

Game Theory

8. Social Choice Theory

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Motivation: Aggregation of individual preferences

Examples:

- political elections
- council decisions
- Eurovision Song Contest

Question: If voters' preferences are private, then how to implement aggregation rules such that voters vote truthfully (no “strategic voting”)?

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Definition (Social Welfare and Social Choice Function)

Let A be a set of alternatives (candidates) and L be the set of all linear orders on A . For n voters, a function

$$F: L^n \rightarrow L$$

is called a **social welfare function**. A function

$$f: L^n \rightarrow A$$

is called a **social choice function**.

Notation: Linear orders $\prec \in L$ express preference relations.

$a \prec_i b$: voter i prefers candidate b over candidate a .

$a \prec b$: candidate b socially preferred over candidate a .

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- **Plurality voting** (aka **first-past-the-post** or **winner-takes-all**):
 - only top preferences taken into account
 - candidate with most top preferences wins

Drawback: Wasted votes, compromising, winner only preferred by minority

- **Plurality voting with runoff**:
 - First round: two candidates with most top votes proceed to second round (unless absolute majority)
 - Second round: runoff

Drawback: still, tactical voting and strategic nomination possible.



■ Instant runoff voting:

- each voter submits his preference order
- iteratively candidates with fewest top preferences are eliminated until one candidate has absolute majority

Drawback: Tactical voting still possible.

■ Borda count:

- each voter submits his preference order over the m candidates
- if a candidate is in position j of a voter's list, he gets $m - j$ points from that voter
- points from all voters are added
- candidate with most points wins

Drawback: Tactical voting still possible (“Voting opponent down”).



- **Condorcet winner:**
 - each voter submits his preference order
 - perform pairwise comparisons between candidates
 - if one candidate wins all his pairwise comparisons, he is the Condorcet winner

Drawback: Condorcet winner does not always exist.

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# voters	8	6	4	3	1	1
1st	e	a	b	c	d	d
2nd	d	b	c	b	c	c
3rd	b	c	d	d	a	b
4th	c	e	a	a	b	e
5th	a	d	e	e	e	a

- Plurality voting:
- Plurality voting with runoff:
 - first round:
 - second round:

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2nd	d	b	c	b	c	c
3rd	b	c	d	d	a	b
4th	c	e	a	a	b	e
5th	a	d	e	e	e	a

- Plurality voting:
- Plurality voting with runoff:
 - first round:
 - second round:

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3rd	b	c	d	d	a	b
4th	c	e	a	a	b	e
5th	a	d	e	e	e	a

- **Plurality voting:** candidate **e** wins (8 votes)
- **Plurality voting with runoff:**
 - first round:
 - second round:

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2nd	d	b	c	b	c	c
3rd	b	c	d	d	a	b
4th	c	e	a	a	b	e
5th	a	d	e	e	e	a

- **Plurality voting:** candidate **e** wins (8 votes)
- **Plurality voting with runoff:**
 - first round:
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2nd	d	b	c	b	c	c
3rd	b	c	d	d	a	b
4th	c	e	a	a	b	e
5th	a	d	e	e	e	a

- **Plurality voting:** candidate **e** wins (8 votes)
- **Plurality voting with runoff:**
 - first round: candidates e (8 votes) and a (6 votes) proceed
 - second round:

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2nd	d	b	c	b	c	c
3rd	b	c	d	d	a	b
4th	c	e	a	a	b	e
5th	a	d	e	e	e	a

- **Plurality voting:** candidate **e** wins (8 votes)
- **Plurality voting with runoff:**
 - first round: candidates **e** (8 votes) and **a** (6 votes) proceed
 - second round: candidate **a** ($6 + 4 + 3 + 1 = 14$ votes) beats candidate **e** ($8 + 1 = 9$ votes)

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- Instant runoff voting:

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4th	c	e	a	a	b	e
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- Instant runoff voting:
First elimination: d

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4th	c	e	a	a	b	e
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- **Instant runoff voting:**
First elimination: d
Second elimination: b

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3rd	b	c	d	d	a	b
4th	c	e	a	a	b	e
5th	a	d	e	e	e	a

- **Instant runoff voting:**
First elimination: d
Second elimination: b
Third elimination: a

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3rd	b	c	d	d	a	b
4th	c	e	a	a	b	e
5th	a	d	e	e	e	a

■ **Instant runoff voting:**

First elimination: d

Second elimination: b

Third elimination: a

Now **c** has absolute majority and wins.

