

# Honor Among Bandits: No-Regret Learning for Online Fair Division

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NeurIPS 2024

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20 June 2025



# Outline

- 1 Introduction & Motivation
- 2 Definitions and Problem Setup
- 3 Fairness Machinery
- 4 Explore-Then-Commit Algorithm
- 5 Theoretical Results
- 6 Discussion & Future Work



# Online Fair Division Problem

- We have  $n$  players and  $m$  item types. Items arrive over time (rounds  $t = 1, 2, \dots, T$ ) and one at a time.
- Each arriving item  $j_t$  has a type  $k_t \in [m]$ , where  $k_t \sim \mathcal{D}$  not depending on  $T$ .
- Allocate each item immediately and irrevocably to a single player.
- Player  $i$ 's **value** for an item of type  $k$  is an unknown random variable  $V_i(j)$  (sub-Gaussian) with mean  $\mu_{ik}^*$ .
- **Goal:** Maximize social welfare **under fairness constraints**.

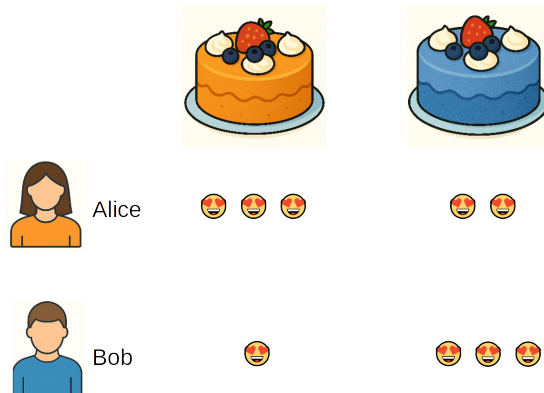


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  - social welfare: Utilitarian Social Welfare
  - fairness: envy-free and proportionality **in expectation**.



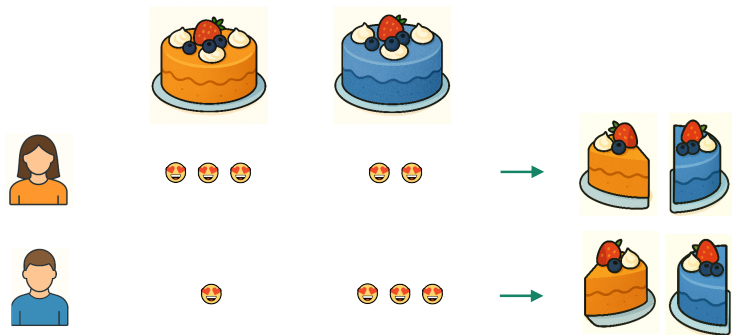
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# Envy-freeness for allocating indivisible goods

## Two-Partition Problem

Given a multiset  $S$  of positive integers, determine if it is possible to partition  $S$  into two disjoint subsets, say  $S_1$  and  $S_2$ , such that the sum of the integers in  $S_1$  is equal to the sum of the integers in  $S_2$ .

- $S = \{1, 5, 11, 5\}$





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- $S = \{1, 5, 11, 5\}$
- $S_1 = \{11\},$   
 $S_2 = \{1, 5, 5\}.$
- $S = \{3, 5, 8, 10, 11, 14, 17, 19, 21, 22, 25, 33\}.$
- $S_1 = \{33, 25, 22, 14\},$   
 $S_2 = \{3, 5, 8, 10, 11, 17, 19, 21\}.$



# Envy-freeness for allocating indivisible goods

NP-complete

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# Motivating Example: Food Bank

- A food bank receives **perishable** food donations **sequentially**.
- Must allocate each donation **immediately** to one of several food pantries.
- Each pantry has **unknown** true utility for different food types.
- Need to allocate **fairly** (no pantry envies another) while maximizing total utility distributed.



# Key Goals and Challenges

- **Fairness:** Envy-freeness (EFE) or proportionality (PE) in expectation, enforced *every round*.
- **Learning:** Player values  $\mu_{ik}^*$  unknown, must be learned via observed rewards.
- **Online Allocation:** Must balance exploration (learning values) and exploitation (maximizing welfare).
- **Metric:** Regret against optimal fair allocation (if  $\mu^*$  were known).



# Fractional Allocations and Welfare

- A **fractional allocation** is a matrix  $X \in \mathbb{R}^{n \times m}$  with

$$X_{ik} \geq 0, \quad \sum_{i=1}^n X_{ik} = 1 \quad (\forall k \in [m]).$$

- Interpret  $X_{ik}$  as the probability that a type- $k$  item is given to player  $i$ .
- If  $\mu^* \in \mathbb{R}^{n \times m}$  is the matrix of true means, the expected **welfare** of  $X$  is:

$$\langle X, \mu^* \rangle_F = \sum_{i=1}^n \sum_{k=1}^m X_{ik} \mu_{ik}^*.$$

- $Y^{\mu^*} = \arg \max_{X \in \mathcal{F}(\mu^*)} \langle X, \mu^* \rangle_F$  is the optimal fair allocation if  $\mu^*$  is known.
  - $F$ : Frobenius inner product of two matrices.
  - $\mathcal{F}(\mu^*)$ : the set of all fair, feasible fractional allocations under the true means  $\mu^*$ .



