SYSTEMS

- Voinov (2008) defines a system as "*a combination of parts that interact and produce some new quality of functions in their interactions*"

- There are three important characteristics of systems:
  - Systems are made of **parts**, or **elements**;
  - These elements are in **interaction**;
  - The interactions between elements **result in new features** of the whole

Elements

System

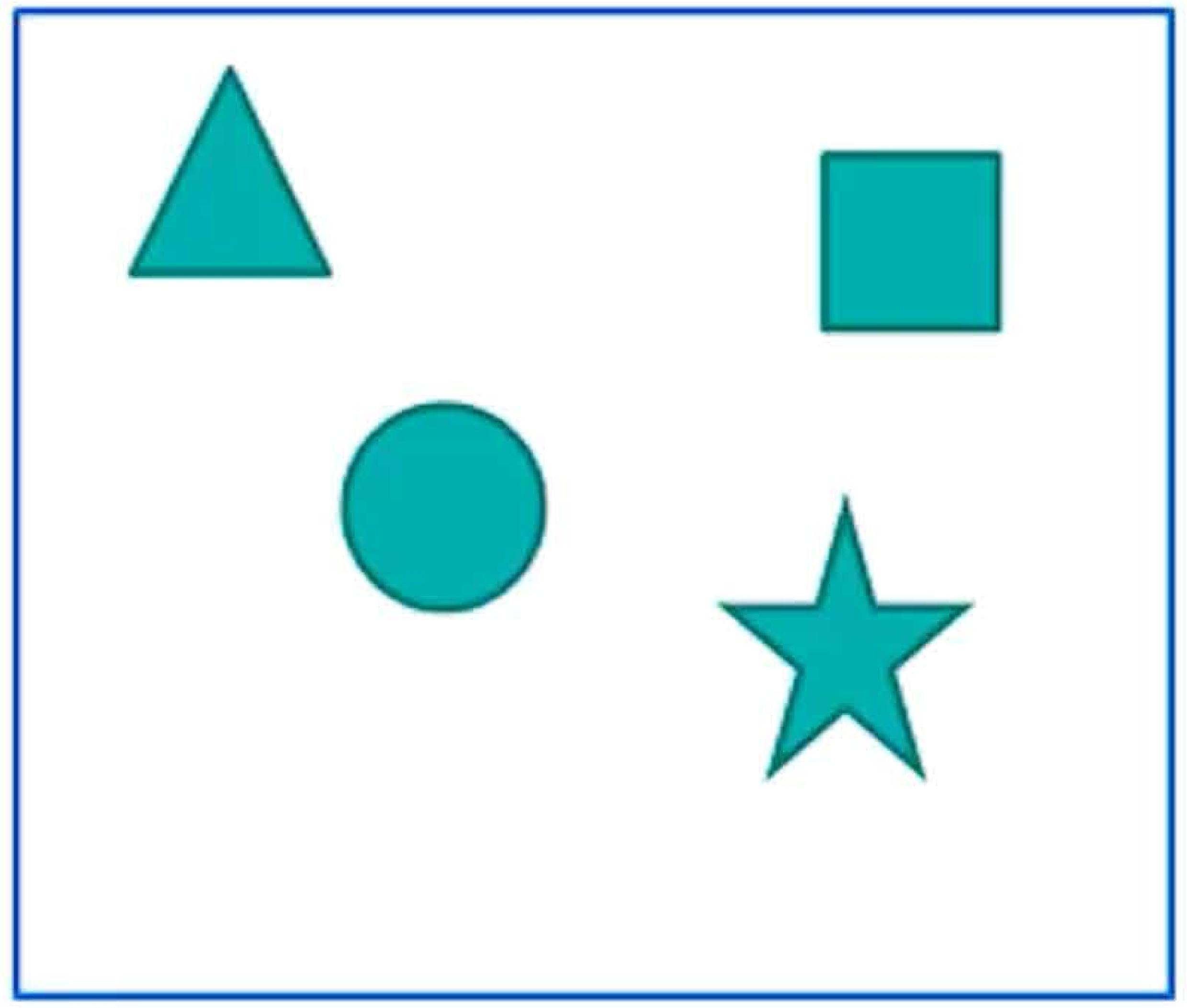
Images: Kovalenko (no date) | Rawpixels (no date)

SYSTEMS

- The elements of a system **differ from each other** (are not identical)

- The elements have a particular **order/position**

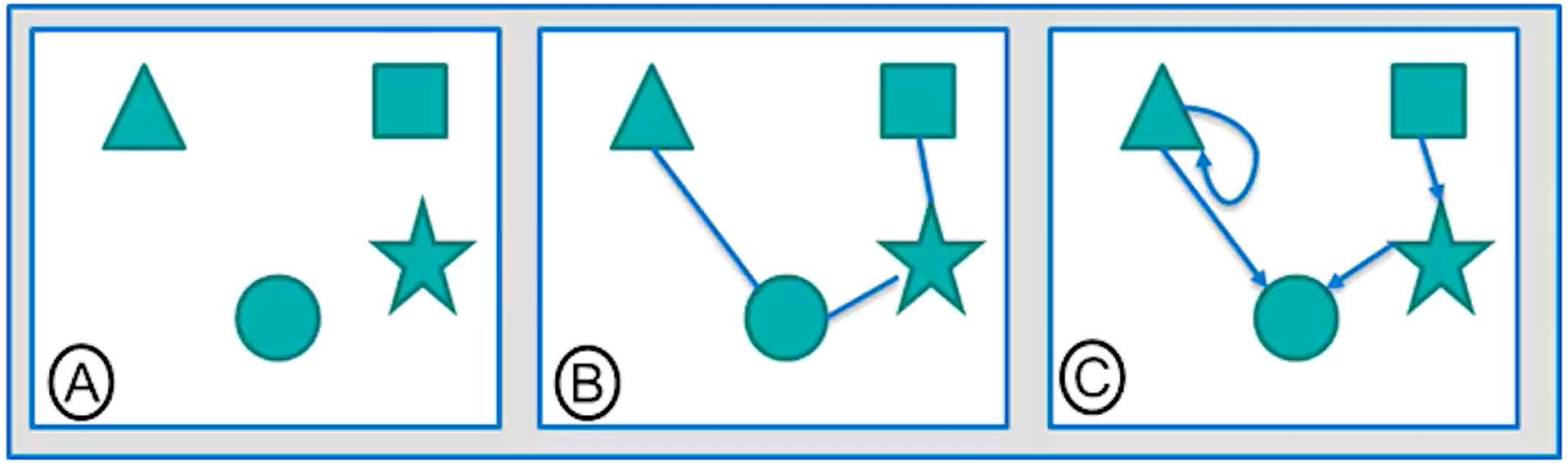
Identical Pieces



Images: Ellen-Wien Augustijn

INTERACTIONS

- The **interactions, relationships** between the elements are essential to describe the system
- Relationships between elements can be described as **flows:**
  - Flow of materials, and
  - Flow of information

