Intro to Communication System
EE140
Fall, 2020

Assignment 7

Due time : 10:15, Nov 20, 2020 (Friday)

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Grade : ________

Problem 1 (2.1 Coin flip.) Score: ________. A fair coin is flipped until the first head occurs. Let X denote the number of flips required.

(a) Find the entropy $H(X)$ in bits. The following expression may be useful:

$$\sum_{n=0}^{\infty} r^n = \frac{1}{1-r}, \quad \sum_{n=0}^{\infty} nr^n = \frac{r}{(1-r)^2}.$$

(b) A random variable X is drawn according to this distribution. Find an "efficient" sequence of yes-no questions of the form, "Is X contained in the set S?" Compare $H(X)$ to the expected number of questions required to determine X.

Solution: (a) The PMF of X is

$$P(X=n) = \left(\frac{1}{2}\right)^{n-1}\frac{1}{2} = \frac{1}{2^n}, \quad n = 1, 2, 3, \cdots \tag{1}$$

The entropy of X in bits is

$$H(X) = -\sum_{n=1}^{\infty} P(X=n)\log_2 P(X=n) = -\sum_{n=1}^{\infty}\frac{1}{2^n}\log_2\frac{1}{2^n} = \sum_{n=1}^{\infty}\frac{n}{2^n} = \frac{\frac{1}{2}}{\left(1-\frac{1}{2}\right)^2} = 2 \text{ (bits)}. \tag{2}$$

(b) We can use Huffman code to represent the possible X's according to the PMF of X. That is,

$$\begin{aligned}
X = 1 &\rightarrow 1,\\
X = 2 &\rightarrow 01,\\
X = 3 &\rightarrow 001,\\
&\cdots\\
X = n &\rightarrow \overbrace{00\cdots0}^{n-1 \text{ zeros in total}}\ 1,\\
&\cdots
\end{aligned}$$

Then, we can ask in such way: "Is the first symbol of the code 1?" If the answer is "Yes", we know that $X = 1$. If not, we continue to ask: "Is the second symbol of the code 1". If the answer is "Yes", then we know that $X = 2$. If not, we continue such asking method until the answer is "Yes" and thus we can determine the X represented by the code.
This asking method is equivalent to ask: "Is $X = 1$?" "If not, is $X = 2$?" "If not, is $X = 3$?"......
In such way, the expected number of questions required to determine X is

$$\frac{1}{2}\times 1 + \frac{1}{2}\times\frac{1}{2}\times 2 + \frac{1}{2}\times\frac{1}{2}\times\frac{1}{2}\times 3\cdots = \sum_{n=1}^{\infty}\frac{n}{2^n} = 2, \tag{3}$$

which equals $H(X)$ in bits.

□

Problem 2 (2.2 Entropy of functions.) Score: ________. Let X be a random variable taking on a finite number of values. What is the (general) inequality relation of $H(X)$ and $H(Y)$ if

(a) $Y = 2^X$?

(b) $Y = \cos X$?

Solution: (a) Suppose the set of possible values that X can take on to be $\{x_1, x_2, \cdots, x_N\}$. The entropy of X is

$$H(X) = -\sum_{n=1}^{N} P(X = x_n) \log_2 P(X = x_n). \tag{4}$$

Since $Y = 2^X$ is a one-to-one mapping, the set of the possible values that Y can take on is $\{y_1 = 2^{x_1}, y_2 = 2^{x_2}, \cdots, y_n = 2^{x_N}\}$ and the PMF of Y is

$$P(Y = 2^{x_n}) = P(X = x_n). \tag{5}$$

The entropy of Y is equal to X's:

$$H(Y) = -\sum_{n=1}^{N} P(Y = 2^{x_n}) \log_2 P(Y = 2^{x_n}) = -\sum_{n=1}^{N} P(X = x_n) \log_2 P(X = x_n) = H(X). \tag{6}$$

(b) Since $Y = \cos X$ is not necessarily one-to-one, the PMF of Y is

$$P(Y = y) = \sum_{x \in \{x | y = \cos x\}} P(X = x) \tag{7}$$

The entropy of Y is equal to or less than X's:

$$\begin{aligned} H(Y) &= -\sum_{y} P(Y = y) \log_2 P(Y = y) \\ &= -\sum_{y} \left[\sum_{x \in \{x | y = cos x\}} P(X = x) \right] \log_2 \left[\sum_{x \in \{x | y = \cos x\}} P(X = x) \right] \\ &\leq -\sum_{y} \sum_{x \in \{x | y = cos x\}} P(X = x) \log_2 P(X = x) \\ &= -\sum_{x} P(X = x) \log_2 P(X = x) = H(X). \end{aligned} \tag{8}$$

□

Problem 3 (2.4 Entropy of functions of a random variable.) Score: _________. Let X be a discrete random variable. Show that the entropy of a function of X is less than or equal to the entropy of X by justifying the following steps:

$$\begin{aligned} H(X, g(X)) &\overset{(a)}{=} H(X) + H(g(X)|X) \\ &\overset{(b)}{=} H(X); \\ H(X, g(X)) &\overset{(c)}{=} H(g(X)) + H(X|g(X)) \\ &\overset{(d)}{\geq} H(g(X)). \end{aligned}$$

Thus, $H(g(X)) \leq H(X)$.

