A Distributed and Stochastic Algorithmic Framework for Active Matter

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Active Matter

“Condensed matter in a fundamentally new nonequilibrium regime:

- The energy input takes place directly at the scale of each active particle and is thus homogeneously distributed through the bulk of the system, unlike sheared fluids or three-dimensional bulk granular matter, where the forcing is applied at the boundaries.
- Self-propelled motion, unlike sedimentation, is force free: The forces that the particle and fluid exert on each other cancel.
- The direction of self-propelled motion is set by the orientation of the particle itself, not fixed by an external field”

[S. Ramaswamy. The mechanics and statistics of active matter. Annual Review of Condensed Matter Physics, 1(1):323–345, 2010]

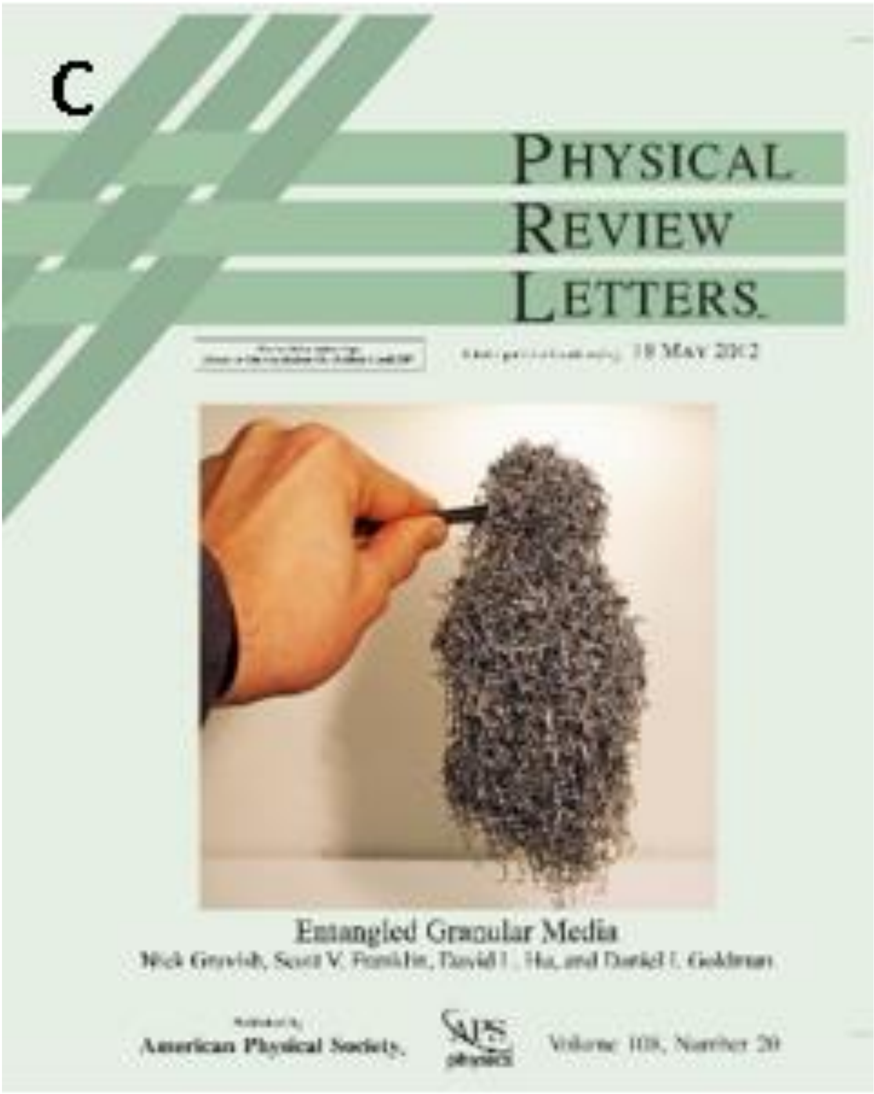
Programmable Active Matter

- Swarm robotics systems of programmable particles (smarticles) with close analogies to physical systems.
  - Smarticles are small in scale, ranging in size from millimeters to centimeters,
  - crowded (i.e., dense) environments
  - behave as active matter

