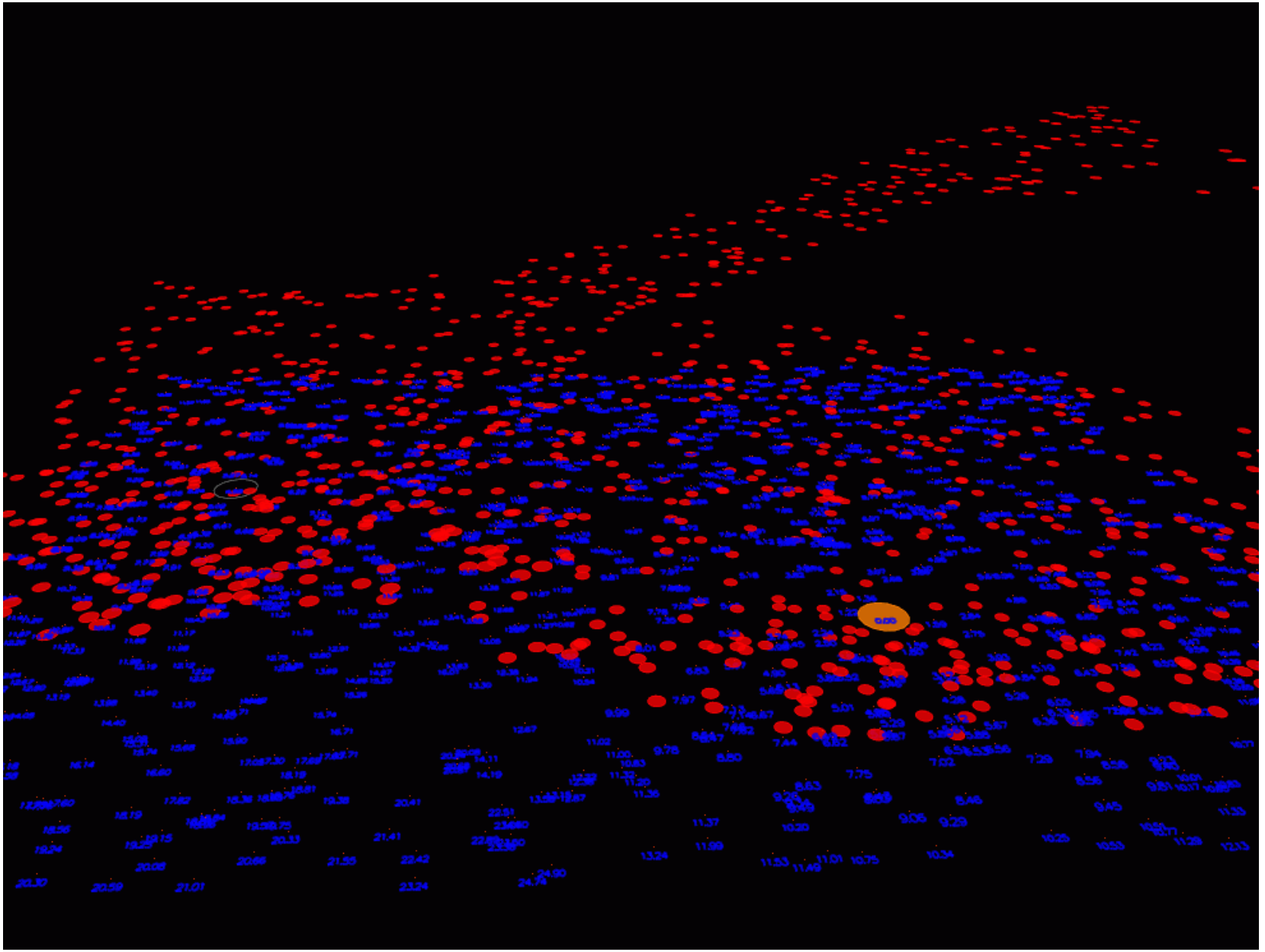
Field-Based Coordination



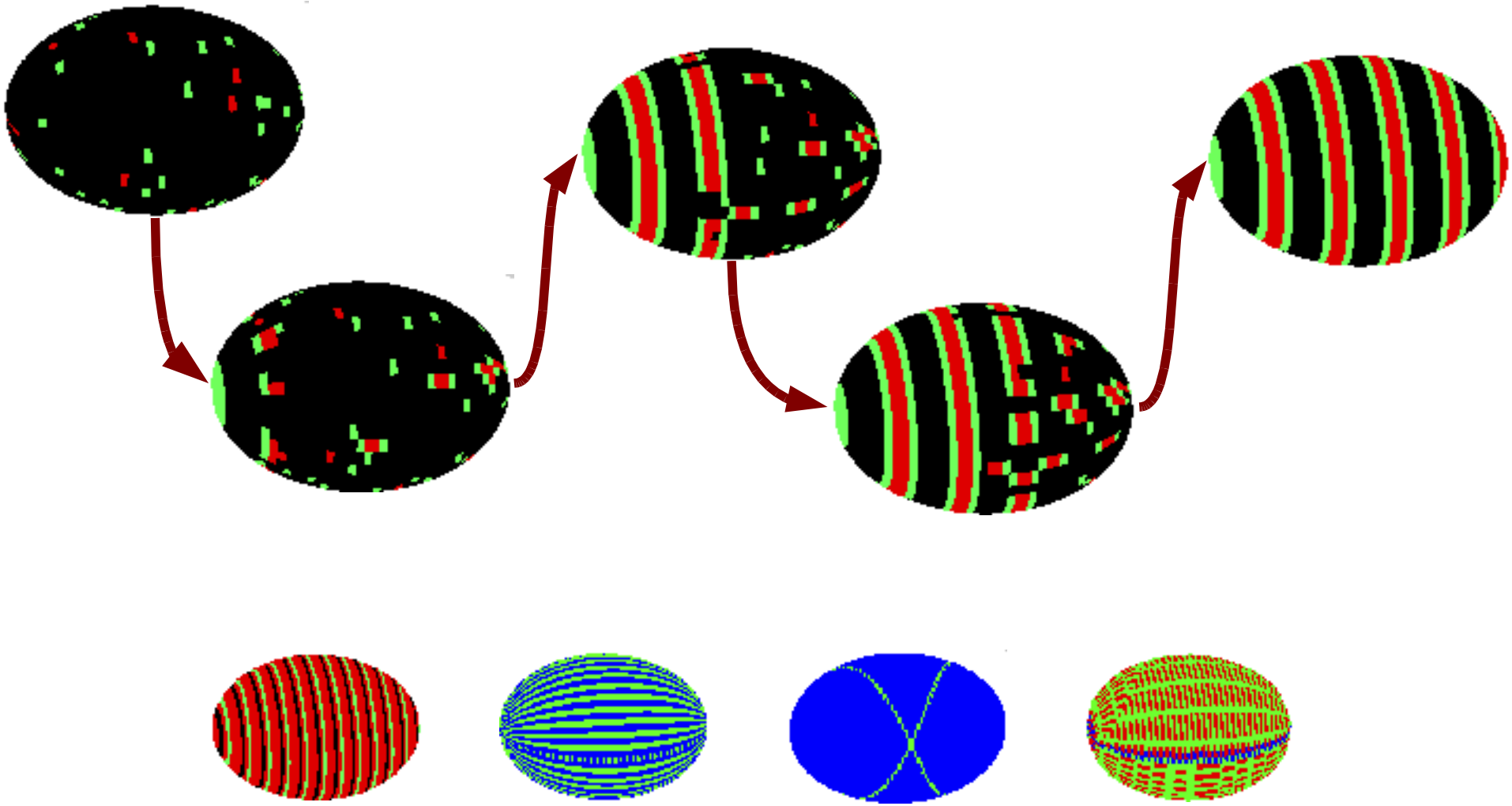


Mamei & Zambonelli

Self-Healing Gradients



Local Check-Schemes



Yamins

Other Non-Composable Approaches

- hood (Whitehouse, et. al.)
  - nesC library for interacting with neighbors
- McLurkin's “Stupid Robot Tricks”
  - Swarm behaviors intended mainly for time-wise multiplexing.
- *Countless one-shot systems...*

