# Collective decision-making on networked systems: from social networks to smart homes

Angela Fontan
angfon@kth.se

Division of Decision and Control Systems
KTH Royal Institute of Technology, Sweden

digital futures

# Outline

- Background and motivating examples
- Problem: Collective decision-making in presence of antagonism
  - Social networks as signed networks
  - The notion of frustration
  - Analysis of proposed model for collective decision-making over signed networks
  - Application: Process of government formation over signed parliamentary networks
- Problem: Design of energy-efficient smart homes
  - Smart homes as cooperative networks
  - Application: Study of social influence at KTH Live-In Lab

# Background

Context: Interpretation of urban systems as cyber-physical-human systems (CPHS)



[Control for Societal Scale Challenges: Road Map 2030, eds. Annaswamy, Johansson, Pappas (2023)]

# Motivating examples

Characterize models of (human) decision-making within interconnected communities...
...and how they adapt during the interaction with smart technologies

1. From collaborative to antagonistic collective decision-making systems



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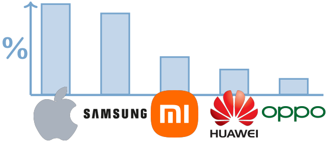
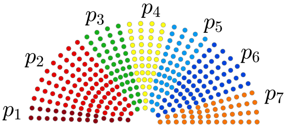
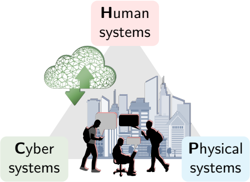
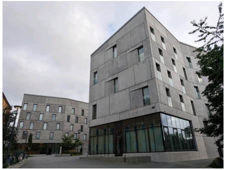





2. Design of energy-efficient smart homes
   - Building automation and control of energy-efficient smart homes
   - Integrated real-life experimental building infrastructure: KTH Live-In Lab



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- Motivating examples
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  - Analysis of proposed model for collective decision-making over signed networks
  - Application: Process of government formation over signed parliamentary networks
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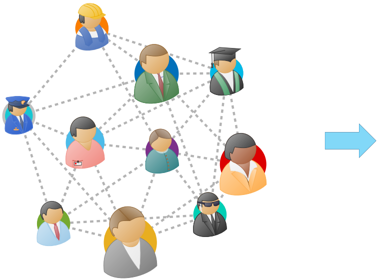
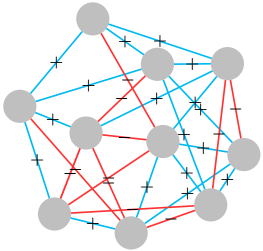
In collaboration with: Claudio Altafini, Linköping University, Sweden

# Problem: Collective decision-making in presence of antagonism

Application: Social networks



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



1. Model for collective decision-making
   - $x$: vector of opinions
   - equilibrium points: possible decisions

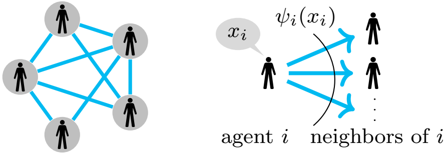
2. Signed networks
   - Positive weight: cooperative interaction
   - Negative weight: antagonistic interaction

# Model for collective decision-making over cooperative networks

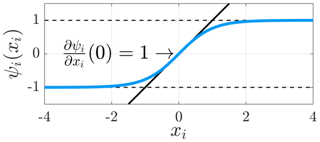
$$\dot{x} = -\Delta x + \pi A \psi(x)$$

- $n$ 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 $\mathcal{G}(A)$




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




- $\pi > 0$ scalar parameter

[Gray, Leonard, et al., IEEE TCNS (2018)]

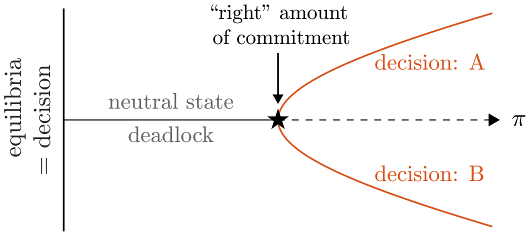
# Model for collective decision-making over cooperative networks

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

- $\pi$ = "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 $\pi$ is varied

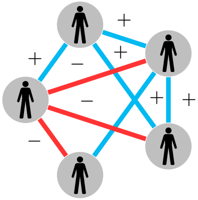


# Model for collective decision-making over *signed networks*

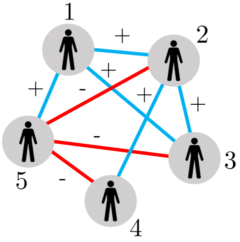
**Task:** Study the decision-making process in a community of agents where both cooperative and antagonistic interactions coexist

**Model:** $\dot{x} = -\Delta x + \pi A \psi(x)$, $\pi$: social effort between the agents

**Assumptions**: $\mathcal{G}(A)$ is a signed network



# Signed networks and signed Laplacian matrix

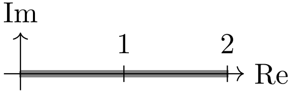



$$A = \begin{bmatrix} 0 & + & + & 0 & + \\ + & 0 & + & + & - \\ + & + & 0 & 0 & - \\ 0 & + & 0 & 0 & - \\ + & - & - & - & 0 \end{bmatrix} \begin{matrix} \Rightarrow \delta_1 \\ \\ \dots \\ \\ \Rightarrow \delta_5 \end{matrix} \qquad \mathcal{L} = \begin{bmatrix} 1 & - & - & 0 & - \\ - & 1 & - & - & +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

