From AI to Computational Social Choice

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CNRS & Université Paris-Dauphine PSL

IJCAI-22
Social choice theory

Designing and analysing methods for collective decision making

Vote share – 1st round

<table>
<thead>
<tr>
<th>Candidate</th>
<th>Vote Share</th>
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</thead>
<tbody>
<tr>
<td>Emmanuel Macron</td>
<td>27.85%</td>
</tr>
<tr>
<td>Marine Le Pen</td>
<td>23.15%</td>
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<tr>
<td>Jean-Luc Mélenchon</td>
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<tr>
<td>Éric Zemmour</td>
<td>7.07%</td>
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<tr>
<td>Valérie Pécresse</td>
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<tr>
<td>Yannick Jadot</td>
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<td>Jean Lassalle</td>
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<td>Fabien Roussel</td>
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<td>Nicolas Dupont-Aignan</td>
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<td>Anne Hidalgo</td>
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<td>Philippe Poutou</td>
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<td>Nathalie Arthaud</td>
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Vote share – 2nd round

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<td>58.55%</td>
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<td>Marine Le Pen</td>
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Social choice theory

Designing and analysing methods for collective decision making
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:
https://ijcai-21.org/videos-slides/?video=InvT1
Social Choice Rules

- **input**: agents express preferences over alternatives/candidates
- **output**: an alternative

Choose the temperature in the room? **Various input formats**

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<td>Ann</td>
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ordinal

approvals

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.
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

Committee election

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 will 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?

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

→ 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

→ 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

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The table above represents the consent of experts to vote on a number of statements. The number of votes for each statement is shown in the last row.
2. Epistemic Voting and Crowdsourcing

Crowdsourcing via approval voting

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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: $b \succ c \succ d \succ a \succ e$

Chances are that we have reached convergence.
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  $b \succ c \succ d \succ a \succ e$

winner: $a$
3. Iterated Voting

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

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- 2 voters: $b \succ c \succ d \succ a \succ e$

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 \[ a \succ b \succ c \succ d \succ e \quad a \succ b \succ c \succ d \succ e \]
3 voters \[ e \succ d \succ b \succ c \succ a \quad e \succ d \succ b \succ c \succ a \]
2 voters \[ c \succ e \succ b \succ a \succ d \quad c \succ e \succ b \succ a \succ d \]
2 voters \[ b \succ c \succ d \succ a \succ e \quad b \succ c \succ d \succ a \succ e \]

winner \[ a \quad b \]

- 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.

$$\frac{n}{2} + \varepsilon \text{ voters}$$

$$\frac{n}{2} - \varepsilon \text{ voters}$$

- $a$ has a global cost $\sim \frac{3n}{4}$ ... and is the majority winner
- $b$ has a global cost $\sim \frac{n}{4}$
- 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

3
4. Distortion and low-communication voting

Metric setting

5

4.23

3

Copeland (2015)

variant of Copeland (2019)

References: supplementary slides + paper!
4. Distortion and low-communication voting

Metric setting

- 5 \: \text{Copeland (2015)}
- 4.23 \: \text{variant of Copeland (2019)}
- 3 \: \text{a complex rule (2020)}

References: supplementary slides + paper!
4. Distortion and low-communication voting

Metric setting

- Copeland (2015)
- variant of Copeland (2019)
- a complex rule (2020)
  + a very simple rule: IJCAI-2022, Friday 10am
  needs voters to submit only $2 \log m$ bits each
  low-communication voting rule

References: supplementary slides + paper!
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 to hear about $t_1$ or $t_3$, and about $t_2$ or $t_4$.
- Bob: likes $t_1$ and $t_4$, and in case $t_1$ is not selected then $t_2$.
- Carol: likes $t_3$ and that’s all.

