Course
Theory of Complex Systems

Clélia de Mulatier

April 2 to May 31, 2024

Generalities

Course Staff: Clélia de Mulatier, lecturer
Ebo Peerbooms, TA
Maxim Zewe, TA
Leander Post, TA

Canvas:
Home page: general information + all the links
Announcements
Modules: will have all the material
Assignments: submit homework
Quizzes
Grades

Timing???
Lectures: from 11h to 12h40 (Including 10min break)
Tutorials: from 13h10 to 14h45 (including 5min break)

Students, you! : Master Computational Science
Master Physics & Astronomy
other Masters (Math, AI, ?)

Advice: **Make mixed working groups. Help each others!**

campuswire Link **Code: 4432**

— Ask questions about exercises or lectures;
— Report typos/mistakes in the questions of the exercises;
— Ask questions related to the organization of the course.

Don't hesitate to try replying to the questions! (when you can)

Contact: If needed, contact us using the **messaging system in Canvas** (see "Inbox" section)
This is better than by email.

Watch out!
Course overlap, **Exam overlap**

L0: Introduction

Theory of Complex Systems: What is it?

Theory of Complex Systems: What is it?

Introductory Lecture

Goals: Examples of Complex Systems?

What are Complex Systems?

What is “the” Theory of Complex Systems”?

Expectations: Participate in the discussions

Additional material: Outreach talk “What is a complex system?”, by Karoline Wiesner & James Ladyman (here)

Website and booklet “Complexity explained” (here)

Book: Chapter 1 of Introduction to the Theory of Complex Systems, by S. Thurner, R. Hanel, and P. Klimek (2018) (link)

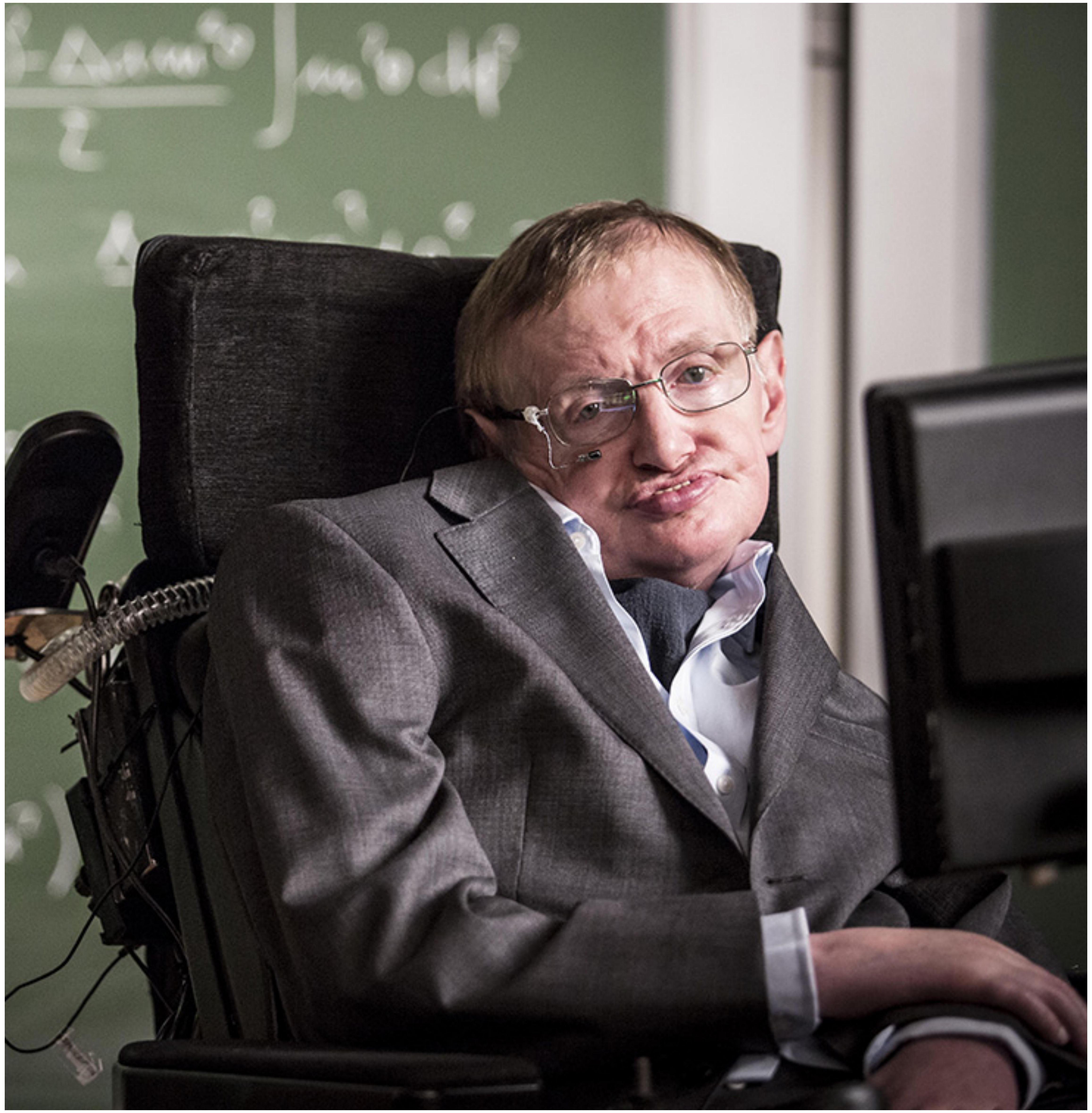
Before we begin: Complexity Science is a very young field compared to more traditional fields in physics/math. There are not a lot of general textbooks on Complex Systems. Currently available textbooks often approach Complex Systems from different fields and different points of view.

“ I think the next century will be the century of complexity. ”

— Stephen Hawking

Unified Theory Is Getting Closer, Hawking Predicts,

Interview with San Jose Mercury News, **January 23, 2000**.



Pointing towards the increasing importance of a set of scientific ideas that emerged in the 1980s-90s that allow us to find order within highly complex, interconnected systems (e.g. weather, traffic movement, stock market, ecosystem).

The Nobel Prize in Physics 2021

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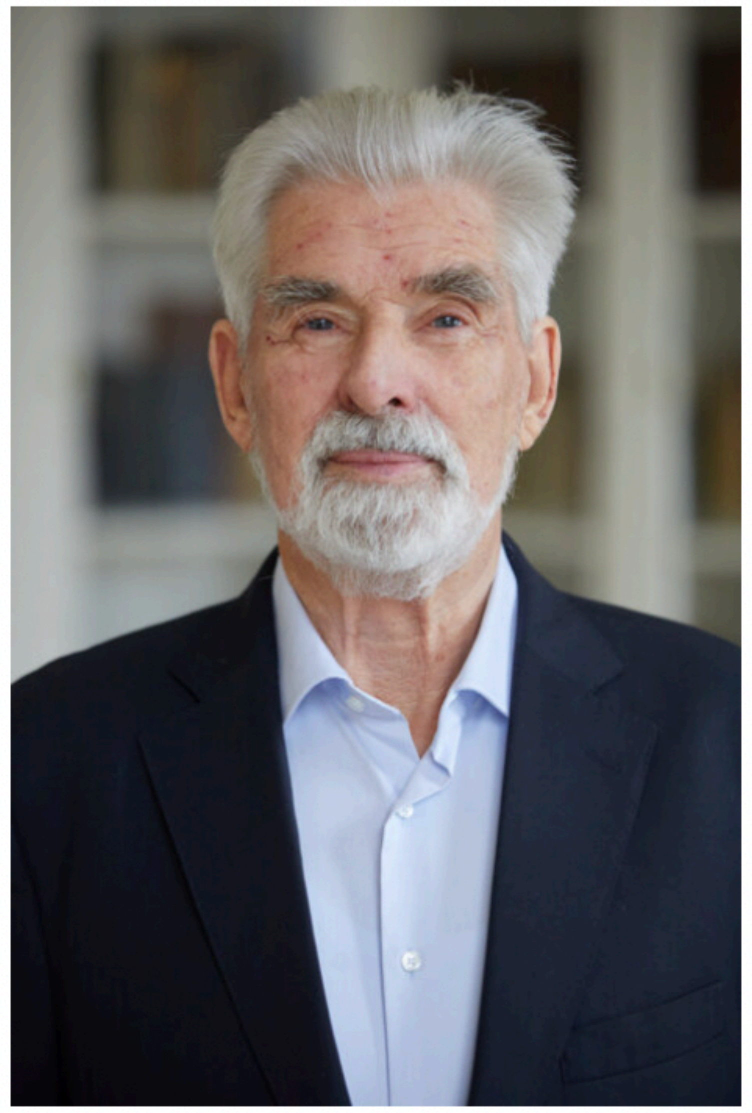
Syukuro Manabe

