Complex systems and complex networks: a talk for *palaeo* and *neo*ecologists

Alessio Cardillo (@a_cardillo)

Pyrenean Institute of Ecology (IPE) – CSIC, Zaragoza (Spain)

IPE's talks — Thursday, October 3rd 2024

Instituto Pirenaico de Ecología CSIC

¿Que demonios hace un físico de sistemas complejos entre nosotros?

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CSIC

Who is Alessio Cardillo?

UNIVERSITÀ degli STUDI di CATANIA

- BSc and MSc (2010) in Physics.
- Studying urban street networks.

Universidad Zaragoza

Instituto Universitario de Investigación Biocomputación y Física de Sistemas Complejos Universidad Zaragoza

- PhD in Physics (2011 – 2014).
- Switch from structure to dynamics on networks.

Who is Alessio Cardillo?

- High mobility.
- Very broad range of research topics: linguistics, archaeology, mobility, humanities, collective behaviors (vaccination, cooperation, synchronization), etc..
- Working in highly multidisciplinary teams.

UNIVERSITÀ degli STUDI di CATANIA
Instituto Universitario de Investigación Biocomputación y Física de Sistemas Complejos Universidad Zaragoza
Universidad Zaragoza
EPFL
IPHES Institut Català de Paleoecologia Humana i Evolució Social
University of BRISTOL
UNIVERSITAT ROVIRA i VIRGILI
Universitat Oberta de Catalunya
Instituto Pirenaico de Ecología CSIC

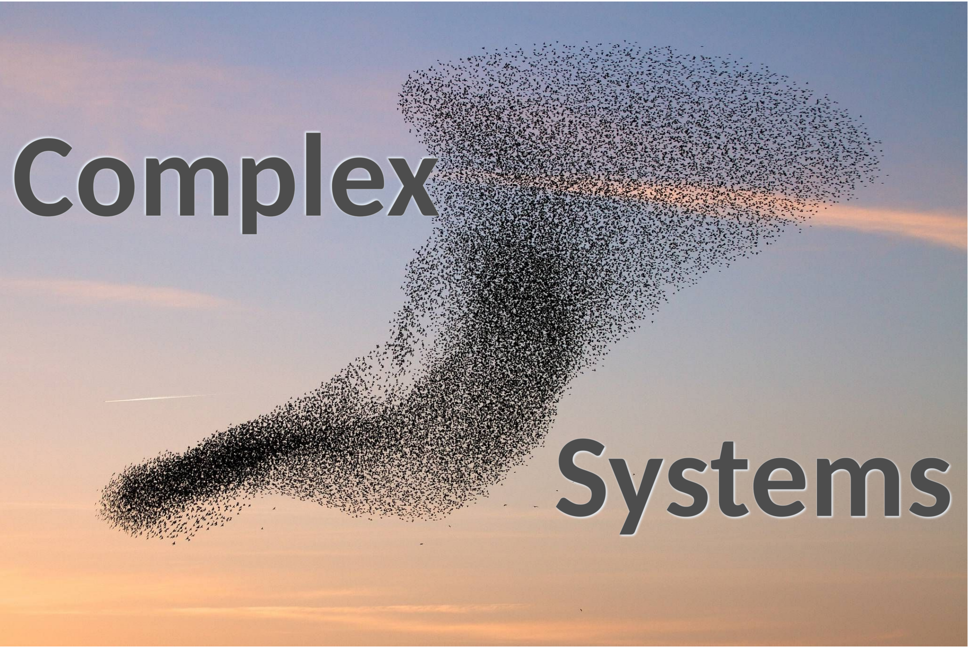
Who is Alessio Cardillo?

... Not a dog. Not a wolf. All he knows is what he's not. ...

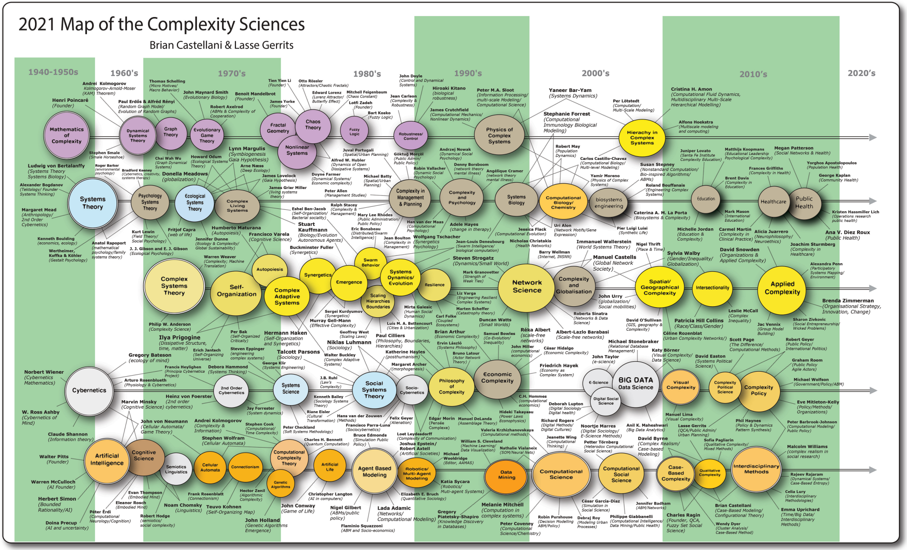
- https://en.wikiquote.org/wiki/Balto

Outline

- ~~Short self presentation~~.
- Complex systems.
- Graph theory/network science in a nutshell.
- Networks and neo-ecology (nestedness).
- Networks and palaeoecology (time-varying networks).


