

Math 481

- ▶ Instructor: Chenxi Wu wuchenxi2013@gmail.com
- ▶ Office: Hill 434, Office hours: 10-11 am Tu, Wed or by appointment, starting from Jan 28.
- ▶ Grading policy: 10% weekly homework (lowest dropped), 20% each of the two midterms, 50% final exam.
- ▶ Prerequisite: Probability. Will finish review of basic probability on Feb 12.
- ▶ Weekly assignments: 2-3 homework problems a week, grade for correctness, similar to exams. There will also be questions from textbook assigned for practice which you don't need to hand in.
- ▶ No late homework or make up midterms.

Main topics we will cover:

- ▶ Review of probability
- ▶ Point estimate
- ▶ p-values and hypothesis testing
- ▶ Confidence intervals
- ▶ Bayesian statistics

Bayesian and non-Bayesian approaches to statistics

- ▶ Non-Bayesian approach: Set up a null hypothesis and try to show that observation is highly unlikely if null hypothesis is true.
- ▶ Bayesian approach: Assume prior distribution of some parameter, calculate posterior via Bayes formula

DID THE SUN JUST EXPLODE?

(IT'S NIGHT, SO WE'RE NOT SURE.)

THIS NEUTRINO DETECTOR MEASURES
WHETHER THE SUN HAS GONE NOVA.

THEN, IT ROLLS TWO DICE. IF THEY
BOTH COME UP SIX, IT LIES TO US.
OTHERWISE, IT TELLS THE TRUTH.

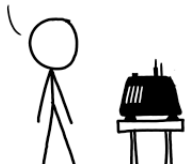
LET'S TRY.

DETECTOR! HAS THE
SUN GONE NOVA?



FREQUENTIST STATISTICIAN:

THE PROBABILITY OF THIS RESULT
HAPPENING BY CHANCE IS $\frac{1}{36} = 0.027$.
SINCE $p < 0.05$, I CONCLUDE
THAT THE SUN HAS EXPLODED.



BAYESIAN STATISTICIAN:

BET YOU \$50
IT HASN'T.



Some review of basic probability

- ▶ Two random events A and B are called **independent** if $P(A \cap B) = P(A)P(B)$
- ▶ If A and B are two random events, $P(A) > 0$. The conditional probability of B when A is given is $P(B|A) = P(A \cap B)/P(A)$.

Example

Suppose you are given a coin, you flip it 5 times and get head on all 5 of them.

- ▶ Suppose the coin is fair, what is the odds that it gets head for 5 times in 5 flips?
- ▶ **Null hypothesis**
- ▶ **p-value**

JELLY BEANS
CAUSE ACNE!

SCIENTISTS!
INVESTIGATE!

BUT WE'RE
PLAYING
MINECRAFT!

... FINE.



WE FOUND NO
LINK BETWEEN
JELLY BEANS AND
ACNE ($P > 0.05$).



THAT SETTLES THAT.

I HEAR IT'S ONLY
A CERTAIN COLOR
THAT CAUSES IT.

SCIENTISTS!

BUT
MINECRAFT!



WE FOUND NO
LINK BETWEEN
PURPLE JELLY
BEANS AND ACNE
($P > 0.05$).



WE FOUND NO
LINK BETWEEN
BROWN JELLY
BEANS AND ACNE
($P > 0.05$).



WE FOUND NO
LINK BETWEEN
PINK JELLY
BEANS AND ACNE
($P > 0.05$).



WE FOUND NO
LINK BETWEEN
BLUE JELLY
BEANS AND ACNE
($P > 0.05$).



WE FOUND NO
LINK BETWEEN
TEAL JELLY
BEANS AND ACNE
($P > 0.05$).



LINK BETWEEN
GREY JELLY
BEANS AND ACNE
($P > 0.05$).



LINK BETWEEN
TAN JELLY
BEANS AND ACNE
($P > 0.05$).



LINK BETWEEN
CYAN JELLY
BEANS AND ACNE
($P > 0.05$).



LINK BETWEEN
GREEN JELLY
BEANS AND ACNE
($P < 0.05$).

WHOA!



LINK BETWEEN
MAUVE JELLY
BEANS AND ACNE
($P > 0.05$).



WE FOUND NO
LINK BETWEEN
BEIGE JELLY
BEANS AND ACNE
($P > 0.05$).



WE FOUND NO
LINK BETWEEN
LILAC JELLY
BEANS AND ACNE
($P > 0.05$).



