Organic Computing

Lecture

Organic Computing II

Summer term 2019

Chapter 2: Self-organised Order

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Agenda

Content

- A first example: water temples in Bali
- A second example: ants
- Emergence
- Term definition
- Quantification of emergence
- A refined approach to emergence quantification
- Conclusion and further readings

Goals

Students should be able to:

- Explain the relation between self-organisation and emergence.
- Briefly summarise the term emergence.
- Give examples for emergent phenomena, e.g. in nature.
- Quantify emergence in technical systems based on discrete attributes.
- Outline how emergence detection is done for systems with continuous attributes.

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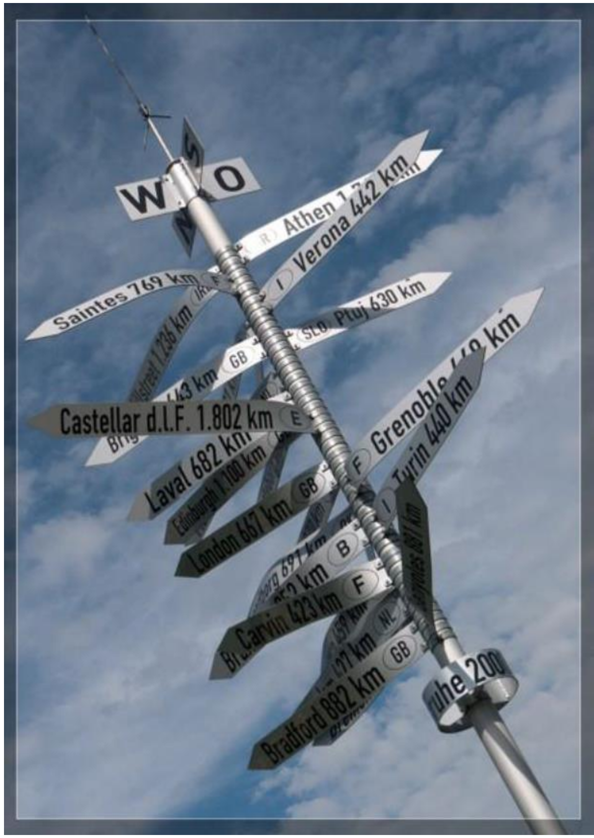

A journey to Bali

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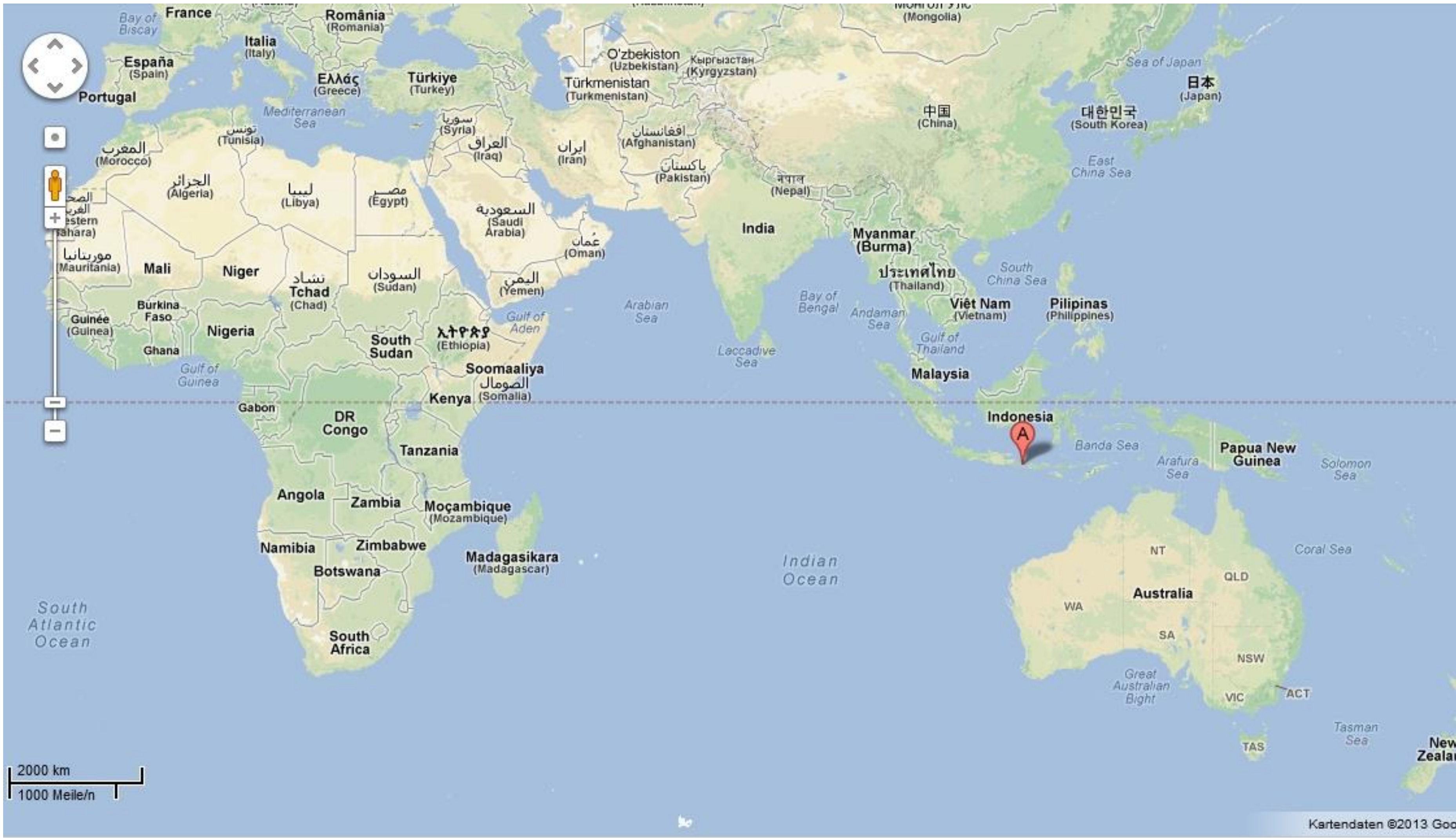

Water temples in Bali

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Water temples in Bali (2)

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Watering system for the cultivation of rice

- Main factors:
  - Water circulation
  - Alternation between dry and wet periods
- Objectives
  - PH-values
  - Activity of micro-organisms
  - Distribution of mineral nutrient
  - Herbicide
  - Pest control (for large areas)
  - Stabilisation of temperature
- Problem: Synchronous watering leads to peak demand of water!

Water temples in Bali (4)

Problem for each farmer:

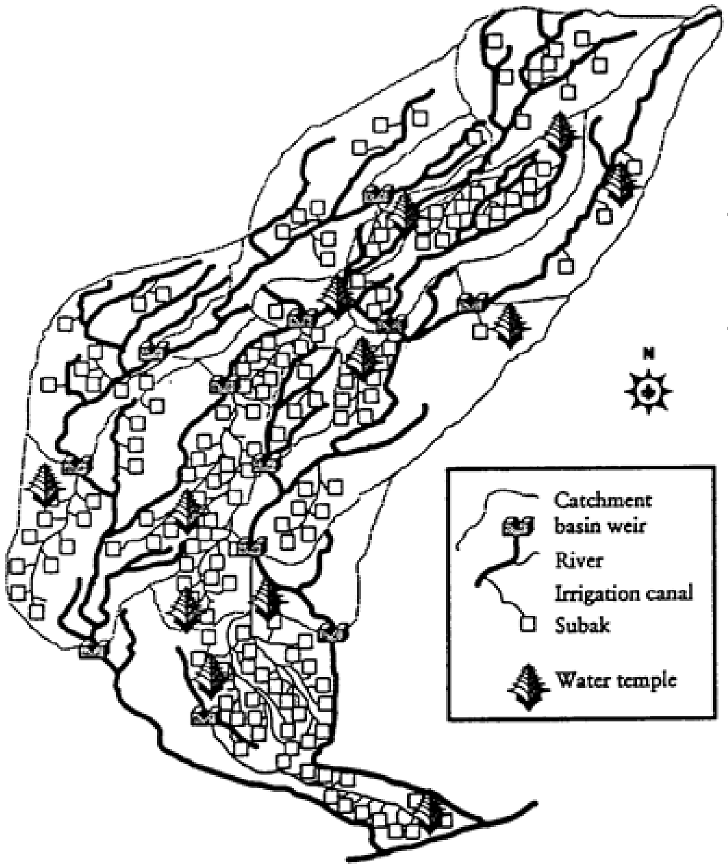
- Determine cultivation sequence

Goal:

- Maximise crop

Attributes of cultivation sequence:

- Phases of cropping (date)
- Cultivar (kind of plant)
- Watering
- Drying



The Oos and Petanu rivers in south-central Bali (not to scale).[16]

Source: Lansing and Kremer

How to determine the optimal sequence?

