

# Math 481

- ▶ Instructor: Chenxi Wu [wuchenxi2013@gmail.com](mailto: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.

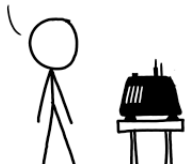
LET'S TRY.

DETECTOR! HAS THE  
SUN GONE NOVA?



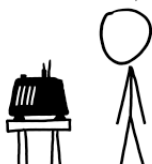
FREQUENTIST STATISTICIAN:

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  
( $P < 0.05$ ).



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  $\sigma$ -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:**  $x \in \mathbb{R}^d$ ,  $\Sigma$  positive definite  $d \times d$  symmetric matrix,  
 $f(x) = (2\pi)^{-d/2} |\Sigma|^{-1/2} e^{-\frac{1}{2}(x-\mu)^T \Sigma^{-1} (x-\mu)}$ .
- ▶  $\chi^2$  **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  $\sigma^2$ , the first term is  $\chi^2(n)$  and second  $\chi^2(1)$ .



## $\chi^2$ 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  $Y$ .

# Probability Review

- ▶ Probability, cdf and pdf for continuous random variables:
  - ▶ **Probability to cdf:**  $F_X(t) = P(X \leq t)$
  - ▶ **cdf to pdf:**  $f_X(t) = \frac{d}{dt} F_X(t)$
  - ▶ **pdf to probability:**  $P(X \in A) = \int_A f_X(s) ds$
- ▶ Probability, cdf and pd for discrete random variables:
  - ▶ **Probability to cdf:**  $F_X(t) = P(X \leq t)$
  - ▶ **cdf to pd:**  $F_X(t) = \sum_{s \leq t} g_X(s)$
  - ▶ **pd to probability:**  $P(X \in A) = \sum_{s \in A} g_X(s)$
- ▶ Joint cdf/pdf/pd, independence, conditional probability.
- ▶ Expectation, variance, covariance
- ▶ LLN and CLT
- ▶ Special distributions: binomial, uniform, normal,  $\chi^2$ , etc.

# Point estimates

Basic setting:

- ▶  $\mathcal{F}$ : a family of possible distributions (represented by a family of cdf, pdf, or pd)
- ▶  $\theta : \mathcal{F} \rightarrow \mathbb{R}$  population parameter
- ▶  $X_1, \dots, X_n$  i.i.d. with distribution  $F \in \mathcal{F}$
- ▶  $\hat{\theta} = \hat{\theta}(X_1, \dots, X_n)$  a function of  $X_i$ , which is an estimate of  $\theta(F)$ , is called a point estimate.

Example:  $\mathcal{F}$ : all distributions with an expectation, then  $\bar{X}$  is a point estimate of the expectation.

$\hat{\theta}$  is a point estimate of  $\theta$ .

- ▶ The **bias** is  $E[\hat{\theta}] - \theta$ .  $\hat{\theta}$  is called unbiased if  $E[\hat{\theta}] = \theta$ .
- ▶ The **variance** is  $Var(\hat{\theta})$ .
- ▶  $\hat{\theta}$  is called **minimum variance unbiased estimate** if it has the smallest variance among all unbiased estimates.
- ▶  $\hat{\theta}_1$  and  $\hat{\theta}_2$  are two unbiased estimates, the relative efficiency is the ratio of their variance. When they are biased, one can use the mean squared error  $E[(\hat{\theta} - \theta)^2]$  instead.
- ▶  $\hat{\beta}$  is called **asymptotically unbiased** if bias converges to 0 as  $n \rightarrow \infty$ .
- ▶  $\hat{\beta}$  is called **consistent** if  $\hat{\beta}$  converges to  $\beta$  in distribution.

# Review of definitions regarding point estimates

$\hat{\theta}$  is a point estimate of  $\theta$

- ▶ Unbiased
- ▶ Minimal Variance Unbiased
- ▶ Asymptotically unbiased
- ▶ Consistent

Properties:

- ▶ Minimal Variance Unbiased can be verified via Cramer-Rao
- ▶ Mean squared error
$$E[(\hat{\theta} - \theta)^2] = E[((\hat{\theta} - E[\hat{\theta}]) + (E[\hat{\theta}] - \theta))^2] = \text{Var}(\hat{\theta}) + (E[\hat{\theta}] - \theta)^2$$
- ▶ Mean squared error  $\rightarrow 0$  implies consistence:

$$P(|\hat{\theta} - \theta| > \epsilon) < \frac{E[(\hat{\theta} - \theta)^2]}{\epsilon^2}$$

But consistence does not imply mean squared error  $\rightarrow 0$ .



# Maximal Likelihood Estimate (MLE)

Suppose  $X_i \sim F(\theta)$ , i.i.d., observation is  $x_1, \dots, x_k$ , then  
 $\hat{\theta} = \arg \max_{\theta} L(x_1, \dots, x_k, \theta)$ .

- ▶ When  $F$  is a continuous distribution with p.d.f.  $f(x, \theta)$ , let  
 $L(x_1, \dots, x_k, \theta) = \prod_i f(x_i, \theta)$
- ▶ When  $F$  is a discrete distribution with p.d.  $g(x, \theta)$ , let  
 $L(x_1, \dots, x_k, \theta) = \prod_i g(x_i, \theta)$

When there are multiple parameters, we can get their MLE by taking  $\arg \max$  to all of them altogether.

Sometimes we maximize  $\log(L)$  (log likelihood) instead of  $L$ , which is equivalent.

# The basic idea of Bayesian statistics

- ▶ Input:
  - ▶ Some (possibly vector valued) random variable  $\Theta$  with given distribution (**prior**)
  - ▶ Some (possibly vector valued) random variable  $X$  with known conditional distribution conditioned at a value of  $\Theta$ ,  $X \sim F(X|\Theta)$ . (**observable**)
- ▶ Output: the conditional distribution of  $\Theta$  conditioned at a value of  $X$  (**posterior**)  $\Theta \sim F(\Theta|X)$ .

Example:

- ▶ **Prior**  $Y \sim \text{Bernoulli}(\frac{1}{100})$
- ▶ **Observable**  $X_1, X_2$  conditionally i.i.d. when  $Y = y$ , and their conditional distribution is Bernoulli with  $p = \frac{1+8Y}{10}$ .

Calculation of the posterior:

$$\begin{aligned} P(Y = 1|X_1, X_2) &= \frac{P(Y = 1, X_1, X_2)}{P(X_1, X_2)} \\ &= \frac{P(X_1, X_2|Y = 1)P(Y = 1)}{P(X_1, X_2|Y = 0)P(Y = 0) + P(X_1, X_2|Y = 1)P(Y = 1)} \\ &= \frac{(9/10)^{X_1+X_2}(1/10)^{2-X_1-X_2} \times \frac{1}{100}}{(9/10)^{X_1+X_2}(1/10)^{2-X_1-X_2} \times \frac{1}{100} + (1/10)^{X_1+X_2}(9/10)^{2-X_1-X_2} \times \frac{99}{100}} \\ &= \frac{9^{X_1+X_2}}{9^{X_1+X_2} + 99 \times 9^{2-X_1-X_2}} \end{aligned}$$

So, for example, if we know both  $X_i$  takes a value of 1, then the probability of  $Y = 1$  is 9/20.

We can answer many questions using posterior, for example:

- ▶ What is the probability of  $\Theta$  taking value in  $A$  given  $X$ ?
- ▶ What is the “most likely” value of  $\Theta$ ?  
 $\hat{\Theta}_{MAP} = \arg \max_s f_{\Theta|X}(s)$ , where  $f$  is p.d.f. when  $\Theta|X$  is continuous and p.d. when it is discrete. This is called the **maximum a posteriori (MAP)** estimate.
- ▶ What is the average value of  $\Theta$ ?  $\hat{\Theta} = E[\Theta|X]$ . This is called the **Bayesian point estimate with  $L^2$  lost**.
- ▶ In general, let  $l(\cdot, \cdot)$  be a lost function (a positive function such that  $l(a, a) = 0$ ), then  $\hat{\Theta} = \arg \min_{\theta} E[l(\Theta, \theta)|X]$  is called the **Bayesian point estimate**.

# MLE vs. Point estimate using Bayesian statistics

MLE:

- ▶ Input: Assumption on the distribution of  $X$ :  $X \sim F(\alpha)$ . A likelihood function  $L(X, \alpha)$ .
- ▶ Output:  $\hat{\alpha}_{MLE} = \arg \max_{\alpha} L(X, \alpha)$ .

Bayesian statistics:

- ▶ Input: Prior:  $\alpha \sim F_0$ , Conditional distribution:  $X|\alpha \sim F(\alpha)$ .
- ▶ Calculated output: Posterior:  $\alpha|X \sim F'(X)$
- ▶ MAP Point estimate:  $\hat{\alpha} = \arg \max_{\alpha} f_{\alpha|X}(\alpha)$
- ▶  $L^2$ -Bayesian Point estimate:  $\hat{\alpha} = E[\alpha|X]$ .

### Input:

- ▶  $\mu \sim \mathcal{N}(0, 1)$
- ▶  $X_i | \mu$  cond. i.i.d.,  $\sim \mathcal{N}(\mu, 1)$

### Posterior:

$$\begin{aligned} f_{\mu|X_i}(s) &= \frac{f_{\mu, X_i}(s, X_1, \dots, X_n)}{f_{X_i}(X_1, \dots, X_n)} = \frac{f_{\mu, X_i}(s, X_1, \dots, X_n)}{\int_{\mathbb{R}} f_{\mu, X_i}(t, X_1, \dots, X_n) dt} \\ &= \frac{\prod_i f_{X_i|\mu=s}(X_i) f_{\mu}(s)}{\int_{\mathbb{R}} \prod_i f_{X_i|\mu=t}(X_i) f_{\mu}(t) dt} = \frac{(2\pi)^{-\frac{n+1}{2}} e^{-\sum_i (X_i - s)^2 / 2 - s^2 / 2}}{\int_{\mathbb{R}} (2\pi)^{-\frac{n+1}{2}} e^{-\sum_i (X_i - t)^2 / 2 - t^2 / 2} dt} \end{aligned}$$

So

$$\mu | X_i \sim \mathcal{N}\left(\frac{\sum_i X_i}{n+1}, \frac{1}{n+1}\right)$$

The MAP and  $L^2$  Bayesian estimate of  $\mu$  are both  $\hat{\mu} = \frac{\sum_i X_i}{n+1}$ .

