

STAT 240

Personal Notes

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Chapter 1: What is Probability?

RANDOM EXPERIMENTS (1.1)

A "random experiment" is the process of obtaining a random observed result.

Random experiments can be split into two types:

① Controlled experiments; and

eg flipping a coin, rolling a die

② Observational studies.

eg # of students taking STAT 240 in F2021

FEATURES OF RANDOM EXPERIMENTS

Note that random experiments have the following common features:

- ① The outcomes/results cannot be predicted with certainty; and
- ② All the possible outcomes are known beforehand with certainty.

SAMPLE SPACE (1.2)

OUTCOME

An "outcome" is an observed result of interest from a random experiment.

eg the number rolled after rolling a die.

SAMPLE SPACE

The "sample space" of a random experiment is the set of all possible distinct outcomes of said experiment.

eg when rolling a 6-sided die:

$$S = \{1, 2, 3, 4, 5, 6\}$$

EVENTS

An "event" of a random experiment is a group or set of outcomes of said experiment; ie subsets of the sample space.

There are two types of events:

① Simple events - consist of one outcome

eg rolling a 1 on a 6-sided die:

$$S = \{1, \dots, 6\} \quad E = \{1\}$$

② Compound events - consist of multiple outcomes

eg rolling an odd number on a 6-sided die:

$$S = \{1, \dots, 6\} \quad E = \{1, 3, 5\}$$

Note that

① Two simple events will never occur simultaneously; eg can never roll a 1 & 3 at the same time with one die.

② A compound event occurs if and only if one of its simple events occurs; and
eg odd # rolled \Leftrightarrow 1 rolled or 3 rolled or 5 rolled (on a 6-sided die)

③ Two compound events can occur simultaneously.
eg 3 rolled \Rightarrow {odd number rolled ($E = \{1, 3, 5\}$) and multiple of 3 rolled ($E = \{3, 6\}$)}

DEFINITIONS OF PROBABILITY (1.3)

💡 "Probability" is a quantitative measure of how likely an event is to occur.

CLASSICAL DEFINITION

💡 The "classical definition" of probability states that each distinct outcome in the sample space is equally likely to occur.

💡 In this case, the probability of an event E is equal to

eg roll a 6-sided die once.

E = number is odd.

$$\Rightarrow E = \{1, 3, 5\}, \quad S = \{1, 2, 3, 4, 5, 6\}.$$

$$\text{So } P(E) = \frac{3}{6} = \frac{1}{2}.$$

RELATIVE FREQUENCY DEFINITION

💡 The "relative frequency" definition of probability states that the probability of an event occurring is the proportion it occurs in a very long series of repetitions of the experiment.

eg rolling a 6-sided die 300 times

\Rightarrow 3 shows up 49 of those 300 times

\Rightarrow so $P(\text{die}=3) \approx \frac{49}{300} \approx \frac{1}{6}$.

SUBJECTIVE PROBABILITY DEFINITION

💡 In the "subjective probability" definition of probability, the probability of an event is determined by an opinion (ie what a person thinks the probability is).

eg the probability of COVID-19 being eradicated by 2022.

💡 Note that this plays a role in fields like "Bayesian Statistics".

DISCRETE PROBABILITY MODELS (1.4)

💡 In discrete probability models:

- ① The sample space S satisfies $|S| \leq |\mathbb{N}|$; ie there are either a finite or countably infinite number of basic events; and
- ② Each probability p_i satisfies $0 \leq p_i \leq 1$; and
- ③ The probabilities of each basic event sum to 1; ie $\sum p_i = 1$.

CLASSIC DISCRETE MODELS (1.5)

💡 In classic discrete models:

- ① The sample space S satisfies $|S| < |\mathbb{N}|$ (ie it is finite); and
- ② All basic events are equally likely to occur;
ie $P(a_1) = \dots = P(a_{|S|}) = \frac{1}{|S|}$.

Chapter 2: Counting Techniques

FULL FACTORIAL: $n!$ (2.1)

💡 The factorial of n , denoted as " $n!$ " and defined to be

$$n! = n(n-1) \dots 1$$

is the number of ways to put n distinguishable objects in a row.

COMBINATIONS: C_n^r OR ${}^n C_r$ (2.2)

💡 " n choose r ", denoted as " C_n^r " or " ${}^n C_r$ ", defined to be

$$C_n^r = \frac{n!}{r!(n-r)!} = \frac{n(n-1) \dots (n-(r-1))}{r!}$$

is the number of ways to select r objects from n distinguishable objects.

PERMUTATIONS: P_n^r OR ${}^n P_r$ (2.3)

💡 " P_n^r " or " ${}^n P_r$ ", defined to be

$$P_n^r = \frac{n!}{(n-r)!} = n(n-1) \dots (n-(r-1)) = C_r^n \cdot r!$$

is the number of ways to select r objects from n distinguishable objects and put them in a row.

GENERALIZATION OF COMBINATIONS (2.4)

💡 we can show the number of ways to arrange n objects in a row, where n_1 objects are of type 1, n_2 objects are of type 2, ..., n_k objects are of type k , where $n_1 + n_2 + \dots + n_k = n$, is

$$\# \text{ of outcomes} = \frac{n!}{n_1! \dots n_k!} = C_n^{n_1} C_{n-n_1}^{n_2} C_{n-n_1-n_2}^{n_3} \dots C_{n_{k-1}+n_k}^{n_k} C_{n_k}^{n_k}$$

eg Roll a die 4 times. Find $P(\text{the sum}=10)$.

Soln. This is equivalent to distributing 10 balls into 4 sections, where each section has at least 1 ball.



9 different spaces for the "dividers", 4 "dividers"

$\Rightarrow C_9^4$ ways of "positioning" the dividers.

But, we exclude the option where one of the sections has 7 balls, ie

$$C_9^4 - 4$$

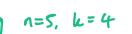
Hence $P(\text{event}) = \frac{C_9^4 - 4}{6^4}$, since there are 6^4 outcomes of rolling a 6 sided die twice. \blacksquare

STARS & BARS WITHOUT "EMPTY" SECTIONS

💡 Given n stars, the # of ways to divide them up into k sections with $k-1$ rods without one of the sections containing zero elements is

$$\# = C_{k-1}^{n-1}$$

eg $n=5, k=4$



STARS & BARS WITH "EMPTY" SECTIONS

💡 Given n stars, the # of ways to divide them up into k sections with $k-1$ rods with one (or more) sections containing zero elements is

$$\# = C_{n+k-1}^{k-1}$$



eg $n=5, k=4$

2nd section has no elements.

Chapter 3: Probability Rules

RELATIONS AMONGST EVENTS

(3.1)

EVERY EVENT $\subseteq S$ (THE "CERTAIN" EVENT)

Let A be an event.

Then necessarily

$A \subseteq S = \{\text{the event that always occurs}\}$.

\emptyset (THE "IMPOSSIBLE" EVENT)

We use " \emptyset " to denote the event that never occurs.

UNION OF EVENTS: $A \cup B$

Let A, B be events.

Then " $A \cup B$ " is the event that at least one of the two occurs.



INTERSECTION OF EVENTS: $A \cap B$

Let A, B be events.

Then, " $A \cap B$ " is the event that both A & B occur.

We also denote $A \cap B = AB$.



MUTUALLY EXCLUSIVE / DISJOINT

Let A, B be events.

Then, we say A & B are "mutually exclusive" (or "disjoint") if $A \cap B = \emptyset$.

INCLUSION: $A \subseteq B$

Let A, B be events.

Then, we say " $A \subseteq B$ " if B occurs whenever A occurs; ie

A occurs $\Rightarrow B$ occurs.

COMPLEMENT: $A^c = \bar{A}$

Let A be an event.

Then, \bar{A} is the event such that \bar{A} occurs $\Leftrightarrow A$ does not occur.

PARTITION OF S

Let B_1, \dots, B_n be events.

Then, we say B_1, \dots, B_n form a "partition" of S if

$$B_1 \cup \dots \cup B_n = S \quad \& \quad B_i \cap B_j = \emptyset \quad \forall i \neq j.$$

PROBABILITY RULES (3.2)

A probability function $P: P(S) \rightarrow [0, 1]$ is any function that satisfies the following for any $A, B \subseteq S$:

- ① $P(\emptyset) = 0$;
- ② $P(S) = 1$;
- ③ $P(A) \geq 0 \quad \forall A \subseteq S$;
- ④ $A \subseteq B \Rightarrow P(A) \leq P(B)$;
- ⑤ $P(A \cup B) = P(A) + P(B) - P(A \cap B)$; & (addition law of probability)
- this generalizes to more variables as well.
- ⑥ $P(A^c) = 1 - P(A)$.

Chapter 4: Conditional Probability and Event Independence

CONDITIONAL PROBABILITY (4.1)

💡 Let A, B be events.
 Then, the probability that A happens given B already happens, denoted as " $P(A|B)$ ", is equal to

$$P(A|B) = \frac{P(A \cap B)}{P(B)}.$$

* note $P(B) \neq 0$ necessarily.

INDEPENDENCE [OF TWO EVENTS] (4.2)

💡 Let A, B be events.
 Then, we say A & B are "independent" if and only if

$$P(A \cap B) = P(A)P(B).$$

💡 Note that if $P(A), P(B) \neq 0$, then A & B cannot be mutually exclusive (ie $P(A \cap B) = 0$) if they are independent.

💡 If A & B are independent, then

- ① A & B^c are independent;
- ② A^c & B are independent; and
- ③ A^c & B^c are independent.

💡 Note that independence arises from independent random events.

INDEPENDENCE [OF > 2 EVENTS] (4.3)

💡 Let A_1, \dots, A_n be n events.
 Then, we say A_1, \dots, A_n are (mutually) independent if

$$P(A_{n_1} A_{n_2} \dots A_{n_k}) = P(A_{n_1}) \dots P(A_{n_k}) \quad \forall \{n_1, \dots, n_k\} \in \binom{\{1, \dots, n\}}{k}.$$

💡 For the $n=3$ case, A_1, A_2 & A_3 are independent if

- ① $P(A_1 A_2) = P(A_1)P(A_2);$
- ② $P(A_1 A_3) = P(A_1)P(A_3);$
- ③ $P(A_2 A_3) = P(A_2)P(A_3);$ and
- ④ $P(A_1 A_2 A_3) = P(A_1)P(A_2)P(A_3).$

A_1, \dots, A_n ARE INDEPENDENT $\Rightarrow P(\prod_{i=1}^n A_i) = \prod_{i=1}^n P(A_i | A_1 \dots A_{i-1})$

(THE MULTIPLICATION FORMULA) (4.4.1)

💡 Let A_1, \dots, A_n be independent events.

