CSC2556

Lecture 2

Voting II

Credit for many visuals: Ariel D. Procaccia

Which rule to use?

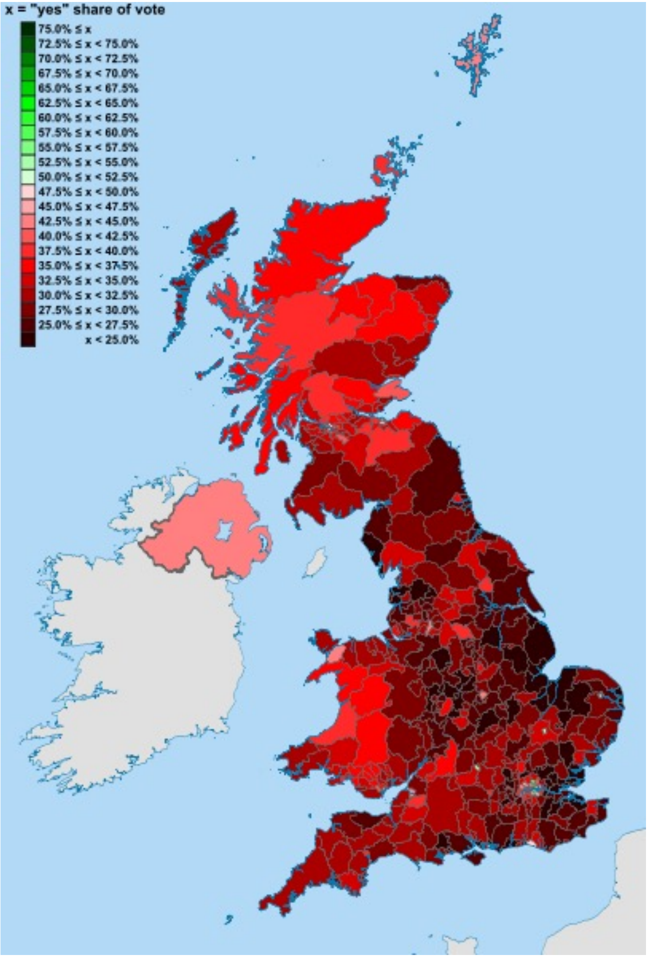
- We just introduced infinitely many rules
  - (Recall positional scoring rules…)

- How do we know which is the "right" rule to use?
  - Various approaches
  - Axiomatic, statistical, utilitarian, …

- How do we ensure good incentives without using money?
  - Bad luck!   [Gibbard-Satterthwaite, next lecture]

Is Social Choice Practical?

- UK referendum: Choose between plurality and STV for electing MPs
- Academics agreed STV is better...
- ...but STV seen as beneficial to the hated Nick Clegg
- Hard to change political elections!



ROBOVOTE

Voting:
For the People,
By the People

- Voting can be useful in day-to-day activities

- On such a platform, easy to deploy the rules that we believe are the best

Incentives

- Can a voting rule incentivize voters to truthfully report their preferences?

- Strategyproofness
  - A voting rule is strategyproof if a voter cannot submit a false preference and get a more preferred alternative (under her true preference) elected, irrespective of the preferences of other voters
  - Formally, a voting rule f is strategyproof if for every preference profile $\overrightarrow{\succ}$, voter i, and preference $\succ_i'$, we have

$$f(\overrightarrow{\succ}) \succcurlyeq_i f(\overrightarrow{\succ}_{-i}, \succ_i')$$

  - Question: What is the relation between $f(\overrightarrow{\succ})$ and $f(\overrightarrow{\succ}_{-i}, \succ_i')$ according to $\succcurlyeq_i'$?

Strategyproofness

- None of the rules we saw are strategyproof!

- Example: Borda Count
  - In the true profile, b wins
  - Voter 3 can make a win by pushing b to the end

1	2	3
b	b	a
a	a	b
c	c	c
d	d	d

Winner
b

1	2	3
b	b	a
a	a	c
c	c	d
d	d	b

Winner
a

Borda's Response to Critics

My scheme is intended only for honest men!

Random 18th century French dude

Strategyproofness

- Are there any strategyproof rules?
  - Sure
- Dictatorial voting rule
  - The winner is always the most preferred alternative of voter i
- Constant voting rule
  - The winner is always the same
- Not satisfactory (for most cases)

Dictatorship


Constant function

Three Properties

- Strategyproof: Already defined. No voter has an incentive to misreport.

- Onto: Every alternative can win under some preference profile.

- Nondictatorial: There is no voter i such that $f(\overrightarrow{\succ})$ is always the alternative most preferred by voter i.

Gibbard-Satterthwaite

- Theorem: For $m \geq 3$, no deterministic social choice function is strategyproof, onto, and nondictatorial simultaneously ☹

- Proof: We will prove this for $n = 2$ voters.
  - Step 1: Show that SP ⇒ "strong monotonicity" [Assignment]
  - Strong Monotonicity (SM): If $f(\overrightarrow{\succ}) = a$, and $\overrightarrow{\succ}'$ is such that $\forall i \in N, x \in A$: $a \succ_i x \Rightarrow a \succ_i' x$, then $f(\overrightarrow{\succ}') = a$.
    - If, for each i, the set of alternatives defeated by a in $\succ_i'$ is a superset of what it defeats in $\succ_i$, then if it was winning under $\overrightarrow{\succ}$, it should also win under $\overrightarrow{\succ}'$

Gibbard-Satterthwaite

- Theorem: For $m \geq 3$, no deterministic social choice function is strategyproof, onto, and nondictatorial simultaneously ☹

- Proof: We will prove this for $n = 2$ voters.
  - Step 2: Show that SP + onto ⇒ "Pareto optimality" [Assignment]
  - Pareto Optimality (PO): If $a \succ_i b$ for all $i \in N$, then $f(\vec{\succ}) \neq b$.
    - If there is a different alternative a that *everyone* prefers to b, then b should not be the winner.

Gibbard-Satterthwaite

- Proof for n=2: Consider problem instance $I(a,b)$

$I(a,b)$

$\succ_1$	$\succ_2$
a	b
b	a

$\succ_1$	$\succ_2'$
a	b
b	
	a

$\succ_1''$	$\succ_2''$
a	A N Y
A N Y	

$f(\succ_1, \succ_2) \in \{a, b\}$

- ➢ PO

Say $f(\succ_1, \succ_2) = a$

$f(\succ_1, \succ_2') = a$

- PO: $f(\succ_1, \succ_2') \in \{\mathrm{a}, \mathrm{b}\}$
- SP: $f(\succ_1, \succ_2') \neq b$

$f(\succ'') = \mathrm{a}$

- ➢ SM

Gibbard-Satterthwaite

- Proof for n=2:
  - If f outputs a on instance $I(a, b)$, voter 1 can get a elected whenever she puts a first.
    - In other words, voter 1 becomes dictatorial for a.
    - Denote this property by the notation $D(1, a)$.
  - If f outputs b on $I(a, b)$
    - Voter 2 becomes dictatorial for b, i.e., we have $D(2, b)$.
- For every (a, b), f either satisfies the property $D(1, a)$ or the property $D(2, b)$.
  - We're not done! (Why?)

