Counterfactual Model for Learning Systems

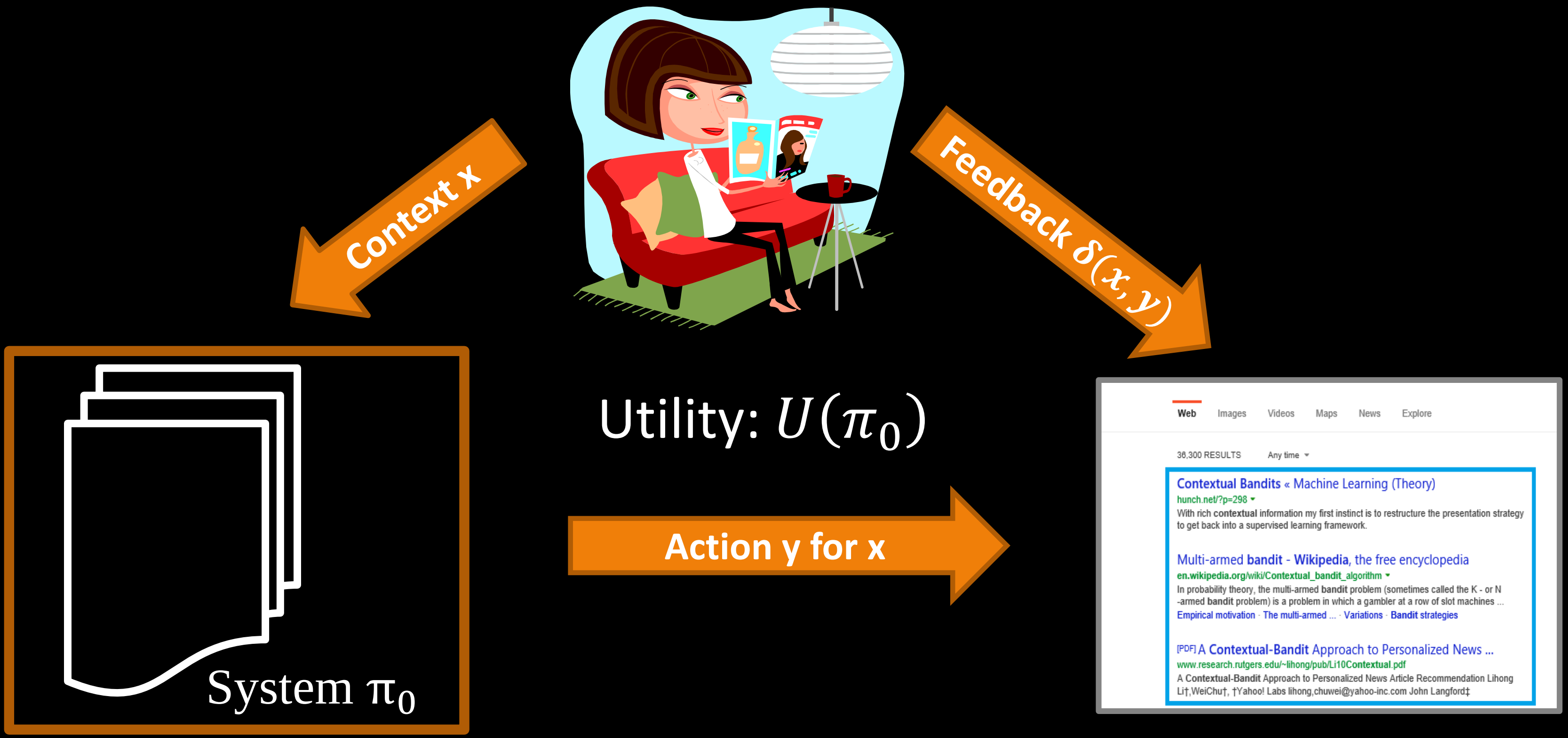
CS 7792 - Fall 2018

Thorsten Joachims

Department of Computer Science & Department of Information Science
Cornell University

Imbens, Rubin, Causal Inference for Statistical Social Science, 2015. Chapters 1,3,12.

Interactive System Schematic

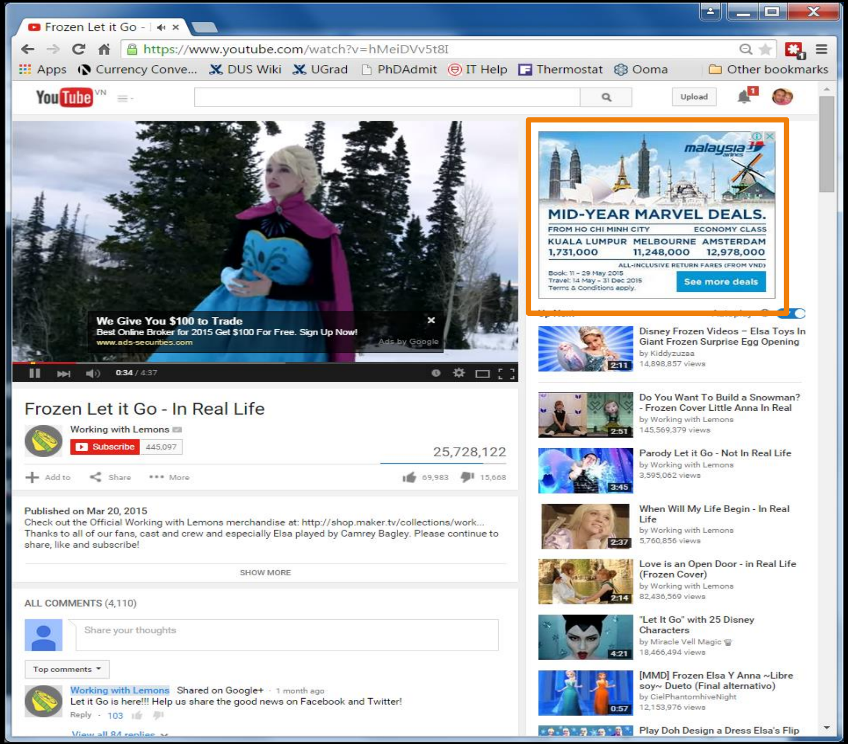


News Recommender

- Context x:
  - User
- Action y:
  - Portfolio of newsarticles
- Feedback $\delta(x, y)$:
  - Reading time in minutes

