Announcements

- Proposals graded

Hypothesis testing

Machine Learning – CSE546

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October 30, 2018

Anomaly detection

You are Amazon and wish to detect transactions with stolen credit cards.

For each transaction we observe a **feature vector X**:
{ email-address, age of account, anonymous PO box, price of items, copies of purchased item, etc. }
and the transaction is either **real (Y=0)** or **fraudulent (Y=1)**

Hypothesis testing:

H0: $X \sim P_0$

H1: $X \sim P_1$

$$P_k = \mathbb{P}(X = x | Y = k)$$

Your job is to build a (possibly randomized) decision function $\delta(x) \in \{0, 1\}$

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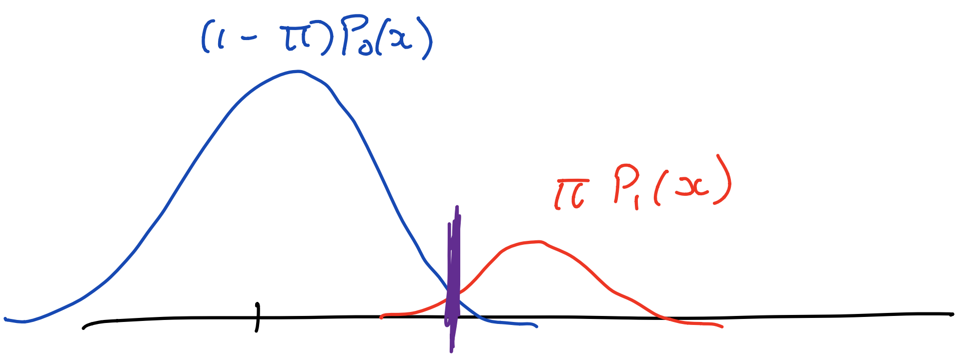
Bayesian Hypothesis Testing:

Assume $\mathbb{P}(Y = 1) = \pi$

$$\mathbb{P}(X = x) = \pi P_1(x) + (1 - \pi) P_0(x)$$

$$\arg\min_{\delta} \mathbb{P}_{XY}(Y \neq \delta(X))$$



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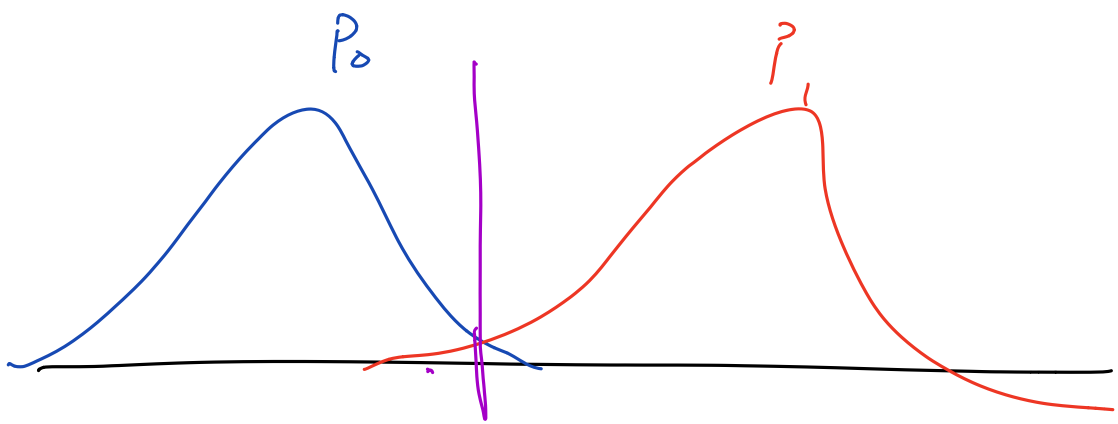
Minimax Hypothesis Testing:

$$\arg\min_{\delta} \max\{\mathbb{P}(\delta(X) = 0 | Y = 1), \mathbb{P}(\delta(X) = 1 | Y = 0)\}$$