Prize share: 1/4



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Klaus Hasselmann

Prize share: 1/4

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Giorgio Parisi

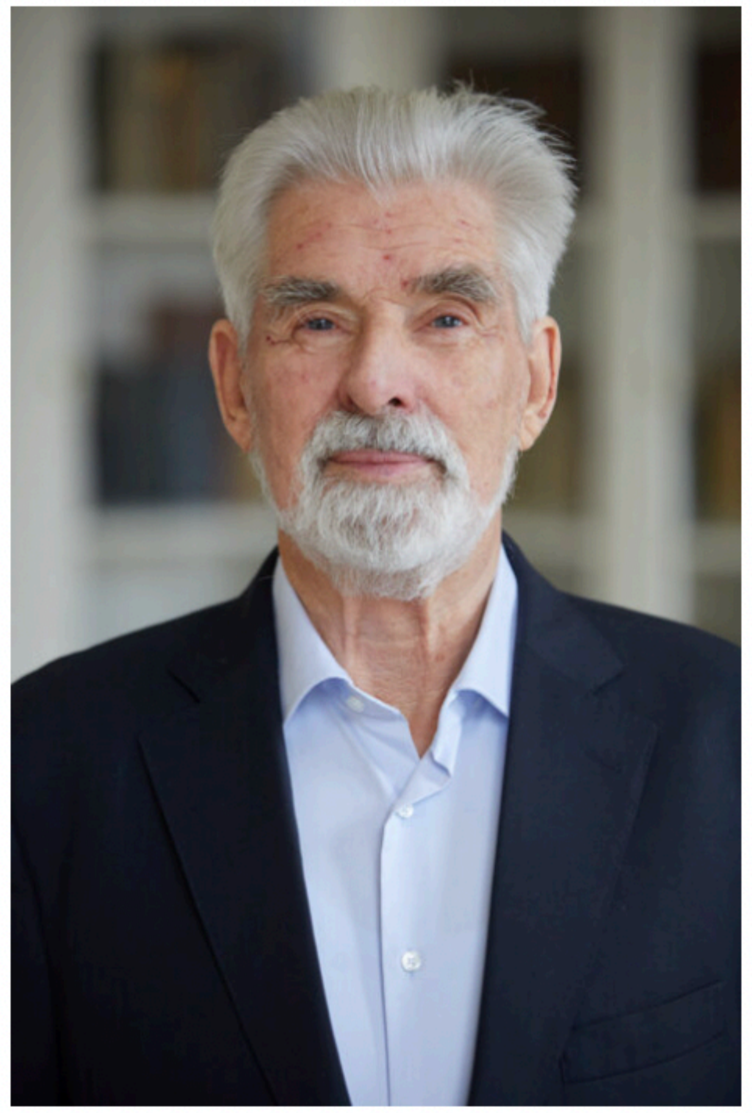
Prize share: 1/2

“ for groundbreaking contributions to our understanding of **complex physical systems** ”

The Nobel Prize in Physics 2021

Syukuro Manabe

Prize share: 1/4



Klaus Hasselmann

Prize share: 1/4

Giorgio Parisi

Prize share: 1/2

One half

“for the physical modelling of Earth’s climate, quantifying variability and reliably predicting global warming”

The Nobel Prize in Physics 2021

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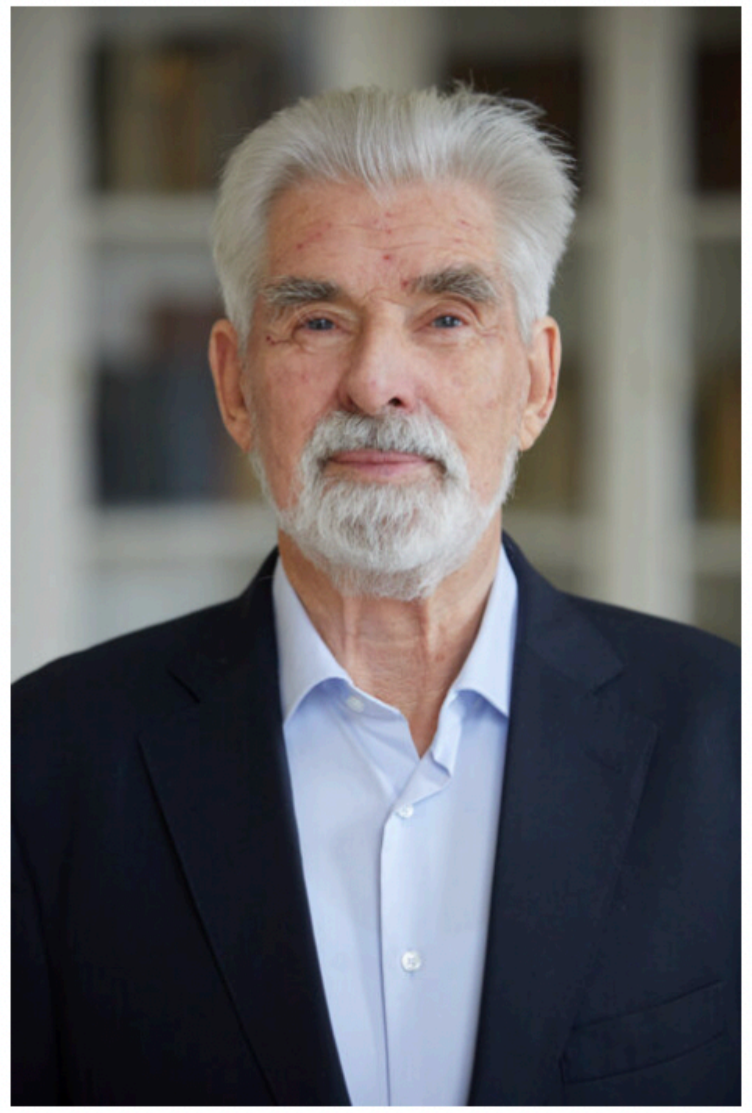
Syukuro Manabe

Prize share: 1/4



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Klaus Hasselmann

Prize share: 1/4

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Giorgio Parisi

Prize share: 1/2

and the other half

"for the discovery of the interplay of disorder and fluctuations in physical systems from atomic to planetary scales"