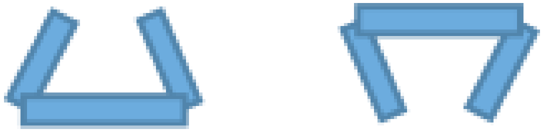
- "task-oriented" approach:
  - start from desired macroscopic emergent collective behavior, and develop the distributed and stochastic algorithmic underpinnings that each robot (smarticle) will run

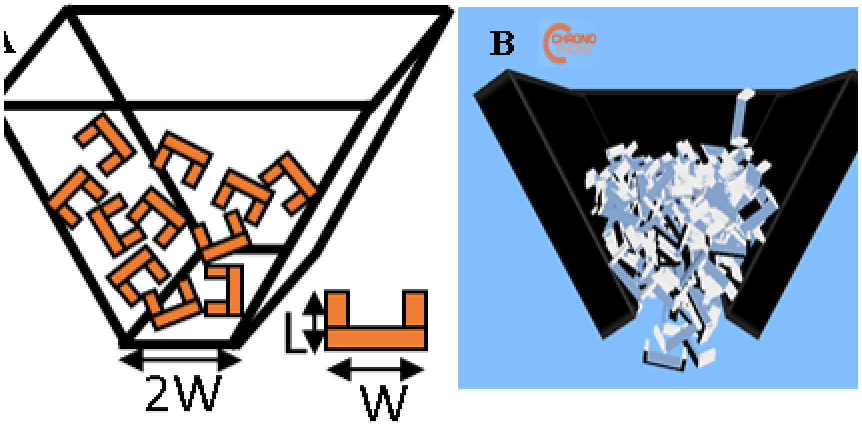
- provide the understanding for yet unexplored collective and emergent systems.

U-shaped Smarticles



Goals: control entanglement or jamming by varying angles of the "U"



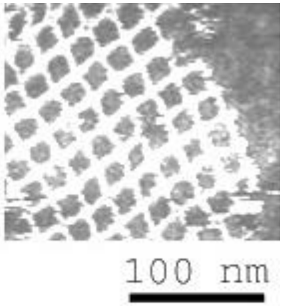


Other Programmable Matter

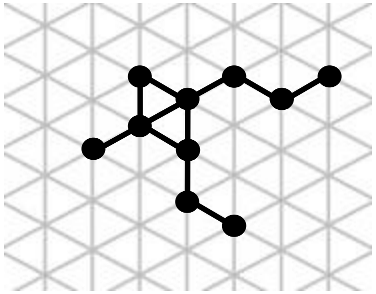
- Modular and swarm robotics
- DNA computing: not self-propelled
- Smart materials

Kilobots:

DNA self-assembly:



- **Self-organizing particle systems:** Collection of simple computational elements that self-organize to solve system-wide problems of movement, configuration, and coordination
  - constant memory
  - fully distributed, local algorithms
  - Amoebot model



[Derakhshandeh, Gmyr, R, Schedeiler, Strothman]

AitF Collaboration: Goals

- Understand minimal computational requirements for certain "tasks"
- Learn to program the ensemble to control emergent collective behavior
- Remove centralized control by having the particles locally respond to their environment
- Provide a **stochastic distributed algorithmic framework** for (programmable) active matter

