Online Linear Programming: Applications and Extensions

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Linear Programming

$$\begin{array}{lll} \text{maximize}_{\mathbf{x}} & \sum_{t=1}^{n} r_t x_t & \\ \text{subject to} & \sum_{t=1}^{n} \mathbf{a}_t x_t \leq \mathbf{b}, & \\ & 0 \leq x_t \leq 1, & \forall t = 1, ..., n. \end{array}$$

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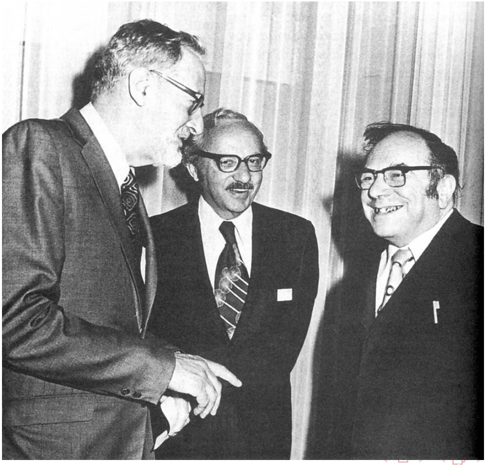

Online Linear Programming: A Toy Example

Consider an auction/revenue-management problem:

	Bid 1($t=1$)	Bid 2($t=2$)	.....	Inventory($\mathbf{b}$)
Reward(r_t)	\$100	\$30	...	
Decision	x_1	x_2	...	
Pants	1	0	...	100
Shoes	1	0	...	50
T-shirts	0	1	...	500
Jackets	0	0	...	200
Hats	1	1	...	1000

where the decision for each customer/bidder is "accept" ($x_t = 1$) or "reject" ($x_t = 0$)

Offline vs. Online Linear Programming

$$
\begin{array}{lll}
OPT(A,\mathbf{r}) := & \text{maximize}_{\mathbf{x}} & \sum_{t=1}^{n} r_t x_t \\
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$$

- r_t: reward/revenue offered by the t-th customer/order
- $\mathbf{a}_t \in R^m$: the bundle of resources requested by the t-th order
- x_t: acceptance or rejection decision to the t-th order
- $\mathbf{b} \in R^m$: initially available budget/resource amounts
- The objective $\sum_{t=1}^{n} r_t x_t$: the total collected revenue.

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- the bidder data $(r_t, \mathbf{a}_t)$ arrive sequentially.
- an irrevocable decision must be made as soon as an order arrives (without knowing the future data).
- Conform to resource capacity constraints at the end.

Price Mechanism for OLP I

The problem would be easy if there are "ideal itermized prices":

	Bid 1($t = 1$)	Bid 2($t = 2$)	.....	Inventory($\mathbf{b}$)	$\mathbf{p}^*$
Bid(r_t)	\$100	\$30	...		
Decision	$x_1 = 0$	$x_2 = 1$	...		
Pants	1	0	...	100	\$45
Shoes	1	0	...	50	\$45
T-shirts	0	1	...	500	\$10
Jackets	0	0	...	200	\$55
Hats	1	1	...	1000	\$15

so that the online decision can be made by comparing the reward and "bundle cost" for each bid.

Primal and Dual Offline LPs

$$P: \quad \begin{array}{ll} \max & \mathbf{r}^\top \mathbf{x} \\ \text{s.t.} & A\mathbf{x} \le \mathbf{b} \\ & \mathbf{0} \le \mathbf{x} \le \mathbf{e} \end{array} \qquad D: \quad \begin{array}{ll} \min & \mathbf{b}^\top \mathbf{p} + \mathbf{e}^\top \mathbf{s} \\ \text{s.t.} & A^\top \mathbf{p} + \mathbf{s} \ge \mathbf{r} \\ & \mathbf{p} \ge \mathbf{0}, \mathbf{s} \ge \mathbf{0} \end{array}$$

where the decision variables are $\mathbf{x} \in R^n$, $\mathbf{p} \in R^m$, $\mathbf{s} \in R^n$, where $\mathbf{e}$ is the vector of all ones.

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Denote the primal/dual optimal solution as $\mathbf{x}^*$, $\mathbf{p}^*$, $\mathbf{s}^*$, then LP duality/complementarity theory tells that for $t = 1, ..., n$,

$$x_t^* = \begin{cases} 1, & r_t > \mathbf{a}_t^\top \mathbf{p}^* \\ 0, & r_t < \mathbf{a}_t^\top \mathbf{p}^* \end{cases}$$

(few x_t^* may take non-integer value when $r_t = \mathbf{a}_t^\top \mathbf{p}^*$).

