Learning to Act and Causality

CS4780/5780 – Machine Learning
Fall 2019

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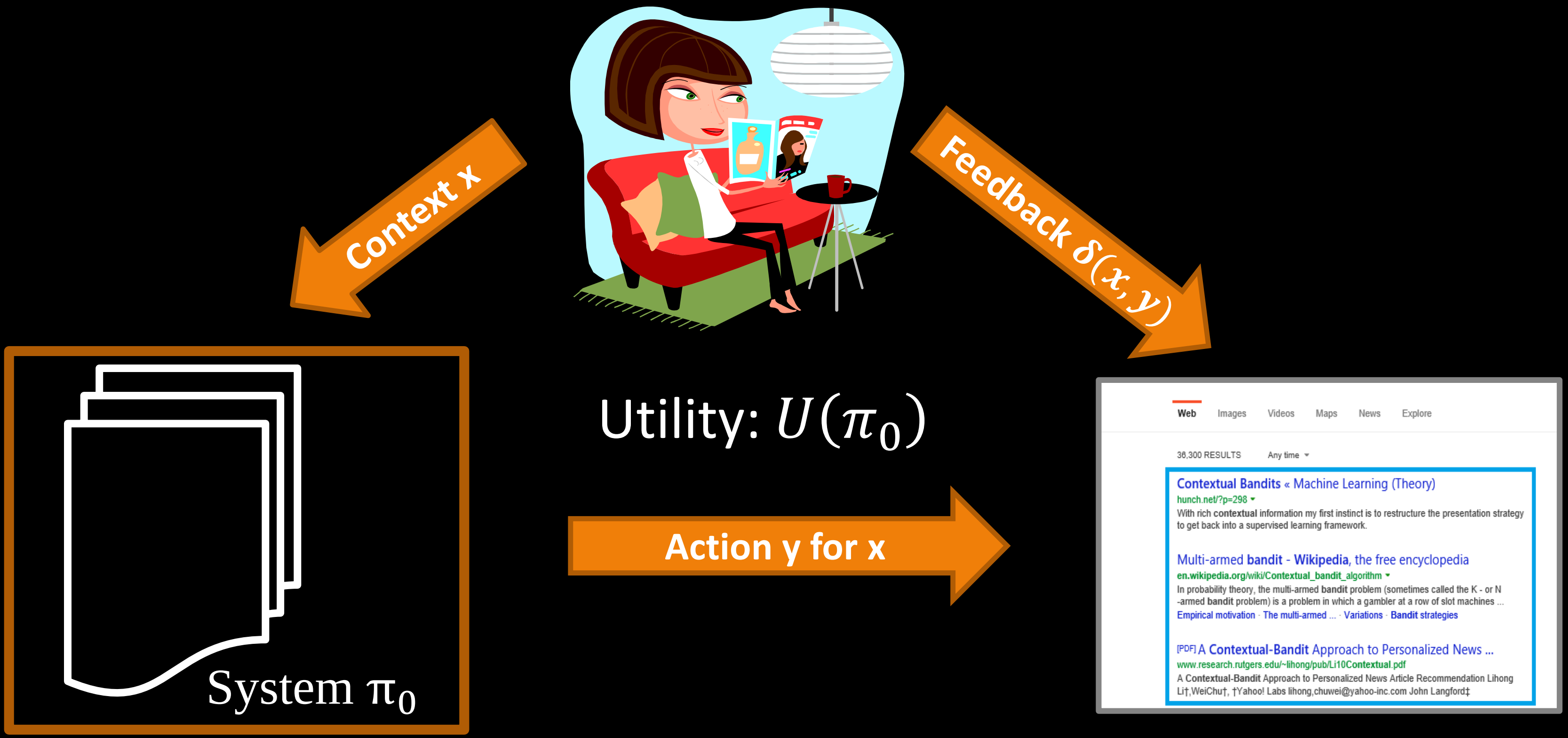
Reading:
G. Imbens, D. Rubin, Causal Inference for Statistics …, 2015. Chapter 1.