Collective Behaviors

1. Compression

2. Bridging

3. Alignment

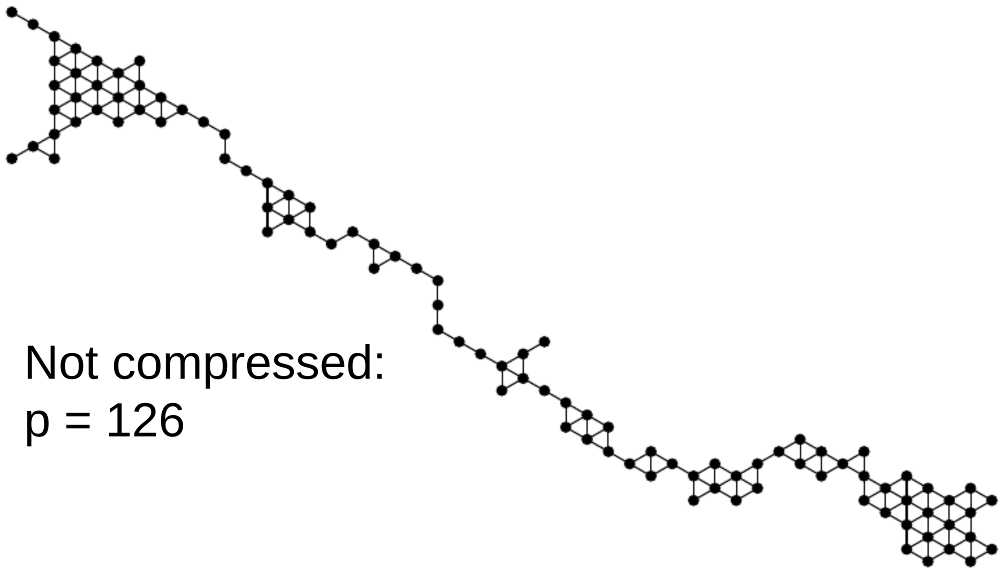
4. Locomotion

Action 1: Compression

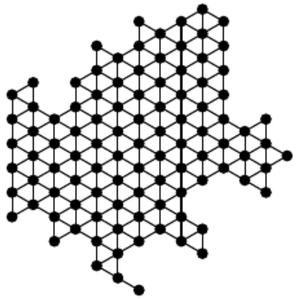
<u>**Q**</u>: Under local, distributed rules, can a connected set of particles "gather" or "compress" to reduce their perimeter?

<u>**Def'n**</u>: A particle configuration is **α-compressed** if its perimeter is at most α times the **minimum perimeter** for these particles.

$$p(\sigma) = 3n - e(\sigma) - 3$$



Not compressed:
p = 126



Compressed:
p = 51

Compression Algorithm

[Cannon, Daymude, Randall, Richa, PODC '16]:

A distributed, stochastic algorithm based on the amoebot model that:

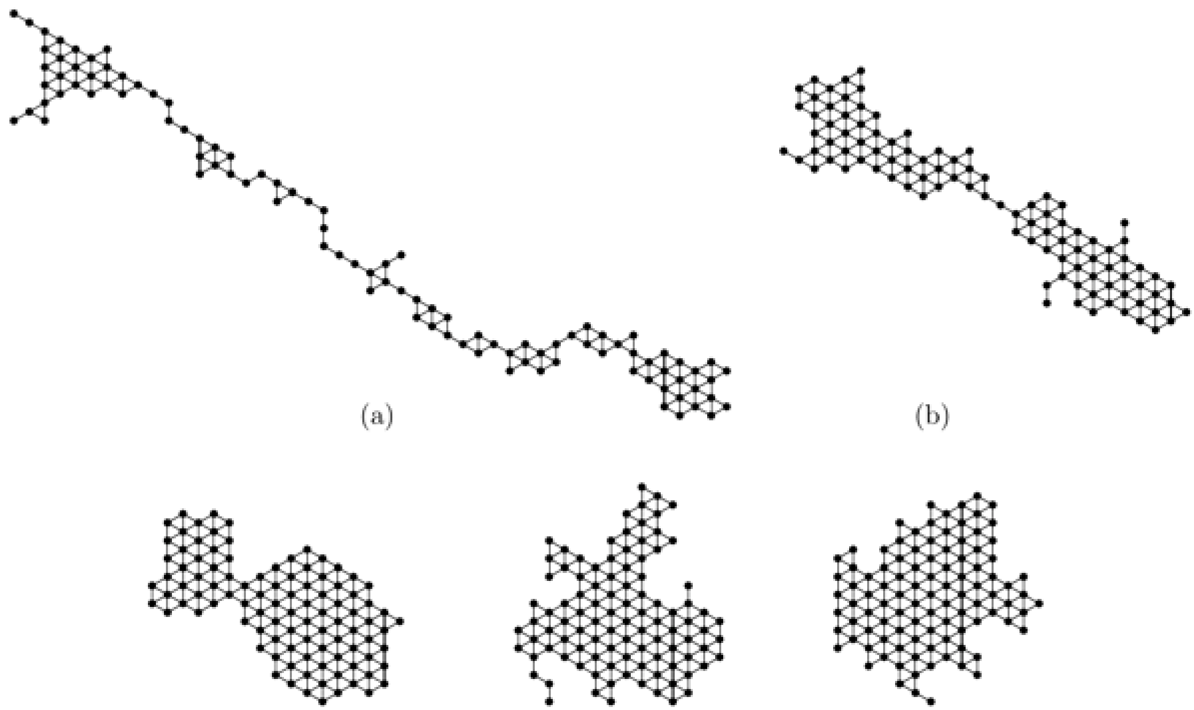
1. Maintains simply connected configurations in the triangular lattice
2. Uses Poisson clocks to find potential moves asynchronously
3. Accepts moves with Metropolis prob. to converge to $\pi(\sigma) = \lambda^{e(\sigma)} / Z$

