

# Random Numbers

Mukunda reddy

## CONTENTS

1	Uniform Random Numbers	1
2	Central Limit Theorem	2
3	From Uniform to Other	4
4	Triangular Distribution	4
5	Maximul Likelihood	6
6	Gaussian to Other	6
7	Conditional Probability	8
8	Two Dimensions	8

<https://github.com/mohilmukundareddy/Assignment1/blob/main/ex1/1.2/main.py>

Run the following command in the terminal to run the code.

```
python3 main.py
```

## 1 UNIFORM RANDOM NUMBERS

Let  $U$  be a uniform random variable between 0 and 1.

- 1.1 Generate  $10^6$  samples of  $U$  using a C program and save into a file called uni.dat .

**Solution:** Download the following files and execute the C program.

```
wget https://github.com/mohilmukundareddy/Assignment1/blob/main/ex1/1.1/exrand.c
we get https://github.com/mohilmukundareddy/Assignment1/blob/main/ex1/1.1/coeffs.h
```

Use the below command in the terminal to run the code

```
gcc exrand.c -lm
./a.out
```

- 1.2 Load the uni.dat file into python and plot the empirical CDF of  $U$  using the samples in uni.dat. The CDF is defined as

$$F_U(x) = \Pr(U \leq x) \quad (1.1)$$

**Solution:** The graph 1.2 is obtained by running the below code

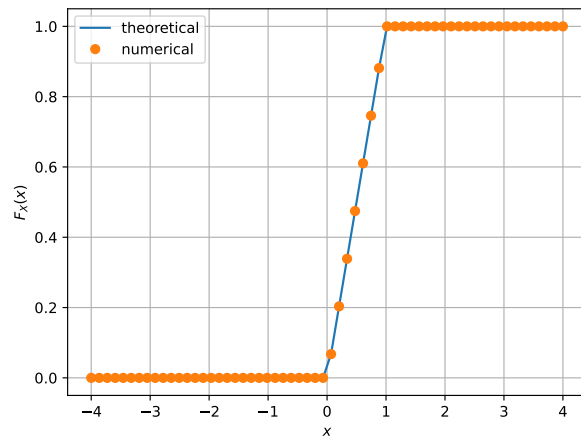


Fig. 1.2: The CDF of  $U$

- 1.3 Find a theoretical expression for  $F_U(x)$ .

**Solution:** Given  $U$  is uniform random variable so

$$f_X(x) = \begin{cases} 1 & 0 \leq x \leq 1 \\ 0 & \text{otherwise} \end{cases}$$

$$\begin{aligned} F_X(x) &= \int_{-\infty}^x f_X(x) dx \\ &= 0 + \int_0^x 1 dx \\ &= \begin{cases} 1 & x > 1 \\ x & 0 \leq x \leq 1 \\ 0 & x < 0 \end{cases} \end{aligned}$$

1.4 The mean of  $U$  is defined as

$$E[U] = \frac{1}{N} \sum_{i=1}^N U_i \quad (1.2)$$

and its variance as

$$\text{var}[U] = E[U - E[U]]^2 \quad (1.3)$$

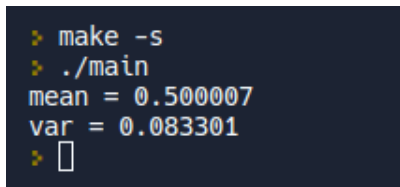
Write a C program to find the mean and variance of  $U$ .