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(few x_t^* may take non-integer value when $r_t = \mathbf{a}_t^\top \mathbf{p}^*$).

Online LP algorithms are based on learning $\mathbf{p}^*$ by dynamically solving small sample-sized LPs based on revealed data.

Simple Price-Learning Algorithm

We illustrate a simple Learning Algorithm:

- Set $x_t = 0$ for all $1 \leq t \leq \epsilon n$ and average allocation per bidder/buyer: $\mathbf{d} = \mathbf{b}/n$;

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and get the optimal dual solution $\hat{\mathbf{p}}$;

- Determine the future allocation x_t as:

$$x_t = \begin{cases} 0 & \text{if } r_t \leq \hat{\mathbf{p}}^T \mathbf{a}_t \\ 1 & \text{if } r_t > \hat{\mathbf{p}}^T \mathbf{a}_t \end{cases}$$

One may update the prices periodically and/or set $x_t = 0$ as soon as a resource is exhausted.

Data/Model Assumptions for Analyses

Stochastic Input (i.i.d) Model:

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Both assume boundedness:

(b) $|r_t| \leq \bar{r}$ and $\|\mathbf{a}_t\|_\infty \leq \bar{a}$ for all t

(c) The right-hand-side $\mathbf{b} = n \cdot \mathbf{d}(> \mathbf{0})$ in Regret Analysis.

Early work assumes $r_t \geq 0, \mathbf{a}_t \geq 0$ (knapsack or one-sited market).

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- What are the necessary and sufficient conditions on the right-hand-side $\mathbf{b}$ to achieve $(1-\epsilon)$-competitive ratio of the expected total online reward over the optimal total offline reword OPT for all $(A, \mathbf{r})$?

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- If the right-hand-side $\mathbf{b} = O(n)$, what is the best achievable sublinear gap or regret between the two?

Competitive Ratio Summary of One-Sited Market

The conditions to design $(1-\epsilon)$-competitive online algorithms based on $B = \min_i b_i$:

	Sufficient Condition
Kleinberg (2005)	$B \geq \frac{1}{\epsilon^2}$ for $m = 1$
Devanur et al (2009)	$OPT \geq \frac{m^2 \log n}{\epsilon^3}$
Feldman et al (2010)	$B \geq \frac{m \log n}{\epsilon^3}$ and $OPT \geq \frac{m \log n}{\epsilon}$
Agrawal/Wang/Y (2010,14)	$B \geq \frac{m \log n}{\epsilon^2}$ or $OPT \geq \frac{m^2 \log n}{\epsilon^2}$
Molinaro/Ravi (2013)	$B \geq \frac{m^2 \log m}{\epsilon^2}$
Kesselheim et al (2014)	$B \geq \frac{\log m}{\epsilon^2}$
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	Necessary Condition
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Remarks

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- The optimal online algorithms have been designed for the competitive ratio analyses and for one-sited market and random permutation data model!
- Recent focuses are on dealing with
  - two-sited markets/platforms, dual convergence, and regret analyses, and simple and fast algorithms,
  - online algorithm with interior-point LP solver,
  - extensions to bandit models and the Fisher market,
  - regret analysis with non i.i.d. input data.

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Regret Analysis

Let "offline" optimal solution be $\mathbf{x}^*$ and "online" solution of n orders be $\mathbf{x}_n$, and

$$R_n^* = \sum_{j=1}^{n} r_j x_j^*, \quad R_n = \sum_{j=1}^{n} r_j x_j.$$

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$$R_n^* = \sum_{j=1}^{n} r_j x_j^*, \quad R_n = \sum_{j=1}^{n} r_j x_j.$$

Then define

$$\Delta_n = \sup \mathbb{E}\left[R_n^* - R_n\right], \quad v(\mathbf{x}) = \sup \mathbb{E}\left[\| (A\mathbf{x} - \mathbf{b})^+ \|_2\right]$$

where the expectation is taken with respect to i.i.d distribution or random permutation, and the sup operator is over all permissible distributions and admissible data.

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where the expectation is taken with respect to i.i.d distribution or random permutation, and the sup operator is over all permissible distributions and admissible data.

Remark: A bi-criteria performance measure, but one can easily modify the algorithms by early stopping such that the constraints are always satisfied at the end of the process.