- Trial and error vs. planning
- Coordination: global or local?
- Is the solution suitable for the local problem?
- Is the solution adaptable?

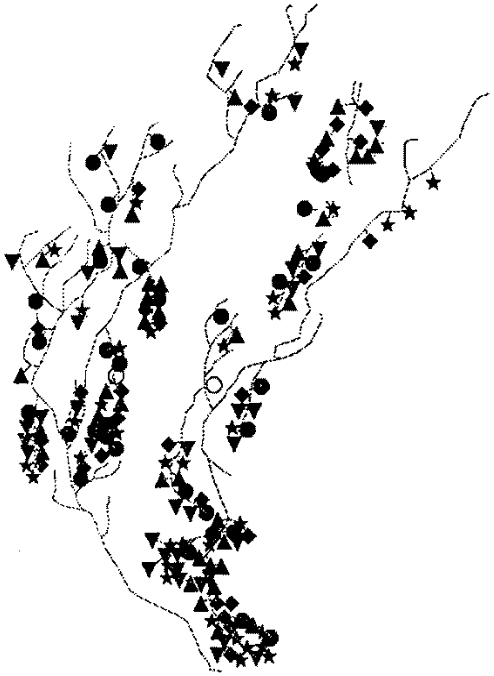
Hypothesis:

- Coordination algorithm
- Synchronous, local, like the best neighbour
- Co-adaptation

Verification of hypothesis: simulation

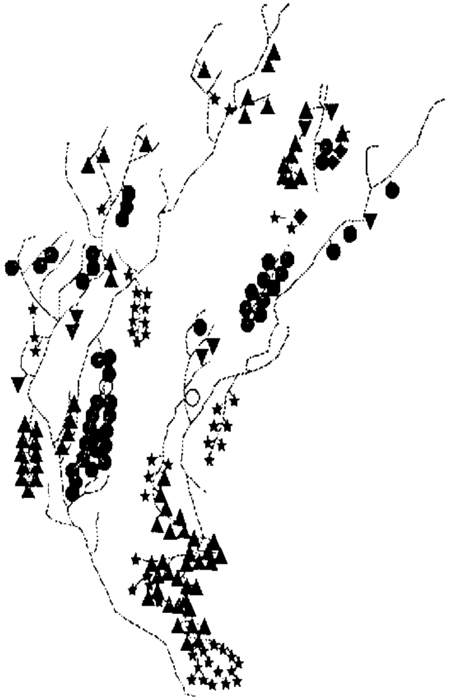
- Crop is modelled as a function of cultivation sequence and environment.
- Start: randomised initialisation

Water temples in Bali (6)



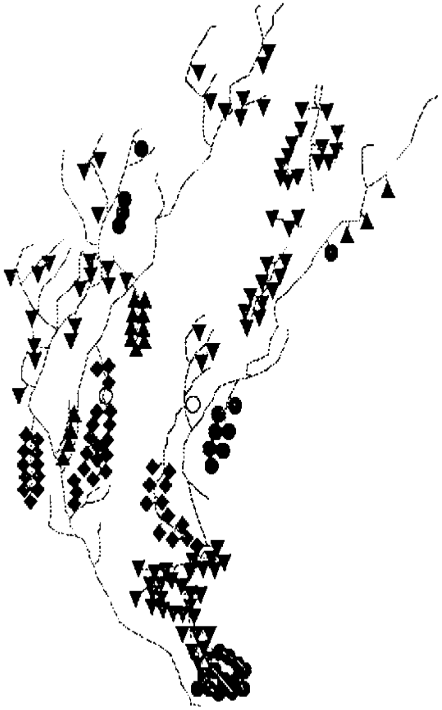
Randomised distribution at start-up

4.9 tons/ha



Simulated pattern after co-adaptation cycles

8.6 tons/ha



Traditional system of cave temples at Bali

Cultivation sequences

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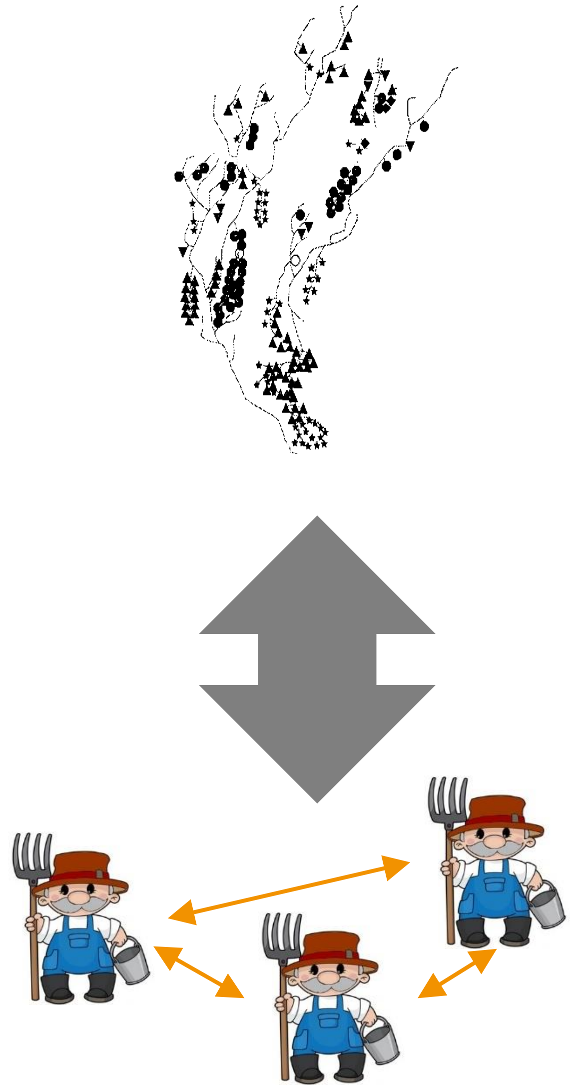
Conclusions to be drawn from the water temple networks:

- Contains locally behaving and self-motivated farmers (nodes, agents).
- Cooperation leads to globally optimal (or „good enough“) patterns.
  → An emergent effect.
- Bottom-up evolved problem-solving networks are adaptive: react to changing environmental conditions (e.g. reduced rainfall).
- Success of the networks depends on: (1) ability of local nodes to collect local information and (2) react to it locally.
- There is no central authority needed, the system is decentralised.
- There is no external authority needed, the system is self-organised.
- Co-adaptation requires large populations of interacting agents.
- Agents decide on their own but in close and regular coordination with their neighbours. They are semi-autonomous.
- The system learns and adapts in evolutionary cycles.
- Evolutionary steps are subject to random variations.

Self-organised order

Insight: self-organised order

- A global pattern emerges
- System is structured
- Nobody is in charge
- Nobody has a global view
- Nothing is planned
- Distinguish between micro- and macro-level
  → actions at micro-level, effects at macro-level
  → “good enough” solutions at macro-level



Macro-level:
- Global view
- Pattern
- Structure

Micro-level:
- Interaction
- Local view

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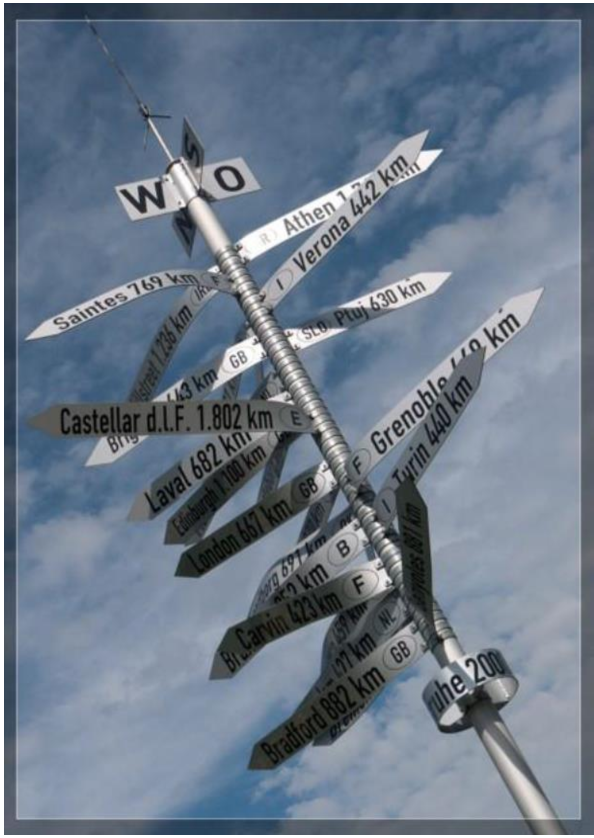


Ants

- Related to wasps and bees
- About 100 million years old
- Extremely successful:
  - About 30% of bio mass in
    the Amazonas are (with termites)
  - About 9% of bio mass world-wide
  - Comparable to bio mass of humans
- No or only limited vision
- Distribution of labour:
  - soldiers,
  - construction workers,
  - gardeners,
  - reproduction
  - …

Source: Ants at Work (1999) by Deborah Gordon

Ants (2)

Abilities of ants

- Find shortest paths
- Build bridges
- Sort
- Efficient logistics
- Farming / food production
- Construction of complex structures
- Caring about brood and offspring
- Caring about useful entities
- Distribution of labour
- ...

