ST2132
AY23/24 SEM 1
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01. PROBABILITY

- **probability** of an event $\to$ the limiting relative frequency of its occurrence as the experiment is repeated many times
- the **realisation** x is a constant, and X is a generator
  - running r experiments gives us r realisations $x_1, \dots, x_r$

Expectation

discrete: (mass function)
$$E(X) := \sum_{i=1}^{n} x_i p_i$$

continuous: (density function)
$$E(X) := \int_{-\infty}^{\infty} x f(x)\, dx$$

expectation of a function $h(X)$

$$E\{h(X)\} = \begin{cases} \sum_{i=1}^{n} h(x_i) p_i & X \text{ is discrete} \\ \int_{-\infty}^{\infty} h(x) f(x)\, dx & X \text{ is continuous} \end{cases}$$

Variance

variance, $\mathrm{var}(X) := E\{(X-\mu)^2\}$
standard deviation, $SD(X) := \sqrt{\mathrm{var}(X)}$

- $\mathrm{var}(X) = E(X^2) - E(X)^2$
- $E(X - \mu) = 0$

Law of Large Numbers

mean and variance of r realisations:
$$\bar{x} := \frac{1}{r}\sum_{i=1}^{r} x_i \qquad v := \frac{1}{r}\sum_{i=1}^{r}(x_i - \bar{x})^2$$

LLN: for a function h, as $r \to \infty$,
$$\frac{1}{r}\sum_{i=1}^{r} h(x_i) \to E\{h(X)\}$$
$$\bar{x} \to E(X), \quad v \to \mathrm{var}(X)$$

Monte Carlo approximation

simulate $x_1, \dots, x_r$ from X. by LLN, as $r \to \infty$, the approximation becomes exact
$$E\{h(X)\} \approx \frac{1}{r}\sum_{i=1}^{r} h(x_i)$$

Joint Distribution

(**discrete**) mass function:
$$P(X = x_i, Y = y_j) = p_{ij}$$
(**continuous**) density function:
$$f : \mathbb{R}^2 \to [0, \infty), \int_{-\infty}^{\infty} f(x,y)\, dx\, dy = 1$$
(**expectation**) for $h : \mathbb{R}^2 \to \mathbb{R}$,
$$E\{h(X,Y)\} = \begin{cases} \sum_{i=1}^{I}\sum_{j=1}^{J} h(x_i, y_j) p_{ij} & X \text{ is discrete} \\ \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} h(x,y) f(x,y)\, dx\, dy & Y \text{ is continuous} \end{cases}$$

Algebra of RV's

let X, Y be RVs and a, b, c be constants
- $Z = aX + bY + c$ is also an RV
  - $z = ax + by + c$ is a realisation of Z
- linearity of expectation: $E(Z) = aE(X) + bE(Y) + c$
- any theorem about a RV is true about a constant

Covariance

let $\mu_X = E(X), \mu_Y = E(Y)$.

covariance, $\mathrm{cov}(X,Y) = E\{(X - \mu_X)(Y - \mu_Y)\}$
- $\mathrm{cov}(X,Y) = E(XY) - \mu_X \mu_Y$
- $\mathrm{cov}(X,Y) = \mathrm{cov}(Y,X)$
- $\mathrm{cov}(X,X) = \mathrm{var}(X)$
- $\mathrm{cov}(W, aX + bY + c) = a\,\mathrm{cov}(W,X) + b\,\mathrm{cov}(W,Y)$
- $\mathrm{var}(aX + bY + c) = a^2\,\mathrm{var}(X) + b^2\,\mathrm{var}(Y) + 2ab\,\mathrm{cov}(X,Y)$

joint $=$ marginal $\times$ conditional distributions

$$f(x,y) = f_X(x) f_Y(y|x) = f_Y(y) f_X(x|y), \quad x, y \in \mathbb{R}$$

- $f(x,y)$ is the *joint density*
- $f_X(x), f_Y(y)$ are the *marginal densities*
- $f_Y(\cdot|x)$ is the **conditional** density of Y given $X = x$
- $f_X(\cdot|y)$ is the **conditional** density of X given $Y = y$
- for discrete case, *density* $\equiv$ *probability*, $x \equiv x_i$, $y \equiv y_j$