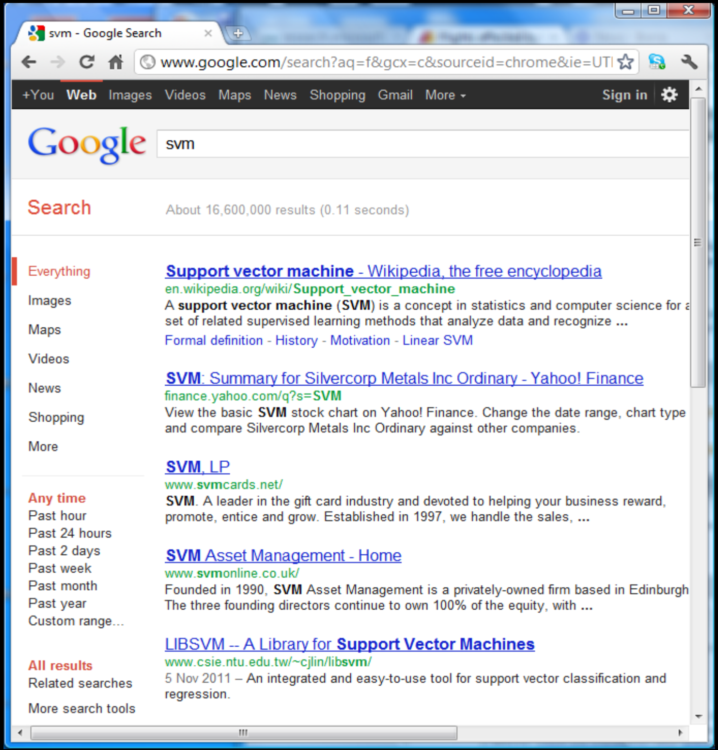
Ad Placement

- Context x:
  - User and page
- Action y:
  - Ad that is placed
- Feedback $\delta(x, y)$:
  - Click / no-click



Search Engine

- Context x:
  - Query
- Action y:
  - Ranking
- Feedback $\delta(x, y)$:
  - Click / no-click



Log Data from Interactive Systems

context

π_0 action

reward / loss

- Data

$$S = \big((x_1, y_1, \delta_1), \ldots, (x_n, y_n, \delta_n)\big)$$

→ Partial Information (aka "Contextual Bandit") Feedback

- Properties
  - Contexts x_i drawn i.i.d. from unknown $P(X)$
  - Actions y_i selected by existing system $\pi_0 : X \rightarrow Y$
  - Feedback δ_i from unknown function $\delta : X \times Y \rightarrow \Re$

[Zadrozny et al., 2003] [Langford & Li], [Bottou, et al., 2014]

Goal: Counterfactual Evaluation

- Use interaction log data

$$S = \big((x_1, y_1, \delta_1), \dots, (x_n, y_n, \delta_n)\big)$$

for evaluation of system π:

    - Estimate online measures of some system π offline.
    - System π can be different from π_0 that generated log.

Evaluation: Outline

- Evaluating Online Metrics Offline
  - A/B Testing (on-policy)
    → Counterfactual estimation from logs (off-policy)
- Approach 1: “Model the world”
  - Estimation via reward prediction
- Approach 2: “Model the bias”
  - Counterfactual Model
  - Inverse propensity scoring (IPS) estimator

Online Performance Metrics

Example metrics

- CTR
- Revenue
- Time-to-success
- Interleaving
- Etc.

→ Correct choice depends on application and is not the focus of this lecture.

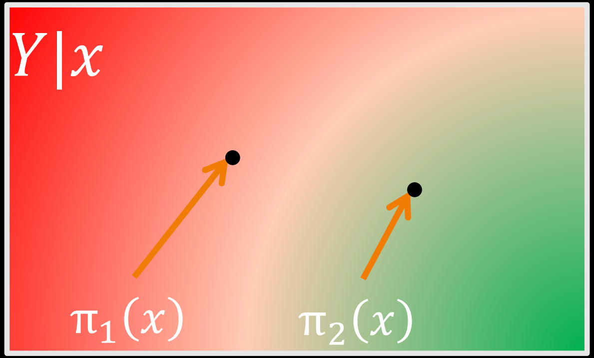
This lecture:

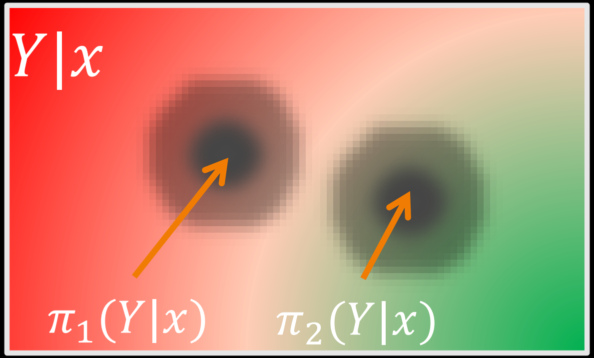
Metric encoded as $\delta(x, y)$ [click/payoff/time for (x,y) pair]

System

- Definition [Deterministic Policy]:
  Function
  $$y = \pi(x)$$
  that picks action y for context x.

