22: MAP

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May 27, 2020

Quick slide reference

Maximum a Posteriori Estimator

Maximum Likelihood Estimator

Consider a sample of n i.i.d. random variables $X_1, X_2, \dots, X_n$ (data).

Maximum Likelihood Estimator (MLE)

What is the parameter θ that **maximizes the likelihood** of our observed data $(X_1, X_2, \dots, X_n)$?

$$L(\theta) = f(X_1, X_2, \dots, X_n|\theta) = \prod_{i=1}^{n} f(X_i|\theta)$$

$$\theta_{MLE} = \arg\max_{\theta} \underbrace{f(X_1, X_2, \dots, X_n|\theta)}_{\text{likelihood of data}}$$

Observations:

- MLE maximizes probability of observing data given a parameter θ.
- If we are estimating θ, shouldn't we maximize the probability of θ directly?

Today: **Bayesian estimation** using the Bayesian definition of probability!

Maximum A Posterior (MAP) Estimator

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Maximum Likelihood Estimator (MLE)

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$$\theta_{MLE} = \arg\max_{\theta} \underbrace{f(X_1, X_2, \dots, X_n|\theta)}_{\text{likelihood of data}}$$

Maximum a Posteriori (MAP) Estimator

Given our observed data $(X_1, X_2, \dots, X_n)$, what is the **most likely parameter** θ?

$$\theta_{MAP} = \arg\max_{\theta} \underbrace{f(\theta|X_1, X_2, \dots, X_n)}_{\text{posterior distribution of } \theta}$$

Maximum A Posterior (MAP) Estimator

Consider a sample of n i.i.d. random variables $X_1, X_2, \dots, X_n$ (data).

def The **Maximum a Posteriori (MAP) Estimator** of θ is the value of θ that maximizes the posterior distribution of θ.

$$\theta_{MAP} = \arg\max_{\theta} f(\theta | X_1, X_2, \dots, X_n)$$

Intuition with Bayes' Theorem:

$L(\theta)$, probability of data given parameter θ

After seeing data, posterior belief of θ

$$\underbrace{P(\theta|\text{data})}_{\text{posterior}} = \frac{\underbrace{P(\text{data}|\theta)}_{\text{likelihood}}\underbrace{P(\theta)}_{\text{prior}}}{P(\text{data})}$$

Before seeing data, prior belief of θ

Solving for θ_{MAP}

- Observe data: $X_1, X_2, \dots, X_n$, all i.i.d.
- Let likelihood be same as MLE: $f(X_1, X_2, \dots, X_n|\theta) = \prod_{i=1}^{n} f(X_i|\,\theta)$
- Let the prior distribution of θ be $g(\theta)$.

$$\theta_{MAP} = \arg\max_\theta f(\theta|X_1, X_2, \dots, X_n) = \arg\max_\theta \frac{f(X_1, X_2, \dots, X_n|\theta)g(\theta)}{h(X_1, X_2, \dots, X_n)}$$ (Bayes' Theorem)

$$= \arg\max_\theta \frac{g(\theta)\prod_{i=1}^{n} f(X_i|\,\theta)}{h(X_1, X_2, \dots, X_n)}$$ (independence)

$$= \arg\max_\theta g(\theta) \prod_{i=1}^{n} f(X_i|\,\theta)$$ ($1/h(X_1, X_2, \dots, X_n)$ is a positive constant w.r.t. θ)

$$= \arg\max_\theta \left(\log g(\theta) + \sum_{i=1}^{n} \log f(X_i|\,\theta) \right)$$

θ_{MAP}: Interpretation 1

- Observe data: $X_1, X_2, \ldots, X_n$, all i.i.d.
- Let likelihood be same as MLE: $f(X_1, X_2, \ldots, X_n|\theta) = \prod_{i=1}^{n} f(X_i|\,\theta)$
- Let the prior distribution of θ be $g(\theta)$.

$$\theta_{MAP} = \arg\max_{\theta} f(\theta|X_1, X_2, \ldots, X_n) = \arg\max_{\theta} \frac{f(X_1, X_2, \ldots, X_n|\theta)g(\theta)}{h(X_1, X_2, \ldots, X_n)}$$ (Bayes' Theorem)

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$$= \arg\max_{\theta} \left(\log g(\theta) + \sum_{i=1}^{n} \log f(X_i|\,\theta) \right)$$

θ_{MAP} maximizes
log prior + log-likelihood

θ_{MAP}: Interpretation 2

- Observe data: $X_1, X_2, \ldots, X_n$, all i.i.d.
- Let likelihood be same as MLE: $f(X_1, X_2, \ldots, X_n|\theta) = \prod_{i=1}^{n} f(X_i|\,\theta)$
- Let the prior distribution of θ be $g(\theta)$.

$$\theta_{MAP} = \arg\max_{\theta} f(\theta|X_1, X_2, \ldots, X_n) = \text{arg}$$

The mode of the posterior distribution of θ

(Bayes' Theorem)

$$= \arg\max_{\theta} \frac{g(\theta)\prod_{i=1}^{n} f(X_i|\,\theta)}{h(X_1, X_2, \ldots, X_n)}$$

(independence)

$$= \arg\max_{\theta} g(\theta) \prod_{i=1}^{n} f(X_i|\,\theta)$$

($1/h(X_1, X_2, \ldots, X_n)$ is a positive constant w.r.t. θ)

$$= \arg\max_{\theta} \left(\log g(\theta) + \sum_{i=1}^{n} \log f(X_i|\,\theta) \right)$$

θ_{MAP} maximizes log prior + log-likelihood

Mode: A statistic of a random variable

The **mode** of a random variable X is defined as:

(X discrete, PMF $p(x)$) $\arg\max_x p(x)$

$\arg\max_x f(x)$ (X continuous, PDF $f(x)$)

- Intuitively: The value of X that is "most likely."
- Note that some distributions may not have a unique mode (e.g., Uniform distribution, or Bernoulli(0.5))

$$\theta_{MAP} = \arg\max_\theta f(\theta | X_1, X_2, \dots, X_n)$$

θ_{MAP} is the most likely θ given the data $X_1, X_2, \dots, X_n$.

