Collective decision-making on networked systems in presence of antagonistic interactions

Angela Fontan, angfon@kth.se
Division of Decision and Control Systems
KTH Royal Institute of Technology, Sweden

in collaboration with
Prof. Claudio Altafini, Linköping University, Sweden

Outline

- **Background**
  Motivation and problem statement
- **Signed networks**
  Notions of structural balance and frustration
- **Model for collective decision-making over signed networks**
  Bifurcation analysis on structurally balanced and structurally unbalanced networks
- **Application**
  Process of government formation over signed “parliamentary networks”

Background

Motivation

 

Animal groups

$\Rightarrow$ decision reached through collaboration

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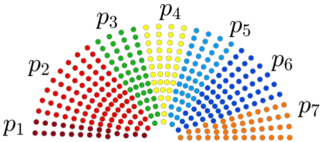
$\Rightarrow$ decision reached through collaboration

Social Networks



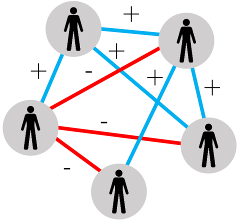
Parliamentary Systems

$\Rightarrow$ both cooperative and antagonistic interactions may coexist

Background

Problem: collective decision-making in presence of antagonism

$$\dot{x} = f(x, \text{network}, \pi)\ ,$$



1. Signed networks
   - positive weight: cooperative interaction
   - negative weight: antagonistic interaction
2. Model for collective decision-making
   - x: vector of opinions
   - equilibrium points: possible decisions

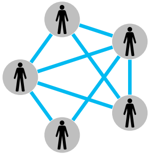
Model for collective decision-making

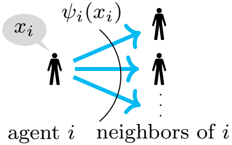
$$\dot{x} = -\Delta x + \pi A \psi(x)$$

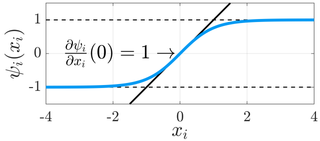
- n agents, $x \in \mathbb{R}^n$ vector of opinions
- "inertia" of the agents: $\Delta = \mathrm{diag}\{\delta_1, \ldots, \delta_n\}$, $\delta_i > 0$
- interactions between the agents:

unsigned (connected) network $\mathcal{G}(A)$

$\psi(x) = [\psi_1(x_1) \; \ldots \; \psi_n(x_n)]^T$







and $\pi > 0$ scalar parameter

Gray et al, "Multiagent Decision-Making Dynamics Inspired by Honeybees", IEEE TCNS, 2018

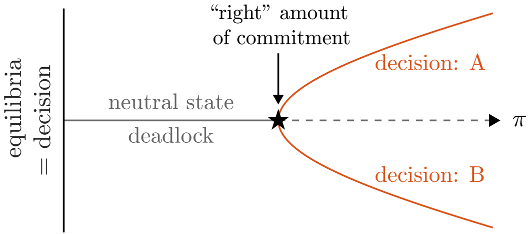
Model for collective decision-making

$$\dot{x} = -\Delta x + \pi A \psi(x) \qquad (\star)$$

- π = "social effort" or "strength of commitment" among the agents
- equilibria = decisions

Assumption: $\delta_i = \sum_j a_{ij} \quad \Rightarrow \quad L = \Delta - A$: Laplacian of $\mathcal{G}(A)$

Task: Study qualitative behavior of $(\star)$ as social effort parameter π is varied

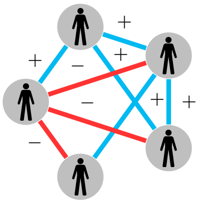


Model for collective decision-making *over signed networks*

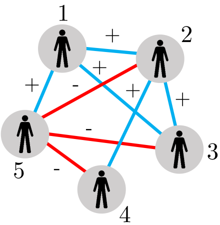
Task: Study the decision-making process in a community of agents where both cooperative and antagonistic interactions coexist

Model: $\dot{x} = -\Delta x + \pi A \psi(x)$

Assumptions: $\mathcal{G}(A)$ is signed, π: "social effort" between the agents



Signed networks and signed Laplacian matrix

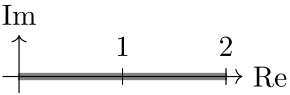


$$A = \begin{bmatrix} 0 & + & + & 0 & + \\ + & 0 & + & + & - \\ + & + & 0 & 0 & - \\ 0 & + & 0 & 0 & - \\ + & - & - & - & 0 \end{bmatrix} \begin{matrix} \Rightarrow \delta_1 \\ \\ \dots \\ \\ \Rightarrow \delta_5 \end{matrix} \qquad \mathcal{L} = \begin{bmatrix} 1 & - & - & 0 & - \\ - & 1 & - & - & + \\ - & - & 1 & 0 & + \\ 0 & - & 0 & 1 & + \\ - & + & + & + & 1 \end{bmatrix}$$

Signed Laplacian:

$$L = \Delta - A$$

$$\Delta = \text{diag}\{\delta_1, \dots, \delta_n\} : \ \delta_i = \sum_{j=1}^{n} |a_{ij}| > 0 \quad \forall\ i$$



