National Aeronautics and
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Jet Propulsion Laboratory
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Complex systems science: A new framework for understanding Earth system models

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Outline

- Introduction
- What is complex systems science?
- Networks
- Complex networks
- Complex networks and climate
- Multilayer networks
- Multilayer networks for ESM's
- Discussion

Introduction

This talk is

- a high-level synthesis of what I have learned about complex systems science (a lit review)
- a mapping of these ideas onto the problem of quantitative characterization of highly multivariate relationships in ESM's.

Introduction

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I am the Head of the Complex Multilayer Networks (CoMuNe) Research Unit at the Center for Information Technology of Fondazione Bruno Kessler, where I also co-coordinate the Computational Human Behavior (CHuB) FBK's Flagship Project.

A (non-exhaustive) list of my research interests includes:

- Structure and dynamics of **complex systems**, mostly modeled as **multilayer networks**
- Information and other **emergent behavior** of complex systems (e.g., life, consciousness, collective intelligence)
- **Resilience** of complex networks to random and targeted structural/dynamical perturbations
- **Information diffusion** in (multilayer) systems
- **Information theory** of complex networks
- Advanced mathematical techniques for **dimensionality reduction**
- Complex analysis of (big) data

My research on complex networks finds applications in systems biology, systems medicine, computational social sciences, computational epidemiology and data-driven policy making.

I am co-director of the Mediterranean School of Complex Networks and member of the Complex Systems Society Council.

I am not an expert, but Manlio is.

What is complex system science?

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. . . The properties of the collection may not be understood or predicted from the full knowledge of its constituents alone.

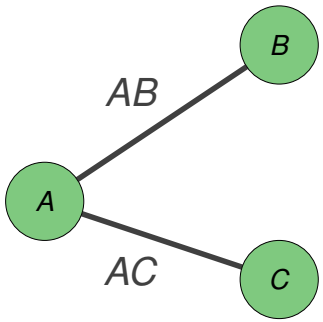
–De Domenico and Sayama (*Complexity Explained*, 2019)

Networks

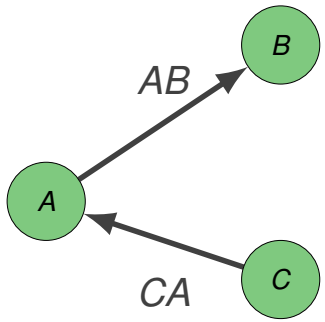
A network is a mathematical model of relationships among entities, instantiated as a graph:

$$\mathcal{G} = \{\mathcal{V}, \mathcal{E}\},$$

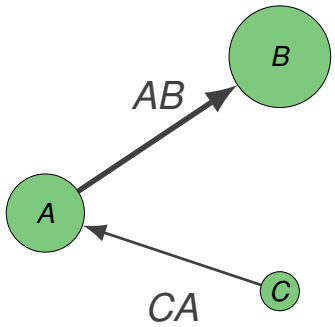
where $\mathcal{V}$ is the set of vertices, and $\mathcal{E}$ is the set of edges.



$\mathcal{V} = \{A, B, C\}$,
$\mathcal{E} = \{AB, AC\}$
(undirected)



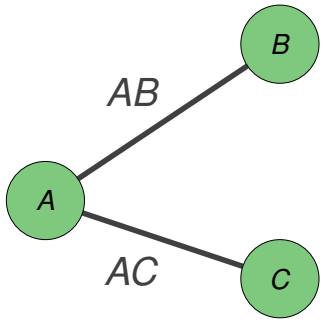
$\mathcal{V} = \{A, B, C\}$,
$\mathcal{E} = \{AB, CA\}$
(directed)