Signed Laplacian:

$$L = \Delta - A$$

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




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

Focus on:

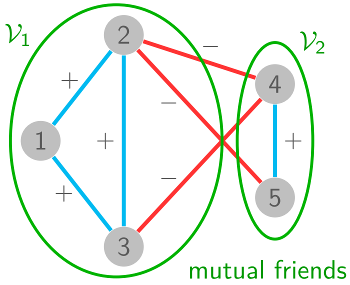
normalized signed Laplacian: $\mathcal{L} = I - \Delta^{-1} A$

# Structural balance

A connected signed graph $\mathcal{G}(A)$ is structurally balanced if $\mathcal{V} = \mathcal{V}_1 \cup \mathcal{V}_2$ such that every edge:

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

[F. Harary, Mich. Math. J. (1953)]



# Structural balance

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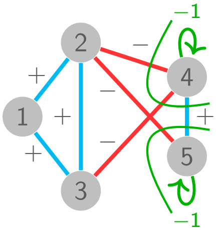
[F. Harary, Mich. Math. J. (1953)]

**Lemma:** $\mathcal{G}(A)$ is structurally balanced iff

- ▸ $\exists$ signature matrix $S = \mathrm{diag}\{s_1, \dots, s_n\}$, $s_i = \pm 1$, s.t. $S\mathcal{L}S$ has all nonpositive off-diagonal entries
- ▸ $\lambda_1(\mathcal{L}) = 0$




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

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

$$\Rightarrow S\mathcal{L}S = \begin{bmatrix} 1 & - & - & & \\ - & 1 & - & - & - \\ - & - & 1 & - & \\ & - & - & 1 & - \\ & - & & - & 1 \end{bmatrix}$$

A connected signed graph $\mathcal{G}(A)$ is **structurally balanced** if $\mathcal{V} = \mathcal{V}_1 \cup \mathcal{V}_2$ such that every edge:

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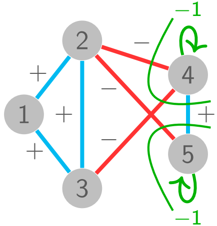


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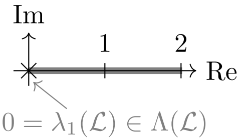
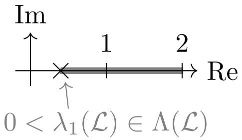
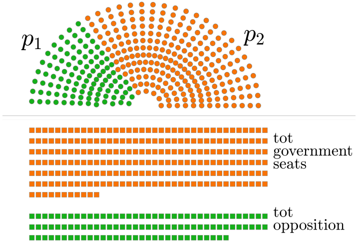
**Lemma:** $\mathcal{G}(A)$ is **structurally balanced** iff

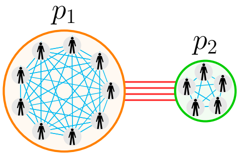
- $\exists$ signature matrix $S = \mathrm{diag}\{s_1, \dots, s_n\}$, $s_i = \pm 1$, s.t. $S\mathcal{L}S$ has all nonpositive off-diagonal entries
- $\lambda_1(\mathcal{L}) = 0$

| $\mathcal{G}(A)$ structurally balanced | $\mathcal{G}(A)$ structurally unbalanced |
|---|---|
|  |  |

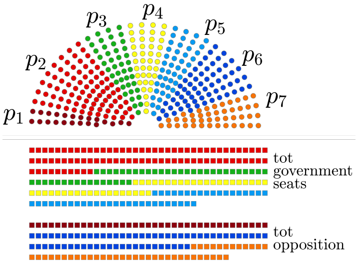
# Example: Parliamentary systems

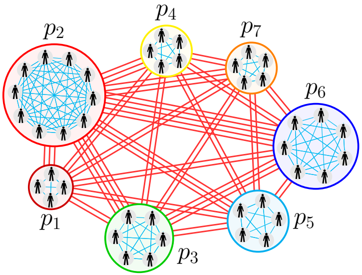
Structurally balanced network




Structurally unbalanced network



# Frustration index and algebraic conflict

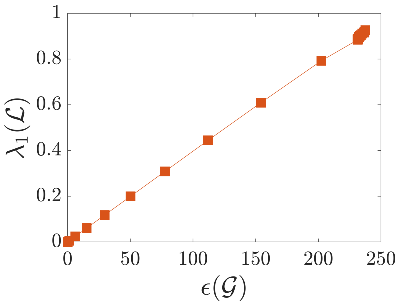
**Task:** characterize the graph distance from structurally balanced state

- Frustration Index
  (computation: NP-hard problem)

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

- Algebraic Conflict

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




$\Longrightarrow$

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

[Fontan and Altafini, IEEE CDC (2018)]

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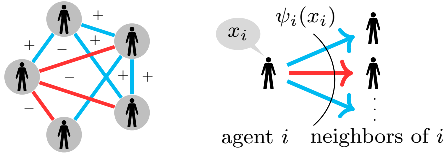
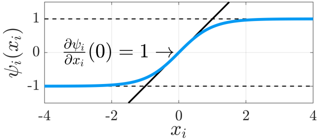
signed (connected) network $\mathcal{G}(A)$

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




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

[Fontan and Altafini, IEEE TAC (2021)]