Ants (3)

Building bridges

- Chains of ants clamping together
- To bridges gaps in path
- Other ants use these chains as path
- E.g. to better reach food
- Chains of ants to pull leaves down
- Alternative: use silk from larvae as materia

Ants (4)

Food production

- Ant species that cultivates fungi
- Ground and substrate is processed for fungi.
- "Gardens" are laid out and cultivated.
- Fungal spores are planted.
- Competing fungi (i.e. light or water) is eliminated.
  → Like weeding the garden!
- Fertilisation of chewed larval cases.

Ants (5)

Distribution of labour

- Different types of ants in a colony:
  - Worker
  - Medium-sized ants
  - Small ants
  - Queen
  - Male ants
- Workers search for food (leaves) in the surroundings (up to hundreds of meters from nest).
- Workers organise ant trails for transport of food.
- Medium-sized ants carry leaves.

Ants (6)

Symbiosis

- Ants cannot digest cellulose.
- But fungus can!
  → Eat hyphal tips
- Ants provide leaves as breeding ground for fungus.

Gardens

- Sculptured with many furrows ("Furche") and cavities ("Höhle") for brood.
- System of lower passages to drain wet chambers.
- Other tunnels for temporary control
- Ants swab floor clean.
- If foreign fungus develops, it is removed.
- Garden lasts 3-4 weeks / in various stages
- Founding queen brings fungal spores from old colony.
- Up to 500,000 per colony.

> Alternative: Some ant species (e.g. Lasius niger, common black ant in Britain) herd aphids ("ant cattle"), protecting and even constructing them shelters.

Ants (7)

Protection

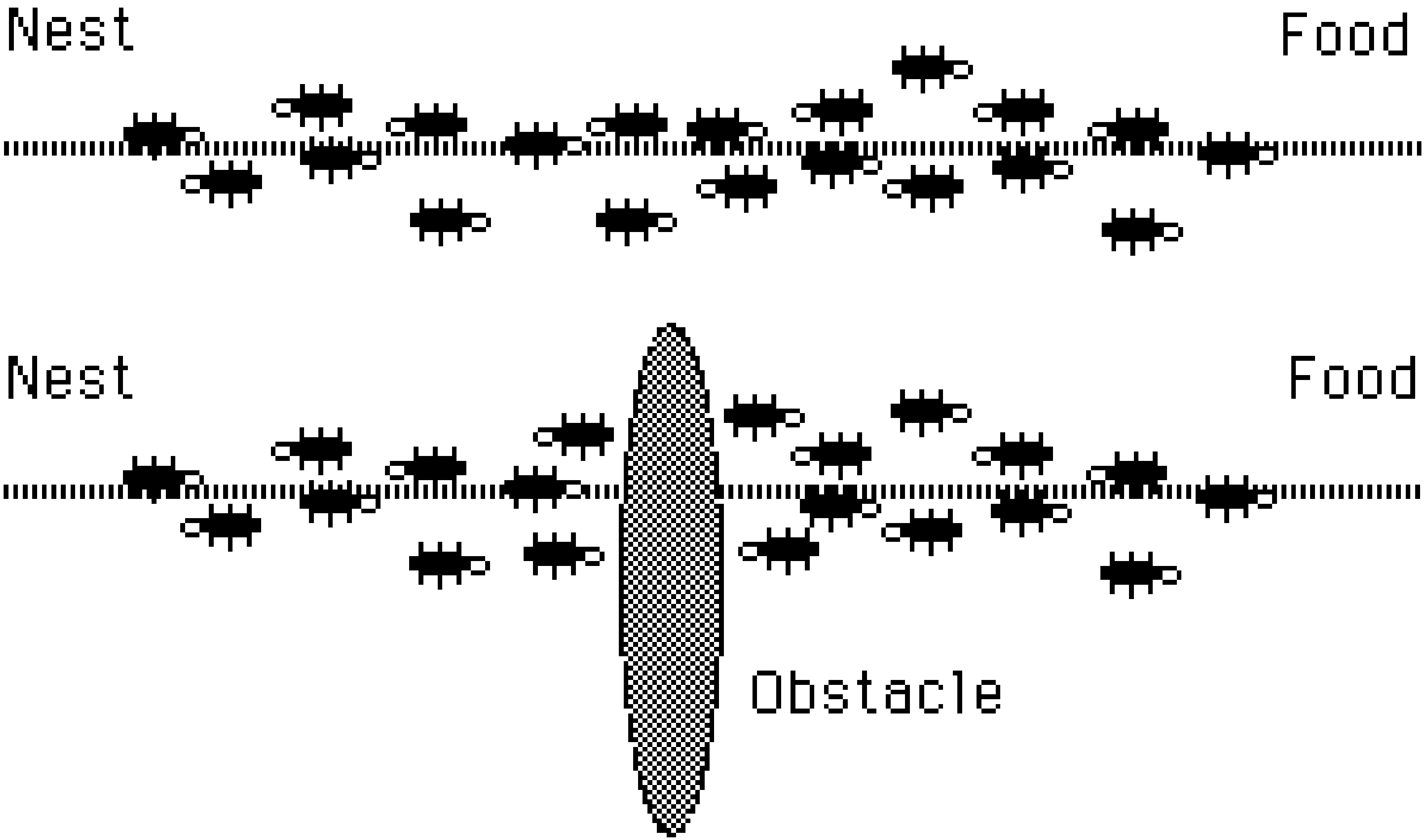
- Problem: large ants are victims of parasites.
- I.e. small flies try to deposit their eggs at head or neck of ants.
- Causes illness.
- Solution: small ants “ride“ piggy-back and chase attackers.

Ants (8)

Finding shortest paths:

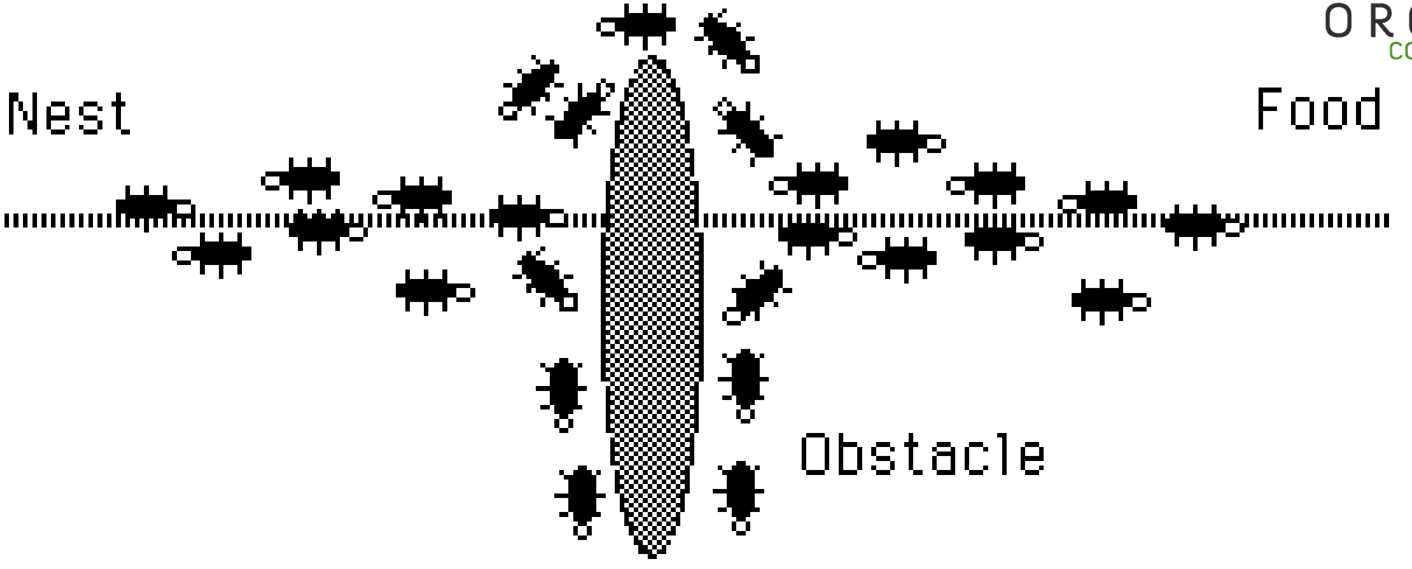
- Prioritisation of food sources based on distance and reachability
- Dynamic adaption of participating ants, e.g. depending on:
  - Size of colony (in number of ants)
  - Amount of stored food
  - Available food sources in vicinity
  - Other colonies and their location