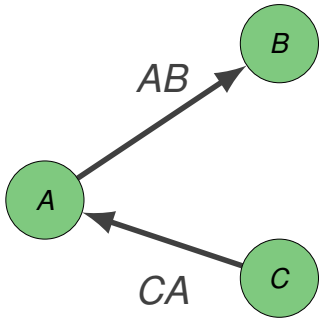


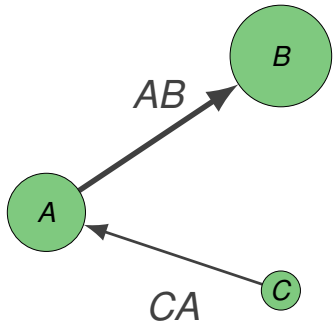
$\mathcal{V} = \{A, B, C\}$,
$\mathcal{E} = \{AB, CA\}$
(directed, weighted)

Networks

Vector/matrix representation:







$$V_1 = [1, 1, 1],$$

$$A_1 = \begin{bmatrix} 1 & 1 & 1 \\ 1 & 1 & 0 \\ 1 & 0 & 1 \end{bmatrix}$$

$$V_2 = [1, 1, 1],$$

$$A_2 = \begin{bmatrix} 1 & 1 & 0 \\ 0 & 1 & 0 \\ 1 & 0 & 1 \end{bmatrix}$$

$$V_3 = [1, 1.3, .5],$$

$$A_3 = \begin{bmatrix} 1 & 1 & 0 \\ 0 & 1 & 0 \\ .5 & 0 & 1 \end{bmatrix}$$

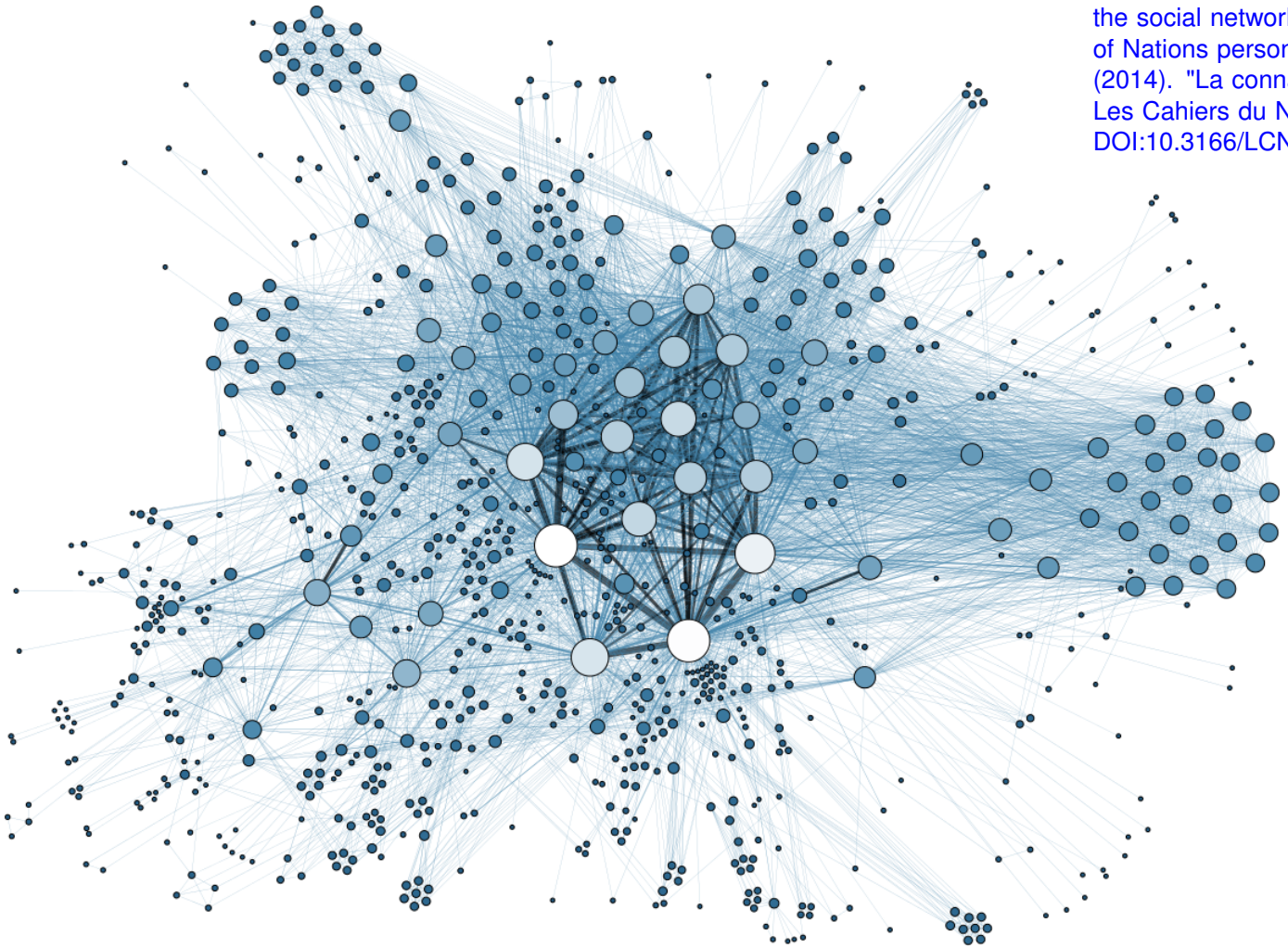
Complex networks

Types of networks:

- Simple networks: few components
  - regular/lattice
  - random
- Complex networks: “many” interacting components
  - small world and networks with given degree distribution
  - scale-free (degree distribution obeys power law)

Good introduction in Newman, M.E. (2003). The Structure and Function of Complex Networks *SIAM Review*, Vol. 45, No. 2, pp. 167–256.

Complex networks



Graph representing the metadata of thousands of archive documents, documenting the social network of hundreds of League of Nations personals. Grandjean, Martin (2014). "La connaissance est un réseau". Les Cahiers du Numérique, 10 (3): 37-54. DOI:10.3166/LCN.10.3.37-54.

Complex networks and climate

Some previous work:

- Rind (1999). Complexity and Climate, *Science*, 284(2).
- Tsonis, Swanson, and Roebber (2006). What do networks have to do with climate? *Bulletin of the American Meteorological Society*, doi: 10.1175/BAMS-87-5-585.
- Donges et al. (2009). Complex networks in climate dynamics, *The European Physical Journal Special Topics* 174(1).
- Steinhaeuser, Chawla, and Ganguly (2010). Complex Networks as a Unified Framework for Descriptive Analysis and Preditive Modeling in Climate Science, *Statistical Analysis and Data Mining*, (4).
- Steinhaeuser, Ganguly, and Chawla (2011). Multivariate and multiscale dependence in the global climate system revealed through complex networks, *Climate Dynamics*, 39, doi: 10.1007/s00382-011-1135-9.

