Cellular Automata Models of Traffic on Ant Trails

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Introduction

Organized traffic not only in human systems !!

- different forms of traffic in other biological systems
- similarities and differences to human traffic?
- optimized by evolution

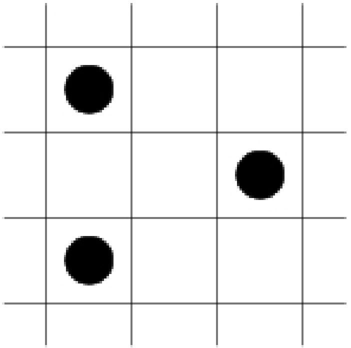
biology: "collective intelligence"

interactions between units of low intelligence can create behaviour that appears to be "intelligent"

physics:
- general aspects (non-equilibrium!)
- collective phenomena

Asymmetric
Simple
Exclusion
Process

Cellular Automata



Cellular automata (CA) are discrete in

- space
- time
- state variable   (e.g. occupancy, velocity)

Advantage:

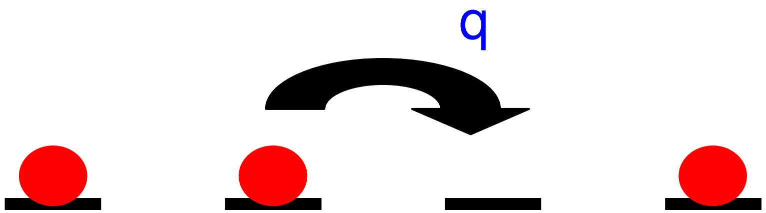
- dynamics in form of intuitive “rules”
- efficient implementation for large-scale computer simulations

often: stochastic dynamics

Asymmetric Simple Exclusion Process

Caricature of traffic:

Asymmetric Simple Exclusion Process (ASEP):



1. directed motion
2. exclusion (1 particle per site)
3. stochastic dynamics

For applications: different modifications necessary

ASEP

ASEP = “Ising” model of nonequilibrium physics

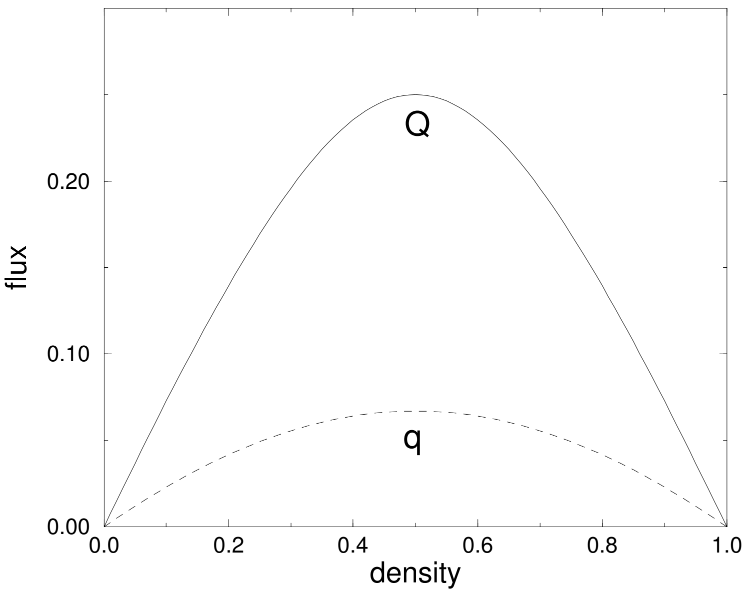
- simple
- exactly solvable
- many applications

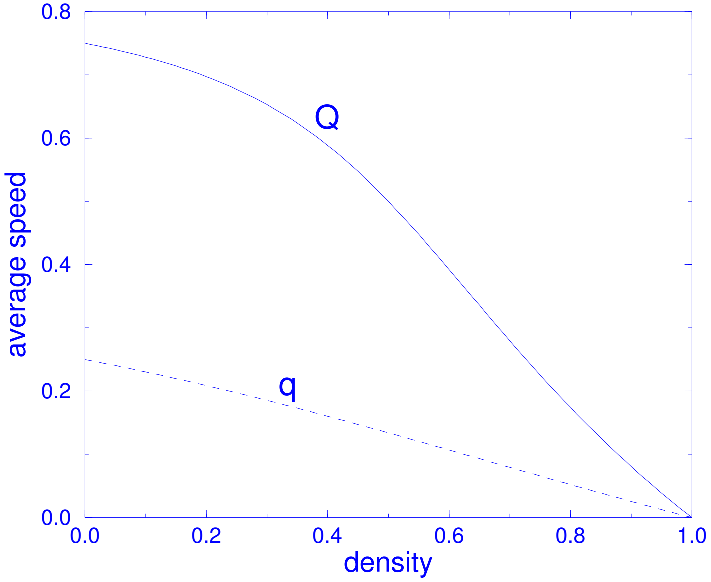
Applications:

- Protein synthesis
- Surface growth
- Traffic
- Boundary induced phase transitions