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# voters	8	6	4	3	1	1	
1st	e	a	b	c	d	d	4 points
2nd	d	b	c	b	c	c	3 points
3rd	b	c	d	d	a	b	2 points
4th	c	e	a	a	b	e	1 point
5th	a	d	e	e	e	a	0 points

■ Borda count:

- Cand. a: $8 \cdot 0 + 6 \cdot 4 + 4 \cdot 1 + 3 \cdot 1 + 1 \cdot 2 + 1 \cdot 0 = 33$ pts
- Cand. b: $8 \cdot 2 + 6 \cdot 3 + 4 \cdot 4 + 3 \cdot 3 + 1 \cdot 1 + 1 \cdot 2 = 62$ pts
- Cand. c: $8 \cdot 1 + 6 \cdot 2 + 4 \cdot 3 + 3 \cdot 4 + 1 \cdot 3 + 1 \cdot 3 = 50$ pts
- Cand. d: $8 \cdot 3 + 6 \cdot 0 + 4 \cdot 2 + 3 \cdot 2 + 1 \cdot 4 + 1 \cdot 4 = 46$ pts
- Cand. e: $8 \cdot 4 + 6 \cdot 1 + 4 \cdot 0 + 3 \cdot 0 + 1 \cdot 0 + 1 \cdot 1 = 39$ pts

↪ Candidate **b** wins.

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2nd	d	b	c	b	c	c
3rd	b	c	d	d	a	b
4th	c	e	a	a	b	e
5th	a	d	e	e	e	a

- **Condorcet winner:** Ex.: $a \succ_j b$ 16 times, $b \succ_j a$ 7 times

	a	b	c	d	e
a	–	0	0	0	1
b	1	–	1	1	1
c	1	0	–	1	1
d	1	0	0	–	0
e	0	0	0	1	–

← candidate **b** wins.



23 voters, candidates a, b, c, d, e.

# voters	8	6	4	3	1	1
1st	e	a	b	c	d	d
2nd	d	b	c	b	c	c
3rd	b	c	d	d	a	b
4th	c	e	a	a	b	e
5th	a	d	e	e	e	a

- **Plurality voting:** candidate **e** wins.
- **Plurality voting with runoff:** candidate **a** wins.
- **Instant runoff voting:** candidate **c** wins.
- **Borda count / Condorcet winner:** candidate **b** wins.
- Different winners for different voting systems.
- Which voting system to prefer? Can even strategically choose voting system!

Condorcet Paradox

Why Condorcet Winner not Always Exists



Example: Preferences of voters 1, 2 and 3 on candidates a , b and c .

$$a \succ_1 b \succ_1 c$$

$$b \succ_2 c \succ_2 a$$

$$c \succ_3 a \succ_3 b$$

Then we have cyclical preferences.

	a	b	c
a	-	0	1
b	1	-	0
c	0	1	-

$a \succ b$, $b \succ c$, $c \succ a$: violates transitivity of linear order consistent with these preferences.



Definition

A **Condorcet method** return a Condorcet winner, if one exists.

One particular Condorcet method: the **Schulze method**.

Relatively new: Proposed in 1997

Already many users: Debian, Ubuntu, Pirate Party, ...

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Notation: $d(X, Y)$ = number of pairwise comparisons won by X against Y

Definition

For candidates X and Y , there exists a **path** C_1, \dots, C_n **between X and Y of strength z** if

- $C_1 = X$,
- $C_n = Y$,
- $d(C_i, C_{i+1}) > d(C_{i+1}, C_i)$ for all $i = 1, \dots, n - 1$, and
- $d(C_i, C_{i+1}) \geq z$ for all $i = 1, \dots, n - 1$ and there exists $j = 1, \dots, n - 1$ s.t. $d(C_j, C_{j+1}) = z$

Example: path of strength 3.

$$a \xrightarrow{8} b \xrightarrow{5} c \xrightarrow{3} d$$

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Definition

Let $p(X, Y)$ be the maximal value z such that there exists a path of strength z from X to Y , and $p(X, Y) = 0$ if no such path exists.

Then, the **Schulze winner** is the Condorcet winner, if it exists. Otherwise, a **potential winner** is a candidate a such that $p(a, X) \geq p(X, a)$ for all $X \neq a$.

Tie-Breaking is used between potential winners.

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# voters	3	2	2	2
1st	a	d	d	c
2nd	b	a	b	b
3rd	c	b	c	d
4th	d	c	a	a

Is there a Condorcet winner?

	a	b	c	d
a	–	1	1	0
b	0	–	1	1
c	0	0	–	1
d	1	0	0	–

⇒ No!

