



# Modelling the Division of Labor: A Spiking Neuron Net Approach

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TAO

Joint work with Sylvain Chevallier, H el ene Paugam-Moisy

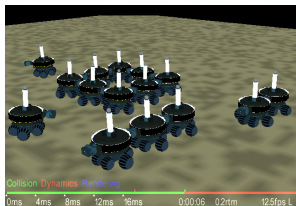


SocPAR 2010





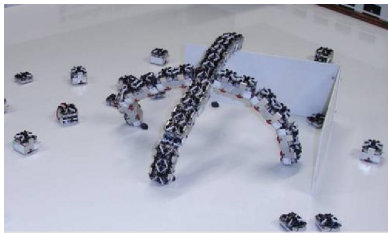
# Framework: Swarm Robotics



Swarm-bot (2001-2005)



Swarm Foraging, UWE



Symbion IP, 2008-2013; <http://symbion.org/>



# Swarm Robotics: Why and What

## WHAT

- ▶ Simple agents  
simple micro-motives for macro-behaviors
- ▶ No pacemakers  
decentralized, distributed, randomized systems
- ▶ More is different

## An alternative to complex robots

- ▶ Inexpensive → Many → Reliable
- ▶ The “invisible hand”  
(*Hayek's inheritance ?*)





# Swarms: HOW

## Principles

Local information  $I_\ell$   $\rightarrow$  estimates global quantities  $I$

Local information  $\rightarrow$  individual behaviour  $b(I_\ell)$

Aggregate  $b(I_\ell)$   $=$  Behaviour[ $I$ ]

## Examples

- ▶ Sounds & clusters of birds and frogs;
- ▶ Bees & air-conditioning of the hive

Melhuish 99

Auman 08



# Swarms: HOW

## Principles

- Local information  $l_\ell$  → estimates global quantities  $I$
- Local information → individual behaviour  $b(l_\ell)$
- Aggregate  $b(l_\ell)$  = Behaviour[ $I$ ]

## Examples

- ▶ Sounds & clusters of birds and frogs; Melhuish 99
- ▶ Bees & air-conditioning of the hive Auman 08

## From observing to designing emergence

### Main Issues

- ▶ Communication feasibility, cost
- ▶ Convergence individual and collective safety
- ▶ Reality Gap in simulation vs *in-situ*
- ▶ Bootstrapping how to prime the pump



This talk focuses on

Division of labor



Synchronization





How do social agents proceed to synchronize their activities?





# Overview

- ▶ Swarm Robotics
- ▶ Biological / Artificial models
- ▶ SpikeAnts
  - ▶ Spiking Neurons
  - ▶ Network Architecture
- ▶ Analysis
- ▶ Discussion and Perspectives



Battery

Motors

Software

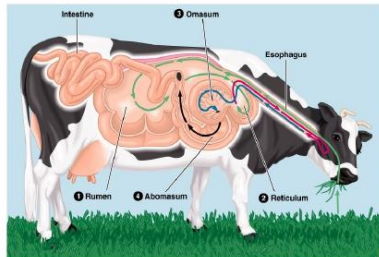
The hardware perspective



## Battery

Motors

Software



Division of labor

the social stomach ?

The hardware perspective



## Social stomach: Macro-modelling

X Foraging robots

S Stocking robots

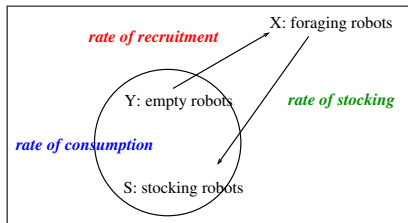
Y Other robots

$\beta$  rate of energy stocking

$\mu$  rate of energy consumption

$(\theta + X_t)$  rate of recruitment

$$\frac{\partial X}{\partial t} = (\theta + X_t)(N - X - S) - \beta X$$
$$\frac{\partial S}{\partial t} = \beta X - \mu S$$





## Division of labor, 2

### Finding food/resting

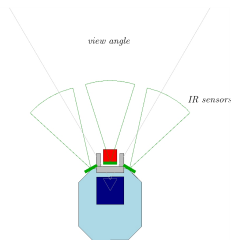
- ▶ Finding food delivers energy
- ▶ Searching costs energy
- ▶ bumping into other robots costs energy