# Solving the LP when $\mu^*$ is known

$$\begin{aligned} Y^{\mu^*} &:= \arg \max \langle X, \hat{\mu}^* \rangle_F \\ \text{s.t. } &\langle B_\ell(\mu^*), X \rangle_F \geq c_\ell, \quad \forall \ell = 1, 2, \dots, L, \\ &\sum_{i=1}^n X_{ik} = 1, \quad \forall k = 1, 2, \dots, m, \quad X_{ik} \geq 0. \end{aligned}$$



# Nash Social Welfare (NSW)

- For a discrete allocation  $A = (A_1, A_2, \dots, A_n)$  of indivisible goods, each player  $i$  has utility  $v_i(A_i)$ .
- The **Nash Social Welfare** of allocation  $A$  is defined as:

$$\text{NSW}(A) = \left( \prod_{i=1}^n v_i(A_i) \right)^{1/n}.$$

- In the fractional setting with mean values  $\mu^*$ , player  $i$ 's utility is  $v_i(X) = \sum_{k=1}^m X_{ik} \mu_{ik}^*$ . [additive] Therefore,

$$\text{NSW}(X) = \left( \prod_{i=1}^n \sum_{k=1}^m X_{ik} \mu_{ik}^* \right)^{1/n}.$$

- NSW allocations are known to achieve *Pareto optimality* and *EF1* (envy-freeness up to one good) [e.g., Caragiannis et al., 2016].





# Nash Social Welfare (NSW) vs. Sum-of-Utilities (SW)

- **Sum-of-Utilities (SW):** The utilitarian social welfare (USW) used in this paper is  $SW(X) = \langle X, \mu^* \rangle_F = \sum_{i=1}^n \sum_{k=1}^m X_{ik} \mu_{ik}^*$ .
- Connection: NSW balances fairness (geometric mean) and efficiency; SW focuses purely on total welfare (arithmetic sum).
  - NSW  $\Rightarrow$  fairness: EF1; efficiency: PO.
- This work maximizes SW under fairness constraints (EFE or PE), rather than optimizing NSW.



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- Connection: NSW balances fairness (geometric mean) and efficiency; SW focuses purely on total welfare (arithmetic sum).
  - $NSW \Rightarrow$  fairness: EF1; efficiency: PO.
- This work maximizes SW under fairness constraints (EFE or PE), rather than optimizing NSW.
- Computational hardness:
  - Maximizing USW with EF1 is strongly NP-hard [Aziz et al. 2023].
  - Maximizing NSW is NP-hard [Lipton et al. EC'04] and APX-hard [Lee 2017]. Best known approx. ratio: 2.889 [Cole & Gkatzelis STOC'15]



Criterion	Utilitarian Social Welfare (USW) / "Welfare" in (Individual Utility)	Nash Social Welfare (NSW)
Definition (Individual/Social)	Sum of values in an agent's bundle (Individual Utility); Sum of all individual utilities (Social Welfare)	Geometric mean of agents' individual utilities (Social Welfare)
Mathematical Objective	$\sum_{j \in A_i} v_i(j)$ (for individual $i$ ) / $\sum_{i=1}^n v_i(A_i)$ (for social)	$(\prod_{i=1}^n v_i(A_i))^{1/n}$ or $\sum_{i=1}^n \log v_i(A_i)$
Primary Focus	Maximizing total aggregate utility/efficiency	Balancing efficiency with fairness/equity
Treatment of Agent Utilities	Summation; zero utility for one agent does not zero out total social welfare	Product/Geometric Mean; zero utility for one agent zeros out total NSW
Impact on Minorities/Least Satisfied Agents	Can lead to highly unequal distributions; potentially unfair to those with low values <sup>2</sup>	Encourages more balanced distributions; implicitly protects agents from receiving very low utility <sup>4</sup>
Key Properties (for maximization)	Pareto Optimal (PO) <sup>6</sup>	Pareto Optimal (PO), Envy-Freeness up to One Good (EF1), Scale-Free <sup>1</sup>
General Computational Complexity (for maximization of indivisible goods)	NP-hard <sup>1</sup> ; often requires additional constraints for fairness	NP-hard <sup>1</sup> ; challenging to approximate; FPT for small 'n' in some cases



# Fairness notions as linear constraints

Fairness in expectation relative to the mean values.

- Represent  $\langle B, X \rangle_F \geq c$  as  $(B, c)$ .
- a set if  $L$  linear constraints:  $\{B_\ell, c_\ell\}_{\ell=1}^L$   
 $\Leftrightarrow \langle B_\ell, X \rangle_F \geq c_\ell$  for all  $\ell \in [L]$ .
- $B_\ell(\mu^*)$ : a function of the mean value matrix  $\mu^*$ .



# Online Allocation Process

- Time steps  $t = 1, 2, \dots, T$ . At round  $t$ :
  - 1 An item  $j_t$  of type  $k_t \sim D$  arrives.
  - 2 The algorithm chooses a fractional allocation  $X_t = \text{ALG}(H_t)$  based on history  $H_t$ .
  - 3 The item of type  $k_t$  is given to player  $i_t$  drawn from distribution  $X_{\cdot, k_t}$ .
  - 4 The algorithm observes reward  $V_{i_t}(j_t)$  (value of that item to  $i_t$ ).
- History  $H_t = \{(k_1, i_1, V_{i_1}(j_1)), \dots, (k_{t-1}, i_{t-1}, V_{i_{t-1}}(j_{t-1}))\}$ .