- Definition [Stochastic Policy]:
  Distribution
  $$\pi(y|x)$$
  that samples action y given context x





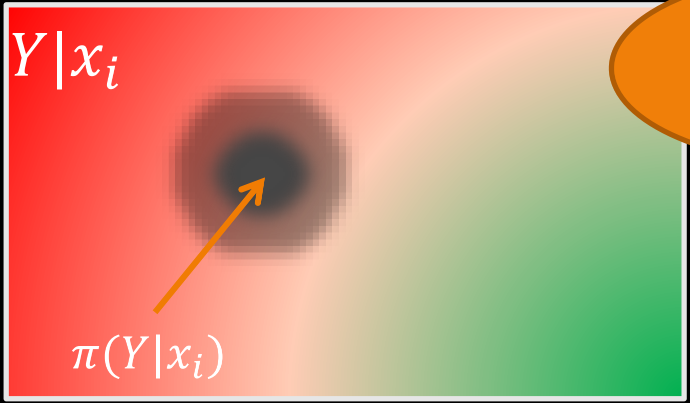
System Performance

Definition [Utility of Policy]:

The expected reward / utility $U(\pi)$ of policy π is

$$U(\pi) = \int\int \delta(x, y)\pi(y|x)P(x)\, dx\, dy$$

e.g. reading time of user x for portfolio y



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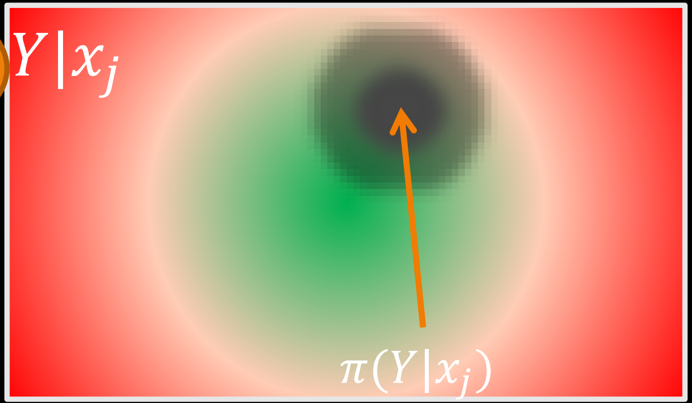

Online Evaluation: A/B Testing

Given $S = \big((x_1, y_1, \delta_1), \ldots, (x_n, y_n, \delta_n)\big)$ collected under π_0,

$$\widehat{U}(\pi_0) = \frac{1}{n}\sum_{i=1}^{n} \delta_i$$

→ A/B Testing

Deploy π_1: Draw $x \sim P(X)$, predict $y \sim \pi_1(Y|x)$, get $\delta(x, y)$

Deploy π_2: Draw $x \sim P(X)$, predict $y \sim \pi_2(Y|x)$, get $\delta(x, y)$

⋮

Deploy $\pi_{|H|}$: Draw $x \sim P(X)$, predict $y \sim \pi_{|H|}(Y|x)$, get $\delta(x, y)$

Pros and Cons of A/B Testing

- Pro
  - User centric measure
  - No need for manual ratings
  - No user/expert mismatch
- Cons
  - Requires interactive experimental control
  - Risk of fielding a bad or buggy π_i
  - Number of A/B Tests limited
  - Long turnaround time

Evaluating Online Metrics Offline

- Online: On-policy A/B Test

Draw S_1 from π_1 → $\hat{U}(\pi_1)$

Draw S_2 from π_2 → $\hat{U}(\pi_2)$

Draw S_3 from π_3 → $\hat{U}(\pi_3)$

Draw S_4 from π_4 → $\hat{U}(\pi_4)$

Draw S_5 from π_5 → $\hat{U}(\pi_5)$

Draw S_6 from π_6 → $\hat{U}(\pi_6)$

Draw S_7 from π_7 → $\hat{U}(\pi_7)$

- Offline: Off-policy Counterfactual Estimates

Draw S from π_0 →

$\hat{U}(\pi_6)$

$\hat{U}(\pi_{12})$

$\hat{U}(\pi_{18})$

$\hat{U}(\pi_{24})$

$\hat{U}(\pi_{30})$

Evaluation: Outline

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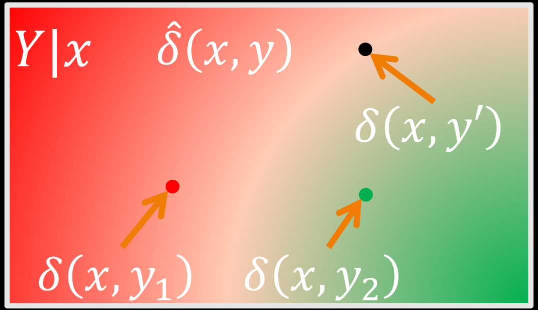
Approach 1: Reward Predictor