Complex
Systems

Complex systems



https://www.art-sciencefactory.com/complexity-map_feb09.html

Complex systems

The Nobel Prize in Physics 2021

Syukuro Manabe
Klaus Hasselmann
Giorgio Parisi

Share this

Giorgio Parisi
Facts

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Giorgio Parisi
The Nobel Prize in Physics 2021

Born: 4 August 1948, Rome, Italy

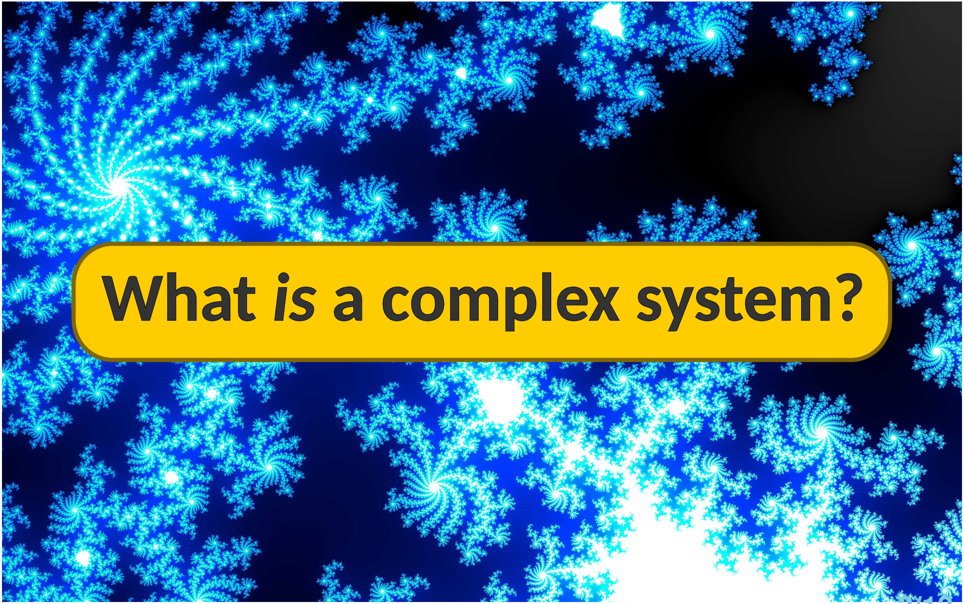
Affiliation at the time of the award: Sapienza University of Rome, Rome, Italy

Prize motivation: “for the discovery of the interplay of disorder and fluctuations in physical systems from atomic to planetary scales”

Prize share: 1/2

https://www.nobelprize.org/prizes/physics/2021/parisi/facts/

Complex systems



Complex systems

Complex systems

Journal of Physics: Complexity

EDITORIAL • OPEN ACCESS

Complex systems in the spotlight: next steps after the 2021 Nobel Prize in Physics

Ginestra Bianconi[30,1,2], Alex Arenas[3], Jacob Biamonte[4], Lincoln D Carr[5,6,7], Byungnam Kahng[8], Janos Kertesz[9,10,11], Jürgen Kurths[12,13], Linyuan Lü[14], Cristina Masoller[15], Adilson E Motter[16,17], Matjaž Perc[10,18,19,20], Filippo Radicchi[21], Ramakrishna Ramaswamy[22], Francisco A Rodrigues[23], Marta Sales-Pardo[24], Maxi San Miguel[25], Stefan Thurner[10,26,27] and Taha Yasseri[28,29] – Hide full author list

Published 16 January 2023 •

Journal of Physics: Complexity, Volume 4, Number 1

Celebrating Complex Systems in honour of the 2021 Nobel Prize in Physics

Citation Ginestra Bianconi *et al* 2023 *J. Phys. Complex.* **4** 010201

DOI 10.1088/2632-072X/ac7f75

G. Bianconi *et al.*, J. Phys. Complex., **4** 010201 (2023). DOI: `10.1088/2632-072X/ac7f75`

Complex systems

"... *any system consisting of many interconnected parts which, as a whole, display properties that are not trivial aggregates of those of its constituents*"

Complex systems

> "... *any system consisting of many interconnected parts which, as a whole, display properties that are not trivial aggregates of those of its constituents*"

4 August 1972, Volume 177, Number 4047

SCIENCE

More Is Different

Broken symmetry and the nature of the hierarchical structure of science.

P. W. Anderson

less relevance they seem to have to the very real problems of the rest of science, much less to those of society.

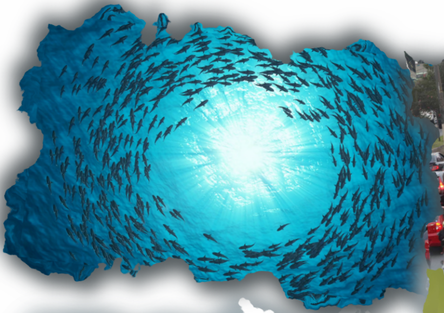
The constructionist hypothesis breaks down when confronted with the twin difficulties of scale and complexity. The behavior of large and complex aggregates of elementary particles, it turns out, is not to be understood in terms of a simple extrapolation of the properties of a few particles. Instead, at each level of complexity entirely new properties appear, and the understanding of the new behaviors requires research which I think is as fundamental in its nature as any other. That is, it

P.W. Anderson. Science **177**(4047), 393-396 (1972). DOI: `10.1126/science.177.4047.393`

Complex systems

"*any system consisting of many* ***interconnected parts*** *which, as a whole, display* ***properties that are not trivial aggregates of those of its constituents***"