$\lambda = 4$

100 particles after:

a) 1 million
b) 2 million
c) 3 million
d) 4 million
e) 5 million

iterations.



(a) (b) (c) (d) (e)

Compression Algorithm

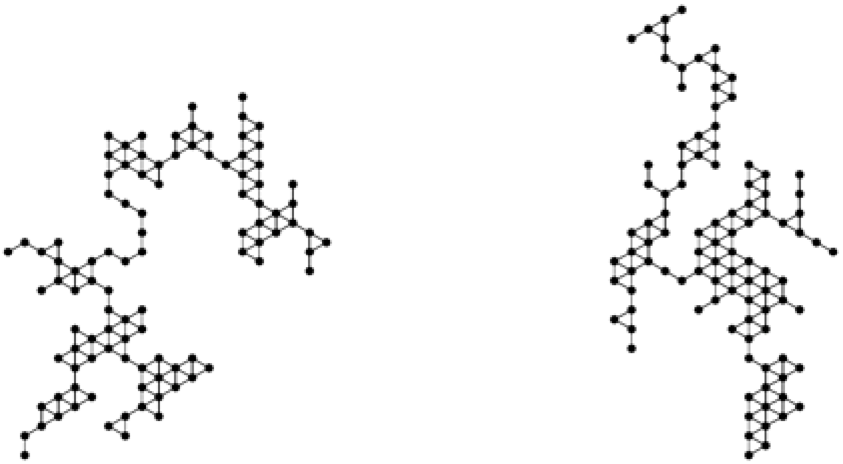
[Cannon, Daymude, Randall, Richa, PODC '16]:

A distributed, stochastic algorithm based on the amoebot model that:

1. Maintains simply connected configurations in the triangular lattice
2. Uses Poisson clocks to find potential moves asynchronously
3. Accepts moves with Metropolis probs to converge to $\pi(\sigma) = \lambda^{e(\sigma)} / Z$

$\lambda = 2$

100 particles after:
a) 10 million
b) 20 million
iterations.



(a) (b)

No compression.