- 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:

<table>
<thead>
<tr>
<th></th>
<th>$t_1$</th>
<th>$t_2$</th>
<th>$t_3$</th>
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</tr>
</thead>
<tbody>
<tr>
<td>8 voters</td>
<td>+</td>
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<td>3 voters</td>
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<td>1 voter</td>
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</table>

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 \(\rightarrow\) Multiwinner elections

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

<table>
<thead>
<tr>
<th></th>
<th>(t_1)</th>
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</table>

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

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</table>
5. Complex alternatives $\rightarrow$ Participatory budgeting

- topics now have durations
- total budget: 30 minutes

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A more common interpretation:

- $t_1, \ldots, t_6$ are projects with costs
- total budget: 30 M€
5. Complex alternatives → Participatory budgeting

The greedy method

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available budget: 30

Good?
## 5. Complex alternatives → Participatory budgeting

<table>
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Available budget: 30

Need to ensure fairness to groups of voters through proportionality
5. Complex alternatives → Judgment aggregation

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

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<td>2 voters</td>
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Admissible committees are those that satisfy the constraint

$$(t_1 \lor t_3) \land (t_2 \lor t_5) \land \neg (t_1 \land t_4 \land t_5) \land \neg (t_2 \land t_4 \land t_5) \land (t_3 \rightarrow t_4)$$

- focus on complex feasibility constraints
5. Complex alternatives

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<th>complex preferences</th>
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<td>judgment aggregation</td>
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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, 75 % senior.

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<tr>
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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, 75% senior. × (50 / 50)

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<td>S</td>
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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.
  - ≥ 25% junior, ≥ 50 % senior.

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<tr>
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</table>

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.
  - ≥ 25% junior, ≥ 50 % senior.

<table>
<thead>
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</table>

Which committee should be elected?
6. Diversity: application to composing citizens’ assemblies

- variant with randomized, fair selection
- variant with online selection
6. Diversity: application to composing citizens’ assemblies

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

- 50% male, 50% female
- 25% area 1, 50% area 2, 25% area 3.
- 25% junior, 75% senior.

<table>
<thead>
<tr>
<th>Gender</th>
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<tbody>
<tr>
<td>M</td>
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6. Diversity: application to composing citizens’ assemblies

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<tr>
<td>F</td>
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6. Diversity: application to composing citizens’ assemblies

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- if the probability distribution on arrivals is known → Markov decision processes
- if not → reinforcement learning
7. Fair Division of Indivisible Items

<table>
<thead>
<tr>
<th></th>
<th>a</th>
<th>b</th>
<th>c</th>
<th>d</th>
<th>e</th>
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<tbody>
<tr>
<td>Ann</td>
<td>15</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>6</td>
</tr>
<tr>
<td>Bob</td>
<td>7</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>7</td>
</tr>
<tr>
<td>Carol</td>
<td>20</td>
<td>3</td>
<td>3</td>
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</tbody>
</table>

- \(v_{Bob}(b) = 5\) = value of item \(b\) for Bob
- Assume agents have *additive* valuations:
  \[v_{Bob}(\{b, e\}) = 5 + 7 = 12\]

- *envy-freeness* (EF): every agent \(i\) weakly prefers her share to the share of any other agent \(j\)
- Ann prefers Bob’s share \(\{b, e\}\) to her own \(\{c, d\}\): the blue allocation is not envy-free
- There is no envy-free allocation!
7. Fair Division of Indivisible Items

\[
\begin{array}{c|cccccc}
 & a & b & c & d & e \\
\hline
Ann & 15 & 3 & 2 & 2 & 6 \\
Bob & 7 & 5 & 5 & 5 & 7 \\
Carol & 20 & 3 & 3 & 3 & 3 \\
\end{array}
\]

- A 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

<table>
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<tr>
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<th>$a$</th>
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</table>

- 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

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</table>

- 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

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- Between EF1 and EF: *envy-freeness up to any good* (EFX)
- the red allocation is EFX
- does an EFX allocation always exist?
7. Fair Division of Indivisible Items

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

EF → EFX → EF1
- not guaranteed for additive valuations
- open problem
- guaranteed for additive valuations
7. Fair Division of Indivisible Items

![Diagram showing relationships between different terms.]

- EEF → PROP → MMS → $\frac{3}{4}$-MMS
- EF → EFX → EFR → EF1
- HEF1 → PROPX → PROPM → PROP1
- GMMS → PMMS → 0.618-EFX
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

Example: two sided matching

- two groups of \( n \) agents each
- each agent ranks the agents of the other group
- can we guarantee stability and fair treatment of both groups?
- no as soon as \( n \geq 3! \)