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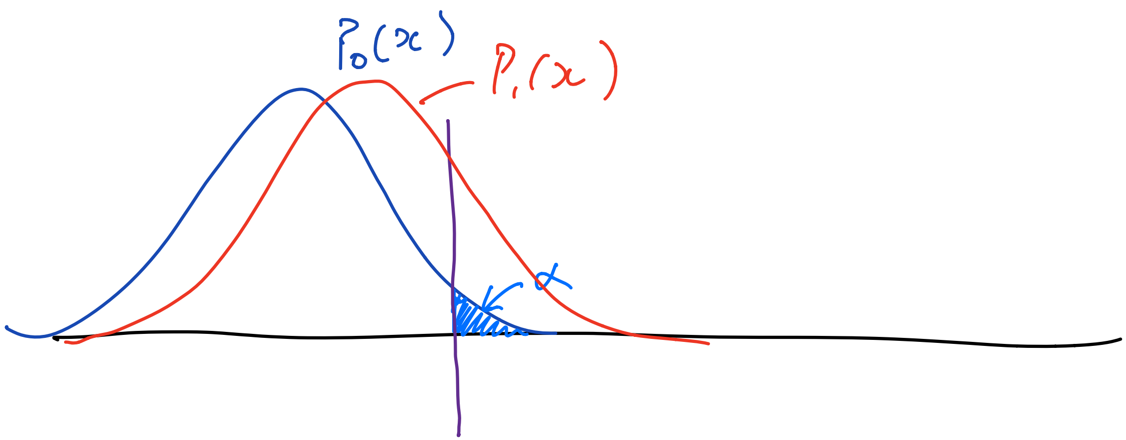
Neyman-Pearson Hypothesis Testing:

$$\arg\max_{\delta} \mathbb{P}(\delta(X) = 1 | Y = 1), \text{ subject to } \mathbb{P}(\delta(X) = 1 | Y = 0) \leq \alpha$$



Neyman-Pearson Testing

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Theorem: The optimal test δ^* has the form

$$\mathbb{P}(\delta^*(X) = 1) = \begin{cases} 1 & \text{if } \frac{P_1(x)}{P_0(x)} > \eta \\ \gamma & \text{if } \frac{P_1(x)}{P_0(x)} = \eta \\ 0 & \text{if } \frac{P_1(x)}{P_0(x)} < \eta \end{cases}$$

and satisfies $\mathbb{P}(\delta^*(X) = 1 | Y = 0) = \alpha$

Neyman-Pearson Testing

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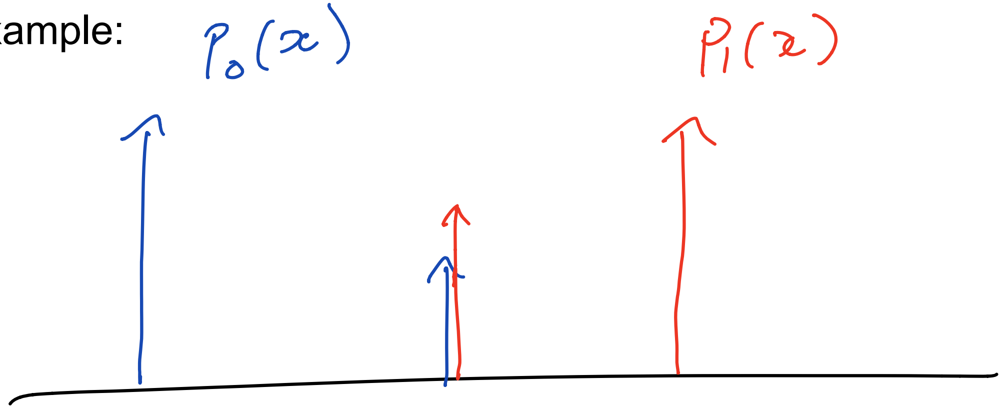
Example:



ROC Curve

Hypothesis testing:

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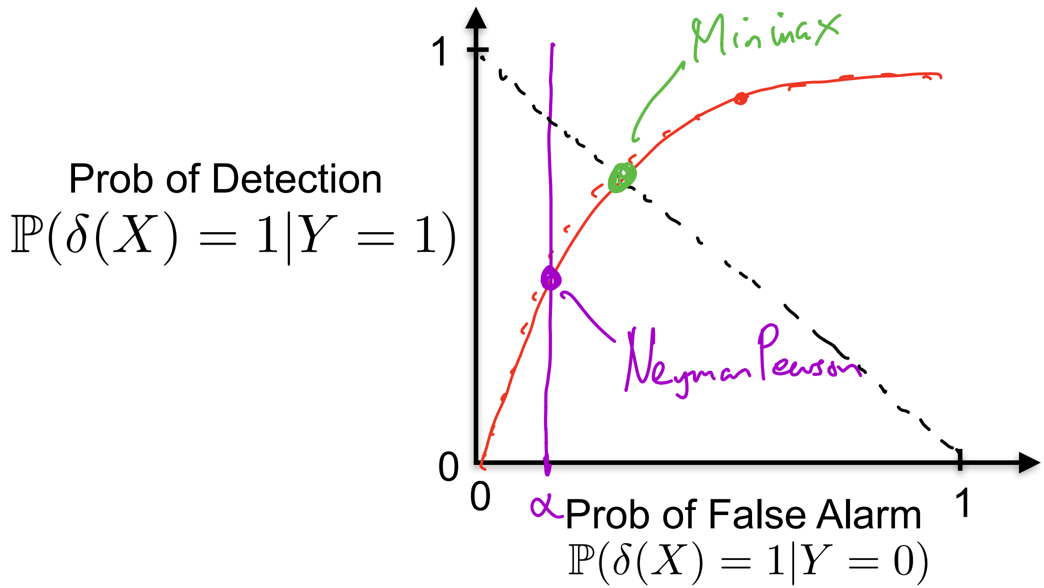

p-values

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Natural to have model for P_0 (regular purchases).
But what if we have no model for P_1 since people are strategic?

p-value

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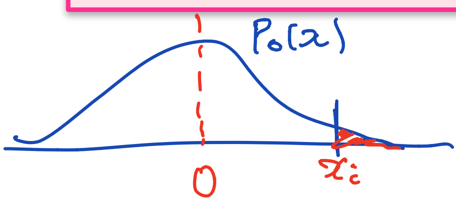
Definition p-value: probability of finding the observed, or more extreme, re- ~~sults when the null hypothesis H0 is true (e.g., $X \sim P_0$)~~

Definition p-value: a uniformly distributed random variable under the null hypothesis (e.g., $X \sim P_0$)

WARNING: A small p-value is **NOT** evidence that H1 is true.



$\mathbb{P}(X > x_i \mid \mathbb{E}[X] = 0)$

p-value

Hypothesis testing:

H0: $X \sim P_0$

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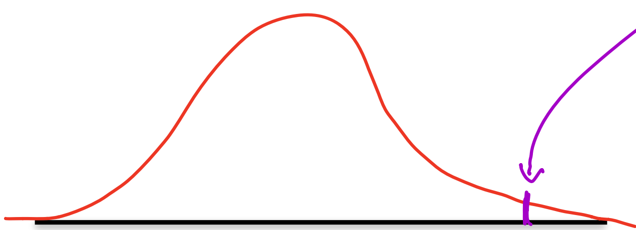
$$P_k = \mathbb{P}(X = x | Y = k)$$

Your job is to build a (possibly randomized) decision function $\delta(x) \in \{0, 1\}$

> **Definition** p-value: a uniformly distributed random variable under the null hypothesis (e.g., $X \sim P_0$)

$$P_0(x) = \mathcal{N}(x; \mu_0, \sigma^2)$$

$P_0(x)$



Observe: $x_i \in \mathbb{R}$

p-value: $p_i = P_0(X \geq x_i)$

$$= \int_{x=x_i}^{\infty} \frac{1}{\sqrt{2\pi\sigma^2}} e^{-(x-\mu_0)^2/2\sigma^2} dx$$

$$= 1 - F\left(\frac{x_i - \mu_0}{\sigma}\right)$$

$Z \sim F$

Then $\mathbb{P}(Z \leq t) = F(t)$, $F(Z) \in (0,1)$

p-value: used the right way

Hypothesis testing:

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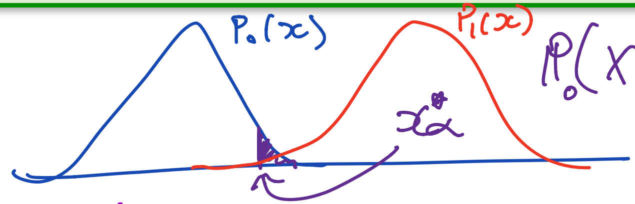

$P_0(X \geq x^*_\alpha) = \alpha$

Set: $\alpha = .05$

Observe: $x_i \in \mathbb{R}$

p-value: $p_i = P_0(X \geq x_i)$ (p_i is uniformly dist on [0,1] under H0)

Test: If $p_i \leq \alpha$ then **reject** the null hypothesis H0

p-value: used the **wrong** way

Hypothesis testing:

H0: $X \sim P_0$

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$$P_k = \mathbb{P}(X = x | Y = k)$$

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Test: If $p_i \leq \alpha$ then **reject** the null hypothesis H0

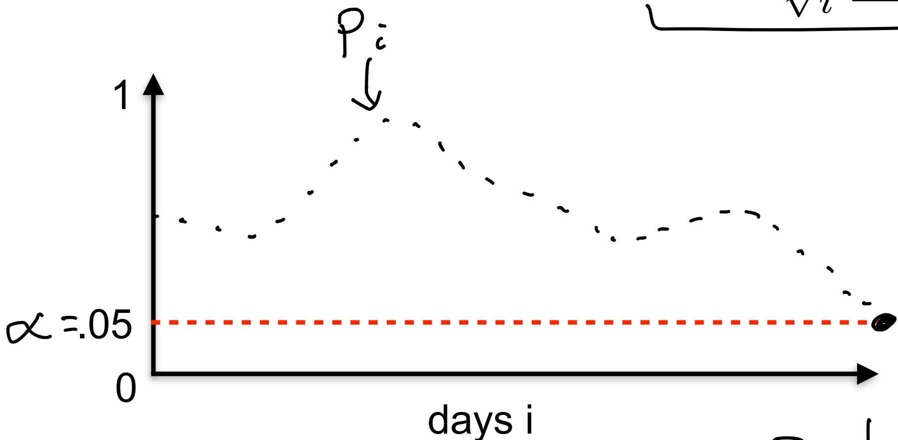
BAD If $p_i > \alpha$ repeat the experiment with new x_i until $p_i \leq \alpha$

p-value: used the **wrong** way

Each day i=1,2,… you measure an iid $x_i \sim \mathcal{N}(\mu, 1)$

H0: $\mu = 0$

Under H0 the statistic $Z_i = \frac{1}{\sqrt{i}} \sum_{j=1}^{i} x_j \sim \mathcal{N}(0,1)$



$$p_i = \frac{1}{\sqrt{2\pi}} \int_{z=z_i}^{\infty} e^{-z^2/2} dz$$

p-hacking

Multiple testing

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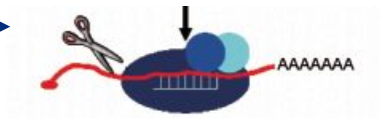
Case study in adaptive sampling tradeoffs

"Drosophila RNAi screen identifies host genes important for influenza virus replication," Nature 2008.

Wild type strain with 13,071 genes → Inhibit a single gene → infect with fluorescing virus (indicating gene's influence)



microwell array

Each gene i=1,2,…,n you measure an $x_i \sim \mathcal{N}(\mu_i, 1)$

H0(i): $\mu_i = 0$

Consider procedure for individual hypothesis testing:

- **Set:** $\alpha = .05$
- **Observe:** $x_i \in \mathbb{R}$

  p-value: $p_i = P_0(X \geq x_i)$

  Test: If $p_i \leq \alpha$ then **reject** the null hypothesis H0

Under H0, how many genes do we expect to reject the null hypothesis?