Periodic boundary conditions

fundamental diagram

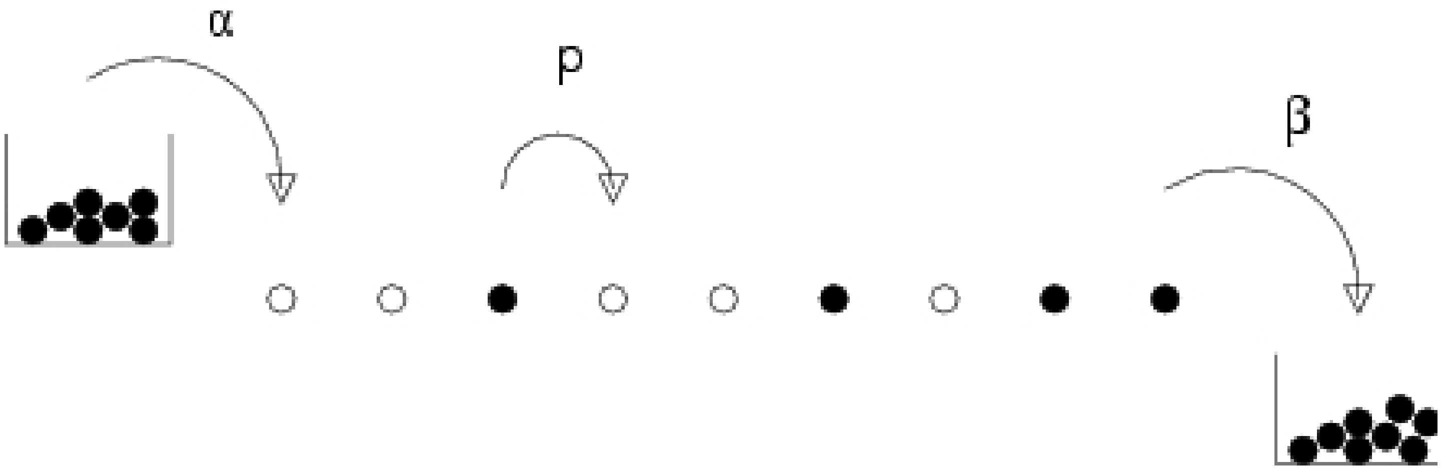




no or short-range correlations

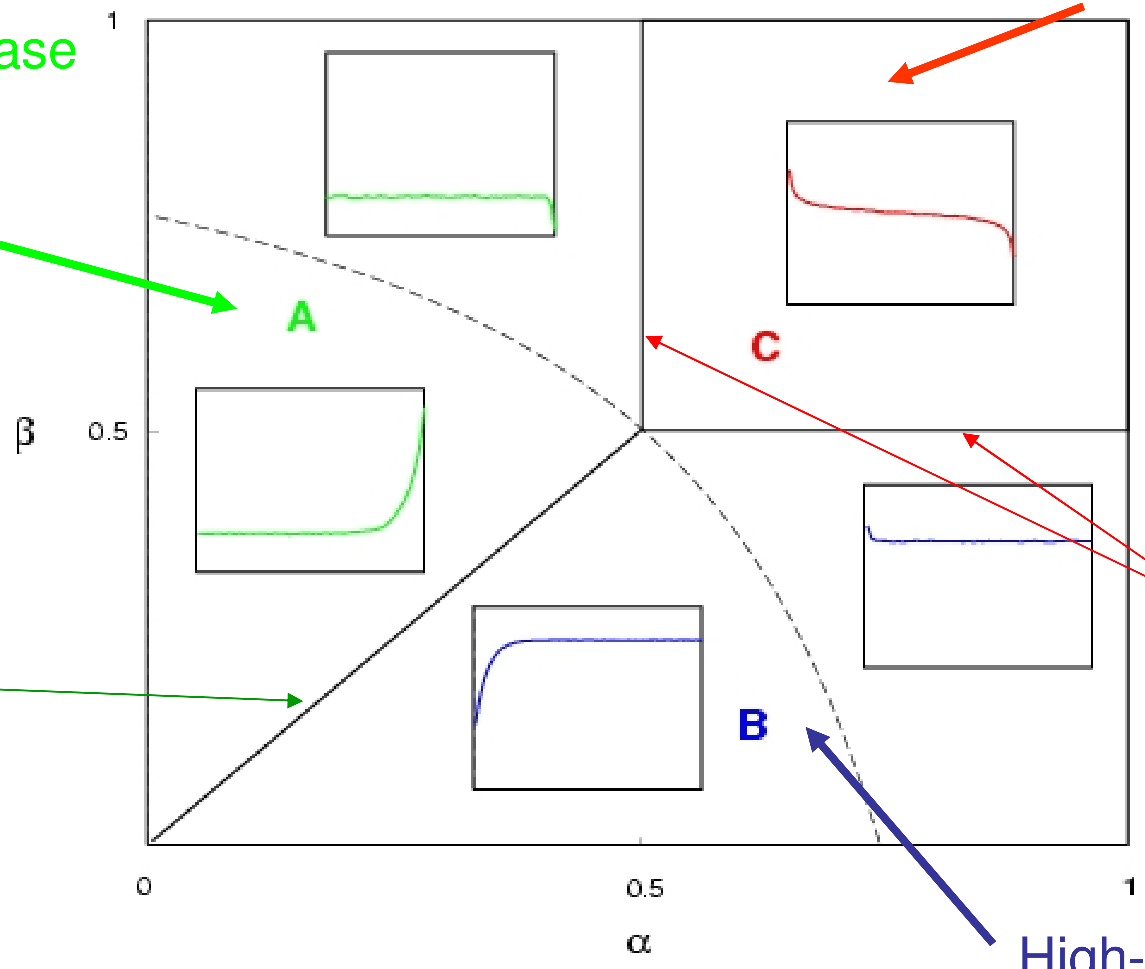
Influence of Boundary Conditions

open boundaries: density not conserved!



exactly solvable for all parameter values!