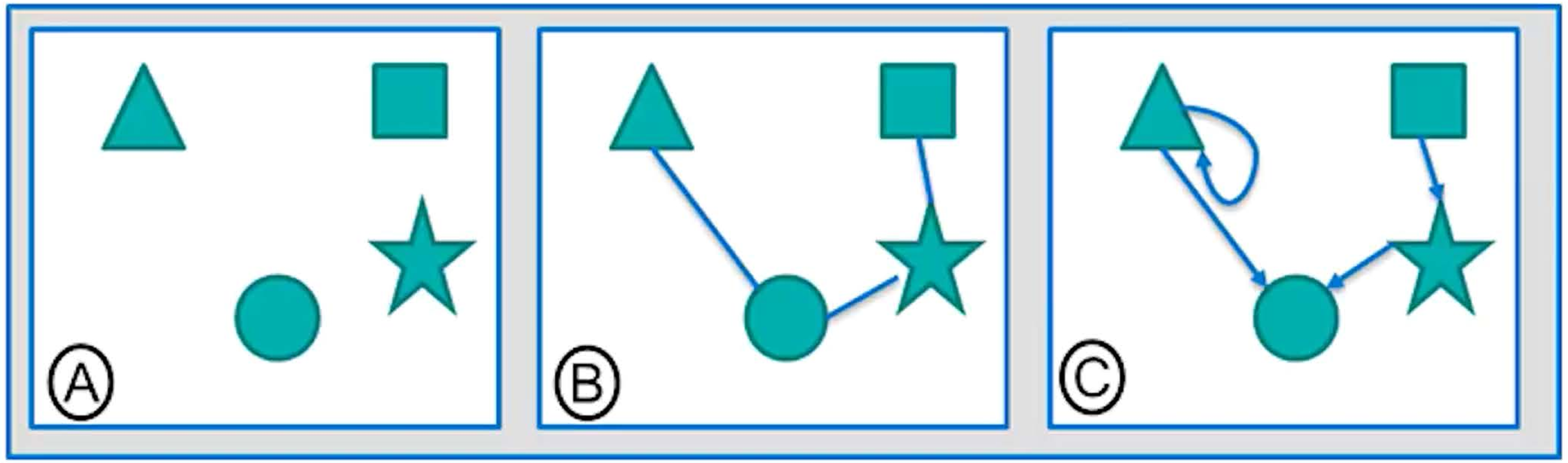


The Core of GIScience – ITC (2012)

INTERACTIONS

- When **A** impacts **B**, while at the same time **B** impacts **A**

- **Positive feedback loops**: A larger population leads to more births occurring (the larger the number of people in the population, the more babies are born)
- **Negative feedback loops:** a system with negative feedback tries to stabilize itself according to the rules: **the larger something is** – the **smaller something becomes**. (if there is a limited food supply and the population grows – the less food per person)



The Core of GIScience – ITC (2012)

In this course you will learn how to create a model that represents a part of reality.

To do this well, you must know how to look at our world with a modeller's eye. Let us take this step together.

In this lecture we will address 3 problems.

- **What is a system?**
- **What makes a system a complex system?**
- **And what is the link between a complex system and agent-based modelling?**

Let us start with the first problem.

1. What is a system?

- A former colleague of mine, Alexei Voinov, defined a system as a combination of parts that interact and produce some new quality or function in their interaction.
- Systems consist of elements or parts, for example, the parts of a car, like the steering wheel, the windshield, or the wheels of that car.
- Note that all of these parts are different.
- The second important aspect of a system is that there is interaction between the elements.
- When we do not put that car together, it will never become a vehicle we can drive.
- Driving is what we call a new feature that a complete car has, but none of its parts can do it on their own.
- The parts of a pie are not the pieces you cut out of that pie. The parts of the pie are the whipping cream you used for the filling, and the dough that was used for the crust.
- Each element has a particular order or position in the system.
- The interactions are just as important as the elements.
- They represent flow of information, for example like on social media, or flows of materials, for example the wind that moves the sand on the beach to form dunes.
- **When we have a closer look at the interactions, we distinguish two types of loops:**
    - i. **positive feedback loops:**
        1. An example of a positive feedback loop is a population where more babies are born.
        2. Because of this, there will be more people. These babies will have more children and the population will keep on growing.
    - ii. **negative feedback loops:**
        1. With a negative feedback loop, more leads to less.

2. When there is a limited food supply and the population grows, each person will get less food, leading to more deaths, and the population will become smaller.

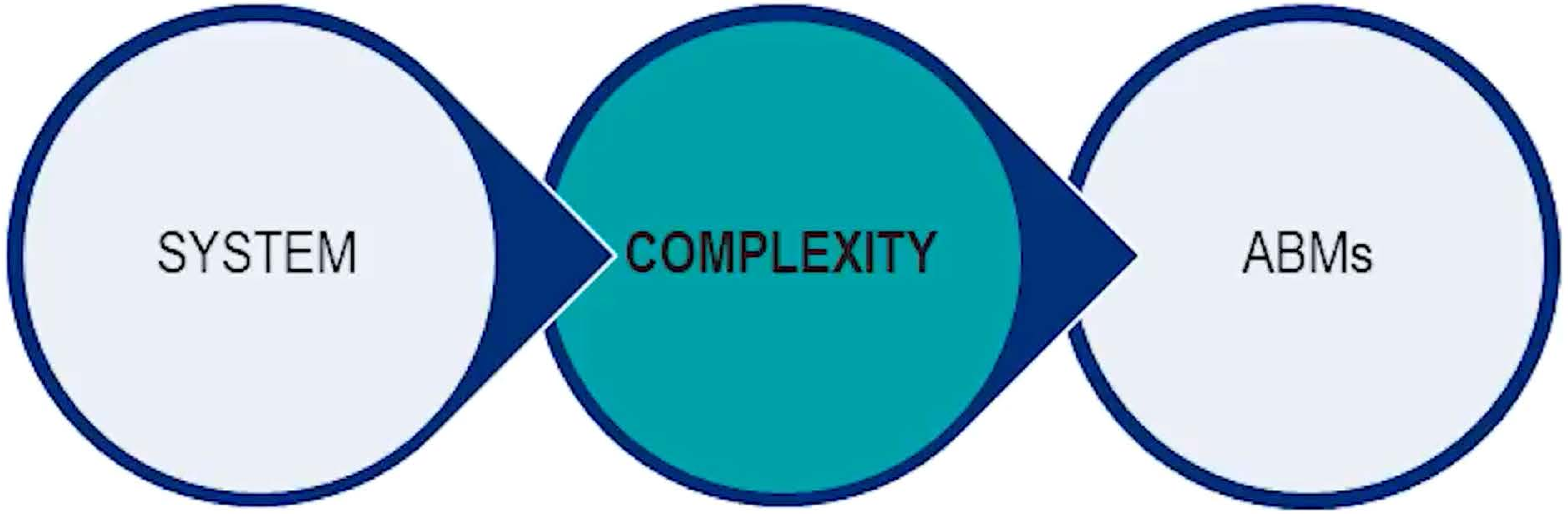
- **Subsequently, there will be more food per person and the population will grow again.**

COMPLEX SYSTEMS

Complex systems are those that consist of **many interconnected components**, where the behavior of the system **as a whole** cannot be predicted from the behavior of its **individual** components.

Complex systems are **hierarchical.**

Sub-systems are **nested in larger systems.**



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HIERARCHICAL

- A living organism consists of **cells** – these cells **interact** to form such an organism
- Fish form a **school of fish**
- Fish **interact** with vegetation to find places to reproduce (lay eggs), are eaten by larger fish and humans, they change the geomorphology by disturbing the bottom of the lake → **they are part of an ecosystem**

