Amoeba-inspired Self-organizing Particle Systems

BDA 2013

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Motivation

*"Over the next few decades, two emerging technologies—microfabrication and cellular engineering—will make it possible to assemble systems incorporating myriads of information-processing units at almost no cost [...] but we have few ideas for programming them effectively. The opportunity to exploit these new technologies poses a broad conceptual challenge—the challenge of **amorphous computing**."* [AAC$^+$00]

Our goal: rigorous algorithmic research on self-organizing particle systems

→ First step: appropriate model

Properties

- particles are **physical entities**
- particles have to **stay connected**
- all particles are **programmed identically**
- particles have **local knowledge**
  - no position
  - no orientation
  - only perceive immediate neighborhood
- particles have **modest computational power**
  - finite automata
- **unlimited number** of particles

A New Model

Previous models do not fit

- DNA computing, population protocols, ...
  → **no active movement**
- swarm robotics
  → **no collisions, no connectivity**
- modular robotics, metamorphic robotics
  → **global information, powerful particles (Turing machines)**

Further considerations

- **implementation** should be **feasible**
- allow particles to make **local decisions** and act in a **distributed** fashion
- for now: **2D** and **synchronous rounds**

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Model

Particles

- are placed on a **hexagonal grid**
- assume one of **two shapes**
- assume one of **six orientations**
- are in one of **finitely many states**
- have to stay **connected**

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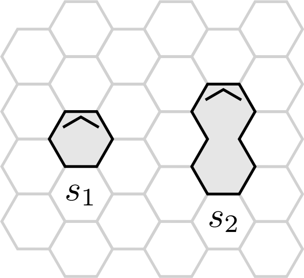

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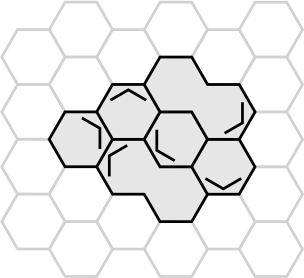

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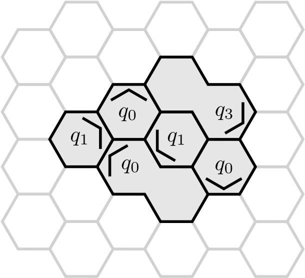

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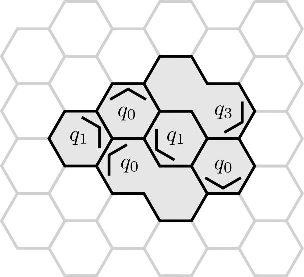

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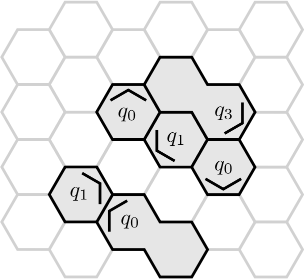

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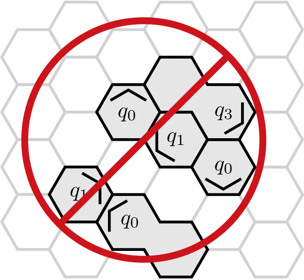

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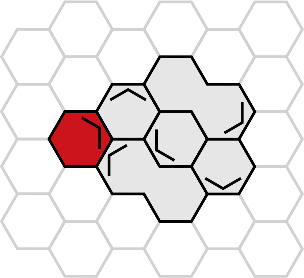

In every round, a particle can **change its state** and execute one of **six actions**

1. **null**
2. turn
3. expand
4. contract
5. duplicate
6. kill

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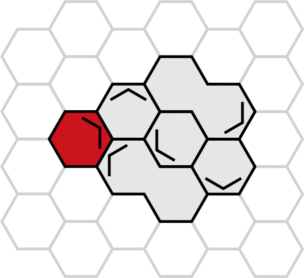

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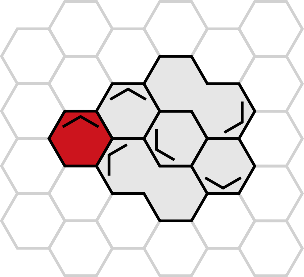

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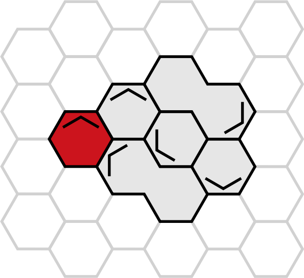

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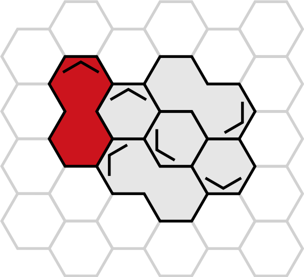