Stability for \( n = 3 \): conjunction of 419,904 clauses

\[
\bigwedge_{p \in R_3 !^3 \times L_3 !^3} \bigwedge_{i \in 1,2,3} \bigwedge_{j \in 1,2,3} \bigwedge_{i' : l_i \succ_r l_{i'}} \bigwedge_{l_i \in p} \bigwedge_{j' : r_j \succ_l r_{j'}} \bigwedge_{r_j \in p} \neg x_{p \succ_r (i,j')} \lor \neg x_{p \succ_l (i',j)}
\]

Thanks: Ulle Endriss
9. Collective decision making datasets

<table>
<thead>
<tr>
<th>Building &amp; maintaining</th>
<th>Exploiting</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dataset for voting data: PrefLib.Org</td>
<td>Gap between theory and real-world instances?</td>
</tr>
<tr>
<td>Other datasets: matching, participatory budgeting</td>
<td>Assessing the validity of preference models</td>
</tr>
<tr>
<td>all open access</td>
<td>Learning/ discovering structure</td>
</tr>
</tbody>
</table>

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

Thanks: Piotr Faliszewski, Nick Mattei
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

“Map of real-world elections”

Source:
Boehmer, Bredereck, Faliszewski, 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
    ⇒ 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)
Social Choice Engineering

What we know how to do

simple input

output

What is missing

human agents

complex input

user modelling

NLP

output

KR

UAI
Summary: Social Choice and AI

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

- multiagent systems
- planning/MDP
- statistical learning
  - KR&R
  - online learning
  - SAT

- user modelling?
- NLP?

Special thanks: François Durand
References

General


Liquid democracy: ranked delegations

▶ Markus Brill, Théo Delemazure, Anne-Marie George, Martin Lackner, Ulrike Schmidt-Kraepelin, Liquid Democracy with Ranked Delegations, *AAAI-22*


Iterated voting

Introduced in

▶ Reshef Meir, Maria Polukarov, Jeffrey S. Rosenschein, Nicholas R. Jennings: Convergence to Equilibria in Plurality Voting. *AAAI 2010*

Survey:

References

Epistemic voting and crowdsourcing

Survey:

Voting rules as maximum likelihood estimators:

Approval-based crowdsourcing:
- Tahar Allouche, Jérôme Lang, Florian Yger, Truth-tracking via Approval Voting: Size Matters, AAAI-22

Aggregating linguistic annotations:
- Ciyang Qing, Ulle Endriss, Raquel Fernández, Justin Kruger, Empirical Analysis of Aggregation Methods for Collective Annotation, *COLING 2014*
References

Distortion and low-communication voting

Introduced:

- Ariel D. Procaccia, Jeffrey S. Rosenschein: The Distortion of Cardinal Preferences in Voting. *CIA 2006*

Survey:


Rules with distortion 3:

- Vasilis Gkatzelis, Daniel Halpern, Nisarg Shah: Resolving the Optimal Metric Distortion Conjecture. *FOCS 2020*

Distortion 5: Anshelevich, Onkar Bhardwaj, John Postl, AAAI 15.
References

Voting on combinatorial domains, survey:


Multiwinner voting, surveys:


Participatory budgeting

Survey:


Proportionality in participatory budgeting:

- Dominik Peters, Grzegorz Pierczynski, Piotr Skowron: Proportional Participatory Budgeting with Additive Utilities. *NeurIPS 2021*
References

Judgment aggregation

Surveys:


Judgment aggregation & participatory budgeting:


Fair division of indivisible goods

A recent survey on how to relax envy-freeness:


Older surveys:

References

Diversity

Multiwinner elections with diversity:

▷ Robert Bredereck, Piotr Faliszewski, Ayumi Igarashi, Martin Lackner, Piotr Skowron: Multiwinner Elections with Diversity Constraints. *AAAI 18*
▷ L. Elisa Celis, Lingxiao Huang, Nisheeth K. Vishnoi: Multiwinner Voting with Fairness Constraints. *IJCAI 2018*
▷ Xiaohui Bei, Shengxin Liu, Chung K. Poon, Hongao Wang: Candidate selections with proportional fairness constraints. *J. AAMAS*, 2022

Diversity in two-sided matching:


Selecting citizens’ assemblies:

References

Automated theorem proving for social choice

Started:


Survey:


Impossibility of stability and left/right fairness:


Collective decision making datasets

Survey:


Maps of real-world elections:

Thanks to my frequent and/or recent coauthors


Vote on your preferred topics!

Informal paper and other resources coming with this talk:

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