Semi-parametric dynamic contextual pricing

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Dynamic pricing

- Several platforms have access to data describing history of different users.
- Platforms can leverage this information to price different products and optimize revenue.
- This requires learning online the mapping from user context to optimal price, efficiently.

Basic Framework

- Discrete times $1, 2, \dots, n$, one user arrives per time step
- Each user is shown one product, which is ex-ante fixed
- Let V_t be the value t^{th} user assigns to the product.
- Let p_t be the price set by the platform.
- The user buys the product if $p_t \leq V_t$.
- Platform does not know or observe V_t, but has access to covariates $X_t \in \mathbb{R}^d$ which may describe user's history and product's type
- Goal: set prices $p_1, \dots, p_n$ so as to maximize $\sum_{t=1}^n p_t \mathbf{1}\{p_t \leq V_t\}$.

Predicting V_t: The Data

- Input: $\{X_i, p_i\}_{i=1}^{t-1}$.
  X_t : covariate. p_t: price

- Output: $\{Y_i\}_{i=1}^{t-1}$, where

$$Y_i = \begin{cases} 1 \text{ if } V_i - p_i \geq 0 \\ 0 \text{ otherwise} \end{cases} .$$

  In other words, Y_i captures whether i^{th} was success or failure.

Predicting V_t: The Model

- Suppose,
$$V_i = \theta_0^\intercal X_i + Z_i,$$
θ_0: unknown parameters, Z_i: unknown demand-shock/noise.

- If we assume $Z_1, \ldots, Z_{t-1}$ are i.i.d. **Gaussian**, then we obtain **Probit model** with input $\{X_i, p_i\}_{i=1}^t$.

- Similarly, we obtain Logistic model for i.i.d. Logistic distributed demand-shocks.

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- Even if we knew θ_0 exactly, the actual structure of distribution of demand-shocks is important to set optimal markups.
- Can we learn the actual distribution of shocks along with θ_0?

Predicting V_t: Our Semi-parametric Model

- Let
$$\ln V_i = \theta_0^\intercal X_i + Z_i,$$
θ_0: unknown parameters, Z_i: unknown demand-shock/noise.

- Demand-shocks are i.i.d. with arbitrary (non-parametric) distribution.

- Input: $\{X_i, p_i\}_{i=1}^{t-1}$, Output: $\{Y_i\}_{i=1}^{t-1}$ where $Y_i = \mathbf{1}\{V_i - p_i \geq 0\}$.

Semi-parametric Model: Curse of Dimensionality

- Usually, such semi-parametric models with binary feedback are hard to learn.
- That is one of the reasons why previous works on dynamic contextual pricing only consider probit/logistic/generalized-linear models.

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- That is one of the reasons why previous works on dynamic contextual pricing only consider probit/logistic/generalized-linear models.
- Key leverage we find and use: Platform controls prices, and it is possible to focus learning in the regions which are revenue maximizing.

Price Experimentation

Conflicting goals:

- Observe X_t. Set price p_t to better learn θ_0 and distribution of Z. (exploration)
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As we learn more, we can zero in the further exploration near profit maximizing regions.

The Oracle

Let us first consider a simpler problem.

- Consider an Oracle which actually knows θ_0 and the distribution of Z.
- Now, let

$$F(z) = z\mathbb{P}(Z \geq \ln z), \text{ and } z^* = \arg\sup_z F(z).$$

Proposition

The following pricing policy maximizes revenue for the Oracle*: At each time t set price p_t^* such that*

$$\ln p_t^* = \theta_0^\intercal X_t + \ln z^*.$$

Regret

- Platform's revenue: $\Gamma_n = \sum_{t=1}^{n} p_t \mathbf{1}\left\{p_t \leq V_t\right\}$.
- Oracle's expected revenue: $\Gamma_n^* = \sum_{t=1}^{n} p_t^* \mathbf{1}\left\{p_t^* \leq V_t\right\}$.
- Expected regret: $\mathbb{E}[R_n] = \mathbb{E}[\Gamma_n^*] - \mathbb{E}[\Gamma_n]$.
- Maximizing $\mathbb{E}[\Gamma_n]$ is equivalent to minimizing $\mathbb{E}[R_n]$.
- We will focus on minimizing $\mathbb{E}[R_n]$, asymptotically in n.

Designing Optimal Algorithm: Key Ideas

- Recall, revenue maximizing policy for Oracle: $\ln p_t^* = \theta_0^\intercal X_t + \ln z^*$.
- For each z and θ, think of (z, θ) as an arm (i.e. a potential option). Pulling arm (z, θ) is equivalent to setting price p_t such that $\ln p_t = \theta^\intercal X_t + \ln z$.
- $(z, \theta) \in \mathbb{R}^{d+1}$: Curse of dimensionality?
- Important observation: Given X_t, for each choice of price p_t we *simultaneously* obtain information about the expected revenue for a *range* of pairs (z, θ).

DEEP-C Pricing Algorithm: Summary

DEEP-C: Dynamic Experimentation and Elimination of Prices - with Covariates.

- Maintain a set $A(t)$ of 'active arms' (z, θ) at each time.
- At time t, observe X_t and compute the set of active prices:

$$P(t) = \{p_t : \exists (z, \theta) \in A(t) \text{ s.t. } \ln p_t = \theta^\intercal X_t + \ln z\}.$$

- Choose price p_t at random from $P(t)$.
- Observe the revenue obtained. Eliminate (z, θ)'s from $A(t)$ for which there is enough information about sub-optimality.

The main result

Under some smoothness, compactness, independence, etc. assumptions, the following holds.

Theorem

The expected regret of DEEP-C algorithm satisfies the following: there exists a constant c such that

$$\mathbb{E}[R_n] = O\left(d^c\sqrt{n}\right).$$

Conclusions

- To learn via price experimentation, we do not need to make parametric (probit/logistic type) assumptions.
- We have a provably efficient algorithm which works under a 'very general' setting.