$\Lambda(\mathcal{L})$ = spectrum of $\mathcal{L}$

Focus on:

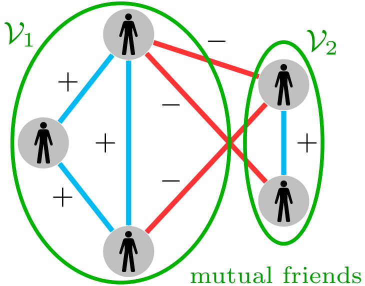
normalized signed Laplacian: $\mathcal{L} = I - \Delta^{-1} A$

Structural balance

A connected signed graph is
structurally balanced
if $\mathcal{V} = \mathcal{V}_1 \cup \mathcal{V}_2$ s.t. every edge:

- between $\mathcal{V}_1$ and $\mathcal{V}_2$ is negative
- within $\mathcal{V}_1$ or $\mathcal{V}_2$ is positive

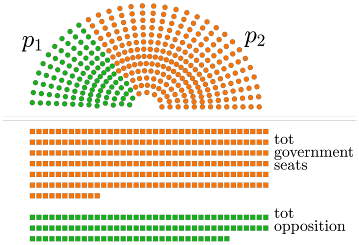
It is structurally unbalanced
otherwise

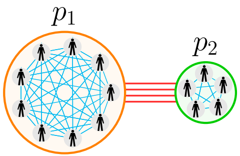


F. Harary, "On the notion of balance of a signed graph", Michigan Mathematical Journal, 1953

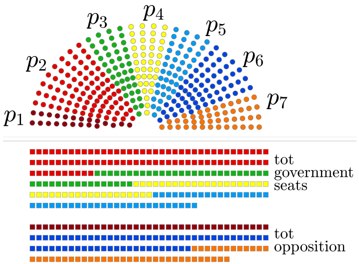
Example: Parliamentary systems

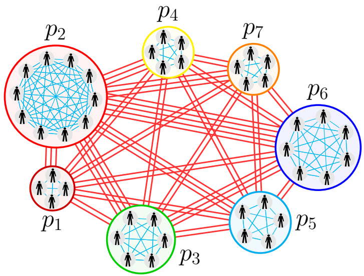
Structurally balanced network





Structurally unbalanced network

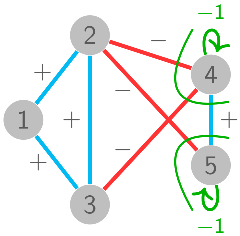




Structural balance: equivalent conditions

$\mathcal{G}(A)$ connected signed graph is structurally balanced iff

1. $\exists$ signature matrix $S = \text{diag}\{s_1, \dots, s_n\}$, $s_i = \pm 1$, s.t. $S\mathcal{L}S$ has all nonpositive off-diagonal entries ($SAS \geq 0$)



$$A = \begin{bmatrix} 0 & + & + & & \\ + & 0 & + & - & - \\ + & + & 0 & - & \\ & - & - & 0 & + \\ & - & & + & 0 \end{bmatrix} \qquad \mathcal{L} = \begin{bmatrix} 1 & - & - & & \\ - & 1 & - & + & + \\ - & & 1 & + & \\ & + & + & 1 & - \\ & + & & - & 1 \end{bmatrix}$$

$$S = \text{diag}\{1,\ 1,\ 1,\ -1,\ -1\}$$

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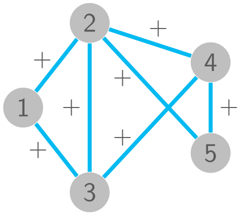

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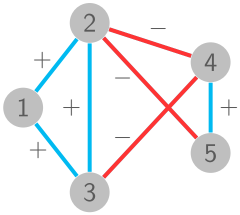
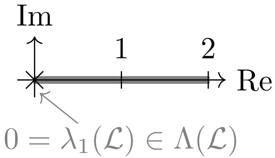
2. $\lambda_1(\mathcal{L}) = 0$





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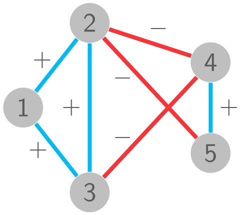
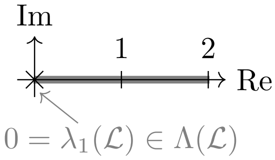
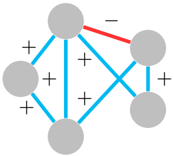
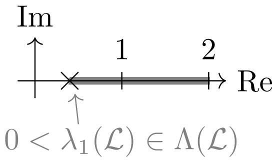




$\Rightarrow$ $\mathcal{G}(A)$ connected signed graph is structurally unbalanced iff $\lambda_1(\mathcal{L}) > 0$





Frustration index and algebraic conflict

Task: characterize the graph distance from structurally balanced state

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- Frustration Index
  (computation: NP-hard problem)

$$\epsilon(\mathcal{G}) = \min_{\substack{S=\mathrm{diag}\{s_1,\ldots,s_n\} \\ s_i=\pm 1}} \underbrace{\frac{1}{2} \cdot \sum_{i \neq j} \left[|\mathcal{L}| + S\mathcal{L}S \right]_{ij}}_{=e(S):\ \text{“energy functional”}}$$

