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Measuring Emergence in Cooperative Autonomy

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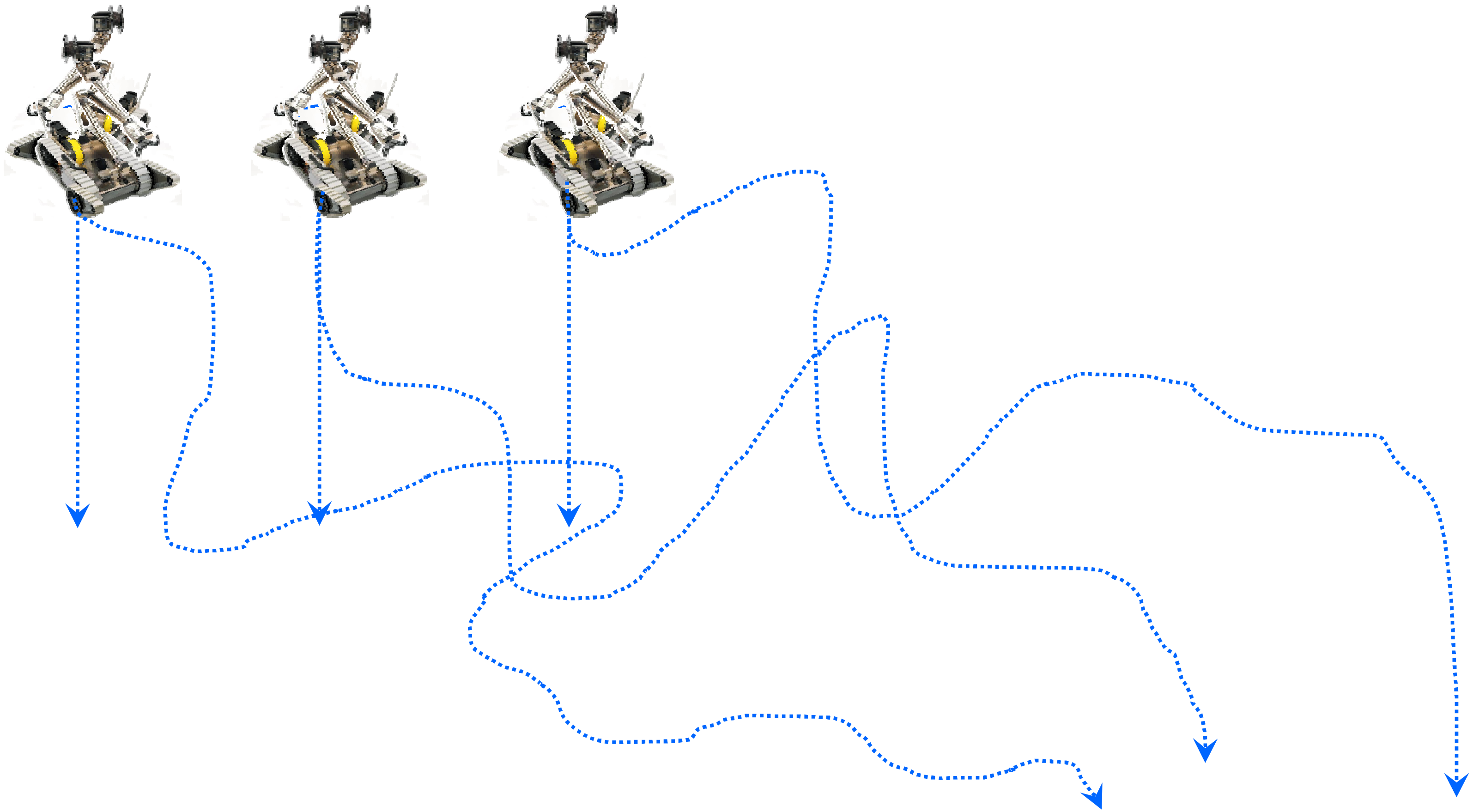
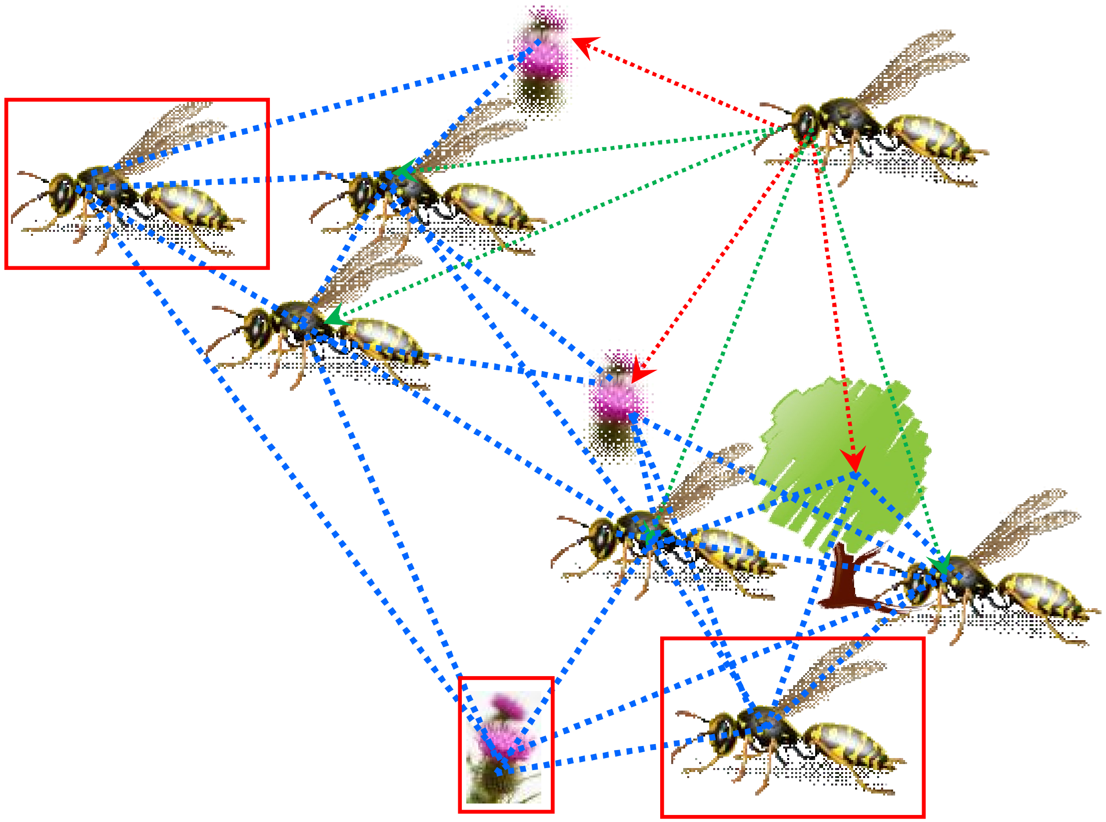
Contents