Equivalent Form of the Dual Problem

Recall the dual problem

$$\min \ \mathbf{b}^\top \mathbf{p} + \sum_{t=1}^{n} s_t \quad \text{s.t. } s_t \ge r_t - \mathbf{a}_t^\top \mathbf{p}, \forall t; \quad \mathbf{p}, \mathbf{s} \ge \mathbf{0}$$

can be rewritten as

$$\min \ \mathbf{b}^\top \mathbf{p} + \sum_{t=1}^{n} \left(r_t - \mathbf{a}_t^\top \mathbf{p} \right)^+ \quad \text{s.t. } \ \mathbf{p} \ge \mathbf{0}$$

where $(\cdot)^+$ is the positive-part or ReLU function.

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where $(\cdot)^+$ is the positive-part or ReLU function.

After normalizing the objective, it becomes

$$\min_{\mathbf{p} \geq \mathbf{0}} \mathbf{d}^\top \mathbf{p} + \frac{1}{n} \sum_{t=1}^{n} \left(r_t - \mathbf{a}_t^\top \mathbf{p} \right)^+$$

which can be viewed as a simple-sample-average (SSA) (with n sample points) of a stochastic optimization problem under an i.i.d distribution.

Convergence of Sample Dual $\mathbf{p}_n^*$

Theorem (Li & Y (2019, OR 2021))

Denote the n-sample SSA optimal solution by $\mathbf{p}_n^*$. Then, for the stochastic input model under moderate conditions that guarantee a local strong convexity of the underlying stochastic program $f(p)$ around its optimal solution $\mathbf{p}^*$, there exists a constant C such that

$$\mathbb{E}\|\mathbf{p}_n^* - \mathbf{p}^*\|_2^2 \leq \frac{Cm \log \log n}{n}$$

holds for all $n > m$.

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This is L_2 convergence for the dual optimal solution. Heuristically,

$$\mathbf{p}_n^* \approx \mathbf{p}^* + \frac{1}{\sqrt{n}} \cdot \textbf{Noise}$$

Dual-Gradient Online Algorithm for Binary LP

LP-Solver Free Method:

1: Input: $\mathbf{d} = \mathbf{b}/n$ and initialize $\mathbf{p}_1 = \mathbf{0}$

2: For $t = 1, 2, ..., n$

$$x_t = \begin{cases} 1, & \text{if } r_t > \mathbf{a}_t^\top \mathbf{p}_t \\ 0, & \text{if } r_t \le \mathbf{a}_t^\top \mathbf{p}_t \end{cases}$$

3: Compute

$$\begin{cases} \mathbf{p}_{t+1} = \mathbf{p}_t + \gamma_t \left(\mathbf{a}_t x_t - \mathbf{d} \right) \\ \mathbf{p}_{t+1} = \mathbf{p}_{t+1}^{+} \end{cases}$$

4: $\mathbf{x} = (x_1, ..., x_n)$

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Line 5 performs (projected) stochastic gradient descent in the dual, where step-size $\gamma_t = \frac{1}{\sqrt{n}}$ or $\gamma_t = \frac{1}{\sqrt{t}}$.

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This seems a classical online convex optimization algorithm, but the analysis is on $\mathbf{r}^T\mathbf{x}$ where $\mathbf{x}$ is obtained onlinely.

Performance Analysis

Theorem (Li, Sun & Y (2020, NeurIPS))

With step size $\gamma_t = 1/\sqrt{n}$, the regret and expected constraint violation of the algorithm satisfy

$$\mathbb{E}[R_n^* - R_n] \leq \tilde{O}(m\sqrt{n}), \quad \mathbb{E}\,[v(\mathbf{x})] \leq \tilde{O}(m\sqrt{n}).$$

under both the stochastic input and the random permutation models of two-sited data.

- $\tilde{O}$ omits the logarithm terms and the constants related to $(\bar{a}, \bar{r})$, but the algorithm does not require any prior knowledge on the constants.
- The optimal offline reward is in the range $O(mn)$.
- The algorithms runs in nm times - the time to read in the data.

Adaptive Fast Online Algorithm for Binary LP

1: Initialize $\mathbf{b}_1 = \mathbf{b}$ and $\mathbf{p}_1 = \mathbf{0}$

2: For $t = 1, 2, ..., n$

$$x_t = \begin{cases} 1, & \text{if } r_t > \mathbf{a}_t^\top \mathbf{p}_t \\ 0, & \text{if } r_t \leq \mathbf{a}_t^\top \mathbf{p}_t \end{cases}$$

3: Compute

$$\begin{aligned} \mathbf{p}_{t+1} &= \mathbf{p}_t + \gamma_t \left(\mathbf{a}_t x_t - \tfrac{1}{n-t+1} \mathbf{b}_t \right) \\ \mathbf{p}_{t+1} &= \mathbf{p}_{t+1} \vee \mathbf{0} \end{aligned}$$

4: Update remaining inventory: $\mathbf{b}_{t+1} = \mathbf{b}_t - \mathbf{a}_t x_t$.