Complex systems

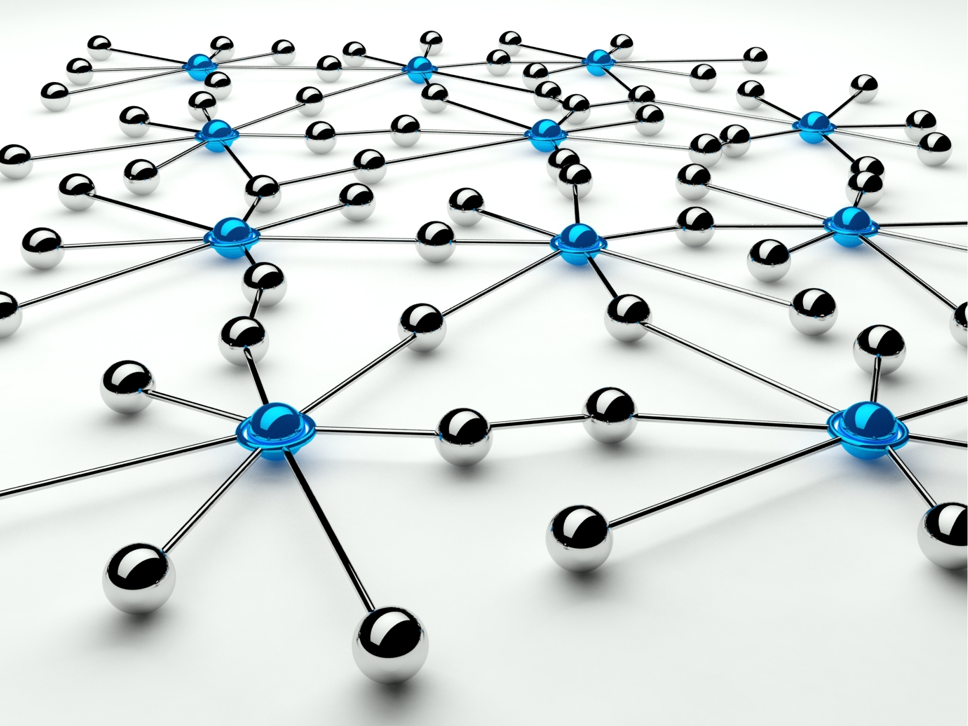


Complex systems

"*any system consisting of many* ***interconnected parts*** *which, as a whole, display* ***properties that are not trivial aggregates of those of its constituents***"

Complex systems

Using networks to study complex systems is like paleontology ...



Graph theory/network science in a nutshell

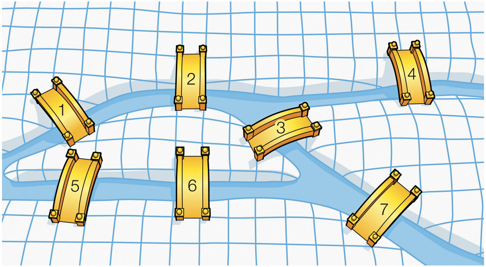
Once upon a time ...

In 173x a mathematical puzzle based on the city of Königsberg was posed.

Graph theory/network science in a nutshell

Once upon a time ...

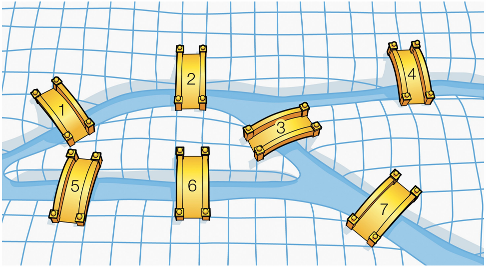
In 173x a mathematical puzzle based on the city of Königsberg was posed.



Graph theory/network science in a nutshell

The puzzle

Can we find a path that makes us explore the city passing from each bridge just once?

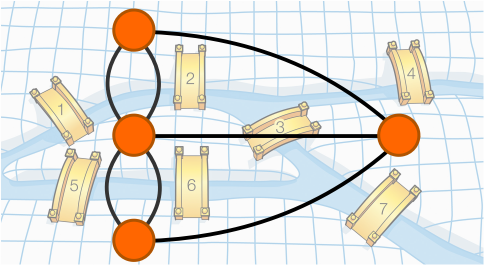


https://en.wikipedia.org/wiki/Seven_Bridges_of_K%C3%B6nigsberg

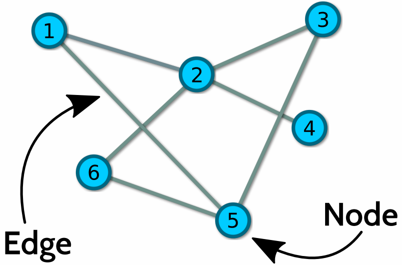
Graph theory/network science in a nutshell

The solution

In 1736 Leonard Euler found the answer and gave birth to graph theory.



Graph theory/network science in a nutshell



$N \times N$ Adjacency matrix

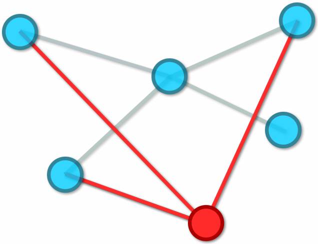
$$\mathcal{A} = \begin{pmatrix} 0 & 1 & 0 & 0 & 1 & 0 \\ 1 & 0 & 1 & 1 & 0 & 1 \\ 0 & 1 & 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 1 & 0 & 1 & 0 & 0 & 1 \\ 0 & 1 & 0 & 0 & 1 & 0 \end{pmatrix}$$

Graph theory/network science in a nutshell

Advantages

- Easy mathematical formalism.
- Ability to go beyond visual inspection.
- Possibility to adopt many techniques from statistical physics/nonlinear dynamics.

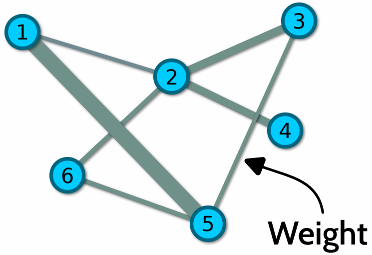
Graph theory/network science in a nutshell



Degree

$$k_i = \sum_j a_{ij} \, .$$

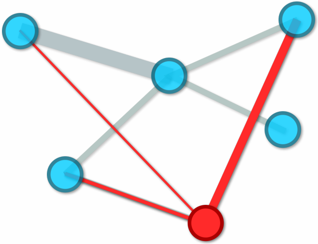
Graph theory/network science in a nutshell



$N \times N$ Weight matrix

$$\mathcal{W} = \begin{pmatrix} 0 & 2 & 0 & 0 & 7 & 0 \\ 2 & 0 & 3 & 1 & 0 & 1 \\ 0 & 3 & 0 & 0 & 5 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 7 & 0 & 5 & 0 & 0 & 1 \\ 0 & 1 & 0 & 0 & 1 & 0 \end{pmatrix}$$

Graph theory/network science in a nutshell



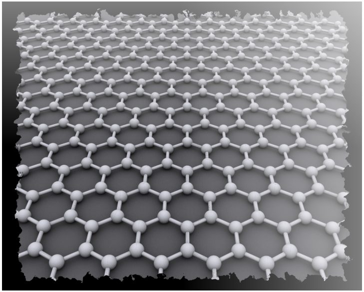
Strength

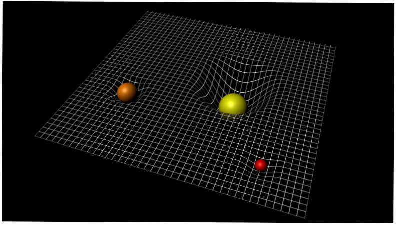
$$s_i = \sum_j w_{ij}\ .$$

Graph theory/network science in a nutshell

lattice / random

continuum



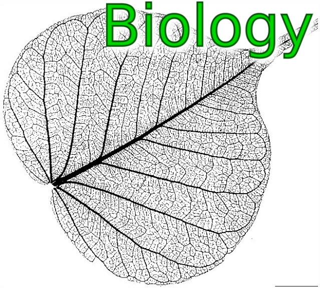


Complex systems

Graph theory/network science in a nutshell

Social Science

Biology



Neuroscience

Transportation

Graph theory/network science in a nutshell

Network science's flavors

- Spatial networks
- Networks of networks
- Time-varying networks
- Multiple interactions (multilayer/multiplex)
- High-order networks
- ...