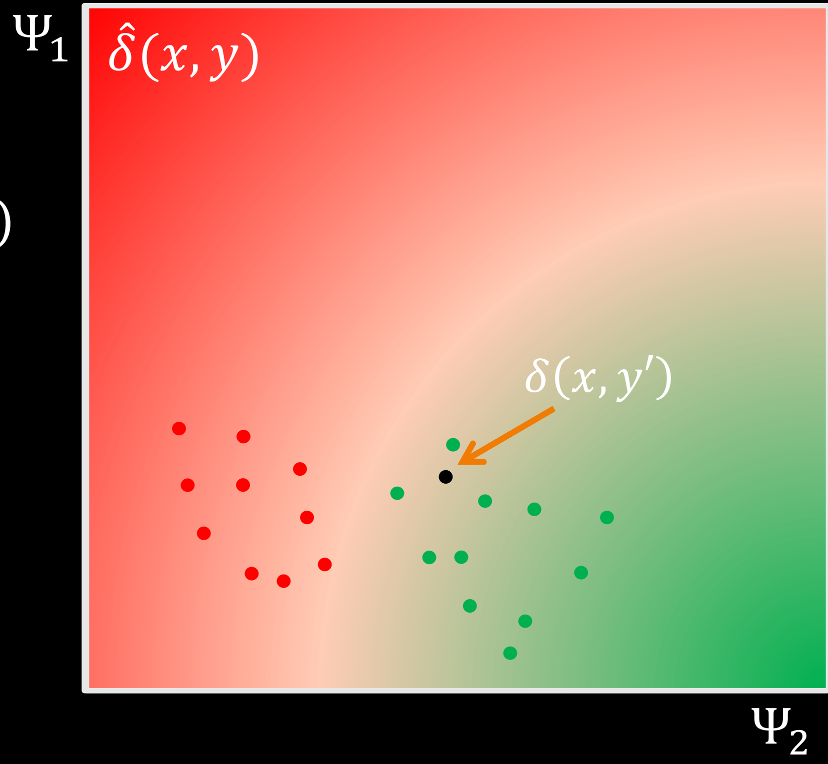


- Idea:
  - Use $S = ((x_1, y_1, \delta_1), \ldots, (x_n, y_n, \delta_n))$ from π_0 to estimate reward predictor $\hat{\delta}(x,y)$
- Deterministic π: Simulated A/B Testing with predicted $\hat{\delta}(x,y)$
  - For actions $y_i' = \pi(x_i)$ from new policy π, generate predicted log $S' = \left(\left(x_1, y_1', \hat{\delta}(x_1, y_1')\right), \ldots, \left(x_n, y_n', \hat{\delta}(x_n, y_n')\right)\right)$
  - Estimate performace of π via $\hat{U}_{rp}(\pi) = \frac{1}{n}\sum_{i=1}^{n} \hat{\delta}(x_i, y_i')$
- Stochastic π: $\hat{U}_{rp}(\pi) = \frac{1}{n}\sum_{i=1}^{n} \sum_{y} \hat{\delta}(x_i, y)\, \pi(y|x_i)$

Regression for Reward Prediction

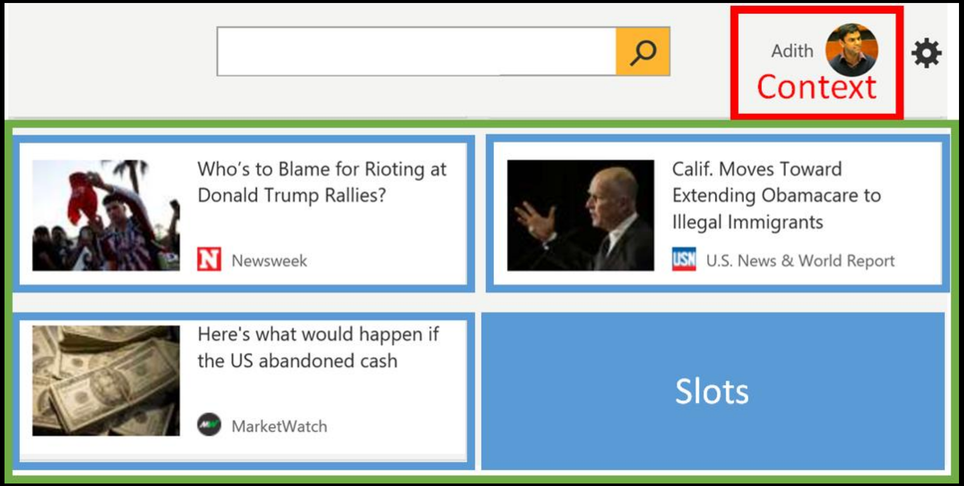
Learn $\hat{\delta}: x \times y \to \Re$

1. Represent via features $\Psi(x, y)$
2. Learn regression based on $\Psi(x, y)$ from S collected under π_0
3. Predict $\hat{\delta}(x, y')$ for $y' = \pi(x)$ of new policy π



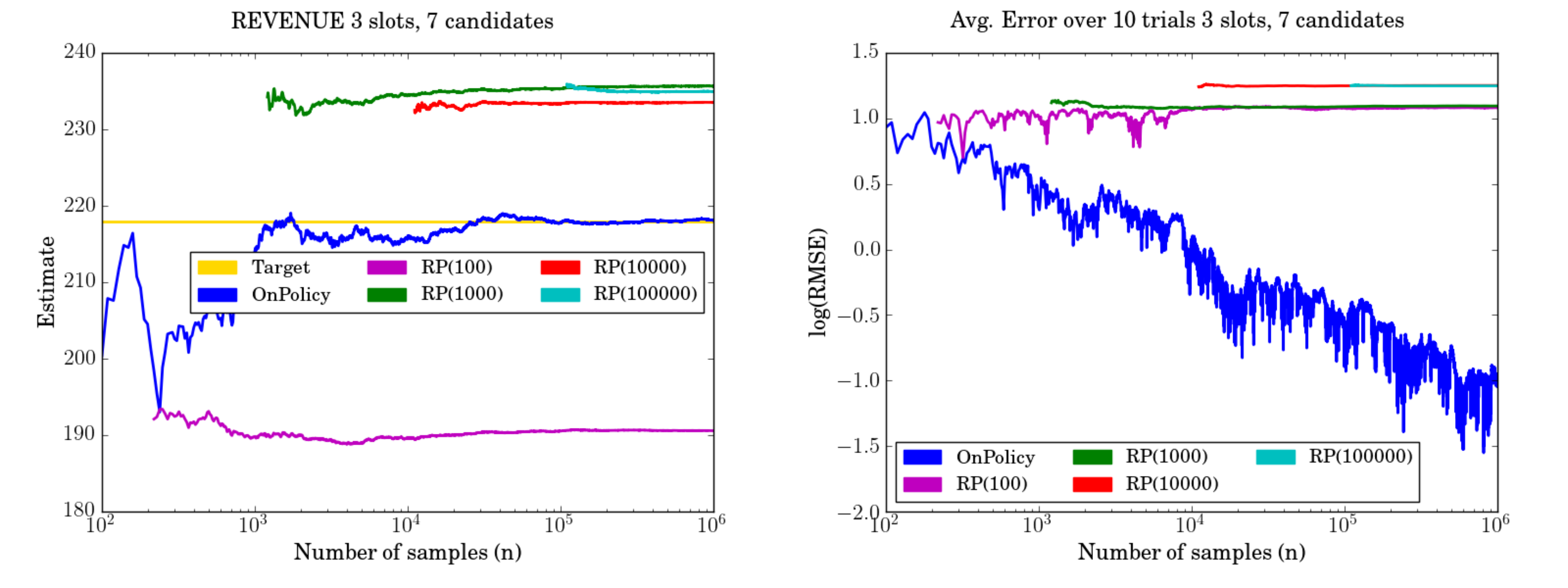
News Recommender: Exp Setup

- Context x: User profile
- Action y: Ranking
  - Pick from 7 candidates to place into 3 slots
- Reward δ: “Revenue”
  - Complicated hidden function