# Online Item Allocation (Pseudo-code summary)

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**Algorithm 2** [Online Item Allocation]

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**Require:** ALG

- 1:  $\forall i, A_i^0 \leftarrow \{\}, H_0 \leftarrow \{\}$
  - 2: **for**  $t \leftarrow 1$  to  $T$  **do**
  - 3:      $X_t \leftarrow \text{ALG}(H_t)$
  - 4:      $k_t \sim \mathcal{D}$
  - 5:     Generate item  $j_t$  of type  $k_t$  (i.e.  $V_i(j_t) \sim N(\mu_{ik_t}^*, 1), \forall i \in N$ )
  - 6:      $i_t \leftarrow \text{Sample from } (X_t)_{k_t}^\top$
  - 7:      $A_{i_t}^t = A_{i_t}^{t-1} + \{j_t\}$
  - 8:      $H_t \leftarrow H_{t-1} + (k_t, i_t, V_{i_t}(j_t))$
  - 9: **end for**
  - 10: **return**  $A = (A_1^T, A_2^T, \dots, A_n^T)$
- 



# Multi-Armed Bandit Perspective

- There exists an arm for each player's value for each type of good.
- Pulling an arm represents allocating a specific item type to a specific player.



# Fairness Definitions (In Expectation)

## Envy-Freeness in Expectation (EFE)

For each time  $t$  and history  $H_t$ , the chosen  $X_t$  must satisfy, for every pair  $i, i' \in [n]$ :

$$\langle X_{i,\cdot}^{(t)}, \mu_i^* \rangle \geq \langle X_{i',\cdot}^{(t)}, \mu_i^* \rangle.$$

No player  $i$  expects to prefer another player's allocation over their own.

## Proportionality in Expectation (PE)

For each time  $t$  and history  $H_t$ ,  $X_t$  must also satisfy, for all  $i \in [n]$ :

$$\langle X_{i,\cdot}^{(t)}, \mu_i^* \rangle \geq \frac{1}{n} \sum_{i'=1}^n \langle X_{i',\cdot}^{(t)}, \mu_i^* \rangle.$$

Each player's expected share is  $\geq 1/n \times \{\text{they would get from all items}\}$ .





# Equivalence of EFE and PE for Two Players

When  $n = 2$ , the two fairness notions coincide:

**EFE**

$$\begin{aligned} X_1 \cdot \mu_1 &\geq X_2 \cdot \mu_1, \\ X_2 \cdot \mu_2 &\geq X_1 \cdot \mu_2. \end{aligned}$$

**PE**

$$X_i \cdot \mu_i \geq \frac{(X_1 + X_2) \cdot \mu_i}{2} = \frac{1}{2} \sum_k \mu_{ik}, \forall i.$$

$$X_2 \cdot \mu_1 = \sum_k (1 - X_{1k}) \mu_{1k} = \sum_k \mu_{1k} - X_1 \cdot \mu_1$$

$$\text{Thus, } X_1 \cdot \mu_1 \geq X_2 \cdot \mu_1 \iff X_1 \cdot \mu_1 \geq \frac{1}{2} \sum_k \mu_{1k}.$$



# Fairness Definitions (In Terms of Linear Constraints)

envy-freeness in expectation;  $\text{efe}(\mu^*) := \{(B_\ell^{\text{efe}}(\mu^*), 0)\}_{\ell=1}^{n^2}$

For every  $\ell \in [n^2]$ , construct  $B_\ell^{\text{efe}}(\mu^*)$ :

- Define  $i = \lceil \frac{\ell}{n} \rceil$  and  $i' = (\ell \bmod n) + 1$ .
- For every  $k \in [m]$ , let  $(B_\ell^{\text{efe}}(\mu^*))_{ik} = \mu_{ik}^*$  and  $(B_\ell^{\text{efe}}(\mu^*))_{i'k} = -\mu_{ik}^*$ .
- Let  $(B_\ell^{\text{efe}}(\mu^*))_{i''k} = 0$  for all  $i'' \notin \{i, i'\}$ ,  $k \in [m]$ .

proportionality in expectation;  $\text{pe}(\mu^*) := \{(B_\ell^{\text{pe}}(\mu^*), 0)\}_{\ell=1}^n$

For every  $\ell \in [n]$ , construct  $B_\ell^{\text{pe}}(\mu^*)$ :

- For every  $k \in [m]$ , let  $(B_\ell^{\text{pe}}(\mu^*))_{\ell k} = \frac{n-1}{n} \mu_{\ell k}^*$  and  $(B_\ell^{\text{pe}}(\mu^*))_{i k} = -\frac{1}{n} \mu_{\ell k}^*$  for every  $i \neq \ell$ .