## Formula for Posterior

$$f_{\mu|X}(s) \propto f_{X|\mu=s}(X)f_{\mu}(s)$$

This works for discrete  $\mu$  or  $X$  as well!

Example:  $P$  uniform on  $[0, 1]$ ,  $X|P \sim \text{Binomial}(5, P)$ , then  $f_{P|X}(s) \propto s^X(1-s)^{5-X} \cdot 1$ , hence  $P|X \sim \text{Beta}(X+1, 6-X)$ .

Often in practice we build “hierarchical models” by stacking multiple layers of Bayesian and non Bayesian models together. For example:

$$\sigma_i^2 \sim \Gamma(\alpha, \beta)$$

$$\sigma^2 \sim \Gamma(\alpha', \beta')$$

$$\mu_i \sim \mathcal{N}(0, \sigma^2)$$

$$X_{ij} \text{ ind. } \sim \mathcal{N}(\mu_i, \sigma_i^2)$$

How would you estimate  $\sigma_i$  and  $\mu_i$  from the values of  $X_{ij}$ ?

We will talk about models like this if we have more time at the end of the semester.



## More examples

1.  $t$  has p.d.f.  $f_t(x) = \begin{cases} 0 & x < 0 \\ e^{-x} & x > 0 \end{cases}$ .

$P(Y = n|t) = (1 - e^{-t})e^{-nt}$ . Knowing  $Y$ , find  $\hat{t}_{MAP}$  and  $E[t|Y]$ .

2.  $a, t$  indep.  $\sim \text{Uniform}([0, 1])$ .  $X_i|a, t$  i.i.d.  $\sim \text{Uniform}([a, a + t])$ , find  $\hat{t}_{MAP}$ .

**Answer:**  $M = \max(X_i)$ ,  $m = \min(X_i)$ , then:

$$f_{a,t|X_i} \propto \begin{cases} t^{-n} & 0 \leq a \leq m \leq M \leq a + t \leq a + 1 \\ 0 & \text{otherwise} \end{cases}$$

So

$$f_{t|X_i} \propto \begin{cases} t^{-n} \cdot (\min(1, m) - (M - t)) & M - \min(1, m) \leq t \leq 1 \\ 0 & \text{otherwise} \end{cases}$$

$$\hat{t}_{MAP} = \min\left(1, \frac{n}{n-1}(M - \min(1, m))\right)$$

## Review: Point estimate

- ▶ Problem:  $X \sim F(\Theta)$ , want to know unknown parameter  $\Theta$ .
- ▶ Solution: Build a random variable  $\hat{\Theta}$  depending on  $X$  via:
  - ▶ MOM
  - ▶ MLE
  - ▶ Bayesian-based methods like MAP or Bayesian point estimate
  - ▶ Other methods

# Hypothesis testing

- ▶ Problem: want to know if the distribution of  $X$  satisfy certain propositions (**null hypothesis**), for example:
  - ▶ Will anyone be infected by covid-19 2 years from now?
  - ▶ Will the expectation of our midterm 2 grade be better than midterm 1?
  - ▶ Is the performance of a machine learning algorithm better than random chance?
- ▶ Solution: Find a random variable  $Z$  (**test statistics**) depending on  $X$  and a set  $A$  (**critical region**), and reject the hypothesis when  $Z \in A$ .

- ▶  $(Z, A)$  is called a **statistical test** to null hypothesis  $H_0$ .
- ▶ If  $Z \in A \iff Z' \in A'$  we consider  $(Z, A)$  and  $(Z', A')$  to be the same test.
- ▶ If  $H_0$  completely determines  $P(Z \in A)$  (**simple hypothesis**),  $p = P(Z \in A|H_0)$  is called the **significance level**.

Example 1: Suppose your grade for midterm 1 is  $X_1$ , your grade for midterm 2 is  $X_2$ ,  $Y = X_2 - X_1$  satisfies normal distribution with variance 25. How do we test the null hypothesis  $E[Y] = 0$ ?

► Answer 1:  $Z = Y$ ,  $A = (-\infty, -M) \cup (M, \infty)$ .

$$\begin{aligned} p &= P(Y < -M \cup Y > M | H_0) \\ &= P(Y < -M | Y \sim \mathcal{N}(0, 25)) \\ &\quad + P(Y > M | Y \sim \mathcal{N}(0, 25)) \\ &= 2 \int_M^\infty \frac{1}{\sqrt{50\pi}} e^{-t^2/50} dt \end{aligned}$$

► Answer 2:  $Z = Y$ ,  $A = (M, \infty)$ ,  $p = \int_M^\infty \frac{1}{\sqrt{50\pi}} e^{-t^2/50} dt$

► Answer 3:  $Z = Y$ ,  $A = (-M, M)$ ,  $p = \int_{-M}^M \frac{1}{\sqrt{50\pi}} e^{-t^2/50} dt$

Which of the three is more reasonable?

# Ways to evaluate a test

- ▶ **Alternative hypothesis**: an alternative to the null hypothesis  $H_0$ , called  $H_1$ .
- ▶  $P(Z \in A|H_0)$  is called **Significance level** or **type I error**.
- ▶ If  $H_1$  is a simple hypothesis,  $P(Z \notin A|H_1)$  is called **type II error**.
- ▶ If  $H_1$  is a simple hypothesis,  $1 - P(Z \notin A|H_1) = P(Z \in A|H_1)$  is called **(statistical) power**
- ▶ If  $X \sim F(\theta)$ ,  $\pi(\theta) = P(Z \in A|\theta)$  is called the **power function**. If  $H_0 : \theta = \theta_0$ ,  $H_1 : \theta = \theta_1$ , then significance is  $\pi(\theta_0)$  and power is  $\pi(\theta_1)$ .

In Example 1, let  $Y = \mathcal{N}(\theta, 25)$ , what is the power function of the three tests?

Example 2:  $Y_i$  i.i.d.  $\sim \mathcal{N}(\theta, 25)$ ,  $H_0 : \theta = 0$ .

Example 3:  $Y_i$  i.i.d. Bernoulli distribution with parameter  $\theta$ ,  
 $H_0 : \theta = 1/2$ .

# Review

- ▶  $X \sim F(\theta)$ . Null hypothesis:  $H_0 : \theta = \theta_0$ , alternative hypothesis  $H_1 : \theta = \theta_1$ .
- ▶ Statistical test:  $(Z, A)$ ,  $Z$ : test statistics,  $A$ : critical region
- ▶ Type I error:  $P(Z \in A | H_0)$
- ▶ Type II error:  $P(Z \notin A | H_1)$
- ▶ Power:  $P(Z \in A | H_1)$
- ▶ Power function:  $\pi(t) = P(Z \in A | \theta = t)$



# Intuition behind statistical tests

- ▶ If  $(Z, A)$  is a test such that the significance level is very small.
- ▶ Suppose  $H_0$  is true.
- ▶ It must mean that  $P(Z \in A)$  is very small.
- ▶ However, in an experiment we get  $Z \in A$
- ▶ Hence the assumption earlier is probably untrue.
- ▶ Hence  $H_0$  is probably false.

## Example 2

$X_i$   $i = 1, \dots, 6$  i.i.d., Bernoulli with  $P(X_i = 1) = p$ .

$H_0 : p = 0.5$ ,  $H_1 : p = 0.9$ .

Test statistics:  $Z = \sum_i X_i$ .  $A = [M, 6]$ ,  $M$  is an integer.

Then power function is:

$$\pi(p) = P(Z \geq M | p) = \sum_{i=M}^6 \binom{6}{i} p^i (1-p)^{6-i}$$

Significance is  $\pi(0.5) = \frac{1}{64} \sum_{i=M}^6 \binom{6}{i}$ .

Power is  $\pi(0.9) = \sum_{i=M}^6 \binom{6}{i} (0.9)^i (0.1)^{6-i}$ .

- ▶  $M = 6$ : significance=0.0156, power=0.531
- ▶  $M = 5$ : significance=0.109, power=0.886
- ▶  $M = 4$ : significance=0.344, power=0.984

There is trade-off between significance and power. Which  $M$  to choose depends on the purpose of the test, in particular whether false positive or false negative would be more costly.

# Neyman-Pearson test

Recall that the likelihood function is  $L(x, \theta) = f_{X|\theta}(x)$ , which is the p.d.f. when  $X$  is continuous and p.d. when  $X$  is discrete.

The Neyman-Pearson test for  $H_0 : \theta = \theta_0$ ,  $H_1 : \theta = \theta_1$  is:

$$(X, \{x : L(x, \theta_0)/L(x, \theta_1) \leq k\})$$

## Example 2, Neyman-Pearson test

$$p_0 = 0.5, p_1 = 0.9$$

$$L(X_1, \dots, X_6, p_0) = \prod_i p_0^{X_i} (1 - p_0)^{1-X_i} = \frac{1}{4^6}$$

$$L(X_1, \dots, X_6, p_1) = \prod_i p_1^{X_i} (1 - p_1)^{1-X_i}$$

$$= 0.9^{\sum_i X_i} \cdot 0.1^{6 - \sum_i X_i} = 0.1^6 \cdot 9^{\sum_i X_i}$$

Sometimes we need to consider **composite hypothesis**, i.e. cases when  $H_0$  and  $H_1$  does not completely determine the distribution of  $X$ . Suppose  $H_0 : \theta \in D_0$ ,  $H_1 : \theta \in D_1$ , the likelihood ratio test becomes:

$$(X, \{x : \frac{\sup_{\theta \in D_0} L(x, \theta)}{\sup_{\theta \in D_0 \cup D_1} L(x, \theta)} \leq k\})$$

How would you do likelihood ratio test for the following examples:

- ▶  $X_i$  i.i.d. Bernoulli( $p$ ).  $H_0 : p = 0.5$ ,  $H_1 : p \neq 0.5$ .
- ▶  $X_i$  i.i.d.  $\mathcal{N}(\mu, 1)$ .  $H_0 : \mu = 0$ ,  $H_1 : \mu \neq 0$ .

# Review

- ▶ Because  $(Z, A)$  and  $(Z', A')$  are the same test if  $Z \in A \iff Z' \in A'$ , we sometimes don't specify test statistics and critical region and just call the proposition  $Z \in A$  a statistical test.
- ▶ Neyman-Pearson test:  $f_{X|H_0}(X)/f_{X|H_1}(X) \leq k$
- ▶ Likelihood ratio test:  $H_0 : \theta \in D_0, H_1 : \theta \in D_1$ .

$$\frac{\sup_{\theta \in D_0} f_{X|\theta}(X)}{\sup_{\theta \in D_0 \cup D_1} f_{X|\theta}(X)} \leq k$$

- ▶ Correction: type I error should be called the **significance level** of a test.