Some of Giorgio Parisi's contributions

Spin Glasses

Optimisation algorithms

Turbulence

Kardar-Parisi-Zhang equation

Stochastic Resonance —> climate change

Quantum chromodynamics

Random Matrix Theory

Flock, emergent behaviour in active matter

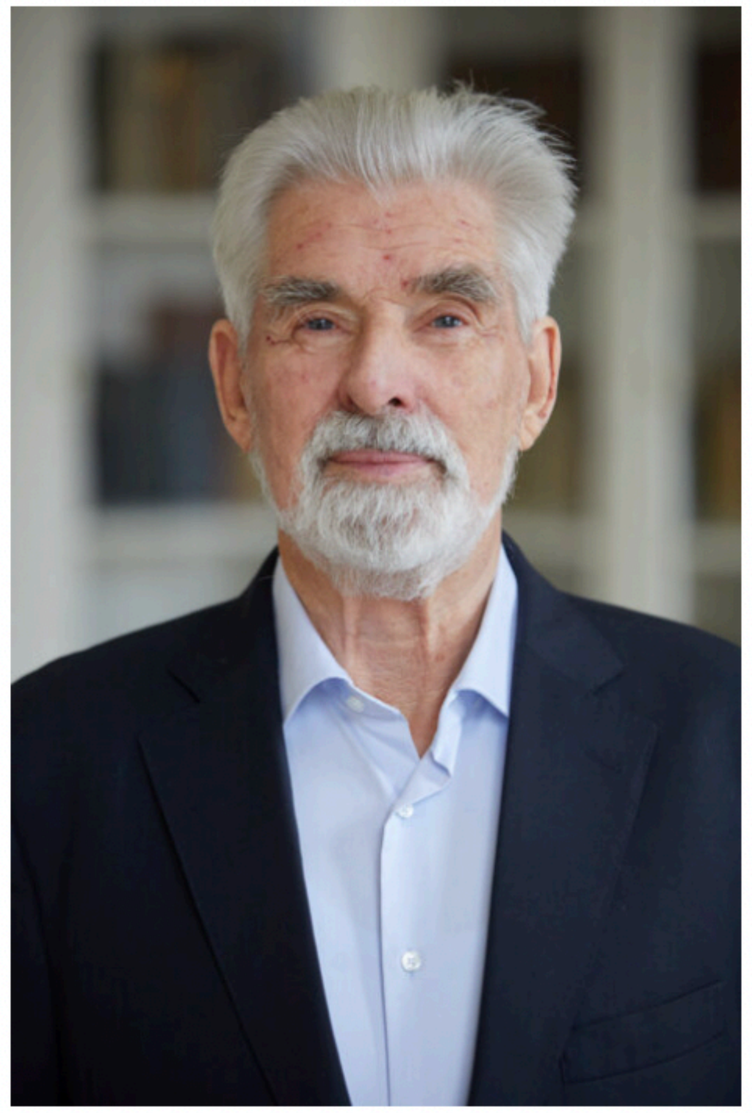
Hard sphere glasses and jamming

See: Lecture on the Nobel Prize organised by the Physics & Astronomy Division of the KNAW By Said Rodriguez. —> in Canvas

The Nobel Prize in Physics 2021

Syukuro Manabe

Prize share: 1/4



Klaus Hasselmann

Prize share: 1/4

Giorgio Parisi

Prize share: 1/2

The prize is shared.
What is the link between them?

Answer **here** at 25:10 min

The Nobel Prize in Physics 2021

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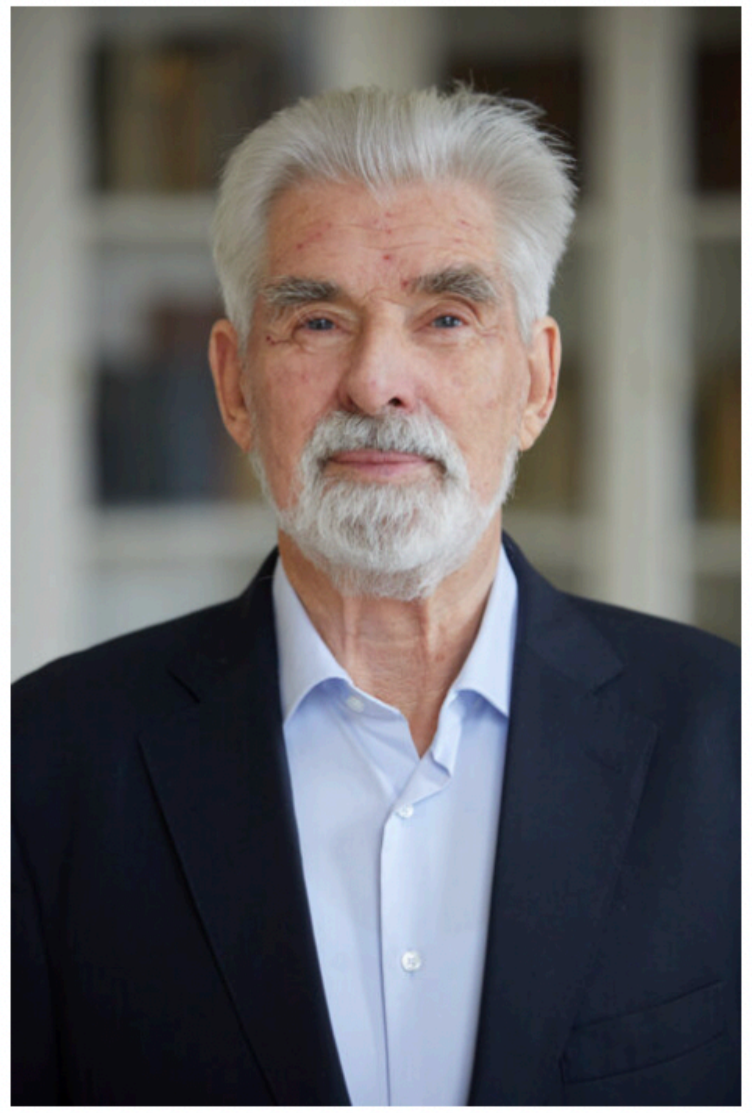
Syukuro Manabe

Prize share: 1/4



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Klaus Hasselmann

Prize share: 1/4

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Giorgio Parisi

Prize share: 1/2

The prize is shared.
What is the link between them?

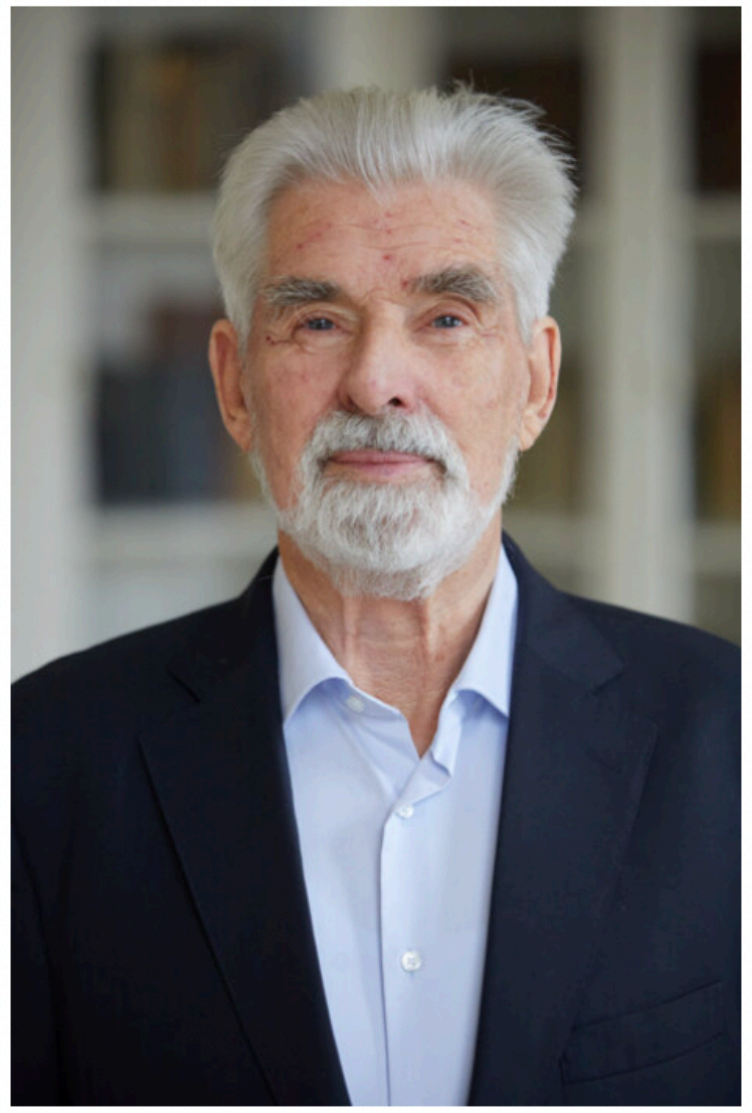
Common theme:

" How disorder and fluctuations, together, can give rise to something we can understand and something we can predict. "

The Nobel Prize in Physics 2021

Syukuro Manabe

Prize share: 1/4



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Prize share: 1/4

Giorgio Parisi

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Common theme:

“ How disorder and fluctuations, together, can give rise to something we can understand and something we can predict. ”

“Building from the disorder and fluctuations of a CS at their microscopic constituents and predicting the macroscopic behaviour”

