From AI to Computational Social Choice

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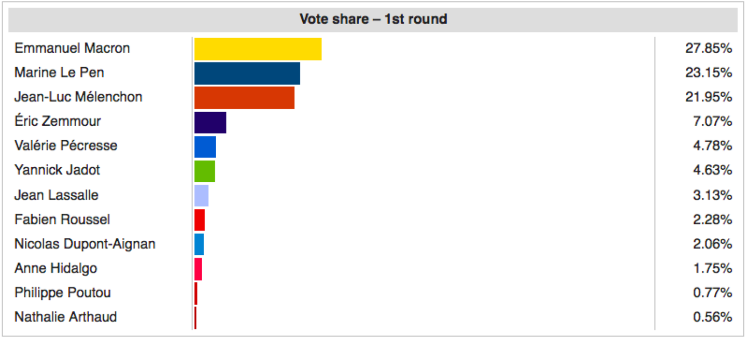
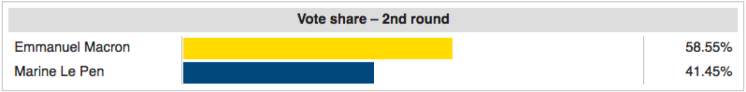
IJCAI-22

Social choice theory

Designing and analysing methods for collective decision making





Social choice theory

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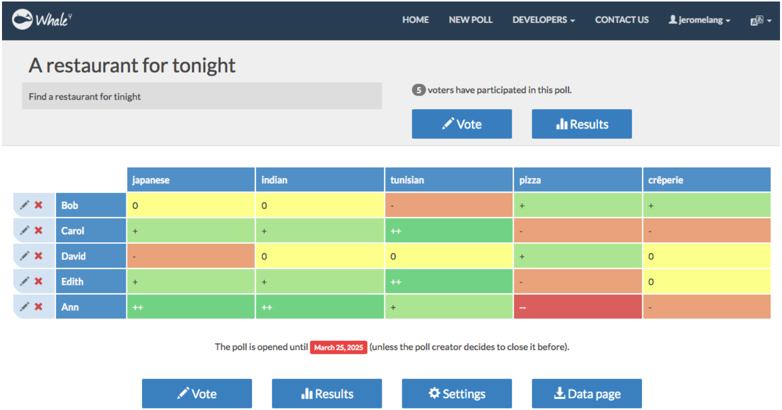


	japanese	indian	tunisian	pizza	crêperie
Bob	0	0	-	+	+
Carol	+	+	++	-	-
David	-	0	0	+	0
Edith	+	+	++	-	0
Ann	++	++	+	--	-

Social choice theory

Designing and analysing methods for collective decision making

A very rough history of social choice

1. around 1789: Condorcet and Borda (IJCAI-1789, Bastille)
2. 1951: birth of social choice theory (economics/mathematics); mostly axiomatic results such as impossibility theorems (most celebrated: Arrow's)
3. from the 1990's: computational turn.

Edith Elkind's IJCAI-21 talk:

Social Choice Rules

- input: agents express preferences over possible alternatives
- output: an alternative

Various input formats

Ann:	17
Bob:	20
Carol:	19
David:	17

uninominal

Ann:	$17 \succ 18 \succ 19 \succ 20$
Bob:	$20 \succ 19 \succ 18 \succ 17$
Carol:	$19 \succ 20 \succ 18 \succ 17$
David:	$17 \succ 18 \succ 19 \succ 20$

ordinal

	17	18	19	20
Ann	+	+	+	
Bob				+
Carol		+	+	+
David	+	+		

approvals

	17	18	19	20
Ann	50	30	20	0
Bob	0	0	0	100
Carol	0	40	50	10
David	40	30	20	10

evaluations

AI and Computational Social Choice

AI / CS have contributed to reshape social choice:

- new techniques
- new paradigms
- new objects of study, new applications

This talk: a quick guided tour of computational social choice via a **non-exhaustive, biased** selection of problems.

