NOT IN SYLLABUS

CSC304 Lecture 21

Fair Division 3:

Leximin Allocation
(computational resources, matching with dichotomous prefs, classroom allocation)

Utilitarian Allocation
(rent division)

Computational Resources

- Setting: We have a cluster with a number of different resources (CPU, RAM, network bandwidth, etc.)
- A set of players collectively own the cluster.
- Assumption: Each player wants the resources in a fixed proportion (Leontief preferences)
- Example:
  - Player 1 requires (2 CPU, 1 RAM) for each copy of task.
  - Indifferent between (4,2) and (5,2), but prefers (5,2.5)
  - That is, "fractional" copies are allowed

Model

- Set of players $N = \{1, \dots, n\}$
- Set of resources R, $|R| = m$
- Demand of player i is $d_i = (d_{i1}, \dots, d_{im})$
  - $0 < d_{ir} \leq 1$ for every r, $d_{ir} = 1$ for some r
- Allocation: $A_i = (A_{i1}, \dots, A_{im})$ where A_{ir} is the fraction of available resource r allocated to i
  - Thus, the utility to player i is $u_i(A_i) = \min_{r \in R} A_{ir}/d_{ir}$.
- We'll assume a non-wasteful allocation:
  - Allocates resources proportionally to the demand.

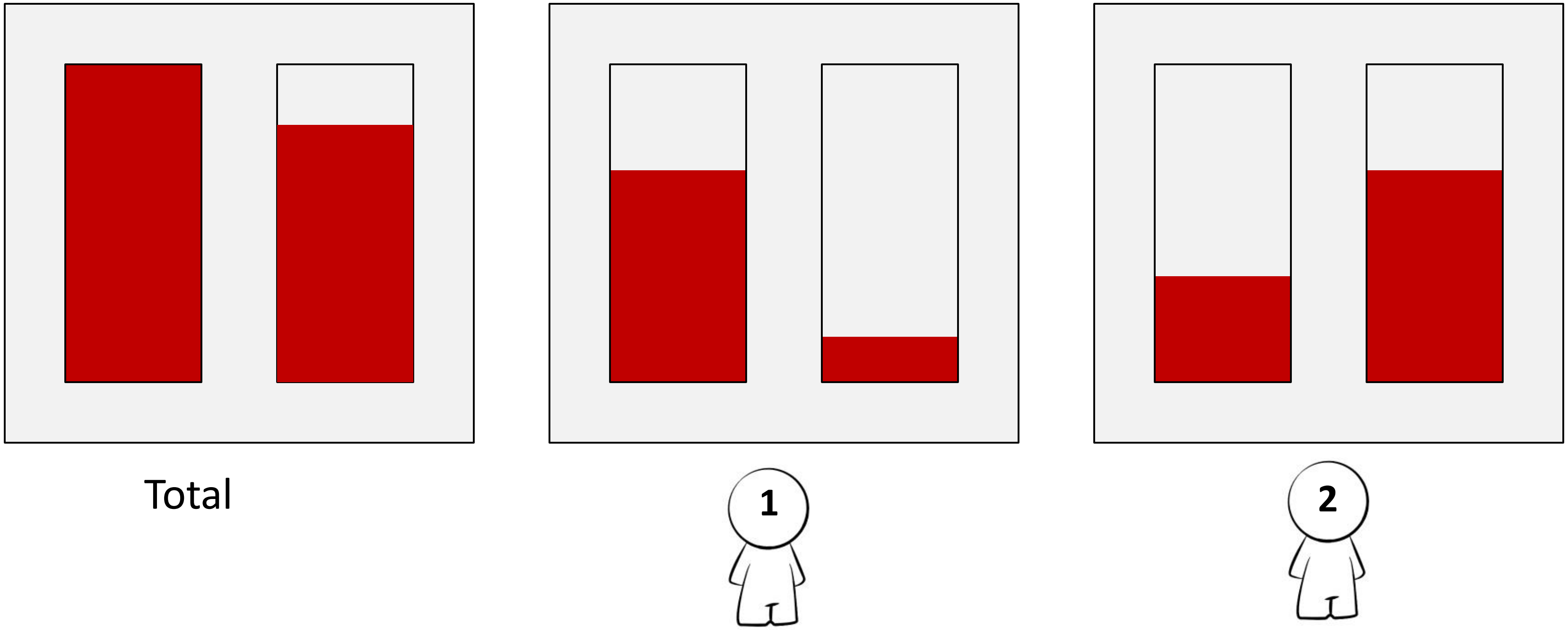
Dominant Resource Fairness

- Dominant resource of i = r such that $d_{ir} = 1$

- Dominant share of i = A_{ir} for dominant resource r

- Dominant Resource Fairness (DRF) Mechanism
  - Allocate maximal resources while maintaining equal dominant shares.

