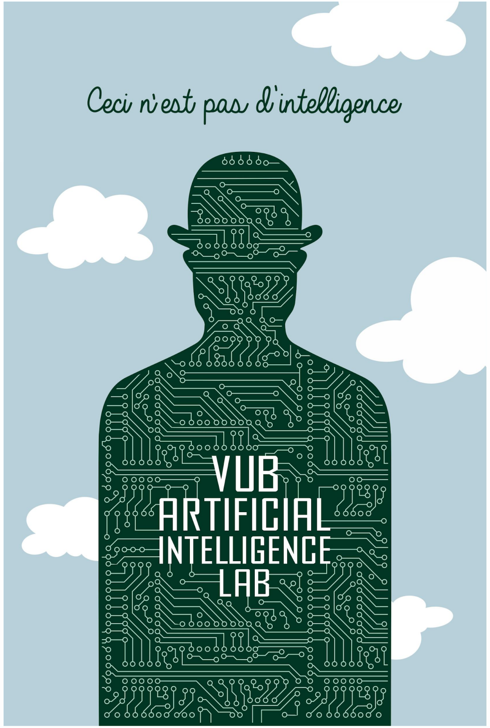

Decision Making with Multiple Agents that Care about More than One Objective

Diederik M. Roijers (Vrije Universiteit Brussel & City of Amsterdam)
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@DiederikRo @rox_teo #aamasT1

AAMAS Tutorial 1, London, 2023

Pleased to meet you

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Hi, I'm Diederik!

- Academic Liaison for AI Research
  Urban Innovation and R&D, City of Amsterdam

- Senior Researcher
  AI lab, Vrije Universiteit Brussel

@DiederikRo

Sources: here and here

Hi, I'm Roxana!

- (FWO) Postdoctoral Fellow at the Artificial Intelligence Research Group, VUB, Belgium

- Project: Decision-making in team-reward multi-objective multi-agent domains

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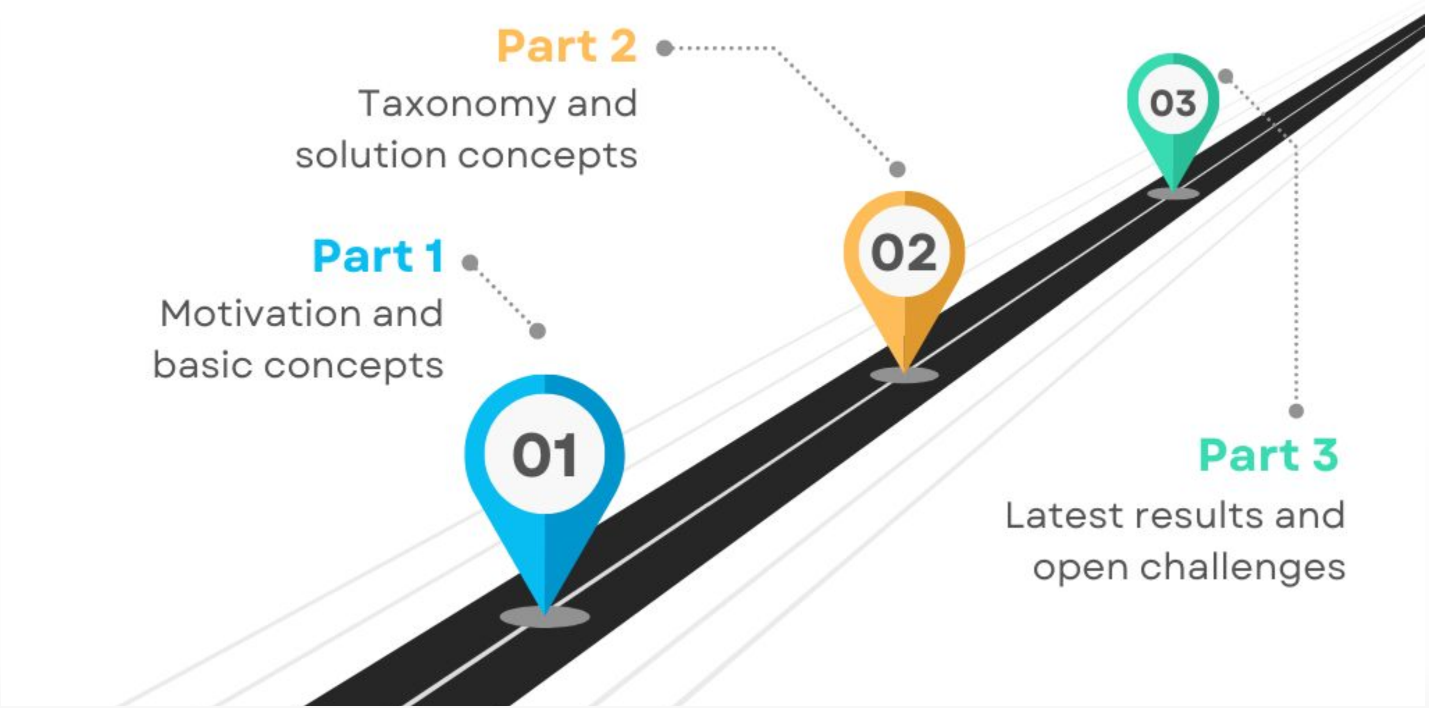
http://roxanaradulescu.com

Tutorial Roadmap



Part 1 - Multi-objective decision making in multi-agent systems

Motivation and basic concepts

Going to the conference

Two players

- rewards are public
- utility is private

MONFG

Why hard?

	Taxi	Tram	Walking
Taxi	(10€, 5min); (10€, 5min)	(20€, 5min); (2€, 15min)	(20€, 5min); (0€, 35min)
Tram	(2€, 15min); (20€, 5min)	(2€, 15min); (2€, 15min)	(2€, 15min); (0€, 35min)
Walking	(0€, 35min); (20€, 5min)	(0€, 35min); (2€, 15min)	(0€, 35min); (0€, 35min)

Why?

Multiple objectives

Because life is not simple

- What are your objectives for your current research project?
  - Publishing asap?
  - Quality of conference/journal?
  - Collaboration potential?
  - Flag-posting?
  - Increasing funding potential?
  - Finishing your PhD?

Because life really is not simple

- What are your objectives for your current research project?
  - Publishing asap?
  - Quality of conference/journal?
  - Collaboration potential?
  - Flag-posting?
  - Increasing funding potential?
  - Finishing your PhD?

- How about your co-authors?

Multiple objectives!

- Most decision problems have multiple objectives

- Cannot scalarise a priori
  - Unknown, uncertain, or private utility
  - Non-linear utility
  - Changeable preferences/utility
  - Adjustability
  - Explainability for oversight and review purposes

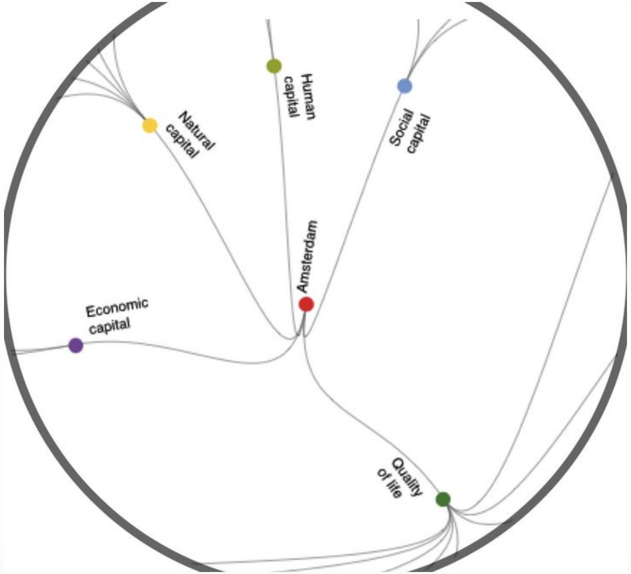
- To scalarise is to throw away information

