



MALLA REDDY COLLEGE OF ENGINEERING AND TECHNOLOGY

(AUTONOMOUS INSTITUTION: UGC, GOVT. OF INDIA)

ELECTRONICS AND COMMUNICATION ENGINEERING



II ECE I SEM

**PROBABILITY THEORY
AND STOCHASTIC
PROCESSES**

CONTENTS

- ❖ SYLLABUS
- ❖ UNIT-I-PROBABILITY AND RANDOM VARIABLE
- ❖ UNIT-II- DISTRIBUTION AND DENSITY FUNCTIONS AND OPERATIONS ON ONE RANDOM VARIABLE
- ❖ UNIT-III-MULTIPLE RANDOM VARIABLES AND OPERATIONS
- ❖ UNIT-IV-STOCHASTIC PROCESSES-TEMPORAL CHARACTERISTICS
- ❖ UNIT-V- STOCHASTIC PROCESSES-SPECTRAL CHARACTERISTICS
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PROBABILITY THEORY AND STOCHASTIC PROCESS

Course Objectives:

- To provide mathematical background and sufficient experience so that student can read, write and understand sentences in the language of probability theory.
- To introduce students to the basic methodology of “probabilistic thinking” and apply it to problems.
- To understand basic concepts of Probability theory and Random Variables, how to deal with multiple Random Variables.
- To understand the difference between time averages statistical averages.
- To teach students how to apply sums and integrals to compute probabilities, and expectations.

UNIT I:

Probability and Random Variable

Probability: Set theory, Experiments and Sample Spaces, Discrete and Continuous Sample Spaces, Events, Probability Definitions and Axioms, Mathematical Model of Experiments, Joint Probability, Conditional Probability, Total Probability, Bayes' Theorem, and Independent Events, Bernoulli's trials.

The Random Variable: Definition of a Random Variable, Conditions for a Function to be a Random Variable, Discrete and Continuous, Mixed Random Variable

UNIT II:

Distribution and density functions and Operations on One Random Variable

Distribution and density functions: Distribution and Density functions, Properties, Binomial, Poisson, Uniform, Exponential Gaussian, Rayleigh and Conditional Distribution, Methods of defining Conditioning Event, Conditional Density function and its properties, problems.

Operation on One Random Variable: Expected value of a random variable, function of a random variable, moments about the origin, central moments, variance and skew, characteristic function, moment generating function, transformations of a random variable, monotonic transformations for a continuous random variable, non monotonic transformations of continuous random variable, transformations of Discrete random variable

UNIT III:

Multiple Random Variables and Operations on Multiple Random Variables

Multiple Random Variables: Vector Random Variables, Joint Distribution Function and Properties, Joint density Function and Properties, Marginal Distribution and density Functions, conditional Distribution and density Functions, Statistical Independence, Distribution and density functions of Sum of Two Random Variables and Sum of Several Random Variables, Central Limit Theorem - Unequal Distribution, Equal Distributions

Operations on Multiple Random Variables: Expected Value of a Function of Random Variables, Joint Moments about the Origin, Joint Central Moments, Joint Characteristic Functions, and Jointly Gaussian Random Variables: Two Random Variables case and N Random Variable case, Properties, Transformations of Multiple Random Variables

UNIT IV:

Stochastic Processes-Temporal Characteristics: The Stochastic process Concept, Classification of Processes, Deterministic and Nondeterministic Processes, Distribution and Density Functions, Statistical Independence and concept of Stationarity: First-Order Stationary Processes, Second-Order and Wide-Sense Stationarity, Nth-Order and Strict-Sense Stationarity, Time Averages and Ergodicity, Mean-Ergodic Processes, Correlation-Ergodic Processes Autocorrelation Function and Its Properties, Cross-Correlation Function and Its Properties, Covariance Functions and its properties, Gaussian Random Processes.

Linear system Response: Mean and Mean-squared value, Autocorrelation, Cross-Correlation Functions.

UNIT V:

Stochastic Processes-Spectral Characteristics: The Power Spectrum and its Properties, Relationship between Power Spectrum and Autocorrelation Function, the Cross-Power Density Spectrum and Properties, Relationship between Cross-Power Spectrum and Cross-Correlation Function.

Spectral characteristics of system response: power density spectrum of response, cross power spectral density of input and output of a linear system

TEXT BOOKS:

1. Probability, Random Variables & Random Signal Principles -Peyton Z. Peebles, TMH, 4th Edition, 2001.
2. Probability and Random Processes-Scott Miller, Donald Childers, 2Ed, Elsevier, 2012

REFERENCE BOOKS:

1. Theory of probability and Stochastic Processes-Pradip Kumar Gosh, University Press
2. Probability and Random Processes with Application to Signal Processing - Henry Stark and John W. Woods, Pearson Education, 3rd Edition.
3. Probability Methods of Signal and System Analysis- George R. Cooper, Clive D. MC Gillem, Oxford, 3rd Edition, 1999.
4. Statistical Theory of Communication -S.P. Eugene Xavier, New Age Publications 2003
5. Probability, Random Variables and Stochastic Processes Athanasios Papoulis and S.Unnikrishna Pillai, PHI, 4th Edition, 2002.

UNIT I

Probability and Random Variable

Probability:

- Set theory
- Experiments
- Sample Spaces, Discrete and Continuous Sample Spaces
- Events
- Probability Definitions and Axioms
- Mathematical Model of Experiments
- Joint Probability
- Conditional Probability
- Total Probability
- Bayes' Theorem
- Independent Events
- Bernoulli's trials

Random Variable:

- Definition of a Random Variable
- Conditions for a Function to be a Random Variable
- Discrete and Continuous, Mixed Random Variable

UNIT – 1

PROBABILITY AND RANDOM VARIABLE

PROBABILITY

Introduction

It is remarkable that a science which began with the consideration of games of chance should have become the most important object of human knowledge.

A brief history

Probability has an amazing history. A practical gambling problem faced by the French nobleman *Chevalier de Méré* sparked the idea of probability in the mind of *Blaise Pascal* (1623-1662), the famous French mathematician. Pascal's correspondence with Pierre de Fermat (1601-1665), another French Mathematician in the form of seven letters in 1654 is regarded as the genesis of probability. Early mathematicians like Jacob Bernoulli (1654-1705), Abraham de Moivre (1667-1754), Thomas Bayes (1702-1761) and Pierre Simon De Laplace (1749-1827) contributed to the development of probability. Laplace's *Theory Analytique des Probabilités* gave comprehensive tools to calculate probabilities based on the principles of permutations and combinations. Laplace also said, "*Probability theory is nothing but common sense reduced to calculation.*"

Later mathematicians like Chebyshev (1821-1894), Markov (1856-1922), von Mises (1883-1953), Norbert Wiener (1894-1964) and Kolmogorov (1903-1987) contributed to new developments. Over the last four centuries and a half, probability has grown to be one of the most essential mathematical tools applied in diverse fields like economics, commerce, physical sciences, biological sciences and engineering. It is particularly important for solving practical electrical-engineering problems in *communication*, *signal processing* and *computers*. Notwithstanding the above developments, a precise definition of probability eluded the mathematicians for centuries. Kolmogorov in 1933 gave the *axiomatic definition of probability* and resolved the problem.

Randomness arises because of

- random nature of the generation mechanism
- Limited understanding of the signal dynamics inherent imprecision in measurement, observation, etc.

For example, *thermal noise* appearing in an electronic device is generated due to random motion of electrons. We have deterministic model for weather prediction; it takes into account of the factors affecting weather. We can locally predict the temperature or the rainfall of a place on the basis of previous data. Probabilistic models are established from observation of a random phenomenon. While *probability* is concerned with analysis of a random phenomenon, *statistics* help in building such models from data.

Deterministic versus probabilistic models

A *deterministic model* can be used for a physical quantity and the process generating it provided sufficient information is available about the initial state and the dynamics of the process generating the physical quantity. For example,

- We can determine the position of a particle moving under a constant force if we know the initial position of the particle and the magnitude and the direction of the force.
- We can determine the current in a circuit consisting of resistance, inductance and capacitance for a known voltage source applying Kirchoff's laws.

Many of the physical quantities are *random* in the sense that these quantities cannot be predicted with *certainty* and can be described in terms of *probabilistic models* only. For example,

- The outcome of the tossing of a coin cannot be predicted with certainty. Thus the outcome of tossing a coin is random.
- The number of ones and zeros in a packet of binary data arriving through a communication channel cannot be precisely predicted is random.
- The ubiquitous *noise* corrupting the signal during acquisition, storage and transmission can be modelled only through statistical analysis.

How to Interpret Probability

Mathematically, the probability that an event will occur is expressed as a number between 0 and 1. Notationally, the probability of event A is represented by $P(A)$.

- If $P(A)$ equals zero, event A will almost definitely not occur.
- If $P(A)$ is close to zero, there is only a small chance that event A will occur.
- If $P(A)$ equals 0.5, there is a 50-50 chance that event A will occur.
- If $P(A)$ is close to one, there is a strong chance that event A will occur.
- If $P(A)$ equals one, event A will almost definitely occur.

In a statistical experiment, the sum of probabilities for all possible outcomes is equal to one. This means, for example, that if an experiment can have three possible outcomes (A, B, and C), then $P(A) + P(B) + P(C) = 1$.

Applications

Probability theory is applied in everyday life in risk assessment and in trade on financial markets. Governments apply probabilistic methods in environmental regulation, where it is called pathway analysis

Another significant application of probability theory in everyday life is reliability. Many consumer products, such as automobiles and consumer electronics, use reliability theory in product design to reduce the probability of failure. Failure probability may influence a manufacturer's decisions on a product's warranty.

THE BASIC CONCEPTS OF SET THEORY

Some of the basic concepts of set theory are:

Set: A set is a well defined collection of objects. These objects are called elements or members of the set. Usually uppercase letters are used to denote sets.

The set theory was developed by George Cantor in 1845-1918. Today, it is used in almost every branch of mathematics and serves as a fundamental part of present-day mathematics.

In everyday life, we often talk of the collection of objects such as a bunch of keys, flock of birds, pack of cards, etc. In mathematics, we come across collections like natural numbers, whole numbers, prime and composite numbers.

We assume that,

- the word set is synonymous with the word collection, aggregate, class and comprises of elements.
- Objects, elements and members of a set are synonymous terms.
- Sets are usually denoted by capital letters A, B, C,, etc.
- Elements of the set are represented by small letters a, b, c,, etc.

If 'a' is an element of set A, then we say that 'a' belongs to A. We denote the phrase 'belongs to' by the Greek symbol ' \in ' (epsilon). Thus, we say that **$a \in A$** .

If 'b' is an element which does not belong to A, we represent this as **$b \notin A$** .

Examples of sets:

1. Describe the set of vowels.

If A is the set of vowels, then A could be described as **$A = \{a, e, i, o, u\}$** .

2. Describe the set of positive integers.

Since it would be impossible to list *all* of the positive integers, we need to use a rule to describe this set. We might say A consists of all integers greater than zero.

3. Set $A = \{1, 2, 3\}$ and Set $B = \{3, 2, 1\}$. Is Set A equal to Set B ?

Yes. Two sets are equal if they have the same elements. The order in which the elements are listed does not matter.

4. What is the set of men with four arms?

Since all men have two arms at most, the set of men with four arms contains no elements. It is the null set (or empty set).

5. Set $A = \{1, 2, 3\}$ and Set $B = \{1, 2, 4, 5, 6\}$. Is Set A a subset of Set B ?

Set A would be a subset of Set B if every element from Set A were also in Set B . However, this is not the case. The number 3 is in Set A , but not in Set B . Therefore, Set A is not a subset of Set B .

Some important sets used in mathematics are

N: the set of all natural numbers = $\{1, 2, 3, 4, \dots\}$

Z: the set of all integers = $\{\dots, -3, -2, -1, 0, 1, 2, 3, \dots\}$

Q: the set of all rational numbers

R: the set of all real numbers

Z₊: the set of all positive integers

W: the set of all whole numbers

The different types of sets are explained below with examples.

1. Empty Set or Null Set:

A set which does not contain any element is called an empty set, or the null set or the void set and it is denoted by \emptyset and is read as phi. In roster form, \emptyset is denoted by $\{\}$. An empty set is a finite set, since the number of elements in an empty set is finite, i.e., 0.

For example: (a) the set of whole numbers less than 0.

(b) Clearly there is no whole number less than 0.

Therefore, it is an empty set.

(c) $N = \{x : x \in N, 3 < x < 4\}$

- Let $A = \{x : 2 < x < 3, x \text{ is a natural number}\}$

Here A is an empty set because there is no natural number between 2 and 3.

- Let $B = \{x : x \text{ is a composite number less than } 4\}$.

Here B is an empty set because there is no composite number less than 4.

Note:

$\emptyset \neq \{0\} \therefore$ has no element.

$\{0\}$ is a set which has one element 0.

The cardinal number of an empty set, i.e., $n(\emptyset) = 0$

2. Singleton Set:

A set which contains only one element is called a singleton set.

For example:

- $A = \{x : x \text{ is neither prime nor composite}\}$

It is a singleton set containing one element, i.e., 1.

- $B = \{x : x \text{ is a whole number, } x < 1\}$

This set contains only one element 0 and is a singleton set.

- Let $A = \{x : x \in N \text{ and } x^2 = 4\}$

Here A is a singleton set because there is only one element 2 whose square is 4.

- Let $B = \{x : x \text{ is a even prime number}\}$

Here B is a singleton set because there is only one prime number which is even, i.e., 2.

3. Finite Set:

A set which contains a definite number of elements is called a finite set. Empty set is also called a finite set.

For example:

- The set of all colors in the rainbow.
- $N = \{x : x \in N, x < 7\}$
- $P = \{2, 3, 5, 7, 11, 13, 17, \dots, 97\}$

4. Infinite Set:

The set whose elements cannot be listed, i.e., set containing never-ending elements is called an infinite set.

For example:

- Set of all points in a plane
- $A = \{x : x \in N, x > 1\}$
- Set of all prime numbers
- $B = \{x : x \in W, x = 2n\}$

Note:

All infinite sets cannot be expressed in roster form.

For example:

The set of real numbers since the elements of this set do not follow any particular pattern.

5. Cardinal Number of a Set:

The number of distinct elements in a given set A is called the cardinal number of A. It is denoted by $n(A)$. And read as 'the number of elements of the set'.

For example:

- $A = \{x : x \in \mathbb{N}, x < 5\}$

$$A = \{1, 2, 3, 4\}$$

$$\text{Therefore, } n(A) = 4$$

- $B = \text{set of letters in the word ALGEBRA}$

$$B = \{A, L, G, E, B, R\}$$

$$\text{Therefore, } n(B) = 6$$

6. Equivalent Sets:

Two sets A and B are said to be equivalent if their cardinal number is same, i.e., $n(A) = n(B)$. The symbol for denoting an equivalent set is ' \leftrightarrow '.

For example:

$$A = \{1, 2, 3\} \text{ Here } n(A) = 3$$

$$B = \{p, q, r\} \text{ Here } n(B) = 3$$

$$\text{Therefore, } A \leftrightarrow B$$

7. Equal sets:

Two sets A and B are said to be equal if they contain the same elements. Every element of A is an element of B and every element of B is an element of A.

For example:

$$A = \{p, q, r, s\}$$

$$B = \{p, s, r, q\}$$

$$\text{Therefore, } A = B$$

8. Disjoint Sets:

Two sets A and B are said to be disjoint, if they do not have any element in common.

For example;

$A = \{x : x \text{ is a prime number}\}$

$B = \{x : x \text{ is a composite number}\}.$

Clearly, A and B do not have any element in common and are disjoint sets.

9. Overlapping sets:

Two sets A and B are said to be overlapping if they contain at least one element in common.

For example;

• $A = \{a, b, c, d\}$

$B = \{a, e, i, o, u\}$

• $X = \{x : x \in \mathbb{N}, x < 4\}$

$Y = \{x : x \in \mathbb{I}, -1 < x < 4\}$

Here, the two sets contain three elements in common, i.e., (1, 2, 3)

10. Definition of Subset:

If A and B are two sets, and every element of set A is also an element of set B, then A is called a subset of B and we write it as $A \subseteq B$ or $B \supseteq A$

The symbol \subset stands for 'is a subset of' or 'is contained in'

- Every set is a subset of itself, i.e., $A \subset A$, $B \subset B$.
- Empty set is a subset of every set.
- Symbol ' \subseteq ' is used to denote 'is a subset of' or 'is contained in'.
- $A \subseteq B$ means A is a subset of B or A is contained in B.
- $B \subseteq A$ means B contains A.

Examples;

1. Let $A = \{2, 4, 6\}$

$B = \{6, 4, 8, 2\}$

Here A is a subset of B

Since, all the elements of set A are contained in set B.

But B is not the subset of A

Since, all the elements of set B are not contained in set A.

Notes:

If $A \subset B$ and $B \subset A$, then $A = B$, i.e., they are equal sets.

Every set is a subset of itself.

Null set or \emptyset is a subset of every set.

2. The set N of natural numbers is a subset of the set Z of integers and we write $N \subset Z$.

3. Let $A = \{2, 4, 6\}$

$B = \{x : x \text{ is an even natural number less than } 8\}$

Here $A \subset B$ and $B \subset A$.

Hence, we can say $A = B$

4. Let $A = \{1, 2, 3, 4\}$

$B = \{4, 5, 6, 7\}$

Here $A \not\subset B$ and also $B \not\subset A$

[$\not\subset$ denotes 'not a subset of']

11. Super Set:

Whenever a set A is a subset of set B, we say the B is a superset of A and we write, $B \supseteq A$.

Symbol \supseteq is used to denote 'is a super set of'

For example;

$$A = \{a, e, i, o, u\}$$

$$B = \{a, b, c, \dots, z\}$$

Here $A \subseteq B$ i.e., A is a subset of B but $B \supseteq A$ i.e., B is a super set of A

12. Proper Subset:

If A and B are two sets, then A is called the proper subset of B if $A \subseteq B$ but $B \supseteq A$ i.e., $A \neq B$. The symbol ' \subset ' is used to denote proper subset. Symbolically, we write $A \subset B$.

For example;

1. $A = \{1, 2, 3, 4\}$

Here $n(A) = 4$

$$B = \{1, 2, 3, 4, 5\}$$

Here $n(B) = 5$

We observe that, all the elements of A are present in B but the element '5' of B is not present in A.

So, we say that A is a proper subset of B.
Symbolically, we write it as $A \subset B$

Notes:

No set is a proper subset of itself.

Null set or \emptyset is a proper subset of every set.

2. $A = \{p, q, r\}$

$$B = \{p, q, r, s, t\}$$

Here A is a proper subset of B as all the elements of set A are in set B and also $A \neq B$.

Notes:

No set is a proper subset of itself.

Empty set is a proper subset of every set.

13. Power Set:

The collection of all subsets of set A is called the power set of A. It is denoted by $P(A)$. In $P(A)$, every element is a set.

For example;

If $A = \{p, q\}$ then all the subsets of A will be

$$P(A) = \{\emptyset, \{p\}, \{q\}, \{p, q\}\}$$

$$\text{Number of elements of } P(A) = n[P(A)] = 4 = 2^2$$

In general, $n[P(A)] = 2^m$ where m is the number of elements in set A.

14. Universal Set

A set which contains all the elements of other given sets is called a **universal set**. The symbol for denoting a universal set is U or ξ .

For example;

$$1. \text{ If } A = \{1, 2, 3\} \quad B = \{2, 3, 4\} \quad C = \{3, 5, 7\}$$

$$\text{then } U = \{1, 2, 3, 4, 5, 7\}$$

$$[\text{Here } A \subseteq U, B \subseteq U, C \subseteq U \text{ and } U \supseteq A, U \supseteq B, U \supseteq C]$$

2. If P is a set of all whole numbers and Q is a set of all negative numbers then the universal set is a set of all integers.

$$3. \text{ If } A = \{a, b, c\} \quad B = \{d, e\} \quad C = \{f, g, h, i\}$$

then $U = \{a, b, c, d, e, f, g, h, i\}$ can be taken as universal set.

Operations on sets:

1. Definition of Union of Sets:

Union of two given sets is the smallest set which contains all the elements of both the sets.

To find the union of two given sets A and B is a set which consists of all the elements of A and all the elements of B such that no element is repeated.

The symbol for denoting union of sets is ' \cup '.

Some properties of the operation of union:

- (i) $A \cup B = B \cup A$ (Commutative law)
- (ii) $A \cup (B \cap C) = (A \cup B) \cap C$ (Associative law)
- (iii) $A \cup \Phi = A$ (Law of identity element, is the identity of \cup)
- (iv) $A \cup A = A$ (Idempotent law)
- (v) $U \cup A = U$ (Law of U) U is the universal set.

Notes:

$A \cup \Phi = \Phi \cup A = A$ i.e. union of any set with the empty set is always the set itself.

Examples:

1. If $A = \{1, 3, 7, 5\}$ and $B = \{3, 7, 8, 9\}$. Find union of two set A and B.

Solution:

$$A \cup B = \{1, 3, 5, 7, 8, 9\}$$

No element is repeated in the union of two sets. The common elements 3, 7 are taken only once.

2. Let $X = \{a, e, i, o, u\}$ and $Y = \{\phi\}$. Find union of two given sets X and Y.

Solution:

$$X \cup Y = \{a, e, i, o, u\}$$

Therefore, union of any set with an empty set is the set itself.

2. Definition of Intersection of Sets:

Intersection of two given sets is the largest set which contains all the elements that are common to both the sets.

To find the intersection of two given sets A and B is a set which consists of all the elements which are common to both A and B.

The symbol for denoting intersection of sets is ' \cap '.

Some properties of the operation of intersection

(i) $A \cap B = B \cap A$ (Commutative law)

(ii) $(A \cap B) \cap C = A \cap (B \cap C)$ (Associative law)

(iii) $\Phi \cap A = \Phi$ (Law of Φ)

(iv) $U \cap A = A$ (Law of U)

(v) $A \cap A = A$ (Idempotent law)

(vi) $A \cap (B \cup C) = (A \cap B) \cup (A \cap C)$ (Distributive law) Here \cap distributes over \cup

Also, $A \cup (B \cap C) = (A \cup B) \cap (A \cup C)$ (Distributive law) Here \cup distributes over \cap

Notes:

$A \cap \Phi = \Phi \cap A = \Phi$ i.e. intersection of any set with the empty set is always the empty set.

Solved examples :

1. If $A = \{2, 4, 6, 8, 10\}$ and $B = \{1, 3, 8, 4, 6\}$. Find intersection of two set A and B.

Solution:

$$A \cap B = \{4, 6, 8\}$$

Therefore, 4, 6 and 8 are the common elements in both the sets.

2. If $X = \{a, b, c\}$ and $Y = \{\phi\}$. Find intersection of two given sets X and Y.

Solution:

$$X \cap Y = \{ \}$$

3. Difference of two sets

If A and B are two sets, then their difference is given by $A - B$ or $B - A$.

• If $A = \{2, 3, 4\}$ and $B = \{4, 5, 6\}$

$A - B$ means elements of A which are not the elements of B.

i.e., in the above example $A - B = \{2, 3\}$

In general, $B - A = \{x : x \in B, \text{ and } x \notin A\}$

- If A and B are disjoint sets, then $A - B = A$ and $B - A = B$

Solved examples to find the difference of two sets:

1. $A = \{1, 2, 3\}$ and $B = \{4, 5, 6\}$.

Find the difference between the two sets:

- (i) A and B
- (ii) B and A

Solution:

The two sets are disjoint as they do not have any elements in common.

- (i) $A - B = \{1, 2, 3\} = A$
- (ii) $B - A = \{4, 5, 6\} = B$

2. Let $A = \{a, b, c, d, e, f\}$ and $B = \{b, d, f, g\}$.

Find the difference between the two sets:

- (i) A and B
- (ii) B and A

Solution:

- (i) $A - B = \{a, c, e\}$

Therefore, the elements a, c, e belong to A but not to B

- (ii) $B - A = \{g\}$

Therefore, the element g belongs to B but not A.

4. Complement of a Set

In complement of a set if S be the universal set and A a subset of S then the complement of A is the set of all elements of S which are not the elements of A.

Symbolically, we denote the complement of A with respect to S as A' .

Some properties of complement sets

- (i) $A \cup A' = A' \cup A = U$ (Complement law)
- (ii) $(A \cap B') = \phi$ (Complement law) - The set and its complement are disjoint sets.
- (iii) $(A \cup B)' = A' \cap B'$ (De Morgan's law)
- (iv) $(A \cap B)' = A' \cup B'$ (De Morgan's law)
- (v) $(A')' = A$ (Law of complementation)
- (vi) $\Phi' = U$ (Law of empty set - The complement of an empty set is a universal set.
- (vii) $U' = \Phi$ and universal set) - The complement of a universal set is an empty set.

For Example; If $S = \{1, 2, 3, 4, 5, 6, 7\}$

$A = \{1, 3, 7\}$ find A' .

Solution:

We observe that 2, 4, 5, 6 are the only elements of S which do not belong to A .

Therefore, $A' = \{2, 4, 5, 6\}$

Algebraic laws on sets:

1. Commutative Laws:

For any two finite sets A and B ;

- (i) $A \cup B = B \cup A$
- (ii) $A \cap B = B \cap A$

2. Associative Laws:

For any three finite sets A , B and C ;

- (i) $(A \cup B) \cup C = A \cup (B \cup C)$
- (ii) $(A \cap B) \cap C = A \cap (B \cap C)$

Thus, union and intersection are associative.

3. Idempotent Laws:

For any finite set A;

(i) $A \cup A = A$

(ii) $A \cap A = A$

4. Distributive Laws:

For any three finite sets A, B and C;

(i) $A \cup (B \cap C) = (A \cup B) \cap (A \cup C)$

(ii) $A \cap (B \cup C) = (A \cap B) \cup (A \cap C)$

Thus, union and intersection are distributive over intersection and union respectively.

5. De Morgan's Laws:

For any two finite sets A and B;

(i) $A - (B \cup C) = (A - B) \cap (A - C)$

(ii) $A - (B \cap C) = (A - B) \cup (A - C)$

De Morgan's Laws can also be written as:

(i) $(A \cup B)' = A' \cap B'$

(ii) $(A \cap B)' = A' \cup B'$

More laws of algebra of sets:

6. For any two finite sets A and B;

(i) $A - B = A \cap B'$

(ii) $B - A = B \cap A'$

(iii) $A - B = A \Leftrightarrow A \cap B = \emptyset$

(iv) $(A - B) \cup B = A \cup B$

(v) $(A - B) \cap B = \emptyset$

$$(vi) (A - B) \cup (B - A) = (A \cup B) - (A \cap B)$$

Definition of De Morgan's law:

The complement of the union of two sets is equal to the intersection of their complements and the complement of the intersection of two sets is equal to the union of their complements. These are called **De Morgan's laws**.

For any two finite sets A and B;

(i) $(A \cup B)' = A' \cap B'$ (which is a De Morgan's law of union).

(ii) $(A \cap B)' = A' \cup B'$ (which is a De Morgan's law of intersection).

Venn Diagrams:

Pictorial representations of sets represented by closed figures are called set diagrams or Venn diagrams.

Venn diagrams are used to illustrate various operations like union, intersection and difference.

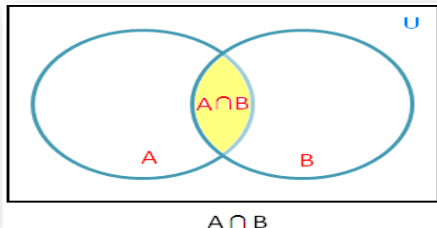
We can express the relationship among sets through this in a more significant way.

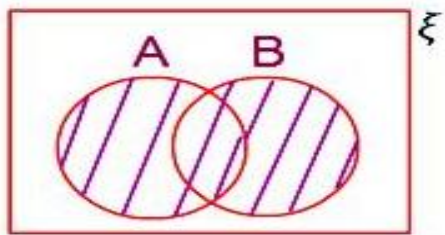
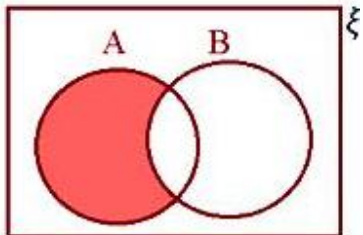
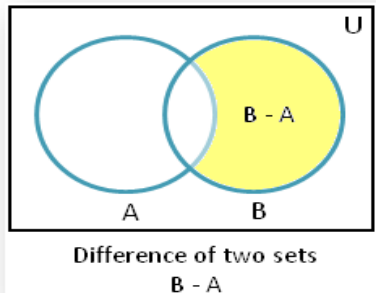
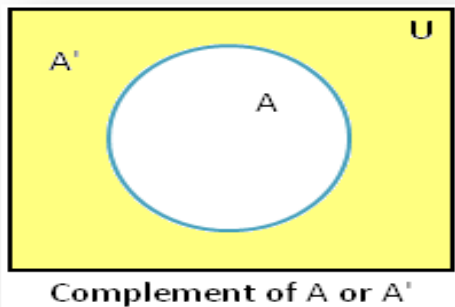
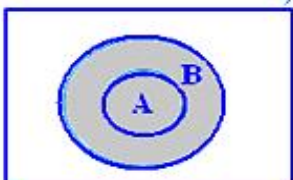
In this,

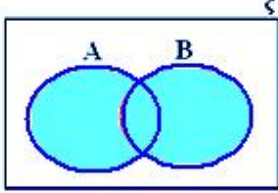
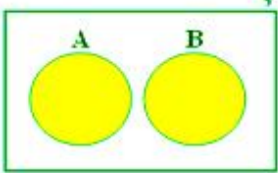
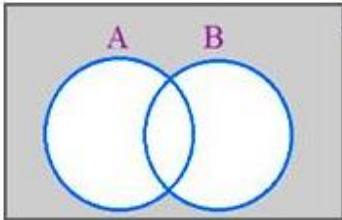
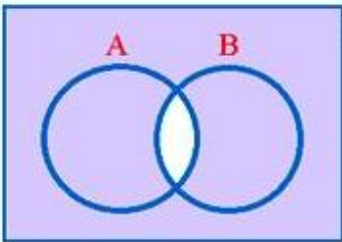
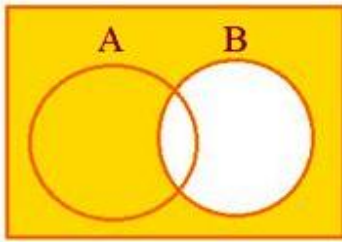
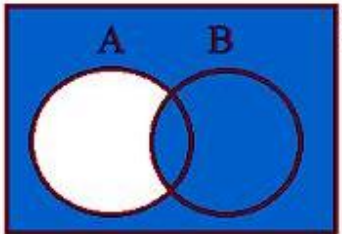
- A rectangle is used to represent a universal set.
- Circles or ovals are used to represent other subsets of the universal set.

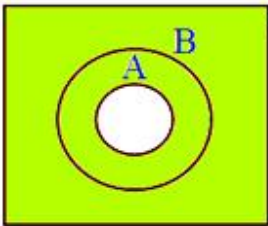
Venn diagrams in different situations

In these diagrams, the universal set is represented by a rectangular region and its subsets by circles inside the rectangle. We represented disjoint set by disjoint circles and intersecting sets by intersecting circles.

S.No	Set & Its relation	Venn Diagram
1	Intersection of A and B	

2	Union of A and B	
3	Difference : A-B	
4	Difference : B-A	
5	Complement of set A	
6	$A \cup B$ when $A \subset B$	

7	$A \cup B$ when neither $A \subset B$ nor $B \subset A$	
8	$A \cup B$ when A and B are disjoint sets	
9	$(A \cup B)'$ (A union B dash)	
10	$(A \cap B)'$ (A intersection B dash)	
11	B' (B dash)	
12	$(A - B)'$ (Dash of sets A minus B)	

13	$(A \subset B)'$ (Dash of A subset B)	
----	---------------------------------------	---

Problems of set theory:

1. Let A and B be two finite sets such that $n(A) = 20$, $n(B) = 28$ and $n(A \cup B) = 36$, find $n(A \cap B)$.

Solution:

Using the formula $n(A \cup B) = n(A) + n(B) - n(A \cap B)$.

then $n(A \cap B) = n(A) + n(B) - n(A \cup B)$

$$= 20 + 28 - 36$$

$$= 48 - 36$$

$$= 12$$

2. If $n(A - B) = 18$, $n(A \cup B) = 70$ and $n(A \cap B) = 25$, then find $n(B)$.

Solution:

Using the formula $n(A \cup B) = n(A - B) + n(A \cap B) + n(B - A)$

$$70 = 18 + 25 + n(B - A)$$

$$70 = 43 + n(B - A)$$

$$n(B - A) = 70 - 43$$

$$n(B - A) = 27$$

Now $n(B) = n(A \cap B) + n(B - A)$

$$= 25 + 27$$

$$= 52$$

3. In a group of 60 people, 27 like cold drinks and 42 like hot drinks and each person likes at least one of the two drinks. How many like both coffee and tea?

Solution:

Let A = Set of people who like cold drinks.

B = Set of people who like hot drinks.

Given

$$n(A \cup B) = 60 \quad n(A) = 27 \quad n(B) = 42 \text{ then;}$$

$$n(A \cap B) = n(A) + n(B) - n(A \cup B)$$

$$= 27 + 42 - 60$$

$$= 69 - 60 = 9$$

$$= 9$$

Therefore, 9 people like both tea and coffee.

4. There are 35 students in art class and 57 students in dance class. Find the number of students who are either in art class or in dance class.

- When two classes meet at different hours and 12 students are enrolled in both activities.
- When two classes meet at the same hour.

Solution:

$$n(A) = 35, \quad n(B) = 57, \quad n(A \cap B) = 12$$

(Let A be the set of students in art class.
B be the set of students in dance class.)

$$(i) \text{ When 2 classes meet at different hours } n(A \cup B) = n(A) + n(B) - n(A \cap B)$$

$$= 35 + 57 - 12$$

$$= 92 - 12$$

$$= 80$$

(ii) When two classes meet at the same hour, $A \cap B = \emptyset$ $n(A \cup B) = n(A) + n(B) - n(A \cap B)$

$$= n(A) + n(B)$$

$$= 35 + 57$$

$$= 92$$

5. In a group of 100 persons, 72 people can speak English and 43 can speak French. How many can speak English only? How many can speak French only and how many can speak both English and French?

Solution:

Let A be the set of people who speak English.

B be the set of people who speak French.

A - B be the set of people who speak English and not French.

B - A be the set of people who speak French and not English.

$A \cap B$ be the set of people who speak both French and English.

Given,

$$n(A) = 72 \quad n(B) = 43 \quad n(A \cup B) = 100$$

$$\text{Now, } n(A \cap B) = n(A) + n(B) - n(A \cup B)$$

$$= 72 + 43 - 100$$

$$= 115 - 100$$

$$= 15$$

Therefore, Number of persons who speak both French and English = 15

$$n(A) = n(A - B) + n(A \cap B)$$

$$\Rightarrow n(A - B) = n(A) - n(A \cap B)$$

$$= 72 - 15$$

$$= 57$$

$$\text{and } n(B - A) = n(B) - n(A \cap B)$$

$$= 43 - 15$$

$$= 28$$

Therefore, Number of people speaking English only = 57

Number of people speaking French only = 28

Probability Concepts

Before we give a definition of probability, let us examine the following concepts:

1. Experiment:

In probability theory, an **experiment** or **trial** (see below) is any procedure that can be infinitely repeated and has a well-defined set of possible outcomes, known as the sample space. An experiment is said to be *random* if it has more than one possible outcome, and *deterministic* if it has only one. A random experiment that has exactly two (mutually exclusive) possible outcomes is known as a Bernoulli trial.

Random Experiment:

An experiment is a random experiment if its outcome cannot be predicted precisely. One out of a number of outcomes is possible in a random experiment. A single performance of the random experiment is called a *trial*.

Random experiments are often conducted repeatedly, so that the collective results may be subjected to statistical analysis. A fixed number of repetitions of the same experiment can be thought of as a **composed experiment**, in which case the individual repetitions are called **trials**. For example, if one were to toss the same coin one hundred times and record each result, each toss would be considered a trial within the experiment composed of all hundred tosses.

Mathematical description of an experiment:

A random experiment is described or modeled by a mathematical construct known as a probability space. A probability space is constructed and defined with a specific kind of experiment or trial in mind.

A mathematical description of an experiment consists of three parts:

1. A sample space, Ω (or S), which is the set of all possible outcomes.
2. A set of events, where each event is a set containing zero or more outcomes.
3. The assignment of probabilities to the events—that is, a function P mapping from events to probabilities.

An *outcome* is the result of a single execution of the model. Since individual outcomes might be of little practical use, more complicated *events* are used to characterize groups of outcomes. The collection of all such events is a *sigma-algebra*. Finally, there is a need to specify each event's likelihood of happening; this is done using the *probability measure* function, P .

2. **Sample Space:** The sample space S is the collection of all possible outcomes of a random experiment. The elements of S are called **sample points**.

- A sample space may be *finite*, *countably infinite* or *uncountable*.
- A finite or countably infinite sample space is called a *discrete sample space*.
- An uncountable sample space is called a *continuous sample space*.

Ex:1. For the coin-toss experiment would be the results “Head” and “Tail”, which we may represent by $S = \{H, T\}$.

Ex. 2. If we toss a die, one sample space or the set of all possible outcomes is

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

The other sample space can be

$$S = \{\text{odd}, \text{even}\}$$

Types of Sample Space:

1. Finite/Discrete Sample Space:

Consider the experiment of tossing a coin twice.

The sample space can be

$S = \{HH, HT, TH, TT\}$ the above sample space has a finite number of sample points. It is called a finite sample space.

2. Countably Infinite Sample Space:

Consider that a light bulb is manufactured. It is then tested for its life length by inserting it into a socket and the time elapsed (in hours) until it burns out is recorded. Let the measuring instrument is capable of recording time to two decimal places, for example 8.32 hours.

Now, the sample space becomes count ably infinite i.e.

$$S = \{0.0, 0.01, 0.02\}$$

The above sample space is called a countable infinite sample space.

3. Un Countable/ Infinite Sample Space:

If the sample space consists of unaccountably infinite number of elements then it is called Un Countable/ Infinite Sample Space.

- 3. Event:** An event is simply a set of possible outcomes. To be more specific, an event is a subset A of the sample space S.

- $A \subseteq S$
- For a discrete sample space, all subsets are events.

Ex: For instance, in the coin-toss experiment the events $A=\{\text{Heads}\}$ and $B=\{\text{Tails}\}$ would be mutually exclusive.

An event consisting of a single point of the sample space 'S' is called a simple event or elementary event.

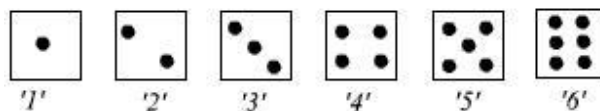
Some examples of event sets:

Example 1: tossing a fair coin

The possible outcomes are **H (head)** and **T (tail)**. The associated sample space is $S = \{H, T\}$ It is a finite sample space. The events associated with the sample space S are: $S, \{H\}, \{T\}$ and ϕ .

Example 2: Throwing a fair die:

The possible 6 outcomes are:



The associated finite sample space is $S = \{'1', '2', '3', '4', '5', '6'\}$. Some events are

A = The event of getting an odd face={ '1', '3', '5' }.

B = The event of getting a six={ '6' }

And so on.

Example 3: Tossing a fair coin until a head is obtained

We may have to toss the coin any number of times before a head is obtained. Thus the possible outcomes are:

H, TH, TTH, TTTH,

How many outcomes are there? The outcomes are countable but infinite in number. The countably infinite sample space is $S = \{H, TH, TTH, \dots\}$.

Example 4 : Picking a real number at random between -1 and +1

The associated Sample space is

$$S = \{s \mid s \in \mathbb{R}, -1 \leq s \leq 1\} = [-1, 1]$$

Clearly S is a continuous sample space.

Example 5: Drawing cards

Drawing 4 cards from a deck: Events include all spades, sum of the 4 cards is (assuming face cards have a value of zero), a sequence of integers, a hand with a 2, 3, 4 and 5. There are many more events.

Types of Events:

1. Exhaustive Events:

A set of events is said to be exhaustive, if it includes all the possible events.

Ex. In tossing a coin, the outcome can be either Head or Tail and there is no other possible outcome. So, the set of events { H , T } is exhaustive.

2. Mutually Exclusive Events:

Two events, A and B are said to be mutually exclusive if they cannot occur together.

i.e. if the occurrence of one of the events precludes the occurrence of all others, then such a set of events is said to be mutually exclusive.

If two events are mutually exclusive then the probability of either occurring is

$$P(A \text{ or } B) = P(A \cup B) = P(A) + P(B).$$

Ex. In tossing a die, both head and tail cannot happen at the same time.

3. Equally Likely Events:

If one of the events cannot be expected to happen in preference to another, then such events are said to be Equally Likely Events. (Or) Each outcome of the random experiment has an equal chance of occurring.

Ex. In tossing a coin, the coming of the head or the tail is equally likely.

4. Independent Events:

Two events are said to be independent, if happening or failure of one does not affect the happening or failure of the other. Otherwise, the events are said to be dependent.

If two events, A and B are independent then the joint probability is

$$P(A \text{ and } B) = P(A \cap B) = P(A)P(B),$$

5. Non-. Mutually Exclusive Events:

If the events are not mutually exclusive then

$$P(A \text{ or } B) = P(A) + P(B) - P(A \text{ and } B).$$

Probability Definitions and Axioms:

1. Relative frequency Definition:

Consider that an experiment E is repeated n times, and let A and B be two events associated with E . Let n_A and n_B be the number of times that the event A and the event B occurred among the n repetitions respectively.

The relative frequency of the event A in the ' n ' repetitions of E is defined as

$$f(A) = n_A / n$$

$f(A) = n_A / n$

The Relative frequency has the following properties:

$$1.0 \leq f(A) \leq 1$$

2. $f(A) = 1$ if and only if A occurs every time among the n repetitions.

If an experiment is repeated n times under similar conditions and the event A occurs in n_A times, then the probability of the event A is defined as

$$P(A) = \lim_{n \rightarrow \infty} \frac{n_A}{n}$$

Limitation:

Since we can never repeat an experiment or process indefinitely, we can never know the probability of any event from the relative frequency definition. In many cases we can't even obtain a long series of repetitions due to time, cost, or other limitations. For example, the probability of rain today can't really be obtained by the relative frequency definition since today can't be repeated again.

2. The classical definition:

Let the sample space (denoted by S) be the set of all possible distinct outcomes to an experiment. The probability of some event is

$$\frac{\text{number of ways the event can occur}}{\text{number of outcomes in } S},$$

provided all points in S are equally likely. For example, when a die is rolled the probability of getting a 2 is $\frac{1}{6}$ because one of the six faces is a 2.

Limitation:

What does "equally likely" mean? This appears to use the concept of probability while trying to define it! We could remove the phrase "provided all outcomes are equally likely", but then the definition would clearly be unusable in many settings where the outcomes in S did not tend to occur equally often.

Example1: A fair die is rolled once. What is the probability of getting a '6' ?

Here $S = \{ '1', '2', '3', '4', '5', '6' \}$ and $A = \{ '6' \}$

$$\therefore N = 6 \text{ and } N_A = 1$$

$$\therefore P(A) = \frac{1}{6}$$

Example2: A fair coin is tossed twice. What is the probability of getting two 'heads'?

Here $S = \{ HH, TH, HT, TT \}$ and $A = \{ HH \}$.

Total number of outcomes is 4 and all four outcomes are equally likely.