- Logging policy π_0: Non-uniform randomized logging system
  - Placket-Luce “explore around current production ranker”

News Recommender: Results



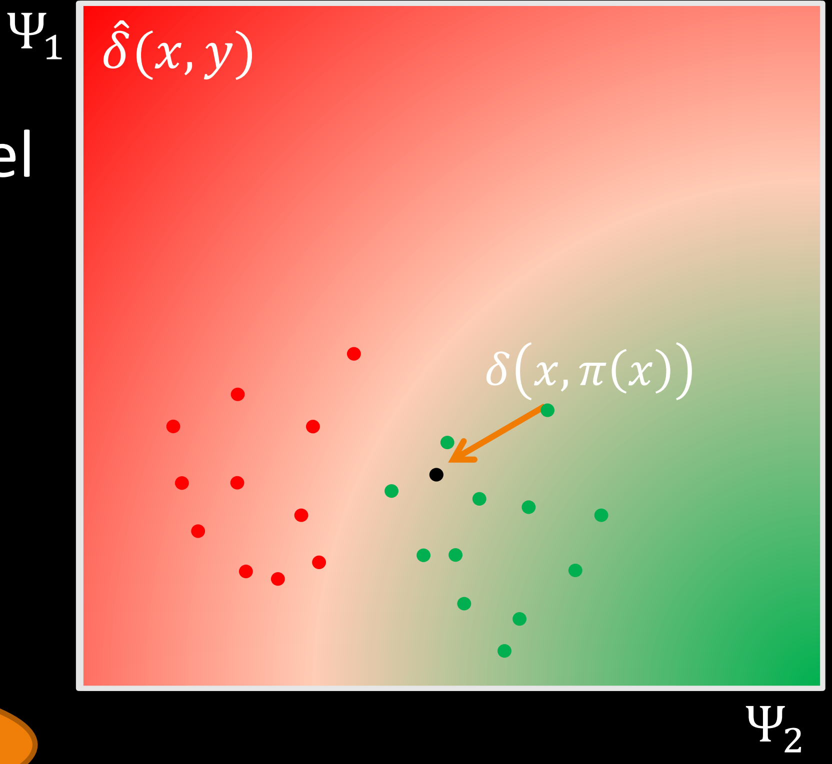
RP is inaccurate even with more training and logged data

Problems of Reward Predictor

- Modeling bias
  - choice of features and model
- Selection bias
  - π_0's actions are over-represented

$$\rightarrow \hat{U}_{rp}(\pi) = \frac{1}{n}\sum_i \hat{\delta}(x_i, \pi(x_i))$$

Can be unreliable and biased



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  - Inverse propensity score (IPS) weighting estimator

Approach "Model the Bias"

- Idea:

  Fix the mismatch between the distribution $\pi_0(Y|x)$ that generated the data and the distribution $\pi(Y|x)$ we aim to evaluate.

$$\mathrm{U}(\overset{\pi}{\cancel{\pi_0}}) = \int\int \delta(x,y)\overset{\pi(y|x)}{\cancel{\pi_0(y|x)}}P(x)\,dx\,dy$$

Counterfactual Model

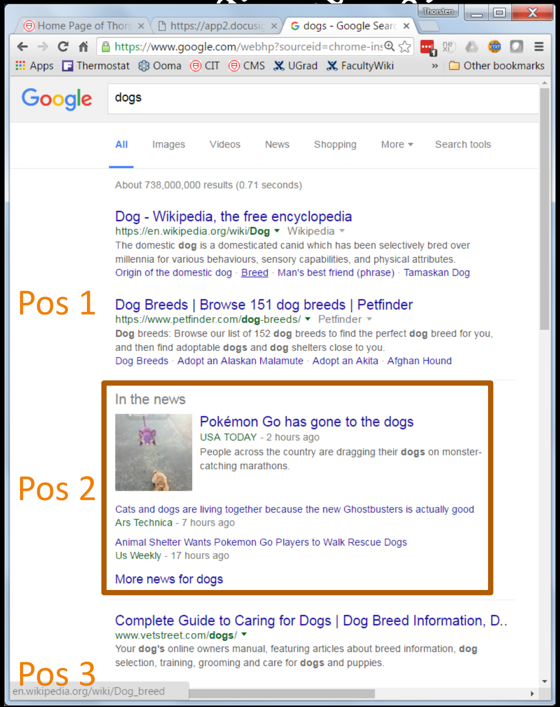
- Example: Treating Heart Attacks
  - Treatments: Y
    - Bypass / Stent / Drugs
  - Chosen treatment for patient x_i: y_i
  - Outcomes: δ_i
    - 5-year survival: 0 / 1
  - Which treatment is best?

$$
\begin{array}{c c}
 & \begin{array}{ccc} \text{Bypass} & \text{Stent} & \text{Drugs} \end{array} \\
\text{Patients } \mathrm{x}_i \in \{1, \ldots, n\} & \begin{bmatrix}
0 & & \\
 & 1 & \\
 & & 1 \\
 & 0 & \\
 & & 1 \\
1 & & \\
 & & 1 \\
 & & 0 \\
0 & & \\
 & 1 & \\
1 & &
\end{bmatrix}
\end{array}
$$

Counterfactual Model

Placing Vertical

- Example: ~~Treating Heart Attacks~~
  - Treatments: Y
    - ~~Bypass / Stent / Drugs~~ Pos 1 / Pos 2/ Pos 3
  - Chosen treatment for patient x_i: y_i
  - Outcomes: δ_i
    - ~~5-year survival: 0 / 1~~ Click / no Click on SERP
  - Which treatment is best?