More and more MO

- AI has ever increasing impact on people's lives
- Ethical aspects more important
  - Human-aligned AI is a multi-objective problem [Vamplew et al., 2018]
- Explainability more important
  - Legal frameworks incoming
- Environmental concerns

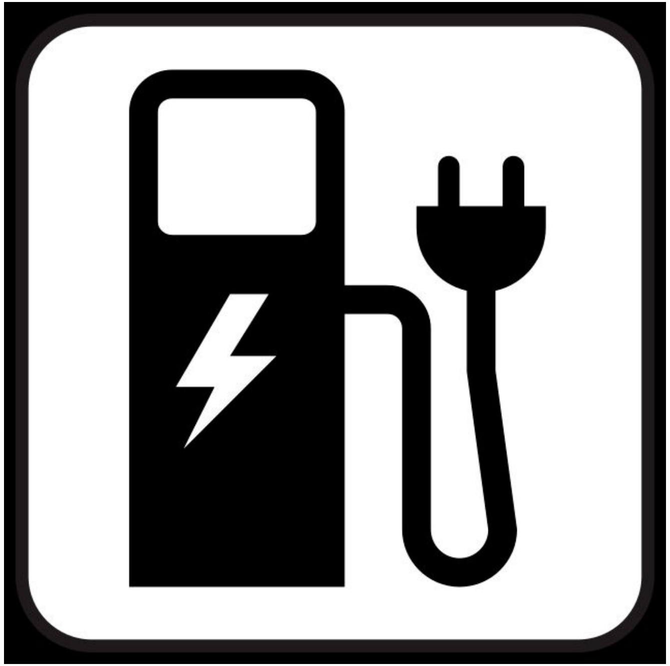
Policy level / paradigm shifts

- New ways of thinking are premuating the policy domain.
- Amsterdam: Brede Welvaart (Broad Wellbeing)
- Both EU and business domain: ESG (environmental, social, governance)



Example: electric vehicle charging

- meeting demands
- minimising costs
- preventing grid overloads



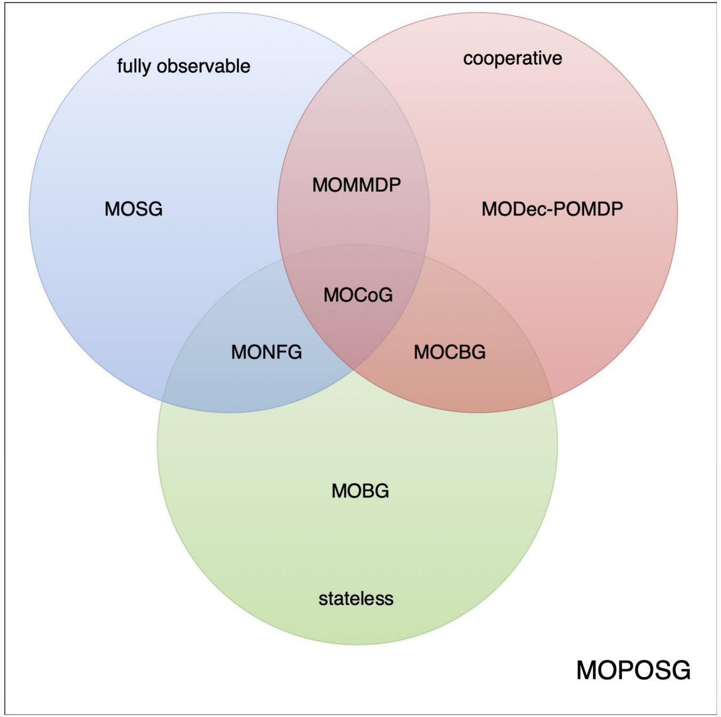
Modelling and dealing w/

Multiple objectives

User utility is central to modelling

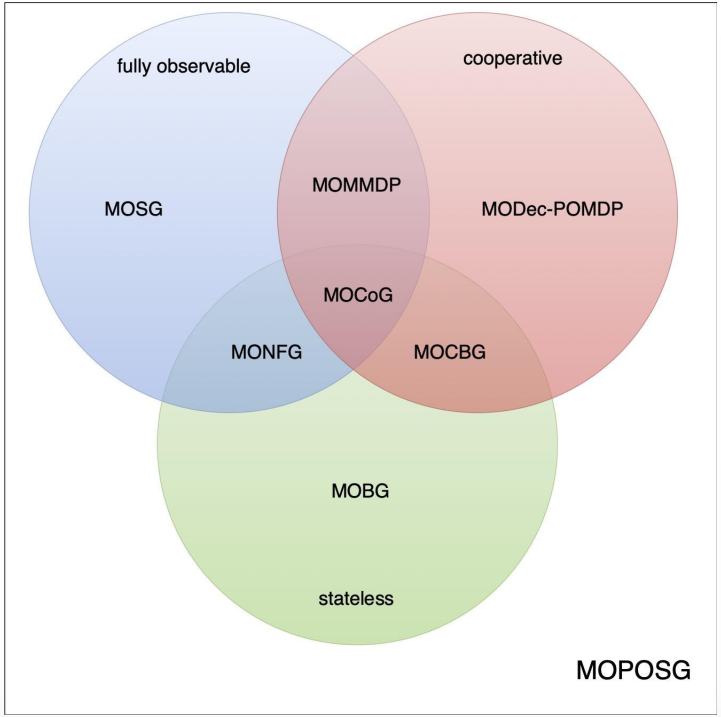
- User utility determines what is desirable for agents
- Stems from meaningful objectives (to the user)
  - Explainable
  - E.g., euros, minutes
- Identifying objectives
  - And then events that trigger rewards
- Decision-theoretic problem setting

MOPOSG



Models:
On the basis of rewards (in objectives) and observations (about states).

MOPOSG



Models:
On the basis of rewards (in objectives) and observations (about states).

But utility is not yet modelled!

Life is still not simple

- What are your objectives for your current research project?
  - Publishing asap?
  - Quality of conference/journal?
  - Collaboration potential?
  - Flag-posting?
  - Increasing funding potential?
  - Finishing your PhD?

- Setting?

Life is still not simple at all?

- What are your objectives for your current research project?
  - Publishing asap?
  - Quality of conference/journal?
  - Collaboration potential?
  - Flag-posting?
  - Increasing funding potential?
  - Finishing your PhD?
- Truly cooperative though?

Policy-based example

- Making a city climate adaptable requires a lot of changes (on almost every street)
  - Green management
  - Water management
  - Circular economy
  - ...
- It also has a lot of impact besides Environmental:
  - Social, disturbing people's live rhythms
  - Economical, ...
- Many stakeholders (citizens, businesses, etc.), many neighbourhoods

Utility-based approach

- Utility function, u_i, maps vector to scalar utility
- Total preference order (can always make a decision between alternatives)
- Utility determines what is optimal within available policies

Utility-based approach

- Solution should be derived from utility
  - Not axiomatically assumed
- This leads to a taxonomy based on rewards and utilities (Part 2)

How to deal with MO problems

- Collect available information about user utility.
- Decide which policies (e.g., stochastic vs deterministic) are allowed.
- Derive the optimal solution concept from the resulting information of the first two points.
- Select or design an algorithm that fits the solution concept.
- When multiple policies are required for the solution, design a method for the user to select the desired policy among these optimal policies.