**Solution:**

```
wget https://github.com/mohilmukundareddy/
Assignment1/blob/main/ex1/1.4/exrand.c
weget https://github.com/mohilmukundareddy/
Assignment1/blob/main/ex1/1.4/coeffs.h
```

Use below command to run file,

```
gcc exrand.c -lm
./a.out
```



```
> make -s
> ./main
mean = 0.500007
var = 0.083301
> 
```

Fig. 1.4: Caption

1.5 Verify your result theoretically given that

Given

$$E[U^k] = \int_{-\infty}^{\infty} x^k dF_X(x)$$

$$\begin{aligned} E[U] &= \int_{-\infty}^{\infty} x^k f_X(x) dx \\ &= \int_0^1 x \times 1 dx \\ &= \left[ \frac{x^2}{2} \right]_0^1 = \frac{1}{2} \end{aligned}$$

if  $k=2$

$$\begin{aligned} E[U^2] &= \int_0^1 x^2 \times 1 dx \\ &= \left[ \frac{x^3}{3} \right]_0^1 = \frac{1}{3} \end{aligned}$$

$$\begin{aligned} \text{variance} &= E[u - E[u]]^2 \\ &= E[U^2] - E^2[U] \\ &= \frac{1}{3} - \frac{1}{4} = 0.0833 \end{aligned}$$

## 2 CENTRAL LIMIT THEOREM

2.1 Generate  $10^6$  samples of the random variable

$$X = \sum_{i=1}^{12} U_i - 6 \quad (2.1)$$

using a C program, where  $U_i, i = 1, 2, \dots, 12$  are a set of independent uniform random variables between 0 and 1 and save in a file called gau.dat

**Solution:**

```
wget https://github.com/mohilmukundareddy/
Assignment1/blob/main/ex2/2.1/exrand.c
wget https://github.com/mohilmukundareddy/
Assignment1/blob/main/ex2/2.1/coeffs.h
```

Running the above codes generates uni.dat and gau.dat file. Use the command

```
gcc exrand.c -lm
./a.out
```

2.2 Load gau.dat in python and plot the empirical CDF of  $X$  using the samples in gau.dat. What properties does a CDF have?

**Solution:** The CDF of  $X$  is plotted in plot, Properties of the CDF:

- $F_X(x) = P(X \leq x)$
- $Q_X(x) = P(X > x)$
- $F_X(x) = 1 - Q_X(x)$  This can be used to calculate  $F(x)$ .

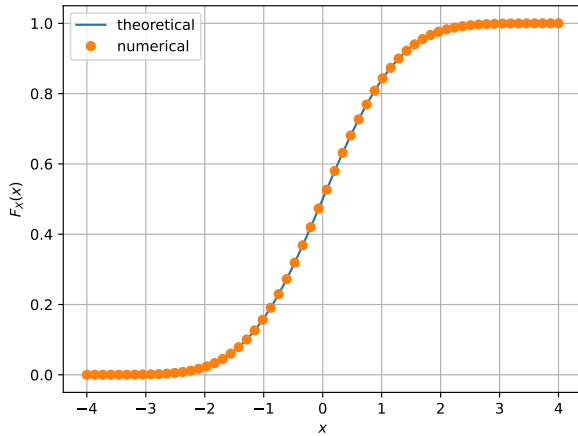


Fig. 2.2: The CDF of  $X$

2.3 Load `gau.dat` in python and plot the empirical PDF of  $X$  using the samples in `gau.dat`. The PDF of  $X$  is defined as

$$p_X(x) = \frac{d}{dx} F_X(x) \quad (2.2)$$

What properties does the PDF have?

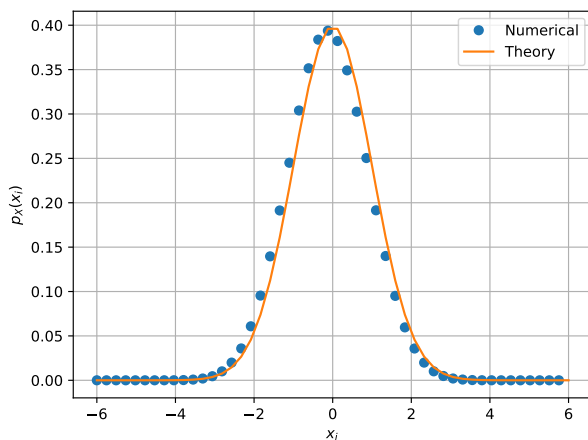


Fig. 2.3: The PDF of  $X$

**Solution:** The PDF of  $X$  is plotted using the code below

```
https://github.com/mohilmukundareddy/Assignment1/blob/main/ex2/2.3/main.py
```