# Regret

## Regret

Let  $Y^{\mu^*}$  be the optimal fair allocation (fraction) if  $\mu^*$  is known. If the algorithm uses allocations  $X_1, \dots, X_T$ , then

$$R(T) = T \langle Y^{\mu^*}, \mu^* \rangle_F - \sum_{t=1}^T \mathbb{E}[\langle X_t, \mu^* \rangle_F]$$

is the **regret** compared to the optimal fair policy.



# An Illustrating Example

Say there are  $n = 2$  players,  $m = 2$  item types, Bernoulli rewards, and WLOG  $\mu^* \in [0, 1]^{n \times m}$ . Define

$$\mu^{(1)} = \begin{pmatrix} 1/T^2 & 0 \\ 1 & 0.5 \end{pmatrix}, \quad \mu^{(2)} = \begin{pmatrix} 0 & 1/T^2 \\ 1 & 0.5 \end{pmatrix}.$$

Any EFE-satisfying algorithm must behave (nearly) uniformly to cover both cases.



# Indistinguishability Argument

- Under either  $\mu^{(1)}$  or  $\mu^{(2)}$ , Player 1's chance of “seeing an item” in any round is  $\leq 1/T^2$ .
- Over  $T$  rounds, with probability  $\geq 1/2$ , Player 1 sees no successes in both worlds (using Markov's inequality).
- Thus no strategy can, with probability  $> 1/2$ , reliably tell which of  $\mu^{(1)}, \mu^{(2)}$  holds.



# Regret of the Only Safe Allocation

- The *only* fractional allocation that remains envy-free for both instances is *Uniform-At-Random*:  $X_{ik} = 1/2$ .
- But under  $\mu^{(2)}$ , the optimal EFE allocation is

$$Y^{\mu^{(2)}} = \begin{pmatrix} 0 & 0.5 \\ 1 & 0.5 \end{pmatrix},$$

which gives Player 2 all items of type 1.

- Uniform-at-Random incurs  $\Omega(T)$  regret in this case.



$$\begin{aligned}
 \langle M^{(2)}, Y^* \rangle_F &= \left\langle \begin{pmatrix} 0 & 1/T^2 \\ 1 & 0.5 \end{pmatrix}, \begin{pmatrix} x & y \\ 1-x & 1-y \end{pmatrix} \right\rangle_F \\
 &= (1-x) + \frac{1}{2} + \left( \frac{1}{T^2} - \frac{1}{2} \right) y \\
 &\Rightarrow \max : \begin{matrix} x=0 \\ y=0.5 \end{matrix}
 \end{aligned}$$

envyness for player 1:

$$\begin{aligned}
 \frac{1}{T^2} y - (0 \cdot (1-x) + \frac{1}{T^2} \cdot (1-y)) &= \frac{1}{T^2} (y - (1-y)) \\
 &= \frac{1}{T^2} (2y - 1) \Rightarrow y \geq 0.5
 \end{aligned}$$

envyness for player 2:

$$(1-x) + \frac{1}{2} (1-y) - (1 \cdot x + \frac{1}{2} \cdot y) = \frac{3}{2} - 2x - y \Rightarrow x \leq 0.5$$



# Lower bound on means

- No algorithm can enforce envy-freeness in expectation at each round *and* achieve  $o(T)$  regret if means can be arbitrarily close to zero.
- This justifies the lower bound on means ( $\mu_{ik}^* \geq a > 0$ ) in our upper-bound results.





# Problem Statement

## Problem

- Given  $n, m, a, b$  such that  $0 < a \leq \mu_{ik}^* \leq b$  for all  $i \in [n], k \in [m]$ .
- Given a family of fairness constraints  $\left\{ \{B_\ell(\mu), c_\ell\}_{\ell=1}^L \right\}$ .

**Goal:** Design an online algorithm ALG such that, with prob.  $\geq 1 - 1/T$ ,

- ①  $X_t$  satisfies EFE (or PE) at every round  $t$  (fairness).
- ②  $R(T) = o(T)$  sublinear; specifically, achieve  $\tilde{O}(T^{2/3})$  regret.



# Property 1: Equal Treatment Guarantees Fairness

- If players involved in a constraint share **identical**  $X_{i,\cdot}$ , the fairness constraint holds.

## Property 1

For any  $\ell \in [L]$ , suppose that a fractional allocation  $X \in \mathbb{R}^{n \times m}$  satisfies  $X_{i_1} = X_{i_2}$  for any  $i_1, i_2 \in \{i : B_\ell(\mu)_i \neq \mathbf{0}\}$ . Then,  $\langle B_\ell(\mu), X \rangle_F \geq c_\ell$ .

- **Uniform-at-Random (UAR)** ( $X_{ik} = 1/n$ ) satisfies all EFE and PE constraints.
- Ensure safe exploration: allocate **uniformly** to remain fair without any knowledge.



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- Ensure safe exploration: allocate **uniformly** to remain fair without any knowledge.

## Observation 1

The EFE and PE constraints satisfy Property 1.