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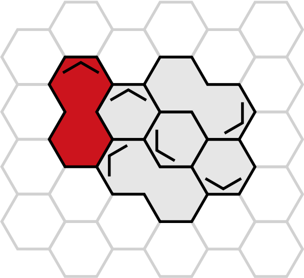

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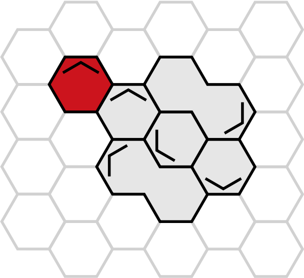

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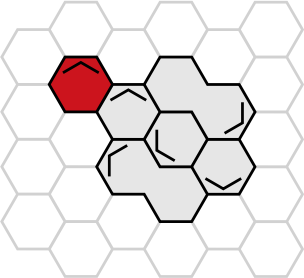

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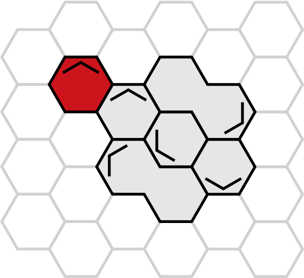

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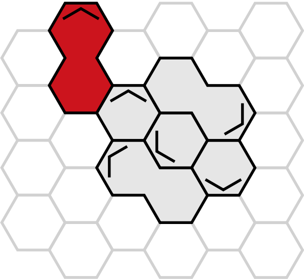

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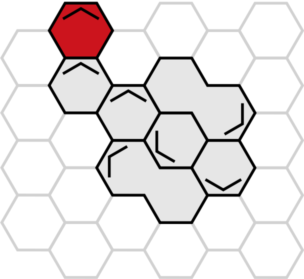

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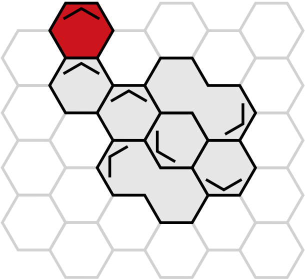

In every round, a particle can **change its state** and execute one of **six actions**

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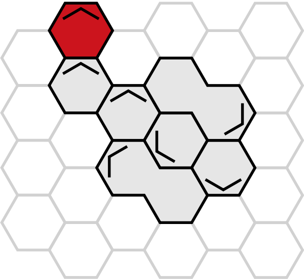

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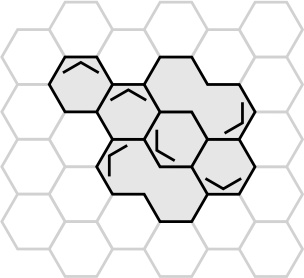

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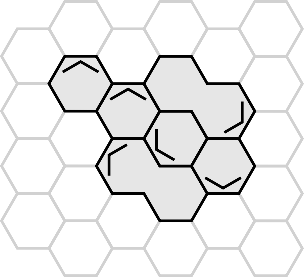

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Amoeboid Movement [AE07]

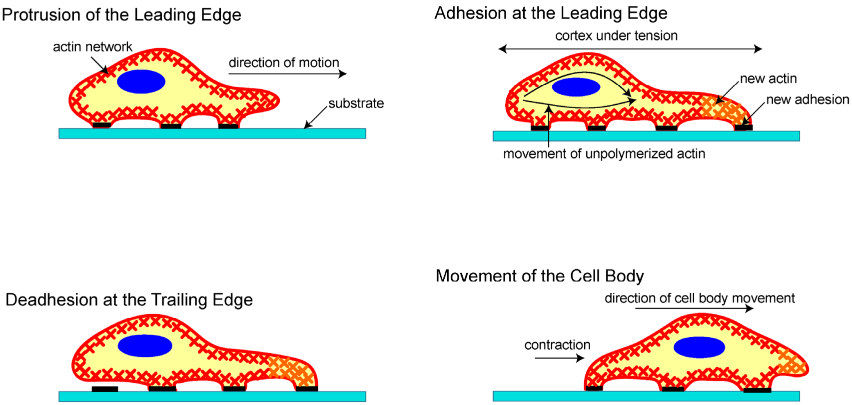

Figure adopted from [AE07].

