A Spatial Computing Approach to Distributed Algorithms

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Asilomar Signals, Systems, & Computers
November, 2010

BBN TECHNOLOGIES

If the problem structure is geometric... take advantage of it!

Pervasive Computing

Disaster Relief

Sensor Networks

… but can we deepen the mathematical foundations?

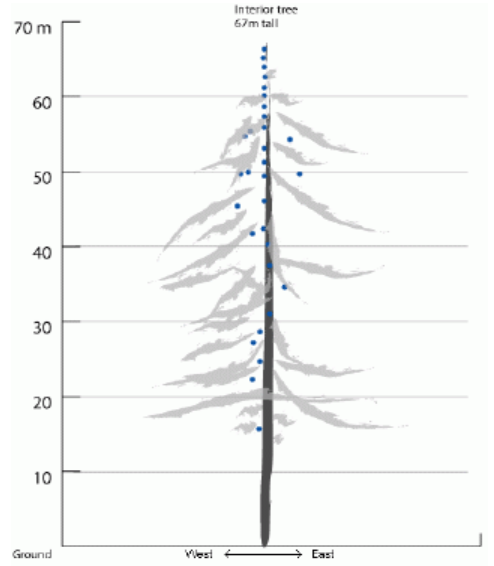
Outline

- **What is Spatial Computing?**
- Global → Local → Global
- From Space to Robustness & Scalability