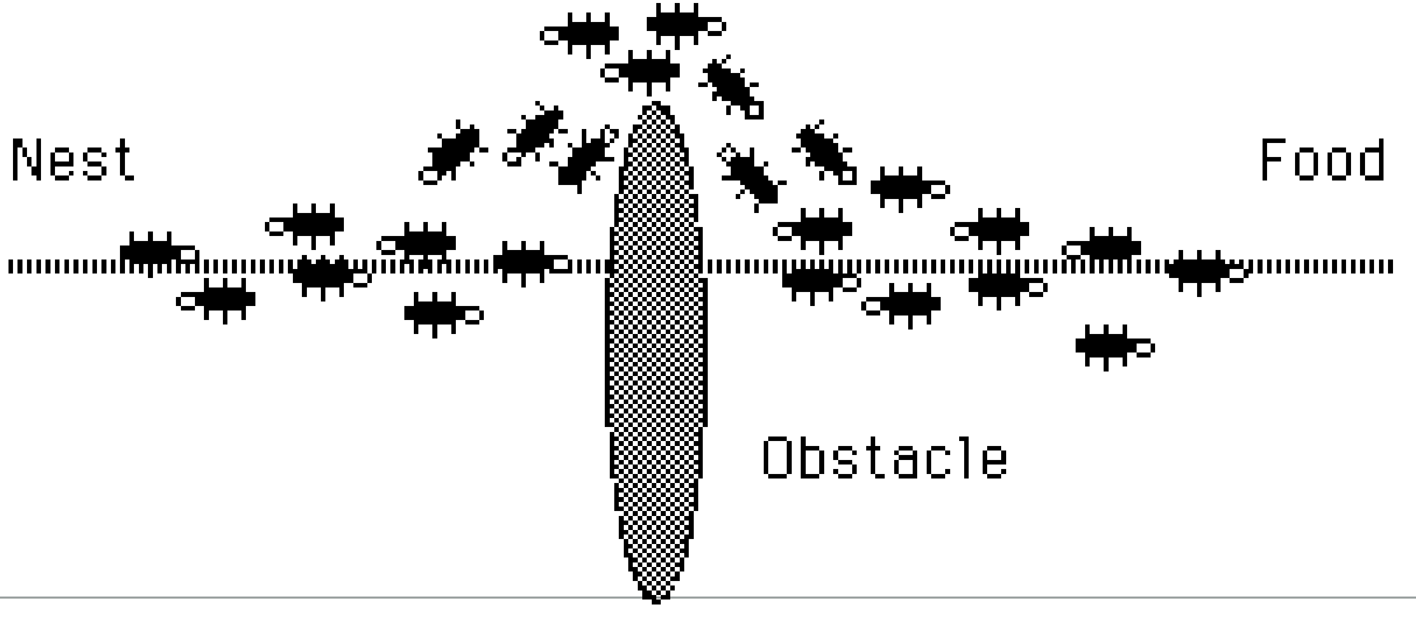
Adaptive path optimisation



[Source: iridia.ulb.ac.be/~mdorigo]

Ants (10)



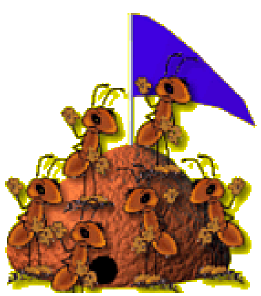


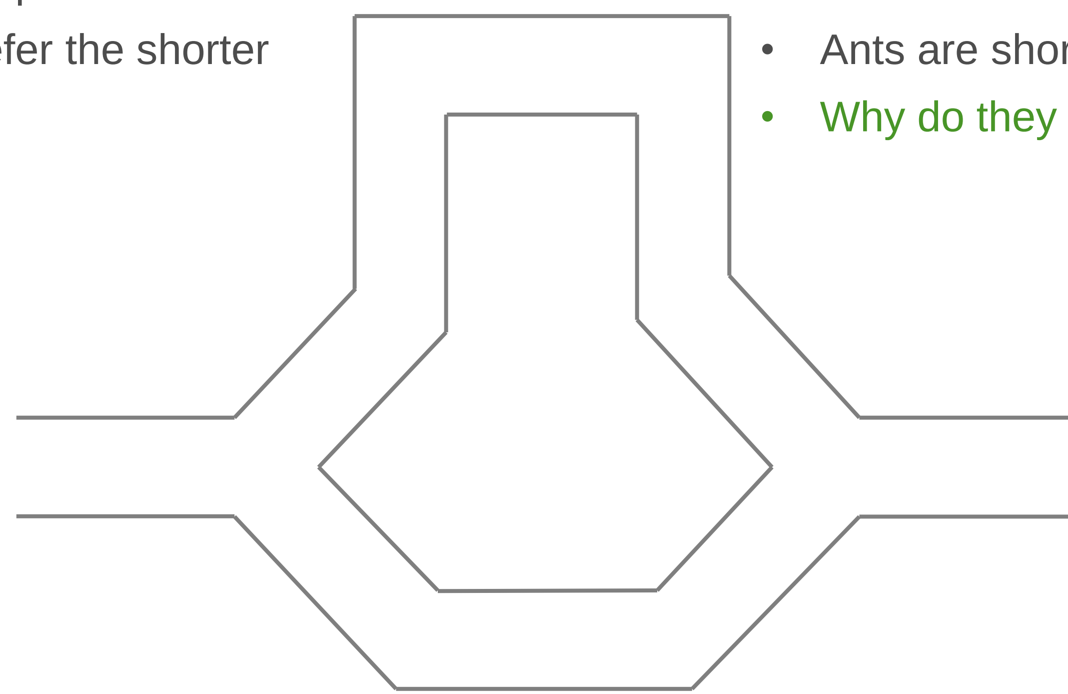
Behaviour of ants

[Deneubourg et al., Dorigo, around 1990]

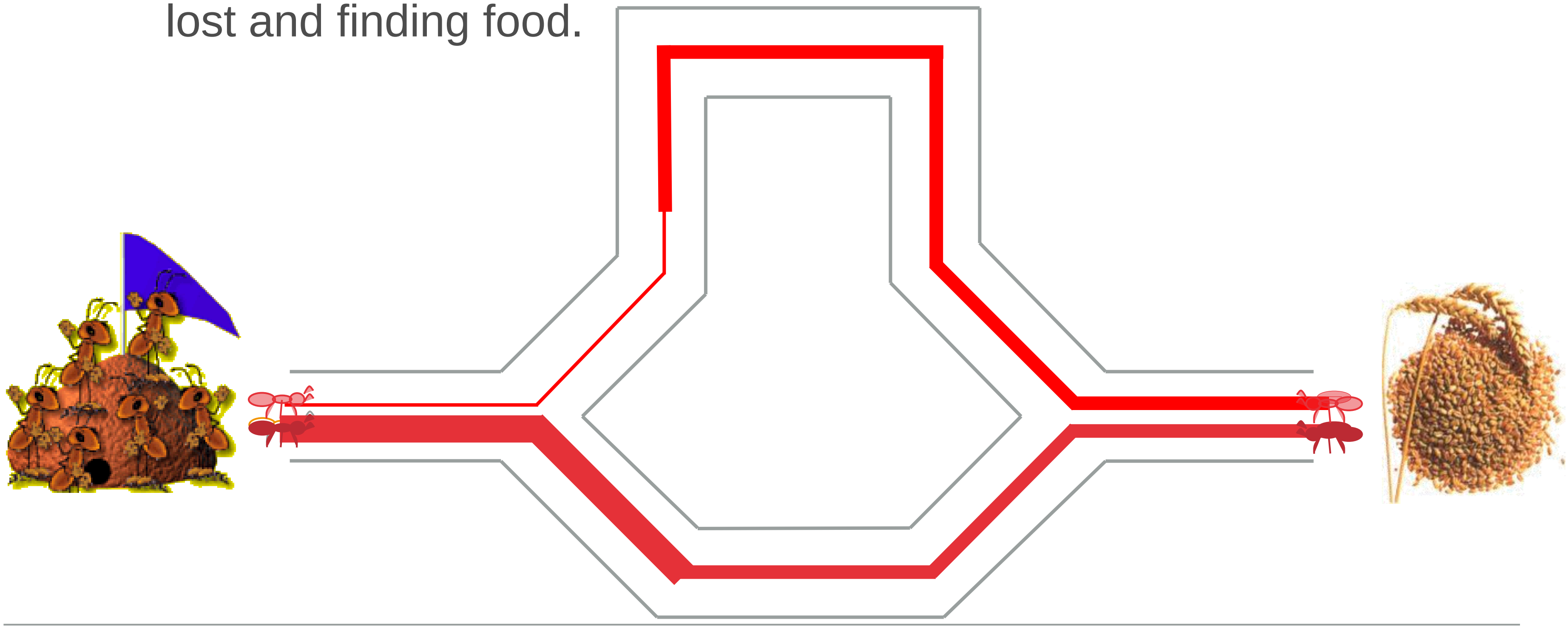
- Ants explore both paths.
- They find and prefer the shorter path.

- Distances are unknown!
- Ants are short sighted!
- Why do they find the shortest path?