# Explicit Constraint Formulation: Cake Example



## Explicit Constraint Formulation: Cake Example

Define fractional allocations and valuations:

$$X = \begin{pmatrix} X_{\text{Alice}, \text{Orange}} & X_{\text{Alice}, \text{Blue}} \\ X_{\text{Bob}, \text{Orange}} & X_{\text{Bob}, \text{Blue}} \end{pmatrix}, \quad \mu = \begin{pmatrix} 3 & 2 \\ 1 & 3 \end{pmatrix}$$

**Envy-Freeness Constraints (EFE)** expressed as  $\langle B_\ell(\mu), X \rangle_F \geq c_\ell$ :

$$B_1(\mu) = \begin{pmatrix} 3 & 2 \\ -3 & -2 \end{pmatrix}, \quad c_1 = 0, \quad B_2(\mu) = \begin{pmatrix} -1 & -3 \\ 1 & 3 \end{pmatrix}, \quad c_2 = 0$$

These matrices illustrate Property 1:

- (Property 1) Equal allocations ( $X_{A,O} = X_{B,O}$ ,  $X_{A,B} = X_{B,B}$ ) imply constraints hold trivially.



## Property 2: Near-Optimal Fair Allocation with Slack

### Property 2

- For the optimal fair allocation  $Y^{\mu^*}$ , there exists an  $X'$  such that:
  - ①  $\langle X', \mu^* \rangle_F \geq \langle Y^{\mu^*}, \mu^* \rangle_F - O(\gamma)$  (near-optimal),
  - ② For each fairness constraint  $\ell$ , either:
    - $\langle B_\ell(\mu^*), X' \rangle_F \geq c_\ell + \gamma$  (slack  $\gamma$ ),
    - or all players involved in constraint  $\ell$  have equal allocation in  $X'$  (Property 1 holds).
- Key for handling unknown  $\mu^*$ : we can tolerate small estimation errors and still find a feasible fair  $X'$ .



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  - 2 For each fairness constraint  $\ell$ , either:
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    - or all players involved in constraint  $\ell$  have equal allocation in  $X'$  (Property 1 holds).
- Key for handling unknown  $\mu^*$ : we can tolerate small estimation errors and still find a feasible fair  $X'$ .
- The loss  $O(\gamma)$  has a (hidden) factor of  $O(n^3)$  and  $\gamma = O(T^{-1/3})$ .



## Property 3: Lipschitz Continuity of Constraints

- The fairness constraints (EFE/PE) depend linearly on  $\mu$ .
- Thus, for any  $X$ , if  $\|\mu - \mu'\|_1 \leq \epsilon$ , then:

$$|\langle B_\ell(\mu), X \rangle_F - \langle B_\ell(\mu'), X \rangle_F| \leq K\epsilon$$

- Implies that if  $X$  satisfies a constraint for  $\mu$ , then for any  $\mu'$  close by,  $X$  still nearly satisfies it.

### Property 3

There exists  $K > 0$  such that  $\forall \mu, \mu' \in [a, b]^{n \times m}$ ,  $\forall X$  and  $\forall \epsilon > 0$ , if  $\|\mu - \mu'\|_1 \leq \epsilon$ , then  $\|\langle B_\ell(\mu), X \rangle_F - \langle B_\ell(\mu'), X \rangle_F\|_1 \leq K\epsilon$ .





## Property 4: Invariance of Constraint Structure

- For a given constraint  $\ell$  (e.g., envy between  $i$  and  $i'$ ), the *set of players* it compares does not depend on the actual  $\mu$ .
- The indices appearing in  $B_\ell(\mu)$  (the non-zero rows) are fixed.
- Ensures we know exactly which players each constraint refers to, regardless of unknown means.

### Property 4

For any  $\mu, \mu' \in [a, b]^{n \times m}$ ,  $\{i : B_\ell(\mu)_i \neq \mathbf{0}\} = \{i : B_\ell(\mu')_i \neq \mathbf{0}\}$ .



# Explicit Constraint Formulation: Cake Example

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**Envy-Freeness Constraints (EFE)** expressed as  $\langle B_\ell(\mu), X \rangle_F \geq c_\ell$ :

$$B_1(\mu') = \begin{pmatrix} 4 & 1 \\ -4 & -1 \end{pmatrix}, \quad c_1 = 0, \quad B_2(\mu') = \begin{pmatrix} -2 & -5 \\ 2 & 5 \end{pmatrix}, \quad c_2 = 0$$

These matrices illustrate Property 4:

- (Property 4) The locations of nonzero entries are independent of actual valuations.



## Lemmas for Property 2

### Lemma 1 (EFE satisfies Property 2)

There is a constructive algorithm (Algorithms 3 & 4) that transforms the optimal envy-free allocation  $Y^{\mu^*}$  into an allocation  $X'$  satisfying Property 2.

- It uses “**envy-with-slack- $\alpha$** ” graphs, equivalence classes, and iterative merging/removal steps to ensure either slack or equal treatment, while losing only  $O(\gamma)$  welfare.

### Lemma 2 (PE satisfies Property 2)

The family of PE constraints satisfies Property 2.

- Check total slack in the proportionality constraints. One can either directly use  $X' = \text{UAR}$  if slack is small, or transfer allocations from high-slack players to a communal pot and **redistribute evenly** if slack is large.