Frustration index and algebraic conflict

Task: characterize the graph distance from structurally balanced state

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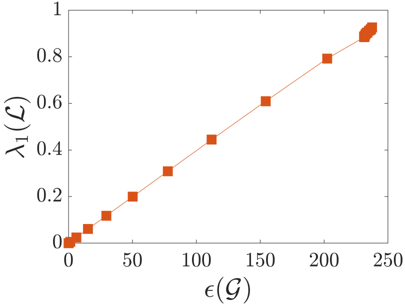
- Algebraic Conflict

$$\xi(\mathcal{G}) = \lambda_1(\mathcal{L})$$



$\Longrightarrow$

$\lambda_1(\mathcal{L})$ good approximation of $\epsilon(\mathcal{G})$

Model for collective decision-making over signed networks

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- n agents, $x \in \mathbb{R}^n$ vector of opinions
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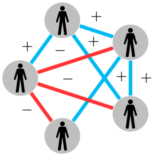
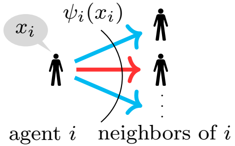
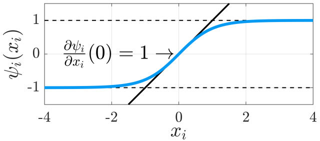




$\psi(x) = [\psi_1(x_1) \, \ldots \, \psi_n(x_n)]^T$



and $\pi > 0$ "social effort" (or "strength of commitment")

A. Fontan and C. Altafini, "The role of frustration in collective decision-making dynamical processes on multiagent signed networks", IEEE TAC, 2022

Dynamical interpretation of structural balance

$$\dot{x} = -\Delta x + \pi A\psi(x) = \Delta(-x + \pi \underbrace{\Delta^{-1}A}_{:=H}\psi(x)) \qquad (\star)$$

"Laplacian" assumption: $\delta_i = \sum_j |a_{ij}| > 0 \ \forall i \quad \Rightarrow \quad \mathcal{L} = I - H$

Then at the origin for $\pi = 1$:

Jacobian: $\quad J = -L = \Delta(-\mathcal{L})$

and

$$(\star) \text{ is monotone} \quad \Leftrightarrow \quad \mathcal{G}(A) \text{ is structurally balanced} \quad \Leftrightarrow \quad \lambda_1(\mathcal{L}) = 0.$$

Task

$$\dot{x} = -\Delta x + \pi A \psi(x) = \Delta\big(-x + \pi H \psi(x)\big) \qquad (\star)$$

Investigate how:

- the social effort parameter π affects the existence and stability of the equilibrium points of the system $(\star)$
  Tool: bifurcation theory ($\mathcal{L} = I - H$ has simple eigenvalues)
- the presence of antagonistic interactions affects the behavior of $(\star)$
  Tool: signed networks theory (frustration)

Bifurcation analysis: structurally balanced networks

$$\dot{x} = \Delta(-x + \pi H \psi(x)), \quad x \in \mathbb{R}^n$$

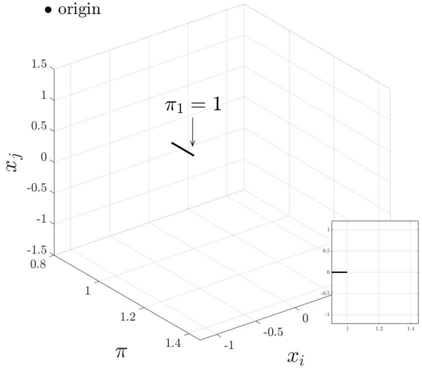
$\pi < 1$: $x = 0$ only eq. point (GAS)

$\pi = 1$: pitchfork bifurcation

- $x = 0$ saddle point
- new equilibria: x^*, $-x^*$ (loc. AS $\forall \pi > 1$)

$\pi = \pi_2 = \frac{1}{1-\lambda_2(\mathcal{L})}$: pitchfork bifurcation

- new equilibria (stable/unstable for $\pi > \pi_2$)



Bifurcation diagram

A. Fontan and C. Altafini, "Multiequilibria analysis for a class of collective decision-making networked systems", IEEE TCNS, 2018

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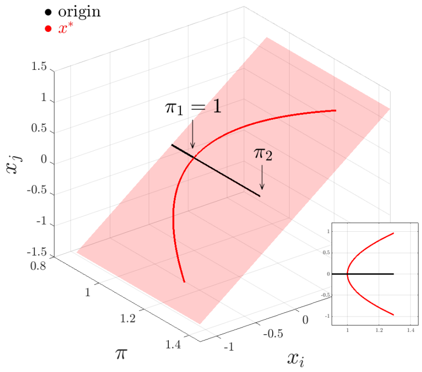

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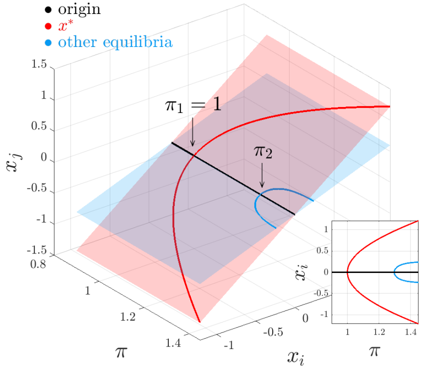