Significant Non-Spatial Approaches

- “roll-your-own” (e.g. C/C++)
- TinyDB
  - Distributed database queries for sensor networks
- Kairos
  - Distributed graph algorithms
- WaveScript
  - Distributed streaming language
  - Follow-on to Regiment w/o the spatial primitives

Summary

- Many approaches exist to programming pervasive applications for spatial computers
- Only approaches based on local dynamics currently offer predictable composition, correct execution, and spatial primitives
- Challenge: obtaining long-range coherent behavior from local dynamics

Agenda

- Spatial Computing
- Survey of Existing Approaches
- **Proto & Amorphous Medium**

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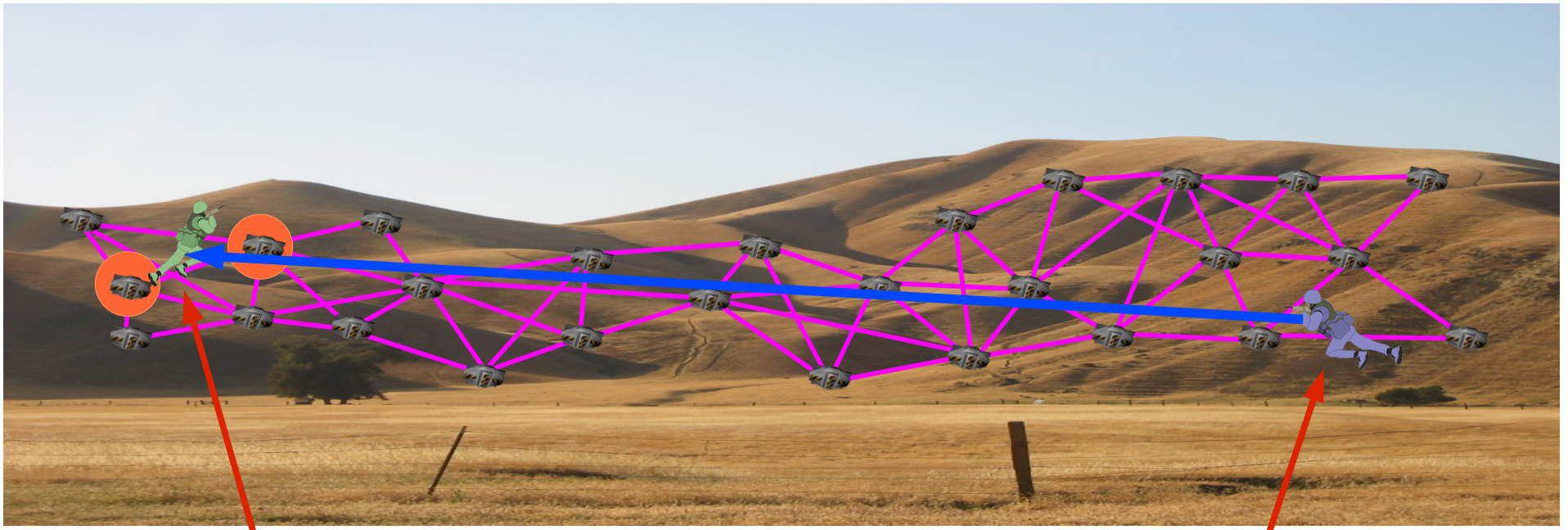

Geometric Program: Channel

(cf. Butera)

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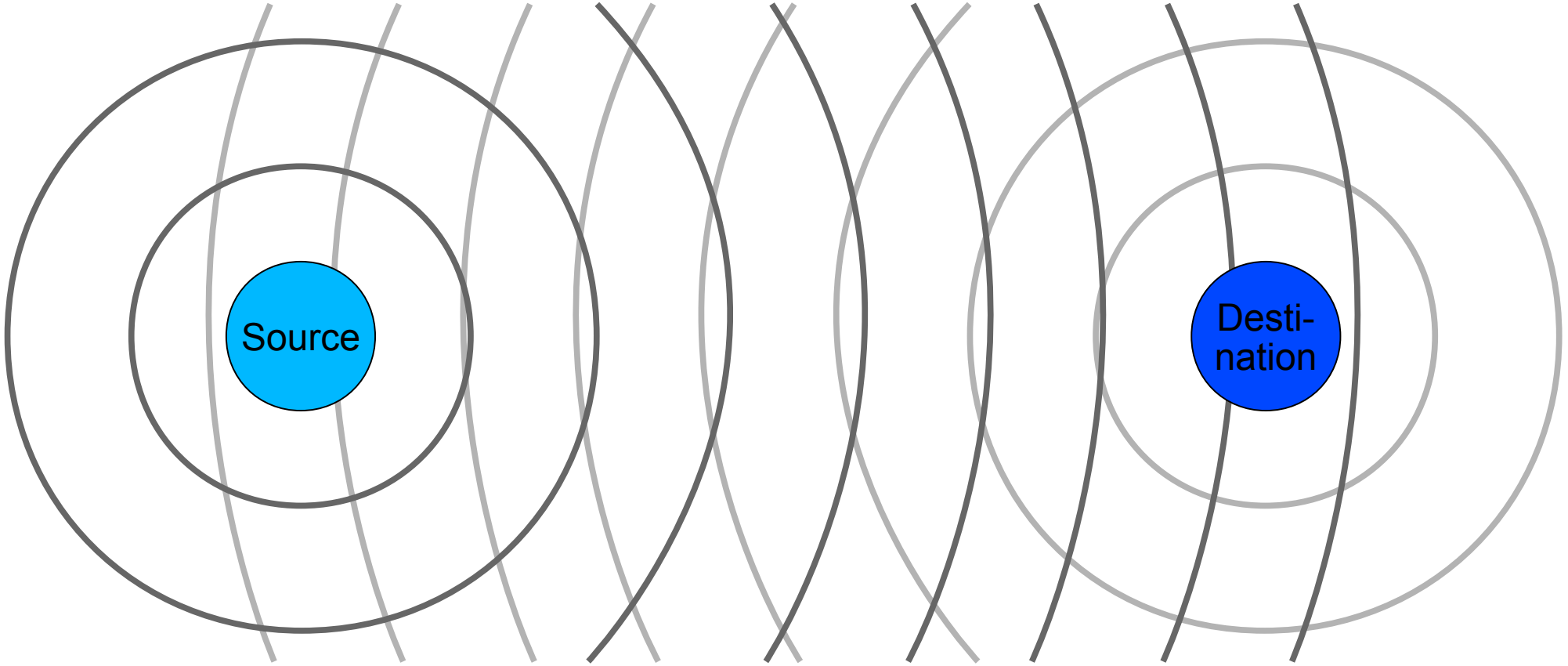