Use the below command to run the code:

```
python3 main.py
```

Properties of PDF:

- PDF is symmetric about  $x \approx 0$
- graph is similar to bell shaped
- mean of graph is situated at the symmetrical point

2.4 Find the mean and variance of  $X$  by writing a C program.

**Solution:** Running the below code gives  
Mean = 0.000326 Variance= 1.000906

```
wget https://github.com/mohilmukundareddy/Assignment1/blob/main/ex2/2.4/exrand.c
```

Command used:

```
gcc exrand.c -lm  
./a.out
```

2.5 Given that

$$p_X(x) = \frac{1}{\sqrt{2\pi}} e^{-\frac{x^2}{2}}, -\infty < x < \infty$$

by property of probability

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

$$\begin{aligned} F_X(x) &= \int_{-\infty}^x p_X(x) dx \\ &= \int_{-\infty}^x \frac{1}{\sqrt{2\pi}} e^{-\frac{x^2}{2}} dx \end{aligned}$$

$$\begin{aligned} E[X] &= \int_{-\infty}^{\infty} x p(x) dx \\ &= \int_{-\infty}^{\infty} \frac{x}{\sqrt{2\pi}} e^{-\frac{x^2}{2}} dx \end{aligned}$$

$\frac{x}{\sqrt{2\pi}} e^{-\frac{x^2}{2}}$  is an odd function so integral is zero  
i.e  $E[X] = 0$ .

$$\begin{aligned}
E[X^2] &= \int_{-\infty}^{\infty} x^2 p(x) dx \\
&= x \int_{-\infty}^{\infty} x p(x) dx - \int_{-\infty}^{\infty} \left( \int_{-\infty}^{\infty} x p(x) dx \right) dx \\
&= \left[ -x \frac{1}{\sqrt{2\pi}} e^{-\frac{x^2}{2}} \right]_{-\infty}^{\infty} - \int_{-\infty}^{\infty} -\frac{1}{\sqrt{2\pi}} e^{-\frac{x^2}{2}} dx \\
&= 0 - (-1) = 1
\end{aligned}$$

we know that

$$\int_{-\infty}^{\infty} e^{-\frac{x^2}{2}} = \sqrt{2\pi}$$

$$\text{var}(x) = E[x^2] - E[x]^2 = 1 - 0 = 1$$

### 3 FROM UNIFORM TO OTHER

#### 3.1 Generate samples of

$$V = -2 \ln(1 - U) \quad (3.1)$$

and plot its CDF.

#### **Solution:**

Running the below code generates samples of V from file uni.dat(U).

<https://github.com/mohilmukundareddy/Assignment1/blob/main/ex3/main.py>

Use the below command in the terminal to run the code:

```
python3 main.py
```

Now these samples are used to plot by running the below code

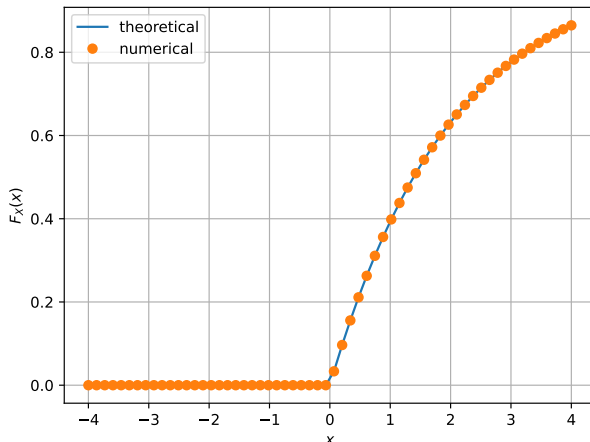


Fig. 3.5: CDF for (3)