Images: Ellen-Wien Augustijn

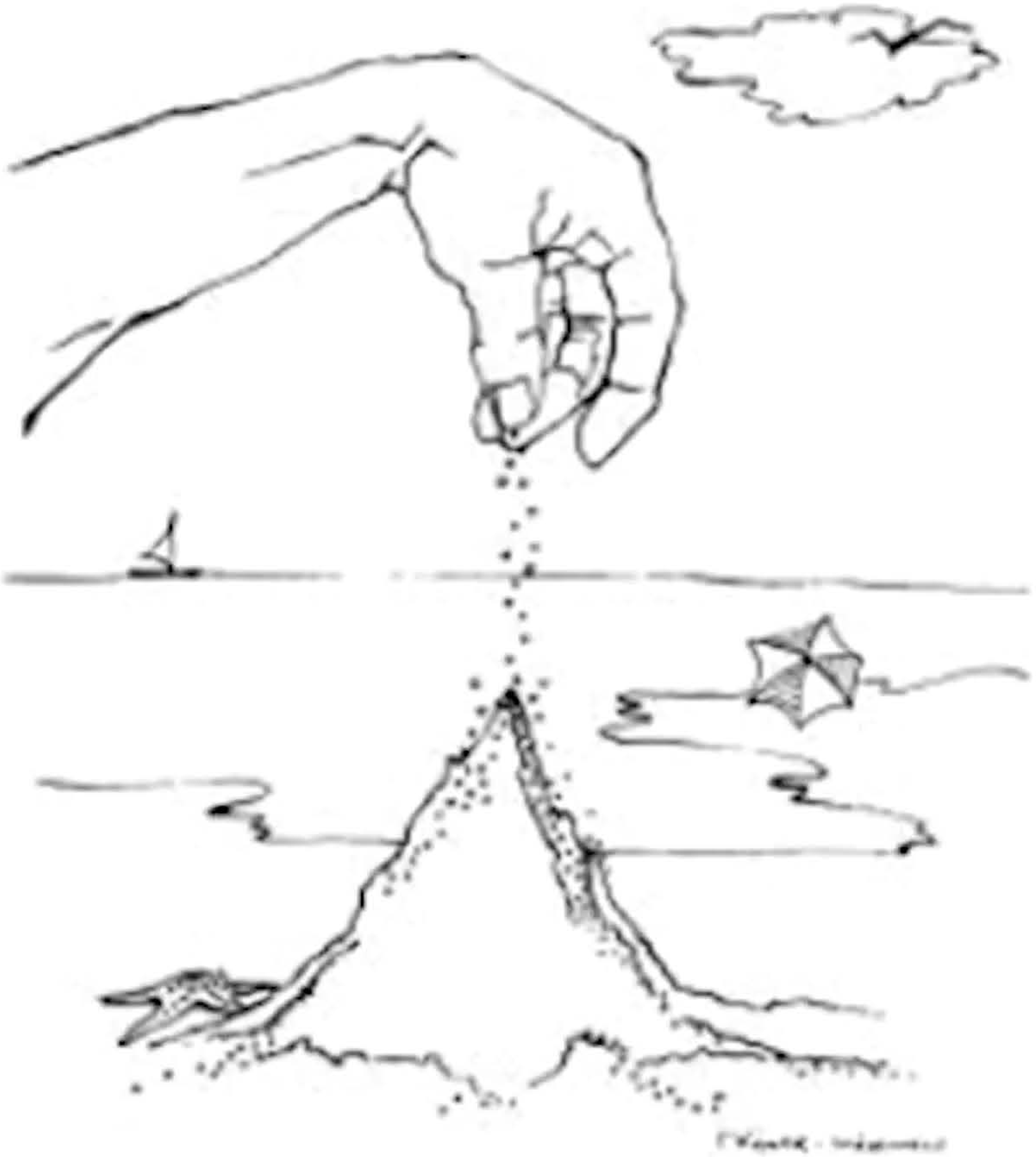
COMPLEX SYSTEMS

NON-LINEARITY DUE TO INTERDEPENDENCY OF ELEMENTS

Complex systems are those that consist of **many interconnected components**, where the behavior of the system **as a whole** cannot be predicted from the behavior of its **individual** components.

1. Complex systems are **hierarchical**, sub-systems are **nested in larger systems**
2. Complex systems are **non-linear** due to **interdependency** of the elements
    1. State transitions
    2. Small changes can have large impacts
    3. Scaleless behavior (fractals)
    4. Tipping points

STATE TRANSITIONS



Per Bak

Images: Bak (1996) | The Paula Gordon Show (no date)

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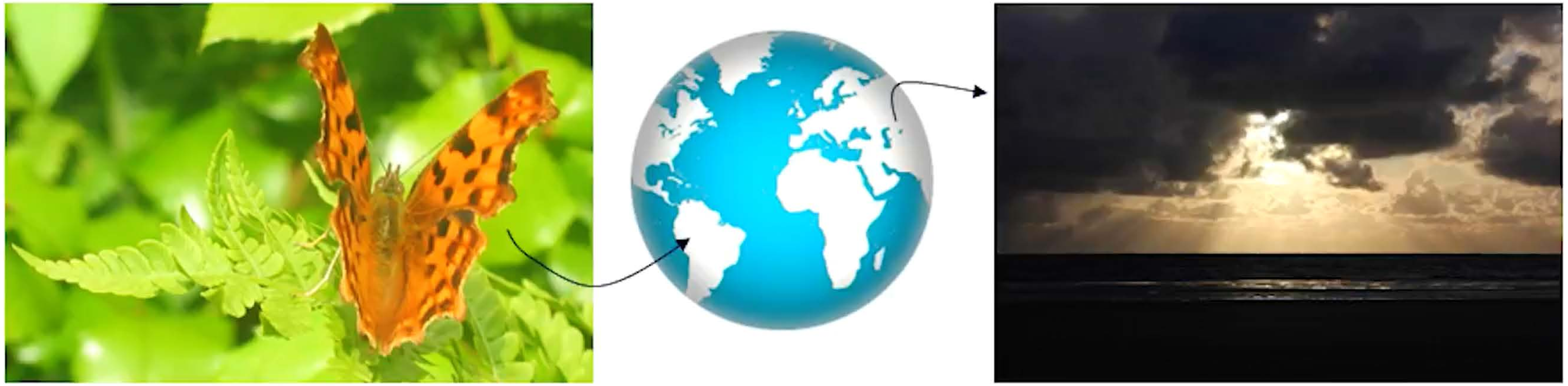
THE BUTTERFLY EXAMPLE

SMALL CHANGE WITH LARGE EFFECT

The **butterfly effect** is a concept that states that "small causes can have larger effects". (introduced by Edward Lorentz)

The sensitive dependence on initial conditions in which a small change in one state of a deterministic nonlinear system can result in large differences in a later state