Bernoulli MAP: Choosing a prior

How does MAP work? (for Bernoulli)

Observe data n heads, m tails

Choose model Bernoulli(p)

Choose prior on θ (some $g(\theta)$)

Find $\theta_{MAP} = \arg\max_{\theta} f(\theta | X_1, X_2, \dots, X_n)$

maximize
log prior + log-likelihood

$$\log g(\theta) + \sum_{i=1}^{n} \log f(X_i | \theta)$$

- Differentiate, set to 0
- Solve

A lot of our effort in MAP depends on the $g(\theta)$ we choose.

MAP for Bernoulli

- Flip a coin 8 times. Observe $n = 7$ heads and $m = 1$ tail.
- Choose a prior on θ. What is θ_{MAP}?

Suppose we pick a prior $\theta \sim \mathcal{N}(0.5, 1^2)$. $g(\theta) = \frac{1}{\sqrt{2\pi}} e^{-(p-0.5)^2/2}$

1. Determine log prior + log likelihood

$$\log g(\theta) + \log f(X_1, X_2, \ldots, X_n | \theta)$$

$$= \log\left(\frac{1}{\sqrt{2\pi}} e^{-(p-0.5)^2/2}\right) + \log\left(\binom{n+m}{n} p^n (1-p)^m\right)$$

$$= -\log\left(\sqrt{2\pi}\right) - (p-0.5)^2/2 + \log\binom{n+m}{n} + n\log p + m\log(1-p)$$

2. Differentiate w.r.t. (each) θ, set to 0

$$-(p-0.5) + \frac{n}{p} - \frac{m}{1-p} = 0$$

3. Solve resulting equations

cubic equations why

We should choose an ”easier” prior. This one is hard!

A better approach: Use conjugate distributions

Observe data — n heads, m tails

Choose model — Bernoulli(p) → (choose conjugate distribution)

Choose prior on θ — (some $g(\theta)$)

Find $\theta_{MAP} = \arg\max_{\theta} f(\theta|X_1, X_2, \ldots, X_n)$

maximize
log prior + log-likelihood

$$\log g(\theta) + \sum_{i=1}^{n} \log f(X_i|\theta)$$

- Differentiate, set to 0
- Solve

⭐ Up next: Conjugate priors are great for MAP!

Bernoulli MAP: Conjugate prior

Beta is a conjugate distribution for Bernoulli

Beta is a **conjugate distribution** for Bernoulli, meaning:

- Prior and posterior parametric forms are the same
- Practically, conjugate means easy update:
  Add numbers of "successes" and "failures" seen to Beta parameters.
- You can set the prior to reflect how fair/biased you think the experiment is apriori.

Prior	$\text{Beta}(a = n_{imag} + 1, b = m_{imag} + 1)$
Experiment	Observe n successes and m failures
Posterior	$\text{Beta}\left(a = n_{imag} + n + 1, b = m_{imag} + m + 1\right)$

Mode of Beta(a, b): $\dfrac{a-1}{a+b-2}$

(we'll prove this in a few minutes)

Beta parameters a, b are called **hyperparameters.**
Interpret Beta(a, b): $a + b - 2$ trials,
of which $a - 1$ are successes

How does MAP work? (for Bernoulli)

Observe data — n heads, m tails

Choose model — Bernoulli(p)

Choose prior on θ — (some $g(\theta)$) — (choose conjugate distribution)

Find $\theta_{MAP} = \underset{\theta}{\arg\max}\ f(\theta|X_1, X_2, \dots, X_n)$

maximize
log prior + log-likelihood

$$\log g(\theta) + \sum_{i=1}^{n} \log f(X_i|\theta)$$

- Differentiate, set to 0
- Solve

Mode of posterior distribution of θ

(posterior is also conjugate)

Conjugate strategy: MAP for Bernoulli

- Flip a coin 8 times. Observe $n = 7$ heads and $m = 1$ tail.
- Choose a prior on θ. What is θ_{MAP}?

Define as data, D

1. Choose a prior — Suppose we pick a prior $\theta \sim \text{Beta}(a, b)$.
2. Determine posterior — Because Beta is a conjugate distribution for Bernoulli, the posterior distribution is $\theta | D \sim \text{Beta}(a+n, b+m)$
3. Compute MAP — $$\theta_{MAP} = \frac{a+n-1}{a+n+b+m-2}$$ (mode of $\text{Beta}(a+n, b+m)$)

MAP in practice

- Flip a coin 8 times. Observe $n = 7$ heads and $m = 1$ tail.
- What is the MAP estimator of the Bernoulli parameter p, if we assume a prior on p of $\text{Beta}(2, 2)$?