Then necessarily

$$P(A_1 \dots A_n) = P(A_1)P(A_2 | A_1)P(A_3 | A_1 A_2) \dots P(A_n | A_1 \dots A_{n-1}).$$

Proof. Note that for any $k=1, \dots, n$, we have

$$P(A_k | A_1 \dots A_{k-1}) = \frac{P(A_1 \dots A_{k-1} A_k)}{P(A_1 \dots A_{k-1})} = P(A_k).$$

The proof follows trivially. \square

A_1, \dots, A_n PARTITION $S \Rightarrow P(B) = \sum_{i=1}^{\infty} P(A_i)P(B | A_i)$

(TOTAL PROBABILITY FORMULA) (4.4.2)

💡 Let A_1, A_2, \dots form a partition of S , ie we have that

$$A_i A_j = \emptyset \quad \forall i \neq j \quad \text{and} \quad \bigcup_{i=1}^{\infty} A_i = S.$$

Let B be an event. Then necessarily

$$P(B) = P(BS) = \sum_{i=1}^{\infty} P(A_i B) = \sum_{i=1}^{\infty} P(A_i)P(B | A_i).$$

* this also works for finite collections of events as well.

A_1, \dots, A_n PARTITION $S \Rightarrow$

$$P(A_i | B) = \frac{P(A_i)P(B | A_i)}{\sum_{j=1}^{\infty} P(A_j)P(B | A_j)}$$

(THE BAYES FORMULA) (4.4.3)

💡 Let A_1, A_2, \dots form a partition of S , and let B be such that $P(B) \neq 0$.

Then necessarily, for any $i \in \mathbb{N}$, we have that

$$P(A_i | B) = \frac{P(A_i B)}{P(B)} = \frac{P(A_i)P(B | A_i)}{P(B)} = \frac{\sum_{j=1}^{\infty} P(A_j)P(B | A_j)}{P(B)}.$$

* again, this also generalises to the finite case.

Chapter 5:

Discrete Random Variables and Probability Models

RANDOM VARIABLES (5.1)

RANDOM VARIABLE (RV) (5.1)

Let S be a sample space.

Then, a "random variable" is defined to be some $X: S \rightarrow \mathbb{R}$.

Note that we usually denote random variables by capital letters. (e.g. X, Y, Z , etc.)

DISCRETE [r.v.]

Let $X: S \rightarrow \mathbb{R}$ be a r.v.
Then, we say X is "discrete" if $\text{range}(X) \subseteq \mathbb{N}$.

PROBABILITY MASS FUNCTION (PMF)

Let $X: S \rightarrow \mathbb{R}$ be a r.v.

Then, the "probability mass function" (or pmf) of X is defined to be the function $f: \text{range}(X) \rightarrow [0, 1]$ by $f(x) = P[X=x] \quad \forall x \in \text{range}(X)$.

By construction of f , note that $\sum_{x \in \text{range}(X)} f(x) = 1$.

CUMULATIVE DISTRIBUTION FUNCTION (CDF)

Let $X: S \rightarrow \mathbb{R}$ be a r.v.

Then, the "cumulative distribution function" (or cdf) of X is defined to be the function $F: \mathbb{R} \rightarrow [0, 1]$ by $F(x) = P[X \leq x] \quad \forall x \in \mathbb{R}$.

Properties of cdf:
 ① $F(x_1) \leq F(x_2) \Leftrightarrow x_1 \leq x_2 \quad \forall x_1, x_2 \in \mathbb{R}$; and
 ② $\lim_{x \rightarrow -\infty} F(x) = 0$ & $\lim_{x \rightarrow \infty} F(x) = 1$.

PMF CAN BE OBTAINED BY CDF, AND VICE VERSA

Let $X: S \rightarrow \mathbb{R}$ be discrete.

Then, given the pmf f of X , we can obtain X 's cdf F , and vice versa.

Proof. Let $x \in \text{range}(X)$. See that $f(x) = P[X=x] = P[X \leq x] - P[X \leq x-\epsilon] = F(x) - F(x-\epsilon)$, where $\epsilon > 0$ is such that $\text{range}(X) \cap [x-\epsilon, x] = \{x\}$. (Since X is discrete, such an ϵ will exist.)

FINDING PMF (E1)

Let X be the number of heads after flipping a fair coin n times.

Find the pmf of X .

Solⁿ. See that $\text{range}(X) = \{0, 1, \dots, n\}$.

Then

$$P[X=k] = C_n^k \left(\frac{1}{2}\right)^k \left(\frac{1}{2}\right)^{n-k} = C_n^k \left(\frac{1}{2}\right)^n$$

and so the pmf of X is $f: \{0, \dots, n\} \rightarrow [0, 1]$ given by

$$f(k) = P[X=k] = C_n^k \left(\frac{1}{2}\right)^n \quad \forall k=0, \dots, n.$$

BERNOULLI TRIALS & RELATED RV (5.2)

BERNOULLI TRIALS (5.2.1)

A "Bernoulli trial" focuses on a particular random experiment with only two possible outcomes: success or failure.

We call the random variables and the experiment obtained from Bernoulli trials as "Bernoulli random variables" and a "Bernoulli experiment" respectively.

BERNOULLI RV (5.2.2)

In particular, if B is a Bernoulli rv:

① then $P[B=\text{Success}]$, or $P(B)$, is equal to $P(B) = p$ (where p = probability of success); and

② $P[B=\text{Failure}]$, or $P(B^c)$, is equal to $P(B^c) = 1-p$.

Thus, the pmf of B is

$$f: \{0, 1\} \rightarrow [0, 1] \text{ by } f(0) = 1-p \text{ & } f(1) = p,$$

or equivalently by

$$f(x) = p^x (1-p)^{1-x} \quad \forall x \in \{0, 1\}.$$

BERNOULLI SEQUENCE (5.2.3)

A "Bernoulli sequence" occurs when

- ① we repeat a Bernoulli trial many times;
- ② the results are all independent; and
- ③ the success probability p stays the same.

BINOMIAL DISTRIBUTION: $X \sim \text{Binomial}(n, p)$ / $X \sim \text{Bin}(n, p)$ (5.2.4)

Let X be the rv equal to the number of successes after repeating a Bernoulli trial n times independently, with probability of success p .

Then, we say X follows a binomial distribution, and write $X \sim \text{Binomial}(n, p)$.

In this case, the pmf of X is equal to

$$f: \{0, \dots, n\} \rightarrow [0, 1] \text{ by } f(k) = C_n^k p^k (1-p)^{n-k} \quad \forall k \in \mathbb{N}.$$

GEOMETRIC DISTRIBUTION: $X \sim \text{Geometric}(p)$ / $X \sim \text{Geo}(p)$ (5.2.5)

Repeat independent Bernoulli trials, with success probability p , until a trial is successful.

Let the rv X be equal to the number of failures before the success was reached.

Then, we say X follows a geometric distribution, and write $X \sim \text{Geometric}(p)$.

In this case, the pmf of X is equal to

$$f: \mathbb{N} \rightarrow [0, 1] \text{ by } f(k) = (1-p)^k p \quad \forall k \in \mathbb{N}.$$

Note that $P(X \geq n) = (1-p)^n$ $\forall n \in \mathbb{N}$; and

$$\text{Proof. } P(X \geq n) = \sum_{k=n}^{\infty} (1-p)^k p = (1-p)^n p \sum_{k=0}^{\infty} (1-p)^k = (1-p)^n p \left(\frac{1}{1-(1-p)}\right) = (1-p)^n.$$

$$\text{② } P(X \geq m+n | X \geq n) = P(X \geq m) \quad \forall m, n \in \mathbb{N} \quad (\text{the memory-less property}).$$

$$\text{Proof. } P(X \geq m+n | X \geq n) = \frac{P(X \geq m+n \cap X \geq n)}{P(X \geq n)} = \frac{P(X \geq m+n)}{P(X \geq n)} = \frac{(1-p)^{m+n}}{(1-p)^n} = (1-p)^m = P(X \geq m).$$

NEGATIVE BINOMIAL DISTRIBUTION:

$X \sim \text{Negative Binomial}(k, p) / X \sim \text{NB}(k, p)$ (5.2.6)

- Repeat independent Bernoulli trials, with success probability p , until the k^{th} success is reached.
- Let the rv X be the number of failures before the k^{th} success.

Then, we say X follows a negative binomial distribution, and write $X \sim \text{Negative Binomial}(k, p)$.

In this case, the pmf of X is equal to

$$f: N \rightarrow [0, 1] \text{ by } f(n) = C_{n+k-1}^n p^k (1-p)^n \quad \forall n \in N.$$

Proof. See that

$$\begin{aligned} P[X=n] &= P[\text{having } n \text{ failures before } k^{\text{th}} \text{ success}] \\ &= P[n \text{ failures \& } k-1 \text{ successes, followed by } k^{\text{th}} \text{ success}] \\ &= \frac{(n+k-1)!}{n!(k-1)!} (1-p)^n p^{k-1}. \\ \therefore P[X=n] &= C_{n+k-1}^n (1-p)^n p^k. \end{aligned}$$

HYPERGEOMETRIC DISTRIBUTION:

$X \sim \text{Hypergeometric}(N, M, n) / X \sim \text{Hyp}(N, M, n)$ (5.3)

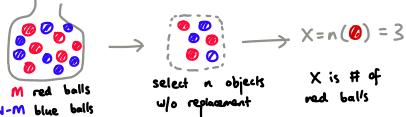
- Suppose we have a collection of N objects; M of one type, and $N-M$ of another (distinct) type.

Randomly select n objects without replacement, where $n \leq \min\{M, N-M\}$.

Let the rv X be the number of objects of the first type in these n objects.

Then, we say X follows a "hypergeometric distribution", and write

$$X \sim \text{Hypergeometric}(N, M, n).$$



In this case, the pmf of X is equal to

$$f: \{0, \dots, n\} \rightarrow [0, 1] \text{ by } f(k) = \frac{\binom{M}{k} \binom{N-M}{n-k}}{\binom{N}{n}} \quad \forall k=0, \dots, n.$$

VANDERMONDE'S IDENTITY: $\sum_{k=0}^n \binom{M}{k} \binom{N-M}{n-k} = \binom{N}{n}$

Let $n \leq M, N-M$.

Then necessarily

$$\binom{N}{n} = \sum_{k=0}^n \binom{M}{k} \binom{N-M}{n-k}.$$

POISSON DISTRIBUTION:

$X \sim \text{Poisson}(\lambda) / X \sim \text{Poi}(\lambda)$ (5.4)

- In some observational studies, events happen over time or space.

We say such an event follows a Poisson process if the following conditions are satisfied:

- Events in non-overlapping time intervals are independent; $\left\{ \text{independence} \right\}$
- $P[\geq 2 \text{ events in } [t, t+\Delta t]] = o(\Delta t)$, where $\left\{ \text{individuality} \right\}$
- $\lim_{\Delta t \rightarrow 0} \frac{o(\Delta t)}{\Delta t} = 0$ and $\Delta t \ll t$; and
- $P[\text{one event in } [t, t+\Delta t]] = \lambda \Delta t + o(\Delta t)$, $\lambda \in \mathbb{R}$. $\left\{ \text{homogeneity} \right\}$

Note that we call " λ " in ③ the "intensity parameter".

- Let the rv X be the number of events in $[0, t]$.

Then we say X follows a Poisson distribution, and write

$$X \sim \text{Poisson}(\lambda).$$

In this case, the pmf of X is given by

$$f: N \rightarrow [0, 1] \text{ by } f(x) = \frac{e^{-\lambda t} (\lambda t)^x}{x!}.$$

Proof. First, divide $[0, t]$ into n small intervals:

$$\Delta t, \frac{t}{n}, \dots, \frac{t}{n}$$

Note that $\Delta t \rightarrow 0$ as $n \rightarrow \infty$.