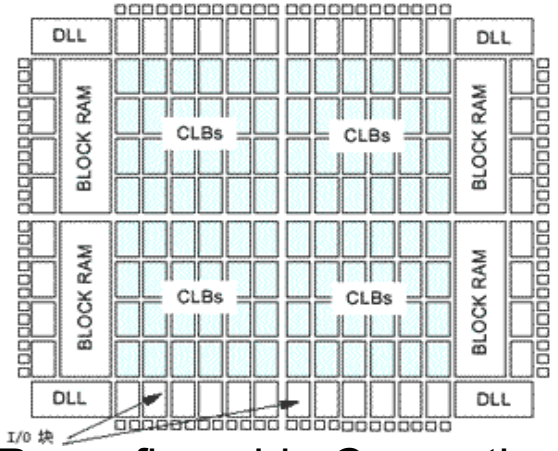
Spatial Computers

Robot Swarms

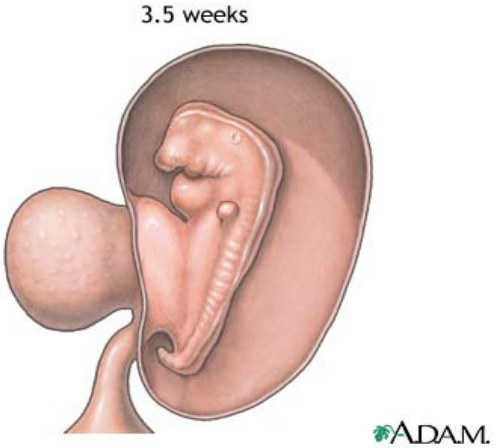
Biological Computing



Sensor Networks

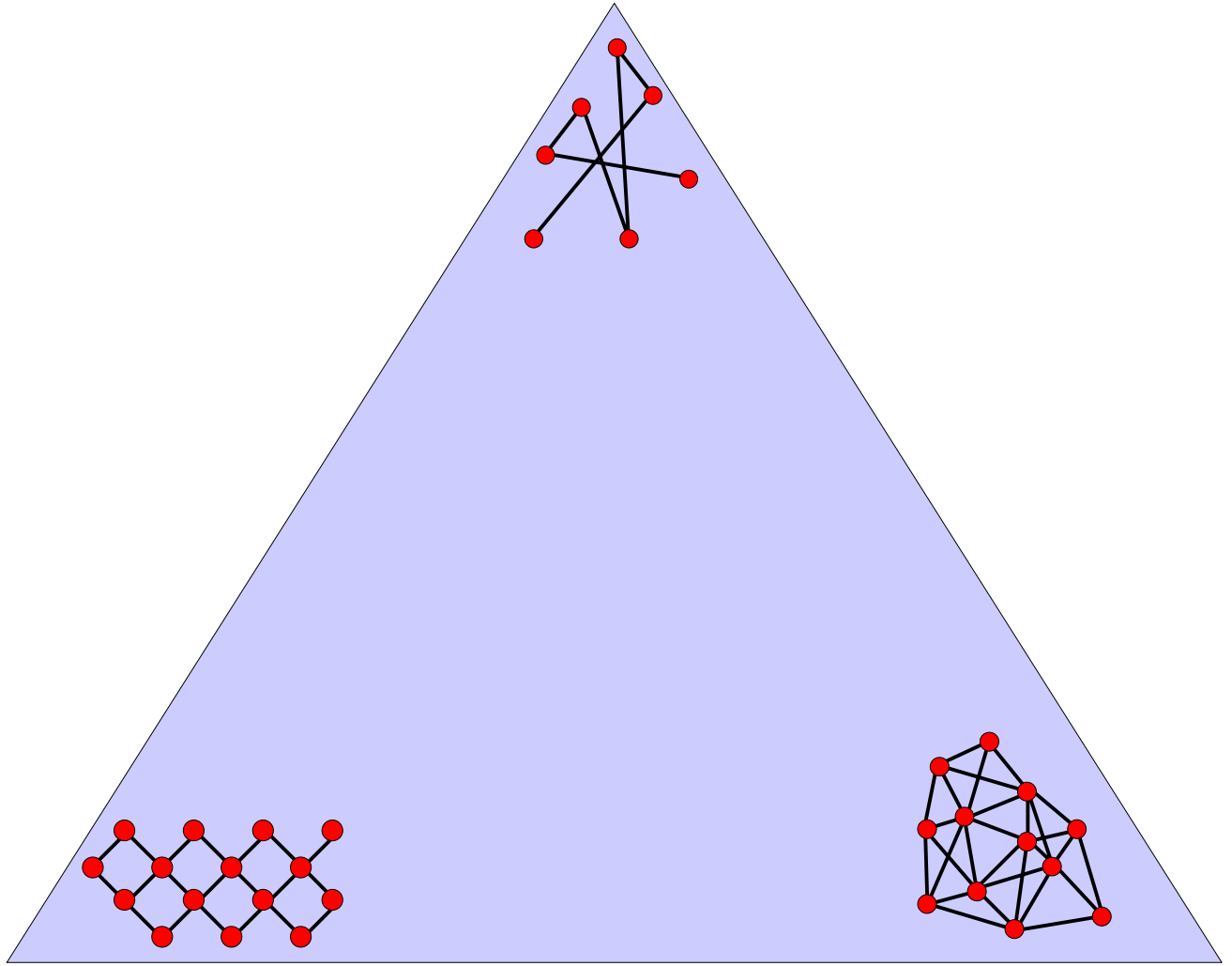


Reconfigurable Computing

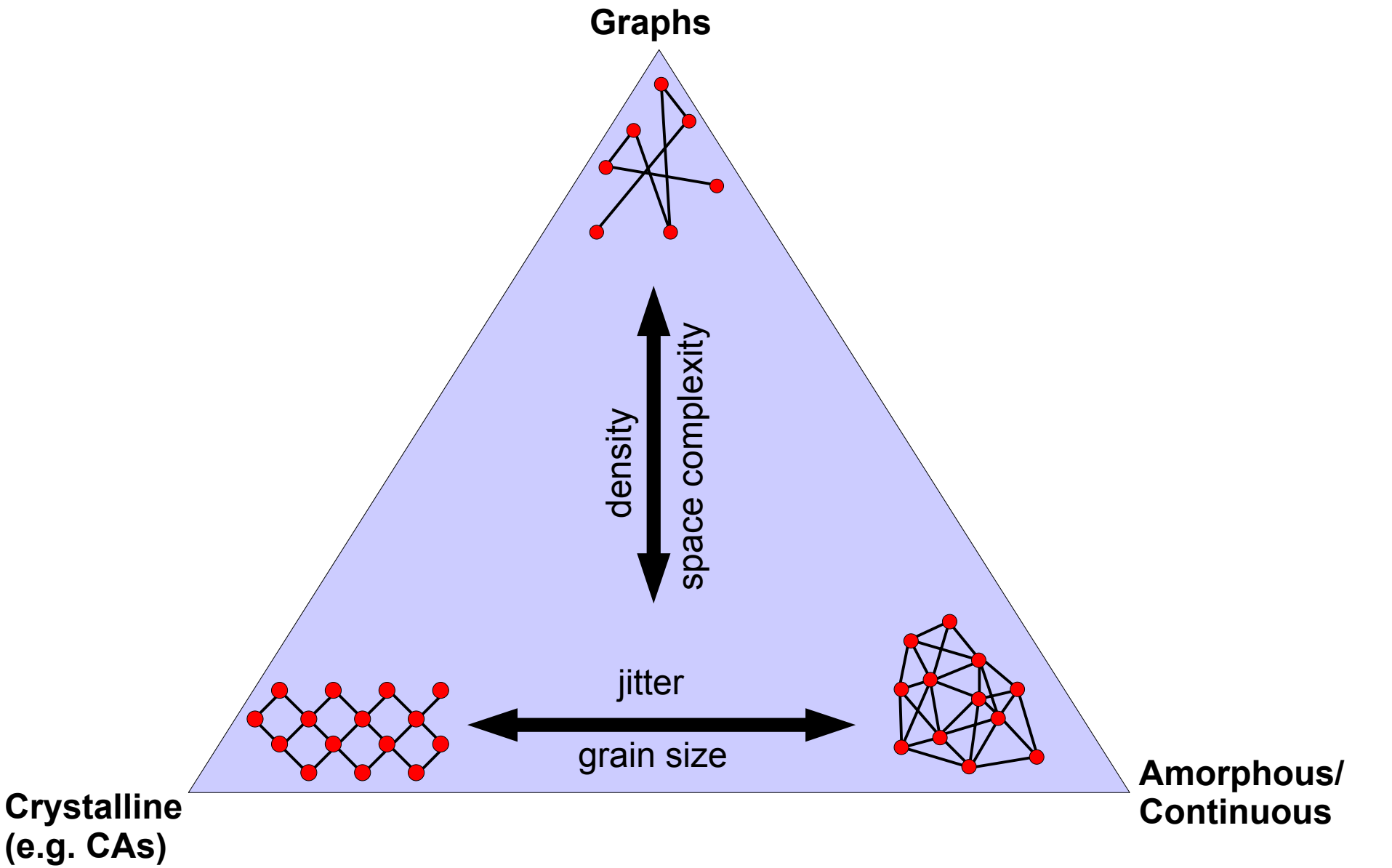


Cells during Morphogenesis

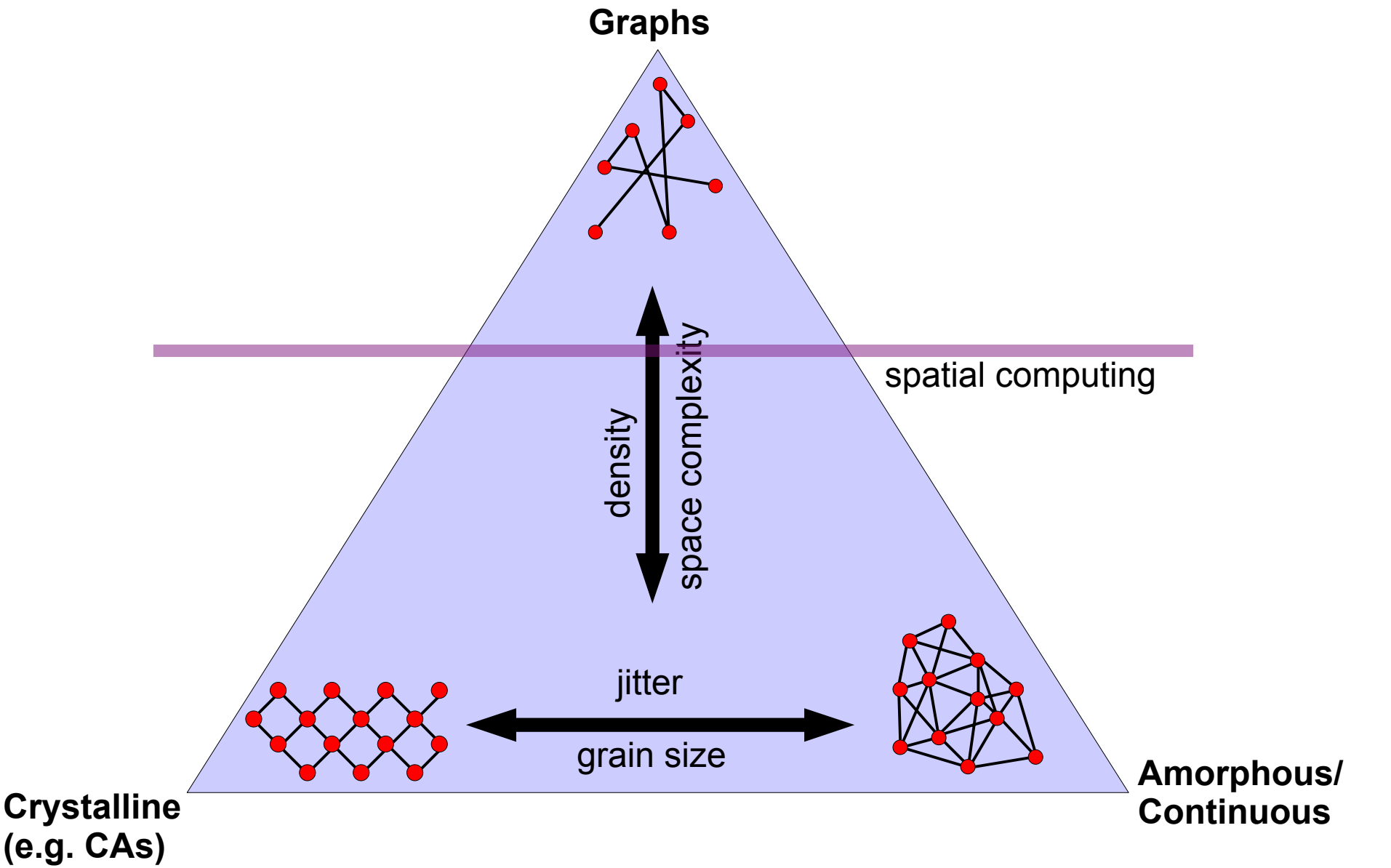
Modular Robotics



(w. Dan Yamins)


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

(w. Dan Yamins)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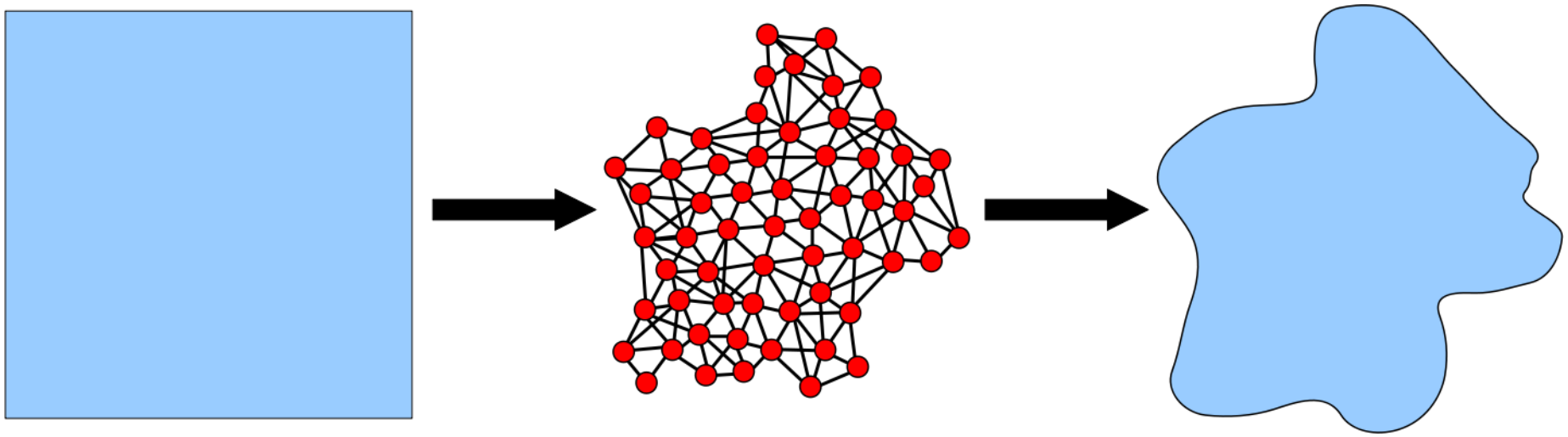
Space/Network Duality

How well does the network cover space?



What space is covered well by the network?