WARNING: My slides contain no references.
Key references are on supplementary slides, and also on a text that comes with it

`https://www.lamsade.dauphine.fr/~lang/IJCAI22.html`

1. Liquid democracy

- Representative democracy: citizens choose their delegates.
- **Liquid/fluid democracy**: citizens can choose either to vote on an issue, or to delegate to someone else.
- Direct democracy: citizens express their opinion on any issue.

1. Liquid democracy

Selecting projects

Who should be elected at the new steering board?

Do you want to vote yourself or delegate your vote to a trusted peer?

Classical social choice
Aggregating *preferences*
No ground truth

1. Liquid democracy

English idioms

> You will be given English idioms, and asked to identify their meaning.

Do you want to vote yourself or delegate your vote to a trusted peer?

→ 

Landmarks

> You wil be shown pictures of landmarks, and asked to say in which country they are.

Do you want to vote yourself or delegate your vote to a trusted peer?

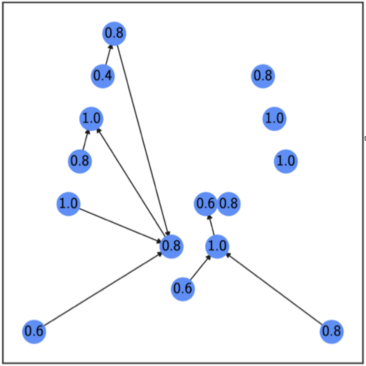
→ don't delegate

Epistemic social choice: Aggregating *beliefs* about a *ground truth*

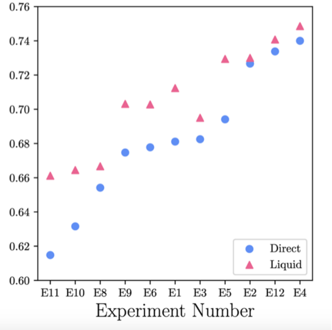
1. Liquid democracy

English idioms

You will be given English idioms, and asked to identify their meaning. Do you want to vote yourself or delegate your vote to a trusted peer?



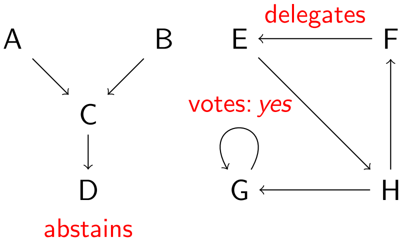
Delegation graph



Accuracy

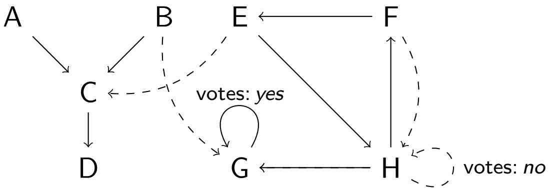
Source: Manon Revel

1. Liquid democracy



Cycles?
Delegations leading nowhere?

→ Ranked delegations



Thanks: Manon Revel, Markus Brill, Théo Delemazure, Umberto Grandi

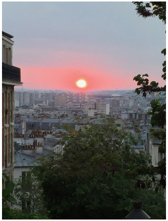
2. Epistemic Voting and Crowdsourcing

Epistemic social choice:

- there is a ground truth to be uncovered
- votes are noisy reports
- voting rules are maximum likelihood estimators.
- starts with Condorcet's jury theorem, 1785

$\rightarrow$ Statistical machine learning

2. Epistemic Voting and Crowdsourcing



Crowdsourcing via approval voting

In which of the 20 districts of Paris was this picture taken? You may give several answers. You will get a reward if your selection contains the true answer, minus a penalty that increases with the size of your selection.