MAP in practice

- Flip a coin 8 times. Observe $n = 7$ heads and $m = 1$ tail.
- What is the MAP estimator of the Bernoulli parameter p, if we assume a prior on p of $\text{Beta}(2, 2)$?

1. Choose a prior

$\theta \sim \text{Beta}(2,2)$.

Before flipping the coin, we imagined 2 trials: 1 imaginary head, 1 imaginary tail.

2. Determine posterior

Posterior distribution of θ given observed data is $\text{Beta}(9, 3)$

3. Compute MAP

$$\theta_{MAP} = \frac{8}{10}$$

After the coin, we saw 10 trials: 8 heads (imaginary and real), 2 tails (imaginary and real).

Proving the mode of Beta

Observe data — n heads, m tails

Choose model — Bernoulli(p)

Choose prior on θ — (some $g(\theta)$) / (choose conjugate) Beta(a, b)

Find $\theta_{MAP} = \arg\max_{\theta} f(\theta | X_1, X_2, \dots, X_n)$

maximize
log prior + log-likelihood

$$\log g(\theta) + \sum_{i=1}^{n} \log f(X_i|\theta)$$

- Differentiate, set to 0
- Solve

Mode of posterior distribution of θ

(posterior is also conjugate)

These are equivalent interpretations of θ_{MAP}. We'll use this equivalence to prove the mode of Beta.

From first principles: MAP for Bernoulli, conjugate prior

- Flip a coin 8 times. Observe $n = 7$ heads and $m = 1$ tail.
- Choose a prior on θ. What is θ_{MAP}?

Suppose we pick a prior $\theta \sim \text{Beta}(a, b)$. $g(\theta = p) = \frac{1}{\beta} p^{a-1}(1-p)^{b-1}$

normalizing constant, β

1. Determine log prior + log likelihood

$$\log g(\theta) + \log f(X_1, X_2, \ldots, X_n | \theta) = \log\left(\frac{1}{\beta} p^{a-1}(1-p)^{b-1}\right) + \log\left(\binom{n+m}{n} p^n (1-p)^m\right)$$

$$= \log\frac{1}{\beta} + (a-1)\log(p) + (b-1)\log(1-p) + \log\binom{n+m}{n} + n\log p + m\log(1-p)$$

2. Differentiate w.r.t. (each) θ, set to 0

$$\frac{a-1}{p} + \frac{n}{p} - \frac{b-1}{1-p} - \frac{m}{1-p} = 0$$

3. Solve

(next slide)

From first principles: MAP for Bernoulli, conjugate prior

- Flip a coin 8 times. Observe $n = 7$ heads and $m = 1$ tail.
- Choose a prior θ. What is θ_{MAP}?

Suppose we pick a prior $\theta \sim \text{Beta}(a, b)$. $g(\theta) = \frac{1}{\beta} p^{a-1}(1-p)^{b-1}$

normalizing constant, β

3. Solve for p

$$\frac{a-1}{p} + \frac{n}{p} - \frac{b-1}{1-p} - \frac{m}{1-p} = 0$$

(from previous slide)

$$\Rightarrow \frac{a+n-1}{p} - \frac{b+m-1}{1-p} = 0$$

$$\theta_{MAP} = \frac{a+n-1}{a+n+b+m-2}$$ ✅

The mode of the posterior, $\text{Beta}(a+n, b+m)$!

If we choose a conjugate prior, we avoid calculus with MAP: just report mode of posterior.

(live)

22: MAP

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May 27, 2020

How does MAP work?

Observe data

Choose model with parameter θ

Choose prior on θ

Two valid interpretations of θ_{MAP}

Mode of posterior distribution of θ

or

maximize
log prior + log-likelihood

Find $\theta_{MAP} = \arg\max_{\theta} f(\theta | X_1, X_2, \ldots, X_n)$

$$= \arg\max_{\theta} \left(\log g(\theta) + \sum_{i=1}^{n} \log f(X_i | \theta) \right)$$

If we choose a conjugate prior, we avoid calculus with MAP: just report mode of posterior.

Conjugate distributions

Quick MAP for Bernoulli and Binomial

Review

Beta(a, b) is a conjugate prior for the probability of success in the Bernoulli and Binomial distributions.

$$f(a) = \frac{1}{B(a,b)} x^{a-1}(1-x)^{b-1}$$

Prior Beta(a, b)
Saw $a+b-2$ imaginary trials: $a-1$ successes, $b-1$ failures

Experiment Observe $n+m$ new trials: n successes, m failures

Posterior Beta$(a+n, b+m)$

MAP: $$p = \frac{a+n-1}{a+b+n+m-2}$$

Conjugate distributions

MAP estimator:

$$\theta_{MAP} = \arg\max_{\theta} f(\theta | X_1, X_2, \ldots, X_n)$$

The mode of the posterior distribution of θ

Distribution parameter	Conjugate distribution
Bernoulli p	Beta
Binomial p	Beta
Multinomial p_i	Dirichlet
Poisson λ	Gamma
Exponential λ	Gamma
Normal μ	Normal
Normal σ^2	Inverse Gamma

CS109: We'll only focus on MAP for Bernoulli/Binomial p, Multinomial p_i, and Poisson λ.

Multinomial is Multiple times the fun

Dirichlet$(a_1, a_2, \dots, a_m)$ is a conjugate for Multinomial.

