Underlying Logic of Interdisciplinary Systems
Emergence

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Interdisciplinary Science
Outline

Interdisciplinary Science

Reaction Networks and Organizations

The Underlying Logic
More and more authorities of the establishment speak about interdisciplinarity as a good thing.
The foundational problem

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- Sustainability and resilience are mantras
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- It is right there where the foundational problems are!
- Shortcut example: Resilience has more than 150 definitions!
Example: Complexity-Stability Debate

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  - **Stability**: resilience, resistance, robustness, etc.
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Ecological systems are faced with species extinctions and invasions. A fundamental question is how systems vary when they suffer these changes. A major problem in theoretical ecology is to resolve how ecosystem stability respond to changes in its complexity. This question is known as the Complexity-Stability (CS) problem. Stability: resilience, resistance, robustness, etc. Complexity: diversity, richness, connectivity, etc.

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We assess the scientific and policy literature and show that this disconnect is one consequence of an inconsistent and one-dimensional approach that ecologists have taken to both disturbances and stability. This has led to confused communication of the nature of stability and the level of our insight into it. Disturbances and stability are multidimensional. Our understanding of them is not. Donohue et. al., Ecology Letters (2016)
Example: Same problem in other Interdisciplinary-like areas

- Interplay between Systemic Risk and Stability in finance
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How to study the CS problem? Dynamical Models

- Provide an analytic description of the interactions and dynamics by means of equations

\[
\frac{dx}{dt} = \alpha x - \beta xy \\
\frac{dy}{dt} = \delta xy - \gamma y
\]
How to study the CS problem? Dynamical Models

- Provide an analytic description of the interactions and dynamics by means of *equations*

\[
\frac{dx}{dt} = \alpha x - \beta xy \\
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- But can be solved only for small ecosystems
How to study the CS problem? Network Models

- Provide an analytic description of the interactions and can be developed for ecosystems with many species by means of *links*.
How to study the CS problem? Network Models

- Provide an analytic description of the interactions and can be developed for ecosystems with many species by means of *links*.

- But can encompass only one type of interaction at a time.
Provide a description of the interactions of different type and their dynamics by means of *rules*.
How to study the CS problem? Agent Based Models

- Provide a description of the interactions of different type and their dynamics by means of *rules*.

- But lack of analytic methods of study.
Summary of the problem

The following table summarizes the methodological problem of the study of the CS debate

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We provide a shift in perspective towards a solution
Reaction Networks: Intro

Represents the reaction

$$2H_2 + O_2 \rightarrow 2H_2O$$
We have in mind large reaction networks (many species/interactions). 

Represented by the reactions:

\[ 2H_2 + O_2 \rightarrow 2H_2O \]
\[ S_8 + 8O_2 \rightarrow 8SO_2 \]
We have in mind large reaction networks (many species/interactions)

Drug Treatment, Metabolisms, Emergence of life, etc.
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**Object of study:** sub-networks of a large reaction network
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Object of study: sub-networks of a large reaction network

Goal: The relation between structure and dynamical stability
A reaction network is composed by
- A set of species $\mathcal{M} = \{s_1, \ldots, s_n\}$
- A set of reactions $\mathcal{R} = \{r_1, \ldots, r_k\}$
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Each $C \subseteq \mathcal{M}$ activates a set $\mathcal{R}_C \subseteq \mathcal{R}$.

A set of species $C \subseteq \mathcal{M}$ is:
1. **Closed** iff all the produced species in $\mathcal{R}_C$ are in $C$.
2. **Semi-self-maintaining** iff every species consumed in $\mathcal{R}_C$ is produced in $\mathcal{R}_C$. 
Reaction Networks: Basics

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Tomás Veloz (CLEA)
Reaction Networks: Processes

A *process* is a specification of how the reactions will occur within a certain time interval.

Let $M = \{a, b, c\}$, $R = \{r_1, r_2, r_3\}$, with

- $r_1 = a + b \rightarrow 2c$,
- $r_2 = b + c \rightarrow 2a$,
- $r_3 = a + c \rightarrow 2b$.

A process is self-maintaining if it produces the same or more than what it consumes.

Can we use the notion of self-maintaining process to understand the dynamics of large reaction networks?
Reaction Networks: Processes

- A *process* is a specification of how the reactions will occur within a certain time interval.
- A process implies a collective transformation of species.
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Process $r_1$ consumes $(1a, 1b, 0c)$, and produces $(0a, 0b, 2c)$.
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Can we use the notion of self-maintaining process to understand the dynamics of large reaction networks?
Definition: An Organization is a set of species that is closed and has self-maintaining processes
**Chemical Organization Theory**

- **Definition:** An *Organization* is a set of species that is *closed* and has *self-maintaining processes*.

- **Theorem:** Fixed points of the dynamical equations of a reaction network correspond to organizations (Dittrich 2005).
**Reaction Networks and Organizations**

**Chemical Organization Theory**

- **Definition:** An *Organization* is a set of species that is *closed* and has *self-maintaining processes*.

- **Theorem:** Fixed points of the dynamical equations of a reaction network correspond to organizations (Dittrich 2005).

- **Corollary:** Organizations of a reaction network contain all *stationary states*.

![Diagram of a reaction network and organizations](image)
What do we have? - Abstract Reflexion

- COT model systems made of collective transformations, objects are organizations and emerge out of these fundamental processes.

- Many species & many interactions - Stable meta-structures emerge

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Expensive and Cheap dynamics
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Tomás Veloz (CLEA)
If we consider sub-networks of a reaction network as propositions we see that COT could represent logical structures.
The lattice of organizations

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If $A, B$ are organizations then $A \land_{O} B = G_{O}(A \cup B)$ and $A \lor_{O} B = G_{O}(A \cap B)$ are organizations.
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- There are various results extending this idea from algorithmic and network-classification point of view
- This is an example of an ecological system with non-boolean structure
Structural change as an operator

- In traditional dynamical systems change is seen as a modification of the state.
The Underlying Logic

Structural change as an operator

- In traditional dynamical systems change is seen as a modification of the state
- Note that a change of state does not modify the lattice of organizations

We extend this type of change to two other forms of change:

- Process change: The rules defining how time-evolution occurs are modified (feasible organizations change)
- Structural change: Reactions are added/eliminated (organizational structure changes)

COT allows to modify the lattice of organizations under these types of change.

This permits an operationalization of changes of structure and behaviour (operation) of systems, compatible with notions such as resilience, agency, etc.
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- Organizations cover the set of structures that can possibly emerge
- Organizations can be subjected to perturbations and be combined, they can be seen as a logic where propositions are structures persistent enough to be observable (objects)
- We are currently working on the formalization of the taxonomy of systemic concepts (resilience, diversity, robustness) in this setting