Example: Target Tracking

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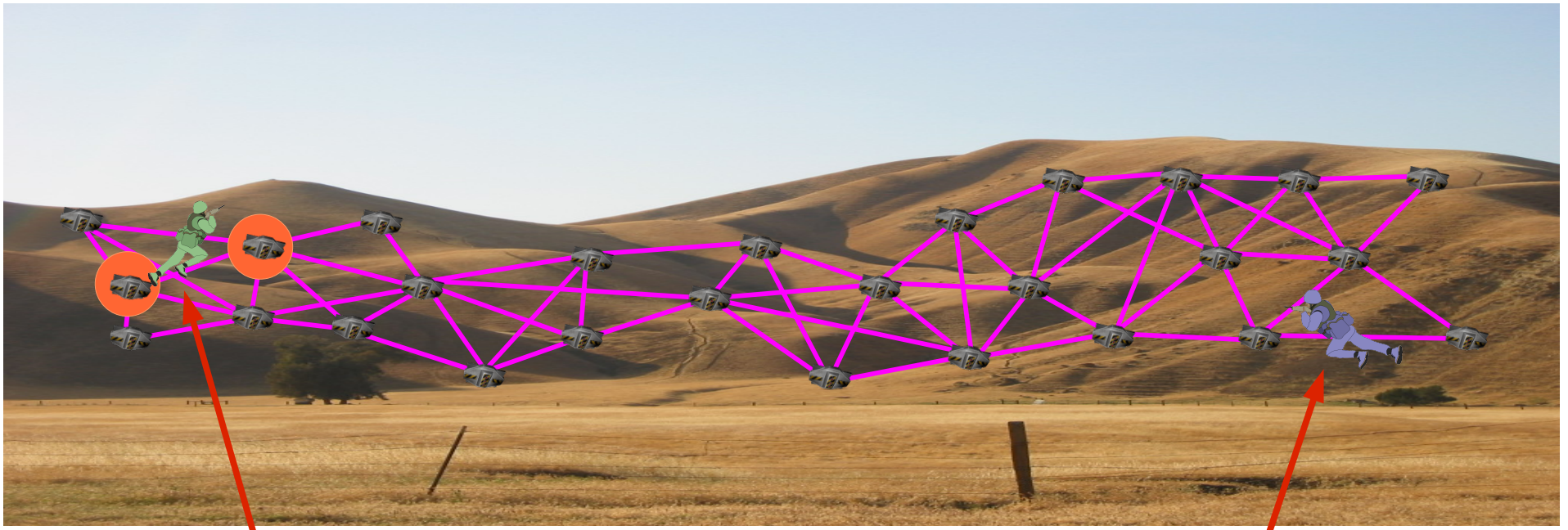

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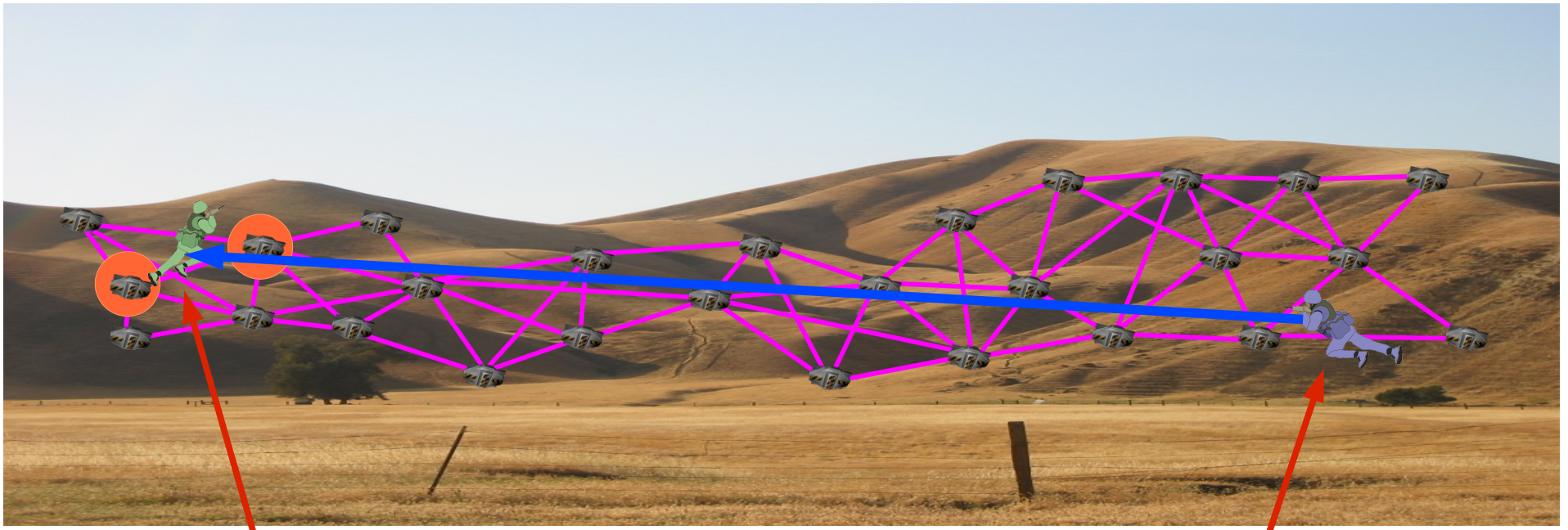

Programming Languages Need:

- 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

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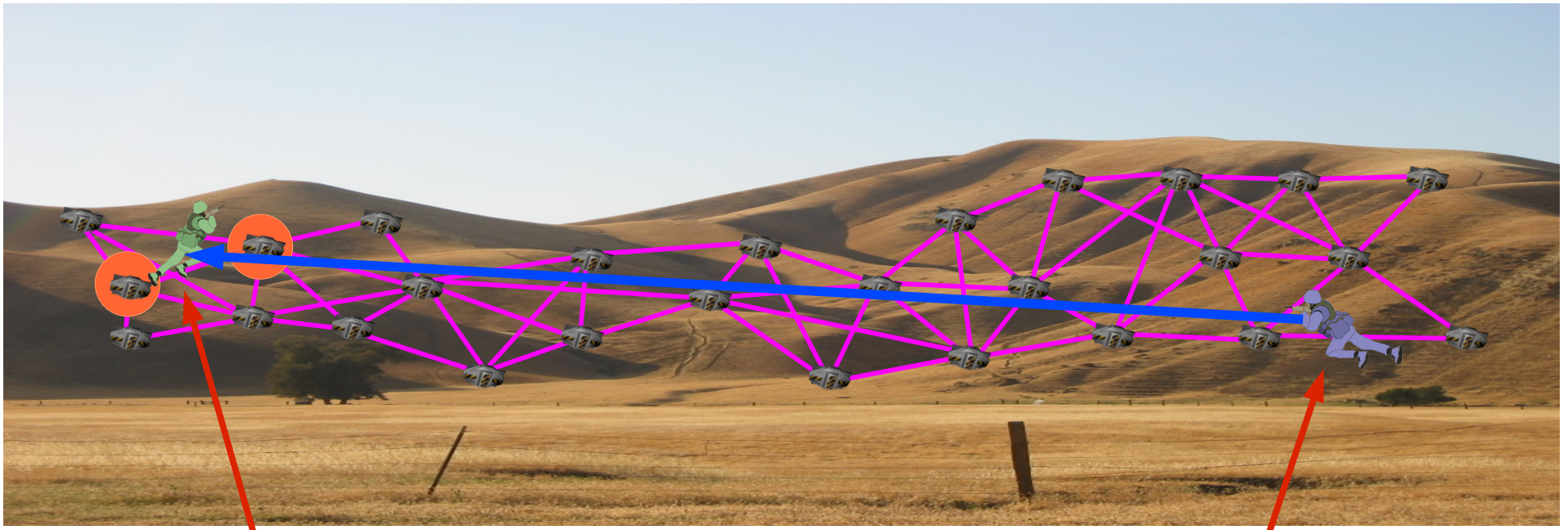
Example: Target Tracking



Geometric Program: Channel

(cf. Butera)

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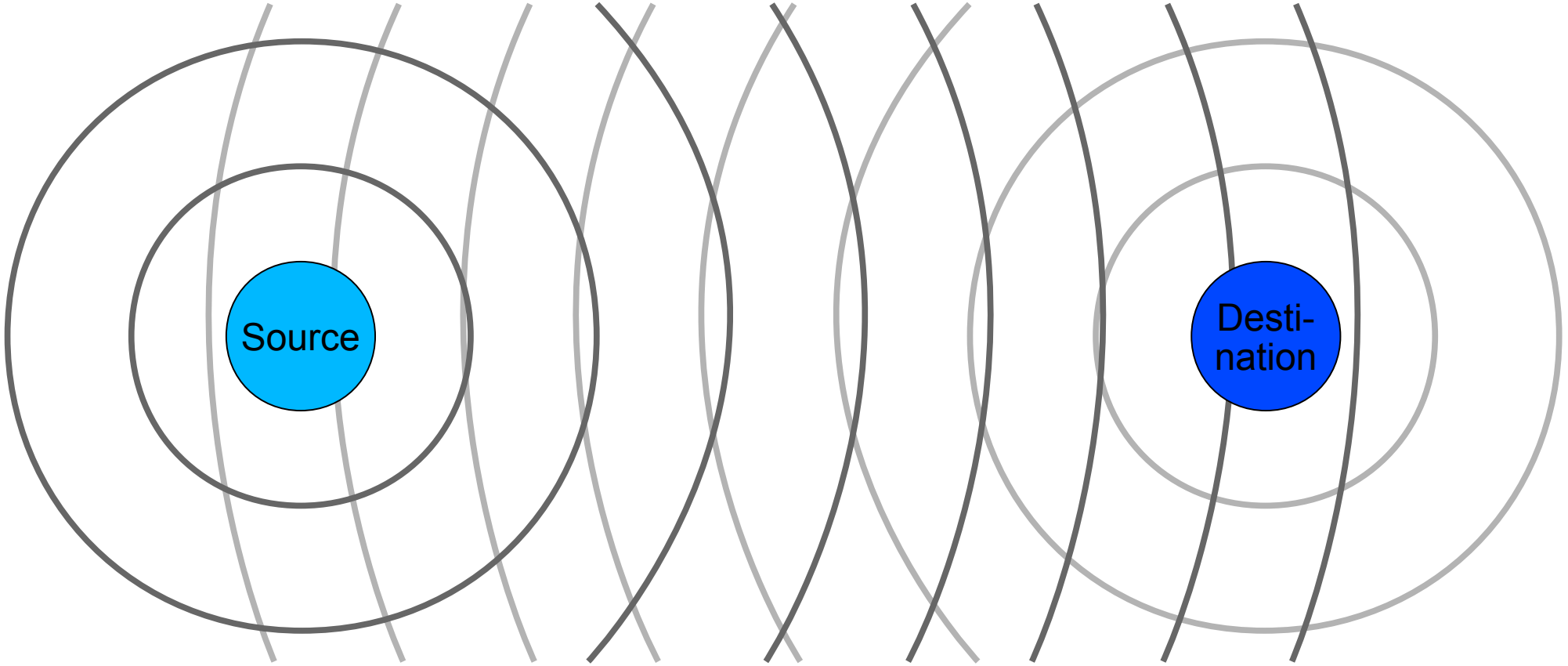