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# voters	3	2	2	2
1st	a	d	d	c
2nd	b	a	b	b
3rd	c	b	c	d
4th	d	c	a	a

Weights $d(X, Y)$:

	a	b	c	d
a	–	5	5	3
b	4	–	7	5
c	4	2	–	5
d	6	4	4	–

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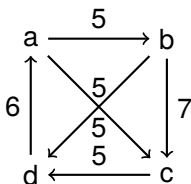
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# voters	3	2	2	2
1st	a	d	d	c
2nd	b	a	b	b
3rd	c	b	c	d
4th	d	c	a	a

Weights $d(X, Y)$:

	a	b	c	d
a	–	5	5	3
b	4	–	7	5
c	4	2	–	5
d	6	4	4	–

As a graph:



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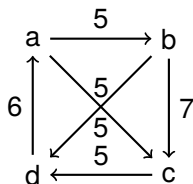
Summary

# voters	3	2	2	2
1st	a	d	d	c
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3rd	c	b	c	d
4th	d	c	a	a

Weights $d(X, Y)$:

	a	b	c	d
a	–	5	5	3
b	4	–	7	5
c	4	2	–	5
d	6	4	4	–

As a graph:



Path strengths $p(X, Y)$:

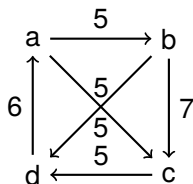
	a	b	c	d
a	–	5	5	5
b	5	–	7	5
c	5	5	–	5
d	6	5	5	–

# voters	3	2	2	2
1st	a	d	d	c
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4th	d	c	a	a

Weights $d(X, Y)$:

	a	b	c	d
a	-	5	5	3
b	4	-	7	5
c	4	2	-	5
d	6	4	4	-

As a graph:



Path strengths $p(X, Y)$:

	a	b	c	d
a	-	5	5	5
b	5	-	7	5
c	5	5	-	5
d	6	5	5	-

Potential winners: **b and d.**



According to Wikipedia

(http://en.wikipedia.org/wiki/Schulze_method), the method satisfies a large number of desirable criteria:

Unrestricted domain, non-imposition, non-dictatorship, Pareto criterion, monotonicity criterion, majority criterion, majority loser criterion, Condorcet criterion, Condorcet loser criterion, Schwartz criterion, Smith criterion, independence of Smith-dominated alternatives, mutual majority criterion, independence of clones, reversal symmetry, mono-append, mono-add-plump, resolvability criterion, polynomial runtime, prudence, MinMax sets, Woodall's plurality criterion if winning votes are used for $d[X, Y]$, symmetric-completion if margins are used for $d[X, Y]$.

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Motivation



Motivation: It appears as if all considered voting systems encourage **strategic voting**.

Question: Can this be **avoided** or is it a fundamental problem?

Answer (simplified): It is a **fundamental problem!**

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Desirable properties of social welfare functions:

Definition (Unanimity)

A social welfare function satisfies

- **total unanimity** if for all $\succ \in L$, $F(\succ, \dots, \succ) = \succ$.
- **partial unanimity** if for all $\succ_1, \succ_2, \dots, \succ_n \in L$, $a, b \in A$,

$$a \succ_i b \text{ for each } i = 1, \dots, n \implies a \succ b$$

where $\succ := F(\succ_1, \dots, \succ_n)$.

Remark

Partial unanimity implies total unanimity, but not vice versa.

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Desirable properties of social welfare functions:

Definition (Non-Dictatorship)

A voter i is called a **dictator** for F , if $F(\succ_1, \dots, \succ_i, \dots, \succ_n) = \succ_i$ for all orders $\succ_1, \dots, \succ_n \in L$.

F is called **non-dictatorial** if there is no dictator for F .

Definition (Independence of Irrelevant Alternatives, IIA)

F satisfies **IIA** if for all alternatives a, b the social preference between a and b depends only on the preferences of the voters between a and b .

Formally, for all $(\succ_1, \dots, \succ_n), (\succ'_1, \dots, \succ'_n) \in L^n$,

$\prec := F(\succ_1, \dots, \succ_n)$, and $\prec' := F(\succ'_1, \dots, \succ'_n)$,

$a \prec_i b$ iff $a \prec'_i b$, for each $i = 1, \dots, n \implies a \prec b$ iff $a \prec' b$.

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Lemma

Total unanimity and independence of irrelevant alternatives together imply partial unanimity.

Proof

Consider any $\succsim_1, \dots, \succsim_n \in L$ with $a \succsim_i b$ for all voters i .

To show: $a \succ b$ (with $\succ := F(\succsim_1, \dots, \succsim_n)$).

Define $\succsim'_1, \dots, \succsim'_n$ with $\succsim'_i := \succsim_1$ for each voter i .

By total unanimity, $\succ' := F(\succsim'_1, \dots, \succsim'_n) = F(\succsim_1, \dots, \succsim_1) = \succsim_1$.

Hence, we have $a \succ' b$.

Moreover, $a \succ_i b$ iff $a \succ'_i b$, for all voters i .

By IIA, it follows $a \succ b$ iff $a \succ' b$.

From $a \succ' b$ we conclude that $a \succ b$ must hold.

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Moreover, $a \succsim_i b$ iff $a \succsim'_i b$, for all voters i .

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Proof

Consider any $\succsim_1, \dots, \succsim_n \in L$ with $a \succsim_i b$ for all voters i .