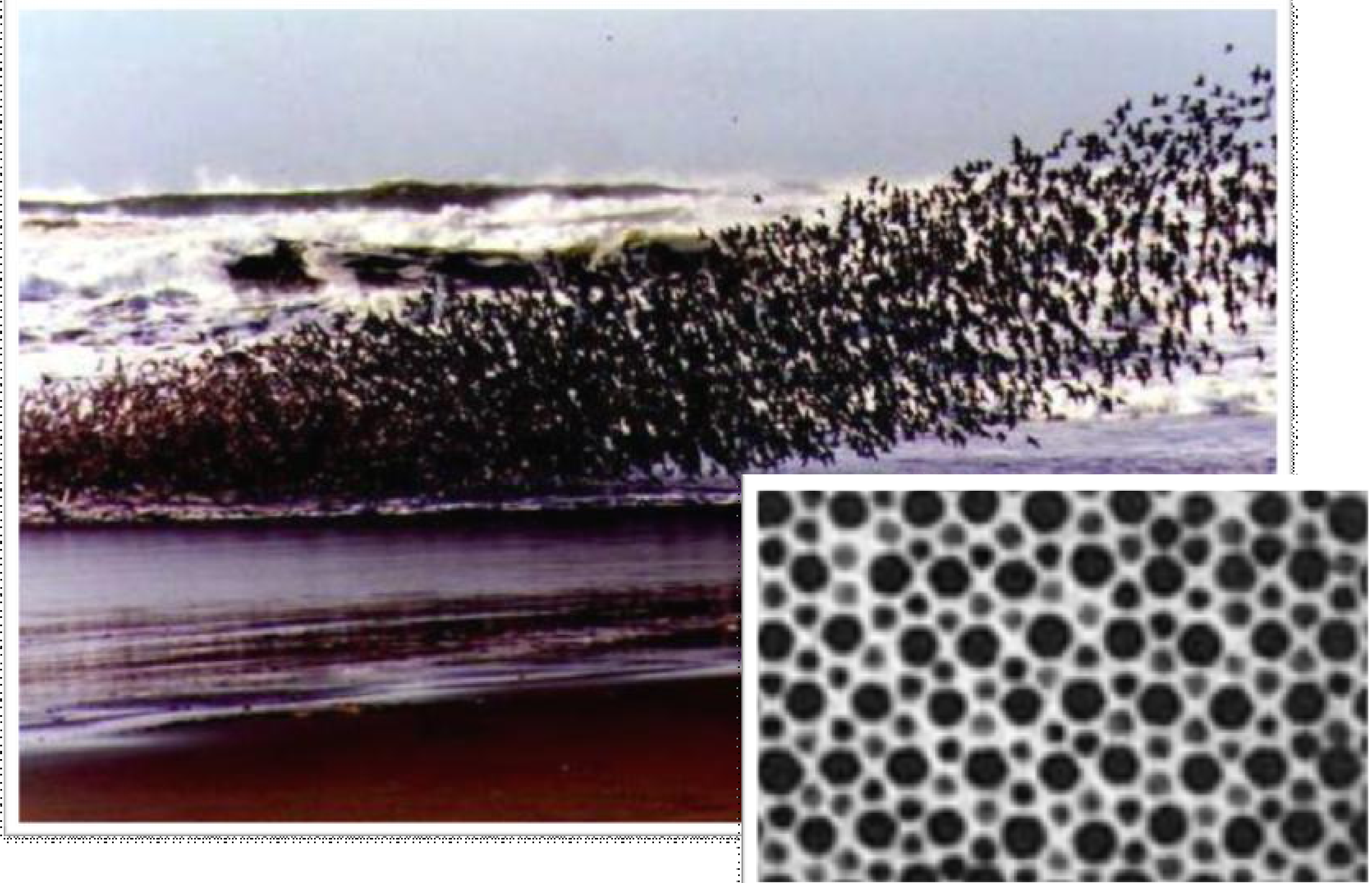
Background: Emergence



Background: Cooperative Autonomy



Background: Examples of Emergence



Background

Emergence:

- § holds a great potential – desired emergent global behaviour from simple individual behaviours,
- § also holds a great risk – undesired emergent global behaviour

Managing emergence:

- § requires understanding,
- § is essential to cooperative system's success

Why measure?

- § In order to manage emergence one must first be able to measure it!

Goal

To identify the systems engineering know-how needed to design a multi-agent cooperative control system

For that two significant questions need to be answered:

1. How can we predict the emergent behaviour through the analysis of the proposed design?
2. How can we reverse this engineering process and determine the design given a desired emergent behaviour?

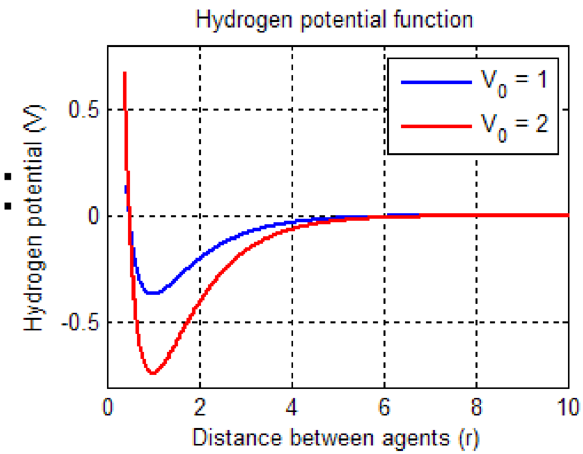
Measure of Emergence

- based on the Shannon entropy
- successfully employed as feedback to a system to design in desired behaviours
- constructed as $\Omega = 2^S$
- where $S = -\sum_{i=1}^{M} s_i \log_2 s_i$ and
- where s_i – normalised singular values calculated from a matrix of successive observations of the time-series of position and velocity of the agents in the system

System Model

Lagrangian model:

- Local interactions between agents:
  - <u>attraction-repulsion</u> force
  - <u>velocity matching</u> force



- Dimensional form

$$m\ddot{x}_i + V_0 \sum_{j\neq i}^{N} \frac{\partial V_i(r_{ij})}{\partial x} + m \sum_{\substack{j\neq i \\ j:r_{ij}\leq r_D}}^{N} \left(\dot{x}_i - \dot{x}_j\right) = 0$$

m – mass, kg
x – coordinate, m
V_0 – depth of V, $kg{\cdot}m/s^2$
V – hydrogen potential
r – distance, m
N – number of agents
M – number of time samples
μ – damping coefficient, m/s
r_D – effective range, m