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5: Return $\mathbf{x} = (x_1, ..., x_n)$

Only Difference: The average allocation vector $\mathbf{b}/n$ in Step 3 is adaptively replaced based on the previous realizations/decisions – this is a non-stationary approach.

Nonadaptive vs. Adaptive

The first resource (sequential) usages in 10 runs of the algorithms.

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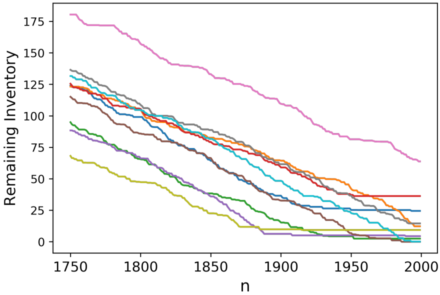

Figure: Nonadaptive

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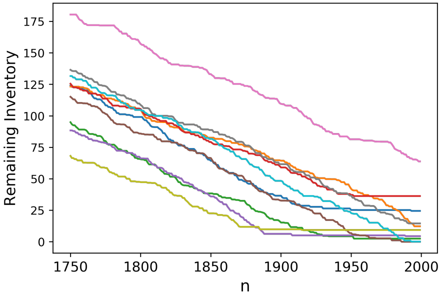

Figure: Nonadaptive

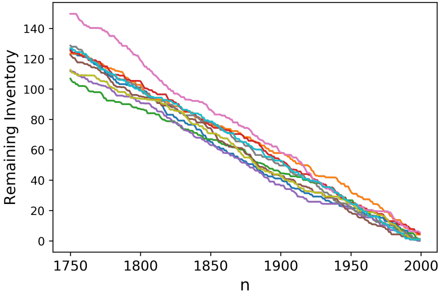

Figure: Adaptive

Fast Algorithm as a Pre-Solver for the Offline LP Solver Development

More precisely, the fast online LP solution can be interpreted as a presolver and establish a "score" of how likely a variable is to be optimal basic (nonzero).

We run online algorithm to obtain $\hat{\mathbf{x}}$, set a threshold ε and select the columns in $\mathbb{I}_{\{\hat{\mathbf{x}}>\varepsilon\}}$ in the column-generation scheme. For a benchmark LP problem in the Mittelmann's Simplex Benchmark, this reduces solution time from hundreds to 8 seconds (or 3 seconds by IPM).

This technique has been adopted in the emerging LP solver COPT - one of the state of art LP solvers nowadays.

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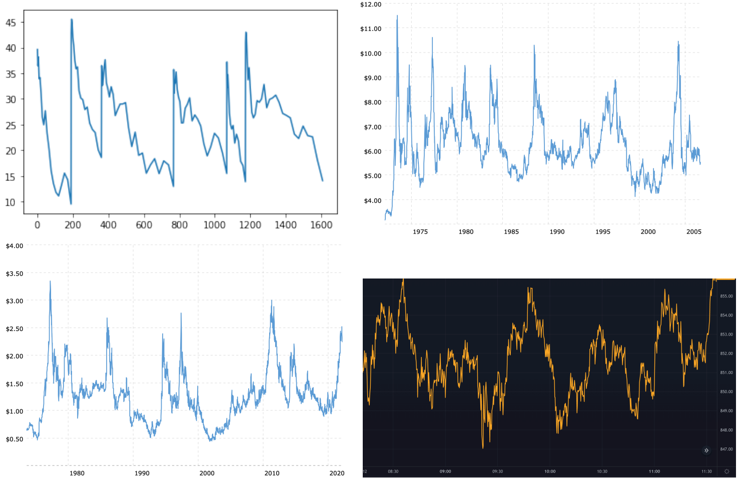
Are other types of data learn-able?

Regenerative Data of Different Scales

Figure: 1) Simulated Regenerative Data; 2)Soybean price (years); 3) Coffee Price (years); 4) TSLA (15 seconds)



Regenerative Dual Convergence, Owen Shen 2022

Theorem (Regenerative Dual Convergence)

Suppose $\mathbf{a}_t$ *follows an i.i.d process and* r_j *follows a regenerative process with bounded regenerative time, and under the same boundedness and non-degeneracy assumptions as in the i.i.d Dual Convergence Theorem, there exists a constant* C *such that*

$$\mathbb{E}\left[\|\boldsymbol{p}_n^* - \boldsymbol{p}^*\|_2^2\right] \leq \frac{Cm \log m \log \log n}{n}$$

holds for all $n \geq \max\{m, 3\}, m \geq 2$. *Additionally,*

$$\mathbb{E}\left[\|\boldsymbol{p}_n^* - \boldsymbol{p}^*\|_2\right] \leq C\sqrt{\frac{m \log m \log \log n}{n}}$$

.