Phase Diagram



Low-density phase

$J=J(p,\alpha)$

Maximal current phase

$J=J(p)$

1.order transition

2.order transitions

High-density phase

$J=J(p,\beta)$

Dynamics on
Ant Trails

Ant Trails

ants build “road” networks: trail system

Chemotaxis

Ants can communicate on a chemical basis:

chemotaxis

Ants create a chemical trace of pheromones

trace can be “smelled” by other ants
follow trace to food source etc.

Chemotaxis

chemical trace: pheromones

Ant Trail Model

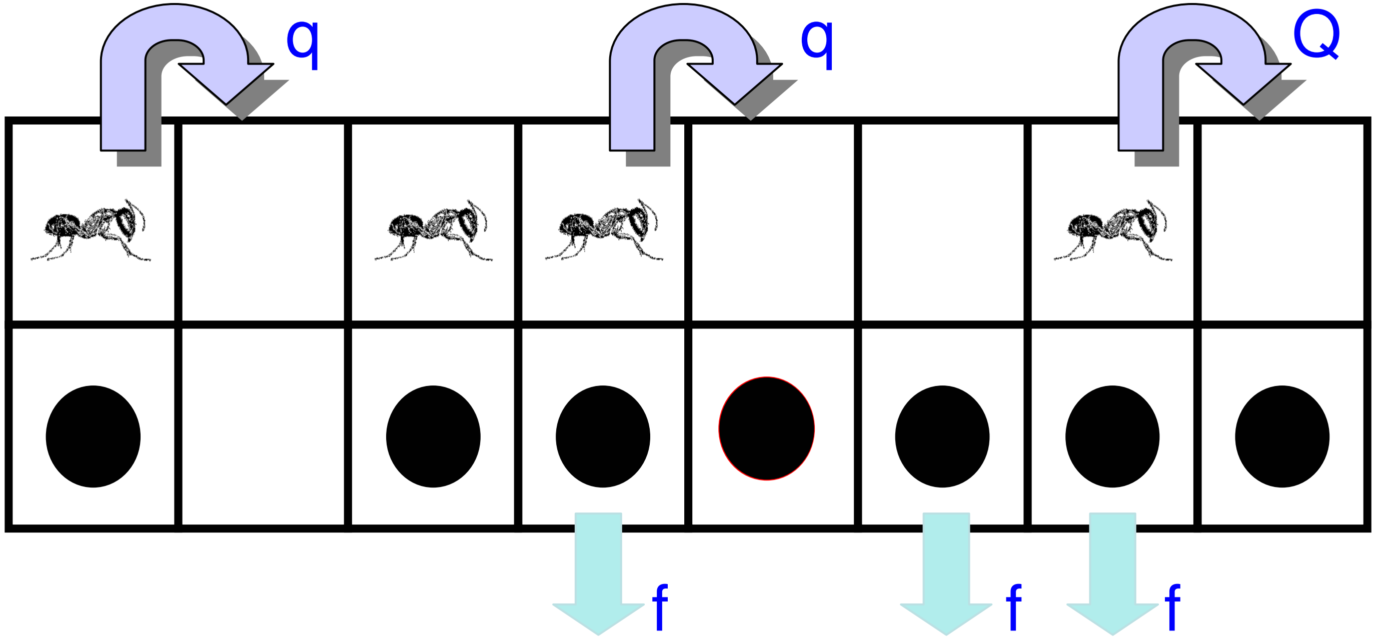
Basic ant trail model: ASEP + pheromone dynamics

- ants create pheromones
- hopping probability depends on density of pheromones
- distinguish only presence/absence of pheromones
- ‘free’ pheromones evaporate

Ant Trail Model

Dynamics:

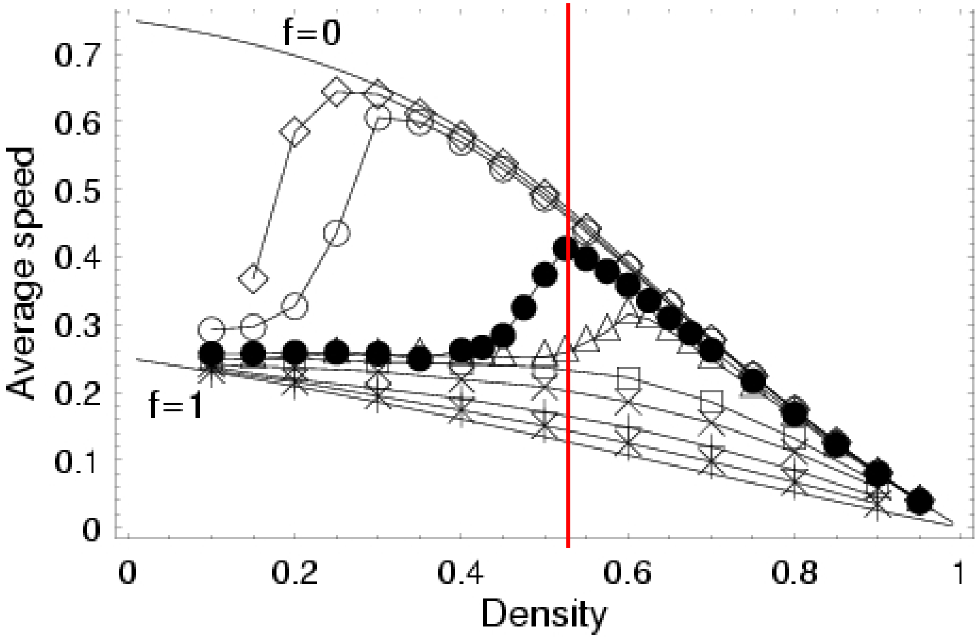
1. motion of ants
2. pheromone update (creation + evaporation)



parameters: $q < Q$, f

Fundamental diagram of ant trails

velocity vs. density



non-monotonicity
at small
evaporation rates!!

Experiments:

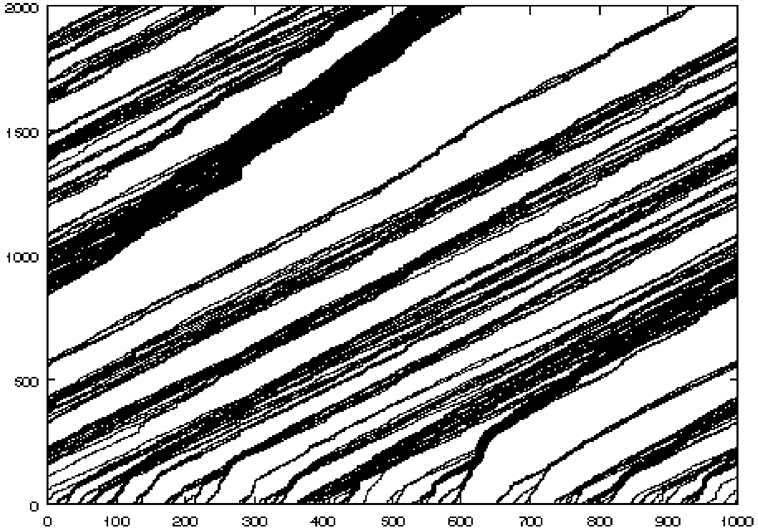
Burd et al. (2002, 2005)

John et al. (2006)

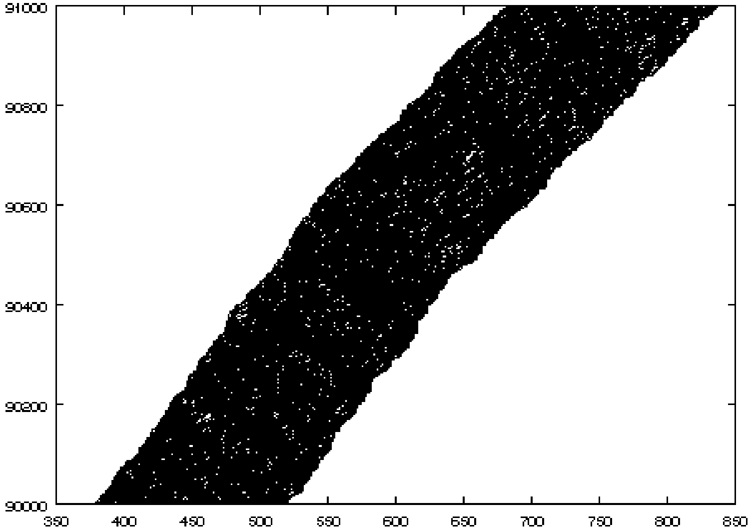
different from highway traffic: no egoism

Spatio-Temporal Organization

dynamical disorder: formation of “loose clusters”



early times



steady state

coarsening dynamics:

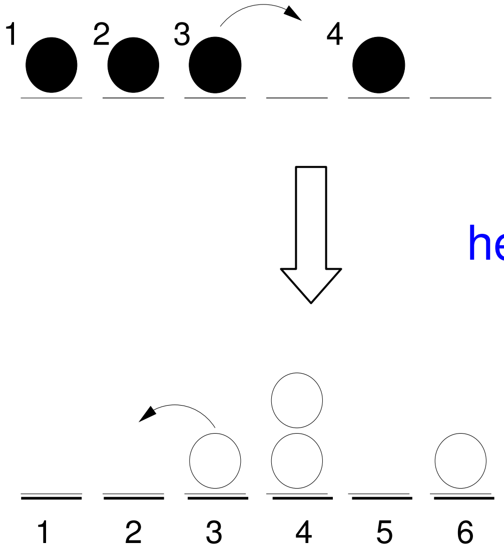
cluster velocity ~ gap to preceding cluster