# Task

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

- Normalized adjacency matrix $H = \Delta^{-1}A = I - \mathcal{L}$
- Dynamical interpretation: $(\star)$ is monotone $\Leftrightarrow$ $\mathcal{G}(A)$ is structurally balanced $\Leftrightarrow$ $\lambda_1(\mathcal{L}) = 0$

Investigate how:

- the social effort parameter $\pi$ 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)
Not enough commitment: Deadlock

$\pi = 1$: pitchfork bifurcation

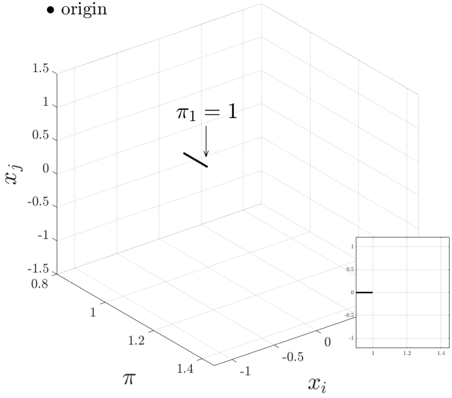
- $x = 0$ saddle point
- new equilibria: $x^*$, $-x^*$ (loc. AS $\forall \pi > 1$)

Right commitment: Two alternative decisions $x^*$

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

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

Overcommitment: Several decisions




Bifurcation diagram

[Fontan and Altafini, IEEE TCNS (2018)]

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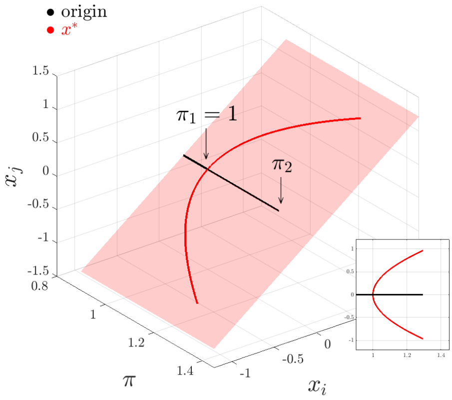


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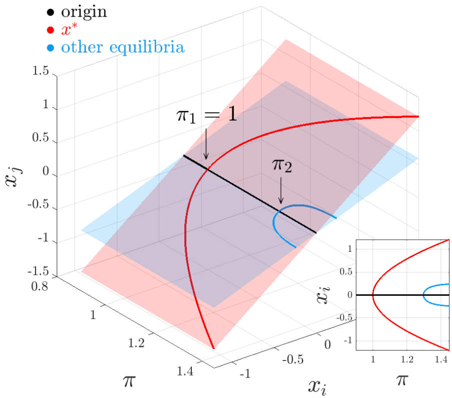



Bifurcation diagram

[Fontan and Altafini, IEEE TCNS (2018)]

# Bifurcation analysis: Structurally unbalanced networks

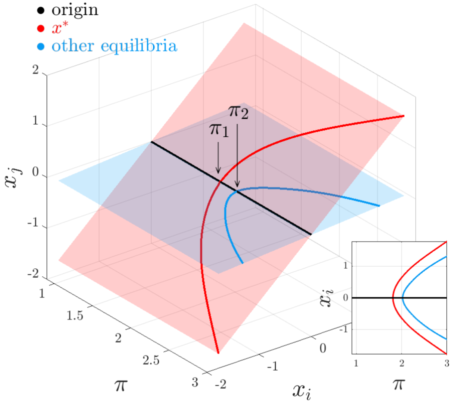
$$\dot{x} = \Delta(-x + \pi H\psi(x)), \quad x \in \mathbb{R}^n$$

**With:** $\pi_1 = \dfrac{1}{1-\lambda_1(\mathcal{L})}$, $\pi_2 = \dfrac{1}{1-\lambda_2(\mathcal{L})}$

$\pi < \pi_1$: Not enough commitment
Deadlock

$\pi = \pi_1$: Right commitment
Two alternative decisions $x^*$

$\pi = \pi_2$: Overcommitment
Several decisions




Bifurcation diagram

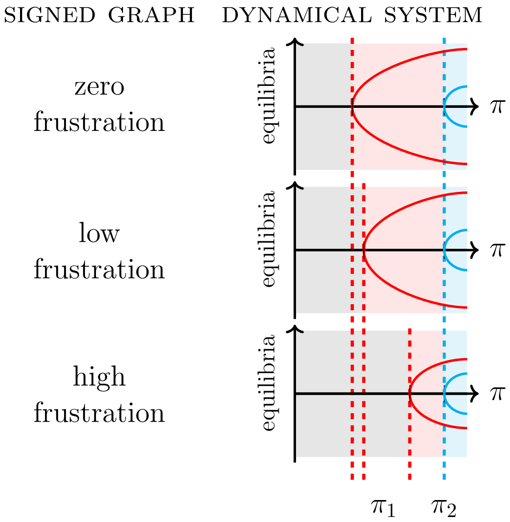
[Fontan and Altafini, IEEE TAC (2021)]