### Goal

- ▶ Allocate time between search and rest

<http://www.brl.uwe.ac.uk/projects/swarm/index.html>

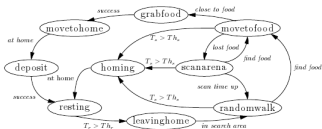
### Winfield & Liu 08





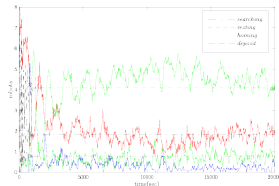
# Adaptive Foraging in Swarm Robotic Systems, 2

## Probabilistic Finite State Machine



## Design

- ▶ Find transition probabilities
- ▶ Rest and Search thresholds
- ▶ Input:
  - ▶ internal cues (food retrieved)
  - ▶ environment cues (bumping into other robots)
  - ▶ social cues (success/failure of relatives)





# Controller design in Swarm Robotics

## Constraints

- ▶ Spatially distributed
- ▶ Decentralized (no pacemaker)
- ▶ Asynchronous

design of emergence

## Available information

- ▶ Cues from relatives
- ▶ Internal time (hunger-like)

## Can it be avoided ?

- ▶ Random generator
- ▶ Sophisticated skills

probabilistic model  
counting ability



# Overview

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- ▶ SpikeAnts
  - ▶ Spiking Neurons
  - ▶ Network Architecture
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# Spiking neurons vs std neurons

## Standard neurons

- ▶ Directed graph  $\mathcal{G} = (\mathcal{E}, \mathcal{V})$  and weights  $W$
- ▶ An activation function: (linear, sigmoid, RBF)

$$e_i(t+1) = \leftarrow f\left(\sum_j w_{ij} e_j(t)\right)$$



## Spiking neurons

Hodgkin Huxley 52

- ▶ Internal state (membrane potential)
- ▶ Activation function  $\equiv$  differential equation

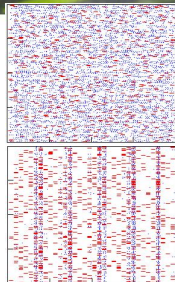
$\frac{\partial e(t)}{\partial t} = f(e(t), \text{Excitations, Inhibitions})$  if  $e(t) < \vartheta$   
else fires a spike and  $e(t)$  is set to  $V_{reset}$



## Spiking neurons, 2

### What is new

- ▶ An asynchronous process
- ▶ What matters is the dynamics of the input



### Modelling/studying dynamics

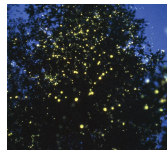
- ▶ Synchrony in cell assemblies  
Hebb, 49
- ▶ Complete synchrony  
Mirollo, 90
- ▶ Transient synchrony  
Hopfield, 01
- ▶ Order-chaos phase transition  
Schrauwen, 08
- ▶ Polychronization  
Izhikevich, 06
- ▶ Rhythmic oscillations  
Brunel, 03



# Synchronization

## In biological systems

- ▶ Fireflies
- ▶ Cricket chirping
- ▶ Pacemaker cells of the heart
- ▶ Neural cells



## Questions

- ▶ Why (synchronized patterns are more efficient ?)
- ▶ How ?

## Claim

*Emergence/Dynamics results from individual interactions*

Cole 91, Gordon 92



# Division of labor among foraging ants

## Principle

The ant goes foraging  
iff she does not see sufficiently many ants foraging

## Related problems

- ▶ The Dying seminar
- ▶ The El Farol bar

Schelling 1978

Arthur 1994

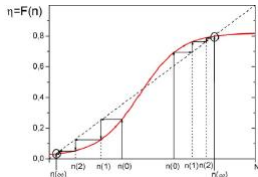


# The Dying Seminar

Schelling, 1978; Nadal et al. 2009

## Individual Utility Function

- ▶  $N$  scientists are asked to go to a seminar:
- ▶ ... scientist  $i$  will go if #attendees  $> n(i)$



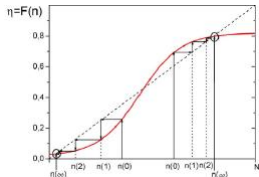


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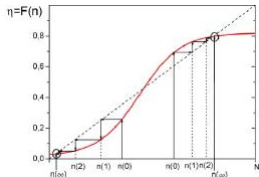


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# The El Farol bar

Arthur 1994

100 scientists

## Individual Utility Function

- ▶ The best option is to go to El Farol bar
- ▶ ... if not too many people go to the bar...
- ▶ otherwise, better stay at home...