Gibbard-Satterthwaite

- Proof for n=2:
  - Fix a^* and b^*. Suppose $D(1, a^*)$ holds.
  - Then, we show that voter 1 is a dictator.
    - That is, $D(1, c)$ also holds for every $c \neq a^*$
  - Take $c \neq a^*$. Because $|A| \geq 3$, there exists $d \in A \backslash \{a^*, c\}$
  - Consider $I(c, d)$; f sastisifies either $D(1, c)$ or $D(2, d)$
  - But $D(2, d)$ is incompatible with $D(1, a^*)$
    - Who would win if voter 1 puts a^* first and voter 2 puts d first?
  - Thus, we have $D(1, c)$, as required ■

Circumventing G-S

- Restricted preferences (later in the course)
  - Not allowing all possible preference profiles
  - Example: single-peaked preferences
    - Alternatives are on a line (say 1D political spectrum)
    - Voters are also on the same line
    - Voters prefer alternatives that are closer to them
- Use of money (later in the course)
  - Require payments from voters that depend on the preferences they submit
  - Prevalent in auctions

Circumventing G-S

- Randomization (later in this lecture)
- Equilibrium analysis
  - How will strategic voters act under a voting rule that is not strategyproof?
  - Will they reach an "equilibrium" where each voter is happy with the (possibly false) preference she is submitting?
- Restricting information required for manipulation
  - Can voters successfully manipulate if they don't know the votes of the other voters?

Circumventing G-S

- Computational complexity
  - We need to use a rule that is the rule is manipulable
  - Can we make it NP-hard for voters to manipulate?
    [Bartholdi et al., SC&W 1989]
  - NP-hardness can be a good thing!
- f-Manipulation problem (for a given voting rule f)
  - Input: Manipulator i, alternative p, votes of other voters (non-manipulators)
  - Output: Can the manipulator cast a vote that makes p uniquely win under f?

Example: Borda

- Can voter 3 make a win?
    - Yes

1	2	3
b	b	
a	a	
c	c	
d	d	

→

1	2	3
b	b	a
a	a	c
c	c	d
d	d	b

A Greedy Algorithm

- Goal:
  - The manipulator wants to make alternative p win uniquely

- Algorithm:
  - Rank p in the first place
  - While there are unranked alternatives:
    - If there is an alternative that can be placed in the next spot without preventing p from winning, place this alternative.
    - Otherwise, return false.

Example: Borda

1	2	3
b	b	a
a	a	
c	c	
d	d	

1	2	3
b	b	a
a	a	b
c	c	
d	d	

1	2	3
b	b	a
a	a	c
c	c	
d	d	

1	2	3
b	b	a
a	a	c
c	c	b
d	d	

1	2	3
b	b	a
a	a	c
c	c	d
d	d	

1	2	3
b	b	a
a	a	c
c	c	d
d	d	b

Example: Copeland

1	2	3	4	5
a	b	e	e	a
b	a	c	c	
c	d	b	b	
d	e	a	a	
e	c	d	d	

Preference profile

	a	b	c	d	e
a	-	2	3	5	3
b	3	-	2	4	2
c	2	2	-	3	1
d	0	0	1	-	2
e	2	2	3	2	-

Pairwise elections

Example: Copeland

1	2	3	4	5
a	b	e	e	a
b	a	c	c	c
c	d	b	b	
d	e	a	a	
e	c	d	d	

Preference profile

	a	b	c	d	e
a	-	2	3	5	3
b	3	-	2	4	2
c	2	3	-	4	2
d	0	0	1	-	2
e	2	2	3	2	-

Pairwise elections

Example: Copeland

1	2	3	4	5
a	b	e	e	a
b	a	c	c	c
c	d	b	b	d
d	e	a	a	
e	c	d	d	

Preference profile

	a	b	c	d	e
a	-	2	3	5	3
b	3	-	2	4	2
c	2	3	-	4	2
d	0	1	1	-	3
e	2	2	3	2	-

Pairwise elections

Example: Copeland

1	2	3	4	5
a	b	e	e	a
b	a	c	c	c
c	d	b	b	d
d	e	a	a	e
e	c	d	d	

Preference profile

	a	b	c	d	e
a	-	2	3	5	3
b	3	-	2	4	2
c	2	3	-	4	2
d	0	1	1	-	3
e	2	3	3	2	-

Pairwise elections

Example: Copeland

1	2	3	4	5
a	b	e	e	a
b	a	c	c	c
c	d	b	b	d
d	e	a	a	e
e	c	d	d	b

Preference profile

	a	b	c	d	e
a	-	2	3	5	3
b	3	-	2	4	2
c	2	3	-	4	2
d	0	1	1	-	3
e	2	3	3	2	-

Pairwise elections

When does this work?

- Theorem [Bartholdi et al., SCW 89]:

  Fix voter i and votes of other voters. Let f be a rule for which $\exists$ function $s(\succ_i, x)$ such that:

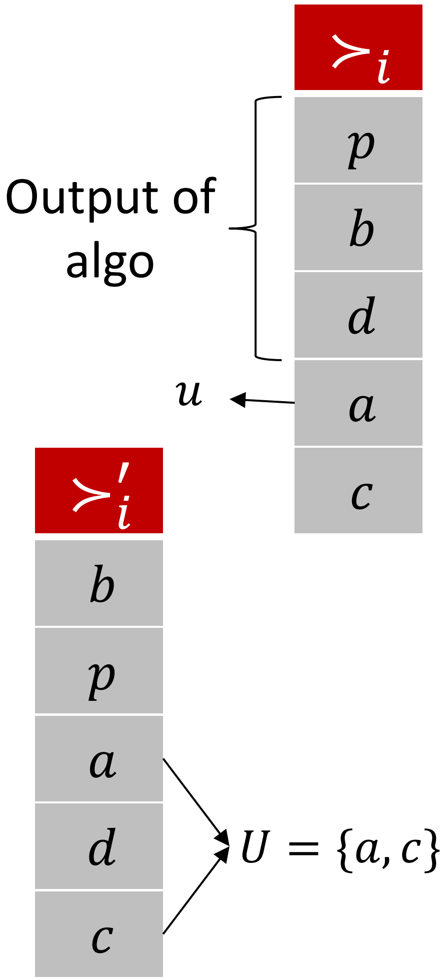
  1. For every $\succ_i$, f chooses candidates maximizing $s(\succ_i\,,\ \cdot)$
  2. $\{y : x \succ_i y\} \subseteq \{y : x \succ_i' y\} \Rightarrow s(\succ_i, x) \leq s(\succ_i', x)$

  Then the greedy algorithm solves f-MANIPULATION correctly.

- Question: What is the function s for the plurality rule?