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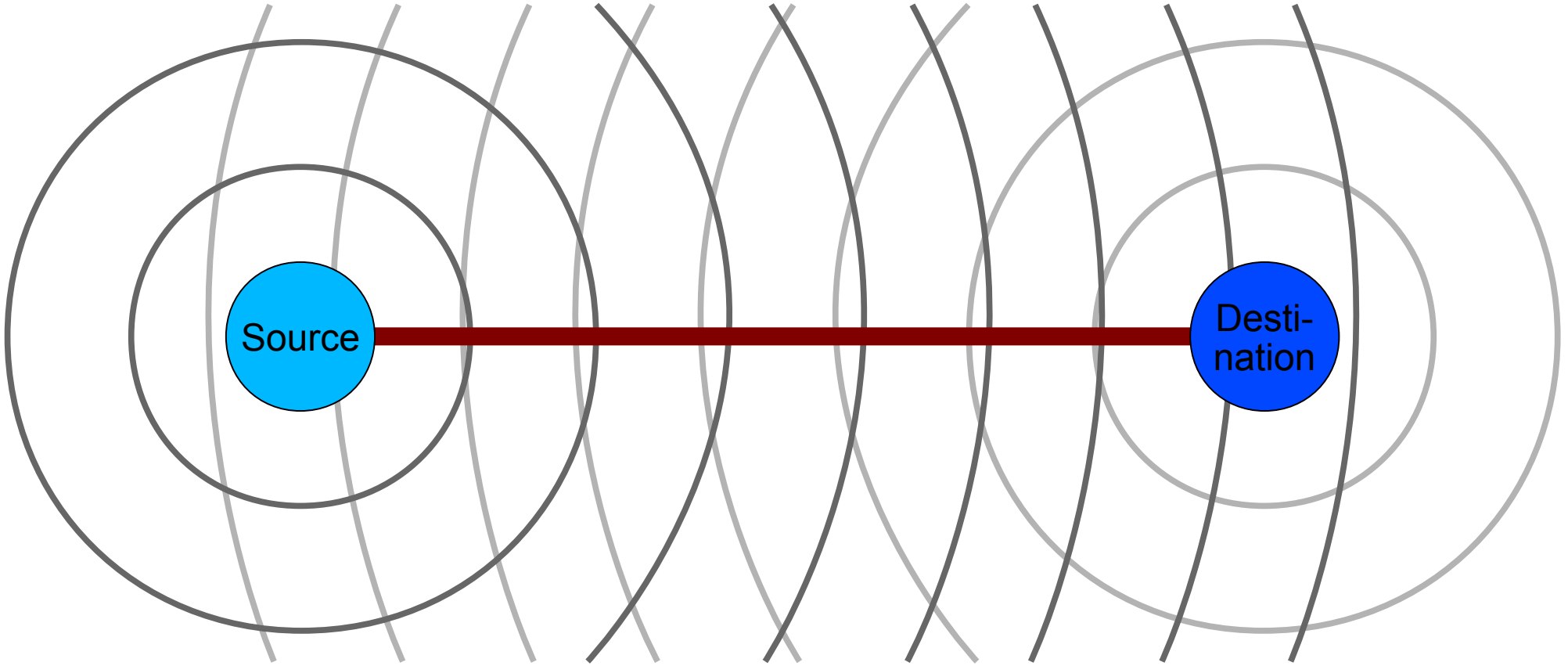

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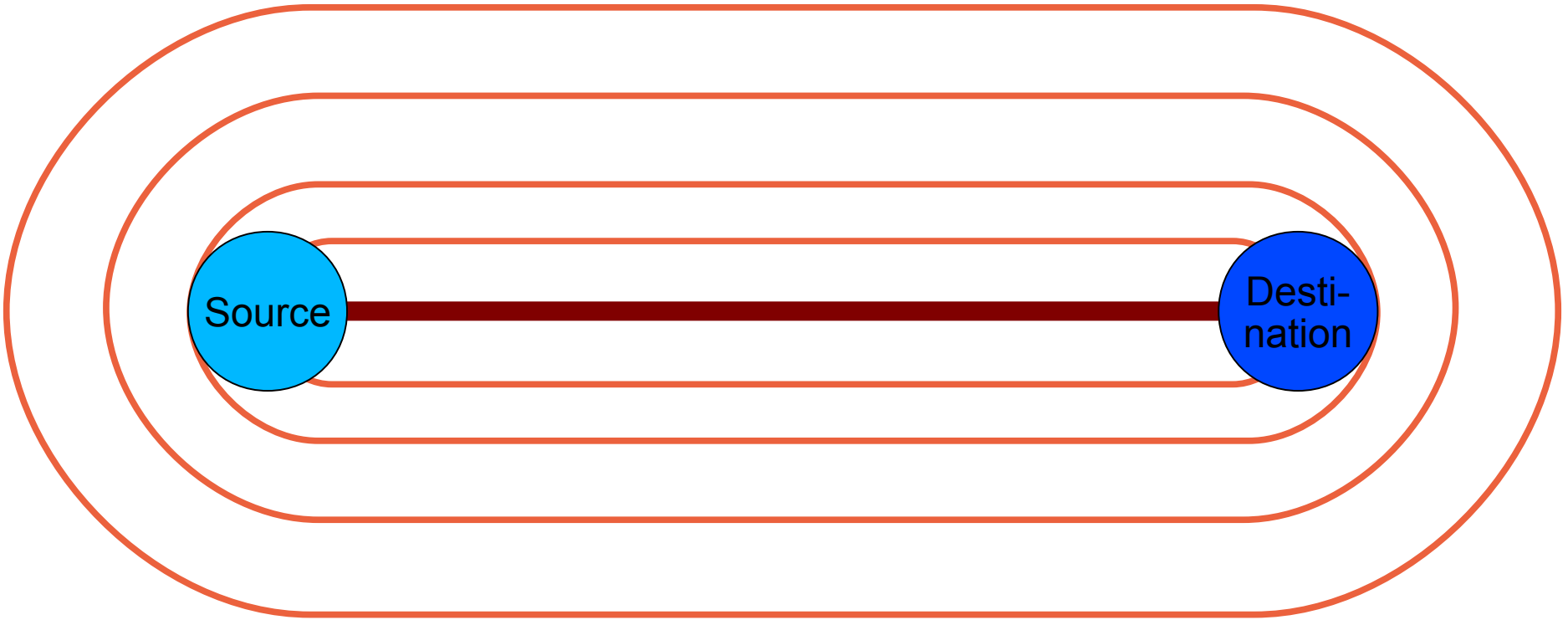