$< 60$



## Devising a policy

- ▶ Random draw: go to the bar with probability .6
- ▶ Find rules to predict the attendance, based on the history



# Division of labor among foraging ants

## Principle

The ant goes foraging  
iff she does not see sufficiently many ants foraging

## Related problems

- ▶ The Dying seminar
- ▶ The El Farol bar

Schelling 1978

Arthur 1994

## Differences

- ▶ Not an imitation game
- ▶ No synchronization

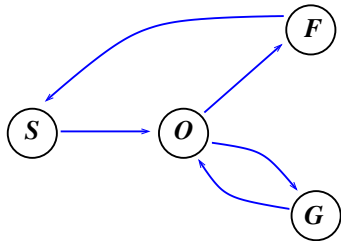
survival of the colony



# The foraging colony

## A 4 state agent model

- ▶ Sleep
- ▶ Observe
- ▶ Forage
- ▶ General Interest



## Ant policy

1. If I don't see "sufficiently many" foraging ants, I go foraging (then sleeping)
2. Otherwise, I go for General Interest tasks
3. After any task, back to Observation



# The ant model: Two spiking neurons

Passive neuron

Leaky Integrate-and-Fire (LIF)

$$\frac{dV_p}{dt} = -\lambda(V_p(t) - V_{\text{rest}}) + I_{\text{exc}}(t), \quad \text{if } V_p < \vartheta$$

else fires a spike and  $V_p$  is set to  $V_{\text{reset}}^p$

Excitation: signal of working ants

Active neuron

Quadratic Integrate-and-Fire (QIF)

$$\frac{dV_a}{dt} = -\lambda(V_a(t) - V_{\text{rest}})(V_a(t) - V_{\text{thres}}) + I_{\text{inh}}(t) + I_{\text{clock}}(t), \quad \text{if } V_a < \vartheta$$

else fires a spike and  $V_a$  is set to  $V_{\text{reset}}^a$

Inhibition: signal of working ants

Excitation: internal clock

Bistable:  $\begin{cases} > V_{\text{rest}} & \text{bursting regime} \\ < V_{\text{rest}} & \text{goto } V_{\text{reset}}^a \end{cases}$



# The ant model: Two spiking neurons, foll'd

*During the observation state,*

**Decision making:** Competition of active and passive neuron

- ▶ if Active wins, goto  $\mathcal{F}$  (and emits spikes, sent to neighbor ants)
- ▶ If Passive wins, goto  $\mathcal{G}$
- ▶ if none wins before  $t_0$ , goto  $\mathcal{F}$ .

*wins= emits a spike*

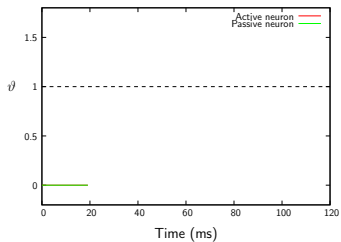
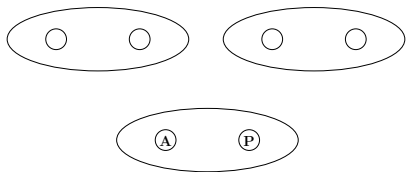
**Other states**

- ▶ Passive and Active neurons are not excited/inhibited.



# Microscopic Scale

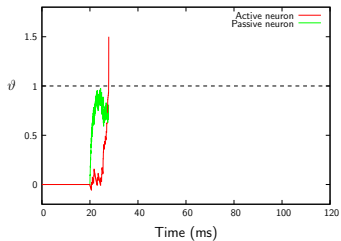
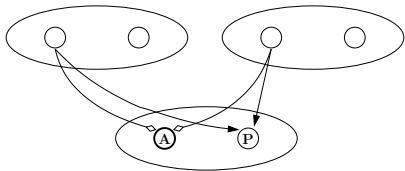
## Sleep state





# Microscopic Scale

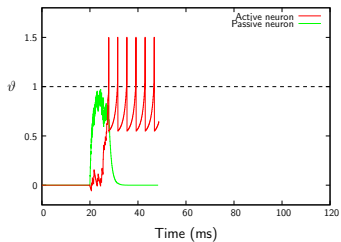
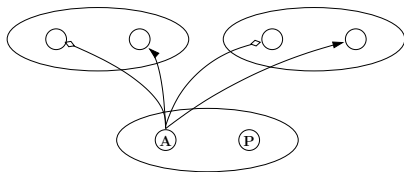
## Observation state