Traffic on Ant Trails

Formation of clusters

Mapping on Zero-Range Process

ASEP-type model



headway of particle j ⟹ # particles at site j

zero-range process

Zero-range process:

hopping rate from site j to site k
depends only on state at site j

Mapping on Zero-Range Process

Approximation: hopping rates depend only on headway

$$\boxed{p(T) = q + (Q - q)(1 - f)^T}$$

(T=time since pheromone has been created)

$$T = \frac{d}{v}$$

(d=distance headway, v=velocity)

→ in equivalent ZRP: hopping rate p(n) (n=d)

requires self-consistent determination of velocity v

Mapping on Zero-Range Process

Zero-range process exactly solvable !
$\Longrightarrow$ product measure (mean-field exact)

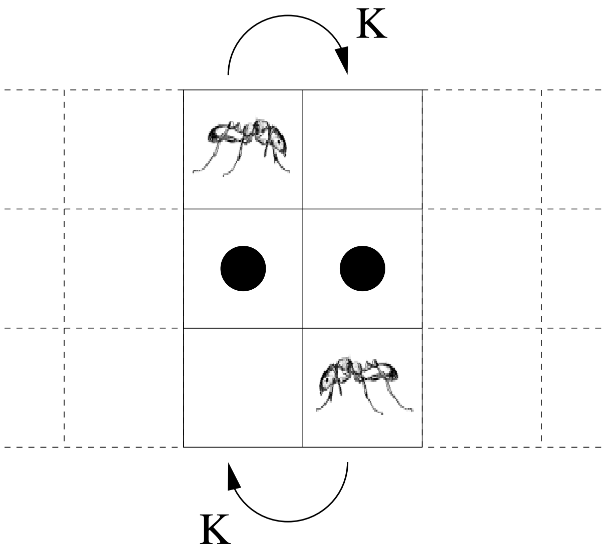
good agreement for fundamental diagrams!

Phase transition ??

only in limit $f \rightarrow 0$ (does not commute with limit $L \rightarrow \infty$)

Counterflow

model: 2 separate lanes with common pheromone trail

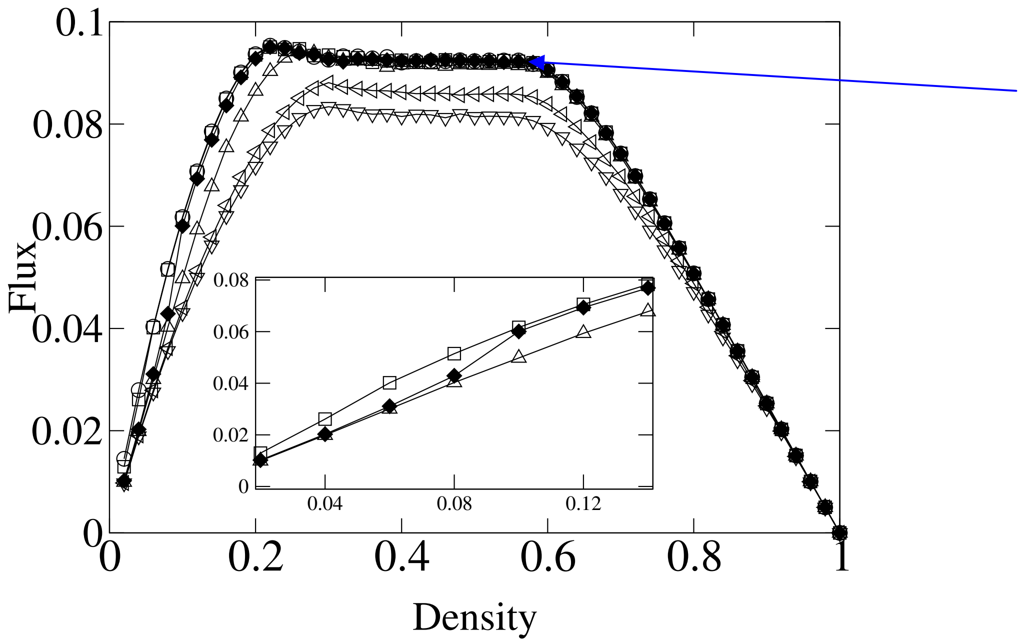


hindrance effect through interactions

(e.g. for communication)

$K < Q$

Counterflow



biological function:

stable flow guarantees continuous supply with food etc.

localized clusters are formed !

Ant Trails – Empirical Results

Field Studies: Setup

Data Collection

- stable trail with single-lane traffic (uni- or bidirectional)