DRF animated



Properties of DRF

- Proportionality: $u_i(A_i) \geq 1/n$ for every player i
  - Why?
- Envy-free: $u_i(A_i) \geq u_i(A_j)$ for all players i, j
  - Why?
  - Note that we no longer have additive values across resources, so EF does not imply Proportionality (Why?)
- Pareto optimality (Why?)
- Group strategyproofness
  - If a group of players manipulate, it can't be that none of them lose, and some of them strictly gain.

The Leximin Mechanism

- Generalizes the DRF Mechanism

- Mechanism:
  - Choose an allocation A that maximizes the minimum of all utilities $\{u_i(A_i)\}_{i \in N}$
    - Sum = utilitarian welfare, product = Nash welfare, minimum = egalitarian welfare
  - If there are ties…
    - Break in favor of allocations that has a higher second minimum
    - Then break in favor of a higher third minimum
    - And so on…

The Leximin Mechanism

- DRF is the leximin mechanism applied to allocation of computational resources
  - It does not need to use tie-breaking because we assumed $d_{ir} > 0$ for every $i \in N, r \in R$.
  - In practice, not all the players need all the resources.

- Theorem [Parkes, Procaccia, S '12]:
  - Even when $d_{ir} = 0$ is allowed, the leximin mechanism retains all four properties (proportionality, envy-freeness, Pareto optimality, group strategyproofness).

Dynamic Environments

- We assumed that all agents are present from the start, and we want a one-shot allocation.
- Real-life environments are dynamic. Agents arrive and depart, and their demands change over time.

- Theorem [Kash, Procaccia, S '14]:
  - A dynamic variant of the leximin mechanism satisfies proportionality, Pareto optimality, and strategyproofness along with a relaxed version of envy-freeness when agents arrive over time.

Dynamic Environments

- Fair and game-theoretic allocation of resources in dynamic environments is a relatively new research area, and we do not know much.

- E.g., we do not have good algorithms that can handle departing agents, demands changing over time, or agents submitting/withdrawing multiple jobs over time.
  - Lots of open questions!

Matching + Dichotomous Prefs

- Let's revisit the problem of matching n men to n women.

- Recall that the Gale-Shapley algorithm used ranked preferences from both sides to find a stable matching.

- Consider a different case in which every man (resp. woman) has a subset of women (resp. men) that are acceptable (utility 1) and the rest are unacceptable.

Matching + Dichotomous Prefs

- Formally, for each man m, there is a subset of "acceptable" women P_m such that the man has utility 1 for being matched to any woman in P_m, and utility 0 otherwise.

- If there exists a perfect matching, that's awesome.
  - But what if there isn't?
- Any solution that wants to achieve fairness (proportionality or envy-freeness) must randomize!
  - Utility to agent = probability of being matched to an acceptable partner

Matching + Dichotomous Prefs

- Randomized mechanisms:
  - We can think of all men and women as “divisible” (oops!)
  - When we say that a woman w is “allocated” 0.3 fraction of a man m, it means the probability that w will be matched to m is 0.3.
  - You can just compute the fractional allocation that maximizes the minimum utility (then the second minimum etc).
    - Birkoff von-Neumann Theorem: Every fractional assignment can be written as a probability distribution over integral assignments.

Matching + Dichotomous Prefs

- Theorem [Bogomolnaia, Moulin '04]:
  - The randomized leximin mechanism satisfies proportionality, envy-freeness, Pareto optimality, and group-strategyproofness (for both sides simultaneously!).

- Compare this to the case of ranked preferences in which an algorithm can only be strategyproof for one side of the market, but not both.