Non-Dimensional System Model

- Dimensional equation depends on 5 parameters
- Wright et al. came up with 2 non-dimensional parameters but other factors could still affect the behaviour of the system
- Non-dimensional form of the equation used in this study uses three non-dimensional parameters

$$\ddot{X}_i + w^2 \sum_{j \neq i}^{N} DV_i(R_{ij}) + wV \sum_{\substack{j \neq i \\ j:R_{ij} \leq b}}^{N} \left(\dot{X}_i - \dot{X}_j \right) = 0$$

ω – strength of the 1st term
ς – strength ratio of the forces
β – effective range of the 2nd term

Rule-based System Model

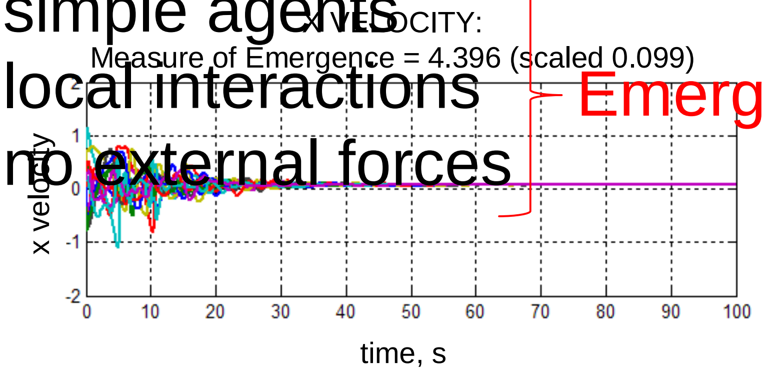
Rules:

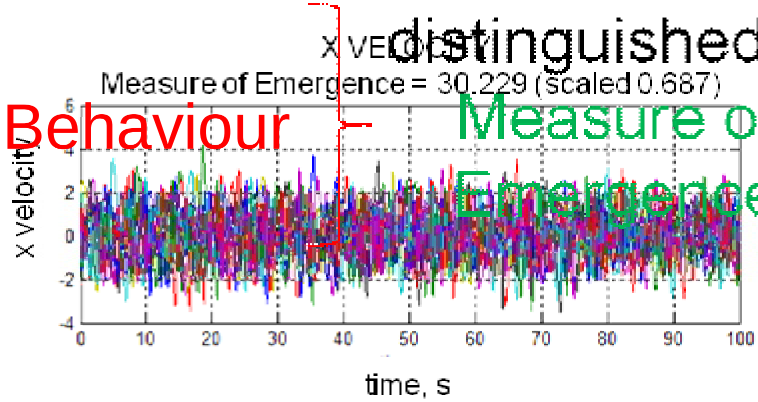
- keep pace, current speed " normal speed
- look for agents nearby, success?
- no, then move randomly
- yes, then
  - move towards the average position of local agents
  - align velocity with local agents'
  - move to avoid collision with other agents
  - add randomness into the movements