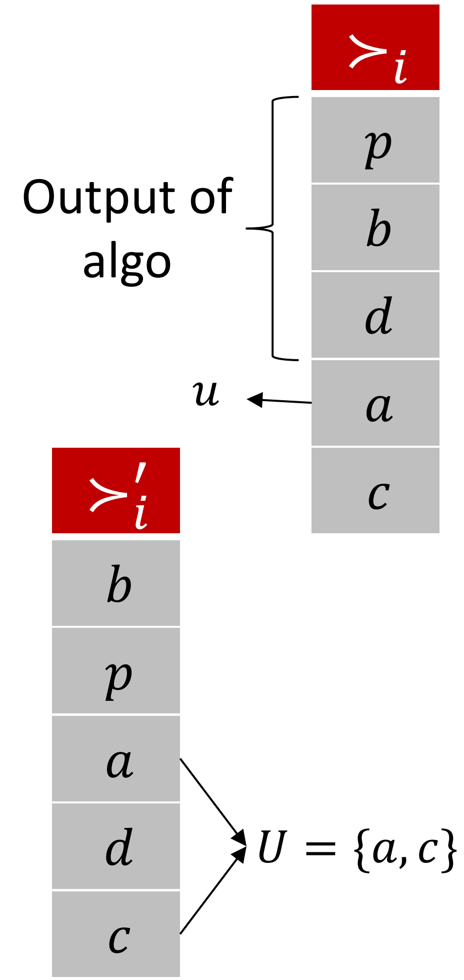
Proof of the Theorem

- Suppose for contradiction:
  - Algo creates a partial ranking $\succ_i$ and then fails, i.e., every next choice prevents p from winning
  - But $\succ_i'$ could have made p uniquely win
- $U \leftarrow$ alternatives not ranked in $\succ_i$
- $u \leftarrow$ highest ranked alternative in U according to $\succ_i'$
- Complete $\succ_i$ by adding u next, and then other alternatives arbitrarily



Proof of the Theorem

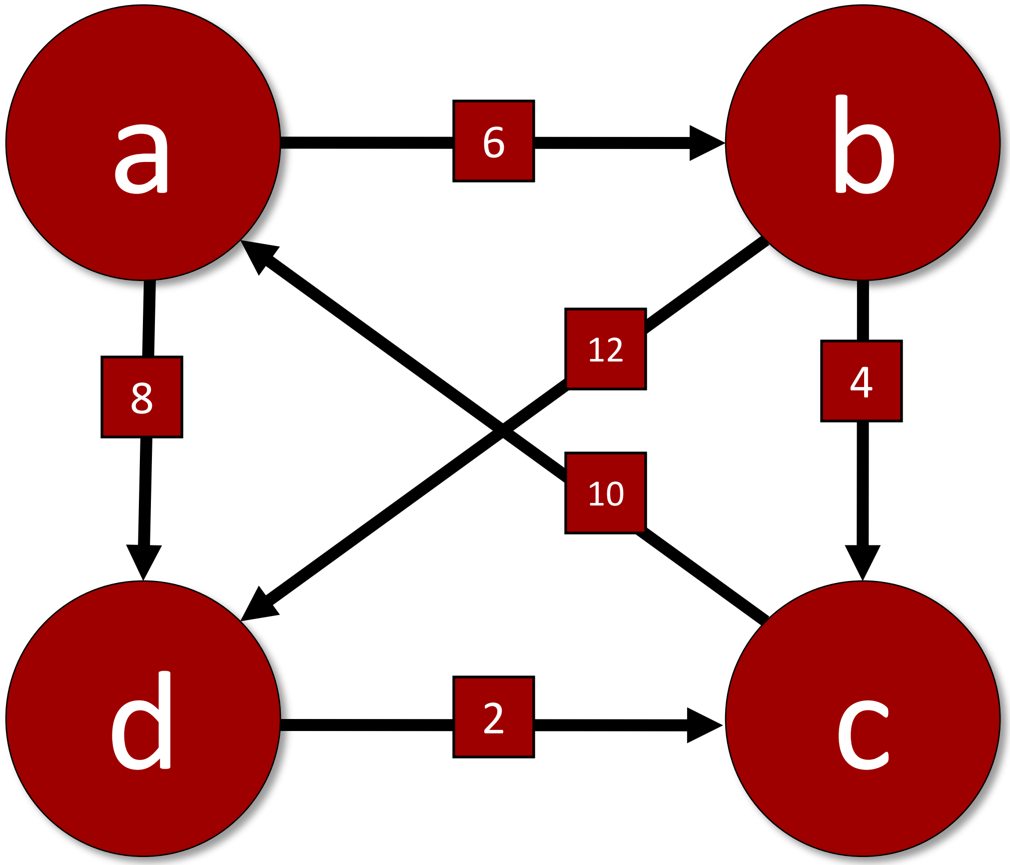
- $s(\succ_i, p) \geq s(\succ_i', p)$
  - Property 2
- $s(\succ_i', p) > s(\succ_i', u)$
  - Property 1 & p uniquely wins under $\succ_i'$
- $s(\succ_i', u) \geq s(\succ_i, u)$
  - Property 2
- Conclusion
  - Putting u in the next position wouldn't have prevented p from winning
  - So the algorithm should have continued