# Interpretation of the results as we vary the frustration

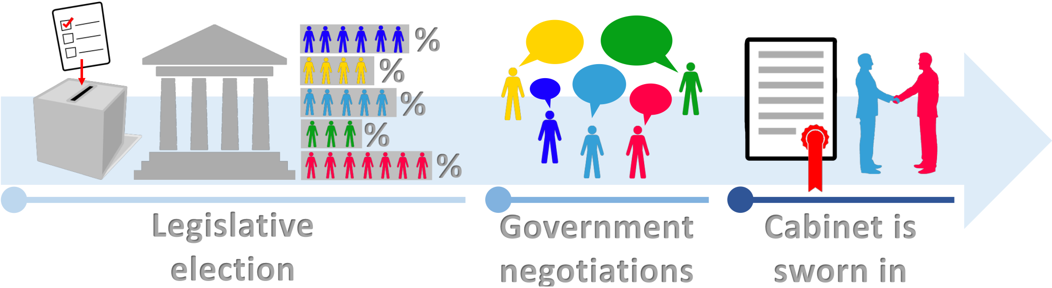
- $\pi_1 = \frac{1}{1-\lambda_1(\mathcal{L})}$ depends on the frustration ($\lambda_1(\mathcal{L}) \approx$ frustration)
- $\pi_2 = \frac{1}{1-\lambda_2(\mathcal{L})}$ depends on the topology, independent from the frustration

Then, the higher the frustration:

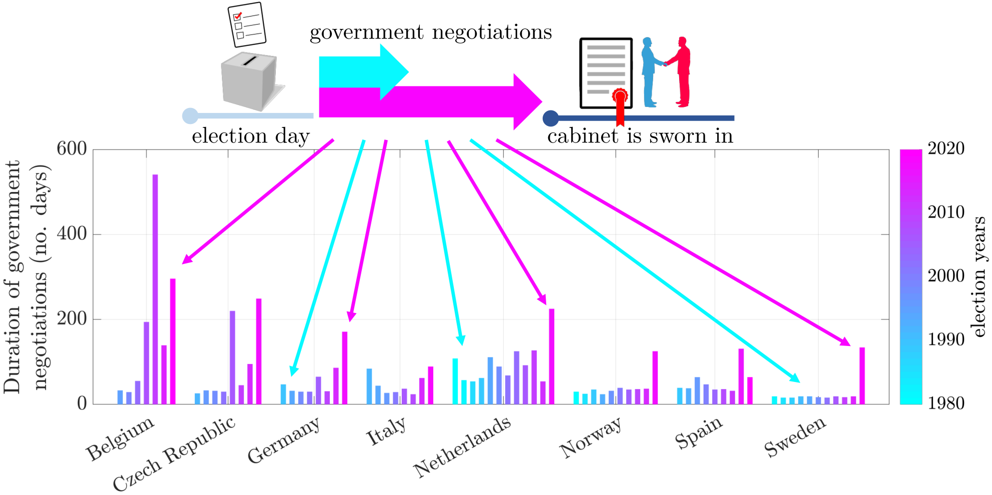
- the higher the social effort needed to achieve a decision
- the smaller the interval for which only two alternative decisions exist



# Application: Government formation in parliamentary democracies



# Duration of government negotiation phase



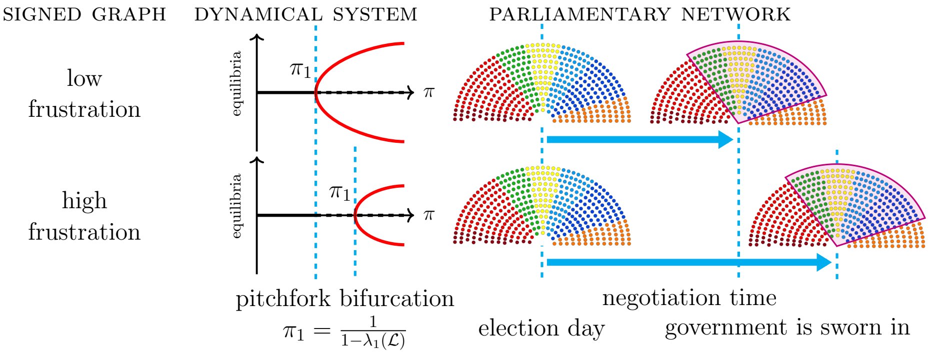

**Question**: can we use our model to explain this behavior?

# Dynamics of the formation of a government

- Signed network: parliament
- Social effort: duration of the government negotiation phase
- Decision: vote of confidence of the parliament

$\lambda_1(\mathcal{L}) \sim$ 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

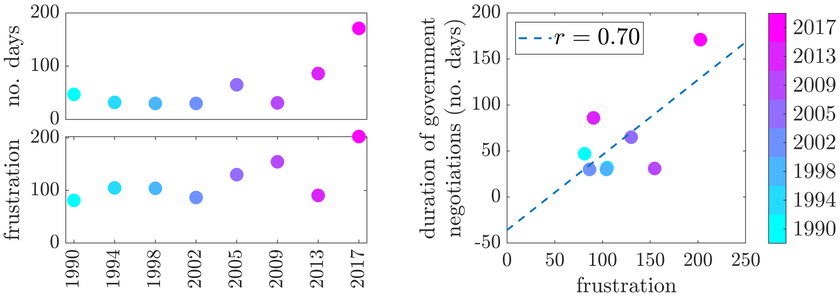


# Frustration vs duration of government negotiations

**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

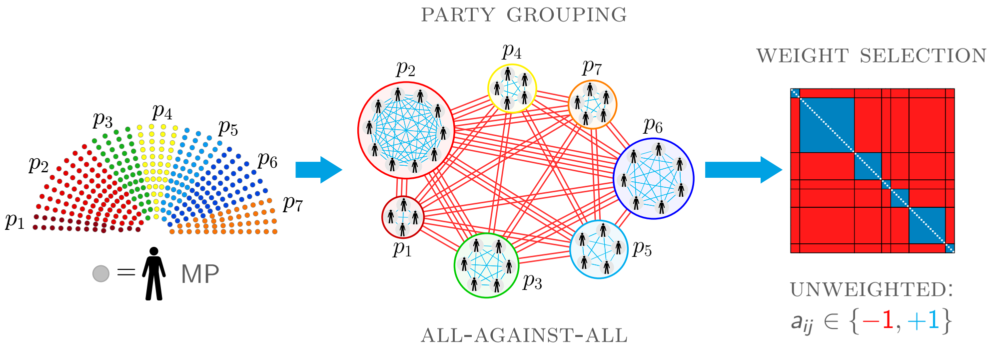
Example: German elections




[Fontan and Altafini, Scientific Reports (2021)]