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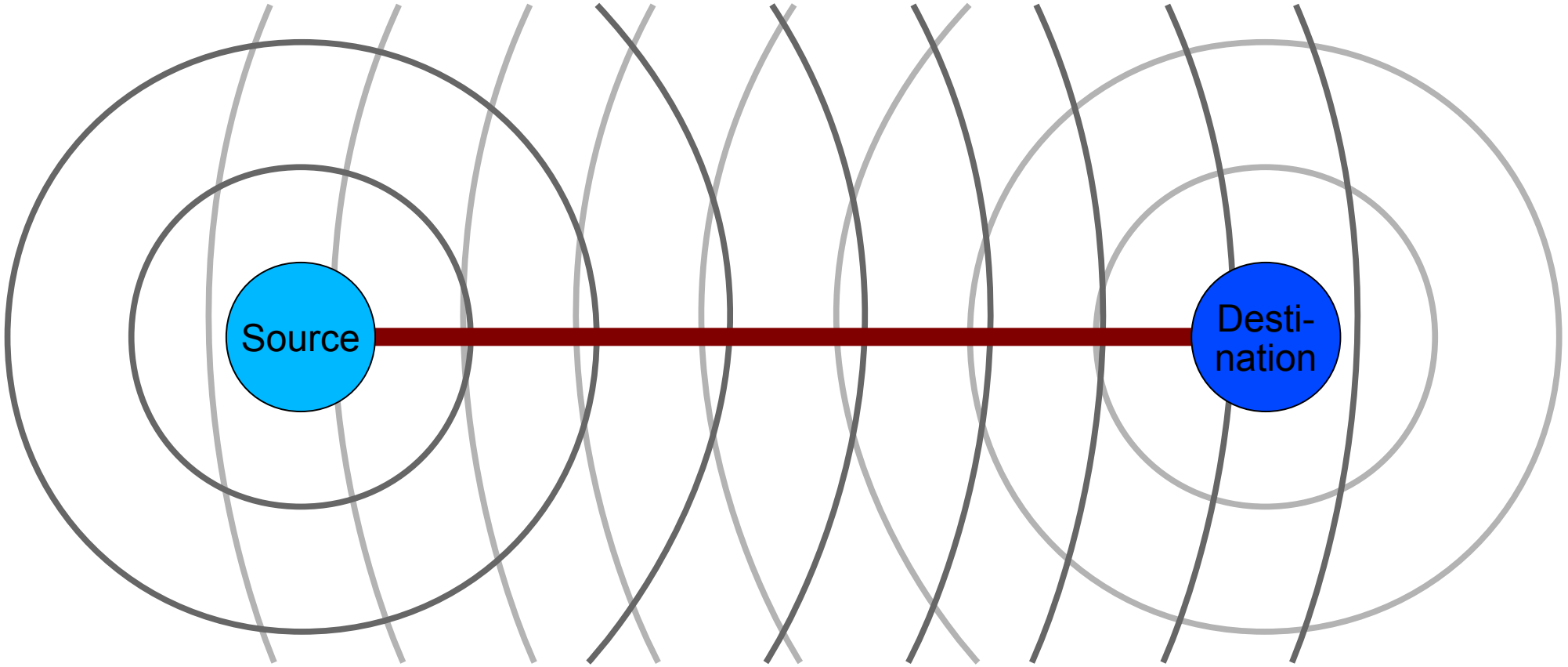

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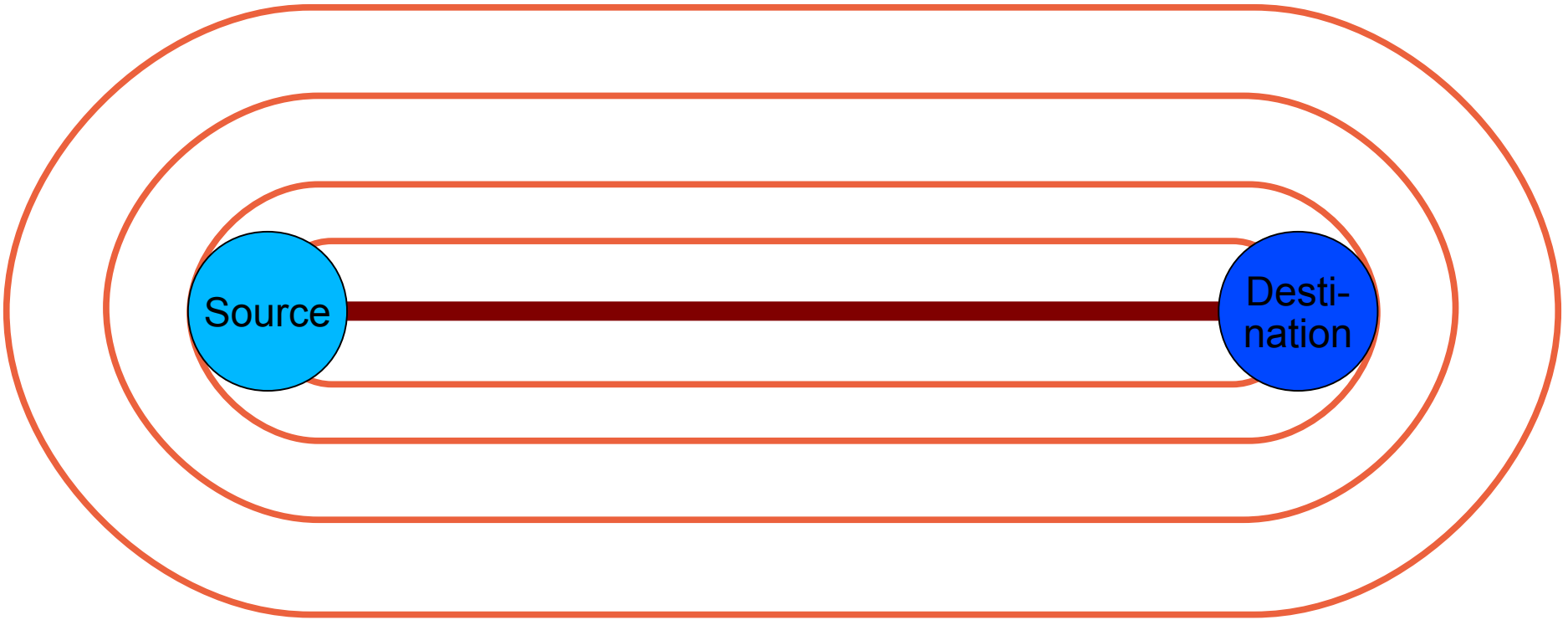

