

MATH-472: Homework 2

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Question 1

The definition of the Gamma function where $n \in \mathbb{Z}^+$ is

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

This can be replicated in R using the `factorial()` function.

```
posint_gamma <- function(n) {  
  if (any(!is.integer(n) | n <= 0)) stop("n must be a positive integer.")  
  
  factorial(n - 1)  
}  
  
all(posint_gamma(1:4) == gamma(1:4))
```

```
[1] TRUE
```

Question 2

We have

$$f(x; p) = \begin{cases} p(1-p)^x, & x = 0, 1, 2, 3, \dots \\ 0, & \text{otherwise.} \end{cases}$$

We want the recursive formula for $f(x+1; p) = L \cdot f(x; p)$.

Solving for L , we see

$$\begin{aligned} f(x+1; p) &= L \cdot f(x; p) \\ p(1-p)^{(x+1)} &= L \cdot p(1-p)^x \\ p(1-p)^x(1-p)^1 &= L \cdot p(1-p)^x \\ (1-p) &= L. \end{aligned}$$

Question 3

Let X be a discrete R.V. where $x_1 = 10, x_2 = 30, x_3 = 50, x_4 = 70, x_5 = 90$, and having the following cdf:

X	10	30	50	70	90
$F(x) = P(X \leq x)$	0.27	0.41	0.64	0.92	1.00

```
set.seed(20230208)

f <- function(print_check = FALSE) {
  u <- runif(1, 0, 1)
  x <- c(10, 30, 50, 70, 90)
  p <- c(0.27, 0.41, 0.64, 0.92, 1)
  keep <- dplyr::lag(p, default = 0) < u & u <= p

  if (print_check) print(data.frame(x, p, u, keep))

  x[keep]
}

f(print_check = TRUE) # run once as an example
```

```
      x      p      u keep
1 10 0.27 0.7946032 FALSE
2 30 0.41 0.7946032 FALSE
3 50 0.64 0.7946032 FALSE
4 70 0.92 0.7946032  TRUE
5 90 1.00 0.7946032 FALSE
```

```
[1] 70
```

```
x <- replicate(10000, f()) # examine the distribution, take 10k samples
x |> table() |> prop.table() |> cumsum() |> round(2)
```

```
      10      30      50      70      90
0.27 0.41 0.64 0.92 1.00
```

Question 4

- (a) Calculate the inverse function of $u = F(x)$, i.e., $F_X^{-1}(u) = x$.

$$\begin{aligned} F(x) = u &\implies 1 - e^{-(0.25x^3)} = u \\ &\implies 1 - u = e^{-(0.25x^3)} \\ &\implies \ln(1 - u) = -\frac{1}{4}x^3 \\ &\implies -4\ln(1 - u) = x^3 \\ &\implies (-4\ln(1 - u))^{\frac{1}{3}} = x \\ &\implies F_X^{-1}(u) = x. \end{aligned}$$

- (b) Calculate values of x for $u = 0.37, 0.45, 0.82$.

```
f_inv <- function(u) (-4*log(1 - u))^(1/3)
f_inv(c(0.37, 0.45, 0.82)) |> round(digits = 5)
```

```
[1] 1.22719 1.33726 1.90002
```

Question 5

The Rayleigh density is

$$f(x) = \frac{x}{\sigma^2} e^{-x^2/2\sigma^2}, x \geq 0, \sigma > 0.$$

Develop an algorithm to generate random samples from a *Rayleigh*(σ) distribution. Generate samples for several choices of $\sigma > 0$ and check that the mode of the generated samples is close to the theoretical mode σ (check the histogram).