Images: Ellen-Wien Augustijn

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SCALE-LESS BEHAVIOR

FRACTALS

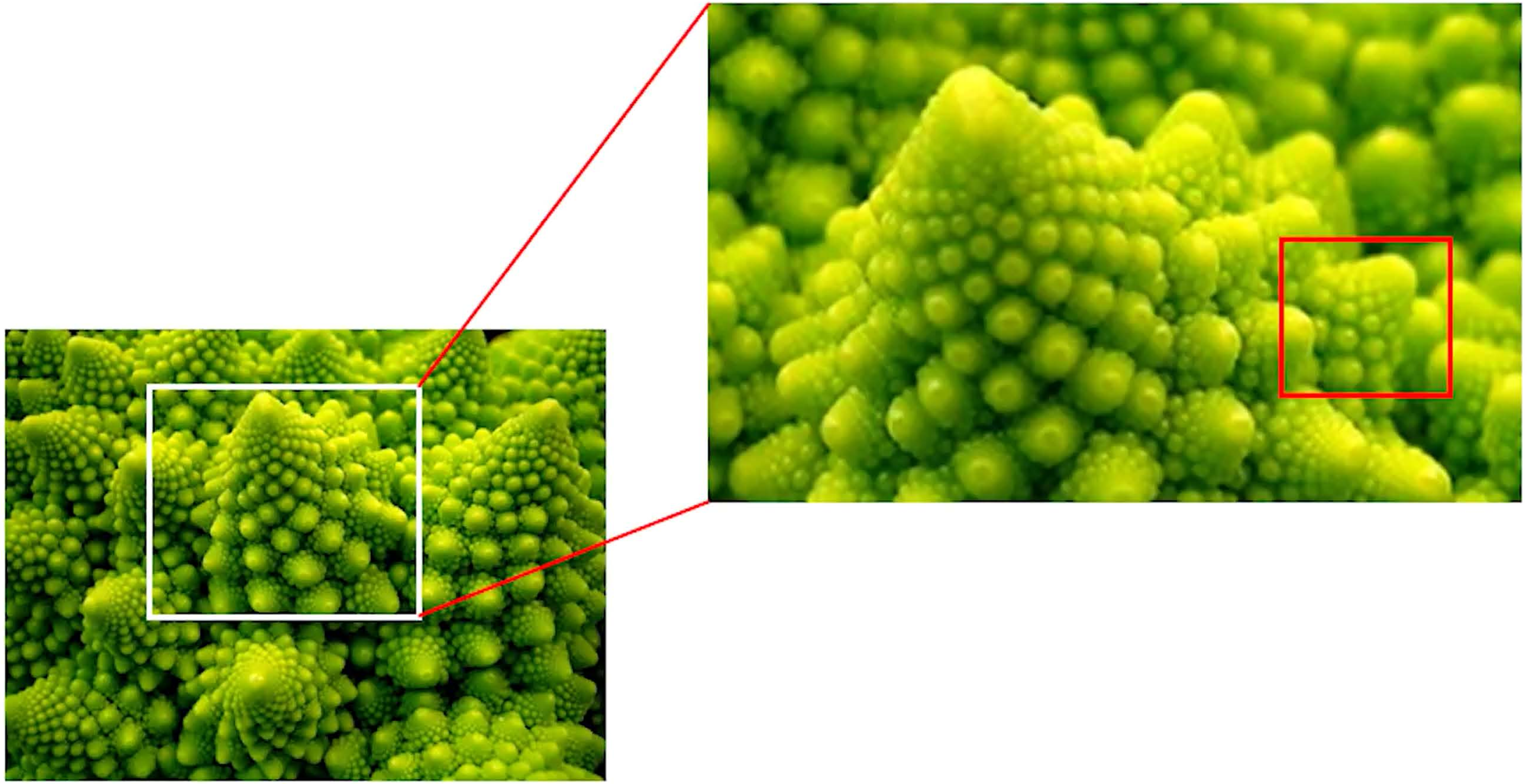
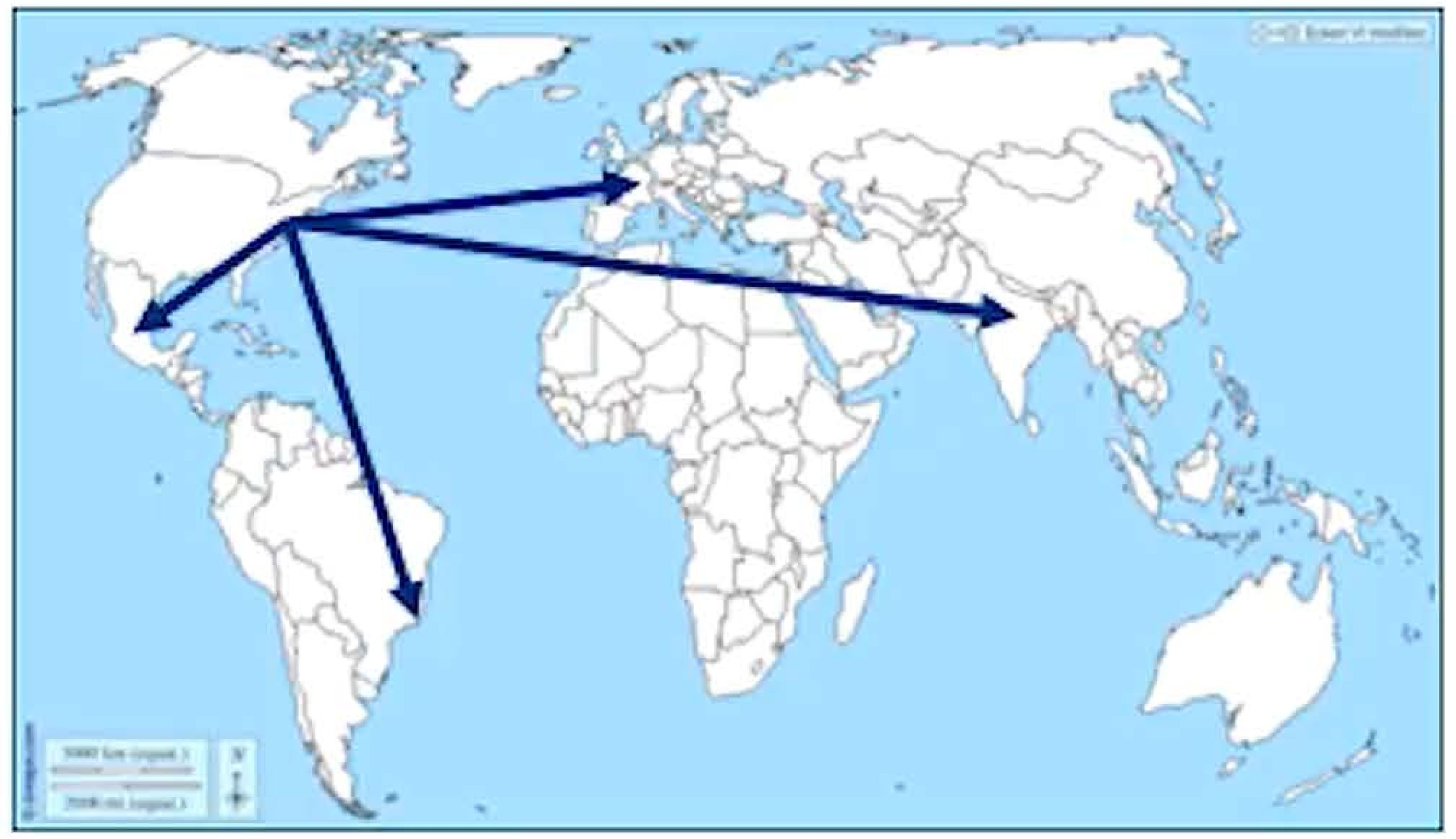


Image: tin.G (2005)

SCALE-LESS BEHAVIOR



Images: d-maps.com (2023) - Plenisphere World (Europe-Africa), Europe: States, and Netherlands: Provinces

SYSTEM EARTH AND DYNAMICS

Video source: Ellen-Wien Augustijn

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CONNECTIVITY

Complex systems are those that consist of many **interconnected** components, where the behavior of the system **as a whole** cannot be predicted from the behavior of its **individual** components.

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2. Complex systems are **non-linear** due to **interdependency** of the elements
   a. State transitions
   b. Small changes can have large impacts
   c. Scaleless behavior (fractals)
   d. Tipping points
3. The system is defined by its **connections** (connectivity)

CONNECTIVITY

- What is connected to what
- A network develops
- Topology of connectivity
- Elements have a degree of connectivity and a position in the network structure