- Generalizes Beta in the same way Multinomial generalizes Bernoulli/Binomial:

$$f(x_1, x_2, \dots, x_m) = \frac{1}{B(a_1, a_2, \dots, a_m)} \prod_{i=1}^{m} x_i^{a_i - 1}$$

Prior Dirichlet$(a_1, a_2, \dots, a_m)$
Saw $\left(\sum_{i=1}^{m} a_i\right) - m$ imaginary trials, with $a_i - 1$ of outcome i

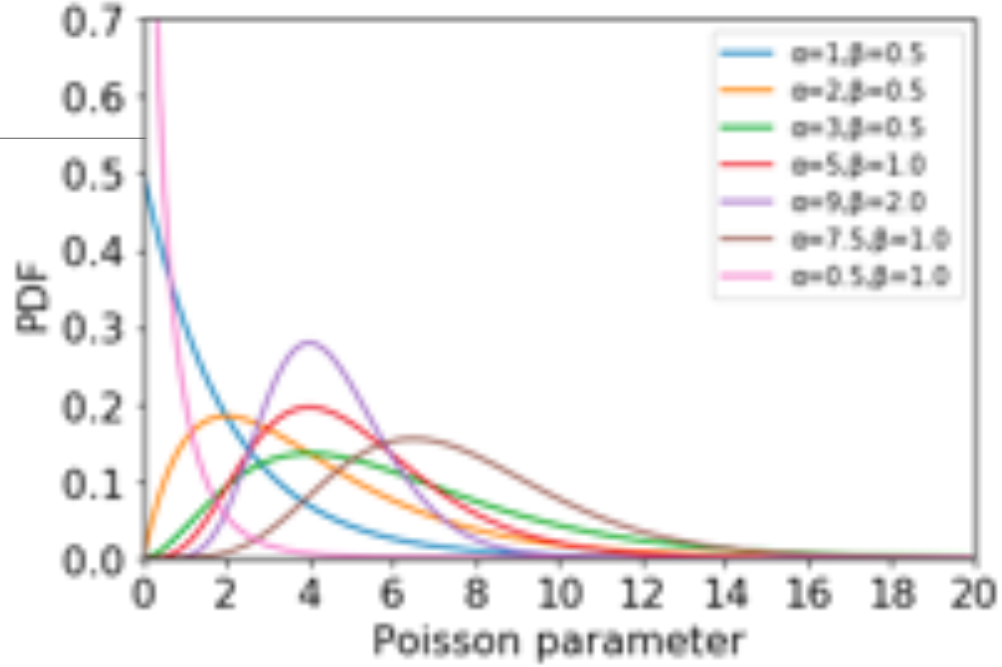
Experiment Observe $n_1 + n_2 + \cdots + n_m$ new trials, with n_i of outcome i

Posterior Dirichlet$(a_1 + n_1, a_2 + n_2, \dots, a_m + n_m)$

MAP:

$$p_i = \frac{a_i + n_i - 1}{\left(\sum_{i=1}^{m} a_i\right) + \left(\sum_{i=1}^{m} n_i\right) - m}$$

Good times with Gamma



Gamma(α, β) is a conjugate for Poisson.

- Also conjugate for Exponential, but we won't delve into that
- Mode of gamma: $(\alpha - 1)/\beta$

Prior $\theta \sim \text{Gamma}(\alpha, \beta)$
Saw $\alpha - 1$ total imaginary events during β prior time periods

Experiment Observe n events during next k time periods

Posterior $(\theta | n \text{ events in } k \text{ periods}) \sim \text{Gamma}(\alpha + n, \beta + k)$

MAP:

$$\theta_{MAP} = \frac{a + n - 1}{\beta + k}$$

MAP for Poisson

$\text{Gamma}(\alpha, \beta)$ is conjugate for Poisson   Mode: $\frac{\alpha-1}{\beta}$

Let λ be the average # of successes in a time period.

1. What does it mean to have a prior of $\theta \sim \text{Gamma}(11,5)$?

Observe 10 imaginary events
in 5 time periods,
i.e., observe at Poisson rate = 2

Now perform the experiment and see 11 events in next 2 time periods.

2. Given your prior, what is the posterior distribution?

3. What is θ_{MAP}?

MAP for Poisson

$\text{Gamma}(\alpha, \beta)$ is conjugate for Poisson Mode: $\frac{\alpha-1}{\beta}$

Let λ be the average # of successes in a time period.

1. What does it mean to have a prior of $\theta \sim \text{Gamma}(11,5)$?

Observe 10 imaginary events in 5 time periods, i.e., observe at Poisson rate = 2

Now perform the experiment and see 11 events in next 2 time periods.