To show: $a \prec b$ (with $\prec := F(\succsim_1, \dots, \succsim_n)$).

Define $\succsim'_1, \dots, \succsim'_n$ with $\succsim'_i := \succsim_1$ for each voter i .

By total unanimity, $\succsim' := F(\succsim'_1, \dots, \succsim'_n) = F(\succsim_1, \dots, \succsim_1) = \succsim_1$.

Hence, we have $a \prec' b$.

Moreover, $a \prec_i b$ iff $a \prec'_i b$, for all voters i .

By IIA, it follows $a \prec b$ iff $a \prec' b$.

From $a \prec' b$ we conclude that $a \prec b$ must hold.

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Lemma

Total unanimity and independence of irrelevant alternatives together imply partial unanimity.

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Consider any $\succsim_1, \dots, \succsim_n \in L$ with $a \succsim_i b$ for all voters i .

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Lemma (pairwise neutrality)

Let F be a social welfare function satisfying (total or partial) unanimity and independence of irrelevant alternatives.

Let $(\succsim_1, \dots, \succsim_n)$ and $(\succsim'_1, \dots, \succsim'_n)$ be two preference profiles, $\succ := F(\succsim_1, \dots, \succsim_n)$ and $\succ' := F(\succsim'_1, \dots, \succsim'_n)$.

Then,

$$a \succ_i b \text{ iff } c \succ'_i d \text{ for each } i = 1, \dots, n \implies a \succ b \text{ iff } c \succ' d.$$

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Construct a new preference profile $(\prec''_1, \dots, \prec''_n)$, where $c \prec''_i a$ (unless $c = a$) and $b \prec''_i d$ (unless $b = d$) for all $i = 1, \dots, n$, whereas the order of the pairs (a, b) is copied from \prec_i and the order of the pairs (c, d) is taken from \prec'_i .

By unanimity, we get $c \prec'' a$ and $b \prec'' d$ ($\prec'' := F(\prec''_1, \dots, \prec''_n)$).

Because of IIA, we have $a \prec'' b$.

By transitivity, we obtain $c \prec'' d$.

With IIA, it follows $c \prec' d$.

The proof for the opposite direction is similar.

Turns out the proof [Nisan 2007] is incomplete [Nipkow 2009].

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Pick c and create \succ''_i from \succ_i by moving c directly below b , i.e., $a \succ_i b$ iff $a \succ''_i c$. This implies $a \succ b$ iff $a \succ'' c$ (by the previous part). Construct \succ'''_i from \succ''_i by moving b directly below a .

Construct \succ''''_i from \succ'''_i by moving a directly below c . It follows that $a \succ'' c$ iff $b \succ''' c$ and $b \succ''' c$ iff $b \succ'''' a$. Comparing \succ'''' with \succ , we notice: $a \succ_i b$ iff $b \succ''''_i a$, hence $a \succ'_i b$ iff $a \succ''''_i b$.

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Pick c and create \succ''_i from \succ_i by moving c directly below b , i.e., $a \succ_i b$ iff $a \succ''_i c$. This implies $a \succ b$ iff $a \succ'' c$ (by the previous part).

Construct \succ'''_i from \succ''_i by moving b directly below a .

Construct \succ''''_i from \succ'''_i by moving a directly below c . It follows that $a \succ'' c$ iff $b \succ''' c$ and $b \succ''' c$ iff $b \succ'''' a$. Comparing \succ'''' with \succ , we notice: $a \succ_i b$ iff $b \succ''''_i a$, hence $a \succ'_i b$ iff $a \succ''''_i b$.

By IIA, it follows, $a \succ' b$ iff $a \succ'''' b$, yielding $a \succ b$ iff $b \succ' a$ as desired.

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Proof

Let us assume $a \succ b$ and $a = d$ and $b = c$. I.e., we want to show: $a \succ_i b$ iff $b \succ'_i a$ for each $i \implies a \succ b$ iff $b \succ' a$.

Pick c and create \succ''_i from \succ_i by moving c directly below b , i.e., $a \succ_i b$ iff $a \succ''_i c$. This implies $a \succ b$ iff $a \succ'' c$ (by the previous part).

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By IIA, it follows, $a \succ' b$ iff $a \succ'''' b$, yielding $a \succ b$ iff $b \succ' a$ as desired.

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Arrow's Impossibility Theorem

Every social welfare function over more than two alternatives that satisfies unanimity and independence of irrelevant alternatives is necessarily dictatorial.

Proof

We assume unanimity and independence of irrelevant alternatives.

Consider two elements $a, b \in A$ mit $a \neq b$ and construct a sequence $(\pi^i)_{i=0, \dots, n}$ of preference profiles such that in π^i exactly the first i voters prefer b to a , i.e., $a \prec_j b$ iff $j \leq i$:

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Proof (ctd.)