Independence

- X, Y are independent $\iff \forall x, y \in \mathbb{R}$,
  1. $f(x,y) = f_X(x) f_Y(y)$
  2. $f_Y(y|x) = f_Y(y)$
  3. $f_X(x|y) = f_X(x)$
- X, Y are independent $\Rightarrow$
  - $E(XY) = E(X)E(Y)$
  - $\mathrm{cov}(X,Y) = 0$

  (the converse does not hold)

Conditional expectation

discrete case

let $f_Y(\cdot|x_i)$ be the conditional pmf of Y given $X = x_i$.
$$E[Y|x_i] := \sum_{j=1}^{J} y_j f_Y(y_j|x_i)$$
$$\mathrm{var}[Y|x_i] := \sum_{j=1}^{J} (y_j - E[Y|x_i])^2 f_Y(y_j|x_i)$$

$E[Y|x_i]$ is like $E(Y)$, with conditional distribution replacing marginal distribution $f_Y(\cdot)$. likewise, $\mathrm{var}[Y|x_i]$ like $\mathrm{var}(Y)$.

continuous case

$$E[Y|x] := \int_{-\infty}^{\infty} y f_Y(y|x)\, dy$$
$$\mathrm{var}[Y|x] := \int_{-\infty}^{\infty} (y - E[Y|x])^2 f_Y(y|x)\, dy = E(Y^2|x) - \{E(Y|x)\}^2$$

Distributions

if X is iid with expectation μ, SD σ and $S_n = \sum_{i=1}^{n} X_i$,
- $E(S_n) = n\mu$
- $SD(S_n) = \sqrt{n}\sigma$
- variance of sum = sum of variances
  $\mathrm{var}(\sum_{i=1}^{n} X_i) = \sum_{i=1}^{n} \mathrm{var}(x_i)$

bernoulli

$X \sim Bernoulli(p) \quad \Rightarrow$ coin flip with probability p
$$E(X_i) = p \qquad \mathrm{var}(X_i) = p(1-p)$$
$$E(S_n) = np \qquad \mathrm{var}(S_n) = np(1-p)$$

binomial

$X \sim Bin(n,p) \quad \Rightarrow X_i \overset{i.i.d.}{\sim} Bernoulli(p)$
$$E(X) = np, \quad \mathrm{var}(X) = np(1-p)$$
$$E(X) = \sum_{k=1}^{n} k \binom{n}{k} p^k (1-p)^{n-k}$$

multinomial

$X \sim Multinomial(n, \mathbf{p})$
- for k outcomes $E_1, \dots, E_k$, $Pr(E_i) = p_i$. For some $1 \le i \le k$, E_i occurs X_i times in n runs.

$(X_1, \dots, X_k)$ has the **multinomial distribution:**
$$Pr(X_1 = x_1, \dots, X_k = x_k) = \binom{n}{x_1 \dots x_k} \Pi_{i=1}^{k} p_i^{x_i}$$
- where $\binom{n}{x_1 \dots x_k} = \frac{n!}{x_1! x_2! \dots x_k!}$
  - combinatorially, # of arrangements of $x_1, \dots, x_k$
  - $\sum_{i=1}^{n} x_i = n, \quad x_i \ge 0$

$$E(X) = \begin{bmatrix} np_1 \\ np_2 \\ \vdots \\ np_k \end{bmatrix}, \quad \mathrm{var}(X_i) = np_i(1-p_i)$$
$\mathrm{var}(X) =$ *covariance matrix* M with
$$m_{ij} = \begin{cases} \mathrm{var}(X_i) & \text{if } i = j \\ \mathrm{cov}(X_i, X_j) & \text{if } i \ne j \end{cases}$$
- $\mathrm{cov}(X_i, X_j) < 0$
- $X_i \sim Bin(n, p_i)$
- $X_i + X_j \sim Bin(n, p_i + p_j)$