So what?

So what?

1. Which structural features/indicators of the network capture relevant aspects (*e.g.*, stability) of the ecosystem?

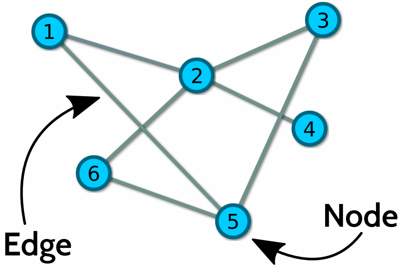
So what?

1. Which structural features/indicators of the network capture relevant aspects (*e.g.*, stability) of the ecosystem?
2. Can we use network/complexity science to see *underneath the underneath* and extract information/get insight **invisible** to "*traditional*" methods?

Networks and *neo*-ecology

Mesoscopic structures

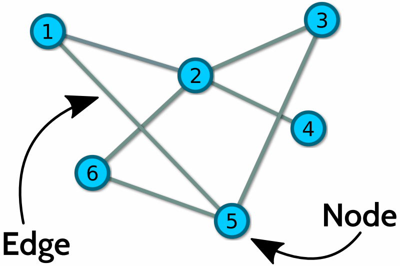
Mesoscopic structures



$N \times N$ Adjacency matrix

$$\mathcal{A} = \begin{pmatrix} 0 & 1 & 0 & 0 & 1 & 0 \\ 1 & 0 & 1 & 1 & 0 & 1 \\ 0 & 1 & 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 1 & 0 & 1 & 0 & 0 & 1 \\ 0 & 1 & 0 & 0 & 1 & 0 \end{pmatrix}$$

Mesoscopic structures

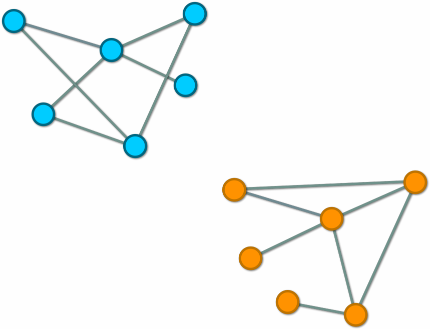


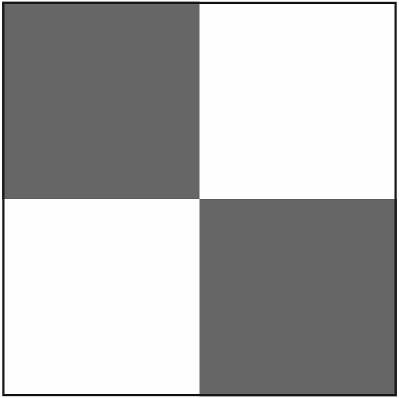
$N \times N$ Adjacency matrix

$$\mathcal{A} = \begin{pmatrix} \square & \blacksquare & \square & \square & \blacksquare & \square \\ \blacksquare & \square & \blacksquare & \blacksquare & \square & \blacksquare \\ \square & \blacksquare & \square & \square & \blacksquare & \square \\ \square & \blacksquare & \square & \square & \square & \square \\ \blacksquare & \square & \blacksquare & \square & \square & \blacksquare \\ \square & \blacksquare & \square & \square & \blacksquare & \square \end{pmatrix}$$

Mesoscopic structures

Communities

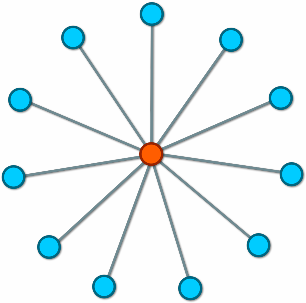


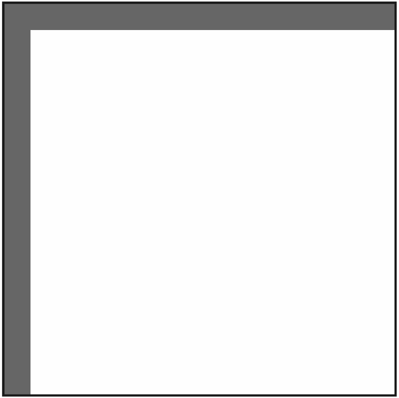


- S. Fortunato, & M. E. J. Newman, Nature Physics, **18**, 848 (2022). DOI: 10.1038/s41567-022-01716-7

Mesoscopic structures

Core-periphery

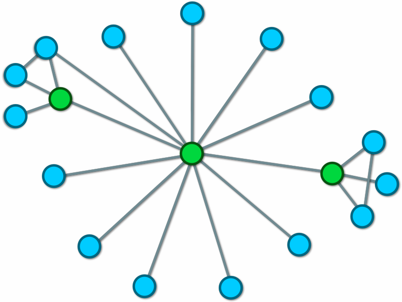


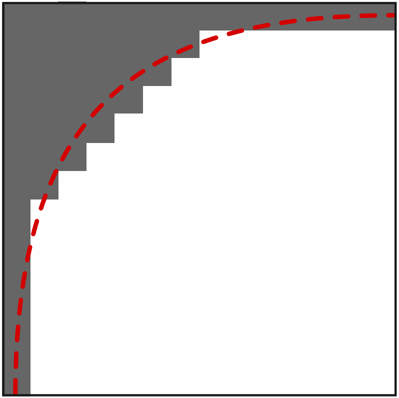


- S. P. Borgatti, & M. G. Everett, Soc. Net., **21** 375 (2000). DOI: `10.1016/S0378-8733(99)00019-2`