- Ants deposit pheromones on their path.
- Ants prefer paths having higher pheromone concentration.
- Pheromones evaporate.
  → Ants do not care about shortest paths, only about not getting lost and finding food.



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Question: What governs here?
→ Centralised control is impossible!

Characteristics

- Colony size ~ ⟦8∗10⟧^6
- Without central authority: no one is “in charge”!
- Colony lifetime ~ 15 years (about the lifetime of one queen)
- Colonies have a “life cycle”
- Older ants behave differently from younger:
  - Older are more fixed in ways.
  - Younger are more responsive to environmental conditions.
  - Younger, though smaller, are more persistent & aggressive.
- But ants live no longer than one year!
  - Males live one day (fight & mate).
  - Colonies in an area (which may be as large as Southern England) coordinate their Nuptial Flight to one single evening.

Insight: Emergence

- Something just appears:
  - A shortest path
  - Protection
  - Role assignment
  - Gardens
- Not predictable from individual entities
- Ingredients
  - Self-organisation
  - Autonomous decisions
  - Interaction

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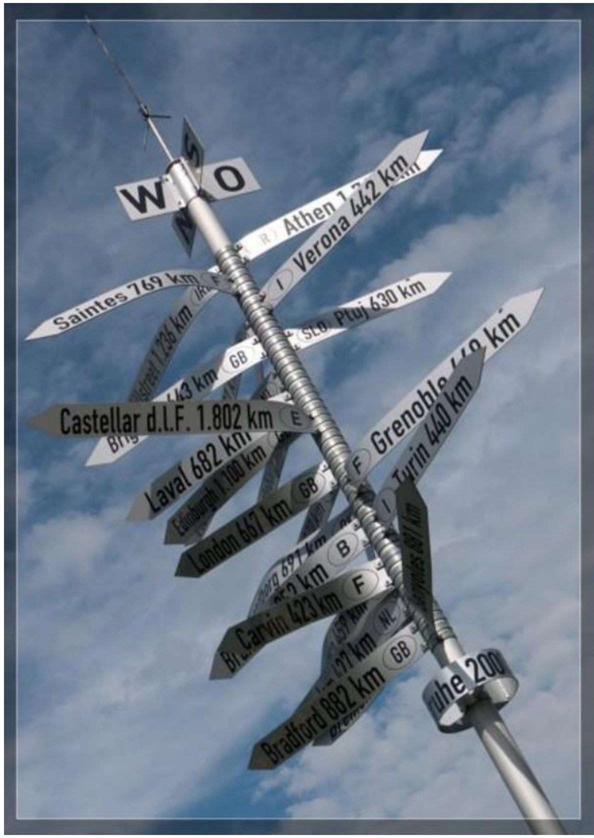


Emergence

- Emergence is a phenomenon that can be observed in various systems (especially in nature).
- In principle, it can be found if the following “ingredients“ exist:
  - A set of multiple (homogeneous) individuals
  - Individuals are self-motivated and self-organised
  - Individuals interact with each other
  - No centralised authority controls the process
- “The whole is more than the sum of its parts!”
- Let‘s have a look at some examples:
  1. From nature
  2. From technical systems
  3. From social systems

Examples from nature: swarms

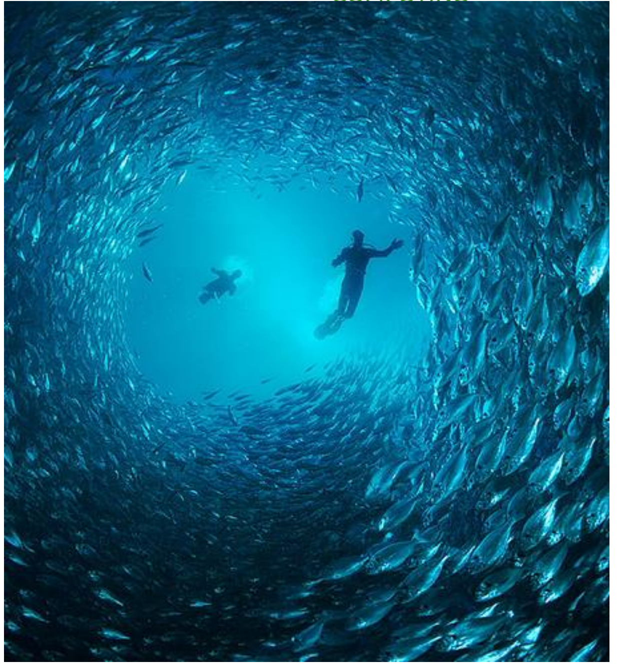
Swarms

- Flock of birds
- School of fish

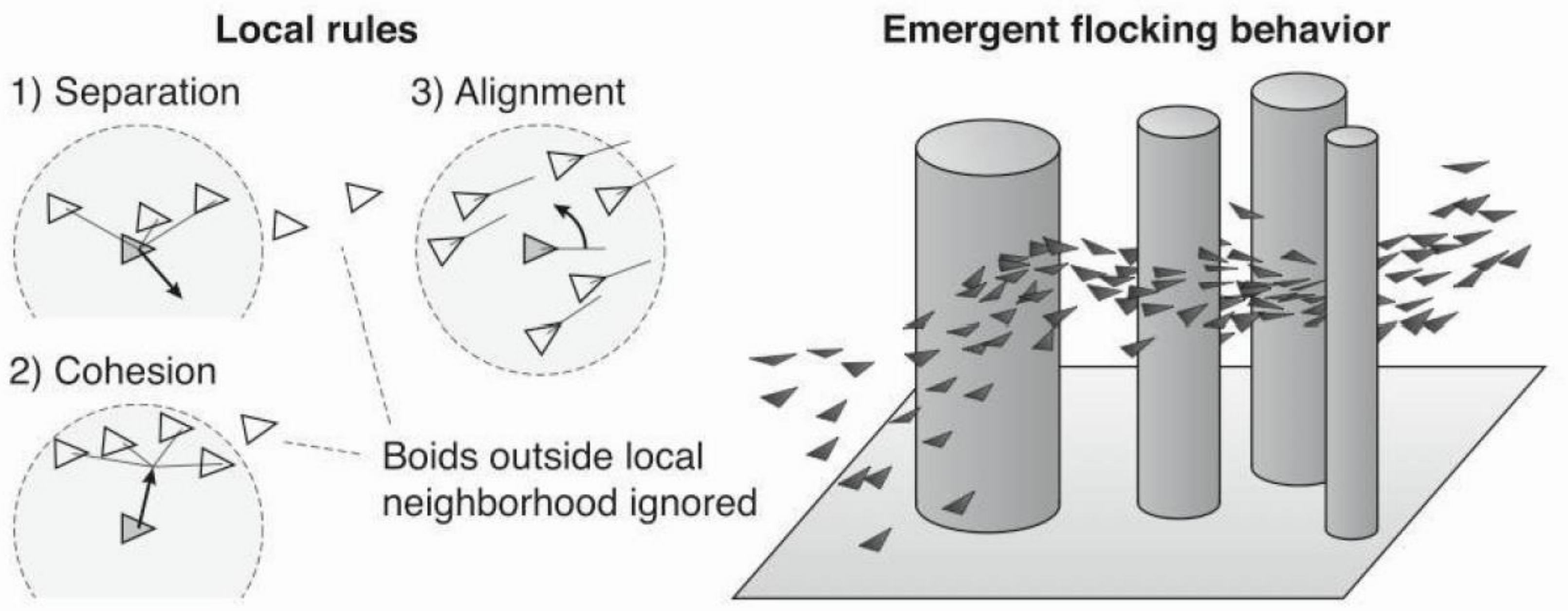
- Behave as a unified organism
- No leader, no control
- Very simple rules

Advantageous for participants:

- Avoid attackers (appear as huge fish)
- Highly resource efficient (wind for birds)



Examples from nature: swarms (2)



1. **Separation:** Boid maintains a given distance from other boids
2. **Cohesion:** Boid moves towards center of mass of neighboring boids
3. **Alignment:** Boid aligns its angle along those of neighboring boids

Termite colonies

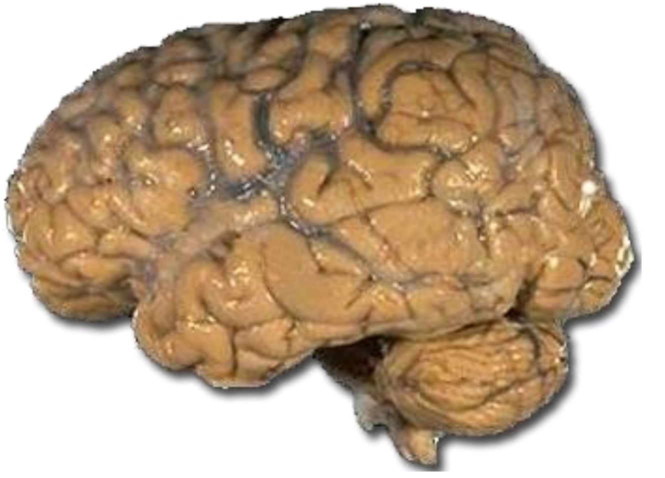
- Are able to build large “cathedral” structures.
- Structures consist of cone-shaped outer walls and ventilation ducts („Kanäle“).
- Brood chambers are situated in central hive.
- Spiral cooling vents („Öffnung“), support pillars.