Bifurcation diagram

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Bifurcation analysis: structurally unbalanced networks

$$\dot{x} = \Delta(-x + \pi H \psi(x)), \quad x \in \mathbb{R}^n$$

$$\pi_1 = \frac{1}{1-\lambda_1(\mathcal{L})} \qquad \pi_2 = \frac{1}{1-\lambda_2(\mathcal{L})}$$

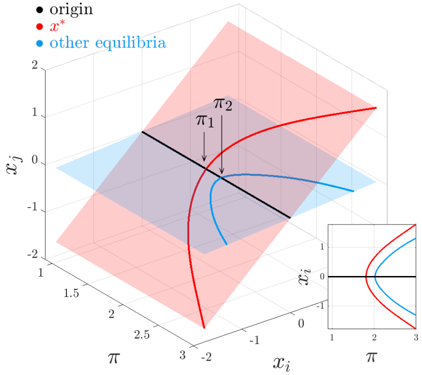
$\pi < \pi_1$: $x = 0$ only eq. point (GAS)

$\pi = \pi_1$: pitchfork bifurcation

- $x = 0$ saddle point
- new equilibria: x^*, $-x^*$ (loc. AS)

$\pi = \pi_2$: pitchfork bifurcation

- new equilibria (stable/unstable for $\pi > \pi_2$)



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Sketch of the proof: first bifurcation

Theorem

Assuming:

- S-shaped ψ: $\forall i$ ψ_i is odd, saturated, sigmoidal, monotonically increasing with $\frac{\partial \psi_i}{\partial x_i}(0) = 1$
- $\lambda_1(\mathcal{L}) > 0$ simple

Then:

$x^* \neq 0$ is equilibrium point of $\dot{x} = \Delta\left(-x + \pi H \psi(x)\right)$ $\iff$ $\pi > \pi_1 = \frac{1}{1-\lambda_1(\mathcal{L})}$

Sketch of the proof: first bifurcation

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Assuming:

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Then:

$$x^* \neq 0 \text{ is equilibrium point of } \dot{x} = \Delta\left(-x + \pi H \psi(x)\right) \iff \pi > \pi_1 = \frac{1}{1-\lambda_1(\mathcal{L})}$$

Proof: Sufficiency [$x = 0$ is GAS when $\pi \leq \pi_1$]

Lyap. function $V : \mathbb{R}^n \to \mathbb{R}_+$, $V(x) = \sum_i \int_0^{x_i} \psi_i(s) ds \geq 0$ (radially unbounded)

$$\dot{V}(x) = \psi(x)^T \dot{x} = -\underbrace{\psi(x)^T \Delta x}_{>\psi(x)^T \Delta x} + \psi(x)^T \underbrace{\Delta(\pi H)}_{=\Delta^{\frac{1}{2}}(\pi \Delta^{\frac{1}{2}} H \Delta^{-\frac{1}{2}})\Delta^{\frac{1}{2}}} \psi(x)$$

$$< -\psi(x)^T \Delta^{\frac{1}{2}} \underbrace{\left(I - \pi \Delta^{\frac{1}{2}} H \Delta^{-\frac{1}{2}}\right)}_{\text{symmetric, psd } (\succeq 0)} \Delta^{\frac{1}{2}} \psi(x) \leq 0 \qquad \forall x \neq 0$$

Sketch of the proof: first bifurcation

Proof: Necessity [pitchfork bifurcation when $\pi = \pi_1 = \frac{1}{1-\lambda_1(\mathcal{L})} = \frac{1}{\lambda_n(H)}$]

$$\Phi(x,\pi) = -x + \pi H \psi(x) = 0, \quad J := \frac{\partial \Phi}{\partial x}(0,\pi_1) = -I + \pi_1 H$$

Lyapunov-Schimdt reduction:

- v (right), w (left) eigenvectors of J relative to 0 $\Rightarrow$ $\begin{array}{r} E = I - vw^T : \mathbb{R}^n \to \mathrm{range}(J) \\ I - E : \mathbb{R}^n \to \ker(J) \end{array}$
- split $x = yv + r$, $y \in \mathbb{R}$ and $r = Ex$ $\Rightarrow$ near $(0,\pi_1)$: $\begin{cases} 0 = E\,\Phi(yv + r, \pi) \\ 0 = (I - E)\,\Phi(yv + r, \pi) \end{cases}$
- implicit function theorem: $\exists!\, r = R(yv,\pi) : E\,\Phi(yv + R(yv,\pi),\pi) = 0$
- define center manifold $g : \mathbb{R} \times \mathbb{R} \mapsto \mathbb{R}$ by: $g(y,\pi) := w^T(I - E)\,\Phi(yv + R(yv,\pi),\pi)$
- partial derivatives at $(0,\pi_1)$ satisfy

$$g_y = g_{yy} = g_\pi = 0,\ g_{\pi y} > 0,\ g_{yyy} < 0 \quad \Rightarrow \quad \text{pitchfork bifurcation at } \pi = \pi_1!$$