# Neyman-Pearson Lemma

Neyman-Pearson test has the highest power for given significance, and lowest significance level for given power.

Proof in continuous case: Let  $X$  taking value in  $\mathbb{R}^n$ ,  $k$  be the threshold of the Neyman-Pearson test with significance  $\alpha$ . In other words,

$$\int_{\frac{f_{X|H_0}(x)}{f_{X|H_1}(x)} \leq k} f_{X|H_0}(x) dx = \alpha$$

Then its power is  $\beta_0 = \int_{\frac{f_{X|H_0}(x)}{f_{X|H_1}(x)} \leq k} f_{X|H_1}(x) dx$ .

Suppose another test  $(Z, A)$  has significance  $\alpha$ , then by definition of conditional p.d.f.,

$$\int_{\mathbb{R}^n} P(Z \in A | X) f_{X|H_0}(x) dx = \alpha$$



While the power is

$$\begin{aligned} & \int_{\mathbb{R}^n} P(Z \in A|X) f_{X|H_1}(x) dx \\ &= \int_{\frac{f_{X|H_0}(x)}{f_{X|H_1}(x)} \leq k} P(Z \in A|X) f_{X|H_1}(x) dx + \int_{\frac{f_{X|H_0}(x)}{f_{X|H_1}(x)} > k} P(Z \in A|X) f_{X|H_1}(x) dx \\ &= \beta_0 - \int_{\frac{f_{X|H_0}(x)}{f_{X|H_1}(x)} \leq k} P(Z \notin A|X) f_{X|H_1}(x) dx + \int_{\frac{f_{X|H_0}(x)}{f_{X|H_1}(x)} > k} P(Z \in A|X) f_{X|H_1}(x) dx \\ &\leq \beta_0 - \frac{1}{k} \int_{\frac{f_{X|H_0}(x)}{f_{X|H_1}(x)} \leq k} P(Z \notin A|X) f_{X|H_0}(x) dx + \frac{1}{k} \int_{\frac{f_{X|H_0}(x)}{f_{X|H_1}(x)} > k} P(Z \in A|X) f_{X|H_0}(x) dx \\ &= \beta_0 - \frac{1}{k} \int_{\frac{f_{X|H_0}(x)}{f_{X|H_1}(x)} \leq k} f_{X|H_0}(x) dx + \frac{1}{k} \int_{\mathbb{R}^n} P(Z \in A|X) f_{X|H_0}(x) dx \\ &= \beta_0 \end{aligned}$$

# Significance and p-value

$X \sim F(\theta)$ ,  $H_0 : \theta \in D_0$ .

Suppose a family of statistical tests with parameter  $k$  is  $X \in A(k)$ .  
Then:

- ▶ The significance level of the test  $X \in A(k)$  is  
 $\alpha = \sup_{\theta \in D_0} P(X \in A(k) | \theta)$ .  $k \leq k' \implies A(k) \subseteq A(k')$ .
- ▶ The p-value for  $x$ , which is an observed value of  $X$ , is

$$p = \inf_{k \in \{k : x \in A(k)\}} \sup_{\theta \in D_0} P(X \in A(k))$$

- ▶ Suppose the test  $X \in A(k_0)$  has significance level  $\alpha_0$ . Then  $x \in A(k_0)$  (i.e.  $X = x$  results in rejection of  $H_0$  under this test) implies that  $x$  has a p-value no larger than  $\alpha_0$ , and  $x$  has p-value less than  $\alpha_0$  implies that  $x \in A(k_0)$ .

## Relationship between significance and p-value

Proof: Let  $\alpha(k) = \sup_{\theta \in D_0} P(X \in A(k) | \theta)$ , then because  $P(X \in A(k) | \theta)$  is non-increasing,  $k \mapsto \alpha(k)$  is non increasing. Furthermore, by assumption,  $\alpha(k_0) = \alpha_0$ , and  $\alpha(k) > \alpha_0 \implies k > k_0$ , and the p-value for  $x$  is

$$p = \inf_{k \in \{k: x \in A(k)\}} \alpha(k)$$

Suppose  $x \in A(k_0)$ , then the p-value of  $x$  is

$$p = \inf_{k \in \{k: x \in A(k)\}} \alpha(k) \leq \alpha(k_0) = \alpha_0.$$

Now suppose the p-value of  $x$  is less than  $\alpha_0$ , then there is some  $k'$  such that  $x \in A(k')$  and  $\alpha(k') < \alpha_0$ . Hence,  $k' \leq k_0$ ,  $x \in A(k') \subset A(k_0)$ .

## Example 1: Normal approximation for large sample

$X_i$  i.i.d., Bernoulli distribution with parameter  $p$ .  $H_0 : p = p_0$ ,  
 $H_1 : p \neq p_0$ . Likelihood ratio test:

$$\frac{\prod_i p_0^{X_i} (1 - p_0)^{1-X_i}}{\sup_p \prod_i p^{X_i} (1 - p)^{1-X_i}} \leq k$$

$$\frac{p_0^{\sum_i X_i} (1 - p_0)^{n - \sum_i X_i}}{(\frac{1}{n} \sum_i X_i)^{\sum_i X_i} (1 - \frac{1}{n} \sum_i X_i)^{n - \sum_i X_i}} \leq k$$

$$\log(LHS) = n\bar{X}(\log(p_0) - \log(\bar{X})) + n(1 - \bar{X})(\log(1 - p_0) - \log(1 - \bar{X}))$$

Which is non positive and 0 iff  $\bar{X} = p_0$ . So for  $k$  close to 1 the test should be of the form:

$$|\bar{X} - p_0| > \epsilon$$

From CLT, if  $n \gg 1$ , under  $H_0$ ,  $\sqrt{\frac{n}{p_0(1-p_0)}} \cdot (\bar{X} - p_0)$  has distribution close to  $\mathcal{N}(0, 1)$ , so the test with significance level  $\alpha$  is roughly  $|\bar{X} - p_0| \geq \Phi^{-1}(1 - \alpha/2) \sqrt{\frac{p_0(1-p_0)}{n}}$  where  $\Phi$  is the cdf of  $\mathcal{N}(0, 1)$ .

And the p-value for given  $\bar{X} = \bar{x}$  is

$$\begin{aligned} p &= \inf\{\alpha : |\bar{x} - p_0| \geq \Phi^{-1}(1 - \alpha/2) \sqrt{\frac{p_0(1 - p_0)}{n}}\} \\ &= 2(1 - \Phi(\sqrt{\frac{n}{p_0(1 - p_0)}} \cdot |\bar{x} - p_0|)) \end{aligned}$$

Suppose  $n = 100$ ,  $p_0 = 0.5$ , 60 of the  $X_i$  has a value of 1 and 40 has a value of 0. We want to test if  $H_0 : p = p_0$  is true with a significance level 0.05.

- ▶ **Method 1:** The test with significance level 0.05 is roughly

$$|\bar{X} - p_0| \geq \Phi^{-1}(1 - 0.05/2) \sqrt{\frac{p_0(1-p_0)}{n}} = 0.0980.$$

$\bar{X} - p_0 = 0.1$  which is larger than the threshold, hence we should reject  $H_0$ .

- ▶ **Method 2:** Calculate the p-value, we get

$$p = 2(1 - \Phi(\sqrt{\frac{n}{p_0(1-p_0)}} \cdot |\bar{X} - p_0|)) = 0.0455 \leq 0.05, \text{ so we should reject } H_0.$$

# Review

- ▶ Neyman-Pearson test:  $f_{X|H_0}(X)/f_{X|H_1}(X) \leq k$
- ▶ Likelihood ratio test:  $H_0 : \theta \in D_0, H_1 : \theta \in D_1$ .

$$\frac{\sup_{\theta \in D_0} f_{X|\theta}(X)}{\sup_{\theta \in D_0 \cup D_1} f_{X|\theta}(X)} \leq k$$

- ▶ Significance level of a test: highest possible probability of false positive under  $H_0$ . It is an increasing function of the threshold  $k$ .
- ▶ p-value of a possible value of  $X$ : the significance level of the test with the lowest threshold that rejects  $H_0$ .
- ▶ How to test  $H_0$  with given significance level  $\alpha$ :
  - ▶ Method I: Find the threshold  $k$  corresponding to  $\alpha$ , test the observed value of  $X$  using threshold  $k$ .
  - ▶ Method II: Find the p-value corresponding to the observed value of  $X$ , compare it with  $\alpha$ .

## Example 2: single sample t-test

$X_i$  i.i.d.  $\mathcal{N}(\mu, \sigma^2)$ , here  $\mu$  and  $\sigma^2$  are both unknown.  $H_0 : \mu = 0$ ,  
 $H_1 : \mu \neq 0$ .

Likelihood ratio test:

$$\frac{\sup_{\sigma^2} (2\pi\sigma^2)^{-n/2} \prod_i e^{-X_i^2/2\sigma^2}}{\sup_{\mu, \sigma^2} (2\pi\sigma^2)^{-n/2} \prod_i e^{-(X_i - \mu)^2/2\sigma^2}} \leq k$$

Do the optimization we get the optimal  $\mu$  is  $\bar{X}$ , the optimal  $\sigma^2$  in denominator is  $\frac{1}{n} \sum_i X_i^2$ , and the optimal  $\sigma^2$  in the numerator is  $\frac{1}{n} \sum_i (X_i - \bar{X})^2 = \frac{1}{n} \sum_i X_i^2 - \bar{X}^2$ . (Recall examples we did in MLE).



Hence

$$\begin{aligned}\log(LHS) &= -\frac{n}{2}(\log(\frac{1}{n} \sum_i X_i^2) - \log(\frac{1}{n} \sum_i X_i^2 - \bar{X}^2)) + \frac{n}{2} - \frac{n}{2} \\ &= \frac{n}{2} \log(1 - \frac{\bar{X}^2}{\frac{1}{n} \sum_i X_i^2}) = h(|\frac{\bar{X}}{\sqrt{S^2/n}}|)\end{aligned}$$

Where  $h(t) = \frac{n}{2} \log(1 - \frac{1}{1 + \frac{1}{(n-1)t^2}})$  is a decreasing function of  $t^2$ .