Examples from nature: termites (2)

Characteristics

- No central plan!
- No intelligence required from the individual termites, just simple individual behaviours.
- Local and global interaction between termites achieve emergence.
- To ensure that the “cathedral” adapts to local conditions, a randomness to the individual’s behaviour is necessary.
- Central, top-down control would actually suppress the positive effect of emergence in termite cathedrals.

Examples from nature: the human brain



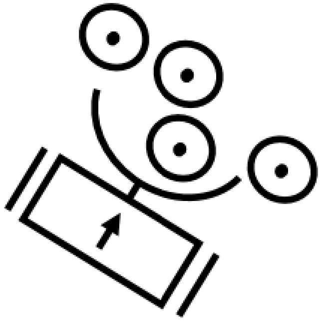
The human brain:

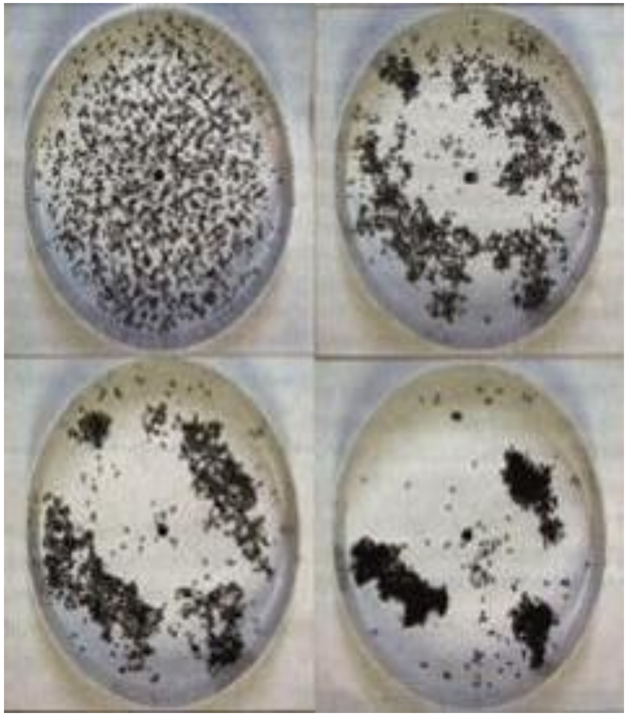
- Micro-level: the neuron
  - exhibits very simple behaviour
  - equals single-bit memory
  - has some stochastic characteristics
- Macro-level: the brain
  - About 1.5 kg, volume of around 1130 (f) / 1260 (m) cm^3
  - Consists of billions of neurons
  - Displays an infinitely sophisticated and complicated behaviour
  - I.e. language, visual, aural, and tactile I/O, the arts, culture, emotions, as well as logical thought and processing
  - Is robust, adaptive, innovative
- An examination of individual neurons cannot predict the behaviour of billions of them working together!

Technical examples: the candle mover

"Candle Mover"

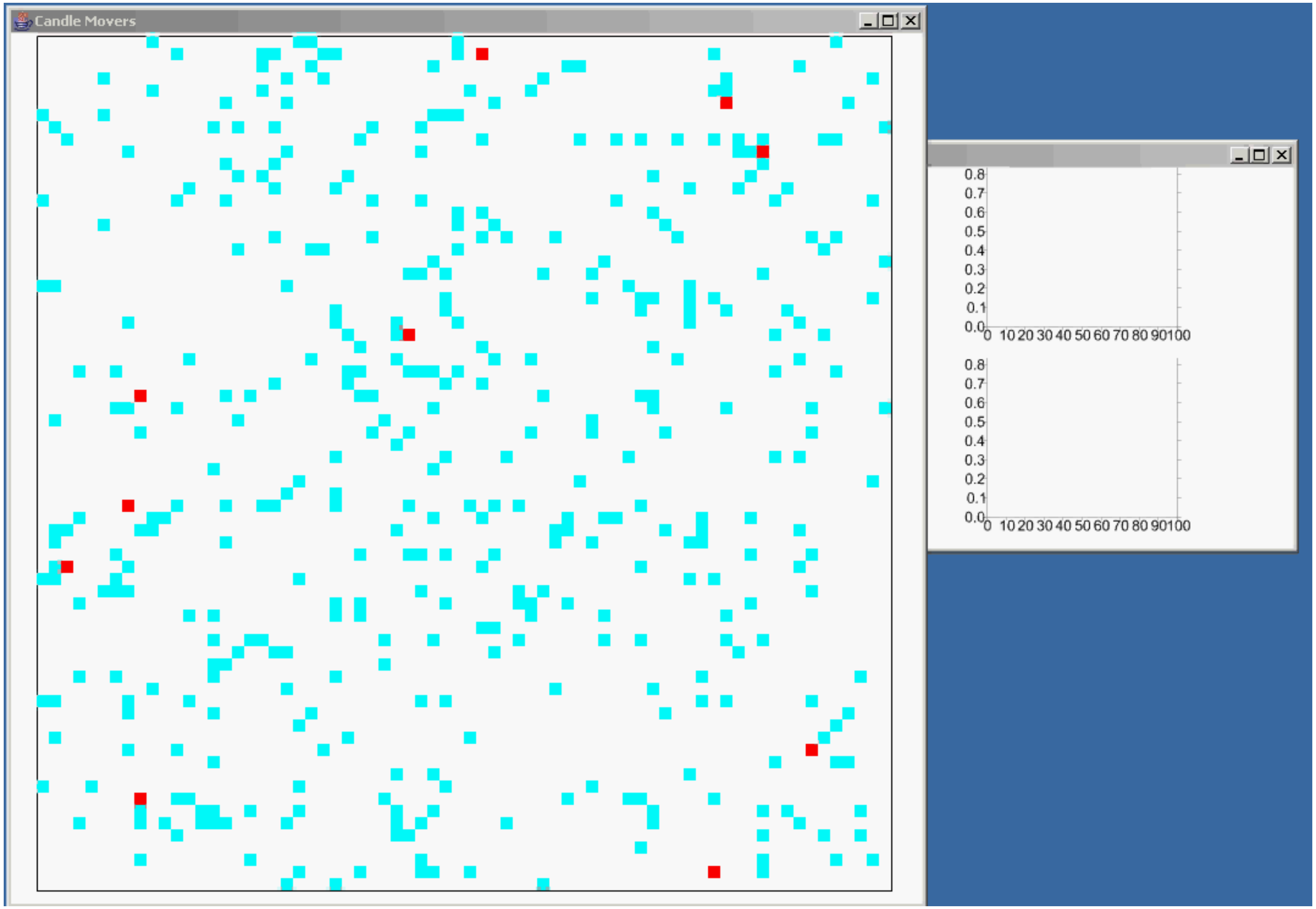
- 1 sensor (pressure)
- 1 actuator (direction)
- In case of 2 candles: move backward, turn, continue to move forward





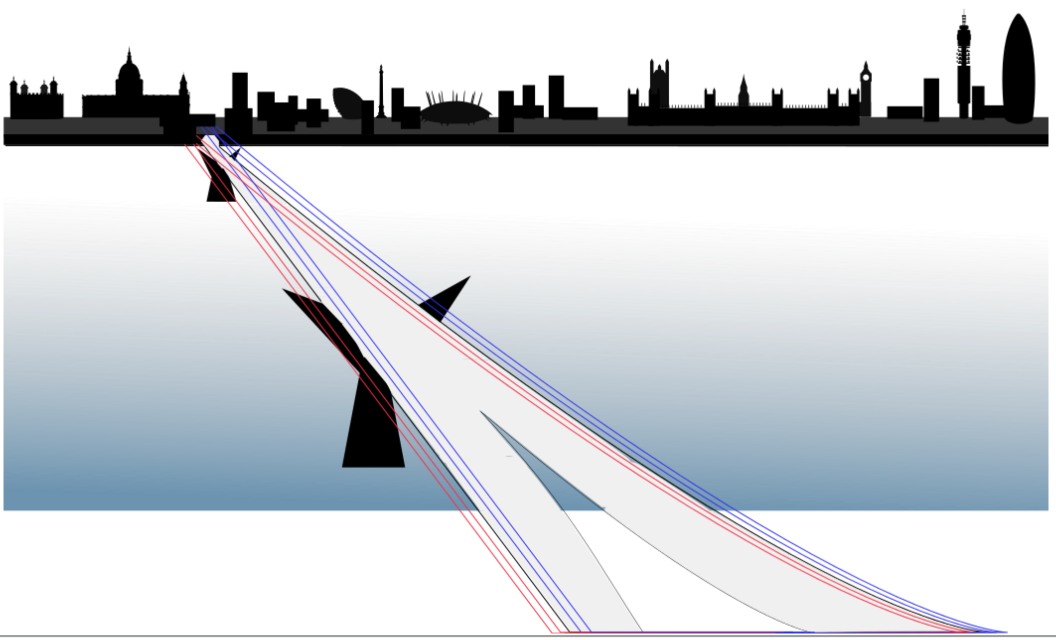
Technical examples: the candle mover (2)

What happens?