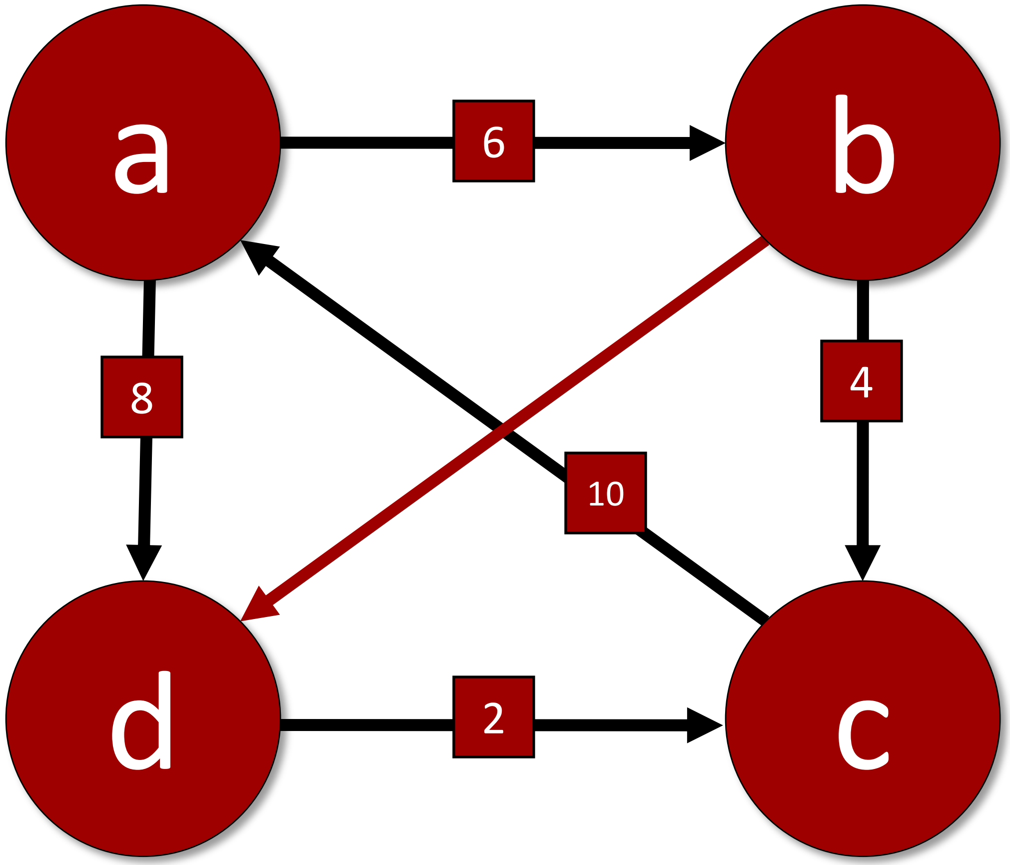
Hard-to-Manipulate Rules

- Natural rules
  - Copeland with second-order tie breaking [Bartholdi et al. SCW 89]
    - In case of a tie, choose the alternative for which the sum of Copeland scores of defeated alternatives is *the largest*
  - STV [Bartholdi & Orlin, SCW 91]
  - Ranked Pairs [Xia et al., IJCAI 09]
    - Iteratively lock in pairwise comparisons by their margin of victory (largest first), ignoring any comparison that would form cycles.
    - Winner is the top ranked candidate in the final order.
  - Can also “tweak” easy to manipulate voting rules [Conitzer & Sandholm, IJCAI 03]