Interactive System Schematic



News Recommender

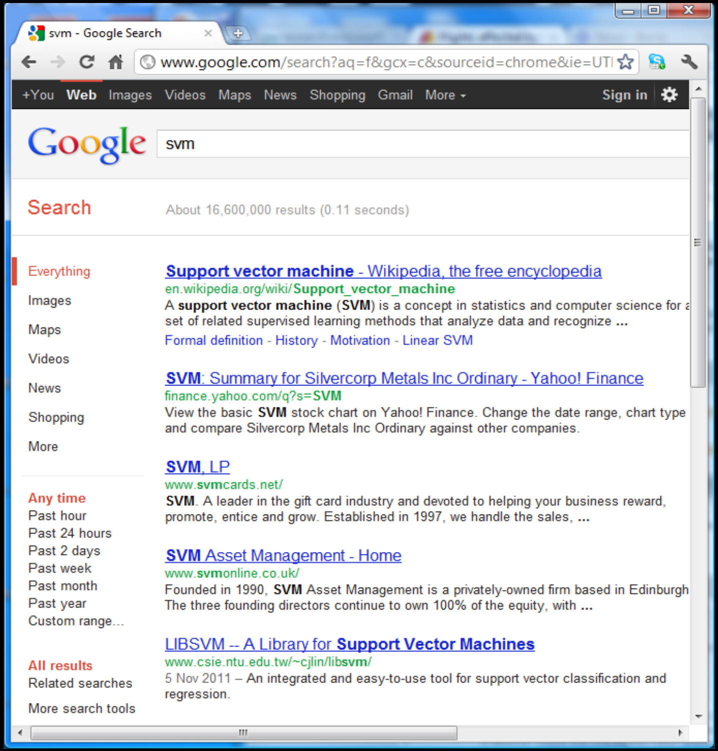
- Context x:
  - User
- Action y:
  - Portfolio of newsarticles
- Feedback $\delta(x, y)$:
  - Reading time in minutes

Music Voice Assistant

- Context x:
  - User and speech
- Action y:
  - Track that is played
- Feedback $\delta(x, y)$:
  - Listened to the end

Search Engine

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



Log Data from Interactive Systems

- Data

context

π_0 action

reward / loss

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

→ 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 $\pi_0 \colon X \to Y$
  – Feedback δ_i from unknown function $\delta \colon X \times Y \to \Re$

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

Goal

Use interaction log data

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

- for evaluation of system π
  - Offline estimate of online performace of some system π.
  - System π can be different from π_0 that generated log.
- for learning new system π

Evaluation: Outline

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

Online Performance Metrics

Example metrics

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

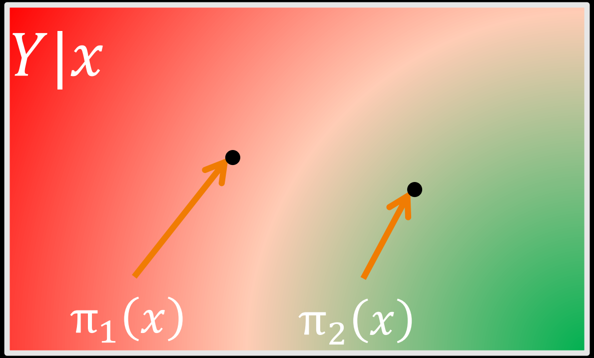
→ Correct choice depends on application and is not the focus of this lecture.

This lecture:

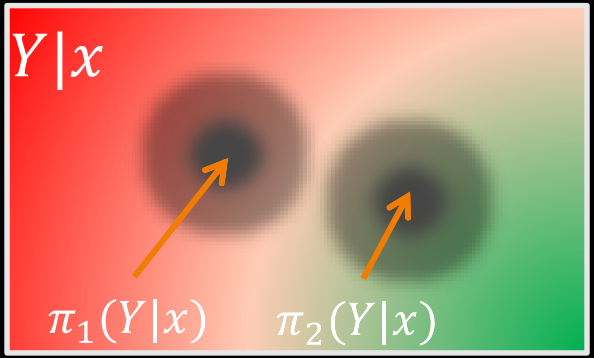
Metric encoded as $\delta(x, y)$ [click/payoff/time for (x,y) pair]