02. PROBABILITY (2)

Mean Square Error (MSE)

$$MSE = E\{(Y-c)^2\}$$
- predicting Y:
  $MSE = \mathrm{var}(Y) + \{E(Y) - c\}^2$
  - min $MSE = \mathrm{var}(Y)$ when $c = E(Y)$
- Y and X are correlated:
  $MSE = \mathrm{var}[Y|x] + \{E[Y|x] - c\}^2$
  $MSE = E[(Y-c)^2|x] = E[\{Y - E(Y)\}^2|x]$
  - min $MSE = \mathrm{var}(Y|x)$ when $c = E[Y|x]$
  - if $c = E(Y)$ instead of $E(Y|x) \Rightarrow$ the MSE increases by $(E(Y|x) - E(Y))^2$

mean MSE

$$\frac{1}{n}\sum_{i=1}^{n} \mathrm{var}[Y|x_i] \approx E\{\mathrm{var}[Y|X]\}$$

random conditional expectations

let X, Y be r.v.s.
- $E[Y|X]$ is a r.v. which takes value $E[Y|x]$ with probability/density $f_X(x)$
- $\mathrm{var}[Y|X]$ is a r.v. which takes value $\mathrm{var}[Y|x]$ with probability/density $f_X(x)$

$$E(E[X_2|X_1]) = E(X_2)$$
$$\mathrm{var}(E[X_2|X_1]) + E(\mathrm{var}[X_2|X_1]) = \mathrm{var}(X_2)$$

CDF (cumulative distribution function)

for r.v. X, let $F(x) = P(X \le x)$
- domain: $\mathbb{R}$; codomain: $[0,1]$

$$F(x) = \int_{-\infty}^{\infty} f(x)\, dx$$

Standard Normal Distribution

$Z \sim N(0,1)$ has density function
$$\phi(z) = \frac{1}{\sqrt{2\pi}} \exp\{-\frac{z^2}{2}\}, \quad -\infty < z < \infty$$
$$E(Z) = 0, \quad \mathrm{var}(Z) = 1$$
CDF, $\Phi(x) = P(Z \le x) = \int_{-\infty}^{x} \phi(z)\, dz$
- $E(Z) = \int_{-\infty}^{\infty} z\phi(z)\, dz = 0$
  - $E(Z^2) = \int_{-\infty}^{\infty} z^2 \phi(z)\, dz = 1$
  - $E(Z^{2k+1}) = 0 \quad \forall k \in \mathbb{Z}_{\ge 0}$

general normal distribution

let $X \sim N(\mu, \sigma^2)$ and $Y \sim N(\nu, \tau^2)$

standardisation: $\frac{X - \mu}{\sigma} \sim N(0,1)$
- summations:
  - for constants $a, b \ne 0$,
    $a + bX \sim N(a + b\mu,\ b^2\sigma^2)$
  - $X + Y \sim N(\mu + \nu,\ \sigma^2 + \tau^2 + 2\,\mathrm{cov}(X,Y))$
    - $\mathrm{cov}(X,Y) = 0, \quad \Rightarrow \quad X \perp Y$
    - $X \perp Y \quad \Rightarrow \quad X + Y \sim N(\mu + \nu,\ \sigma^2 + \tau^2)$
- for $W = a + bX$,
  - density, $f_W(w) = \frac{d}{dw} F_W(w)$
  - CDF, $\quad F_W(w) = P(X \le \frac{w-a}{b}) = \Phi(\frac{w-a}{b})$

Central Limit Theorem

let $X_1, \dots, X_n$ be iid rv's with expectation μ and SD σ, with $S_n = \sum_{i=1}^{n} X_i$

CLT
as $n \to \infty$, the distribution of the standardised $S_n = \frac{S_n - n\mu}{\sqrt{n}\sigma}$ converges to $N(0,1)$
- $E(S_n) = n\mu$, $\mathrm{var}(S_n) = n\sigma^2$
- for large n, approximately $S_n \sim N(n\mu, n\sigma^2)$

bernoulli

let $X_i \sim Bernoulli(p)$. then $S_n \sim Binom(n, p)$
- for large n, $S_n = N(np, np(1-p))$
- CLT: standardised $\frac{S_n - np}{\sqrt{n}\sqrt{p(1-p)}} \to N(0,1)$ as $n \to \infty$