2. Epistemic Voting and Crowdsourcing

Crowdsourcing via approval voting

	12	13	14	15	16	17	18	19	20	expertise?
Ann							+			
Bob			+		+			+	+	
Carol		+		+		+		+		
David							+		+	
Eva			+	+	+	+	+	+	+	
Fred	+									
Gloria					+		+	+	+	
#	2	2	2	2	3	2	**4**	**4**	**4**	

2. Epistemic Voting and Crowdsourcing

Crowdsourcing via approval voting

	12	13	14	15	16	17	18	19	20	expertise?
Ann							+			high
Bob			+		+			+	+	med–
Carol		+		+		+		+		med–
David							+		+	med+
Eva			+	+	+	+	+	+	+	low
Fred	+									high?
Gloria					+		+	+	+	med–
#	2	2	2	2	3	2	4	4	4	

2. Epistemic Voting and Crowdsourcing

Crowdsourcing via approval voting

	12	13	14	15	16	17	18	19	20	expertise?
Ann							+			high
Bob			+		+			+	+	med–
Carol		+		+		+		+		med–
David							+		+	med+
Eva			+	+	+	+	+	+	+	low
Fred	+									low!
Gloria					+		+	+	+	med–
#	2	2	2	2	3	2	4	4	4	

2. Epistemic Voting and Crowdsourcing

Crowdsourcing via approval voting

	12	13	14	15	16	17	18	19	20	expertise?
Ann							+			high
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Carol		+		+		+		+		med–
David							+		+	med+
Eva			+	+	+	+	+	+	+	low
Fred	+									low!
Gloria					+		+	+	+	med–
#							●			

Epistemic voting can also be applied to

aggregating linguistic annotations

3. Iterated Voting

Plurality voting: the candidate named by the largest number of voters wins.

4 voters	$a \succ b \succ c \succ d \succ e$
3 voters	$e \succ d \succ b \succ c \succ a$
2 voters	$c \succ e \succ b \succ a \succ d$
2 voters	$b \succ c \succ d \succ a \succ e$

3. Iterated Voting

Plurality voting: the candidate named by the largest number of voters wins.

4 voters	$a \succ b \succ c \succ d \succ e$
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2 voters	$b \succ c \succ d \succ a \succ e$

winner: a

3. Iterated Voting

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4 voters	$a \succ b \succ c \succ d \succ e$
3 voters	$e \succ d \succ b \succ c \succ a$
2 voters	$c \succ e \succ b \succ a \succ d$
2 voter	$b \succ c \succ d \succ a \succ e$

previous winner: a

winner: e

3. Iterated Voting

Plurality voting: the candidate named by the largest number of voters wins.

4 voters	$a \succ b \succ c \succ d \succ e$
3 voters	$e \succ d \succ b \succ c \succ a$
2 voters	$c \succ e \succ b \succ a \succ d$
2 voters	$b \succ c \succ d \succ a \succ e$

previous winner: e

winner: b

Chances are that we have reached convergence.

3. Iterated Voting

4 voters	$a \succ b \succ c \succ d \succ e$	$a \succ b \succ c \succ d \succ e$
3 voters	$e \succ d \succ b \succ c \succ a$	$e \succ d \succ b \succ c \succ a$
2 voters	$c \succ e \succ b \succ a \succ d$	$c \succ e \succ b \succ a \succ d$
2 voters	$b \succ c \succ d \succ a \succ e$	$b \succ c \succ d \succ a \succ e$
winner	a	b

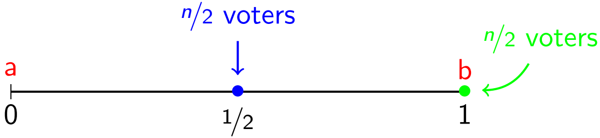
- voting rule + voter behaviour model $\rightarrow$ equilibrium reached?
- equilibria sometimes of better quality than sincere outcomes

Thanks: Reshef Meir

4. Distortion and low-communication voting

Metric setting

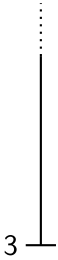
- alternatives and voters are in a metric space with distance d
- cost (or disutility) of alternative x to voter i: $c_i(x) = d(i, x)$
- f voting rule *with ordinal input*?
- *distortion* of f: worst-case ratio between the cost of the winner according to f, and the optimal cost.



- a has a global cost $3n/4$ ... and can be the majority winner
- b has a global cost $n/4$
- when $n = 2$, all reasonable voting rules with ordinal input degenerate to majority
- no voting rule with can have distortion smaller than 3 !
- can we find a rule that achieves 3?