# Microscopic Scale

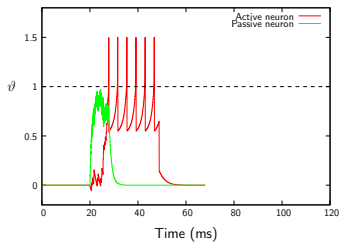
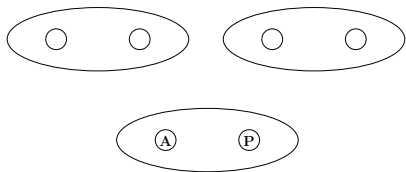
## Foraging state





# Microscopic Scale

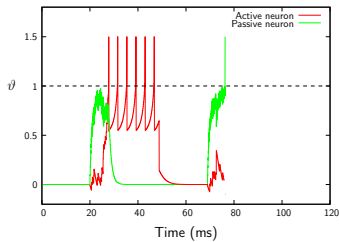
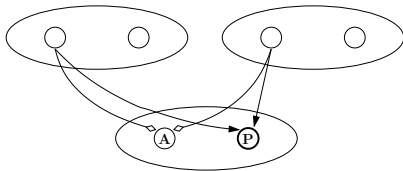
## Sleep state





# Microscopic Scale

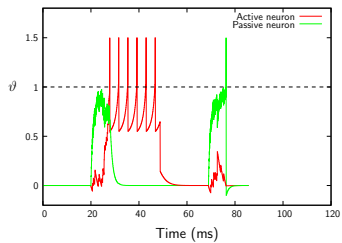
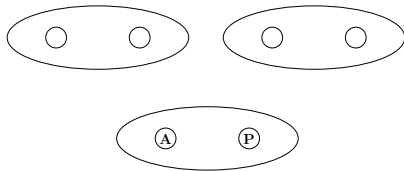
## Observation state





# Microscopic Scale

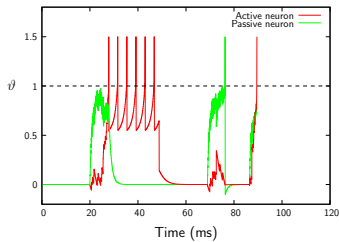
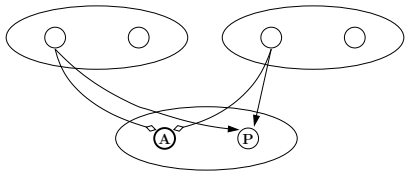
## General Interest state





# Microscopic Scale

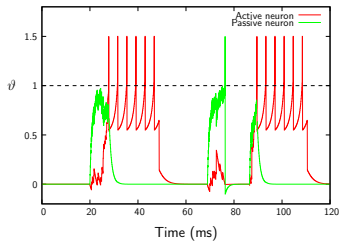
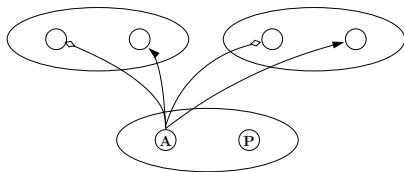
## Observation state





# Microscopic Scale

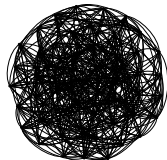
## Foraging state





## Ant colony

- ▶  $M$  ants =  $M$  (active, passive) neurons
- ▶ A spiking neuron network
- ▶ Sparsely connected (connectivity  $\rho$ )



## What happens ?

$n(t)$ : number of foraging ants at time  $t$

$$\text{Foraging effort } \mathcal{F} = \sum_t n(t)$$



# Parameters of the model

Parameter type	Symbol	Description	Value	(units)
Neural	$\lambda$	Membrane relaxation constant	0.1	$\text{mV}^{-1}$
	$V_{\text{rest}}$	Resting potential	0.0	mV
	$\vartheta$	Spike firing threshold	1.0	mV
	$V_{\text{reset}}^P$	Passive neuron reset potential	-0.1	mV
	$V_{\text{thres}}$	Active neuron bifurcation threshold	0.5	mV
	$V_{\text{reset}}^a$	Active neuron reset potential	0.55	mV
	$I_{\text{clock}}$	Active neuron constant input current	0.1	mV
	$w$	Synaptic weight	0.01	$\text{mV}^{-1}$
Agent	$t_{\mathcal{F}}$	Foraging duration	47.1	ms
	$t_{\mathcal{O}}$	Maximum observation duration	10.5	ms
	$t_{\mathcal{S}}$	Sleeping duration	45.7	ms
	$t_{\mathcal{G}}$	General I. duration	16.7	ms
Population	$\rho$	Connection probability	0.3	%
	$M$	Population size	150	agents