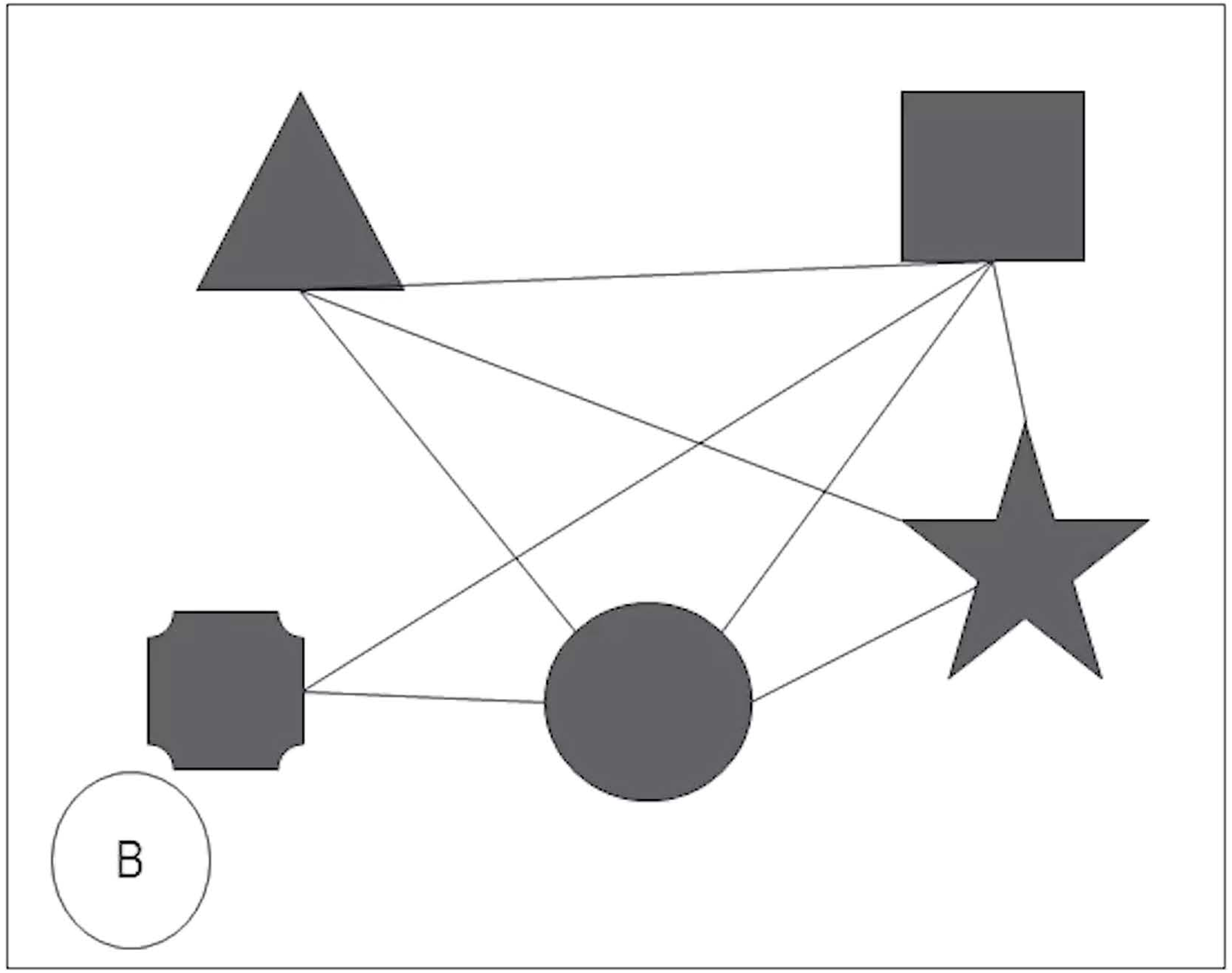

Image: Ellen-Wien Augustijn

PATTERNS

Complex systems are those that consist of many **interconnected** components, where the behavior of the system **as a whole** cannot be predicted from the behavior of its **individual** components.

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3. The system is defined by its **connections** (connectivity)
4. Due to adaptation, **patterns** like flocking of birds **emerge**

EMERGENCE

- Emergent phenomena are characterized by stable macroscopic patterns arising from local interaction of individual entities

- The whole is more than the sum of the parts

- Similar to self-organization, chaos, etc.

What can emerge:

- Patterns
- Structures
- Behavior (An **emergent behavior** or **emergent property** can appear when several simple entities operate in an environment, forming more complex behaviors as a collective)
- American Chemical Society video on how snowflakes form https://www.youtube.com/watch?v=-6zr2eLpdul

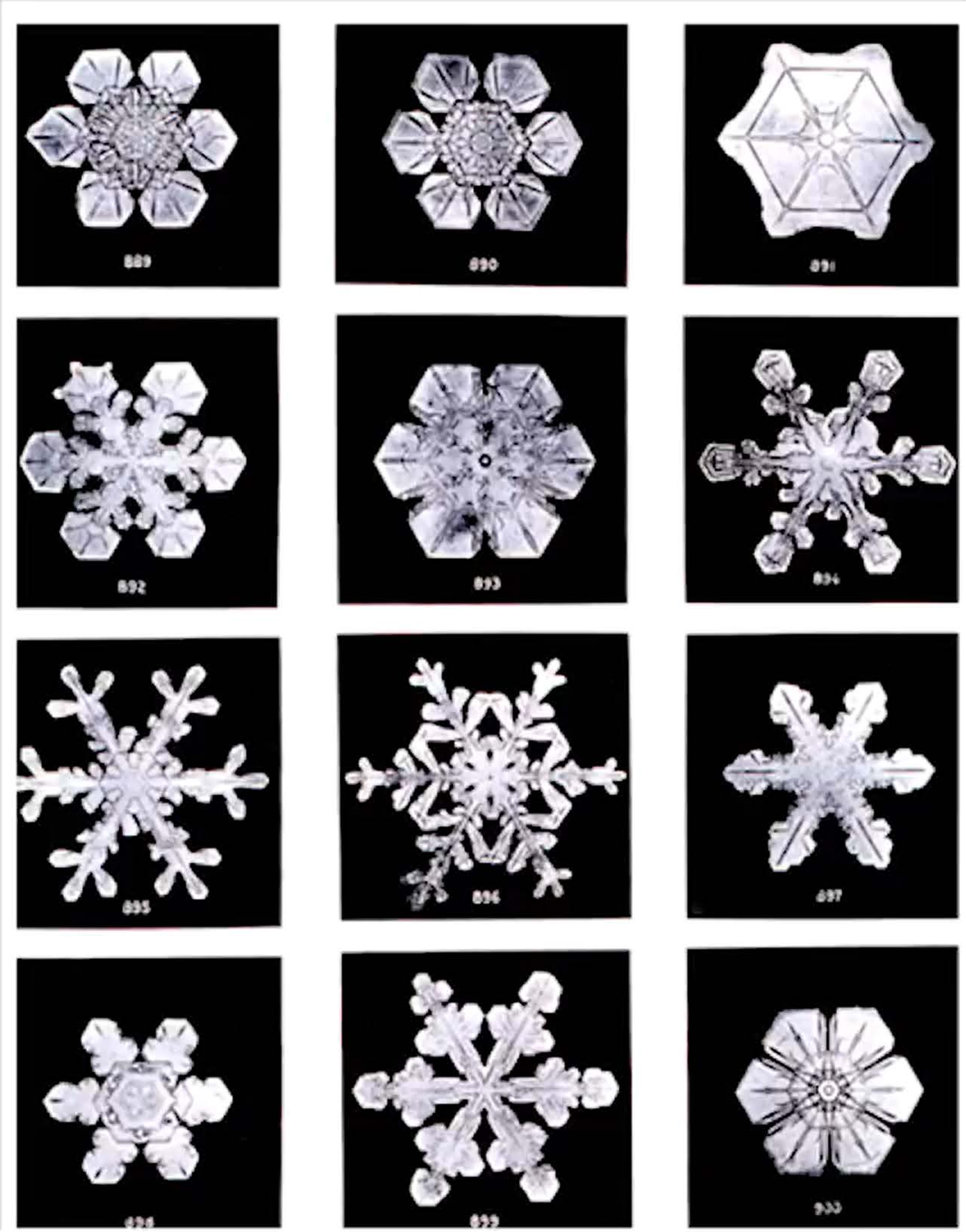

Image: Bentley (1902)

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Image: Mint_Images (no date)

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SUMMARY

- **Complex systems** are those that consist of many **interconnected** components, where the behavior of the system **as a whole** cannot be predicted from the behavior of its **individual** components.

1. Complex systems are **hierarchical**, sub-systems are **nested** in larger systems
2. Complex systems are **non-linear** due to **interdependency** of the elements
   - State transitions
   - Small changes can have large impacts
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2. What makes a system a complex system?

- In our daily life we call something complex when we mean complicated, but in science we have a definition for complexity.

- Complex systems are systems that consist of many interconnected elements, where the behaviour of the whole system cannot be predicted from the behaviour of its individual components.