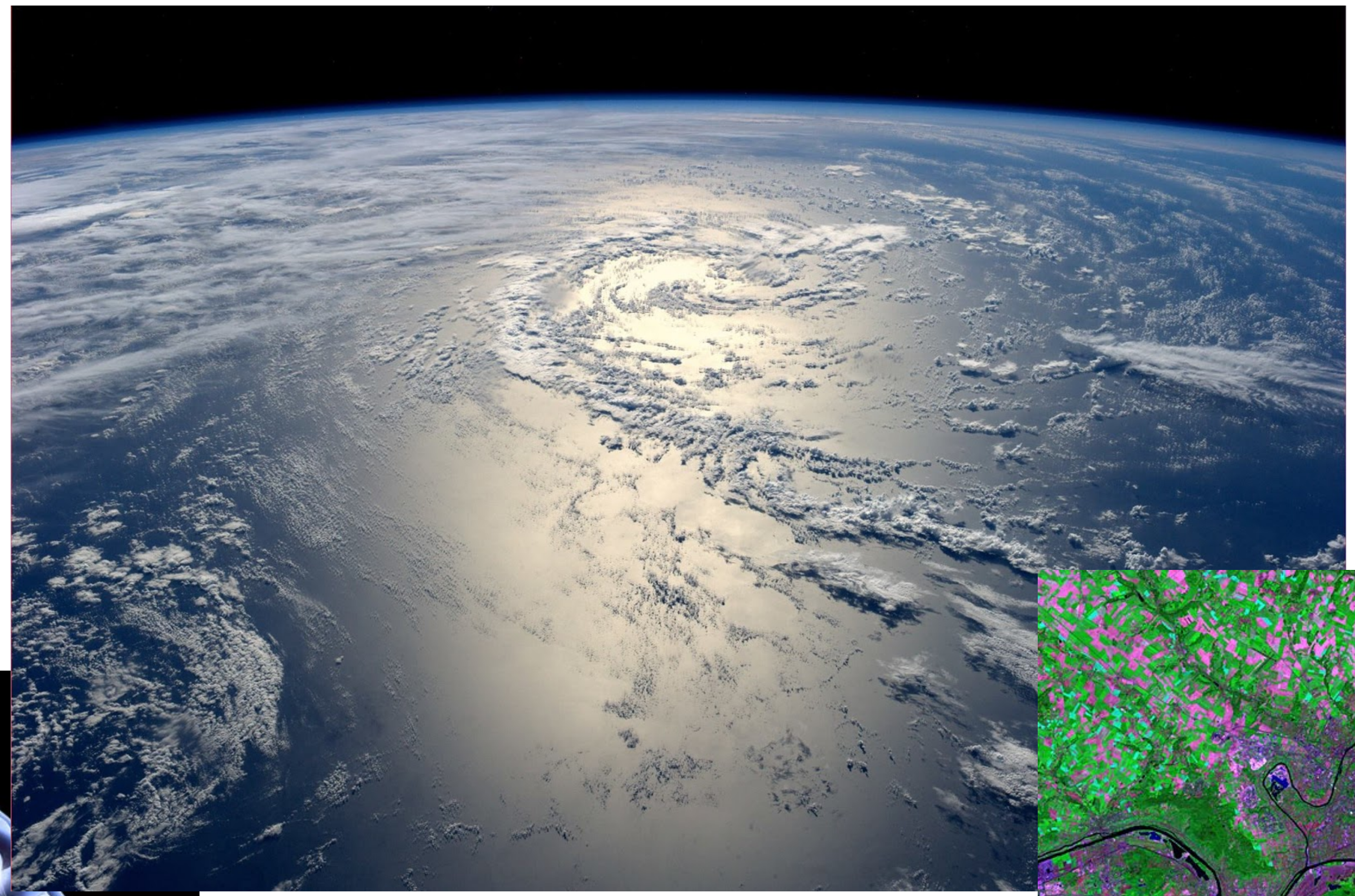
Uncovering the hidden structure.

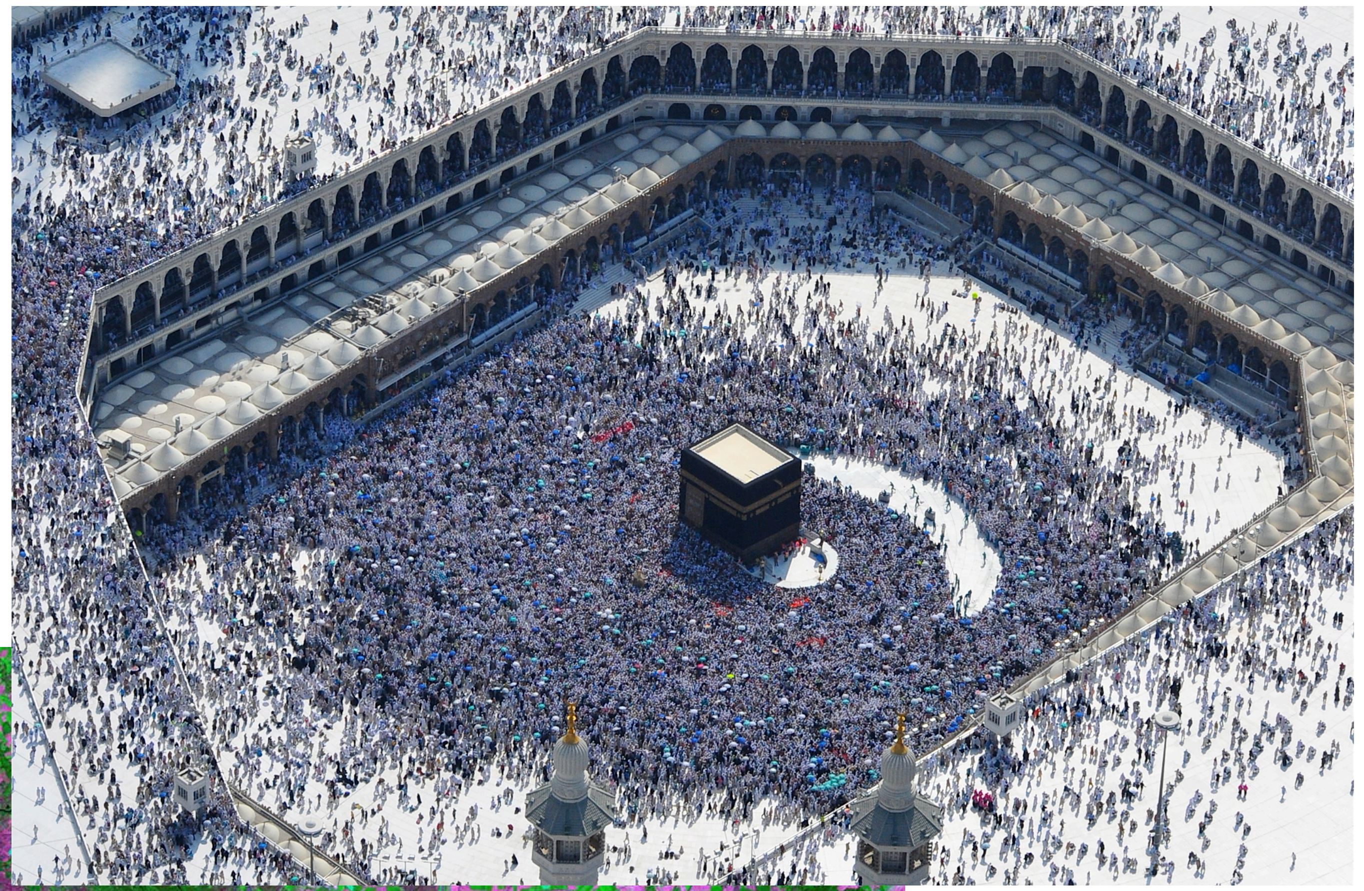
What is a “Complex System”?