	π^0	...	π^{i^*-1}	π^{i^*}	...	π^n
1:	$b \succ_1 a$...	$a \succ_1 b$	$a \succ_1 b$...	$a \succ_1 b$
\vdots	\vdots	\ddots	\vdots	\vdots	\ddots	\vdots
$i^* - 1$:	$b \succ_{i^*-1} a$...	$a \succ_{i^*-1} b$	$a \succ_{i^*-1} b$...	$a \succ_{i^*-1} b$
i^* :	$b \succ_{i^*} a$...	$b \succ_{i^*} a$	$a \succ_{i^*} b$...	$a \succ_{i^*} b$
$i^* + 1$:	$b \succ_{i^*+1} a$	...	$b \succ_{i^*+1} a$	$b \succ_{i^*+1} a$	...	$a \succ_{i^*+1} b$
\vdots	\vdots	\ddots	\vdots	\vdots	\ddots	\vdots
n :	$b \succ_n a$	...	$b \succ_n a$	$b \succ_n a$	...	$a \succ_n b$
F :	$b \succ^0 a$	...	$b \succ^{i^*-1} a$	$a \succ^{i^*} b$	...	$a \succ^n b$

Unanimity $\Rightarrow b \succ^0 a$ for $\succ^0 = F(\pi^0)$, $a \succ^n b$ for $\succ^n := F(\pi^n)$.

Thus, there must exist a minimal index i^* such that $b \succ^{i^*-1} a$ and $a \succ^{i^*} b$ for $\succ^{i^*-1} := F(\pi^{i^*-1})$ and $\succ^{i^*} = F(\pi^{i^*})$.

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	π^0	...	π^{i^*-1}	π^{i^*}	...	π^n
1:	$b \succ_1 a$...	$a \succ_1 b$	$a \succ_1 b$...	$a \succ_1 b$
\vdots	\vdots	\ddots	\vdots	\vdots	\ddots	\vdots
$i^* - 1$:	$b \succ_{i^*-1} a$...	$a \succ_{i^*-1} b$	$a \succ_{i^*-1} b$...	$a \succ_{i^*-1} b$
i^* :	$b \succ_{i^*} a$...	$b \succ_{i^*} a$	$a \succ_{i^*} b$...	$a \succ_{i^*} b$
$i^* + 1$:	$b \succ_{i^*+1} a$...	$b \succ_{i^*+1} a$	$b \succ_{i^*+1} a$...	$a \succ_{i^*+1} b$
\vdots	\vdots	\ddots	\vdots	\vdots	\ddots	\vdots
n :	$b \succ_n a$...	$b \succ_n a$	$b \succ_n a$...	$a \succ_n b$
F :	$b \succ^0 a$...	$b \succ^{i^*-1} a$	$a \succ^{i^*} b$...	$a \succ^n b$

Unanimity $\Rightarrow b \succ^0 a$ for $\succ^0 = F(\pi^0)$, $a \succ^n b$ for $\succ^n := F(\pi^n)$.

Thus, there must exist a minimal index i^* such that $b \succ^{i^*-1} a$ and $a \succ^{i^*} b$ for $\succ^{i^*-1} := F(\pi^{i^*-1})$ and $\succ^{i^*} = F(\pi^{i^*})$.

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Proof (ctd.)

Show that i^* is a dictator.

Consider two alternatives $c, d \in A$ with $c \neq d$ and show that for all $(\prec_1, \dots, \prec_n) \in L^n$, $c \prec_{i^*} d$ implies $c \prec d$, where $\prec = F(\prec_1, \dots, \prec_{i^*}, \dots, \prec_n)$.

Consider $e \notin \{c, d\}$ and construct preference profile $(\prec'_1, \dots, \prec'_n)$, where:

for $j < i^*$: $e \prec'_j c \prec'_j d$ or $e \prec'_j d \prec'_j c$

for $j = i^*$: $c \prec'_j e \prec'_j d$ or $d \prec'_j e \prec'_j c$

for $j > i^*$: $c \prec'_j d \prec'_j e$ or $d \prec'_j c \prec'_j e$

depending on whether $c \prec_j d$ or $d \prec_j c$.

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Proof (ctd.)

Show that i^* is a dictator.

Consider two alternatives $c, d \in A$ with $c \neq d$ and show that for all $(\prec_1, \dots, \prec_n) \in L^n$, $c \prec_{i^*} d$ implies $c \prec d$, where $\prec = F(\prec_1, \dots, \prec_{i^*}, \dots, \prec_n)$.

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Proof (ctd.)

Let $\prec' = F(\prec'_1, \dots, \prec'_n)$.

Independence of irrelevant alternatives implies $c \prec' d$ iff $c \prec d$.