Only outcome favourable to A is $\{ HH \}$

$$\therefore P(A) = \frac{1}{4}$$

Probability axioms:

Given an event E in a sample space S which is either finite with N elements or countably infinite with $N = \infty$ elements, then we can write

$$S \equiv \left(\bigcup_{i=1}^N E_i \right),$$

and a quantity $P(E_i)$, called the probability of event E_i , is defined such that

Axiom1: The probability of any event A is positive or zero. Namely $P(A) \geq 0$. The probability measures, in a certain way, the difficulty of event A happening: the smaller the probability, the more difficult it is to happen. i.e

$$0 \leq P(E_i) \leq 1$$

Axiom2: The probability of the sure event is 1. Namely $P(\Omega) = 1$. And so, the probability is always greater than 0 and smaller than 1: probability zero means that there is no possibility for it to happen (it is an impossible event), and probability 1 means that it will always happen (it is a sure event).i.e

$$P(S) = 1.$$

Axiom3: The probability of the union of any set of two by two incompatible events is the sum of the probabilities of the events. That is, if we have, for example, events A, B, C , and these are two by two incompatible, then $P(A \cup B \cup C) = P(A) + P(B) + P(C)$. i.e Additivity:

$$P(E_1 \cup E_2) = P(E_1) + P(E_2), \text{ where } E_1 \text{ and } E_2 \text{ are mutually exclusive.}$$

$$P\left(\bigcup_{i=1}^n E_i\right) = \sum_{i=1}^n P(E_i) \text{ for } n = 1, 2, \dots, N \text{ where } E_1, E_2, \dots \text{ are mutually exclusive (i.e., } E_1 \cap E_2 = \emptyset).$$

Main properties of probability: If A is any event of sample space S then

1. $P(A) + P(\bar{A}) = 1$. Or $P(\bar{A}) = 1 - P(A)$
2. Since $A \cup \bar{A} = S$, $P(A \cup \bar{A}) = 1$
3. The probability of the impossible event is 0, i.e $P(\emptyset) = 0$
4. If $A \subset B$, then $P(A) \leq P(B)$.
5. If A and B are two incompatible events, and therefore, $P(A - B) = P(A) - P(A \cap B)$. and $P(B - A) = P(B) - P(A \cap B)$.
6. Addition Law of probability:

$$P(A \cup B) = P(A) + P(B) - P(A \cap B)$$

Rules of Probability:

Rule of Subtraction:

Rule of Subtraction The probability that event A will occur is equal to 1 minus the probability that event A will not occur.

$$P(A) = 1 - P(A')$$

Rule of Multiplication:

Rule of Multiplication The probability that Events A and B both occur is equal to the probability that Event A occurs times the probability that Event B occurs, given that A has occurred.

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

Rule of addition:

Rule of Addition The probability that Event A or Event B occurs is equal to the probability that Event A occurs plus the probability that Event B occurs minus the probability that both Events A and B occur.

$$P(A \cup B) = P(A) + P(B) - P(A \cap B)$$

Note: Invoking the fact that $P(A \cap B) = P(A)P(B|A)$, the Addition Rule can also be expressed as

$$P(A \cup B) = P(A) + P(B) - P(A)P(B|A)$$

PERMUTATIONS and COMBINATIONS:

S.No.	PERMUTATIONS	COMBINATIONS:
1	Arrangement of things in a specified order is called permutation. Here all things are taken at a time	In permutations, the order of arrangement of objects is important. But, in combinations, order is not important, but only selection of objects.
2	Arrangement of 'r' things taken at a time from 'n' things ,where $r < n$ in a specified order in called r-permutation.	
3	Consider the letters a,b and c . Considering all the three letters at a time, the possible permutations are ABC ,a c b , b c a , b a c , c b a and c a b .	
4	The number of permutations taking r things at a time from 'n' available things is denoted as $p(n, r)$ or $n P_r$	The number of combinations taking r things at a time from 'n' available things is denoted as $C(n, r)$ or $n C_r$
5	$n P_r = \frac{n!}{n-r!}$	$n C_r = \frac{n!}{r!(n-r)!}$

Example 1: An urn contains 6 red balls, 5 green balls and 4 blue balls. 9 balls were picked at random from the urn without replacement. What is the probability that out of the balls 4 are red, 3 are green and 2 are blue?

Sol:

$$9 \text{ balls can be picked from a population of 15 balls in } {}^{15}C_9 = \frac{15!}{9!6!}.$$

$$\frac{{}^6C_4 \times {}^5C_3 \times {}^4C_2}{{}^{15}C_9}$$

Therefore the required probability is

Example2: What is the probability that in a throw of 12 dice each face occurs twice.

Solution: The total number of elements in the sample space of the outcomes of a single throw of 12 dice is $= 6^{12}$

The number of favourable outcomes is the number of ways in which 12 dice can be arranged in six groups of size 2 each – group 1 consisting of two dice each showing 1, group 2

consisting of two dice each showing 2 and so on.
Therefore, the total number distinct groups

$$= \frac{12!}{2!2!2!2!2!2!}$$

Hence the required probability is
$$= \frac{12!}{(2)^6 6^{12}}$$

Conditional probability

The answer is the *conditional probability of B given A* denoted by $P(B/A)$. We shall develop the concept of the conditional probability and explain under what condition this conditional probability is same as $P(B)$.

<p style="text-align: center;"><i>Notation</i></p> <p>$P(B/A)$ = Conditional probability of B given A</p>
--

Let us consider the case of *equiprobable* events discussed earlier. Let N_{AB} sample points be favourable for the joint event $A \cap B$

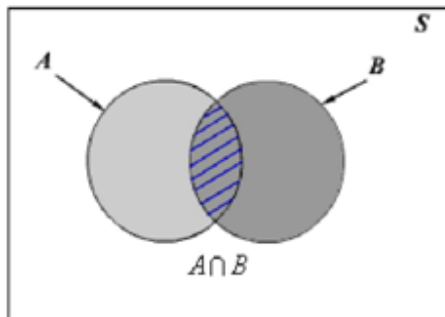


Figure 1

$$\begin{aligned}
 P(B/A) &= \frac{\text{Number of outcomes favourable to A and B}}{\text{Number of outcomes in A}} \\
 &= \frac{n(AB)}{n(A)} = \frac{\frac{n(AB)}{n}}{\frac{n(A)}{n}} = \frac{P(A \cap B)}{P(A)}
 \end{aligned}$$

This concept suggests us to define conditional probability. The probability of an event B under the condition that another event A has occurred is called the *conditional probability of B given A* and defined by

$$P(B / A) = \frac{P(A \cap B)}{P(A)}, \quad P(A) \neq 0$$

We can similarly define the *conditional probability of A given B*, denoted by $P(A / B)$.

From the definition of conditional probability, we have the joint probability $P(A \cap B)$ of two events A and B as follows

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

Problems:

Example 1 Consider the example tossing the fair die. Suppose

A = event of getting an even number = {2, 4, 6}

B = event of getting a number less than 4 = {1, 2, 3}

$\therefore A \cap B = \{2\}$

$$\therefore P(B / A) = \frac{P(A \cap B)}{P(A)} = \frac{1/6}{3/6} = \frac{1}{3}$$

Example 2 A family has two children. It is known that at least one of the children is a girl. What is the

probability that both the children are girls?

A = event of at least one girl

B = event of two girls

$S = \{gg, gb, bg, bb\}$, $A = \{gg, gb, bg\}$ and $B = \{gg\}$

$A \cap B = \{gg\}$

$$\therefore P(B / A) = \frac{P(A \cap B)}{P(A)} = \frac{1/4}{3/4} = \frac{1}{3}$$

Properties of Conditional probability:

1. If $B \subseteq A$, then $P(B/A) = 1$ and $P(A/B) \geq P(A)$

We have, $A \cap B = B$

$$\therefore P(B/A) = \frac{P(A \cap B)}{P(A)} = \frac{P(A)}{P(A)} = 1$$

and

$$\begin{aligned} P(A/B) &= \frac{P(A \cap B)}{P(B)} \\ &= \frac{P(A)P(B/A)}{P(B)} \\ &= \frac{P(A)}{P(B)} \\ &\geq P(A) \end{aligned}$$

2. Since $P(A \cap B) \geq 0, P(A) > 0$

$$\therefore P(B/A) = \frac{P(A \cap B)}{P(A)} \geq 0$$

3. We have, $\therefore P(S/A) = \frac{P(S \cap A)}{P(A)} = \frac{P(A)}{P(A)} = 1$

4. Chain Rule of Probability/Multiplication theorem:

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

We have,

$$\begin{aligned} (A \cap B \cap C) &= (A \cap B) \cap C \\ P(A \cap B \cap C) &= P(A \cap B)P(C/A \cap B) \\ &= P(A)P(B/A)P(C/A \cap B) \end{aligned}$$

$$\therefore P(A \cap B \cap C) = P(A)P(B/A)P(C/A \cap B)$$

We can generalize the above to get the *chain rule of probability for n events as*

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

Joint probability

Joint probability is defined as the probability of both A and B taking place, and is denoted by $P(AB)$ or $P(A \cap B)$

Joint probability is not the same as conditional probability, though the two concepts are often confused. Conditional probability assumes that one event has taken place or will take place, and then asks for the probability of the other (A, given B). Joint probability does not have such conditions; it simply asks for the chances of both happening (A and B). In a problem, to help distinguish between the two, look for qualifiers that one event is conditional on the other (conditional) or whether they will happen concurrently (joint).

Probability definitions can find their way into CFA exam questions. Naturally, there may also be questions that test the ability to calculate joint probabilities. Such computations require use of the multiplication rule, which states that the joint probability of A and B is the product of the conditional probability of A given B, times the probability of B. In probability notation:

$$P(AB) = P(A | B) * P(B)$$

Given a conditional probability $P(A | B) = 40\%$, and a probability of $B = 60\%$, the joint probability $P(AB) = 0.6 * 0.4$ or 24%, found by applying the multiplication rule.

$$P(A \cup B) = P(A) + P(B) - P(A \cap B)$$

For independent events: $P(AB) = P(A) * P(B)$

Moreover, the rule generalizes for more than two events provided they are all independent of one another, so the joint probability of three events $P(ABC) = P(A) * P(B) * P(C)$, again assuming independence.

Summary of probabilities

Event	Probability
A	$P(A) \in [0, 1]$
not A	$P(A^c) = 1 - P(A)$
A or B	$P(A \cup B) = P(A) + P(B) - P(A \cap B)$ $P(A \cup B) = P(A) + P(B)$ if A and B are mutually exclusive
A and B	$P(A \cap B) = P(A B)P(B) = P(B A)P(A)$ $P(A \cap B) = P(A)P(B)$ if A and B are independent
A given B	$P(A B) = \frac{P(A \cap B)}{P(B)} = \frac{P(B A)P(A)}{P(B)}$

Total Probability theorem:

Let A_1, A_2, \dots, A_n be n events such that
 $S = A_1 \cup A_2 \dots \cup A_n$ and $A_i \cap A_j = \emptyset$ for $i \neq j$. Then for any event B ,

$$P(B) = \sum_{i=1}^n P(A_i)P(B|A_i)$$

Proof: We have

$$\begin{aligned}\therefore P(B) &= P\left(\bigcup_{i=1}^n B \cap A_i\right) \\ &= \sum_{i=1}^n P(B \cap A_i) \\ &= \sum_{i=1}^n P(A_i)P(B|A_i)\end{aligned}$$

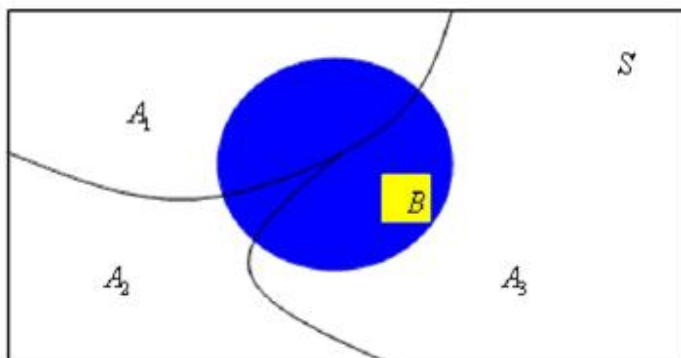


Figure 3

Remark

(1) A decomposition of a set S into 2 or more disjoint nonempty subsets is called a *partition* of S . The subsets A_1, A_2, \dots, A_n form a partition of S if
 $S = A_1 \cup A_2 \dots \cup A_n$ and $A_i \cap A_j = \emptyset$ for $i \neq j$.

(2) The theorem of total probability can be used to determine the probability of a complex event in terms of related simpler events. This result will be used in Bayes' theorem to be discussed to the end of the lecture.

Bayes' Theorem:

Suppose A_1, A_2, \dots, A_n are partitions on S such that $S = A_1 \cup A_2 \cup \dots \cup A_n$ and $A_i \cap A_j = \emptyset$ for $i \neq j$.

Suppose the event B occurs if one of the events A_1, A_2, \dots, A_n occurs. Thus we have the information of the probabilities $P(A_i)$ and $P(B|A_i)$, $i = 1, 2, \dots, n$. We ask the following question:

Given that B has occurred what is the probability that a particular event A_k has occurred? In other words what is $P(A_k|B)$?

We have $P(B) = \sum_{i=1}^n P(A_i) P(B|A_i)$ (Using the theorem of total probability)

$$\begin{aligned}\therefore P(A_k|B) &= \frac{P(A_k) P(B|A_k)}{P(B)} \\ &= \frac{P(A_k) P(B|A_k)}{\sum_{i=1}^n P(A_i) P(B|A_i)}\end{aligned}$$

This result is known as the Bayes' theorem. The probability $P(A_k)$ is called the *a priori* probability and $P(A_k|B)$ is called the *a posteriori* probability. Thus the Bayes' theorem enables us

to determine the *a posteriori* probability $P(A_k|B)$ from the observation that B has occurred. This result is of practical importance and is the heart of Bayesian classification, Bayesian estimation etc.

Example1:

In a binary communication system a zero and a one is transmitted with probability 0.6 and 0.4 respectively. Due to error in the communication system a zero becomes a one with a probability 0.1 and a one becomes a zero with a probability 0.08. Determine the probability (i) of receiving a one and (ii) that a one was transmitted when the received message is one

Solution:

Let S is the sample space corresponding to binary communication. Suppose T_0 be event of

Transmitting 0 and T_1 be the event of transmitting 1 and R_0 and R_1 be corresponding events of receiving 0 and 1 respectively.

Given $P(T_0) = 0.6$, $P(T_1) = 0.4$, $P(R_1/T_0) = 0.1$ and $P(R_0/T_1) = 0.08$.

$$\begin{aligned} \text{(i) } P(R_1) &= \text{Probability of receiving 'one'} \\ &= P(T_1)P(R_1/T_1) + P(T_0)P(R_1/T_0) \\ &= 0.4 \times 0.92 + 0.6 \times 0.1 \\ &= 0.448 \end{aligned}$$

(ii) Using the Baye's rule

$$\begin{aligned} P(T_1/R_1) &= \frac{P(T_1)P(R_1/T_1)}{P(R_1)} \\ &= \frac{P(T_1)P(R_1/T_1)}{P(T_1)P(R_1/T_1) + P(T_0)P(R_1/T_0)} \\ &= \frac{0.4 \times 0.92}{0.4 \times 0.92 + 0.6 \times 0.1} \\ &= 0.8214 \end{aligned}$$

Example 7: In an electronics laboratory, there are identically looking capacitors of three makes A_1, A_2 and A_3 in the ratio 2:3:4. It is known that 1% of A_1 , 1.5% of A_2 and 2% of A_3 are defective. What percentages of capacitors in the laboratory are defective? If a capacitor picked at defective is found to be defective, what is the probability it is of make A_3 ?

Let D be the event that the item is defective. Here we have to find $P(D)$ and $P(A_3/D)$.

$$\begin{aligned} P(A_1) &= \frac{2}{9}, P(A_2) = \frac{1}{3} \text{ and } P(A_3) = \frac{4}{9} \\ P(D/A_1) &= 0.01, P(D/A_2) = 0.015 \text{ and } P(D/A_3) = 0.02 \end{aligned}$$

$$\begin{aligned} \therefore P(D) &= P(A_1)P(D/A_1) + P(A_2)P(D/A_2) + P(A_3)P(D/A_3) \\ &= \frac{2}{9} \times 0.01 + \frac{1}{3} \times 0.015 + \frac{4}{9} \times 0.02 \\ &= 0.0167 \end{aligned}$$

and

$$\begin{aligned} P(A_3/D) &= \frac{P(A_3)P(D/A_3)}{P(D)} \\ &= \frac{\frac{4}{9} \times 0.02}{0.0167} \\ &= 0.533 \end{aligned}$$

Independent events

Two events are called *independent* if the probability of occurrence of one event does not affect the probability of occurrence of the other. Thus the events A and B are independent if

$$P(B|A) = P(B) \text{ and } P(A|B) = P(A)$$

where $P(A)$ and $P(B)$ are assumed to be non-zero.

Equivalently if A and B are independent, we have

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

or

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

Joint probability is the product of individual probabilities.

Two events A and B are called statistically *dependent* if they are not independent. Similarly, we can define the independence of n events. The events A_1, A_2, \dots, A_n are called independent if and only if

$$P(A_i \cap A_j) = P(A_i)P(A_j)$$

$$P(A_i \cap A_j \cap A_k) = P(A_i)P(A_j)P(A_k)$$

$$P(A_i \cap A_j \cap A_k \cap \dots A_n) = P(A_i)P(A_j)P(A_k) \dots P(A_n)$$

Example: Consider the example of tossing a fair coin twice. The resulting sample space is given by $S = \{HH, HT, TH, TT\}$ and all the outcomes are equiprobable.

Let $A = \{TH, TT\}$ be the event of getting 'tail' in the first toss and $B = \{TH, HH\}$ be the event of getting 'head' in the second toss. Then

$$P(A) = \frac{1}{2} \text{ and } P(B) = \frac{1}{2}$$

Again, $(A \cap B) = \{TH\}$ so that

$$P(A \cap B) = \frac{1}{4} = P(A)P(B)$$

Hence the events A and B are independent.

Problems:

Example 1. A dice of six faces is tailored so that the probability of getting every face is proportional to the number depicted on it.

a) What is the probability of extracting a 6?

In this case, we say that the probability of each face turning up is not the same, therefore we cannot simply apply the rule of Laplace. If we follow the statement, it says that the probability of each face turning up is proportional to the number of the face itself, and this means that, if we say that the probability of face 1 being turned up is k which we do not know, then:

$$P(\{1\})=k, P(\{2\})=2k, P(\{3\})=3k, P(\{4\})=4k,$$

$$P(\{5\})=5k, P(\{6\})=6k.$$

Now, since $\{1\}, \{2\}, \{3\}, \{4\}, \{5\}, \{6\}$ form an events complete system, necessarily

$$P(\{1\})+P(\{2\})+P(\{3\})+P(\{4\})+P(\{5\})+P(\{6\})=1$$

Therefore

$$k+2k+3k+4k+5k+6k=1$$

which is an equation that we can already solve:

$$21k=1$$

thus

$$k=1/21$$

And so, the probability of extracting 6 is $P(\{6\})=6k=6 \cdot (1/21)=6/21$.

b) What is the probability of extracting an odd number?

The cases favourable to event A = "to extract an odd number" are: $\{1\}, \{3\}, \{5\}$. Therefore, since they are incompatible events,

$$P(A)=P(\{1\})+P(\{3\})+P(\{5\})=k+3k+5k=9k=9 \cdot (1/21)=9/21$$

Example2: Roll a red die and a green die. Find the probability the total is 5.

Solution: Let (x,y) represent getting x on the red die and y on the green die.

$$S = \{ \begin{array}{cccccc} (1,1) & (1,2) & (1,3) & \cdots & (1,6) \\ (2,1) & (2,2) & (2,3) & \cdots & (2,6) \\ (3,1) & (3,2) & (3,3) & \cdots & (3,6) \\ & \text{---} & \text{---} & \text{---} & \\ (6,1) & (6,2) & (6,3) & \cdots & (6,6) \end{array} \}$$

Then, with these as simple events, the sample space is

The sample points giving a total of 5 are (1,4) (2,3) (3,2), and (4,1).

$$\text{Therefore } P(\text{total is 5}) = \frac{4}{36}$$

Example3: Suppose the 2 dice were now identical red dice. Find the probability the total is 5.

Solution : Since we can no longer distinguish between (x,y) and (y,x) , the only distinguishable points in S are

$$S = \{ \begin{array}{cccc} (1,1) & (1,2) & (1,3) & \cdots & (1,6) \\ & (2,2) & (2,3) & \cdots & (2,6) \\ & & (3,3) & \cdots & (3,6) \\ & & & \cdots & \cdots \\ & & & & (6,6) \end{array} \} :$$

Using this sample space, we get a total of 5 from points (1,4) and (2,3) only. If we assign equal probability $\frac{1}{21}$ to each point (simple event) then we get $P(\text{total is 5}) = \frac{2}{21}$.

Example4: Draw 1 card from a standard well-shuffled deck (13 cards of each of 4 suits - spades, hearts, diamonds, and clubs). Find the probability the card is a club.

Solution 1: Let $S = \{ \text{spade, heart, diamond, club} \}$. (The points of S are generally listed between brackets $\{ \}$.) Then S has 4 points, with 1 of them being "club", so $P(\text{club}) = \frac{1}{4}$.

Solution 2: Let $S = \{ \text{each of the 52 cards} \}$. Then 13 of the 52 cards are clubs, so

$$P(\text{club}) = \frac{13}{52} = \frac{1}{4}.$$

Example 5: Suppose we draw a card from a deck of playing cards. What is the probability that we draw a spade?

Solution: The sample space of this experiment consists of 52 cards, and the probability of each sample point is $1/52$. Since there are 13 spades in the deck, the probability of drawing a spade is

$$P(\text{Spade}) = (13)(1/52) = 1/4$$

Example 6: Suppose a coin is flipped 3 times. What is the probability of getting two tails and one head?

Solution: For this experiment, the sample space consists of 8 sample points.

$$S = \{TTT, TTH, THT, THH, HTT, HTH, HHT, HHH\}$$

Each sample point is equally likely to occur, so the probability of getting any particular sample point is $1/8$. The event "getting two tails and one head" consists of the following subset of the sample space.

$$A = \{TTH, THT, HTT\}$$

The probability of Event A is the sum of the probabilities of the sample points in A. Therefore,

$$P(A) = 1/8 + 1/8 + 1/8 = 3/8$$

Example7: An urn contains 6 red marbles and 4 black marbles. Two marbles are drawn *without replacement* from the urn. What is the probability that both of the marbles are black?

Solution: Let A = the event that the first marble is black; and let B = the event that the second marble is black. We know the following:

- In the beginning, there are 10 marbles in the urn, 4 of which are black. Therefore, $P(A) = 4/10$.
- After the first selection, there are 9 marbles in the urn, 3 of which are black. Therefore, $P(B|A) = 3/9$.

Therefore, based on the rule of multiplication:

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

$$P(A \cap B) = (4/10) * (3/9) = 12/90 = 2/15$$

RANDOM VARIABLE

INTRODUCTION

In many situations, we are interested in numbers associated with the outcomes of a random experiment. In application of probabilities, we are often concerned with numerical values which are random in nature. For example, we may consider the number of customers arriving at a service station at a particular interval of time or the transmission time of a message in a communication system. These random quantities may be considered as real-valued function on the sample space. Such a real-valued function is called real random variable and plays an important role in describing random data. We shall introduce the concept of random variables in the following sections.

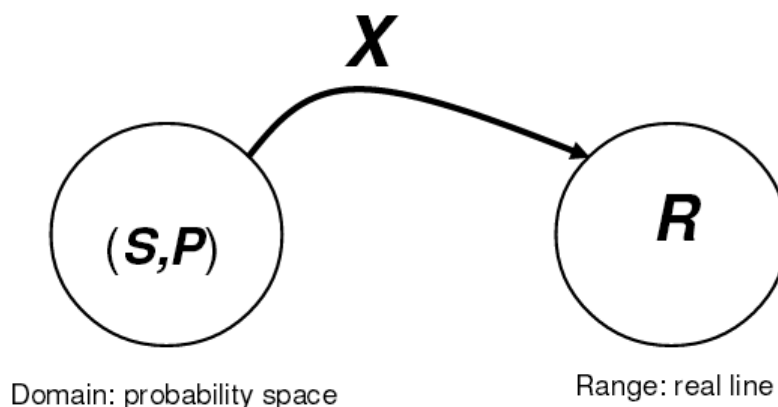
Random Variable Definition

A random variable is a function that maps outcomes of a random experiment to real numbers. (or)

A random variable associates the points in the sample space with real numbers

A (real-valued) random variable, often denoted by X (or some other capital letter), is a function mapping a probability space $(S; P)$ into the real line R . This is shown in Figure 1. Associated with each point s in the domain S the function X assigns one and only one value $X(s)$ in the range R . (The set of possible values of $X(s)$ is usually a proper subset of the real line; i.e., not all real numbers need occur. If S is a finite set with m elements, then $X(s)$ can assume at most an m different value as s varies in S .)

A random variable: a function



Example1

A fair coin is tossed 6 times. The number of heads that come up is an example of a random variable.

HHTTHT – 3, THHTTT -- 2.

These random variables can only take values between 0 and 6. The

Set of possible values of random variables is known as its Range.

Example2

A box of 6 eggs is rejected once it contains one or more broken eggs. If we examine 10 boxes of eggs and define the random variables X_1 , X_2 as

1 X_1 - the number of broken eggs in the 10 boxes

2 X_2 - the number of boxes rejected

Then the range of X_1 is $\{0, 1, 2, 3, 4, \dots, 60\}$ and X_2 is $\{0, 1, 2, \dots, 10\}$

Figure 2: A (real-valued) function of a random variable is itself a random variable, i.e., a function mapping a probability space into the real line.

Example 3 Consider the example of tossing a fair coin twice. The sample space is $S = \{HH, HT, TH, TT\}$ and all four outcomes are equally likely. Then we can define a random variable X as follows

Sample Point	Value of the random Variable
HH	0
HT	1
TH	2
TT	3

Here $R_X = \{0, 1, 2, 3\}$.

Example 4 Consider the sample space associated with the single toss of a fair die. The sample space is given by $S = \{1, 2, 3, 4, 5, 6\}$.

If we define the random variable X that associates a real number equal to the number on the face of the die, then $R_X = \{1, 2, 3, 4, 5, 6\}$.

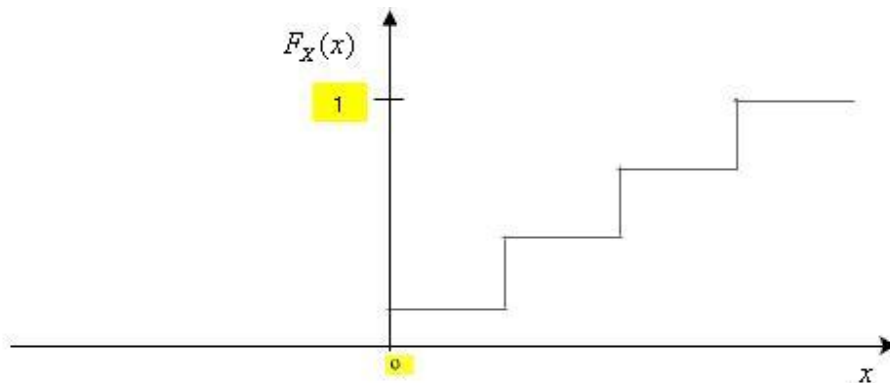
Types of random variables:

There are two types of random variables, *discrete* and *continuous*.

1. Discrete random variable:

A *discrete random variable* is one which may take on only a countable number of distinct values such as 0, 1, 2, 3, 4, Discrete random variables are usually (but not necessarily) counts. If a random variable can take only a finite number of distinct values, then it must be discrete
(Or)

A random variable X is called a **discrete random variable** if $F_X(x)$ is piece-wise constant. Thus $F_X(x)$ is flat except at the points of jump discontinuity. If the sample space S is discrete the random variable X defined on it is always discrete.



Plot of Distribution function of *discrete random variable*

- A discrete random variable has a finite number of possible values or an infinite sequence of countable real numbers.
- X: number of hits when trying 20 free throws.
- X: number of customers who arrive at the bank from 8:30 – 9:30AM Mon--Fri.
- E.g. Binomial, Poisson...

2. Continuous random variable:

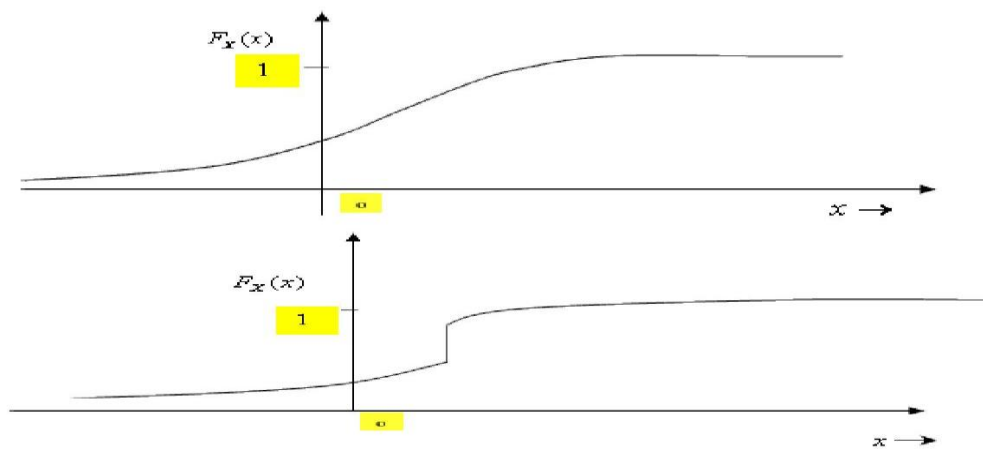
A **continuous random variable** is one which takes an infinite number of possible values. Continuous random variables are usually measurements. E

A continuous random variable takes all values in an interval of real numbers.
(or)

X is called a **continuous random variable** if $F_X(x)$ is an absolutely continuous function of x . Thus $F_X(x)$ is continuous everywhere on \mathbb{R} and $F_X'(x)$ exists everywhere except at finite or countably infinite points

3. Mixed random variable:

X is called a **mixed random variable** if $F_X(x)$ has jump discontinuity at countable number of points and increases continuously at least in one interval of X . For a such type RV X .



Plot of Distribution function of *continuous and mixed random variables*

UNIT II

Distribution and density functions and Operations on One Random Variable

Distribution and density functions:

- Distribution function and its Properties
- Density function and its Properties
- Important Types of Distribution and density functions
 - Binomial, Poisson
 - Uniform
 - Exponential
 - Gaussian
 - Rayleigh
- Conditional Distribution
- Methods of defining Conditioning Event
- Conditional Density function and its properties
- Problems

Operation on One Random Variable:

- Expected value of a random variable, function of a random variable
- Moments about the origin
- Central moments - variance and skew
- Characteristic function
- Moment generating function
- Transformations of a random variable
 - Monotonic transformations for a continuous random variable
 - Non monotonic transformations of continuous random variable
 - Transformations of Discrete random variable

UNIT-II

DISTRIBUTION AND DENSITY FUNCTIONS AND OPERATIONS ON ONE RANDOM VARIABLE

Probability Distribution

The probability distribution of a discrete random variable is a list of probabilities associated with each of its possible values. It is also sometimes called the probability function or the probability mass function.

More formally, the probability distribution of a discrete random variable X is a function which gives the probability $p(x_i)$ that the random variable equals x_i , for each value x_i :

$$p(x_i) = P(X=x_i)$$

It satisfies the following conditions:

- a. $0 \leq p(x_i) \leq 1$
- b. $\sum p(x_i) = 1$

Cumulative Distribution Function

All random variables (discrete and continuous) have a cumulative distribution function. It is a function giving the probability that the random variable X is less than or equal to x , for every value x .

Formally, the cumulative distribution function $F(x)$ is defined to be:

$$F(x) = P(X \leq x)$$

for

$$-\infty < x < \infty$$

For a discrete random variable, the cumulative distribution function is found by summing up the probabilities as in the example below.

For a continuous random variable, the cumulative distribution function is the integral of its probability density function.

Example

Discrete case : Suppose a random variable X has the following probability distribution $p(x_i)$:

$$x_i \quad 0 \quad 1 \quad 2 \quad 3 \quad 4 \quad 5$$

$$p(x_i) \quad 1/32 \quad 5/32 \quad 10/32 \quad 10/32 \quad 5/32 \quad 1/32$$

This is actually a binomial distribution: $Bi(5, 0.5)$ or $B(5, 0.5)$. The cumulative distribution function $F(x)$ is then:

$$x_i \quad 0 \quad 1 \quad 2 \quad 3 \quad 4 \quad 5$$

$$F(x_i) \quad 1/32 \quad 6/32 \quad 16/32 \quad 26/32 \quad 31/32 \quad 32/32$$

$F(x)$ does not change at intermediate values. For example:

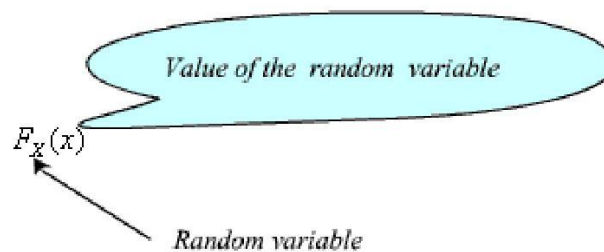
$$F(1.3) = F(1) = 6/32 \quad \text{and} \quad F(2.86) = F(2) = 16/32$$

Probability Distribution Function

The probability $P(\{X \leq x\}) = P(\{s \mid X(s) \leq x, s \in S\})$ is called the *probability distribution function* (also called the *cumulative distribution function*, abbreviated as *CDF*) of X and

denoted by $F_X(x)$. Thus

$$F_X(x) = P(\{X \leq x\})$$



Properties of the Distribution Function

$$1. \quad 0 \leq F_X(x) \leq 1$$

$$2. \quad F_X(x) \text{ is a non-decreasing function of } X. \text{ Thus, if } x_1 < x_2, \text{ then } F_X(x_1) < F_X(x_2)$$

$$x_1 < x_2$$

$$\Rightarrow \{X(s) \leq x_1\} \subseteq \{X(s) \leq x_2\}$$

$$\Rightarrow P\{X(s) \leq x_1\} \leq P\{X(s) \leq x_2\}$$

$$\therefore F_X(x_1) < F_X(x_2)$$

$$\square \quad F_X(x) \text{ Is right continuous.}$$

$$F_X(x^+) = \lim_{\substack{h \rightarrow 0 \\ h > 0}} F_X(x+h) = F_X(x)$$

$$\text{Because, } \lim_{\substack{h \rightarrow 0 \\ h > 0}} F_X(x+h) = \lim_{\substack{h \rightarrow 0 \\ h > 0}} P\{X(s) \leq x+h\}$$

$$= P\{X(s) \leq x\}$$

$$= F_X(x)$$

$$3. \quad F_X(-\infty) = 0$$

Because, $F_X(-\infty) = P(S | X(S) \leq -\infty) = P(\emptyset) = 0$.

4. $F_X(\infty) = 1$
5. $P(\{x_1 < X \leq x_2\}) = F_X(x_2) - F_X(x_1 | \leq \infty) = P(S) = 1$

We have,

$$\begin{aligned}
 F_X(x^-) &= \lim_{\substack{h \rightarrow 0 \\ h > 0}} F_X(x - h) \\
 &= \lim_{h \rightarrow 0} P\{X(s) \leq x - h\} \\
 6. \quad P(\{X > x\}) &= P(\{x < X < \infty\}) = 1 - F_X(x) \\
 &= P\{X(s) \leq x\} - P(X(s) = x) \\
 &= F_X(x) - P(X = x)
 \end{aligned}$$

Example: Consider the random variable X in the above example. We have

Value of the random Variable $X = x$	$P(\{X = x\})$
0	1/4
1	1/4
2	1/4
3	1/4

For $x < 0$,

$$F_X(x) = P(\{X \leq x\}) = 0$$

For $0 \leq x < 1$,

$$F_X(x) = P(\{X \leq x\}) = P(\{X = 0\}) = \frac{1}{4}$$

For $1 \leq x < 2$,

$$\begin{aligned}
 F_X(x) &= P(\{X \leq x\}) \\
 &= P(\{X = 0\} \cup \{X = 1\}) \\
 &= P(\{X = 0\}) + P(\{X = 1\}) \\
 &= \frac{1}{4} + \frac{1}{4} = \frac{1}{2}
 \end{aligned}$$

For $2 \leq x < 3$,

$$\begin{aligned}
 F_X(x) &= P(\{X \leq x\}) \\
 &= P(\{X = 0\} \cup \{X = 1\} \cup \{X = 2\}) \\
 &= P(\{X = 0\}) + P(\{X = 1\}) + P(\{X = 2\}) \\
 &= \frac{1}{4} + \frac{1}{4} + \frac{1}{4} = \frac{3}{4}
 \end{aligned}$$

For $x \geq 3$,

$$\begin{aligned}
 F_X(x) &= P(\{X \leq x\}) \\
 &= P(S) \\
 &= 1
 \end{aligned}$$

For $2 \leq x < 3$,

$$\begin{aligned} F_X(x) &= P(\{X \leq x\}) \\ &= P(\{X = 0\} \cup \{X = 1\} \cup \{X = 2\}) \\ &= P(\{X = 0\}) + P(\{X = 1\}) + P(\{X = 2\}) \\ &= \frac{1}{4} + \frac{1}{4} + \frac{1}{4} = \frac{3}{4} \end{aligned}$$

Thus we have seen that given $F_X(x)$, $-\infty < x < \infty$, we can determine the probability of any event involving values of the random variable X . Thus $F_X(x) \forall x \in X$ is a complete description of the random variable X .

Example 5 Consider the random variable X defined by

$$\begin{aligned} F_X(x) &= 0, & x < -2 \\ &= \frac{1}{8}x + \frac{1}{4}, & -2 \leq x < 0 \\ &= 1, & x \geq 0 \end{aligned}$$

Find a) $P(X = 0)$.

b) $P\{X \leq 0\}$.

c) $P\{X > 2\}$.

d) $P\{-1 < X \leq 1\}$.

Solutio

$$\begin{aligned} \text{a) } P(X = 0) &= F_X(0^+) - F_X(0^-) \\ &= 1 - \frac{1}{4} = \frac{3}{4} \end{aligned}$$

$$\begin{aligned} \text{b) } P\{X \leq 0\} &= F_X(0) \\ &= 1 \end{aligned}$$

$$\begin{aligned} \text{c) } P\{X > 2\} &= 1 - F_X(2) \\ &= 1 - 1 = 0 \end{aligned}$$

Probability Density Function

The probability density function of a continuous random variable is a function which can be integrated to obtain the probability that the random variable takes a value in a given interval.

More formally, the probability density function, $f(x)$, of a continuous random variable X is the derivative of the cumulative distribution function $F(x)$:

$$f(x) = \frac{d}{dx} F(x)$$

Since $F(x) = P(X \leq x)$ it follows that:

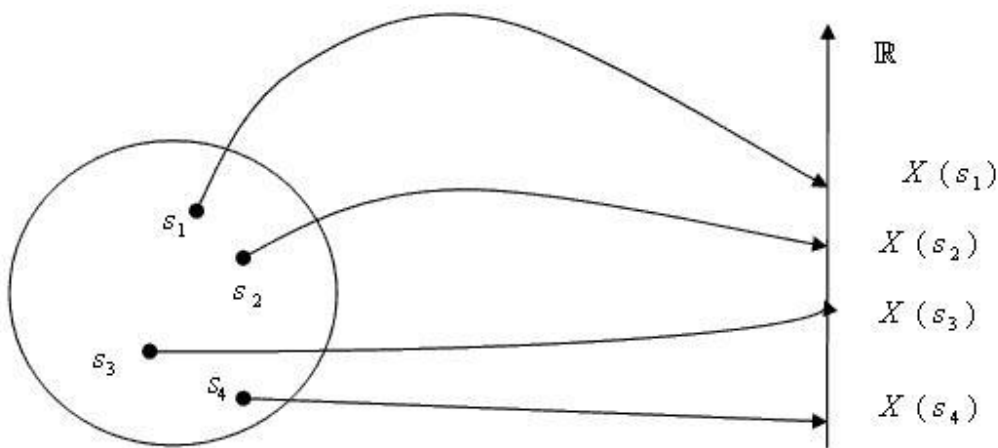
$$\int_a^b f(x) dx = F(b) - F(a) = P(a < X < b)$$

If $f(x)$ is a probability density function then it must obey two conditions:

- that the total probability for all possible values of the continuous random variable X is 1:

$$\int_{-\infty}^{\infty} f(x) dx = 1$$

- that the probability density function can never be negative: $f(x) \geq 0$ for all x .

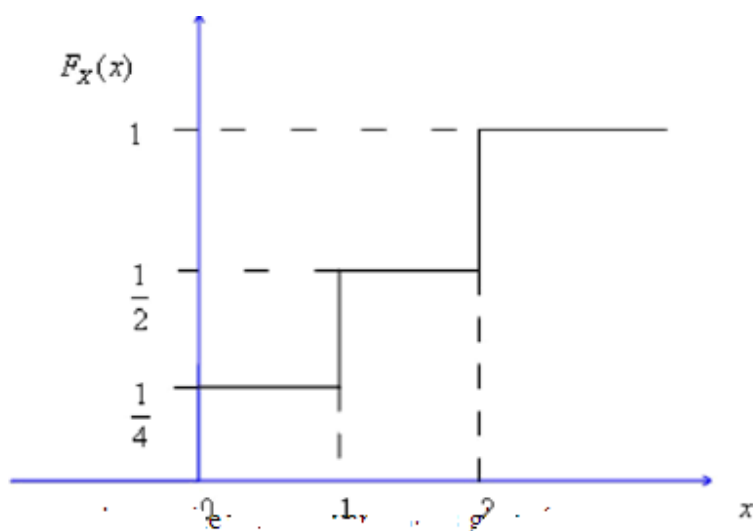


Example 1

Consider the random variable X with the distribution function

$$F_X(x) = \begin{cases} 0 & x < 0 \\ \frac{1}{4} & 0 \leq x < 1 \\ \frac{1}{2} & 1 \leq x < 2 \\ 1 & x \geq 2 \end{cases}$$

The plot of the $F_X(x)$ is shown in Figure 7 on next page.



The probability mass function of the random variable is given by

Value of the random variable $X = x$	$p_X(x)$
0	$\frac{1}{4}$
1	$\frac{1}{4}$
2	$\frac{1}{2}$

Properties of the Probability Density Function

1. $f_X(x) \geq 0$.----- This follows from the fact that $F_X(x)$ is a non-decreasing function

2.
$$F_X(x) = \int_{-\infty}^x f_X(u) du$$

3.
$$\int_{-\infty}^{\infty} f_X(x) dx = 1$$

4.
$$P(x_1 < X \leq x_2) = \int_{x_1}^{x_2} f_X(x) dx$$

Other Distribution and density functions of Random variable:

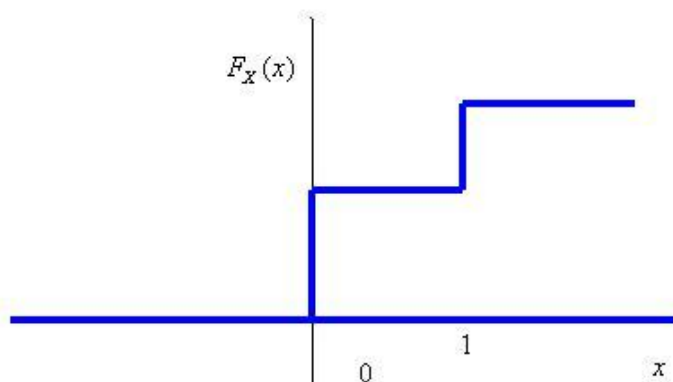
1. Bernoulli random variable:

Suppose X is a random variable that takes two values 0 and 1, with probability mass functions

$$\begin{aligned} p_X(1) &= P\{X=1\} = p \\ \text{And} \quad p_X(0) &= 1-p, \quad 0 \leq p \leq 1 \end{aligned}$$

Such a random variable X is called a **Bernoulli random variable**, because it describes the outcomes of a **Bernoulli trial**.

The typical CDF of the Bernoulli RV X is as shown in Figure 2



Mean and variance of the Bernoulli random:

$$\mu_X = EX = \sum_{k=0}^1 k p_X(k) = 1 \times p + 0 \times (1-p) = p$$

$$EX^2 = \sum_{k=0}^1 k^2 p_X(k) = 1 \times p + 0 \times (1-p) = p$$

$$\therefore \sigma_X^2 = EX^2 - \mu_X^2 = p(1-p)$$

Remark

- The Bernoulli RV is the simplest discrete RV. It can be used as the building block for many discrete RVs.
- For the Bernoulli RV,

$$EX^m = p \quad m = 1, 2, 3, \dots$$

Thus all the moments of the Bernoulli RV have the same value of p .

2. Binomial random variable

Suppose X is a discrete random variable taking values from the set $\{0, 1, \dots, n\}$. X is called a binomial random variable with parameters n and $0 \leq p \leq 1$ if

$$p_X(k) = {}^nC_k p^k (1-p)^{n-k} \quad k = 0, 1, \dots, n$$

where

$${}^nC_k = \frac{n!}{k!(n-k)!}$$

The trials must meet the following requirements:

- a. the total number of trials is fixed in advance;
- b. there are just two outcomes of each trial; success and failure;
- c. the outcomes of all the trials are statistically independent;
- d. all the trials have the same probability of success.

As we have seen, the probability of k successes in n independent repetitions of the Bernoulli trial is given by the binomial law. If X is a discrete random variable representing the number of successes in this case, then X is a binomial random variable. For example, the number of heads in 'n' independent tossing of a fair coin is a binomial random variable.