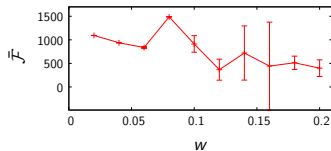
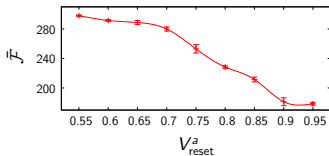
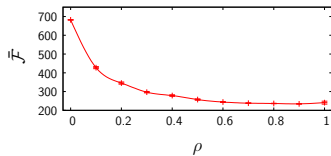
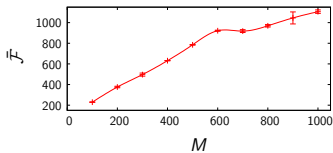
## Initialization

every ant sleeps and wakes up after  $U[0, 2t_{\mathcal{S}}]$



# Foraging effort: Sensitivity analysis

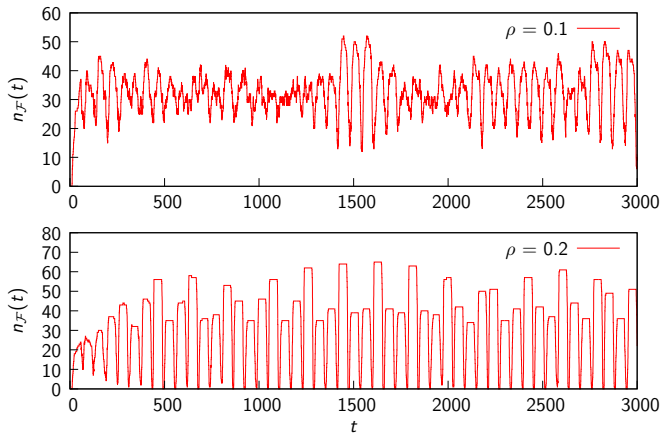
Average on 10 independent runs *times* 100,000 time steps



vs population size  $M$ , connectivity  $\rho$ ,  
active neuron reset potential  $V_{\text{reset}}^a$  and synaptic weight  $w$ .



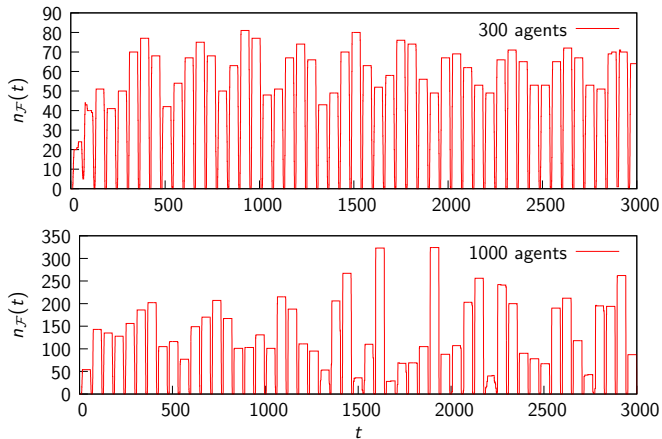
# Influence of connectivity $\rho$



Emergence of workshift as  $\rho$  increases.



# Influence of population size $M$



Variance of workshift size increases with  $M$



# Macroscopic study, foll'd

**First indicator:** Foraging effort  $\mathcal{F}$

- ▶ Behaves as expected
- ▶ high variance in some regions.

**Second indicator:** Entropy of synchronization  $\mathcal{H}$

- ▶ Consider  $n(t)$  number of foraging agents at  $t$
- ▶ Discard orphan time steps  $t$  s.t.  $n(t-1) \neq n(t) \neq n(t+1)$

- ▶ Let

$$\mathcal{N} = \{n(t), t = 1 \dots T, n(t) = n(t+1) \text{ or } n(t) = n(t-1)\}$$

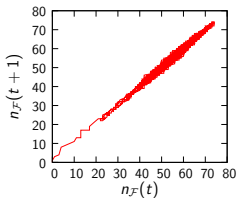
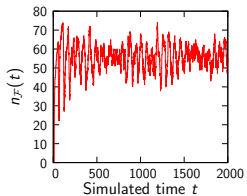
- ▶ Let  $p_n \propto |\{t, n(t) = n, n \in \mathcal{N}\}|$

$$\mathcal{H} = - \sum_{n \in \mathcal{N}} p_n \log p_n$$



# Three different regimes

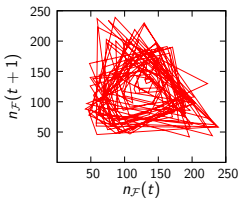
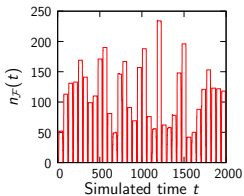
(A) Asynchronous