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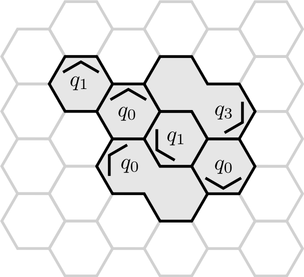

A particle uses

- its own **state** and **shape** and
- the **state**, **shape**, **relative position**, and **relative orientation** of immediate neighbors

to **probabilistically** determine its next state and action.

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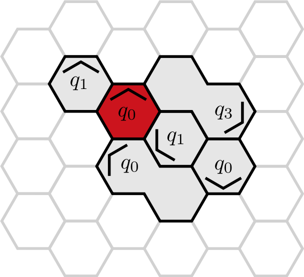

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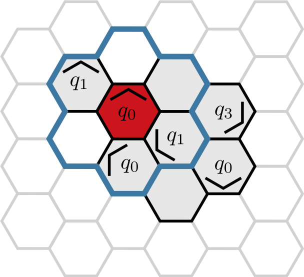

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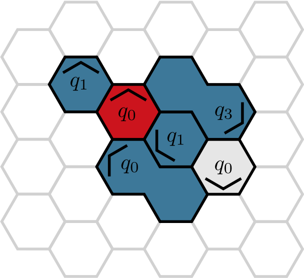

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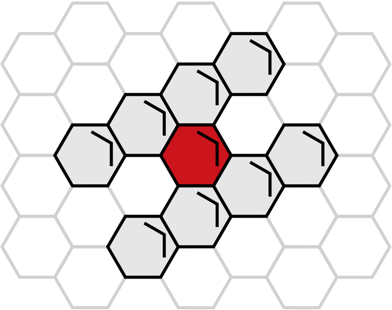

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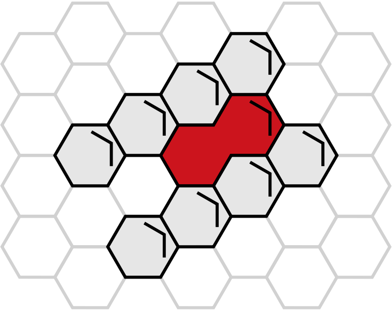

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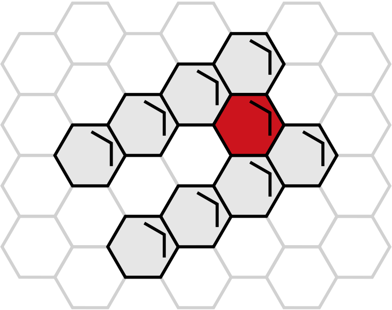

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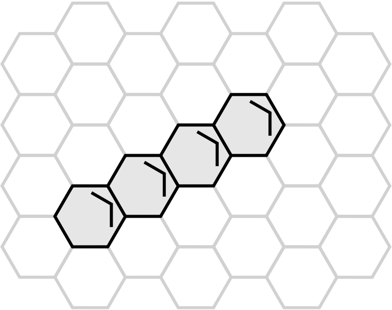

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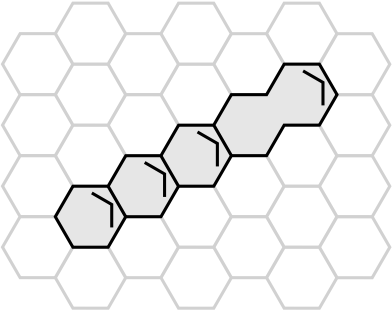

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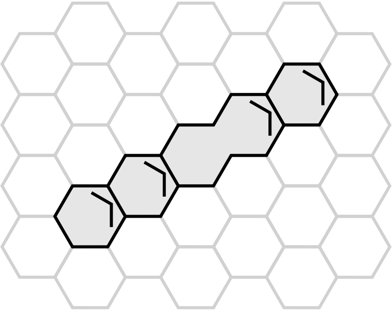

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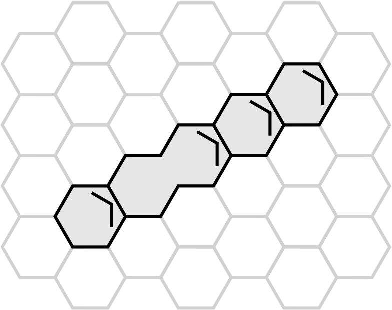

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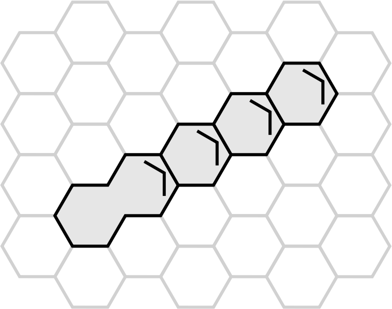