- The notation $X \sim B(n, p)$ is used to represent a binomial RV with the parameters n and

- p .
- $\sum_{k=0}^n p_X(k) = \sum_{k=0}^n {}^nC_k p^k (1-p)^{n-k} = [p + (1-p)]^n = 1$.
 - The sum of n independent identically distributed Bernoulli random variables is a binomial random variable.
 - The binomial distribution is useful when there are two types of objects - good, bad; correct, erroneous; healthy, diseased etc

Example1: In a binary communication system, the probability of bit error is 0.01. If a block of 8 bits are transmitted, find the probability that

- Exactly 2 bit errors will occur
- At least 2 bit errors will occur
- More than 2 bit errors will occur
- All the bits will be erroneous

Suppose X is the random variable representing the number of bit errors in a block of 8 bits. Then $X \sim B(8, 0.01)$.

Therefore,

- Probability that exactly 2 bit errors will occur

$$\begin{aligned}
 &= p_X(2) \\
 &= {}^8C_2 \times 0.01^2 \times 0.99^6 \\
 &= 0.0026
 \end{aligned}$$

- Probability that at least 2 bit errors will occur

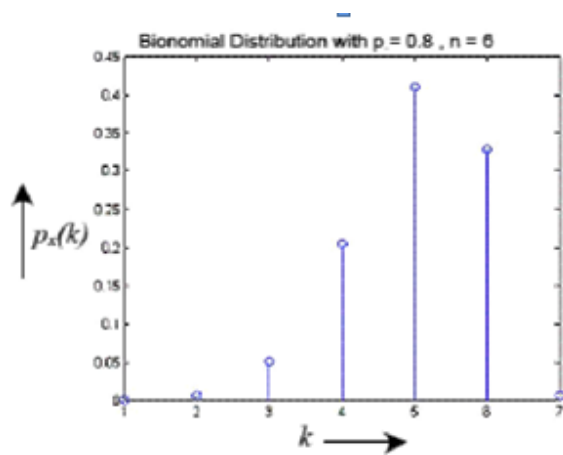
$$\begin{aligned}
 &= p_X(0) + p_X(1) + p_X(2) \\
 &= 0.99^8 + {}^8C_1 \times 0.01^1 \times 0.99^7 + {}^8C_2 \times 0.01^2 \times 0.99^6 \\
 &= 0.9999
 \end{aligned}$$

- Probability that more than 2 bit errors will occur

$$\begin{aligned}
 &= 1 - \sum_{k=0}^2 p_X(k) \\
 &= 1 - 0.9999 \\
 &= 0.0001
 \end{aligned}$$

- Probability that all 8 bits will be erroneous

$$\begin{aligned}
 &= p_X(8) \\
 &= 0.01^8 = 10^{-16}
 \end{aligned}$$



The probability mass function for a binomial random variable with $n = 6$ and $p = 0.8$

Mean and Variance of the Binomial Random Variable

We have

$$\begin{aligned} EX &= \sum_{k=0}^n k p_X(k) \\ &= \sum_{k=0}^n k {}^n C_k p^k (1-p)^{n-k} \\ &= 0 \times q^n + \sum_{k=1}^n k {}^n C_k p^k (1-p)^{n-k} \\ &= \sum_{k=1}^n k \frac{n!}{k!(n-k)!} p^k (1-p)^{n-k} \\ &= \sum_{k=1}^n \frac{n!}{(k-1)!(n-k)!} p^k (1-p)^{n-k} \\ &= np \sum_{k=1}^n \frac{n-1!}{(k-1)!(n-k)!} p^{k-1} (1-p)^{n-1-(k-1)} \\ &= np \sum_{k_1=0}^{n-1} \frac{n-1!}{k_1!(n-1-k_1)!} p^{k_1} (1-p)^{n-1-k_1} \quad (\text{Substituting } k_1 = k-1) \\ &= np(p+1-p)^{n-1} \\ &= np \end{aligned}$$

Similarly

$$\begin{aligned}
EX^2 &= \sum_{k=0}^n k^2 p_X(k) \\
&= \sum_{k=0}^n k^2 {}^nC_k p^k (1-p)^{n-k} \\
&= 0^2 \times q^n + \sum_{k=1}^n k^2 {}^nC_k p^k (1-p)^{n-k} \\
&= \sum_{k=1}^n k^2 \frac{n!}{k!(n-k)!} p^k (1-p)^{n-k} \\
&= \sum_{k=1}^n k \frac{n!}{(k-1)!(n-k)!} p^k (1-p)^{n-k} \\
&= np \sum_{k=1}^n (k-1) \frac{n-1!}{(k-1)!(n-1-k)!} p^{k-1} (1-p)^{n-1-(k-1)} \\
&= np \sum_{k=1}^n (k-1) \frac{n-1!}{(k-1)!(n-1-k+1)!} p^{k-1} (1-p)^{n-1-(k-1)} + np \sum_{k=1}^n \frac{n-1!}{(k-1)!(n-1-k+1)!} p^{k-1} (1-p)^{n-1-(k-1)} \\
&= np \times (n-1)p + np \\
&= n(n-1)p^2 + np
\end{aligned}$$

Where

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

is the mean of $B(n-1, p)$

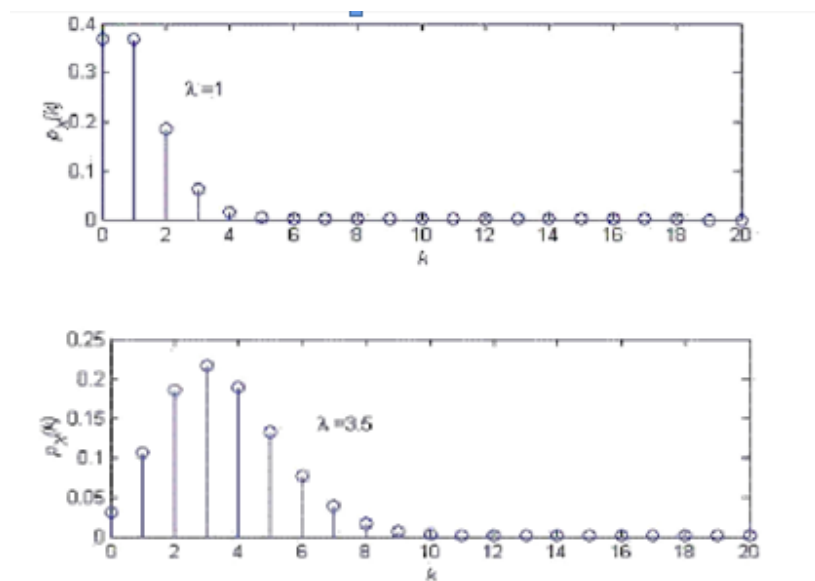
$$\begin{aligned}
\therefore \sigma_X^2 &= \text{variance of } X \\
&= n(n-1)p^2 + np - n^2p^2 \\
&= np(1-p)
\end{aligned}$$

3. Poisson Random Variable

A discrete random variable X is called a *Poisson random variable* with the parameter λ if $\lambda > 0$ and

$$P_X(k) = (e^{-\lambda} \lambda^k) / k!$$

The plot of the pmf of the Poisson RV is shown



Mean and Variance of the Poisson RV

The mean of the Poisson RV X is given by

$$\begin{aligned}\mu_X &= \sum_{k=0}^{\infty} k p_X(k) \\&= 0 + \sum_{k=1}^{\infty} k \frac{e^{-\lambda} \lambda^k}{k!} \\&= \lambda e^{-\lambda} \sum_{k=1}^{\infty} \frac{\lambda^{k-1}}{(k-1)!} \\&= \lambda\end{aligned}$$

$$\begin{aligned}EX^2 &= \sum_{k=0}^{\infty} k^2 p_X(k) \\&= 0 + \sum_{k=1}^{\infty} k^2 \frac{e^{-\lambda} \lambda^k}{k!} \\&= e^{-\lambda} \sum_{k=1}^{\infty} \frac{k \lambda^k}{(k-1)!} \\&= e^{-\lambda} \sum_{k=1}^{\infty} \frac{(k-1+1) \lambda^k}{(k-1)!} \\&= e^{-\lambda} \left(0 + \sum_{k=2}^{\infty} \frac{\lambda^k}{(k-2)!} \right) + e^{-\lambda} \sum_{k=1}^{\infty} \frac{\lambda^k}{(k-1)!} \\&= e^{-\lambda} \lambda^2 \sum_{k=2}^{\infty} \frac{\lambda^{k-2}}{(k-2)!} + e^{-\lambda} \lambda \sum_{k=1}^{\infty} \frac{\lambda^{k-1}}{(k-1)!} \\&= e^{-\lambda} \lambda^2 e^{\lambda} + e^{-\lambda} \lambda e^{\lambda} \\&= \lambda^2 + \lambda \\&\therefore \sigma_X^2 = EX^2 - \mu_X^2 = \lambda\end{aligned}$$

Example: The number of calls received in a telephone exchange follows a Poisson distribution with an average of 10 calls per minute. What is the probability that in one-minute duration?

- i. no call is received
- ii. exactly 5 calls are received
- iii. More than 3 calls are received.

Solution: Let X be the random variable representing the number of calls received. Given

Where $\lambda = 10$. Therefore,

- i. probability that no call is received $= p_X(0) = e^{-10} = 0.000095$
- ii. probability that exactly 5 calls are received $= p_X(5) = \frac{e^{-10} \times 10^5}{5!} = 0.0378$
- iii. probability that more the 3 calls are received
 $= 1 - \sum_{k=0}^3 p_X(k) = 1 - e^{-10} \left(1 + \frac{10}{1} + \frac{10^2}{2!} + \frac{10^3}{3!} \right) = 0.9897$

Poisson Approximation of the Binomial Random Variable

The Poisson distribution is also used to approximate the binomial distribution $B(n, p)$ when n is very large and p is small.

Consider binomial RV with $X \sim B(n, p)$ with
 $n \rightarrow \infty, p \rightarrow 0$ so that $EX = np = \lambda$ remains constant.

Then

$$\begin{aligned} p_X(k) &= {}^nC_k p^k (1-p)^{n-k} \\ &= \frac{n!}{k!(n-k)!} p^k (1-p)^{n-k} \\ &= \frac{n(n-1)(n-2)\dots(n-k+1)}{k!} p^k (1-p)^{n-k} \end{aligned}$$

$$\begin{aligned} &= \frac{n^k \left(1 - \frac{1}{n}\right) \left(1 - \frac{2}{n}\right) \dots \left(1 - \frac{k-1}{n}\right)}{k!} p^k (1-p)^{n-k} \\ &= \frac{\left(1 - \frac{1}{n}\right) \left(1 - \frac{2}{n}\right) \dots \left(1 - \frac{k-1}{n}\right)}{k!} (np)^k (1-p)^{n-k} \end{aligned}$$

$$\begin{aligned}
&= \frac{n^k (1 - \frac{1}{n})(1 - \frac{2}{n}) \dots (1 - \frac{k-1}{n})}{k!} p^k (1-p)^{n-k} \\
&= \frac{(1 - \frac{1}{n})(1 - \frac{2}{n}) \dots (1 - \frac{k-1}{n})}{k!} (np)^k (1-p)^{n-k} \\
&= \frac{(1 - \frac{1}{n})(1 - \frac{2}{n}) \dots (1 - \frac{k-1}{n}) (\lambda)^k (1 - \frac{\lambda}{n})^n}{k! (1 - \frac{\lambda}{n})^k}
\end{aligned}$$

Note that $\lim_{n \rightarrow \infty} (1 - \frac{\lambda}{n})^n = e^{-\lambda}$.

$$\therefore p_X(k) = \lim_{n \rightarrow \infty} \frac{(1 - \frac{1}{n})(1 - \frac{2}{n}) \dots (1 - \frac{k-1}{n}) (\lambda)^k (1 - \frac{\lambda}{n})^n}{k! (1 - \frac{\lambda}{n})^k} = \frac{e^{-\lambda} \lambda^k}{k!}$$

Thus the Poisson approximation can be used to compute binomial probabilities for large n . It also makes the analysis of such probabilities easier. Typical examples are:

- number of bit errors in a received binary data file
- Number of typographical errors in a printed page

Example 4 Suppose there is an error probability of 0.01 per word in typing. What is the probability that there will be more than 1 error in a page of 120 words?

Solution: Suppose X is the RV representing the number of errors per page of 120 words.

$X \sim B(120, p)$ Where $p = 0.01$. Therefore,

$$\therefore \lambda = 120 \times 0.01 = 0.12$$

P(more than one errors)

$$= 1 - p_X(0) - p_X(1)$$

$$\simeq 1 - e^{-\lambda} - \lambda e^{-\lambda}$$

$$= 0.0066$$

In the following we shall discuss some important continuous random variables.

4. Uniform Random Variable

A continuous random variable X is called uniformly distributed over the interval $[a, b]$,

$-\infty < a < b < \infty$, if its probability density function is given by

$$f_X(x) = \begin{cases} \frac{1}{b-a}, & a \leq x \leq b \\ 0, & \text{otherwise} \end{cases}$$

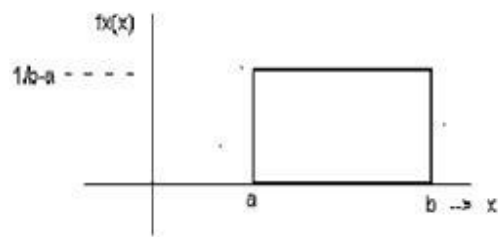


Figure 1

We use the notation $X \sim U(a, b)$ to denote a random variable X uniformly distributed over the interval $[a, b]$

Distribution function $F_X(x)$

For $x < a$

$$F_X(x) = 0$$

For $a \leq x \leq b$

$$\begin{aligned} & \int_{-\infty}^x f_X(u) du \\ &= \int_a^x \frac{1}{b-a} du \\ &= \frac{x-a}{b-a} \end{aligned}$$

For $x > b$,

$$F_X(x) = 1$$

Figure 2 illustrates the CDF of a uniform random variable.

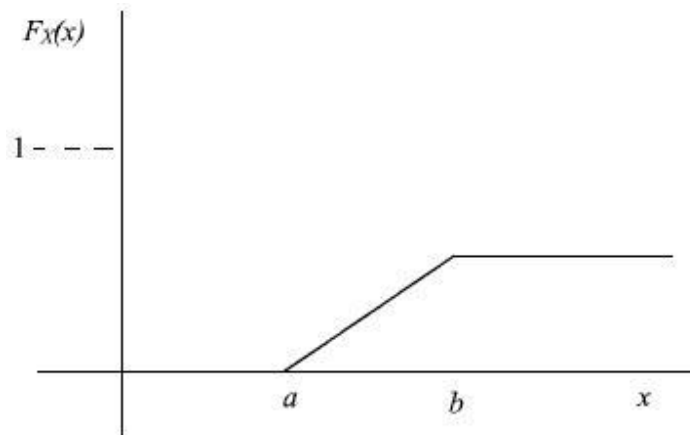


Figure 2: CDF of a uniform random variable

Mean and Variance of a Uniform Random Variable:

$$\begin{aligned}
 \mu_X = EX &= \int_{-\infty}^{\infty} xf_X(x)dx = \int_a^b \frac{x}{b-a} dx \\
 &= \frac{a+b}{2} \\
 EX^2 &= \int_{-\infty}^{\infty} x^2 f_X(x)dx = \int_a^b \frac{x^2}{b-a} dx \\
 &= \frac{b^2 + ab + a^2}{3} \\
 \therefore \sigma_X^2 &= EX^2 - \mu_X^2 = \frac{b^2 + ab + a^2}{3} - \frac{(a+b)^2}{4} \\
 &= \frac{(b-a)^2}{12}
 \end{aligned}$$

The characteristic function of the random variable $X \sim U(a, b)$ is given by

$$\begin{aligned}
 \phi_X(\omega) &= Ee^{j\omega X} = \int_a^b \frac{e^{j\omega x}}{b-a} dx \\
 &= \frac{e^{j\omega b} - e^{j\omega a}}{j\omega(b-a)}
 \end{aligned}$$

5. Normal or Gaussian Random Variable

The normal distribution is the most important distribution used to model natural and man made phenomena. Particularly, when the random variable is the result of the addition of large number of independent random variables, it can be modeled as a normal random variable.

continuous random variable X is called a *normal or a Gaussian random variable* with parameters μ_X and σ_X^2 if its probability density function is given by,

$$f_X(x) = \frac{1}{\sqrt{2\pi}\sigma_X} e^{-\frac{1}{2}\left(\frac{x-\mu_X}{\sigma_X}\right)^2}, \quad -\infty < x < \infty$$

Where μ_X and $\sigma_X > 0$ are real numbers.

We write that X is $N(\mu_X, \sigma_X^2)$ distributed.

If $\mu_X = 0$ and $\sigma_X^2 = 1$, and the random variable X is called the *standard normal variable*.

$$f_X(x) = \frac{1}{\sqrt{2\pi}} e^{-\frac{1}{2}x^2}$$

Figure 3 illustrates two normal variables with the same mean but different variances.

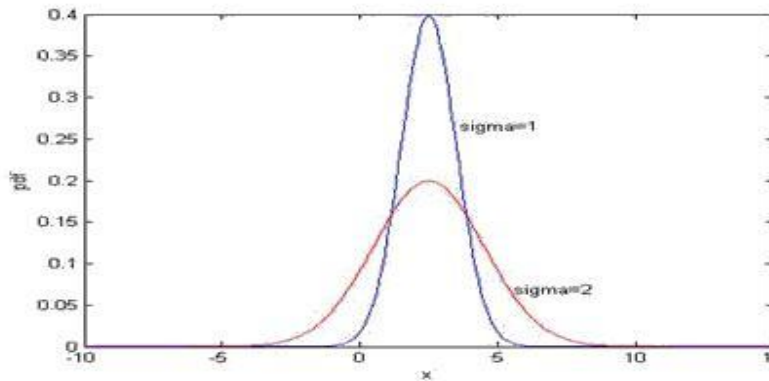


Figure 3

- $f_X(x)$ Is a bell-shaped function, symmetrical about $x = \mu_X$.
- σ_X^2 Determines the spread of the random variable X . If σ_X^2 is small X is more concentrated around the mean μ_X .
- Distribution function of a Gaussian variable is

$$F_X(x) = P(X \leq x) \\ = \frac{1}{\sqrt{2\pi}\sigma_X} \int_{-\infty}^x e^{-\frac{1}{2}\left(\frac{t-\mu_X}{\sigma_X}\right)^2} dt$$

Substituting $u = \frac{t - \mu_X}{\sigma_X}$, we get

$$F_X(x) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\frac{x-\mu_X}{\sigma_X}} e^{-\frac{1}{2}u^2} du \\ = \Phi\left(\frac{x - \mu_X}{\sigma_X}\right)$$

where $\Phi(x)$ is the distribution function of the *standard normal variable*.

Thus $F_X(x)$ can be computed from tabulated values of $\Phi(x)$. The table $\Phi(x)$ was very useful in the pre-computer days.

In communication engineering, it is customary to work with the Q function defined by,

$$Q(x) = 1 - \Phi(x) \\ = \frac{1}{\sqrt{2\pi}} \int_x^{\infty} e^{-\frac{u^2}{2}} du$$

Note that $Q(0) = \frac{1}{2}$, $Q(-x) = Q(x)$ and

$$Q(x) = 1 - \Phi(-x)$$

These results follow from the symmetry of the Gaussian pdf. The function $Q(x)$ is tabulated and the tabulated results are used to compute probability involving the Gaussian random variable.

Using the Error Function to compute Probabilities for Gaussian Random Variables

The function $Q(x)$ is closely related to the error function $erf(x)$ and the complementary error function $erfc(x)$.

$$erf(x) = \frac{2}{\sqrt{\pi}} \int_0^x e^{-u^2} du$$

Note that,

And the complementary error function $erfc(x)$ is given

$$\begin{aligned} erfc(x) &= \frac{2}{\sqrt{\pi}} \int_x^\infty e^{-u^2} du \\ &= 1 - erf(x) \\ \therefore Q(x) &= \frac{1}{\sqrt{2\pi}} \int_x^\infty e^{-\frac{u^2}{2}} du \\ &= \frac{1}{2} erfc\left(\frac{x}{\sqrt{2}}\right) \\ &= \frac{1}{2} \left(1 - erf\left(\frac{x}{\sqrt{2}}\right)\right) \end{aligned}$$

Mean and Variance of a Gaussian Random Variable

If X is $N(\mu_X, \sigma_X^2)$ distributed, then

$$EX = \mu_X$$

$$\text{var}(X) = \sigma_X^2$$

Proof:

$$\begin{aligned} EX &= \int_{-\infty}^{\infty} xf_X(x)dx = \frac{1}{\sqrt{2\pi}\sigma_X} \int_{-\infty}^{\infty} xe^{-\frac{1}{2}\left(\frac{x-\mu_X}{\sigma_X}\right)^2} dx \\ &= \frac{\sigma_X}{\sqrt{2\pi}} \int_{-\infty}^{\infty} (u\sigma_X + \mu_X) e^{-\frac{1}{2}u^2} \sigma_X du \\ &= \frac{1}{\sigma_X\sqrt{2\pi}} \int_{-\infty}^{\infty} u du + \frac{\mu_X}{\sqrt{2\pi}} \int_{-\infty}^{\infty} e^{-\frac{1}{2}u^2} du \\ &= 0 + \mu_X \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} e^{-\frac{1}{2}u^2} du \\ &= \frac{\mu_X}{\sqrt{2\pi}} 2 \int_0^\infty e^{-\frac{u^2}{2}} du = \mu_X \end{aligned}$$

$$\text{Substituting } \frac{x - \mu_X}{\sigma_X} = u$$

$$\text{so that } x = u\sigma_X + \mu_X$$

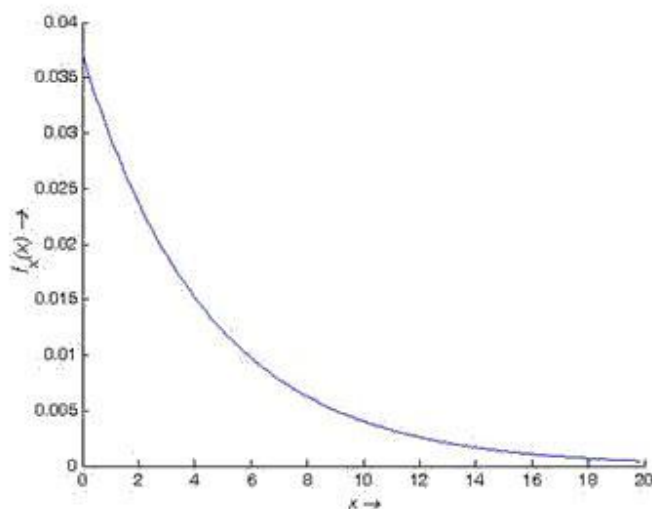
$$\begin{aligned}
 \text{Var}(X) &= E(X - \mu_X)^2 \\
 &= \frac{1}{\sqrt{2\pi}\sigma_X} \int_{-\infty}^{\infty} (x - \mu_X)^2 e^{-\frac{1}{2}\left(\frac{x - \mu_X}{\sigma_X}\right)^2} dx \\
 &= \frac{1}{\sqrt{2\pi}\sigma_X} \int_{-\infty}^{\infty} \sigma_X^2 u^2 e^{-\frac{1}{2}u^2} \sigma_X du \quad (\text{substituting } u = \frac{x - \mu_X}{\sigma_X}) \\
 &= 2 \times \frac{\sigma_X^2}{\sqrt{2\pi}} \int_0^{\infty} u^2 e^{-\frac{1}{2}u^2} du \\
 &= 2 \times \frac{\sigma_X^2}{\sqrt{2\pi}} \sqrt{2} \int_0^{\infty} t^{\frac{1}{2}} e^{-t} dt \quad (\text{substituting } t = \frac{u^2}{2}) \\
 &= 2 \times \frac{\sigma_X^2}{\sqrt{\pi}} \Gamma\left(\frac{3}{2}\right) \\
 &= 2 \times \frac{\sigma_X^2}{\sqrt{\pi}} \frac{1}{2} \Gamma\left(\frac{1}{2}\right) \\
 &= \frac{\sigma_X^2}{\sqrt{\pi}} \times \sqrt{\pi} \\
 &= \sigma_X^2
 \end{aligned}$$

6. Exponential Random Variable

A continuous random variable X is called exponentially distributed with the parameter

$$f_X(x) = \begin{cases} \lambda e^{-\lambda x}, & x \geq 0 \\ 0, & \text{otherwise} \end{cases}$$

$\lambda > 0$ if the probability density function is of the PDF of Exponential Random Variable is



Example 1

Suppose the waiting time of packets in X in a computer network is an exponential RV with

$$f_X(x) = 0.5e^{-0.5x} \quad x \geq 0$$

Then,

$$\begin{aligned} P((0.1 < X \leq 0.5)) &= \int_{0.1}^{0.5} 0.5e^{-0.5x} dx \\ &= e^{-0.5 \times 0.5} - e^{-0.5 \times 0.1} \\ &= 0.0241 \end{aligned}$$

Rayleigh Random Variable

A Rayleigh random variable X is characterized by the PDF

$$f_X(x) = \begin{cases} \frac{x}{\sigma^2} e^{-x^2/2\sigma^2}, & x \geq 0 \\ 0, & x < 0 \end{cases}$$

where σ is the parameter of the random variable.

probability density functions for the Rayleigh RVs are illustrated in Figure

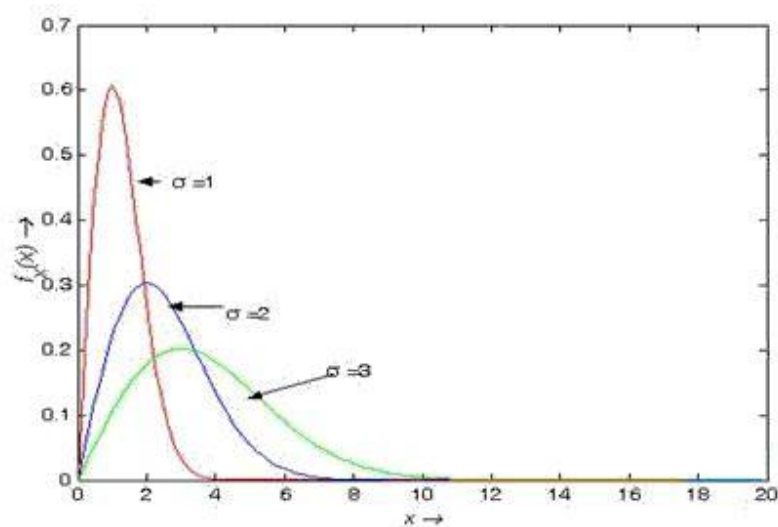


Figure 6

Mean and Variance of the Rayleigh Distribution

$$\begin{aligned}
 EX &= \int_{-\infty}^{\infty} xf_X(x)dx \\
 &= \int_0^{\infty} x \frac{x}{\sigma^2} e^{-x^2/2\sigma^2} dx \\
 &= \frac{\sqrt{2\pi}}{\sigma} \int_0^{\infty} \frac{x^2}{\sqrt{2\pi}\sigma} e^{-x^2/2\sigma^2} dx \\
 &= \frac{\sqrt{2\pi}}{\sigma} \frac{\sigma^2}{2} \\
 &= \sqrt{\frac{\pi}{2}} \sigma
 \end{aligned}$$

similarly

$$\begin{aligned}
 EX^2 &= \int_{-\infty}^{\infty} x^2 f_X(x) dx \\
 &= \int_0^{\infty} x^2 \frac{x}{\sigma^2} e^{-x^2/2\sigma^2} dx \\
 &= 2\sigma^2 \int_0^{\infty} u e^{-u} du \quad (\text{Substituting } u = \frac{x^2}{2\sigma^2}) \\
 &= 2\sigma^2 \quad (\text{Noting that } \int_0^{\infty} u e^{-u} du \text{ is the mean of the exponential RV with } \lambda=1) \\
 \therefore \sigma_X^2 &= 2\sigma^2 - \left(\sqrt{\frac{\pi}{2}} \sigma \right)^2 \\
 &= \left(2 - \frac{\pi}{2} \right) \sigma^2
 \end{aligned}$$

Relation between the Rayleigh Distribution and the Gaussian distribution

A Rayleigh RV is related to Gaussian RVs as follow: If $X_1 \sim N(0, \sigma^2)$ and $X_2 \sim N(0, \sigma^2)$ are independent, then the envelope $X = \sqrt{X_1^2 + X_2^2}$ has the Rayleigh distribution with the parameter σ .

We shall prove this result in a later lecture. This important result also suggests the cases where the Rayleigh RV can be used.

Application of the Rayleigh RV

- ✓ Modeling the *root mean square error*-
- ✓ Modeling the envelope of a signal with two *orthogonal components* as in the case of a signal of the following form:

Conditional Distribution and Density functions

We discussed conditional probability in an earlier lecture. For two events A and B with $P(B) \neq 0$, the conditional probability $P(A/B)$ was defined as

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

Clearly, the conditional probability can be defined on events involving a Random Variable X

Conditional distribution function:

Consider the event $\{X \leq x\}$ and any event B involving the random variable X . The conditional distribution function of X given B is defined as

$$\begin{aligned} F_X(x/B) &= P[\{X \leq x\} / B] \\ &= \frac{P[\{X \leq x\} \cap B]}{P(B)} \quad P(B) \neq 0 \end{aligned}$$

We can verify that $F_X(x/B)$ satisfies all the properties of the distribution function. Particularly.

- $F_X(-\infty/B) = 0$ And $F_X(\infty/B) = 1$.
- $0 \leq F_X(x/B) \leq 1$.
- $F_X(x/B)$ Is a non-decreasing function of x .
- $P(\{x_1 < X \leq x_2\} / B) = P(\{X \leq x_2\} / B) - P(\{X \leq x_1\} / B)$
 $= F_X(x_2/B) - F_X(x_1/B)$

Conditional Probability Density Function

In a similar manner, we can define the conditional density function $f_X(x/B)$ of the random variable X given the event B as

$$f_X(x/B) = \frac{d}{dx} F_X(x/B)$$

All the properties of the pdf applies to the conditional pdf and we can easily show that

- $f_X(x/B) \geq 0$
- $\int_{-\infty}^{\infty} f_X(x/B) dx = F_X(\infty/B) = 1$
- $F_X(x/B) = \int_{-\infty}^x f_X(u/B) du$

$$\begin{aligned} P(\{x_1 < X \leq x_2\} / B) &= F_X(x_2/B) - F_X(x_1/B) \\ &= \int_{x_1}^{x_2} f_X(x/B) dx \end{aligned}$$

Example 1 Suppose X is a random variable with the distribution function $F_X(x)$. Define $B = \{X \leq b\}$

$$\begin{aligned} F_X(x/B) &= \frac{P(\{X \leq x\} \cap B)}{P(B)} \\ &= \frac{P(\{X \leq x\} \cap \{X \leq b\})}{P\{X \leq b\}} \\ &= \frac{P(\{X \leq x\} \cap \{X \leq b\})}{F_X(b)} \end{aligned}$$

Case 1: $x < b$

Then

$$\begin{aligned} F_X(x/B) &= \frac{P(\{X \leq x\} \cap \{X \leq b\})}{F_X(b)} \\ &= \frac{P(\{X \leq x\})}{F_X(b)} = \frac{F_X(x)}{F_X(b)} \end{aligned}$$

And

$$f_X(x|B) = \frac{d F_X(x)}{dx F_X(b)} = \frac{f_X(x)}{F_X(b)}$$

Case 2: $x \geq b$

$$\begin{aligned} F_X(x|B) &= \frac{P(\{X \leq x\} \cap \{X \leq b\})}{F_X(b)} \\ &= \frac{P(\{X \leq b\})}{F_X(b)} = \frac{F_X(b)}{F_X(b)} = 1 \end{aligned}$$

$F_X(x|B)$ and $f_X(x|B)$ are plotted in the following figures.

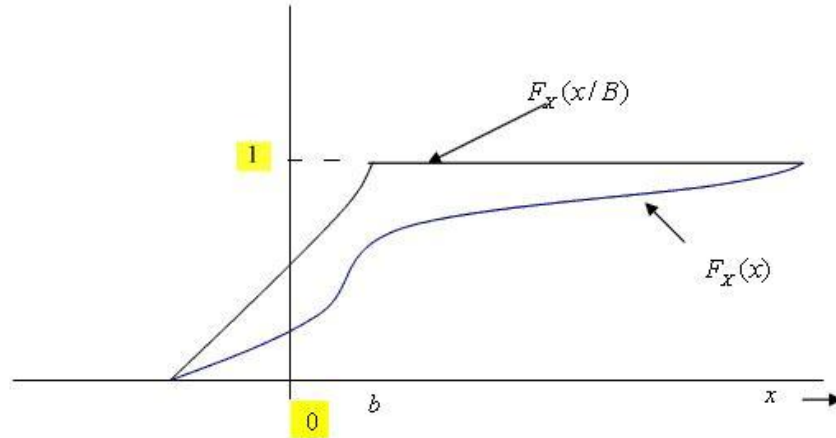
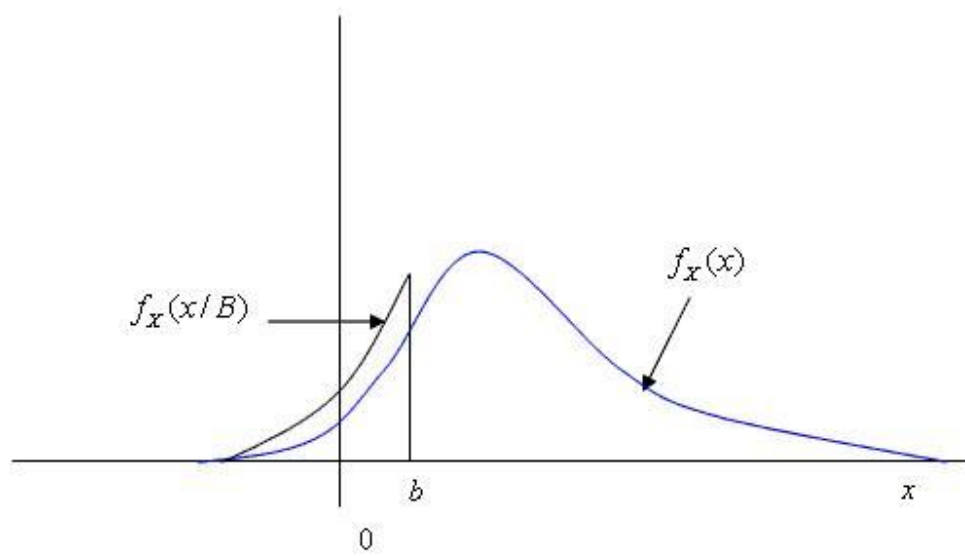


Figure 1



Example2: Suppose X is a random variable with the distribution function $F_X(x)$ and $B = \{X > b\}$.

$$\begin{aligned} F_X(x/B) &= \frac{P(\{X \leq x\} \cap B)}{P(B)} \\ &= \frac{P(\{X \leq x\} \cap \{X > b\})}{P\{X > b\}} \\ &= \frac{P(\{X \leq x\} \cap \{X > b\})}{1 - F_X(b)} \end{aligned}$$

Then

For $x \leq b$, $\{X \leq x\} \cap \{X > b\} = \emptyset$. Therefore,

$$F_X(x/B) = 0 \quad x \leq b$$

For $x > b$, $\{X \leq x\} \cap \{X > b\} = \{b < X \leq x\}$. Therefore,

$$\begin{aligned} F_X(x/B) &= \frac{P(\{b < X \leq x\})}{1 - F_X(b)} \\ &= \frac{F_X(x) - F_X(b)}{1 - F_X(b)} \end{aligned}$$

Thus,

$$F_X(x/B) = \begin{cases} 0, & x \leq b \\ \frac{F_X(x) - F_X(b)}{1 - F_X(b)}, & \text{otherwise} \end{cases}$$

the corresponding pdf is given by

$$f_X(x/B) = \begin{cases} 0, & x \leq b \\ \frac{f_X(x)}{1 - F_X(b)}, & \text{otherwise} \end{cases}$$

OPERATION ON RANDOM VARIABLE-EXPECTATIONS

Expected Value of a Random Variable

- The *expectation* operation extracts a few parameters of a random variable and provides a summary description of the random variable in terms of these parameters.
- It is far easier to estimate these parameters from data than to estimate the distribution or density function of the random variable.
- Moments are some important parameters obtained through the expectation operation.

Expected value or mean of a random variable

The expected value of a random variable X is defined by

$$EX = \int_{-\infty}^{\infty} xf_X(x)dx$$

Provided $\int_{-\infty}^{\infty} xf_X(x)dx$ exists.

EX is also called the mean or statistical average of the random variable X and is denoted by μ_X .

Note that, for a discrete RV X with the *probability mass function* (pmf) $p_X(x_i), i = 1, 2, \dots, N$, the pdf $f_X(x)$ is given by

$$\begin{aligned} f_X(x) &= \sum_{i=1}^N p_X(x_i) \delta(x - x_i) \\ \therefore \mu_X = E[X] &= \int_{-\infty}^{\infty} x \sum_{i=1}^N p_X(x_i) \delta(x - x_i) dx \\ &= \sum_{i=1}^N p_X(x_i) \int_{-\infty}^{\infty} x \delta(x - x_i) dx \\ &= \sum_{i=1}^N x_i p_X(x_i) \quad \because \int_{-\infty}^{\infty} x \delta(x - x_i) dx \end{aligned}$$

Thus for a discrete random variable X with $p_X(x_i), i = 1, 2, \dots, N$,

$$\mu_X = \sum_{i=1}^N x_i p_X(x_i)$$

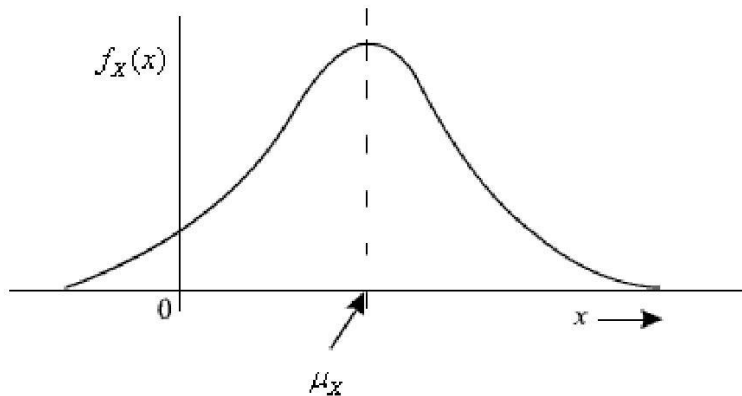


Figure1 Mean of a random variable

Example 1

Suppose X is a random variable defined by the pdf

$$f_X(x) = \begin{cases} \frac{1}{b-a}, & a \leq x \leq b \\ 0, & \text{otherwise} \end{cases}$$

Then

$$\begin{aligned} \mu_X &= \int_{-\infty}^{\infty} x f_X(x) dx \\ &= \int_a^b x \frac{1}{b-a} dx \\ &= \frac{a+b}{2} \end{aligned}$$

Example 2

Consider the random variable X with the pmf as tabulated below

Value of the random variable x	0	1	2	3
$p_X(x)$	$\frac{1}{8}$	$\frac{1}{8}$	$\frac{1}{4}$	$\frac{1}{2}$

Then

$$\begin{aligned} \mu_X &= \sum_{i=1}^N x_i p_X(x_i) \\ &= 0 \times \frac{1}{8} + 1 \times \frac{1}{8} + 2 \times \frac{1}{4} + 3 \times \frac{1}{2} \\ &= \frac{17}{8} \end{aligned}$$

Example 3 Let X be a continuous random variable with

$$f_X(x) = \frac{\alpha}{\pi(x^2 + \alpha^2)} \quad -\infty < x < \infty, \alpha > 0$$

Then

$$\begin{aligned} EX &= \int_{-\infty}^{\infty} x f_X(x) dx \\ &= \frac{\alpha}{\pi} \int_0^{\infty} \frac{2x}{x^2 + \alpha^2} dx \end{aligned}$$

$$= \frac{\alpha}{\pi} \ln(1+x^2) \Big|_0^\infty$$

Hence EX does not exist. This density function is known as the *Cauchy density function*.

Expected value of a function of a random variable

Suppose $Y = g(X)$ is a real-valued function of a random variable X as discussed in the last class.

Then,

$$EY = E g(X) = \int_{-\infty}^{\infty} g(x) f_X(x) dx$$

We shall illustrate the above result in the special case $g(X)$ when $y = g(x)$ is one-to-one and monotonically increasing function of x . In this case,

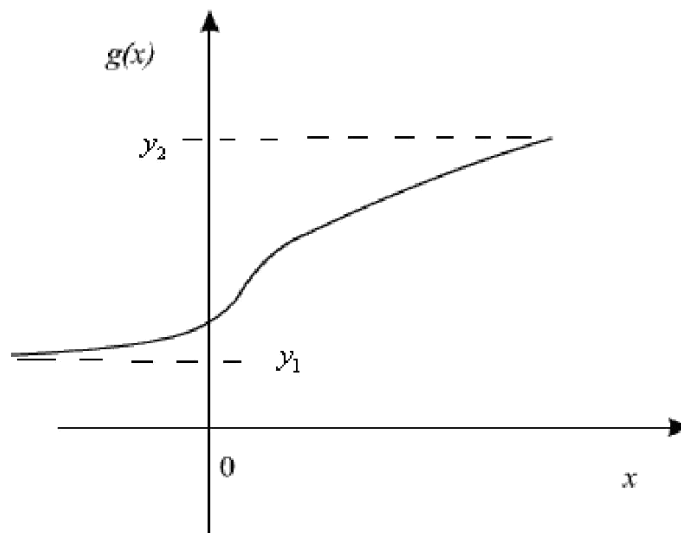


Figure 2

$$f_Y(y) = \frac{f_X(x)}{g'(x)} \Big|_{x=g^{-1}(y)}$$

$$\begin{aligned} EY &= \int_{-\infty}^{\infty} y f_Y(y) dy \\ &= \int_{y_1}^{y_2} y \frac{f_X(g^{-1}(y))}{g'(g^{-1}(y))} dy \end{aligned}$$

where $y_1 = g(-\infty)$ and $y_2 = g(\infty)$.

Substituting $x = g^{-1}(y)$ so that $y = g(x)$ and $dy = g'(x)dx$, we get

$$EY = \int_{-\infty}^{\infty} g(x) f_X(x) dx$$

The following important **properties of the expectation operation** can be immediately derived:

(a) If c is a constant, $Ec = c$

$$Ec = \int_{-\infty}^{\infty} cf_X(x) dx = c \int_{-\infty}^{\infty} f_X(x) dx = c$$

Clearly

(b) If $g_1(X)$ and $g_2(X)$ are two functions of the random variable X and c_1 and c_2 are constants,

$$E[c_1 g_1(X) + c_2 g_2(X)] = c_1 E g_1(X) + c_2 E g_2(X)$$

$$\begin{aligned} E[c_1 g_1(X) + c_2 g_2(X)] &= \int_{-\infty}^{\infty} c_1 [g_1(x) + c_2 g_2(x)] f_X(x) dx \\ &= \int_{-\infty}^{\infty} c_1 g_1(x) f_X(x) dx + \int_{-\infty}^{\infty} c_2 g_2(x) f_X(x) dx \\ &= c_1 \int_{-\infty}^{\infty} g_1(x) f_X(x) dx + c_2 \int_{-\infty}^{\infty} g_2(x) f_X(x) dx \\ &= c_1 E g_1(X) + c_2 E g_2(X) \end{aligned}$$

The above property means that E is a linear operator.

MOMENTS ABOUT THE ORIGIN:

Mean-square value

$$EX^2 = \int_{-\infty}^{\infty} x^2 f_X(x) dx$$

MOMENTS ABOUT THE MEAN

Variance

Second central moment is called as variance

For a random variable X with the pdf $f_X(x)$ and mean μ_X , the variance of X is denoted by σ_X^2 and

defined as
$$\sigma_X^2 = E(X - \mu_X)^2 = \int_{-\infty}^{\infty} (x - \mu_X)^2 f_X(x) dx$$

Thus for a discrete random variable X with $p_X(x_i), i = 1, 2, \dots, N$,

$$\sigma_X^2 = \sum_{i=1}^N (x_i - \mu_X)^2 p_X(x_i)$$

The standard deviation of X is defined as $\sigma_X = \sqrt{E(X - \mu_X)^2}$

Example 4

Find the variance of the random variable in the above example

$$\begin{aligned}\sigma_X^2 &= E(X - \mu_X)^2 \\ &= \int_a^b \left(x - \frac{a+b}{2}\right)^2 \frac{1}{b-a} dx \\ &= \frac{1}{b-a} \left[\int_a^b x^2 dx - 2 \times \frac{a+b}{2} \int_a^b x dx + \left(\frac{a+b}{2}\right)^2 \int_a^b dx \right] \\ &= \frac{(b-a)^2}{12}\end{aligned}$$

Example 5

Find the variance of the random variable discussed in above example. As already computed

$$\mu_X = \frac{17}{8}$$

$$\begin{aligned}
 \sigma_X^2 &= E(X - \mu_X)^2 \\
 &= (0 - \frac{17}{8})^2 \times \frac{1}{8} + (1 - \frac{17}{8})^2 \times \frac{1}{8} + (2 - \frac{17}{8})^2 \times \frac{1}{4} + (3 - \frac{17}{8})^2 \times \frac{1}{2} \\
 &= \frac{71}{64}
 \end{aligned}$$

For example, consider two random variables X_1 and X_2 with pmf as shown below. Note that each of X_1 and X_2 has zero mean. The variances are given by $\sigma_{X_1}^2 = \frac{1}{2}$ and $\sigma_{X_2}^2 = \frac{5}{3}$ implying that X_2 has more spread about the mean.