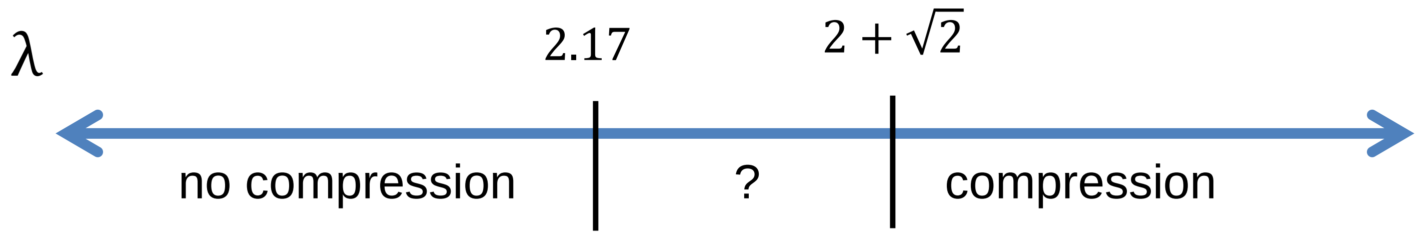
Compression: Theorems

[CDRR'16]

<u>Def'n:</u> A particle configuration is **α-compressed** if its perimeter is at most α times the **minimum perimeter** for these particles.

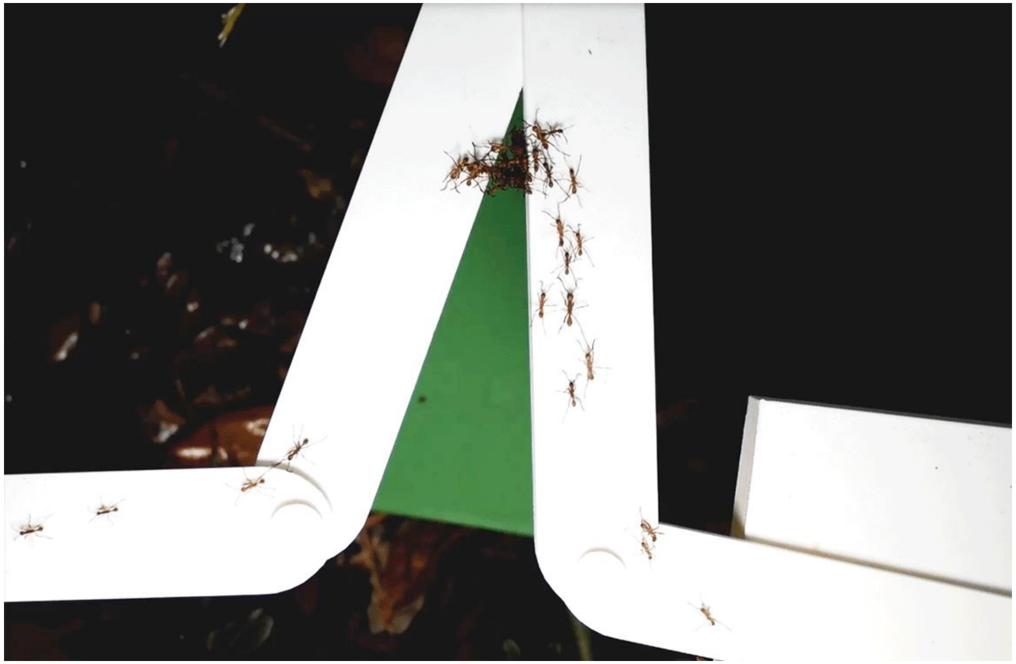
<u>Thm:</u> When $\lambda > 2 + \sqrt{2}$, there exists $\alpha = \alpha(\lambda)$ s.t. particles are α-compressed at stationarity with all but an exp. small probability. (When $\lambda = 4$, $\alpha = 9$.)

<u>Thm:</u> When $\lambda < 2.17$, for *any* $\alpha > 1$, the probability that particles are α-compressed at stationarity is exponentially small.