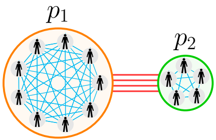
# Construction of the parliamentary networks

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



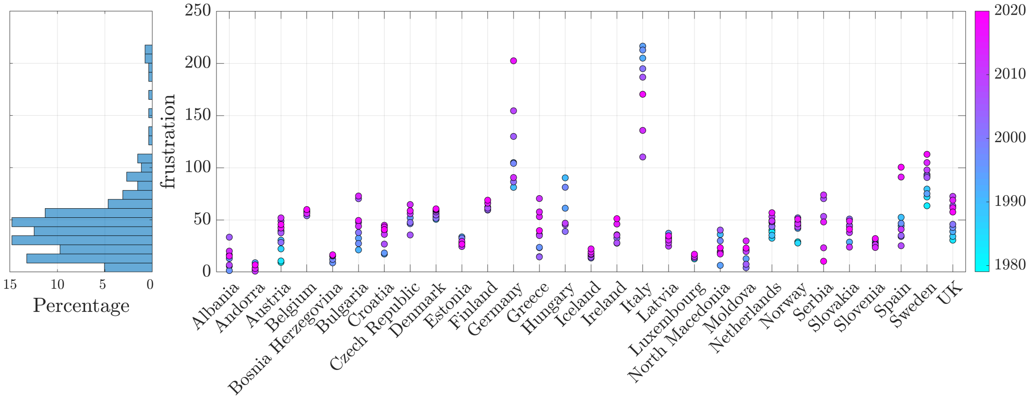

collaboration: MPs belong to the **same** party
rivalry: MPs belong to **different** parties

# Are the parliamentary networks structurally balanced?



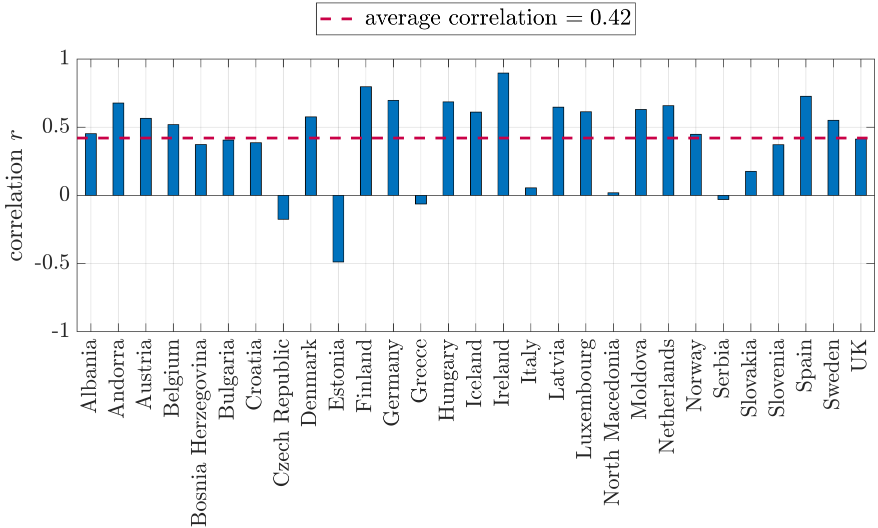

Structurally balanced parliamentary network

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



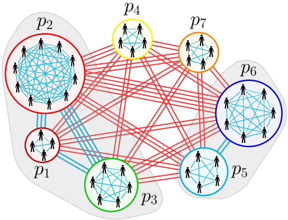
# Correlation for all 29 European countries

## Duration of the government negotiations vs frustration of the parliamentary networks



# More complex scenarios: Coalitions and ideological differences

PARTY GROUPING

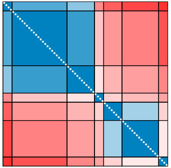



PRE-ELECTORAL COALITIONS

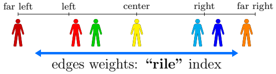
collaboration: MPs belong to the same party or pre-electoral coalition

rivalry: otherwise

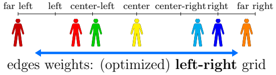
WEIGHT SELECTION

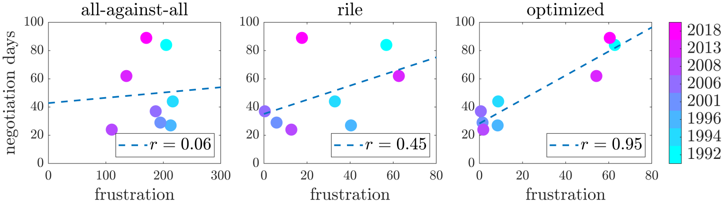


RILE (manifesto database)