- **We will discuss 4 aspects of complex systems:**
    - i. **Hierarchies**
    - ii. **non-linearity**
    - iii. **connectivity**
    - iv. **emergence**

- Let us start with the first characteristic of complex systems:
    - i. **Hierarchies:**
        1. In a complex system, we can identify organisation at various hierarchical levels.

        2. When we look at an individual fish, this fish consists of cells that together form the fish and give it its ability to function.

        3. Fish can also be studied as groups that form schools and that swim together in an organised way at an even higher complexity level.

        4. The fish is part of an ecosystem.

        5. It interacts with it with its environment, with vegetation for example. It will hide or lay eggs.

        6. At all of these levels, the parts of the system and their interactions can be identified.

    - ii. **non-linearity:**
        1. Due to the interdependence of the elements, the system can show different levels of non-linear behaviour.
        2. Let us look at a few of them.
            - a. **The first example of non-linearity is state transitions.**
                - i. **The state transition is often irreversible.**
                - ii. **An example are the sand piles of Pearl Buck. When we install a tube and let sand particles drop through this tube, A nice symmetrical sand pile will emerge.**

                - iii. It will steadily grow and become larger and larger.

iv. The certain moment, one more sand particle will fall and it will cause a landslide to occur.

v. When the sand pile was a stable system, it now becomes unstable.

b. **Our second example of non-linearity is that a small change can have a large impact.**
    i. **You have probably heard that when a butterfly flaps its wings on one part of the world, it can cause a hurricane somewhere else.**

    ii. **Or when you drop a stone in a river, you will change the way this river flows forever.**

c. **The third example of non-linearity is that complex systems are often scaleless.**
    i. **When they are scaleless, they show the same pattern at different scales.**

    ii. **This is also referred to as a fractal.**

        1. **A Romanesco broccoli, for example, is a fractal.**
            a. **When we zoom in, we see the same shape repeat itself at different scales.**

        2. **The diffusion of a pandemic like COVID-19 is also a fractal.**
            a. **It will locally spread to a large population, for example to New York.**

            b. From this centre, via air connection, it will reach other large cities in other parts of the world. Maybe it will come to Paris, and from Paris it will spread to similar cities in Europe, to London, Amsterdam, Madrid.

            c. And from these cities, it will again spread to larger cities in these countries, and so on and so on.

d. **The last example of non-linearity are tipping points.**

i. **We often associate tipping points with climate change.**

ii. **Tipping points are critical thresholds, and when crossed, they can have a severe impact on the system, and they are often irreversible.**

iii. **connectivity:**

1. So, we have seen four examples of nonlinearity. Now let us look at connectivity.

2. **When we focus at connections between the elements, we see that they form networks.**

3. **Not all elements have the same degree of connectivity.**

4. **Some are only connected to one other element, and others have many connections.**

iv. **Emergence:**

1. Our last characteristic that makes a system complex is called emergence.

2. **Due to the connections between the elements, new product properties of the system can emerge.**

3. **For example, the parts of the car, like the steering wheel, the tyres, they cannot drive on their own, but together a new property emerges that we call driving.**

4. **Many different things can emerge. Sometimes patterns emerge, sometimes structure, but also behaviour can emerge.**

5. **There are many different examples of emergence, for example the flocking of birds or shock waves in traffic.**

- **Question to think,** can you identify different aspects of complex systems, that are related to hierarchies, nonlinearity, connectivity and emergence?

COMPLEX SYSTEMS

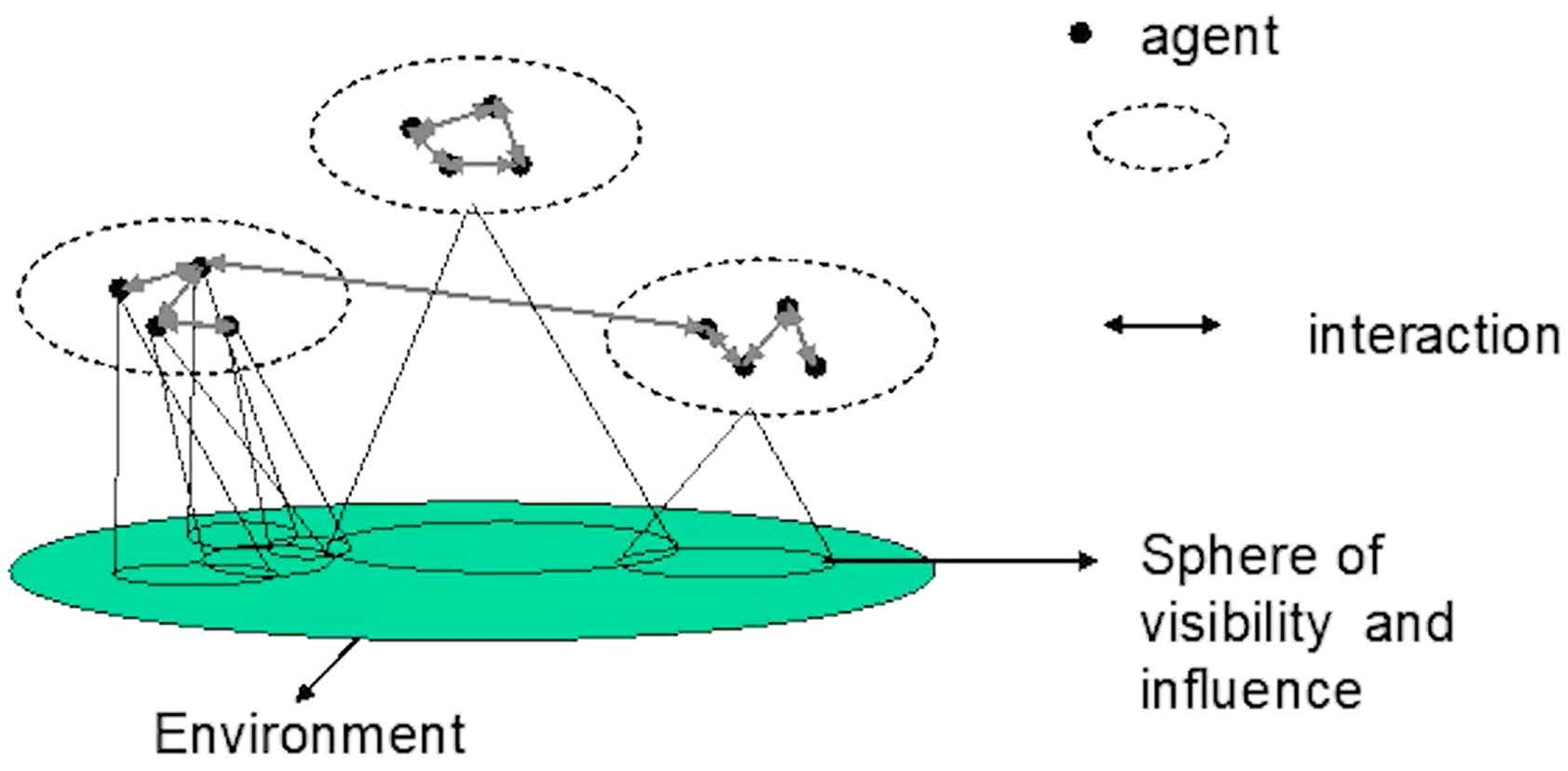
SET-UP OF THE LECTURE

- What is a system?
- What are complex systems?
- What is the link between complex systems and agent-based models?

WHAT IS AGENT-BASED MODELING?

MULTI-AGENT SYSTEMS (MAS)

Components are **agents**, **environments** and **time**.