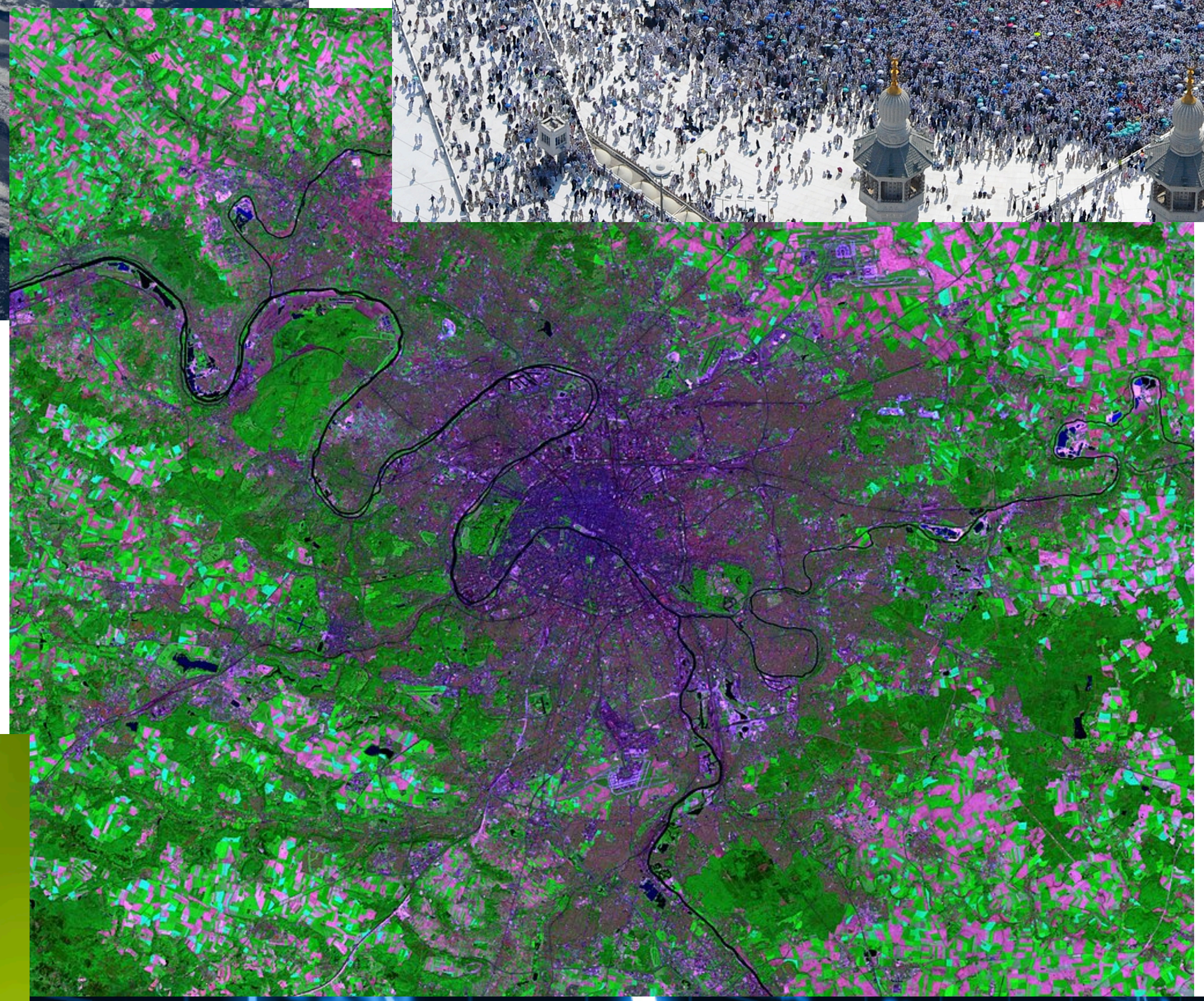
Examples of Complex Systems

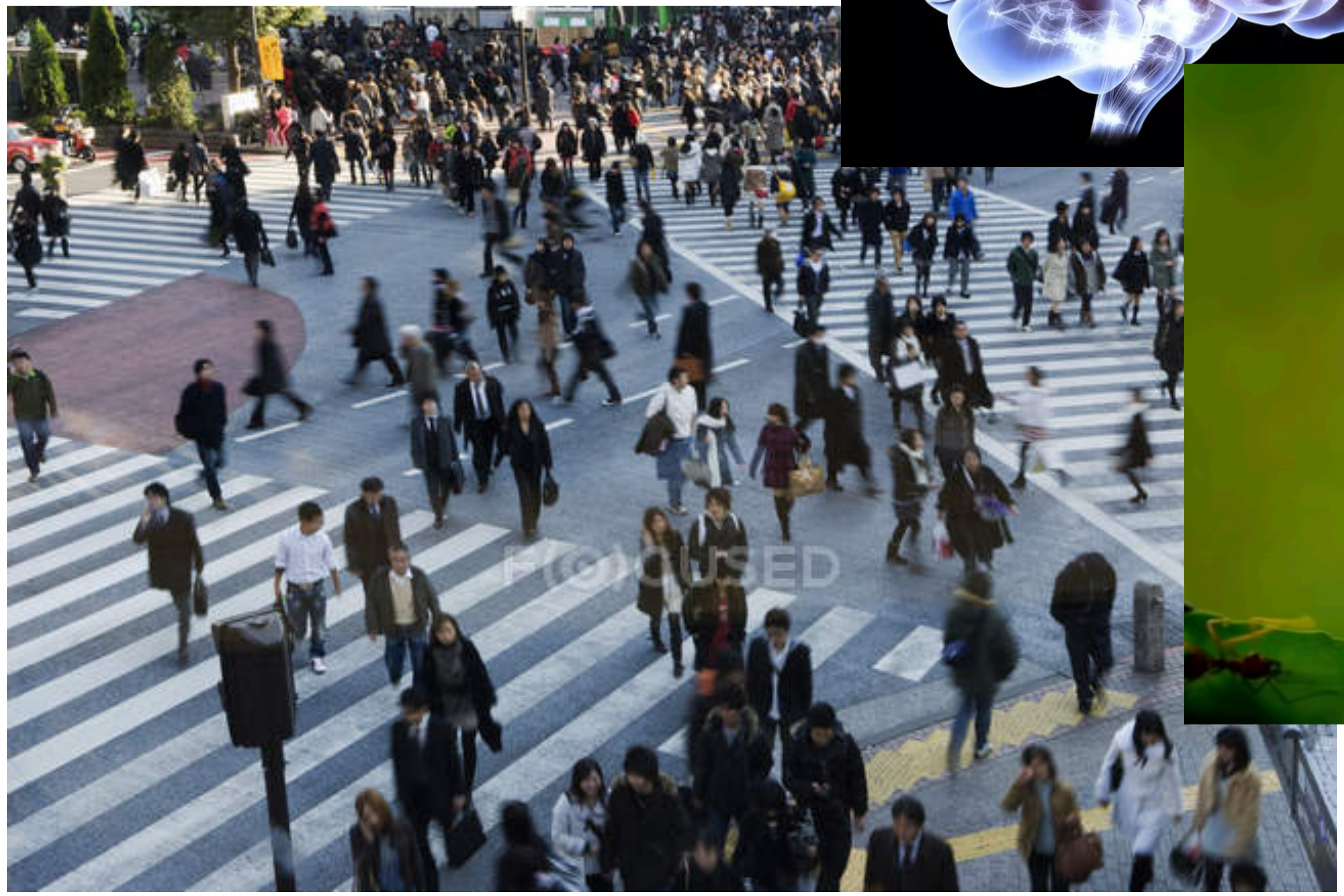
https://app.wooclap.com/CTAKGP

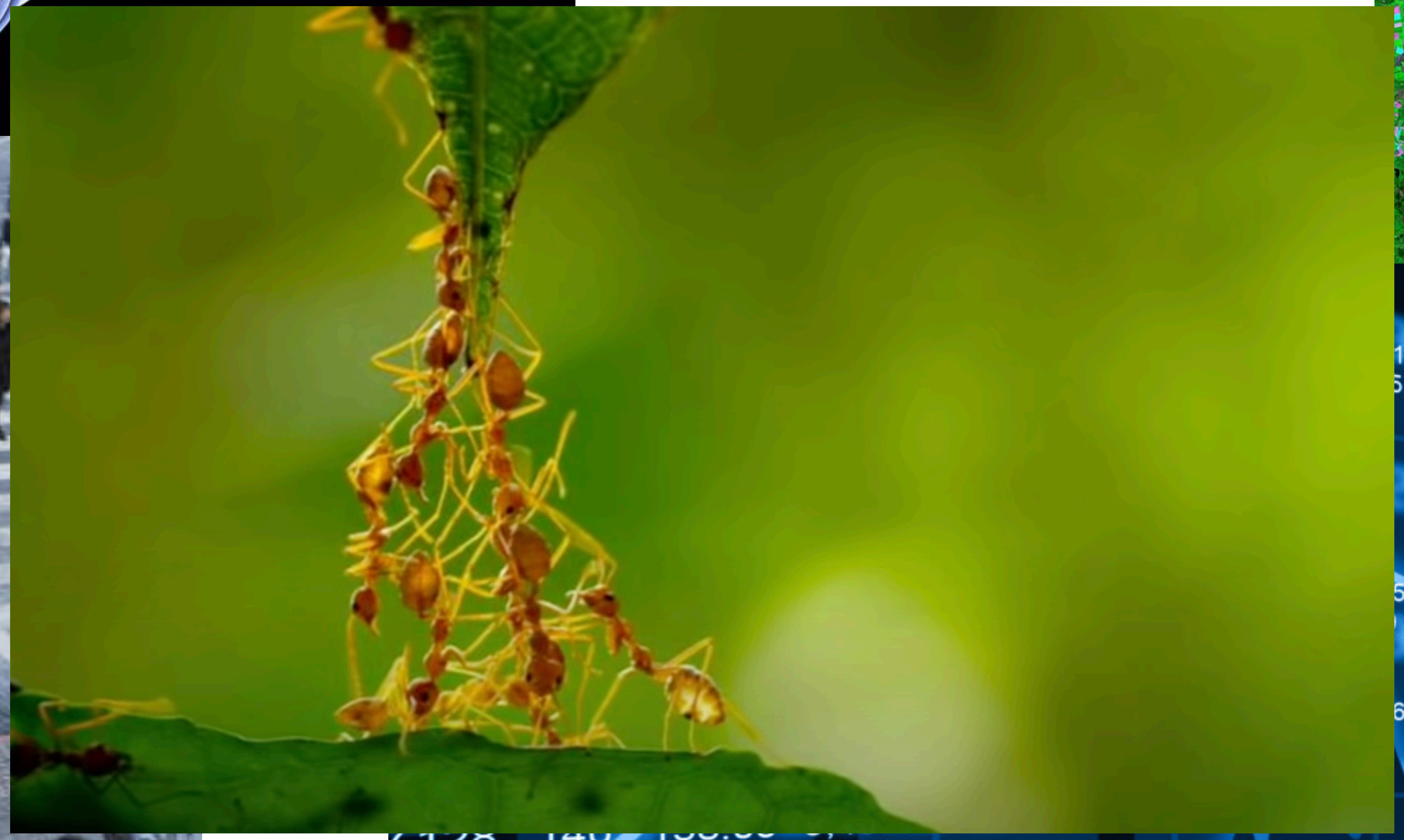
Examples of CS











Examples of Complex Systems

Examples

Earth climate

Brain

traffic problems

Immune system

Urban organisation

Health

Psychological phenomena

Systems displaying collective behavior
(Crowd movement, bird flock, school of fish,...)

Every

Living system (most...)

Social system

Economic system

Financial system

Ecosystem

is a Complex System

What features characterise a complex system?

https://app.wooclap.com/CTAKGP

What are characteristics of complex systems?

What are characteristics of complex systems?

Interactions
with environment

**Many
interacting components**

Interactions
that changes in time

Adaptation

Dynamics

Evolution/Co-evolution

Networks of interactions

Tipping points

Collective behaviour