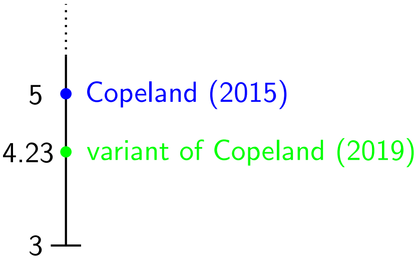
4. Distortion and low-communication voting

Metric setting



4. Distortion and low-communication voting

Metric setting



References: supplementary slides + paper!

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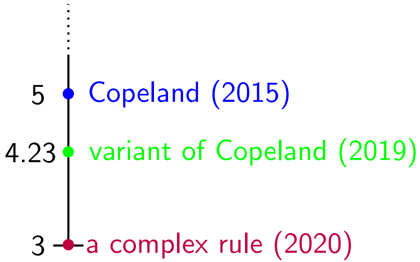

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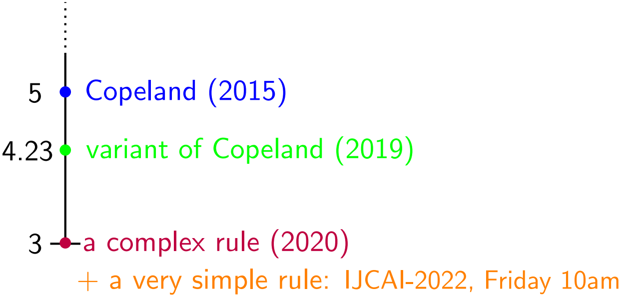
Metric setting



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4. Distortion and low-communication voting

A low-communication rule: Plurality-Veto

- $s(x)$ plurality score of alternative x
- we fix a sequence of $n-1$ voters
- at each step the designated voter decrements $s(x)$ where x is her worst alternative such that $s(x) > 0$
- the remaining candidate after $n-1$ steps is the winner

Ann	$a \succ b \succ c \succ d$
Bob	$a \succ c \succ d \succ b$
Carol	$b \succ c \succ d \succ a$
David	$b \succ c \succ a \succ d$
Edith	$c \succ d \succ b \succ a$
Fred	$d \succ c \succ b \succ a$

$$
\begin{array}{rl}
 & (a:2, b:2, c:1, d:1) \\
\rightarrow_{Ann} & (a:2, b:2, c:1, d:0) \\
\rightarrow_{Bob} & (a:2, b:1, c:1, d:0) \\
\rightarrow_{Carol} & (a:1, b:1, c:1, d:0) \\
\rightarrow_{David} & (a:0, b:1, c:1, d:0) \\
\rightarrow_{Edith} & (a:0, b:0, \mathbf{c:1}, d:0)
\end{array}
$$

- each voter sends at most $2 \log m$ bits
- metric distortion 3: good trade-off simplicity/quality

5. Complex alternatives → Combinatorial domains

- there are several possible topics I can speak during my talk
- I have time to talk only about two topics
- Ann: would like one odd topic (t_1 or t_3) and one even topic (t_2 or t_4), and is especially interested in t_1, t_2 and t_3.
- Bob: likes t_3 and that's all.
- Carol: likes t_1 and t_4, and in case t_1 is not selected then t_2.

- focus on preferential dependencies
- use compact preference representation languages, *e.g.* CP-nets

5. Complex alternatives → Multiwinner elections

We can now select three topics. The votes of the attendees:

	t_1	t_2	t_3	t_4	t_5
8 voters	+	+	+		
3 voters				+	
1 voter					+

Three possible criteria → three families of rules

excellence	t_1, t_2, t_3
diversity	t_1, t_3, t_4
proportionality	t_1, t_2, t_5

5. Complex alternatives → Multiwinner elections

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3 voters				+	
1 voter					+

Three possible criteria → three families of rules

excellence	t_1, t_2, t_3
diversity	t_1, t_3, t_4
proportionality	t_1, t_2, t_5

- focus on properties, especially proportionality

5. Complex alternatives → Participatory budgeting

- topics now have durations
- total budget: 30 minutes

	t_1	t_2	t_3	t_4	t_5	t_6
100×	+	+				
90×			+			
30×				+	+	+
30×				+	+	
10×	+			+		
cost	9	9	9	4	4	4