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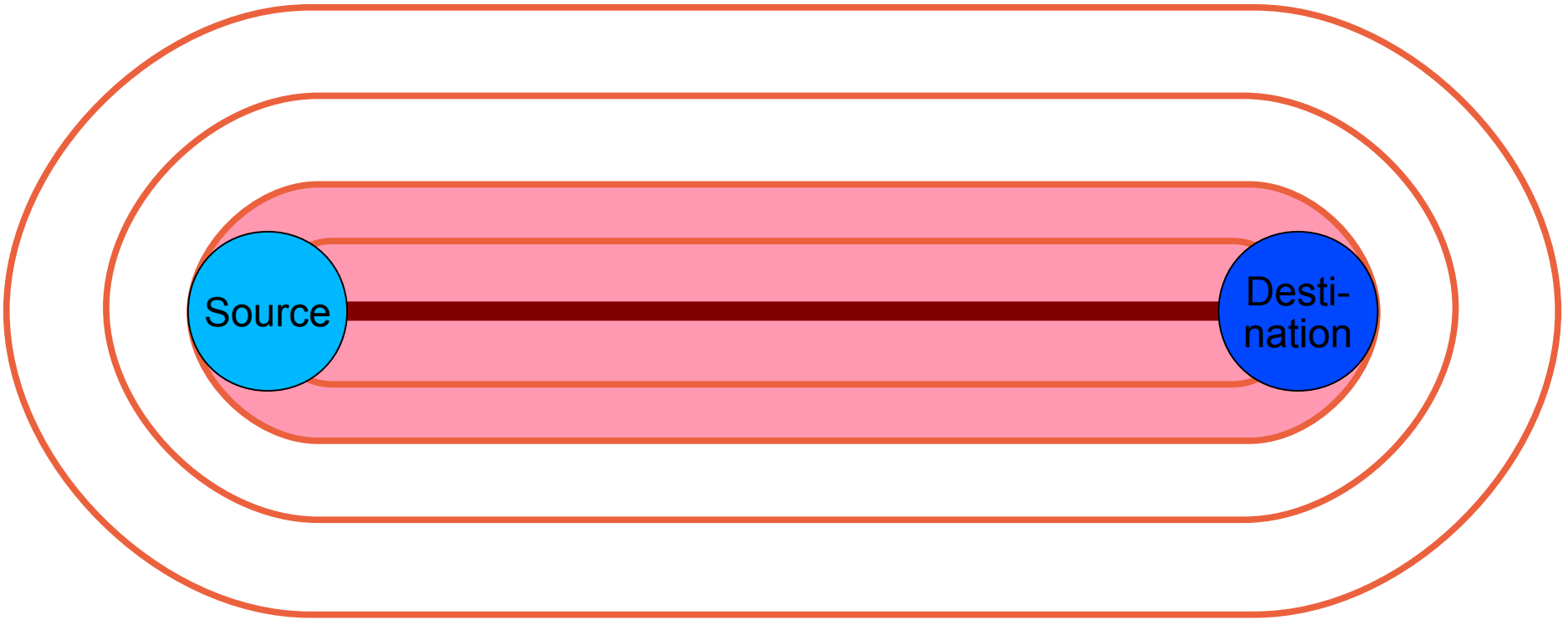

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Geometric Program: Channel

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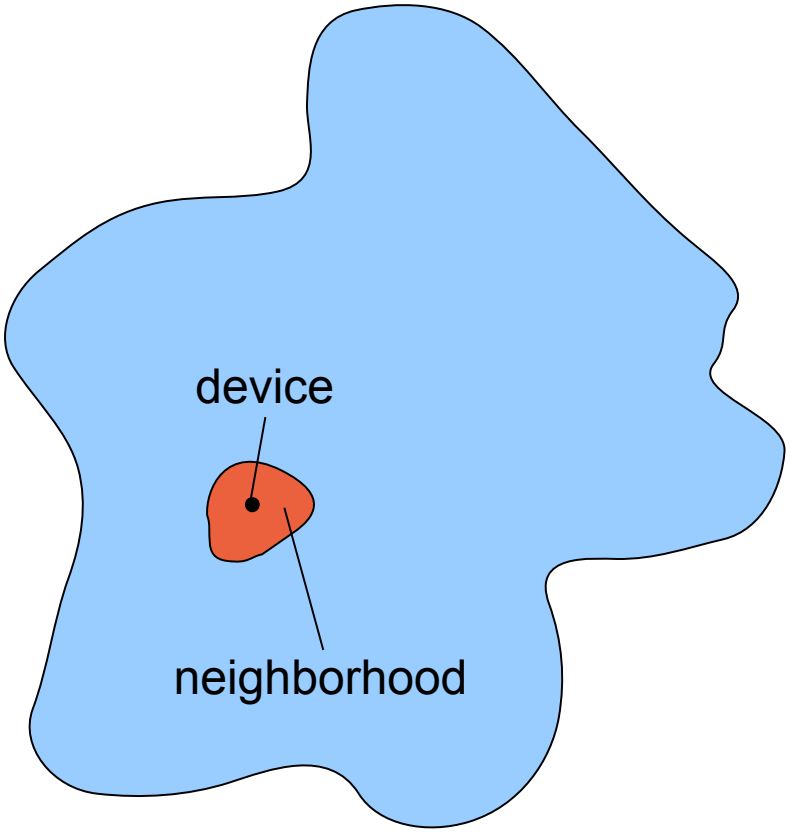
Why use continuous space?

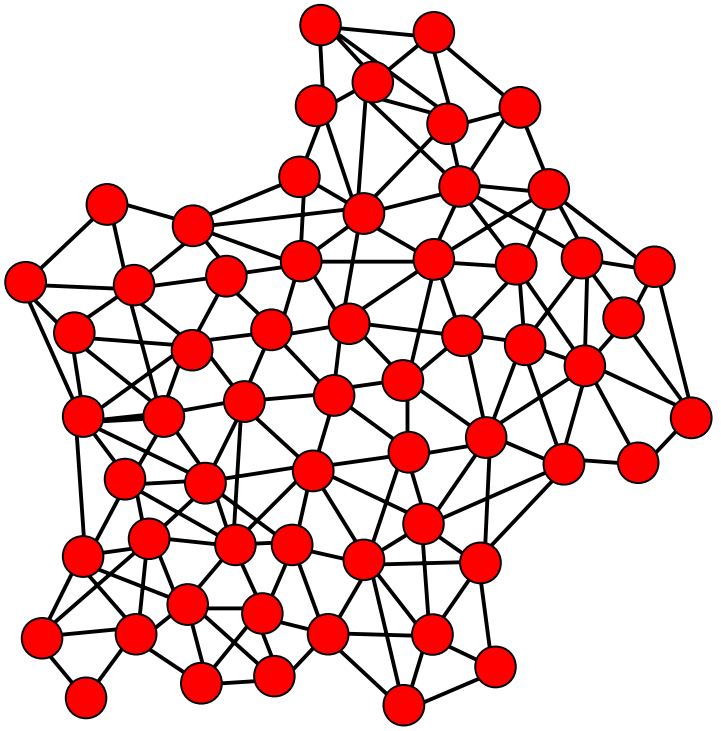
- Simplicity
- Scaling & Portability
- Robustness

(we'll come back to this in a bit...)