London Millennium Foot Bridge

- Built according to classical engineering.
- Analysis showed that the bridge was sufficiently strong and rigid.
- Immediately after opening, it had to be closed due to strong lateral swinging caused by a number of walking pedestrians.

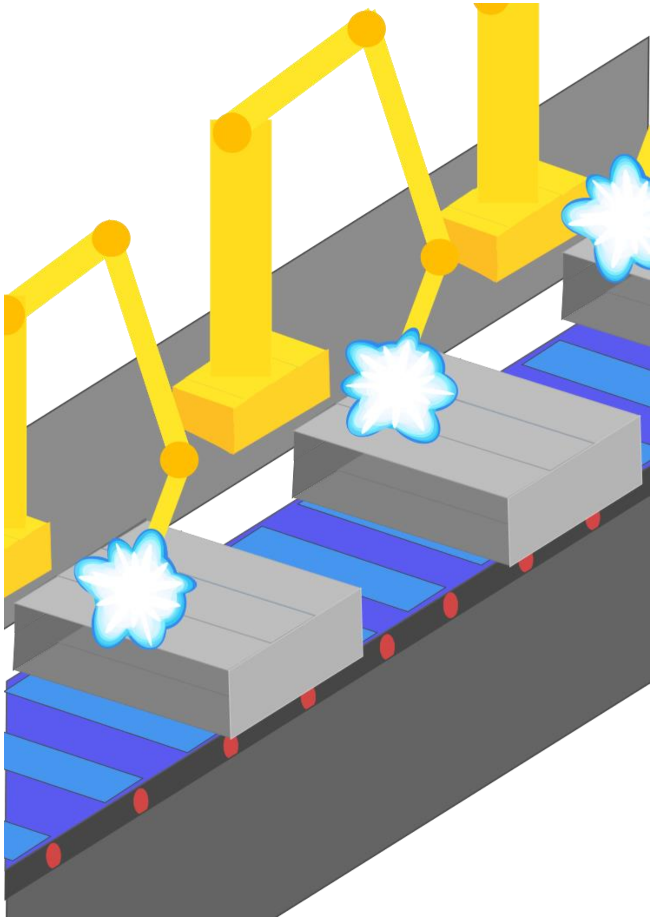


- Analysis of the emergent swinging effect
  - Natural lateral frequency of the bridge was close to the normal walking frequency of pedestrians.
  - Pedestrians were becoming synchronised in phase and frequency to each other.
    → Humans on a swaying surface tend to subconsciously synchronise their footsteps to the sway.
  - The bridge designers did not anticipate this phenomenon.
- Individual behaviour responded to the common network (the swaying bridge), thereby resulting in an unexpected top-level system behaviour.
  → This is communication, not control!

Technical examples: welding robots

Automotive Welding Robots
("Schweißroboter")

- The weld's quality depends upon the line voltage.
- Set of robots were installed in a factory.
- Random irregularities/defects were observed.
- Quality management techniques did not work.



Technical examples: welding robots (2)

Failures

- Caused by line voltage drops.
- Due to simultaneous welds from several robots.
- Design assumed random (non-synchronised) operation.
- All robots share the same networked voltage line.

Approach to alleviate the problem:

- Robot monitors the line voltage and waits until it is high enough.
  → Problem became worse: increased synchronisation.
- Result: No synchronisation due to random delays.
  → Note the importance of stochastic behaviour.

Technical examples: hard drives

"Enterprise" Server Disk Drives

- Sensitive to vibration
- Especially in case of synchronised seek activity
- Set of disk drives mounted together → Data faults were experienced.
- I.e. computer system database searches caused several disk drives to seek simultaneously, thereby building up synchronised vibration that disturbed each other's operation.

Technical examples: hard drives (2)

Emergent behaviour

- Simultaneous disk drive seek operations are inherent to large enterprise servers – inducing emergent behaviour among multiple disk drives.
- The disk drives have to be especially designed for such applications.
  → Much more expensive than “ordinary” disk drives.

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Freeway Traffic Jams

- Drivers act egoistically (avoid traffic jams).
- Observation: Minor perturbation in high traffic periods cause traffic jams.
  - Areas of light and areas of jammed traffic appear periodically.
  - Especially at fast lanes.
  - Total effective flow rate of cars is significantly reduced.

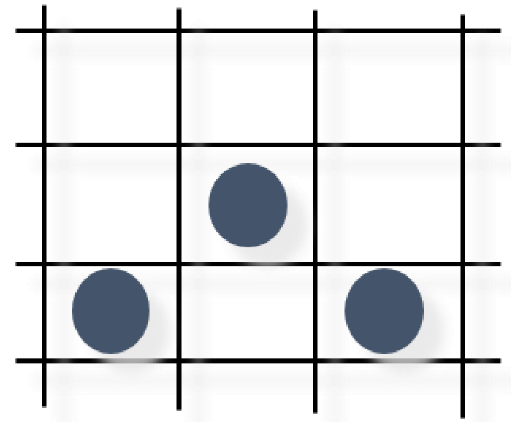
v=const 85km/h -> full stop	v=const 85km/h -> break hard	v=const 85km/h -> break	v=const 85km/h -> slow down	v=const 80km/h

Technical examples: traffic jams (2)

- Result of emergent behaviour!
  - Individual drivers attempt to respond to minor perturbations, but with delay.
  - Drivers in the fast lane have more “gain” in their behaviour.
  - Combination of non-linear delays and high gain leads to oscillations.
    → Result: congestion and reduced flow rate.
- Solution: relax, go with the flow (i.e., reduce your driving “gain”).
  → Leads to variability in separation distances.
  → Net flow rate is only slightly decreased.

Technical examples: Cellular Automata

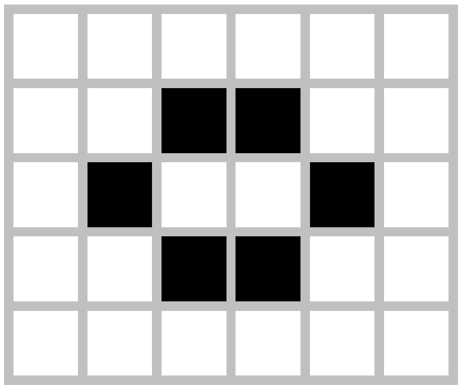
- Field of Finite State Machines (FSM)
- Automaton changes its state depending on the states of its neighbours
- Example: Game of Life (John Conway) http://www.bitstorm.org/gameoflife/



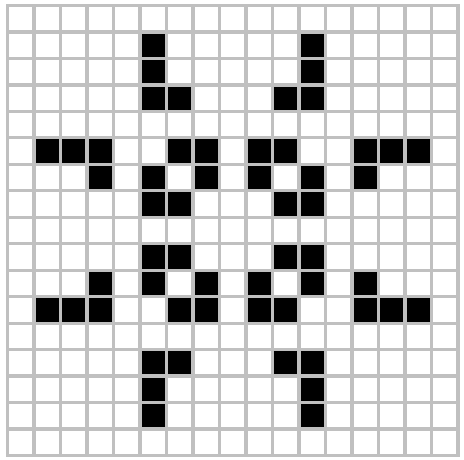
- Example rule set:

≤ 1	neighbour	dead
2	neighbours	const
3	neighbours	alive
≥ 4	neighbours	dead

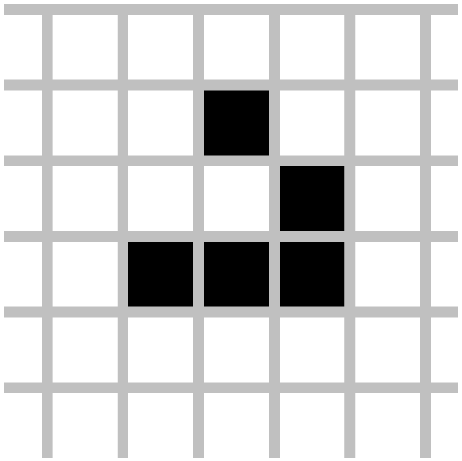
The “Game of Life“



Static



Oscillating

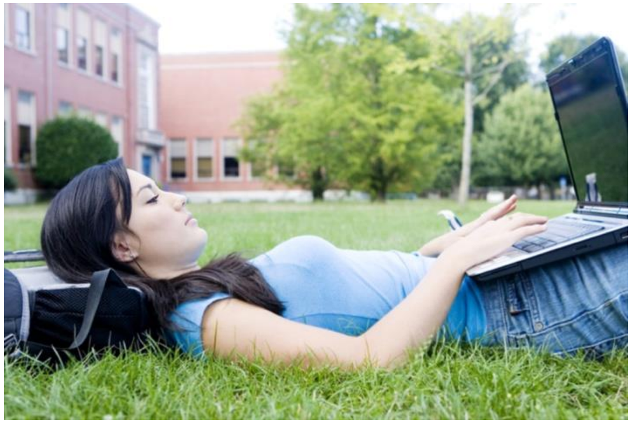


Moving

- Generalisation based on: form, position, colour, communication, etc.
  → Used to simulate united cell structures.