So the LRT must be of the form  $\left| \frac{\bar{X}}{\sqrt{S^2/n}} \right| \geq M$ . From the definition of  $t$ -distribution, we know that if

$$X_i \sim \mathcal{N}(0, \sigma^2)$$

Then

$$\begin{aligned}(n-1)S^2/\sigma^2 &\sim \chi(n-1) \\ \bar{X}/\sqrt{\sigma^2/n} &\sim \mathcal{N}(0, 1)\end{aligned}$$

So

$$\frac{\bar{X}}{\sqrt{S^2/n}} = \frac{\bar{X}/\sqrt{\sigma^2/n}}{\sqrt{((n-1)S^2/\sigma^2)/(n-1)}} \sim t(n-1)$$

For any observed value  $x_i$ , let  $\bar{x}$  and  $s^2$  be the sample mean and sample variance, then the largest threshold  $M$  which yield positive result (which corresponds to the smallest  $k$ ) is:

$$M_0 = \left| \frac{\bar{x}}{\sqrt{s^2/n}} \right|$$

The p-value, which is the significance level of the test with threshold  $M_0$ , is:

$$\begin{aligned} p &= P\left(\left| \frac{\bar{X}}{\sqrt{S^2/n}} \right| \geq M_0 \mid \frac{\bar{X}}{\sqrt{S^2/n}} \sim t(n-1)\right) \\ &= 2(1 - T\left(\left| \frac{\bar{x}}{\sqrt{s^2/n}} \right| \right)) \end{aligned}$$

Where  $T$  is the cdf of  $t(n-1)$ .

### Example 3: one sided single sample t-test

$X_i$  i.i.d.  $\mathcal{N}(\mu, \sigma^2)$ , here  $\mu$  and  $\sigma^2$  are both unknown.  $H_0 : \mu \leq 0$ ,  
 $H_1 : \mu > 0$ .

Likelihood ratio test:

$$\frac{\sup_{\mu \leq 0, \sigma^2} (2\pi\sigma^2)^{-n/2} \prod_i e^{-(X_i - \mu)^2 / 2\sigma^2}}{\sup_{\mu, \sigma^2} (2\pi\sigma^2)^{-n/2} \prod_i e^{-(X_i - \mu)^2 / 2\sigma^2}} \leq k$$

The likelihood ratio is 1 if  $\sum_i X_i \leq 0$ , and the same as Example 2 if  $\sum_i X_i > 0$ . Hence, the LRT is of the form:

$$\left| \frac{\bar{X}}{\sqrt{S^2/n}} \right| \geq M \text{ and } \bar{X} > 0$$

Hence

$$\frac{\bar{X}}{\sqrt{S^2/n}} \geq M$$

Hence, for given significant level  $\alpha$  we let

$$M = T^{-1}(1 - \alpha)$$

For given value  $x_i$  we can calculate the p-value as

$$p = 1 - T\left(\frac{\bar{x}}{\sqrt{s^2/n}}\right)$$

Where  $\bar{x}$  and  $s^2$  are the calculated sample mean and sample variance.

## Some conceptual questions

- ▶ Suppose a statistical test with significance level 0.05 is used to test covid-19, null hypothesis being not having covid-19. If your test come out positive, what do you know about your probability of getting covid-19?
- ▶ Let  $p$  be a function that sends observed value  $X$  to a p-value. What can you say about the c.d.f. of random variable  $p(X)$  when  $H_0$  is true?

## Midterm 2 Review

- ▶ Regular OHs: 10-11 am Tu Wed Fr, Extra OH: 5-8 pm April 6.
- ▶ Please make sure you understand the examples fully before doing homework.
- ▶ If you find a homework problem too challenging, write down your thought process and where you get stuck, and make sure to read the posted solution after it is due!
- ▶ All homework grades lower than your final grades will be replaced by your final grades.
- ▶ Please tell me to stop if there is anything you do not understand.
- ▶ April 10 is the last day to drop the class.

## Midterm 2 review

- ▶ MOM
- ▶ Bayesian-based point estimates: expectation of posterior, MAP, etc.
- ▶ Neyman-Pearson test (the proof that it is optimal will not be tested in the exam)
- ▶ Likelihood ratio test
- ▶ Significance, power, and p-value

# How to read examples and do homework problems

When reviewing the examples, please do not focus on the calculation part and focus on the concepts and ideas.

For example, this is part of the HW7 due yesterday:

$X_i, i = 1, 2, 3$  are i.i.d. with p.d.f.  $f_{X_i}(x) = \begin{cases} 0 & x < 0 \\ ce^{-cx} & x > 0 \end{cases}$ .

- ▶ Let  $H_0 : c = 1, H_1 : 0 < c < 1$  or  $c > 1$ . Find the likelihood ratio test.
- ▶ Find the threshold in the likelihood ratio test above that makes type I error  $\alpha$  equals 0.01.



## Relevant examples from the lectures

LRT for  $X_i$  i.i.d.  $\mathcal{N}(\mu, 1)$ .  $H_0 : \mu = 0$ ,  $H_1 : \mu \neq 0$ .

Likelihood under  $H_0$  is

$$L_0 = \prod_i \frac{1}{\sqrt{2\pi}} e^{-x_i^2/2} = (2\pi)^{-n/2} e^{-\frac{\sum_i x_i^2}{2}}$$

maximum likelihood under  $H_0$  or  $H_1$  is

$$\begin{aligned} L_1 &= \sup_{\mu} \prod_i \frac{1}{\sqrt{2\pi}} e^{-(x_i - \mu)^2/2} \\ &= \sup_{\mu} (2\pi)^{-n/2} e^{-\frac{\sum_i (x_i - \mu)^2}{2}} \\ &= (2\pi)^{-n/2} e^{-\frac{\sum_i x_i^2 - (\sum_i x_i)^2/n}{2}} \end{aligned}$$

So

$$L_0/L_1 = e^{-\frac{(\sum_i x_i)^2}{2n}}$$

So the likelihood ratio test must be of the form  $|\sum_i x_i| \geq C$ .

## Strategy for the HW problem

So, to find the LRT, find the maximal likelihood (here we are dealing with continuous random variables, so just the joint p.d.f.) under  $H_0$  and  $H_0$  or  $H_1$  respectively as  $L_0(X_1, X_2, X_3)$  and  $L_1(X_1, X_2, X_3)$ , and the test is  $L_0(X_1, X_2, X_3)/L_1(X_1, X_2, X_3) \leq k$ . For each  $k$ , the type I error is by definition

$$\alpha = P(L_1(X_1, X_2, X_3)/L_2(X_1, X_2, X_3) \leq k | H_0)$$

Recall that to get probability of a continuous random variable on certain range one integrate its pdf. So here integrate the joint pdf of  $X_1$ ,  $X_2$  and  $X_3$  on the region defined by the LRT.

## Solution to this HW problem

LRT:

$$\frac{L_0}{L_1} = \frac{e^{-X_1} \cdot e^{-X_2} \cdot e^{-X_3}}{\sup_c ce^{-cX_1} \cdot ce^{-cX_2} \cdot ce^{-cX_3}} \leq k$$

So

$$3 + 3(\log(\bar{X}) - \bar{X}) \leq \log(k)$$

Let  $a < b$  be the two numbers such that  $ae^{-a} = be^{-b}$ , and

$$\int_{x_1, x_2, x_3 \geq 0, x_1 + x_2 + x_3 \leq a} e^{-(x_1 + x_2 + x_3)} dx_1 dx_2 dx_3 +$$

$\int_{x_1, x_2, x_3 \geq 0, x_1 + x_2 + x_3 \geq b} e^{-(x_1 + x_2 + x_3)} dx_1 dx_2 dx_3 = 0.01$ , then the threshold  $k$  is  $a^3 e^{3-3a}$ . You will get full credit if you write up to this or something equivalent to this.

One can further simplify this statement by doing the integration, for instance, and get something like:

$$\frac{1}{2}e^{-3a}(9a^2 + 6a + 2) - \frac{1}{2}e^{-3b}(9b^2 + 6b + 2) = 0.99$$

$$k = a^3 e^{3-3a} = b^3 e^{3-3b}$$

## Practice Midterm 2

1.  $X$  is a random variable with uniform distribution on  $[0, 1]$ ,  $Y_i$ ,  $i = 1, 2$  i.i.d. conditioned at any value of  $X$ , and are of the distribution  $\mathcal{N}(0, 1 + X)$ .
- ▶ Write down the joint p.d.f. of  $X, Y_1, Y_2$ .
  - ▶ Find the conditional distribution of  $X$  conditioned at  $Y_1 = 1, Y_2 = 2$ .
  - ▶ Find the conditional expectation of  $X$  when  $Y_1 = 1, Y_2 = 2$ .

Answer:

$$\begin{aligned} \blacktriangleright f_{X,Y_1,Y_2}(x,y_1,y_2) = & \\ \begin{cases} 0 & x \notin [0,1] \\ (2\pi(1+x))^{-1}e^{-(y_1^2+y_2^2)/(2+2x)} & x \in [0,1] \end{cases} \end{aligned}$$

$$\blacktriangleright f_{X|Y_1=1,Y_2=2}(x) = \begin{cases} 0 & x \notin [0,1] \\ \frac{(2\pi(1+x))^{-1}e^{-5/(2+2x)}}{\int_0^1 (2\pi(1+s))^{-1}e^{-5/(2+2s)} ds} & x \in [0,1] \end{cases}$$

$$\blacktriangleright \frac{\int_0^1 (2\pi(1+s))^{-1}se^{-5/(2+2s)} ds}{\int_0^1 (2\pi(1+s))^{-1}e^{-5/(2+2s)} ds}.$$

2.  $X_i, i = 1, \dots, n$  i.i.d. with p.d.f.  $f(x) = ae^{-2a|x-b|}$ . Find the estimate of  $a$  and  $b$  using method of moments.

Answer:

$$\hat{b} = \frac{1}{n} \sum_i X_i$$

$$\hat{b}^2 + \frac{1}{2\hat{a}^2} = \frac{1}{n} \sum_i X_i^2$$

So

$$\hat{a} = \sqrt{\frac{1}{2(\frac{1}{n} \sum_i X_i^2 - \frac{1}{n^2} (\sum_i X_i)^2)}}$$

3.  $X_i$ ,  $i = 1, 2, 3$  i.i.d.,  $H_0$  is that they are standard normal,  $H_1$  is that they are uniform on  $[0, 1]$ .