	π^{i^*-1}	$(\prec'_j)_{j=1, \dots, n}$	π^{i^*}	$(\prec'_j)_{j=1, \dots, n}$
1:	$a \prec_1 b$	$e \prec'_1 c$	$a \prec_1 b$	$e \prec'_1 d$
$i^* - 1$:	$a \prec_{i^*-1} b$	$e \prec'_{i^*-1} c$	$a \prec_{i^*-1} b$	$e \prec'_{i^*-1} d$
i^* :	$b \prec_{i^*} a$	$c \prec'_{i^*} e$	$a \prec_{i^*} b$	$e \prec'_{i^*} d$
n :	$b \prec_n a$	$c \prec'_n e$	$b \prec_n a$	$d \prec'_n e$
F :	$b \prec_{i^*-1} a$	$c \prec' e$	$a \prec_{i^*} b$	$e \prec' d$

For (e, c) we have the same preferences in $\prec'_1, \dots, \prec'_n$ as for (a, b) in π^{i^*-1} . Pairwise neutrality implies $c \prec' e$.

For (e, d) we have the same preferences in $\prec'_1, \dots, \prec'_n$ as for (a, b) in π^{i^*} . Pairwise neutrality implies $e \prec' d$.

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Proof (ctd.)

With transitivity, we get $c \succ' d$.

By construction of \succ' and independence of irrelevant alternatives, we get $c \succ d$.

Opposite direction: similar. □

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Remark:

Unanimity and non-dictatorship often satisfied in social welfare functions. Problem usually lies with **independence of irrelevant alternatives**.

Closely related to possibility of **strategic voting**: insert “irrelevant” candidate between favorite candidate and main competitor to help favorite candidate (only possible if independence of irrelevant alternatives is violated).

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Motivation:

- Arrow's Impossibility Theorem only applies to **social welfare functions**.
- Can this be transferred to **social choice functions**?
- **Yes!** Intuitive result: Every “reasonable” social choice function is susceptible to manipulation (strategic voting).

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Strategic Manipulation and Incentive Compatibility



Definition (Strategic Manipulation, Incentive Compatibility)

A social choice function f can be **strategically manipulated** by voter i if there are preferences $\succsim_1, \dots, \succsim_i, \dots, \succsim_n, \succsim'_i \in L$ such that $a \succsim_i b$ for $a = f(\succsim_1, \dots, \succsim_i, \dots, \succsim_n)$ and $b = f(\succsim_1, \dots, \succsim'_i, \dots, \succsim_n)$.

The function f is called **incentive compatible** if f cannot be strategically manipulated.

Definition (Monotonicity)

A social choice function is **monotone** if $f(\succsim_1, \dots, \succsim_i, \dots, \succsim_n) = a$, $f(\succsim_1, \dots, \succsim'_i, \dots, \succsim_n) = b$ and $a \neq b$ implies $b \succsim_i a$ and $a \not\succsim'_i b$.

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Proposition

A social choice function is monotone iff it is incentive compatible.

Proof

Let f be monotone. If $f(\succsim_1, \dots, \succsim_i, \dots, \succsim_n) = a$,
 $f(\succsim_1, \dots, \succsim'_i, \dots, \succsim_n) = b$ and $a \neq b$, then also $b \succsim_i a$ and $a \succsim'_i b$.

Then there cannot be any $\succsim_1, \dots, \succsim_n, \succsim'_i \in L$ such that
 $f(\succsim_1, \dots, \succsim_i, \dots, \succsim_n) = a$, $f(\succsim_1, \dots, \succsim'_i, \dots, \succsim_n) = b$ and $a \succsim_i b$.

Conversely, violated monotonicity implies that there is a possibility for strategic manipulation. □

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Incentive Compatibility and Monotonicity



Proposition

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Let f be monotone. If $f(\succsim_1, \dots, \succsim_i, \dots, \succsim_n) = a$,
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 $f(\succsim_1, \dots, \succsim_i, \dots, \succsim_n) = a$, $f(\succsim_1, \dots, \succsim'_i, \dots, \succsim_n) = b$ and $a \succsim_i b$.

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Then there cannot be any $\succsim_1, \dots, \succsim_n, \succsim'_i \in L$ such that
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Definition (Dictatorship)

Voter i is a **dictator** in a social choice function f if for all $\succ_1, \dots, \succ_i, \dots, \succ_n \in L$, $f(\succ_1, \dots, \succ_i, \dots, \succ_n) = a$, where a is the unique candidate with $b \prec_i a$ for all $b \in A$ with $b \neq a$.

The function f is a **dictatorship** if there is a dictator in f .

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Gibbard-Satterthwaite Theorem

Reduction to Arrow's Theorem



Approach:

- We prove the result by Gibbard and Satterthwaite using Arrow's Theorem.
- To that end, construct social welfare function from social choice function.

Notation:

Let $S \subseteq A$ and $\prec \in L$. By \prec^S we denote the order obtained by moving all elements from S "to the top" in \prec , while preserving the relative orderings of the elements in S and of those in $A \setminus S$.