Amorphous Medium



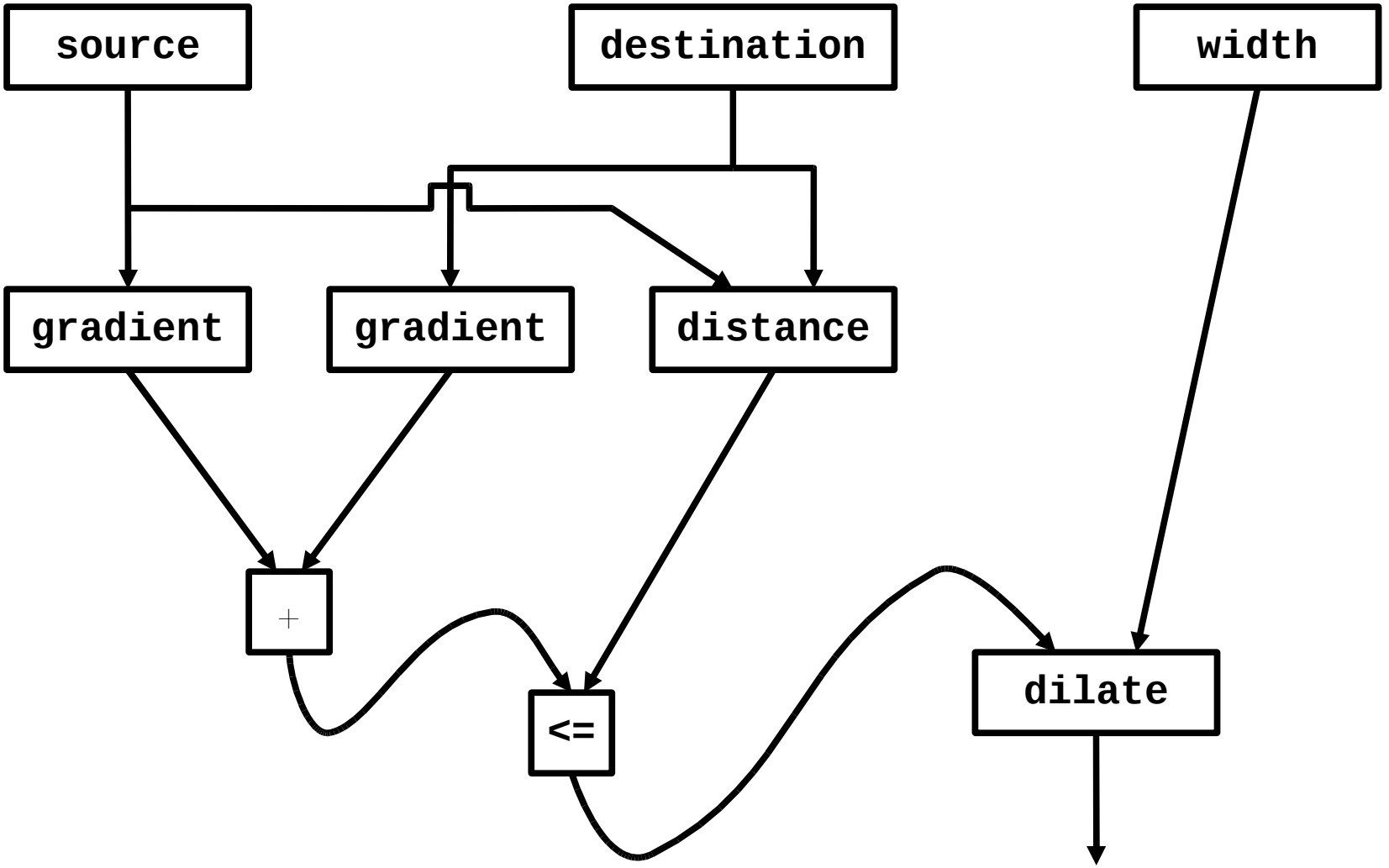
- Continuous space & time
- Infinite number of devices
- See neighbors' past state



Approximate with:

- Discrete network of devices
- Signals transmit state

Computing with fields



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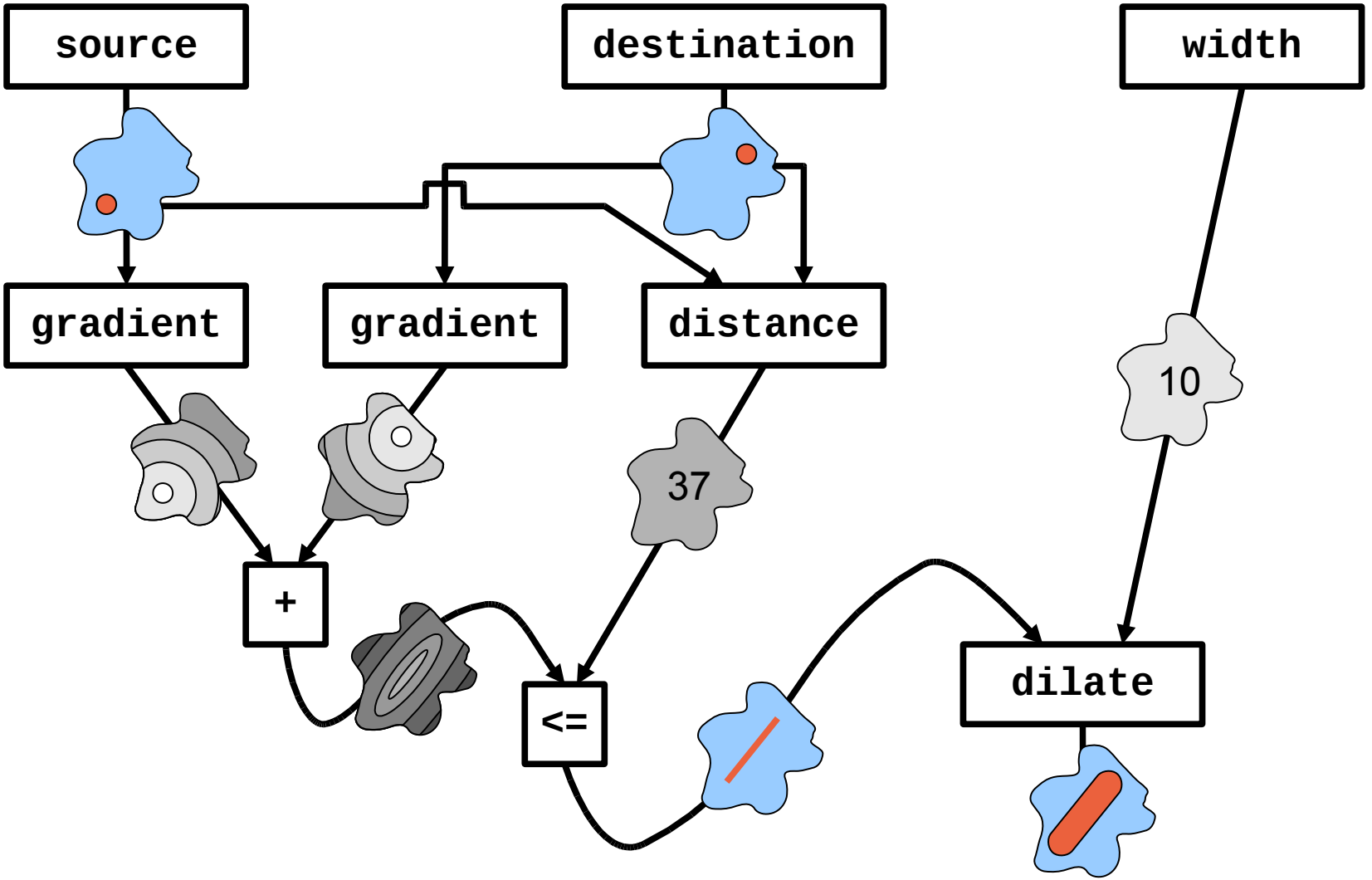