Short break

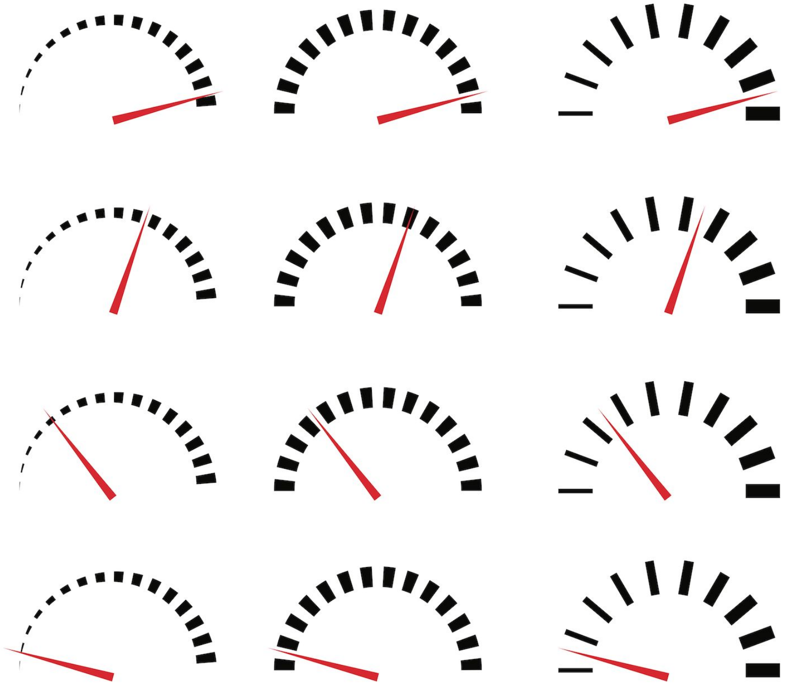
Part 2 - Structuring the MOMADM field

Taxonomy and solution concepts

Optimisation criteria

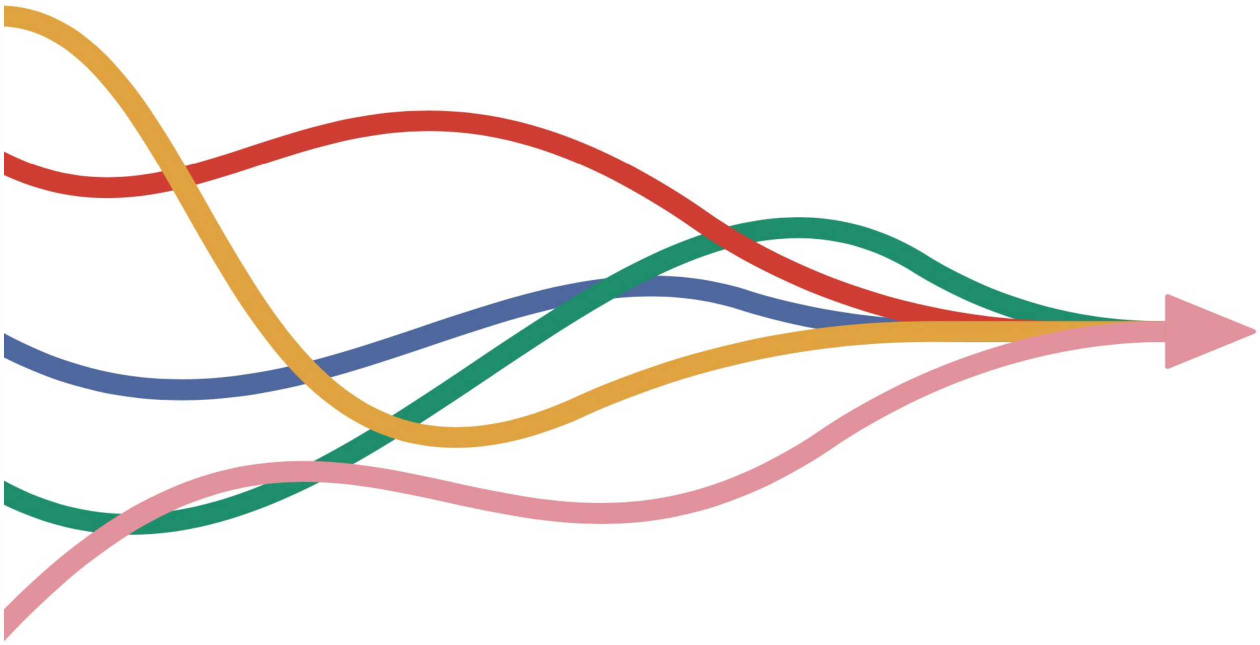
- Vectorial reward function
- Utility-based perspective

$$u_i : \mathbb{R}^d \rightarrow \mathbb{R}$$



Optimisation criteria

Optimisation criteria



Optimisation criteria

- Expected Scalarised Returns (ESR)
  - Calculate the expectation of the utility from the payoffs
  - Utility of an individual policy execution

Optimisation criteria

- Expected Scalarised Returns (ESR)
  - Calculate the expectation of the utility from the payoffs
  - Utility of an individual policy execution

- Scalarised Expected Returns (SER)
  - Calculate the utility of the expected payoff
  - Utility of the average payoff from several executions of the policy

Optimisation criteria

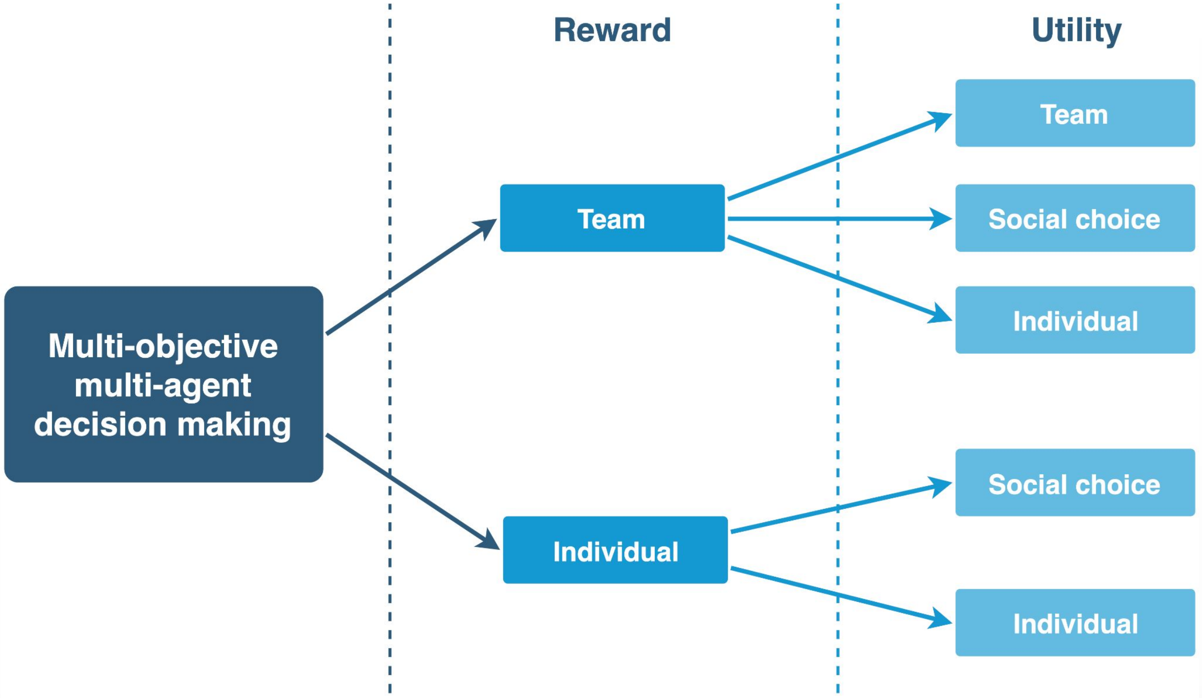
- Expected Scalarised Returns (ESR)

$$V_u^{\pi} = \mathbb{E}\left[u\left(\sum_{t=0}^{\infty} \gamma^t \mathbf{r}_t \right) \mid \pi, \mu_0 \right]$$

- Scalarised Expected Returns (SER)