More formally:

- for $a, b \in S$: $a \prec^S b$ iff $a \prec b$,
- for $a, b \notin S$: $a \prec^S b$ iff $a \prec b$,
- for $a \notin S, b \in S$: $a \prec^S b$.

These conditions uniquely define \prec^S .

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Lemma (Top Preference)

Let f be an incentive compatible and surjective social choice function. Then for all $\succsim_1, \dots, \succsim_n \in L$ and all $\emptyset \neq S \subseteq A$, we have $f(\succsim_1^S, \dots, \succsim_n^S) \in S$.

Proof

Let $a \in S$.

Since f is surjective, there are $\succsim'_1, \dots, \succsim'_n \in L$ such that $f(\succsim'_1, \dots, \succsim'_n) = a$.

Now, sequentially, for $i = 1, \dots, n$, change the relation \succsim'_i to \succsim_i^S . At no point during this sequence of changes will f output any candidate $b \notin S$, because f is monotone.

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Let $a \in S$.

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Extension of a Social Choice Function



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Definition (Extension of a Social Choice Function)

The function $F : L^n \rightarrow L$ that **extends** the social choice function f is defined as $F(\succ_1, \dots, \succ_n) = \prec$, where $a \prec b$ iff $f(\succ_1^{\{a,b\}}, \dots, \succ_n^{\{a,b\}}) = b$ for all $a, b \in A, a \neq b$.

Lemma

If f is an incentive compatible and surjective social choice function, then its extension F is a social welfare function.

Proof

We show that \prec is a strict linear order, i.e., asymmetric, total and transitive.

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Gibbard-Satterthwaite Theorem

Extension of a Social Choice Function



Proof (ctd.)

- **Asymmetry and Totality:** Because of the Top-Preference Lemma, $f(\succsim_1^{\{a,b\}}, \dots, \succsim_n^{\{a,b\}})$ is either a or b , i.e., $a \prec b$ or $b \prec a$, but not both (asymmetry) and not neither (totality).
- **Transitivity:** We may already assume totality. Suppose that \prec is not transitive, i.e., $a \prec b$ and $b \prec c$, but not $a \prec c$, for some a, b and c . Because of totality, $c \prec a$. Consider $S = \{a, b, c\}$ and WLOG $f(\succsim_1^{\{a,b,c\}}, \dots, \succsim_n^{\{a,b,c\}}) = a$. Due to monotonicity of f , we get $f(\succsim_1^{\{a,b\}}, \dots, \succsim_n^{\{a,b\}}) = a$ by successively changing $\succsim_i^{\{a,b,c\}}$ to $\succsim_i^{\{a,b\}}$. Thus, we get $b \prec a$ in contradiction to our assumption. \square

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Lemma (Extension Lemma)

If f is an incentive compatible, surjective, and non-dictatorial social choice function, then its extension F is a social welfare function that satisfies unanimity, independence of irrelevant alternatives, and non-dictatorship.

Proof

We already know that F is a social welfare function and still have to show unanimity, independence of irrelevant alternatives, and non-dictatorship.

- **Unanimity:** Let $a \prec_i b$ for all i . Then $(\prec_i^{\{a,b\}})_{\{b\}} = \prec_i^{\{a,b\}}$.
Because of the Top-Preference Lemma,
 $f(\prec_1^{\{a,b\}}, \dots, \prec_n^{\{a,b\}}) = b$, hence $a \prec b$.
- **Independence of irrelevant alternatives:** ...

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Proof (ctd.)

- **Independence of irrelevant alternatives:** If for all i , $a \prec_i b$ iff $a \prec'_i b$, then $f(\prec_1^{\{a,b\}}, \dots, \prec_n^{\{a,b\}}) = f(\prec_1'^{\{a,b\}}, \dots, \prec_n'^{\{a,b\}})$ must hold, since due to monotonicity the result does not change when $\prec_i^{\{a,b\}}$ is successively replaced by $\prec_i'^{\{a,b\}}$.
- **Non-dictatorship:** Obvious. □



Theorem (Gibbard-Satterthwaite)

If f is an incentive compatible and surjective social choice function with three or more alternatives, then f is a dictatorship. □

The purpose of **mechanism design** is to alleviate the negative results of Arrow and Gibbard and Satterthwaite by changing the underlying model. The two usually investigated modifications are:

- Introduction of money
- Restriction of admissible preference relations

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We had some negative results on social choice and welfare functions so far: Arrow, Gibbard-Satterthwaite.

Question: Are there also positive results for special cases?

First special case: Only **two alternatives**.

Intuition: With only two alternatives, no point in misrepresenting preferences.

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Axioms for voting systems:

- **Neutrality:** “Names” of candidates/alternatives should not be relevant.
- **Anonymity:** “Names” of voters should not be relevant.
- **Monotonicity:** If a candidate wins, he should still win if one voter ranks him higher.