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



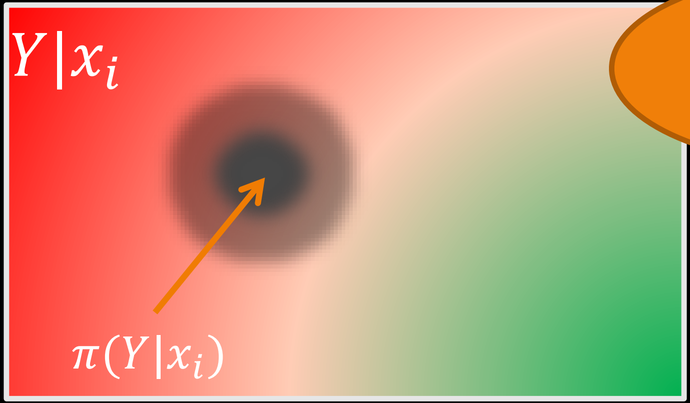
System Performance

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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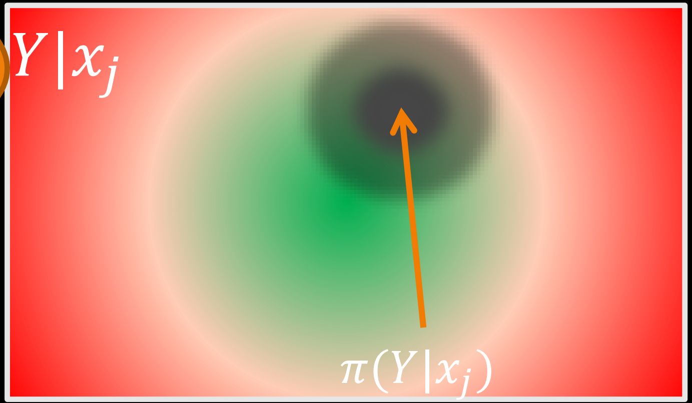

Online Evaluation: A/B Testing

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

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

→ 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 →

$\hat{U}(\pi_6)$ $\hat{U}(\pi_{12})$ $\hat{U}(\pi_{18})$ $\hat{U}(\pi_{24})$ $\hat{U}(\pi_{30})$

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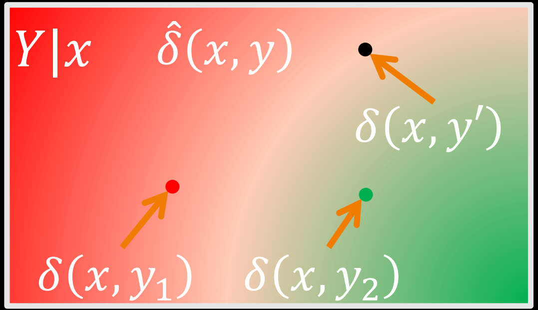
Approach 1: Reward Predictor

- Idea:
  - Use $S = \left((x_1, y_1, \delta_1), \dots, (x_n, y_n, \delta_n)\right)$ from π_0 to estimate reward predictor $\hat{\delta}(x, y)$