Properties of variance

$$(1) \sigma_X^2 = EX^2 - \mu_X^2$$

$$\begin{aligned}
 \sigma_X^2 &= E(X - \mu_X)^2 \\
 &= E(X^2 - 2\mu_X X + \mu_X^2) \\
 &= EX^2 - 2\mu_X EX + E\mu_X^2 \\
 &= EX^2 - 2\mu_X^2 + \mu_X^2 \\
 &= EX^2 - \mu_X^2
 \end{aligned}$$

$$\therefore \sigma_X^2 = EX^2 - \mu_X^2$$

$$(2) \text{ If } Y = cX + b, \text{ where } c \text{ and } b \text{ are constants, then } \sigma_Y^2 = c^2 \sigma_X^2$$

$$\begin{aligned}
 \sigma_Y^2 &= E(cX + b - c\mu_X - b)^2 \\
 &= Ec^2(X - \mu_X)^2 \\
 &= c^2 \sigma_X^2
 \end{aligned}$$

$$(3) \text{ If } c \text{ is a constant,}$$

$$\text{var}(c) = 0.$$

n th moment of a random variable

We can define the n th moment and the n th central- moment of a random variable X by the following relations

$$\text{nth-order moment } EX^n = \int_{-\infty}^{\infty} x^n f_X(x) dx \quad n=1, 2, \dots$$

$$\text{nth-order central moment } E(X - \mu_X)^n = \int_{-\infty}^{\infty} (x - \mu_X)^n f_X(x) dx \quad n=1, 2, \dots$$

Note that

- The mean $\mu_X = EX$ is the first moment and the mean-square value EX^2 is the second moment
- The first central moment is 0 and the variance $\sigma_X^2 = E(X - \mu_X)^2$ is the second central moment

SKEWNESS

- The third central moment measures lack of symmetry of the pdf of a random variable $\frac{E(X - \mu_X)^3}{\sigma_X^3}$ is called the *coefficient of skewness* and if the pdf is symmetric this coefficient will be zero.
- The fourth central moment measures flatness or peakedness of the pdf of a random variable. $\frac{E(X - \mu_X)^4}{\sigma_X^4}$ is called *kurtosis*. If the peak of the pdf is sharper, then the random variable has a higher kurtosis.

Characteristic function

Consider a random variable X with probability density function $f_X(x)$. The characteristic function of X denoted by $\phi_X(\omega)$, is defined as

$$\begin{aligned} \phi_X(\omega) &= Ee^{j\omega X} \\ &= \int_{-\infty}^{\infty} e^{j\omega x} f_X(x) dx \\ \text{where } j &= \sqrt{-1} \end{aligned}$$

Note the following:

- $\phi_X(\omega)$, is a complex quantity, representing the Fourier transform of $f_X(x)$ and traditionally using $e^{j\omega X}$ instead of $e^{-j\omega X}$. This implies that the properties of the Fourier transform applies to the characteristic function.

We can get

$f_X(x)$ from $\phi_X(\omega)$, by the inverse transform

$$f_X(x) = \frac{1}{2\pi} \int_{-\infty}^{\infty} \phi_X(\omega) e^{-j\omega x} d\omega$$

Example 1

Consider the random variable X with pdf $f_X(x)$ given by

$$f_X(x) = \frac{1}{b-a} \quad a \leq x \leq b \quad = 0 \text{ otherwise. The characteristics function is given by}$$

$$\phi_X(\omega) = \frac{1}{j\omega(b-a)} (e^{j\omega b} - e^{j\omega a})$$

Solution:

$$\begin{aligned} \phi_X(\omega) &= \int_a^b \frac{1}{b-a} e^{j\omega x} dx \\ &= \frac{1}{b-a} \left[\frac{e^{j\omega x}}{j\omega} \right]_a^b \\ &= \frac{1}{j\omega(b-a)} (e^{j\omega b} - e^{j\omega a}) \end{aligned}$$

Example 2

The characteristic function of the random variable X with

$$\begin{aligned} f_X(x) &= \lambda e^{-\lambda x} \quad \lambda > 0, x > 0 \text{ is} \\ \phi_X(\omega) &= \int_0^{\infty} e^{j\omega x} \lambda e^{-\lambda x} dx \\ &= \lambda \int_0^{\infty} e^{-(\lambda - j\omega)x} dx \\ &= \frac{\lambda}{\lambda - j\omega} \end{aligned}$$

Characteristic function of a discrete random variable

Suppose X is a random variable taking values from the discrete set $R_X = \{x_1, x_2, \dots\}$ with corresponding probability mass function $p_X(x_i)$ for the value x_i

Then,

$$\begin{aligned}\phi_X(\omega) &= Ee^{j\omega X} \\ &= \sum_{X_i \in R_X} p_X(X_i) e^{j\omega X_i}\end{aligned}$$

$$\begin{aligned}\phi_X(\omega) &= Ee^{j\omega X} \\ &= \sum_{X_i \in R_X} p_X(X_i) e^{j\omega X_i}\end{aligned}$$

If R_X is the set of integers, we can write

In this case $\phi_X(\omega)$, can be interpreted as the discrete-time Fourier transform with $e^{j\omega X}$ substituting $e^{-j\omega X}$ in the original discrete-time Fourier transform. The inverse relation is

$$p_X(k) = \frac{1}{2\pi} \int_{-\pi}^{\pi} e^{-j\omega k} \phi_X(\omega) d\omega$$

$p_X(k) = p(1-p)^k$, $k = 0, 1, \dots$, is given by

$$\begin{aligned}\phi_X(\omega) &= \sum_{k=0}^{\infty} e^{j\omega k} p(1-p)^k \\ &= p \sum_{k=0}^{\infty} e^{j\omega k} (1-p)^k \\ &= \frac{p}{1 - (1-p)e^{j\omega}}\end{aligned}$$

Moments and the characteristic function

Given the characteristics function $\phi_X(\omega)$, the n th moment is given by

$$EX^n = \frac{1}{j^n} \frac{d^n}{d\omega^n} \phi_X(\omega) \Big|_{\omega=0}$$

To prove this consider the power series expansion of $e^{j\omega X}$

$$e^{j\omega X} = 1 + j\omega X + \frac{(j\omega)^2 X^2}{2!} + \dots + \frac{(j\omega)^n X^n}{n!} + \dots$$

Taking expectation of both sides and assuming EX, EX^2, \dots, EX^n to exist, we get

$$\phi_X(\omega) = 1 + j\omega EX + \frac{(j\omega)^2 EX^2}{2!} + \dots + \frac{(j\omega)^n EX^n}{n!} + \dots$$

Taking the first derivative of $\phi_X(\omega)$, with respect to ω at $\omega=0$ we get

$$\left. \frac{d\phi_X(\omega)}{d\omega} \right|_{\omega=0} = jEX$$

Similarly, taking the n th derivative of $\phi_X(\omega)$, with respect to ω at $\omega=0$ we get

$$\left. \frac{d^n \phi_X(\omega)}{d\omega^n} \right|_{\omega=0} = j^n EX^n$$

Thus ,

$$EX = \frac{1}{j} \left. \frac{d\phi_X(\omega)}{d\omega} \right|_{\omega=0}$$

and generally

$$EX^n = \frac{1}{j^n} \left. \frac{d^n \phi_X(\omega)}{d\omega^n} \right|_{\omega=0}$$

TRANSFORMATION OF A RANDOM VARIABLE

Description:

Suppose we are given a random variable X with density $f_X(x)$. We apply a function g to produce a random variable $Y = g(X)$. We can think of X as the input to a black box, and Y the output.

UNIT III

Multiple Random Variables and Operations on Multiple Random Variables

Multiple Random Variables:

- Vector Random Variables
- Joint Distribution Function and Properties
- Joint density Function and Properties
- Marginal Distribution and density Functions
- Conditional Distribution and density Functions
- Statistical Independence
- Distribution and density functions of Sum of Two Random Variables and Sum of Several Random Variables
- Central Limit Theorem

Operations on Multiple Random Variables:

- Expected Value of a Function of Random Variables
- Joint Moments about the Origin
- Joint Central Moments
- Joint Characteristic Functions
- Jointly Gaussian Random Variables: Two Random Variables case and N Random Variable case, Properties
- Transformations of Multiple Random Variables

UNIT-3 MULTIPLE RANDOM VARIABLES

Multiple Random Variables

In many applications we have to deal with more than two random variables. For example, in the navigation problem, the position of a space craft is represented by three random variables denoting the x, y and z coordinates. The noise affecting the R, G, B channels of colour video may be represented by three random variables. In such situations, it is convenient to define the vector-valued random variables where each component of the vector is a random variable.

In this lecture, we extend the concepts of joint random variables to the case of multiple random variables. A generalized analysis will be presented for n random variables defined on the same sample space.

Jointly Distributed Random Variables

We may define two or more random variables on the same sample space. Let X and Y be two real random variables defined on the same probability space (S, \mathcal{F}, P) . The mapping $S \rightarrow \mathbb{R}^2$ such that for $s \in S$, $(X(s), Y(s)) \in \mathbb{R}^2$ is called a joint random variable.

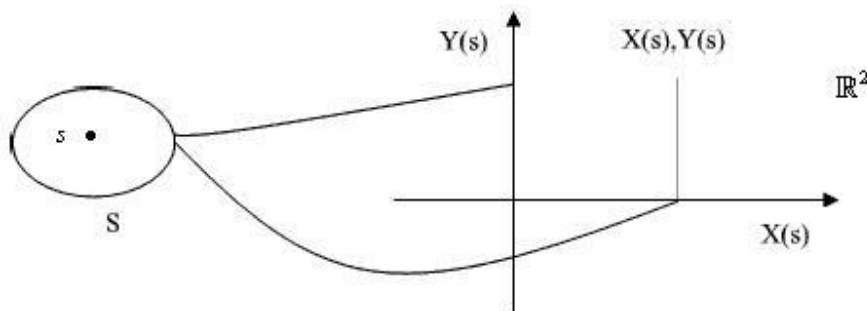


Figure 1

Joint Probability Distribution Function

Recall the definition of the distribution of a single random variable. The event $\{X \leq x\}$ was used to define the probability distribution function $F_X(x)$. Given $F_X(x)$, we can find the

probability of any event involving the random variable. Similarly, for two random variables X and Y , the event $\{X \leq x, Y \leq y\} = \{X \leq x\} \cap \{Y \leq y\}$ is considered as the representative event.

The probability $P(\{X \leq x, Y \leq y\}) \forall (x, y) \in \mathbb{R}^2$ is called the *joint distribution function* or the *joint cumulative distribution function (CDF)* of the random variables X and Y and denoted by $F_{X,Y}(x, y)$.

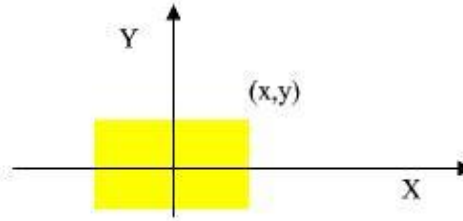


Figure 2

Properties of JPDF

$F_{X,Y}(x, y)$ satisfies the following properties:

$$1) F_{X,Y}(x_1, y_1) \leq F_{X,Y}(x_2, y_2) \text{ if } x_1 \leq x_2 \text{ and } y_1 \leq y_2$$

$$\begin{aligned} 2) & \text{ If } x_1 < x_2 \text{ and } y_1 < y_2, \\ & \{X \leq x_1, Y \leq y_1\} \subseteq \{X \leq x_2, Y \leq y_2\} \\ & \therefore P\{X \leq x_1, Y \leq y_1\} \leq P\{X \leq x_2, Y \leq y_2\} \\ & \therefore F_{X,Y}(x_1, y_1) \leq F_{X,Y}(x_2, y_2) \end{aligned}$$

$$3) F_{X,Y}(-\infty, y) = F_{X,Y}(x, -\infty) = 0$$

Note that $\{X \leq -\infty, Y \leq y\} \subseteq \{X \leq -\infty\}$

$$4) F_{X,Y}(\infty, \infty) = 1$$

$$5) F_{X,Y}(x, y) \text{ is right continuous in both the variables.}$$

$$6) \text{ If } x_1 < x_2 \text{ and } y_1 < y_2$$

$$P(\{x_1 < X \leq x_2, y_1 < Y \leq y_2\}) = F_{X,Y}(x_2, y_2) - F_{X,Y}(x_1, y_2) - F_{X,Y}(x_2, y_1) + F_{X,Y}(x_1, y_1)$$

Given $F_{X,Y}(x,y)$, $-\infty < x < \infty, -\infty < y < \infty$, we have a complete description of the random variables X and Y .

$$7) F_X(x) = F_{X,Y}(x, +\infty)$$

To prove this

$$\{X \leq x\} = \{X \leq x\} \cap \{Y \leq +\infty\}$$

$$\therefore F_X(x) = P(\{X \leq x\}) = P(\{X \leq x, Y \leq \infty\}) = F_{X,Y}(x, +\infty)$$

Similarly $F_Y(y) = F_{X,Y}(\infty, y)$.

Given $F_{X,Y}(x,y)$, $-\infty < x < \infty, -\infty < y < \infty$, each of $F_X(x)$ and $F_Y(y)$ is called a marginal

Distribution function or marginal cumulative distribution function (CDF).

Jointly Distributed Discrete Random Variables

If X and Y are two discrete random variables defined on the same probability space (S, \mathcal{F}, P) such that X takes values from the countable subset R_X and Y takes values from the countable subset R_Y . Then the joint random variable (X, Y) can take values from the countable subset in $R_X \times R_Y$. The joint random variable (X, Y) is completely specified by their *joint probability mass function*

$$p_{X,Y}(x,y) = P(s | X(s) = x, Y(s) = y), \quad \forall (x,y) \in R_X \times R_Y$$

Given $p_{X,Y}(x,y)$, we can determine other probabilities involving the random variables X and Y

Remark

- $p_{X,Y}(x,y) = 0$ for $(x,y) \notin R_X \times R_Y$

- $\sum_{(x,y) \in R_X \times R_Y} p_{X,Y}(x,y) = 1$

$$\begin{aligned}
\sum_{(x,y) \in R_X \times R_Y} p_{X,Y}(x,y) &= P\left(\bigcup_{(x,y) \in R_X \times R_Y} \{x,y\}\right) \\
&= P(R_X \times R_Y) \\
&= P\{s \mid (X(s), Y(s)) \in (R_X \times R_Y)\} \\
&= P(S) = 1
\end{aligned}$$

This is because

• **Marginal Probability Mass Functions:** The probability mass functions $p_X(x)$ and $p_Y(y)$ are obtained from the joint probability mass function as follows

$$\begin{aligned}
p_X(x) &= P(\{X = x\} \cup R_Y) \\
&= \sum_{y \in R_Y} p_{X,Y}(x,y)
\end{aligned}$$

and similarly

$$p_Y(y) = \sum_{x \in R_X} p_{X,Y}(x,y)$$

These probability mass functions $p_X(x)$ and $p_Y(y)$ obtained from the joint probability mass functions are called *marginal probability mass functions*.

Example 4 Consider the random variables X and Y with the joint probability mass function as tabulated in Table 1. The marginal probabilities $p_X(x)$ and $p_Y(y)$ are as shown in the last column and the last row respectively.

$X \backslash Y$	0	1	2	$p_Y(y)$
0	0.25	0.1	0.15	0.5
1	0.14	0.35	0.01	0.5
$p_X(x)$	0.39	0.45	0.16	

Table 1

Joint Probability Density Function

If X and Y are two continuous random variables and their joint distribution function is continuous in both x and y , then we can define *joint probability density function* $f_{X,Y}(x,y)$ by

$$f_{X,Y}(x,y) = \frac{\partial^2}{\partial x \partial y} F_{X,Y}(x,y)$$

provided it exists.

Clearly
$$F_{X,Y}(x,y) = \int_{-\infty}^x \int_{-\infty}^y f_{X,Y}(u,v) dv du$$

Properties of Joint Probability Density Function

- $f_{X,Y}(x,y)$ is always a non-negative quantity. That is,

$$f_{X,Y}(x,y) \geq 0 \quad \forall (x,y) \in \mathbb{R}^2$$

- $$\int_{-\infty}^{\infty} \int_{-\infty}^{\infty} f_{X,Y}(x,y) dx dy = 1$$

- The probability of any Borel set can be obtained by

$$P(B) = \iint_{(x,y) \in B} f_{X,Y}(x,y) dx dy$$

Marginal density functions

The marginal density functions $f_X(x)$ and $f_Y(y)$ of two joint RVs X and Y are given by the derivatives of the corresponding marginal distribution functions. Thus

$$\begin{aligned} f_X(x) &= \frac{d}{dx} F_X(x) \\ &= \frac{d}{dx} F_X(x, \infty) \\ &= \frac{d}{dx} \int_{-\infty}^x \left(\int_{-\infty}^{\infty} f_{X,Y}(u,y) dy \right) du \\ &= \int_{-\infty}^{\infty} f_{X,Y}(x,y) dy \end{aligned}$$

$$\therefore f_X(x) = \int_{-\infty}^{\infty} f_{X,Y}(x,y) dy$$

Thus
$$f_X(x) = \int_{-\infty}^{\infty} f_{X,Y}(x,y) dy$$

and similarly
$$f_Y(y) = \int_{-\infty}^{\infty} f_{X,Y}(x,y) dx$$

Example 5 The joint density function $f_{X,Y}(x,y)$ of the random variables in *Example 3* is

$$\begin{aligned}
 f_{X,Y}(x,y) &= \frac{\partial^2}{\partial x \partial y} F_{X,Y}(x,y) \\
 &= \frac{\partial^2}{\partial x \partial y} [(1 - e^{-2x})(1 - e^{-y})] \quad x \geq 0, y \geq 0 \\
 &= 2e^{-2x}e^{-y} \quad x \geq 0, y \geq 0
 \end{aligned}$$

Example 6 The joint pdf of two random variables X and Y are given by

$$\begin{aligned}
 f_{X,Y}(x,y) &= cxy \quad 0 \leq x \leq 2, 0 \leq y \leq 2 \\
 &= 0 \quad \text{otherwise}
 \end{aligned}$$

- Find c .
- Find $F_{X,Y}(x,y)$.
- Find $f_X(x)$ and $f_Y(y)$.
- What is the probability $P(0 < X \leq 1, 0 < Y \leq 1)$?

$$\begin{aligned}
 \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} f_{X,Y}(x,y) dy dx &= c \int_0^2 \int_0^2 xy dy dx \\
 &= c \int_0^2 x dx \int_0^2 y dy \\
 &= 4c \\
 \therefore 4c &= 1 \\
 \Rightarrow c &= \frac{1}{4}
 \end{aligned}$$

$$\begin{aligned}
 F_{X,Y}(x,y) &= \frac{1}{4} \int_0^y \int_0^x uv du dv \\
 &= \frac{x^2 y^2}{16} \quad 0 \leq x \leq 2, 0 \leq y \leq 2
 \end{aligned}$$

$$\begin{aligned}
 f_X(x) &= \int_0^2 \frac{xy}{4} dy \quad 0 \leq y \leq 2 \\
 &= \frac{x}{2}
 \end{aligned}$$

$$\therefore f_X(x) = \frac{x}{2} \quad 0 \leq x \leq 2$$

Similarly

$$f_Y(y) = \frac{y}{2} \quad 0 \leq y \leq 2$$

$$\begin{aligned}
P(0 < X \leq 1, 0 < Y \leq 1) \\
&= F_{X,Y}(1,1) + F_{X,Y}(0,0) - F_{X,Y}(0,1) - F_{X,Y}(1,0) \\
&= \frac{1}{16} + 0 - 0 - 0 \\
&= \frac{1}{16}
\end{aligned}$$

Conditional Distributions

We discussed the conditional CDF and conditional PDF of a random variable conditioned on some events defined in terms of the same random variable. We observed that

$$F_X(x|B) = \frac{P(\{X \leq x\} \cap B)}{P(B)} \quad P(B) \neq 0$$

and

$$f_X(x|B) = \frac{d}{dx} F_X(x|B)$$

We can define these quantities for two random variables. We start with the *conditional probability mass functions* for two random variables.

Conditional Probability Density Functions

Suppose X and Y are two discrete jointly random variable with the joint PMF $p_{X,Y}(x,y)$. The conditional PMF of Y given $X = x$ is denoted by $p_{Y|X}(y|x)$ and defined as

$$\begin{aligned}
p_{Y|X}(y|x) &= P(\{Y = y\} | \{X = x\}) \\
&= \frac{P(\{X = x\} \cap \{Y = y\})}{P(X = x)} \\
&= \frac{p_{X,Y}(x,y)}{p_X(x)} \quad \text{provided } p_X(x) \neq 0
\end{aligned}$$

Thus,

$$p_{Y|X}(y|x) = \frac{p_{X,Y}(x,y)}{p_X(x)} \quad \text{provided } p_X(x) \neq 0$$

Similarly we can define the conditional probability mass function

$$p_{X|Y}(x|y) = \frac{p_{X,Y}(x,y)}{p_Y(y)} \quad \text{provided } p_Y(y) \neq 0$$

Conditional Probability Distribution Function

Consider two continuous jointly random variables X and Y with the joint probability distribution function $F_{X,Y}(x,y)$. We are interested to find the conditional distribution function of one of the random variables on the condition of a particular value of the other random variable.

We *cannot* define the conditional distribution function of the random variable Y on the condition of the event $\{X = x\}$ by the relation

$$\begin{aligned} F_{Y/X}(y/x) &= P(Y \leq y / X = x) \\ &= \frac{P(Y \leq y, X = x)}{P(X = x)} \end{aligned}$$

as $P(X = x) = 0$ in the above expression. The conditional distribution function is defined in the *limiting sense* as follows:

$$\begin{aligned} F_{Y/X}(y/x) &= \lim_{\Delta x \rightarrow 0} P(Y \leq y / x < X \leq x + \Delta x) \\ &= \lim_{\Delta x \rightarrow 0} \frac{P(Y \leq y, x < X \leq x + \Delta x)}{P(x < X \leq x + \Delta x)} \\ &= \lim_{\Delta x \rightarrow 0} \frac{\int_0^y f_{X,Y}(x,u) \Delta x du}{f_X(x) \Delta x} \\ &= \frac{\int_0^y f_{X,Y}(x,u) du}{f_X(x)} \end{aligned}$$

$$\therefore F_{Y/X}(y/x) = \frac{\int_0^y f_{X,Y}(x,u) du}{f_X(x)}$$

Conditional Probability Density Function

$f_{Y/X}(y/x) = f_{Y/X}(y/x)$ is called the *conditional probability density function* of Y given X

Let us define the conditional distribution function .

The conditional density is defined in the limiting sense as follows

$$f_{Y|X}(y/X=x) = \lim_{\Delta y \rightarrow 0} (F_{Y|X}(y + \Delta y/X=x) - F_{Y|X}(y/X=x)) / \Delta y$$

$$\therefore f_{Y|X}(y/X=x) = \lim_{\Delta y \rightarrow 0, \Delta x \rightarrow 0} (F_{Y|X}(y + \Delta y/x < X \leq x + \Delta x) - F_{Y|X}(y/x < X \leq x + \Delta x)) / \Delta y$$

$$\text{Because, } (X=x) = \lim_{\Delta x \rightarrow 0} (x < X \leq x + \Delta x)$$

The right hand side of the highlighted equation is

$$\begin{aligned} \lim_{\Delta y \rightarrow 0, \Delta x \rightarrow 0} (F_{Y|X}(y + \Delta y/x < X < x + \Delta x) - F_{Y|X}(y/x < X < x + \Delta x)) / \Delta y \\ &= \lim_{\Delta y \rightarrow 0, \Delta x \rightarrow 0} (P(y < Y \leq y + \Delta y/x < X \leq x + \Delta x)) / \Delta y \\ &= \lim_{\Delta y \rightarrow 0, \Delta x \rightarrow 0} (P(y < Y \leq y + \Delta y, x < X \leq x + \Delta x)) / P(x < X \leq x + \Delta x) \Delta y \\ &= \lim_{\Delta y \rightarrow 0, \Delta x \rightarrow 0} f_{X,Y}(x, y) \Delta x \Delta y / f_X(x) \Delta x \Delta y \\ &= f_{X,Y}(x, y) / f_X(x) \end{aligned}$$

$$\therefore f_{Y|X}(y/x) = f_{X,Y}(x, y) / f_X(x)$$

Similarly we have

$$\therefore f_{X|Y}(x/y) = f_{X,Y}(x, y) / f_Y(y)$$

Two random variables are *statistically independent* if for all $(x, y) \in \mathbb{R}^2$,

$$f_{Y|X}(y/x) = f_Y(y)$$

or equivalently

$$f_{X,Y}(x, y) = f_X(x) f_Y(y)$$

•

Example 2 X and Y are two jointly random variables with the joint pdf given by

$$\begin{aligned} f_{X,Y}(x, y) &= k \text{ for } 0 \leq x \leq 1 \\ &= 0 \text{ otherwise} \end{aligned}$$

find,

- (a) k
- (b) $f_X(x)$ and $f_Y(y)$
- (c) $f_{X|Y}(x/y)$

Solution:

Since $\int_{-\infty}^{\infty} \int_{-\infty}^{\infty} f_{X,Y}(x,y) dy dx = 1$

We get

$$k \int_0^1 \int_0^x x dy dx = 1$$

$$\Rightarrow k = 2$$

$$\therefore f_{X,Y}(x,y) = 2 \text{ for } 0 \leq x \leq 1 \text{ as } y \leq x \\ = 0 \text{ otherwise}$$

$$f_X(x) = \int_{-\infty}^{\infty} f_{X,Y}(x,y) dy = 2 \int_0^x dy = 2x$$

$$f_Y(y) = \int_{-\infty}^{\infty} f_{X,Y}(x,y) dx = 2 \int_y^1 dx = 2(1-y)$$

Independent Random Variables (or) Statistical Independence

Let X and Y be two random variables characterized by the joint distribution function

$$F_{X,Y}(x,y) = P\{X \leq x, Y \leq y\}$$

and the corresponding joint density function $f_{X,Y}(x,y) = \frac{\partial^2}{\partial x \partial y} F_{X,Y}(x,y)$

Then X and Y are independent if $\forall (x,y) \in \mathbb{R}^2$, $\{X \leq x\}$ and $\{Y \leq y\}$ are independent events.
Thus,

$$\begin{aligned}
 F_{X,Y}(x,y) &= P\{X \leq x, Y \leq y\} \\
 &= P\{X \leq x\}P\{Y \leq y\} \\
 &= F_X(x)F_Y(y)
 \end{aligned}$$

$$\begin{aligned}
 \therefore f_{X,Y}(x,y) &= \frac{\partial^2 F_{X,Y}(x,y)}{\partial x \partial y} \\
 &= \frac{dF_X(x)}{dx} \frac{dF_Y(y)}{dy} \\
 &= f_X(x)f_Y(y) \\
 \therefore f_{X,Y}(x,y) &= f_X(x)f_Y(y)
 \end{aligned}$$

and equivalently $f_{Y/X}(y) = f_Y(y)$

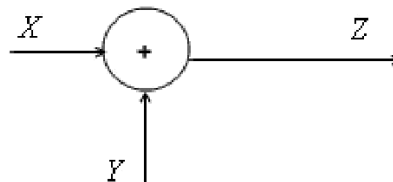
Sum of Two Random Variables

We are often interested in finding out the probability density function of a function of two or more RVs. Following are a few examples.

- The received signal by a communication receiver is given by

$$Z = X + Y$$

where Z is received signal which is the superposition of the message signal X and the noise Y .



- The frequently applied operations on communication signals like modulation, demodulation, correlation etc. involve multiplication of two signals in the form $Z = XY$.

We have to know about the probability distribution of Z in any analysis of Z . More formally, given two random variables X and Y with joint probability density function $f_{X,Y}(x,y)$ and a function $Z = g(X,Y)$, we have to find $f_Z(z)$.

In this lecture, we shall address this problem.

Probability Density of the Function of Two Random Variables

We consider the transformation $g : \mathbb{R}^2 \rightarrow \mathbb{R}$.

Consider the event $\{Z \leq z\}$ corresponding to each z . We can find a variable subset $D_z \subseteq \mathbb{R}^2$ such that $D_z = \{(x, y) \mid g(x, y) \leq z\}$.

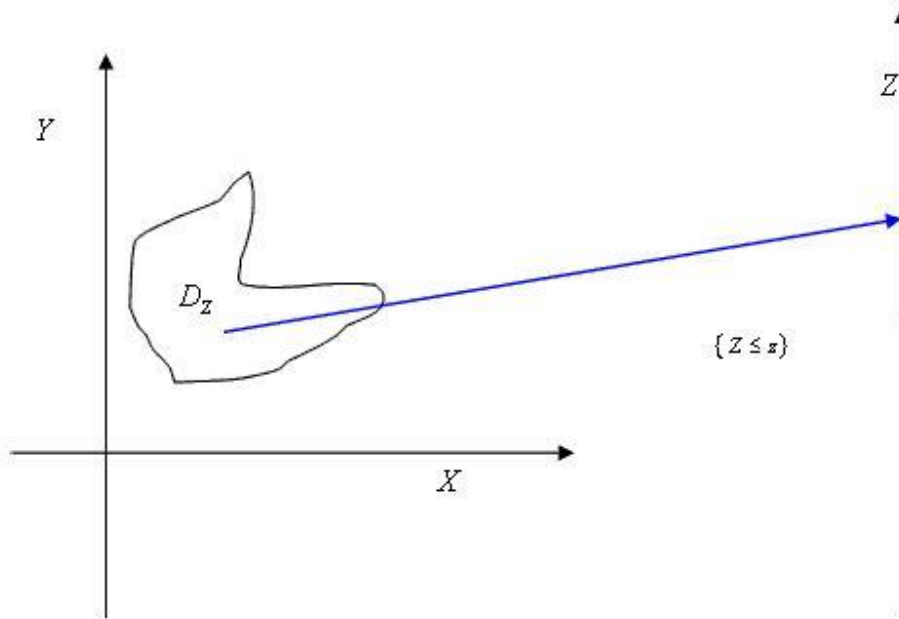


Figure 1

$$\begin{aligned} \therefore F_Z(z) &= P(\{Z \leq z\}) \\ &= P(\{(x, y) \mid (x, y) \in D_z\}) \\ &= \iint_{(x, y) \in D_z} f_{X,Y}(x, y) \, dy \, dx \end{aligned}$$

$$\text{and } f_Z(z) = \frac{dF_Z(z)}{dz}$$

Probability density function of $Z = X + Y$.

Consider Figure 2

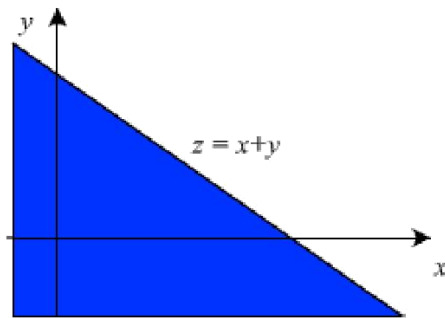


Figure 2

We have

$$Z \leq z$$

$$\Rightarrow X + Y \leq z$$

Therefore, D_Z is the colored region in the Figure 2.

$$\begin{aligned} \therefore F_Z(z) &= \iint_{(x,y) \in D_z} f_{X,Y}(x,y) dx dy \\ &= \int_{-\infty}^{\infty} \left[\int_{-\infty}^{z-x} f_{X,Y}(x,y) dy \right] dx \\ &= \int_{-\infty}^{\infty} \left[\int_{-\infty}^z f_{X,Y}(x, u-x) du \right] dx \quad \text{substituting } y = u - x \\ &= \int_{-\infty}^z \left[\int_{-\infty}^{\infty} f_{X,Y}(x, u-x) dx \right] du \quad \text{interchanging the order of integration} \\ \therefore f_Z(z) &= \frac{d}{dz} \int_{-\infty}^z \left[\int_{-\infty}^{\infty} f_{X,Y}(x, u-x) dx \right] du \\ &= \int_{-\infty}^{\infty} f_{X,Y}(x, z-x) dx \end{aligned}$$

$$\therefore f_Z(z) = \int_{-\infty}^{\infty} f_{X,Y}(x, z-x) dx$$

If X and Y are independent

$$f_{X,Y}(x, z-x) = f_X(x) f_Y(z-x)$$

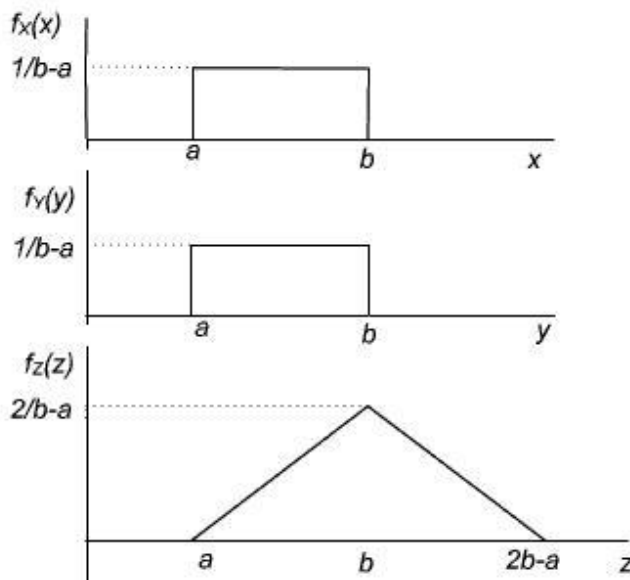
$$\therefore f_Z(z) = \int_{-\infty}^{\infty} f_X(x) f_Y(z-x) dx$$

$$= f_X(z) * f_Y(z)$$

Where $*$ is the convolution operation.

Example 1

Suppose X and Y are independent random variables and each uniformly distributed over (a, b) . $f_X(x)$ And $f_Y(y)$ are as shown in the figure below.



The PDF of $Z = X + Y$ is a triangular probability density function as shown in the figure.

Central Limit Theorem

Consider n **independent** random variables X_1, X_2, \dots, X_n . The mean and variance of each of the random variables are assumed to be known. Suppose $E(X_i) = \mu_{X_i}$ and $\text{var}(X_i) = \sigma_{X_i}^2$. Form a random variable

$$Y_n = X_1 + X_2 + \dots + X_n$$

The mean and variance of Y_n are given by

$$EY_n = \mu_{Y_n} = \mu_{X_1} + \mu_{X_2} + \dots + \mu_{X_n}$$

$$\begin{aligned} \text{var}(Y_n) &= \sigma_{Y_n}^2 = E\left\{\sum_{i=1}^n (X_i - \mu_{X_i})\right\}^2 \\ &= \sum_{i=1}^n E(X_i - \mu_{X_i})^2 + \sum_{i=1}^n \sum_{j=1, j \neq i}^n E(X_i - \mu_{X_i})(X_j - \mu_{X_j}) \\ &= \sigma_{X_1}^2 + \sigma_{X_2}^2 + \dots + \sigma_{X_n}^2 \end{aligned}$$

and

$\because X_i$ and X_j are independent for $i \neq j$.

Thus we can determine the mean and the variance of Y_n .

Can we guess about the probability distribution of Y_n ?

The central limit theorem (CLT) provides an answer to this question.

$$\left\{Y_n = \sum_{i=1}^n X_i\right\}$$

The CLT states that under very general conditions converges in distribution to $Y \sim N(\mu_Y, \sigma_Y^2)$ as $n \rightarrow \infty$. The conditions are:

1. The random variables X_1, X_2, \dots, X_n are independent and identically distributed.
2. The random variables X_1, X_2, \dots, X_n are independent with same mean and variance, but not identically distributed.
3. The random variables X_1, X_2, \dots, X_n are independent with different means and same variance and not identically distributed.
4. The random variables X_1, X_2, \dots, X_n are independent with different means and each variance being neither too small nor too large.

We shall consider the first condition only. In this case, the central-limit theorem can be stated as follows:

Proof of the Central Limit Theorem:

We give a less rigorous proof of the theorem with the help of the characteristic function.

Further we consider each of X_1, X_2, \dots, X_n to have zero mean. Thus, $Y_n = (X_1 + X_2 + \dots + X_n)/\sqrt{n}$.

$$\mu_{Y_n} = 0,$$

$$\sigma_{Y_n}^2 = \sigma_X^2,$$

Clearly, $E(Y_n^3) = E(X^3)/\sqrt{n}$ and so on.

The characteristic function of Y_n is given by

$$\phi_{Y_n}(\omega) = E\left(e^{j\omega Y_n}\right) = E\left(e^{j\omega \frac{1}{\sqrt{n}} \sum_{i=1}^n X_i}\right)$$

We will show that as $n \rightarrow \infty$ the characteristic function ϕ_{Y_n} is of the form of the characteristic function of a Gaussian random variable.

Expanding $e^{j\omega Y_n}$ in power series

$$e^{j\omega Y_n} = 1 + j\omega Y_n + \frac{(j\omega)^2}{2!} Y_n^2 + \frac{(j\omega)^3}{3!} Y_n^3 + \dots$$

Assume all the moments of Y_n to be finite. Then

$$\phi_{Y_n}(\omega) = E\left(e^{j\omega Y_n}\right) = 1 + j\omega \mu_{Y_n} + \frac{(j\omega)^2}{2!} E(Y_n^2) + \frac{(j\omega)^3}{3!} E(Y_n^3) + \dots$$

Substituting $\mu_{Y_n} = 0$ and $E(Y_n^2) = \sigma_{Y_n}^2 = \sigma_X^2$, we get

$$\phi_{Y_n}(\omega) = 1 - (\omega^2 / 2!) \sigma_X^2 + R(\omega, n)$$

where $R(\omega, n)$ is the average of terms involving ω^3 and higher powers of ω .

Note also that each term in $R(\omega, n)$ involves a ratio of a higher moment and a power of n and therefore,

$$\lim_{n \rightarrow \infty} R(\omega, n) = 0$$

$$\therefore \lim_{n \rightarrow \infty} \phi_{Y_n}(\omega) = 1 - \frac{\omega^2}{2!} \sigma_X^2 = e^{-\frac{\omega^2 \sigma_X^2}{2}}$$

which is the characteristic function of a Gaussian random variable with 0 mean and variance σ_X^2 .

$$Y_n \xrightarrow{d} N(0, \sigma_X^2)$$

OPERATIONS ON MULTIPLE RANDOM VARIABLES

Expected Values of Functions of Random Variables

If $Y = g(X)$ is a function of a continuous random variable X , then

If $Y = g(X)$ is a function of a discrete random variable X , then $EY = Eg(X) = \sum_{x \in \mathcal{R}_X} g(x)p_X(x)$

Suppose $Z = g(X, Y)$ is a function of continuous random variables X and Y then the expected value of Z is given by

$$\begin{aligned} EZ = Eg(X, Y) &= \int_{-\infty}^{\infty} zf_Z(z)dz \\ &= \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} g(x, y)f_{X,Y}(x, y)dxdy \end{aligned}$$

Thus EZ can be computed without explicitly determining $f_Z(z)$.

We can establish the above result as follows.

Suppose $Z = g(X, Y)$ has n roots (x_i, y_i) , $i = 1, 2, \dots, n$ at $Z = z$. Then

$$\{z < Z \leq z + \Delta z\} = \bigcup_{i=1}^n \{(x_i, y_i) \in \Delta D_i\}$$

Where

ΔD_i is the differential region containing (x_i, y_i) . The mapping is illustrated in Figure 1 for $n = 3$.

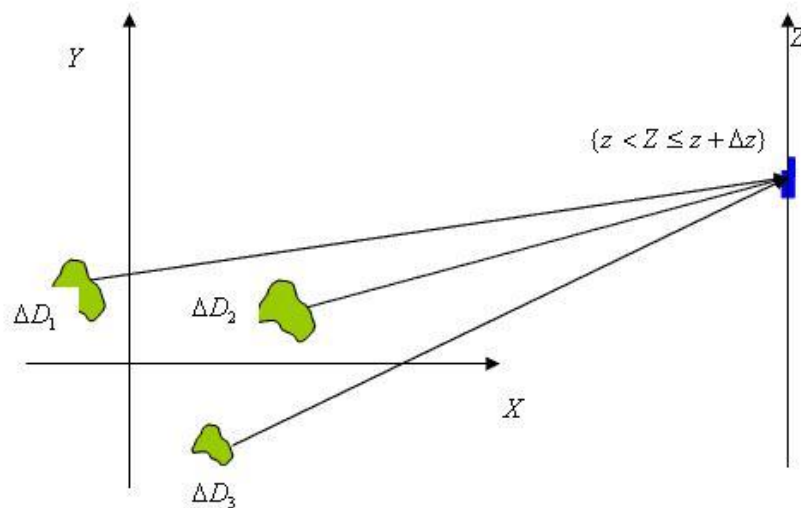


Figure 1

Note that

$$\begin{aligned}
 P(\{z < Z \leq z + \Delta z\}) &= f_Z(z) \Delta z = \sum_{(x_i, y_i) \in D_i} f_{X,Y}(x_i, y_i) \Delta x_i \Delta y_i \\
 \therefore z f_Z(z) \Delta z &= \sum_{(x_i, y_i) \in D_i} z f_{X,Y}(x_i, y_i) \Delta x_i \Delta y_i \\
 &= \sum_{(x_i, y_i) \in D_i} g(x_i, y_i) f_{X,Y}(x_i, y_i) \Delta x_i \Delta y_i
 \end{aligned}$$

As Z is varied over the entire Z axis, the corresponding (non-overlapping) differential regions in $X-Y$ plane cover the entire plane.

$$\therefore \int_{-\infty}^{\infty} z f_Z(z) dz = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} g(x, y) f_{X,Y}(x, y) dx dy$$

Thus,

$$Eg(X, Y) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} g(x, y) f_{X,Y}(x, y) dx dy$$

If $Z = g(X, Y)$ is a function of discrete random variables X and Y , we can similarly show that

$$EZ = Eg(X, Y) = \sum_{x, y \in \mathbb{R}_X \times \mathbb{R}_Y} g(x, y) p_{X,Y}(x, y)$$

Example 1 The joint pdf of two random variables X and Y is given by

$$\begin{aligned}
 f_{X,Y}(x, y) &= \frac{1}{4} xy \quad 0 \leq x \leq 2, 0 \leq y \leq 2 \\
 &= 0 \quad \text{otherwise}
 \end{aligned}$$

Find the joint expectation of $g(X, Y) = X^2Y$

$$\begin{aligned}
 Eg(X, Y) &= EX^2Y \\
 &= \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} g(x, y) f_{X,Y}(x, y) dx dy \\
 &= \int_0^2 \int_0^2 x^2 y \frac{1}{4} xy dx dy \\
 &= \frac{1}{4} \int_0^2 x^3 dx \int_0^2 y^2 dy \\
 &= \frac{1}{4} \times \frac{2^4}{4} \times \frac{2^3}{3} \\
 &= \frac{8}{3}
 \end{aligned}$$

Example 2 If $Z = aX + bY$, where a and b are constants, then

$$EZ = aEX + bEY$$

Proof:

$$\begin{aligned}
 EZ &= \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} (ax + by) f_{X,Y}(x, y) dx dy \\
 &= \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} ax f_{X,Y}(x, y) dx dy + \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} by f_{X,Y}(x, y) dx dy \\
 &= \int_{-\infty}^{\infty} ax \int_{-\infty}^{\infty} f_{X,Y}(x, y) dy dx + \int_{-\infty}^{\infty} by \int_{-\infty}^{\infty} f_{X,Y}(x, y) dx dy \\
 &= a \int_{-\infty}^{\infty} x f_X(x) dx + b \int_{-\infty}^{\infty} y f_Y(y) dy \\
 &= aEX + bEY
 \end{aligned}$$

Thus, expectation is a linear operator.

Example 3

Consider the discrete random variables X and Y discussed in Example 4 in lecture 18. The joint probability mass function of the random variables are tabulated in Table . Find the joint expectation of $g(X, Y) = XY$.