- ▶ Find the Neyman-Pearson test.
- ▶ What is the smallest possible type I error for a Neyman-Pearson test that has non-zero power?

Answer: The Neyman-Pearson test is:

$$(2\pi)^{-3/2} e^{-\frac{1}{2} \sum_i X_i^2} \leq k, X_i \in [0, 1]$$

To make sure that the power is non-zero, we must let

$$k > \min_{X_i \in [0, 1]} (2\pi)^{-3/2} e^{-\frac{1}{2} \sum_i X_i^2} = (2\pi)^{-3/2} e^{-3/2}$$

Hence the type I error

$$\alpha = \int_{x_i \in [0,1], \sum_i x_i^2 \geq -2 \log((2\pi)^{3/2} k)} (2\pi)^{-3/2} e^{-\frac{1}{2} \sum_i x_i^2} dx_1 dx_2 dx_3$$

decreases as  $k$  decreases. The function being integrated is bounded, and the region of integration has area that goes to 0 as  $k$  goes to  $(2\pi)^{-3/2} e^{-3/2}$ , hence the type I error can be as close to 0 as one wants.



4.  $X_i$ ,  $i = 1, 2, \dots, n$  i.i.d. and are discrete random variables taking value on  $\{-2, -1, 1, 2\}$ .  $H_0$ :  $P(X_i = n) = P(X_i = -n)$  for all  $n$ ,  
 $H_1$ :  $P(X_i = n) \neq P(X_i = -n)$  for some  $n$ .

- ▶ Find the likelihood ratio test.
- ▶ Find the p-value for the observation:  $X_1 = -1$ ,  $X_2 = -1$ ,  
 $X_3 = -2$ ,  $X_4 = 2$ .
- ▶ Find a sequence  $X_i$  with the smallest possible  $n$  and a p-value less than 0.05.

Answer: Let  $n_{-2}$ ,  $n_{-1}$ ,  $n_1$  and  $n_2$  be the number of  $X_i$  taking value at  $-2$ ,  $-1$ ,  $1$ , and  $2$  respectively. The likelihood ratio test is:

$$\frac{\sup_{p+q=1} (p/2)^{n_{-2}+n_2} (q/2)^{n_{-1}+n_1}}{\sup_{a+b+c+d} a^{n_{-2}} b^{n_{-1}} c^{n_1} d^{n_2}} \leq k$$

In other words,

$$(n_{-2} + n_2) \log\left(\frac{n_{-2} + n_2}{2}\right) + (n_{-1} + n_1) \log\left(\frac{n_{-1} + n_1}{2}\right)$$

$$-n_{-2} \log(n_{-2}) - n_{-1} \log(n_{-1}) - n_1 \log(n_1) - n_2 \log(n_2) \leq \log k$$

Here  $0 \log 0 = 0$ .

When  $n = 4$ ,  $n_{-2} = 1$ ,  $n_2 = 1$ ,  $n_{-1} = 2$ ,  $n_1 = 0$ , the left-hand-side of the inequality above becomes  $-2 \log 2$ . So the smallest possible  $k$  is  $1/4$ . Now we find out the possible cases where the likelihood ratio is no larger than  $1/4$ : Assuming

$$p/2 = P(X_i = 2) = P(X_i = -2),$$

$$q/2 = P(X_i = 1) = P(X_i = -1).$$

1. If  $n_1 + n_{-1} = n_2 + n_{-2} = 2$ , the likelihood ratio is  $1/4$  if one of the  $n_i$  is 2,  $1/16$  if two of them are 2. Total probability is  $(p/2)^2(q/2)^2 \frac{4!}{1!1!2!} \cdot 2 \cdot 2 + 2^2 \cdot \frac{4!}{2!2!} = 72(p/2)^2(q/2)^2$ .
2. If  $n_1 + n_{-1} = 1$ ,  $n_2 + n_{-2} = 3$ , the likelihood ratio is no larger than  $1/4$  iff one of the  $n_j$  is 3. Total probability is  $(p/2)^3(q/2) \cdot 2 \cdot 2 \cdot 4$ .
3. Similarly, if  $n_1 + n_{-1} = 3$ ,  $n_2 + n_{-2} = 1$ , we get  $(p/2)(q/2)^3 \cdot 2 \cdot 2 \cdot 4$ .
4. Lastly, if  $n_2 + n_{-2} = 4$  or  $n_1 + n_{-1} = 4$ , the only possibility for getting likelihood ratio less than  $1/4$  is if one of the  $n_j$  is 4. So, total probability is  $((p/2)^4 + (q/2)^4) \cdot 2$

So, total probability is  $\frac{9p^2q^2}{2} + (p^3q + pq^3) + \frac{p^4+q^4}{8}$ . The minimum is taken at  $p = q = 1/2$ , so the p-value is

$$9/32 + 1/8 + 1/64 = 27/64.$$

For every  $n$ , it is evident that the smallest  $k$  is  $2^{-n}$  and it is obtained when either  $n_1$  or  $n_{-1}$  is 0, either  $n_2$  or  $n_{-2}$  is 0. Hence, the total probability for that is

$$\sum_{i=1}^{n-1} 2^2 \binom{n}{i} (p/2)^i (q/2)^{n-i} + 2(p/2)^n + 2(q/2)^n =$$

$$2^2(p/2 + q/2)^n - 2(p/2)^n - 2(q/2)^n = 2^{-n+2} - 2^{-n+1}(p^n + q^n).$$

So the maximum is obtained when  $p = q = \frac{1}{2}$ , and is  $2^{-n+2} - 2^{-2n+2}$ . Hence the smallest  $n$  is 6. We can pick this sequence 1, 1, 1, 1, 1, 1, the p-value is  $2^{-4} - 2^{-6} = \frac{3}{64} < 0.05$ .

Example:  $X_i$ ,  $i = 1, 2$  independent and normal, with same variance and expectations  $\mu$  and  $2\mu$  respectively.

- ▶ If variance is 1 and  $\mu$  has  $\mathcal{N}(0, 1/\lambda)$  prior, what is its posterior?
- ▶  $H_0 : \mu = 0$ , and  $H_1 : \mu \neq 0$ . Find the likelihood ratio test and p-value.

Answer:

- ▶  $f_{\mu|X_i}(t) \propto e^{-t^2\lambda/2} e^{-\sum_k (X_k - kt)^2/2}$ , so  $\mu|X_i \sim \mathcal{N}(\frac{X_1 + 2X_2}{5+\lambda}, \frac{1}{5+\lambda})$ .  
(this prior is call the prior for ridge regression or  $L^2$  regularization)

- ▶ LRT:

$$\frac{\sup_{\sigma} (2\pi\sigma^2)^{-1} e^{-\sum_k X_k^2/2\sigma^2}}{\sup_{\sigma, \mu} (2\pi\sigma^2)^{-1} e^{-\sum_k (X_k - k\mu)^2/2\sigma^2}} \leq k$$

$$\log(LHS) = (-\log(\frac{\sum_k X_k^2}{2}) - 1)$$

$$-(-\log(\frac{\sum_k (X_k - k(\frac{\sum_k kX_k}{5}))^2}{2}) - 1)$$

So the LRT is of the form:

$$\frac{\sum_k (X_k - k(\frac{\sum_k kX_k}{5}))^2}{\sum_k X_k^2} = \frac{(2X_1 - X_2)^2}{(X_1 + 2X_2)^2 + (2X_1 - X_2)^2} \leq C$$

Which is equivalent to

$$\frac{(2X_1 - X_2)^2}{(X_1 + 2X_2)^2} \leq M$$

Where  $M/(1 + M) = C$ . It is easy to see that under  $H_0$ , the test statistics  $\frac{(2X_1 - X_2)^2}{(X_1 + 2X_2)^2} \sim F(1, 1)$ . So the p-value when  $X_1 = x_1$ ,  $X_2 = x_2$  is  $p = F_{F(1,1)}\left(\frac{(2x_1 - x_2)^2}{(x_1 + 2x_2)^2}\right)$ .

## Midterm 2

Mean and Median: about 70

1.  $X_i, i = 1, 2, \dots, n$  are i.i.d. random variables that satisfies normal distribution with expectation  $\lambda$  and variance  $1 + \lambda$ .

- ▶ Find the MOM estimate for  $\lambda$ . (10 points)
- ▶ Is the MOM estimate for  $\lambda$  biased or unbiased? (10 points)

Answer:  $\hat{\lambda}_{MOM} = \frac{1}{n} \sum_i X_i$ . Yes.



2.  $c$  has uniform distribution on  $[1, 2]$ ,  $X_i$ ,  $i = 1, 2$ , are conditionally i.i.d. for given value of  $c$ , and has conditional p.d.f. of the form  $f_{X_i|c}(x) = ce^{-2c|x|}$ .

- ▶ Find the conditional p.d.f. of  $c$  when  $X_1 = 1$ ,  $X_2 = -2$ . (10 points)
- ▶ Find the MAP estimate for  $c$  when  $X_1 = 1$ ,  $X_2 = -2$ . In other words, find the value  $\hat{c}_{MAP}$  that maximizes the conditional p.d.f. you calculated above. (10 points)
- ▶ Find the conditional expectation of  $c$  when  $X_1 = 1$ ,  $X_2 = -2$ . (10 points)

$$\text{Answer: } f_{c|X_1=1, X_2=-2}(x) = \begin{cases} 0 & x < 1 \text{ or } x > 2 \\ \frac{108x^2e^{-6x}}{25e^{-6}-85e^{-12}} & 1 \leq x \leq 2 \end{cases}.$$

$$\hat{c}_{MAP} = 1, \text{ and the conditional expectation is } \frac{61e^{-6}-373e^{-12}}{50e^{-6}-170e^{-12}}.$$

3. Random variable  $X$  has p.d.f.

$$f(x) = \frac{1}{\sqrt{2\pi}} \left( ce^{-(x+1)^2/2} + (1-c)e^{-(x-1)^2/2} \right). \text{ Here } 0 \leq c \leq 1.$$

Let  $H_0 : c = 0$ ,  $H_1 : c > 0$ .

- Find the likelihood ratio test. (10 points)
- If the threshold for likelihood ratio in the test above is set to be 0.5, calculate the significance level. (10 points)

Answer: LRT is  $\frac{e^{-(x-1)^2/2}}{\sup_c (ce^{-(x+1)^2/2} + (1-c)e^{-(x-1)^2/2})} \leq k$ . In the denominator, the optimal  $c$  is 1 if  $x > 0$  and 0 if  $x < 0$ . Hence, if  $k = 1$  then  $x$  can be anything, if  $0 < k < 1$  then  $x \leq \frac{1}{2} \log(k)$ . If  $k = 0.5$ , the significance level is  $F(-1 - \log(2)/2)$  where  $F$  is the c.d.f. of standard normal.