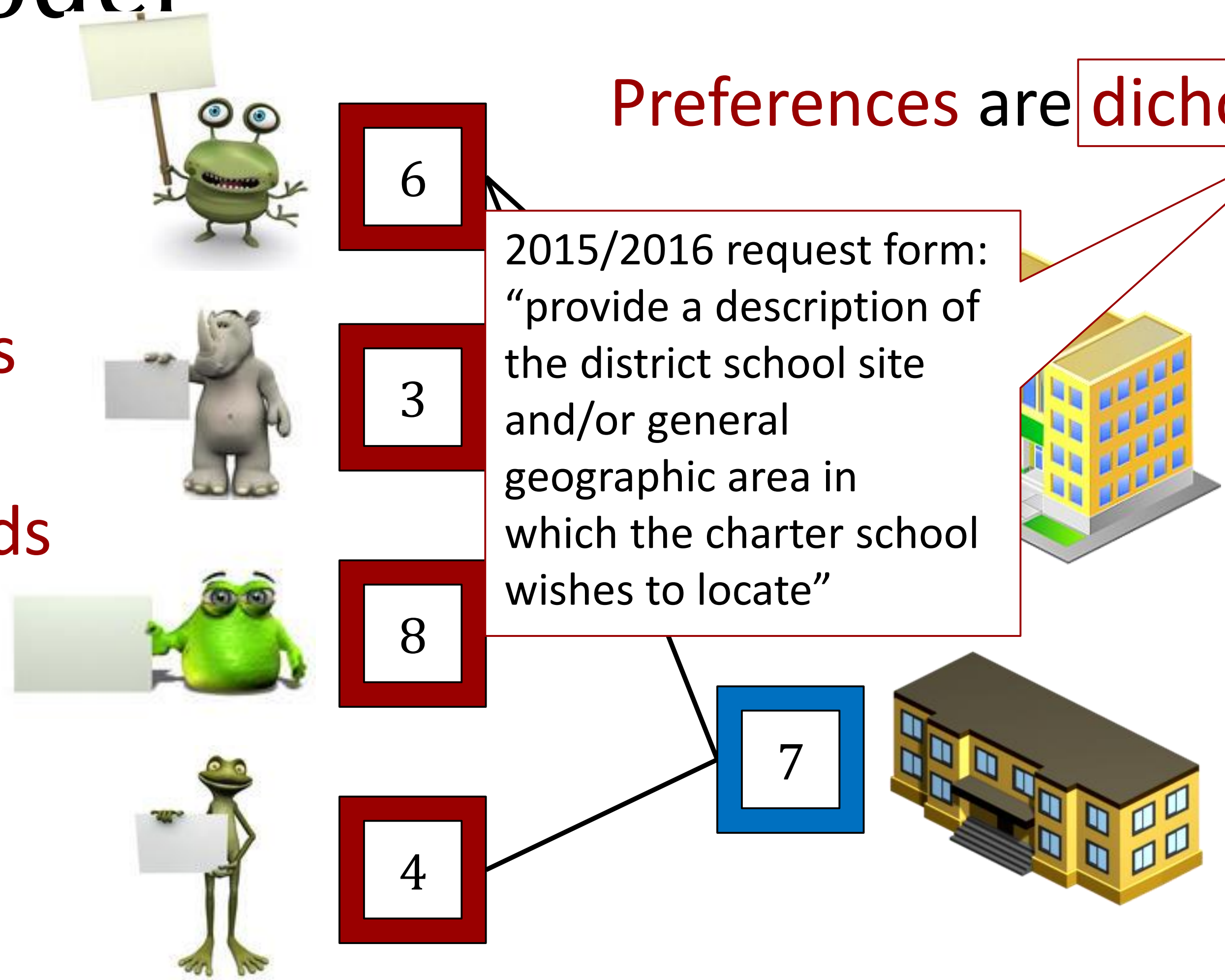
Matching with Capacities

- Proposition 39 in California mandates that unused classrooms in public schools be *fairly* assigned to charter schools that want it.
  - If the charter school receives a sufficient number of classrooms to fit all its students, it can physically relocate to the public school facility (e.g., and save on rent).
- Each charter school (agent) i has a set of acceptable public schools (facilities) F_i, but also has a demand d_i for the number of classrooms.
- Each facility j has a capacity c_j (#classrooms available)

Model

Preferences are dichotomous

Agents have demands



2015/2016 request form: “provide a description of the district school site and/or general geographic area in which the charter school wishes to locate”

Facilities have capacities

Number of unused classrooms

Leximin Strikes Again

- Theorem [Kurokawa, Procaccia, S '15]:
  - The randomized leximin mechanism satisfies proportionality, envy-freeness, Pareto optimality, and group strategyproofness for classroom allocation.

- In fact, the result holds under a wider domain satisfying a "maximal utilization" property.
  - Generalizes DRF, matching with dichotomous preferences, and 8-10 other settings
- For allocating computational resources or matching under dichotomous preferences, the leximin mechanism can be computed in polynomial time.
  - In contrast, it is NP-hard to compute for classroom allocation.

Rent Division

- n roommates rent an apartment with n rooms.
- Roommate i has value $v_{i,r}$ for room r.
- The total rent is R.
  - Assume that $\sum_r v_{i,r} \geq R$ for every roommate i.

- We need to find an allocation A of rooms to roommates and a price vector p such that
  - Total rent: $R = \sum_r p_r$
  - Envy-freeness: $v_{i,A_i} - p_{A_i} \geq v_{i,A_j} - p_{A_j}$

Rent Division: Fascinating Facts

- Existence: An envy-free allocation (A, p) always exists! (hard proof ☹)
- 1st Fundamental Theorem of Welfare Economics:
  - If (A, p) is an envy-free allocation, then A must maximize the sum of values (utilitarian welfare)!
  - Easy proof!
- 2nd Fundamental Theorem of Welfare Economics:
  - If (A, p) is an envy-free allocation, and A' is any allocation maximizing utilitarian welfare, then (A', p) is envy-free.
  - Further, $v_{i,A_i} - p_{A_i} = v_{i,A'_i} - p_{A'_i}$ for every agent i.
  - Easy proof!

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