<https://github.com/mohilmukundareddy/Assignment1/blob/main/ex3/cdf.py>

Use the below command to run the code:

```
python3 cdf.py
```

#### 3.2 Theoretical expression for $F_V(x)$

$$\begin{aligned}
F_V(x) &= P\{V \leq x\} \\
&= P\{-2 \times \ln(1 - U) \leq x\} \\
&= P\{U \leq 1 - e^{(-\frac{x}{2})}\} \\
&= F_U\{1 - e^{(-\frac{x}{2})}\} \\
&= \begin{cases} 1 - e^{(-\frac{x}{2})} & 0 \leq x < \infty \\ 0 & x < 0 \end{cases}
\end{aligned}$$

### 4 TRIANGULAR DISTRIBUTION

#### 4.1 Generate

$$T = U_1 + U_2 \quad (4.1)$$

we get the code

<https://github.com/mohilmukundareddy/Assignment1/blob/main/ex4/1/main.py>

run the command

```
python3 main.py
```

#### 4.2 Find the CDF of $T$ .

$$\begin{aligned}
F_T(t) &= P\{T \leq t\} \\
&= P\{U_1 + U_2 \leq t\}
\end{aligned}$$

let us take two cases if  $0 \leq t \leq 1$  and  $1 < t \leq 2$

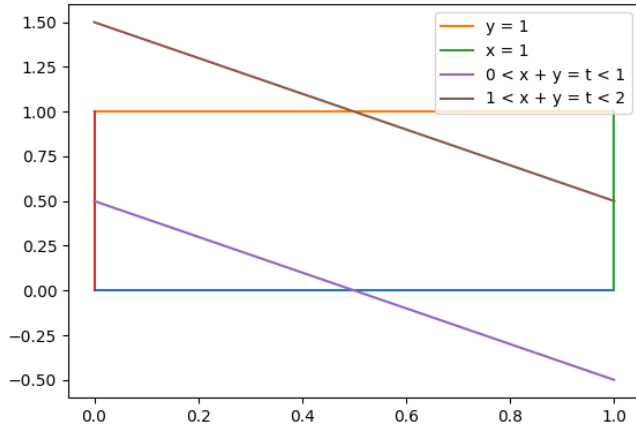


Fig. 4.5: def plot

The above graph is produced by

<https://github.com/mohilmukundareddy/Assignment1/blob/main/ex4/2/find.py>

Run the code in terminal

```
python3 find.py
```

from the figures it is evident that  
 $P(U1 + U2 < t, 0 \leq t < 1) = \frac{t^2}{2}$   
 $P(U1 + U2 < t, 1 \leq t \leq 2) = 1 - \frac{(2-t)^2}{2}$

$$F_T(t) = \begin{cases} 0 & t < 0 \\ \frac{t^2}{2} & 0 \leq t \leq 1 \\ 1 - \frac{(2-t)^2}{2} & 1 < t \leq 2 \\ 1 & t > 2 \end{cases}$$

4.3 Find the PDF of  $T$  **Solution:**

$$P_T(t) = \frac{d(F_T(t))}{dt}$$

$$\therefore P_T(t) = \begin{cases} 0 & t < 0 \\ t & 0 \leq t \leq 1 \\ 2-t & 1 < t \leq 2 \\ 0 & t > 2 \end{cases}$$