4.  $X_i$ ,  $i = 1, 2$  are i.i.d. random variables taking values in  $\{1, 2, 3\}$ . Null hypothesis  $H_0$  is  $P(X_i = 1) = P(X_i = 2) = P(X_i = 3) = \frac{1}{3}$ , and alternative hypothesis  $H_1$  is  $P(X_i = k) = k/6$  for  $k = 1, 2, 3$ .

- ▶ Write down the Neyman-Pearson test for this problem. (10 points)
- ▶ Calculate the p-value for  $X_1 = X_2 = 3$ . (10 points)
- ▶ Find the threshold for the Neyman-Pearson test that minimizes that sum of false positive (probability of rejecting  $H_0$  when  $H_0$  is true) and false negative (probability of not rejecting  $H_0$  when  $H_1$  is true). (10 points)

Answer: Likelihood ratio for choices of possible values of  $X_i$  are

$X_2 \backslash X_1$	1	2	3
1	4	2	4/3
2	2	1	2/3
3	4/3	2/3	4/9

So the N-P test for different threshold  $r$ , as well as the type I and II errors, are:

threshold	test	type I error	type II error
$r < 4/9$	$\emptyset$	0	1
$4/9 \leq r < 2/3$	$X_1 = X_2 = 3$	1/9	3/4
$2/3 \leq r < 1$	$X_1 + X_2 \geq 5$	1/3	5/12
$1 \leq r < 4/3$	$X_1 > 1, X_2 > 1$	4/9	11/36
$4/3 \leq r < 2$	$X_1 + X_2 \geq 4$	2/3	5/36
$2 \leq r < 4$	$X_1 + X_2 \geq 3$	8/9	1/36
$r \geq 4$	everything	1	0

The p-value for  $X_1 = X_2 = 3$  is 1/9, and the threshold that minimize the sum of two types of errors is in the range  $[2/3, 4/3)$ .

# How to use a given statistical test

Some common hypothesis testing problems have well known tests, which are usually either LRT or approximated LRT. We will illustrate via examples how to use some of the tests in Chapter 13 of the textbook.

Usually a statistical test is stated as follows:

**Testing  $H_0$  against  $H_1$ , test statistics  $z = z(X)$ , critical region of size (significance level)  $\alpha$  is  $z \in D_\alpha$ .**

For example, for the **One sample, One sided t-test**:

$X_1, \dots, X_n$ , **i.i.d.**  $\sim \mathcal{N}(\mu, \sigma^2)$ . **Testing**  $\mu \leq 0$  **against**  $\mu > 0$ .

**Test statistics**  $t = \frac{\bar{X}}{\sqrt{S^2/n}}$  **Critical region**  $t \geq T^{-1}(1 - \alpha)$ ,

**where**  $T$  **is the cdf of**  $t(n - 1)$ .

To make use of it, say  $n = 5$  and  $X_i$  are  $-1, 0, 1, 2, 1$ . The  $t$  statistics can be calculated as 1.1767.  $T^{-1}(1 - 0.05) = 2.1318$ , so we can not reject  $H_0$  when significance level is chosen to be 0.05.

The minimal  $\alpha$  such that 1.1767 is in the critical region is  $1 - T(1.1767) = 0.1523$ , so the p-value is 0.1523.

If  $X_i$  are 0, 1, 2, 3, 4 however,  $t = 2.8284 \geq 2.1318$ , so reject  $H_0$  under significance level 0.05. The p-value is 0.0237.

Sometimes we make use of a test indirectly by transforming the observed random variables: from some observed random variables  $X$ , we build random variables  $Y$ , and use a known test on  $Y$ . For example:  $X_i, i = 1, \dots, 10$  i.i.d.  $\mathcal{N}(\mu_1, \sigma_1^2)$ ,  $Y_i, i = 1, \dots, 10$ , i.i.d.  $\mathcal{N}(\mu_2, \sigma_2^2)$ ,  $X_i$  and  $Y_j$  are all independent. Want to test if  $\mu_1 = \mu_2$ . One way to do so would be to consider  $Z_i = X_i - Y_i$ , which are i.i.d. normal, and test if their expectation is 0.

This approach usually won't give us the most powerful test as we are losing information during the transformation. However in many situations this is good enough.

# Some commonly used statistical tests

$X_i$  i.i.d.  $i = 1, \dots, n, \sim \mathcal{N}(\mu, \sigma^2)$ .

- ▶ Test  $\mu = \mu_0$  against  $\mu \neq \mu_0$ .  $t = \frac{\bar{X} - \mu_0}{\sqrt{S^2/n}}$ , critical region  $|t| \geq F_{t(n-1)}^{-1}(1 - \alpha/2)$ , where  $F_{t(n-1)}$  is the c.d.f. of  $t(n-1)$ .
- ▶ Test  $\mu \leq \mu_0$  against  $\mu > \mu_0$ , same  $t$  as above, critical region  $t \geq F_{t(n-1)}^{-1}(1 - \alpha, n-1)$ .
- ▶ Test  $\sigma^2 = \sigma_0^2$ :  $\chi^2 = (n-1)S^2/\sigma_0^2$ , critical region  $\chi^2 \in (-\infty, F_{\chi(n-1)}^{-1}(\alpha/2)] \cup [F_{\chi(n-1)}^{-1}(1 - \alpha/2), \infty)$
- ▶ Test  $\sigma^2 \leq \sigma_0^2$  against  $\sigma^2 > \sigma_0^2$ :  $\chi$  same as above, critical region  $\chi^2 \geq F_{\chi(n-1)}^{-1}(1 - \alpha)$ .
- ▶ Test  $\sigma^2 \geq \sigma_0^2$  against  $\sigma^2 < \sigma_0^2$ :  $\chi$  same as above, critical region  $\chi^2 \leq F_{\chi(n-1)}^{-1}(\alpha)$ .



$X_i, i = 1, \dots, n_1$  i.i.d.  $\mathcal{N}(\mu_1, \sigma_1^2)$ ,  $Y_i, i = 1, \dots, n_2$  i.i.d.  $\mathcal{N}(\mu_2, \sigma_2^2)$ ,  
 $X_i, Y_j$  indep.

- ▶ Test for  $\mu_1 = \mu_2$  against  $\mu_1 \neq \mu_2$ , knowing  $\sigma_1^2$  and  $\sigma_2^2$ .  
 $z = \frac{\bar{x} - \bar{y}}{\sqrt{\sigma_1^2/n_1 + \sigma_2^2/n_2}}$ . Critical region  $|z| \geq F_{\mathcal{N}(0,1)}^{-1}(1 - \alpha/2)$ .
- ▶ If  $\sigma_i^2$  unknown but number of samples is large, can approximate them with  $S^2$ .
- ▶  $\sigma_1^2 = \sigma_2^2$  but unknown, test  $\mu_1 = \mu_2$  against  $\mu_1 \neq \mu_2$ :

$$t = \frac{\bar{X} - \bar{Y}}{\sqrt{(1/n_1 + 1/n_2) \cdot \left( \frac{(n_1-1)S_X^2 + (n_2-1)S_Y^2}{n_1+n_2-2} \right)}}$$

Critical region  $|t| \geq F_{t(n_1+n_2-2)}^{-1}(1 - \alpha/2)$ .

- ▶ One sided tests are similar.

$X_i, i = 1, \dots, n_1$  i.i.d.  $\mathcal{N}(\mu_1, \sigma_1^2)$ ,  $Y_i, i = 1, \dots, n_2$  i.i.d.  $\mathcal{N}(\mu_2, \sigma_2^2)$ ,  
 $X_i, Y_j$  indep.

- ▶ Testing  $\sigma_1^2 = \sigma_2^2$  against  $\sigma_1^2 \neq \sigma_2^2$ .  $f = S_X^2/S_Y^2$ . Critical region  
 $f \in (0, F_{F(n_1-1, n_2-1)}^{-1}(\alpha/2)] \cup [F_{F(n_1-1, n_2-1)}^{-1}(1 - \alpha/2), \infty)$ .
- ▶ One sided tests are similar.

One can check by calculation that all these tests have the significance level  $\alpha$ .

## Pearson's $\chi^2$ test

$X_i$  i.i.d. taking values at  $\{1, 2, \dots, m\}$ . Test for null hypothesis:  
 $P(X = j) = e_j$ , where  $e_j = f(j, \theta_1, \dots, \theta_k)$ . Let  $n_j$  be the number of  $X_i$  taking value  $j$ . Then likelihood ratio test gives:

$$\frac{\sup_{\theta_1, \dots, \theta_k} \prod_j e_j^{n_j}}{\sup_{p_j, \sum_j p_j = 1} \prod_j p_j^{n_j}} \leq k$$

The optimal  $p_j$  is  $n_j/n$  where  $n = \sum_j n_j$ . So

$$\log(LHS) = \sum_j n_j \left( -\log\left(\frac{n_j/n}{\hat{e}_j}\right) \right) = \sum_j n_j \left( -\log\left(1 + \frac{n_j - n\hat{e}_j}{n\hat{e}_j}\right) \right)$$

Here  $\hat{e}_j$  is the MLE of  $e_j$ .

Taylor expansion at  $n_j = ne_j$ , we get approximated LRT:

$$\sum_j \frac{(n_j - n\hat{e}_j)^2}{n\hat{e}_j} \geq m$$

When  $n$  is large, and with some additional assumptions, the test statistics  $\sim \chi^2(m - k - 1)$ .

## Examples of Pearson's $\chi^2$ test:

- ▶  $X_i$  takes value in  $\{1, 2, 3, 4\}$ . To test if  $P(X = 1) = P(X = 2) = P(X = 3) = P(X = 4) = 1/4$ , consider  $\chi^2 = \sum_{j=1}^4 \frac{(n_j - n/4)^2}{n/4}$  satisfies  $\chi^2(3)$ , so critical region is  $\chi^2 \geq F_{\chi^2(3)}^{-1}(1 - \alpha)$ .
- ▶  $X_i, Y_i$  taking values in  $\{0, 1\}$ ,  $(X_i, Y_i)$  i.i.d. Want to test if  $X_i$  and  $Y_i$  are independent. Consider the random variable  $Z_i = 2X_i + Y_i + 1$ , then  $Z_i$  takes value at 1, 2, 3, 4, and this is the same as testing if

$$P(Z_i = k) = \begin{cases} ab & k = 1 \\ a(1 - b) & k = 2 \\ (1 - a)b & k = 3 \\ (1 - a)(1 - b) & k = 4 \end{cases}$$

MLE:  $\hat{a} = \frac{n_1 + n_2}{n}$ ,  $\hat{b} = \frac{n_1 + n_3}{n}$ . Use Pearson's  $\chi^2$  test, there is 1 degrees of freedom.