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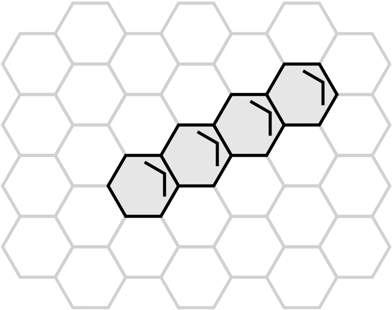

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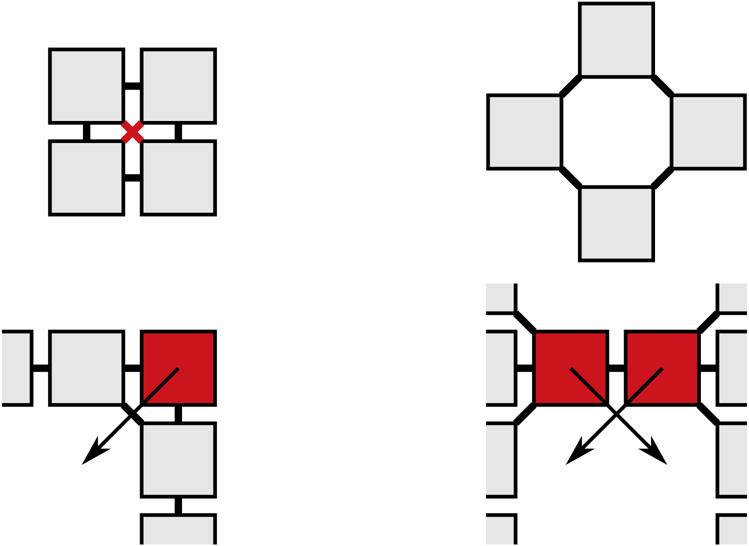
Moore-neighborhood for connectivity



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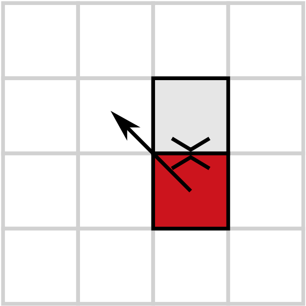

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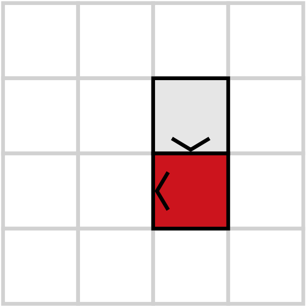

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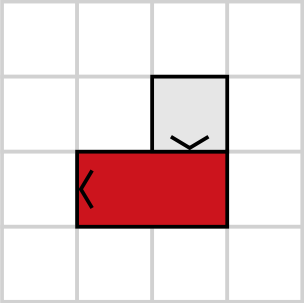

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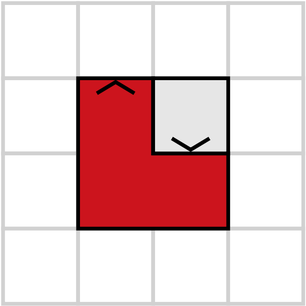

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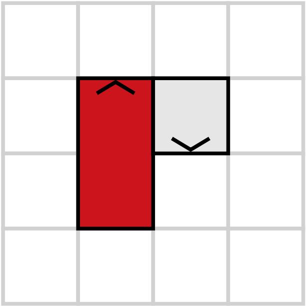

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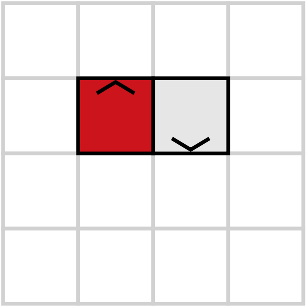

Variants of the Model

- asynchronous
- 3D
- no duplicate and kill action
- action to kill other particles
- failing or byzantine particles
- self-stabilization
- less information from neighbors
- morphogen gradients

Research Problems

”Simple” problems

- covering problems
- shape formation problems
- bridging problems

More involved problems

- macrophage problem

Bibliography

[AAC+00] H. Abelson, D. Allen, D. Coore, C. Hanson, G. Homsy, T. F. Knight, R. Nagpal, E. Rauch, G. J. Sussman, and R. Weiss.
Amorphous computing.
Communications of the ACM, 43(5):74–82, 2000.

[AE07] R. Ananthakrishnan and A. Ehrlicher.
The forces behind cell movement.
International Journal of Biological Sciences, 3(5):303–317, 2007.