Note: Expansion works similarly for smaller λ. [CDRR'16]

Action 2: Bridging



[Lutz and Reid '15]

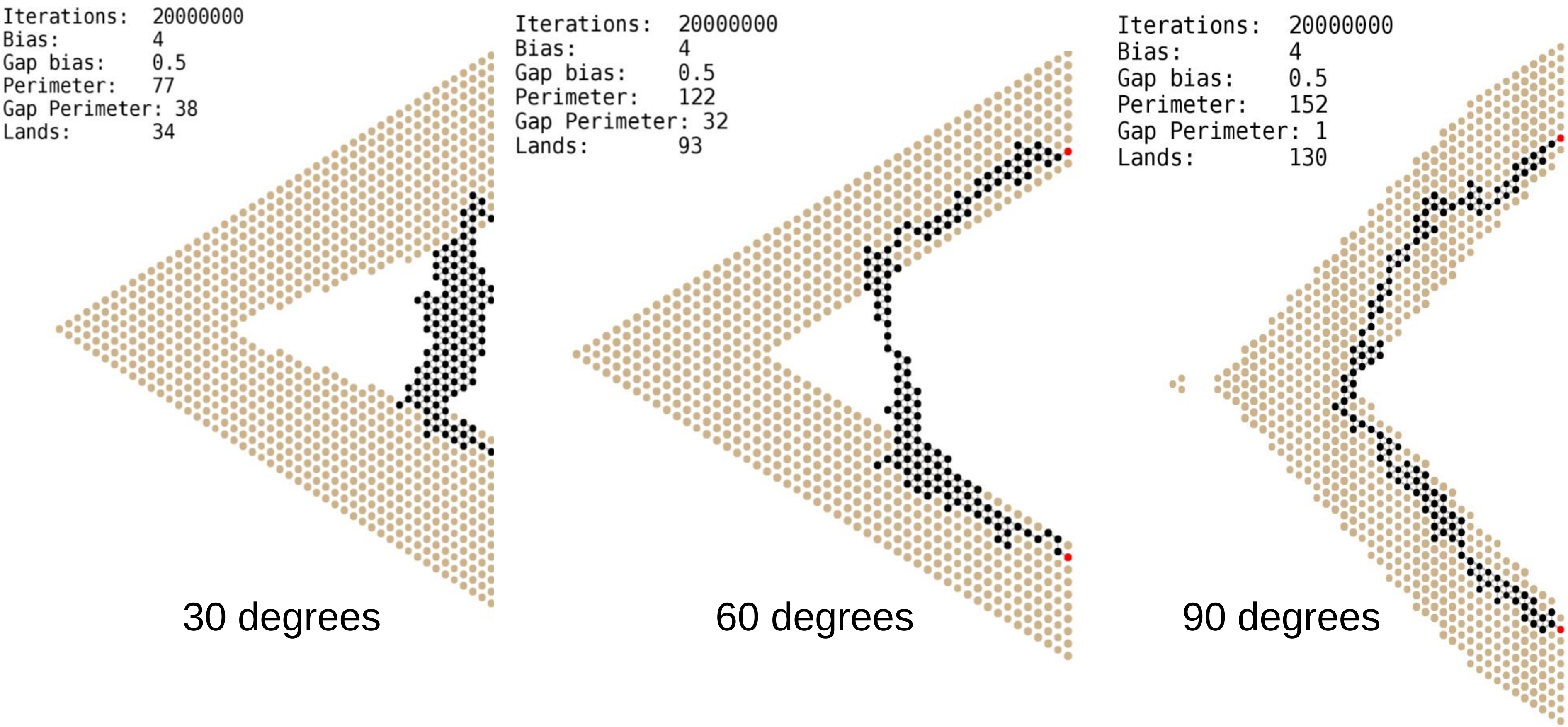
- Army ants construct living bridges to minimize the number of nonworking members of the colony.
- Long bridges are more precarious.

[Arroyo, Cannon, Daymude, Randall, Richa '17]

- Use similar local compression rules favoring neighbors.
- Penalize particles in the gap on the perimeter (for poorer stability).