# Proof Sketch of Lemma 1

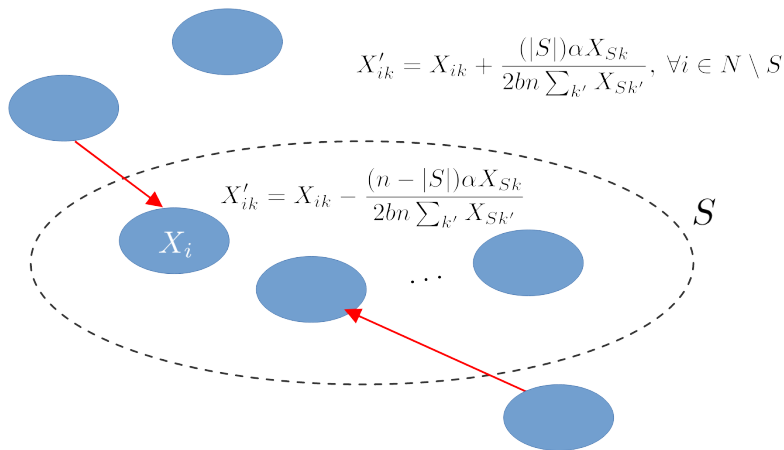
- envy-with-slack- $\alpha$  graphs: track whether a player prefers their allocation by at least  $\alpha$  over another players' allocation.
- Given  $\mu, X, \alpha$ , construct a graph with a set  $N$  of vertices, a set  $E$  of edges such that a directed edge from  $i$  to  $i' \Leftrightarrow X_i \cdot \mu_i - X_{i'} \cdot \mu_i < \alpha$ .
  - The weight of such edge:  $X_i \cdot \mu_i - X_{i'} \cdot \mu_i$ .
- Construct such graphs with progressively smaller  $\alpha$ , for  $\alpha \geq \gamma$ .
- The algorithm operates on sets of nodes: **equivalence classes**.
  - Every pair of nodes in an equivalence class has **the same allocation**.
- The algorithm makes progress in every iteration by either
  - 1 **merging** two equivalence classes, or
  - 2 **removing an edge** from the graph.



## Algorithm 3: Envy-with-Slack Refinement (Overview)

- Maintain an “envy-with-slack- $\alpha$ ” directed graph whose nodes are players and edges  $i \rightarrow i'$  mean player  $i$ 's slack over  $i'$  is **less than  $\alpha$** .
- Track **equivalence classes** of players with identical allocations.
  - Each node in the graph is actually an equivalence class.
- Repeatedly do one of three operations to remove edges or merge classes:
  - 1 **remove-incoming-edge**: If a class  $S$  has in-edges but no out-edges, transfer its allocation to all other players to eliminate all in-edges.
  - 2 **cycle-shift**: Find a directed cycle (each points to **minimal**-slack neighbor). If some  $i^*$  has edges only to some but NOT all members of the cycle, split each cycle member's allocation half-half with its successor to remove one out-edge.
  - 3 **average-clique**: Otherwise, merge all classes in the cycle into one class, averaging their allocations.

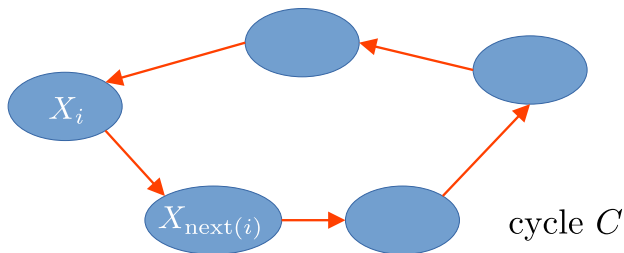




$$X'_{ik} = X_{ik} + \frac{(|S|)\alpha X_{Sk}}{2bn \sum_{k'} X_{Sk'}}, \forall i \in N \setminus S$$

$$X'_{ik} = X_{ik} - \frac{(n - |S|)\alpha X_{Sk}}{2bn \sum_{k'} X_{Sk'}}$$

$$X'_{ik} = \frac{1}{2} (X_{ik} + X_{\text{next}(i)k}), \forall i \in V(C)$$



## Merging two equivalence classes

- Merge two equivalence classes  $S$  and  $T$ : for each item type  $k$ ,

$$X_k = \frac{1}{|S| + |T|} \left( \sum_{i \in S} X_{ik} + \sum_{j \in T} X_{jk} \right).$$

- ★ This operation might incur envy with respect to some equivalence class  $U \notin S \cup T$ .





## Algorithm 4: Envy Removal Subroutine

- After merging (average-clique), envy may appear along some edges.
- Repeatedly find a directed cycle in the envy graph where each edge has non-negative envy.
- Rotate allocations along that cycle: each node takes its successor's allocation.
- This strictly reduces the number of envious edges and preserves the number of slack-edges.
- Welfare loss per call is bounded by  $O(\alpha)$ .



## Termination and Complexity of Algorithm 3 + 4

- Start with an envy-free allocation. Each iteration removes either:
  - At least one edge from the slack graph (every  $n$  steps), or
  - At least one envious edge via Algorithm 4.
- There are at most  $n^2$  edges total, so after  $O(n^3)$  iterations all edges gone.
- Final allocation has slack  $\geq \gamma$  on all constraints or equal treatment, satisfying Property 2.
- Total welfare loss is  $O(\gamma)$ , as each iteration costs at most  $O(\gamma)$ .