Let the events

$$\begin{aligned} B_1^{(n,x)} &= \text{there are } x \text{ small intervals each with one event;} \\ B_2^{(n)} &= \geq 1 \text{ small interval exists with two or more events.} \end{aligned}$$

Then, see that

$$\begin{aligned} P(B_1^{(n,x)}) &= \binom{n}{x} (P[\text{one event in interval of length } \frac{\Delta t}{n} = \Delta t]) (1-p)^{n-x} \\ &\quad \text{(by binomial distn)} \\ &= \binom{n}{x} (\lambda \frac{\Delta t}{n} + o(\frac{\Delta t}{n}))^x (1 - \lambda \frac{\Delta t}{n} - o(\frac{\Delta t}{n}))^{n-x}. \quad \text{(by point ② of defn)} \end{aligned}$$

Notice that since we want to consider infinitely small periods of time for our Poisson variable, we can deduce that

$$\begin{aligned} P(X=x) &= \lim_{n \rightarrow \infty} P(B_1^{(n,x)}) \\ &= \lim_{n \rightarrow \infty} \left[\binom{n}{x} \left(\lambda \frac{\Delta t}{n} + o(\frac{\Delta t}{n}) \right)^x \left(1 - \lambda \frac{\Delta t}{n} - o(\frac{\Delta t}{n}) \right)^{n-x} \right] \\ &= \lim_{n \rightarrow \infty} \left[\frac{n!}{x!(n-x)!} \left(\lambda \frac{\Delta t}{n} + o(\frac{\Delta t}{n}) \right)^x \left(1 - \lambda \frac{\Delta t}{n} - o(\frac{\Delta t}{n}) \right)^{n-x} \right] \\ &= \lim_{n \rightarrow \infty} \left[\frac{1}{x!} \frac{n(n-1)\dots(n-x+1)}{n^x} \left(\lambda t + no(\frac{\Delta t}{n}) \right)^x \left(1 - \lambda \frac{\Delta t}{n} - o(\frac{\Delta t}{n}) \right)^n \cdot \right. \\ &\quad \left. \left(1 - \lambda \frac{\Delta t}{n} - o(\frac{\Delta t}{n}) \right)^{-x} \right] \\ &= \frac{1}{x!} (1)(\lambda t)^x \lim_{n \rightarrow \infty} \left(1 - \lambda \frac{\Delta t}{n} \right)^n (1) \\ &= \frac{1}{x!} (\lambda t)^x e^{-\lambda t} \quad \text{(using the identity } e^x = \lim_{n \rightarrow \infty} (1 + \frac{x}{n})^n \text{)} \\ \therefore P(X=x) &= \frac{e^{-\lambda t} (\lambda t)^x}{x!}, \end{aligned}$$

as needed \blacksquare

Chapter 6: Expectation and Variance

EXPECTED VALUE / EXPECTATION [OF A DISC RV]

(6.1)

Let X be a drv, with $\text{ran}(X) = A$ & pmf $f(x)$. Then, the "expectation" or "expected value" of X , denoted as " $E(X)$ ", is defined to be equal to

$$E(X) = \sum_{x \in A} x f(x). \quad (\text{Def})$$

Note to calculate expectations, we need to:

- ① Identify the rv X involved;
- ② Find the pmf of X ; and
- ③ Compute $E(X)$.

$$X \sim \text{Bernoulli}(p) \Rightarrow E(X) = p \quad (6.2.1)$$

Let $X \sim \text{Bernoulli}(p)$. Then necessarily $E(X) = p$.

$$\begin{aligned} \text{Proof. } E(X) &= \sum_{x \in \{0,1\}} x P(X=x) \\ &= 0P(X=0) + 1P(X=1) \\ &= p. \quad \blacksquare \end{aligned}$$

$$X \sim \text{Binomial}(n, p) \Rightarrow E(X) = np \quad (6.2.2)$$

Let $X \sim \text{Binomial}(n, p)$. Then necessarily $E(X) = np$.

$$\begin{aligned} \text{Proof. } E(X) &= \sum_{k=0}^n k P[X=k] \\ &= \sum_{k=0}^n k \left(\binom{n}{k} p^k (1-p)^{n-k} \right) \\ &= \sum_{k=1}^n k \frac{n!}{k!(n-k)!} p^k (1-p)^{n-k} \\ &= np \sum_{k=1}^n \frac{(n-1)!}{(k-1)!(n-k)!} p^{k-1} (1-p)^{n-k} \\ &= np \sum_{k=0}^n \frac{(n-1)!}{k!(n-k)!} p^k (1-p)^{n-k-1} \\ &= np (1) \quad (\text{by Bin formula}) \\ \therefore E(X) &= np. \quad \blacksquare \end{aligned}$$

$$X \sim \text{Geometric}(p) \Rightarrow E(X) = \frac{1-p}{p} \quad (6.2.3)$$

Let $X \sim \text{Geometric}(p)$. Then necessarily $E(X) = \frac{1-p}{p}$.

$$\begin{aligned} \text{Proof. } E(X) &= \sum_{k=0}^{\infty} k \cdot P(X=k) \\ &= \sum_{k=0}^{\infty} k (1-p)^k p. \\ &= p (1-p) \sum_{k=1}^{\infty} k (1-p)^{k-1}. \end{aligned}$$

$$\text{Recall the identity } \frac{1}{(1-x)^2} = 1 + 2x + 3x^2 + \dots + kx^{k-1}, \quad |x| < 1.$$

Since $|1-p| < 1$, thus

$$\frac{1}{p^2} = \frac{1}{(1-(1-p))^2} = 1 + 2(1-p) + 3(1-p)^2 + \dots = \sum_{k=1}^{\infty} k (1-p)^{k-1},$$

and so

$$E(X) = p (1-p) \left(\frac{1}{p^2} \right) = \frac{1-p}{p}. \quad \blacksquare$$

$$X \sim \text{NB}(k, p) \Rightarrow E(X) = \frac{k(1-p)}{p} \quad (6.2.4)$$

Let $X \sim \text{NB}(k, p)$. Then necessarily $E(X) = \frac{k(1-p)}{p}$.

$$\begin{aligned} \text{Proof. } E(X) &= \sum_{n=0}^{\infty} n \cdot P(X=n) \\ &= \sum_{n=1}^{\infty} n \left(\binom{n+k-1}{n} p^k (1-p)^n \right) \\ &= \sum_{n=1}^{\infty} n \frac{(n+k-1)!}{n! (k-1)!} (1-p)^n p^k \\ &= \sum_{n=1}^{\infty} K \frac{(1-p)^k}{p} \cdot \frac{((n-1)+(k-1)-1)!}{(n-1)! k!} (1-p)^{n-1} p^{k-1} \\ &= \frac{k(1-p)}{p} \sum_{n=1}^{\infty} \binom{(n-1)+(k-1)-1}{n-1} (1-p)^{n-1} p^{k-1} \\ &= \frac{k(1-p)}{p} \sum_{n=0}^{\infty} \binom{n+(k-1)-1}{n} (1-p)^n p^{k-1} \\ &= \frac{k(1-p)}{p} (1) \\ \therefore E(X) &= \frac{k(1-p)}{p}. \quad \blacksquare \end{aligned}$$

$$X \sim \text{Hyp}(N, M, n) \Rightarrow E(X) = \frac{nM}{N} \quad (6.2.5)$$

Let $X \sim \text{Hyp}(N, M, n)$. Then necessarily $E(X) = \frac{nM}{N}$.

$$\begin{aligned} \text{Proof. } E(X) &= \sum_{k=0}^n k \cdot P(X=k) \\ &= \sum_{k=1}^n k \cdot \frac{\binom{M}{k} \binom{N-M}{n-k}}{\binom{N}{n}} \\ &= \frac{n! (N-n)!}{N!} \sum_{k=1}^n k \cdot \frac{M!}{k! (m-k)!} \frac{(N-m)!}{(n-k)! (N-m-n+k)!} \\ &= \frac{M(n!) (N-n)!}{N!} \sum_{k=1}^n \frac{(M-1)!}{(k-1)! (m-k)!} \frac{(N-m)!}{(n-k)! (N-m-n+k)!} \\ &= \frac{M \cdot n! (N-n)!}{N!} \sum_{k=0}^n \frac{(M-1)!}{k!} \frac{(N-m)!}{(n-k-1)!} \\ &= M \frac{n! (N-n)!}{N!} \binom{N-1}{n-1} \quad (\text{by Vandermonde Identity}) \\ &= M \frac{n! (N-n)!}{N!} \cdot \frac{(N-1)!}{(n-1)! (N-n)!} \\ \therefore E(X) &= \frac{Mn}{N}. \quad \blacksquare \end{aligned}$$

$$X \sim \text{Po}(\mu) \Rightarrow E(X) = \mu \quad (6.2.6)$$

Let $X \sim \text{Po}(\mu)$. Then necessarily $E(X) = \mu$.

$$\begin{aligned} \text{Proof. } E(X) &= \sum_{n=0}^{\infty} n \frac{e^{-\mu} \mu^n}{n!} \\ &= \sum_{n=1}^{\infty} \frac{e^{-\mu} \mu^n}{(n-1)!} \\ &= \mu \sum_{n=0}^{\infty} \frac{e^{-\mu} \mu^n}{n!} \\ &= \mu (1) = \mu. \quad \blacksquare \end{aligned}$$

$$E[g(X)] = \sum_{x \in A} g(x) f(x) \quad ((\text{THE LAW OF THE UNCONSCIOUS STATISTICIAN})) \quad (6.3)$$

Let g be a function on the drv X , which has range A and pmf X .

$$\text{Then necessarily } E[g(X)] = \sum_{x \in A} g(x) f(x).$$

Proof. Let $Y = g(X)$, and let $D_Y = \{x \in X : g(x) = y\}$, and let $B = \text{ran}(Y)$.

Then

$$P[Y=y] = P[g(X)=y] = \sum_{x \in D_Y} P[X=x].$$

Hence

$$\begin{aligned} E(Y) &= \sum_{y \in B} y \cdot P[g(X)=y] \\ &= \sum_{y \in B} y \cdot \sum_{x \in D_Y} P[X=x] \\ &= \sum_{y \in B} \sum_{x \in D_Y} g(x) P[X=x] \\ \therefore E(Y) &= E[g(X)] = \sum_{x \in A} g(x) f(x). \quad \blacksquare \end{aligned}$$

$$E[ag(X) + b] = aE[g(X)] + b; \quad E[ag_1(X) + bg_2(X)] = aE[g_1(X)]$$

$$+ bE[g_2(X)] \quad ((\text{LINEAR PROPERTIES OF EXPECTATION}))$$

Let g, g_1, g_2 be functions on the drv X , and let $a, b \in \mathbb{R}^+$.