$\begin{matrix} X \\ Y \end{matrix}$	0	1	2	$p_Y(y)$
0	0.25	0.1	0.15	0.5
1	0.14	0.35	0.01	0.5
$p_X(x)$	0.39	0.45	0.16	

$$\begin{aligned}
 \text{Clearly, } EXY &= \sum_{x,y \in \mathbb{R}_x \times \mathbb{R}_y} \sum g(x,y) p_{X,Y}(x,y) \\
 &= 1 \times 1 \times 0.35 + 1 \times 2 \times 0.01 \\
 &= 0.37
 \end{aligned}$$

Remark

(1) We have earlier shown that expectation is a linear operator. We can generally write

$$E[a_1 g_1(X,Y) + a_2 g_2(X,Y)] = a_1 E g_1(X,Y) + a_2 E g_2(X,Y)$$

$$\text{Thus} \quad E(XY + 5 \log_e XY) = EXY + 5E \log_e XY$$

(2) If X and Y are independent random variables and $g(X,Y) = g_1(X)g_2(Y)$, then

$$\begin{aligned}
 E g(X,Y) &= E g_1(X) g_2(Y) \\
 &= \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} g_1(X) g_2(Y) f_{X,Y}(x,y) dx dy \\
 &= \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} g_1(X) g_2(Y) f_X(x) f_Y(y) dx dy \\
 &= \int_{-\infty}^{\infty} g_1(X) f_X(x) dx \int_{-\infty}^{\infty} g_2(Y) f_Y(y) dy \\
 &= E g_1(X) E g_2(Y)
 \end{aligned}$$

Joint Moments of Random Variables

Just like the moments of a random variable provide a summary description of the random variable, so also the *joint moments* provide summary description of two random variables. For two continuous random variables X and Y , the *joint moment of order $m+n$* is defined as

$$E(X^m Y^n) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} x^m y^n f_{X,Y}(x,y) dx dy$$

And the joint central moment of order $m+n$ is defined as

$$E(X - \mu_X)^m (Y - \mu_Y)^n = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} (x - \mu_X)^m (y - \mu_Y)^n f_{X,Y}(x, y) dx dy$$

where $\mu_X = EX$ and $\mu_Y = EY$

Remark

(1) If X and Y are discrete random variables, the joint expectation of order m and n is defined as

$$E(X^m Y^n) = \sum_{(x,y) \in \mathcal{R}_{X,Y}} x^m y^n p_{X,Y}(x, y)$$

$$E(X - \mu_X)^m (Y - \mu_Y)^n = \sum_{(x,y) \in \mathcal{R}_{X,Y}} (x - \mu_X)^m (y - \mu_Y)^n p_{X,Y}(x, y)$$

(2) If $m = 1$ and $n = 1$, we have the second-order moment of the random variables X and Y given by

$$E(XY) = \begin{cases} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} xy f_{X,Y}(x, y) dx dy & \text{if } X \text{ and } Y \text{ are continuous} \\ \sum_{(x,y) \in \mathcal{R}_{X,Y}} xy p_{X,Y}(x, y) & \text{if } X \text{ and } Y \text{ are discrete} \end{cases}$$

(3) If X and Y are independent, $E(XY) = EXEY$

Covariance of two random variables

The *covariance* of two random variables X and Y is defined as

$$\text{Cov}(X, Y) = E(X - \mu_X)(Y - \mu_Y)$$

$\text{Cov}(X, Y)$ is also denoted as $\sigma_{X,Y}$.

Expanding the right-hand side, we get

$$\begin{aligned} \text{Cov}(X, Y) &= E(X - \mu_X)(Y - \mu_Y) \\ &= E(XY - \mu_Y X - \mu_X Y + \mu_X \mu_Y) \\ &= EXY - \mu_Y EX - \mu_X EY + \mu_X \mu_Y \\ &= EXY - \mu_X \mu_Y \end{aligned}$$

The ratio $\rho(X, Y) = \frac{\text{Cov}(X, Y)}{\sigma_X \sigma_Y}$ is called the **correlation coefficient**.

If $\rho_{X,Y} > 0$ then X and Y are called positively correlated.

If $\rho_{X,Y} < 0$ then X and Y are called negatively correlated

If $\rho_{X,Y} = 0$ then X and Y are uncorrelated.

We will also show that $|\rho(X,Y)| \leq 1$. To establish the relation, we prove the following result:

For two random variables X and Y $E^2(XY) \leq EX^2 EY^2$

Proof:

Consider the random variable $Z = aX + Y$

$$\begin{aligned} E(aX + Y)^2 &\geq 0 \\ \Rightarrow a^2 EX^2 + EY^2 + 2aEXY &\geq 0. \end{aligned}$$

Non-negativity of the left-hand side implies that its minimum also must be nonnegative.

For the minimum value,

$$\frac{dEZ^2}{da} = 0 \Rightarrow a = -\frac{EXY}{EX^2}$$

so the corresponding minimum is

$$\begin{aligned} \frac{E^2 XY}{EX^2} + EY^2 - 2 \frac{E^2 XY}{EX^2} \\ = EY^2 - \frac{E^2 XY}{EX^2} \end{aligned}$$

Since the minimum is nonnegative,

$$\begin{aligned} EY^2 - \frac{E^2 XY}{EX^2} &\geq 0 \\ \Rightarrow E^2 XY &\leq EX^2 EY^2 \\ \Rightarrow |EXY| &\leq \sqrt{EX^2} \sqrt{EY^2} \end{aligned}$$

Now

$$\begin{aligned}
\rho(X, Y) &= \frac{\text{Cov}(X, Y)}{\sigma_X \sigma_Y} \\
&= \frac{E(X - \mu_X)(Y - \mu_Y)}{\sqrt{E(X - \mu_X)^2} \sqrt{E(Y - \mu_Y)^2}} \\
\therefore |\rho(X, Y)| &= \frac{|E(X - \mu_X)(Y - \mu_Y)|}{\sqrt{E(X - \mu_X)^2} \sqrt{E(Y - \mu_Y)^2}} \\
&\leq \frac{\sqrt{E(X - \mu_X)^2} \sqrt{E(Y - \mu_Y)^2}}{\sqrt{E(X - \mu_X)^2} \sqrt{E(Y - \mu_Y)^2}} \\
&= 1
\end{aligned}$$

Thus $|\rho(X, Y)| \leq 1$

Uncorrelated random variables

Two random variables X and Y are called *uncorrelated* if

$$\text{Cov}(X, Y) = 0$$

which also means

$$E(XY) = \mu_X \mu_Y$$

Recall that if X and Y are independent random variables, then $f_{X,Y}(x, y) = f_X(x) f_Y(y)$.

$$\begin{aligned}
EXY &= \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} xy f_{X,Y}(x, y) dx dy \quad \text{assuming } X \text{ and } Y \text{ are continuous} \\
&= \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} xy f_X(x) f_Y(y) dx dy \\
&= \int_{-\infty}^{\infty} x f_X(x) dx \int_{-\infty}^{\infty} y f_Y(y) dy \\
&= EX EY
\end{aligned}$$

then

Thus two independent random variables are always uncorrelated.

Note that independence implies uncorrelated. But uncorrelated generally does not imply independence (except for jointly Gaussian random variables).

Joint Characteristic Functions of Two Random Variables

The *joint characteristic function* of two random variables X and Y is defined by

$$\phi_{X,Y}(\omega_1, \omega_2) = E e^{j\omega_1 X + j\omega_2 Y}$$

If X and Y are jointly continuous random variables, then

$$\phi_{X,Y}(\omega_1, \omega_2) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} f_{X,Y}(x, y) e^{j\omega_1 x + j\omega_2 y} dy dx$$

Note that $\phi_{X,Y}(\omega_1, \omega_2)$ is same as the two-dimensional Fourier transform with the basis function $e^{j\omega_1 x + j\omega_2 y}$ instead of $e^{-(j\omega_1 x + j\omega_2 y)}$.

$f_{X,Y}(x, y)$ is related to the joint characteristic function by the Fourier inversion formula

$$f_{X,Y}(x, y) = \frac{1}{4\pi^2} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \phi_{X,Y}(\omega_1, \omega_2) e^{-j\omega_1 x - j\omega_2 y} d\omega_1 d\omega_2$$

If X and Y are discrete random variables, we can define the joint characteristic function in terms of the joint probability mass function as follows:

$$\phi_{X,Y}(\omega_1, \omega_2) = \sum_{(x,y) \in \mathbf{R}_X \times \mathbf{R}_Y} p_{X,Y}(x, y) e^{j\omega_1 x + j\omega_2 y}$$

Properties of the Joint Characteristic Function

The joint characteristic function has properties similar to the properties of the characteristic function of a single random variable. We can easily establish the following properties:

1. $\phi_X(\omega) = \phi_{X,Y}(\omega, 0)$
2. $\phi_Y(\omega) = \phi_{X,Y}(0, \omega)$
3. If X and Y are independent random variables, then

$$\begin{aligned} \phi_{X,Y}(\omega_1, \omega_2) &= E e^{j\omega_1 X + j\omega_2 Y} \\ &= E(e^{j\omega_1 X} e^{j\omega_2 Y}) \\ &= E e^{j\omega_1 X} E e^{j\omega_2 Y} \\ &= \phi_X(\omega_1) \phi_Y(\omega_2) \end{aligned}$$

4. We have,

$$\begin{aligned}
\phi_{X,Y}(\omega_1, \omega_2) &= Ee^{j\omega_1 X + j\omega_2 Y} \\
&= E\left(1 + j\omega_1 X + j\omega_2 Y + \frac{j^2(\omega_1 X + j\omega_2 Y)^2}{2} + \dots\right) \\
&= 1 + j\omega_1 EX + j\omega_2 EY + \frac{j^2 \omega_1^2 EX^2}{2} + \frac{j^2 \omega_2^2 EY^2}{2} + \omega_1 \omega_2 EXY + \dots
\end{aligned}$$

Hence,

$$\begin{aligned}
\phi_{X,Y}(0, 0) &= 1 \\
EX &= \frac{1}{j} \frac{\partial}{\partial \omega_1} \phi_{X,Y}(\omega_1, \omega_2) \Big|_{\omega_1=0} \\
EY &= \frac{1}{j} \frac{\partial}{\partial \omega_2} \phi_{X,Y}(\omega_1, \omega_2) \Big|_{\omega_2=0} \\
EXY &= \frac{1}{j^2} \frac{\partial^2 \phi_{X,Y}(\omega_1, \omega_2)}{\partial \omega_1 \partial \omega_2} \Big|_{\omega_1=0, \omega_2=0}
\end{aligned}$$

In general, the $(m+n)th$ order joint moment is given by

$$EX^m Y^n = \frac{1}{j^{m+n}} \frac{\partial^m \partial^n \phi_{X,Y}(\omega_1, \omega_2)}{\partial \omega_1^m \partial \omega_2^n} \Big|_{\omega_1=0, \omega_2=0}$$

Example 2 The joint characteristic function of the jointly Gaussian random variables X and Y with the joint pdf

$$f_{X,Y}(x, y) = \frac{e^{-\frac{1}{2(1-\rho_{X,Y}^2)} \left[\left(\frac{x-\mu_X}{\sigma_X} \right)^2 - 2\rho_{X,Y} \left(\frac{x-\mu_X}{\sigma_X} \right) \left(\frac{y-\mu_Y}{\sigma_Y} \right) + \left(\frac{y-\mu_Y}{\sigma_Y} \right)^2 \right]}}{2\pi\sigma_X\sigma_Y\sqrt{1-\rho_{X,Y}^2}}$$

Let us recall the characteristic function of a Gaussian random variable

$$X \sim N(\mu_X, \sigma_X^2)$$

$$\begin{aligned}
\phi_X(\omega) &= E e^{j\omega X} \\
&= \frac{1}{\sqrt{2\pi}\sigma_X} \int_{-\infty}^{\infty} e^{-\frac{1}{2}\left(\frac{x-\mu_X}{\sigma_X}\right)^2} \cdot e^{j\omega x} dx \\
&= \frac{1}{\sqrt{2\pi}\sigma_X} \int_{-\infty}^{\infty} e^{-\frac{1}{2} \frac{x^2 - 2(\mu_X - \sigma_X^2 j\omega)x + (\mu_X - \sigma_X^2 j\omega)^2 - (\mu_X - \sigma_X^2 j\omega)^2 + \mu_X^2}{\sigma_X^2}} dx \\
&= e^{\frac{1}{2} \frac{(-\sigma_X^2 \omega^2 + 2\mu_X \sigma_X^2 j\omega)}{\sigma_X^2}} \underbrace{\frac{1}{\sqrt{2\pi}\sigma_X} \int_{-\infty}^{\infty} e^{-\frac{1}{2}\left(\frac{x-\mu_X - \sigma_X^2 j\omega}{\sigma_X}\right)^2} dx}_{\text{Area under a Gaussian}} \\
&= e^{\mu_X j\omega - \sigma_X^2 \omega^2 / 2} \times 1 \\
&= e^{\mu_X j\omega - \sigma_X^2 \omega^2 / 2}
\end{aligned}$$

If X and Y is jointly Gaussian,

$$f_{X,Y}(x,y) = \frac{e^{-\frac{1}{2(1-\rho_{X,Y}^2)} \left[\left(\frac{x-\mu_X}{\sigma_X} \right)^2 - 2\rho_{X,Y} \left(\frac{x-\mu_X}{\sigma_X} \right) \left(\frac{y-\mu_Y}{\sigma_Y} \right) + \left(\frac{y-\mu_Y}{\sigma_Y} \right)^2 \right]}}{2\pi\sigma_X\sigma_Y\sqrt{1-\rho_{X,Y}^2}}$$

we can similarly show that

$$\begin{aligned}
\phi_{X,Y}(\omega_1, \omega_2) &= E e^{j(X\omega_1 + Y\omega_2)} \\
&= e^{j\mu_X\omega_1 + j\mu_Y\omega_2 - \frac{1}{2}(\sigma_X^2\omega_1^2 + 2\rho_{X,Y}\sigma_X\sigma_Y\omega_1\omega_2 + \sigma_Y^2\omega_2^2)}
\end{aligned}$$

We can use the joint characteristic functions to simplify the probabilistic analysis as illustrated on next page:

Jointly Gaussian Random Variables

Many practically occurring random variables are modeled as jointly Gaussian random variables. For example, noise samples at different instants in the communication system are modeled as *jointly Gaussian random variables*.

Two random variables X and Y are called jointly Gaussian if their joint probability density

$$f_{X,Y}(x,y) = \frac{1}{2\pi\sigma_X\sigma_Y\sqrt{1-\rho_{X,Y}^2}} e^{-\frac{1}{2(1-\rho_{X,Y}^2)} \left[\frac{(x-\mu_X)^2}{\sigma_X^2} - 2\rho_{X,Y} \frac{(x-\mu_X)(y-\mu_Y)}{\sigma_X\sigma_Y} + \frac{(y-\mu_Y)^2}{\sigma_Y^2} \right]}, \quad -\infty < x < \infty, -\infty < y < \infty$$

The joint pdf is determined by 5 parameters

- means μ_X and μ_Y
- variances σ_X^2 and σ_Y^2
- correlation coefficient $\rho_{X,Y}$

We denote the jointly Gaussian random variables X and Y with these parameters as

$$(X, Y) \sim N(\mu_X, \mu_Y, \sigma_X^2, \sigma_Y^2, \rho_{X,Y})$$

The joint pdf has a bell shape centered at (μ_X, μ_Y) as shown in the Figure 1 below. The variances σ_X^2 and σ_Y^2 determine the spread of the pdf surface and $\rho_{X,Y}$ determines the orientation of the surface in the $X-Y$ plane.

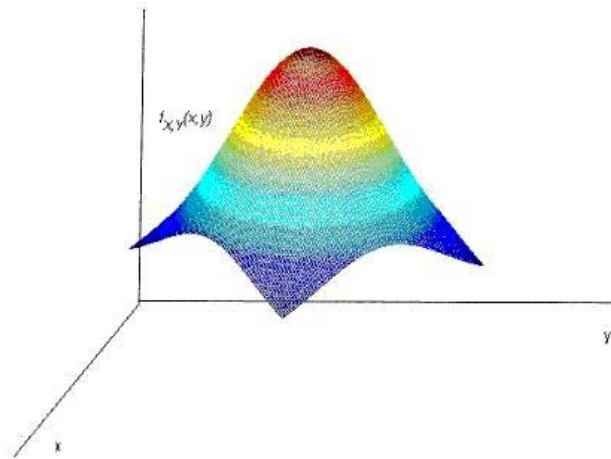


Figure 1 Jointly Gaussian PDF surface

Properties of jointly Gaussian random variables

- (1) If X and Y are jointly Gaussian, then X and Y are both Gaussian.

We have

$$\begin{aligned}
 f_X(x) &= \int_{-\infty}^{\infty} f_{X,Y}(x,y) dy \\
 &= \int_{-\infty}^{\infty} \frac{1}{2\pi\sigma_X\sigma_Y\sqrt{1-\rho_{XY}^2}} e^{-\frac{1}{2(1-\rho_{XY}^2)} \left[\frac{(x-\mu_X)^2}{\sigma_X^2} - 2\rho_{XY} \frac{(x-\mu_X)(y-\mu_Y)}{\sigma_X\sigma_Y} + \frac{(y-\mu_Y)^2}{\sigma_Y^2} \right]} dy \\
 &= \frac{e^{-\frac{1}{2} \left(\frac{x-\mu_X}{\sigma_X} \right)^2}}{\sqrt{2\pi}\sigma_X} \int_{-\infty}^{\infty} \frac{1}{\sqrt{2\pi}\sigma_Y\sqrt{1-\rho_{XY}^2}} e^{-\frac{1}{2(1-\rho_{XY}^2)} \left[\frac{\rho_{XY}^2(x-\mu_X)^2}{\sigma_X^2} - 2\rho_{XY} \frac{(x-\mu_X)(y-\mu_Y)}{\sigma_X\sigma_Y} + \frac{(y-\mu_Y)^2}{\sigma_Y^2} \right]} dy \\
 &= \frac{e^{-\frac{1}{2} \left(\frac{x-\mu_X}{\sigma_X} \right)^2}}{\sqrt{2\pi}\sigma_X} \int_{-\infty}^{\infty} \frac{1}{\sqrt{2\pi}\sigma_Y\sqrt{1-\rho_{XY}^2}} e^{-\frac{1}{2\sigma_Y^2(1-\rho_{XY}^2)} \left[(y-\mu_Y - \frac{\rho_{XY}\sigma_Y}{\sigma_X}(x-\mu_X))^2 \right]} dy \\
 &= \frac{1}{\sqrt{2\pi}\sigma_X} e^{-\frac{1}{2} \left(\frac{x-\mu_X}{\sigma_X} \right)^2}
 \end{aligned}$$

Similarly

$$f_Y(y) = \frac{1}{\sqrt{2\pi}\sigma_Y} e^{-\frac{1}{2} \left(\frac{y-\mu_Y}{\sigma_Y} \right)^2}$$

(2) The converse of the above result is not true. If each of X and Y is Gaussian, X and Y are not necessarily jointly Gaussian. Suppose

$$f_{X,Y}(x,y) = \frac{1}{2\pi\sigma_X\sigma_Y} e^{-\frac{1}{2} \left[\frac{(x-\mu_X)^2}{\sigma_X^2} + \frac{(y-\mu_Y)^2}{\sigma_Y^2} \right]} (1 + \sin x \sin y)$$

$f_{X,Y}(x,y)$ in this example is non-Gaussian and qualifies to be a joint pdf. Because,

$$f_{X,Y}(x,y) \geq 0 \quad \text{And}$$

$$\begin{aligned}
& \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \frac{1}{2\pi\sigma_X\sigma_Y} e^{-\frac{1}{2}\left[\frac{(x-\mu_X)^2}{\sigma_X^2} + \frac{(y-\mu_Y)^2}{\sigma_Y^2}\right]} (1 + \sin x \sin y) dy dx \\
&= \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \frac{1}{2\pi\sigma_X\sigma_Y} e^{-\frac{1}{2}\left[\frac{(x-\mu_X)^2}{\sigma_X^2} + \frac{(y-\mu_Y)^2}{\sigma_Y^2}\right]} dy dx + \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \frac{1}{2\pi\sigma_X\sigma_Y} e^{-\frac{1}{2}\left[\frac{(x-\mu_X)^2}{\sigma_X^2} + \frac{(y-\mu_Y)^2}{\sigma_Y^2}\right]} \sin x \sin y dy dx \\
&= 1 + \frac{1}{2\pi\sigma_X\sigma_Y} \int_{-\infty}^{\infty} e^{-\frac{1}{2}\frac{(x-\mu_X)^2}{\sigma_X^2}} \sin x dx \underbrace{\int_{-\infty}^{\infty} e^{-\frac{1}{2}\frac{(y-\mu_Y)^2}{\sigma_Y^2}} \sin y dy}_{\text{integration of an odd function}} \\
&= 1 + 0 \\
&= 1
\end{aligned}$$

The marginal density $f_X(x)$ is given by

$$\begin{aligned}
f_X(x) &= \int_{-\infty}^{\infty} \frac{1}{2\pi\sigma_X\sigma_Y} e^{-\frac{1}{2}\left[\frac{(x-\mu_X)^2}{\sigma_X^2} + \frac{(y-\mu_Y)^2}{\sigma_Y^2}\right]} (1 + \sin x \sin y) dy \\
&= \int_{-\infty}^{\infty} \frac{1}{2\pi\sigma_X\sigma_Y} e^{-\frac{1}{2}\left[\frac{(x-\mu_X)^2}{\sigma_X^2} + \frac{(y-\mu_Y)^2}{\sigma_Y^2}\right]} dy + \int_{-\infty}^{\infty} \frac{1}{2\pi\sigma_X\sigma_Y} e^{-\frac{1}{2}\left[\frac{(x-\mu_X)^2}{\sigma_X^2} + \frac{(y-\mu_Y)^2}{\sigma_Y^2}\right]} \sin x \sin y dy \\
&\quad \underbrace{\hspace{10em}}_{\text{integration of an odd function}} \\
&= \frac{1}{\sqrt{2\pi}\sigma_X} e^{-\frac{1}{2}\left(\frac{x-\mu_X}{\sigma_X}\right)^2} + 0 \\
&= \frac{1}{\sqrt{2\pi}\sigma_X} e^{-\frac{1}{2}\left(\frac{x-\mu_X}{\sigma_X}\right)^2}
\end{aligned}$$

Similarly, $f_Y(y) = \frac{1}{\sqrt{2\pi}\sigma_Y} e^{-\frac{1}{2}\left(\frac{y-\mu_Y}{\sigma_Y}\right)^2}$

Thus X and Y are both Gaussian, but not jointly Gaussian.

(3) If X and Y are jointly Gaussian, then for any constants a and b , the random variable Z given by $Z = aX + bY$ is Gaussian with mean $\mu_Z = a\mu_X + b\mu_Y$ and variance $\sigma_Z^2 = a^2\sigma_X^2 + b^2\sigma_Y^2 + 2ab\sigma_X\sigma_Y\rho_{X,Y}$

(4) Two jointly Gaussian RVs X and Y are independent if and only if X and Y are uncorrelated ($\rho_{X,Y} = 0$). Observe that if X and Y are uncorrelated, then

$$\begin{aligned}
 f_{X,Y}(x,y) &= \frac{1}{2\pi\sigma_X\sigma_Y} e^{-\frac{1}{2}\left[\frac{(x-\mu_X)^2}{\sigma_X^2} + \frac{(y-\mu_Y)^2}{\sigma_Y^2}\right]} \\
 &= \frac{1}{\sqrt{2\pi}\sigma_X} e^{-\frac{(x-\mu_X)^2}{2\sigma_X^2}} \frac{1}{\sqrt{2\pi}\sigma_Y} e^{-\frac{(y-\mu_Y)^2}{2\sigma_Y^2}} \\
 &= f_X(x)f_Y(y)
 \end{aligned}$$

Example 1 Suppose X and Y are two jointly-Gaussian 0-mean random variables with variances of 1 and 4 respectively and a covariance of 1. Find the joint PDF $f_{X,Y}(x,y)$

$$\mu_X = \mu_Y = 0, \sigma_X^2 = 1, \sigma_Y^2 = 4 \text{ and } \text{cov}(X,Y) = 1.$$

$$\therefore \rho_{X,Y} = \frac{\text{Cov}(X,Y)}{\sigma_X\sigma_Y} = \frac{1}{1 \times 2} = \frac{1}{2}$$

and

$$\begin{aligned}
 f_{X,Y}(x,y) &= \frac{1}{2\pi \times 1 \times 2 \sqrt{1 - \frac{1}{4}}} e^{-\frac{1}{2 \times \frac{1}{4}} \left[x^2 - 2 \times \frac{1}{2} \times \frac{xy}{1} + \frac{y^2}{4} \right]} \\
 &= \frac{1}{2\sqrt{3}\pi} e^{-\frac{1}{3} \left[x^2 - \frac{xy}{1} + \frac{y^2}{4} \right]}
 \end{aligned}$$

We have

Example 2 Linear transformation of two random variables

Suppose $Z = aX + bY$. then

$$\phi_Z(\omega) = Ee^{j\omega Z} = Ee^{j(aX+bY)\omega} = \phi_{X,Y}(a\omega, b\omega)$$

If X and Y are jointly Gaussian, then

$$\begin{aligned}
 \phi_Z(\omega) &= \phi_{X,Y}(a\omega, b\omega) \\
 &= e^{j(\mu_X + \mu_Y)\omega - \frac{1}{2}(a^2\sigma_X^2 + 2\rho_{X,Y}a\omega b\omega\sigma_X\sigma_Y + b^2\sigma_Y^2)\omega^2}
 \end{aligned}$$

Which is the characteristic function of a Gaussian random variable

with mean $\mu_Z = \mu_X + \mu_Y$ and variance $\sigma_Z^2 = \sigma_X^2 + 2\rho_{X,Y}\sigma_X\sigma_Y + \sigma_Y^2$

thus the linear transformation of two Gaussian random variables is a Gaussian random variable.

Example 3 If $Z = X + Y$ and X and Y are independent, then

$$\begin{aligned}\phi_Z(\omega) &= \phi_{X,Y}(\omega, \omega) \\ &= \phi_X(\omega) \phi_Y(\omega)\end{aligned}$$

Using the property of the Fourier transform, we get

$$f_Z(z) = f_X(z) * f_Y(z)$$

Hence proved.

Univariate transformations

When working on the probability density function (pdf) of a random variable X , one is often led to create a new variable Y defined as a function $f(X)$ of the original variable X . For example, if $X \sim N(\mu, \sigma^2)$, then the new variable:

$$Y = f(X) = (X - \mu)/\sigma$$

Is $N(0, 1)$.

It is also often the case that the quantity of interest is a function of another (random) quantity whose distribution is known. Here are a few examples:

*Scaling: from degrees to radians, miles to kilometers, light-years to parsecs, degrees Celsius to degrees Fahrenheit, linear to logarithmic scale, χ^2 to the distribution of the variance

* Laws of physics: what is the distribution of the kinetic energy of the molecules of a gas if the distribution of the speed of the molecules is known ?

So the general question is:

- * If $Y = h(X)$,
- * And if $f(x)$ is the pdf of X ,

Then what is the pdf $g(y)$ of Y ?

TRANSFORMATION OF A MULTIPLE RANDOM VARIABLES

Multivariate transformations

The problem extends naturally to the case when **several** variables Y_j are defined from **several** variables X_i through a transformation $\mathbf{y} = \mathbf{h}(\mathbf{x})$.

Here are some examples:

Rotation of the reference frame

Let $f(x, y)$ be the probability density function of the pair of r.v. $\{X, Y\}$. Let's rotate the reference frame $\{x, y\}$ by an angle θ . The new axes $\{x', y'\}$ define two new r. v. $\{X', Y'\}$. What is the joint probability density function of $\{X', Y'\}$?

Polar coordinates

Let $f(x, y)$ be the joint probability density function of the pair of r. v. $\{X, Y\}$, expressed in the Cartesian reference frame $\{x, y\}$. Any point (x, y) in the plane can also be identified by its polar coordinates (r, θ) . So any realization of the pair $\{X, Y\}$ produces a pair of values of r and θ , therefore defining two new r. v. R and θ .

What is the joint probability density function of R and θ ? What are the (marginal) distributions of R and of θ ?

Sampling distributions

Let $f(x)$ is the pdf of the r. v. X . Let also $Z_1 = z_1(x_1, x_2, \dots, x_n)$ be a statistic, e.g. the sample mean. What is the pdf of Z_1 ?

Z_1 is a function of the n r. v. X_i (with n the sample size), that are iid with pdf $f(x)$. If it is possible to identify $n - 1$ other independent statistics $Z_i, i = 2, \dots, n$, then a transformation $\mathbf{Z} = \mathbf{h}(\mathbf{X})$ is defined, and $g(\mathbf{z})$, the joint distribution of $\mathbf{Z} = \{Z_1, Z_2, \dots, Z_n\}$ can be calculated. The pdf of Z_1 is then calculated as one of the marginal distributions of \mathbf{Z} by integrating $g(\mathbf{z})$ over $z_i, i = 2, \dots, n$.

Integration limits

Calculations on joint distributions often involve multiple integrals whose integration limits are themselves variables. An appropriate change of variables sometimes allows changing all these variables but one into fixed integration limits, thus making the calculation of the integrals much simpler.

Linear Transformations of Random Variables

A **linear transformation** is a change to a variable characterized by one or more of the following operations: adding a constant to the variable, subtracting a constant from the variable, multiplying the variable by a constant, and/or dividing the variable by a constant.

When a linear transformation is applied to a random variable, a new random variable is created. To illustrate, let X be a random variable, and let m and b be constants. Each of the following examples show how a linear transformation of X defines a new random variable Y .

- Adding a constant: $Y = X + b$
- Subtracting a constant: $Y = X - b$

- Multiplying by a constant: $Y = mX$
- Dividing by a constant: $Y = X/m$
- Multiplying by a constant and adding a constant: $Y = mX + b$
- Dividing by a constant and subtracting a constant: $Y = X/m - b$

Suppose the vector of random variables $X = (X_1, \dots, X_N)^T$ has the joint distribution $f(x) = f(x_1, \dots, x_N)$. Set $Y = AX + B$ for some square matrix A and vector B . If $\det A \neq 0$ then Y has the joint distribution $\frac{1}{\det A} f(A^{-1}(y - B))$.

Indeed, suppose $Y \sim g(y)$ (this is the notation for "the $g(y)$ is the distribution density of Y ") and $X \sim f(x)$. For any domain D of the Y -space we can

$$\int_D g(y) dy = \text{Prob}(Y \in D) = \text{Prob}(AX + B \in D) =$$

write

$$= \text{Prob}(X \in A^{-1}(D - B)) = \int_{A^{-1}(D - B)} f(x) dx =$$

We make the change of variables

$y = Ax + B$ in the last integral.

$$= \int_D f(A^{-1}(y - B)) \left| \frac{D(x)}{D(y)} \right| dy = \int_D f(A^{-1}(y - B)) \frac{1}{\det A} dy. \quad (\text{Linear transformation of random variables})$$

The linear transformation $\sigma\xi + \mu$ is distributed as $N(\mu, \sigma^2)$. The ξ was defined in the section (Definition of normal variable).

For two independent standard normal variables (s.n.v.) ξ_1 and ξ_2 the combination $\sigma_1\xi_1 + \sigma_2\xi_2$ is distributed as $N(0, \sqrt{\sigma_1^2 + \sigma_2^2})$.

A product of normal variables is not a normal variable. See the section on the chi-squared distribution.

UNIT IV

Stochastic Processes-Temporal Characteristics

- The Stochastic process Concept
- Classification of Processes, Deterministic and Nondeterministic Processes
- Distribution and Density Functions
- Statistical Independence
- Concept of Stationarity: First-Order Stationary Processes, Second-Order and Wide-Sense Stationarity, Nth-Order and Strict-Sense Stationarity
- Time Averages and Ergodicity
- Mean-Ergodic Processes
- Correlation-Ergodic Processes
- Autocorrelation Function and Its Properties
- Cross-Correlation Function and Its Properties
- Covariance Functions and its properties
- Gaussian Random Processes.

Linear system Response:

- Mean
- Mean-squared value
- Autocorrelation
- Cross-Correlation Functions

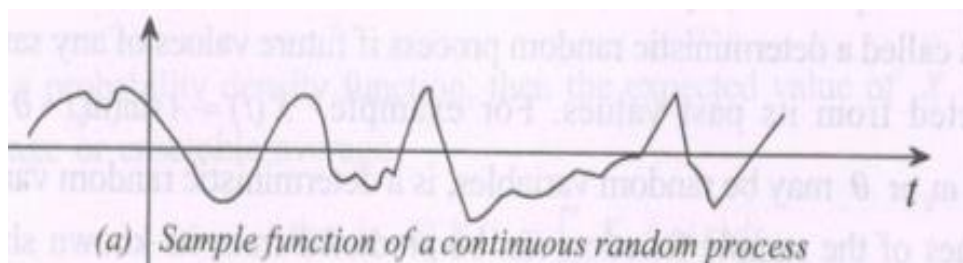
RANDOM PROCESSES: TEMPORAL CHARACTERISTICS

The random processes are also called as stochastic processes which deal with randomly varying time wave forms such as any message signals and noise. They are described statistically since the complete knowledge about their origin is not known. So statistical measures are used. Probability distribution and probability density functions give the complete statistical characteristics of random signals. A random process is a function of both sample space and time variables. And can be represented as $\{X \leq x(s, t)\}$.

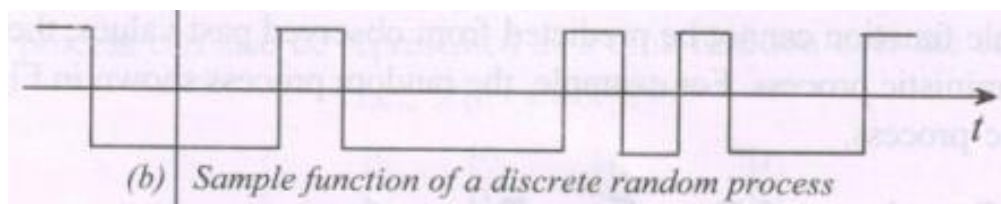
Deterministic and Non-deterministic processes: In general a random process may be deterministic or non deterministic. A process is called as deterministic random process if future values of any sample function can be predicted from its past values. For example, $X(t) = A \sin(\omega_0 t + \Theta)$, where the parameters A , ω_0 and Θ may be random variables, is deterministic random process because the future values of the sample function can be detected from its known shape. If future values of a sample function cannot be detected from observed past values, the process is called non-deterministic process.

Classification of random process: Random processes are mainly classified into four types based on the time and random variable X as follows.

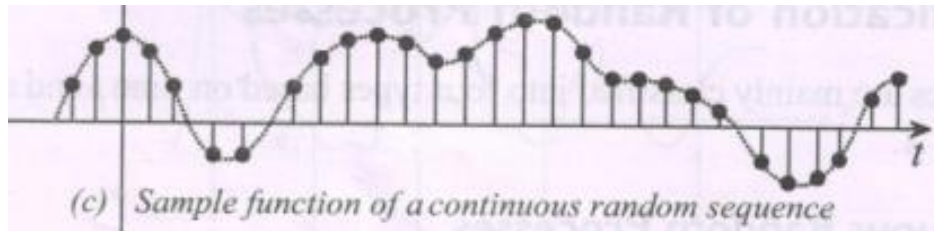
1. Continuous Random Process: A random process is said to be continuous if both the random variable X and time t are continuous. The below figure shows a continuous random process. The fluctuations of noise voltage in any network is a continuous random process.



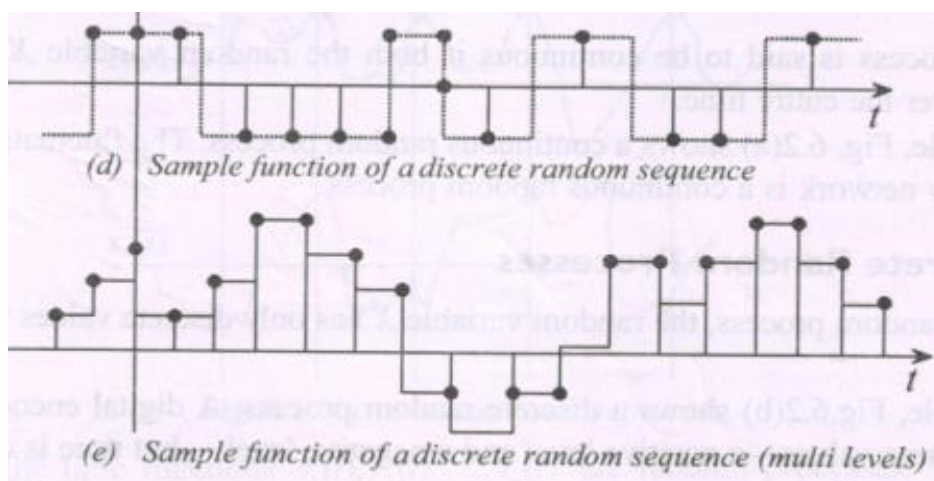
2. Discrete Random Process: In discrete random process, the random variable X has only discrete values while time, t is continuous. The below figure shows a discrete random process. A digital encoded signal has only two discrete values a positive level and a negative level but time is continuous. So it is a discrete random process.



3. Continuous Random Sequence: A random process for which the random variable X is continuous but t has discrete values is called continuous random sequence. A continuous random signal is defined only at discrete (sample) time intervals. It is also called as a discrete time random process and can be represented as a set of random variables $\{X(t)\}$ for samples $t_k, k=0, \pm 1, \pm 2, \dots$



4. Discrete Random Sequence: In discrete random sequence both random variable X and time t are discrete. It can be obtained by sampling and quantizing a random signal. This is called the random process and is mostly used in digital signal processing applications. The amplitude of the sequence can be quantized into two levels or multi levels as shown in below figure s (d) and (e).



Joint distribution functions of random process: Consider a random process $X(t)$. For a single random variable at time t_1 , $X_1=X(t_1)$, The cumulative distribution function is defined as $F_X(x_1; t_1) = P \{X(t_1) \leq x_1\}$ where x_1 is any real number. The function $F_X(x_1; t_1)$ is known as the first order distribution function of $X(t)$. For two random variables at time instants t_1 and t_2 $X(t_1) = X_1$ and $X(t_2) = X_2$, the joint distribution is called the second order joint distribution function of the random process $X(t)$ and is given by

$F_X(x_1, x_2 ; t_1, t_2) = P \{(X(t_1) \leq x_1, X(t_2) \leq x_2)\}$. In general for N random variables at N time intervals $X(t_i) = X_i, i=1, 2, \dots, N$, the N^{th} order joint distribution function of $X(t)$ is defined as

$$F_X(x_1, x_2, \dots, x_N ; t_1, t_2, \dots, t_N) = P \{(X(t_1) \leq x_1, X(t_2) \leq x_2, \dots, X(t_N) \leq x_N)\}.$$

Joint density functions of random process:: Joint density functions of a random process can be obtained from the derivatives of the distribution functions.

1. First order density function: $f_X(x_1; t_1) = \frac{dF_X(x_1; t_1)}{dx_1}$
2. Second order density function: $f_X(x_1, x_2; t_1, t_2) = \frac{\partial^2 F_X(x_1, x_2; t_1, t_2)}{\partial x_1 \partial x_2}$
3. N^{th} order density function: $f_X(x_1, x_2, \dots, x_N; t_1, t_2, \dots, t_N) = \frac{\partial^2 F_X(x_1, x_2, \dots, x_N; t_1, t_2, \dots, t_N)}{\partial x_1 \partial x_2 \dots \partial x_N}$

Independent random processes: Consider a random process $X(t)$. Let $X(t_i) = x_i$, $i = 1, 2, \dots, N$ be N Random variables defined at time constants t_1, t_2, \dots, t_N with density functions $f_X(x_1; t_1)$, $f_X(x_2; t_2)$, \dots $f_X(x_N; t_N)$. If the random process $X(t)$ is statistically independent, then the N^{th} order joint density function is equal to the product of individual joint functions of $X(t)$ i.e.

$f_X(x_1, x_2, \dots, x_N; t_1, t_2, \dots, t_N) = f_X(x_1; t_1) f_X(x_2; t_2) \dots f_X(x_N; t_N)$. Similarly the joint distribution will be the product of the individual distribution functions.

Statistical properties of Random Processes: The following are the statistical properties of random processes.

1. **Mean:** The mean value of a random process $X(t)$ is equal to the expected value of the random process i.e. $\bar{X}(t) = E[X(t)] = \int_{-\infty}^{\infty} x f_X(x; t) dx$
2. **Autocorrelation:** Consider random process $X(t)$. Let X_1 and X_2 be two random variables defined at times t_1 and t_2 respectively with joint density function $f_X(x_1, x_2; t_1, t_2)$. The correlation of X_1 and X_2 , $E[X_1 X_2] = E[X(t_1) X(t_2)]$ is called the autocorrelation function of the random process $X(t)$ defined as
 $R_{XX}(t_1, t_2) = E[X_1 X_2] = E[X(t_1) X(t_2)]$ or

$$R_{XX}(t_1, t_2) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} x_1 x_2 f_X(x_1, x_2; t_1, t_2) dx_1 dx_2$$

3. **Cross correlation:** Consider two random processes $X(t)$ and $Y(t)$ defined with random variables X and Y at time instants t_1 and t_2 respectively. The joint density function is $f_{XY}(x, y; t_1, t_2)$. Then the correlation of X and Y , $E[XY] = E[X(t_1) Y(t_2)]$ is called the cross correlation function of the random processes $X(t)$ and $Y(t)$ which is defined as
 $R_{XY}(t_1, t_2) = E[XY] = E[X(t_1) Y(t_2)]$ or

$$R_{XY}(t_1, t_2) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} xy f_{X,Y}(x, y; t_1, t_2) dx dy$$

Stationary Processes: A random process is said to be stationary if all its statistical properties such as mean, moments, variances etc... do not change with time. The stationarity which depends on the density functions has different levels or orders.

1. **First order stationary process:** A random process is said to be stationary to order one or first order stationary if its first order density function does not change with time or shift in time value. If $X(t)$ is a first order stationary process then

$f_X(x_1; t_1) = f_X(x_1; t_1 + \Delta t)$ for any time t_1 . Where Δt is shift in time value. Therefore the condition for a process to be a first order stationary random process is that its mean value must be constant at any time instant. i.e. $E[X(t)] = \bar{X} = \text{constant}$.

2. **Second order stationary process:** A random process is said to be stationary to order two or second order stationary if its second order joint density function does not change with time or shift in time value i.e. $f_X(x_1, x_2; t_1, t_2) = f_X(x_1, x_2; t_1 + \Delta t, t_2 + \Delta t)$ for all t_1, t_2 and Δt . It is a function of time difference (t_2, t_1) and not absolute time t . Note that a second order stationary process is also a first order stationary process. The condition for a process to be a second order stationary is that its autocorrelation should depend only on time differences and not on absolute time. i.e. If

$R_{XX}(t_1, t_2) = E[X(t_1) X(t_2)]$ is autocorrelation function and $\tau = t_2 - t_1$ then

$R_{XX}(t_1, t_1 + \tau) = E[X(t_1) X(t_1 + \tau)] = R_{XX}(\tau)$. $R_{XX}(\tau)$ should be independent of time t .

3. **Wide sense stationary (WSS) process:** If a random process $X(t)$ is a second order stationary process, then it is called a wide sense stationary (WSS) or a weak sense stationary process. However the converse is not true. The condition for a wide sense stationary process are 1. $E[X(t)] = \bar{X} = \text{constant}$. 2. $E[X(t) X(t + \tau)] = R_{XX}(\tau)$ is independent of absolute time t .

Joint wide sense stationary process: Consider two random processes $X(t)$ and $Y(t)$. If they are jointly WSS, then the cross correlation function of $X(t)$ and $Y(t)$ is a function of time difference $\tau = t_2 - t_1$ only and not absolute time. i.e. $R_{XY}(t_1, t_2) = E[X(t_1) Y(t_2)]$. If $\tau = t_2 - t_1$ then $R_{XY}(t, t + \tau) = E[X(t) Y(t + \tau)] = R_{XY}(\tau)$. Therefore the conditions for a process to be joint wide sense stationary are 1. $E[X(t)] = \bar{X} = \text{constant}$.

2. $E[Y(t)] = \bar{Y} = \text{constant}$ 3. $E[X(t) Y(t + \tau)] = R_{XY}(\tau)$ is independent of time t .

4. **Strict sense stationary (SSS) processes:** A random process $X(t)$ is said to be strict sense stationary if its N th order joint density function does not change with time or shift in time value. i.e.

$f_X(x_1, x_2, \dots, x_N; t_1, t_2, \dots, t_N) = f_X(x_1, x_2, \dots, x_N; t_1 + \Delta t, t_2 + \Delta t, \dots, t_N + \Delta t)$ for all t_1, t_2, \dots, t_N and Δt . A process that is stationary to all orders $n=1, 2, \dots, N$ is called strict sense stationary process. Note that SSS process is also a WSS process. But the reverse is not true.