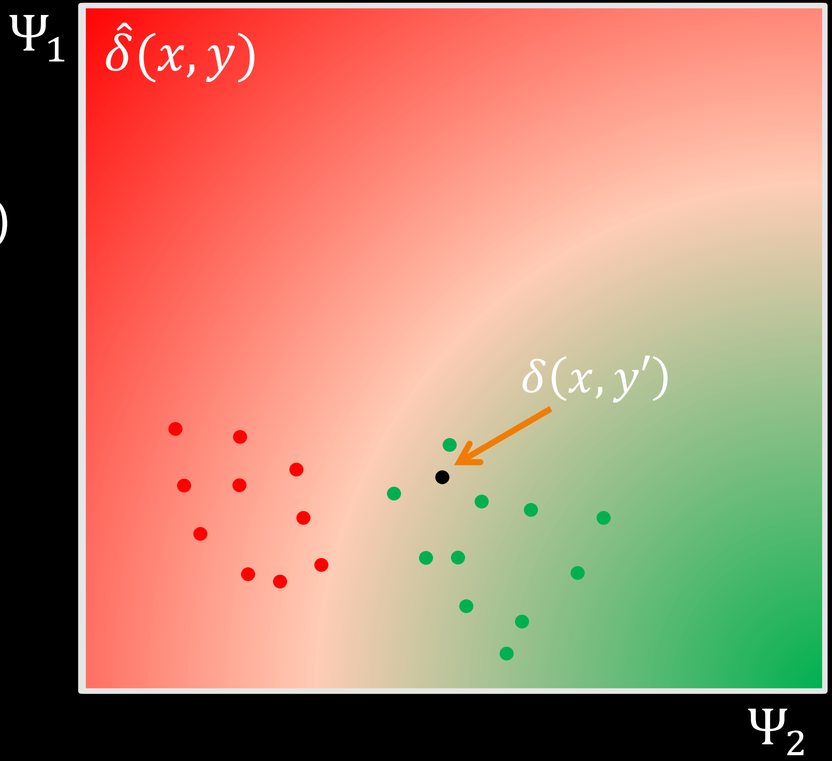


- Deterministic π: Simulated A/B Testing with predicted $\hat{\delta}(x, y)$
  - For actions $y_i' = \pi(x_i)$ from new policy π, generate predicted log $S' = \left(\left(x_1, y_1', \hat{\delta}(x_1, y_1')\right), \dots, \left(x_n, y_n', \hat{\delta}(x_n, y_n')\right)\right)$
  - Estimate performace 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

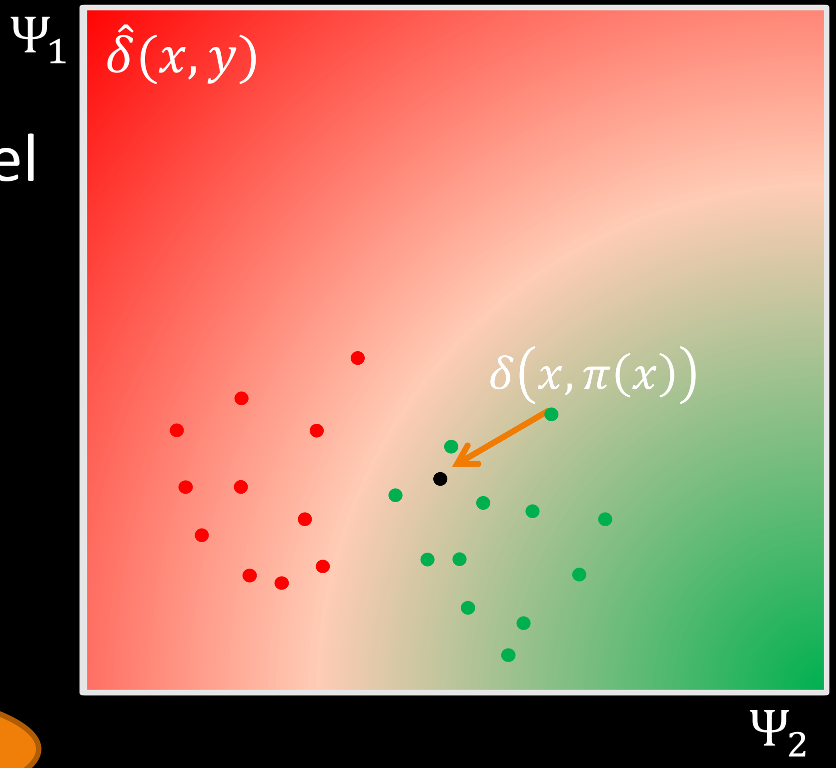


Problems of Reward Predictor

- 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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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.

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

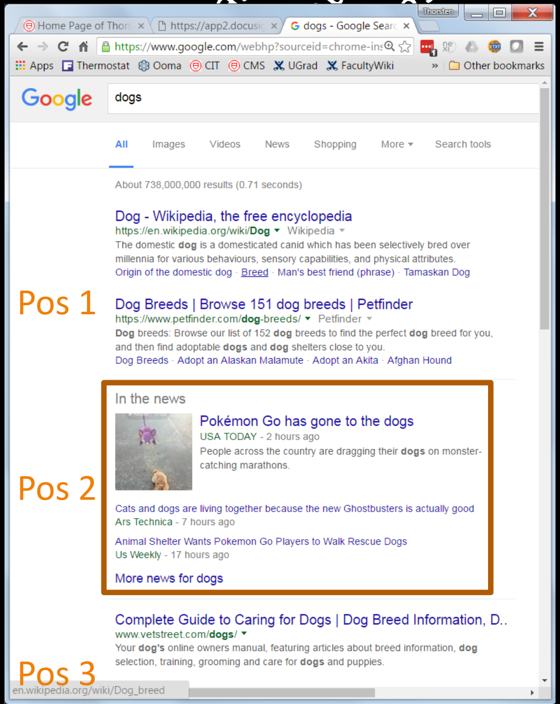
Potential Outcome Model

- 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?