Then necessarily

$$\textcircled{1} \quad E[ag(X) + b] = aE[g(X)] + b; \quad \text{and}$$

$$\textcircled{2} \quad E[ag_1(X) + bg_2(X)] = aE[g_1(X)] + bE[g_2(X)].$$

Proof. Follows almost directly from LOUS. \blacksquare

VARIANCE (6.4)

Let X be a drv.

Then, the "variance" of X , denoted as " $\text{Var}(X)$ " or " σ^2 ", is defined to be equal to

$$\text{Var}(X) = E[(X - E[X])^2].$$

* we use " μ " to denote " $E(X)$ ", so

$$\text{Var}(X) = E[(X - \mu)^2].$$

\mathbb{E}_2 $\text{Var}(X)$ is used to measure the "variability" of a sample, ie how "concentrated" the data is.

\mathbb{E}_3 The "standard deviation" of X , denoted as " σ ", is defined to be

$$\sigma = \sqrt{\text{Var}(X)}.$$

$$\text{Var}(X) = \sum_{x \in A} (x - E(X))^2 f(x) = E(X^2) - [E(X)]^2$$

\mathbb{E} (let X be a drv, with $\text{ran}(X) = A$ & pmf f .

Then necessarily

$$\text{① } \text{Var}(X) = \sum_{x \in A} (x - E(X))^2 f(x); \text{ and}$$

$$\text{② } \text{Var}(X) = E(X^2) - [E(X)]^2.$$

Proof. By defn,

$$\text{Var}(X) = E[(X - E(X))^2]$$

$$= \sum_{x \in A} (x - E(X))^2 f(x) \quad (\text{by LOUS}),$$

Showing ①.

$$\text{Then } \sum_{x \in A} (x - E(X))^2 f(x) = \sum_{x \in A} (x^2 - 2xE(X) + E(X)^2) f(x),$$

$$= \sum_{x \in A} x^2 f(x) - 2E(X) \sum_{x \in A} x + E(X)^2$$

$$= \sum_{x \in A} x^2 f(x) - 2E(X) E(X) + E(X) E(X)$$

$$= E(X^2) - [E(X)]^2,$$

showing ②. \square

PROPERTIES OF VARIANCE

\mathbb{E} (let X be a drv. Note the following:

$$\text{① } \text{Var}(X) \geq 0;$$

$$\text{② } E(X^2) \geq (E(X))^2;$$

$$\text{③ } \text{Var}(X) = 0 \Leftrightarrow P(X=c)=1 \text{ for some constant } c; \text{ and}$$

$$\text{④ } \text{Var}(aX+b) = a^2 \text{Var}(X).$$

Proof. By defn of variance,

$$\text{Var}(X) = \sum_{x \in A} (x - E(X))^2 f(x) = \sum_{x \in A} (x - E(X))^2 P(X=x),$$

and as $P[X=x]$, $(x - E(X))^2 \geq 0 \quad \forall x \in A$. ① follows.

Thus

$$E(X^2) - (E(X))^2 \geq 0 \Rightarrow E(X^2) \geq (E(X))^2, \text{ showing ②.}$$

Next,

$$\text{Var}(X) = 0 \Leftrightarrow \sum_{x \in A} \frac{(x - \mu)^2}{\geq 0} f(x) = 0$$

$$\Leftrightarrow (x - \mu)^2 = 0 \quad \forall x \in A$$

$$\Leftrightarrow x = \mu \quad \forall x \in A \quad (\text{ie } A = \{\mu\})$$

$$\Leftrightarrow P[X=\mu] = 1, \text{ showing ③;}$$

and

$$\text{Var}(aX+b) = E[(aX+b)^2] - (E(aX+b))^2$$

$$= a^2 E(X^2) + 2ab E(X) + b^2 - (aE(X) + b)^2$$

$$= a^2 E(X^2) + 2ab E(X) + b^2 - a^2 E(X)^2 - 2ab E(X) - b^2$$

$$= a^2 E(X^2) - a^2 E(X)^2$$

$$= a^2 \text{Var}(X),$$

showing ④. \square

$$X \sim \text{Bernoulli}(p) \Rightarrow \text{Var}(X) = p(1-p) \quad (6.5.1)$$

\mathbb{E} (let $X \sim \text{Bernoulli}(p)$. Then necessarily $\text{Var}(X) = p(1-p)$.

Proof. $\text{Var}(X) = E(X^2) - (E(X))^2$

$$= \sum_{x=0}^1 x^2 p[X=x] - p^2$$

$$= p - p^2$$

$$\therefore \text{Var}(X) = p(1-p). \quad \square$$

$$X \sim \text{Binomial}(n, p) \Rightarrow \text{Var}(X) = np(1-p) \quad (6.5.2)$$

\mathbb{E} (let $X \sim \text{Binomial}(n, p)$. Then necessarily $\text{Var}(X) = np(1-p)$.

Proof. First, see that

$$\text{Var}(X) = E(X^2) - (E(X))^2$$

$$= E(X(X-1)) - (E(X))^2 + E(X).$$

Then,

$$E(X(X-1)) = \sum_{k=0}^n k(k-1) p[X=k]$$

$$= \sum_{k=2}^n k(k-1) \frac{n!}{k!(n-k)!} p^k (1-p)^{n-k}$$

$$= \sum_{k=2}^n n(n-1) \cdot \frac{(n-2)!}{(n-2)!(n-k)!} p^k (1-p)^{n-k}$$

$$= n(n-1)p \sum_{k=0}^{n-2} \frac{(n-2)!}{k!(n-k-2)!} p^k (1-p)^{n-2-k}$$

$$= n(n-1)p^2 (1)$$

$$\therefore E(X(X-1)) = n(n-1)p^2.$$

Thus

$$\text{Var}(X) = E(X(X-1)) - (E(X))^2 + E(X)$$

$$= n(n-1)p^2 - (np)^2 + np$$

$$= np[(n-1)p - np + 1]$$

$$\therefore \text{Var}(X) = np(1-p). \quad \square$$

$$X \sim \text{Geometric}(p) \Rightarrow \text{Var}(X) = \frac{(1-p)^2}{p^2} + \frac{1-p}{p} \quad (6.5.3)$$

\mathbb{E} (let $X \sim \text{Geometric}(p)$. Then necessarily $\text{Var}(X) = \frac{(1-p)^2}{p^2} + \frac{1-p}{p}$.

Proof. See that

$$\text{Var}(X) = E(X^2) - (E(X))^2$$

$$= E(X(X-1)) - (E(X))^2 + E(X).$$

Then

$$E(X(X-1)) = \sum_{n=0}^{\infty} n(n-1) \cdot P[X=n]$$

$$= \sum_{n=2}^{\infty} n(n-1) \cdot (1-p)^n p$$

$$= p(1-p)^2 [(1 \times 2) + (2 \times 3)(1-p) + (3 \times 4)(1-p)^2 + \dots]$$

$$= 2p(1-p)^2 [1 + 3(1-p) + 6(1-p)^2 + \dots]$$

$$= 2p(1-p)^2 \left(\frac{1}{1-(1-p)^2} \right)$$

$$\therefore E(X(X-1)) = \frac{2(1-p)^2}{p^2}.$$

Thus

$$\text{Var}(X) = E(X(X-1)) - (E(X))^2 + E(X)$$

$$= \frac{2(1-p)^2}{p^2} - \left(\frac{1-p}{p} \right)^2 + \left(\frac{1-p}{p} \right)$$

$$= \left(\frac{1-p}{p} \right)^2 + \left(\frac{1-p}{p} \right). \quad \square$$

$$X \sim \text{Poisson}(\mu) \Rightarrow \text{Var}(X) = \mu \quad (6.5.4)$$

\mathbb{E} (let $X \sim \text{Poisson}(\mu)$. Then necessarily $\text{Var}(X) = \mu$.

Proof. $\text{Var}(X) = E(X(X-1)) - (E(X))^2 + E(X).$

Then

$$E(X(X-1)) = \sum_{n=0}^{\infty} n(n-1) P[X=n]$$

$$= \sum_{n=2}^{\infty} n(n-1) \frac{e^{-\mu} \mu^n}{n!}$$

$$= \mu \sum_{n=2}^{\infty} \frac{e^{-\mu} \mu^{n-2}}{(n-2)!}$$

$$= \mu^2 \sum_{n=0}^{\infty} \frac{e^{-\mu} \mu^n}{n!}$$

$$= \mu^2 (1) = \mu^2.$$

$$\text{Hence } \text{Var}(X) = E(X(X-1)) - (E(X))^2 + E(X)$$

$$= \mu^2 - (\mu)^2 + \mu$$

$$= \mu. \quad \square$$

Chapter 7:

Discrete Multivariate Distributions

BIVARIATE DISTRIBUTIONS (7.1)

I: "Bivariate distributions" are probability distributions that deal with two random variables.

JOINT PMF: $(x, y) \sim f(x, y)$

I: Let x, y be drvs. Then, the "joint probability mass function", ie the "joint pmf", of X & Y is the function f defined by

I: In this case, we write

$$(x, y) \sim f(x, y).$$

$$f(x, y) : \text{ran}(X) \times \text{ran}(Y) \rightarrow [0, 1] \text{ by } f(x, y) = P[X=x, Y=y].$$

I: Properties of joint pmf:

- ① $f(x, y) \geq 0$ (by defn of f); and
- ② $\sum_y \sum_x f(x, y) = 1$.

I: In general, for drvs X_1, \dots, X_n , the joint pmf of X_1, \dots, X_n is defined by

$$f: \prod_{i=1}^n \text{ran}(X_i) \rightarrow [0, 1] \text{ by } f(x_1, \dots, x_n) = P[X_1=x_1, \dots, X_n=x_n].$$

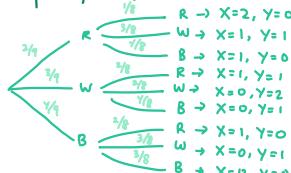
eg: A box contains 2 red, 3 white & 4 black ones. Randomly select 2 balls w/o replacement.

(Let

$$X = \# \text{ of red balls selected}; \quad Y = \# \text{ of white balls selected}.$$

Find the joint pmf of X & Y .

Soln.



Let $f(x, y)$ be the joint pmf of f .

By adding the probabilities for each case, you eventually get that

	0	1	2
0	2/36	8/36	1/36
1	12/36	6/36	0
2	3/36	0	0

MARGINAL PMF: $f_X(x)$, $f_Y(y)$ (7.1.1)

I: Let f be the joint pmf of some drvs X & Y .

Then, the "marginal pmfs" of X & Y , denoted as " f_X " & " f_Y " respectively, is defined to be equal to

$$f_X(x) = P[X=x] = \sum_y P[X=x, Y=y] = \sum_y f(x, y),$$

and

$$f_Y(y) = P[Y=y] = \sum_x P[X=x, Y=y] = \sum_x f(x, y).$$

* we also denote

$$f_X := f_1 \quad \& \quad f_Y := f_2.$$

I: In general, for drvs X_1, \dots, X_n , we have that

$$f_{X_i}(x_i) = P[X_i=x_i] = \sum_{x_1} \dots \sum_{x_{i-1}} \sum_{x_{i+1}} \dots \sum_{x_n} P[X_1=x_1, \dots, X_n=x_n]$$

$$= \sum_{x_1} \dots \sum_{x_{i-1}} \sum_{x_{i+1}} \dots \sum_{x_n} f(x_1, \dots, x_n).$$

* we also denote

$$f_{X_i} := f_i.$$

Note that

- ① $f(x, y)$ determines $f_X(x)$ & $f_Y(y)$; but
- ② We cannot generally find $f(x, y)$ from $f_X(x)$ & $f_Y(y)$.