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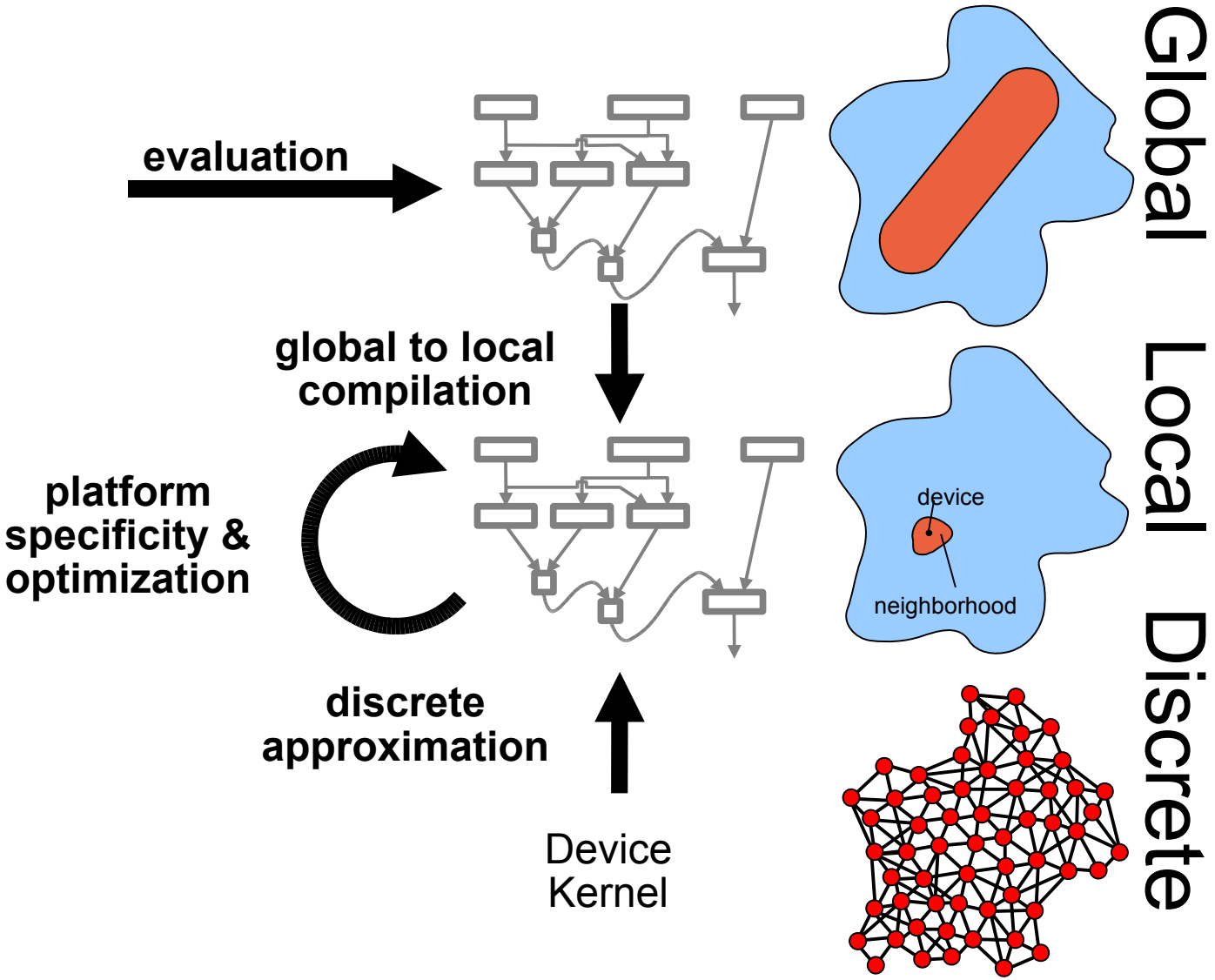
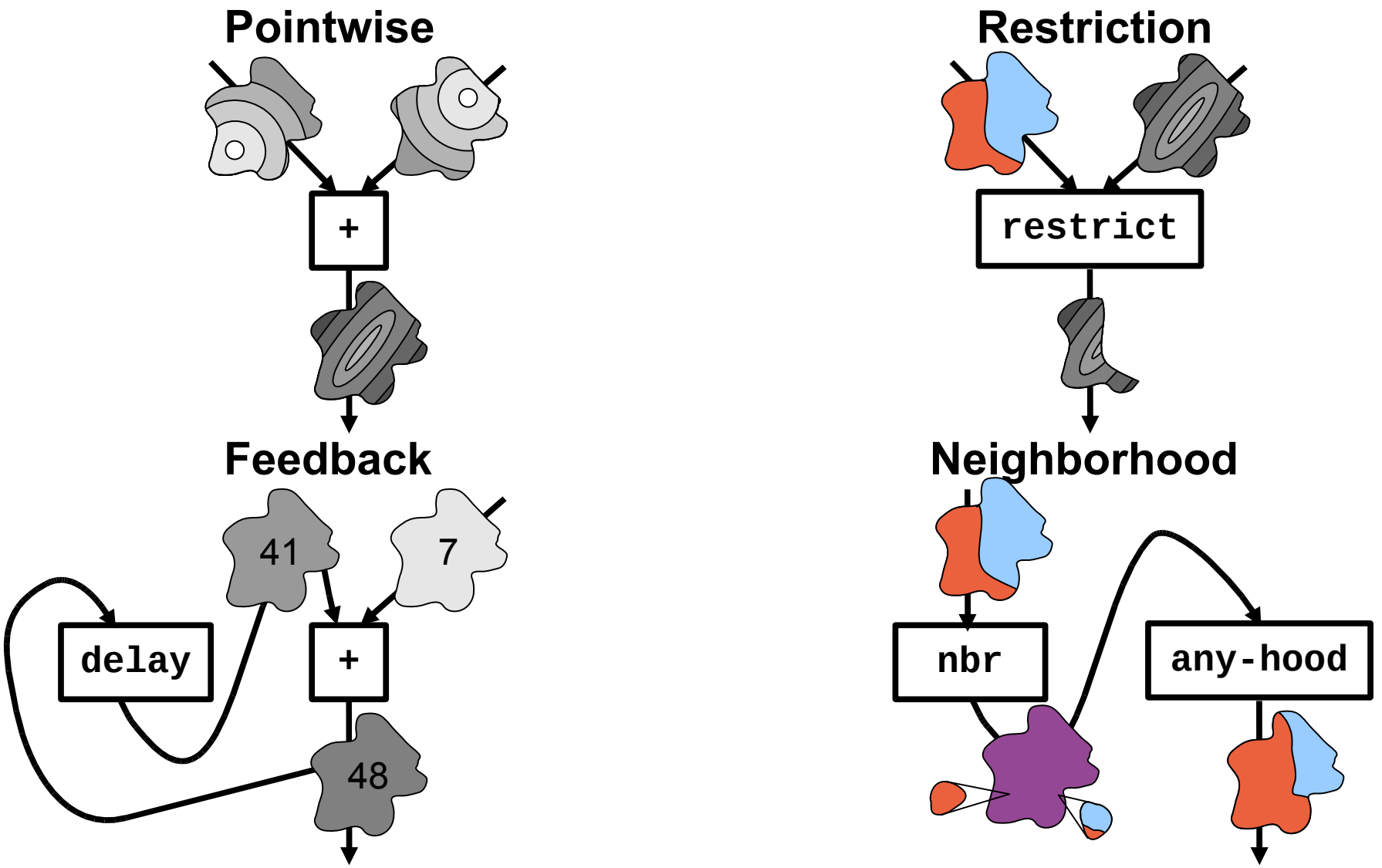
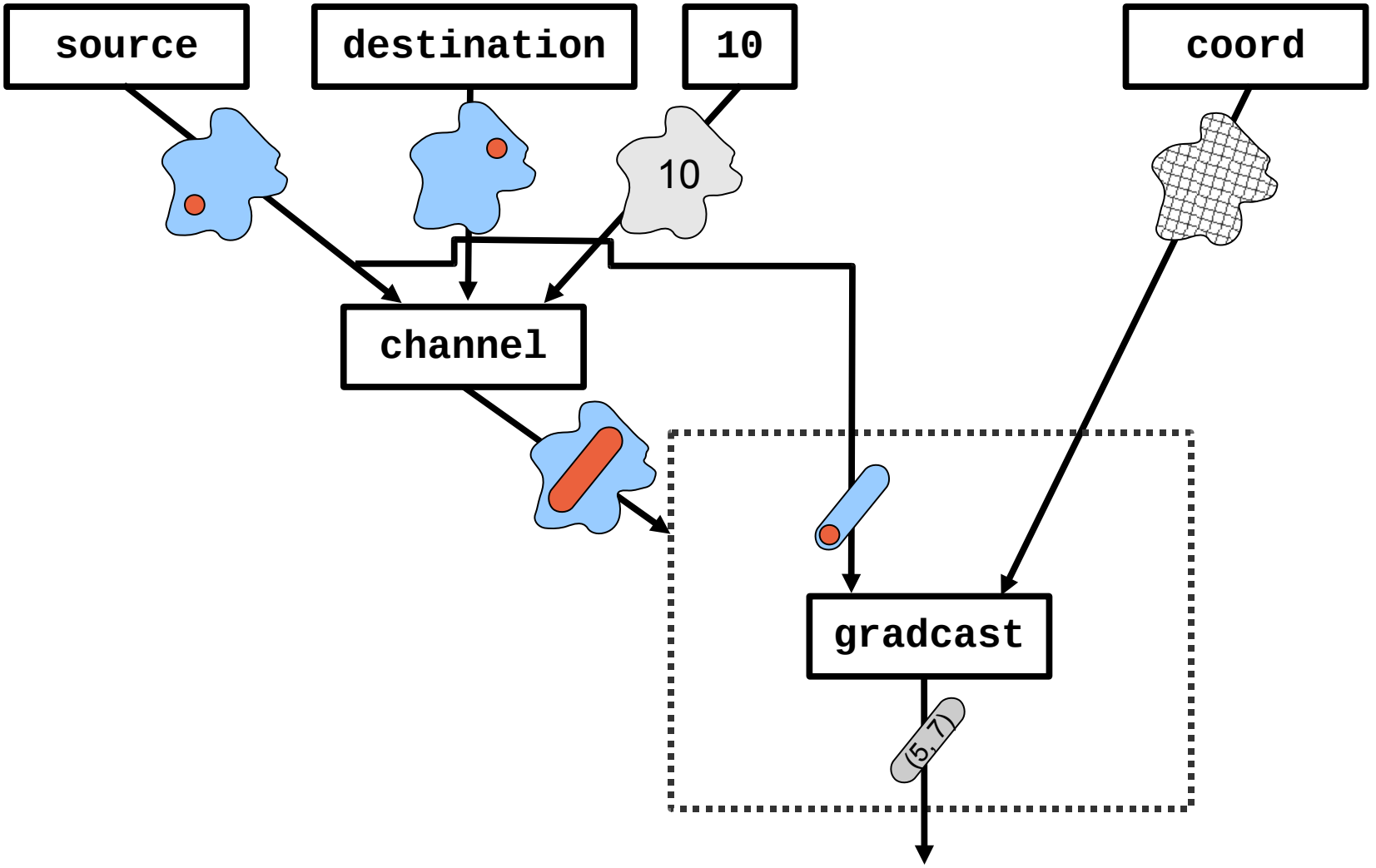