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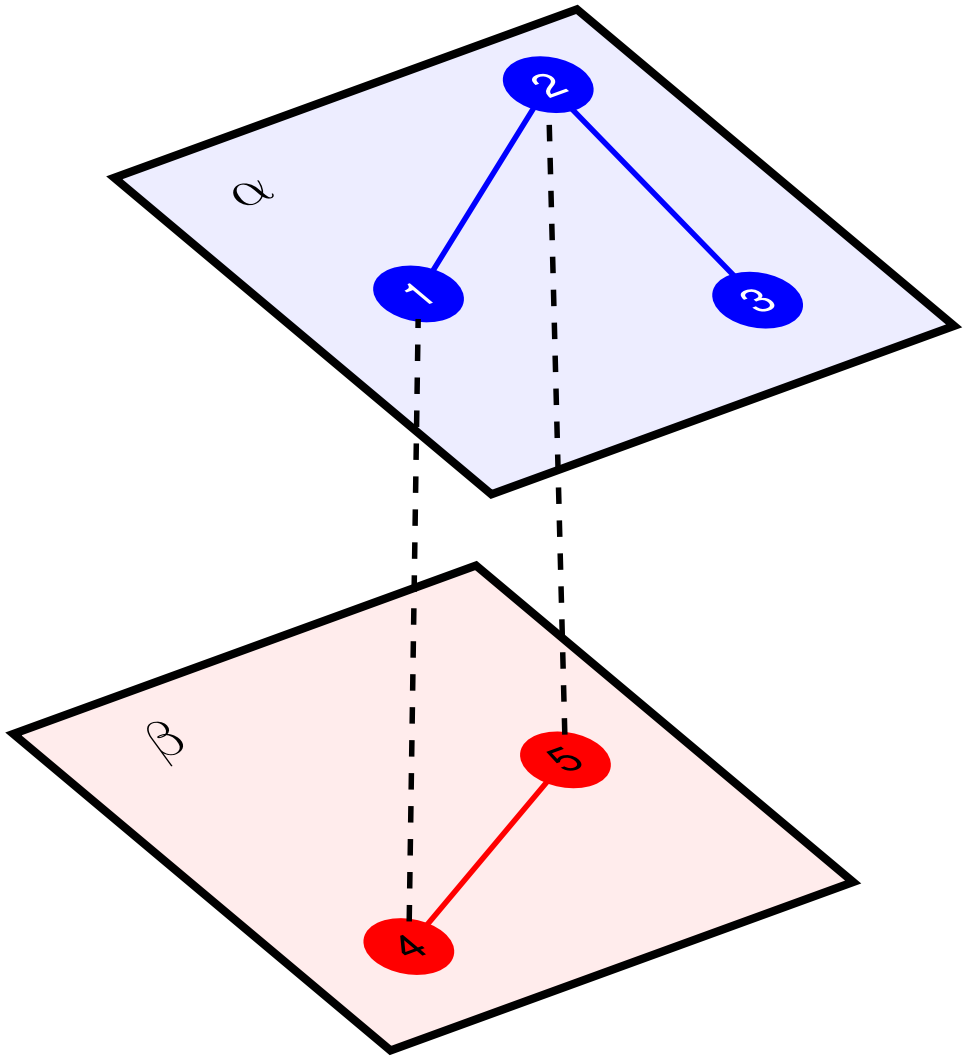
Multilayer networks



Adapted from Aleta, A. and Moreno, Y. (2018). Multilayer Networks in a Nutshell, *Annual Review of Condensed Matter Physics*, doi: 10.1146/annurev-conmatphys-031218-013259.

$$A = \left[\begin{array}{ccc|cc} 0 & 1 & 0 & 1 & 0 \\ 1 & 0 & 1 & 0 & 1 \\ 0 & 1 & 0 & 0 & 0 \\ \hline 1 & 0 & 0 & 0 & 1 \\ 0 & 1 & 0 & 1 & 0 \end{array}\right]$$