CONDITIONAL PMF: $f_1(x|y)$ (7.1.2)

I: Let X & Y be drvs.

Then, the "conditional pmf of X given $Y=y$ ", denoted as " $f_1(x|y)$ ", is defined to be

$$f_1(x|y) = \frac{f(x, y)}{f_2(y)} = \frac{P[X=x, Y=y]}{P[Y=y]},$$

given that $f_2(y) > 0$.

Note that:

- ① $f_1(x|y) \geq 0$ (as $f(x, y) \geq 0$, $f_2(y) > 0$); &
- ② $\sum_x f_1(x|y) = 1 \quad \forall y \in \text{ran}(Y)$.

$$\text{Proof: } \sum_x f_1(x|y) = \sum_x \frac{f(x, y)}{f_2(y)}$$

$$= \frac{1}{f_2(y)} \sum_x f(x, y)$$

$$= \frac{1}{f_2(y)} f_2(y) \quad (\text{by defn})$$

$$= 1. \quad \blacksquare$$

INDEPENDENT [RANDOM VARIABLES] (7.1.3)

I: Let X & Y be rv, with pmf f .

Then, we say X and Y are "independent" if

$$f(x, y) = P[X=x, Y=y] = P[X=x]P[Y=y] = f_X(x)f_Y(y)$$

for each $x \in \text{ran}(X)$, $y \in \text{ran}(Y)$.

I: So, to show X & Y are not independent, it suffices to find some $x \in \text{ran}(X)$, $y \in \text{ran}(Y)$ such that

$$f(x, y) \neq f_X(x)f_Y(y).$$

eg: $X \sim \text{Geo}(p)$; $Y \sim \chi^2$: Show X & Y are not independent.

→ Let $x=0$, $y=1$.

$$\text{Then } f(0, 1) = P[X=0, Y=1] = P[X=0, Y=1]$$

$= 0$ (since this is impossible).

$$\text{But } f_X(0)f_Y(1) = P[X=0]P[Y=1]$$

$$= P[X=0]P[X^2=1]$$

$$= P[X=0]P[X=1]$$

$$= p(1-p) \cdot p \quad (\neq 0). \quad \blacksquare$$

I: In general, the rv X_1, \dots, X_n (with pmf f) are independent if

$$f(x_1, \dots, x_n) = f_1(x_1) \dots f_n(x_n) \quad \forall x_i \in \text{ran}(X_i), 1 \leq i \leq n.$$

DISTRIBUTION OF A FUNCTION OF RANDOM VARIABLES (7.2)

To find the pmf for $T = g(X, Y)$, we use the following method:

- ① Evaluate $\text{ran}(T) = \text{ran}(g(X, Y))$;
- ② Find the values of (x, y) such that $g(x, y) |_{X=x, Y=y} = t$ for each $t \in \text{ran}(T)$; then
- ③ Use $f_{X,Y}(x, y)$ to get the respective probabilities of each (x, y) , and "merge" them accordingly under each $t \in \text{ran}(T)$ to obtain the pmf for T .

e.g. A box contains 2 red, 3 white & 4 black ones. Randomly select 2 balls w/o replacement.

Let
 $X = \# \text{ of red balls selected}$;
 $Y = \# \text{ of white balls selected}$.

let $T = 2XY - 1$. Find the pmf of T . (E3)

Soln.

	X		
T	0	1	2
0	-1	-1	-1
1	-1	1	3
2	-1	3	7

From earlier we found the pmf of X, Y in a tabular form:

	x		
y	0	1	2
0	6/36	8/36	1/36
1	12/36	6/36	0
2	3/36	0	0

By "comparing" the two tables, see that

$$\begin{aligned} P[T=-1] &= P(X=0, Y=0) + P(X=0, Y=1) + P(X=0, Y=2) \\ &\quad + P(X=1, Y=0) + P(X=1, Y=2) \\ &= 6/36 + 8/36 + 1/36 + 12/36 + 3/36 = 30/36. \end{aligned}$$

$P[T=1]$, $P[T=3]$ & $P[T=7]$ are calculated similarly.

$X \sim \text{Bin}(n, p)$, $Y \sim \text{Bin}(m, p)$, X, Y INDEPENDENT \Rightarrow

$X+Y \sim \text{Bin}(n+m, p)$ (E4)

Let $X \sim \text{Bin}(n, p)$ be independent from $Y \sim \text{Bin}(m, p)$. We can show $X+Y \sim \text{Bin}(n+m, p)$ by a pmf argument.

Proof. Let f be the joint pmf of X & Y .

Since X, Y are indep., thus $f_{X,Y}(x, y) = f_X(x)f_Y(y) \forall x, y$.

Let $T = X+Y$. See that

$$\begin{aligned} P[T=t] &= \sum_{x=0}^t P(X=x)P(Y=t-x) \\ &= \sum_{x=0}^t \binom{n}{x} p^x (1-p)^{n-x} \binom{m}{t-x} p^{t-x} (1-p)^{m-(t-x)} \\ &= \sum_{x=0}^t \binom{n}{x} \binom{m}{t-x} p^t (1-p)^{n+m-t+x} \\ &= p^t (1-p)^{n+m-t} \sum_{x=0}^t \binom{n}{x} \binom{m}{t-x} \\ &= p^t (1-p)^{n+m-t} \binom{n+m}{t} \quad (\text{by Vandermonde's identity}), \end{aligned}$$

and so this suffices to show

$$T \sim \text{Bin}(n+m, p).$$

Let's find the conditional pmf of X given $T=t$ also.

Soln. See that

$$\begin{aligned} P[X=x | T=t] &= \frac{P(X=x, T=t)}{P(T=t)} \\ &= \frac{P(X=x, X+Y=t)}{P(T=t)} \\ &= \frac{P(X=x, Y=t-x)}{P(T=t)} \\ &= \frac{P_X(x)P_Y(t-x)}{P(T=t)} \\ &= \frac{\binom{n}{x} p^x (1-p)^{n-x} \binom{m}{t-x} p^{t-x} (1-p)^{m-(t-x)}}{\binom{n+m}{t} p^t (1-p)^{n+m-t}} \\ &= \frac{\binom{n}{x} \binom{m}{t-x}}{\binom{n+m}{t}}. \end{aligned}$$

$$\therefore P[X=x | T=t] = \frac{\binom{n}{x} \binom{m}{t-x}}{\binom{n+m}{t}}.$$

\Rightarrow see that by construction, this is what a hypergeometric distribution is "finding"!

$X \sim \text{Po}(\mu_1)$, $Y \sim \text{Po}(\mu_2) \Rightarrow X+Y \sim \text{Po}(\mu_1+\mu_2)$ (E5)

Let $X \sim \text{Po}(\mu_1)$ be independent to $Y \sim \text{Po}(\mu_2)$. Then we can similarly show that $X+Y \sim \text{Po}(\mu_1+\mu_2)$.

Proof. Let $T = X+Y$.

$$\begin{aligned} \text{See that } P[T=t] &= \sum_{x=0}^t P[X=x, Y=t-x] \\ &= \sum_{x=0}^t P[X=x]P[Y=t-x] \quad (\text{as } X, Y \text{ are independent}) \\ &= \sum_{x=0}^t \frac{e^{-\mu_1} \mu_1^x}{x!} \frac{e^{-\mu_2} \mu_2^{t-x}}{(t-x)!} \\ &= e^{-\mu_1-\mu_2} \sum_{x=0}^t \frac{\mu_1^x \mu_2^{t-x}}{x!(t-x)!} \\ &= \frac{e^{-\mu_1-\mu_2}}{t!} \sum_{x=0}^t \frac{t!}{x!(t-x)!} \mu_1^x \mu_2^{t-x} \\ &= \frac{e^{-\mu_1-\mu_2}}{t!} \sum_{x=0}^t \binom{t}{x} \mu_1^x \mu_2^{t-x} \\ &= \frac{e^{-\mu_1-\mu_2}}{t!} (\mu_1+\mu_2)^t \quad (\text{by the binomial formula}) \end{aligned}$$

which suffices to show $T \sim \text{Po}(\mu_1+\mu_2)$.

We can similarly find $f_X(x|t)$.

$$\begin{aligned} f_X(x|t) &= \frac{P[X=x, T=t]}{P(T=t)} \\ &= \frac{P(X=x, T=t)}{P(T=t)} \\ &= \frac{P(X=x, X+Y=t)}{P(T=t)} \\ &= \frac{P(X=x, Y=t-x)}{P(T=t)} \\ &= \frac{P(X=x)P(Y=t-x)}{P(T=t)} \\ &= \frac{P(X=x)P(Y=t-x)}{P(T=t)} \quad (\text{by independence of } X, Y) \\ &= \frac{\left(\frac{e^{-\mu_1} \mu_1^x}{x!}\right)\left(\frac{e^{-\mu_2} \mu_2^{t-x}}{(t-x)!}\right)}{P(T=t)} \\ &= \frac{\left(\frac{e^{-\mu_1} \mu_1^x}{x!}\right)\left(\frac{e^{-\mu_2} \mu_2^{t-x}}{(t-x)!}\right)}{t!} \\ &= \frac{t!}{x!(t-x)!} \cdot \frac{e^{-\mu_1-\mu_2}}{t!} \cdot \frac{\mu_1^x \mu_2^{t-x}}{(\mu_1+\mu_2)^t} \\ &= \binom{t}{x} \frac{\mu_1^x \mu_2^{t-x}}{(\mu_1+\mu_2)^t}. \end{aligned}$$

TRINOMIAL DISTRIBUTION:

$$(X_1, X_2, X_3) \sim \text{Tri}(n, p_1, p_2, p_3) \quad (7.3)$$

\exists_1 In a "trinomial distribution":

- ① there are three possible outcomes A, B, C for a trial; and
- ② n trials occur independently.

\exists_2 In particular,

- ① If $P(A) = p_1$, $P(B) = p_2$ & $P(C) = p_3$, then $p_1 + p_2 + p_3 = 1$, and
- ② If $X_1 = \#(A)$, $X_2 = \#(B)$ & $X_3 = \#(C)$, then $X_1 + X_2 + X_3 = n$.

\exists_3 In this case, we write

$$(X_1, X_2, X_3) \sim \text{Trinomial}(n, p_1, p_2, p_3).$$

or

$$(X_1, X_2, X_3) \sim \text{Tri}(n, p_1, p_2, p_3).$$

JOINT PMF [OF TRINOMIAL DISTRIBUTIONS]:

$$f(x_1, x_2, x_3) = \frac{n!}{x_1! x_2! x_3!} p_1^{x_1} p_2^{x_2} p_3^{x_3} \quad (7.3.1)$$

\exists_1 Let the rv X_1, X_2, X_3 form a trinomial distribution, with $X_1 + X_2 + X_3 = n$.