We will use the inverse-transformation method. First, we need to find the cdf $F_X(x)$:

$$\begin{aligned} F_X(x) &= \int_{-\infty}^x f(t) dt \\ &= \int_{-\infty}^0 0 dt + \int_0^x \frac{t}{\sigma^2} e^{-t^2/2\sigma^2} dt \\ &= \int_0^x \frac{t}{\sigma^2} e^{-t^2/2\sigma^2} dt \\ &= - \int_0^x e^u du \quad (\text{let } u = \frac{-t^2}{2\sigma^2} \text{ and } du = \frac{-t}{\sigma^2} dt) \\ &= -e^u \Big|_{t=0}^{t=x} \\ &= -e^{\frac{-x^2}{2\sigma^2}} \Big|_{t=0}^{t=x} = \left(-e^{\frac{-x^2}{2\sigma^2}} - (-1) \right) = 1 - e^{\frac{-x^2}{2\sigma^2}}, x \geq 0, \sigma > 0. \end{aligned}$$

We now need to find $F_X^{-1}(u) = x$:

$$\begin{aligned} F_X(x) = u &\implies 1 - e^{-x^2/2\sigma^2} = u \\ &\implies 1 - u = e^{-x^2/2\sigma^2} \\ &\implies -2\sigma^2 \ln(1 - u) = x^2 \\ &\implies \sqrt{-2\sigma^2 \ln(1 - u)} = x \\ &\implies F_X^{-1}(u) = x. \end{aligned}$$

We can then apply the algorithm:

1. Generate $u \sim U(0, 1)$
2. Compute $X'(u) = F_X^{-1}(u)$ to get realizations from X .

Demonstrations with several values of σ , using R.

```

library(tidyverse)
library(patchwork)

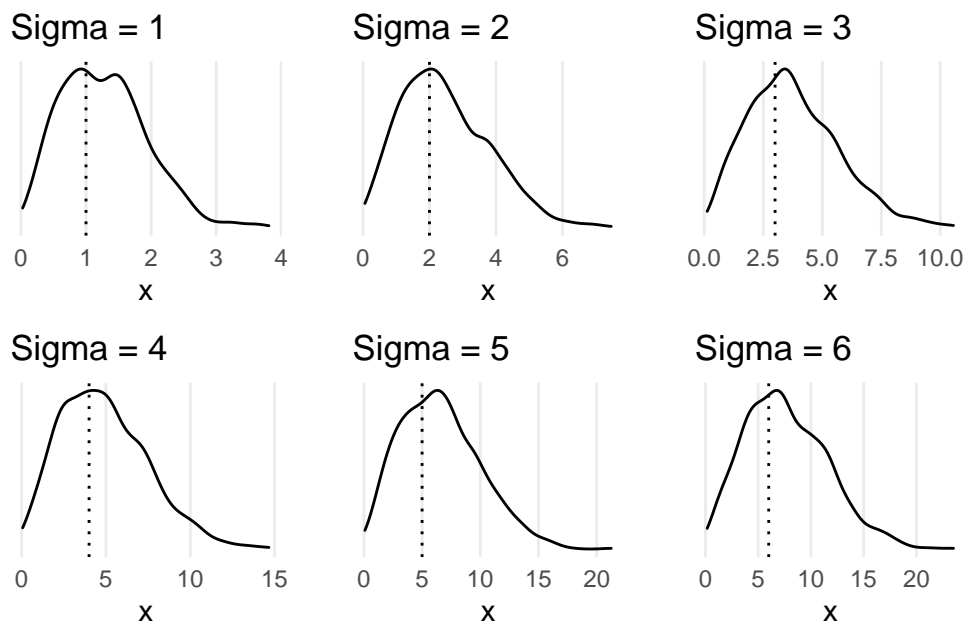
finv <- function(u, sigma) sqrt(-2*sigma^2 * log(1- u))

gen_density <- function(n = 1000, sigma = 1) {
  dat <- tibble(u = runif(n, 0, 1), x = finv(u, sigma))

  ggplot(dat, aes(x = x)) +
    geom_vline(xintercept = sigma, lty = "dotted") +
    geom_density() +
    labs(title = str_glue("Sigma = {sigma}"), x = "x", y = "") +
    theme_minimal(base_size = 11) +
    theme(
      axis.text.y = element_blank(),
      panel.grid.minor = element_blank(), panel.grid.major.y = element_blank()
    )
}

(gen_density(sigma = 1) | gen_density(sigma = 2) | gen_density(sigma = 3)) /
  (gen_density(sigma = 4) | gen_density(sigma = 5) | gen_density(sigma = 6))