## Proof Sketch of Lemma 2 (for PE)

- Define the slack  $S_i := Y_i^\mu \cdot \mu_i - \frac{1}{n} \|\mu_i\|_1$  of player  $i$ .
- **Case 1:**  $\sum_{i=1}^n S_i \leq \frac{b}{a} n\gamma$ .
  - Take  $X' = \text{UAR}$ .
- **Case 2:**  $\sum_{i=1}^n S_i > \frac{b}{a} n\gamma$ .
  - Define  $\Delta_{ik} = \frac{Y_{ik}^\mu}{\sum_{k'=1}^m Y_{ik'}^\mu} \cdot \frac{S_i}{\sum_{i'=1}^n S_{i'}} \cdot \frac{n\gamma}{a}$ .
  - Construct  $X'$  as  $X'_{ik} := Y_{ik}^\mu - \Delta_{ik} + \frac{1}{n} \sum_{i'=1}^n \Delta_{i'k}$  (redistribution).
  - By carefully deductions, we can prove that
    - $X'_i \cdot \mu_i - \frac{1}{n} \|\mu_i\|_1 \geq \gamma$ .
    - $\langle Y^\mu, \mu \rangle_F - \langle X', \mu \rangle_F \leq \frac{b}{a} n\gamma$ .



# The main algorithm



# Algorithm 1: Fair Explore-Then-Commit (Fair-ETC)

**Input:**  $n, m, T$ . Bounds  $a \leq \mu_{ik}^* \leq b$ . Fairness constraints  $\{(B_\ell(\mu), c_\ell)\}_{\ell=1}^L$ .

## 1 Explore Phase (Rounds $t = 1$ to $T^{2/3} - 1$ ):

- Use Uniform-at-Random:  $X_t(i, k) = 1/n$  for all  $i, k$ .
- Collect observations: Let  $N_{ik} = \#$  times player  $i$  got type- $k$  item.
- Compute empirical means  $\hat{\mu}_{ik} = (1/N_{ik}) \sum V_i(j)$  over those samples.
- Set confidence radius  $\epsilon_{ik} = \sqrt{\frac{\log^2(4Tnm)}{2N_{ik}}}$ .

## 2 Commit Phase (Rounds $t = T^{2/3}$ to $T$ ):

- Define confidence set  $\hat{\mu} \pm \epsilon$  (i.e.,  $\mu^* \in [\hat{\mu}_{ik} \pm \epsilon_{ik}] \forall i, k$  with prob.  $1 - 1/T$ ).
- Solve the semi-infinite LP:

$$X^{\hat{\mu}} = \arg \max_X \langle X, \hat{\mu} \rangle_F$$

$$\text{s.t. } \langle B_\ell(\mu), X \rangle_F \geq c_\ell, \quad \forall \ell = 1, 2, \dots, L, \quad \forall \mu \in [\hat{\mu} \pm \epsilon],$$

$$\sum_{i=1}^n X_{ik} = 1, \quad \forall k = 1, 2, \dots, m, \quad X_{ik} \geq 0.$$

- For each subsequent round, use fixed fractional allocation  $X_t = X^{\hat{\mu}}$ .



# Implementation Details

- The exploration phase yields  $N_{ik} = \Omega(T^{2/3})$  samples for each  $(i, k)$  w.h.p.
  - Thus  $\epsilon_{ik} = O(T^{-1/3}\sqrt{\log T})$ ,  $\|\epsilon\|_1 = \tilde{O}(T^{-1/3})$ .
- The LP has infinitely many constraints.
- However, since each constraint is linear in  $\mu$ , it suffices to enforce it at extreme points of  $[\hat{\mu} \pm \epsilon]$  — a finite (exponential) set.
- Alternatively, use a separation oracle + ellipsoid method to solve in polynomial time.
- Key property: any  $X'$  from Lemma 1 & 2 is feasible for the LP, so the LP is not empty.
- The solution  $X^{\hat{\mu}}$  ensures fairness for all  $\mu$  in  $\hat{\mu} \pm \epsilon$ , so in particular for  $\mu^*$  w.h.p.



# Linear Dependence on $\mu$ & Finite Constraint Reduction

- Suppose each fairness constraint has the form

$$\langle B(\mu), X \rangle_F = \sum_{i,k} (\beta_{ik} \mu_{ik}) X_{ik} = \sum_{i,k} \alpha_{ik} \mu_{ik}.$$

- As a function of  $\mu$ , this is just the linear map  $\mu \mapsto \sum_{i,k} \alpha_{ik} \mu_{ik}$ .
- We require this to hold for *all*  $\mu$  in the confidence region

$$[\hat{\mu} - \epsilon, \hat{\mu} + \epsilon]:$$

$$\sum_{i,k} \alpha_{ik} \mu_{ik} \geq c \quad \forall \mu \in [\hat{\mu} - \epsilon, \hat{\mu} + \epsilon].$$

- A linear functional achieves its minimum over a convex polytope at one of the polytope's *vertices*  $\Rightarrow$  enforce  $\sum_{i,k} \alpha_{ik} \mu_{ik} \geq c$  only at the finitely many (i.e.,  $2^{nm}$ ) extreme points of the hyperrectangle  $[\hat{\mu} \pm \epsilon]$ .