□

M. Golubitsky, I. Stewart, D. Schaeffer, "Singularities and Groups in Bifurcation Theory", 2000

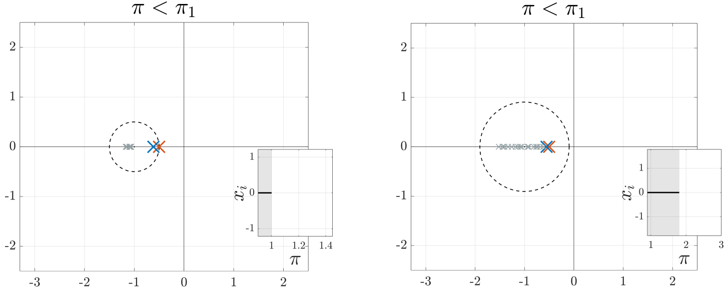
Interpretation of the results.. as we vary π

Pitchfork bifurcation at: $\pi_1 = \frac{1}{1-\lambda_1(\mathcal{L})}$, $\pi_2 = \frac{1}{1-\lambda_2(\mathcal{L})}$

(norm.) linearization at 0:
$-I + \pi H = -I + \pi(I - \mathcal{L})$

× $\lambda_1(-I + \pi(I - \mathcal{L}))$
× $\lambda_2(-I + \pi(I - \mathcal{L}))$

structurally balanced | structurally unbalanced



$\pi < \pi_1$
(small effort)
- no decision (deadlock)

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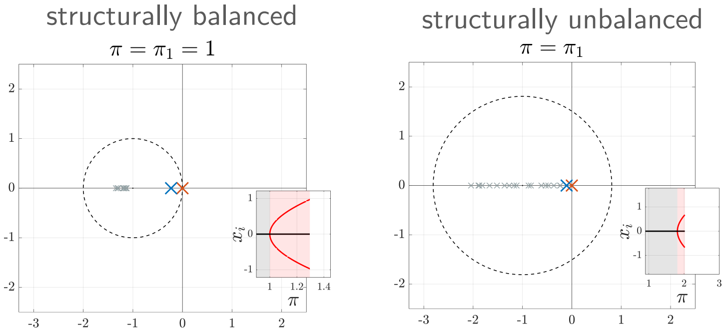
- × $\lambda_1(-I + \pi(I - \mathcal{L}))$
- × $\lambda_2(-I + \pi(I - \mathcal{L}))$



$\pi < \pi_1$	$\pi \in (\pi_1, \pi_2)$	
(small effort)	"right" commitment	
■ no decision (deadlock)	■ two (alternative) decisions	

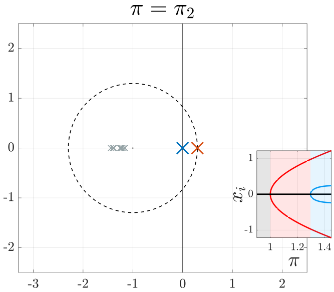
Interpretation of the results.. as we vary π

Pitchfork bifurcation at: $\pi_1 = \frac{1}{1-\lambda_1(\mathcal{L})}$, $\pi_2 = \frac{1}{1-\lambda_2(\mathcal{L})}$

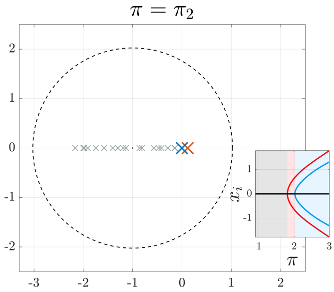
(norm.) linearization at 0:
$-I + \pi H = -I + \pi(I - \mathcal{L})$

× $\lambda_1(-I + \pi(I - \mathcal{L}))$
× $\lambda_2(-I + \pi(I - \mathcal{L}))$

structurally balanced



structurally unbalanced



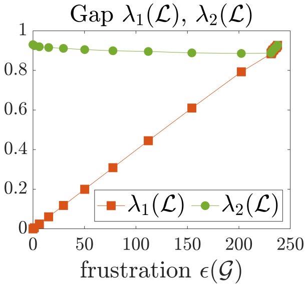
$\pi < \pi_1$	$\pi \in (\pi_1, \pi_2)$	$\pi > \pi_2$
(small effort)	"right" commitment	"overcommitment"
■ no decision (deadlock)	■ two (alternative) decisions	■ several decisions

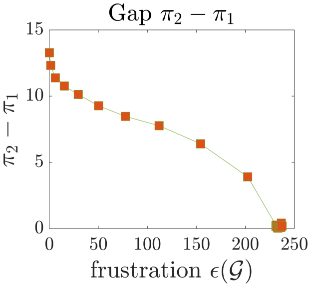
Interpretation of the results.. as we vary the frustration

Signed network $\mathcal{G}$ with frustration $\epsilon(\mathcal{G})$

$$\pi_1 = \frac{1}{1-\lambda_1(\mathcal{L})} \begin{cases} = 1 \text{ fixed}, & \text{structurally balanced } \mathcal{G} \\ \text{depends on } \epsilon(\mathcal{G}), & \text{structurally unbalanced } \mathcal{G} \end{cases}$$