2. Given your prior, what is the posterior distribution?

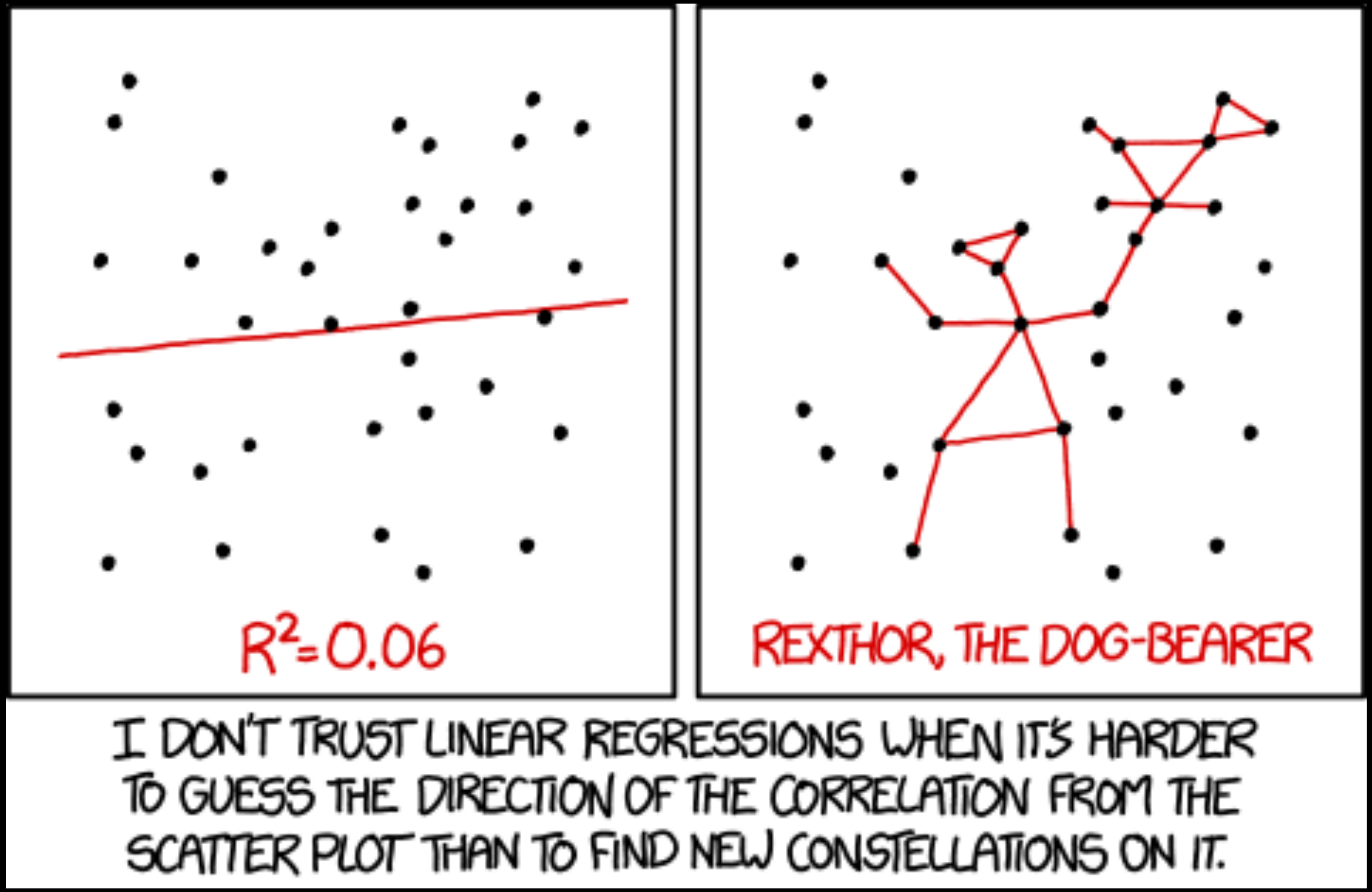
$(\theta | n$ events in k periods$) \sim \text{Gamma}(22, 7)$

3. What is θ_{MAP}?

$\theta_{MAP} = 3$, the updated Poisson rate

Interlude for jokes/announcements

https://xkcd.com/1725/



Announcements

<u>Problem Set 6 Extension!</u>

New deadline: Thur, 8/13, 1pm

Note: You don't have to wait for the final live lecture to finish p-set 6. All relevant material is covered by prior lectures and the recorded videos.

Interesting probability news

What Role Should Employers Play in Testing Workers?

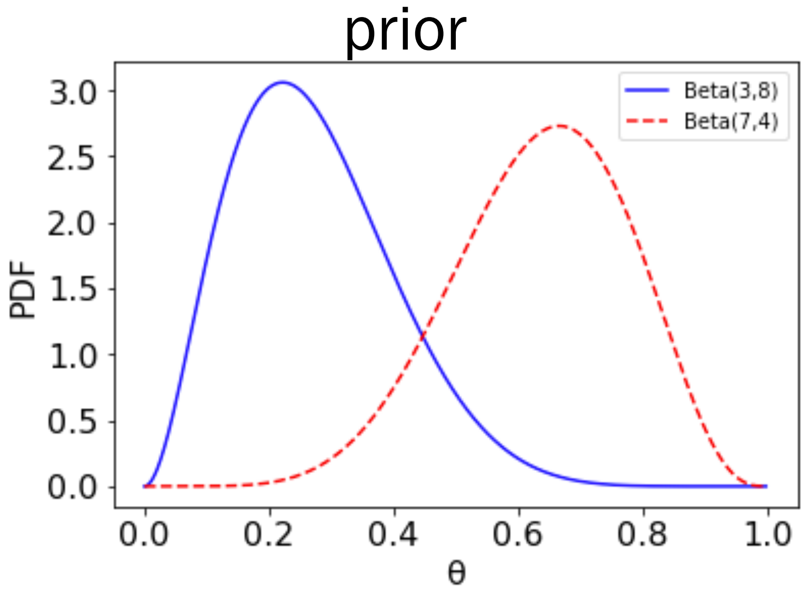
One nascent strategy circulating among public health experts is running **"pooled" coronavirus tests**, in which a workplace could combine multiple saliva or nasal swabs into one larger sample representing dozens of employees.

https://www.nytimes.com/2020/05/22/business/employers-coronavirus-testing.html

Choosing hyperparameters for conjugate prior

Where'd you get them priors?