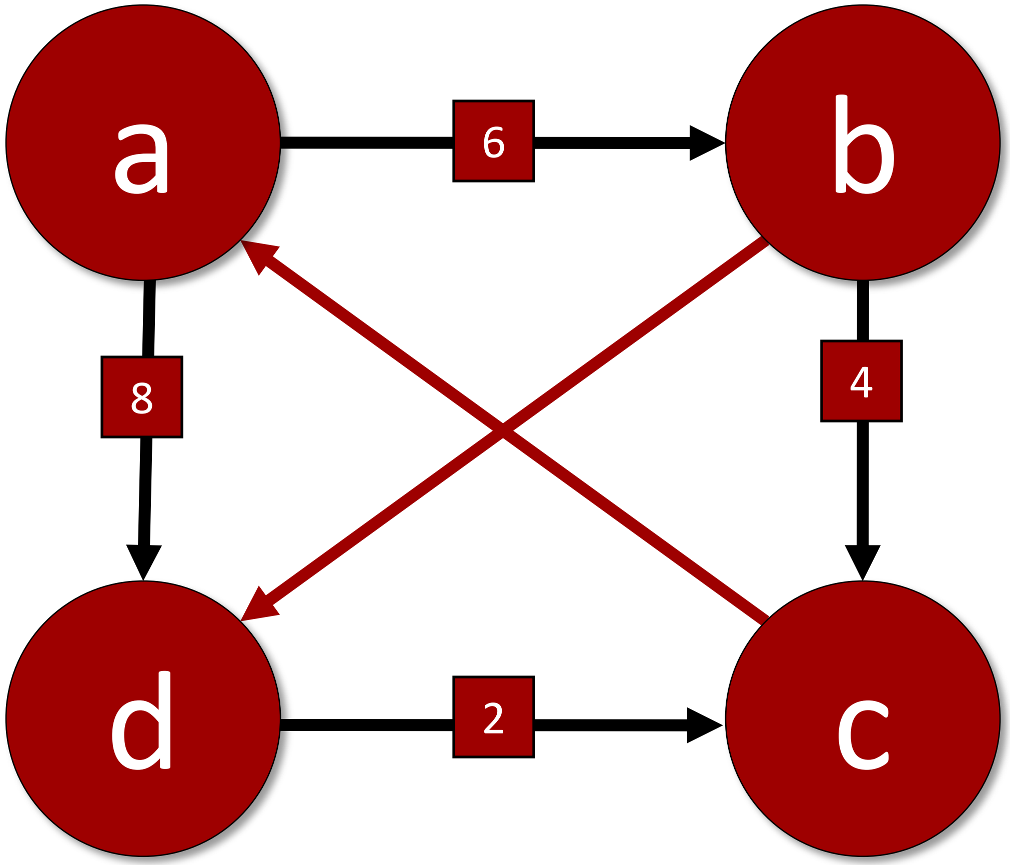
Example: Ranked Pairs



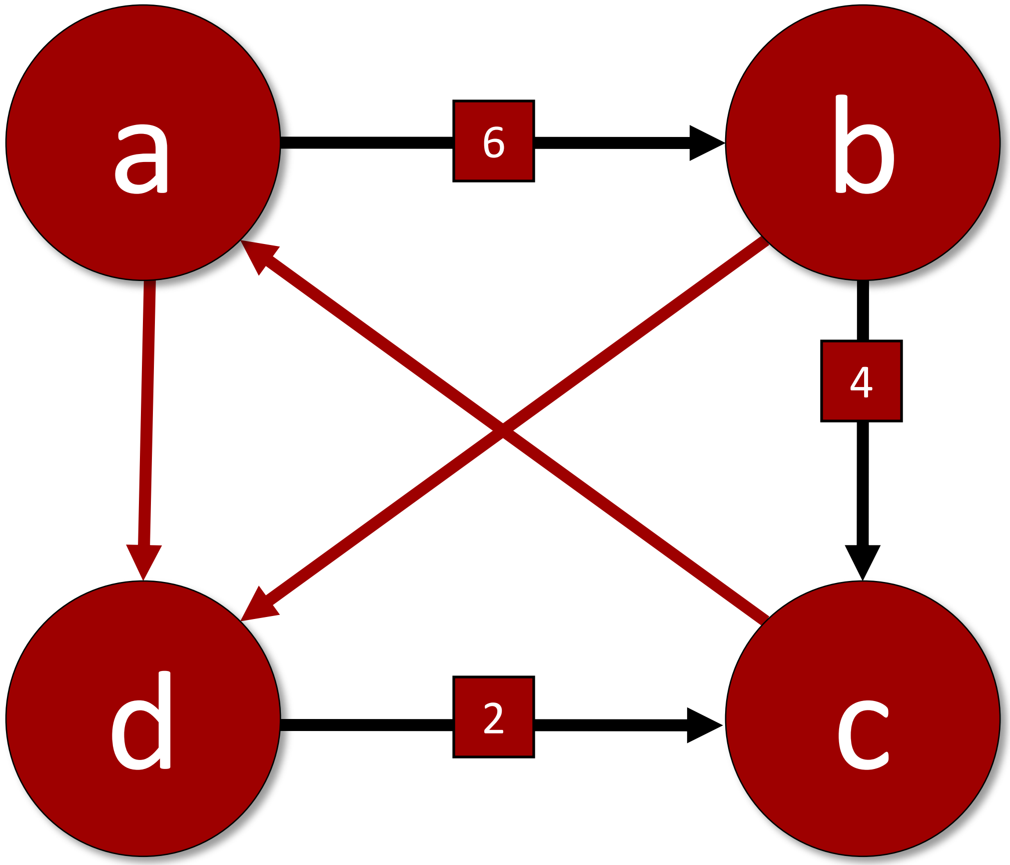
Example: Ranked Pairs



Example: Ranked Pairs



Example: Ranked Pairs



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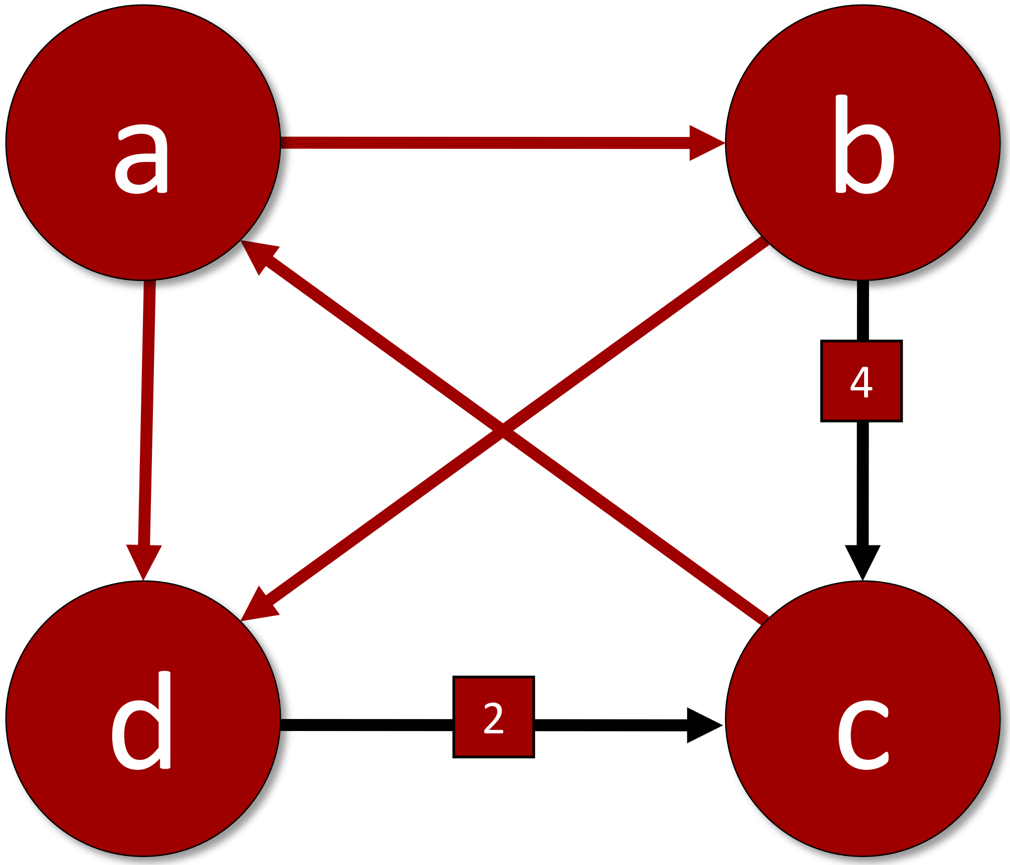
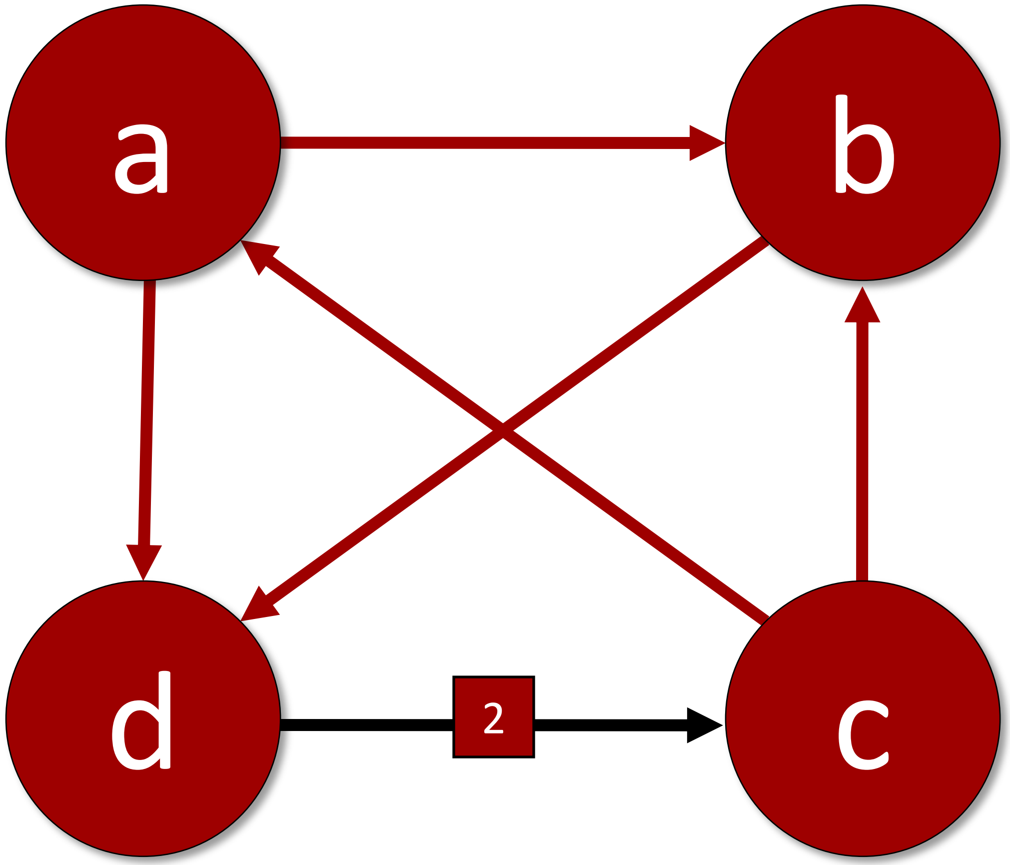
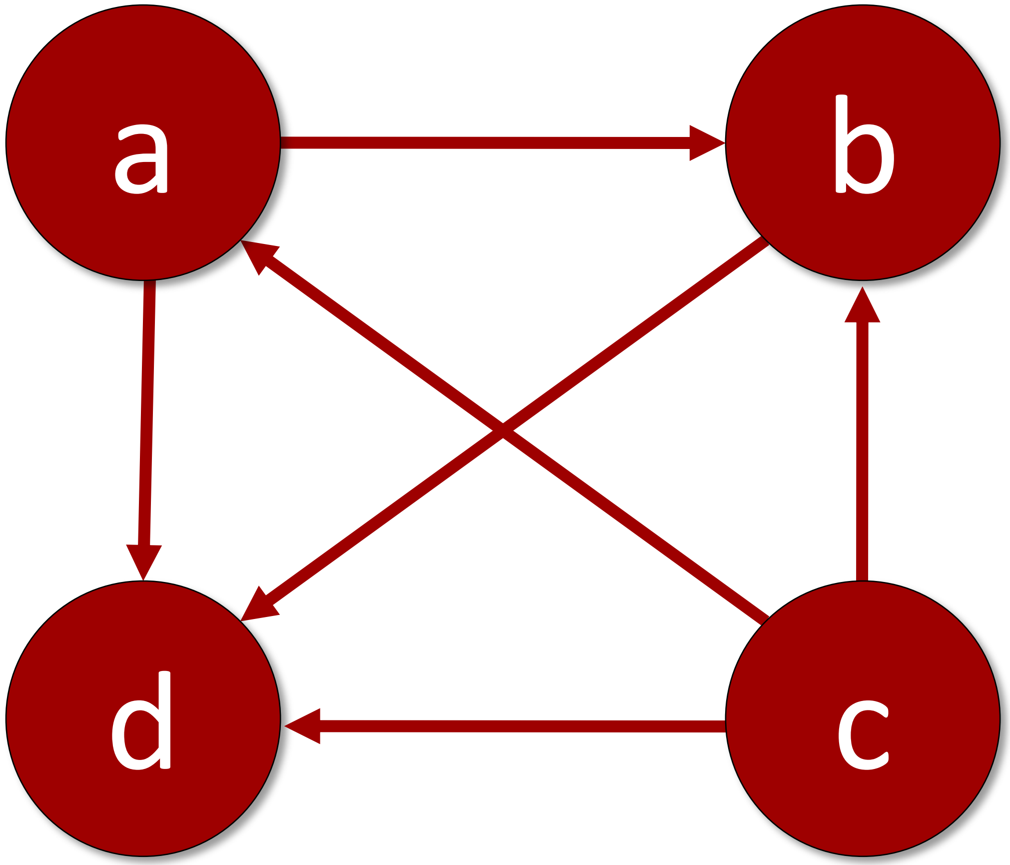