Canonical View of an Agent based System (Jennings, 2000)

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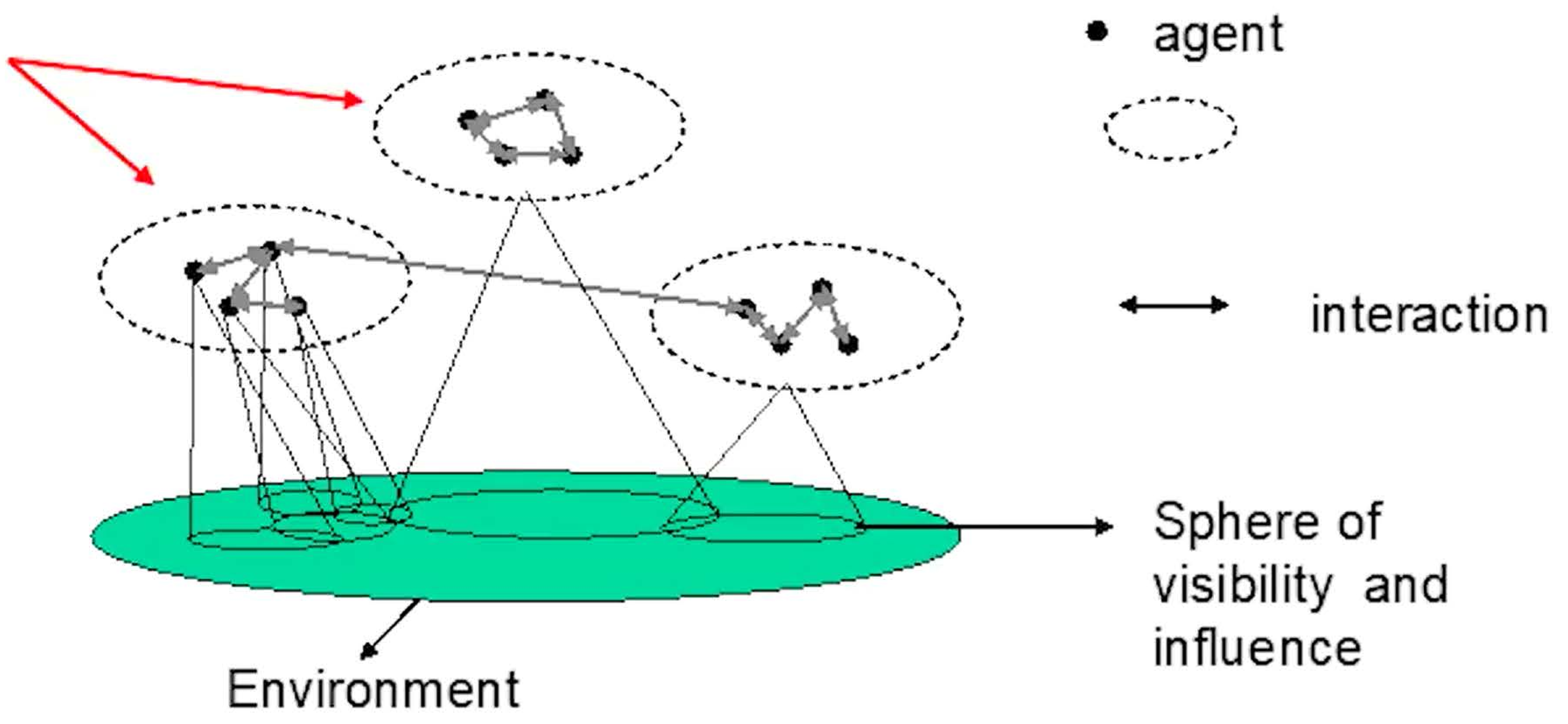

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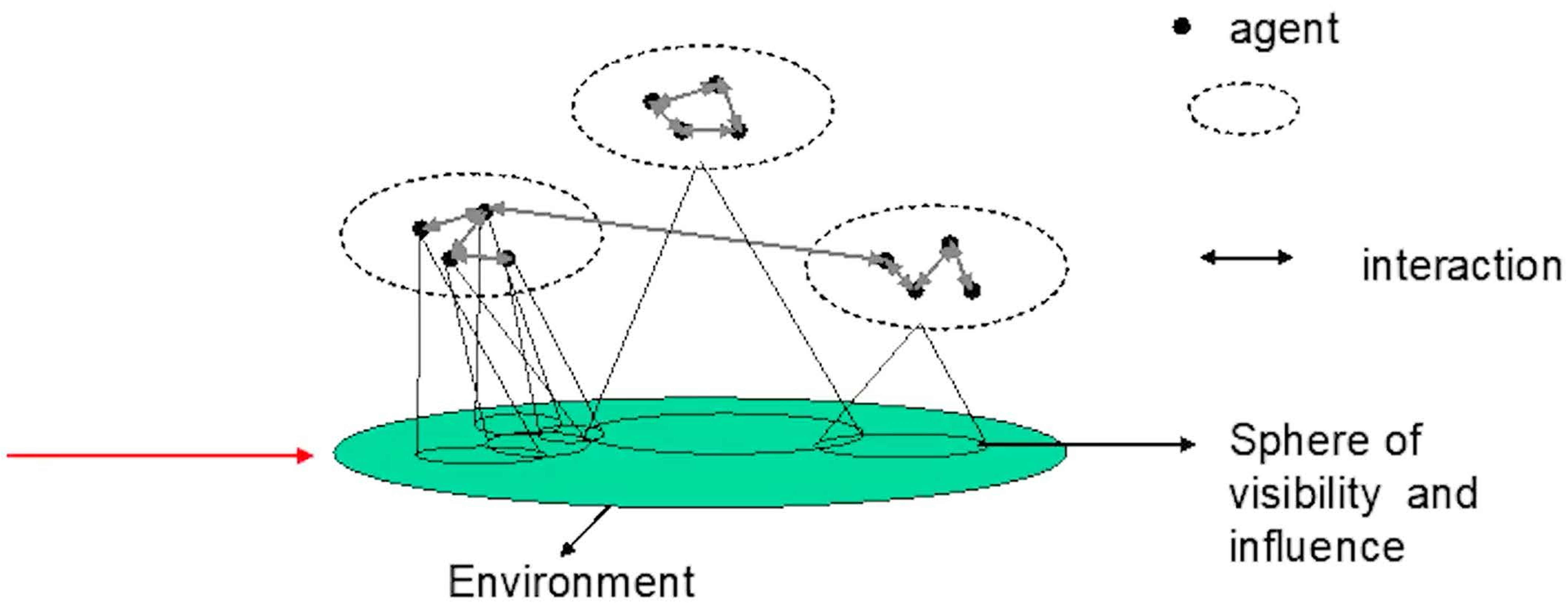