Regrets for Online Algorithms

Since the regenerative data has the same dual convergence rate, we can show the regrets are as well bounded by the same order :

Theorem (Regenerative Regret by Using Optimal Stochastic Prices)

With the online policy π_1 specified by Algorithm 1 with regenerative data,

$$\Delta_n \leq O(\sqrt{n})$$

Theorem (Regenerative Regret by LP Learning)

With the online policy π_2 specified by Algorithm 2 with regenerative data,

$$\Delta_n \leq O(\sqrt{n} \log n)$$

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A "Solution-Uniqueness" Assumption in Online LP Algorithm

A Common Assumption: the learning target, solution of the offline LP problem, is unique or non-generate.

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Let T bidders (changed from n as in the literature) bidders have a finite types, $i = 1, ..., K$, with $\mathbb{P}((r_t, \mathbf{a}_t) = (\mu_i, \mathbf{c}_i)) = p_i$ (unknown to the decision maker). Then, the offline problem reduces to:

$$\max \sum_{i=1}^{K} p_i \mu_i y_i \quad \text{s.t.} \quad \sum_{i=1}^{K} p_i \mathbf{c}_i y_i \leq \mathbf{b}/T, \quad y_i \in [0, 1]$$

where y_i is the acceptance rate/probability for customer type i (some are zeros or "nonbasic"!)

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	Benchmark	Regret Bound	Key Assumption(s)
Jasin and Kumar (2012)	Fluid	Bounded	Nondeg., distrib. known
Jasin (2015)	Fluid	$\tilde{O}(\log T)$	Nondeg.
Vera et al. (2019)	Hindsight	Bounded	Distrib. known
Bumpensanti and Wang (2020)	Hindsight	Bounded	Distrib. known
Asadpour et al. (2019)	Full flex.	Bounded	Long-chain, ξ-Hall condition
Chen, Li & Y (2021)	Fluid	Bounded	Partial Nondeg.

Behavior of the Simplex and Interior-Point

The key in Chen et al. (2021) paper is to use the interior-point algorithm for solving the sample LPs with sample proportion $\hat{p}_j$

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since the sample and offline LP may be degenerate or with multiple optimal solutions - a common property for real-life LP problems.

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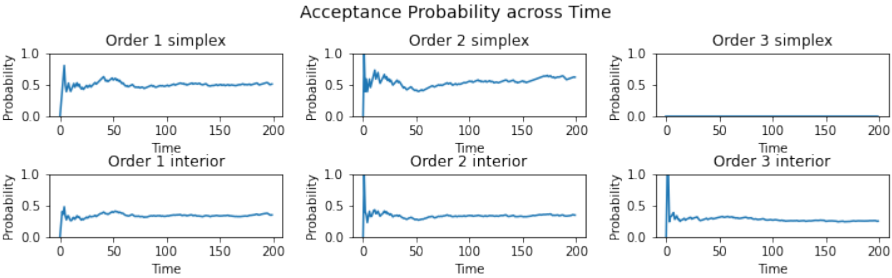

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But these individuals/groups could have different sensitive features, such as demographic, race, and gender, and areas in Hospital Admission and Hotel/Flight booking application.

Could we design an online algorithm/allocation-rule such as, while maintain the efficiency in objective value, all individual/groups get a fairer allocation shares?

Fairer Solution for the Offline Problem

We define $\mathbf{y}^*$, the fair offline optimal solution of the LP problem

$$\max \sum_{i=1}^{K} p_i \mu_i y_i, \quad \text{s.t.} \quad \sum_{i=1}^{K} p_i \mathbf{c}_i y_i \leq \mathbf{b}/T, \quad y_i \in [0,1]$$

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Let $\mathbf{y}_t$ be allocation solution at time t which encodes the accepting rates/probabilities under algorithm π. Then we define the cumulative unfairness of the online algorithm π as

$$\text{UF}_T(\pi) = \mathbb{E}\left[\sum_{t=1}^{T} \|\mathbf{y}_t - \mathbf{y}^*\|_2^2\right].$$

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This definition is consistent with the definition of so-called fair classifiers/regressors in machine learning.