Example: Ranked Pairs



Example: Ranked Pairs



Randomized Voting Rules

- Input: preference profile
- Output: *distribution* over alternatives
  - To think about successful manipulations, we need numerical utilities
- u_i is consistent with $\succ_i$ if

$$a \succ_i b \Rightarrow u_i(a) \geq u_i(b)$$

- Strategyproofness:
  - For all i, $\vec{\succ}_{-i}$, $\succ_i$, $\succ_i'$, and u_i consistent with $\succ_i$

$$\mathbb{E}\left[u_i\left(f(\vec{\succ})\right)\right] \geq \mathbb{E}\left[u_i\left(f(\vec{\succ}_{-i}, \succ_i')\right)\right]$$

where $\succ_i$ is consistent with u_i.

Randomized Voting Rules

- A (deterministic) voting rule is
  - unilateral if it only depends on one voter
  - duple if its range contains at most two alternatives

- Question:
  - What is a unilateral rule that is not strategyproof?
  - What is a duple rule that is not strategyproof?

Randomized Voting Rules

- A probability mixture f over rules $f_1, \dots, f_k$ is a rule given by some probability distribution $(\alpha_1, \dots, \alpha_k)$ s.t. on every profile $\overrightarrow{\succ}$, f returns $f_j(\overrightarrow{\succ})$ w.p. α_j.

- Example:
  - With probability 0.5, output the top alternative of a randomly chosen voter
  - With the remaining probability 0.5, output the winner of the pairwise election between a^* and b^*

- Theorem [Gibbard 77]
  - A randomized voting rule is strategyproof only if it is a probability mixture over unilaterals and duples.

Approximating Voting Rules

- Idea: Can we use strategyproof voting rules to approximate popular voting rules?
- Fix a rule (e.g., Borda) with a clear notion of score denoted $\mathrm{sc}(\vec{\succ}, a)$
- A randomized voting rule f is a c-approximation to sc if for every profile $\vec{\succ}$

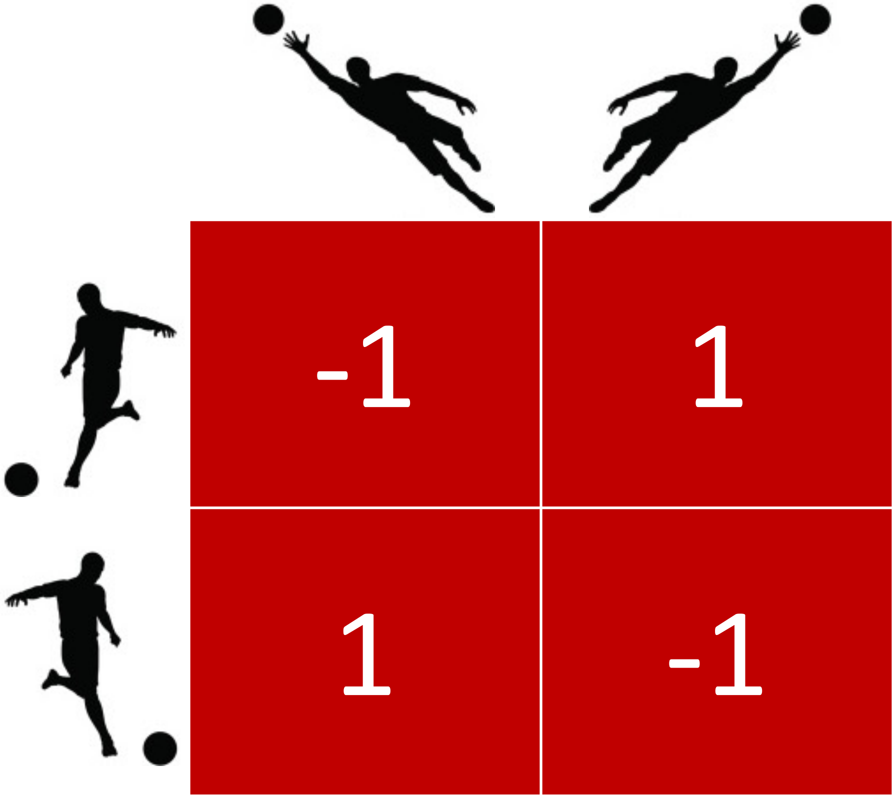
$$\frac{\mathbb{E}[\mathrm{sc}\left(\vec{\succ}, f\left(\vec{\succ}\right)\right)}{\max_a \mathrm{sc}(\vec{\succ}, a)} \geq c$$

Approximating Borda

- Question: How well does choosing a random alternative approximate Borda?
  1. $\Theta(1/n)$
  2. $\Theta(1/m)$
  3. $\Theta(1/\sqrt{m})$
  4. $\Theta(1)$

- Theorem [Procaccia 10]:
  No strategyproof voting rule gives $1/2 + \omega\left(1/\sqrt{m}\right)$ approximation to Borda.