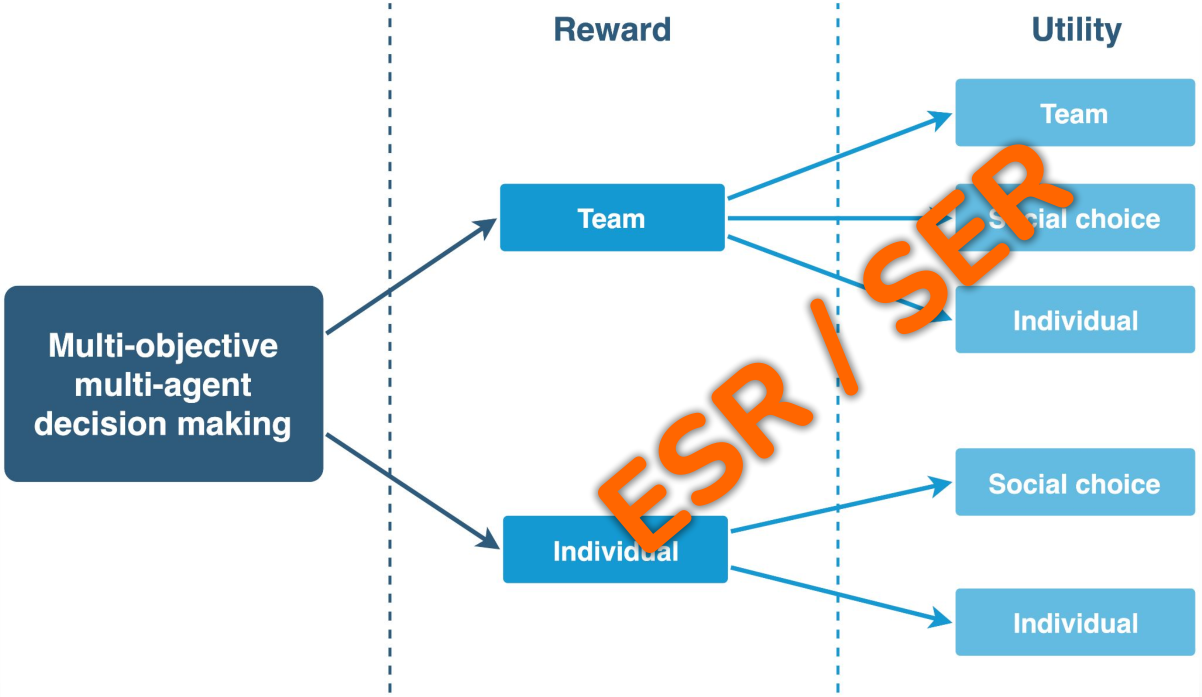
$$V_u^{\pi} = u\left(\mathbb{E}\left[\sum_{t=0}^{\infty} \gamma^t \mathbf{r}_t \mid \pi, \mu_0 \right] \right)$$

Taxonomy



Rădulescu, R., Mannion, P., Roijers, D. M., & Nowé, A. (2020). Multi-objective multi-agent decision making: a utility-based analysis and survey. *Autonomous Agents and Multi-Agent Systems*, *34*(1), 1-52.

Taxonomy



Reward
Utility
Multi-objective multi-agent decision making
Team
Individual
Team
Social choice
Individual
Social choice
Individual
ESR / SER

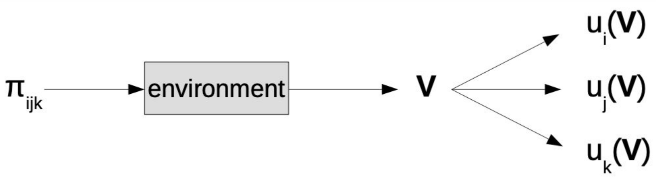
Examples - Team Reward

- Team utility
  - a company that aims to be environmentally responsible, while maximising profits

Examples - Team Reward

- Team utility

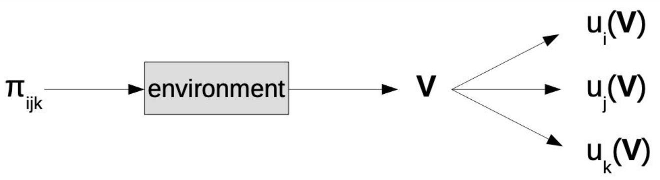
- Individual utility
  - Climate change policies, resource management



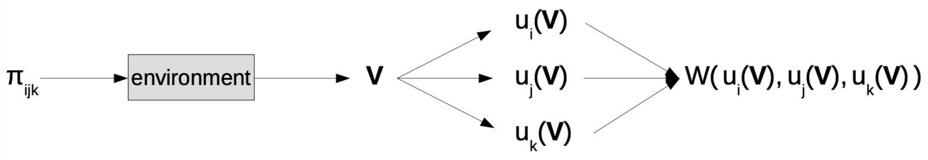
Examples - Team Reward

- Team utility

- Individual utility

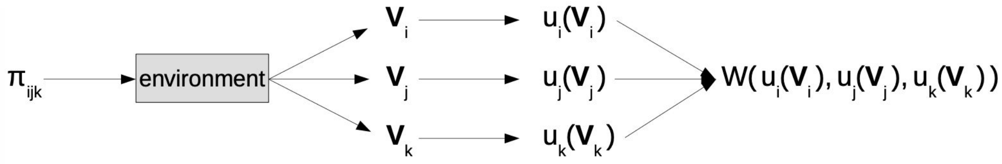


- Social Choice
  - urban planning/environmental management/social welfare policies



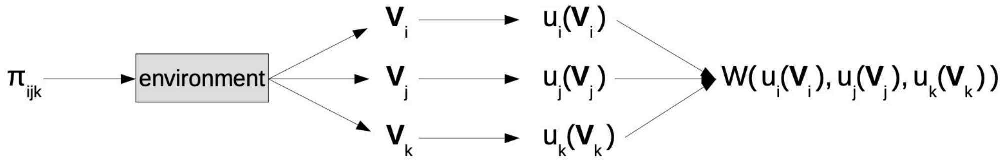
Examples - Individual Reward

- Social choice
  - international trade negotiations

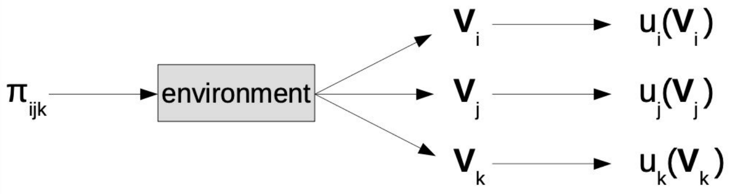


Examples - Individual Reward

- Social choice
  - international trade negotiations



- Individual utility
  - participating in city traffic, work commutes



Solution concepts

Reward \ Utility	Team	Social choice	Individual
Team	Coverage sets	Mechanism design	Coverage sets (+ Negotiation) Equilibria and stability concepts
Individual		Mechanism design	Equilibria and stability concepts Coverage Sets as best responses

Coverage sets

Reward \ Utility	Team	Social choice	Individual
Team	Coverage sets	Mechanism design	Coverage sets (+ Negotiation) Equilibria and stability concepts
Individual		Mechanism design	Equilibria and stability concepts Coverage Sets as best responses

- Contain at least one optimal policy for each possible utility function

- **TRTU**: rewards and derived utility is shared between agents, with one utility function selected during execution
- **TRIU**: agent can (contractually) agree which policy to execute
- **IRIU**: set of possible best responses to the behaviour of other agents

Coverage sets: negotiation

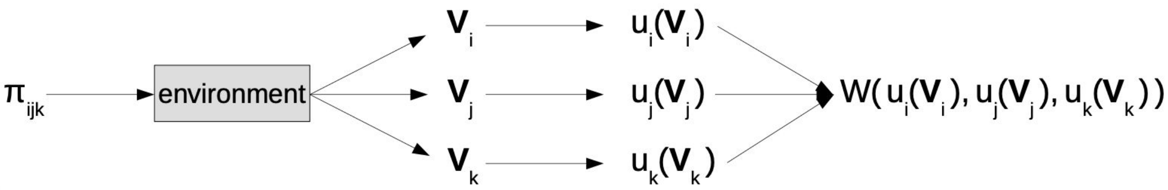
- Automated negotiation
  - Autonomous negotiating agents, representing their user's interests/preferences
  - Reach a compromise that satisfies all the involved parties
  - Pursue equity (i.e., fairness and justice)

- Baarslag, T., Kaisers, M., Gerding, E., Jonker, C. M., & Gratch, J. (2017). When will negotiation agents be able to represent us? The challenges and opportunities for autonomous negotiators. International Joint Conferences on Artificial Intelligence.
- Aydoğan, R., & Jonker, C. M. (2023). A Survey of Decision Support Mechanisms for Negotiation. In Recent Advances in Agent-Based Negotiation: Applications and Competition Challenges (pp. 30-51). Singapore: Springer Nature Singapore.