Distributions

chi-square (χ^2)

let $Z \sim N(0,1)$. $\Rightarrow$ then $Z^2 \sim \chi^2_1$
- Z^2 has χ^2 distribution with 1 degree of freedom
- degrees of freedom = number of RVs in the sum

$$E(Z^2) = 1, \quad E(Z^4) = 3$$
$$\mathrm{var}(Z^2) = E(Z^4) - \{E(Z^2)\}^2 = 2$$

let $V_1, \dots, V_n$ be iid χ^2_1 RVs and $V = \sum_{i=1}^n V_i$. then
$$V \sim \chi^2_n$$
$$E(V) = n \quad \mathrm{var}(V) = 2n$$

gamma

let $\alpha, \lambda > 0$. The $Gamma(\alpha, \lambda)$ density is
$$\frac{\lambda^\alpha}{\Gamma(\alpha)} x^{\alpha-1} e^{-\lambda x}, \quad x > 0$$
where $\Gamma(\alpha)$ is a number that makes density integrate to 1
- χ^2_n RV $\sim Gamma(\frac{n}{2}, \frac{1}{2})$
  - χ^2_n is a special case of Gamma!
  - density of χ^2_1 RV $= \frac{1}{\sqrt{2\pi}} v^{-1/2} e^{-v/2}, \quad v > 0$ $= Gamma(\frac{1}{2}, \frac{1}{2})$
- if $X_1 \sim Gamma(\alpha_1, \lambda)$ and $X_2 \sim Gamma(\alpha_2, \lambda)$ are independent, then $X_1 + X_2 \sim Gamma(\alpha_1 + \alpha_2, \lambda)$

t distribution

let $Z \sim N(0,1)$ and $V \sim \chi^2_n$ be independent.
$$\frac{Z}{\sqrt{V/n}} \sim t_n$$
has a t distribution with n degrees of freedom.
- t distribution is symmetric around 0
- $t_n \to Z$ as $n \to \infty$ (because $\frac{V}{n} \to 1$)

F distribution

let $V \sim \chi^2_m$ and $W \sim \chi^2_n$ be independent.
$$\frac{V/m}{W/n} \sim F_{m,n}$$
has an F distribution with (m, n) degrees of freedom.
- even if $m = n$, still two RVs V, W as they are independent
- for $T \sim t_n$, $T^2 = \frac{Z^2}{V/n} \sim F_{1,n}$

IID Random Variables

let $X_1, \dots, X_n$ be iid RVs with mean $\bar{X}$.
$$\textbf{sample variance}, S^2 = \frac{1}{n-1} \sum_{i=1}^n (X_i - \bar{X})^2$$
S is an estimate of σ

let $X_1, \dots, X_n$ be iid $N(\mu, \sigma^2)$. $\bar{X} = \frac{1}{n} \sum_{i=1}^n X_i$.
$$\bar{X} \sim N(\mu, \frac{\sigma^2}{n})$$
$$E(\bar{X}) = \mu, \quad \mathrm{var}(\bar{X}) = \frac{\sigma^2}{n}$$
more distributions:
$$\frac{\bar{X}-\mu}{\sigma/\sqrt{n}} \sim N(0,1)$$
$$\frac{(n-1)S^2}{\sigma^2} \sim \chi^2_{n-1}$$
$$\frac{\bar{X}-\mu}{S/\sqrt{n}} \sim t_{n-1}$$
- $\bar{X}$ and S^2 are independent

Multivariate Normal Distribution

let $\boldsymbol{\mu}$ be a $k \times 1$ vector and $\boldsymbol{\Sigma}$ be a *positive-definite* symmetric $k \times k$ matrix.