WE FOUND NO
LINK BETWEEN
BLACK JELLY
BEANS AND ACNE
($P > 0.05$).



WE FOUND NO
LINK BETWEEN
PEACH JELLY
BEANS AND ACNE
($P > 0.05$).



WE FOUND NO
LINK BETWEEN
ORANGE JELLY
BEANS AND ACNE
($P > 0.05$).



News

GREEN JELLY BEANS LINKED TO ACNE!

95% CONFIDENCE

ONLY 5% CHANCE
OF COINCIDENCE!



SCIENTISTS...

- ▶ Suppose the coin is biased and gets head at probability p .
 - ▶ What is the probability that it gets head for 5 times in 5 flips?
 - ▶ What is the p that maximizes this probability?
 - ▶ What is the range of p such that the probability for 5 heads in 5 flips is no less than 0.05?
- ▶ **Maximum likelihood estimate (MLE)**
- ▶ **Confidence interval**

- ▶ Suppose you pick the coin among a pile of 100 coins, 99 of which is fair and 1 has head on both sides. What is the chance of the coin being unfair given the results of the 5 flips?
- ▶ **Prior and posterior**

- ▶ Suppose the odds for getting a head is uniformly distributed in $[0, 1]$, given the results of the 5 flips, what do you think is the most likely value for p ? How about the expectation?
- ▶ **Maximum a posteriori (MAP) estimate**

Basic definitions in probability

A **Probability** is a triple (S, F, P) where S is called the **sample space** denoting all possible states of the world, $F \subset \mathcal{P}(S)$ the **event space** and $P : F \rightarrow \mathbb{R}$ a real-valued function on F , such that:

1. F is closed under complement and countable union.
2. P is non negative.
3. $P(S) = 1$
4. If $\{E_i\}$ is a countable sequence of disjoint events in F ,
 $P(\bigcup_i E_i) = \sum_i P(E_i)$.

Random variables

- ▶ A (real valued) **random variable** X is a function $S \rightarrow \mathbb{R}$ such that the preimage of any open interval is in \mathcal{F} . Multivariate random variables can be defined similarly.
- ▶ The **cumulative distribution function (cdf)** of a random variable X is $F(x) = P(X \leq x)$.
- ▶ If $F(x) = \int_{-\infty}^x f(t)dt$ we call f the **probability density function (pdf)**
- ▶ If there is a countable set C and $g : C \rightarrow \mathbb{R}$ such that $F(x) = \sum_{y \in C, y \leq x} g(y)$ we call X **discrete** and g the **probability distribution**
- ▶ The **expectation** of a random variable X is defined as $E[X] = \int_S X dP$.

For those who know analysis

- ▶ A probability is a measure $P : F \rightarrow \mathbb{R}$, where F is a σ -algebra on sample space S and $P(S) = 1$.
- ▶ A random variable X is a P -measurable function on S .
- ▶ The expectation of a random variable X is the integral $\int_S X dP$.

Some questions

- ▶ Must the cdf of a random variable be left or right continuous?
- ▶ X is the number of heads in 2 fair coin flips. What is the cdf of X ? What is the expectation of X ? What is the expectation of $(X - E[X])^2$?
- ▶ Can you write down a random variable that is neither discrete nor has a pdf?
- ▶ Can you write down a random variable which has no expectation?

Independence and conditional probability

- ▶ X and Y are 2 random variables, X and Y are independent iff $F_{X,Y}(s,t) = P(X \leq s \cap Y \leq t) = F_X(s)F_Y(t)$.
- ▶ If A is some event with non zero probability, $F_{X|A}(s) = P(X \leq s|A) = P(X \leq s \cap A)/P(A)$.
- ▶ If X and Y has joint p.d.f. $f_{X,Y}$ with non zero marginal density f_Y , then $f_{X|Y=a}(s) = f_{X,Y}(s,a)/f_Y(a)$.
- ▶ If A_i are disjoint events with non zero probabilities, $B \subset \mathbb{R}$, $P(X \in B | \cup_i A_i) = \sum_i (P(A_i)P(X \in B|A_i)) / \sum_i P(A_i)$.
- ▶ If Y has p.d.f. f_Y , $A \subset \mathbb{R}$ such that $P(Y \in A) > 0$, B is a random event, then $P(B|Y \in A) = \int_A f_Y(s)P(B|Y=s)ds / P(Y \in A)$.

Special random variables

- ▶ **Discrete:** Takes on countably values, has p.d.
- ▶ **Continuous:** has p.d.f.