5. Complex alternatives → Participatory budgeting

- topics now have durations
- total budget: 30 minutes

	t_1	t_2	t_3	t_4	t_5	t_6
100×	+	+				
90×			+			
30×				+	+	+
30×				+	+	
10×	+			+		
cost	9	9	9	4	4	4

A more common interpretation:

- $t_1, \ldots, t_6$ are projects with costs
- total budget: 30 M€

5. Complex alternatives → Participatory budgeting

	t_1	t_2	t_3	t_4	t_5	t_6
100×	+	+				
90×			+			
30×				+	+	+
30×				+	+	
10×	+			+		
cost	9	9	9	4	4	4

available budget: 30

The greedy method

topic	#*votes*	*cost*	
t_1	110	9	●
t_2	100	9	●
t_3	90	9	●
t_4	70	4	
t_5	60	4	
t_6	30	4	

Good?

5. Complex alternatives → Participatory budgeting

	t_1	t_2	t_3	t_4	t_5	t_6
100×	+	+				
90×			+			
30×				+	+	+
30×				+	+	
10×	+			+		
cost	9	9	9	4	4	4

available budget: 30

topic	#*votes*	*cost*		
t_1	110	9	●	●
t_2	100	9	●	
t_3	90	9	●	●
t_4	70	4		●
t_5	60	4		●
t_6	30			●

Need to ensure fairness to groups of voters through proportionality

5. Complex alternatives $\rightarrow$ Judgment aggregation

We can select three topics. The votes of the attendees:

	t_1	t_2	t_3	t_4	t_5
5 voters	+	+	+		
3 voters	+	+			+
1 voter				+	+
1 voter			+		+
2 voters				+	

Admissible committees are those that satisfy the constraint

$$(t_1 \vee t_3) \wedge (t_2 \vee t_5) \wedge \neg(t_1 \wedge t_4 \wedge t_5) \wedge \neg(t_2 \wedge t_4 \wedge t_5) \wedge (t_3 \rightarrow t_4)$$

- focus on complex feasibility constraints

5. Complex alternatives

focus on	proportionality guarantees	complex preferences	complex constraints
combinatorial domains		+	
multiwinner elections	+		
participatory budgeting	+		(+)
judgment aggregation			+

Thanks: Dominik Peters

6. Diversity

- select 4 members for a committee
- ideal representation objectives
  - 50% male, 50% female
  - 25% area 1, 50 % area 2, 25 % area 3.
  - 25% junior, 50 % senior.

	Gender	Area	Seniority
c_1	F	1	J
c_2	M	2	J
c_3	M	2	S
c_4	F	3	S
c_5	M	2	J
c_6	M	2	J
c_7	M	2	J
c_8	F	1	J

Which committee should be elected?

6. Diversity

- select 4 members for a committee
- constraints:
  - 50% male, 50% female
  - 25%-50 % area 1, 40%-60 % area 2, 10%-25 % area 3.
  - $\geq$ 25% junior, $\geq$ 50 % senior.

	Gender	Area	Seniority
c_1	F	1	J
c_2	M	2	J
c_3	M	2	S
c_4	F	3	S
c_5	M	2	J
c_6	M	2	J
c_7	M	2	J
c_8	F	1	J

Which committee should be elected?

6. Diversity

- select 4 members for a committee
- votes
- hard constraints:
  - 50% male, 50% female
  - 25%-50 % area 1, 40%-60 % area 2, 10%-25 % area 3.
  - $\geq$ 25% junior, $\geq$ 50 % senior.

	Gender	Area	Seniority	v_1	v_2	v_3	v_4	v_5	v_6	v_7
c_1	F	1	J	+				+		+
c_2	M	2	J	+						+
c_3	M	2	S	+	+		+			
c_4	F	3	S				+			
c_5	M	2	J		+		+			
c_6	M	2	J						+	+
c_7	M	2	J			+	+			
c_8	F	1	J			+		+		

Which committee should be elected?