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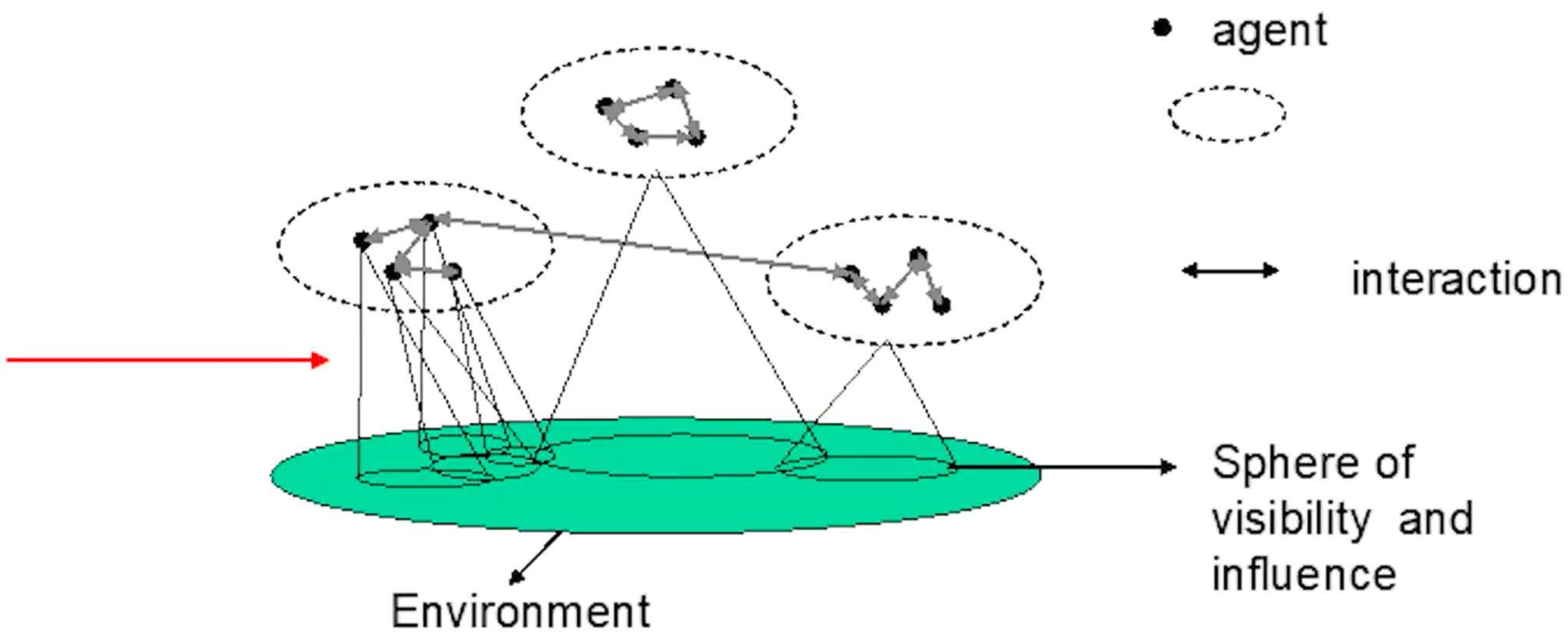

Canonical View of an Agent based System (Jennings, 2000)

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SUMMARY

- What is a **system**?
- What are **complex systems**?
  1. Complex systems are **hierarchical**, sub-systems are **nested** in larger systems
  2. Complex systems are **non-linear** due to **interdependency** of the elements
     1. State transitions
     2. Small changes can have large impacts
     3. Scaleless behavior (fractals)
     4. Tipping points
  3. The system is defined by its **connections** (connectivity)
  4. Due to **adaptation**, patterns like flocking of birds **emerge**

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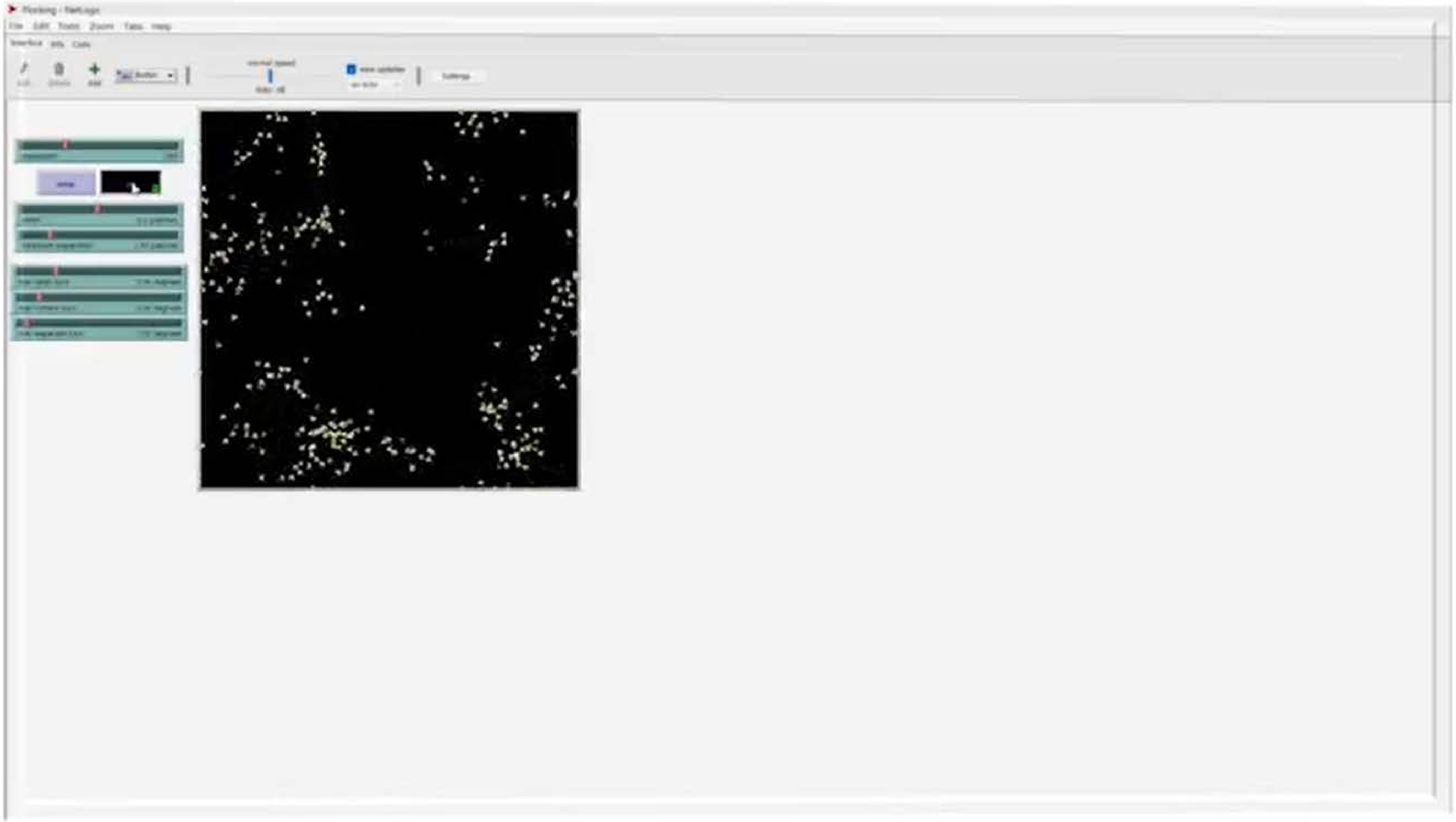
FLOCKING OF BIRDS



Video source: Wilensky (1998)

3. What is the link between a complex system and agent-based modelling?

- We will first link ABMs to parts and interactions.

- Then we will look at agent-based models and complexity.

- **Like systems, agent-based models are also made-up from parts.**

- **We distinguish three types of parts:**
    i. **agents**
    ii. **environments**
    iii. **time**
- **agents:**
    i. An example is shown on this slide.

    ii. **Agents are represented as dots. You see three clusters of dots with a dashed line around them. Each of these groups of agents can represent a family, a class of students, or any other entity.**

    iii. **There are interactions between agents within the group, but also between the groups.**

- **environments**

    i. **An agent-based model can also have one or many environments.**

    ii. **There are interactions between environments and between agents and environments.**

    iii. **Like in a system, these interactions can lead to new, emerging patterns over time.**

    iv. **In the previous video, we saw that complex systems are systems where the system's behaviour is more than the behaviour of the individual components.**

    v. **We saw four aspects of complex systems: hierarchies, non-linearity, connectivity and emergence.**

    vi. **In the previous slide, you already saw an example of hierarchies in agent-based models. We saw that agents can be grouped together, like the school of fish we saw in the previous video.**

    vii. **Because of the interactions between the parts of an ABM, agent-based models can provide unexpected outcomes.**

viii. Which outcomes exactly? That depends on the type of model you are creating.

ix. But there are many famous examples, like the flocking of birds,Using a few very simple rules, we can show how flocks will emerge from a random distribution of birds in a limited number of time stamps.