Social Welfare and Mechanism Design

- System perspective: what is a socially desirable outcome

Reward \ Utility	Team	Social choice	Individual
Team	Coverage sets	Mechanism design	Coverage sets (+ Negotiation) Equilibria and stability concepts
Individual		Mechanism design	Equilibria and stability concepts Coverage Sets as best responses



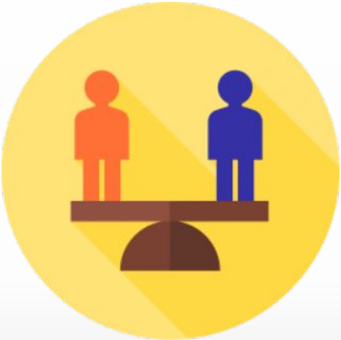
Design a system that forces agents to the truthful about their utilities and leads to optimal solution under W

Equilibria and stability concepts

Reward \ Utility	Team	Social choice	Individual
Team	Coverage sets	Mechanism design	Coverage sets (+ Negotiation) Equilibria and stability concepts
Individual		Mechanism design	Equilibria and stability concepts Coverage Sets as best responses

- Stable outcomes from which self-interested agents have no incentive to deviate

- Nash equilibria, correlated equilibria, cyclic equilibria, coalition formation



Nash Equilibrium

- No agent can improve their utility by unilaterally deviating from the joint strategy π^{NE}

- Nash equilibrium under SER:

$$\mathbb{E}u_i\left[\mathbf{p}_i(\pi_i^{NE}, \pi_{-i}^{NE})\right] \geq \mathbb{E}u_i\left[\mathbf{p}_i(\pi_i, \pi_{-i}^{NE})\right]$$

- Nash equilibrium under ESR:

$$u_i\left[\mathbb{E}\mathbf{p}_i(\pi_i^{NE}, \pi_{-i}^{NE})\right] \geq u_i\left[\mathbb{E}\mathbf{p}_i(\pi_i, \pi_{-i}^{NE})\right]$$

Correlated Equilibrium - SO

- Introduced by Aumann, in 1974

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- Correlated strategy - probability vector σ on A
- External mechanism

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Correlated Equilibrium - SO

- Introduced by Aumann, in 1974
- Correlated strategy - probability vector σ on A
- External mechanism
- No agent can improve their utility by unilaterally deviating from the recommendation of the correlated signal

- A correlated strategy σ^{CE} is a CE if: $\mathbb{E}p_i(\sigma^{CE}) \geq \mathbb{E}p_i(\delta_i(\sigma^{CE}))$

  for any strategy modification $\delta_i : A_i \rightarrow A_i$

Correlated Equilibrium - SO

- Correlated equilibria in real-life:

Correlated Equilibrium

- Correlated equilibria under SER:

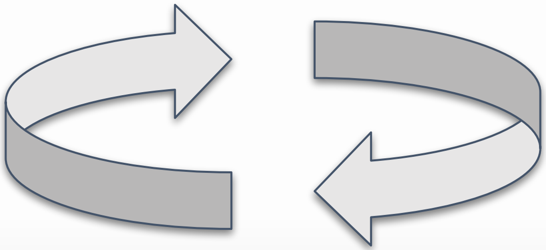
$$u_i\left[\mathbb{E}\mathbf{p}_i(\sigma^{CE})\right] \geq u_i\left[\mathbb{E}\mathbf{p}_i(\delta_i(\sigma^{CE}))\right]$$

- Correlated equilibria under ESR:

$$\mathbb{E}u_i\left(\mathbf{p}_i(\sigma^{CE})\right) \geq \mathbb{E}u_i\left(\mathbf{p}_i(\delta_i(\sigma^{CE}))\right)$$

Other solution concepts

- Cyclic Nash equilibria
    - No agent can improve their utility by unilaterally deviating from a joint cyclic strategy



Multi-Objective Normal Form Games

- Introduced by Blackwell in 1956
- MONFG - tuple (N , A, **p**), with $n \geq 2$ and $C \geq 2$ objectives, where:
  - $N = \{1, ..., n\}$ – set of players
  - $A = A_1 \times \cdots \times A_n$ – set of actions
  - $\mathbf{p} = (\mathbf{p}_1, ..., \mathbf{p}_n)$ – vectorial payoffs

Example - SER

$$u(p_1, p_2) = p_1 \cdot p_2$$

	A	B
A	(10, 2); (10, 2)	(0, 0); (0, 0)
B	(0, 0); (0, 0)	(2, 10); (2, 10)

Example - Nash equilibrium

$$u(p_1, p_2) = p_1 \cdot p_2$$

$$u(10, 2) = 10 \cdot 2 = 20$$

	A	B
A	(10, 2); (10, 2)	(0, 0); (0, 0)
B	(0, 0); (0, 0)	(2, 10); (2, 10)

Example - Cyclic Nash equilibrium

$$u(p_1, p_2) = p_1 \cdot p_2$$

	A	B
A	(10, 2); (10, 2)	(0, 0); (0, 0)
B	(0, 0); (0, 0)	(2, 10); (2, 10)

$$u(\frac{10+2}{2}, \frac{2+10}{2}) = u(6,6) = 36$$

- Joint cyclic strategy
  - Player 1: {A, B}
  - Player 2: {A, B}

Example - Correlated equilibrium

$$u(p_1, p_2) = p_1 \cdot p_2$$

$$u(\frac{10+2}{2}, \frac{2+10}{2}) = u(6,6) = 36$$

	A	B
A	(10, 2); (10, 2)	(0, 0); (0, 0)
B	(0, 0); (0, 0)	(2, 10); (2, 10)

- Correlated strategy σ
  - 50% (A, A)
  - 50% (B, B)

Part 3 - SOTA

Latest results and open challenges

(Im)balancing Act Game

- 2 players, 2 objective
- Same payoff vector for both players

	L	M	R
L	[4,0]	[3,1]	[2,2]
M	[3,1]	[2,2]	[1,3]
R	[2,2]	[1,3]	[0,4]

$$u_1([p_1, p_2]) = p_1^2 + p_2^2$$
$$u_2([p_1, p_2]) = p_1 \cdot p_2$$

Let's play the (Im)balancing Act Game

https://docs.google.com/forms/d/e/1FAIpQLSfHyr_yL0VsLSyOWDAXvcfecCAM4L2aoqbdSUh19XQocZS9Dg/viewform?vc=0&c=0&w=1&flr=0

ESR Equilibrium

- equilibrium 1: (0.75, 0, 0.25) and (0, 1, 0)
  expected utilities: 10 and 3
- equilibrium 2: (0.25, 0, 0.75) and (0, 1, 0)
  expected utilities: 10 and 3

	L	M	R
L	[4,0]	[3,1]	[2,2]
M	[3,1]	[2,2]	[1,3]
R	[2,2]	[1,3]	[0,4]

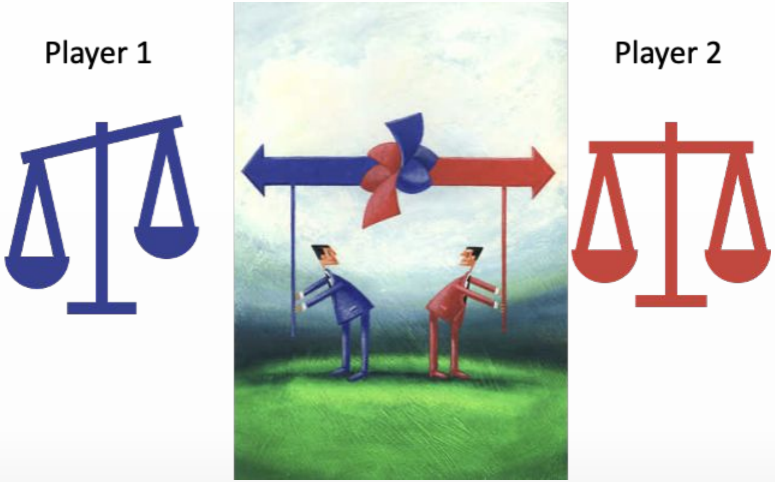
ESR	L	M	R
L	16,0	10,3	8,4
M	10,3	8,4	10,3
R	8,4	10,3	16,0

$$u_1([p_1, p_2]) = p_1^2 + p_2^2$$
$$u_2([p_1, p_2]) = p_1 \cdot p_2$$

Rădulescu, R., Mannion, P., Zhang, Y., Roijers, D. M., & Nowé, A. (2020). A utility-based analysis of equilibria in multi-objective normal-form games. *The Knowledge Engineering Review*, *35*.