4.4 Find the theoretical expressions for the PDF and CDF of  $T$ . **Solution:** As we have already showed

Run in terminal

```
python3 main1.py
```

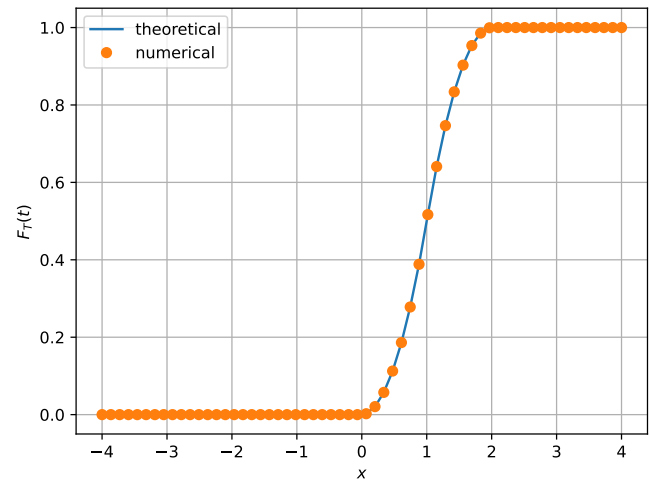


Fig. 4.5: t-cdf

Take the code for pdf

<https://github.com/mohilmukundareddy/Assignment1/blob/main/ex4/5/main2.py>

Run in terminal

```
python3 main2.py
```

4.5 Verify your results through a plot Take the code for cdf

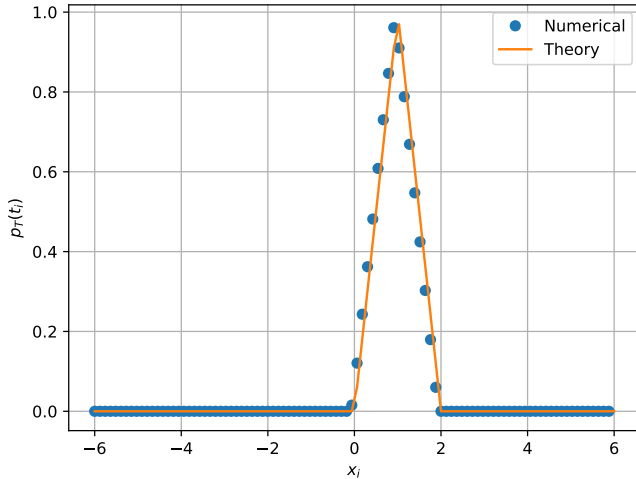


Fig. 4.5: t-pdf

## 5 MAXIMUM LIKELIHOOD

### 5.1 Generate

$$Y = AX + N, \quad (5.1)$$

where  $A = 5$  dB,  $X_1 \{1, -1\}$ , is Bernoulli and  $N \sim 01$ .

### 5.2 Plot $Y$ .

### 5.3 Guess how to estimate $X$ from $Y$ .

### 5.4 Find

$$P_{e|0} = \Pr(\hat{X} = -1 | X = 1) \quad (5.2)$$

and

$$P_{e|1} = \Pr(\hat{X} = 1 | X = -1) \quad (5.3)$$

### 5.5 Find $P_e$ .

### 5.6 Verify by plotting the theoretical $P_e$ .

## 6 GAUSSIAN TO OTHER

### 6.1 Let $X_1 \sim 01$ and $X_2 \sim 01$ . Plot the CDF and PDF of

$$V = X_1^2 + X_2^2 \quad (6.1)$$

**Solution:** The sum of squares of  $n$  independent standard random normal variables is  $\chi^2$  distribution with  $n$  degrees of freedom.

$$P_{\chi^2}(x|n) = \frac{x^{\frac{n}{2}-1} e^{-\frac{x}{2}}}{2^{\frac{n}{2}} \Gamma(\frac{n}{2})}, \forall x \geq 0$$

Here  $k=2$ ,

$$P_{\chi^2}(x|2) = P_V(v) = \frac{e^{-\frac{v}{2}}}{2}$$

For the cumulative distribution

$$\begin{aligned} F_V(v) &= \int_0^v \frac{e^{-\frac{v}{2}}}{2} dv \\ &= 1 - e^{-\frac{v}{2}} \end{aligned}$$

To generate data for  $V$ , run the following code,

```
https://github.com/
mohilmukundareddy/
Assignment1/blob/main/ex6/1/
main.py
```

Run the below command in terminal,

```
python3 main.py
```

The PDF plot of the  $\chi^2(2)$  can be obtained by running the code below,

```
https://github.com/
mohilmukundareddy/
Assignment1/blob/main/ex6/1/
main1.py
```