Mesoscopic structures

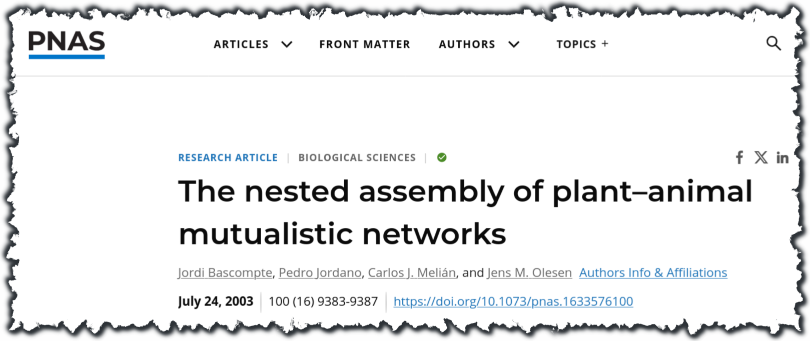
Nested structures





- M. S. Mariani, *et al.* Phys. Rep., **813**, 1 (2019). DOI: `10.1016/j.physrep.2019.04.001`

Mesoscopic structures


PNAS

ARTICLES FRONT MATTER AUTHORS TOPICS +

RESEARCH ARTICLE | BIOLOGICAL SCIENCES

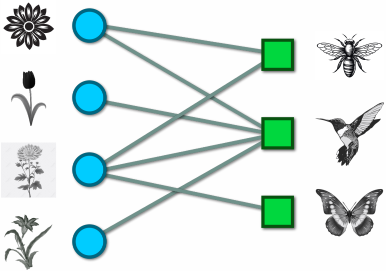
The nested assembly of plant–animal mutualistic networks

Jordi Bascompte, Pedro Jordano, Carlos J. Melián, and Jens M. Olesen Authors Info & Affiliations

July 24, 2003 | 100 (16) 9383-9387 | https://doi.org/10.1073/pnas.1633576100

- J. Bascompte, *et al.* Proc. Nat. Acad. Sci. USA, **100**, 9383, (2003). DOI: `10.1073/pnas.1633576100`

Mesoscopic structures



- J. Bascompte, *et al.* Proc. Nat. Acad. Sci. USA, **100**, 9383, (2003). DOI: `10.1073/pnas.1633576100`

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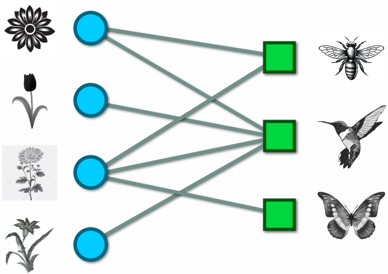

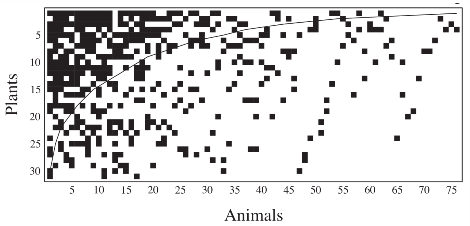

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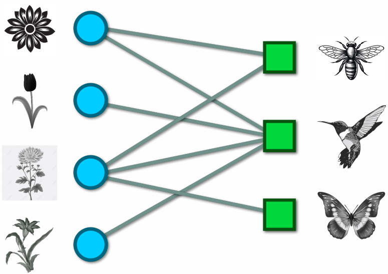
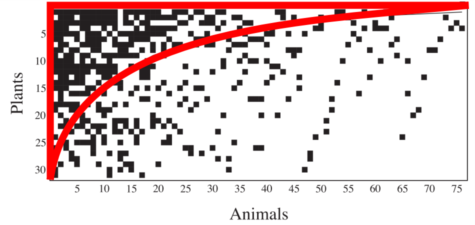
Mesoscopic structures





- J. Bascompte, *et al.* Proc. Nat. Acad. Sci. USA, **100**, 9383, (2003). DOI: `10.1073/pnas.1633576100`

Networks and *palaeo*-ecology

Project CORREDORAS

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Estabilidad y resiliencia de COmunidades vegetales en escalas tempoRales largas: evaluación de REDes de co-Ocurrencia a partir de Registros paleoAmbientaleS

IPE CSIC

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Universidad Zaragoza

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CHRISTCHURCH NEW ZEALAND

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Universidad del País Vasco
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AGENCIA ESTATAL DE INVESTIGACIÓN

PID2022-141558NB-I00

Project CORREDORAS

Objectives

- Tracing (Pyrenean) ecosystem's stability over (long) time.
- Determine how ecological communities re-organize after (external) disturbance (*e.g.*, introduction of agriculture).
- Studying networks of taxa over long time.

Project CORREDORAS

Data

Source Basa de la Mora (1913m asl).

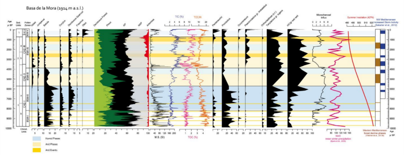
Project CORREDORAS

Data

Source Basa de la Mora (1913m asl).

Type-A Plant and fungi taxa derived from fossil spores and pollen grains.

Project CORREDORAS



Data

Source Basa de la Mora (1913m asl).

Type-A Plant and fungi taxa derived from fossil spores and pollen grains.

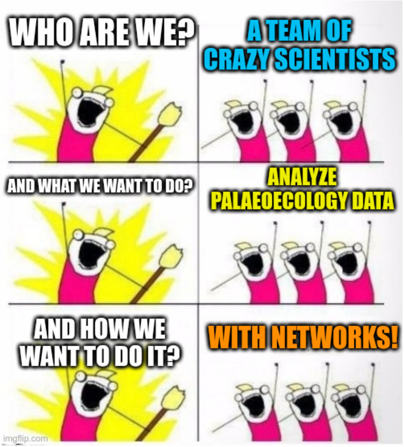
Type-B Abiotic conditions as erosion rates, lake level fluctuations or temperature reconstructions (chironomid-based).