SER Equilibrium?

- In finite MONFGs, where each agent seeks to maximise the utility under **SER, Nash equilibria need not exist.**



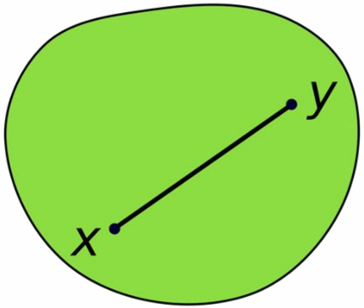
	L	M	R
L	[4,0]	[3,1]	[2,2]
M	[3,1]	[2,2]	[1,3]
R	[2,2]	[1,3]	[0,4]

$$u_1([p_1, p_2]) = p_1^2 + p_2^2$$
$$u_2([p_1, p_2]) = p_1 \cdot p_2$$

Rădulescu, R., Mannion, P., Zhang, Y., Roijers, D. M., & Nowé, A. (2020). A utility-based analysis of equilibria in multi-objective normal-form games. *The Knowledge Engineering Review*, *35*.

Bridging continuous games and MONFGs

- Continuous games:
  - Single objective
  - Infinite number of pure strategies
  - Continuous payoff functions
  - Benefit from many theoretical results
  - Algorithmically challenging



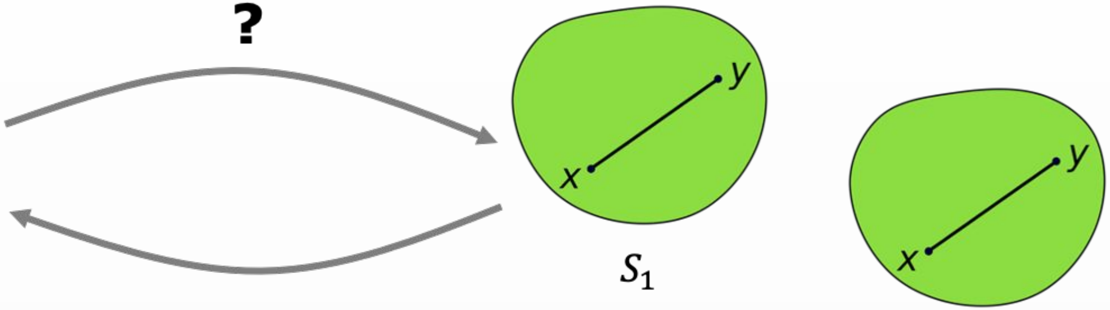
Assumption: convex strategy set

Röpke, W., Groenland, C., Rădulescu, R., Nowé, A., & Roijers, D. M. (2023). Bridging the Gap Between Single and Multi Objective Games. *AAMAS 2023.*

Bridging continuous games and MONFGs

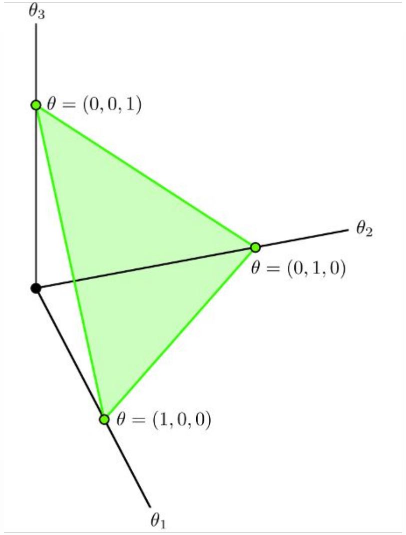
- Build mapping between MONFGs and continuous games
- Ensure that it preserves key dynamics
- Leverage the link for theoretical and algorithmic improvements

	A	B
A	(10, 2); (10, 2)	(2, 3); (2, 3)
B	(4, 2); (4, 2)	(6, 3); (6, 3)



Bridging continuous games and MONFGs

- Every mixed strategy in the MONFG becomes a pure strategy in the continuous game



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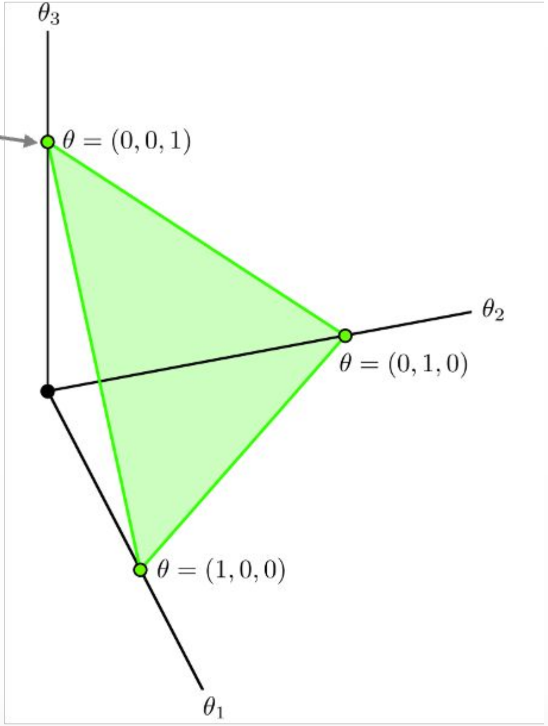
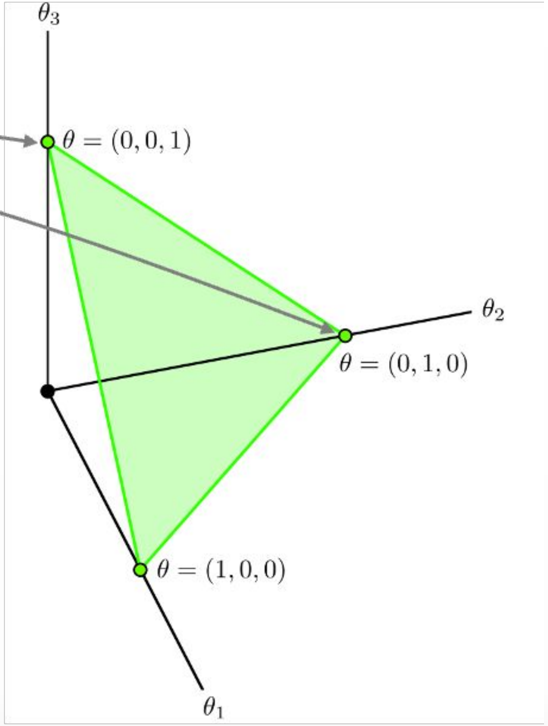
Bridging continuous games and MONFGs

	A	B	C
A	(4, 1); (4, 1)	(1, 2); (4, 2)	(2, 1); (1, 2)
B	(3, 1); (2, 3)	(3, 2); (6, 3)	(1, 2); (2, 1)
C	(1, 2); (2, 1)	(2, 1); (1, 2)	(1, 3); (1, 3)