Our Result

We develop an online algorithm [Chen, Li & Y (2021)] that achieves

$$\text{UF}_T(\pi) = O(\log T) \text{ and } \text{Reg}_T(\pi) = \text{ Bounded w.r.t } T$$

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Key ideas in algorithm design:

- At each time t, we use interior-point method to obtain the analytic-center solution $\mathbf{y}_t$ of sampled LPs, and it is necessary to achieve the performance under non-uniqueness assumption while maintain fairness.
- We also adaptively adjust the right-hand-side of the LP constraints properly to ensure (i) the depletion of binding resources and (ii) non-binding resources not affecting the fairness.

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An advantage of interior-point method over simplex method!

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Bandits with Knapsacks

Reverse the order of decisions and observations in online LP setting: in each time t, the decision maker decides an arm(/customer/order) among K arms to play/sell and then observe $(\hat{r}_t, \hat{\mathbf{c}}_t)$.

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At each time $t \in [T]$, an arm i is selected to pull. The realized reward $\hat{r}_t$ and resources cost $\hat{\mathbf{c}}_t$ satisfying

$$\mathbb{E}[\hat{r}_t | i] = \mu_i, \quad \mathbb{E}[\hat{\mathbf{c}}_t | i] = \mathbf{c}_i.$$

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Goal: Select a subset of winning/optimal arms to pull in order to maximize the total reward subject to the resource capacity constraints - pro-actively explore arms and exploit learned data.

Offline Linear Program (LP) and Regret

With mean reward $\boldsymbol{\mu} = (\mu_1, ..., \mu_K)$ and mean resource-cost $(\mathbf{c}_1, ..., \mathbf{c}_K)$ of arms, consider the following deterministic offline LP,

$$\max_{\mathbf{x}} \sum_{i=1}^{K} \mu_i x_i \quad \text{s.t.} \quad \sum_{i=1}^{K} \mathbf{c}_i x_i \leq \mathbf{b}, x_i \geq \mathbf{0}, i \in [k]$$

Here x_i represents the optimal times of playing i-th arm if everything is deterministic and known – only m of them positive (basic).

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Denote its optimal value as OPT (the benchmark) and let τ be the stopping time as soon as one of the resources is depleted. Then the problem-dependent regret

$$Regret(\mathcal{P}) = OPT - \mathbb{E}\left[\sum_{t=1}^{\tau} r_t\right],$$

where $\mathcal{P}$ encapsulates the parameters related to the underlying data distribution.

Literature and Our Result

	Paper	Result
$\mathcal{P}$-Independent	Badanidiyuru et. al. (13) Agrawal and Devanur (14)	$O(poly(m,k) \cdot \sqrt{T})$
$\mathcal{P}$-Dependent	Flajolet and Jaillet (15) Sankararaman and Slivkins (20) Li, Sun & Y (21)	$\tilde{O}(2^{m+k} \log T)$ $\tilde{O}(k \log T)$ for $m = 1$ $\tilde{O}\left(m^4 + k \log T\right)$

The problem-dependent bounds all involve parameters related to the non-degeneracy and the reduced cost of the underlying LP, while our work has the mildest assumption and requires no prior knowledge of these parameters.

Dual LP and Reduced Cost

$$\textit{Primal}: \quad \max \quad \boldsymbol{\mu}^\top \mathbf{x} \quad \text{s.t.} \quad C\mathbf{x} \le \mathbf{b}, \mathbf{x} \ge \mathbf{0} \qquad \textit{Dual}: \quad \min \quad \mathbf{b}^\top \mathbf{y} \quad \text{s.t.} \quad C^\top \mathbf{y} \ge \boldsymbol{\mu}, \mathbf{y} \ge \mathbf{0}$$

Denote $\mathbf{x}^* \in R^K$ and $\mathbf{y}^* \in R^m$ as optimal solutions
Define reduced cost (profit) for i-th arm $\Delta_i := \mathbf{c}_i^\top \mathbf{y}^* - \mu_i$ and the "nonbasic" variable set $\mathcal{I}' = \{i : \Delta_i > 0\}$.

Proposition (Li, Sun & Y 2021, ICML)

The regret of a BwK algorithm has the following upper bound:

$$Regret(\mathcal{P}) \le \sum_{i \in \mathcal{I}'} \Delta_i \mathbb{E}[n_i(\tau)] + \mathbb{E}[\mathbf{b}^{(\tau)}]^\top \mathbf{y}^*$$

- $\mathbf{b}^{(t)}$: remaining resources at time t
- $n_i(t)$: the number of times that i-th (non-optimal) arm is played up to time t.

Implications of the Regret Upper Bound

Two tasks to accomplish to reduce the regret:

Task I: Control the number of plays $n_i(\tau)$ for non-optimal arms $i \in \mathcal{I}'$ which corresponds to the first component in the regret bound

$$\sum_{i \in \mathcal{I}'} \Delta_i \mathbb{E}[n_i(\tau)]$$

Playing each non-optimal arm will induce a cost/waste of Δ_i.