Proto's Families of Primitives



Modulation by Restriction



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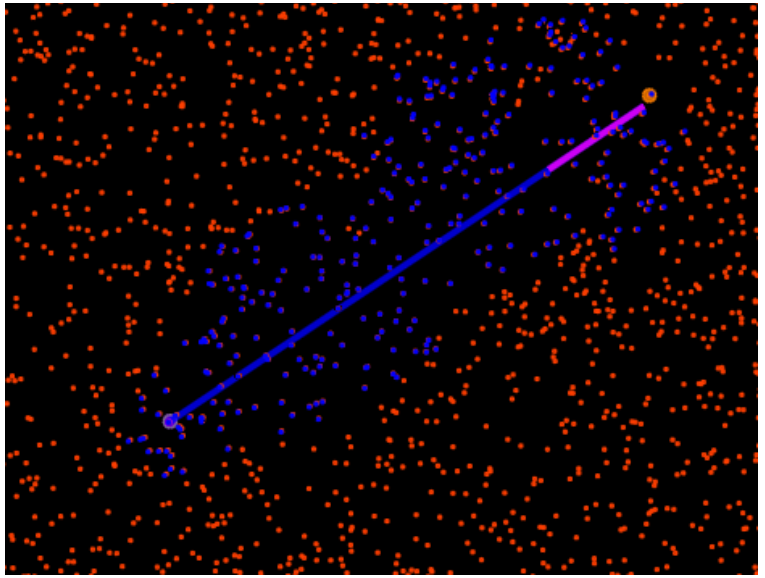
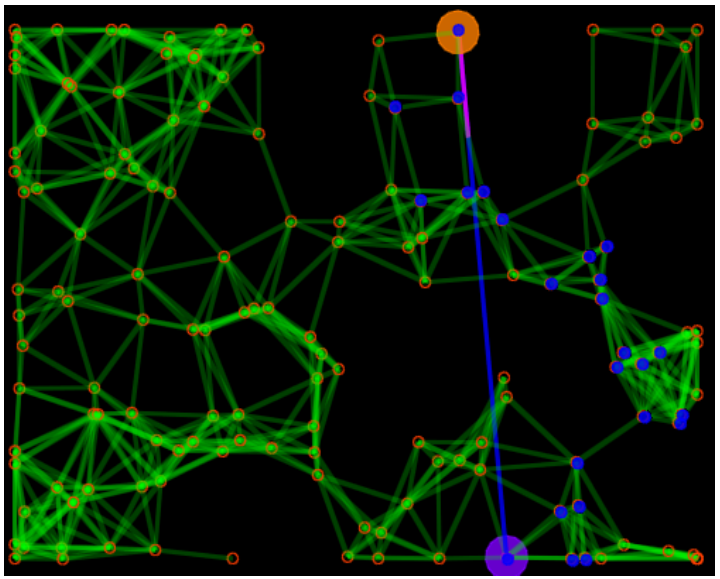