Self-organisation

Organisation

Transition order/disorder

Emergent behaviour

Properties of the system
change with the size of the system

Scaling
Organisation at large scale
power law behaviour

Pattern formation

These are many aspects common to Complex Systems
But…

What are Complex Systems?

What are Complex Systems?

Loosely

Complex System — composed of **many components interacting** with each other and their environment in multiple ways.

— that display **behaviours** that **cannot be understood by** the reductive **study of each of its individual component**.

The system is not just the “sum” of the behaviour of each part.

Ex.

Impossible to predict where traffic jams will occur by only studying the behaviour of individual drivers

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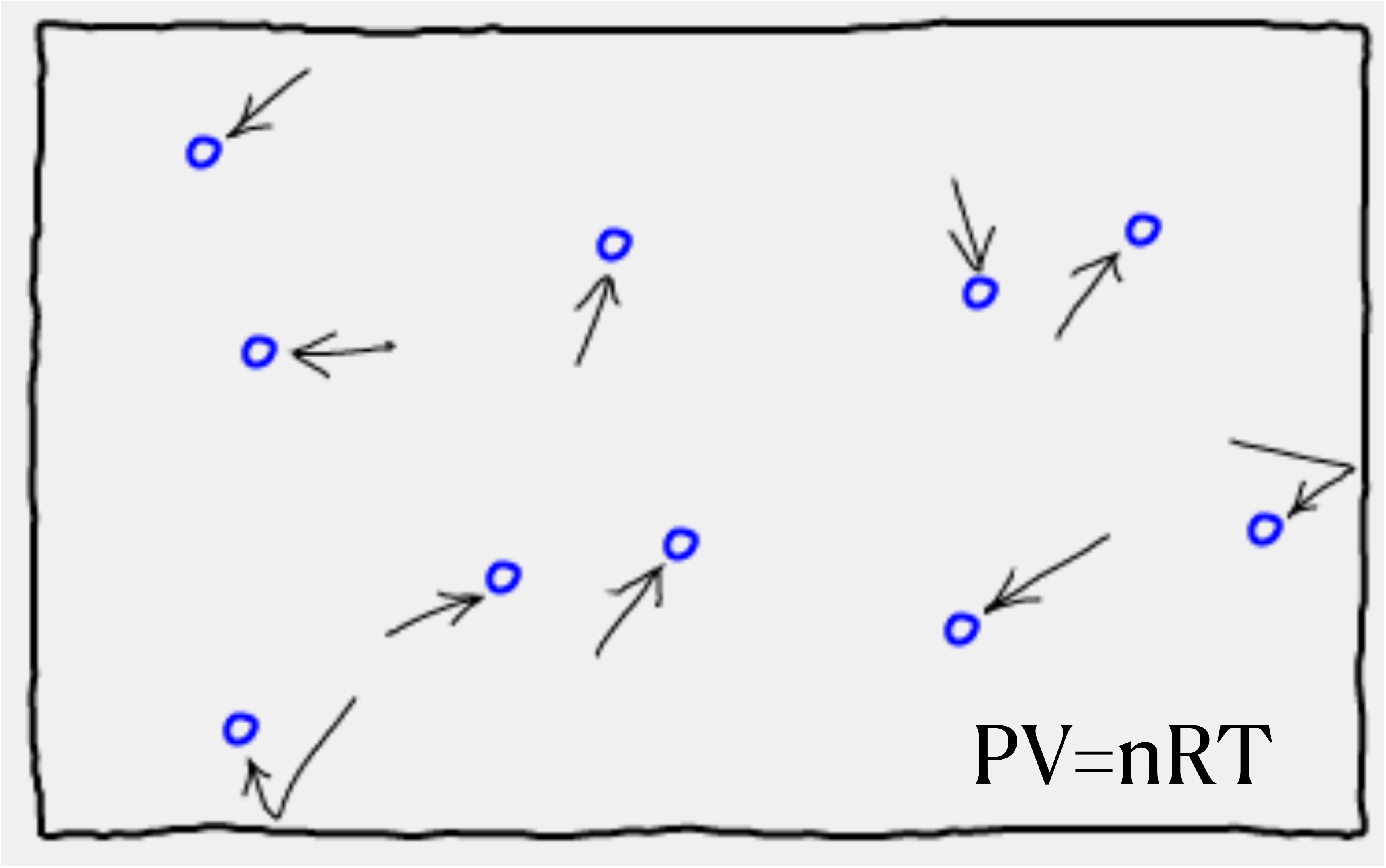
Stephen Thurner: "Complex systems are co-evolving multilayer networks." See talk here.

What is not complex?