Use the following command in the terminal to run the code

```
python3 main1.py
```

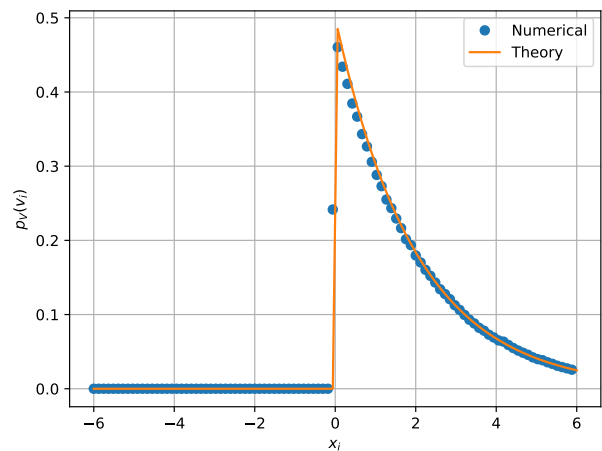


Fig. 6.5: PDF plot

The CDF plot of the  $\chi^2(2)$  can be obtained by running the code below,

[https://github.com/  
mohilmukundareddy/  
Assignment1/blob/main/ex6/1/  
main2.py](https://github.com/mohilmukundareddy/Assignment1/blob/main/ex6/1/main2.py)

Use the following command in the terminal to run the code

```
python3 main2.py
```

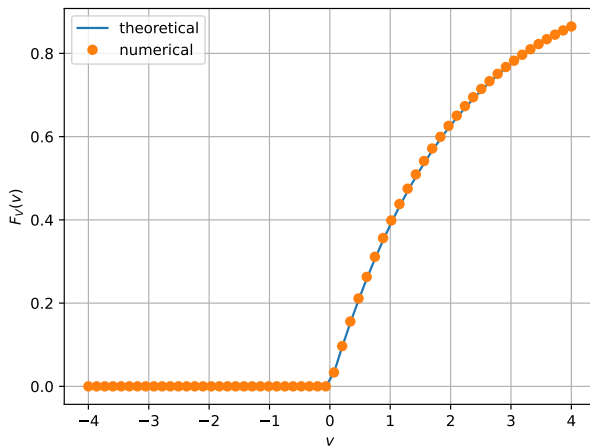


Fig. 6.5: CDF plot

6.2 If

$$F_V(x) = \begin{cases} 1 - e^{-\alpha x} & x \geq 0 \\ 0 & x < 0, \end{cases}$$

find  $\alpha$ .

**Solution:** From 6.1 we know that  $\alpha = 0.5$

6.3 Plot the CDF and Pdf of

$$A = \sqrt{V}$$

**Solution:**

To generate data for A , run the following code,

[https://github.com/  
mohilmukundareddy/  
Assignment1/blob/main/ex6/3/  
main.py](https://github.com/mohilmukundareddy/Assignment1/blob/main/ex6/3/main.py)

Run the below command in terminal,

```
python3 main.py
```

The PDF plot of A can be obtained by running the code below,

[https://github.com/  
mohilmukundareddy/  
Assignment1/blob/main/ex6/3/  
main1.py](https://github.com/mohilmukundareddy/Assignment1/blob/main/ex6/3/main1.py)

Use the following command in the terminal to run the code

```
python3 main1.py
```