Time Average Function: Consider a random process $X(t)$. Let $x(t)$ be a sample function which exists for all time at a fixed value in the given sample space S . The average value of $x(t)$ taken over all times is called the time average of $x(t)$. It is also called mean value of $x(t)$. It can be expressed as $\bar{x} = A[x(t)] = \lim_{T \rightarrow \infty} \frac{1}{2T} \int_{-T}^T x(t) dt$.

Time autocorrelation function: Consider a random process $X(t)$. The time average of the product $X(t)$ and $X(t + \tau)$ is called time average autocorrelation function of $x(t)$ and is denoted as $R_{xx}(\tau) = A[X(t) X(t + \tau)]$ or $R_{xx}(\tau) = \lim_{T \rightarrow \infty} \frac{1}{2T} \int_{-T}^T x(t) x(t + \tau) dt$.

Time mean square function: If $\tau = 0$, the time average of $x^2(t)$ is called time mean square value of $x(t)$ defined as $= A[X^2(t)] = \lim_{T \rightarrow \infty} \frac{1}{2T} \int_{-T}^T x^2(t) dt$.

Time cross correlation function: Let $X(t)$ and $Y(t)$ be two random processes with sample functions $x(t)$ and $y(t)$ respectively. The time average of the product of $x(t)$ $y(t + \tau)$ is called time cross correlation function of $x(t)$ and $y(t)$. Denoted as

$$R_{xy}(\tau) = \lim_{T \rightarrow \infty} \frac{1}{2T} \int_{-T}^T x(t) y(t + \tau) dt.$$

Ergodic Theorem and Ergodic Process: The Ergodic theorem states that for any random process $X(t)$, all time averages of sample functions of $x(t)$ are equal to the corresponding statistical or ensemble averages of $X(t)$. i.e. $\bar{x} = \bar{X}$ or $R_{xx}(\tau) = R_{XX}(\tau)$. Random processes that satisfy the Ergodic theorem are called Ergodic processes.

Joint Ergodic Process: Let $X(t)$ and $Y(t)$ be two random processes with sample functions $x(t)$ and $y(t)$ respectively. The two random processes are said to be jointly Ergodic if they are individually Ergodic and their time cross correlation functions are equal to their respective statistical cross correlation functions. i.e. 1. $\bar{x} = \bar{X}$, $\bar{y} = \bar{Y}$ 2. $R_{xx}(\tau) = R_{XX}(\tau)$, $R_{xy}(\tau) = R_{XY}(\tau)$ and $R_{yy}(\tau) = R_{YY}(\tau)$.

Mean Ergodic Random Process: A random process $X(t)$ is said to be mean Ergodic if time average of any sample function $x(t)$ is equal to its statistical average, \bar{X} which is constant and the probability of all other sample functions is equal to one. i.e. $E[X(t)] = \bar{X} = A[x(t)] = \bar{x}$ with probability one for all $x(t)$.

Autocorrelation Ergodic Process: A stationary random process $X(t)$ is said to be Autocorrelation Ergodic if and only if the time autocorrelation function of any sample function $x(t)$ is equal to the statistical autocorrelation function of $X(t)$. i.e. $A[x(t) x(t+\tau)] = E[X(t) X(t+\tau)]$ or $R_{xx}(\tau) = R_{XX}(\tau)$.

Cross Correlation Ergodic Process: Two stationary random processes $X(t)$ and $Y(t)$ are said to be cross correlation Ergodic if and only if its time cross correlation function of sample functions $x(t)$ and $y(t)$ is equal to the statistical cross correlation function of $X(t)$ and $Y(t)$. i.e. $A[x(t) y(t+\tau)] = E[X(t) Y(t+\tau)]$ or $R_{xy}(\tau) = R_{XY}(\tau)$.

Properties of Autocorrelation function: Consider that a random process $X(t)$ is at least WSS and is a function of time difference $\tau = t_2 - t_1$. Then the following are the properties of the autocorrelation function of $X(t)$.

1. Mean square value of $X(t)$ is $E[X^2(t)] = R_{XX}(0)$. It is equal to the power (average) of the process, $X(t)$.

Proof: We know that for $X(t)$, $R_{XX}(\tau) = E[X(t) X(t+\tau)]$. If $\tau = 0$, then $R_{XX}(0) = E[X(t) X(t)] = E[X^2(t)]$ hence proved.

2. Autocorrelation function is maximum at the origin i.e. $|R_{XX}(\tau)| \leq R_{XX}(0)$.

Proof: Consider two random variables $X(t_1)$ and $X(t_2)$ of $X(t)$ defined at time intervals t_1 and t_2 respectively. Consider a positive quantity $[X(t_1) \pm X(t_2)]^2 \geq 0$

Taking Expectation on both sides, we get $E[X(t_1) \pm X(t_2)]^2 \geq 0$

$$E[X^2(t_1) + X^2(t_2) \pm 2X(t_1) X(t_2)] \geq 0$$

$$E[X^2(t_1)] + E[X^2(t_2)] \pm 2E[X(t_1) X(t_2)] \geq 0$$

$$R_{XX}(0) + R_{XX}(0) \pm 2 R_{XX}(t_1, t_2) \geq 0 \text{ [Since } E[X^2(t)] = R_{XX}(0)]$$

Given $X(t)$ is WSS and $\tau = t_2 - t_1$.

$$\text{Therefore } 2 R_{XX}(0) \pm 2 R_{XX}(\tau) \geq 0$$

$$R_{XX}(0) \pm R_{XX}(\tau) \geq 0 \text{ or}$$

$$|R_{XX}(\tau)| \leq R_{XX}(0) \text{ hence proved.}$$

3. $R_{XX}(\tau)$ is an even function of τ i.e. $R_{XX}(-\tau) = R_{XX}(\tau)$.

Proof: We know that $R_{XX}(\tau) = E[X(t) X(t+\tau)]$

Let $\tau = -\tau$ then

$$R_{XX}(-\tau) = E[X(t) X(t-\tau)]$$

Let $u = t - \tau$ or $t = u + \tau$

$$\text{Therefore } R_{XX}(-\tau) = E[X(u+\tau) X(u)] = E[X(u) X(u+\tau)]$$

$R_{XX}(-\tau) = R_{XX}(\tau)$ hence proved.

4. If a random process $X(t)$ has a non zero mean value, $E[X(t)] \neq 0$ and Ergodic with no periodic components, then $\lim_{|\tau| \rightarrow \infty} R_{XX}(\tau) = \bar{X}^2$.

Proof: Consider a random variable $X(t)$ with random variables $X(t_1)$ and $X(t_2)$. Given the mean value is $E[X(t)] = \bar{X} \neq 0$. We know that

$R_{XX}(\tau) = E[X(t)X(t+\tau)] = E[X(t_1) X(t_2)]$. Since the process has no periodic components, as $|\tau| \rightarrow \infty$, the random variable becomes independent, i.e.

$$\lim_{|\tau| \rightarrow \infty} R_{XX}(\tau) = E[X(t_1) X(t_2)] = E[X(t_1)] E[X(t_2)]$$

Since $X(t)$ is Ergodic $E[X(t_1)] = E[X(t_2)] = \bar{X}$

Therefore $\lim_{|\tau| \rightarrow \infty} R_{XX}(\tau) = \bar{X}^2$ hence proved.

5. If $X(t)$ is periodic then its autocorrelation function is also periodic.

Proof: Consider a Random process $X(t)$ which is periodic with period T_0

Then $X(t) = X(t \pm T_0)$ or

$X(t + \tau) = X(t + \tau \pm T_0)$. Now we have $R_{XX}(\tau) = E[X(t)X(t+\tau)]$ then

$$R_{XX}(\tau \pm T_0) = E[X(t)X(t+\tau \pm T_0)]$$

Given $X(t)$ is WSS, $R_{XX}(\tau \pm T_0) = E[X(t)X(t+\tau)]$

$$R_{XX}(\tau \pm T_0) = R_{XX}(\tau)$$

Therefore $R_{XX}(\tau)$ is periodic hence proved.

6. If $X(t)$ is Ergodic has zero mean, and no periodic components then

$$\lim_{|\tau| \rightarrow \infty} R_{XX}(\tau) = 0.$$

Proof: It is already proved that $\lim_{|\tau| \rightarrow \infty} R_{XX}(\tau) = \bar{X}^2$. Where \bar{X} is the mean value of $X(t)$ which is given as zero.

Therefore $\lim_{|\tau| \rightarrow \infty} R_{XX}(\tau) = 0$ hence proved.

7. The autocorrelation function of random process $R_{XX}(\tau)$ cannot have any arbitrary shape.

Proof: The autocorrelation function $R_{XX}(\tau)$ is an even function of τ and has maximum value at the origin. Hence the autocorrelation function cannot have an arbitrary shape hence proved.

8. If a random process $X(t)$ with zero mean has the DC component A as $Y(t) = A + X(t)$, Then $R_{YY}(\tau) = A^2 + R_{XX}(\tau)$.

Proof: Given a random process $Y(t) = A + X(t)$.

We know that $R_{YY}(\tau) = E[Y(t)Y(t+\tau)] = E[(A + X(t))(A + X(t+\tau))]$

$$= E[A^2 + AX(t) + AX(t+\tau) + X(t)X(t+\tau)]$$

$$= E[A^2] + AE[X(t)] + E[AX(t+\tau)] + E[X(t)X(t+\tau)]$$

$$= A^2 + 0 + 0 + R_{XX}(\tau).$$

Therefore $R_{YY}(\tau) = A^2 + R_{XX}(\tau)$ hence proved.

9. If a random process $Z(t)$ is sum of two random processes $X(t)$ and $Y(t)$ i.e, $Z(t) = X(t) + Y(t)$. Then $R_{ZZ}(\tau) = R_{XX}(\tau) + R_{XY}(\tau) + R_{YX}(\tau) + R_{YY}(\tau)$

Proof: Given $Z(t) = X(t) + Y(t)$.

We know that $R_{ZZ}(\tau) = E[Z(t)Z(t+\tau)]$

$$= E[(X(t) + Y(t))(X(t+\tau) + Y(t+\tau))]$$

$$= E[X(t)X(t+\tau) + X(t)Y(t+\tau) + Y(t)X(t+\tau) + Y(t)Y(t+\tau)]$$

$$= E[X(t)X(t+\tau)] + E[X(t)Y(t+\tau)] + E[Y(t)X(t+\tau)] + E[Y(t)Y(t+\tau)]$$

Therefore $R_{ZZ}(\tau) = R_{XX}(\tau) + R_{XY}(\tau) + R_{YX}(\tau) + R_{YY}(\tau)$ hence proved.

Properties of Cross Correlation Function: Consider two random processes $X(t)$ and $Y(t)$ are at least jointly WSS. And the cross correlation function is a function of the time difference $\tau = t_2 - t_1$. Then the following are the properties of cross correlation function.

1. $R_{XY}(\tau) = R_{YX}(-\tau)$ is a Symmetrical property.

Proof: We know that $R_{XY}(\tau) = E[X(t)Y(t+\tau)]$ also

$$R_{YX}(\tau) = E[Y(t)X(t+\tau)]$$

Let $\tau = -\tau$ then

$$R_{YX}(-\tau) = E[Y(t) X(t-\tau)]$$

Let $u=t-\tau$ or $t=u+\tau$. then

$$R_{YX}(-\tau) = E[Y(u+\tau) X(u)] = E[X(u) Y(u+\tau)]$$

Therefore $R_{YX}(-\tau) = R_{XY}(\tau)$ hence proved.

2. If $R_{XX}(\tau)$ and $R_{YY}(\tau)$ are the autocorrelation functions of $X(t)$ and $Y(t)$ respectively then the cross correlation satisfies the inequality: $|R_{XY}(\tau)| \leq \sqrt{R_{XX}(0)R_{YY}(0)}$.

Proof: Consider two random processes $X(t)$ and $Y(t)$ with auto correlation functions $R_{XX}(\tau)$ and $R_{YY}(\tau)$. Also consider the inequality

$$E\left[\frac{X(t)}{\sqrt{R_{XX}(0)}} \pm \frac{Y(t+\tau)}{\sqrt{R_{YY}(0)}}\right]^2 \geq 0$$

$$E\left[\frac{X^2(t)}{\sqrt{R_{XX}(0)}} + \frac{Y^2(t+\tau)}{\sqrt{R_{YY}(0)}} \pm 2 \frac{X(t)Y(t+\tau)}{\sqrt{R_{XX}(0)R_{YY}(0)}}\right] \geq 0$$

$$E\left[\frac{X^2(t)}{\sqrt{R_{XX}(0)}}\right] + E\left[\frac{Y^2(t+\tau)}{\sqrt{R_{YY}(0)}}\right] \pm 2 E\left[\frac{X(t)Y(t+\tau)}{\sqrt{R_{XX}(0)R_{YY}(0)}}\right] \geq 0$$

We know that $E[X^2(t)] = R_{XX}(0)$ and $E[Y^2(t)] = R_{YY}(0)$ and $E[X(t) X(t+\tau)] = R_{XX}(\tau)$

$$\text{Therefore } \frac{R_{XX}(0)}{R_{XX}(0)} + \frac{R_{YY}(0)}{R_{YY}(0)} \pm 2 \frac{R_{XY}(\tau)}{\sqrt{R_{XX}(0)R_{YY}(0)}} \geq 0$$

$$2 \pm 2 \frac{R_{XY}(\tau)}{\sqrt{R_{XX}(0)R_{YY}(0)}} \geq 0$$

$$1 \pm \frac{R_{XY}(\tau)}{\sqrt{R_{XX}(0)R_{YY}(0)}} \geq 0$$

$$\sqrt{R_{XX}(0)R_{YY}(0)} \geq |R_{XY}(\tau)| \text{ Or}$$

$$|R_{XY}(\tau)| \leq \sqrt{R_{XX}(0)R_{YY}(0)} \text{ hence proved.}$$

Hence the absolute value of the cross correlation function is always less than or equal to the geometrical mean of the autocorrelation functions.

3. If $R_{XX}(\tau)$ and $R_{YY}(\tau)$ are the autocorrelation functions of $X(t)$ and $Y(t)$ respectively then the cross correlation satisfies the inequality: $|R_{XY}(\tau)| \leq \frac{1}{2} [R_{XX}(0) + R_{YY}(0)]$.

Proof: We know that the geometric mean of any two positive numbers cannot exceed their arithmetic mean that is if $R_{XX}(\tau)$ and $R_{YY}(\tau)$ are two positive quantities then at $\tau=0$,

$$\sqrt{R_{XX}(0)R_{YY}(0)} \leq \frac{1}{2} [R_{XX}(0) + R_{YY}(0)]. \text{ We know that } |R_{XY}(\tau)| \leq \sqrt{R_{XX}(0)R_{YY}(0)}$$

$$\text{Therefore } |R_{XY}(\tau)| \leq \frac{1}{2} [R_{XX}(0) + R_{YY}(0)]. \text{ Hence proved.}$$

4. If two random processes $X(t)$ and $Y(t)$ are statistically independent and are at least WSS, then $R_{XY}(\tau) = \bar{X} \bar{Y}$.

Proof: Let two random processes $X(t)$ and $Y(t)$ be jointly WSS, then we know that

$$R_{XY}(\tau) = E[X(t) Y(t+\tau)] \text{ Since } X(t) \text{ and } Y(t) \text{ are independent}$$

$$R_{XY}(\tau) = E[X(t)]E[Y(t+\tau)]$$

Therefore $R_{XY}(\tau) = \bar{X} \bar{Y}$ hence proved.

5. If two random processes $X(t)$ and $Y(t)$ have zero mean and are jointly WSS, then $\lim_{|\tau| \rightarrow \infty} R_{XY}(\tau) = 0$.

Proof: We know that $R_{XY}(\tau) = E[X(t) Y(t + \tau)]$. Taking the limits on both sides

$$\lim_{|\tau| \rightarrow \infty} R_{XY}(\tau) = \lim_{|\tau| \rightarrow \infty} E[X(t) Y(t + \tau)].$$

As $|\tau| \rightarrow \infty$, the random processes $X(t)$ and $Y(t)$ can be considered as independent processes therefore

$$\lim_{|\tau| \rightarrow \infty} R_{XY}(\tau) = E[X(t)]E[Y(t + \tau)] = \bar{X} \bar{Y}$$

Given $\bar{X} = \bar{Y} = 0$

Therefore $\lim_{|\tau| \rightarrow \infty} R_{XY}(\tau) = 0$. Similarly $\lim_{|\tau| \rightarrow \infty} R_{YX}(\tau) = 0$. Hence proved.

Covariance functions for random processes:

Auto Covariance function: Consider two random processes $X(t)$ and $X(t + \tau)$ at two time intervals t and $t + \tau$. The auto covariance function can be expressed as

$$C_{XX}(t, t + \tau) = E[(X(t) - E[X(t)]) (X(t + \tau) - E[X(t + \tau)])] \text{ or}$$

$$C_{XX}(t, t + \tau) = R_{XX}(t, t + \tau) - E[X(t) E[X(t + \tau)]]$$

If $X(t)$ is WSS, then $C_{XX}(\tau) = R_{XX}(\tau) - \bar{X}^2$. At $\tau = 0$, $C_{XX}(0) = R_{XX}(0) - \bar{X}^2 = E[X^2] - \bar{X}^2 = \sigma_X^2$

Therefore at $\tau = 0$, the auto covariance function becomes the Variance of the random process. The autocorrelation coefficient of the random process, $X(t)$ is defined as

$$\rho_{XX}(t, t + \tau) = \frac{C_{XX}(t, t + \tau)}{\sqrt{C_{XX}(t, t) C_{XX}(t + \tau, t + \tau)}} \text{ if } \tau \neq 0,$$

$$\rho_{XX}(0) = \frac{C_{XX}(t, t)}{C_{XX}(t, t)} = 1. \text{ Also } |\rho_{XX}(t, t + \tau)| \leq 1.$$

Cross Covariance Function: If two random processes $X(t)$ and $Y(t)$ have random variables $X(t)$ and $Y(t + \tau)$, then the cross covariance function can be defined as

$$C_{XY}(t, t + \tau) = E[(X(t) - E[X(t)]) (Y(t + \tau) - E[Y(t + \tau)])] \text{ or}$$

$$C_{XY}(t, t + \tau) = R_{XY}(t, t + \tau) - E[X(t) E[Y(t + \tau)]]. \text{ If } X(t) \text{ and } Y(t) \text{ are jointly WSS, then}$$

$$C_{XY}(\tau) = R_{XY}(\tau) - \bar{X} \bar{Y}. \text{ If } X(t) \text{ and } Y(t) \text{ are Uncorrelated then}$$

$$C_{XY}(t, t + \tau) = 0.$$

The cross correlation coefficient of random processes $X(t)$ and $Y(t)$ is defined as

$$\rho_{XY}(t, t + \tau) = \frac{C_{XY}(t, t + \tau)}{\sqrt{C_{XX}(t, t) C_{YY}(t + \tau, t + \tau)}} \text{ if } \tau \neq 0,$$

$$\rho_{XY}(0) = \frac{C_{XY}(0)}{\sqrt{C_{XX}(0) C_{YY}(0)}} = \frac{C_{XY}(0)}{\sigma_X \sigma_Y}.$$

Gaussian Random Process: Consider a continuous random process $X(t)$. Let N random variables $X_1 = X(t_1), X_2 = X(t_2), \dots, X_N = X(t_N)$ be defined at time intervals t_1, t_2, \dots, t_N respectively. If random variables are jointly Gaussian for any $N = 1, 2, \dots$. And at any time instants t_1, t_2, \dots, t_N . Then the random process $X(t)$ is called Gaussian random process. The Gaussian density function is given as

$$f_X(x_1, x_2, \dots, x_N; t_1, t_2, \dots, t_N) = \frac{1}{(2\pi)^{N/2} |C_{XX}|^{1/2}} \exp(-[X - \bar{X}]^T [C_{XX}]^{-1} [X - \bar{X}]) / 2$$

where C_{XX} is a covariance matrix.

Poisson's random process: The Poisson process $X(t)$ is a discrete random process which represents the number of times that some event has occurred as a function of time. If the number of occurrences of an event in any finite time interval is described by a Poisson distribution with the average rate of occurrence is λ , then the probability of exactly occurrences over a time interval $(0,t)$ is

$$P[X(t)=K] = \frac{(\lambda t)^K e^{-\lambda t}}{k!}, K=0,1,2, \dots$$

And the probability density function is

$$f_X(x) = \sum_{k=0}^{\infty} \frac{(\lambda t)^K e^{-\lambda t}}{k!} \delta(x-k).$$

UNIT V

Stochastic Processes-Spectral Characteristics

- The Power Spectrum and its Properties
- Relationship between Power Spectrum and Autocorrelation Function
- The Cross-Power Density Spectrum and Properties
- Relationship between Cross-Power Spectrum and Cross-Correlation Function.

Spectral characteristics of system response:

- Power density spectrum of response
- Cross power spectral density of input and output of a linear system

RANDOM PROCESSES:SPECTRAL CHARACTERISTICS

In this unit we will study the characteristics of random processes regarding correlation and covariance functions which are defined in time domain. This unit explores the important concept of characterizing random processes in the frequency domain. These characteristics are called spectral characteristics. All the concepts in this unit can be easily learnt from the theory of Fourier transforms.

Consider a random process $X(t)$. The amplitude of the random process, when it varies randomly with time, does not satisfy Dirichlet's conditions. Therefore it is not possible to apply the Fourier transform directly on the random process for a frequency domain analysis. Thus the autocorrelation function of a WSS random process is used to study spectral characteristics such as power density spectrum or power spectral density (psd).

Power Density Spectrum: The power spectrum of a WSS random process $X(t)$ is defined as the Fourier transform of the autocorrelation function $R_{XX}(\tau)$ of $X(t)$. It can be expressed as

$S_{XX}(\omega) = \int_{-\infty}^{\infty} R_{XX}(\tau) e^{-j\omega\tau} d\tau$ We can obtain the autocorrelation function from the power spectral density by taking the inverse Fourier transform i.e.

$$R_{XX}(\tau) = \frac{1}{2\pi} \int_{-\infty}^{\infty} S_{XX}(\omega) e^{j\omega\tau} d\omega$$

Therefore, the power density spectrum $S_{XX}(\omega)$ and the autocorrelation function $R_{XX}(\tau)$ are Fourier transform pairs.

The power spectral density can also be defined as $S_{XX}(\omega) = \lim_{T \rightarrow \infty} \frac{E[|X_T(\omega)|^2]}{2T}$

Where $X_T(\omega)$ is a Fourier transform of $X(t)$ in interval $[-T, T]$

Average power of the random process: The average power P_{XX} of a WSS random process $X(t)$ is defined as the time average of its second order moment or autocorrelation function at $\tau = 0$.

Mathematically, $P_{XX} = A \{E[X^2(t)]\}$

$$P_{XX} = \lim_{T \rightarrow \infty} \frac{1}{2T} \int_{-T}^T E[X^2(t)] dt$$

$$\text{Or } P_{XX} = R_{XX}(\tau) | \tau = 0$$

We know that from the power density spectrum,

$$R_{XX}(\tau) = \frac{1}{2\pi} \int_{-\infty}^{\infty} S_{XX}(\omega) e^{j\omega\tau} d\omega$$

$$\text{At } \tau = 0 \quad P_{XX} = R_{XX}(0) = \frac{1}{2\pi} \int_{-\infty}^{\infty} S_{XX}(\omega) d\omega$$

Therefore average power of $X(t)$ is

$$P_{XX} = \frac{1}{2\pi} \int_{-\infty}^{\infty} S_{XX}(\omega) d\omega$$

Properties of power density spectrum: The properties of the power density spectrum $S_{XX}(\omega)$ for a WSS random process $X(t)$ are given as

$$(1) S_{XX}(\omega) \geq 0$$

Proof: From the definition, the expected value of a non negative function $E[|X_{T(\omega)}|^2]$ is always non-negative.

Therefore $S_{XX}(\omega) \geq 0$ hence proved.

$$(2) \text{ The power spectral density at zero frequency is equal to the area under the curve of the autocorrelation } R_{XX}(\tau) \text{ i.e. } S_{XX}(0) = \int_{-\infty}^{\infty} R_{XX}(\tau) d\tau$$

Proof: From the definition we know that $S_{XX}(\omega) = \int_{-\infty}^{\infty} R_{XX}(\tau) e^{-j\omega\tau} d\tau$ at $\omega=0$,

$$S_{XX}(0) = \int_{-\infty}^{\infty} R_{XX}(\tau) d\tau \text{ hence proved}$$

$$(3) \text{ The power density spectrum of a real process } X(t) \text{ is an even function i.e.}$$

$$S_{XX}(-\omega) = S_{XX}(\omega)$$

Proof: Consider a WSS real process $X(t)$. then

$$S_{XX}(\omega) = \int_{-\infty}^{\infty} R_{XX}(\tau) e^{-j\omega\tau} d\tau \text{ also } S_{XX}(-\omega) = \int_{-\infty}^{\infty} R_{XX}(\tau) e^{j\omega\tau} d\tau$$

Substitute $\tau = -\tau$ then

$$S_{XX}(-\omega) = \int_{-\infty}^{\infty} R_{XX}(-\tau) e^{-j\omega\tau} d\tau$$

Since $X(t)$ is real, from the properties of autocorrelation we know that, $R_{XX}(-\tau) = R_{XX}(\tau)$

$$\text{Therefore } S_{XX}(-\omega) = \int_{-\infty}^{\infty} R_{XX}(\tau) e^{j\omega\tau} d\tau$$

$$S_{XX}(-\omega) = S_{XX}(\omega) \text{ hence proved.}$$

$$(4) S_{XX}(\omega) \text{ is always a real function}$$

Proof: We know that $S_{XX}(\omega) = \lim_{T \rightarrow \infty} \frac{E[|X_{T(\omega)}|^2]}{2T}$

Since the function $|X_{T(\omega)}|^2$ is a real function, $S_{XX}(\omega)$ is always a real function hence proved.

$$(5) \text{ If } S_{XX}(\omega) \text{ is a psd of the WSS random process } X(t), \text{ then}$$

$$\frac{1}{2\pi} \int_{-\infty}^{\infty} S_{XX}(\omega) d\omega = A \{E[X^2(t)]\} = R_{XX}(0) \text{ or The time average of the mean square value of a WSS random process equals the area under the curve of the power spectral density.}$$

Proof: We know that $R_{XX}(\tau) = A \{E[X(t+\tau)X(t)]\}$

$$= \frac{1}{2\pi} \int_{-\infty}^{\infty} S_{XX}(\omega) d\omega \text{ at } \tau=0,$$

$R_{XX}(0) = A \{E[X^2(t)]\} = \frac{1}{2\pi} \int_{-\infty}^{\infty} S_{XX}(\omega) d\omega$ = Area under the curve of the power spectral density. Hence proved.

(6) If $X(t)$ is a WSS random process with psd $S_{XX}(\omega)$, then the psd of the derivative of $X(t)$ is equal to ω^2 times the psd $S_{XX}(\omega)$. That is $S_{\dot{X}\dot{X}}(\omega) = \omega^2 S_{XX}(\omega)$.

Proof: We know that $S_{XX}(\omega) = \lim_{T \rightarrow \infty} \frac{E[|X_T(\omega)|^2]}{2T}$ and $X_T(\omega) = \int_{-T}^T X(t) e^{-j\omega t} dt$

$$= \dot{X}_T(\omega) = \frac{d X_T(\omega)}{dt} = \frac{d}{dt} \int_{-T}^T X(t) e^{-j\omega t} dt$$

$$= \int_{-T}^T X(t) \frac{d}{dt} e^{-j\omega t} dt$$

$$= \int_{-T}^T X(t) (-j\omega) e^{-j\omega t} dt$$

$$= (-j\omega) \int_{-T}^T X(t) e^{-j\omega t} dt$$

$$\text{Therefore } S_{\dot{X}\dot{X}}(\omega) = \lim_{T \rightarrow \infty} \frac{E[|\dot{X}_T(\omega)|^2]}{2T}$$

$$= \lim_{T \rightarrow \infty} \frac{E[|(-j\omega)X_T(\omega)|^2]}{2T}$$

$$= \lim_{T \rightarrow \infty} \frac{\omega^2 E[|(-j\omega)X_T(\omega)|^2]}{2T}$$

$$S_{\dot{X}\dot{X}}(\omega) = \omega^2 \lim_{T \rightarrow \infty} \frac{E[|X_T(\omega)|^2]}{2T}$$

Therefore $S_{\dot{X}\dot{X}}(\omega) = \omega^2 S_{XX}(\omega)$ hence proved.

Cross power density spectrum: Consider two real random processes $X(t)$ and $Y(t)$. which are jointly WSS random processes, then the cross power density spectrum is defined as the Fourier transform of the cross correlation function of $X(t)$ and $Y(t)$. and is expressed as $S_{XY}(\omega) = \int_{-\infty}^{\infty} R_{XY}(\tau) e^{-j\omega\tau} d\tau$ and $S_{YX}(\omega) = \int_{-\infty}^{\infty} R_{YX}(\tau) e^{-j\omega\tau} d\tau$ by inverse Fourier transformation, we can obtain the cross correlation functions as

$$R_{XY}(\tau) = \frac{1}{2\pi} \int_{-\infty}^{\infty} S_{XY}(\omega) e^{j\omega\tau} d\omega \text{ and } R_{YX}(\tau) = \frac{1}{2\pi} \int_{-\infty}^{\infty} S_{YX}(\omega) e^{j\omega\tau} d\omega$$

Therefore the cross psd and cross correlation functions are forms a Fourier transform pair.

If $X_T(\omega)$ and $Y_T(\omega)$ are Fourier transforms of $X(t)$ and $Y(t)$ respectively in interval $[-T, T]$, Then the cross power density spectrum is defined as

$$S_{XY}(\omega) = \lim_{T \rightarrow \infty} \frac{E\left[\left|X_T(\omega)Y_T(\omega)\right|^1\right]}{2T} \text{ and } S_{YX}(\omega) = \lim_{T \rightarrow \infty} \frac{E\left[\left|Y_T(\omega)X_T(\omega)\right|^1\right]}{2T}$$

Average cross power: The average cross power P_{XY} of the WSS random processes $X(t)$ and $Y(t)$ is defined as the cross correlation function at $\tau=0$. That is

$$P_{XY} = \lim_{T \rightarrow \infty} \frac{1}{2T} \int_{-T}^T R_{XY}(t, t) dt \quad \text{or}$$

$$P_{XY} = R_{XY}(\tau)|_{\tau=0} = R_{XY}(0) \quad \text{Also } P_{XY} = \frac{1}{2\pi} \int_{-\infty}^{\infty} S_{XY}(\omega) d\omega \quad \text{and } P_{YX} = \frac{1}{2\pi} \int_{-\infty}^{\infty} S_{YX}(\omega) d\omega$$

Properties of cross power density spectrum: The properties of the cross power for real random processes $X(t)$ and $Y(t)$ are given by

$$(1) S_{XY}(-\omega) = S_{XY}(\omega) \text{ and } S_{YX}(-\omega) = S_{YX}(\omega)$$

Proof: Consider the cross correlation function $R_{XY}(\tau)$. The cross power density spectrum is

$$S_{XY}(\omega) = \int_{-\infty}^{\infty} R_{XY}(\tau) e^{-j\omega\tau} d\tau$$

Let $\tau = -\tau$ Then

$$S_{XY}(\omega) = \int_{-\infty}^{\infty} R_{XY}(-\tau) e^{j\omega\tau} d\tau \quad \text{Since } R_{XY}(-\tau) = R_{XY}(\tau)$$

$$S_{XY}(\omega) = \int_{-\infty}^{\infty} R_{XY}(\tau) e^{-j\omega\tau} d\tau$$

Therefore $S_{XY}(-\omega) = S_{XY}(\omega)$ Similarly $S_{YX}(-\omega) = S_{YX}(\omega)$ hence proved.

(2) The real part of $S_{XY}(\omega)$ and real part $S_{YX}(\omega)$ are even functions of ω i.e.

$\text{Re}[S_{XY}(\omega)]$ and $\text{Re}[S_{YX}(\omega)]$ are even functions.

Proof: We know that $S_{XY}(\omega) = \int_{-\infty}^{\infty} R_{XY}(\tau) e^{-j\omega\tau} d\tau$ and also we know that

$$e^{-j\omega\tau} = \cos\omega\tau - j\sin\omega\tau, \quad \text{Re}[S_{XY}(\omega)] = \int_{-\infty}^{\infty} R_{XY}(\tau) \cos\omega\tau d\tau$$

Since $\cos\omega\tau$ is an even function i.e. $\cos\omega\tau = \cos(-\omega\tau)$

$$\text{Re}[S_{XY}(\omega)] = \int_{-\infty}^{\infty} R_{XY}(\tau) \cos\omega\tau d\tau = \int_{-\infty}^{\infty} R_{XY}(\tau) \cos(-\omega\tau) d\tau$$

Therefore $S_{XY}(\omega) = S_{XY}(-\omega)$ Similarly $S_{YX}(\omega) = S_{YX}(-\omega)$ hence proved.

(3) The imaginary part of $S_{XY}(\omega)$ and imaginary part $S_{YX}(\omega)$ are odd functions of ω i.e.

$\text{Im}[S_{XY}(\omega)]$ and $\text{Im}[S_{YX}(\omega)]$ are odd functions.

Proof: We know that $S_{XY}(\omega) = \int_{-\infty}^{\infty} R_{XY}(\tau) e^{-j\omega\tau} d\tau$ and also we know that

$$e^{-j\omega\tau} = \cos\omega\tau - j\sin\omega\tau,$$

$$\text{Im}[S_{XY}(\omega)] = \int_{-\infty}^{\infty} R_{XY}(\tau) (-\sin\omega\tau) d\tau = - \int_{-\infty}^{\infty} R_{XY}(\tau) \sin\omega\tau d\tau = - \text{Im}[S_{XY}(\omega)]$$

Therefore $\text{Im}[S_{XY}(\omega)] = - \text{Im}[S_{XY}(\omega)]$ Similarly $\text{Im}[S_{YX}(\omega)] = - \text{Im}[S_{YX}(\omega)]$ hence proved.

(4) $S_{XY}(\omega)=0$ and $S_{YX}(\omega)=0$ if $X(t)$ and $Y(t)$ are Orthogonal.

Proof: From the properties of cross correlation function, We know that the random processes $X(t)$ and $Y(t)$ are said to be orthogonal if their cross correlation function is zero.

i.e. $R_{XY}(\tau) = R_{YX}(\tau) = 0$.

We know that $S_{XY}(\omega) = \int_{-\infty}^{\infty} R_{XY}(\tau) e^{-j\omega\tau} d\tau$

Therefore $S_{XY}(\omega) = 0$. Similarly $S_{YX}(\omega) = 0$ hence proved.

(5) If $X(t)$ and $Y(t)$ are uncorrelated and have mean values \bar{X} and \bar{Y} , then

$$S_{XY}(\omega) = 2\pi \bar{X} \bar{Y} \delta(\omega).$$

Proof: We know that $S_{XY}(\omega) = \int_{-\infty}^{\infty} R_{XY}(\tau) e^{-j\omega\tau} d\tau$

$$= S_{XY}(\omega) = \int_{-\infty}^{\infty} E[X(t)Y(t + \tau)] e^{-j\omega\tau} d\tau$$

Since $X(t)$ and $Y(t)$ are uncorrelated, we know that

$$E[X(t)Y(t + \tau)] = E[X(t)]E[Y(t + \tau)]$$

$$\text{Therefore } S_{XY}(\omega) = \int_{-\infty}^{\infty} E[X(t)]E[Y(t + \tau)] e^{-j\omega\tau} d\tau$$

$$S_{XY}(\omega) = \int_{-\infty}^{\infty} \bar{X}\bar{Y} e^{-j\omega\tau} d\tau$$

$$S_{XY}(\omega) = \bar{X} \bar{Y} \int_{-\infty}^{\infty} e^{-j\omega\tau} d\tau$$

Therefore $S_{XY}(\omega) = 2\pi \bar{X} \bar{Y} \delta(\omega)$. hence proved.

UNIT 5

STOCHASTIC PROCESSES—SPECTRAL CHARACTERISTICS

Definition of Power Spectral Density of a WSS Process

Let us define the truncated random process $\{X_T(t)\}$ as follows

$$\begin{aligned} X_T(t) &= X(t) & -T < t < T \\ &= 0 & \text{otherwise} \\ &= X(t) \text{rect}\left(\frac{t}{2T}\right) \end{aligned}$$

where $\text{rect}\left(\frac{t}{2T}\right)$ is the unity-amplitude rectangular pulse of width $2T$ centering the origin. As $t \rightarrow \infty$, $\{X_T(t)\}$ will represent the random process $\{X(t)\}$ define the mean-square integral

$$FTX_T(\omega) = \int_{-T}^T X_T(t) e^{-j\omega t} dt$$

Applying the Parseval's theorem we find the energy of the signal

$$\int_{-T}^T X_T^2(t) dt = \int_{-\infty}^{\infty} |FTX_T(\omega)|^2 d\omega$$

Therefore, the power associated with $\{X_T(t)\}$ is

$$\frac{1}{2T} \int_{-T}^T X_T^2(t) dt = \frac{1}{2T} \int_{-\infty}^{\infty} |FTX_T(\omega)|^2 d\omega$$

And

The average power is given by

$$\frac{1}{2T} E \int_{-T}^T X_T^2(t) dt = \frac{1}{2T} E \int_{-\infty}^{\infty} |FTX_T(\omega)|^2 d\omega = E \int_{-\infty}^{\infty} \frac{|FTX_T(\omega)|^2}{2T} d\omega$$

Where $\frac{E|FTX_T(\omega)|^2}{2T}$ the contribution to the average is power at frequency ω and represents the power spectral

density of $\{X_T(t)\}$. As $T \rightarrow \infty$, the left-hand side in the above expression represents the

average power of $\{X(t)\}$

Therefore, the PSD $S_X(\omega)$ of the process $\{X(t)\}$ is defined in the limiting sense by

$$S_X(\omega) = \lim_{T \rightarrow \infty} \frac{E|FTX_T(\omega)|^2}{2T}$$

Relation between the autocorrelation function and PSD: Wiener-Khinchin-Einstein theorem

We have

$$\begin{aligned} E \frac{|FTX_T(\omega)|^2}{2T} &= E \frac{FTX_T(\omega) FTX_T^*(\omega)}{2T} \\ &= \frac{1}{2T} \int_{-T}^T \int_{-T}^T EX_T(t_1)X_T(t_2)e^{-j\omega t_1}e^{+j\omega t_2}dt_1dt_2 \\ &= \frac{1}{2T} \int_{-T}^T \int_{-T}^T R_X(t_1 - t_2)e^{-j\omega(t_1 - t_2)}dt_1dt_2 \end{aligned}$$

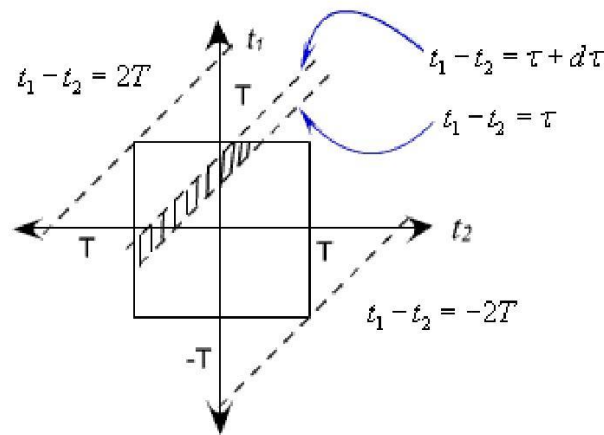


Figure 1

Note that the above integral is to be performed on a square region bounded by $t_1 = \pm T$ and $t_2 = \pm T$ as illustrated in Figure 1. Substitute $t_1 - t_2 = \tau$ so that $t_1 = t_2 + \tau$ is a family of straight lines parallel to $t_1 - t_2 = 0$. The differential area in terms of τ is given by the shaded area and equal to $(2T - |\tau|)d\tau$. The double integral is now replaced by a single integral in τ .

Therefore,

$$\begin{aligned} E \frac{FTX_r(\omega) X_r^*(\omega)}{2T} &= \frac{1}{2T} \int_{-T}^T R_x(\tau) e^{-j\omega\tau} (2T - |\tau|) d\tau \\ &= \int_{-T}^T R_x(\tau) e^{-j\omega\tau} \left(1 - \frac{|\tau|}{2T}\right) d\tau \end{aligned}$$

If $R_x(\tau)$ is integral then the right hand integral converges to $\int_{-\infty}^{\infty} R_x(\tau) e^{-j\omega\tau} d\tau$ as $T \rightarrow \infty$

$$\therefore \lim_{T \rightarrow \infty} \frac{E|FTX_r(\omega)|^2}{2T} = \int_{-\infty}^{\infty} R_x(\tau) e^{-j\omega\tau} d\tau$$

As we have noted earlier, the power spectral density $S_X(\omega) = \lim_{T \rightarrow \infty} \frac{E|FTX_r(\omega)|^2}{2T}$ is the contribution to the average

power at frequency ω and is called the power spectral density of $\{X(t)\}$. Thus ,

$$S_X(\omega) = \int_{-\infty}^{\infty} R_x(\tau) e^{-j\omega\tau} d\tau$$

and using the inverse Fourier transform

$$R_x(\tau) = \frac{1}{2\pi} \int_{-\infty}^{\infty} S_X(\omega) e^{j\omega\tau} d\omega$$

Example 1 The autocorrelation function of a WSS process $\{X(t)\}$ is given by

$$R_x(\tau) = a^2 e^{-b|\tau|} \quad b > 0$$

Find the power spectral density of the process.

$$\begin{aligned} S_X(\omega) &= \int_{-\infty}^{\infty} R_x(\tau) e^{-j\omega\tau} d\tau \\ &= \int_{-\infty}^{\infty} a^2 e^{-b|\tau|} e^{-j\omega\tau} d\tau \\ &= \int_{-\infty}^0 a^2 e^{b\tau} e^{-j\omega\tau} d\tau + \int_0^{\infty} a^2 e^{-b\tau} e^{-j\omega\tau} d\tau \\ &= \frac{a^2}{b - j\omega} + \frac{a^2}{b + j\omega} \\ &= \frac{2a^2 b}{b^2 + \omega^2} \end{aligned}$$

The autocorrelation function and the PSD are shown in Figure 2

Wiener-Khinchin-Einstein theorem

The Wiener-Khinchin-Einstein theorem is also valid for discrete-time random processes. The power spectral density $S_X(\omega)$ of the WSS process $\{X[n]\}$ is the discrete-time Fourier transform of autocorrelation sequence.

$$S_X(\omega) = \sum_{m=-\infty}^{\infty} R_X[m] e^{-j\omega m} \quad -\pi \leq \omega \leq \pi$$

$R_X[m]$ is related to $S_X(\omega)$ by the inverse discrete-time Fourier transform and given by

$$R_X[m] = \frac{1}{2\pi} \int_{-\pi}^{\pi} S_X(\omega) e^{j\omega m} d\omega$$

Thus $R_X[m]$ and $S_X(\omega)$ forms a discrete-time Fourier transform pair. A generalized PSD can be defined in terms of z -transform as follows

$$S_X(z) = \sum_{m=-\infty}^{\infty} R_X[m] z^{-m}$$

clearly,

$$S_X(\omega) = S_X(z) \Big|_{z=e^{j\omega}}$$

Linear time-invariant systems

In many applications, physical systems are modeled as linear time-invariant (LTI) systems. The dynamic behavior of an LTI system to deterministic inputs is described by linear differential equations. We are familiar with time and transform domain (such as Laplace transform and Fourier transform) techniques to solve these differential equations. In this lecture, we develop the technique to analyze the response of an LTI system to WSS random process.

The purpose of this study is two-folds:

- Analysis of the response of a system
- Finding an LTI system that can optimally estimate an unobserved random process from an observed process. The observed random process is statistically related to the unobserved random process. For example, we may have to find LTI system (also called a filter) to estimate the signal from the noisy observations.

Basics of Linear Time Invariant Systems

A system is modeled by a transformation T that maps an input signal $x(t)$ to an output signal $y(t)$ as shown in Figure 1. We can thus write,

$$y(t) = T[x(t)]$$

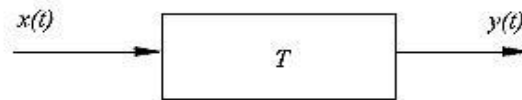


Figure 1

Linear system

The system is called linear if the principle of superposition applies: **the weighted sum of inputs results in the weighted sum of the corresponding outputs.** Thus for a linear system

$$T[a_1 x_1(t) + a_2 x_2(t)] = a_1 T[x_1(t)] + a_2 T[x_2(t)]$$

Example 1 Consider the output of a differentiator, given by

$$y(t) = \frac{d x(t)}{dt}$$

Then,
$$\frac{d}{dt} (a_1 x_1(t) + a_2 x_2(t))$$

$$= a_1 \frac{d}{dt} x_1(t) + a_2 \frac{d}{dt} x_2(t)$$

Hence the linear differentiator is a linear system.