A complex system is **not just a complicated system**

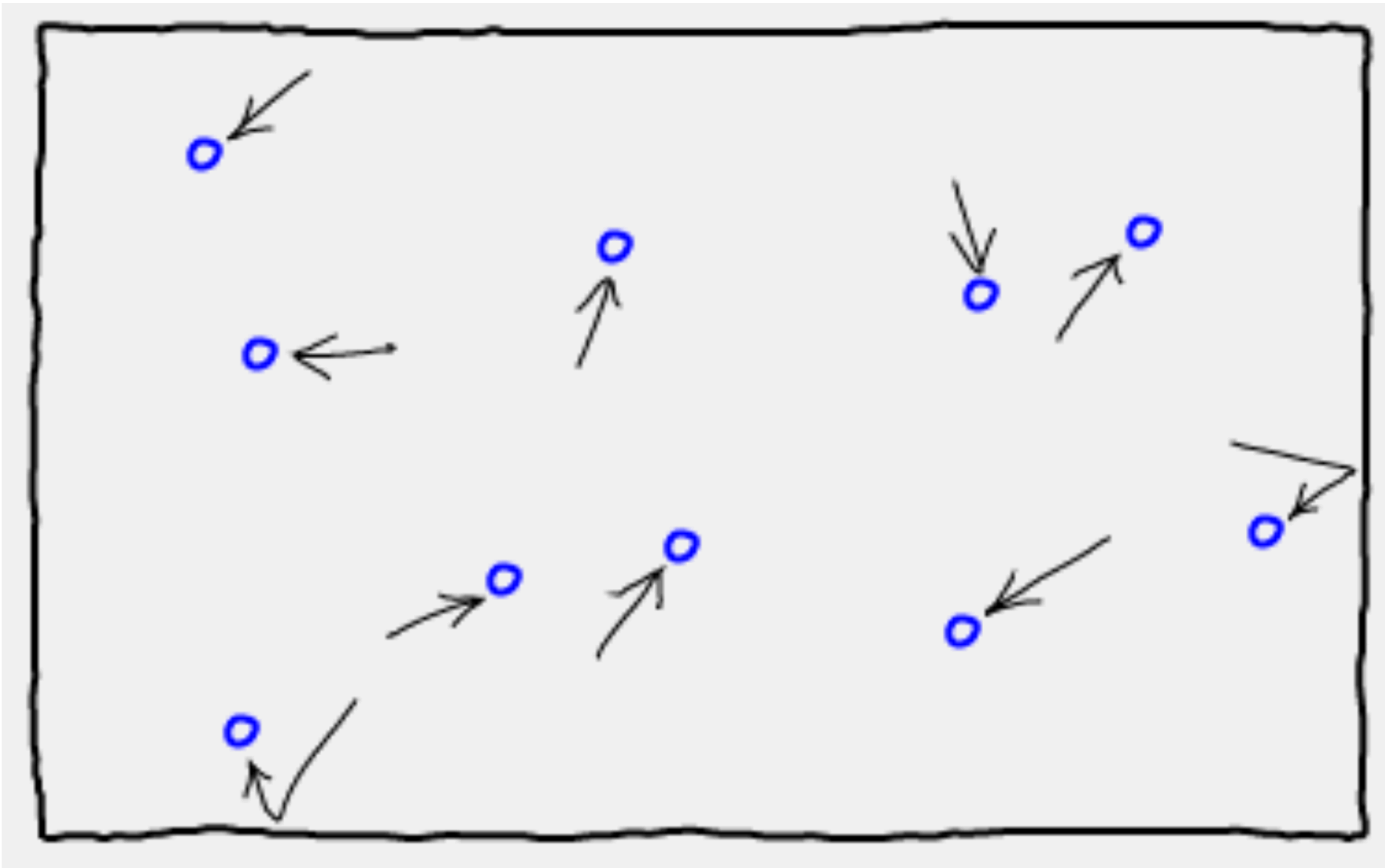
A complicated system: has many interacting components,

but we can predict its behavior by breaking it down into the behavior of each part



A **purely random system** is not a complex system

What is not complex?



A **purely random** is not complex

Warren Weaver (link video) (American mathematician 1948)

- "disorganised complexity" ⟶ Randomness
- "organised complexity" ⟶ Regularity, pattern within the disorder => "Complexity"

A good measure of complexity captures the hidden organisation/structure behind the apparent disorder.

Emergence in Complex Systems

Emergence in Complex Systems —> macroscopic behavior or property of a system that arises as a result of complex interactions between its many constituents,
and that cannot be predicted from the behavior of the constituents alone.

Emergence of collective behaviors in animals, such as flocking

Emergence of cognitive phenomena
(perception/memory/decision making)
in the brain or in artificial neural networks

What are CS?

#ComplexityExplained

Project Explore Concepts References Booklet Credits Contact

What is Complexity Science?

"*I think the next [21st] century will be the century of complexity*" – Stephen Hawking

Complexity science, also called complex systems science, studies how a large collection of components – locally interacting with each other at small scales – can spontaneously self-organize to exhibit non-trivial global structures and behaviors at larger scales, often without external intervention, central authorities or leaders. The properties of the collection may not be understood or predicted from the full knowledge of its constituents alone. Such a collection is called a complex system and it requires new mathematical frameworks and scientific methodologies for its investigation.

A Theory of Complex Systems?

“ I expect we will find a complete unified theory sometime this century. ” **Stephen Hawking**

Theory of complex systems?

A Complex System to study: What do we want to know?

Theory of complex systems?

A Complex System to study: What do we want to know?

Examples:

Link micro rules to macro behavior; Understand emergent behaviors

Understand how interactions at microscopic level create macroscopic behaviour

Predict macroscopic behaviour; Control macroscopic behaviour

Will a traffic jam occur? Can we stop the spread of a disease?

Study how stable is the system

Observations of the system: would like to uncover the hidden patterns, the structure

Reminder: What are characteristics of complex systems?

Interactions
with environment

Interactions
that changes in time

Adaptation

Many
interacting components

Dynamics

Individuals

Evolution/Co-evolution

Tipping points

Networks of interactions

Collective

Self-organisation

Organisation

Transition order/disorder

Emergent behaviour

Properties of the system
change with the size of the system

Organisation at large scale

Pattern formation

What do you think would constitute a theory of complex systems?

https://app.wooclap.com/CTAKGP

What do you think would be the key ingredients for a theory of complex systems?

Complex systems are studied from many different perspectives...

Dynamical Systems and Chaos

Information theory

Data analysis methods

Network Theory

Stochastic processes

Evolutionary processes

Critical Phenomena

Game Theory

Interdisciplinary research

Book Introduction to the Theory of Complex Systems, by S. Thurner, R. Hanel, and P. Klimek (2018). (link)

Theory of CS?

Complex systems are studied from many different perspectives...

Dynamical Systems and Chaos

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Interdisciplinary research

There is not a single/unified theory (yet?)....

Theory of CS?

Complex systems are studied from many different perspectives...

Dynamical Systems and Chaos

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Network Theory

Stochastic processes

Evolutionary processes

Critical Phenomena

Game Theory

Interdisciplinary research

Model-based approaches

Theory of CS?

Complex systems are studied from many different perspectives...

Dynamical Systems and Chaos

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Network Theory

Stochastic processes

Evolutionary processes

Critical Phenomena

Game Theory

Interdisciplinary research

Data-driven approaches

Theory of CS?

Main focus of the course on Phase Transitions and Critical phenomena

Data analysis methods

Dynamical Systems and Chaos

Information theory

Network Theory

Stochastic processes

Phase transitions

Scaling, fractal structures

Critical Phenomena

Emergence

Self-Organised Criticality

Pattern formation

Evolutionary processes

Game Theory

Interdisciplinary research

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Main focus of the course on Phase Transitions and Critical phenomena

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Scaling, fractal structures

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Interdisciplinary research

Theory of CS?

What can you study at UvA if you are interested in complex systems?

Interdisciplinary research

Good bases in probability theory and stochastic processes

Out-of-equilibrium statistical physics

Dynamical systems and Chaos

Information Theory

Critical phenomena

—>> More information to be posted on Canvas towards the end of the course

Data-driven approaches to complex systems

Course Plan

Introduction to the **Theory of Complex Systems** with a main focus on **Critical Phenomena**

Lectures General plan:

0. Introduction to Critical Phenomena

1+2. From micro to macro: Equilibrium descriptions of complex systems

3. Mean-field approximation

4. From micro to macro: complex systems out-of-equilibrium

5. Emergence; Criticality, Scale-invariance and Renormalization

6. Self-organised criticality; 7. Examples of collective behaviors

Simple of models of Complex Systems: Ising model, TASEP (traffic jam), percolation, SIS model (epidemic model), voter model, Vicsek model (bird flocks), Kuramoto model, ...

The goal of the lecture is that you learn general ideas and concepts.