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Task II: Make sure no valuable resources $\mathbf{b}_j^{(\tau)}$ left unused, which corresponds to the second component in the regret bound

$$\mathbb{E}[\mathbf{b}^{(\tau)}]^\top \mathbf{y}^*$$

Recall τ is the time that one of the resources is exhausted.

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Task II is often overlooked in the existing BwK literature.

Our Approach: A Two-Phase Algorithm

- Phase I: Identify the optimal arms with as fewer number of plays as possible by designing an "importance score" for arm i:

$$OPT_i := \max \quad \boldsymbol{\mu}^\top \mathbf{x} \quad \text{s.t.} \quad C\mathbf{x} \le \mathbf{b}, \; x_i = 0, \mathbf{x} \ge \mathbf{0}.$$

Implication: A larger value of $OPT - OPT_i \Rightarrow x_i$ important and likely to represent an optimal arm. Our algorithm then maintains upper confidence bound (UCB)/lower confidence bound (LCB) to estimate OPT and OPT_i based are samples.

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  After $t' = O(\frac{k \log T}{\sigma^2 \delta^2})$ times of Phase I, the non-optimal arm variables are identified as set $\mathcal{I}'$ and they would be removed from further consideration, and then we start
- Phase II: Use the remaining arms to exhaust the resource through an adaptive procedure such that no valuable resources are wasted.

Combining the Two Phases

Proposition (Li, Sun & Y 2021, ICML)

The regret of our two-phase algorithm is bounded by

$$O\left(\frac{m^4}{\sigma^2\delta^2} + \frac{k \log T}{\delta^2}\right).$$

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- σ is the minimum singular value of the sub-matrix of the constraint matrix C that corresponds to the optimal basis.

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- δ measures the difficulty of identifying optimal basic variables:

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These condition numbers generalize the optimality gap for the original (unconstrained) multi-armed bandits (Lai and Robbins (1985), Auer et al. (2002)).

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The Fisher Social Optimization Problem

$$\max_{\mathbf{x}_i's} \quad \sum_{i \in B} w_i \log(\mathbf{u}_i^T \mathbf{x}_i)$$

$$\text{s.t.} \quad \sum_{i \in B} x_{ij} = (\leq) c_j, \quad \forall j \in G, \quad x_{ij} \geq 0, \quad \forall i, j,$$

$\mathbf{u}_i$: linear utility coefficients of buyer i, c_j: capacity of good j.

The Fisher Social Optimization Problem

$$\max_{\mathbf{x}_i' s} \quad \sum_{i\in B} w_i \log(\mathbf{u}_i^T \mathbf{x}_i)$$
$$\text{s.t.} \quad \sum_{i\in B} x_{ij} = (\leq) c_j, \quad \forall j \in G, \quad x_{ij} \geq 0, \quad \forall i,j,$$

$\mathbf{u}_i$: linear utility coefficients of buyer i, c_j: capacity of good j.

Theorem (Eisenberg and Gale (1959))

Optimal dual (Lagrange) multiplier vector of equality constraints is an equilibrium price vector to clear the market.

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Questions: Could the algorithm be implemented while protecting privacy by a price-posting mechanism? How much would the aggregated social welfare be deteriorated from the offline setting? May the market be cleared?

Regret Analysis and Model

Let "offline" optimal solution be $\mathbf{x}_i^*$ and "online" solution be $\mathbf{x}_i$, and

$$R_n^* = \sum_{i=1}^{n} w_i \log(\mathbf{u}_i^T \mathbf{x}_i^*), \quad R_n = \sum_{i=1}^{n} w_i \log(\mathbf{u}_i^T \mathbf{x}_i)$$

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Then define

$$\Delta_n = \sup \mathbb{E}\left[R_n^* - R_n\right], \quad v(\mathbf{x}) = \sup \mathbb{E}\left[\| (A\mathbf{x} - \mathbf{b})^+ \|_2\right]$$

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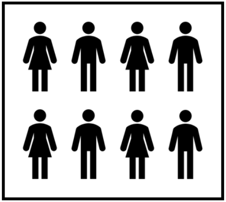
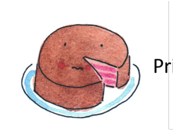
Remark: Again this is a bi-criteria performance measure and, if $\Delta_n \leq o(n)$ (sublinear),

$$\frac{\left(\prod_i (\mathbf{u}_i^T \mathbf{x}_i^*)^{w_i}\right)^{1/n}}{\left(\prod_i (\mathbf{u}_i^T \mathbf{x}_i)^{w_i}\right)^{1/n}} \leq e^{o(n)/n}.$$