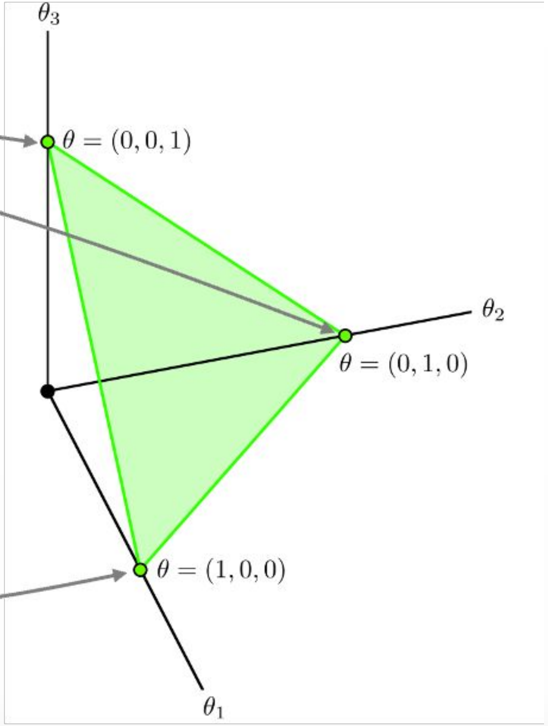
Bridging continuous games and MONFGs

	A	B	C
A	(4, 1); (4, 1)	(1, 2); (4, 2)	(2, 1); (1, 2)
B	(3, 1); (2, 3)	(3, 2); (6, 3)	(1, 2); (2, 1)
C	(1, 2); (2, 1)	(2, 1); (1, 2)	(1, 3); (1, 3)



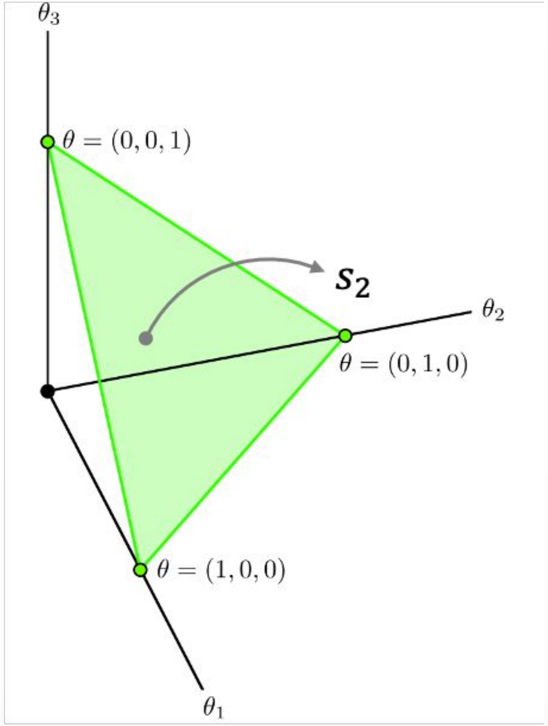
Bridging continuous games and MONFGs

	A	B	C
A	(4, 1); (4, 1)	(1, 2); (4, 2)	(2, 1); (1, 2)
B	(3, 1); (2, 3)	(3, 2); (6, 3)	(1, 2); (2, 1)
C	(1, 2); (2, 1)	(2, 1); (1, 2)	(1, 3); (1, 3)



Bridging continuous games and MONFGs

	$\frac{1}{4}$ A	$\frac{1}{4}$ B	$\frac{2}{4}$ C
A	(4, 1); (4, 1)	(1, 2); (4, 2)	(2, 1); (1, 2)
B	(3, 1); (2, 3)	(3, 2); (6, 3)	(1, 2); (2, 1)
C	(1, 2); (2, 1)	(2, 1); (1, 2)	(1, 3); (1, 3)

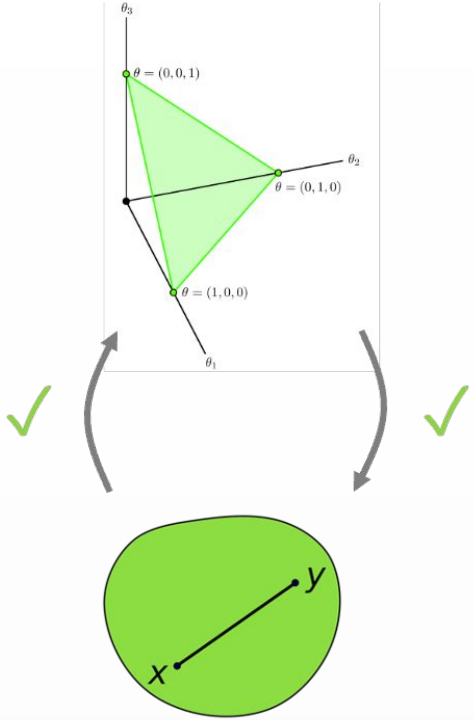


Theoretical insights

- Mixed strategy equilibria in the MONFG are pure strategy equilibria in the continuous game

- Continuous games are not guaranteed to have a pure strategy Nash equilibrium

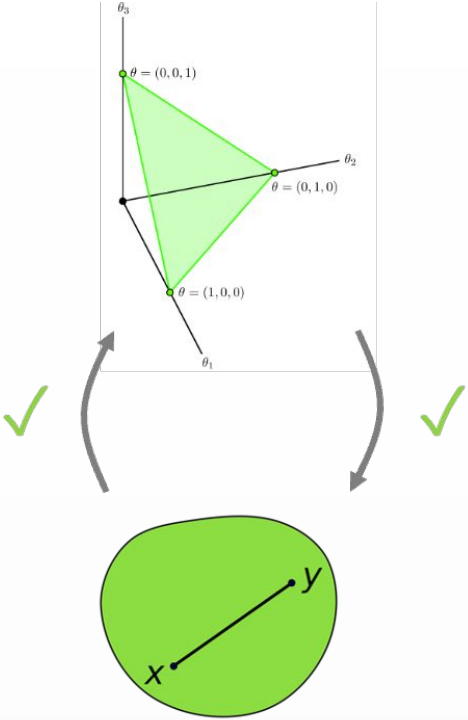
  - Nash equilibria are not guaranteed in MONFGs



More results

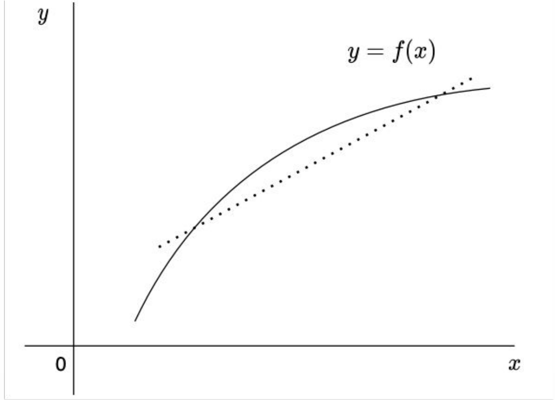
- **Bridging the Gap Between Single and Multi Objective Games**: Röpke, W., Groenland, C., Rădulescu, R., Nowé, A., & Roijers, D. M., AAMAS 2023

- Wednesday (10:45 - 12:30): Equilibria and Complexities of Gamesc session



NE Existence Guarantees

- Existence is guaranteed with (quasi)concave utility functions
  - Used in economics as well
  - Represents “well-behaved” preferences
- Intuition
  - MONFGs can be reduced to continuous games
  - In these game it is known that a pure strategy NE exists when assuming only quasiconcave utility functions
  - This equilibrium is also an equilibrium in the original MONFG



Röpke, W., Roijers, D. M., Nowé, A., & Rădulescu, R. (2022). **On nash equilibria in normal-form games with vectorial payoffs.** *Autonomous Agents and Multi-Agent Systems*, *36*(2), 53.