Multiple Testing

If we make n rejections individually at level α

$$I_0 = \{i : H0(i) \text{ is true}\}$$

Expected # of false discoveries

$$\mathbb{E}\Big[\sum_{i \in I_0} \mathbf{1}\{p_i \leq \alpha\}\Big] = \sum_{i \in I_0} \mathbb{P}(p_i \leq \alpha) = |I_0|\alpha$$

That's a lot of false alarms!

Multiple Testing - FWER

Family-wise error rate FWER$= \mathbb{P}$(reject any true null)

$I_0 = \{i : H0(i) \text{ is true}\}$

Bonferroni rule: Reject i if $p_i \leq \alpha/n$

$R = \{i : p_i \leq \frac{\alpha}{n}\}$

$$FWER = \mathbb{P}\left(\bigcup_{I_0}\{p_i \leq \alpha/n\}\right) \leq \sum_{i \in I_0} \mathbb{P}(p_i \leq \alpha/n)$$

$$= \sum_{i \in I_0} \frac{\alpha}{n} = \frac{|I_0|}{n}\alpha$$

$$\leq \alpha$$

Multiple Testing - FDR

False discovery rate FDR$= \mathbb{E}\left[\frac{|I_0 \cap R|}{|R|}\right]$

$$I_0 = \{i : H0(i) \text{ is true}\}$$

Benjamini-Hochberg procedure:

Sort p-values such that $p_{(1)} \leq p_{(2)} \leq \cdots \leq p_{(n)}$

$$i_{\max} = \max\{i : p_{(i)} \leq \tfrac{i}{n}\alpha\}$$

$$R = \{i : i \leq i_{\max}\}$$

p-value $\mathbb{P}(p_i \leq x) = x$

Theorem: BH(α) satisfies FDR$\leq \alpha$

Bayesian Methods

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MLE Recap - coin flips

- **Data**: sequence *D= (HHTHT…),* **k heads** out of **n flips**
- **Hypothesis:** P(Heads) = θ, P(Tails) = 1-θ

$$P(\mathcal{D}|\theta) = \theta^k (1-\theta)^{n-k}$$

- Maximum likelihood estimation (MLE): Choose θ that maximizes the probability of observed data:

$$\begin{aligned}\widehat{\theta}_{MLE} &= \arg\max_{\theta}\ P(\mathcal{D}|\theta) \\ &= \arg\max_{\theta}\ \log P(\mathcal{D}|\theta)\end{aligned}$$

$$\widehat{\theta}_{MLE} = \frac{k}{n}$$

What about prior

- *Billionaire*: Wait, I know that the coin is “close” to 50-50. What can you do for me now?
- **You say: I can learn it the Bayesian way…**

Bayesian Learning

- Use Bayes rule:

$$P(\theta \mid \mathcal{D}) = \frac{P(\mathcal{D} \mid \theta)P(\theta)}{P(\mathcal{D})}$$

- Or equivalently:

$$P(\theta \mid \mathcal{D}) \propto \underbrace{P(\mathcal{D} \mid \theta)}_{\text{likelihood}}\underbrace{P(\theta)}_{\text{Prior belief about how coins from factory are dist}}$$

likelihood

Prior belief about how coins from factory are dist

Bayesian Learning for Coins

$$P(\theta \mid \mathcal{D}) \propto P(\mathcal{D} \mid \theta) P(\theta)$$

- Likelihood function is simply Binomial:

$$P(\mathcal{D} \mid \theta) = \theta^{\alpha_H} (1 - \theta)^{\alpha_T}$$

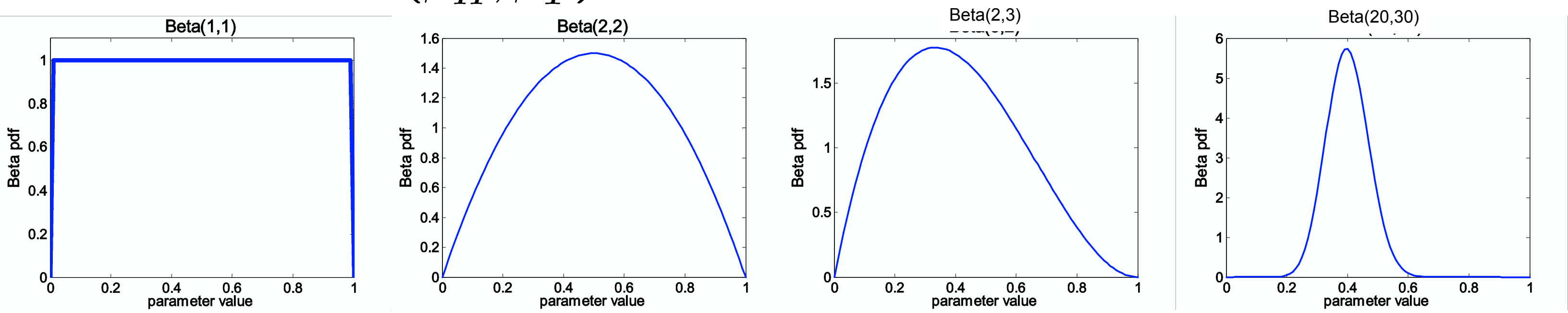
- What about prior?
  - Represent expert knowledge
- Conjugate priors:
  - Closed-form representation of posterior
  - **For Binomial, conjugate prior is Beta distribution**

Beta prior distribution – P(θ)

$$P(\theta) = \frac{\theta^{\beta_H - 1}(1-\theta)^{\beta_T - 1}}{B(\beta_H, \beta_T)} \sim Beta(\beta_H, \beta_T)$$

Mean:

Mode:



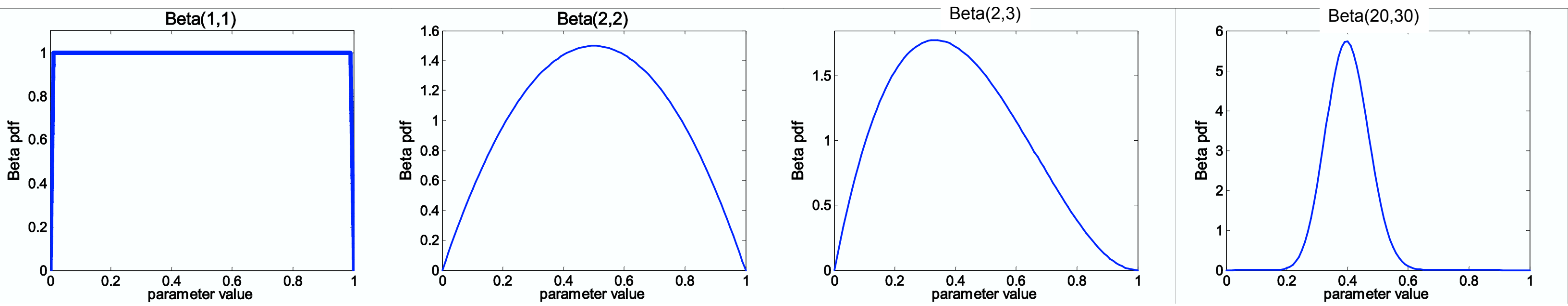
- Likelihood function: $P(\mathcal{D} \mid \theta) = \theta^{\alpha_H}(1-\theta)^{\alpha_T}$
- Posterior: $P(\theta \mid \mathcal{D}) \propto P(\mathcal{D} \mid \theta) P(\theta)$

Posterior distribution

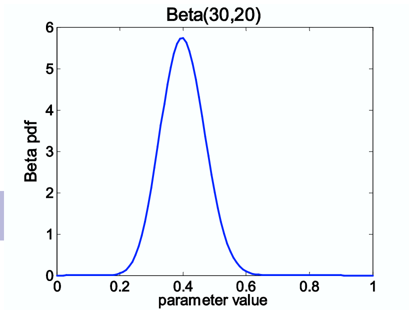
- Prior: $Beta(\beta_H, \beta_T)$
- Data: α_H heads and α_T tails