Linear time-invariant system

Consider a linear system with $y(t) = T x(t)$. The system is called time-invariant if

$$T x(t - t_0) = y(t - t_0) \quad \forall t_0$$

It is easy to check that the differentiator in the above example is a linear time - invariant system.

Response of a linear time-invariant system to deterministic input

As shown in Figure 2, a linear system can be characterised by its impulse response $h(t) = T\delta(t)$ where $\delta(t)$ is the *Dirac delta function*.

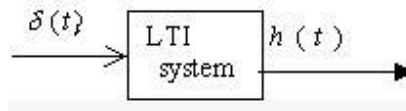


Figure 2

Recall that any function $x(t)$ can be represented in terms of the Dirac delta function as follows

$$x(t) = \int_{-\infty}^{\infty} x(s) \delta(t-s) ds$$

If $x(t)$ is input to the linear system $y(t) = T x(t)$, then

$$\begin{aligned} y(t) &= T \int_{-\infty}^{\infty} x(s) \delta(t-s) ds \\ &= \int_{-\infty}^{\infty} x(s) T\delta(t-s) ds \quad [\text{Using the linearity property}] \\ &= \int_{-\infty}^{\infty} x(s) h(t,s) ds \end{aligned}$$

Where $h(t,s) = T\delta(t-s)$ is the response at time t due to the shifted impulse? $\delta(t-s)$

If the system is time invariant,

$$h(t,s) = h(t-s)$$

Therefore for a linear-time invariant system,

$$y(t) = \int_{-\infty}^{\infty} x(s) h(t-s) ds = x(t) * h(t)$$

where $*$ denotes the convolution operation.

We also note that

$$x(t) * h(t) = h(t) * x(t).$$

Thus for a LTI System,

$$y(t) = x(t) * h(t) = h(t) * x(t)$$

Taking the Fourier transform, we get

$$Y(\omega) = H(\omega) X(\omega)$$

where $H(\omega) = FT h(t) = \int_{-\infty}^{\infty} h(t) e^{-j\omega t} dt$ is the frequency response of the system

Figure 3 shows the input-output relationship of an LTI system in terms of the impulse response and the frequency response.

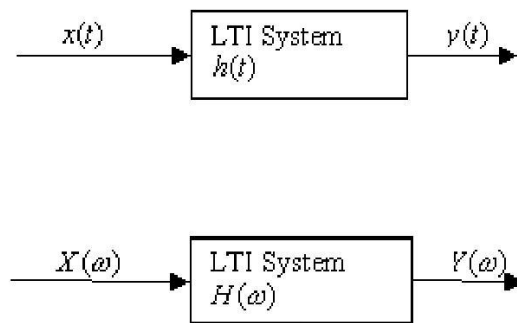


Figure 3

Response of an LTI System to WSS input

Consider an LTI system with impulse response $h(t)$. Suppose $\{X(t)\}$ is a WSS process input to the system. The output $\{Y(t)\}$ of the system is given by

$$Y(t) = \int_{-\infty}^{\infty} h(s) X(t-s) ds = \int_{-\infty}^{\infty} h(t-s) X(s) ds$$

Where we have assumed that the integrals exist in the mean square sense.

Mean and autocorrelation of the output process $\{Y(t)\}$

$$\begin{aligned}
 EY(t) &= E \int_{-\infty}^{\infty} h(s)X(t-s) ds \\
 &= \int_{-\infty}^{\infty} h(s)EX(t-s) ds \\
 &= \int_{-\infty}^{\infty} h(s)\mu_X ds \\
 &= \mu_X \int_{-\infty}^{\infty} h(s) ds \\
 &= \mu_X H(0)
 \end{aligned}$$

Where $H(0)$ is the frequency response at 0 frequency ($\omega = 0$) and given by

$$H(\omega)\Big|_{\omega=0} = \int_{-\infty}^{\infty} h(t)e^{-j\omega t} dt \Big|_{\omega=0} = \int_{-\infty}^{\infty} h(t) dt$$

T The Cross correlation of the input $\{X(t)\}$ and the out put $\{Y(t)\}$ is given by

$$\begin{aligned}
 E\{X(t+\tau)Y(t)\} &= E\{X(t+\tau) \int_{-\infty}^{\infty} h(s)X(t-s) ds\} \\
 &= \int_{-\infty}^{\infty} h(s) E\{X(t+\tau)X(t-s)\} ds \\
 &= \int_{-\infty}^{\infty} h(s) R_X(\tau+s) ds \\
 &= \int_{-\infty}^{\infty} h(-u) R_X(\tau-u) du \quad [\text{ Put } s = -u] \\
 &= h(-\tau) * R_X(\tau)
 \end{aligned}$$

$$\begin{aligned}
 \therefore R_{XY}(\tau) &= h(-\tau) * R_X(\tau) \\
 \text{also } R_{XX}(\tau) &= R_{XY}(-\tau) = h(\tau) * R_X(-\tau) \\
 &= h(\tau) * R_X(\tau)
 \end{aligned}$$

Therefore, the mean of the output process $\{Y(t)\}$ is a constant

The Cross correlation of the input $\{X(t)\}$ and the out put $\{Y(t)\}$ is given by

$$\begin{aligned}
E\{X(t+\tau)Y(t)\} &= E\{X(t+\tau) \int_{-\infty}^{\infty} h(s) X(t-s) ds\} \\
&= \int_{-\infty}^{\infty} h(s) E\{X(t+\tau) X(t-s)\} ds \\
&= \int_{-\infty}^{\infty} h(s) R_X(\tau+s) ds \\
&= \int_{-\infty}^{\infty} h(-u) R_X(\tau-u) du \quad [\text{ Put } s = -u] \\
&= h(-\tau) * R_X(\tau)
\end{aligned}$$

$$\begin{aligned}
\therefore R_{XY}(\tau) &= h(-\tau) * R_X(\tau) \\
\text{also } R_{YX}(\tau) &= R_{XY}(-\tau) = h(\tau) * R_X(-\tau) \\
&= h(\tau) * R_X(\tau)
\end{aligned}$$

Thus we see that $R_{XY}(\tau)$ is a function of lag τ only. Therefore, $\{X(t)\}$ and $\{Y(t)\}$ are jointly wide-sense stationary.

The autocorrelation function of the output process $\{Y(t)\}$ is given by,

$$\begin{aligned}
\therefore E\{Y(t+\tau)Y(t)\} &= E\left\{\int_{-\infty}^{\infty} h(s) X(t+\tau-s) ds \int_{-\infty}^{\infty} h(u) X(t-u) du\right\} \\
&= \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} h(s) h(u) E\{X(t+\tau-s) X(t-u)\} ds du \\
&= \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} h(s) h(u) R_X(\tau-s+u) ds du \\
&= h(\tau) * R_X(\tau) * h(-\tau)
\end{aligned}$$

Thus the autocorrelation of the output process $\{Y(t)\}$ depends on the time-lag τ , i.e.,

$$EY(t)Y(t+\tau) = R_Y(\tau)$$

Thus

$$R_Y(\tau) = R_X(\tau) * h(\tau) * h(-\tau)$$

The above analysis indicates that for an LTI system with WSS input

- the output is WSS and
- The input and output are jointly WSS.

The average power of the output process $\{Y(t)\}$ is given by

$$\begin{aligned} P_Y &= R_Y(0) \\ &= R_X(0) * h(0) * h(0) \end{aligned}$$

Power spectrum of the output process

Using the property of Fourier transform, we get the power spectral density of the output process given by

$$\begin{aligned} S_Y(\omega) &= S_X(\omega) H(\omega) H^*(\omega) \\ &= S_X(\omega) |H(\omega)|^2 \end{aligned}$$

Also note that

$$\begin{aligned} R_{XY}(\tau) &= h(-\tau) * R_X(\tau) \\ \text{and } R_{YX}(\tau) &= h(\tau) * R_X(\tau) \end{aligned}$$

Taking the Fourier transform of $R_{XY}(\tau)$ we get the cross power spectral density $S_{XY}(\omega)$ given by

$$\begin{aligned} S_{XY}(\omega) &= H^*(\omega) S_X(\omega) \\ \text{and} \\ S_{YX}(\omega) &= H(\omega) S_X(\omega) \end{aligned}$$

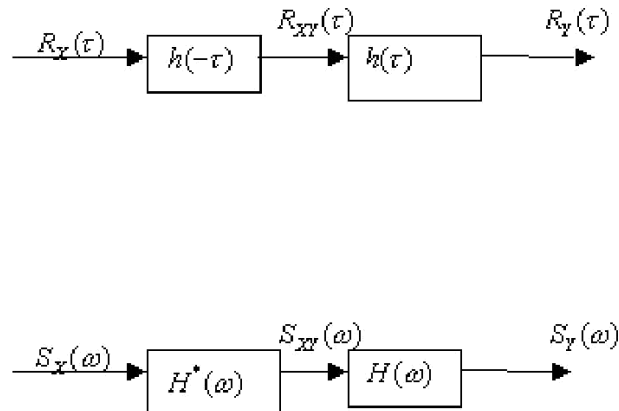


Figure 4

Example 3

A random voltage modeled by a white noise process $\{X(t)\}$ with power spectral density $\frac{N_0}{2}$ is input to an RC network shown in the Figure 7.

- Find (a) output PSD $S_Y(\omega)$
 (b) output auto correlation function $R_Y(\tau)$
 (c) average output power $EY^2(t)$

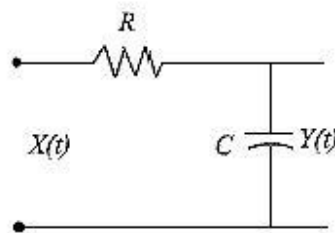


Figure 7

The frequency response of the system is given by

$$\begin{aligned}
 H(\omega) &= \frac{1}{R + \frac{1}{jC\omega}} \\
 &= \frac{1}{jRC\omega + 1}
 \end{aligned}$$

Therefore,

$$\begin{aligned}
 S_Y(\omega) &= |H(\omega)|^2 S_X(\omega) \\
 &= \frac{1}{R^2 C^2 \omega^2 + 1} S_X(\omega) \\
 &= \frac{1}{R^2 C^2 \omega^2 + 1} \frac{N_0}{2}
 \end{aligned}
 \tag{a}$$

(b) Taking the inverse Fourier transform

$$R_Y(\tau) = \frac{N_0}{4RC} e^{-\frac{|\tau|}{RC}}$$

(c) Average output power

$$EY^2(t) = R_Y(0) = \frac{N_0}{4RC}$$

Rice's representation or quadrature representation of a WSS process

An arbitrary zero-mean WSS process $\{X(t)\}$ can be represented in terms of the slowly varying components $X_c(t)$ and $X_s(t)$ as follows:

$$X(t) = X_c(t) \cos \omega_0 t - X_s(t) \sin \omega_0 t \tag{1}$$

where ω_0 is a center frequency arbitrary chosen in the band $\{(\omega_0 - \frac{B}{2} \leq |\omega| \leq \omega_0 + \frac{B}{2})\}$. $X_c(t)$ and $X_s(t)$ are respectively called the in-phase and the quadrature-phase components of $X(t)$.

Let us choose a *dual process* $\{Y(t)\}$ such that

$$\begin{aligned}
X(t) + jY(t) &= (X_c(t) + jX_s(t)) e^{j\omega_0 t} \\
&= \underbrace{(X_c(t) \cos \omega_0 t - X_s(t) \sin \omega_0 t)}_{X(t)} + j \underbrace{(X_c(t) \sin \omega_0 t + X_s(t) \cos \omega_0 t)}_{Y(t)}
\end{aligned}$$

then ,

$$X_c(t) = X(t) \cos \omega_0 t + Y(t) \sin \omega_0 t \quad (2)$$

and

$$X_s(t) = X(t) \cos \omega_0 t - Y(t) \sin \omega_0 t \quad (3)$$

For such a representation, we require the processes $\{X_c(t)\}$ and $\{X_s(t)\}$ to be WSS.

Note that

$$EX(t) = \cos \omega_0 t EX_c(t) - \sin \omega_0 t EX_s(t)$$

As $\{X(t)\}$ is zero mean, we require that

$$EX_c(t) = 0$$

And

$$EX_s(t) = 0$$

Again

$$EX_c(t) = \cos \omega_0 t EX(t) + \sin \omega_0 t EY(t)$$

$$EX_s(t) = \cos \omega_0 t EX(t) - \sin \omega_0 t EY(t)$$

As each of $EX_c(t)$, $EX_s(t)$ and $EX(t)$ is zero-mean, we require that

$$EY(t) = 0$$

Also

$$R_{X_c}(t + \tau, t) = E[X(t + \tau) \cos \omega_0(t + \tau) + Y(t + \tau) \sin \omega_0(t + \tau)][X(t) \cos \omega_0 t + Y(t) \sin \omega_0 t]$$

$$\begin{aligned}
&= R_X(\tau) \cos \omega_0(t + \tau) \cos \omega_0 t + R_Y(\tau) \sin \omega_0(t + \tau) \sin \omega_0 t + R_{XY}(\tau) \cos \omega_0(t + \tau) \sin \omega_0 t \\
&\quad + R_{YX}(\tau) \sin \omega_0(t + \tau) \cos \omega_0 t
\end{aligned}$$

and

$$\begin{aligned}
R_{X_s}(t + \tau, t) &= R_X(\tau) \cos \omega_0(t + \tau) \cos \omega_0 t + R_Y(\tau) \sin \omega_0(t + \tau) \sin \omega_0 t \\
&\quad - R_{XY}(\tau) \cos \omega_0(t + \tau) \sin \omega_0 t - R_{YX}(\tau) \sin \omega_0(t + \tau) \cos \omega_0 t
\end{aligned}$$

and

$$R_{X_c X_s}(t + \tau, t) = R_X(\tau) \cos \omega_0(t + \tau) \cos \omega_0 t - R_Y(\tau) \sin \omega_0(t + \tau) \sin \omega_0 t \\ - R_{XY}(\tau) \cos \omega_0(t + \tau) \sin \omega_0 t + R_{YX}(\tau) \sin \omega_0(t + \tau) \cos \omega_0 t$$

Thus, $R_{X_c}(t + \tau, t)$, $R_{X_s}(t + \tau, t)$ and $R_{X_c X_s}(t + \tau, t)$ will be independent of t if and only if

and

$$R_{X_c X_s}(\tau) = R_X(\tau) \cos \omega_0(t + \tau) \cos \omega_0 t - R_Y(\tau) \sin \omega_0(t + \tau) \sin \omega_0 t \\ - R_{XY}(\tau) \cos \omega_0(t + \tau) \sin \omega_0 t + R_{YX}(\tau) \sin \omega_0(t + \tau) \cos \omega_0 t \\ = R_X(\tau) [\cos \omega_0(t + \tau) \cos \omega_0 t - \sin \omega_0(t + \tau) \sin \omega_0 t] \\ - R_{XY}(\tau) [\cos \omega_0(t + \tau) \sin \omega_0 t - \sin \omega_0(t + \tau) \cos \omega_0 t] \\ = R_X(\tau) \cos \omega_0 \tau - R_{XY}(\tau) \sin(-\omega_0 \tau) \\ = R_X(\tau) \cos \omega_0 \tau - R_{YX}(\tau) \sin \omega_0 \tau$$

How to find $\{Y(t)\}$ satisfying the above two conditions?

For this, consider $\{Y(t)\}$ to be the *Hilbert transform* of $\{X(t)\}$, i.e.

$$Y(t) = \int_{-\infty}^{\infty} X(s) h(t-s) ds$$

Where $h(t) = \frac{1}{\pi t}$ and the integral is defined in the mean-square sense. See the illustration in Figure 2.

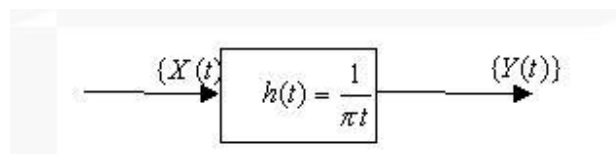


Figure 2

The frequency response $H(\omega)$ of the Hilbert transform is given by

$$H(\omega) = \begin{cases} -j, & \text{if } \omega > 0 \\ j, & \text{if } \omega < 0 \\ 0, & \text{if } \omega = 0 \end{cases}$$

$$\therefore H(\omega) = -j \operatorname{sgn}(\omega)$$

$$\text{and } |H(\omega)|^2 = 1$$

$$\therefore S_Y(\omega) = |H(\omega)|^2 S_X(\omega) = S_X(\omega)$$

and

$$S_{XY}(\omega) = H(\omega) S_{XX}(\omega) = \begin{cases} jS_{XX}(\omega), & \text{for } \omega > 0 \\ -jS_{XX}(\omega), & \text{for } \omega < 0 \end{cases}$$

$$S_{YX}(\omega) = H^*(\omega) S_{XX}(\omega) = \begin{cases} -jS_{XX}(\omega), & \text{for } \omega > 0 \\ jS_{XX}(\omega), & \text{for } \omega < 0 \end{cases}$$

The Hilbert transform of $Y(t)$ satisfies the following spectral relations

$$S_Y(\omega) = S_X(\omega)$$

and

$$S_{XY}(\omega) = -S_{YX}(\omega)$$

From the above two relations, we get

$$R_X(\tau) = R_Y(\tau)$$

and

$$R_{XY}(\tau) = -R_{YX}(\tau)$$

The Hilbert transform of $X(t)$ is generally denoted as $\hat{X}(t)$. Therefore, from (2) and (3) we establish

$$X_c(t) = X(t) \cos \omega_0 t + \hat{X}(t) \sin \omega_0 t,$$

$$X_s(t) = X(t) \cos \omega_0 t - \hat{X}(t) \sin \omega_0 t$$

and

$$X(t) = X_c(t) \cos \omega_0 t - X_s(t) \sin \omega_0 t$$

The realization for the in phase and the quadrature phase components is shown in Figure 3 below.

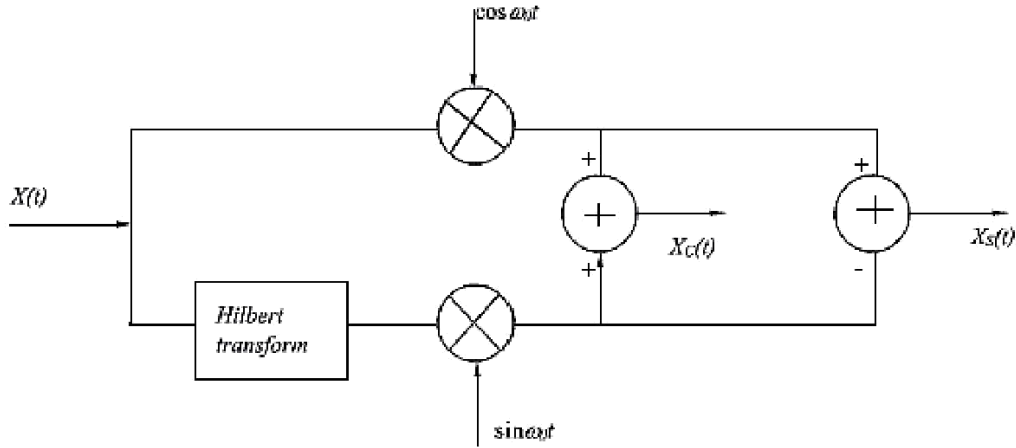


Figure 3

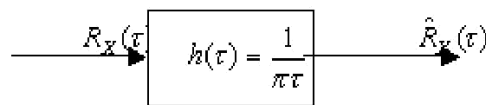
From the above analysis, we can summarize the following expressions for the autocorrelation functions

$$\begin{aligned} R_{X_c}(\tau) &= R_{X_s}(\tau) \\ &= R_X(\tau) \cos \omega_0 \tau + R_{XX}(\tau) \sin \omega_0 \tau \\ &= R_X(\tau) \cos \omega_0 \tau + h(\tau) * R_X(\tau) \sin \omega_0 \tau \quad \because R_{XX}(\tau) = h(\tau) * R_X(\tau) \\ &= R_X(\tau) \cos \omega_0 \tau + \hat{R}_X(\tau) \sin \omega_0 \tau \end{aligned}$$

Where

$$\begin{aligned} \hat{R}_X(\tau) &= \text{Hilbert transform of } R_X(\tau) \\ &= \int_{-\infty}^{\infty} \frac{1}{\pi s} R_X(\tau - s) ds \end{aligned}$$

See the illustration in Figure 4



The variances $\sigma_{X_c}^2$ and $\sigma_{X_s}^2$ are given by

$$\sigma_{X_c}^2 = \sigma_{X_s}^2 = R_X(0).$$

Taking the Fourier transform of $R_{X_c}(\tau)$ and $R_{X_s}(\tau)$, we get

$$S_{X_c}(\omega) = S_{X_s}(\omega) = \begin{cases} S_X(\omega - \omega_0) + S_X(\omega + \omega_0) & |\omega| \leq B \\ 0 & \text{otherwise} \end{cases}$$

Similarly,

$$\begin{aligned} R_{X_c X_s}(\tau) &= R_X(\tau) \sin \omega_0 \tau - R_X(\tau) \cos \omega_0 \tau \\ &= R_X(\tau) \sin \omega_0 \tau - \hat{R}_X(\tau) \cos \omega_0 \tau \end{aligned}$$

and

$$S_{X_c X_s}(\omega) = \begin{cases} j[S_X(\omega + \omega_0) - S_X(\omega - \omega_0)] & |\omega| \leq B \\ 0 & \text{otherwise} \end{cases}$$

Notice that the cross power spectral density $S_{X_c X_s}(\omega)$ is purely imaginary. Particularly, if $S_X(\omega)$ is locally symmetric about ω_0

$$S_{X_c X_s}(\omega) = 0$$

Implying that

$$R_{X_c X_s}(\tau) = 0$$

Consequently, the zero-mean processes $\{X_c(t)\}$ and $\{X_s(t)\}$ are also uncorrelated

PROBABILITY THEORY AND STOCHASTIC PROCESSES

Unitwise Important Questions

UNIT-I

Two marks Questions:

1. Define Demorgans' laws.
2. Give the classical definition of Probability.
3. Define probability using the axiomatic approach.
4. Write the statement of multiplication theorem.
5. What are the conditions for a function to be a random variable?
6. Give the statement of total probability theorem.
7. Define countable and uncountable set?
8. Define universal set with properties?
9. Define Bernoulli trials?
10. Define experiment with example?
11. Give the Statement of multiplication theorem?
12. Define independent events in case of two events A and B?
13. Define Venn diagram and represent joint $P(A \cap B)$ in Venn diagram?
14. Define complement laws of sets?
15. Is it possible to define a Continuous random variable on discrete sample space? If , yes give example.

Three Marks Questions:

1. Define sample space and classify the types of sample space.
2. Define Joint and Conditional Probability.
3. Define equally likely events, Exhaustive events and mutually exclusive events.
4. Show that $P(A \cup B) = P(A) + P(B) - P(A \cap B)$.
5. Define Random variable and Write the classifications of Random variable.
6. In the experiment of tossing a dice, what is the probability of face having 3 dots or 6 dots to appear?
7. Define Probability axioms?
8. For any two events A and B in a Sample space S such that B is a subset of A then Show that $P(A \setminus B) = 1$.
9. Define the properties of probability?
10. Determine the probability of the card being either red or a king when one card is drawn from a regular deck of 52 cards.
11. Define complement of a set and show that $P(A') = 1 - P(A)$
12. Two cards are selected from 6 cards numbered from 1 to 6 . Find the probability that the sum is odd if two cards are drawn together.
13. Explain the concept of total probability with neat Venn diagram.

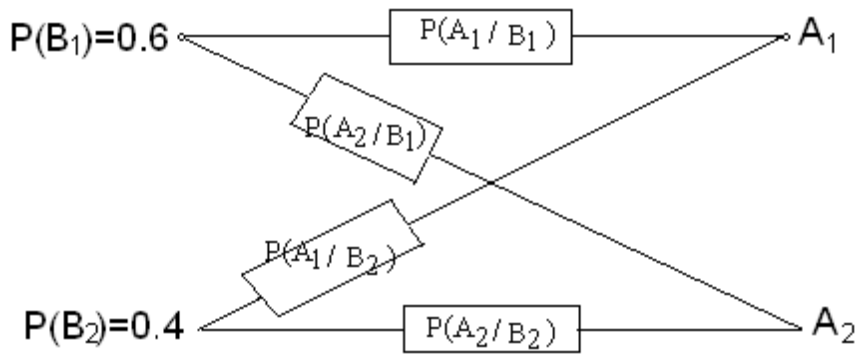
14. What is the probability of selecting two ace cards from a deck of 52 cards?
 15. If the sample space has n elements then show that it has 2^n subsets.

Ten Marks Questions:

- 1.a) State and Prove Bayes' theorem.
 b) Write the Mathematical model of experiment.
2. In a box there are 100 resistors having resistance and tolerance values given in table. Let a resistor be selected from the box and assume that each resistor has the same likelihood of being chosen. Event A: Draw a 47Ω resistor, Event B: Draw a resistor with 5% tolerance, Event C: Draw a 100Ω resistor. Find the individual, joint and conditional probabilities.

Resistance (Ω)	Tolerance		Total
	5%	10%	
22	10	14	24
47	28	16	44
100	24	8	32
Total	62	38	100

3. a) Two boxes are selected randomly. The first box contains 2 white balls and 3 black balls. The second box contains 3 white and 4 black balls. What is the probability of drawing a white ball.
 b) An aircraft is used to fire at a target. It will be successful if 2 or more bombs hit the target. If the aircraft fires 3 bombs and the probability of the bomb hitting the target is 0.4, then what is the probability that the target is hit?
4. a) An experiment consists of observing the sum of the outcomes when two fair dice are thrown. Find the probability that the sum is 7 and find the probability that the sum is greater than 10.
 b) In a factory there are 4 machines produce 10%,20%,30%,40% of an items respectively. The defective items produced by each machine are 5%,4%,3% and 2% respectively. Now an item is selected which is to be defective, what is the probability it being from the 2nd machine. And also write the statement of total probability theorem?
5. Determine probabilities of system error and correct system transmission of symbols for an elementary binary communication system shown in below figure consisting of a transmitter that sends one of two possible symbols (a 1 or a 0) over a channel to a receiver. The channel occasionally causes errors to occur so that a '1' show up at the receiver as a '0' and vice versa. Assume the symbols '1' and '0' are selected for a transmission as 0.6 and 0.4 respectively.



6. In a binary communication system, the errors occur with a probability of “p”, In a block of “n” bits transmitted, what is the probability of receiving

- at the most 1 bit in error
- at least 4 bits in error

\

7. Let A and B are events in a sample space S. Show that if A and B are independent, then so are

- A and \bar{B}
- \bar{A} and B
- \bar{A} and \bar{B}

8.a) An experiment consist of rolling a single die. Two events are defined as $A = \{ \text{a 6 shows up} \}$: and $B = \{ \text{a 2 or a 5 shows up} \}$

- Find $P(A)$ and $P(B)$
 - Define a third event C so that $P(C) = 1 - P(A) - P(B)$
- b) The six sides of a fair die are numbered from 1 to 6. The die is rolled 4 times. How many sequences of the four resulting numbers are possible?

9.a) State and prove the total probability theorem?

- Explain about conditional probability.

10. In the experiment of tossing a die, all the even numbers are equally likely to appear and similarly the odd numbers. An odd number occurs thrice more frequently than an even number. Find the probability that

- an even number appears
- a prime number appears
- an odd numbers appears
- an odd prime number appears.

11. 1. The probability mass function of random variable X is defined as $P(X=0)=3C^2$, $P(X=1)=4C-10C^2$, $P(X=2)=5C-1$, where $C>0$ and $P(X=r)=0$ if $r \neq 0,1,2$ find

- The value of C
- $P(0 < X < 2/X > 0)$

12.a) A sample space contains 3 sample points with associated probabilities given by $2p, p^2$ and $4p-1$. Find the values of p.

- If $P(A)=0.4, P(B)=0.7$ and $P(A \cap B)=0.3$ find $P(A' \cap B')$.

13.a) Two fair dice are thrown independently. Three events A, B, C are respectively defined as follows: i) Odd face with first die ii) Odd face with second die iii) The sum of two numbers in the two dice is odd. Are the events A, B, C mutually independent or pair wise independent?

b) Distinguish between conditional and unconditional probabilities with example.

14. a) If $P(A+B) = \frac{5}{8}$ $P(AB) = 1/8$ and $P(B') = 1/2$. Prove that the events A and B are independent.

b) A pack contains 6 white and 4 green pencils; another pack contains 5 white and 7 green pencils. If one pencil is drawn from each pack, find the probability that i) both are white

ii) One is white and another is green.

15) Urn A contains 5 red marbles and 3 white marbles, urn B contains 2 red marbles and 6 white marbles. (a) If a marble is drawn from each urn, what is the probability that they are both of the same color? (b) If two marbles are drawn from each urn, what is the probability that all four marbles are of same color?

UNIT-II

Two marks Questions:

1. Define Probability density and distribution function.
2. Define the expected value of Discrete Random variable and Continuous Random Variable.
3. Define Moment generating function and Characteristic Function of a Random variable.
4. Define moments about origin and central moments.
5. Show that $\text{Var}(kX) = k^2 \text{var}(X)$, here k is a constant.
6. Define skew and coefficient of skewness.
7. Find the Moment generating function of two independent Random variables X_1 & X_2 .
8. Write the statement of Chebychev's inequality.
9. Define variance of a Discrete random variable.
10. Show that $E(KX) = KE(X)$.
11. Show that $F_X(x) = 1 - P(X > x)$.
12. Draw the distribution and density curves of Gaussian random variable.
13. The mean and variance of the binomial distribution are 4 and 3 respectively. Find $P(X=0)$.
14. Find the mean of uniform density function.
15. Find the maximum value of Gaussian density function.

Three marks Questions:

1. Derive the expression for the density function of Discrete Random variable.
2. Find the variance of X for uniform density function.
3. Define various types of transformation of Random variables.
4. Write the properties of Gaussian density curve.
5. Find the moment generating function of binomial distribution
6. In an experiment when two dice are thrown simultaneously, find expected value of the sum of number of points on them.
7. Derive the expression for distribution function of uniform Random variable.
8. Define moment generating function and write the formula to find mean and variance?
9. The mean and variance of the binomial distribution are 4 and 3 respectively. Find $P(X=0)$?
10. Is the function defined as follows a density by function?

$$f(x) = \begin{cases} 0 & x < 2 \\ \frac{1}{18}(3 + 2x) & 2 \leq x \leq 4 \\ 0 & x > 4 \end{cases}$$

11. In which probability distribution, variance and mean are equal and define corresponding distribution ?
12. If the random variable X has the following probability distribution
X: -2 -1 0 1
P(x): 0.4 K 0.2 0.3 Find k and the mean of x .
13. Derive the expression for variance in terms of first and second moments.
14. Show that $F_X(-\infty) = 0$ and $F_X(\infty) = 1$

15. If the MGF of a uniform distribution for a random variable X is $\frac{1}{v} (e^{5v} - e^{4v})$ Find the $E[X]$?

Ten Marks Questions:

1.a) The exponential density function given by

$$f_X(x) = \begin{cases} (1/b)e^{-(x-a)/b} & x > a \\ 0 & x < a \end{cases}$$

Find the mean and variance.

b) Define Moment Generating Function and write any two properties.

2. Derive the Binomial density function and find mean & variance.

3. Derive the Poisson density function and find mean & variance

4. If X is a discrete random variable with a Moment generating function of $M_X(v)$, find the Moment generating function of

i) $Y=aX+b$ ii) $Y=KX$ iii) $Y=\frac{X+a}{b}$

5. A random variable X has the distribution function

$$F_X(x) = \sum_{n=1}^{12} \frac{n^2}{650} u(x-n)$$

Find the probability of a) $P\{-\infty < X \leq 6.5\}$ b) $p\{X > 4\}$ c) $p\{6 < X \leq 9\}$

6.a) Let X be a Continuous random variable with density function

$$f(x) = \begin{cases} \frac{x}{9} + K & 0 \leq x \leq 6 \\ 0 & \text{otherwise} \end{cases}$$

Find the value of K and also find $P\{2 \leq X \leq 5\}$

b) The probability density function of a random variable X is given by $f(x) = \frac{x^2}{81}$ for $-3 < x < 6$ and equal to zero otherwise. Find the density function of $Y = \frac{1}{3}(12-x)$

7. a) Verify the Characteristic function of a random variable is having its maximum magnitude at $\omega=0$ and find its maximum value.

b) Find the Moment generating function of exponential distribution?

8. a) Write short notes on Gaussian distribution and also find its mean?

b) Consider that a fair coin is tossed 3 times, Let X be a random variable, defined as $X =$ number of tails appeared, find the expected value of X .

9. a) State and prove the chebychev's inequality theorem?

b) Find the probability of getting a total of 5, at-least once in 4 tosses of a pair of fair dice.

10a) If X is uniformly distributed over (0,10) calculate the probability that $3 < x < 8$.

b) If the probability density function of X is $f_X(x) = 2x$, $0 < x < 1$, find the probability density function of $Y = 3X + 1$.

11a). If X and Y are independent poisson variates such that $P[X = 1] = P[X = 2]$ and $P[Y = 2] = P[Y = 3]$ find $v[X - 2Y]$.

b) Let X be a continuous random variable with pdf $f(x) = \begin{cases} 3x & 0 < x < 1 \\ 0 & \text{else} \end{cases}$ find $P(X \leq 0.6)$?

12. Find the moment generating function of a random variable x having the probability density function

$$f(x) = \begin{cases} \frac{1}{2} e^{-\frac{x}{2}} & x > 0 \\ 0 & \text{else} \end{cases}$$

and hence find the mean and variance.

13.a) If X is uniformly distributed in $[-2, 2]$, find (i) $P(x < 0)$ (ii) $P(|X - 1| \geq \frac{1}{2})$

b) If X is uniformly distributed with $E(x) = 1$ and $\text{Var}(x) = 4/3$, find $P(X < 0)$

14. A random variable X has the following probability density function

$$f_X(x) = \begin{cases} x & 0 < x < 1 \\ k(2-x) & 1 \leq x \leq 2 \\ 0 & \text{else} \end{cases}$$

i) Find the value of k?

ii) Find $P(0.2 < x < 1.2)$?

iii) Find the distribution function of X.

15.a) Derive the m.g.f of Poisson distribution and hence or otherwise deduce its mean and variance.

b) If the probability density of X is given by $f(x) = \begin{cases} 2(1-x) & 0 < x < 1 \\ 0 & \text{else} \end{cases}$

Find its r^{th} moment and evaluate $E[(2X+1)^2]$

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UNIT-III

Two marks Questions:

1. Define the statistical Independence of the Random variables.
2. Define point conditioning & interval conditioning distribution function.
3. Give the statement of central limit theorem.
4. Define correlation and covariance of two random variables X & Y.
5. Define the joint Gaussian density function of two random variables.
6. Define marginal distribution and density functions.
7. Define joint density function of two random variables.
8. Give the statement of central limit theorem.
9. Define the joint moments about the origin of two RVS X and Y.
10. Define orthogonal random variables.
11. Define expected value of a function of two and N random variables.
12. Define two joint central moments for two-dimensional random variables X and Y.
13. Define marginal characteristic functions.
14. Define correlation coefficient with two properties.
15. Define joint moment generating function and write its expression for continuous and discrete RVS.

Three Marks Questions:

1. If $E[X]=2$, $E[Y]=3$, $E[XY]=10$, $E[X^2]=9$, and $E[Y^2]=16$ then find variance & covariance of X & Y.
2. The joint probability density function of X & Y is
$$f_{X,Y}(x,y) = \begin{cases} c(2x+y); & 0 \leq x \leq 2, 0 \leq y \leq 3 \\ 0; & \text{else} \end{cases}$$
Then find the value of constant c.
3. If X and Y are two independent RVs such that $E(X)=\lambda_1$, variance of $X=\sigma_1^2$, $E(Y)=\lambda_2$, and variance of $Y=\sigma_2^2$, Show that $\text{var}(XY)=\sigma_1^2 \sigma_2^2 + \lambda_1^2 \sigma_2^2 + \lambda_2^2 \sigma_1^2$.
4. Show that $\text{var}(X+Y) = \text{var}(x) + \text{var}(Y)$, if X & Y are statistical independent random variables.
5. Show that $F_{X,Y}(x, \infty) = F_X(x)$ and $F_{X,Y}(\infty, y) = F_Y(y)$
6. The joint probability density function of the random variable (X, Y) is given by $f(x,y) = Kxy e^{-(x^2+y^2)}$ $x>0, y>0$. Find the value of K.
7. If two random variables X and Y have p.d.f $f(x,y) = k(2x+y)$ for $0 \leq x \leq 2, 0 \leq y \leq 3$, evaluate k.
8. Find the correlation co-efficient of two independent RVS X and Y.
9. If X and Y are two RVs then derive the expression for covariance in terms of correlation.
10. Show that $\Phi_{X,Y}(\omega_1, \omega_2) = \Phi_X(\omega_1)\Phi_Y(\omega_2)$ if X and Y are independent RVs.
11. If X and Y are independent random variables, show that $E[XY] = E[X].E[Y]$
12. Explain when random variables are called jointly random Gaussian, and also list important properties of Gaussian random variables?
13. If X is a random variable for which $E(X) = 10$ and $\text{var}(X) = 25$, for what possible value of 'a' and 'b' does $Y=aX-b$ have exception 0 and variance 1 ?

14. Stastistically independent random variables X and Y have moments $m_{10}=2$, $m_{20}=14$, and $m_{11}= -6$. Find the moment μ_{22} .
15. Show that $\text{cov}(X+a, Y+b)=\text{cov}(X, Y)=C_{XY}$. Where a and b are constants.

Ten Marks Questions:

1. a) State and prove the density function of sum of two random variables.
b) The joint density function of two random variables X and Y is

$$f_{XY}(x, y) = \begin{cases} \frac{(x+y)^2}{40} & ; -1 < x < 1 \text{ and } -3 < y < 3 \\ 0 & ; \text{ otherwise} \end{cases}$$

Find the variances of X and Y.

2. a) Let $Z=X+Y-C$, where X and Y are independent random variables with variance σ^2_X , σ^2_Y and C is constant. Find the variance of Z in terms of σ^2_X , σ^2_Y and C.
b) State and prove any three properties of joint characteristic function.

- 3.a) State and explain the properties of joint density function
b) The joint density function of random variables X and Y is

$$f_{XY}(x, y) = \begin{cases} 8xy; & 0 \leq x < 1, 0 < y < 1 \\ 0, & \text{ otherwise} \end{cases}$$

Find $f(y/x)$ and $f(x/y)$

4. The input to a binary communication system is a random variable X, takes on one of two values 0 and 1, with probabilities $\frac{3}{4}$ and $\frac{1}{4}$ respectively. Due to the errors caused by the channel noise, the output random variable Y, differs from the Input X occasionally. The behavior of the communication system is modeled by the conditional probabilities $P\left(\frac{Y=1}{X=1}\right) = \frac{3}{4}$ and $P\left(\frac{Y=0}{X=0}\right) = \frac{7}{8}$
Find a) The probability for a transmitted message to be received as 0
b) Probability that the transmitted message is a1. If the received is a 1.

5. Let X and Y be the random variables defined as $X=\text{Cos}\theta$ and $Y=\text{Sin}\theta$ where θ is a uniform random variable over $(0, 2\pi)$

- a) Are X and Y Uncorrelated?
b) Are X and Y Independent?

6. a) Define and State the properties of joint cumulative distribution function of two random variables X and Y.

- b) A joint probability density function is $f_{x,y}(x, y) = \begin{cases} \frac{1}{24} & 0 < x < 6, 0 < y < 4 \\ 0 & \text{ else where} \end{cases}$
Find the expected value of the function $g(X, Y) = (XY)^2$

7. State and prove the central limit theorem.

8. Two random variables X and Y have zero mean and variance $\sigma_X^2 = 16$ and $\sigma_Y^2 = 36$ correlation coefficient is 0.5 determine the following

i) The variance of the sum of X and Y

ii) The variance of the difference of X and Y

9. A certain binary system transmits two binary states $X = +1$ and $X = -1$ with equal probability. There are three possible states with the receiver, such as $Y = +1, 0$ and -1 . The performance of the communication system is given as

$P(y = +1/X = +1) = 0.2$; $P(Y = +1/X = -1) = 0.1$; $P(Y = 0/X = +1) = P(Y = 0/X = -1) = 0.05$.

Find a) $P(Y = 0)$

b) $P(X = +1/Y = +1)$

c) $P(X = -1/Y = 0)$.

10. Two random variables X and Y have the joint pdf is

$$f_{x,y}(x,y) = \begin{cases} Ae^{-(2x+y)} & x, y \geq 0 \\ 0 & \text{elsewhere} \end{cases}$$

i. Evaluate A ii. Find the marginal pdf's

iii. Find the marginal pdf's

iv. Find the joint cdf

v. Find the distribution functions and conditional cdf's.

11. Given is the joint distribution of X and Y

		X		
		0	1	2
Y	0	0.02	0.08	0.10
	1	0.05	0.20	0.25
	2	0.03	0.12	0.15

Obtain (i) Marginal Distributions and (ii) The Conditional Distribution of X given $Y=0$.

12. The joint probability mass functions of X and Y is given as

P(x,y)		X		
		0	1	2
X	0	0.1	0.04	0.02
	1	0.08	0.20	0.06
	2	0.06	0.14	0.30

Compute the marginal PMF of X and Y, $P[x \leq 1, y \leq 1]$ and check if X and Y are independent.

13. The joint probability density function of the two random variables is

$$f(x,y) = \begin{cases} \frac{8}{9}xy & 1 < x < y < 2 \\ 0 & \text{else} \end{cases}$$

i) Find the marginal density functions of X and Y

(ii) Find the conditional density function of Y given X

14. a) If the independent random variables X and Y have the variances 36 and 16 respectively, find the correlation coefficient between X+Y and X-Y

b) If the joint PDF of X and Y is $f_{X,Y}(x,y) = \begin{cases} e^{-(x+y)} & x > 0, y > 0 \\ 0 & \text{else} \end{cases}$ check whether X and Y are independent?

15a) The regression equation of X on Y is $3Y - 5x + 108 = 0$. If the mean value of Y is 44 and the variance of X is $9/16^{\text{th}}$ of the variance of Y Find the mean value of X and the correlation coefficient.

b) If X and Y are uncorrelated random variables with variances 16 and 9. Find the Correlation co-efficient between X+Y and X-Y.

UNIT-IV

Two marks Questions:

1. Define wide sense stationary random processes.
2. Give the statement of ergodic theorem.
3. Define the auto covariance & cross covariance functions of Random processes $X(t)$.
4. When two random processes $X(t)$ & $Y(t)$ are said to be independent.
5. Define the cross correlation function between two random processes $X(t)$ & $Y(t)$.
6. Define time – invariant system.
7. Define Poisson Random process.
8. Define random process with example.
9. Define time average of the random process $X(t)$.
10. Define orthogonal random processes.
11. $\{X(s,t)\}$ is a random process , what is the nature of $X(s,t)$ when (a) s is fixed (b) t is fixed?
(c) When s and t both are varying.
12. Define strict sense stationary process
13. Define stationary random process and list various levels of S.R.P.
14. Give the statement of super position principal.
15. Define strict sense stationary random process.

Three Marks Questions:

1. Differentiate between Random Processes and Random variables with example
2. Prove that the Auto correlation function has maximum value at the origin i.e $|R_{XX}(\tau)| = R_{XX}(0)$
3. A stationary ergodic random processes has the Auto correlation function with the periodic components as $R_{XX}(\tau) = 25 + \frac{4}{1+6\tau^2}$ find mean of the random process.
4. Define mean ergodic random processes and correlation ergodic Random processes.
5. Find the mean value of Response of a linear system.
6. Find the mean of the stationary process $X(t)$, whose autocorrelation function is given as $R(\tau) = 16 + \frac{9}{1+16\tau^2}$
7. State any two properties of linear time invariant system.
8. Prove that for a WSS RP $X(t)$, Auto correlation is even function of τ .
9. Define continuous and discrete random process with examples.
10. Define correlation matrix of two random processes $X(t)$ and $Y(t)$.
11. Define jointly Ergodic random processes.
12. If $X(t)$ is a WSS random process with auto correlation function $R_{XX}(\tau) = Ae^{-\alpha|\tau|}$ determine the second order moment of the random variable $\{X(8)-X(5)\}$.
13. Find the variance of the stationary process $\{X(t)\}$ whose ACF is given by $R_{XX}(\tau) = 16 + \frac{9}{1+6\tau^2}$
14. Check whether the following functions are valid auto correlation functions.

a) $\frac{1}{1+4\tau^2}$ b) $2\sin(\pi\tau)$

15. The auto correlation function for a stationary process $X(t)$ is given by $R_{XX}(\tau) = 9 + 2e^{-|\tau|}$. Find the mean of the random variable $Y = \int_0^2 X(t)dt$.