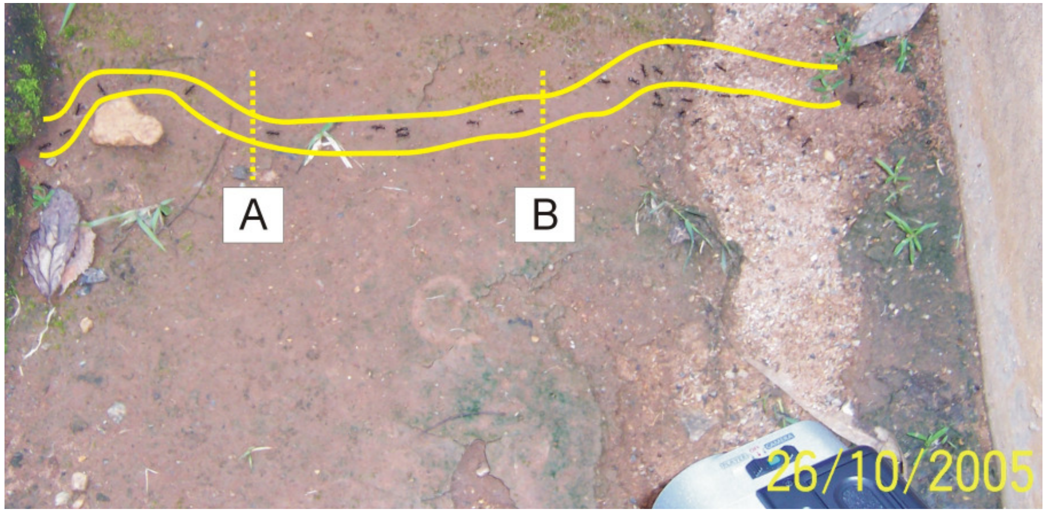
- suitable climate (excluding heavy rainfall or very high temperatures)

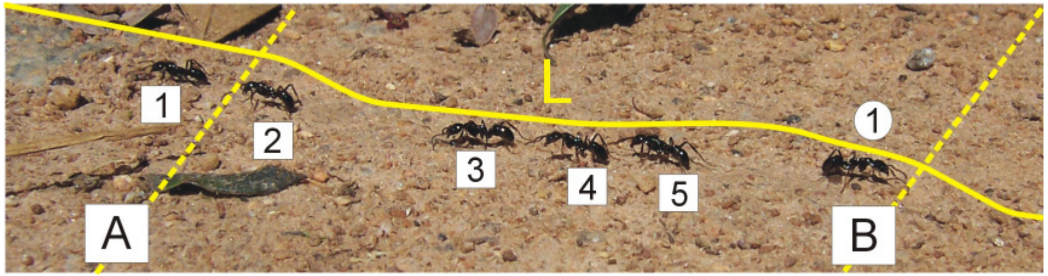
Try to find simple situations excluding additional effects

- observe the bulk of the trail (neglect boundary effects)

- avoid intersections or branching (conservation of particles)

- preferably no obstacles like stones or leaves (translational invariant trail)

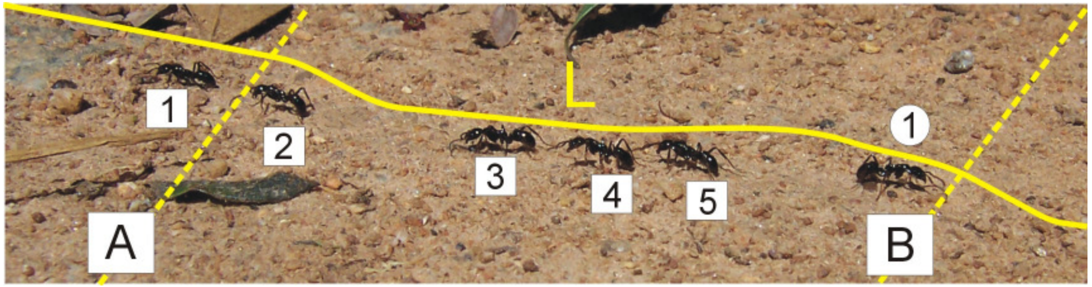




(A. John, Dissertation 2007)

Field Studies: Basic Quantities

- basic quantities are extracted from cumulative counting (t(n),n)
- based on the assumption:
  n-th ant in is also the n-th ant out



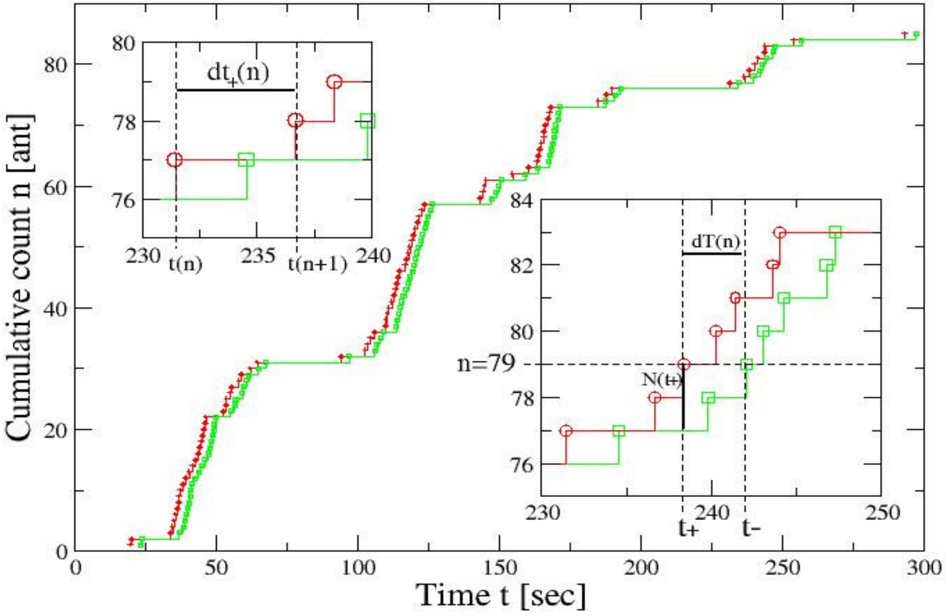
Travel Time and single-ant velocity:

$$dT(n) = t_-(n) - t_+(n)$$

$$v(n) = \frac{L}{dT(n)} = \frac{L}{t_-(n) - t_+(n)}$$

Instantaneous particle number:

$$N(t) = n_+(t) - n_-(t)$$



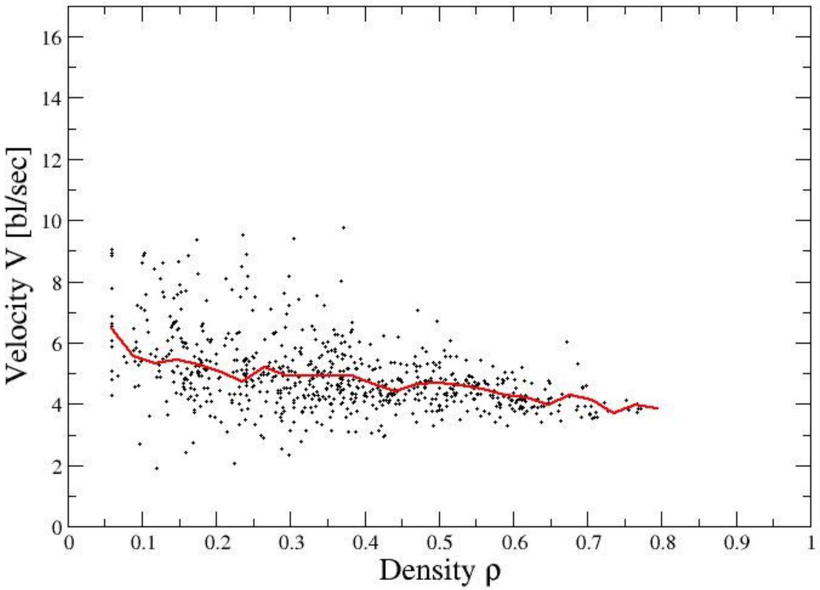
Field Studies: Empirical Results

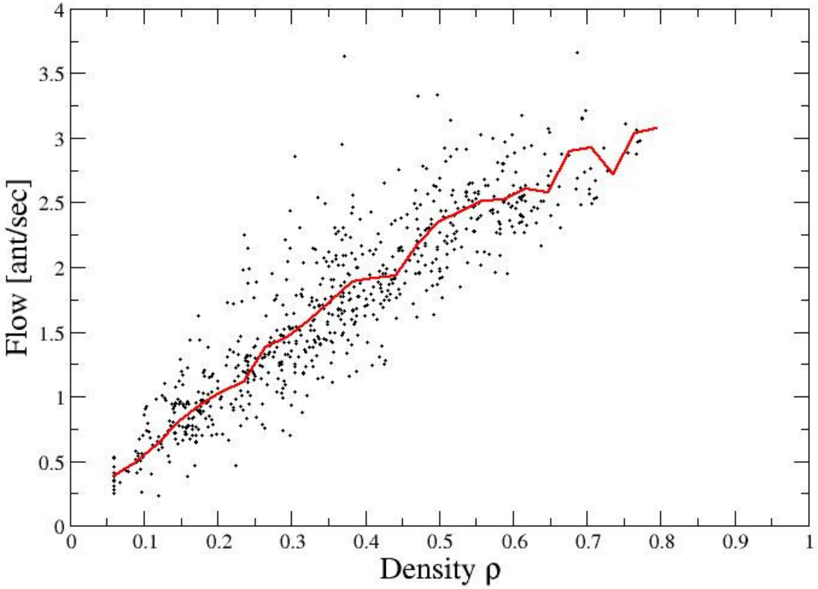
Fundamental Diagrams

- no overtaking
- average velocity shows only weak density dependence
- slight decrease of average velocity leading to non-linear increase of flow

Main Observation:

- mutual blocking seems to be suppressed (no congested state)





Field Studies: Empirical Results

Distance-Headway Distribution

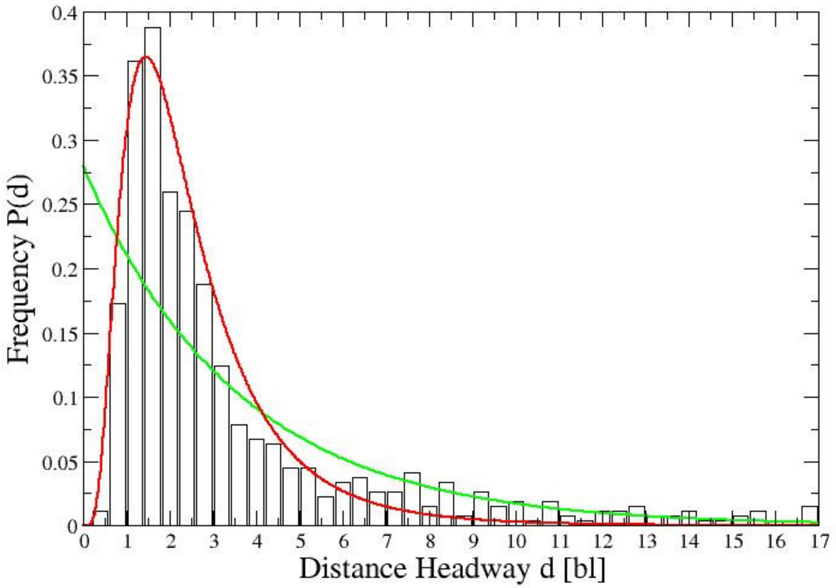
- characterizes the spatial distribution of ants on the trail
- two regimes can be distinguished