# Theorem 1: Regret Upper Bound (Main Theorem)

## Theorem 1

With probability  $1 - 1/T$ , Fair-ETC achieves:

- $X_t$  satisfies fairness constraints (EFE or PE) for all rounds  $t$
- $R(T) = O(T^{2/3} \log T)$





## Proof Sketch of Theorem 1 (1/2)

- 1 **Exploration Phase Regret:** Each of the first  $T^{2/3}$  rounds uses UAR instead of  $Y^{\mu^*}$ . Regret per round at most  $b$ , so total  $O(T^{2/3})$ .
- 2 **High-Probability Event:** UAR sampling yields  $N_{ik} = \Omega(T^{2/3})$  for each  $(i, k)$ . Then  $|\hat{\mu}_{ik} - \mu_{ik}^*| \leq \epsilon_{ik} = \tilde{O}(T^{-1/3})$  w.p.  $\geq 1 - \frac{1}{T}$  (Hoeffding's inequality).
- 3 **Existence of Near-Optimal  $X'$ :** By Property 2 (Lemma 1 & 2), there is  $X'$  with  $\langle X', \mu^* \rangle \geq \langle Y^{\mu^*}, \mu^* \rangle - O(T^{-1/3})$  that satisfies constraints for  $\mu^*$ .



## Proof Sketch of Theorem 1 (2/2)

- 5 **Robustness to Estimation:** By Property 3,  $X'$  satisfies constraints for all  $\mu \in [\hat{\mu} \pm \epsilon]$  because slack  $\gamma$  can dominate  $K\|\epsilon\|_1 = O(T^{-1/3} \log T)$ ; or by equality in Property 2 and Property 4,  $X'$  remains feasible.
- 6 **Commit Phase Regret:** The LP solution  $\hat{X}$  has welfare at least  $\langle X', \hat{\mu} \rangle$ . Relate  $\langle X', \hat{\mu} \rangle$  to  $\langle Y^{\mu^*}, \mu^* \rangle$  via Lipschitz bounds:

$$\begin{aligned} \langle Y^{\mu^*}, \mu^* \rangle_F - \langle \hat{X}, \mu^* \rangle_F &= \langle Y^{\mu^*}, \mu^* \rangle_F - \langle X', \mu^* \rangle_F + \langle X', \mu^* \rangle_F - \langle \hat{X}, \mu^* \rangle_F \\ &\leq \langle Y^{\mu^*}, \mu^* \rangle_F - \langle X', \mu^* \rangle_F + (\langle X', \hat{\mu} \rangle_F - \langle \hat{X}, \hat{\mu} \rangle_F) K\|\epsilon\|_1 \\ &= O(T^{-1/3} \log T). \end{aligned}$$

Thus per-round loss in commit phase is  $O(T^{-1/3} \log T)$ . Over  $T$  rounds, gives  $O(T^{2/3} \log T)$ .



## Theorem 2: Regret Lower Bound

### Theorem 2

There exists  $a, b, n, m$  such that **NO** algorithm can, for all  $\mu^* \in [a, b]^{n \times m}$ , both satisfy EFE constraints (PE, resp.) and achieve **regret**  $< \frac{T^{2/3}}{\log T}$  w.p.  $\geq 1 - 1/T$ .



## Proof Idea of Theorem 2

Construct two instances  $(\mu^{(1)} \text{ \& } \mu^{(2)})$  on  $n = 2$  players,  $m = 2$  types:

$$\mu^{(1)} = \begin{pmatrix} 2 & 3 \\ 1 & 1 \end{pmatrix} \quad , \quad \mu^{(2)} = \begin{pmatrix} 2 & 3 \\ 1 & 1 + T^{-1/3} \end{pmatrix} .$$

- For  $\mu^{(1)}$ :
  - Optimal EFE gives all type-1 items to Player 2 and all type-2 items to Player 1.
- For  $\mu^{(2)}$ :

In  $\mu^{(2)}$ , to be envy-free, we must give some type-2 items to Player 2. In  $\mu^{(1)}$ , giving type-2 to Player 2 is suboptimal. Distinguishing these requires  $\Omega(T^{2/3})$  samples of type-2 by Player 2. Hence any fair algorithm suffers  $\Omega(T^{2/3})$  regret in at least one instance.



# Open Questions

- **Poly( $n, m$ ) Regret:** Can we avoid exponential dependence on  $n$  and  $m$  in regret for EFE?
- **$\sqrt{T}$ -Regret?** Is  $\tilde{O}(\sqrt{T})$  possible if optimal fair solution has slack?
- **Other Fairness Notions:** Extend to equitability, EFX, MMS, etc.
- **Wider Applications:** Online cake cutting, resource scheduling with fairness, etc.
- **Dealing with changing  $\mu_t$ ?**
- **Gradient-based approaches?**



# Thank you!

## Questions & Discussions



# Thank you!

## Questions & Discussions

Why use the title “honor among bandits”??





## 龍與地下城：盜賊榮耀

*Dungeons & Dragons: Honor Among Thieves*



電影海報

<https://tinyurl.com/yxfpxd86>