- Let θ be the probability a coin turns up heads.
- Model θ with 2 different priors:
  - Prior 1: Beta(3,8): 2 imaginary heads, 7 imaginary tails   mode: $\frac{2}{9}$
  - Prior 2: Beta(7,4): 6 imaginary heads, 3 imaginary tails   mode: $\frac{6}{9}$



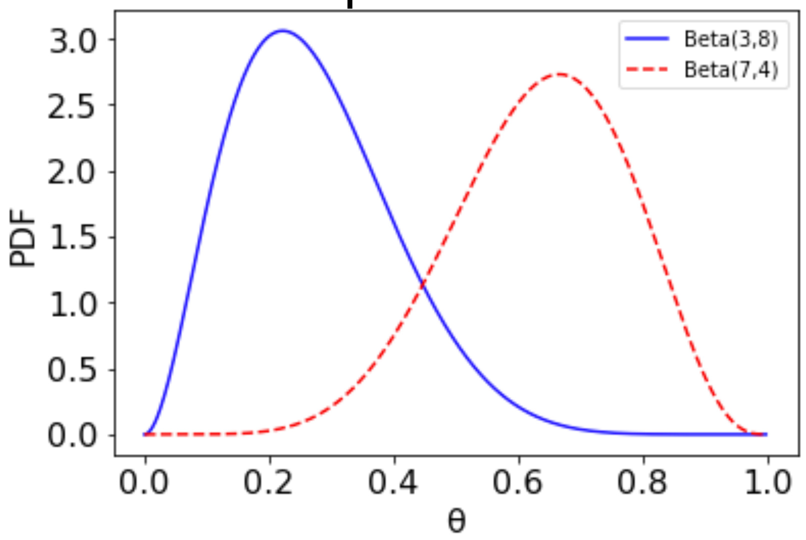
Now flip 100 coins and get 58 heads and 42 tails.

1. What are the two posterior distributions?
2. What are the modes of the two posterior distributions?

Where'd you get them priors?

- Let θ be the probability a coin turns up heads.
- Model θ with 2 different priors:
  - Prior 1: Beta(3,8): 2 imaginary heads, 7 imaginary tails — mode: $\frac{2}{9}$
  - Prior 2: Beta(7,4): 6 imaginary heads, 3 imaginary tails — mode: $\frac{6}{9}$

prior

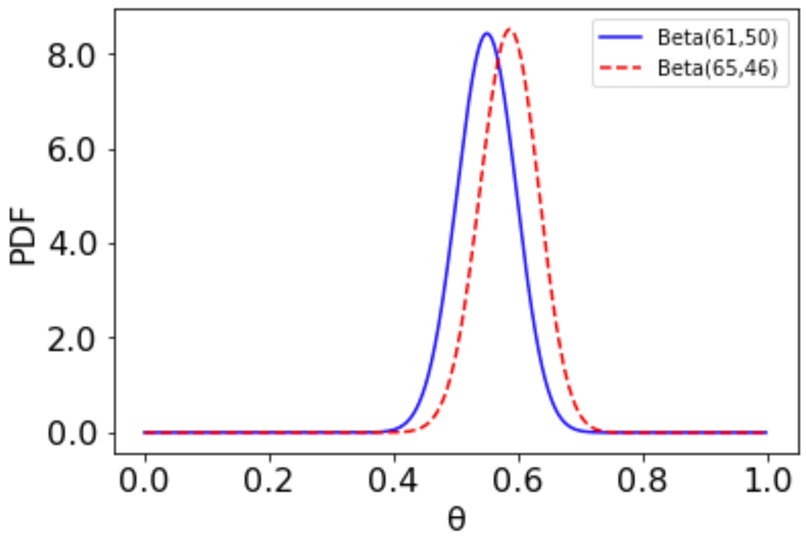


Now flip 100 coins and get 58 heads and 42 tails.

Posterior 1: Beta(61,50) — mode: $\frac{60}{109}$

Posterior 2: Beta(65,46) — mode: $\frac{64}{109}$

posterior



As long as we collect enough data, posteriors will converge to the true value.

Laplace smoothing

MAP with **Laplace smoothing**: a prior which represents k imagined observations of each outcome.

- Categorical data (i.e., Multinomial, Bernoulli/Binomial)
- Also known as additive smoothing

Laplace estimate Imagine $k = 1$ of each outcome (follows from Laplace's "law of succession")

Example: Laplace estimate for coin probabilities from aforementioned experiment (100 coins: 58 heads, 42 tails)

heads $\frac{59}{102}$ tails $\frac{43}{102}$

Laplace smoothing:
- Easy to implement/remember

Back to our happy Laplace

Consider our previous 6-sided die.

- Roll the dice $n = 12$ times.
- Observe: 3 ones, 2 twos, 0 threes, 3 fours, 1 fives, 3 sixes

Recall θ_{MLE}: $p_1 = 3/12, p_2 = 2/12, p_3 = 0/12,$ ⚠️
$p_4 = 3/12, p_5 = 1/12, p_6 = 3/12$

What are your Laplace estimates for each roll outcome?

🤔

Back to our happy Laplace

Consider our previous 6-sided die.