Bridging

For a fixed angle, the thickness and position of the bridge depends on the clustering and gap parameters:



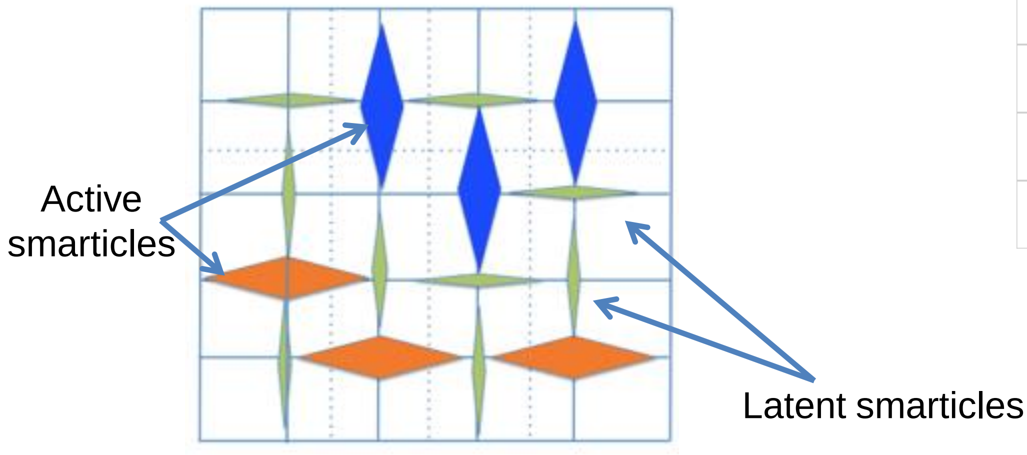
30 degrees

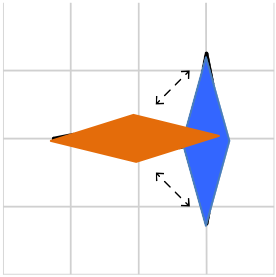
60 degrees

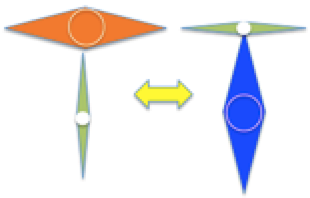
90 degrees

Action 3: Alignment

Smarticles confined to $\mathbf{Z}^2$ that elongate or flatten as they move.





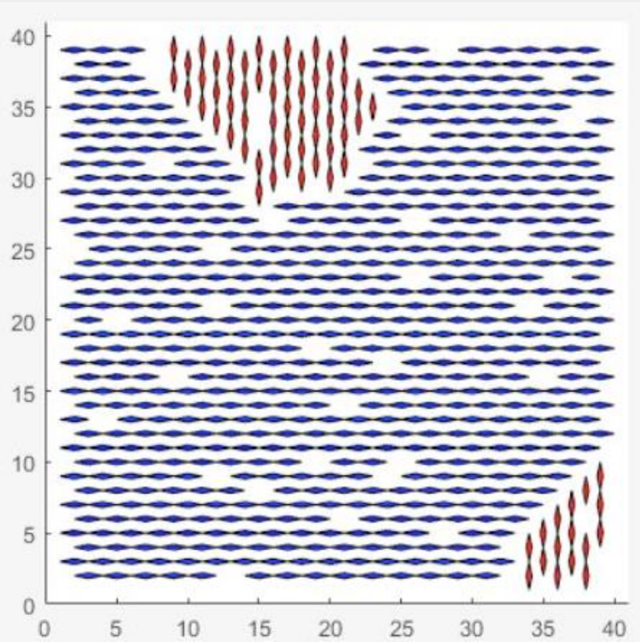


<u>Thm</u>: We get large regions of alignment with mostly vertical or horizontal smarticles.