Then the joint pmf is necessarily the function f , where

$$\begin{aligned} f(x_1, x_2, x_3) &= P[X_1=x_1, X_2=x_2, X_3=x_3] \\ &= P[X_1=x_1, X_2=x_2] = P[X_1=x_1, X_3=x_3] = P[X_2=x_2, X_3=x_3] \\ &= \frac{n!}{x_1! x_2! x_3!} p_1^{x_1} p_2^{x_2} p_3^{x_3}. \end{aligned}$$

Why? $f(x_1, x_2, x_3) = \frac{n!}{x_1! x_2! x_3!} p_1^{x_1} p_2^{x_2} p_3^{x_3}$

of ways to arrange n things w/ x_1 type 1, x_2 type 2 & x_3 type 3 multiplied.

\exists_2 Note that

$$\sum_{x_1=0}^n \sum_{x_2=0}^{n-x_1} P[X_1=x_1, X_2=x_2, X_3=n-x_1] = \sum_{x_1=0}^n \sum_{x_2=0}^{n-x_1} \frac{n!}{x_1! x_2! x_3!} p_1^{x_1} p_2^{x_2} p_3^{x_3} = (p_1 + p_2 + p_3)^n \quad (\text{as } p_1 + p_2 + p_3 = 1).$$

MARGINAL PMFS [OF TRINOMIAL DISTRIBUTIONS]:

$$f_{X_1}(x_1) = \sum_{x_2=0}^{n-x_1} f(x_1, x_2, x_3) = \sum_{x_3=0}^{n-x_1} f(x_1, x_2, x_3) \quad (7.3.2)$$

\exists_1 Let X_1, X_2, X_3 form a trinomial distribution, with joint pmf f .

Denote the marginal pmf of f with X_1 as f_{X_1} .

Then

$$f_{X_1}(x_1) = P[X_1=x_1] = \sum_{x_2=0}^{n-x_1} f(x_1, x_2, x_3)$$

and

$$f_{X_1}(x_1) = P[X_1=x_1] = \sum_{x_3=0}^{n-x_1} f(x_1, x_2, x_3),$$

and f_{X_2}, f_{X_3} are defined similarly.

Proof: $f_{X_1}(x_1) = \sum_{x_2=0}^{n-x_1} f_{1,2}(x_1, x_2)$ (where $f_{1,2}(n, x_2) = P[X_1=x_1, X_2=x_2]$)

$$\begin{aligned} &= \sum_{x_2=0}^{n-x_1} \frac{n!}{x_1!(n-x_1-x_2)!} p_1^{x_1} p_2^{x_2} p_3^{n-x_1-x_2} \\ &= \sum_{x_2=0}^{n-x_1} \frac{n!}{x_1!(n-x_1-x_2)!} p_1^{x_1} p_2^{x_2} p_3^{n-x_1-x_2} \quad (\text{as } X_1+X_2+X_3=n) \\ &= \sum_{x_2=0}^{n-x_1} f(x_1, x_2, n-x_1-x_2), \end{aligned}$$

and the other sum is proved similarly. \square

$$(X_1, X_2, X_3) \sim \text{Tri}(n, p_1, p_2, p_3) \Rightarrow X_i \sim \text{Bin}(n, p_i) \quad (7.3.2)$$

\exists_2 Let X_1, X_2, X_3 form a trinomial distribution.

Then necessarily $X_i \sim \text{Bin}(n, p_i)$. $\forall i \in \{1, 2, 3\}$.

Proof: We prove it for $i=1$; the other cases are similar.

See that

$$\begin{aligned} P[X_1=x_1] &= f_{X_1}(x_1) \\ &= \sum_{x_2=0}^{n-x_1} \frac{n!}{x_1!(n-x_1-x_2)!} p_1^{x_1} p_2^{x_2} p_3^{n-x_1-x_2} \\ &= p_1^{x_1} \frac{n!}{(n-x_1-x_2)!} \sum_{x_2=0}^{n-x_1} \frac{(n-x_1-x_2)!}{x_2!(n-x_1-x_2-x_1)!} p_2^{x_2} p_3^{n-x_1-x_2} \\ &= p_1^{x_1} \binom{n}{x_1} (p_2 + p_3)^{n-x_1} \quad (\text{by bin formula}) \\ &= p_1^{x_1} (p_1 + p_2 + p_3)^{n-x_1}, \end{aligned}$$

which suffices to show that

$$X_1 \sim \text{Bin}(n, p_1)$$

as needed. \square

CONDITIONAL PMFS [FOR TRINOMIAL DISTRIBUTIONS]:

$$(X_1 | X_3=x_3) \sim \text{Bin}(n-x_3, \frac{p_1}{p_1+p_2}) \quad (7.3.3)$$

\exists_1 Let X_1, X_2, X_3 form a trinomial distribution.

Then necessarily

$$(X_1 | X_3=x_3) \sim \text{Bin}(n-x_3, \frac{p_1}{p_1+p_2}),$$

and the other cases (ie $(X_i | X_j=x_j)$) are defined similarly.

$$\begin{aligned} \text{Proof: } P[X_1=x_1 | X_3=x_3] &= \frac{P[X_1=x_1, X_3=x_3]}{P[X_3=x_3]} \\ &= \frac{\frac{n!}{x_1! x_2! x_3!} p_1^{x_1} p_2^{x_2} p_3^{x_3}}{\frac{n!}{(n-x_3)!} (p_1+p_2)^{n-x_3}} \quad (\text{since } X_3 \sim \text{Bin}(n, p_3)) \\ &= \frac{(x_1+x_2)!}{x_1! x_2!} \cdot \frac{p_1^{x_1} p_2^{x_2}}{(p_1+p_2)^{x_1+x_2}} \\ &= \left(\frac{x_1+x_2}{x_2}\right) \left(\frac{p_1}{p_1+p_2}\right)^{x_1} \left(\frac{p_2}{p_1+p_2}\right)^{x_2} \\ &= \binom{n-x_3}{n-x_3-x_1} p_1^{x_1} (1-p_1)^{n-x_3-x_1} \quad (p_1' = \frac{p_1}{p_1+p_2}), \end{aligned}$$

which is sufficient to prove the claim. \square

$$(X_1, X_2, X_3) \sim \text{Tri}(n, p_1, p_2, p_3) \Rightarrow X_1 + X_2 \sim \text{Bin}(n, p_1 + p_2)$$

$$(7.3.4)$$

\exists_1 Let $(X_1, X_2, X_3) \sim \text{Tri}(n, p_1, p_2, p_3)$.

Then necessarily $X_1 + X_2 \sim \text{Bin}(n, p_1 + p_2)$.

$$\text{Proof: } P[X_1+x_2=t] = \sum_{x_1=0}^t P[X_1=x_1, X_2=t-x_1]$$

$$= \sum_{x_1=0}^t \frac{n!}{x_1!(t-x_1)!(n-t)!} p_1^{x_1} p_2^{t-x_1} p_3^{n-t}$$

$$= \frac{n!}{t!(n-t)!} \sum_{x_1=0}^t \frac{t!}{x_1!(t-x_1)!} p_1^{x_1} p_2^{t-x_1} p_3^{n-t}$$

$$= \binom{n}{t} (p_1 + p_2)^t (p_3)^{n-t} \quad (\text{by bin formula}).$$

which suffices to prove the claim. \square

MULTINOMIAL DISTRIBUTION:

$$(X_1, \dots, X_k) \sim \text{Mult}(n, p_1, \dots, p_k) \quad (7.4)$$

\exists_1 In a "multinomial distribution":

- ① Each trial has k outcomes, say A_1, \dots, A_k (where $k \geq 2$); and

- ② we repeat said trial independently n times.

\exists_2 In this case, we say

$$(X_1, \dots, X_k) \sim \text{Multinomial}(n, p_1, \dots, p_k)$$

or

$$(X_1, \dots, X_k) \sim \text{Mult}(n, p_1, \dots, p_k),$$

where $p_i = P(A_i)$. $\forall i \in \{1, \dots, k\}$ and $X_i = \#\{A_i \text{ occurred in the trials}\}$.

JOINT PMF [OF MULTINOMIAL DISTRIBUTIONS]:

$$P[X_1=x_1, \dots, X_k=x_k] = \frac{n!}{x_1! \cdots x_k!} p_1^{x_1} \cdots p_k^{x_k}$$

\exists_1 Let $(X_1, \dots, X_k) \sim \text{Mult}(n, p_1, \dots, p_k)$.

Then the joint pmf of X_1, \dots, X_k is given by f , where

$$f(x_1, \dots, x_k) = P[X_1=x_1, \dots, X_k=x_k] = \frac{n!}{x_1! \cdots x_k!} p_1^{x_1} \cdots p_k^{x_k}.$$

Why? $f(x_1, \dots, x_k) = \frac{n!}{x_1! \cdots x_k!} p_1^{x_1} \cdots p_k^{x_k}$

generalization of combinations multiplying the probabilities out

Week 8:

Expectation and Variance of Multiple Variables

$$E(g(x_1, x_2)) = \sum_{x_1} \sum_{x_2} g(x_1, x_2) f(x_1, x_2)$$

«LAW OF UNCONSCIOUS STATISTICIAN» (8.1)

\square : Let x_1, x_2 be drvs, and let $(x_1, x_2) \sim f(x_1, x_2)$.

Then necessarily

$$E(g(x_1, x_2)) = \sum_{x_1} \sum_{x_2} g(x_1, x_2) f(x_1, x_2).$$

$$E(aX + bY + c) = aE(X) + bE(Y) + c \quad (8.2)$$

\square : Let X, Y be drvs, and let $a, b, c \in \mathbb{R}$.

Then necessarily

$$E(aX + bY + c) = aE(X) + bE(Y) + c.$$

Proof: Let $(x, y) \sim f(x, y)$.

$$\begin{aligned} \Rightarrow E(aX + bY + c) &= \sum_{x,y} (ax + by + c) f(x, y) \\ &= \sum_x \sum_y ax f(x, y) + \sum_x \sum_y by f(x, y) + \sum_x \sum_y c f(x, y) \\ &= a \sum_x \sum_y f(x, y) + b \sum_y \sum_x f(x, y) + c \sum_x \sum_y f(x, y) \\ &\quad [P(X=x)] \quad [P(Y=y)] \quad [] \\ &= aE(X) + bE(Y) + c. \end{aligned}$$

$$X \text{ & } Y \text{ ARE INDEPENDENT} \Rightarrow E[g(x)h(y)] = E[g(x)]E[h(y)]$$

(8.2)

\square : Let X, Y be independent drvs.

Then necessarily

$$E[g(x)h(y)] = E[g(x)]E[h(y)].$$

Proof: Let $(x, y) \sim f(x, y)$.

Then

$$\begin{aligned} E[g(x)]E[h(y)] &= \left(\sum_x g(x)f_x(x) \right) \left(\sum_y h(y)f_y(y) \right) \\ &= \sum_x \sum_y g(x)h(y) f_x(x)f_y(y) \\ &= \sum_x \sum_y g(x)h(y) f(x, y) \quad (\text{since } X, Y \text{ are independent, see 7.1.3}) \\ &= E[g(x)h(y)] \quad (\text{by LOUS}), \end{aligned}$$

as needed. \blacksquare

COVARIANCE: $Cov(X, Y)$ (8.3)

\square : Let X, Y be drvs.