Interlude: Zero-Sum Games



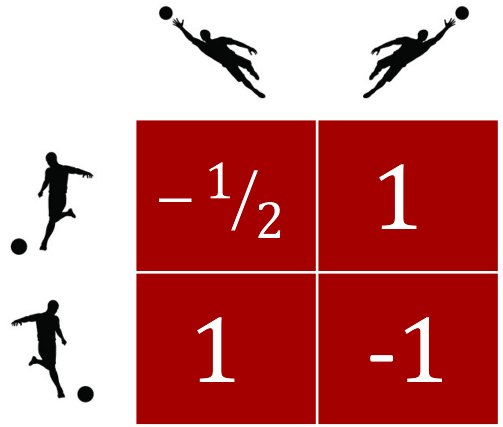
Interlude: Minimiax Strategies

- A minimax strategy for a player is
  - a (possibly) randomized choice of action by the player
  - that minimizes the expected loss (or maximizes the expected gain)
  - in the *worst case* over the choice of action of the other player

- Intuition
  - Suppose I were to act first
  - And the other player could observe my strategy and respond to it (thus picking a response that is the worst case for me)
  - Then, which randomized choice would I make?

- In the previous game, the minimax strategy for each player is $(1/2, 1/2)$. Why?

Interlude: Minimiax Strategies



- In the game above, if the shooter uses $(p, 1-p)$:
  - If goalie jumps left: $p \cdot \left(-\frac{1}{2}\right) + (1-p) \cdot 1 = 1 - \frac{3}{2}p$
  - If goalie jumps right: $p \cdot 1 + (1-p) \cdot (-1) = 2p - 1$
  - Shooter chooses p to maximize $\min\left\{1 - \frac{3p}{2}, 2p - 1\right\}$
    - $p^* = {}^{4}/_{7}$, reward of shooter = $+\,{}^{1}/_{7}$

Interlude: Minimax Theorem

- Theorem
  [von Neumann, 1928]:

  Every 2-player zero-sum game has a unique value v such that
  - Player 1 can guarantee value at least v
  - Player 2 can guarantee loss at most v

  - This value is achieved when each player plays their own minimax strategy.

Yao's Minimax Principle

- Rows as inputs
- Columns as deterministic algorithms
- Cell numbers = running times
- Best randomized algorithm
  - Minimax strategy for the column player

$$\min_{rand\ algo} \max_{input} E[time] =$$

$$\max_{dist\ over\ inputs} \min_{det\ algo} E[time]$$

Yao's Minimax Principle

- To show a lower bound T on the best worst-case running time achievable through randomized algorithms:
  - Show a "bad" distribution over inputs D such that every deterministic algorithm takes time at least T on average, when inputs are drawn according to D

$$\min_{rand\ algo} \max_{input} E[time] \geq \min_{det\ algo} E[time]$$

For any distribution over inputs

Randomized Voting Rules

	$\overrightarrow{\succsim}^1$	…	…	…	…	$\overrightarrow{\succsim}^t$
U_1	$\frac{1}{15}$	…	…	…	…	$\frac{2}{21}$
…	…	…	…	…	…	…
U_k	$\frac{7}{15}$	Approximation ratio				$\frac{5}{21}$
D_1	$\frac{4}{15}$	…	…	…	…	$\frac{8}{21}$
…	…	…	…	…	…	…
D_s	$\frac{13}{15}$	…	…	…	…	$\frac{17}{21}$

Randomized Voting Rules

- Rows = unilaterals and duples
- Columns = preference profiles
- Cell numbers = approximation ratios

- Quantity of interest
  - Expected ratio of the best *distribution* over unilaterals and duples on the worst-case profile
- Equivalent quantity
  - Expected ratio of the best unilateral or duple rule when the profiles are drawn from the worst distribution D
  - Any distribution D gives a lower bound on the quantity of interest

Back to Borda

- Assume $m = n + 1$
- A bad distribution:
  - Choose a random alternative x^*
  - Each voter i chooses a random number $k_i \in \{1, \ldots, \sqrt{m}\}$ and places x^* in position k_i
  - The other alternatives are ranked cyclically

1	2	3
c	b	d
b	a	b
a	d	c
d	c	a

$x^* = b$
$k_1 = 2$
$k_2 = 1$
$k_3 = 2$

Back to Borda

- Question: What is the best lower bound on $\mathrm{sc}(\overrightarrow{\succ}, x^*)$ that holds for every profile $\overrightarrow{\succ}$ generated under this distribution?

1. $\sqrt{n}$
2. $\sqrt{m}$
3. $n \cdot (m - \sqrt{m})$
4. $n \cdot m$

Back to Borda

- How bad are other alternatives?
  - For every other alternative x, $\text{sc}(\vec{\succ}, x) \sim \frac{n(m-1)}{2}$
- How surely can a unilateral/duple rule return x^*?
  - Unilateral: By only looking at a single vote, the rule is essentially guessing x^* among the first $\sqrt{m}$ positions and captures it with probability at most $1/\sqrt{m}$.
  - Duple: By fixing two alternatives, the rule captures x^* with probability at most $2/m$.
- Putting everything together…

Quantitative GS Theorem

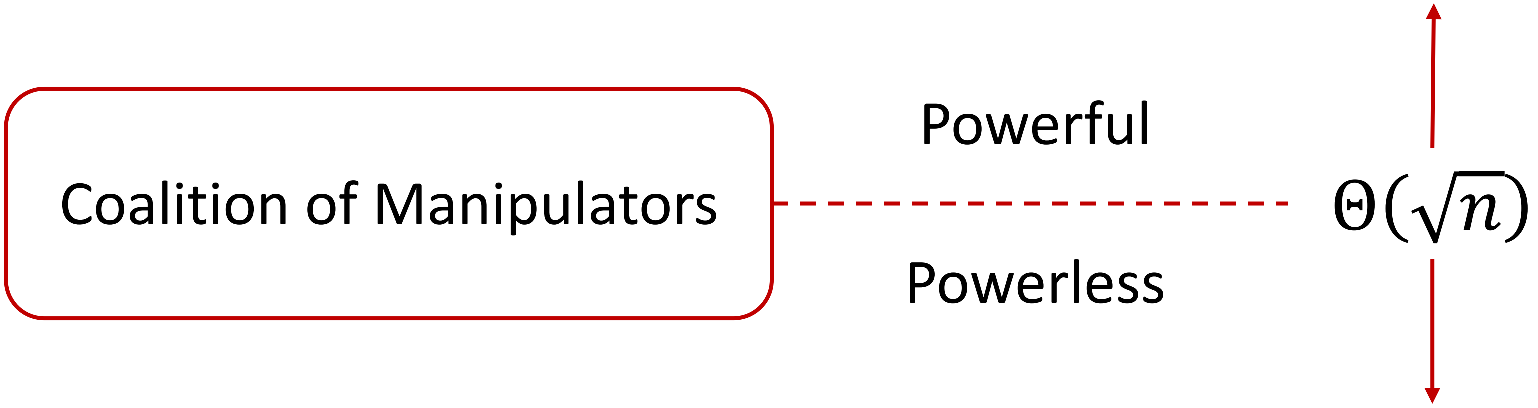
- Regarding the use of NP-hardness to circumvent GS
  - NP-hardness is hardness in the worst case
  - What happens in the average case?