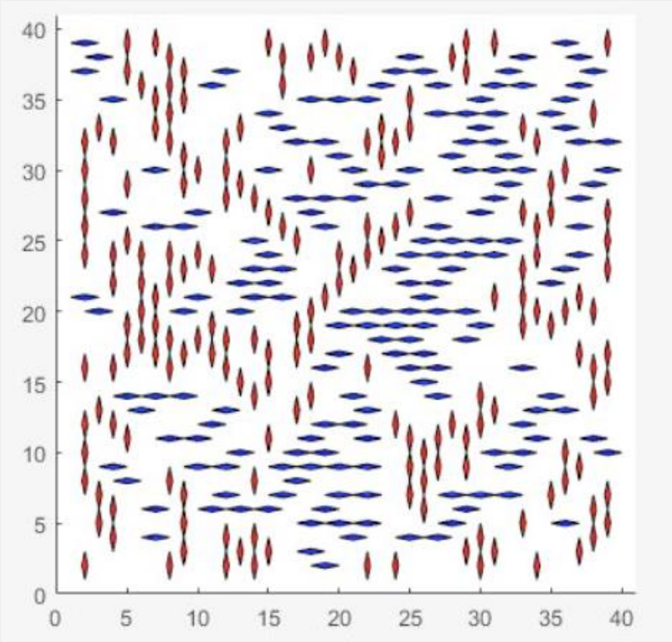
<u>Conj</u>: Also get alignment with limited latent smarticles.

(**Partial proofs*)

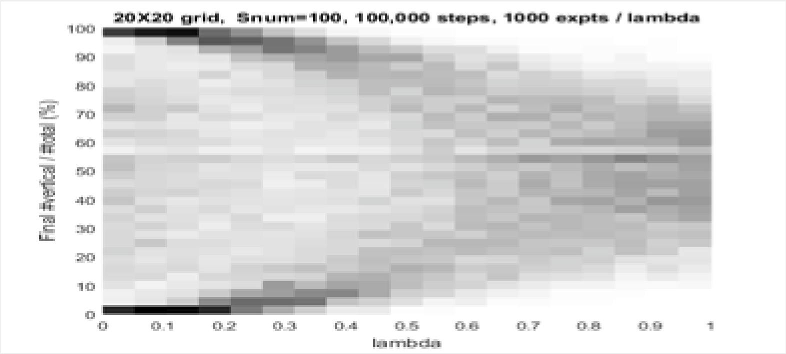
Alignment



Large λ



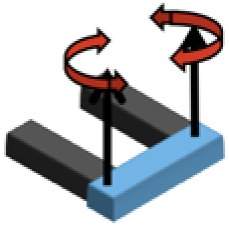
Small λ

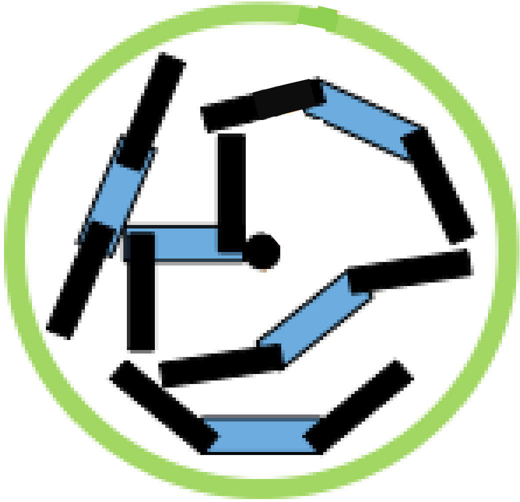


Action 4: Locomotion

[GLS], [CDGLRRS] *(*in progress)*

A robot made of robots





SuperSmarticles

Confine several smarticles in a ring.

- One smarticle: no locomotion
- Allow them to interact through movements: Brownian motion
- Allow interaction, with one inactive smarticle: Brownian motion w/ drift (directed toward inactive smarticle)

Locomotion

Next Steps

1. Composite algorithms that automate transitions in response to the environment.

   Ex. **Foraging**:
   - Use compression around a food source until it's depleted;
   - Transition to expansion when depleted to find a new source;
   - Repeat

2. Build prototypes to refine algorithms (alignment, compression, bridging)
   - New challenges: real space, imperfect interactions, etc.
   - Refines types of interactions between particles.

3. Explore algorithmic foundations underlying:
   - Locomotion
   - "Jamming"
   - Entanglement

Thank you!