Then, the "covariance" between X & Y , denoted as

" $Cov(X, Y)$ ", is defined to be

$$\begin{aligned} Cov(X, Y) &= E[(X - E(X))(Y - E(Y))] \\ &= E(XY) - E(X)E(Y). \end{aligned}$$

Proof: Let $(x, y) \sim f(x, y)$. Then

$$\begin{aligned} Cov(X, Y) &= \sum_{x,y} (x - E(X))(y - E(Y)) f(x, y) \quad (\text{by LOUS}) \\ &= \sum_{x,y} xy f(x, y) - \sum_x \sum_y E(X)y f(x, y) - \sum_x \sum_y E(Y)x f(x, y) + \sum_{x,y} E(X)E(Y) f(x, y) \\ &= E(XY) - E(X)E(Y) - E(Y)E(X) + E(X)E(Y) \\ &= E(XY) - E(X)E(Y). \end{aligned}$$

$$Var(X+Y) = Var(X) + Var(Y) + 2Cov(X, Y) \quad (8.3)$$

\square : Let X, Y be drvs.

Then necessarily

$$Var(X+Y) = Var(X) + Var(Y) + 2Cov(X, Y).$$

$$\begin{aligned} \text{Proof: } Var(X+Y) &= E((X+Y)^2) - (E(X+Y))^2 \\ &= E(X^2) + 2E(XY) + E(Y^2) - (E(X) + E(Y))^2 \\ &= E(X^2) + 2E(XY) + E(Y^2) - E(X)^2 - 2E(X)E(Y) - E(Y)^2 \\ &= (E(X^2) - E(X)^2) + (E(Y^2) - E(Y)^2) + 2E(XY) - E(X)E(Y) \\ &= Var(X) + Var(Y) + 2Cov(X, Y). \end{aligned}$$

$$Cov(X, X) = Var(X)$$

\square : Let X be a drv.

Then necessarily $Cov(X, X) = Var(X)$.

$$\begin{aligned} \text{Proof: } Cov(X, X) &= \frac{2Var(X) - Var(X) - Var(X)}{2} \quad (\text{by rearranging the above equality}) \\ &= Var(X). \end{aligned}$$

X, Y ARE INDEPENDENT $\Rightarrow Cov(X, Y) = 0$

\square : Let X, Y be independent drvs.

Then necessarily $Cov(X, Y) = 0$.

$$\begin{aligned} \text{Proof: } Cov(X, Y) &= E(XY) - E(X)E(Y) \\ &= E(XY) - E(XY) \quad (\text{by 8.2}) \\ &= 0. \end{aligned}$$

\square : However, the converse is not necessarily true!

$$Var(aX + bY + c) = a^2 Var(X) + b^2 Var(Y) + 2ab Cov(X, Y)$$

\square : Let X, Y be drvs, and let $a, b, c \in \mathbb{R}$.

Then necessarily

$$Var(aX + bY + c) = a^2 Var(X) + b^2 Var(Y) + 2ab Cov(X, Y).$$

$$\begin{aligned} \text{Proof: } Var(aX + bY + c) &= E((aX + bY + c)^2) - (E(aX + bY + c))^2 \\ &= E(a^2 X^2 + b^2 Y^2 + c^2 + 2abXY + 2acX + 2bcY) - (aE(X) + bE(Y) + c)^2 \\ &= a^2 E(X^2) + b^2 E(Y^2) + c^2 + 2abE(XY) + 2acE(X) + 2bcE(Y) \\ &\quad - a^2 E(X)^2 - b^2 E(Y)^2 - c^2 - 2abE(X)E(Y) - 2acE(X) - 2bcE(Y) \\ &= a^2 (E(X^2) - E(X)^2) + b^2 (E(Y^2) - E(Y)^2) + 2ab(E(XY) - E(X)E(Y)) \\ &= a^2 Var(X) + b^2 Var(Y) + 2ab Cov(X, Y). \end{aligned}$$

CORRELATION COEFFICIENT: ρ OR $\rho_{x,y}$ (8.4)

Let X, Y be drvs.

Then, the "correlation coefficient" of X & Y , denoted as

" ρ ", is defined to be equal to

$$\rho = \frac{\text{Cov}(X, Y)}{\sqrt{\text{Var}(X) \text{Var}(Y)}},$$

i.e.

$$\rho = \frac{E[(X - E(X))(Y - E(Y))]}{\sqrt{E[(X - E(X))^2]} \sqrt{E[(Y - E(Y))^2]}}.$$

$$|\rho| \leq 1; |\rho|=1 \Leftrightarrow Y = aX+b; a>0 \Rightarrow \rho=1, a<0 \Rightarrow$$

$$\rho=-1$$

Let X, Y be drvs, and let ρ be the correlation coefficient of X & Y .

Then necessarily $|\rho| \leq 1$.

Furthermore, $|\rho|=1$ iff $Y = aX+b$ for some $a, b \in \mathbb{R}$.

① If $a > 0$, then $\rho=1$;

② If $a < 0$, then $\rho=-1$.

Proof. Let $S = X+tY$.

Then

$$\begin{aligned} 0 \leq \text{Var}(S) &= \text{Var}(X+tY) \\ &= \text{Var}(X) + t^2 \text{Var}(Y) + 2t \text{Cov}(X, Y), \end{aligned}$$

which is a quadratic function in t .

Since $0 \leq \text{Var}(S)$, it follows that this quadratic has at most one real root.

Let's evaluate the discriminant:

$$\Delta = (2\text{Cov}(X, Y))^2 - 4(\text{Var}(X))(\text{Var}(Y)) \leq 0$$

$$\Rightarrow 4\text{Cov}(X, Y)^2 - 4\text{Var}(X)\text{Var}(Y) \leq 0$$

$$\Rightarrow \frac{\text{Cov}(X, Y)^2}{\text{Var}(X)\text{Var}(Y)} \leq 1$$

$$\Rightarrow |\rho| \leq 1 \quad (\text{as needed}).$$

In particular, $\Delta=0$ iff $\text{Var}(S)=0$, i.e.

$$4\text{Cov}(X, Y)^2 - 4\text{Var}(X)\text{Var}(Y) = 0,$$

i.e. $|\rho|=1$.

In particular, $\exists t \in \mathbb{R} \ni \text{Var}(X+tY)=0$, i.e. that $X+tY=c$ for some $c \in \mathbb{R}$, i.e. that

$$Y = aX+b \quad \text{for some } a, b \in \mathbb{R}.$$

$$\begin{aligned} \text{Then } \rho &= \frac{\text{Cov}(X, Y)}{\sqrt{\text{Var}(X)\text{Var}(Y)}} = \frac{E[(X-E(X))(aX+b-aE(X)-b)]}{\sqrt{E[(X-E(X))^2]E[(aX+b-aE(X)-b)^2]}} \\ &= \frac{E[a(X-E(X))^2]}{\sqrt{E[(X-E(X))^2]E[(aX+b-aE(X)-b)^2]}} \\ &= \frac{aE[(X-E(X))^2]}{\sqrt{E[(X-E(X))^2]E[(aX+b-aE(X)-b)^2]}} \\ &= \frac{aE[(X-E(X))^2]}{\sqrt{a^2E[(X-E(X))^2]}} \\ &= \frac{aE[(X-E(X))^2]}{|a|E[(X-E(X))^2]} \\ &= \frac{a}{|a|}, \end{aligned}$$

$$\text{so } \rho=1 \Leftrightarrow a>0 \quad \& \quad \rho=-1 \Leftrightarrow a<0. \quad \blacksquare$$

POSITIVE / NEGATIVE CORRELATION

Let X, Y be drvs.

① We say X & Y follow a "positive correlation" if large values of X tend to be associated with large values of Y , and small values of X tend to be associated with small values of Y .

② Conversely, we say X & Y follow a "negative correlation" if large values of X tend to be associated with small values of Y , and small values of X tend to be associated with large values of Y .

$$(X_1, X_2, X_3) \sim \text{Tri}(n, p_1, p_2, p_3) \Rightarrow \rho_{X_1, X_2} = -\sqrt{\frac{p_1 p_2}{(1-p_1)(1-p_2)}}.$$

Let $(X_1, X_2, X_3) \sim \text{Tri}(n, p_1, p_2, p_3)$.

Then necessarily

$$\rho_{X_1, X_2} = -\sqrt{\frac{p_1 p_2}{(1-p_1)(1-p_2)}},$$

and a similar result holds for ρ_{X_1, X_3} & ρ_{X_2, X_3} too.

Proof. Recall that

$$(X_1, X_2, X_3) \sim \text{Tri}(n, p_1, p_2, p_3) \Rightarrow X_i \sim \text{Bin}(n, p_i).$$

Hence

$$E(X_i) = np_i, \quad \text{Var}(X_i) = np_i(1-p_i).$$

Then, see that

$$E(X_1 X_2) = \sum_{X_1=0}^n \sum_{X_2=0}^n X_1 X_2 \cdot \frac{n!}{X_1! X_2! (n-X_1-X_2)!} p_1^{X_1} p_2^{X_2} p_3^{n-X_1-X_2}.$$

On the other hand,

$$X_1 + X_2 \sim \text{Bin}(n, p_1 + p_2),$$

so

$$\text{Var}(X_1 + X_2) = n(p_1 + p_2)(1-(p_1 + p_2)).$$

Thus

$$\begin{aligned} \text{Cov}(X_1, X_2) &= \frac{1}{2}(\text{Var}(X_1 + X_2) - \text{Var}(X_1) - \text{Var}(X_2)) \\ &= \frac{1}{2}(n(p_1 + p_2)(1-(p_1 + p_2)) - np_1(1-p_1) - np_2(1-p_2)) \\ &= -np_1 p_2. \end{aligned}$$

Hence

$$\begin{aligned} \rho_{X_1, X_2} &= \frac{\text{Cov}(X_1, X_2)}{\sqrt{\text{Var}(X_1)\text{Var}(X_2)}} = \frac{-np_1 p_2}{\sqrt{np_1(1-p_1)np_2(1-p_2)}} \\ &= \frac{-np_1 p_2}{n\sqrt{p_1 p_2(1-p_1)(1-p_2)}} \\ &= -\sqrt{\frac{p_1 p_2}{(1-p_1)(1-p_2)}}. \quad \blacksquare \end{aligned}$$

$$(X_1, \dots, X_k) \sim \text{Mult}(n, p_1, \dots, p_k) \Rightarrow \text{Cov}(X_i, X_j) = -np_i p_j$$

Let $(X_1, \dots, X_k) \sim \text{Mult}(n, p_1, \dots, p_k)$.

Then necessarily $\rho_{X_i, X_j} = -np_i p_j \quad \forall 1 \leq i, j \leq k$.