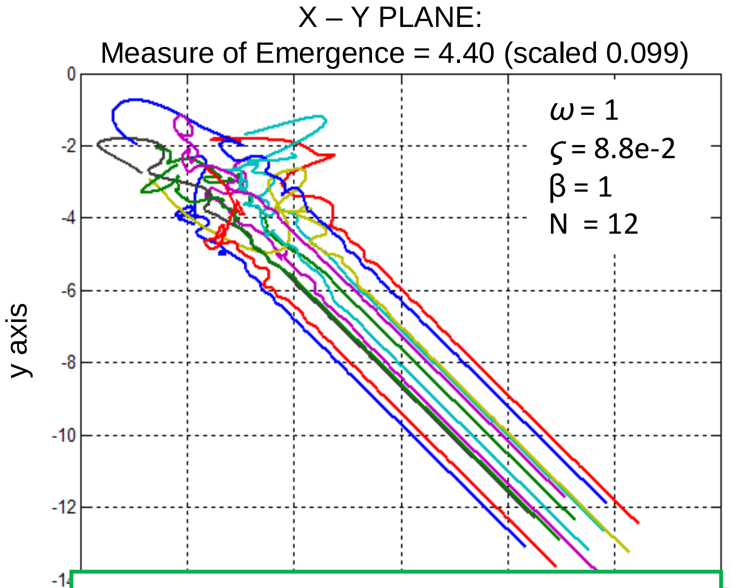
Emergent Behaviour

- simple agents
- local interactions
- no external forces

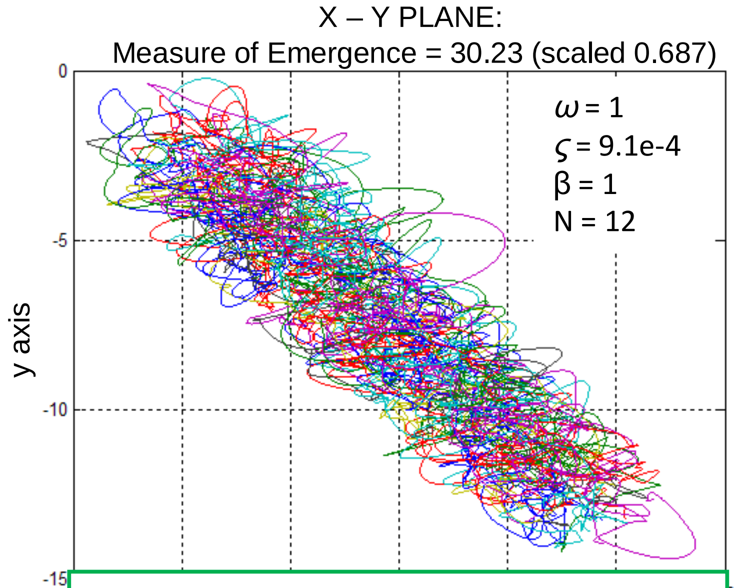
Emergent Behaviour distinguished by Measure of Emergence







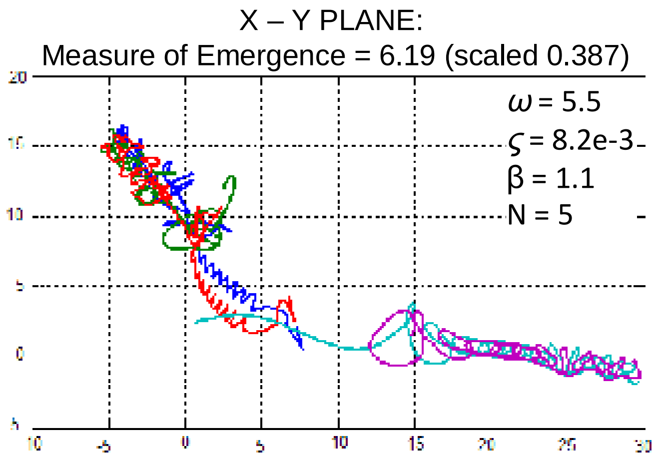
coordinated ordered or crystal behaviour



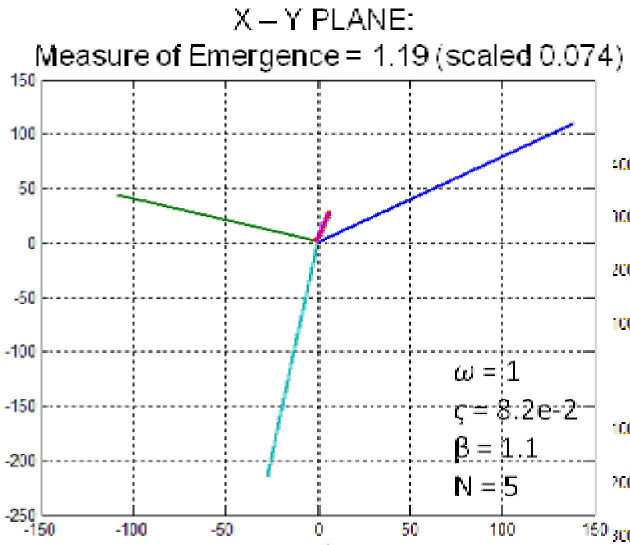
coordinated disordered or swarm behaviour

Fragmentation

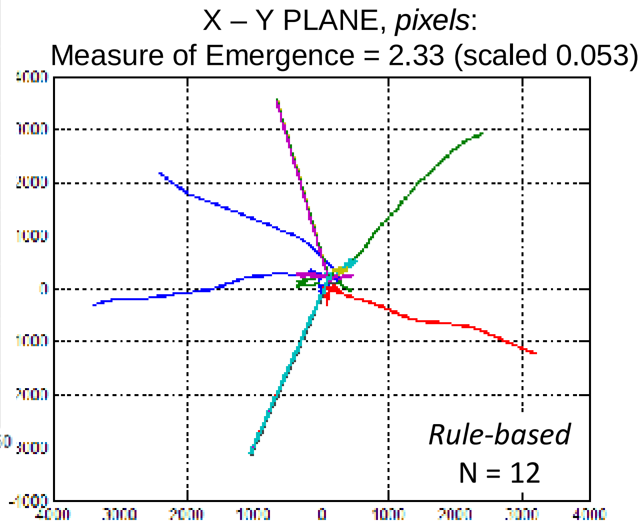
- Fragmentation made it difficult for the measure of emergence to determine the behaviour of the agents.
- A measure of connectivity proposed to identify fragmentation.