The final exam is open book, so there is no need to memorize the tests! You just need to know how to use a given statistical test.

# Confidence interval

Setting:  $X$  has p.d.f. (or p.d.)  $f(x, \theta)$ , where  $\theta$  is unknown.

- ▶ **Point estimate**: find a random variable  $\hat{\theta}$  based on  $X$ , which is close to  $\theta$ .
- ▶ **Hypothesis testing**: given  $\theta_0$ , we can tell how unlikely it is to get the observed value of  $X$  if  $\theta = \theta_0$ .
- ▶ **Confidence interval** is related to both of these concepts:
  - ▶ Conceptually, confidence interval is an extension of point estimate: this is a random variable taking value in the set of sets, such that  $\theta$  is in it with probability  $1 - \alpha$ .
  - ▶ Mathematically, confidence intervals are equivalent to certain types of statistical tests.

# Definition of confidence interval

$X$  has p.d.f. (or p.d.)  $f(x, \theta)$ , where  $\theta$  is unknown.

The  $1 - \alpha$ -**confidence interval** of  $\theta$  is a set  $I(X)$  depending on  $X$ , such that for any possible value of  $\theta$ ,  $P(\theta \in I(X)|\theta) = 1 - \alpha$ .

Here, as in hypothesis testing,  $P(\theta \in I(X)|\theta)$  does not necessarily mean conditional probability. It means the probability after we fix the value of  $\theta$ .

Equivalence between confidence intervals and statistical tests:

- ▶ If  $X \in D(\theta_0)$  is a statistical test of the null hypothesis  $H_0 : \theta = \theta_0$ , which has significance level  $\alpha$ . Then  $I(X) = \{\theta_0 : X \notin D(\theta_0)\}$  is a  $1 - \alpha$  confidence interval for  $\theta$ .
- ▶ If  $I(X)$  is a  $1 - \alpha$  confidence interval for  $X$ , then  $\theta_0 \notin I(X)$  is a statistical test of the null hypothesis  $H_0 : \theta = \theta_0$ .

In some textbooks the CI is defined as  $P(\theta \in I(X)|\theta) \geq 1 - \alpha$ , then, they should correspond to statistical tests of significance level  $\leq \alpha$ . They will not be the focus of this course, but in case we need to mention them in examples, let's call them *CI with confidence level at least  $1 - \alpha$* .



# Proof of equivalence

- ▶ Suppose  $P(X \in D(\theta)|\theta) = \alpha$ . Let

$$I(X) = \{\theta : X \notin D(\theta)\}$$

then

$$\begin{aligned} P(\theta \in I(X)|\theta) &= P(X \notin D(\theta)|\theta) \\ &= 1 - P(X \in D(\theta)|\theta) = 1 - \alpha \end{aligned}$$

- ▶ Suppose  $P(\theta \in I(X)|\theta) = 1 - \alpha$ . Let

$$D(\theta_0) = \{X : \theta_0 \notin I(X)\}$$

Then

$$\begin{aligned} P(X \in D(\theta)|\theta) &= P(\theta \notin I(X)|\theta) \\ &= 1 - P(\theta \in I(X)|\theta) = \alpha \end{aligned}$$

## Example 1

$X$  normal distribution with expectation  $\mu$  and variance 1. Find the 0.95 confidence interval for  $\mu$ .

Likelihood ratio test for  $H_0 : \mu = \mu_0$  against  $H_1 : \mu \neq \mu_0$ :

$$\frac{e^{-(X-\mu_0)^2/2}}{\sup_{\mu} e^{-(X-\mu)^2/2}} \leq k$$

The optimal  $\mu$  is  $X$ , so the LRT is

$$|X - \mu_0| \geq \sqrt{-2 \log(k)}$$

Let  $\Phi$  be the c.d.f. of standard normal distribution. The significance level is the probability of success under null hypothesis, and under null hypothesis,  $X - \mu_0$  is standard normal. So,

$$\alpha = 2(1 - \Phi(\sqrt{-2 \log(k)}))$$

So the test

$$|X - \mu_0| \geq \Phi^{-1}(0.975)$$

Is a test with significance level  $\alpha$ , the confidence interval is

$$I(X) = \{\mu : |X - \mu| \leq \Phi^{-1}(0.975)\} = [X - \Phi^{-1}(0.975), X + \Phi^{-1}(0.975)]$$

## One sided confidence interval

Sometimes we want the confidence interval to be one sided, like  $I = [a(X), \infty)$ . The statistical test associated to it should be  $\mu < a(X)$ , in other words, it should only reject null hypothesis  $\mu = \mu_0$  if  $\mu_0$  is too small. Hence, let's consider  $H_0 : \mu = \mu_0$  and  $H_1 : \mu > \mu_0$ , then the LRT becomes

$$\frac{e^{-(X-\mu_0)^2/2}}{\sup_{\mu \geq \mu_0} e^{-(X-\mu)^2/2}} \leq k$$

So the optimal  $\mu$  is  $\mu_0$  if  $X \leq \mu_0$ ,  $X$  if  $X > \mu_0$ . So the test is

$$X - \mu_0 \geq \sqrt{-2 \log(k)}$$

When  $k < 1$ , and everything when  $k = 1$ . So

$$\alpha = 0.05 = 1 - \Phi(\sqrt{-2 \log(k)})$$

$$X - \mu_0 \geq \Phi^{-1}(0.95)$$

$$I(X) = \{\mu : X - \mu \leq \Phi^{-1}(0.95)\} = [X - \Phi^{-1}(0.95), \infty)$$

- ▶ As an exercise, read Chapter 11 and Chapter 13. For every statistical test in 13.2-13.6, find the corresponding confidence interval, if there are any, from 11.2-11.7.
- ▶ True or false: suppose based on the statistics up to today, the reproductive number  $R_0$  of covid-19 has a 95% confidence interval  $[2.1, 2.5]$ . Then the probability of  $R_0$  being between 2.1 and 2.5 is 0.95.
- ▶ True or false: suppose after the covid-19 outbreak we found a very good model for estimating the  $R_0$  of an epidemic, and this model gives a 95% confidence interval. Then, the probability of  $R_0$  lying in this confidence interval is 0.95.

## Example 2

$X_1, X_2$  i.i.d. with uniform distribution on  $[a - 1/2, a + 1/2]$ . Find  $d$  such that  $[\bar{X} - d, \bar{X} + d]$  is a 95% confidence interval, and find the corresponding statistical tests.  
 $\bar{X}$  has p.d.f.

$$f_{\bar{X}}(x) = \begin{cases} 0 & x \notin [a - 1/2, a + 1/2] \\ 4|x - a| & x \in [a - 1/2, a + 1/2] \end{cases}$$

Because  $a \in [\bar{X} - d, \bar{X} + d]$  iff  $\bar{X} \in [a - d, a + d]$ ,

$$0.95 = P(a \in [\bar{X} - d, \bar{X} + d] | a) = P(\bar{X} \in [a - d, a + d] | a) = \int_{a-d}^{a+d} f_{\bar{X}}(s) ds$$

So  $d = 1/2 - \sqrt{1/80}$ . The test for  $H_0 : a = a_0$  is  
 $a_0 \leq \bar{X} - 1/2 + \sqrt{1/80}$  or  $a_0 \geq \bar{X} + 1/2 - \sqrt{1/80}$ .

## Remark: Bayesian analogy of hypothesis testing and confidence interval

One can create some analogy of hypothesis testing and confidence interval under Bayesian statistics as well, which is conceptually much simpler but completely different from the ones we learn in the non-Bayesian setting:

- ▶ Recall that the output of Bayesian statistics is the posterior, i.e. conditional distribution of  $\theta$  conditioned at  $X$ .
- ▶ For a hypothesis  $H : \theta \in D$ , we can calculate its probability under this posterior  $P(\theta \in D|X)$ , and reject it when this probability is small.
- ▶ The  $1 - \alpha$ -**credible interval** is  $J(X)$  such that  $P(\theta \in J(X)|X) = 1 - \alpha$ .

This slide will not be in the exam.



## Review of LRT, significance level, p value

Likelihood ratio test:

$X$  has p.d.f. (or p.d.)  $f(x, \theta)$ ,  $H_0 : \theta \in D_0$ ,  $H_1 : \theta \in D \setminus D_0$ .

The LRT is:

$$L_0(X)/L_1(X) \leq k$$

Where

$$L_0(X) = \sup_{\theta \in D_0} f(X, \theta), L_1(X) = \sup_{\theta \in D} f(X, \theta)$$

And  $k$  is an arbitrary threshold parameter. The significance level is

$$\alpha = \sup_{\theta \in D_0} P(L_0/L_1 \leq k | \theta)$$

For  $X = x$ , we find the smallest  $k$  that rejects  $H_0$ , which is  $k_m = L_0(x)/L_1(x)$ . The significant level for the LRT with threshold  $k_m$  is called the p-value for  $x$ :

$$p = \sup_{\theta \in H_0} P(L_0(X)/L_1(X) \leq k_m | \theta)$$



Example:  $X$  has p.d.f.  $f(x) = \begin{cases} 0 & x \notin [0, 1] \\ 1 + c(x - 1/2) & x \in [0, 1] \end{cases}$ .  
 $c \in [-2, 2]$ .  $H_0 : c = 0$ ,  $H_1 : c \neq 0$ .

$$L_0(X) = \begin{cases} 1 & X \in [0, 1] \\ 0 & X \notin [0, 1] \end{cases}, L_1(X) = \begin{cases} 1 + 2|X - 1/2| & X \in [0, 1] \\ 0 & X \notin [0, 1] \end{cases}$$

LRT:

$$1/(1 + 2|X - 1/2|) \leq k$$

$$|X - 1/2| \geq 1/(2k) - 1/2$$

If  $k = 2/3$ , the above becomes  $|X - 1/2| \geq 1/4$ . Under null hypothesis  $X$  is uniform on  $[0, 1]$ , so the significance level is  $\alpha = P(|X - 1/2| \geq 1/4) = P(X \in [0, 1/4] \cup [3/4, 1]) = 1/2$ .