Ten Marks Questions:

1. a) Define Wide Sense Stationary Process and write its conditions.

b) A random process is given as $X(t) = At$, where A is a uniformly distributed random variable on $(0,2)$. Find whether $X(t)$ is wide sense stationary or not.

2. $X(t)$ is a stationary random process with a mean of 3 and an auto correlation function of $R_{XX}(\tau) = \exp(-0.2|\tau|)$. Find the second central Moment of the random variable $Y = Z - W$, where 'Z' and 'W' are the samples of the random process at $t=4$ sec and $t=8$ sec respectively.

3. Explain the following

i) Stationarity

ii) Ergodicity

iii) Statistical independence with respect to random processes

4. a) Given the RP $X(t) = A \cos(\omega_0 t) + B \sin(\omega_0 t)$ where ω_0 is a constant, and A and B are uncorrelated Zero mean random variables having different density functions but the same variance σ^2 . Show that $X(t)$ is wide sense stationary.

b) Define Covariance of the Random processes with any two properties.

5. a) A Gaussian RP has an auto correlation function $R_{XX}(\tau) = \frac{6 \sin(\pi\tau)}{\pi\tau}$. Determine a covariance matrix for the Random variable $X(t)$

b) Derive the expression for cross correlation function between the input and output of a LTI system.

6. Explain about Poisson Random process and also find its mean and variance.

7. The function of time $Z(t) = X_1 \cos \omega_0 t - X_2 \sin \omega_0 t$ is a random process. If X_1 and X_2 are independent Gaussian random variables, each with zero mean and variance σ^2 , find $E[Z]$, $E[Z^2]$ and $\text{var}(Z)$.

8. Briefly explain the distribution and density functions in the context of stationary and independent random processes.

9. Explain about the following random process

(i) Mean ergodic process

(ii) Correlation ergodic process

(iii) Gaussian random process

10. State and prove the auto correlation and cross correlation function properties.

11. Examine whether the random process $X(t) = A \cos(\omega t + \theta)$ is a wide sense stationary if A and ω are constants and θ is uniformly distributed random variable in $(0, 2\pi)$.

12. A random process $X(t)$ defined by $X(t) = A \cos(t) + B \sin(t)$, where A and B are independent random variables each of which takes a value $\sqrt{2}$ with Probability $1/3$ and a value 1 with probability $2/3$. Show that $X(t)$ is wide-sense stationary

13. A random process has sample functions of the form $X(t) = A \cos(\omega t + \theta)$ where ω is constant, A is a random variable with mean zero and variance one and θ is a random variable that is uniformly distributed between 0 and 2π . Assume that the random variables A and θ are independent. Is $X(t)$ mean ergodic-process?

14. If the WSS random process $X(t)$ is given as $X(t) = 10 \cos(100t + \theta)$ where θ is a uniformly distributed over $(-\pi, \pi)$. prove that $X(t)$ is correlation ergodic.

15.a) If $X(t)$ and $Y(t)$ are the random processes with auto correlation functions $R_{XX}(\tau)$ and $R_{YY}(\tau)$ then show that $|R_{XY}(\tau)| \leq \sqrt{R_{XX}(0)R_{YY}(0)}$

b) If the input to the LTI system is the WSS random process then show that output is also a WSS random process.

UNIT-V

Two marks Questions:

1. Define Power Spectrum Density.
2. Give the statement of Wiener-Khinchin relation.
3. Define spectrum Band width and RMS bandwidth.
4. Write any two properties of Power Spectrum Density.
5. Define a system. When is it called linear system?
6. Define Fourier and inverse Fourier transform of a deterministic signal $X(t)$.
7. Define transfer function of the system.
8. Define unit impulse response of the system
9. What is the need of power density spectrum?
10. Define energy and power of the random process $X(t)$ within the time interval $[-T, T]$.
11. Sketch the PSD of the RP whose ACF is $R_{XX}(\tau) = \frac{A^2}{2} \sin \omega_0 \tau$
12. Define cross power between two random processes $X(t)$ and $Y(t)$.
13. State any two properties of cross PSD.
14. State the conditions for the existence of Fourier transform of any signal.
15. If the Fourier transform of the RP $X(t)$ is $X(\omega)$ then find the Fourier transform of the RP $X(t-t_0)$.

Three Marks Questions:

1. Show that $S_{XX}(-\omega) = S_{XX}(\omega)$. i.e., Power spectrum density is even function of ω .
2. If the Power spectrum density of $x(t)$ is $S_{XX}(\omega)$, find the PSD of $\frac{d}{dt} x(t)$.
3. If the Auto correlation function of wide sense stationary $X(t)$ is $R_{XX}(\tau) = 4 + 2e^{-2|\tau|}$. Find the area enclosed by the power spectrum density curve of $X(t)$.
4. Define linear system and derive the expression for output response.
5. If $X(t)$ & $Y(t)$ are uncorrelated and have constant mean values \bar{X} & \bar{Y} then show that $S_{XX}(\omega) = 2\pi \bar{X} \bar{Y} \delta(\omega)$
6. Show that real part of $S_{XY}(\omega)$ and $S_{YX}(\omega)$ are even functions of ω .
7. The power spectral density function of a wide sense stationary process is given by $S_{XX}(\omega) = \pi |\omega| < 1$. Find the auto correlation function of the process.
8. Find the power spectral density function of a stationary process if $R(\tau) = e^{-|\tau|}$
9. Show that imaginary part of $S_{XY}(\omega)$ and $S_{YX}(\omega)$ are odd functions of ω .
10. Find the variance of the stationary process $\{X(t)\}$ where $R(\tau) = 2 + 4e^{-2|\tau|}$
11. Show that $S_{XY}(\omega) = S_{XX}(\omega)H(\omega)$.
12. Show that $S_{YX}(\omega) = S_{XX}(\omega)H(-\omega)$.
13. Give the statement of the relation between cross PSD and cross correlation function with corresponding mathematical expressions.
14. Find the cross correlation function for the cross PSD $S_{XY}(\omega) = \frac{1}{25 + \omega^2}$
15. Differentiate between PSD and Cross PSD.

Ten Marks Questions:

1. a) Check the following power spectral density functions are valid or not

i) $\frac{\cos 8(\omega)}{2 + \omega^4}$ ii) $e^{-(\omega-1)^2}$

b) Derive the relation between input PSD and output PSD of an LTI system

2. Derive the relationship between cross-power spectral density and cross correlation function.

3. A stationary random process $X(t)$ has spectral density $S_{XX}(\omega) = 25/(\omega^2 + 25)$ and an independent stationary process $Y(t)$ has the spectral density $S_{YY}(\omega) = \omega^2/(\omega^2 + 25)$. If $X(t)$ and $Y(t)$ are of zero mean, find the:

a) PSD of $Z(t) = X(t) + Y(t)$

b) Cross spectral density of $X(t)$ and $Z(t)$

4. a) The input to an LTI system with impulse response $h(t) = \delta(t) + t^2 e^{-at}$. $U(t)$ is a WSS process with mean of 3. Find the mean of the output of the system.

b) Define Power Spectral density with three properties.

5. a) A random process $Y(t)$ has the power spectral density $S_{YY}(\omega) = \frac{9}{\omega^2 + 64}$

Find i) The average power of the process ii) The Auto correlation function

b) State the properties of power spectral density

6. a) A random process has the power density spectrum $S_{YY}(\omega) = \frac{6\omega^2}{1 + \omega^4}$. Find the average power in the process.

b) Find the auto correlation function of the random process whose psd is $\frac{16}{\omega^2 + 4}$

7. a) Find the cross correlation function corresponding to the cross power spectrum

$$S_{XY}(\omega) = \frac{6}{(9 + \omega^2)(3 + j\omega)^2}$$

b) Write short notes on cross power density spectrum.

8. a) Consider a random process $X(t) = \cos(\omega t + \theta)$ where ω is a real constant and θ is a uniform random variable in $(0, \pi/2)$. Find the average power in the process.

b) Define and derive the expression for average power of Random process.

9. a) The power spectrum density function of a stationary random process is given by

$$S_{XX}(\omega) = \begin{cases} A, & -K < \omega < K \\ 0, & \text{other wise} \end{cases}$$

Find the auto correlation function.

b) Derive the expression for power spectrum density.

10. a) Define and derive the expression for average cross power between two random process $X(t)$ and $Y(t)$.

b) Find the cross power spectral density for $R_{XX}(\tau) = \frac{A^2}{2} \sin(\omega_0 \tau)$

11. Find the power spectral density function of the stationary process whose autocorrelation function is given by $e^{-|\tau|}$

12. $X(t)$ and $Y(t)$ are zero mean and stochastically independent random processes having autocorrelation functions $R_{XX}(\tau) = e^{-|\tau|}$ and $R_{YY}(\tau) = \cos 2\pi\tau$ respectively.

a) Find autocorrelation functions of $W(t) = X(t) + Y(t)$ and $Z(t) = X(t) - Y(t)$.

b) Find cross correlation function between $W(t)$ and $Z(t)$

13. For a input-output linear system $(X(t), h(t), Y(t))$, derive the cross correlation function $R_{XY}(\tau)$ and the output auto correlation function $R_{XX}(\tau)$

14. Consider a system with transfer function $\frac{1}{1+j\omega}$. An input signal with auto correlation function $m\delta(\tau) + m^2$ is fed to as input to the system. Find the mean and mean square value of the output.

15. A random process is defined as $Y(t) = X(t) - X(t-a)$, where $X(t)$ is a WSS process and $a > 0$ is a constant. Find the PSD of $Y(t)$ in terms of the corresponding quantities of $X(t)$.

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Time: 3 hours

Max. Marks: 75

Note: This question paper contains two parts A and B

Part A is compulsory which carries 25 marks and Answer all questions.

Part B Consists of 5 SECTIONS (One SECTION for each UNIT). Answer FIVE Questions, Choosing ONE Question from each SECTION and each Question carries 10 marks.

PART – A

(25 Marks)

1. (a) Given that $P(A) = 0.9$, $P(B) = 0.8$, and $P(A \cap B) = 0.75$, find i) $P(A \cup B)$; ii) $P(A \cap B')$ (2M)
- (b) State and explain Bayes' theorem. (3M)
- (c) Define random variable and list various types of random variables. (2M)
- (d) Define Probability density function. List its properties. (3M)
- (e) State and explain the significance of central limit theorem. (2M)
- (f) Distinguish between joint distribution and marginal distribution. (3M)
- (g) Explain the classification of random processes with neat sketches. (2M)
- (h) Explain Mean Ergodic random process. (3M)
- (i) State Relationship between Cross-Power Spectrum and Cross-Correlation Function (2M)
- (j) Explain Power spectral density. (3M)

PART – B

(50 Marks)

SECTION – I

2. (a) If A and B are any events, not necessarily mutually exclusive events, derive an expression for probability of A Union B. When A and B are mutually exclusive, that happens to the above expression derived. [5M]
- (b) Define the term Independent events. State the conditions for independence of: [5M]
 - i. any two events A and B
 - ii. any three events A, B and C

(OR)

3. (a) Differentiate joint and conditional probability. [5M]
- (b) State and prove total probability theorem. [5M]

SECTION – II

4. (a) Define Probability distribution function and state its properties. [5M]
- (b) Consider the probability density $f(x) = ae^{-bx}$ where x is a random variable Whose allowable values range from $x = -\infty$ to ∞ . [5M]

Find:

- i. the CDF $F(x)$
- ii. The relationship between a and b and
- iii. The probability that the outcome X lies between 1 and 2.

(OR)

5. (a) Derive an expression for the average value and variance associated with the Binomial probability density function. [5M]
- (b) The average life of a certain type of electric bulb is Rs.1200 hours. What percentage of this type of bulbs is expected to fail in the first 800 hours of working? What percentage is expected to fail between 800 is 1000 hours? Assume a normal distribution with $\sigma = 200$ hours. [5M]

SECTION – III

6. a) State and prove any four properties of joint density function. [5M]
(b) Find the density function of the distribution for which the characteristic function is $\phi(t) = e^{-(t^2 \sigma^2)/2}$. [5M]

(OR)

7. (a) Explain statistical independence of two random variables. [5M]
(b) Explain joint moments of two random variables. [5M]

SECTION – IV

8. Explain stationarity of the random process in detail. [10M]

(OR)

9. A random process $Y(t) = X(t) - X(t + \tau)$ is defined in terms of a process $X(t)$ that is at least wide sense stationary. [10M]

(i) Show that $\sigma_{Y^2} = 2[R_{XX}(0) - R_{XX}(\tau)]$

(ii) If $Y(t) = X(t) + X(t + \tau)$ find $E[Y(t)]$ and σ_{Y^2}

SECTION – V

10. State and prove the relation between power spectrum density and auto correlation function. [10M]

(OR)

11. a) Derive the relation between PSDs of input and output random process of an LTI system. [5M]

(b) state and prove any three properties of power spectrum density [5M]

MALLA REDDY COLLEGE OF ENGINEERING & TECHNOLOGY

(Autonomous Institution – UGC, Govt. of India)

II B.Tech I Semester Supplementary Examinations, November 2017

Probability Theory and Stochastic Process

(ECE)

Roll No	1	6	N	3	1	A	0	4	1	6
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Time: 3 hours

Max. Marks: 75

Note: This question paper contains two parts A and B

Part A is compulsory which carries 25 marks and Answer all questions.

Part B Consists of 5 SECTIONS (One SECTION for each UNIT). Answer FIVE Questions, Choosing ONE Question from each SECTION and each Question carries 10 marks.

PART – A

(25 Marks)

1. (a) What is a random variable? Discuss various properties of a random variable 2 MARKS
- (b) Define the following 3 MARKS
 - (i) Event (ii) Sample space (iii) Conditional Probability
- (c) If the Random variable X has uniform density, find its mean and variance 2 MARKS
- (d) Define and explain the Gaussian random variable in brief? 3 MARKS
- (e) State and prove any four properties of characteristic function? 2 MARKS
- (f) Define moment generating function 3 MARKS
- (g) State the condition for wide sense stationary Random process 2 MARKS
- (h) Explain Variance Ergodic random process 3 MARKS
- (i) Explain the Relationship between Power Spectrum and Autocorrelation Function 2 MARKS
- (j) State any two properties of Power density spectrum 3 MARKS

PART – B

(50 Marks)

SECTION – I

2. a) Given that two events A and B are statistically independent, Show that [5]
 A and \bar{B} , B and \bar{A} are also independent
- b) Determine the probability of the card being either red or a king when one card [5]
 is drawn from a regular deck of 52 cards.

(OR)

3. A missile can be accidentally launched if two relays A and B both have failed. The probabilities of A and B failing are known to be 0.01 and 0.03, respectively. It is also known that B is more likely to fail (probability 0.06) if A has failed. [5+5]

- a) What is the probability of an accidental missile launch?
- b) What is the probability that A will fail if B has failed?

SECTION – II

4. a) The Probability density function of X is given by the following table: [5]

X	0	1	2	3	4	5	6
P(x)	K	3K	5K	7K	9K	11K	13K

Find (i) $P(X < 4)$ (ii) $P(X \geq 5)$ (iii) $P(3 < X \leq 6)$

- b) Define Rayleigh density and distribution function and explain them with their plots. [5]

5. a) Find the value of the constant $b > 0$ in the given valid probability density function (OR) [5]
 $f(x) = \frac{1}{b} (e^{-bx/b})$ $0 \leq x \leq b$, other wise 0

- b) Let X be a random variable defined by the density function [5]
 $f_X(x) = 54(1-x^4)$ $0 \leq x \leq 1$
 $= 0$ elsewhere
 Find $E[X]$, $E[X^2]$ and variance.

SECTION - III

6. (a) Define conditional distribution and density function of two random variables X and Y [5]
 (b) The joint probability density function of two random variables X and Y is [5]
 given by $f(x, y) = a(2x + y^2)$ $0 \leq x \leq 2$, $2 \leq y \leq 4$
 Find i.) value of 'a' ii.) $P(X \leq 2, Y > 4)$.

(OR)

7. (a) Define Joint characteristic function and write its properties

- (b) Write down the properties of Joint density function [5]

SECTION - IV

8. (a) A Stationary random process $X(t)$ having an Auto Correlation function [5]
 $R_{XX}(\tau) = 2e^{-4|\tau|}$ find $S_{XX}(\omega)$

- (b) State and Explain Covariance functions and its properties. [5]
 (OR)

9. A random process is defined by $x(t) = A$, Where A is a continuous RV uniformly distributed on $(0, 1)$.

- a) Find whether it is first order stationary or not
 b) Determine whether it is wide sense stationary or not [5+5]

SECTION - V

10. (a) Derive an expression relating Auto correlation and Power Spectral density [5]

- (b) Show the Relationship between Power Spectrum and Autocorrelation Function [5]

(OR)

11. (a) Find the ACF of the following PSD's [5]

i. $S_{XX}(\omega) = 1/(25 + \omega^2)$

ii. $S_{XX}(\omega) = 8/(9 + \omega^2)^2$

- b) Define power Spectral density and discuss its properties [5]

MALLA REDDY COLLEGE OF ENGINEERING & TECHNOLOGY

(Autonomous Institution – UGC, Govt. of India)

II B.Tech I Semester supplementary Examinations, May 2017

Probability Theory and Stochastic Process

(ECE)

[illegible]

Time: 3 hours

Max. Marks: 75

Note: This question paper contains two parts A and B

Part A is compulsory which carries 25 marks and Answer all questions.

Part B Consists of 5 SECTIONS (One SECTION for each UNIT). Answer FIVE Questions, Choosing ONE Question from each SECTION and each Question carries 10 marks.

PART - A

(25 Marks)

1. (a) What is sample space? Explain the Discrete sample space and Continuous sample space each with a suitable example. [3M]
- (b) What is the probability of getting 53 Sundays in a leap year? [2M]
- (c) Explain Gaussian random Variable. [3M]
- (d) Define the moment generating function(MGF). [3M]
- (e) What is Central Limit theorem? [2M]
- (f) What is correlation coefficient and write its significance. [3M]
- (g) What is meant by Correlation ergodic process? [3M]
- (h) What is strict sense stationary process? [2M]
- (i) Write the properties of power density spectrum. [2M]
- (j) Find the mean value of Random variable $Y = -3X + 22$ where the mean of X is 3. [3M]

PART - B

(50 Marks)

SECTION - I

- 2.a) Define i) Conditional Probability (ii) Independent events (iii) Mutually Exclusive Events (iv) Joint Probability

- b) When two dice are thrown find the probability of getting
(i) $\{\text{sum} > 7\}$ (ii) $\{2 < \text{sum} \leq 5\}$ (iii) $\{\text{sum} > 10\}$

OR

3. a) A batch of 50 items contains 10 defective items. Suppose 10 items are selected at random and tested. What is the probability that exactly 5 of the items tested are defective?

- b) State and prove Baye's theorem.

SECTION – II

4. a) Define probability density function and write its properties

b) If random variable X is transformed to the new random variable $Y = CX^2$, find the density function of Y .

OR

5. a) What is Probability distribution function? Explain its properties.

b) A random variable has probability density function

$$f_x(x) = c x(1-x) \quad 0 \leq x \leq 1$$

0

else where

Find i) c ii) $p(1/2 \leq X \leq 3/4)$ iii) $F_x(x)$

SECTION – III

6. a) Explain about joint moments & how they are generated.

b) Mean values of random variables X, Y are 0.5, 2. Mean square values are 1.5, 5.5 and covariance of X and Y is -0.25. Find cross correlation and correlation coefficient.

OR

7. a) Find the conditional density functions for the joint distribution

$$f_{x,y}(x,y) = 4xy \exp(x^2 + y^2) u(x) u(y)$$

b) Let X and Y be the random variables defined as $X = \cos \theta$ and $Y = \sin \theta$, where θ is a uniform random variable over $(0, 2\pi)$. Are X and Y uncorrelated? Are X and Y independent?

SECTION – IV

8. a) Write and prove properties of cross correlation function

b) Find the mean and Auto correlation function of the Random process $X(t) = A \cos(\omega t + \theta)$ where A and ω are constants, θ is random variable uniformly distributed on the interval $(0, 2\pi)$

OR

9. a) a) State and prove Wiener Khinchin theorem.

b) $X(t)$ is a WSS process and $Y(t) = A \cos(\omega_c t + \theta)$ is a random process which is independent of $X(t)$. Here, θ is a uniform random variable over $(-\pi, \pi)$. If the auto-correlation function of $X(t)$ is $R_{XX}(\tau)$, Find the auto correlation of $Z(t) = X(t)Y(t)$.

SECTION – V

10. a) Derive the relationship between cross correlation function and cross power density spectrum.

b) Find the power spectral density (P.S.D) of $X(t) = \cos(\omega t + \theta)$ where θ is a uniform random variable over $(0, \pi/2)$ and also find the average power.

OR

11. a) Find the relation between input and output power spectral density in a LTI System.

b) Check whether the following functions are valid power spectral density (PSD)

i) $\frac{\cos 8\omega^4}{2 + \omega^4}$

ii) $e^{-(\omega-1)^2}$

MALLA REDDY COLLEGE OF ENGINEERING & TECHNOLOGY

(Autonomous Institution – UGC, Govt. of India)

B.Tech. III Semester Regular Examinations, NOV 2016

PROBABILITY THEORY AND STOCHASTIC PROCESS

(ECE)

Roll No	1	5	N	3						
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Time: 3 hours

Max. Marks: 75

Note: This question paper contains two parts A and B

Part A is compulsory which carries 25 marks and Answer all questions.

Part B Consists of 5 SECTIONS (One SECTION for each UNIT). Answer FIVE Questions, Choosing ONE Question from each SECTION and each Question carries 10 marks.

PART - A**(25 Marks)**

1. (a) When do you say that two events are independent? [2M]
- (b) A card is drawn from a pack of 52 cards. Find the probability of getting a king or a heart or a red card. [3M]
- (c) Discuss the conditions for a function to be a random variable. [2M]
- (d) A discrete random variable X has possible values which occur with probabilities 0.4, 0.25, 0.15, 0.1 and 0.1 respectively. Find the mean value X . [3M]
- (e) Explain the physical significance of variance of a random variable. [2M]
- (f) Define joint central moments for the random variables X and Y . [2M]
- (g) What is meant by Mean Ergodic process? [3M]
- (h) Explain the classification of random processes [3M]
- (i) Is power density spectrum an even function of ' ω ' or odd function of ' ω '? Justify. [2M]
- (j) Find the mean value of exponential random variable. [3M]

PART - B**(50 Marks)****SECTION - I**

2.a) Four cards are drawn from a well shuffled pack of playing cards. Find the probability that i) All are clubs ii) Two are spades & two are hearts iii) Four cards are from different suits.

b) Show that Conditional probability satisfies the three axioms of probability
OR

3. a) Telephone calls are initiated through an exchange at the average rate of 75 per minute and are described by a Poisson process. Find the probability that more than 3 calls are initiated in any 5-second period.

b) Explain the terms Joint probability and Conditional probability.

SECTION - II

4. a) Determine $E[X]$ and $VAR[X]$ of Poisson random variable X .

- b) List the properties of conditional density function & conditional distribution function.

OR

5. a) A random variable has probability density function

$$f_X(x) = \begin{cases} cx(1-x) & 0 \leq x \leq 1 \\ 0 & \text{else where} \end{cases}$$

Find a) c b) $P(1/2 \leq X \leq 3/4)$ c) $F_X(x)$

- b) Determine the cumulative distribution function and probability density function of Y

given that $Y = 2X+3$ and that $f_X(x) = 2e^{-x} u(x)$.

SECTION – III

6. a) Define joint central moments for two random variables X and Y and explain the covariance of two random variables.

- b) The joint probability density function of two random variables X and Y is given by

$$f(x,y) = c(2x+y); 0 \leq x \leq 1, 0 \leq y \leq 2; 0; \text{ else where}$$

Find: i) The value of 'c'. ii) Marginal distribution function of x and y.

OR

7. a) Derive the expressions for the distribution and density functions of sum of two statistically independent random variables.

- b) The density function of two random variables X and Y is

$$f_{XY}(x, y) = u(x) u(y) 4e^{-2(x+y)}. \text{ Find the mean value of the function } e^{-(x+y)}.$$

SECTION – IV

8. a) Write and prove the properties of Auto correlation function

b) Find the mean and Auto correlation function of the Random process $X(t) = A \cos(\omega t + \theta)$ where A and ω are constants, θ is random variable uniformly distributed on the interval $(0, 2\pi)$.

OR

9. a) X(t) is a WSS process and $Y(t) = A \cos(\omega t + \theta)$ is a random process which is independent of X(t). Here, θ is a uniform random variable over $(-\pi, \pi)$. If the auto-correlation function of X(t) is $R_{XX}(\tau)$, Find the auto correlation of $Z(t) = X(t)Y(t)$.

- b) For a stationary Ergodic process X(t) with the periodic components the Auto correlation is $R_{XX}(\tau) = 36 + 4/(1 + 5\tau^2)$. Find $E[X(t)]$, $E[X^2(t)]$ and Power in the process X(t).

SECTION – V

10. a) Derive an expression for Auto correlation function of response of a linear system with random input.

- b) Write about power density spectrum of Response of Linear system

OR

11. a) Find the power density spectrum of a random process whose autocorrelation Function is

$$R_{XX}(\tau) = A \cos(\omega \tau).$$

- b) State and prove properties of power spectral density of random process.

MALLA REDDY COLLEGE OF ENGINEERING AND TECHNOLOGY
DEPARTMENT OF ELECTRONICS AND COMMUNICATION ENGINEERING

B.Tech II year – I Semester Examinations, Model Paper-1
PROBABILITY THEORY AND STOCHASTIC PROCESSES

Time: 3 hours

Max. Marks: 75

PART- A (25 Marks)

1. a) Define probability using the axiomatic approach. (2 marks)
- b) Show that $P(A \cup B) = P(A) + P(B) - P(A \cap B)$. (3 marks)
- c) Define Probability density and distribution function. (2 marks)
- d) Define various types of transformation of Random variables. (3 marks)
- e) Define point conditioning & interval conditioning distribution function. (2 marks)
- f) Show that $\text{var}(X+Y) = \text{var}(x) + \text{var}(Y)$, if X & Y are independent random variables. (3 marks)
- g) Define wide sense stationary random processes. (2 marks)
- h) Prove that the ACF has maximum value at the origin i.e $|R_{XX}(\tau)| = R_{XX}(0)$ (3 marks)
- i) Define spectrum Band width and RMS bandwidth. (2 marks)
- j) If the Auto correlation function of wide sense stationary $X(t)$ is $R_{XX}(\tau) = 4 + 2e^{-2|\tau|}$.
Find the area enclosed by the power spectrum density curve of $X(t)$. (3 marks)

Part-B (5*10=50 Marks)

2. a) State and Prove Bayes' theorem.
b) Explain the Mathematical model of experiment.
OR
3. a) An experiment consists of observing the sum of the outcomes when two fair dice are thrown. Find the probability that the sum is 7 and find the probability that the sum is greater than 10.
b) In a factory there are 4 machines produce 10%, 20%, 30%, 40% of an items respectively. The defective items produced by each machine are 5%, 4%, 3% and 2% respectively. Now an item is selected which is to be defective, what is the probability it being from the 2nd machine. And also write the statement of total probability theorem?
4. a) The exponential density function given by
$$f_X(x) = \begin{cases} (1/b)e^{-(x-a)/b} & x > a \\ 0 & x < a \end{cases}$$

Find the mean and variance.
b) Define Moment Generating Function and write any two properties.
OR
5. Derive the Binomial density function and find mean & variance.

6. a) State and prove the density function of sum of two random variables.
 b) The joint density function of two random variables X and Y is

$$f_{XY}(x, y) = \begin{cases} \frac{(x+y)^2}{40} & ; -1 < x < 1 \text{ and } -3 < y < 3 \\ 0 & ; \text{otherwise} \end{cases}$$

Find the variances of X and Y.

OR

7. a) Let $Z=X+Y-C$, where X and Y are independent random variables with variance σ^2_X , σ^2_Y and C is constant. Find the variance of Z in terms of σ^2_X , σ^2_Y and C.
 b) State and prove any three properties of joint characteristic function.

8. a) Define Wide Sense Stationary Process and write it's conditions.
 b) A random process is given as $X(t) = At$, where A is a uniformly distributed random variable on (0,2). Find whether X(t) is wide sense stationary or not.

OR

9. X(t) is a stationary random process with a mean of 3 and an auto correlation function of $6+5 \exp(-0.2|\tau|)$. Find the second central Moment of the random variable $Y=Z-W$, where 'Z' and 'W' are the samples of the random process at t=4 sec and t=8 sec respectively.

10. a) Check the following power spectral density functions are valid or not
 i) $\frac{\cos 8(\omega)}{2+\omega^4}$ ii) $e^{-(\omega-1)^2}$
 b) Derive the relation between input PSD and output PSD of an LTI system

OR

11. Derive the relationship between cross-power spectral density and cross correlation function.

MALLA REDDY COLLEGE OF ENGINEERING AND TECHNOLOGY
DEPARTMENT OF ELECTRONICS AND COMMUNICATION ENGINEERING
B.Tech II year – I Semester Examinations, Model Paper-2
PROBABILITY THEORY AND STOCHASTIC PROCESSES

Time: 3 hours

Max. Marks: 75

PART- A (25 Marks)

1. a. Define subset and state its properties. (2 marks)
- b. Define sample space and classify the types of sample space. (3 marks)
- c. Define the expected value of Discrete and Continuous Random Variables. (2 marks)
- d. Derive the expression for the density function of Discrete Random variable. (3 marks)
- e. Define the statistical Independence of the Random variables. (2 marks)
- f. If $E[X]=2$, $E[Y]=3$, $E[XY]=10$, $E[X^2]=9$, and $E[Y^2]=16$ then find variance & Covariance of X&Y. (3 marks)
- g. Give the statement of ergodic theorem. (2 marks)
- h. Differentiate between Random Processes and Random variables with example (3 marks)
- i. Define Power Spectrum Density. (2 marks)
- j. Show that $S_{XX}(-\omega) = S_{XX}(\omega)$. i.e., Power spectrum density is even function of ω . (3 marks)

Part-B (5*10=50 Marks)

2. In a box there are 100 resistors having resistance and tolerance values given in table. Let a resistor be selected from the box and assume that each resistor has the same likelihood of being chosen. Event A: Draw a 47Ω resistor, Event B: Draw a resistor with 5% tolerance, Event C: Draw a 100Ω resistor. Find the individual, joint and conditional probabilities.

Resistance (Ω)	Tolerance		Total
	5%	10%	
22	10	14	24
47	28	16	44
100	24	8	32
Total	62	38	100

OR

3. a) Two boxes are selected randomly. The first box contains 2 white balls and 3 black balls. The second box contains 3 white and 4 black balls. What is the probability of drawing a white ball?
- b) An aircraft is used to fire at a target. It will be successful if 2 or more bombs hit the target. If the aircraft fires 3 bombs and the probability of the bomb hitting the target is 0.4, then what is the probability that the target is hit?

4. Derive the Poisson density function and find its mean & variance.

OR

5. If X is a discrete random variable with a Moment generating function of $M_X(v)$, find the Moment generating function of

i) $Y=aX+b$ ii) $Y=KX$ iii) $Y=\frac{X+a}{b}$

6. a) State and explain the properties of joint density function
b) The joint density function of random variables X and Y is

$$f_{XY}(x, y) = \begin{cases} 8xy; & 0 \leq x < 1, 0 < y < 1 \\ 0, & \text{otherwise} \end{cases}$$

Find $f(y/x)$ and $f(x/y)$

OR

7. The input to a binary communication system is a RV X, takes on one of two values 0 and 1, with probabilities $\frac{3}{4}$ and $\frac{1}{4}$ respectively. Due to the errors caused by the channel noise, the output random variable Y, differs from the Input X occasionally. The behavior of them communication system is modeled by the conditional probabilities $P\left(\frac{Y=1}{X=1}\right) = \frac{3}{4}$ and $P\left(\frac{Y=0}{X=0}\right) = \frac{7}{8}$ Find
a) The probability for a transmitted message to be received as 0
b) Probability that the transmitted message is a 1. If the received is a 1.

8. Explain the following

- i) Stationary
ii) Ergodicity
iii) Distribution & density functions of random processes

OR

9. a) Given the RP $X(t) = A \cos(\omega_0 t) + B \sin(\omega_0 t)$ where ω_0 is a constant, and A and B are uncorrelated Zero mean random variables having different density functions but the same variance σ^2 . Show that X(t) is wide sense stationary.
b) Define Covariance of the Random processes with any two properties.

10. A stationary random process X(t) has spectral density $S_{XX}(\omega) = 25/(\omega^2 + 25)$ and an independent stationary process Y(t) has the spectral density $S_{YY}(\omega) = \omega^2/(\omega^2 + 25)$. If X(t) and Y(t) are of zero mean, find the:

- a) PSD of $Z(t) = X(t) + Y(t)$
b) Cross spectral density of X(t) and Z(t)

OR

11. a) The input to an LTI system with impulse response $h(t) = \delta(t) + t^2 e^{-at}$. U(t) is a WSS process with mean of 3. Find the mean of the output of the system.
b) Define Power Spectral density with three properties.

MALLA REDDY COLLEGE OF ENGINEERING AND TECHNOLOGY
DEPARTMENT OF ELECTRONICS AND COMMUNICATION ENGINEERING

B.Tech II year – I Semester Examinations, Model Paper-3
PROBABILITY THEORY AND STOCHASTIC PROCESSES

Time: 3 hours

Max. Marks: 75

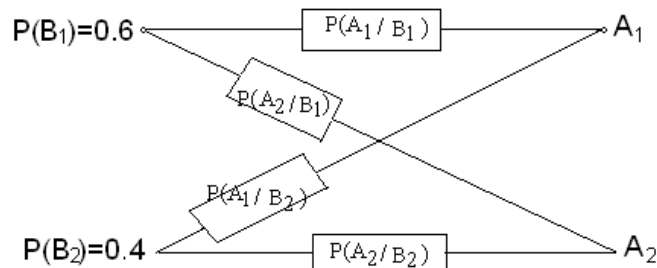
PART- A (25 Marks)

1. a. Give the classical definition of Probability with example. (2 marks)
b. Define Joint and Conditional Probability (3 marks)
c. Define Moment generating function and Characteristic Function of a RV's (2 marks)
d. Find the variance of X for uniform density function. (3 marks)
e. Give the statement of central limit theorem. (2 marks)
f. The joint probability density function of X&Y is
$$f_{X,Y}(x,y) = \begin{cases} c(2x+y); & 0 \leq x \leq 2, 0 \leq y \leq 3 \\ 0; & \text{else} \end{cases}$$

Then find the value of constant c. (3 marks)
g. Define the auto covariance & cross covariance functions of Random processes X(t). (2 marks)
h. A stationary ergodic random processes has the Auto correlation function with the periodic components as $R_{XX}(\tau) = 25 + \frac{4}{1+6\tau^2}$ (3 marks)
i. Give the statement of Wiener-Khinchin relation. (2 marks)
j. If the Power spectrum density of x(t) is $S_{XX}(\omega)$, find the PSD of $\frac{d}{dt} x(t)$. (3 marks)

PART-B (5*10=50 Marks)

2. Determine probabilities of system error and correct system transmission of symbols for an elementary binary communication system shown in below figure consisting of a transmitter that sends one of two possible symbols (a 1 or a 0) over a channel to a receiver. The channel occasionally causes errors to occur so that a '1' show up at the receiver as a '0'? And vice versa. Assume the symbols '1' and '0' are selected for a transmission as 0.6 and 0.4 respectively.



OR

3. In a binary communication system, the errors occur with a probability of “p”, In a block of “n” bits transmitted, what is the probability of receiving
i) at the most 1 bit in error
ii at least 4 bits in error

4. A random variable X has the distribution function

$$F_X(x) = \sum_{n=1}^{12} \frac{n^2}{650} u(x - n)$$

Find the probability of a) $P\{-\infty < X \leq 6.5\}$ b) $P\{X > 4\}$ c) $P\{6 < X \leq 9\}$

OR

5. Let X be a Continuous random variable with density function

$$f(x) = \begin{cases} \frac{x}{9} + K & 0 \leq x \leq 6 \\ 0 & \text{otherwise} \end{cases}$$

Find the value of K and also find $P\{2 \leq X \leq 5\}$

6. Let X and Y be the random variables defined as $X = \cos\theta$ and $Y = \sin\theta$ where θ is a uniform random variable over $(0, 2\pi)$
a) Are X and Y Uncorrelated?
b) Are X and Y Independent?

OR

7. a) Define and State the properties of joint cumulative distribution function of two random variables X and Y.

b) A joint probability density function is $f_{x,y}(x,y) = \begin{cases} \frac{1}{24} & 0 < x < 6, 0 < y < 4 \\ 0 & \text{else where} \end{cases}$

Find the expected value of the function $g(X,Y) = (XY)^2$

8. a) A Gaussian RP has an auto correlation function $R_{XX}(\tau) = \frac{6 \sin(\pi\tau)}{\pi\tau}$. Determine a covariance matrix for the Random variable X(t)
b) Derive the expression for cross correlation function between the input and output of a LTI system.

OR

9. a) Derive the mean and mean square value of response of LTI system.
b) Discuss in detail about first order stationary random process.

10. a) A random process Y(t) has the power spectral density $S_{YY}(\omega) = \frac{9}{\omega^2 + 64}$

Find i) The average power of the process

ii) The Auto correlation function

b) State the properties of power spectral density

OR

11. a) A random process has the power density spectrum $S_{YY}(\omega) = \frac{6\omega^2}{1+\omega^4}$. Find the average power in the process.

b) Find the auto correlation function of the random process whose psd is $\frac{16}{\omega^2 + 4}$

MALLA REDDY COLLEGE OF ENGINEERING AND TECHNOLOGY
DEPARTMENT OF ELECTRONICS AND COMMUNICATION ENGINEERING

B.Tech II year – I Semester Examinations, Model Paper-4
PROBABILITY THEORY AND STOCHASTIC PROCESSES

Time: 3 hours

Max. Marks: 75

PART- A (25 Marks)

1. a. Write the statement of multiplication theorem. (2 marks)
- b. Define Equally likely events, Exhaustive events and Mutually exclusive events. (3 marks)
- c. Define moments about origin and central moments. (2 marks)
- d. Write the properties of Gaussian density curve. (3 marks)
- e. Define correlation and covariance of two random variables X & Y. (2 marks)
- f. Define correlation coefficient with two properties. (3 marks)
- g. When two random processes X(t) & Y(t) are said to be independent. (2 marks)
- h. Define mean ergodic random processes & correlation ergodic Random processes. (3 marks)
- i. Write any two properties of Power Spectrum Density (2 marks)
- j. Define linear system and impulse response. (3 marks)

PART-B (5*10=50 Marks)

2. Let A and B are events in a sample space S. Show that if A and B are independent, then so are
a) A and \bar{B} b) \bar{A} and B c) \bar{A} and \bar{B}

OR

3. In the experiment of tossing a die, all the even numbers are equally likely to appear and similarly the odd numbers. An odd number occurs thrice more frequently than an even number. Find the probability that
a) An even number appears
b) A prime number appears
c) An odd numbers appears
4. a) Verify the Characteristic function of a random variable is having its maximum magnitude at $\omega=0$ and find its maximum value.
b) Find the Moment generating function of exponential distribution?

OR

5. The probability density function of a random variable X is given by $f(x) = \frac{x^2}{81}$ for $-3 < x < 6$ and equal to zero otherwise. Find the density function of $Y = \frac{1}{3}(12-x)$

6. State and prove the central limit theorem

OR

7. Two random variables X and Y have zero mean and variance $\sigma_X^2 = 16$ and $\sigma_Y^2 = 36$ correlation coefficient is 0.5 determine the following

- i) The variance of the sum of X and Y
- ii) The variance of the difference of X and Y

8. The function of time $Z(t) = X_1 \cos \omega_0 t - X_2 \sin \omega_0 t$ is a random process. If X_1 and X_2 are independent Gaussian random variables, each with zero mean and variance σ^2 , find $E[Z]$, $E[Z^2]$ and $\text{var}(Z)$.

OR

9. Briefly explain the distribution and density functions in the context of stationary and independent random processes.

10. a) Find the cross correlation function corresponding to the cross power spectrum

$$S_{XY}(\omega) = \frac{6}{(9 + \omega^2)(3 + j\omega)^2}$$

- b) Write short notes on cross power density spectrum.

OR

11. a) Consider a random process $X(t) = \cos(\omega t + \theta)$ where ω is a real constant and θ is a uniform random variable in $(0, \pi/2)$. Find the average power in the process.

- b) Define and derive the expression for average power of Random process.

MALLA REDDY COLLEGE OF ENGINEERING AND TECHNOLOGY
DEPARTMENT OF ELECTRONICS AND COMMUNICATION ENGINEERING

B.Tech II year – I Semester Examinations, Model Paper-5
PROBABILITY THEORY AND STOCHASTIC PROCESSES

Time: 3 hours

Max. Marks: 75

PART- A (25 Marks)

1. a. What are the conditions for a function to be a random variable? (2 marks)
- b. Define Random variable and Write the classifications of Random variable (3 marks)
- c. Show that $\text{Var}(kX) = k^2 \text{var}(X)$, here k is a constant. (2 marks)
- d. In an experiment when two dice are thrown simultaneously, find expected value of the sum of number of points on them. (3 marks)
- e. Define the joint Gaussian density function of two random variables. (2 marks)
- f. Define Marginal distribution & Density functions. (3 marks)
- g. Define the cross correlation function between two random processes $X(t)$ & $Y(t)$. (2 marks)
- h. Find the mean value of Response of a linear system. (3 marks)
- i. Define linear system. (2 marks)
- j. If $X(t)$ & $Y(t)$ are uncorrelated and have constant mean values \bar{X} & \bar{Y} then show that $S_{XX}(\omega) = 2\pi\bar{X}\bar{Y}\delta(\omega)$ (3 marks)

PART-B (5*10=50 Marks)

2. a) An experiment consist of rolling a single die. Two events are defined as $A = \{6 \text{ shows up}\}$: and $B = \{2 \text{ or } 5 \text{ shows up}\}$
 - i) Find $P(A)$ and $P(B)$
 - ii) Define a third event C so that $P(C) = 1 - P(A) - P(B)$b) The six sides of a fair die are numbered from 1 to 6. The die is rolled 4 times. How many sequences of the four resulting numbers are possible?

OR

3. a) State and prove the total probability theorem?
 - b) Explain about conditional probability
4. a) Write short notes on Gaussian distribution and also find its mean?
 - b) Consider that a fair coin is tossed 3 times, Let X be a random variable, defined as $X = \text{number of tails appeared}$, find the expected value of X .

OR

5. a) Find the characteristic function and first moment for
$$f_X(x) = \begin{cases} (1/b)\exp(-(x-a)/b) & x \geq a \\ 0 & \text{else} \end{cases}$$
b) Find the probability of getting a total of 5 or 11, when tossing a pair of fair dice.
6. A certain binary system transmits two binary states $X = +1$ and $X = -1$ with equal probability. There are three possible states with the receiver, such as $Y = +1, 0$ and -1 . The performance of the communication system is given as
$$P(y = +1/X = +1) = 0.2;$$
$$P(Y = +1/X = -1) = 0.1; P(Y = 0/X = +1) = P(Y = 0/X = -1) = 0.05.$$
 Find

- a) $P(Y = 0)$ b) $P(X = +1/Y = +1)$
 c) $P(X = -1/Y = 0)$.

OR

7. Two random variables X and Y have the joint pdf is

$$f_{x,y}(x,y) = \begin{cases} Ae^{-(2x+y)} & x, y \geq 0 \\ 0 & \text{elsewhere} \end{cases}$$

- i. Evaluate A
- ii. Find the marginal pdf's
- iii. Find the marginal pdf's
- iv. Find the joint cdf
- v. Find the distribution functions and conditional cdf's.

8. Explain about the following random process

- (i) Mean ergodic process
- (ii) Correlation ergodic process
- (iii) Gaussian random process

OR

9. State and prove the auto correlation and cross correlation function properties.

10. a) The power spectrum density function of a stationary random process is given by

$$S_{xx}(\omega) = \begin{cases} A, & -K < \omega < K \\ 0, & \text{other wise} \end{cases}$$

Find the auto correlation function.

- b) Derive the expression for power spectrum density.

OR

11. a) Define and derive the expression for average cross power between two random process X(t) and Y(t).

- b) Find the cross power spectral density for $R_{xx}(\tau) = \frac{A^2}{2} \sin(\omega_0 \tau)$.