1. **Intra-Platoon (log-normal)**

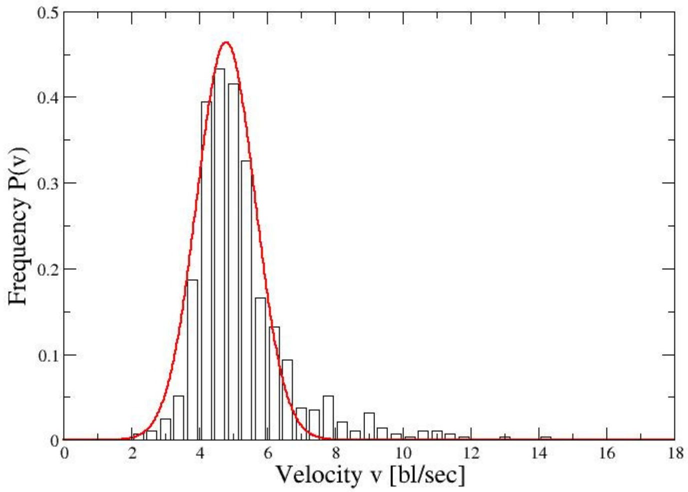
$$P(d) = \frac{1}{d\sigma_L\sqrt{2\pi}} \exp\left(-\frac{(\mu_L - \log(d))^2}{2\sigma_L^2}\right)$$

2. **Inter-Platoon (random-headways)**

$$P(d) = \frac{1}{\lambda} \exp\left(-\frac{d}{\lambda}\right)$$



Field Studies: Empirical Results

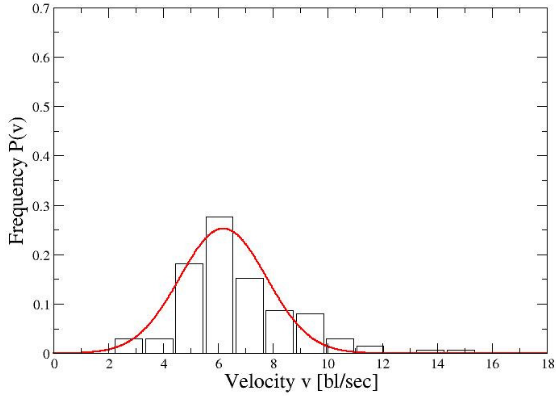


Velocity Distribution

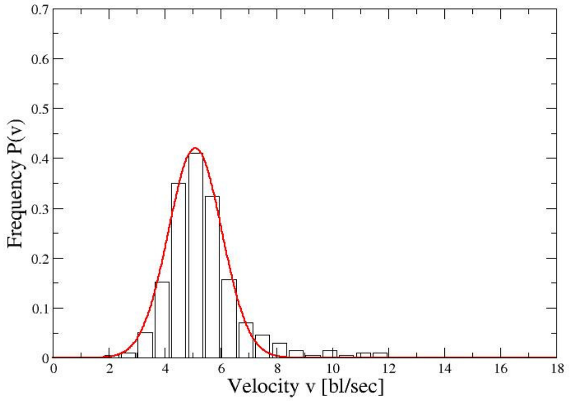
- Gaussian distribution with slight asymmetry

$$P(v) = \frac{1}{\sigma\sqrt{2\pi}} \exp\left(-\frac{(v(n) - V)^2}{2\sigma^2} \right)$$

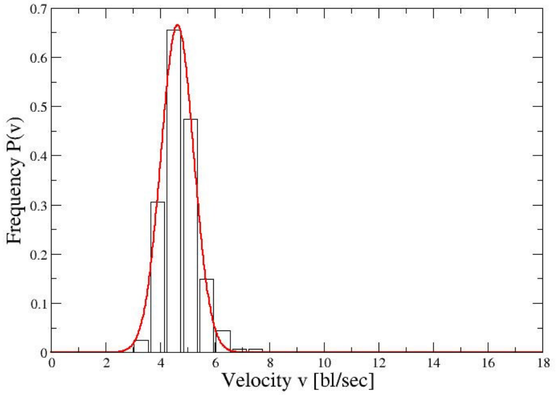
Density Dependent Distributions:



ρ∈[0 , 0.2]



ρ∈[0.2 , 0.4]



ρ∈[0.4 , 0.8]

Summary

- Ant form trail system through chemotaxis
- Chemotaxis also influences dynamics on existing trails
- model based on extended ASEP
- induces tendency of clustering
- fundamental diagram shows non-monotonic behaviour
- empirical studies:
  - clustering
  - velocity density-independent
  - narrow velocity distribution
- Pedestrian dynamics (virtual chemotaxis)

Collaborators

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