OPTIMIZED




Example: Italian elections

Results on average correlation for all 29 European countries:

0.42 (all-against-all), 0.32 (rile), 0.69 (optimized)

$\Rightarrow$ Frustration correlates well with duration of government negotiations

# Outline

- Motivating examples
- Problem: Collective decision-making in presence of antagonism
  - Social networks as signed networks
  - The notion of frustration
  - Analysis of proposed model for collective decision-making over signed networks
  - Application: Process of government formation over signed parliamentary networks
- Problem: Design of energy-efficient smart homes
  - Smart homes as cooperative networks
  - Application: Study of social influence at KTH Live-In Lab

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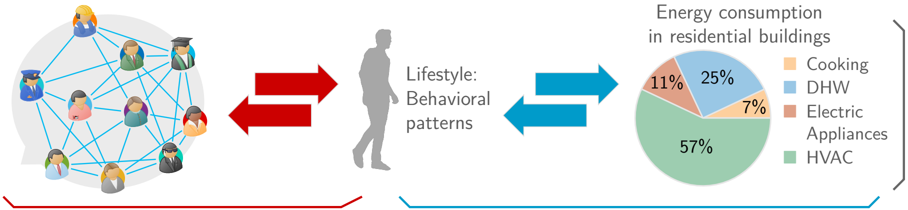
In collaboration with: M. Farjadnia, J. Llewellyn, C. Katzeff, M. Molinari, V. Cvetkovic, and K. H. Johansson, KTH Royal Institute of Technology, Sweden

# Problem: Design of energy-efficient smart homes

- Context: Building sector accounts for more than 40% of the final energy use
- Challenges for control in smart buildings:
  The behavior of occupants have large effects on building energy use




Data-driven control of HVAC systems [Farjadnia et al., Eur. J. Control (2023)]

Social interactions towards a sustainable lifestyle [A. Fontan et al., IFAC WC (2023)]

Bidirectional interactions between tenants and environmental conditions [M. Farjadnia, A. Fontan, et al., IEEE CCTA (2023)]

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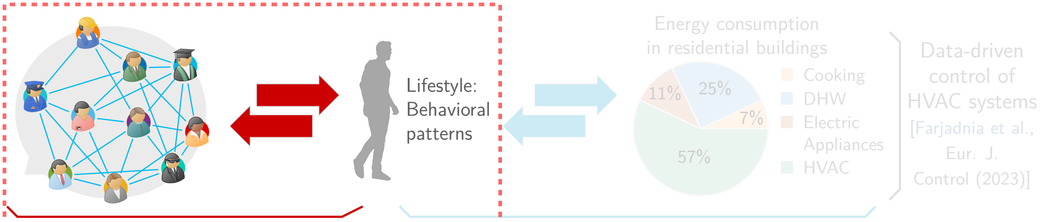


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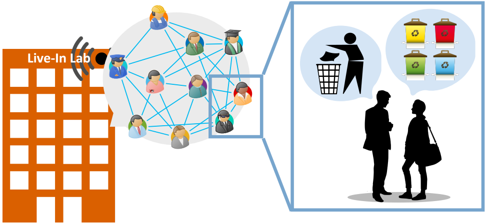
# Problem formulation

Design longitudinal experimental study of social influence in behavioral changes towards sustainability, to be implemented in the KTH Live-In Lab

Combining several factors..

- Modeling household and energy use behavior
  [Wilson and Dowlatabadi (2007), Peng et al. (2012);..]
- Planning ad hoc social interventions on habits
  [Steg and Vlek (2009); Frederiks et al. (2015);..]
- Designing new technologies and infrastructures (flexible Live-In Laboratories)
  [Intille et al. (2006); Das et al. (2020);..]




..and proposing a social network perspective:

Experimental design as collective (household) decision-making process with interconnected tenants of KTH Live-In Lab as the decision-makers

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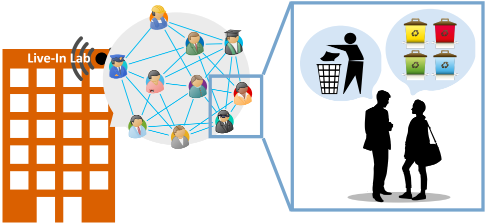


..and proposing a social network perspective:

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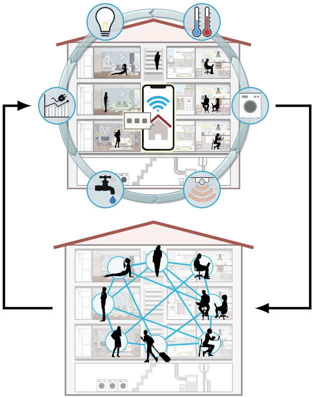
# Exploring diffusion of sustainable behaviors: Smart homes as social networks

**Approach** Observe how tenants' sustainability scores change over time given that:

- Tenants are encouraged to exchange opinions with their neighbors
- Tenants can observe the average household sustainability score

Experimental campaign based on the interpretation:

- Smart home: Social network of interacting tenants
- Lifestyle choices: Decisions $\sim$ sustainability score
- Intuition: Feedback on global state (household) to reduce observed discrepancy between lifestyle choices and opinions on environmental responsibility



# Experimental setup

Campaign run at the KTH Live-In Lab, state-of-the-art platform of building testbeds

- Apartments with extensive sensing, data collection, and control capabilities
- Redesignable apartment layout allowing various experimental environments
- Interaction capability with and between occupants
  (experiments involving 4 apartments and 5 tenants)