If  $X = 2/3$ , the minimal  $k$ ,  $k_m$ , satisfies

$$1/6 = 1/(2k_m) - 1/2$$

So the LRT with threshold  $k_m$  is:

$$|X - 1/2| \geq 1/6$$

The significance level for this test is

$$\alpha_{p_m} = 2/3$$

And the p-value is

$$p = \alpha_{p_m} = 2/3$$

# Review for CI

$$X \sim F(\theta).$$

- ▶ Definition: An CI with  $1 - \alpha$  confidence level is a random set  $I(X)$  depending on  $X$ , such that  $P(\theta \in I(X) | \theta) = 1 - \alpha$ .
- ▶ If there is a statistical test for  $\theta = \theta_0$  with significance level  $\alpha$  of the form  $X \in D(\theta_0)$ , then  $I(X) = \{\theta : X \notin D(\theta_0)\}$  is a  $1 - \alpha$  CI.
- ▶ If  $I(X)$  is a  $1 - \alpha$  CI,  $\theta_0 \notin I(X)$  is a test for  $\theta = \theta_0$  with significance level  $\alpha$ .
- ▶ Sometimes we want  $I(X)$  to be one-sided, e.g. of the form  $[A(X), \infty)$ . Hence the corresponding statistical test must be of the form  $\theta_0 \leq \alpha(X)$ . In other words, the null hypothesis can be rejected is only if  $\theta_0$  is too small, i.e. when  $\theta_0 < \theta$ . Hence the power function of the test must be no more than  $\alpha$  on  $(-\infty, \theta_0]$ , and one can pick the alternative hypothesis as  $\theta_0 < \theta$ .

In practice we often use the following definitions, which will NOT be in the HW or exam:

$X \sim F(\theta)$ .

- ▶ Definition: An CI with confidence level bounded by  $1 - \alpha$  is a random set  $I(X)$  depending on  $X$ , such that  $P(\theta \in I(X) | \theta) \geq 1 - \alpha$ .
- ▶ If there is a statistical test for  $\theta = \theta_0$  with significance level  $\leq \alpha$  of the form  $X \in D(\theta_0)$ , then  $I(X) = \{\theta : X \notin D(\theta_0)\}$  is a CI with CL bounded by  $1 - \alpha$ .
- ▶ If  $I(X)$  is a CI with CL bounded by  $1 - \alpha$ ,  $\theta_0 \notin I(X)$  is a test for  $\theta = \theta_0$  with significance level  $\leq \alpha$ .

## Example 1: normal approximation of binomial distribution

$X \sim B(n, p)$ ,  $n \gg 1$ ,  $p$  not too close to 0 or 1. Want CI of  $p$ .  
From what we learned some weeks ago, we have an approximated LRT based on CLT which says that the test for  $p = p_0$  against  $p \neq p_0$  with significance level  $\alpha$  is

$$|X/n - p_0| \geq \sqrt{\frac{p_0(1-p_0)}{n}} \cdot \Phi^{-1}(1 - \alpha/2)$$

Where  $\Phi$  is the cdf of standard normal.

So the approximated  $1 - \alpha$  CI is

$$\{p : |X/n - p| \leq \sqrt{\frac{p(1-p)}{n}} \cdot \Phi^{-1}(1 - \alpha/2)\} = [p_1, p_2]$$

Where

$$X/n - p_1 = \sqrt{\frac{p_1(1-p_1)}{n}} \cdot \Phi^{-1}(1 - \alpha/2)$$

$$p_2 - X/n = \sqrt{\frac{p_2(1-p_2)}{n}} \cdot \Phi^{-1}(1 - \alpha/2)$$

Because  $n \gg 0$ ,  $p_1, p_2 \approx X/n$ , we have

$$[p_1, p_2] = [X/n - \sqrt{\frac{X(n-X)}{n^3}} \cdot \Phi^{-1}(1 - \alpha/2),$$

$$X/n + \sqrt{\frac{X(n-X)}{n^3}} \cdot \Phi^{-1}(1 - \alpha/2)]$$

## Example 2: Exponential distribution

$X$  has p.d.f.  $f(x) = \begin{cases} ce^{-cx} & x \geq 0 \\ 0 & x \leq 0 \end{cases}$ . Find the one sided CI of the form  $(0, A]$ .

LRT with  $H_0 : c = c_0$  and  $H_1 : c < c_0$ .

$$\frac{c_0 e^{-c_0 X}}{\sup_{c \leq c_0} ce^{-cX}} \leq k$$

If  $X \leq 1/c_0$  the LHS is 1, if  $X > 1/c_0$ , the optimal  $c$  in denominator is  $1/X$ , and we get

$$\log(c_0) - Xc_0 \leq \log(k) - \log(X) - 1$$

$$c_0 X - \log(X) \geq \log(c_0) + 1 - \log(k)$$

The LHS is an increasing function, so the test must be of the form  $X \geq M$ . If we want the significance level to be  $\alpha$ ,

$$\alpha = P(X \geq M | c = c_0) = \int_M^{\infty} f(s) ds$$

So  $M = -\log(\alpha)/c_0$ . The one sided CI is now

$$\{c : X \leq -\log(\alpha)/c\} = (0, -\log(\alpha)/X]$$



### Example 3: Making use of the $t$ -, $\chi^2$ -, $F$ - ... tests

Suppose there are 2 independent i.i.d. normal samples  $X_i$ ,  $i = 1, \dots, n_1$ ,  $Y_j$ ,  $j = 1, \dots, n_2$ , with variance  $\sigma_1^2$  and  $\sigma_2^2$  respectively. Want the one sided CI of  $\sigma_1^2/\sigma_2^2$  of the form  $(0, A]$ .  
 $H_0 : \sigma_1^2/\sigma_2^2 = r$ ,  $H_1 : \sigma_1^2/\sigma_2^2 < r$ . Let  $Y'_j = r^{1/2} Y_j$ , then the test is for  $\text{Var}(X_i) = \text{Var}(Y'_j)$  against  $\text{Var}(X_i) \leq \text{Var}(Y'_j)$ , use one sided F-test with significance level  $\alpha$  is:

$$S_X^2/S_{Y'}^2 = S_X^2/(rS_Y^2) \leq F_{F(n_1-1, n_2-1)}^{-1}(\alpha)$$

So CI with CL  $1 - \alpha$  is

$$\begin{aligned} \{r : S_X^2 / (r S_Y^2) \geq F_{F(n_1-1, n_2-1)}^{-1}(\alpha)\} \\ = (0, \frac{S_X^2}{S_Y^2 F_{F(n_1-1, n_2-1)}^{-1}(\alpha)}] \end{aligned}$$

In the textbook they used the relationship

$$F_{F(n_1-1, n_2-1)}^{-1}(\alpha) = (F_{F(n_2-1, n_1-1)}^{-1}(1 - \alpha))^{-1}$$

The CI for other tests are analogous.

## More approximated CI via CLT

When  $n_1 \gg 1$ ,  $n_2 \gg 1$ , CLT allow us to do normal approximation for the  $\chi^2$  distribution. This can also be used to derive approximated CI for the ratio of variance:

By definition,  $\chi^2(k)$  is the squared sum of  $k$  standard normal, so CLT tells us, if  $X \sim \chi^2(k)$ , when  $k \rightarrow \infty$ ,  $\frac{X-k}{\sqrt{2k}} \rightarrow$  standard normal.

$$\frac{(n_1 - 1)S_X^2}{\sigma_1^2} \sim \chi^2(n_1 - 1)$$

So

$$\frac{(n_1 - 1)(S_X^2 - \sigma_1^2)}{\sigma_1^2 \sqrt{2n_1 - 2}} \rightarrow \mathcal{N}(0, 1)$$

Similarly

$$\frac{(n_2 - 1)(S_Y^2 - \sigma_2^2)}{\sigma_2^2 \sqrt{2n_2 - 2}} \rightarrow \mathcal{N}(0, 1)$$

Hence the distribution of  $S_X^2 - rS_Y^2$  is approximately

$$\begin{aligned} & \mathcal{N}(\sigma_1^2 - r\sigma_2^2, \frac{2\sigma_1^4}{n_1 - 1} + \frac{2\sigma_2^4}{n_2 - 1}) \\ & \approx \mathcal{N}(\sigma_1^2 - r\sigma_2^2, \frac{2S_X^4}{n_1 - 1} + \frac{2r^2 S_Y^4}{n_2 - 1}) \end{aligned}$$

So the test is

$$S_X^2 - rS_Y^2 \leq \Phi^{-1}(1 - \alpha) \sqrt{\frac{2S_X^4}{n_1 - 1} + \frac{2r^2 S_Y^4}{n_2 - 1}}$$

You can now use this to get a corresponding approximated CI.  
Of course there are many other ways to get CI or, through CLT, approximated CI. Can you write down a few more?

# Linear Regression

Setting:  $x_1, \dots, x_n$  real numbers,  $Y_1, \dots, Y_n$  independent,  
 $Y_i \sim \mathcal{N}(cx_i, \sigma^2)$ . How do we estimate  $c$  and  $\sigma^2$ ?

## MLE for $c$ and $\sigma^2$

Likelihood function:

$$L = \prod_i f_{Y_i}(Y_i) = (2\pi\sigma^2)^{-n/2} e^{-\sum_i (Y_i - cx_i)^2 / (2\sigma^2)}$$

$$\log(L) = -\frac{n}{2}(\log(2\pi) + \log(\sigma^2)) - \frac{1}{2\sigma^2} \sum_i (Y_i - cx_i)^2$$

$$\frac{\partial}{\partial c} \log(L) = -\frac{1}{2\sigma^2} \sum_i (2x_i Y_i - 2cx_i^2)$$

$$\hat{c}_{MLE} = \frac{\sum_i x_i Y_i}{\sum_i x_i^2}$$

$$\frac{\partial}{\partial \sigma^2} \log(L) = -\frac{n}{2\sigma^2} + \frac{1}{2\sigma^4} \sum_i (Y_i - cx_i)^2$$

$$\hat{\sigma}^2_{MLE} = \frac{1}{n} \sum_i (Y_i - \hat{c}_{MLE} x_i)^2 = \frac{1}{n} \left( \sum_i Y_i^2 - \left( \sum_i x_i Y_i \right)^2 / \sum_i x_i^2 \right)$$