```



Question 6

We have $f(x) = \frac{1}{2}e^{-|x|}$. This function is symmetric around 0. So, the resulting cdf $F_X(x)$ will be a piecewise function. If $x < 0$, we have

$$\begin{aligned}
 \int_{-\infty}^x f(t) dt &= \int_{-\infty}^x \frac{1}{2}e^{-|t|} dt \\
 &= \frac{1}{2} \int_{-\infty}^x e^t dt && \text{(because } -\infty < t < 0\text{)} \\
 &= \frac{1}{2} e^t \Big|_{-\infty}^x \\
 &= \lim_{n \rightarrow -\infty} \frac{1}{2} e^t \Big|_n^x \\
 &= \lim_{n \rightarrow -\infty} \frac{1}{2} (e^x - e^n) \\
 &= \lim_{n \rightarrow -\infty} \frac{1}{2} e^x - \frac{1}{2} e^n \nearrow 0 \\
 &= \frac{1}{2} e^x.
 \end{aligned}$$

Note that $\int_{-\infty}^0 f(x) dx = \frac{1}{2}$ because

$$\begin{aligned}
 \int_{-\infty}^0 f(x) dx &= \int_{-\infty}^0 \frac{1}{2}e^{-|x|} dx \\
 &= \frac{1}{2} \int_{-\infty}^0 e^x dx && \text{(because } -\infty < x < 0\text{)} \\
 &= \frac{1}{2} e^x \Big|_{-\infty}^0 \\
 &= \lim_{n \rightarrow -\infty} \frac{1}{2} e^x \Big|_n^0 \\
 &= \lim_{n \rightarrow -\infty} \frac{1}{2} (e^0 - e^n) \\
 &= \lim_{n \rightarrow -\infty} \frac{1}{2} - \frac{1}{2} e^n \nearrow 0 \\
 &= \frac{1}{2}.
 \end{aligned}$$

Now, if $x \geq 0$, we have

$$\begin{aligned}
\int_{-\infty}^0 f(t) dt + \int_0^x f(t) dt &= \frac{1}{2} + \frac{1}{2} \int_0^x e^{-|t|} dt \\
&= \frac{1}{2} + \frac{1}{2} \int_0^x e^{-t} dt && \text{(because } 0 \leq t \leq x) \\
&= \frac{1}{2} - \frac{1}{2} e^{-t} \Big|_0^x \\
&= \frac{1}{2} - \frac{1}{2} (e^{-x} - e^0) \\
&= \frac{1}{2} + \frac{1}{2} - \frac{1}{2} e^{-x} \\
&= 1 - \frac{1}{2} e^{-x}.
\end{aligned}$$

Thus, $F_X(x)$ is defined as

$$F_X(x) = \begin{cases} \frac{1}{2}e^x, & x < 0 \\ 1 - \frac{1}{2}e^{-x}, & x \geq 0 \end{cases}$$

and given some x , we have $F_X(x) = u$. We now need an inverse $F_X^{-1}(u)$ satisfying $F_X^{-1}(u) = x$. This function will also be piecewise.

If $x < 0$

$$\begin{aligned}
F_X(x) &= \frac{1}{2}e^x = u \\
\implies e^x &= 2u \\
\implies x &= \ln(2u).
\end{aligned}$$

If $x \geq 0$

$$\begin{aligned}
F_X(x) &= 1 - \frac{1}{2}e^{-x} = u \\
\implies \frac{1}{2}e^{-x} &= 1 - u \\
\implies e^{-x} &= 2 - 2u \\
\implies -x &= \ln(2 - 2u) \\
\implies x &= -\ln(2 - 2u).
\end{aligned}$$

So

$$F_X^{-1}(u) = \begin{cases} \ln(2u) & u < 0.5 \\ -\ln(2 - 2u) & u \geq 0.5. \end{cases}$$