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

Counterfactual Model

- Example: ~~Treating Heart Attacks~~ Placing Vertical
  - 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?



Potential Outcome 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?

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

Treatment Effects

- Average Treatment Effect of Treatment y
  - $\mathrm{U}(y) = \frac{1}{n}\sum_i \delta(x_i, y)$
- Example
  - $\mathrm{U}(bypass) = \frac{5}{11}$
  - $\mathrm{U}(stent) = \frac{7}{11}$
  - $\mathrm{U}(drugs) = \frac{3}{11}$

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
  - $\hat{U}(drugs) = \frac{1}{11}\left(\frac{1}{0.8} + \frac{1}{0.7} + \frac{1}{0.8} + \frac{0}{0.1}\right)$ $= 0.36 < 0.75$

$$\pi_0(Y_i = y|x_i)$$

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

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

Interventional vs Observational

- Interventional Controlled Experiment
  - Assignment Mechanism under our control
  - Propensities $p_i = \pi_0(Y_i = y_i|x_i)$ are known by design
  - Requirement: $\forall y: \pi_0(Y_i = y|x_i) > 0$ (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
  - $\hat{U}_{ips}(\pi) = \frac{1}{n} \sum_i \frac{\mathbb{I}\{y_i = \pi(x_i)\}}{p_i} \delta(x_i, y_i)$

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

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

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

Counterfactual Model = Logs

Recorded in Log

		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.	

Evaluation: Outline

- Evaluating Online Metrics Offline
  - A/B Testing (on-policy)
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- Approach 1: “Model the world”
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System Evaluation via Inverse Propensity Score Weighting

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,

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

→ 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:

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

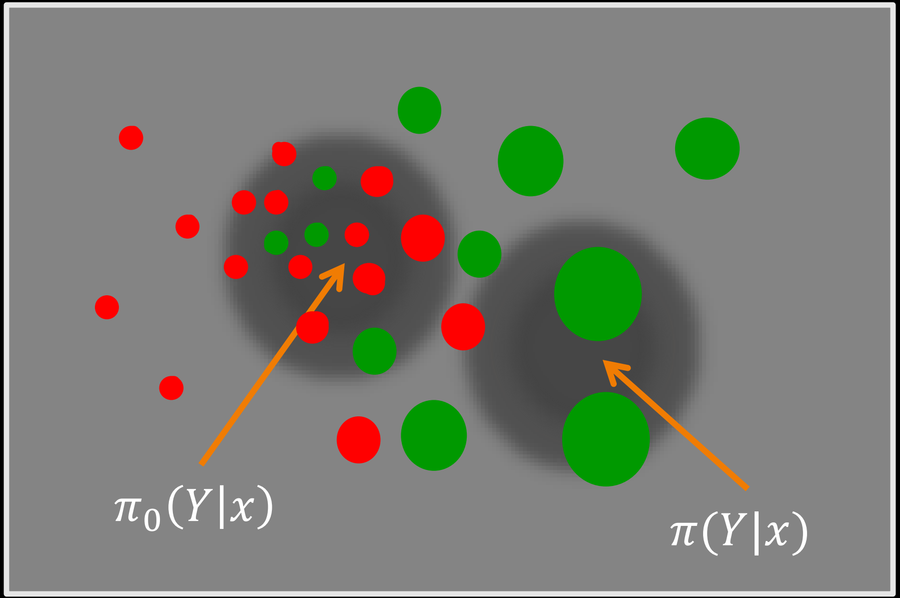
Unbiased:

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

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

- Offline Evaluation of Online Metrics
  - 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

Setting: Batch Learning from Bandit Feedback (BLBF)

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

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

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

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