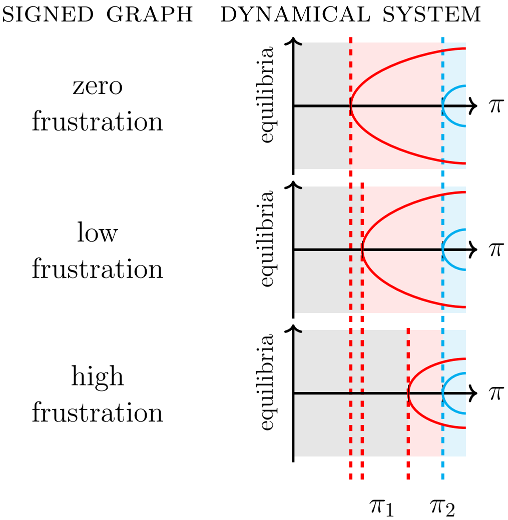
$$\pi_2 = \frac{1}{1-\lambda_2(\mathcal{L})} \begin{cases} \text{depends on algebraic connectivity}, & \text{structurally balanced } \mathcal{G} \\ \text{independent from } \epsilon(\mathcal{G}), & \text{structurally unbalanced } \mathcal{G} \end{cases}$$



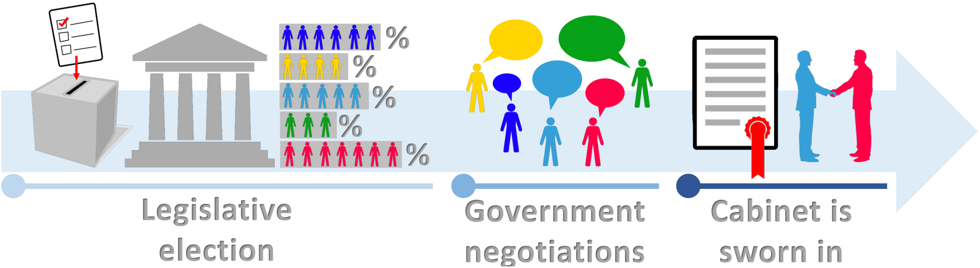


Summary

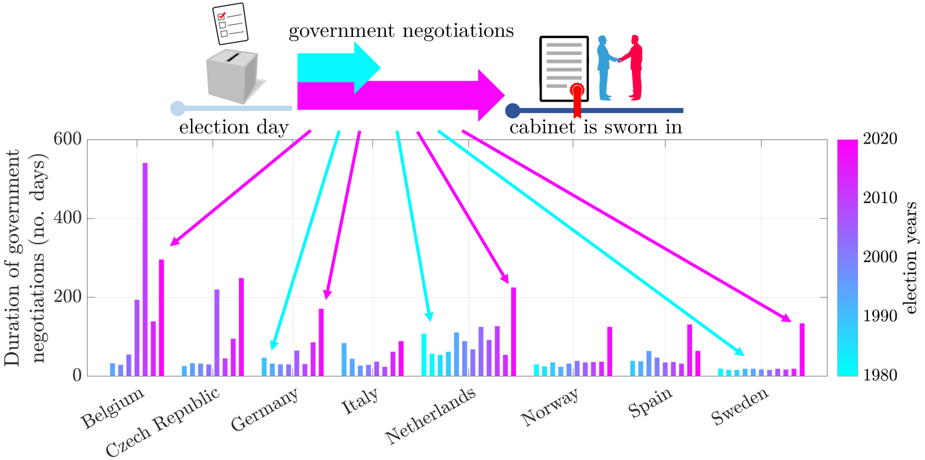
- $\pi_1 = \frac{1}{1-\lambda_1(\mathcal{L})}$ grows with $\lambda_1(\mathcal{L})$
- $\lambda_1(\mathcal{L}) \approx$ frustration
- the higher the frustration:
  - the higher the social effort needed to achieve a decision
  - the smaller the interval for which only two alternative decisions exist



Government formation in parliamentary democracies



Duration of government negotiation phase



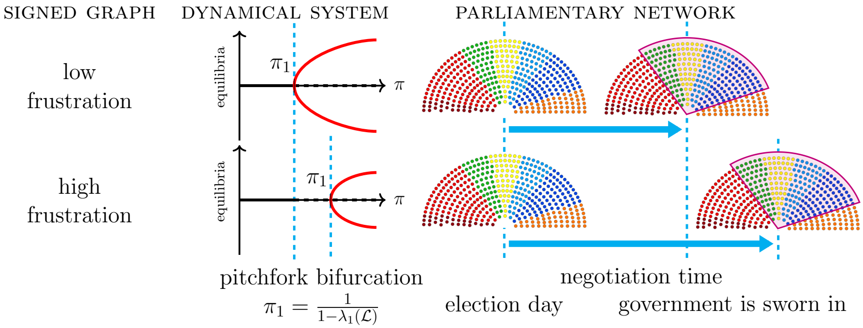
Question: can we use our model to explain this behavior?