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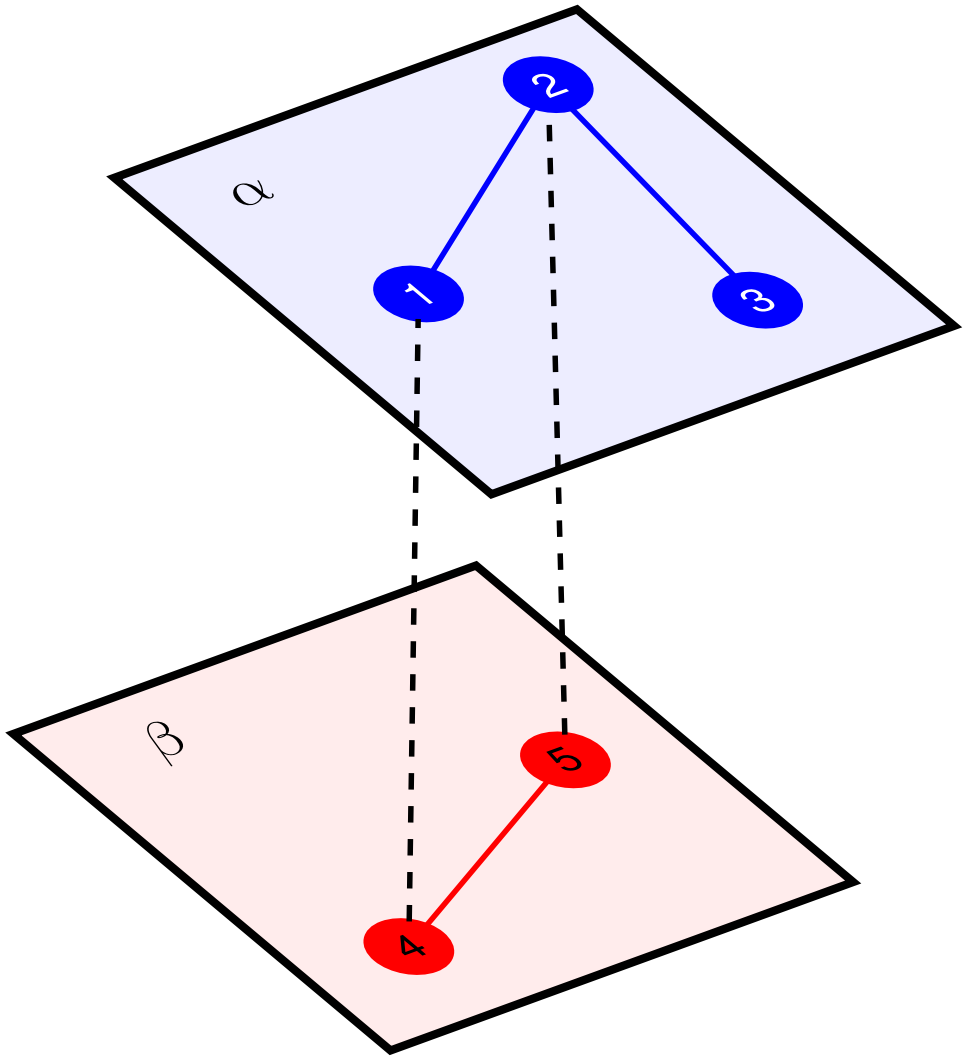
Multilayer networks



- Different layers for different Earth system model components?
- Different layers for different geographic regions?
- Different layers for different model experiments?
- Different layers for different scales?

Discussion

- Tensor mathematics to compactly represent information relationships
- Notions of centrality, clustering, degree distributions, etc carry over
- Capture temporal dynamics using layers to represent time
- Reveal emergent behaviors that are otherwise not detectable
- Percolation, random walks, resiliance. etc
- Successfully applied in biology, genetics, finance, ecology, social networks, politics, communication, transportion, epidemiology, air traffic, and many others

Why not use to quantify and better understand relationships among Earth system model components?

Some good resource:

- De Domenico et al. (2013). Mathematical Formulation of Multilayer Networks, *Physical Review X*, doi: 10.1103/PhysRevX.3.041022.
- Kivela et al. (2014). Multilayer Networks, *Journal of Complex Networks*, doi: 10.1093/comnet/cnu016.
- Boccaletti et al. (2014). The structure and dynamics of multilayer networks, *Physics Reports*, doi: 10.1016/j.physrep.2014.07.001.
- Aleta and Moreno (2018). Multilayer networks in a nutshell, *Annual Review of Condensed Matter Physics*, doi: 10.1146/annurev-conmatphys-031218-013259.
- https://comunelab.fbk.eu/.

Question or comments? Contact Amy.Braverman@jpl.nasa.gov.

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