Project CORREDORAS

Data

Source	Basa de la Mora (1913m asl).
Type-A	Plant and fungi taxa derived from fossil spores and pollen grains.
Type-B	Abiotic conditions as erosion rates, lake level fluctuations or temperature reconstructions (chironomid-based).
How-1	Depth-age model recording the last 10k years with a 10yr/cm resolution.

Project CORREDORAS



Data

Source Basa de la Mora (1913m asl).

Type-A Plant and fungi taxa derived from fossil spores and pollen grains.

Type-B Abiotic conditions as erosion rates, lake level fluctuations or temperature reconstructions (chironomid-based).

How-1 Depth-age model recording the last 10k years with a 10yr/cm resolution.

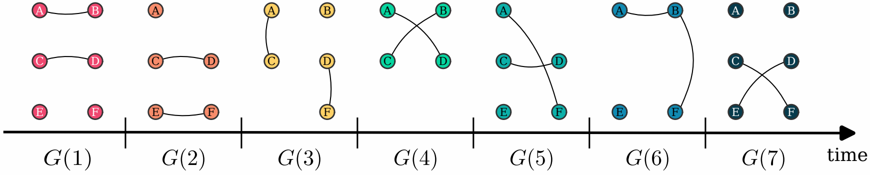
How-2 Analyzing networks of taxa's **co-occurrence**.

Networks and time: time-varying networks

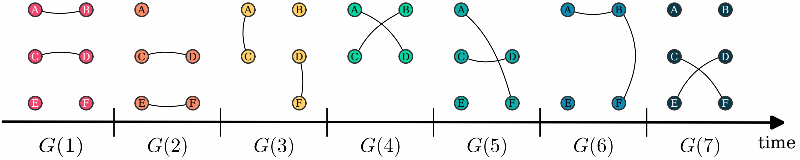
Networks and time: time-varying networks

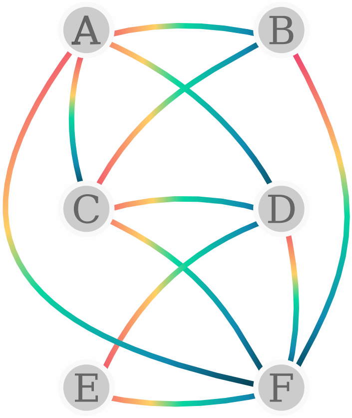
- Interactions
- Constituents

Networks and time: time-varying networks



Networks and time: time-varying networks





https://www.youtube.com/watch?v=faWaqRyR8nY


Grade
Homer S.
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Homer S
D

OXY
ACNE CREAM
Global

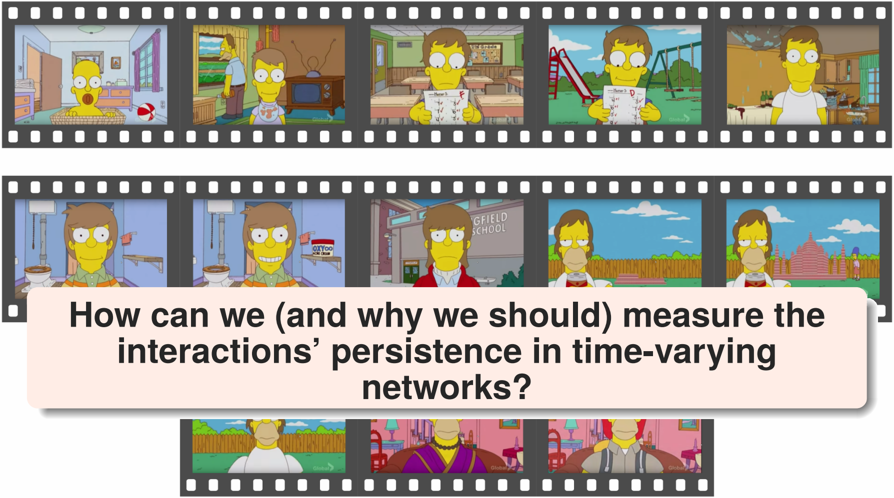

GFIELD
SCHOOL


Global


Global


Global

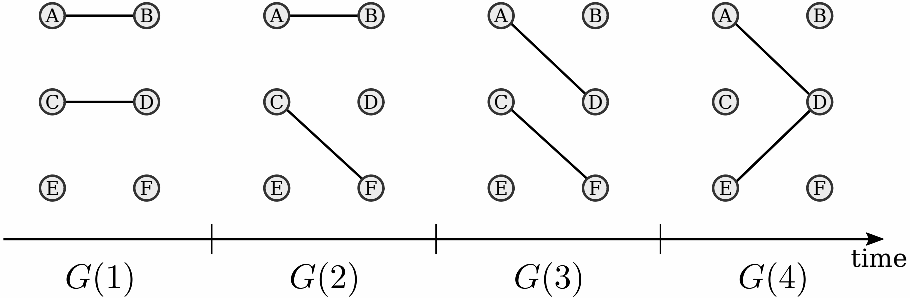

Global



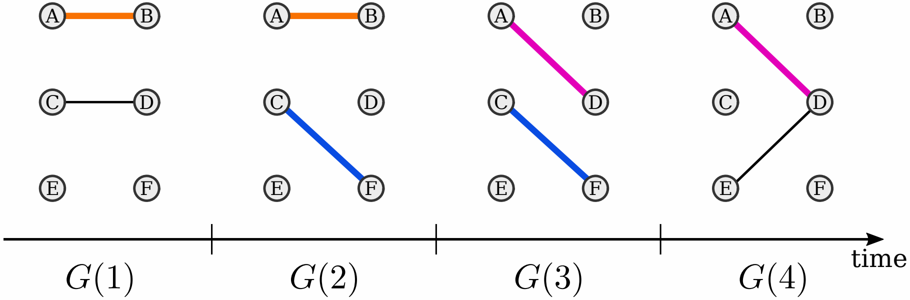
How can we (and why we should) measure the interactions' persistence in time-varying networks?

Temporality

Temporality



Temporality



Temporality

Definition of temporality, $\mathcal{T}$

$$\mathcal{T}_{m,n} = \frac{\bigcup_{m,n} - \bigcap_{m,n}}{\bigcup_{m,n}} = 1 - \frac{\bigcap_{m,n}}{\bigcup_{m,n}} ,$$

$\bigcup_{m,n} \longrightarrow$ Size of the union of the edges' sets of snapshots $G(m)$ and $G(n)$.