Source: http://en.wikipedia.org/wiki/Conway%27s_Game_of_Life

Social examples: sidewalk structures



- Optimised sidewalk structure
  - University of Michigan built a new campus.
  - Concrete sidewalks were to be placed in the Quad between buildings, but how to design?
  - Once installed they are difficult to change.
  - Previous approaches turned out to be not useful.
- Concept:
  - Plant grass and allow students to walk as they want.
  - Concrete sidewalks were installed according to emerging patterns.
  - Students and faculty are cognitive and adaptive elements in a larger system.
  - At a system level, their patterns of walking could not be accurately predicted.
  - Later analysis showed that as a group, an optimum sidewalk structure was derived.

Social examples: social networks

Social network:

- Nodes = people
- Edges = relations between people
  → E.g.: friends, relatives, colleagues
- Paths:
  - Chain of people
  - E.g.: friend of my friend of my friend

Interesting properties:

- Decentralised, self-organising, robust, scalable network
  → E.g.: people are born, die, get to know new people
- Efficient (short) communication paths & decentralised routing
  - See Milgram's Experiment

Social examples: Milgram‘s experiment

- Analysis of paths in social networks
  - Conducted in the 1960s by Stanley Milgram
  - Stanley Milgram (1933 –1984) was an American social psychologist.
- Milgram sends a letter to 160 randomly selected persons from Omaha and Nebraska (USA).
- Letter contains task: Deliver letter to a certain stock broker in Boston, Massachusetts, USA.
- Constraints: Persons must only send letter to someone they know at a “first name basis” (i.e.: friends, colleagues).
- Results:
  - 44 letters reached the target
  - Average number of “hops”: 6
    I.e., short paths in network of 200 million US citizens!

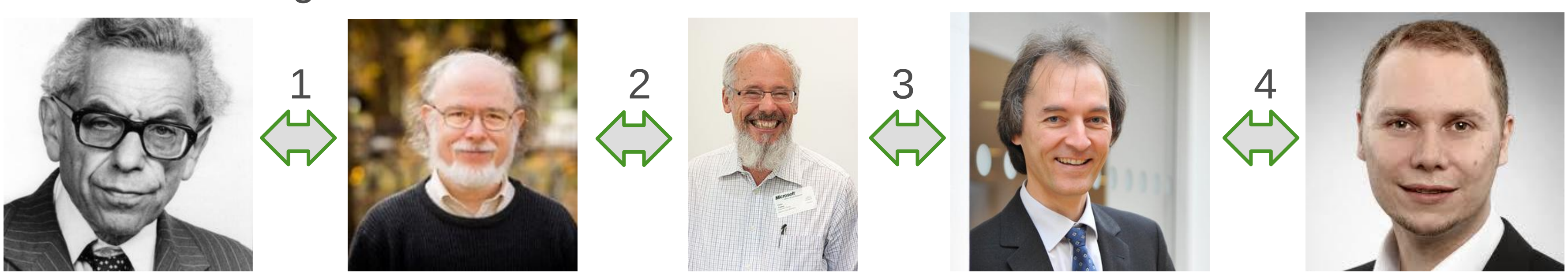
Emergent property: This is a small world!

Further examples for small world networks:

- Network derived from movie database
  - Nodes: actors
  - Edge between two actors if they have acted in same movie
- Bacon number of actor:
  Shortest path between an actor and Kevin Bacon
  - Average bacon number: 2.9
  - Via Kevin Bacon, any actor can be linked to any other in 6 “hops”
- 6 is a typical distance between pairs of nodes in such networks.
  → 6 degrees of separation

Further social examples

- “Die Zeit” linked a Turkish Kebab-shop owner in Frankfurt, Germany, to his favorite actor Marlon Brando in 6 hops:
  - Shop owner has a friend in California who works together with the boyfriend of a woman who is in the same student’s union of the daughter of the producer of the movie “Don Juan” starring Marlon Brando.
- Erdös number: distance in graph of paper (co-) authors
  - Paul Erdös: famous mathematician (> 1500 papers with > 500 co-authors)
  - Average Erdös number: 4.7
  - Average distance between authors: 7.3



Paul Erdös   Brendan D. McKay   Peter Eades   Jürgen Branke   Sven Tomforde

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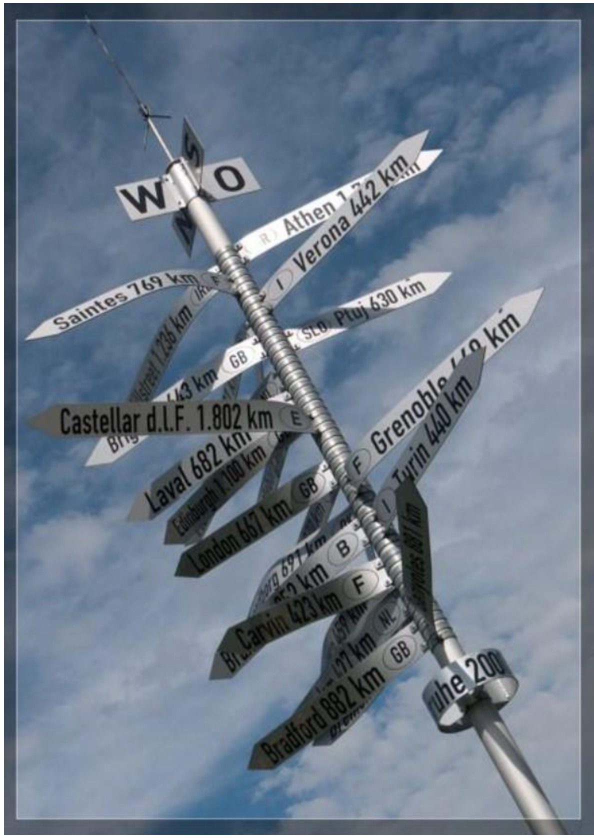
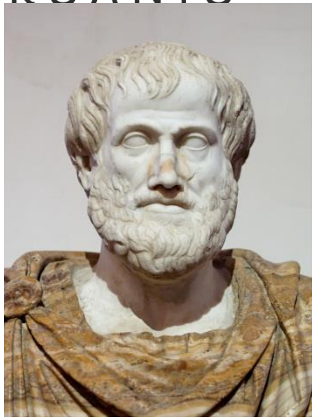


Term definition: “emergence”

- How macroscopic behaviour arises from microscopic behaviour.
- Emergent entities (properties or substances) ‘arise’ out of more fundamental entities and yet are ‘novel’ or ‘irreducible’ with respect to them.
  [Stanford Encyclopedia of Philosophy: http://plato.stanford.edu/entries/properties-emergent/]

- “It is unlikely that a topic as complicated as emergence will submit meekly (“widerspruchslos”) to a concise definition, and I have no such definition to offer.“
  [John Holland: „*Emergence: From Chaos to Order*“]

Emergence (2)



Emergence

- Comes from “*to emerge” (in German: „auftauchen“)*
- Verbal description:
  - “A system is more than the sum of its parts.“
  - From Aristotle (384 BC – 322 BC); Greek philosopher and polymath.
- Is a characteristic of the whole system, not part of the subsystems.

Definition:

- „An emergent system characteristic is a property, which is not only defined by the elements contained in the system, but by the interaction between these elements.“
- Emergent system characteristics are not computable by *summarising* the characteristics of the contained parts.
- Emergent behaviour is the result of interactions between processes.

Emergence (3)

Sources of Emergent Behaviour

- Unwanted/unintended synchronisation, or oscillation
- Local or global networks allowing wanted/unwanted communication (often unintentional networks)
- Non-linear interaction between simple elements
- Thrashing: competition over a scarce resource
- Chaotic (even if deterministic) behaviour
  → Emergence is nature's way of dealing with chaos.
- Intentional, or unintentional, feedback loops with poor gain margins.
- Intelligent, adaptive elements in the system.
  → This means that the behaviour of the elements as well as the system architecture varies with time, depending upon conditions.

Emergence (4)

Management of emergent behaviour

- Prevent or mitigate the sources of emergence.
- Design limits into systems to lessen the negative effects of emergence.
- Add **extra stability and robustness** to the system.
- Use simulations to detect and design for emergence (caution, very sophisticated simulations required; beware of chaos theory).
- Reduce non-linearity.
- Increase scarce resources to minimise thrashing.
- Use the evolutionary (also called incremental or spiral) development life cycle to discover emergent behaviour.

- Goal: Promote its positive effects and suppress its negative effects!