- Theorem [Mossel-Racz '12]:
  - For every voting rule that is at least ϵ-far from being a dictatorship or having range of size 2…
  - …the probability that a uniformly random profile admits a manipulation is at least $p(n, m, {}^{1}/_{\epsilon})$ for some polynomial p

Coalitional Manipulations

- What if multiple voters collude to manipulate?
  - The following result applies to a wide family of voting rules called "generalized scoring rules".

- Theorem [Conitzer-Xia '08]:



Powerful = can manipulate with high probability

Interesting Tidbit

- Detecting a manipulable profile versus finding a beneficial manipulation

- Theorem [Hemaspaandra, Hemaspaandra, Menton '12]
  If integer factoring is NP-hard, then there exists a generalized scoring rule for which:
  - We can efficiently check if there exists a beneficial manipulation.
  - But finding such a manipulation is NP-hard.

Axiomatic Approach

Axiomatic Approach

- Axiom:
  - A requirement that the voting rule must behave in a certain way
- Goal:
  - Define a set of reasonable axioms, and search for voting rules that satisfy them together
  - Ultimate hope: a unique voting rule satisfies the set of axioms simultaneously!
  - What often happens: no voting rule satisfies the axioms together ☹

We have already seen axioms!

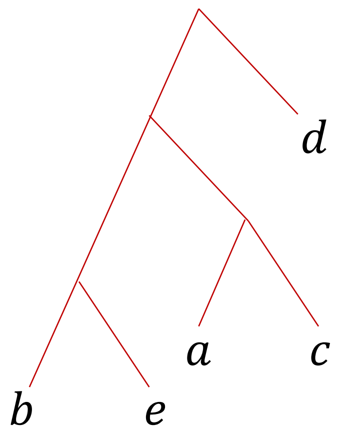
- Condorcet consistency
- Majority consistency
- Strategyproofness
- Ontoness
- Non-dictatorship
- Strong monotonicity
- Pareto optimality

Axiomatic Approach

- Some axioms are weak and satisfied by all natural rules
  - Unanimity:
    - If all voters have the same top choice, that alternative is the winner.

$$(top(\succ_i) = a \ \forall i \in N) \Rightarrow f(\vec{\succ}) = a$$

  - Q: How does this compare to Pareto optimality?
  - Pareto optimality is weak but still violated by natural voting methods like voting trees



Axiomatic Approach

- Anonymity:
  - Permuting the votes does not change the winner
  - In other words, voter identities don't matter
  - Example: these two profiles must have the same winner:
    {voter 1: $a \succ b \succ c$, voter 2: $b \succ c \succ a$}
    {voter 1: $b \succ c \succ a$, voter 2: $a \succ b \succ c$}

- Neutrality:
  - Permuting alternative names just permutes the winner accordingly
  - Example:
    - Say a wins on {voter 1: $a \succ b \succ c$, voter 2: $b \succ c \succ a$}
    - We permute all names: $a \rightarrow b$, $b \rightarrow c$, and $c \rightarrow a$
    - New profile: {voter 1: $b \succ c \succ a$, voter 2: $c \succ a \succ b$}
    - Then, the new winner must be b

Axiomatic Approach

- Neutrality is tricky for deterministic rules
  - Incompatible with anonymity
    - Consider the profile {voter 1: $a \succ b$, voter 2: $b \succ a$}
    - Without loss of generality, say a wins
    - Imagine a different profile: {voter 1: $b \succ a$, voter 2: $a \succ b$}
      - Neutrality ⇒ we exchanged $a \leftrightarrow b$, so winner must be b
      - Anonymity ⇒ we exchanged the votes, so winner must be a

- We usually only require neutrality for…
  - Randomized rules: E.g., a rule could satisfy both by choosing a and b as the winner with probability ½ each, on both profiles
  - Deterministic rules that return a set of tied winners: E.g., a rule could return $\{a, b\}$ as tied winners on both profiles.

Axiomatic Approach

- Consistency: If a is the winner on two profiles, it must be the winner on their union.

$$f(\overrightarrow{\succ}_1) = a \wedge f(\overrightarrow{\succ}_2) = a \Rightarrow f(\overrightarrow{\succ}_1 + \overrightarrow{\succ}_2) = a$$

  - Example: $\overrightarrow{\succ}_1 = \{a \succ b \succ c\}$, $\overrightarrow{\succ}_2 = \{a \succ c \succ b, b \succ c \succ a\}$
  - Then, $\overrightarrow{\succ}_1 + \overrightarrow{\succ}_2 = \{a \succ b \succ c, a \succ c \succ b, b \succ c \succ a\}$

- Theorem [Young '75]:
  - Subject to mild requirements, a voting rule is consistent if and only if it is a positional scoring rule!

Axiomatic Approach

- Weak monotonicity: If a is the winner, and a is "pushed up" in some votes, a remains the winner.
  - $f(\overrightarrow{\succ}) = a \Rightarrow f(\overrightarrow{\succ}') = a$, where
    - $b \succ_i c \Leftrightarrow b \succ_i' c, \forall i \in N,\ b, c \in A \backslash \{a\}$ (Order of others preserved)
    - $a \succ_i b \Rightarrow a \succ_i' b, \forall i \in N,\ b \in A \backslash \{a\}$ (a only improves)
- Contrast with strong monotonicity
  - SM requires $f(\overrightarrow{\succ}') = a$ even if $\overrightarrow{\succ}'$ only satisfies the 2^{nd} condition
  - Too strong; only satisfied by dictatorial or non-onto rules [GS Theorem]

Axiomatic Approach

- Weak monotonicity is satisfied by most voting rules
  - Popular exceptions: STV, plurality with runoff

- But violation of weak monotonicity helps STV be hard to manipulate
  - Theorem [Conitzer-Sandholm '06]:
    "Every weakly monotonic voting rule is easy to manipulate on average."

Axiomatic Approach

- STV violates weak monotonicity

7 voters	5 voters	2 voters	6 voters
a	b	b	c
b	c	c	a
c	a	a	b

7 voters	5 voters	2 voters	6 voters
a	b	a	c
b	c	b	a
c	a	c	b

- First c, then b eliminated
- Winner: a

- First b, then a eliminated
- Winner: c

Axiomatic Approach

- Arrow's Impossibility Theorem
  - Applies to social welfare functions (profile → ranking)
  - Independence of Irrelevant Alternatives (IIA): If the preferences of all voters between a and b are unchanged, the social preference between a and b should not change
  - Pareto optimality: If all prefer a to b, then the social preference should be $a \succ b$
  - Theorem: IIA + Pareto optimality ⇒ dictatorship
- Interestingly, automated theorem provers can also prove Arrow's and GS impossibilities!

Axiomatic Approach

- Polynomial-time computability
  - Can be thought of as a desirable axiom
  - Two popular rules which attempt to make the pairwise comparison graph acyclic by inverting edges are NP-hard to compute:
    - Kemeny's rule: invert edges with minimum total weight
    - Slater's rule: invert minimum number of edges
  - Both rules can be implemented by straightforward integer linear programs
    - For small instances (say, up to 20 alternatives), NP-hardness isn't a practical concern.