Connectivity measure ≈ 0.25



Connectivity measure ≈ 0

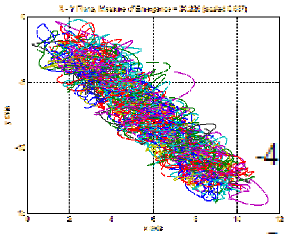


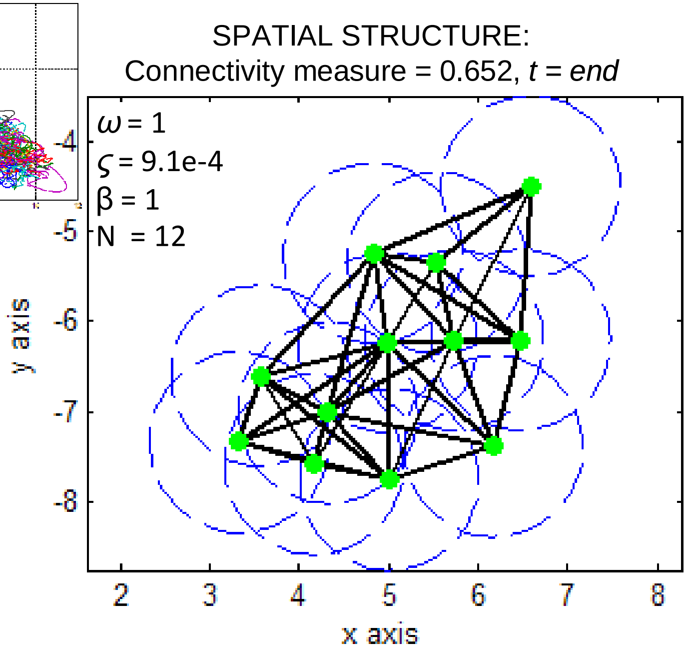
Connectivity measure ≈ 0

Structural Pattern

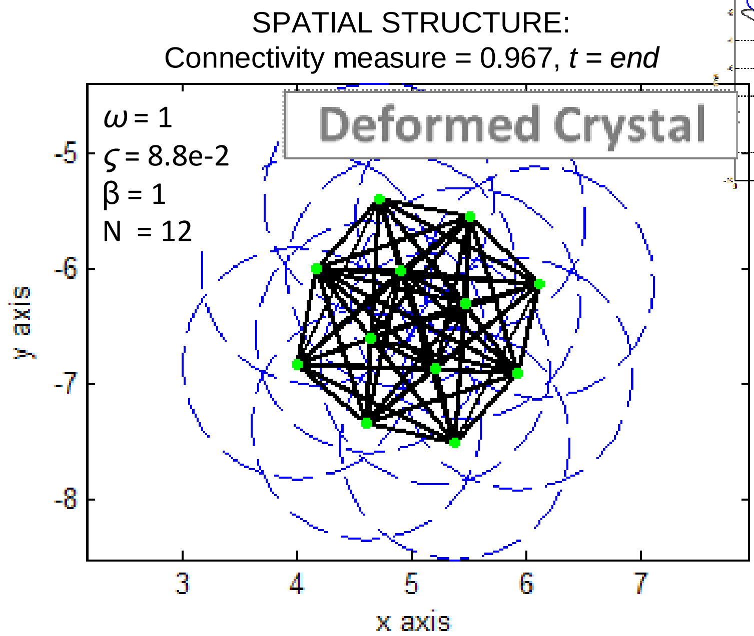
- simple agents
- local interactions
- no external forces

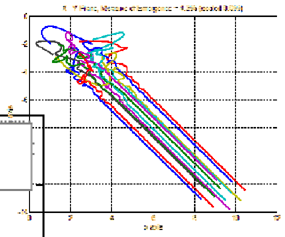
} **Structure: Emergent Property** } identified using **Connectivity Diagrams**