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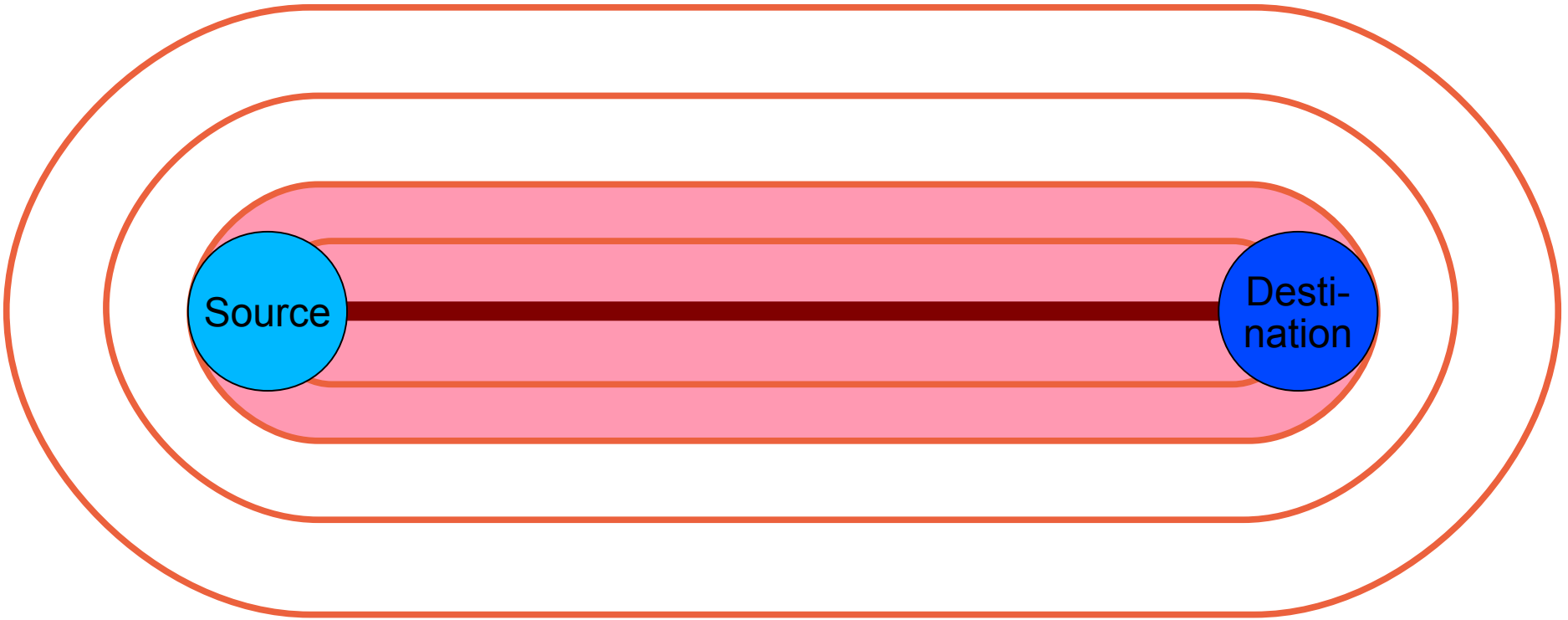
Geometric Program: Channel

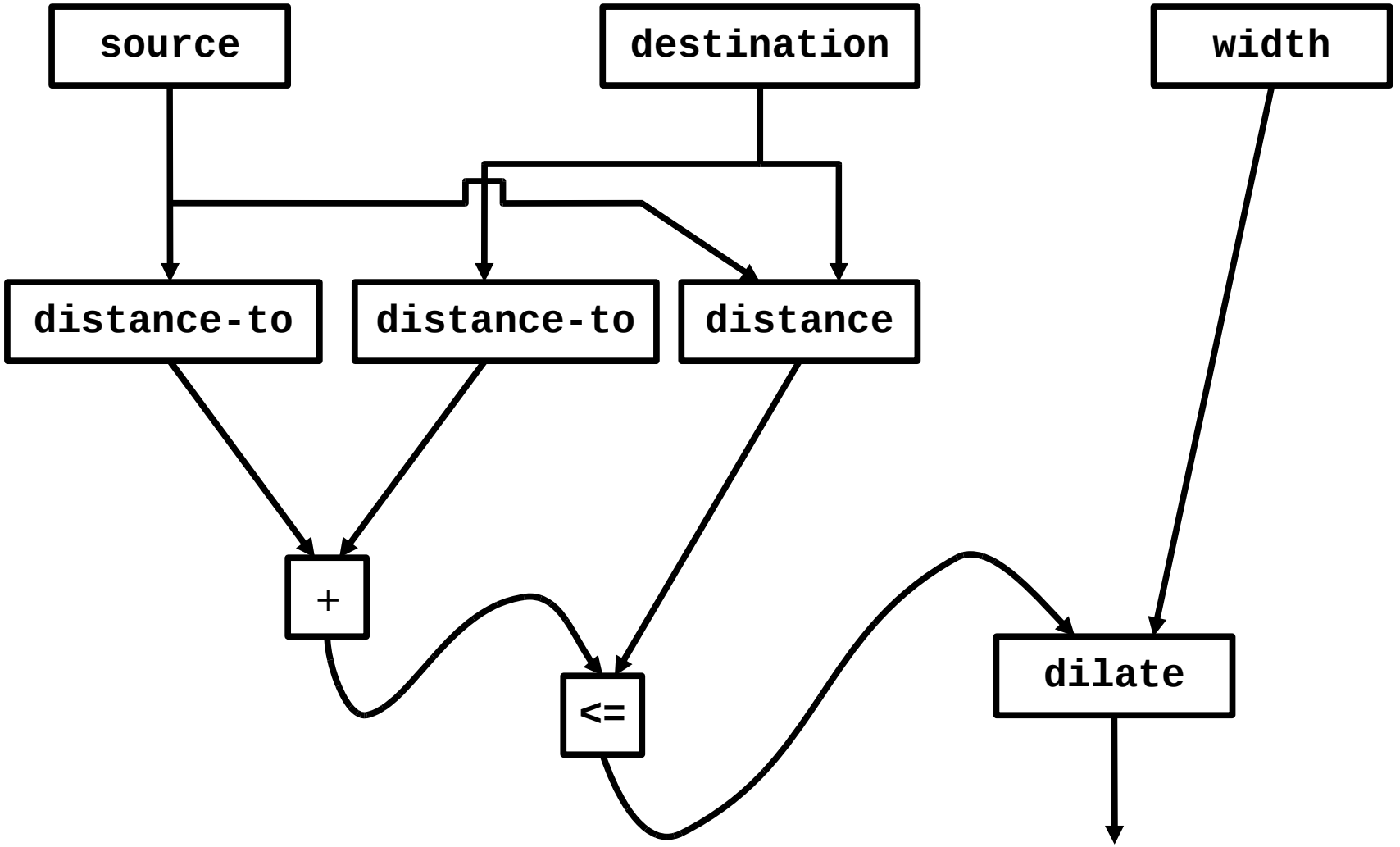


(cf. Butera)

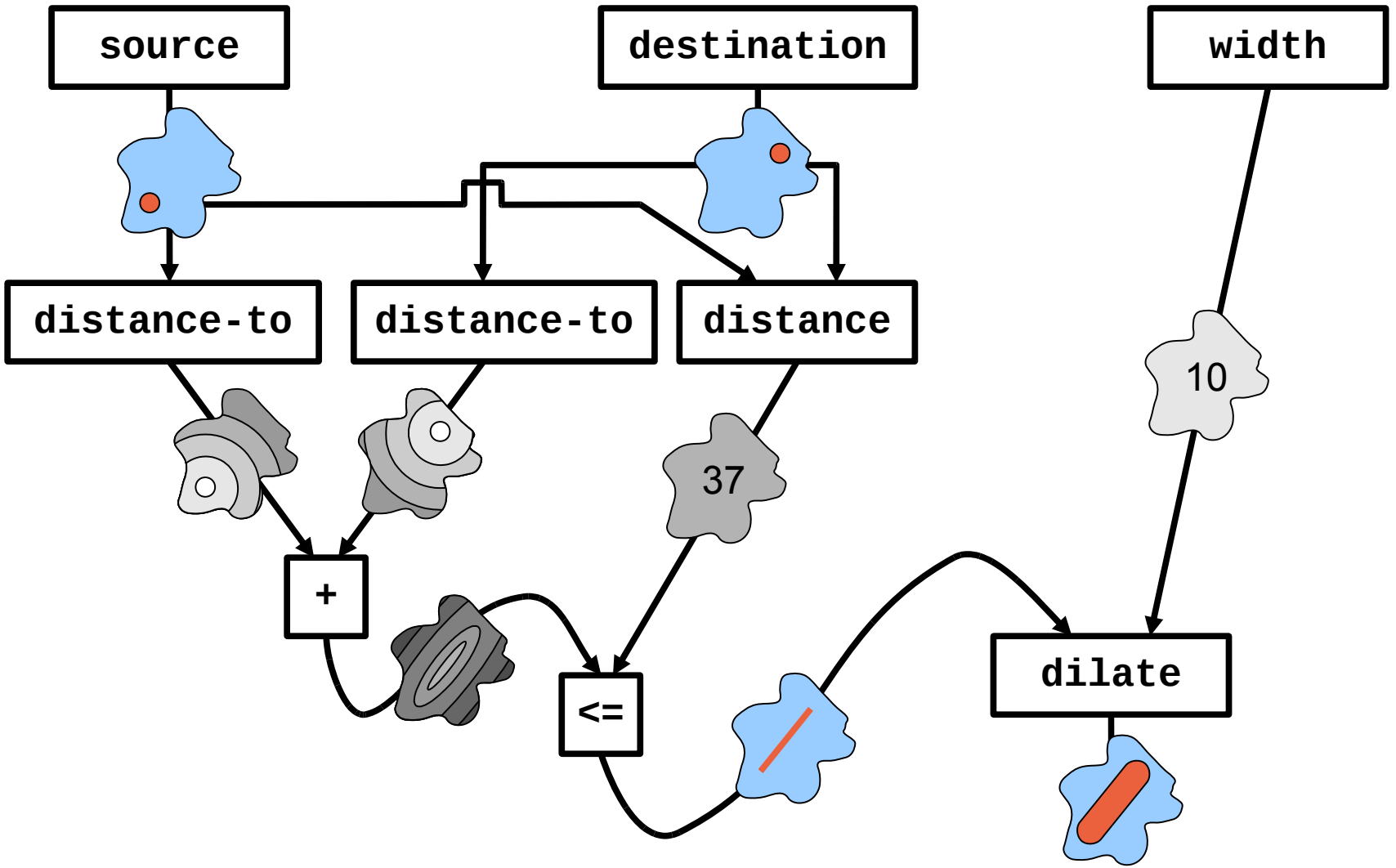
Geometric Program: Channel

(cf. Butera)