Counterfactual Model

- Example: Treating Heart Attacks
  - Treatments: Y
    - Bypass / Stent / Drugs
  - Chosen treatment for patient x_i: y_i
  - Outcomes: δ_i
    - 5-year survival: 0 / 1
  - Which treatment is best?
    - Everybody Drugs
    - Everybody Stent
    - Everybody Bypass

    → Drugs 3/4, Stent 2/3, Bypass 2/4 – really?

$$
\begin{array}{c c}
 & \begin{array}{ccc} \text{Bypass} & \text{Stent} & \text{Drugs} \end{array} \\
\text{Patients } \mathrm{x_i}, i \in \{1,\dots,n\} & \begin{bmatrix}
0 & & \\
 & 1 & \\
 & & 1 \\
 & 0 & \\
 & & 1 \\
1 & & \\
 & & 1 \\
 & & 0 \\
0 & & \\
 & 1 & \\
1 & &
\end{bmatrix}
\end{array}
$$

Treatment Effects

- Average Treatment Effect of Treatment y
  - $\mathrm{U}(y) = \frac{1}{n}\sum_i \delta(x_i, y)$
- Example
  - $\mathrm{U}(bypass) = \frac{4}{11}$
  - $\mathrm{U}(stent) = \frac{6}{11}$
  - $\mathrm{U}(drugs) = \frac{3}{11}$

Factual Outcome

Counterfactual Outcomes

$$
\begin{array}{cc}
 & \begin{array}{ccc} \text{Bypass} & \text{Stent} & \text{Drugs} \end{array} \\
\text{Patients} & \begin{bmatrix}
0 & 1 & 0 \\
1 & 1 & 0 \\
0 & 0 & 1 \\
0 & 0 & 0 \\
0 & 1 & 1 \\
1 & 0 & 0 \\
1 & 0 & 1 \\
0 & 1 & 0 \\
0 & 1 & 0 \\
1 & 1 & 0 \\
1 & 1 & 0
\end{bmatrix}
\end{array}
$$

Assignment Mechanism

- Probabilistic Treatment Assignment
  - For patient i: $\pi_0(Y_i = y|x_i)$
  - Selection Bias
- Inverse Propensity Score Estimator
  - $\hat{U}_{ips}(y) = \frac{1}{n}\sum_i \frac{\mathbb{I}\{y_i = y\}}{p_i}\delta(x_i, y_i)$
  - Propensity: $\mathrm{p_i} = \pi_0(Y_i = y_i|x_i)$
  - Unbiased: $E\left[\hat{U}(y)\right] = U(y)$, if $\pi_0(Y_i = y|x_i) > 0$ for all i
- Example
  - $\hat{U}(drugs) = \frac{1}{11}\left(\frac{1}{0.8} + \frac{1}{0.7} + \frac{1}{0.8} + \frac{0}{0.1}\right) = 0.36 < 0.75$

$\pi_0(Y_i = y|x_i)$

$$\begin{bmatrix} 0.3 & 0.6 & 0.1 \\ 0.5 & 0.4 & 0.1 \\ 0.1 & 0.1 & 0.8 \\ 0.6 & 0.3 & 0.1 \\ 0.2 & 0.5 & 0.7 \\ 0.7 & 0.2 & 0.1 \\ 0.1 & 0.1 & 0.8 \\ 0.1 & 0.8 & 0.1 \\ 0.3 & 0.3 & 0.4 \\ 0.3 & 0.6 & 0.1 \\ 0.4 & 0.4 & 0.2 \end{bmatrix}$$

Patients

$$\begin{array}{ccc} \text{Bypass} & \text{Stent} & \text{Drugs} \end{array}$$
$$\begin{bmatrix} 0 & 1 & 0 \\ 1 & 1 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & 0 \\ 0 & 1 & 1 \\ 1 & 0 & 0 \\ 1 & 0 & 1 \\ 0 & 1 & 0 \\ 0 & 1 & 0 \\ 1 & 1 & 0 \\ 1 & 1 & 0 \end{bmatrix}$$

Experimental vs Observational

- Controlled Experiment
  - Assignment Mechanism under our control
  - Propensities $p_i = \pi_0(Y_i = y_i | x_i)$ are known by design
  - Requirement: $\forall y\colon \pi_0(Y_i = y | x_i) > 0$ (probabilistic)
- Observational Study
  - Assignment Mechanism not under our control
  - Propensities p_i need to be estimated
  - Estimate $\hat{\pi}_0(Y_i | z_i) = \pi_0(Y_i | x_i)$ based on features z_i
  - Requirement: $\hat{\pi}_0(Y_i | z_i) = \hat{\pi}_0(Y_i | \delta_i, z_i)$ (unconfounded)

Conditional Treatment Policies

- Policy (deterministic)
  - Context x_i describing patient
  - Pick treatment y_i based on x_i: $\mathrm{y_i} = \pi(x_i)$
  - Example policy:
    - $\pi(A) = drugs, \pi(B) = stent, \pi(C) = bypass$
- Average Treatment Effect
  - $U(\pi) = \frac{1}{n} \sum_i \delta(x_i, \pi(x_i))$
- IPS Estimator
  - $\hat{U}_{ips}(\pi) = \frac{1}{n} \sum_i \frac{\mathbb{I}\{y_i = \pi(x_i)\}}{p_i} \delta(x_i, y_i)$

$$
\begin{array}{ccc}
 & \begin{array}{ccc} \text{Bypass} & \text{Stent} & \text{Drugs} \end{array} & X \\
\text{Patients} &
\begin{bmatrix}
0 & \boxed{1} & 0 \\
\boxed{1} & 1 & 0 \\
0 & 0 & \boxed{1} \\
0 & \boxed{0} & 0 \\
0 & 1 & \boxed{1} \\
1 & \boxed{0} & 0 \\
1 & 0 & \boxed{1} \\
\boxed{0} & 1 & 0 \\
0 & 1 & \boxed{0} \\
\boxed{1} & 1 & 0 \\
1 & \boxed{1} & 0
\end{bmatrix}
&
\begin{bmatrix}
B \\ C \\ A \\ B \\ A \\ B \\ A \\ C \\ A \\ C \\ B
\end{bmatrix}
\end{array}
$$