- Roll the dice $n = 12$ times.
- Observe: 3 ones, 2 twos, 0 threes, 3 fours, 1 fives, 3 sixes

Recall θ_{MLE}: $p_1 = 3/12, p_2 = 2/12, p_3 = 0/12,$ ⚠️
$p_4 = 3/12, p_5 = 1/12, p_6 = 3/12$

What are your Laplace estimates for each roll outcome?

$$p_i = \frac{X_i + 1}{n + m}$$

$p_1 = 4/18, p_2 = 3/18, p_3 = 1/18,$ ✅
$p_4 = 4/18, p_5 = 2/18, p_6 = 4/18$

Laplace smoothing:
- Easy to implement/remember
- **Avoids estimating a parameter of 0**

Bayesian Envelope Demo

Two envelopes

Two envelopes: One contains $\$X$, the other contains $\$2X$.

- Select an envelope and open it.
- Before opening the envelope, think either equally good.
- Then you can choose to stay with your envelope or switch to the other one.

Is the following reasoning valid?

- Let Y = \$ in envelope you selected.
- Let Z = \$ in other envelope.

$$E[Z|Y] = \frac{1}{2} \cdot \frac{Y}{2} + \frac{1}{2} \cdot 2Y = \frac{5}{4} Y$$

What really happened by opening the envelope?

Two envelopes

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Is the following reasoning valid?

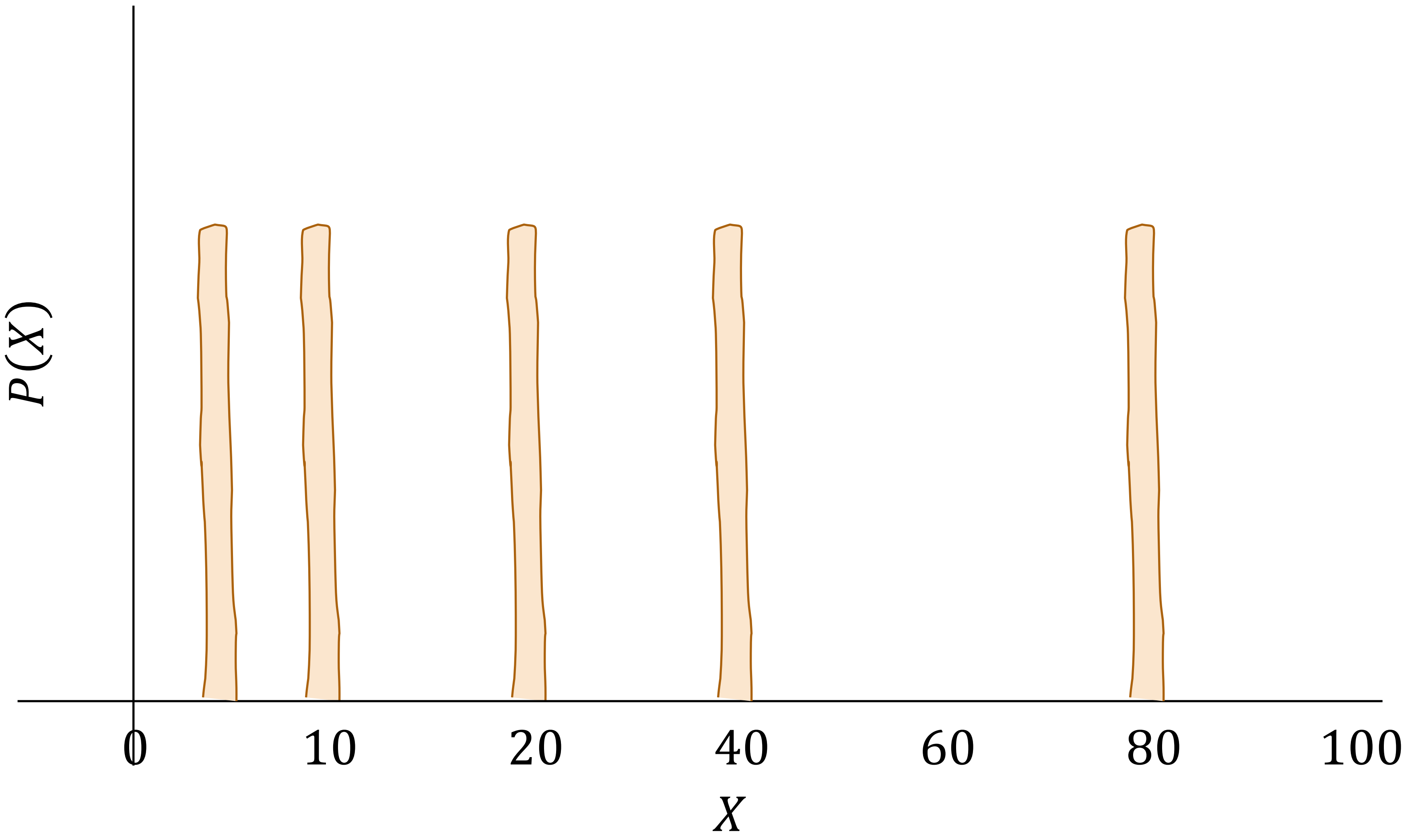
- Let $Y = \$$ in envelope you selected.
- Let $Z = \$$ in other envelope.

$$E[Z|Y] = \frac{1}{2} \cdot \frac{Y}{2} + \frac{1}{2} \cdot 2Y = \frac{5}{4} Y$$

- Assumes all values of X (where $0 < X < \infty$) equally likely
- Infinitely many values of X
- So not a true probability distribution over X (does not integrate to 1)

Follow-up: What happened by opening the envelope?

Are all values equally likely?