Now we can apply the algorithm

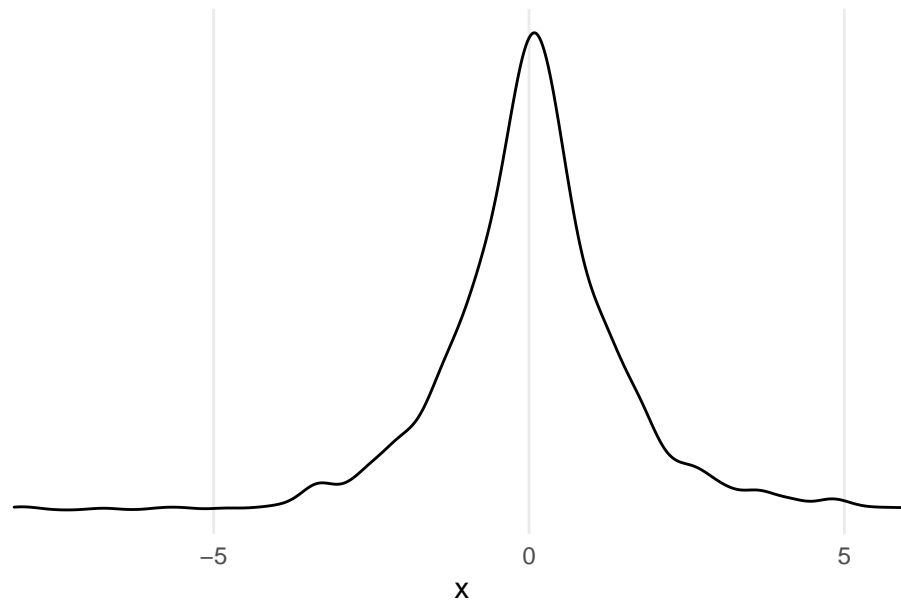
1. Generate $u \sim U(0, 1)$
2. Compute $X'(u) = F_X^{-1}(u)$ to get realizations from X .

Implemented in R code, to generate 1,000 realizations.

```
finv <- function(u) ifelse(u < 0.5, log(2*u), -log(2 - 2*u))
lapl <- function(n = 1000) finv(runif(n, 0, 1))

ggplot(tibble(x = lapl())) +
  geom_density(aes(x = x)) +
  theme_minimal(base_size = 11) +
  theme(
    axis.text.y = element_blank(),
    panel.grid.minor = element_blank(), panel.grid.major.y = element_blank()
  ) +
  labs(y = "", title = "Density plot of 1,000 draws")
```

Density plot of 1,000 draws



Question 7

We will use the Box-Mueller Transform to generate samples from standard normal distributions.

```
bmt <- function(n) {  
  u1 <- runif(n, 0, 1)  
  u2 <- runif(n, 0, 1)  
  
  r <- sqrt(-2*log(u1))  
  theta <- 2*pi*u2  
  x <- r*cos(theta)  
  y <- r*sin(theta)  
  
  data.frame(x, y)  
}
```

(a)

10 values from $\chi^2(5)$.

```
dat <- bmt(25)  
  
indices <- seq(1, 25, 5)  
chi <- numeric()  
for (element in indices) {  
  x2 <- c(sum(dat$x[element:element + 4]^2), sum(dat$y[element:element + 4]^2))  
  chi <- c(chi, x2)  
}  
  
print(chi)
```

```
[1] 0.768997559 0.380225654 3.472371432 1.704080166 0.008472789 0.255175259  
[7] 0.002790484 0.320066156 1.301886762 0.842165637
```

(b)

10 values from $t(3)$.

```

dat <- bmt(30)

z <- dat$x[1:10]
v <- numeric()
q <- 3

indices <- seq(1, q * 10, q)
for (element in indices) {
  x2 <- sum(dat$y[element:element + (q - 1)]^2)
  v <- c(v, x2)
}

z / sqrt(v / q)

```

```

[1] -16.35420125 -1.80444116  1.41025368  4.11248280 -2.87063397
[6]  3.13739856  0.55614796  0.55255069  0.02208829 -0.09158468

```

(c)

10 values from $F(6, 10)$.

```

dat <- bmt(100)

v <- numeric()
m <- 6
vind <- seq(1, m * 10, m)
for (element in vind) {
  x2 <- sum(dat$x[element:element + (m - 1)]^2)
  v <- c(v, x2)
}

w <- numeric()
n <- 10
wind <- seq(1, n * 10, n)
for (element in wind) {
  x2 <- sum(dat$y[element:element + (n - 1)]^2)
  w <- c(w, x2)
}

(v / m) / (w / n)

```

[1] 2.057290e+03 5.044342e-01 3.006081e+00 3.935956e-01 9.975536e+01
[6] 3.793622e+00 5.699611e-03 3.505360e+00 2.946466e+03 1.257410e+01