Stochastic Treatment Policies

- Policy (stochastic)
  - Context x_i describing patient
  - Pick treatment y based on x_i: $\pi(Y|x_i)$
- Note
  - Assignment Mechanism is a stochastic policy as well!
- Average Treatment Effect
  - $U(\pi) = \frac{1}{n}\sum_i \sum_y \delta(x_i, y)\pi(y|x_i)$
- IPS Estimator
  - $\hat{U}(\pi) = \frac{1}{n}\sum_i \frac{\pi(y_i|x_i)}{p_i}\delta(x_i, y_i)$

$$
\begin{array}{c}
 \\
\text{Patients}
\end{array}
\begin{array}{cccc}
\text{Bypass} & \text{Stent} & \text{Drugs} & X \\
\left[\begin{matrix} 0 & 1 & 0 \\ 1 & 1 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & 0 \\ 0 & 1 & 1 \\ 1 & 0 & 0 \\ 1 & 0 & 1 \\ 0 & 1 & 0 \\ 0 & 1 & 0 \\ 1 & 1 & 0 \\ 1 & 1 & 0 \end{matrix}\right] & & & \left[\begin{matrix} B \\ C \\ A \\ B \\ A \\ B \\ A \\ C \\ A \\ C \\ B \end{matrix}\right]
\end{array}
$$

Counterfactual Model = Logs

		der
Context x_i		e
Treatment y_i		ovie
Outcome δ_i		
Propensities p_i		al
New Policy π		ler
T-effect $U(\pi)$	Average quality of new policy.	

Recorded in Log

Evaluation: Outline

- Evaluating Online Metrics Offline
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System Evaluation via Inverse Propensity Scoring

Definition [IPS Utility Estimator]:

Given $S = \left((x_1, y_1, \delta_1), \ldots, (x_n, y_n, \delta_n)\right)$ collected under π_0,

$$\hat{U}_{ips}(\pi) = \frac{1}{n} \sum_{i=1}^{n} \delta_i \frac{\pi(y_i|x_i)}{\pi_0(y_i|x_i)}$$

Propensity
p_i

→ Unbiased estimate of utility for any π, if propensity nonzero whenever $\pi(y_i|x_i) > 0$.

Note:

If $\pi = \pi_0$, then online A/B Test with $\hat{U}_{ips}(\pi_0) = \frac{1}{n} \sum_i \delta_i$

→ Off-policy vs. On-policy estimation.

[Horvitz & Thompson, 1952] [Rubin, 1983] [Zadrozny et al., 2003] [Li et al., 2011]

Illustration of IPS

IPS Estimator:

$$\hat{U}_{IPS}(\pi) = \frac{1}{n}\sum_{i}\frac{\pi(y_i|x_i)}{\pi_0(y_i|x_i)}\delta_i$$

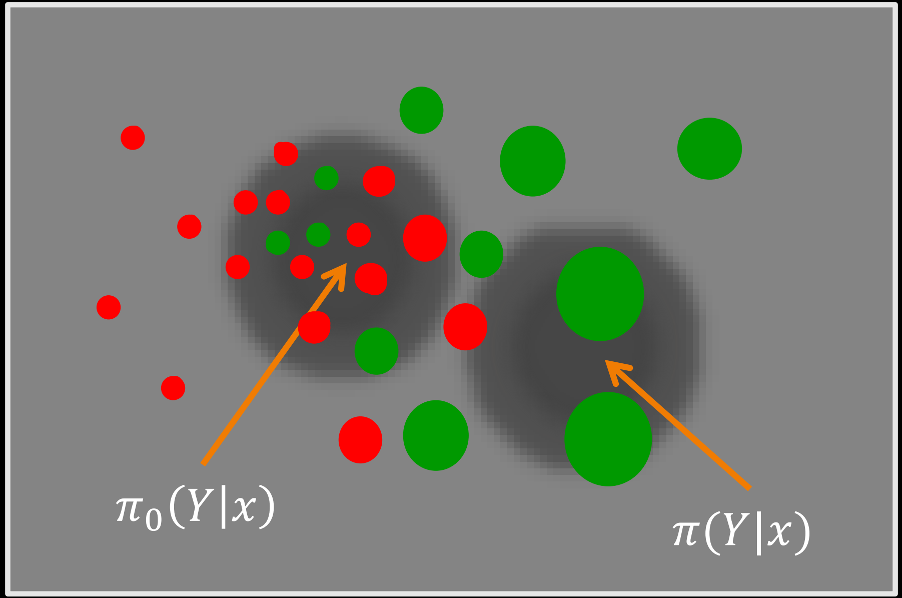
Unbiased:

If

$$\forall x, y{:}\, \pi(y|x)P(x) > 0 \;\rightarrow \pi_0(y|x) > 0$$

then

$$\mathrm{E}\left[\hat{U}_{IPS}(\pi)\right] = U(\pi)$$



IPS Estimator is Unbiased

$$E[\hat{U}_{IPS}(\pi)] = \frac{1}{n}\sum_{x_1,y_1} \dots \sum_{x_n,y_n}\left[\sum_i \frac{\pi(y_i|x_i)}{\pi_0(y_i|x_i)}\delta(x_i,y_i)\right]\pi_0(y_1|x_1)\dots\pi_0(y_n|x_n)P(x_1)\dots P(x_n)$$

independent

$$= \frac{1}{n}\sum_{x_1,y_1}\pi_0(y_1|x_1)P(x_1)\dots\sum_{x_n,y_n}\pi_0(y_n|x_n)P(x_n)\left[\sum_i \frac{\pi(y_i|x_i)}{\pi_0(y_i|x_i)}\delta(x_i,y_i)\right]$$

$$= \frac{1}{n}\sum_i\sum_{x_1,y_1}\pi_0(y_1|x_1)P(x_1)\dots\sum_{x_n,y_n}\pi_0(y_n|x_n)P(x_n)\left[\frac{\pi(y_i|x_i)}{\pi_0(y_i|x_i)}\delta(x_i,y_i)\right]$$