coordinated disordered or swarm behaviour





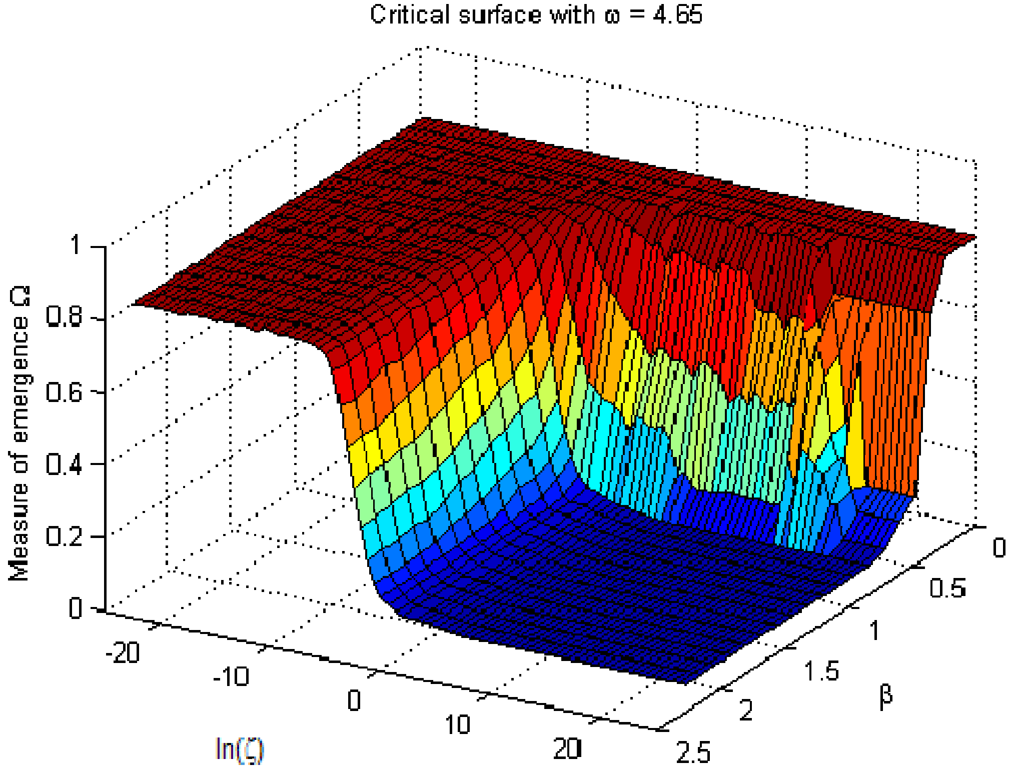
coordinated ordered or crystal behaviour

Critical surface

- A critical surface generated using the measure of emergence
- Possible to assign behaviours to regions of the surface
- Phase transition discovered – area of uncertainty & danger