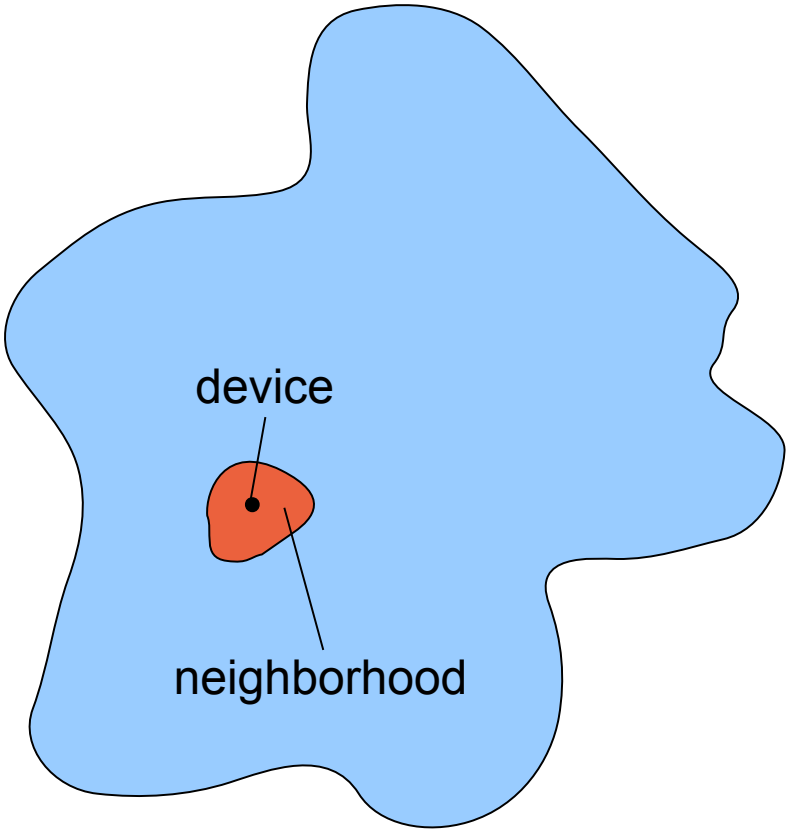
Computing with fields



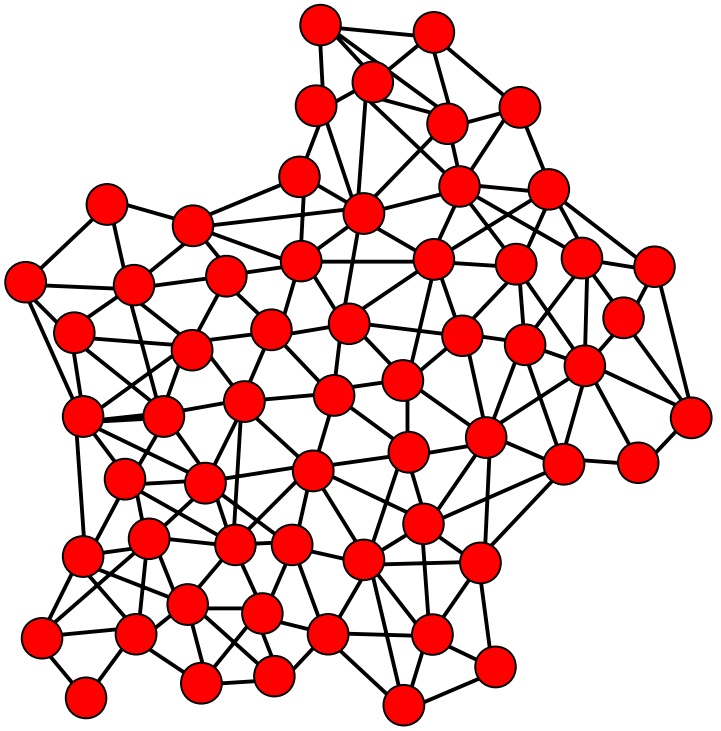
Computing with fields



Amorphous Medium



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

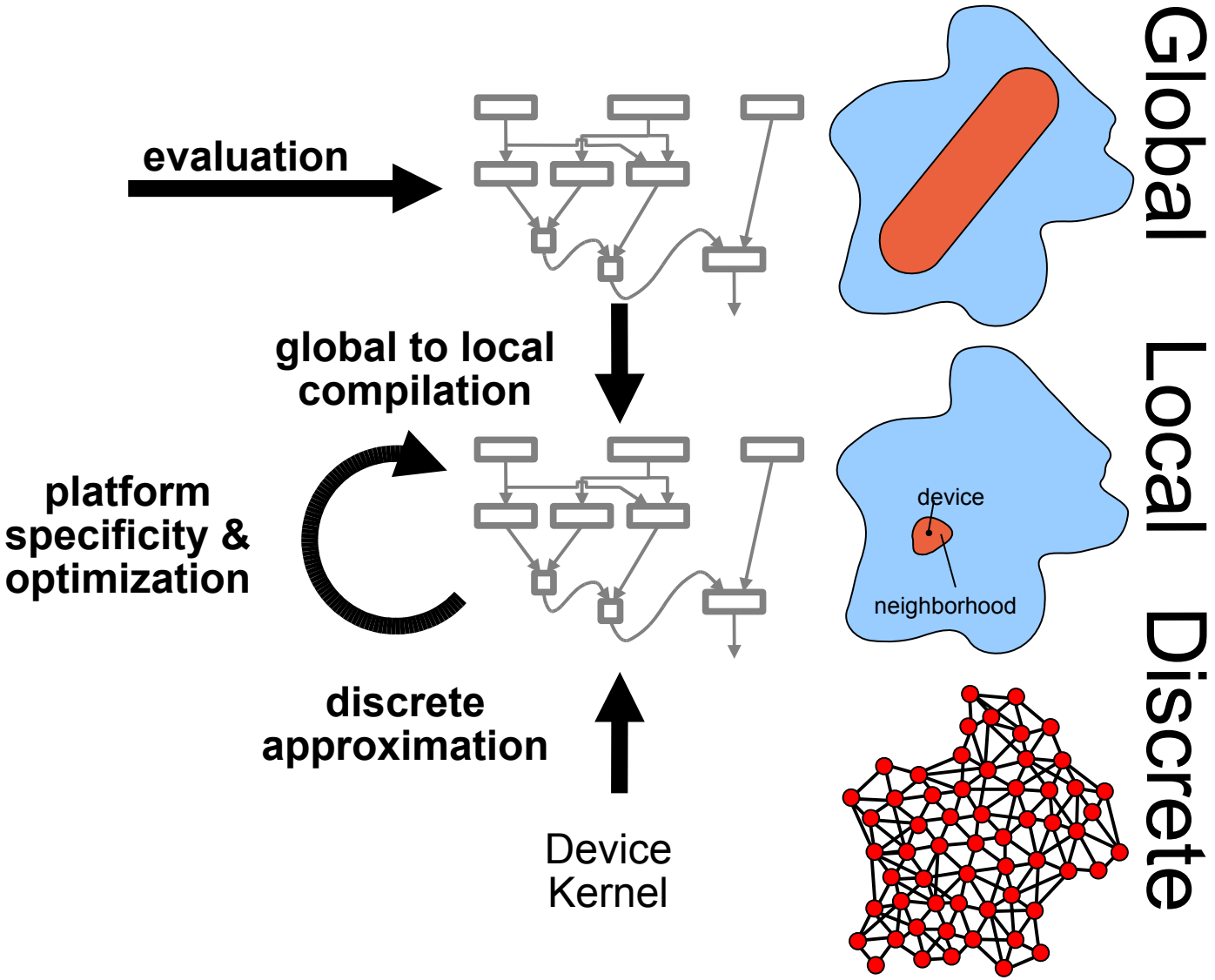


Approximate with:

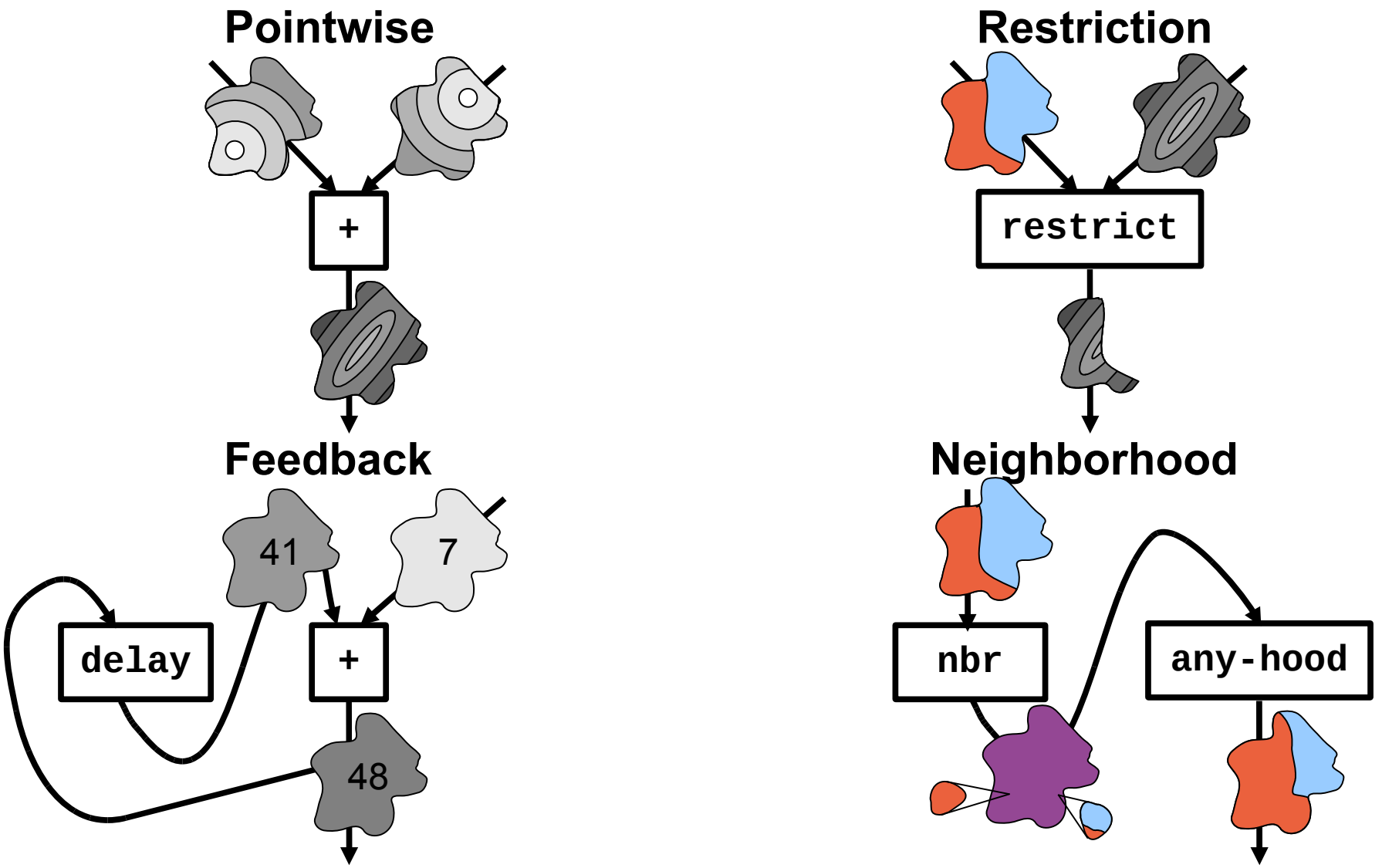
- Discrete network of devices
- Signals transmit state

Proto

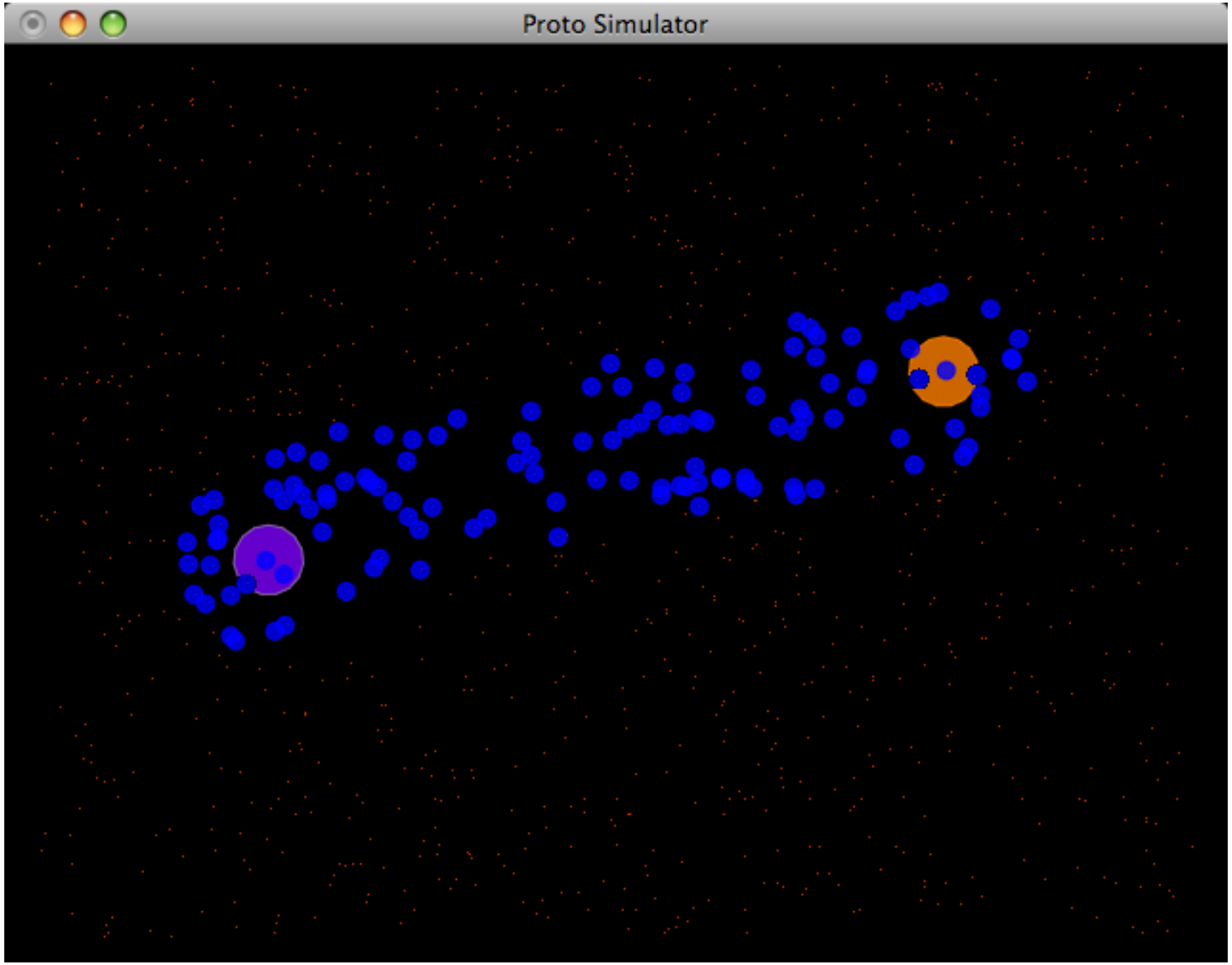
```
(def gradient (src) ...)
(def distance (src dst) ...)
(def dilate (src n)
  (<= (gradient src) n))
(def channel (src dst width)
  (let* ((d (distance src dst))
         (trail (<= (+ (gradient src)
                       (gradient dst))
                    d)))
    (dilate trail width)))
```



Proto's Families of Primitives



In Simulation...