2 random variables X and Y has the same distribution iff they have the same c.d.f., or for any $A \subset \mathbb{R}$, $P(X \in A) = P(Y \in A)$. Random variables with the same distribution are NOT necessarily the same.

Special Probability distributions

► **Bernoulli distribution:** $f(1) = \theta$, $f(0) = 1 - \theta$.

► **Binomial distribution** (sum of iid Bernoulli):

$$f(x) = \binom{n}{x} \theta^x (1 - \theta)^{n-x}, \quad x = 0, 1, \dots, n.$$

► **Negative Binomial distribution** (waiting time for the k -th success of iid trials): $f(x) = \binom{x-1}{k-1} \theta^k (1 - \theta)^{x-k}$,
 $x = k, k+1, \dots$. When $k = 1$ it is the **geometric distribution**.

► **Hypergeometric distribution** (randomly pick n elements at random from N elements, the number of elements picked from a fixed subset of M elements)

$$f(x) = \binom{M}{x} \binom{N-M}{n-x} \binom{N}{n}^{-1}.$$

- ▶ **Poisson distribution** (limit of binomial as $n \rightarrow \infty$, $n\theta \rightarrow \lambda$)

$$f(x) = \lambda^x e^{-\lambda} / x!.$$

- ▶ **Multinomial distribution**

$$f(x_1, \dots, x_k) = \binom{n}{x_1, \dots, x_k} \theta_1^{x_1} \dots \theta_k^{x_k}, \sum_i x_i = n, \theta_i \theta_i = 1.$$

- ▶ **Multivariate Hypergeometric distribution**

$$f(x_1, \dots, x_k) = \prod_i \binom{M_i}{x_i} \cdot \binom{N}{n}^{-1} \cdot \sum_i x_i = n, \\ \sum_i M_i = N.$$

Special Probability Density Functions

$$\Gamma(a) = \int_0^{\infty} x^{a-1} e^{-x} dx. \quad \Gamma(k) = (k-1)! \text{ when } k = 1, 2, \dots$$

- ▶ **Uniform distribution:** $f(x) = \begin{cases} 1/(b-a) & x \in (a, b) \\ 0 & x \notin (a, b) \end{cases}$.
- ▶ **Normal distribution:** $f(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(x-\mu)^2}{2\sigma^2}}$.
- ▶ **Multivariate Normal distribution:** $x \in \mathbb{R}^d$, Σ positive definite $d \times d$ symmetric matrix,
 $f(x) = (2\pi)^{-d/2} |\Sigma|^{-1/2} e^{-\frac{1}{2}(x-\mu)^T \Sigma^{-1} (x-\mu)}$.
- ▶ **χ^2 distribution** d : degrees of freedom. Squared sum of d normal distributions: $f(x) = \begin{cases} \frac{1}{2^{d/2} \Gamma(d/2)} x^{\frac{d-2}{2}} e^{-x/2} & x > 0 \\ 0 & x \leq 0 \end{cases}$.

- ▶ **Exponential distribution** $f(x) = \begin{cases} \frac{1}{\theta} e^{-x/\theta} & x > 0 \\ 0 & x \leq 0 \end{cases}$.
- ▶ **Gamma-distribution:** $f(x) = \begin{cases} \frac{1}{\beta^\alpha \Gamma(\alpha)} x^{\alpha-1} e^{-x/\beta} & x > 0 \\ 0 & x \leq 0 \end{cases}$
- ▶ **Beta distribution:** (conjugate prior of Bernoulli distribution)

$$f(x) = \begin{cases} \frac{\Gamma(\alpha+\beta)}{\Gamma(\alpha)\Gamma(\beta)} x^{\alpha-1} (1-x)^{\beta-1} & x \in (0, 1) \\ 0 & x \notin (0, 1) \end{cases}$$
.

Example: If the bias of a coin p has a uniform **prior** in $[0, 1]$, after n flips there are a heads and b tails, the **posterior** will be Beta distribution with $\alpha = a + 1$, $\beta = b + 1$.

Sample mean and sample variance

X_i i.i.d. (independent with identical distribution)

► **Sample mean:** $\bar{X} = \frac{1}{n} \sum_i X_i$

► **Sample variance:**

$$S^2 = \frac{1}{n-1} \sum_i (X_i - \bar{X})^2 = \frac{1}{n-1} (\sum_i X_i^2 - n\bar{X}^2).$$

Properties:

► $E[\bar{X}] = E[X_1]$

► $\text{Var}(\bar{X}) = \frac{1}{n} \text{Var}(X_1)$

► $\sqrt{\frac{n}{\text{Var}(X_1)}} (\bar{X} - E[X_1]) \rightarrow \mathcal{N}(0, 1)$ (Central Limit Theorem)

► $E[S^2] = \text{Var}(X_1)$

Assuming $X_i \sim \mathcal{N}(\mu, \sigma^2)$:

► \bar{X} and S^2 are independent.