Infinite powers of two...

Two envelopes

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$$E[Z|Y] = \frac{1}{2} \cdot \frac{Y}{2} + \frac{1}{2} \cdot 2Y = \frac{5}{4}Y$$

- Assumes all values of X (where $0 < X < \infty$) equally likely
- Infinitely many values of X
- So not a true probability distribution over X (does not integrate to 1)

What really happened by opening the envelope?

Two envelopes: The subjectivity of probability

Your belief about the content of envelopes:

- Since implied distribution over X is not a true probability distribution, what *is* our distribution over X?

Frequentist

Play game infinitely many times, see how often different values come up

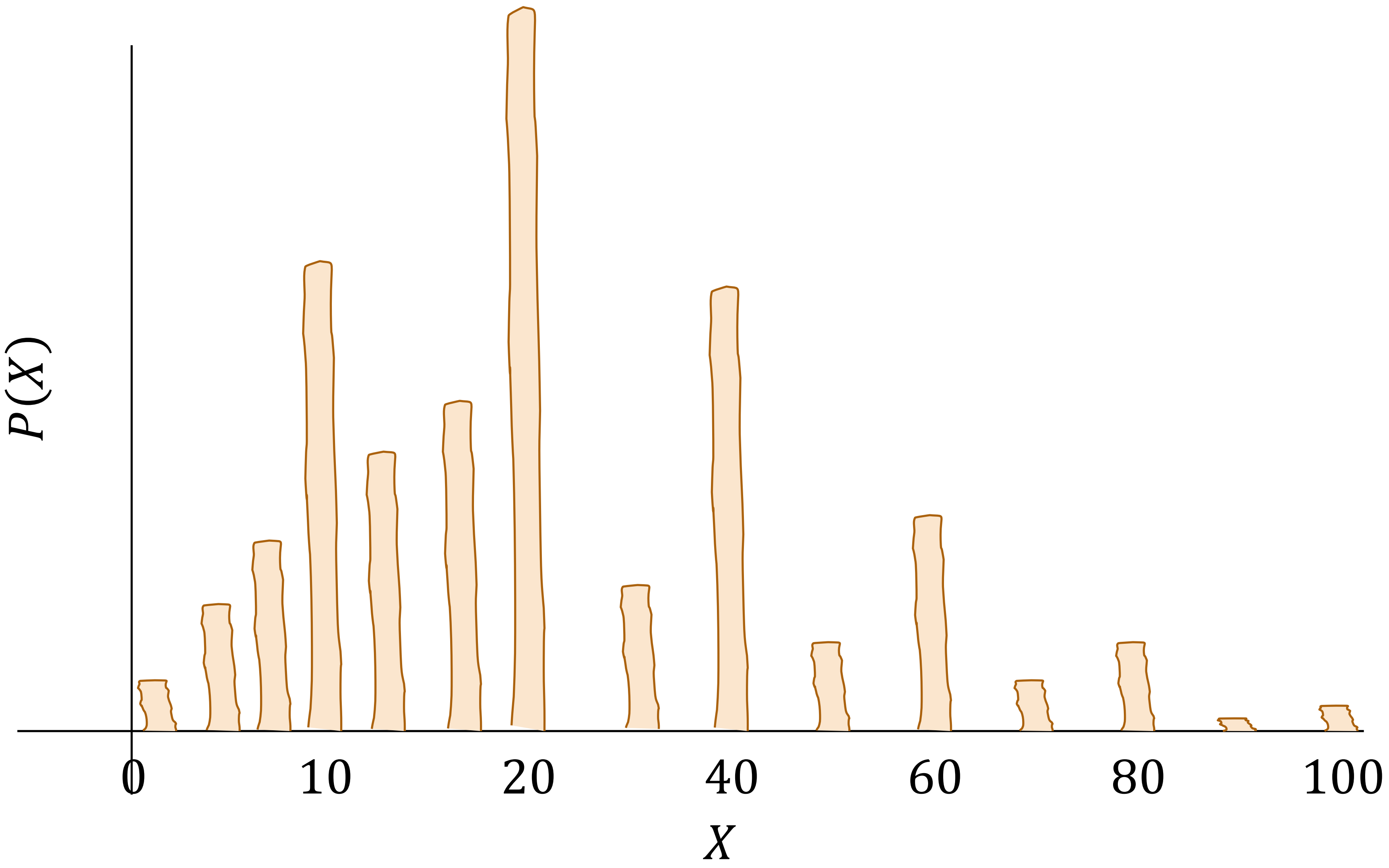
Problem: you can only play game once

Bayesian

Have prior belief of distribution of X

- Prior belief is a *subjective* probability (as are all probabilities)
- Can answer questions when no/limited data
- As we get more data, prior belief "swamped" by data

Two envelopes: The subjectivity of probability



The envelope, please

Bayesian: Have a prior distribution over $X, P(X)$

- Let $Y =$ \$ in envelope you selected. Open envelope to determine Y.
- Let Z = \$ in other envelope.

If $Y > E[Z|Y]$, keep your envelope, otherwise switch. No inconsistency!!

- Opening envelope provides data to compute $P(X|Y)$
- ...which allows you to compute $E[Z|Y]$

Of course, need to think about your prior distribution over X...

Bayesian probability: It doesn't matter how you determine your prior, but you **must** have one (whatever it is)

Imagine if envelope you opened contained \$20.01. Should you switch?

How much is a half cent?

Have a wonderful Wednesday!