$\bigcap_{m,n} \longrightarrow$ Size of the intersection of the same sets.

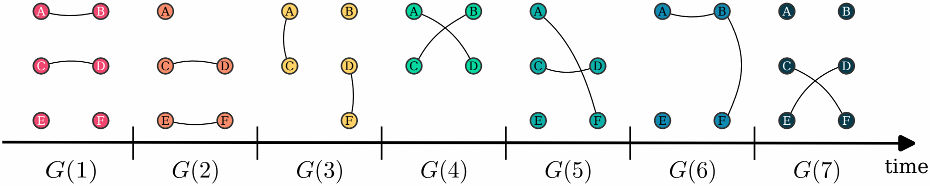
- A. Li, *et al.* Nature Comms., **11**, 2259, (2020). DOI: `10.1038/s41467-020-16088-w`
- F. Bauzá Mingueza, *et al.* Sci. Rep., **13**, 765 (2023). DOI: `10.1038/s41598-022-25907-7`

Temporality

$$\mathcal{T}_{m,n} = \begin{cases} 1 & \text{if} \quad \bigcap_{m,n} = 0 \\ 0 & \text{if} \quad \bigcap_{m,n} = \bigcup_{m,n} \end{cases}$$

Temporality

Temporality



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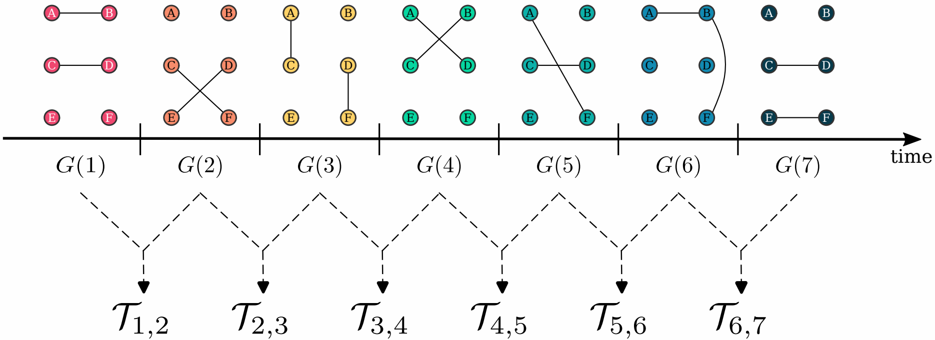


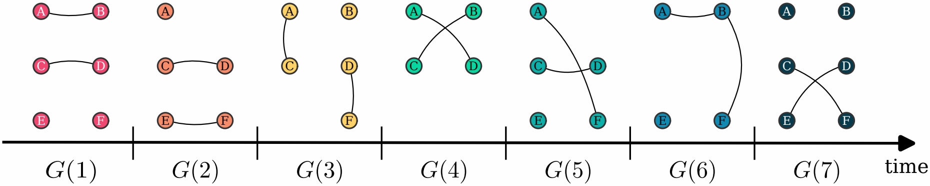
Temporality

Average temporality

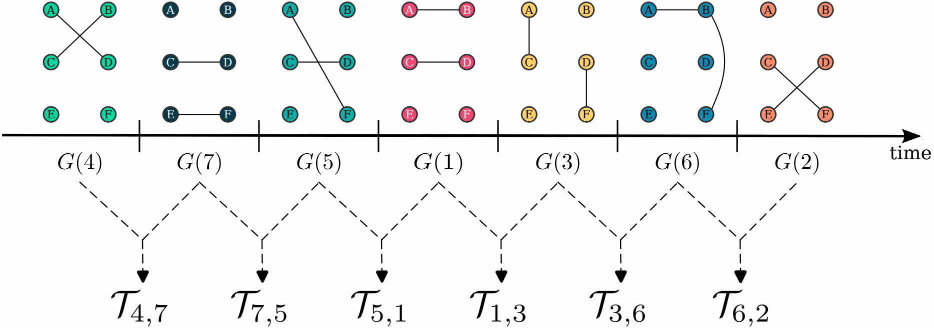
$$\overline{\mathcal{T}} = \frac{1}{N_s - 1} \sum_{m=1}^{N_s - 1} \mathcal{T}_{m,m+1}$$

How *special* your network is: Null model

How *special* your network is: Null model

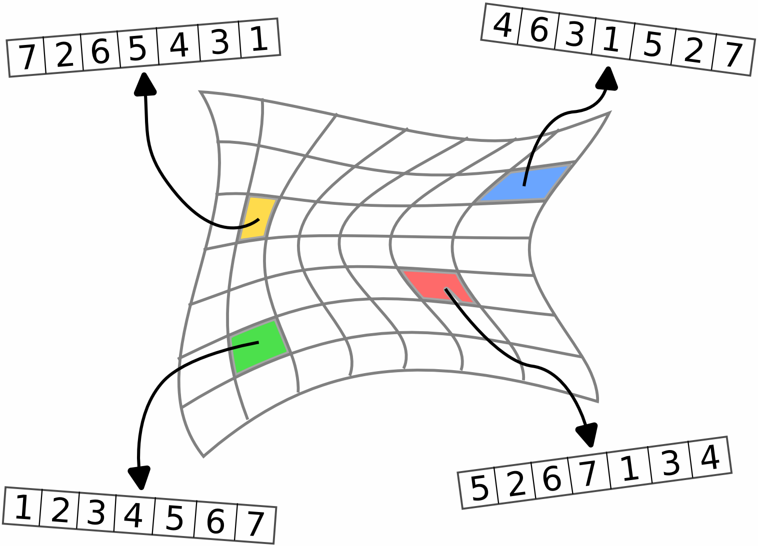


How *special* your network is: Null model



- L. Gauvin, *et al.* SIAM Review, **64**, 763–830, (2022). DOI: `10.1137/19M1242252`

How *special* your network is: Null model



How *special* your network is: Null model

Caveats

- The space of configurations can become quite big (*i.e.*, long computation time).

How *special* your network is: Null model

Caveats

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- The concept of persistence should be extended to weighted edges.