Proof. Similar to binomial case.

$$(X_1, \dots, X_k) \sim \text{Mult}(n, p_1, \dots, p_k) \Rightarrow \rho_{X_i, X_j} = -\sqrt{\frac{p_i p_j}{(1-p_i)(1-p_j)}}$$

Let $(X_1, \dots, X_k) \sim \text{Mult}(n, p_1, \dots, p_k)$.

Then necessarily $\rho_{X_i, X_j} = -\sqrt{\frac{p_i p_j}{(1-p_i)(1-p_j)}}$.

Proof. Similar to binomial case. \blacksquare

$$E\left(\sum_{i=1}^n c_i X_i\right) = \sum_{i=1}^n c_i E(X_i)$$

Let X_1, \dots, X_n be drvs, and let $c_1, \dots, c_n \in \mathbb{R}$.

Then necessarily

$$E\left(\sum_{i=1}^n c_i X_i\right) = \sum_{i=1}^n c_i E(X_i).$$

Proof. This can be proved via induction pretty easily. \blacksquare

$$\text{Var}\left(\sum_{i=1}^n c_i X_i\right) = \sum_{i=1}^n c_i^2 \text{Var}(X_i) + 2 \sum_{i < j} c_i c_j \text{Cov}(X_i, X_j)$$

Let X_1, \dots, X_n be drvs, and let $c_1, \dots, c_n \in \mathbb{R}$.

Then necessarily

$$\begin{aligned} \text{Var}\left(\sum_{i=1}^n c_i X_i\right) &= \sum_{i=1}^n c_i^2 \text{Var}(X_i) + 2 \sum_{i < j} c_i c_j \text{Cov}(X_i, X_j) \\ &= \sum_{i=1}^n c_i^2 \text{Var}(X_i) + 2(c_1 c_2 \text{Cov}(X_1, X_2) + \dots + c_1 c_n \text{Cov}(X_1, X_n) \\ &\quad + c_2 c_3 \text{Cov}(X_2, X_3) + \dots + c_{n-1} c_n \text{Cov}(X_{n-1}, X_n)). \end{aligned}$$

$$\begin{aligned} \text{Proof.} \quad \text{Var}\left(\sum_{i=1}^n c_i X_i\right) &= E\left(\left(\sum_{i=1}^n c_i X_i\right)^2\right) - E\left[\left(\sum_{i=1}^n c_i X_i\right)\right]^2 \\ &= E\left[\sum_{i=1}^n \sum_{j=1}^n c_i c_j X_i X_j\right] - \left(\sum_{i=1}^n c_i E(X_i)\right)^2 \\ &= \sum_{i=1}^n \sum_{j=1}^n c_i c_j E(X_i X_j) - \sum_{i=1}^n \sum_{j=1}^n c_i c_j E(X_i) E(X_j) \\ &= \sum_{i < j} c_i c_j \underbrace{E(X_i X_j) - E(X_i) E(X_j)}_{\text{Var}(X_i)} + \sum_{i < j} c_i c_j \underbrace{(E(X_i X_j) - E(X_i) E(X_j))}_{\text{Cov}(X_i, X_j)} + \sum_{i < j} c_i c_j (E(X_i X_j) - E(X_i) E(X_j)) \\ &= \sum_{i=1}^n c_i^2 \text{Var}(X_i) + 2 \sum_{i < j} c_i c_j \text{Cov}(X_i, X_j). \quad \blacksquare \end{aligned}$$

$$X_1, \dots, X_n \text{ ARE INDEPENDENT} \Rightarrow \text{Var}\left(\sum_{i=1}^n c_i X_i\right) = \sum_{i=1}^n c_i^2 \text{Var}(X_i)$$

Let X_1, \dots, X_n be drvs, and let $c_1, \dots, c_n \in \mathbb{R}$.

Suppose X_1, \dots, X_n are independent.

Then necessarily

$$\text{Var}\left(\sum_{i=1}^n c_i X_i\right) = \sum_{i=1}^n c_i^2 \text{Var}(X_i).$$

Proof. This follows from the fact that

X_i, X_j are independent $\Rightarrow \text{Cov}(X_i, X_j) = 0$,

and applying this to the previous theorem. \blacksquare

INDICATOR FUNCTION TECHNIQUES

USING IFS ON $\text{Bin}(n, p)$

Q: Let $X \sim \text{Bin}(n, p)$. Find $E(X)$ & $\text{Var}(X)$ using indicator variable techniques.

Solⁿ: Let $X_i = 1$ if the i^{th} trial is a success & 0 otherwise, ie $X_i = I[\text{the } i^{\text{th}} \text{ trial is a success}]$.

Then

$$X_i \sim \text{Bernoulli}(p),$$

and since X_1, \dots, X_n are independent, thus

$$\begin{aligned} E(X) &= E\left(\sum_{i=1}^n X_i\right) \\ &= \sum_{i=1}^n E(X_i) \\ &= np, \end{aligned}$$

and

$$\begin{aligned} \text{Var}(X) &= \text{Var}\left(\sum_{i=1}^n X_i\right) \\ &= \sum_{i=1}^n \text{Var}(X_i) + 2 \sum_{1 \leq i < j \leq n} \text{Cov}(X_i, X_j) \\ &= \sum_{i=1}^n \text{Var}(X_i) + 2 \sum_{1 \leq i < j \leq n} (0) \quad (\text{by independence of } X_1, \dots, X_n) \\ &= \sum_{i=1}^n p(1-p) \end{aligned}$$

$$\therefore \text{Var}(X) = np(1-p).$$

USING IFS ON $\text{Hyp}(N, M, n)$

Q: Suppose there are M red balls & $N-M$ blue balls in a box.

Randomly select n balls without replacement from the box.

Let X be the # of red balls selected, so that

$$X \sim \text{Hyp}(N, M, n).$$

We can find $E(X)$ & $\text{Var}(X)$ using IF techniques.

Solⁿ: Let $X_i = 1$ if the i^{th} selection is a red ball, and 0 otherwise; ie $X_i = I[\text{the } i^{\text{th}} \text{ trial is a success}]$.

Then

$$X_i \sim \text{Bernoulli}\left(\frac{M}{N}\right), \text{ but note the } X_i's \text{ are not independent!}$$

$$\Rightarrow E(X_i) = \frac{M}{N}, \quad \text{Var}(X_i) = \frac{M}{N}(1 - \frac{M}{N}).$$

So

$$\begin{aligned} E(X) &= E\left(\sum_{i=1}^n X_i\right) \\ &= \sum_{i=1}^n E(X_i) \\ &= \frac{nM}{N}. \end{aligned}$$

Then,

$$\begin{aligned} \text{Var}(X) &= \text{Var}\left(\sum_{i=1}^n X_i\right) \\ &= \sum_{i=1}^n \text{Var}(X_i) + 2 \sum_{1 \leq i < j \leq n} \text{Cov}(X_i, X_j). \end{aligned}$$

See that

$$\begin{aligned} \text{Cov}(X_i, X_j) &= \sum_{\substack{i,j \\ X_i=X_j=0}} x_i x_j P[X_i=x_i, X_j=x_j] \\ &= 1 \cdot 1 \cdot P[X_i=1, X_j=1] \\ &= P[X_i=1] P[X_j=1 | X_i=1] \quad (\text{by total prob formula}) \\ &= \frac{M}{N} \cdot \frac{M-1}{N-1}, \end{aligned}$$

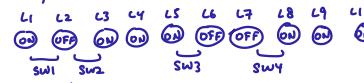
and so

$$\begin{aligned} \text{Var}(X) &= \sum_{i=1}^n \text{Var}(X_i) + 2 \sum_{1 \leq i < j \leq n} \text{Cov}(X_i, X_j) \\ &= n \cdot \frac{M}{N} \cdot (1 - \frac{M}{N}) + 2 \binom{n}{2} \left[\frac{M}{N} \cdot \frac{M-1}{N-1} - \left(\frac{M}{N} \right)^2 \right] \\ &= n \cdot \frac{M}{N} \cdot \left(\frac{N-M}{N} \right) + n(n-1) \left[\frac{M}{N} \left(\frac{M-1}{N-1} - \frac{M}{N} \right) \right] \\ &= n \cdot \frac{M}{N} \cdot \frac{N-M}{N} + n(n-1) \frac{M}{N} \left(\frac{NM-N-MN+M}{N(N-1)} \right) \\ &= n \cdot \frac{M}{N} \cdot \frac{N-M}{N} + n(n-1) \frac{M}{N} \left(\frac{M-N}{N(N-1)} \right) \\ &= n \cdot \frac{M}{N} \cdot \frac{N-M}{N} \left[1 - \frac{(n-1)}{N-1} \right] \\ &= n \cdot \frac{M}{N} \cdot \frac{N-M}{N} \left[\frac{(N-1)-(n-1)}{N-1} \right] \\ &= n \cdot \frac{M}{N} \cdot \frac{N-M}{N} \cdot \frac{N-n}{N-1}. \end{aligned}$$

Example 10 Suppose 10 decoration lights are arranged in a row. Each light can be ON with probability 0.7 or OFF with probability 0.3, independent of each other. Two adjacent lights are called a SWITCH if they are ON-OFF or OFF-ON.

Denote $X = \text{number of SWITCHes}$. For $i = 1, \dots, n$, let $X_i = 1$ if light i and $i+1$ form a switch; 0 otherwise. Therefore, $X = \sum_{i=1}^9 X_i$. Find $E(X)$ and $\text{Var}(X)$.

Solⁿ:



See that

$$X_i \sim \text{Ber}(0.7 \times 0.3 + 0.3 \times 0.7) = \text{Ber}(0.42).$$

$$\therefore E(X_i) = 0.42.$$

Then

$$\begin{aligned} E(X) &= E\left(\sum_{i=1}^9 X_i\right) \\ &= \sum_{i=1}^9 E(X_i) \\ &= \frac{9}{2} \cdot 0.42 = 9(0.42). \end{aligned}$$

Next,

$$\begin{aligned} \text{Var}(X) &= \text{Var}\left(\sum_{i=1}^9 X_i\right) \\ &= \sum_{i=1}^9 \text{Var}(X_i) + 2 \sum_{1 \leq i < j \leq 9} \text{Cov}(X_i, X_j) \end{aligned}$$

However, note that
→ since any lights that cannot form a switch (ie not directly adjacent to one another) do not have any "overlap".

X_i, X_j are independent if $|j-i| > 1$.

$$\begin{aligned} \text{Thus } \sum_{1 \leq i < j \leq 9} \text{Cov}(X_i, X_j) &= \sum_{i=1}^8 \text{Cov}(X_i, X_{i+1}) \\ &= \sum_{i=1}^8 [E(X_i X_{i+1}) - E(X_i) E(X_{i+1})] \\ &= \sum_{i=1}^8 [(0.7 \times 0.3 \times 0.7 + 0.3 \times 0.7 \times 0.3) - 0.42^2] \\ &= 8 \cdot (0.21 - 0.42^2), \end{aligned}$$

and so

$$\begin{aligned} \text{Var}(X) &= \sum_{i=1}^9 \text{Var}(X_i) + 2 \sum_{1 \leq i < j \leq 9} \text{Cov}(X_i, X_j) \\ &= 9(0.42)(1-0.42) + 2 \end{aligned}$$