Dynamics of the formation of a government

- signed network: parliament
- decision: vote of confidence of the parliament
- social effort: duration of the government negotiation phase

$\lambda_1(\mathcal{L}) \sim$ frustration $\quad + \quad \pi_1 \sim$ duration of negotiations $\quad + \quad \pi_1 = \frac{1}{1-\lambda_1(\mathcal{L})}$

$\Rightarrow$ duration of negotiations $\sim$ frustration

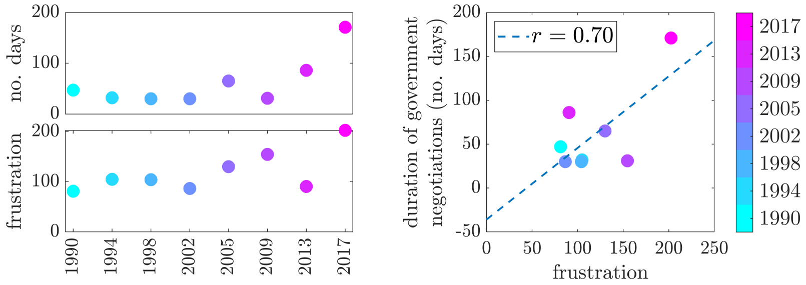


Frustration vs duration of government negotiations

Task: show that the government formation process is influenced by the frustration of the parliamentary network

- Data: elections in 29 European countries (election years: 1978 - 2020)
- Method: Pearson's correlation index (r), frustration vs duration of negotiations

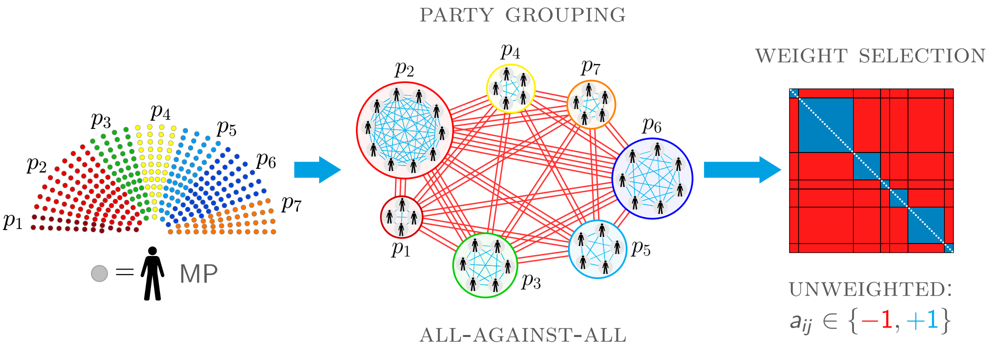
Example: German elections



A. Fontan and C. Altafini, "A signed network perspective on the government formation process in parliamentary democracies", Scientific Reports, 2021

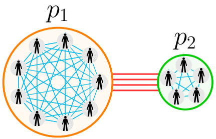
Construction of the parliamentary networks

Definition: complete, undirected, signed graph in which each MP is a node



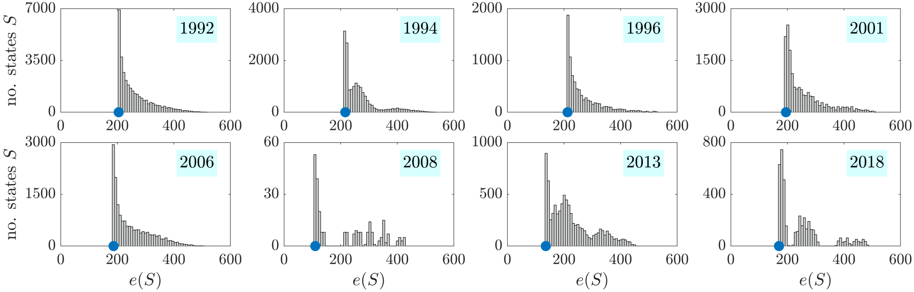
collaboration: MPs belong to the **same** party
rivalry: MPs belong to **different** parties

Are the parliamentary networks structurally balanced?



Structurally balanced parliamentary network

The parliamentary networks have (in general) nonzero frustration..

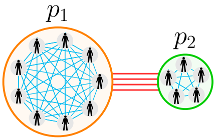


Energy landscape of the Italian parliamentary elections:

● = frustration

2

Are the parliamentary networks structurally balanced?