Summing up ...

Take home messages

- A *quick overview* on complex systems (and networks).

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Take home messages

- A *quick overview* on complex systems (and networks).
- How network science can be used in ecological systems.
- Why a complex system scientist can (and *should*) sit among ecologists.
- (real) Multidisciplinary collaborations can trigger **interesting questions** stemming **from both sides** of the collaboration.

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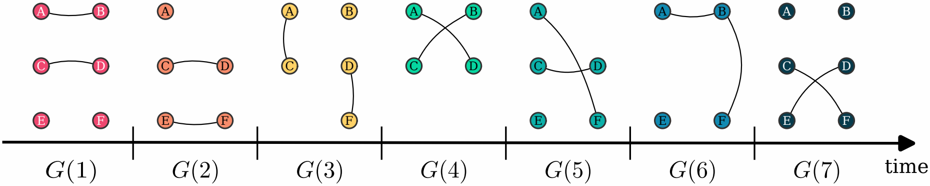
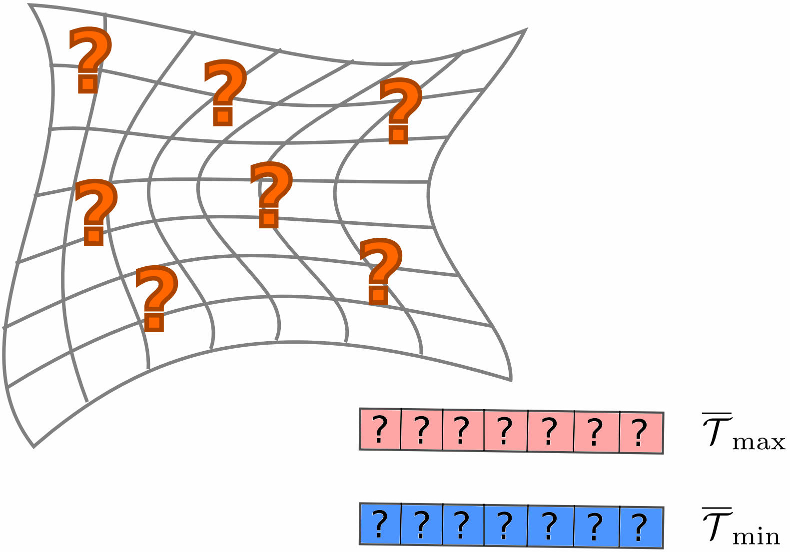
Extra contents

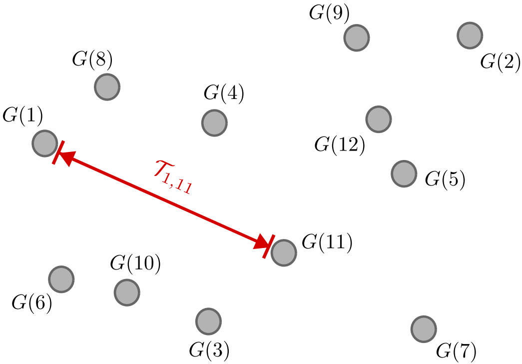
Finding the optimal order



Finding the optimal order



Finding the optimal order



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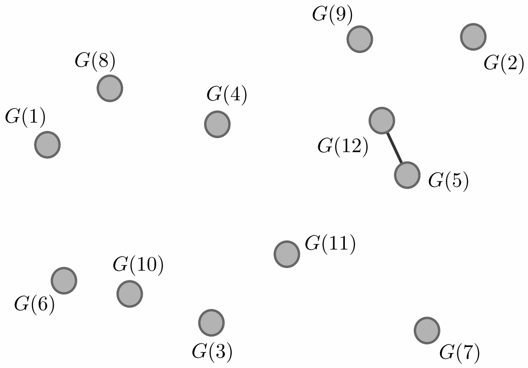
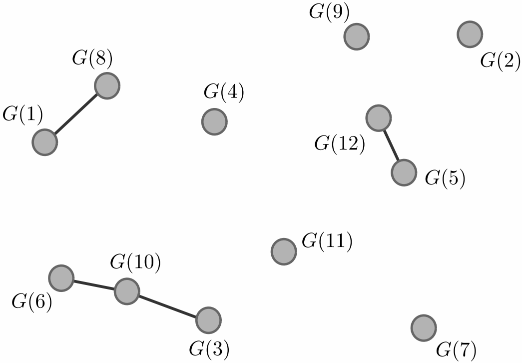
Finding the optimal order



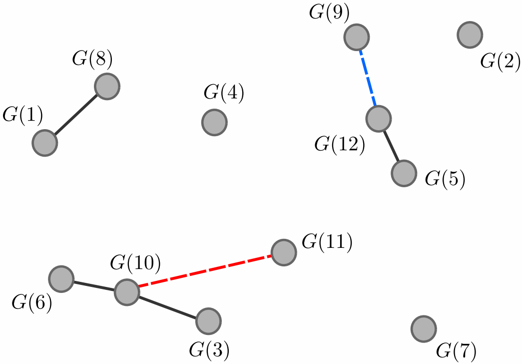
1. Embed snapshots in a metric space with $d_{m,n} = \mathcal{T}_{m,n}$
2. Compute all the temporalities between snapshots and sort them in ascending (descending) order.

Finding the optimal order



1. Embed snapshots in a metric space with $d_{m,n} = \mathcal{T}_{m,n}$
2. Compute all the temporalities between snapshots and sort them in ascending (descending) order.
3. Add edges to the Spanning Tree (chain).

Finding the optimal order



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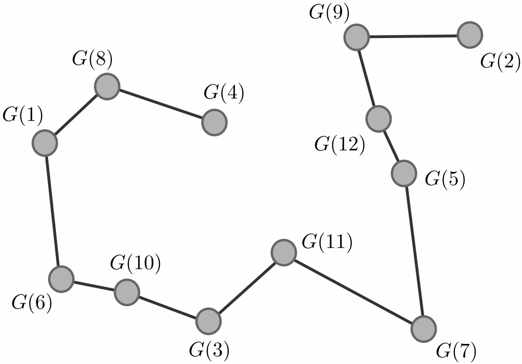

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5. Repeat steps 3 and 4 until getting an open chain.