

Game Theory

11. Mechanisms Without Money

Albert-Ludwigs-Universität Freiburg



**UNI
FREIBURG**

Bernhard Nebel and Robert Mattmüller

Summer semester 2019

1 Motivation



**UNI
FREIBURG**

Motivation

House
Allocation
Problem

Stable
Matchings

Summary

Motivation 1:

- According to Gibbard-Satterthwaite:
In general, **nontrivial social choice functions manipulable**.
- **One way out: Introduction of money**
(cf. VCG mechanisms)
- **Other way out: Restriction of preferences**
(cf. single-peaked preferences; this chapter)

Motivation 2:

- Introduction of central concept from cooperative game theory: **the core**

Examples:

- House allocation problem
- Stable matchings

Motivation

House
Allocation
Problem

Stable
Matchings

Summary

2 House Allocation Problem



- Definitions
- Top Trading Cycle Algorithm

Motivation

House
Allocation
Problem

Definitions

Top Trading Cycle
Algorithm

Stable
Matchings

Summary

- **Players** $N = \{1, \dots, n\}$.
- Each player i owns house i .
- Each player i has **strict linear preference** order \triangleleft_i over the set of houses.
Example: $j \triangleleft_i k$ means player i prefers house k to house j .
- **Alternatives** A : allocations of houses to players (permutations $\pi \in S_n$ of N).
Example: $\pi(i) = j$ means player i gets house j .
- **Objective:** **reallocate the houses** among the agents “appropriately”.

Motivation

House
Allocation
Problem

Definitions

Top Trading Cycle
Algorithm

Stable
Matchings

Summary

- Note on preference relations:
 - Arbitrary (strict linear) preference orders \triangleleft_i over houses,
 - but **no** arbitrary preference orders \preceq_i over A .
- Rather: Player i **indifferent** between different allocations π_1 and π_2 as long as $\pi_1(i) = \pi_2(i)$.
Indifference denoted as $\pi_1 \approx_i \pi_2$.
- If player i is not indifferent: $\pi_1 \prec_i \pi_2$ iff $\pi_1(i) \triangleleft_i \pi_2(i)$.
- Notation: $\pi_1 \preceq_i \pi_2$ iff $\pi_1 \prec_i \pi_2$ or $\pi_1 \approx_i \pi_2$.
- This makes **Gibbard-Satterthwaite inapplicable**.

Motivation

House
Allocation
Problem

Definitions

Top Trading Cycle
Algorithm

Stable
Matchings

Summary

- Important new aspect of house allocation problem: players control resources to be allocated.
- Allocation can be subverted by subset of agents breaking away and trading among themselves.
- How to avoid such allocations?
- How to make allocation mechanism non-manipulable?

Motivation

House
Allocation
Problem

Definitions

Top Trading Cycle
Algorithm

Stable
Matchings

Summary

Notation: For $M \subseteq N$, let

$$A(M) = \{\pi \in A \mid \forall i \in M : \pi(i) \in M\}$$

be the set of allocations that can be achieved by the agents in M trading among themselves.

Definition (blocking coalition)

Let $\pi \in A$ be an allocation. A set $M \subseteq N$ is called a **blocking coalition** for π if there exists a $\pi' \in A(M)$ such that

- $\pi \preceq_i \pi'$ for all $i \in M$ and
- $\pi \prec_i \pi'$ for at least one $i \in M$.

Motivation

House
Allocation
Problem

Definitions

Top Trading Cycle
Algorithm

Stable
Matchings

Summary

Intuition:

A blocking coalition can receive houses everyone from the coalition likes at least as much as under allocation π , with at least one player being strictly better off, by trading among themselves.

Definition (core)

The set of allocations that is not blocked by any subset of agents is called the **core**.

Question: Is the core nonempty?

Motivation

House
Allocation
Problem

Definitions

Top Trading Cycle
Algorithm

Stable
Matchings

Summary

- Algorithm to construct allocation
- Let $G = \langle V, A, c \rangle$ be an arc-colored directed graph where:
 - $V = N$ (i.e., one vertex for each player),
 - $A = V \times V$, and
 - $c : A \rightarrow N$ such that $c(i, j) = k$ if house j is player i 's k th ranked choice according to \triangleleft_j .
- **Note:** Loops (i, i) are allowed. We treat them as cycles of length 0.

Motivation

House
Allocation
Problem

Definitions
Top Trading Cycle
Algorithm

Stable
Matchings

Summary

Pseudocode:

let $\pi(i) = i$ for all $i \in N$.

while players unaccounted for **do**

 consider subgraph G' of G where each vertex has
 only one outgoing arc: the least-colored one from G .

 identify cycles in G' .

 add corresponding cyclic permutations to π .

 delete players accounted for and incident edges from G .

end while

output π .

Notation:

Let N_i be the set of vertices on cycles identified in iteration i .