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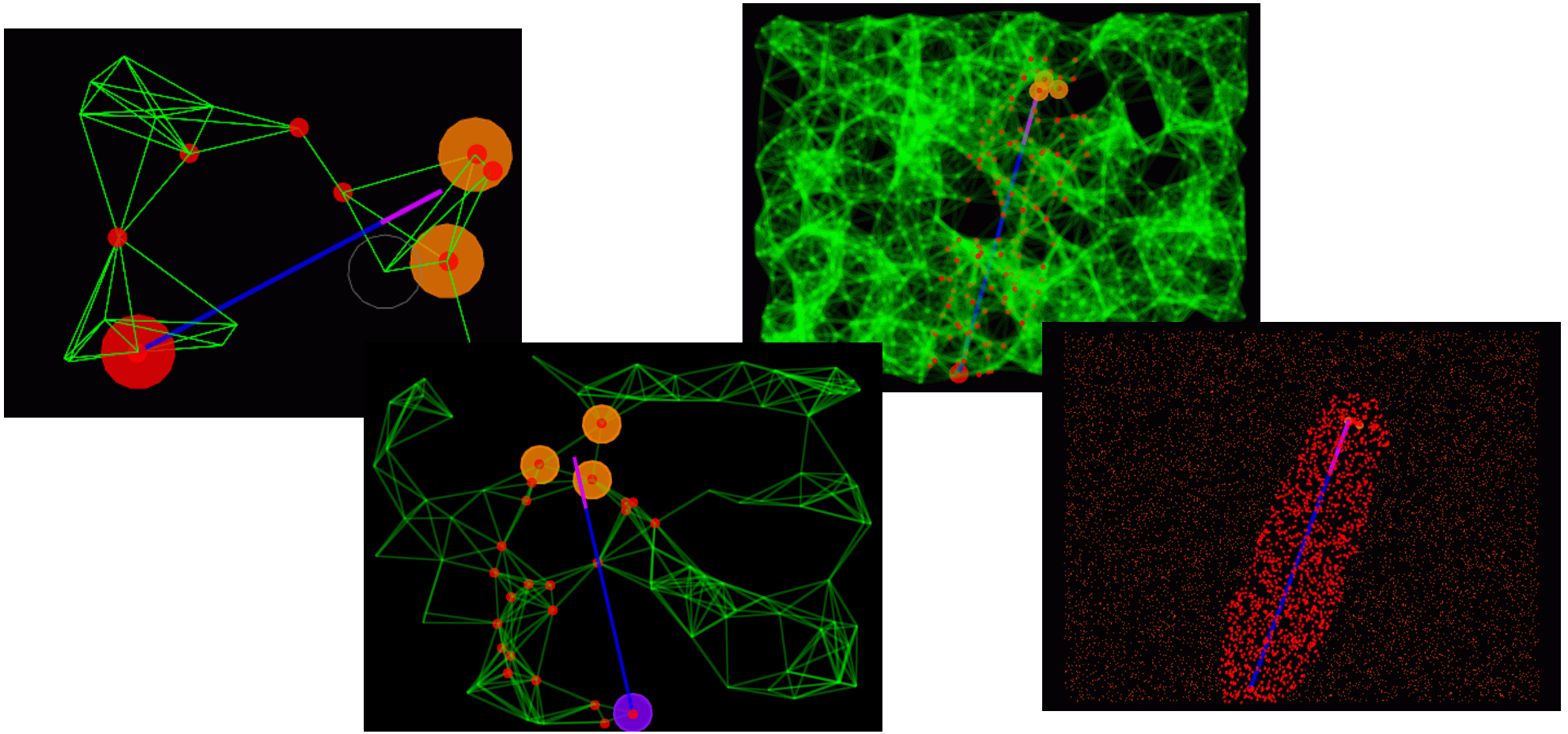
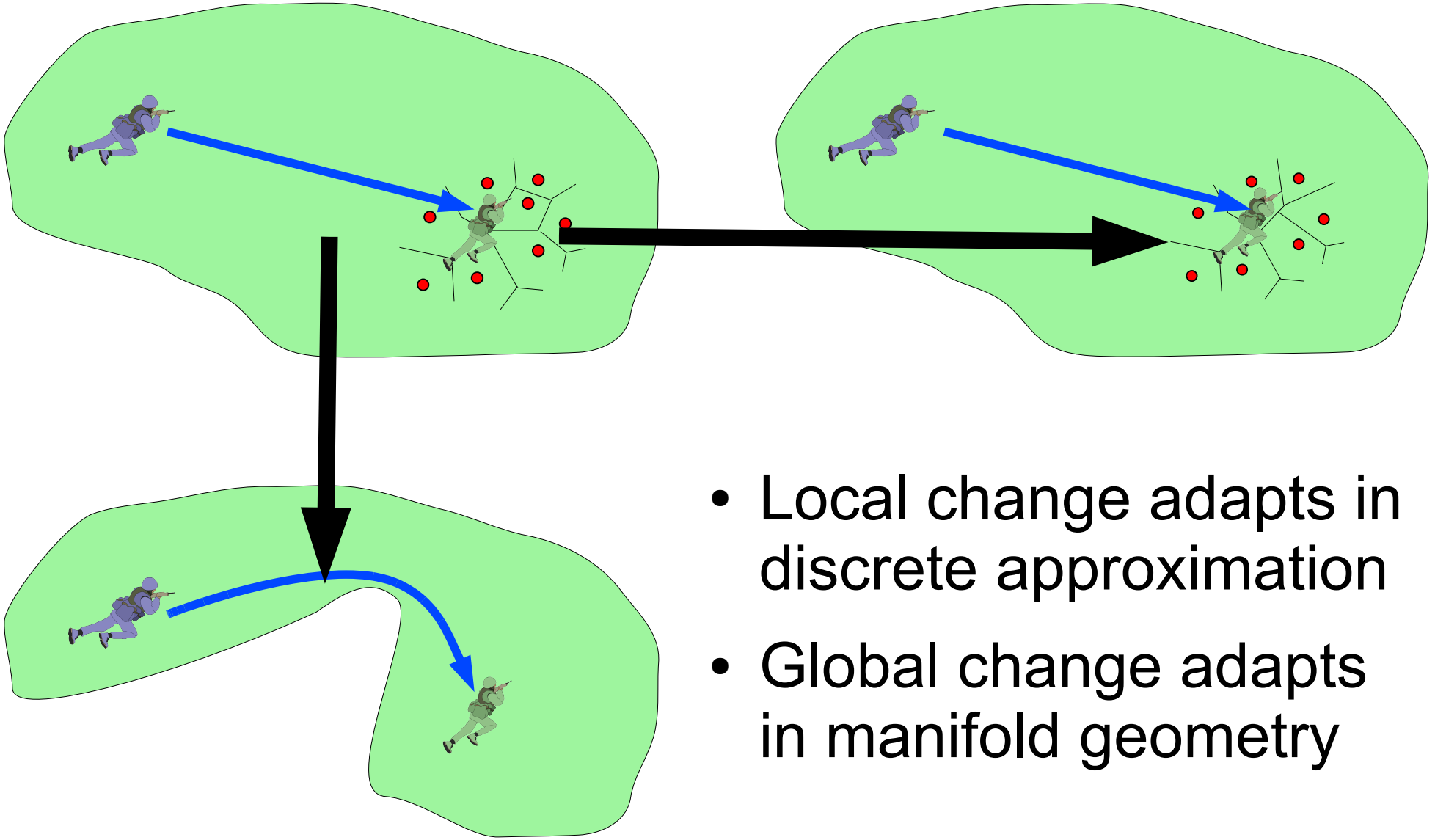
Continuous Programs → Self-Scaling



Target tracking across three orders of magnitude

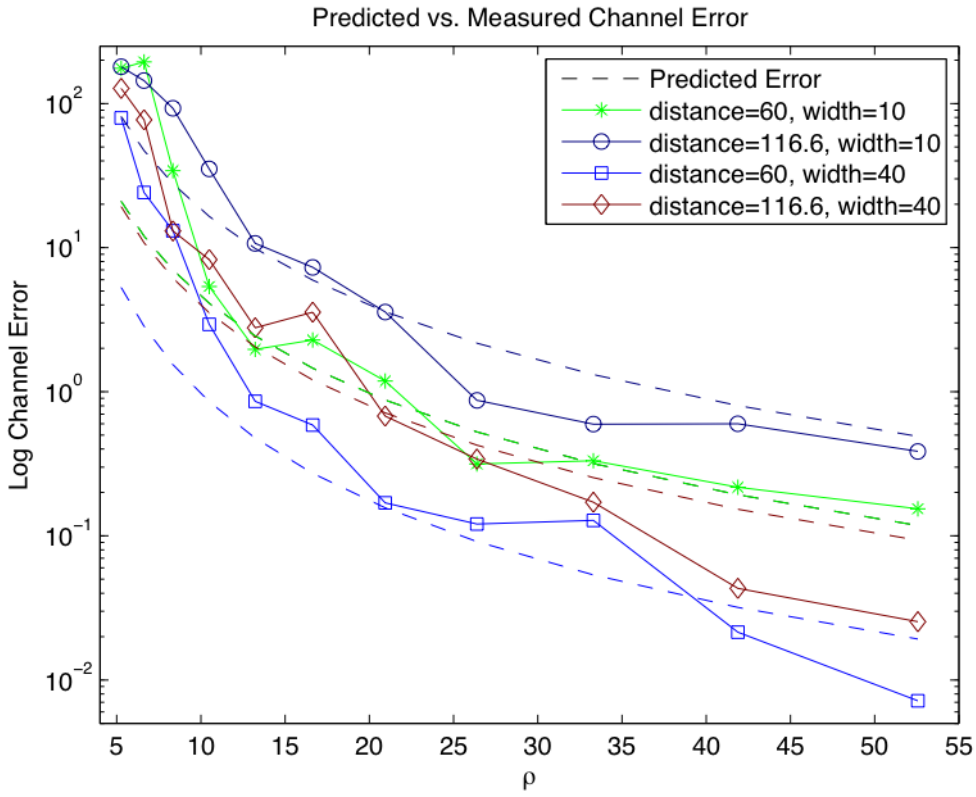
Robustness



- Local change adapts in discrete approximation
- Global change adapts in manifold geometry

Composition

- Purely functional → simpler composition
- Self-stabilizing geometric algorithms can be composed feed-forward
- Approximation error can be predicted



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 simplify the design of distributed algorithms that are scalable, adaptive, and robust.

Open Problems

- What is a method for computing approximation quality, given a primitive approximation model?
- What is a method for determining the critical space/time density for approximation failure?
- Is Proto space/time universal w.r.t. causal, finitely approximable computations?
- What are the lower bound efficiency costs of the continuous space abstraction?

and many more...