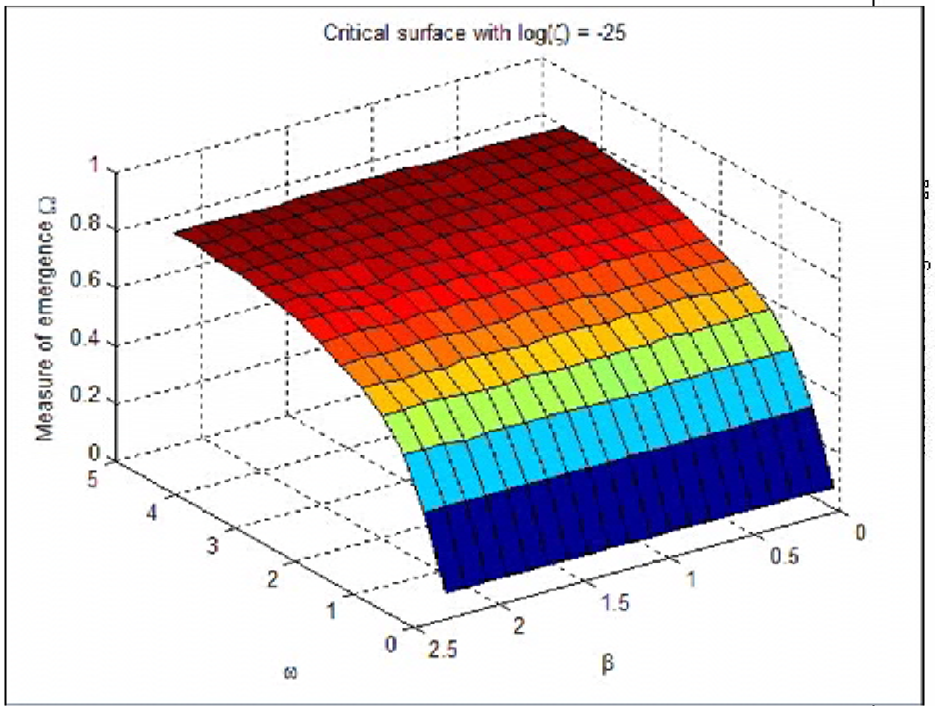
ω – fixed

ω = 4.65

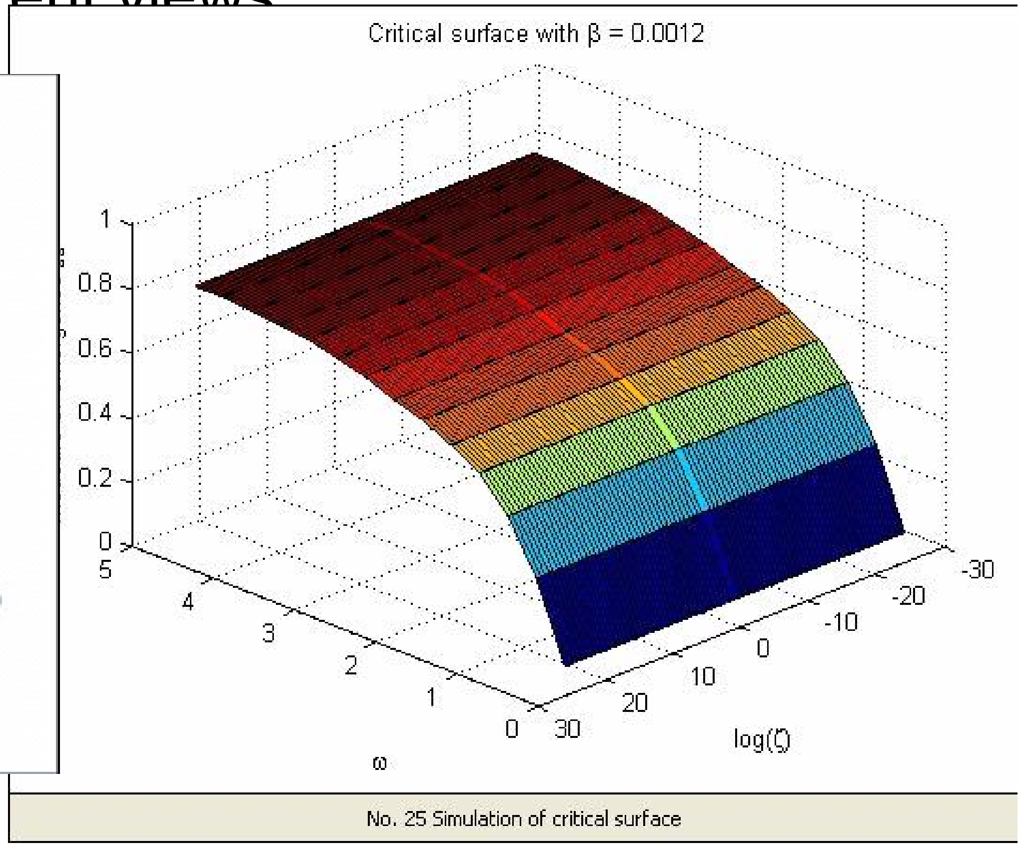


Critical surface *cont.*

§ Critical surface from different views:



ln(ς) – *fixed*



β – *fixed*

Scalability & Flexibility

It was found that emergent behaviours are:

- highly robust to variations in system sizes " **scalable**
  - emergent behaviour for 5, 12 & 17 agents – same stability
  - spatial structure for 12 & 35 agents – same crystal-shaped
  - global behaviour emerges even for 2 agents
- highly robust to obstructions in the environment " **flexible**
  - obstacle with a strong repulsive force – strong reaction
  - obstacle with a weak repulsive force – weak reaction
  - no collisions & yet self-ordered at all times
    - if crystal " crystal after encounter
    - if swarm " swarm after encounter

Applicability

Two options

- for designing a control system so that to achieve a desired emergent behaviour

identified:

1. designing agent behaviours without any explicit goal
2. designing agent behaviours and the dynamics of the whole with explicitly defined goal

    - by choosing appropriate <u>local rules</u>
    - appropriate by using the <u>measure of emergence</u>
    - by controlling the <u>initialisation</u> of the system

Conclusions

- The measure of emergence can clearly differentiate two different stable emergent behaviours of agents remaining in a single group:
  - coordinated ordered or crystal ($\Omega_s \approx 0$)
  - coordinated disordered or swarm ($\Omega_s \approx 1$)
- Critical surface can reveal a phase transition between the two stable emergent behaviours.
- The measure of emergence struggles in case of fragmentation. In this case a measure of connectivity can be used.
- A simple control system is achieved through choosing the local rules, using the measure of emergence & manipulating the initial conditions.
- Great potential for use of the measure of emergence in the control and design of autonomous systems.

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