2000 devices



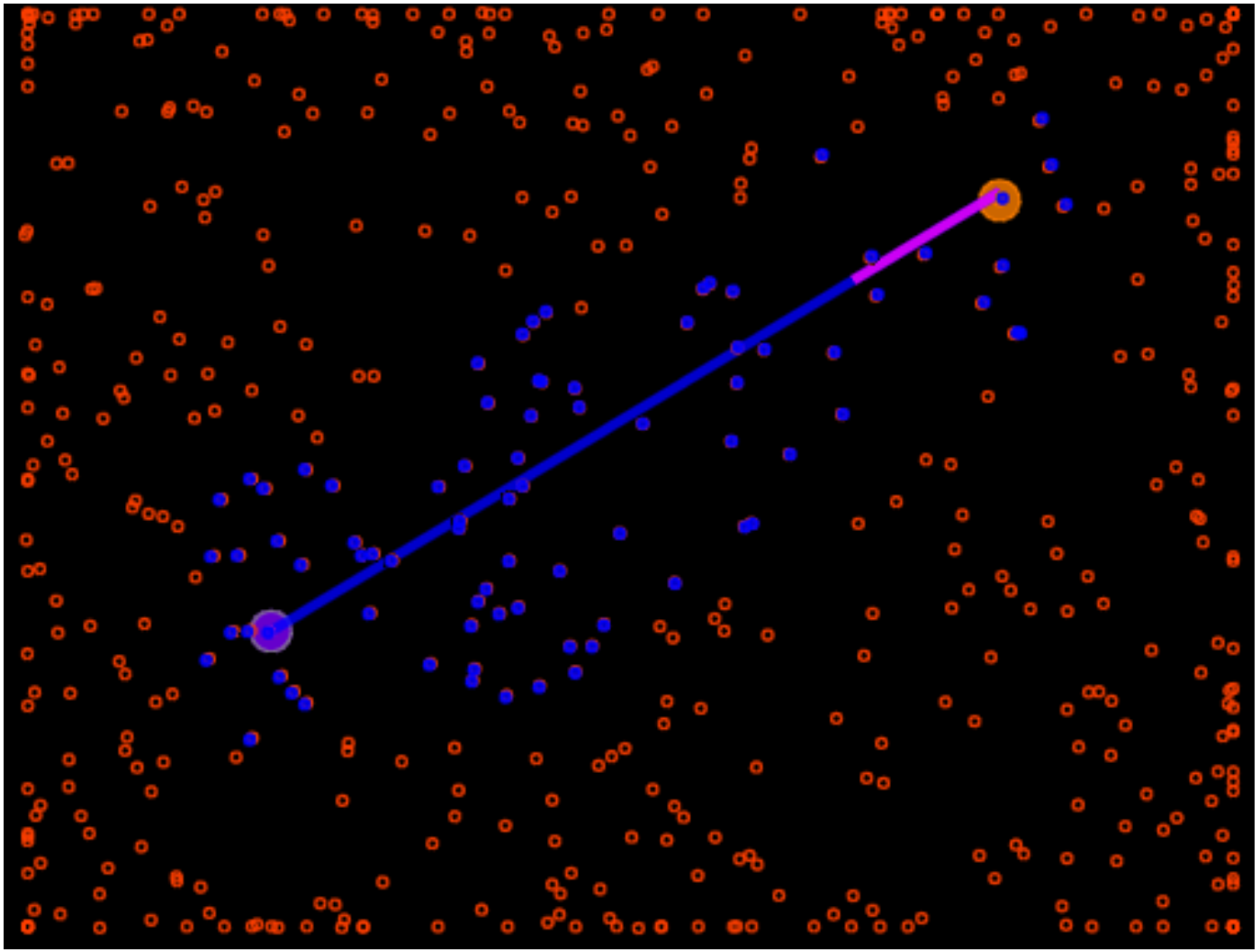
150 devices

Diving into the details

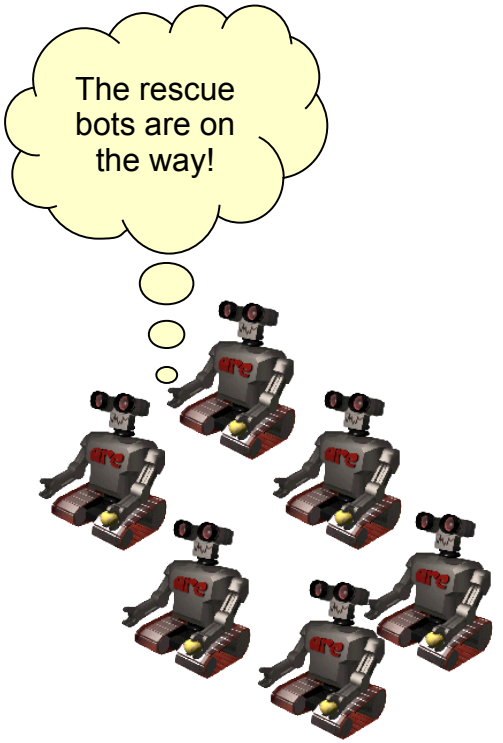
Let's build this up using the Proto simulator, one piece at a time...

(break to work w. simulator)

In simulation...



Example: Search & Rescue



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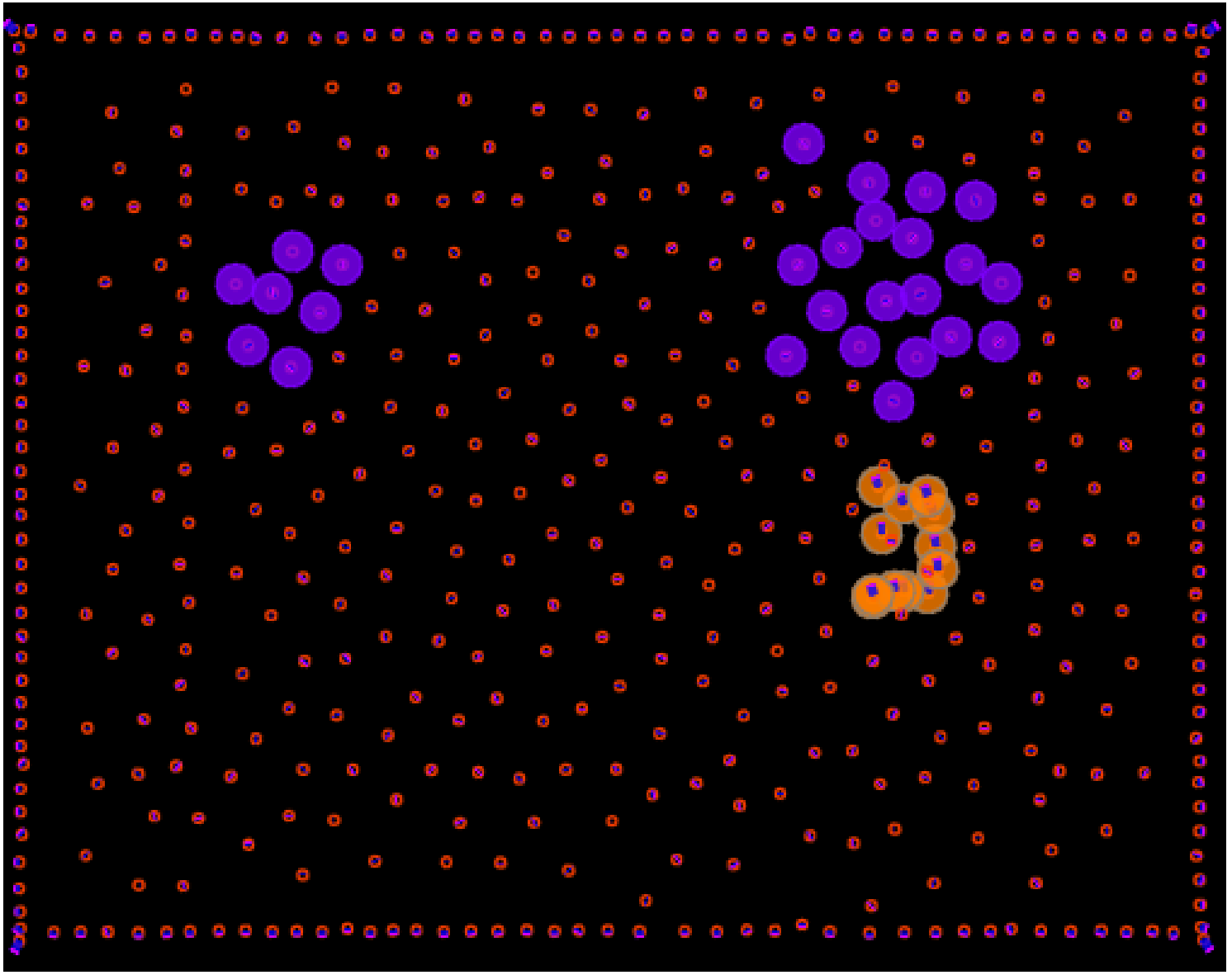

Weaknesses

- Functional programming scares people
- Programmers can break the abstraction
- No dynamic allocation of processes
- No formal proofs available for quality of approximation in a composed program

(active research on last two)

Summary

- Amorphous Medium abstraction simplifies programming of space-filling networks
- Proto has four families of space and time operations, compiles global descriptions into local actions that approximate the global
- Geometric metaphors allow complex spatial computing problems to be solved with very short programs.

Proto is available

http://stpg.csail.mit.edu/proto.html

(or google “MIT Proto”)

- Includes libraries, compiler, kernel, simulator, platforms
- Licensed under GPL (w. libc-type exception)