6. Diversity

- select 4 members for a committee
- hard constraints Γ:
  - 50% male, 50% female
  - 25%-50 % area 1, 40%-60 % area 2, 10%-25 % area 3.
  - $\geq$ 25% junior, $\geq$ 50 % senior.

	Gender	Area	Seniority	v_1	v_2	v_3	v_4	v_5	v_6	v_7
c_1	F	1	J	+				+		+
c_2	M	2	J	+						+
c_3	M	2	S	+	+		+			
c_4	F	3	S				+			
c_5	M	2	J		+		+			
c_6	M	2	J						+	+
c_7	M	2	J			+	+			
c_8	F	1	J			+		+		

- $\{c_1, c_3, c_5, c_7\}$ if we focus on excellence

6. Diversity

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  - 50% male, 50% female
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  - $\geq$ 25% junior, $\geq$ 50 % senior.

	Gender	Area	Seniority	v_1	v_2	v_3	v_4	v_5	v_6	v_7
c_1	F	1	J	+				+		+
c_2	M	2	J	+						+
c_3	M	2	S	+	+		+			
c_4	F	3	S				+			
c_5	M	2	J		+		+			
c_6	M	2	J						+	+
c_7	M	2	J			+	+			
c_8	F	1	J			+		+		

- $\{c_3, c_4, c_6, c_8\}$ if we focus on representation and proportionality

6. Diversity: application to composing citizens' assemblies

- variant with randomized, fair selection
- variant with online selection

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- variant with randomized, fair selection
- variant with online selection

We want a fair representation for all attributes.

Gender	Area	Seniority	select?
M	3	J	yes

6. Diversity: application to composing citizens' assemblies

- variant with randomized, fair selection
- variant with online selection

We want a fair representation for all attributes.

Gender	Area	Seniority	select?
M	3	J	yes
F	3	J	no

6. Diversity: application to composing citizens' assemblies

- variant with randomized, fair selection
- variant with online selection

We want a fair representation for all attributes.

Gender	Area	Seniority	select?
M	3	J	yes
F	3	J	no
M	1	S	yes
F	2	S	yes
M	3	S	no
...	...	...	...

- if the distribution of arrivals is known $\rightarrow$ Markov decision processes
- if not $\rightarrow$ reinforcement learning

7. Fair Division of Indivisible Items

	a	b	c	d	e
Ann	15	**3**	2	2	**6**
Bob	7	5	**5**	**5**	7
Carol	**20**	3	3	3	3

- $v_{Ann}(b) = 3 =$ value of item b for Ann
- Assume agents have *additive* valuations:

$$v_{Ann}(\{b, e\}) = 3 + 6 = 9$$

- *envy-freeness* (EF): every agent i weakly prefers her share to the share of any other agent j
- Ann prefers Carol's share $\{a\}$ to her own $\{b, e\}$: the allocation is not envy-free
- Here: no envy-free allocation!

7. Fair Division of Indivisible Items

	a	*b*	*c*	*d*	*e*
Ann	15	**3**	2	2	**6**
Bob	7	5	**5**	**5**	7
Carol	**20**	3	3	3	3

- A weakening of envy-freeness: *proportional fairness*
- An agent deserves a satisfaction of least $\frac{1}{n}$ the value of the whole set of items
- $v_{Ann}(\{a, b, c, d, e\} = 28$ and $v_{Ann}(\{b, e\}) = 9 < \frac{28}{3}$: the allocation is not *proportional*
- Here: no proportional allocation!

7. Fair Division of Indivisible Items

	a	b	c	d	e
Ann	15	3	**2**	**2**	6
Bob	7	**5**	5	5	**7**
Carol	**20**	3	3	3	3

- Another weakening of EF: *envy-freeness up to one good* (EF1):
- The blue allocation is EF1:
  - Ann no longer envies Bob if we remove one good from Bob's share: $v_{Ann}(\{b,e\} \setminus \{e\}) = 3 \leq v_{Ann}(\{c,d\}) = 4$
  - Ann no longer envies Carol if we remove one good from Carol's share: $v_{Ann}(\{a\} \setminus \{a\}) = 0 \leq v_{Ann}(\{c,d\}) = 4$
  - Bob and Carol do not envy anyone.
- An EF1 allocation is guaranteed to exist (for additive valuations) and can be computed in polynomial time.