Motivation

House
Allocation
Problem

Definitions
Top Trading Cycle
Algorithm

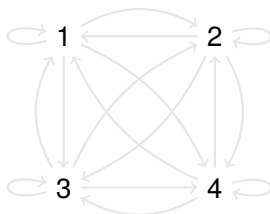
Stable
Matchings

Summary

Example:

- Player 1: 3 \triangleleft_1 1 \triangleleft_1 4 \triangleleft_1 2
- Player 2: 4 \triangleleft_2 2 \triangleleft_2 3 \triangleleft_2 1
- Player 3: 3 \triangleleft_3 4 \triangleleft_3 2 \triangleleft_3 1
- Player 4: 1 \triangleleft_4 4 \triangleleft_4 2 \triangleleft_4 3

Corresponding graph:



- Iteration 1: $\pi(1) = 2, \pi(2) = 1$.
- Iteration 2: $\pi(3) = 4, \pi(4) = 3$.
- Done: $\pi(1) = 2, \pi(2) = 1, \pi(3) = 4, \pi(4) = 3$.

Motivation

House
Allocation
Problem

Definitions
Top Trading Cycle
Algorithm

Stable
Matchings

Summary

Theorem

The core of the house allocation problem consists of exactly one matching.

Proof sketch

At most one matching: Show that if a matching is in the core, it must be the one returned by the TTCA.

In TTCA, each player in N_1 receives his favorite house.

Therefore, N_1 would form a blocking coalition to any allocation that does not assign to all of those players the houses they would receive in TTCA.

...

Motivation

House
Allocation
Problem

Definitions
Top Trading Cycle
Algorithm

Stable
Matchings

Summary

Proof sketch (ctd.)

That is, any core allocation must assign N_1 to houses as TTCA assigns them.

Argument can be extended inductively to N_k , $2 \leq k \leq n$.

At least one matching: Show that TTCA allocation is in the core, i.e., that there is no other blocking coalition $M \subseteq N$.
Homework. □

Motivation

House
Allocation
Problem

Definitions
Top Trading Cycle
Algorithm

Stable
Matchings

Summary



Question: What about manipulability?

Definition (top trading cycle mechanism)

The **top trading cycle mechanism (TTCM)** is the function that, for each profile of preferences, returns the allocation computed by the TTCA.

Theorem

The TTCM cannot be manipulated.

Proof

Homework. □

Motivation

House
Allocation
Problem

Definitions
Top Trading Cycle
Algorithm

Stable
Matchings

Summary

3 Stable Matchings



- Definitions
- Deferred Acceptance Algorithm
- Properties

Motivation

House
Allocation
Problem

**Stable
Matchings**

Definitions
Deferred
Acceptance
Algorithm
Properties

Summary

Problem statement:

- Given disjoint finite sets M of men and W of women.
- Assume WLOG that $|M| = |W|$
(introduce dummy-men/dummy-women).
- Each $m \in M$ has strict preference ordering \prec_m over W .
- Each $w \in W$ has strict preference ordering \prec_w over M .
- **Matching:** “appropriate” assignment of men to women such that each man is assigned to at most one woman and vice versa.

Motivation

House
Allocation
Problem

Stable
Matchings

Definitions

Deferred
Acceptance
Algorithm
Properties

Summary

Note: A group of players can **subvert a matching** by opting out.

Definition (stability, blocking pair)

A matching is called **unstable** if there are two men m, m' and two women w, w' such that

- m is matched to w ,
- m' is matched to w' , and
- $w \prec_m w'$ and $m' \prec_{w'} m$.

The pair $\langle m, w' \rangle$ is called a **blocking pair**.

A matching that has no blocking pairs is called **stable**.

Definition (core)

The **core** of the matching game is the set of all stable matchings.

Motivation

House
Allocation
Problem

Stable
Matchings

Definitions

Deferred
Acceptance
Algorithm

Properties

Summary

Example:

- Man 1: $w_3 \prec_{m_1} w_1 \prec_{m_1} w_2$
- Man 2: $w_2 \prec_{m_2} w_3 \prec_{m_2} w_1$
- Man 3: $w_3 \prec_{m_3} w_2 \prec_{m_3} w_1$
- Woman 1: $m_2 \prec_{w_1} m_3 \prec_{w_1} m_1$
- Woman 2: $m_2 \prec_{w_2} m_1 \prec_{w_2} m_3$
- Woman 3: $m_2 \prec_{w_3} m_3 \prec_{w_3} m_1$

Two matchings:

- Matching $\{\langle m_1, w_1 \rangle, \langle m_2, w_2 \rangle, \langle m_3, w_3 \rangle\}$
 - unstable ($\langle m_1, w_2 \rangle$ is a blocking pair)
- Matching $\{\langle m_1, w_1 \rangle, \langle m_3, w_2 \rangle, \langle m_2, w_3 \rangle\}$
 - stable

Motivation

House
Allocation
Problem

Stable
Matchings

Definitions

Deferred
Acceptance
Algorithm

Properties

Summary



Motivation

House
Allocation
Problem

Stable
Matchings

Definitions

Deferred
Acceptance
Algorithm

Properties

Summary

Question: Is there always a stable matching?

Answer: Yes! And it can even be efficiently constructed.