Structurally balanced parliamentary network

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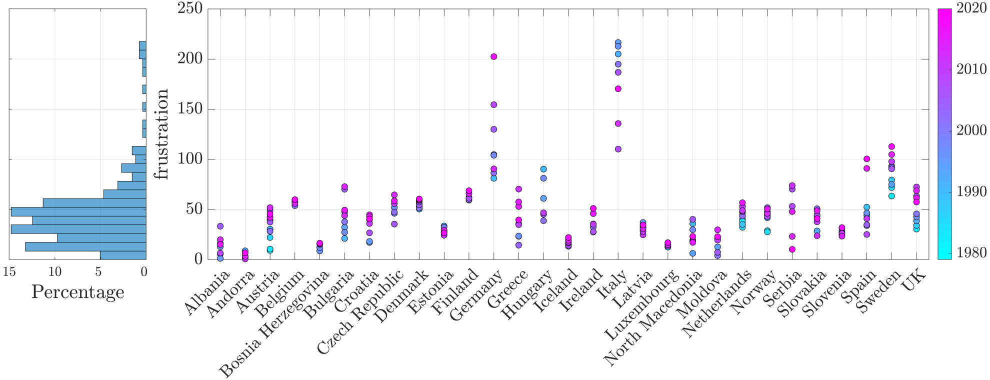
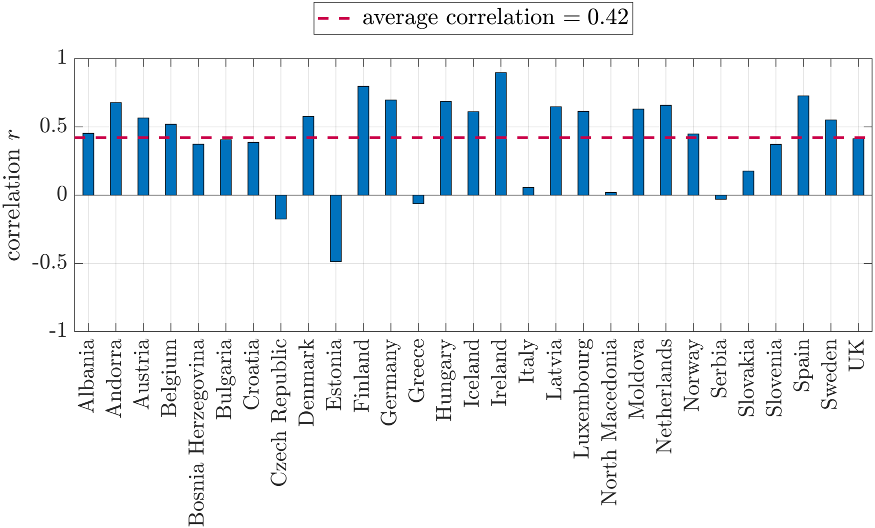
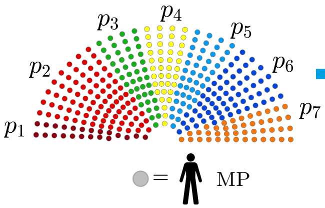


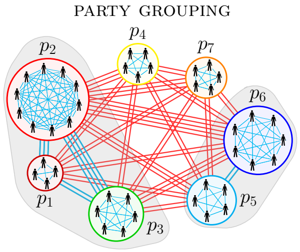
2

Correlation for all 29 European countries

Duration of the government negotiations vs frustration of the parliamentary networks



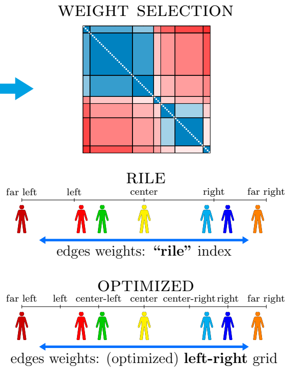




PRE-ELECTORAL COALITIONS

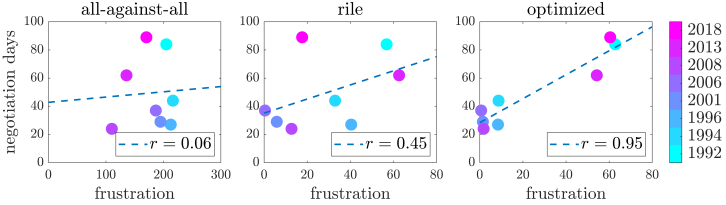
collaboration: MPs belong to the **same** party or **pre-electoral coalition**

rivalry: otherwise

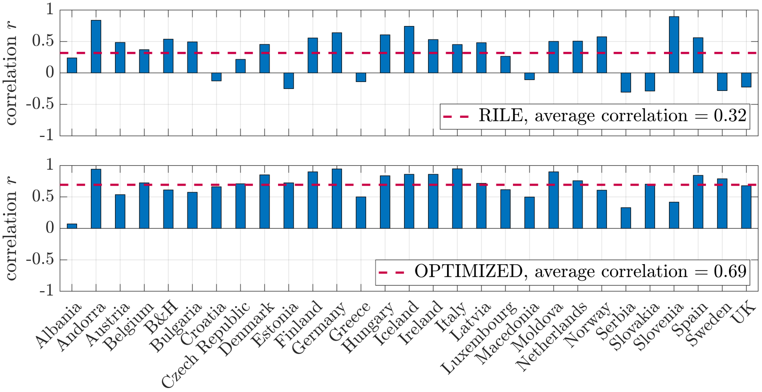


"Rile" Data: Manifesto Project Database

Correlation for all 29 European countries



Example:
Italian
elections



Results on
average correlation:
0.42, 0.32, 0.69

Conclusion

Task: Study the decision-making process in a community of agents where both cooperative and antagonistic interactions coexist

As we vary the social effort: pitchfork bifurcation behavior

- "right" commitment: 2 alternative decisions
- "overcommitment": several (more than 2) alternative decisions

As we vary the frustration (i.e., amount of disorder) of the signed networks

- frustration influences the level of commitment required from the agents to reach a decision

Application: Government formation process

- frustration correlates well with duration of government negotiation phase

Thanks!

Angela Fontan

angfon@kth.se

https://www.kth.se/profile/angfon

https://angelafontan.github.io/