7. Fair Division of Indivisible Items

	a	*b*	*c*	*d*	*e*
Ann	15	3	**2**	**2**	6
Bob	7	**5**	5	5	**7**
Carol	**20**	3	3	3	3

- Between EF1 and EF: *envy-freeness up to any good* (EFX)
- Ann still envies Bob if we remove b from Bob's share: $v_{Ann}(\{b, e\} \setminus \{b\}) = 6 > v_{Ann}(\{c, d\}) = 4$
- the blue allocation is not EFX.

7. Fair Division of Indivisible Items

	a	*b*	*c*	*d*	*e*
Ann	15	**3**	2	2	**6**
Bob	7	5	**5**	**5**	7
Carol	**20**	3	3	3	3

- Between EF1 and EF: *envy-freeness up to any good* (EFX)
- the red allocation is EFX: removing any good from Bob's share eliminates Ann her envy towards Bob; and similarly for her envy to Carol.

7. Fair Division of Indivisible Items

	a	*b*	*c*	*d*	*e*
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- does an EFX allocation always exist?

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- Between EF1 and EF: *envy-freeness up to any good* (EFX)
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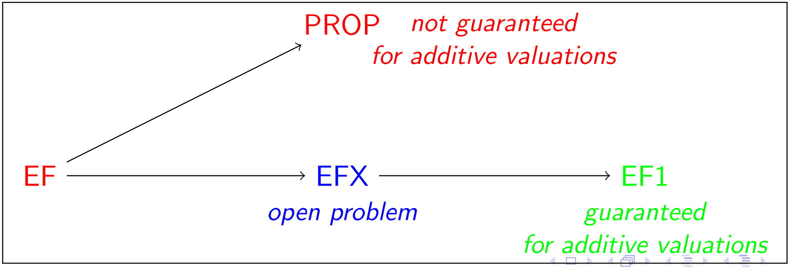
- does an EFX allocation always exist? Long-standing open problem



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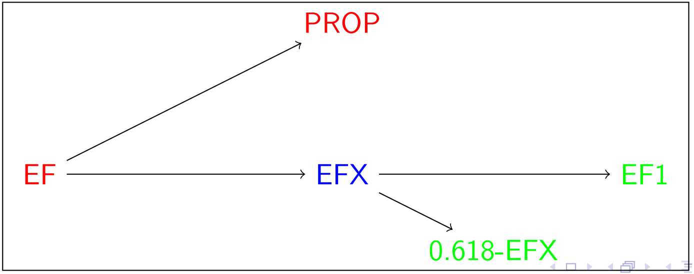

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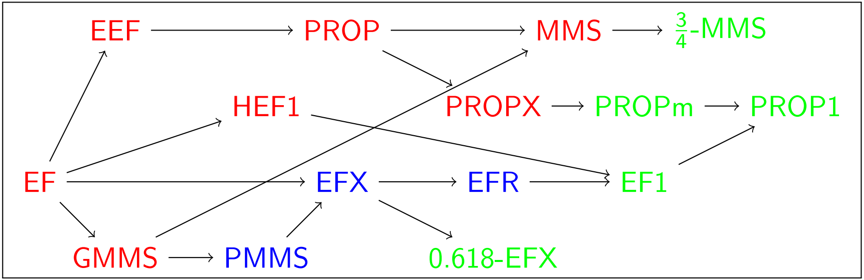

8. Automated Theorem Proving for Social Choice

- Proving (or disproving) theorems in social choice is difficult because it involves large combinatorial structures
- SAT solvers can help!
- Find new proofs for known results; discover new results; uncover mistakes in the literature

8. Automated Theorem Proving for Social Choice

Two-sided matching:

- two groups of n agents each (*left* and *right*)
- each agent ranks the agent of the other group
- find a good one-to-one matching.
- teachers/positions, workers/tasks, kidneys/patients...

The classic Gale-Shapley algorithm (1962):

- guarantees *stability*
- treats the two sides in an asymmetric way: choose between left-optimality and right-optimality

Can we have stability and left/right fairness?