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May's Theorem



Theorem (May, 1958)

A voting method for two alternatives satisfies anonymity, neutrality, and monotonicity if and only if it is the plurality method.

Proof.

⇐: Obvious.

⇒: For simplicity, we assume that the number of voters is odd.

Anonymity and neutrality imply that only the numbers of votes for the candidates matter.

Let A be the set of voters that prefer candidate a , and let B be the set of voters that prefer candidate b . Consider a vote with $|A| = |B| + 1$.

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Proof (ctd.)

- **Case 1: Candidate a wins.** Then by monotonicity, a still wins whenever $|A| > |B|$. With neutrality, we also get that b wins whenever $|B| > |A|$. This uniquely characterizes the plurality method.
- **Case 2: Candidate b wins.** Assume that one voter for a changes his preference to b . Then $|A'| + 1 = |B'|$. By monotonicity, b must still win. This is completely symmetric to the original vote. Hence, by neutrality, a should win. This is a contradiction, implying that case 2 cannot occur. □

Remark: For three or more alternatives, there are no voting methods that satisfy such a small set of desirable criteria.

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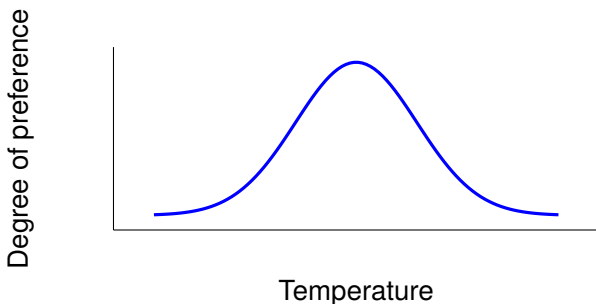
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The results by Arrow and Gibbard-Satterthwaite only apply if there are **no restrictions** on the preference orders.

Second special case: Let us now consider some special cases such as temperature or volume settings.



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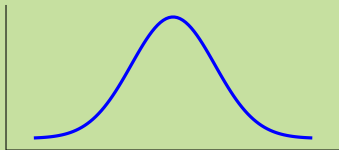
Definition (Single-peaked preference)

A preference relation \succsim_i over the interval $[0, 1]$ is called a **single-peaked preference relation** if there exists a value $p_i \in [0, 1]$ such that for all $x \in [0, 1] \setminus p_i$ and for all $\lambda \in [0, 1]$,

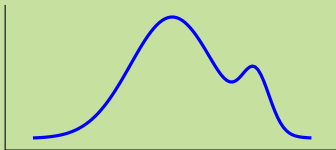
$$x \succsim_i \lambda x + (1 - \lambda)p_i.$$

Example

Single-peaked:



Not single-peaked:



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First idea: Use **arithmetic mean** of all peak values.

Example

Preferred room temperatures:

- Voter 1: 10°C
- Voter 2: 20°C
- Voter 3: 21°C

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Arithmetic mean: 17°C . Is this incentive compatible?

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Arithmetic mean: 17°C . Is this incentive compatible?

No! Voter 1 can misrepresent his peak value as, e.g., -11°C .

Then the mean is 10°C , his favorite value!

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Arithmetic mean: 17°C . Is this incentive compatible?

No! Voter 1 can misrepresent his peak value as, e.g., -11°C .

Then the mean is 10°C , his favorite value!

Question: What is a good way to design incentive compatible social choice functions for this setting?

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Definition (Median rule)

Let p_1, \dots, p_n be the peaks for the preferences $\succsim_1, \dots, \succsim_n$ ordered such that we have $p_1 \leq p_2 \leq \dots \leq p_n$. Then the **median rule** is the social choice function f with

$$f(\succsim_1, \dots, \succsim_n) = p_{\lceil n/2 \rceil}.$$

Theorem

The median rule is surjective, incentive compatible, anonymous, and non-dictatorial.

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Proof.

- **Surjective:** Obvious, because the median rule satisfies unanimity.
- **Incentive compatible:** Assume that p_i is below the median. Then reporting a lower value does not change the median (\rightsquigarrow does not help), and reporting a higher value can only increase the median (\rightsquigarrow does not help, either). Similarly, if p_i is above the median.
- **Anonymous:** Is implicit in the rule.
- **Non-dictatorial:** Follows from anonymity. □

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- **Multitude** of possible **social welfare functions** (plurality voting with or without runoff, instant runoff voting, Borda count, Schulze method, ...).
- All social welfare functions for more than two alternatives suffer from **Arrow's Impossibility Theorem**.
- Typical handling of this issue: Use unanimous, non-dictatorial social welfare functions – **violate independence of irrelevant alternatives**.
- Thus: **Strategic voting inevitable**.
- The same holds for social choice functions (**Gibbard-Satterthwaite Theorem**).

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