marginal

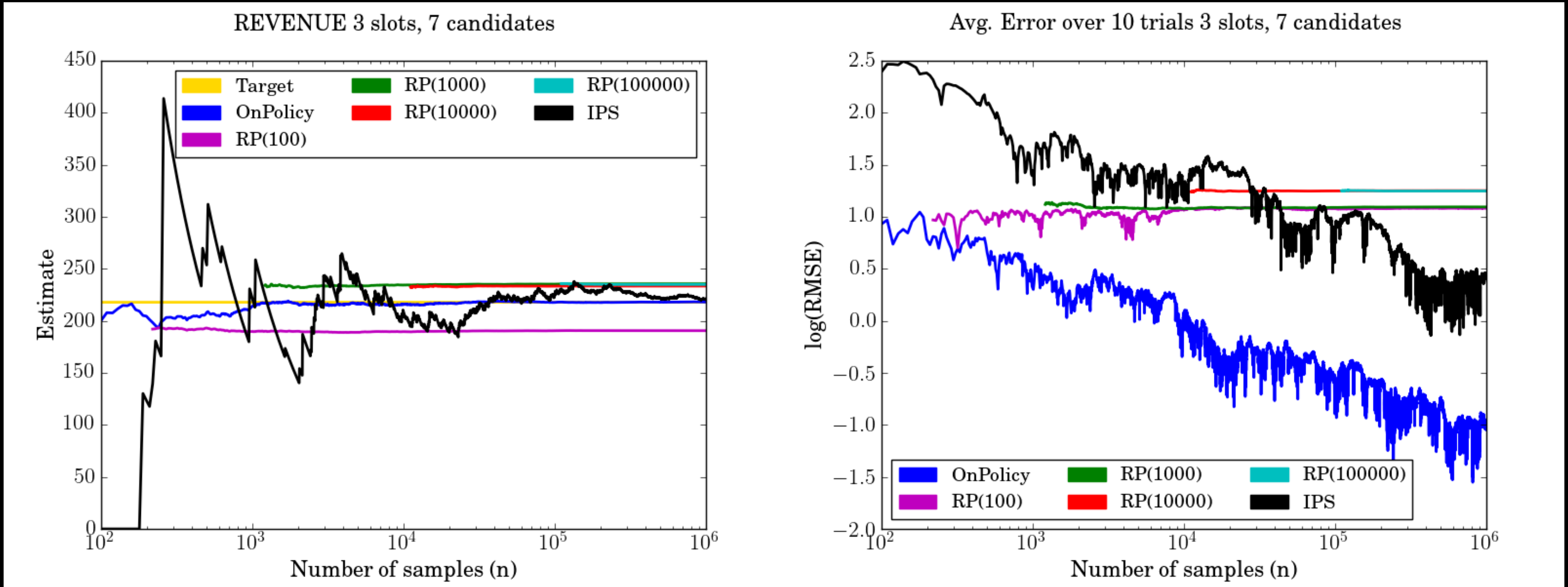
$$= \frac{1}{n}\sum_i\sum_{x_i,y_i}\pi_0(y_i|x_i)P(x_i)\left[\frac{\pi(y_i|x_i)}{\pi_0(y_i|x_i)}\delta(x_i,y_i)\right]$$

full support

$$= \frac{1}{n}\sum_i\sum_{x_i,y_i}P(x_i)\pi(y_i|x_i)\delta(x_i,y_i) = \frac{1}{n}\sum_i \mathrm{U}(\pi) = U(\pi)$$

identical x,y

News Recommender: Results



IPS eventually beats RP; variance decays as $O\left(\frac{1}{\sqrt{n}}\right)$

Counterfactual Policy Evaluation

- Controlled Experiment Setting:
  - Log data: $D = \left((x_1, y_1, \delta_1, p_1), \ldots, (x_n, y_n, \delta_{\mathrm{n}}, p_n)\right)$
- Observational Setting:
  - Log data: $D = \left((x_1, y_1, \delta_1, z_1), \ldots, (x_n, y_n, \delta_{\mathrm{n}}, z_n)\right)$
  - Estimate propensities: $p_i = P(y_i | x_i, z_i)$ based on x_i and other confounders z_i

→ Goal: Estimate average treatment effect of new policy π.

- IPS Estimator

$$\hat{U}(\pi) = \frac{1}{n} \sum_i \delta_i \frac{\pi(y_i | x_i)}{p_i}$$

or many others.

Evaluation: Summary

- Evaluating Online Metrics Offline
  - A/B Testing (on-policy)
    → Counterfactual estimation from logs (off-policy)
- Approach 1: "Model the world"
  - Estimation via reward prediction
  - Pro: low variance
  - Con: model mismatch can lead to high bias
- Approach 2: "Model the bias"
  - Counterfactual Model
  - Inverse propensity scoring (IPS) estimator
  - Pro: unbiased for known propensities
  - Con: large variance

From Evaluation to Learning

- Naïve "Model the World" Learning:
  - Learn: $\hat{\delta}: x \times y \to \Re$
  - Derive Policy:

$$\pi(y|x) = \underset{y'}{\operatorname{argmin}}\left[\hat{\delta}(x, y')\right]$$

- Naïve "Model the Bias" Learning:
  - Find policy that optimizes IPS training error

$$\pi = \underset{\pi'}{\operatorname{argmin}}\left[\sum_i \frac{\pi'(y_i|x_i)}{\pi_0(y_i|x_i)}\delta_i\right]$$

Outline of Class

- Counterfactual and Causal Inference
- Evaluation
  - Improved counterfactual estimators
  - Applications in recommender systems, etc.
  - Dealing with missing propensities, randomization, etc.
- Learning
  - Batch Learning from Bandit Feedback
  - Dealing with combinatorial and continuous action spaces
  - Learning theory
  - More general learning with partial information data (e.g. ranking, embedding)