► $\bar{X} \sim \mathcal{N}(\mu, \frac{\sigma^2}{n})$

► $\frac{(n-1)S^2}{\sigma^2} \sim \chi^2(n-1)$

Proof of $\frac{(n-1)S^2}{\sigma^2} \sim \chi^2(n-1)$

$$\begin{aligned}(n-1)S^2 &= \sum_i (X_i - \bar{X})^2 = \sum_i ((X_i^2 - E[X_i]) - (\bar{X} - E[\bar{X}]))^2 \\ &= \sum_i (X_i^2 - E[X_i])^2 - n(\bar{X} - E[\bar{X}])^2\end{aligned}$$

Now divide by σ^2 , the first term is $\chi^2(n)$ and second $\chi^2(1)$.

χ^2 distribution

Definition: X_i independent, $\mathcal{N}(0, 1)$, then $\sum_{i=1}^n X_i^2 = \chi^2(n)$

PDF:

$$f(x) = \begin{cases} \frac{1}{n/2\Gamma(n/2)} x^{\frac{n-2}{2}} e^{-x/2} & x > 0 \\ 0 & x \leq 0 \end{cases}$$

Calculation of PDF:

$$\begin{aligned} f_{\chi^2(n)}(r) &= \frac{d}{dr} \int_{\sum_i x_i^2 \leq r} (2\pi)^{-n/2} e^{-\sum_i x_i^2/2} dx_1 \dots dx_n \\ &= (2\pi)^{-n/2} e^{-r/2} \frac{d}{dr} \text{Vol}(B(\sqrt{r})) \end{aligned}$$

Where $B(x)$ is the ball of radius x .

t distribution

Definition: X and Y independent, $X \sim \mathcal{N}(0, 1)$, $Y \sim \chi^2(n)$, then $\frac{X}{\sqrt{Y/n}} \sim t(n)$.

By LLN, when $n \rightarrow \infty$ this converges to $\mathcal{N}(0, 1)$.

PDF:

$$f(x) = \frac{\Gamma(\frac{n+1}{2})}{\sqrt{\pi n} \Gamma(\frac{n}{2})} \left(1 + \frac{x^2}{n}\right)^{-\frac{n+1}{2}}$$

Calculation of PDF of t

$$\begin{aligned}f_{t(n)}(s) &= \frac{d}{ds} P(X \leq s\sqrt{Y/n}) = \frac{d}{ds} \int_0^\infty dy \int_{-\infty}^{s\sqrt{y/n}} \\&\quad dx \frac{1}{\sqrt{2\pi}} e^{-x^2/2} \frac{1}{2^{n/2}\Gamma(n/2)} y^{\frac{n-2}{2}} e^{-y/2} \\&= \int_0^\infty dy \sqrt{y/n} \frac{1}{\sqrt{2\pi}} e^{-s^2 y/2n} \frac{1}{2^{n/2}\Gamma(n/2)} y^{\frac{n-2}{2}} e^{-y/2} \\&= \frac{1}{\sqrt{2\pi n} 2^{n/2}\Gamma(n/2)} \int_0^\infty dy y^{\frac{n-1}{2}} e^{-y(1+\frac{s^2}{n})/2}\end{aligned}$$

Now let $z = y(1 + \frac{s^2}{n})/2$ and it's done.

F-distribution

Definition: U and V independent, $U \sim \chi^2(m)$, $V \sim \chi^2(n)$, then

$$\frac{U/m}{V/n} \sim F(m, n)$$

CDF:

$$f(x) = \begin{cases} \frac{\Gamma(\frac{m+n}{2})}{\Gamma(\frac{m}{2})\Gamma(\frac{n}{2})} \left(\frac{m}{n}\right)^{m/2} x^{m/2-1} \left(1 + \frac{m}{n}x\right)^{-\frac{m+n}{2}} & x > 0 \\ 0 & x \leq 0 \end{cases}$$

Strategy for calculating the PDF of $Y = g(X_i)$:

1. Find joint pdf of X_i
2. Write down the CDF of Y as a probability, hence, some integral of the pdf of X_i
3. Differentiate the CDF of Y .