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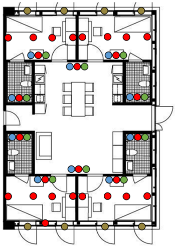

- Magnetic sensors
- Temperature sensors
- RH sensors
- $CO_2$ sensors

Other quantitative:
light, motion,
outside temperature,
and VOC
Qualitative: surveys

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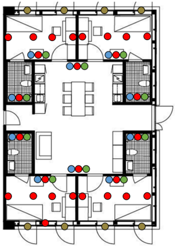

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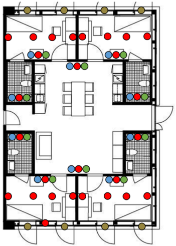

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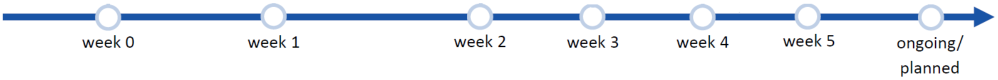
Preparatory phase of the project (winter 2022-spring 2023)

- Small group of participants
- Short time period



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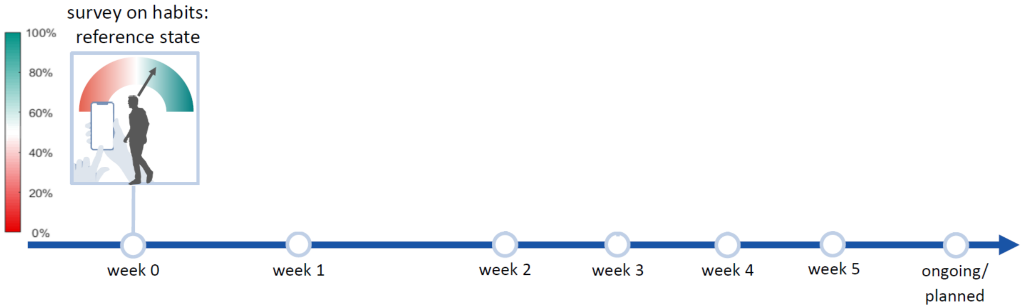

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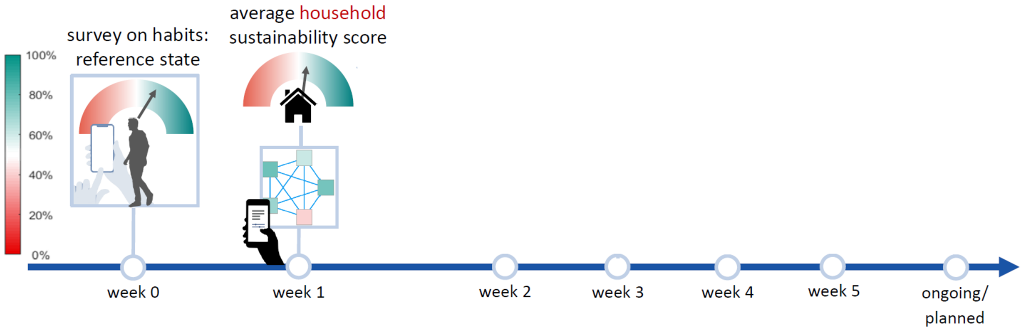

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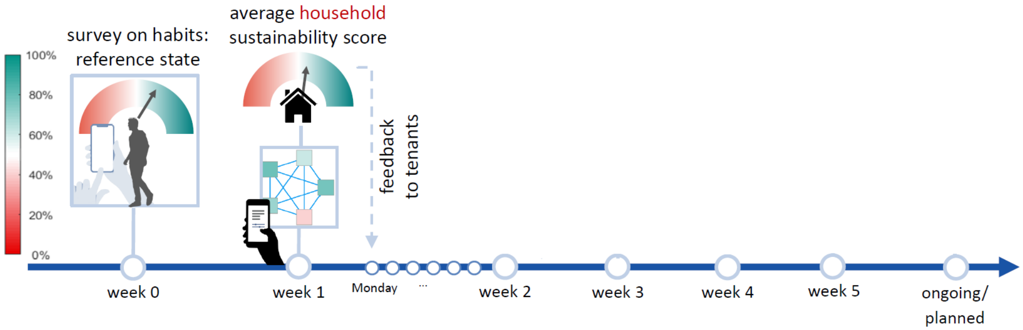

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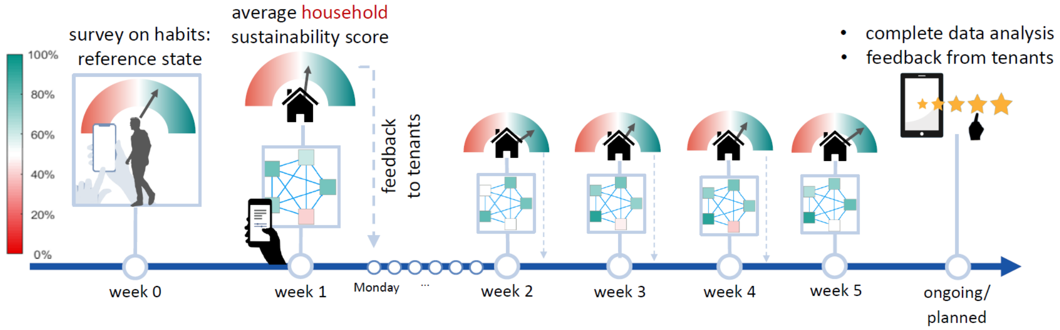