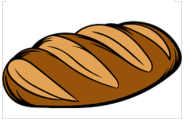
Online Fisher Markets: Price-Posting Mechanism



Each agent i, with budget w_i, purchases an optimal bundle $\boldsymbol{x}_i^t$ given price $\boldsymbol{p}^t$



Price p_1^t



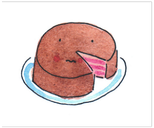
p_2^t

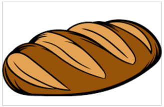
p_3^t

How to setup $\mathbf{p}^t$ for each good before buyer t comes so that the social welfare is maximized and capacity constraint violation is minimized for total n buyers?

Stochastic Market Equilibrium: An Example

2 goods, each with a capacity of n





Two agent types specified by (Utility for Good 1, Utility for Good 2)

Type I: (1, 0)

Arrival Probability = 0.5

Type II: (0, 1)

Arrival Probability = 0.5

Theorem (Jelota & Y (2022))

There is an adaptive price-policy (path-dependent price vector) such that the market is cleared and the expect optimal social value

$$n\log(2) - 1 \leq \mathbb{E}[R_n] = \mathbb{E}[R_n^*] \leq n\log(2).$$

However, for any static pricing-policy, even using the expected optimal equilibrium price-vector, either the expected regret or constraint violation is at least $\Omega\sqrt{n}$.

Simple Price-Learning Algorithm

One may apply a similar primal price-learning algorithm, that is, solve the aggregated social problem based on arrived ϵ portion of buyers:

$$
\begin{array}{lll}
\text{maximize}_{\mathbf{x}} & \sum_{t=1}^{\epsilon n} w_t \log(\mathbf{u}_t^T \mathbf{x}_t) & \\
\text{subject to} & \sum_{t=1}^{\epsilon n} \mathbf{x}_t \leq \epsilon c_j, & j = 1, ..., m \\
& 0 \leq x_t. &
\end{array}
$$

One can set an initial positive price vector $\mathbf{p}^1$ and determine allocation $\mathbf{x}_t$ as the optimal solution for the individual maximization problem under price vector $\mathbf{p}^t$.

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Could the prices be updated in a privacy-preserving manner?

A Privacy-Preserving Algorithm

Consider the dual market:

$$\min \ \mathbf{c}^\top \mathbf{p} - \sum_{t=1}^{n} w_t \log\left(\min_j \frac{p_j}{u_{tj}}\right) + \sum_{t=1}^{n} w_t(\log(w_t) - 1).$$

It can be, after removing the fixed part, equivalently rewritten as

$$\min \ \mathbf{d}^\top \mathbf{p} - \frac{1}{n}\sum_{t=1}^{n} w_t \log\left(\min_j \frac{p_j}{u_{tj}}\right)$$

which can be viewed as a simple-sample-average (SSA) (with n buyers) of a stochastic optimization problem under an i.i.d distribution, where $\mathbf{d} := \frac{1}{n}\mathbf{c}$ is the average resource allocation to each buyer.

Dual-Gradient Online Algorithm for Fisher-Markets

1: Initialize $\mathbf{p}^1 = \mathbf{e}$, and for $t = 1, 2, ..., n$

2: Let $\mathbf{x}_t$ be the individual optimal bundle solution under price vector $\mathbf{p}^t$.

3: Update prices
$$\begin{aligned} \mathbf{p}_{t+1} &= \mathbf{p}_t - \gamma_t (\mathbf{d} - \mathbf{x}_t) \\ \mathbf{p}_{t+1} &= \mathbf{p}_{t+1}^+ \end{aligned}$$

4: $\mathbf{x} = (\mathbf{x}_1, ..., \mathbf{x}_n)$

Again, line 3 performs (projected) stochastic gradient step.

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Theorem (Jelota & Y (2022))

Under i.i.d. budget and utility parameters and when good capacities are $O(n)$, the algorithm achieves an expected regret $\Delta_n \leq O(\sqrt{n})$ and the expected constraint violation $v(\mathbf{x}) \leq O(\sqrt{n})$, where n is the number of arriving buyers.

Takeaways and Open Problems

- Learning-while-doing (taking actions) is common in today's decision making
- The Off-line and On-line Regret measures the learning efficiency
- Could more non-stationary data be learned with sub-linear regret?
- Could learning/decision be based on past data together with future prediction?
- Overall, Linear Programming continues to play a big role in online learning and decisioning.

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Long Live Linear Programming!