the random vector $\boldsymbol{X} = (X_1, \dots, X_k)'$ has a multivariate normal distribution $N(\boldsymbol{\mu}, \boldsymbol{\Sigma})$ if its density function is
$$\frac{1}{(2\pi)^{k/2}\sqrt{det\boldsymbol{\Sigma}}} \exp\left(-\frac{(\boldsymbol{x}-\boldsymbol{\mu})'\boldsymbol{\Sigma}^{-1}(\boldsymbol{x}-\boldsymbol{\mu})}{2}\right)$$
- $E(\boldsymbol{X}) = \boldsymbol{\mu}, \quad \mathrm{var}(\boldsymbol{X}) = \boldsymbol{\Sigma}$
- for any non-zero $k \times 1$ vector $\boldsymbol{a}$,
$$\boldsymbol{a}'\boldsymbol{X} \sim N(\boldsymbol{a}'\boldsymbol{\mu}, \boldsymbol{a}'\boldsymbol{\Sigma}\boldsymbol{a})$$
  - $\boldsymbol{a}'\boldsymbol{\Sigma}\boldsymbol{a} > 0$ because $\boldsymbol{\Sigma}$ is positive-definite
  - the product $\boldsymbol{a}'\boldsymbol{X}$ is a scalar (same for $\boldsymbol{a}'\boldsymbol{\mu}, \boldsymbol{a}'\boldsymbol{\Sigma}\boldsymbol{a}$)
- two multinomial normal random vectors $\boldsymbol{X}_1$ and $\boldsymbol{X}_2$, sizes h and k, are independent if $\mathrm{cov}(\boldsymbol{X}_1, \boldsymbol{X}_2) = \boldsymbol{0}_{h \times k}$
  - $(X_1 - \bar{X}, \dots, X_n - \bar{X})$ has a multivariate normal distribution; the covariance between $\bar{X}$ and $(X_1 - \bar{X}, \dots, X_n - \bar{X})$ is 0, thus they are independent

03. POINT ESTIMATION

for a variable v in population N,
$$\mu = \frac{1}{N} \sum_{i=1}^N v_i \qquad \sigma^2 = \frac{1}{N} \sum_{i=1}^N (v_i - \mu)^2$$
- μ, σ^2 are **parameters** (unknown constants)
- a **simple random sample** is used to estimate parameters: individuals drawn from the population at random without replacement

binary variable

for variable v with proportion p in the population,
$$\mu = p, \qquad \sigma^2 = p(1-p)$$

single random draw

for variable v (population of size N, mean μ, variance σ^2), let X be the chosen v-value.
$$E(X) = \mu, \qquad \mathrm{var}(X) = \sigma^2$$

draws with replacement

let $X_1, \dots, X_n$ be random draws with replacement from a population of mean μ and variance σ^2.
$$\text{random sample mean}, \bar{X} = \frac{1}{n} \sum_{i=1}^n X_i$$
$$X_1, \dots, X_n \text{ are iid with } E(X_i) = \mu, \mathrm{var}(X_i) = \sigma^2$$
$$E(\bar{X}) = TODO, \mathrm{var}(\bar{X}) = TODO$$
let $x_1, \dots, x_n$ be realisations of n random draws with replacement from the population.
$$\text{sample mean}, \bar{x} = \frac{1}{n} \sum_{i=1}^n x_i$$
- as $n \to \infty$, $\bar{x} \to \mu$ (LLN)
- sample distribution, x_i has the same distribution as X_i and the population distribution

representativeness

- $X_1, \dots, X_n$ is **representative** of the population
  - as n gets larger, $\bar{X}$ gets closer to μ
- $x_1, \dots, x_n$ are *likely* representative of the population

estimating mean

given data $x_1, \dots, x_n$,
- sample mean, $\bar{x} = \frac{1}{n} \sum_{i=1}^n x_i$ is an **estimate** of μ
- the error in $\bar{x}$ is $\mu - \bar{x}$; it cannot be estimated
- $\bar{x}$ is a realisation of the **estimator** $\bar{X}$
  - this realisation is used to estimate μ

standard error

the size of error in estimate $\bar{x}$ is roughly $SD(\bar{X}) = \frac{\sigma}{\sqrt{n}}$

the **standard error** (SE) in $\bar{x}$ is $\frac{\sigma}{\sqrt{n}}$
- SE is a constant by definition: $SE = SD(\hat{X}) = \frac{\sigma}{\sqrt{n}}$

estimating σ

intuitive estimate of σ^2, $\hat{\sigma}^2 = \frac{1}{n} \sum_{i=1}^n (x_i - \bar{x})^2$
$$\text{sample variance}, s^2 = \frac{1}{n-1} \sum_{i=1}^n (x_i - \bar{x})^2$$
$$E(s^2) = \sigma^2$$