$H =$

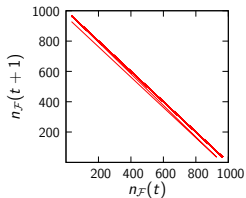
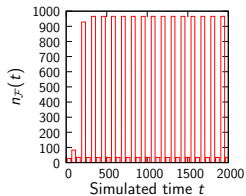
0

(B) Synchronous aperiodic



High

(C) Synchronous periodic

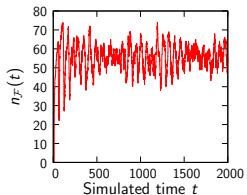


$\text{Log}2$

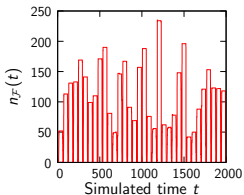


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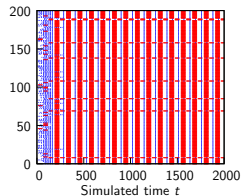
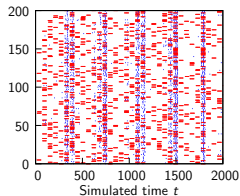
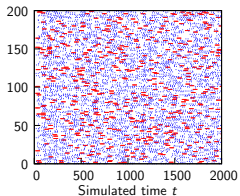
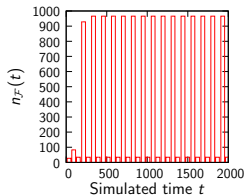
(A) Asynchronous



(B) Synchronous aperiodic



(C) Synchronous periodic



Raster plot: Active = red, passive = blue



# SpikeAnts: Emergent synchronization

## Control parameters

- ▶ Sociability  $\rho\sqrt{M}$
- ▶ Receptivity  $\frac{w}{|\vartheta - V_{\text{rest}}|}$

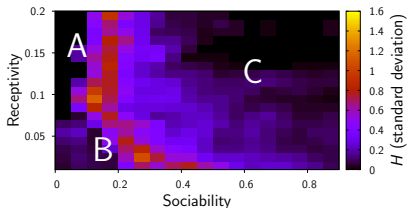
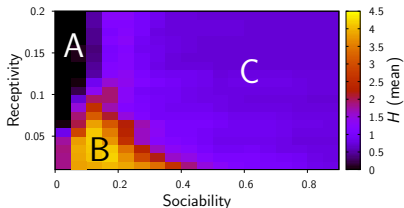


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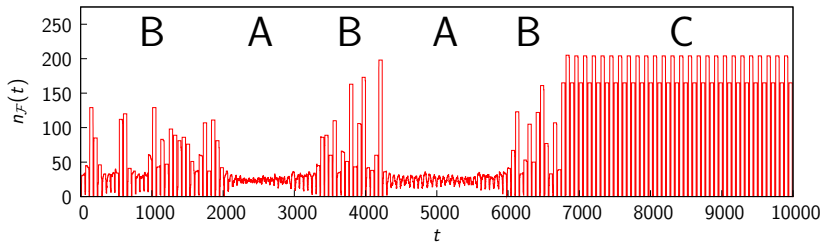
## Phase diagram





# SpikeAnts: A representative run

at the triple point



Stable regime: synchronous periodic.



# Overview

- ▶ Swarm Robotics
- ▶ Biological / Artificial models
- ▶ SpikeAnts
  - ▶ Spiking Neurons
  - ▶ Network Architecture
- ▶ Analysis
- ▶ Discussion and Perspectives



## The model

- ▶ Frugal, deterministic model
- ▶ Biological plausibility / no counting abilities
- ▶ Accounts for the emergence of synchronization

## Further extensions

- ▶ Comparisons with probabilistic models
- ▶ Stochastic parameters



# Further extensions

## Reconsidering excitation/inhibition

From SpikeAnts to an Ising model

## The environment

handling perturbations

What can be learned/optimized within SpikeAnts ?

## Going real

Implementing SpikeAnts





## Thanks

- ▶ Sylvain Chevallier, H el ene Paugam Moisy
- ▶ Jos e Halloy, Jean-Louis Deneubourg
- ▶ Symbion IP

TAO, LRI  
VUB

More in NIPS 2010.