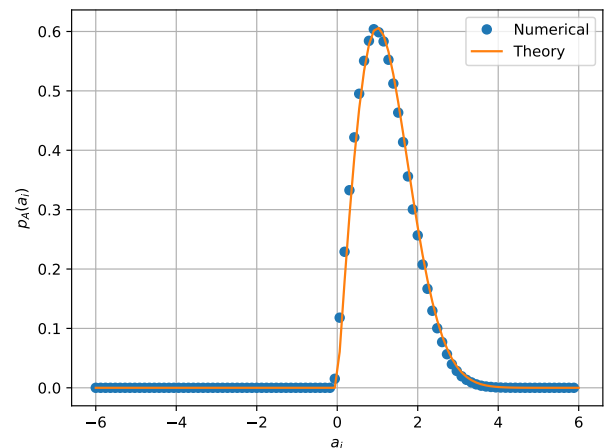


Fig. 6.5: PDF

The CDF plot of the A can be obtained by running the code below,

[https://github.com/  
mohilmukundareddy/  
Assignment1/blob/main/ex6/3/  
main2.py](https://github.com/mohilmukundareddy/Assignment1/blob/main/ex6/3/main2.py)

Use the following command in the terminal to run the code

```
python3 main2.py
```

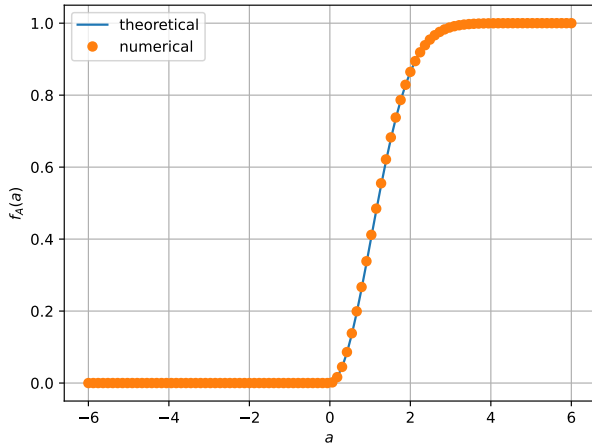


Fig. 6.5: CDF

## 7 CONDITIONAL PROBABILITY

7.1

7.2 Plot

$$P_e = \Pr(\hat{X} = -1 | X = 1) \quad (7.1)$$

for

$$Y = AX + N, \quad (7.2)$$

where  $A$  is Rayleigh with  $E[A^2] = \gamma$ ,  $N \sim \mathcal{N}(0, 1)$ ,  $X \in (-1, 1)$  for  $0 \leq \gamma \leq 10$  dB.

7.3 Assuming that  $N$  is a constant, find an expression for  $P_e$ . Call this  $P_e(N)$

7.4 For a function  $g$ ,

$$E[g(X)] = \int_{-\infty}^{\infty} g(x)p_X(x) dx \quad (7.3)$$

Find  $P_e = E[P_e(N)]$ .

7.5 Plot  $P_e$  in problems 7.7.5 and 7.7.5 on the same graph w.r.t  $\gamma$ . Comment.

## 8 TWO DIMENSIONS

Let

$$\mathbf{y} = A\mathbf{x} + \mathbf{n}, \quad (8.1)$$

where

$$x \in (\mathbf{s}_0, \mathbf{s}_1), \mathbf{s}_0 = \begin{pmatrix} 1 \\ 0 \end{pmatrix}, \mathbf{s}_1 = \begin{pmatrix} 0 \\ 1 \end{pmatrix} \quad (8.2)$$

$$\mathbf{n} = \begin{pmatrix} n_1 \\ n_2 \end{pmatrix}, n_1, n_2 \sim \mathcal{N}(0, 1). \quad (8.3)$$

8.1 Plot

$$\mathbf{y}|\mathbf{s}_0 \text{ and } \mathbf{y}|\mathbf{s}_1 \quad (8.4)$$

on the same graph using a scatter plot.

8.2 For the above problem, find a decision rule for detecting the symbols  $\mathbf{s}_0$  and  $\mathbf{s}_1$ .

8.3 Plot

$$P_e = \Pr(\hat{\mathbf{x}} = \mathbf{s}_1 | \mathbf{x} = \mathbf{s}_0) \quad (8.5)$$

with respect to the SNR from 0 to 10 dB.

8.4 Obtain an expression for  $P_e$ . Verify this by comparing the theory and simulation plots on the same graph.