- No as soon as $n \geq 3$: proof with a SAT solver for $n = 3$ + generalization to arbitrary n

Stability for $n = 3$: conjunction of 419,904 clauses

$$\bigwedge_{p \in R_3!^3 \times L_3!^3} \bigwedge_{i \in 1,2,3} \bigwedge_{j \in 1,2,3} \bigwedge_{i' : l_i \succ_{r_j} l_{i'} \in p} \bigwedge_{j' : r_j \succ_{l_i} r_{j'} \in p} \neg x_{p \rhd (i,j')} \vee \neg x_{p \rhd (i',j)}$$

Thanks: Ulle Endriss

9. Collective decision making datasets

Building & maintaining

Dataset for voting data: PrefLib.Org

Other datasets: matching, participatory budgeting

all open access

Exploiting

Gap between theory and real-world instances?

Assessing the validity of preference models

Learning/ discovering structure

9. Collective decision making datasets

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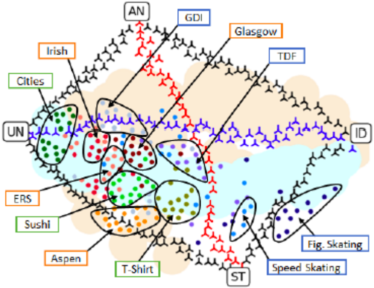


"Map of real-world elections"

Source:
Boehmer, Bredereck, Faliszeswski, Niedermeier & Szufa, 2021

Thanks: Piotr Faliszewski, Nick Mattei

Social choice engineering at Université Paris-Dauphine

- huge construction works in the whole building 2022-2027
- one building, 600 offices, most occupied by one or two persons
- $>$ 90% of the building will be completely rebuilt
- 5 big phases, whose duration is known with some uncertainty
- it is known which offices will be unavailable at each phase
- initial office allocation known, final state (almost) known
- people moving in average twice $+$ possible compression at some intermediate phase

Students: this should not prevent you from coming and studying with us!

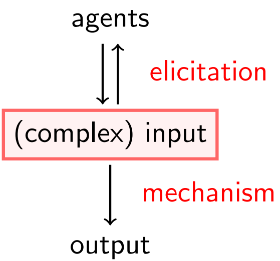
Social choice engineering at Université Paris-Dauphine

- the university asked us* to help finding a fair and efficient reallocation sequence
- expertise needed in AI, OR and social choice
- a fair division problem? Yes but:
  - 6 research labs + teaching departments + central services $\Longrightarrow$ not clear who the agents are: individuals, groups, both?
  - heavily non-additive preferences: desire for labs/departments to remain grouped, for moves to be timewise not too close, ...
  - uncertainty

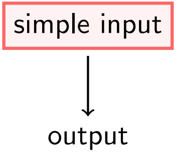
  temporal fair division problem with individual and group fairness, complex nonadditive preferences and uncertainty!
- each of these complications has been studied individually
- no known framework / algorithm for our problem
- social choice engineering! (here and elsewhere)

* Stéphane Airiau, Lucie Galand, JL, Clément Royer, Sonia Toubaline

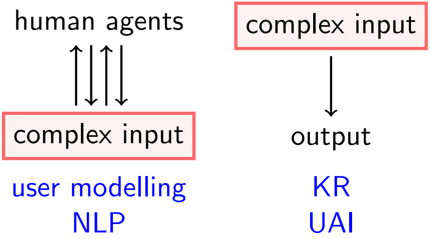
Social Choice Engineering



What we know how to do



What is missing



Summary: Social Choice and AI

new techniques	new paradigms
new objects of study	new applications

multiagent systems	KR&R
planning/MDP	online learning
statistical learning	SAT
user modelling?	NLP?

Informal paper and other resources coming with this talk:

`https://www.lamsade.dauphine.fr/~lang/IJCAI22.html`

Special thanks: Sylvain Bouveret, François Durand

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[Distortion 5: Anshelevich, Onkar Bhardwaj, John Postl, AAAI 15]
[Distortion 4.236: Kamesh Munagala, Kangning Wang, EC 2019]

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