How? Deferred acceptance algorithm!

Definition (deferred acceptance algorithm, male proposals)

- 1 Each man proposes to his top-ranked choice.
- 2 Each woman who has received at least one proposal (including tentatively kept one from earlier rounds) tentatively keeps top-ranked proposal and rejects rest.
- 3 If no man is left rejected, stop.
- 4 Otherwise, each man who has been rejected proposes to his top-ranked choice among the women who have not rejected him. Then, goto 2.

Motivation

House
Allocation
Problem

Stable
Matchings

Definitions
Deferred
Acceptance
Algorithm
Properties

Summary

Note:

- Algorithm has polynomial runtime.
- No man is assigned to more than one woman.
- No woman is assigned to more than one man.
- \rightsquigarrow matching

Motivation

House
Allocation
Problem

Stable
Matchings

Definitions

Deferred
Acceptance
Algorithm

Properties

Summary

Deferred Acceptance Algorithm

Example:

- Man 1: $w_3 \prec_{m_1} w_1 \prec_{m_1} w_2$
- Man 2: $w_2 \prec_{m_2} w_3 \prec_{m_2} w_1$
- Man 3: $w_3 \prec_{m_3} w_2 \prec_{m_3} w_1$
- Woman 1: $m_2 \prec_{w_1} m_3 \prec_{w_1} m_1$
- Woman 2: $m_2 \prec_{w_2} m_1 \prec_{w_2} m_3$
- Woman 3: $m_2 \prec_{w_3} m_3 \prec_{w_3} m_1$

Deferred acceptance algorithm:

- 1 m_1 proposes to w_2 , m_2 to w_1 , and m_3 to w_1 .
- 2 w_1 keeps m_3 and rejects m_2 , w_2 keeps m_1 .
- 3 m_2 now proposes to w_3 .
- 4 w_3 keeps m_2 .

Resulting matching: $\{\langle m_1, w_2 \rangle, \langle m_2, w_3 \rangle, \langle m_3, w_1 \rangle\}$.

Motivation

House
Allocation
Problem

Stable
Matchings

Definitions

Deferred
Acceptance
Algorithm

Properties

Summary

Theorem

The deferred acceptance algorithm with male proposals terminates in a stable matching.

Proof

Suppose not.

Then there exists a blocking pair $\langle m_1, w_1 \rangle$ with m_1 matched to some w_2 and w_1 matched to some m_2 .

Since $\langle m_1, w_1 \rangle$ is blocking and $w_2 \prec_{m_1} w_1$, in the proposal algorithm, m_1 would have proposed to w_1 before w_2 .

Since m_1 was not matched with w_1 by the algorithm, it must be because w_1 received a proposal from a man she ranked higher than m_1

Motivation

House
Allocation
Problem

Stable
Matchings

Definitions
Deferred
Acceptance
Algorithm
Properties

Summary

Proof (ctd.)

Since the algorithm matches her to m_2 it follows that

$$m_1 \prec_{w_1} m_2.$$

This contradicts the fact that $\langle m_1, w_1 \rangle$ is a blocking pair. \square

Analogous version where the women propose: outcome would also be a stable matching.

Motivation

House
Allocation
Problem

Stable
Matchings

Definitions

Deferred
Acceptance
Algorithm

Properties

Summary



Denote a matching by μ . The woman assigned to man m in μ is $\mu(m)$, and the man assigned to woman w is $\mu(w)$.

Definition (optimality)

A matching μ is **male-optimal** if there is no stable matching ν such that $\mu(m) \prec_m \nu(m)$ or $\mu(m) = \nu(m)$ for all $m \in M$ and $\mu(m) \prec_m \nu(m)$ for at least one $m \in M$. **Female-optimal**: similar.

Theorem

- The stable matching produced by the (fe)male-proposal deferred acceptance algorithm is (fe)male-optimal.
- In general, there is no stable matching that is male-optimal and female-optimal. □

Motivation

House
Allocation
Problem

Stable
Matchings

Definitions
Deferred
Acceptance
Algorithm

Properties

Summary

Motivation

House
Allocation
Problem

Stable
Matchings

Definitions

Deferred
Acceptance
Algorithm

Properties

Summary

Theorem

The mechanism associated with the (fe)male-proposal algorithm cannot be manipulated by the (fe)males.



4 Summary



Motivation

House
Allocation
Problem

Stable
Matchings

Summary



- **Avoid Gibbard-Satterthwaite** by restricting domain of preferences.
- **House allocation** problem:
 - Solved using **top trading cycle** algorithm.
 - Algorithm finds **unique solution in the core**, where no **blocking coalition** of players has an incentive to break away.
 - The top trading cycle mechanism **cannot be manipulated**.
- **Stable matchings**:
 - Solved using **deferred acceptance** algorithm.
 - Algorithm finds **a stable matching in the core**, where no **blocking pair** of players has an incentive to break away.
 - The mechanism associated with the (fe)male-proposal algorithm cannot be manipulated by the (fe)males.

Motivation

House
Allocation
Problem

Stable
Matchings

Summary