Course Plan

		Modules		Lecture 1	Lecture 2	Tutorial 1 and 2
April 1 - 5	**Week 1**	**Module 0**	**Introduction**	Introduction to Complex Systems	Introduction to Critical Phenomena	Poisson processes; Markov Processes
April 8 - 12	**Week 2**	**Module 1**	**From Micro to Macro**	From Micro- to Macroscopic desription of complex systems	The Ising Model	Micro to Macro: from out-of-equilibrium to equilibrium description; Application to Metropolis algorithm
April 15 - 19	**Week 3**	**Module 2**	**Example of Equilibrium Critical phenomena**	Percolation problems	Properties of Critical Phenomena +Guest Lecture ?	Exo on Ising and Percolation
April 22 - 26	**Week 4**	**Module 3**	**Mean Field Theory**	Mean-field theory	Landau Theory (1h) + Guest lecture (1h)	Exo Mean-field
	Break	**Homework due before the break**				
May 6 - 10	**Week 6**	**Module 4**	**From Micro to Macro Complex Systems Out-of-Equilibrium**	Epidemic Spreading / Wout Merbis?	Voters / Guest lecture Fernando Santos	Exo Epidemic models and voter models
May 13 - 17	**Week 5**	**Module 5**	**Scale invariance, Criticality, Renormalization; Emergent Phenomena**	Scale invariance, Criticality, Renormalization;	Discussion about Emergent Phenomena (1h) + Guest lecture (1h) Vítor Vasconcelos	Exo random walks, Fokker-Planck equation; renormalisation
May 20 - 24	**Week 7**	**Module 6**	**Self-Organised Criticality + Collective Behavior**	SOC	Collective Behavior	Exo SOC + collective behaviors
May 27 - 31	**Week 8**	**Exam Week**				

Tentative course plan, may change a little bit during the course.

Course Plan

The goal of the tutorials: to learn concretely how to use specific tools/techniques to study complex systems.

0. Poisson processes; Markov processes;
1. Markov Chain; Master equation; detailed balance; macroscopic observables
2. Complex systems at equilibrium: ex. Ising model and Percolation problem;
   Macroscopic observables, Partition function, free energy
3. Apply mean-field approximation, compute critical exponents
4. Complex systems out-of-equilibrium: ex. Epidemic models, voter model
   Master equation, Study stability of a stationary solution
5. Random walks, mean, standard deviation, sum of iid, continuous limit, Fokker-Planck equation
6. Final Examples

13-15 Werkcollege
dr. Clelia de Mulatier SP D1.116
Ebo Peerbooms MSc SP D1.112
Maxim Zewe
Leander Post

Two Tutorial groups:

1. More guided group; with corrections at the blackboard
2. Less guided group, you can go at your own speed,
   TAs will go from group to group to help you with the exercises
   (not all the exercises will be corrected at the blackboard)

Course Plan

Guest lectures by: Fernando P. Santos, Vítor Vasconcelos, Greg Stephens (to be announced)

Evaluation:

3 in-class **quizzes** (**15%**) : every two weeks —> count only the two best grades

1 **homework assignment** (**25%**) : due end of week 4 (just before the break)

1 **optional homework**

In class **Final written Exam** (**60%**) : week 8, on **Thursday 30 May 13h-16h** —> overlap?

Summary organization

Lectures: Introduce general ideas, new concepts, new tools

Tutorials: More technicals, understand how to use specific tools, practice

Homework: More practice!

Final Exam: Exercises will be inspired from the exercises seen during the lectures, tutorials and in the homework assignments.

Advice for the course: **work in groups 2-3 people max. with mixed background** (theory, computational, complex systems, …)

Teaching Assistants: Maxim Zewe, Leander Post, Ebo Peerbooms

Contact us if you have any questions:

Use campuswire (mostly!) Link **Code: 4432**

Use messaging system on **Canvas** (better than by email)

Questions?

References in connection with this lecture

[Webpage of the 2021 Nobel Prize in Physics (link)]

To get a better idea of the scientific contributions that are rewarded

See the video of the prize announcement

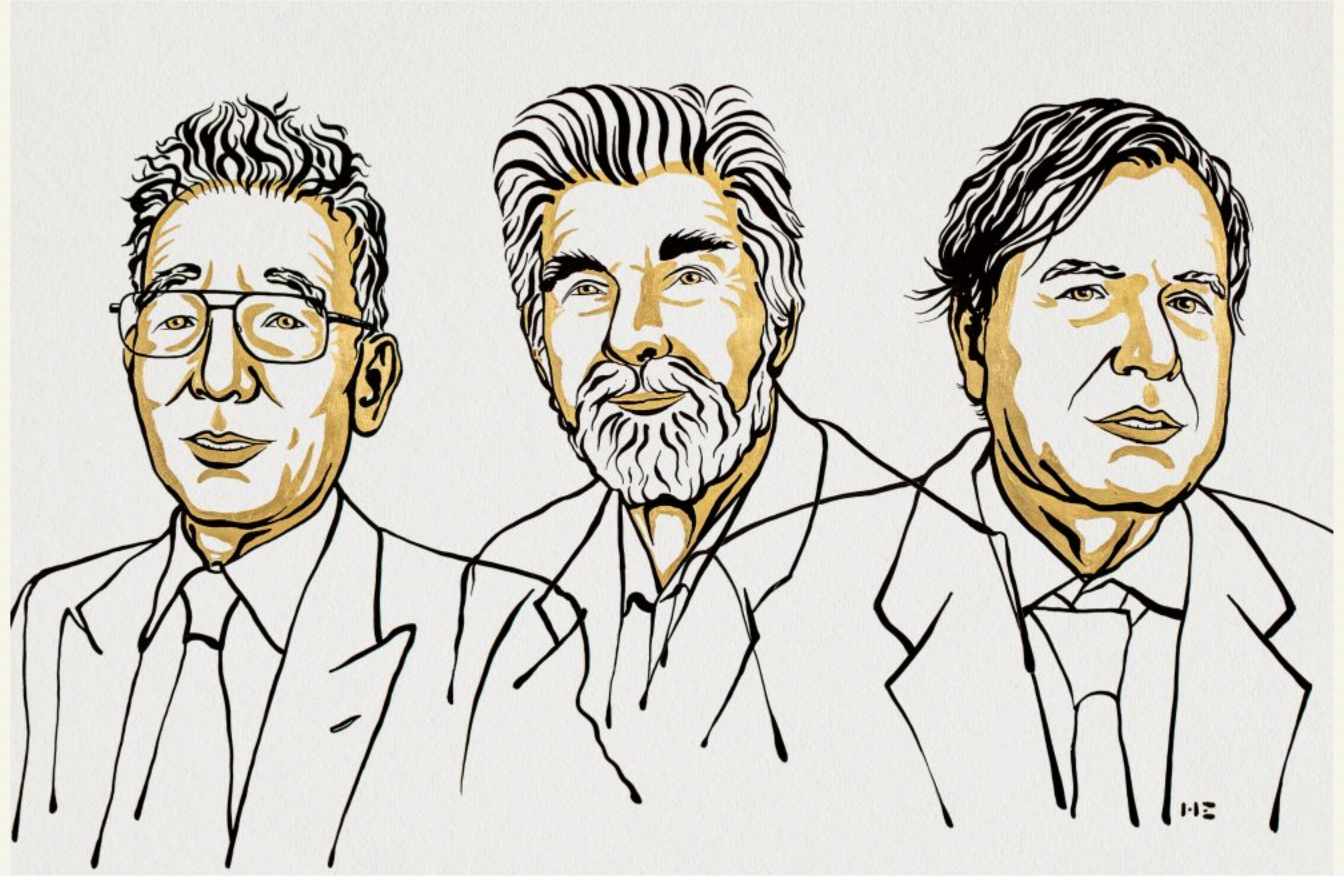
See the Lectures of each laureates

Lecture on the Nobel Prize organized by
the Physics & Astronomy Division of the KNAW
By Said Rodriguez: —> in Canvas

DIEP seminar on the Nobel Prize 2021: link

The 2021 Nobel Prize laureates in Physics

This year's Nobel Prize in Physics is awarded with one half jointly to Syukuro Manabe, Klaus Hasselmann "for the physical modelling of Earth's climate, quantifying variability and reliably predicting global warming" and the other half to Giorgio Parisi "for the discovery of the interplay of disorder and fluctuations in physical systems from atomic to planetary scales".



Ill. Niklas Elmehed © Nobel Prize Outreach.

Outreach talk "What is a complex system?", by Karoline Wiesner & James Ladyman (here)

Website and booklet "Complexity explained" (here)

Book: Chapter 1 of Introduction to the Theory of Complex Systems, by S. Thurner, R. Hanel, and P. Klimek (2018) (link)