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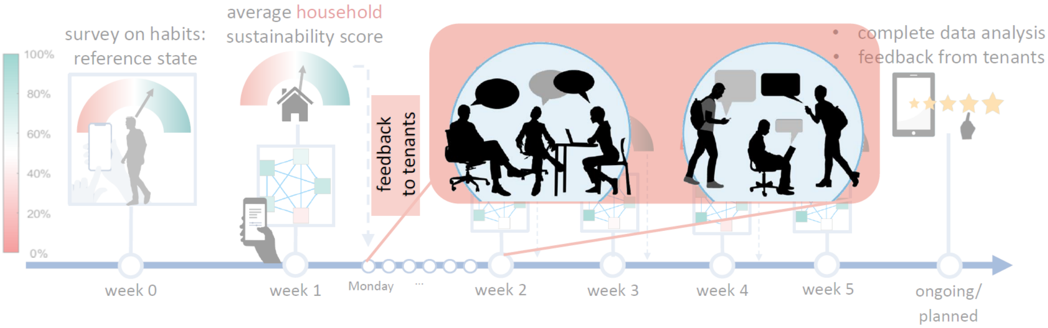
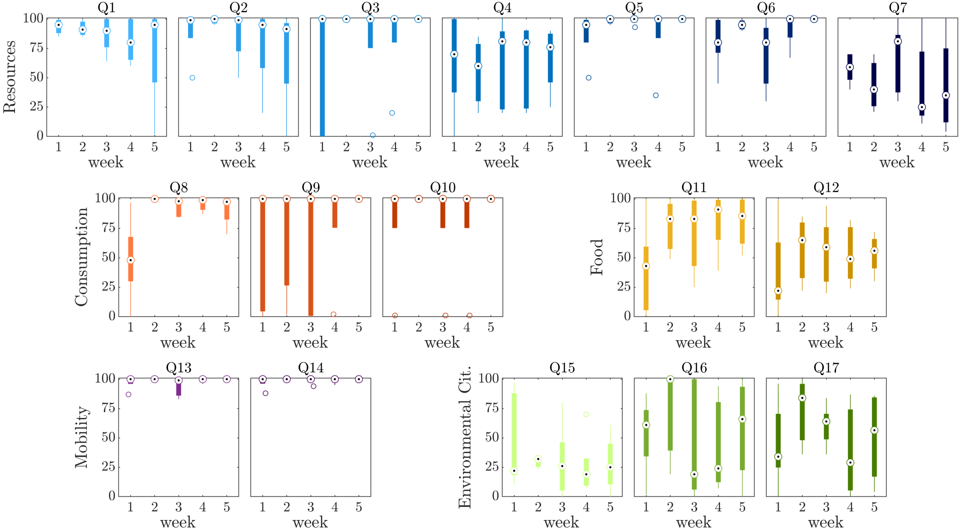


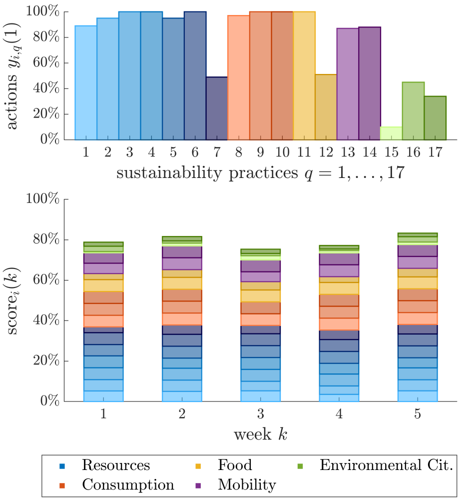
# Preliminary results (I/II)

Summary of actions on sustainability practices Q# (grouped in 5 dimensions)

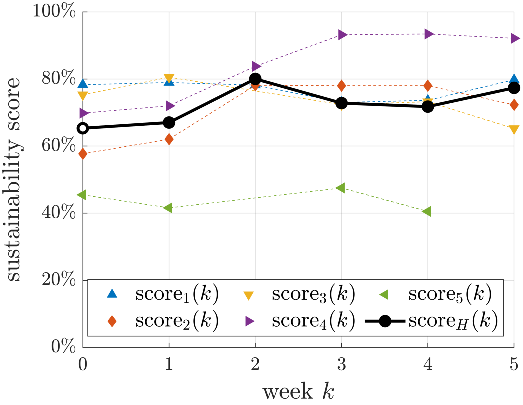


# Preliminary results (II/II)

Actions $y_{i,q}(k)$ and sustainability score of tenant $i$ of the KTH Live-In Lab




Sustainability scores of all tenants and average household sustainability score



# Conclusions

**Context** Urban systems as CPHS

**Focus** Human decision-making within interconnected communities

**Two motivating applications**

1. Political decision-making
   - Government formation process as collective decision-making system over signed parliamentary networks
   - We show that the frustration of the parliamentary networks correlates well with the duration of government negotiation phase
2. Decision-making in smart homes
   - Smart homes as social networks
   - Design of experimental study, to investigate the dynamics of tenants' sustainability scores
   - Ongoing/future directions (to implement at the KTH Live-In Lab):
     - Theoretical analysis on impact of campaigns and incentives design
     - Compare surveys' data with sensor data collected at KTH Live-In Lab

## Thank you for your attention!

Angela Fontan, angfon@kth.se, angelafontan.github.io