Non-existence

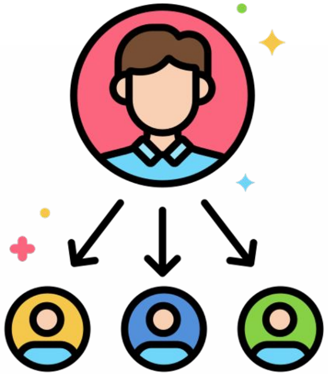
- We can show that no Nash equilibrium exists in this game
  - With **strict convex utility functions**

	A	B
A	(2, 0); (1, 0)	(1, 0); (0, 2)
B	(0, 1); (2, 0)	(0, 2); (0, 1)

$$u_1(p_1, p_2) = u_2(p_1, p_2) = p_1^2 + p_2^2$$

Commitment and Cyclic Strategies

- Commitment
  - One or more players commit to playing a specific strategy
  - Other players condition their own strategies on this commitment

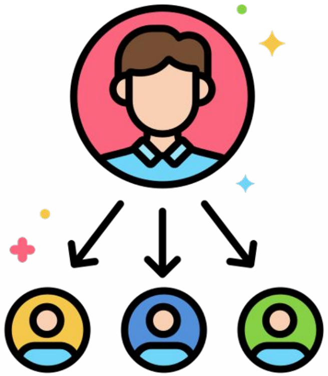


- Leadership equilibria (in two-player games)
  - The leader cannot improve their utility given that the follower plays a best-response
- Weak/strong leadership equilibria
  - Prescribes how an opponent selects their best-response

Röpke, W., Roijers, D. M., Nowé, A., & Rădulescu, R. (2021). **Preference Communication in Multi-Objective Normal-Form Games**. *Neural Computing and Applications (in press).*

Commitment and Cyclic Strategies

- Commitment can be strictly better than all Nash equilibria
  - Commit may avoid the “fixed-point death trap”



$$u(p_1, p_2) = p_1 \cdot p_2$$

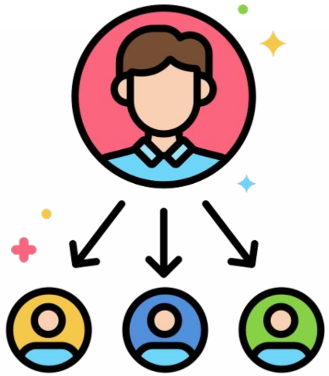
Nash equilibrium

$u(10, 2) = 10 \cdot 2 = 20$ ←

	A	B
A	(10, 2); (10, 2)	(0, 0); (0, 0)
B	(0, 0); (0, 0)	(2, 10); (2, 10)

Theoretical considerations

- Commitment can be strictly better than all Nash equilibria
  - Commit may avoid the “fixed-point death trap”



The optimal mix is to play
50% (A, A) and 50% (B, B)

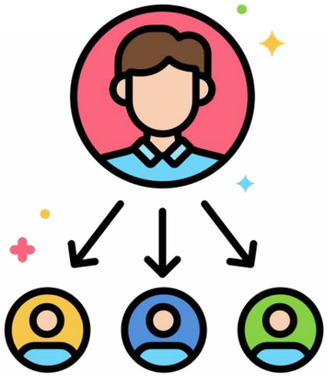
$$u(\frac{10+2}{2}, \frac{2+10}{2}) = u(6,6) = 36$$

$$u(p_1, p_2) = p_1 \cdot p_2$$

	A	B
A	(10, 2); (10, 2)	(0, 0); (0, 0)
B	(0, 0); (0, 0)	(2, 10); (2, 10)

Theoretical considerations

- Commitment can be strictly better than all Nash equilibria
  - Commit may avoid the "fixed-point death trap"



The optimal mix is to play
50% (A, A) and 50% (B, B)

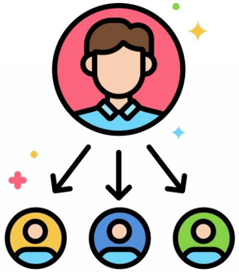
$$u(\frac{10+2}{2}, \frac{2+10}{2}) = u(6,6) = 36$$

- Joint cyclic strategy
  - Player 1: {A, B}
  - Player 2: {A, B}

$$u(p_1, p_2) = p_1 \cdot p_2$$

	A	B
A	(10, 2); (10, 2)	(0, 0); (0, 0)
B	(0, 0); (0, 0)	(2, 10); (2, 10)

Theoretical considerations



- Commitment is not guaranteed to be as good as a Nash equilibrium
  - If a player commits to a strategy, a malicious player might exploit this
  - This has implications for a range of real-world applications

- Cyclic Nash equilibria may exist when no stationary equilibrium exists
  - Stable solutions can still exist
  - Provides a valid alternative for the goal of a learning algorithm

Open questions

- Commitment and cyclic strategies
  - When can we guarantee that commitment cannot be exploited?
  - What is the link between correlated equilibria and hierarchical equilibria?
  - How to extend the Stackelberg game model to n-player games?
  - Open computational problems
    - Algorithm for learning or computing optimal commitment strategies?
    - How to learn hierarchical strategies?

Relations between optimisation criteria

- **Mixed strategies**
  - **No relation** between both optimisation criteria **in general**

	A	B
A	(1, 0); (1, 0)	(0, 1); (0, 1)
B	(0, 1); (0, 1)	(-10, 0); (-10, 0)

Multi-objective reward vectors

$$u(x, y) = 0.1 * x + max(0, x) * max(0, y)$$

	A	B
A	0.1; 0.1	0; 0
B	0; 0	-0.1; -0.1

Scalarised utility for both agents

No sharing of number of equilibria or equilibria themselves

Relations between optimisation criteria

- **Pure strategies**
  - Pure strategy equilibrium under SER is also one under ESR
  - Bidirectional when assuming (quasi)convex utility functions

- We can extend this to **blended settings**
  - Pure strategy equilibrium under SER is also one in any blended setting
  - Bidirectional when assuming (quasi)convex utility functions

MOCGs for ESR with Generative Flow Models

- Team reward, team utility
- ESR set: policies require full distributions over returns rather than expected value to evaluate
    - real-valued non-volume preserving transformations
- Distributional Multi-Objective Variable Elimination (DMOVE)

source

Open questions

- Results for more complex (e.g., sequential, partially observable) settings
- Integrated pipelines for planning -> negotiation -> execution
- Utility modelling
- Strategic disclosure of utility information to the other agents
- Benchmarks

Multi-Objective Decision Making Workshop

- At ECAI 2023
- Kwaków, Poland
- Workshop:
  September 30 / October 1
- Deadline: June 30
- Special Issue: NCAA (IF 5.1)

https://modem2023.vub.ac.be/

Thank you for listening

- Feel free to ask any questions now
- Or drop us a message at:
  - d.roijers@amsterdam.nl
  - roxana.radulescu@vub.be
- Or follow/add us on Twitter / LinkedIn
- Special thanks to Willem Röpke (VUB)!

This tutorial was based (primarily) on

- Rădulescu, R., Mannion, P., Roijers, D. M., & Nowé, A. (2020). Multi-objective multi-agent decision making: a utility-based analysis and survey. Autonomous Agents and Multi-Agent Systems, 34(1), 1-52.
- Rădulescu, R., Mannion, P., Zhang, Y., Roijers, D. M., & Nowé, A. (2020). A utility-based analysis of equilibria in multi-objective normal-form games. The Knowledge Engineering Review, 35.
- Rădulescu, R. (2021). Decision Making in Multi-Objective Multi-Agent Systems: A Utility-Based Perspective. Brussels: Crazy Copy Center Productions.
- Röpke, W., Roijers, D. M., Nowé, A., & Rădulescu, R. (2022). Preference communication in multi-objective normal-form games. Neural Computing and Applications, 1-26.
- Röpke, W., Roijers, D. M., Nowé, A., & Rădulescu, R. (2022). On Nash equilibria in normal-form games with vectorial payoffs. Autonomous Agents and Multi-Agent Systems, 36(2), 53.
- Röpke, W., Groenland, C., Rădulescu, R., Nowé, A., & Roijers, D. M. (2023). Bridging the Gap Between Single and Multi Objective Games. AAMAS 2023.