- Posterior distribution:

$$P(\theta \mid \mathcal{D}) \sim Beta(\beta_H + \alpha_H, \beta_T + \alpha_T)$$



Using Bayesian posterior



- Posterior distribution:

$$P(\theta \mid \mathcal{D}) \sim Beta(\beta_H + \alpha_H, \beta_T + \alpha_T)$$

- Bayesian inference:
  - Estimate mean

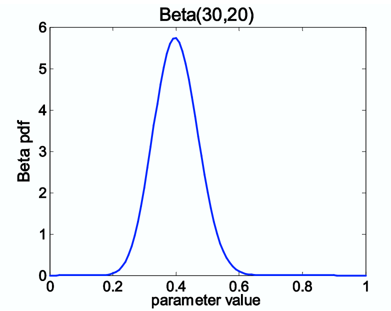
$$E[\theta] = \int_0^1 \theta P(\theta|\mathcal{D}) d\theta$$

  - Estimate arbitrary function f

$$E[f(\theta)] = \int_0^1 f(\theta) P(\theta \mid \mathcal{D}) d\theta$$

  - For arbitrary f integral is often hard to compute

MAP: Maximum a posteriori approximation



$$P(\theta \mid \mathcal{D}) \sim Beta(\beta_H + \alpha_H, \beta_T + \alpha_T)$$

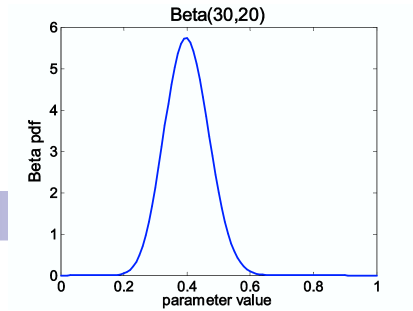
$$E[f(\theta)] = \int_0^1 f(\theta) P(\theta \mid \mathcal{D}) d\theta$$

- As more data is observed, Beta is more certain

- MAP: use most likely parameter:

$$\widehat{\theta} = \arg\max_{\theta} P(\theta \mid \mathcal{D}) \qquad E[f(\theta)] \approx f(\widehat{\theta})$$

MAP for Beta distribution

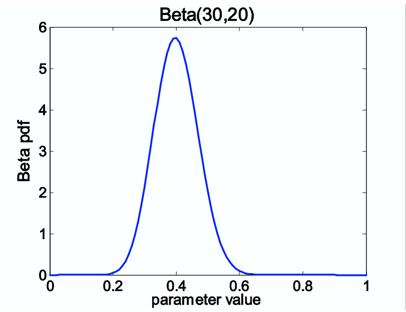


$$P(\theta \mid \mathcal{D}) = \frac{\theta^{\beta_H+\alpha_H-1}(1-\theta)^{\beta_T+\alpha_T-1}}{B(\beta_H+\alpha_H, \beta_T+\alpha_T)} \sim Beta(\beta_H+\alpha_H, \beta_T+\alpha_T)$$

- MAP: use most likely parameter:

$$\widehat{\theta} = \arg\max_{\theta} P(\theta \mid \mathcal{D}) =$$

MAP for Beta distribution



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- MAP: use most likely parameter:

$$\widehat{\theta} = \arg\max_{\theta} P(\theta \mid \mathcal{D}) = \frac{\beta_H + \alpha_H - 1}{\beta_H + \beta_T + \alpha_H + \alpha_T - 2}$$

- Beta prior equivalent to extra coin flips
- As $N \to 1$, prior is "forgotten"
- **But, for small sample size, prior is important!**

Bayesian vs Frequentist

- Data: $\mathcal{D}$ Estimator: $\widehat{\theta} = t(\mathcal{D})$ loss: $\ell(t(\mathcal{D}), \theta)$
- Frequentists treat unknown θ ***as fixed*** and the data D ***as random***.
- Bayesian treat the data D **as fixed** and the unknown θ ***as random***

Recap for Bayesian learning

Bayesians are optimists:

- "If we model it correctly, we output most likely answer"
- Assumes one can accurately model:
  - Observations and link to unknown parameter θ: $p(x|\theta)$
  - Distribution, structure of unknown θ: $p(\theta)$

Frequentist are pessimists:

- "All models are wrong, prove to me your estimate is good"
- Makes very few assumptions, e.g. $\mathbb{E}[X^2] < \infty$ and constructs an estimator (e.g., median of means of disjoint subsets of data)
- Must analyze each estimate