Proof: (a)

$$\begin{aligned} H(X, g(X)) &= -\sum_{x,y} P(X = x, g(X) = y) \log_2 P(X = x, g(X) = y) \\ &= -\sum_{x,y} P(X = x) P(g(X) = y | X = x) \log_2 \left[P(X = x) P(g(X) = y | X = x) \right] \end{aligned}$$

$$
\begin{aligned}
&= -\sum_{x,y} P(X=x)P(g(X)=y|X=x)\log_2 P(X=x) \\
&\quad -\sum_{x,y} P(X=x)P(g(X)=y|X=x)\log_2 P(g(X)=y|X=x) \\
&= -\sum_{x} P(X=x)\log_2 P(X=x) - \sum_{x} P(X=x)H(g(X)|X=x) \\
&= H(X) + H(g(X)|X).
\end{aligned}
$$

(b) Once the value of X is given, $g(X)$ is determined, so

$$H(g(X)|X=x) = 0, \tag{9}$$

$$\Longrightarrow H(g(X)|X) = \sum_{x} P(X=x)H(g(X)|X=x) = 0, \tag{10}$$

and

$$H(X, g(X)) = H(X) + H(g(X)|X) = H(X). \tag{11}$$

(c)

$$
\begin{aligned}
H(X, g(X)) &= -\sum_{x,y} P(X=x, g(X)=y)\log_2 P(X=x, g(X)=y) \\
&= -\sum_{x,y} P(g(X)=y)P(X=x|g(X)=y)\log_2 [P(g(X)=y)P(X=x|g(X)=y)] \\
&= -\sum_{x,y} P(g(X)=y)P(X=x|g(X)=y)\log_2 P(g(X)=y) \\
&\quad -\sum_{x,y} P(g(X)=y)P(X=x|g(X)=y)\log_2 P(X=x|g(X)=y) \\
&= -\sum_{y} P(g(X)=y)\log_2 P(g(X)=y) + \sum_{y} P(g(X)=y)H(X|g(X)=y) \\
&= H(g(X)) + H(X|g(X)).
\end{aligned}
$$

(d) Since entropy of any discrete random variable is no less than 0,

$$H(X|g(X)) \geq 0, \tag{12}$$

we have

$$H(X, g(X)) = H(g(X)) + H(X|g(X)) \geq H(g(X)). \tag{13}$$

Using (a)-(d), we can obtain $H(g(X)) \leq H(X)$. □

Problem 4 (2.5 Zero conditional entropy.) Score: ________. Show that if $H(Y|X) = 0$, then Y is a function of X [i.e., for all x with $p(x) > 0$, there is only one possible value of y with $p(x, y) > 0$].

Proof: The entropy of $Y|X$ is

$$H(Y|X) = -\sum_{x,y} P(X=x, Y=y)\log_2 P(Y=y|X=x).$$

Since

$$-P(X=x, Y=y)\log_2 P(Y=y|X=x) \geq 0, \quad \forall x, y, \tag{14}$$

for given x_0 and y_0,

$$\begin{aligned}H(Y|X)\geq&-P(X=x_0,Y=y_0)\log_2 P(Y=y_0|X=x_0)\\=&P(X=x_0)P(Y=y_0|X=x_0)\log_2 P(Y=y_0|X=x_0)\geq 0.\end{aligned}\tag{15}$$

If $H(Y|X)=0$, then

$$0\geq -P(X=x_0)P(Y=y_0|X=x_0)\log_2 P(Y=y_0|X=x_0)\geq 0,\tag{16}$$

so there must be

$$-P(Y=y_0|X=x_0)\log_2 P(Y=y_0|X=x_0)=0,\tag{17}$$

for $P(X=x_0)>0$. That is,

$$P(Y=y_0|X=x_0)=0,\ \text{or}\ P(Y=y_0|X=x_0)=1,\tag{18}$$

for $P(X=x_0)>0$, which means that for all x_0 with $P(X=x_0)>0$, there is only one possible value of y_0 with $p(X=x_0,Y=y_0)=p(X=x_0)p(Y=y_0|X=x_0)=P(X=x_0)>0$.
Therefore, if $H(Y|X)=0$, then Y is a function of X. □

Problem 5 (2.11 Measure of correlation.) Score: _________. Let X_1 and X_2 be identically distributed but not necessarily independent. Let

$$\rho=1-\frac{H(X_2|X_1)}{H(X_1)}.$$

(a) Show that $\rho=\frac{I(X_1;X_2)}{H(X_1)}$.

(b) Show that $0\leq\rho\leq 1$.

(c) When is $\rho=0$?

(d) When is $\rho=1$?

Solution: (a)

$$\begin{aligned}\rho=&1-\frac{H(X_2|X_1)}{H(X_1)}\\=&\frac{H(X_1)-H(X_2|X_1)}{H(X_1)}\\&\text{(since X_1 and X_2 are identically distributed, $H(X_1)=H(X_2)$)}\\=&\frac{H(X_2)-H(X_2|X_1)}{H(X_1)}\\=&\frac{I(X_1;X_2)}{H(X_1)}.\end{aligned}\tag{19}$$

(b) Since $H(X_2|X_1)\geq 0$ and $H(X_1)\geq 0$, we have

$$\rho=1-\frac{H(X_2|X_1)}{H(X_1)}\leq 1.\tag{20}$$

Since $H(X_2)\geq H(X_2|X_1)$, we have

$$\rho=\frac{H(X_2)-H(X_2|X_1)}{H(X_1)}\geq 0.\tag{21}$$

(c) When X_1 and X_2 are independent, $\rho = 0$.

Proof.

$$\rho = \frac{I(X_1;X_2)}{H(X_1)} = 0 \Longleftrightarrow I(X_1;X_2) = 0 \Longleftrightarrow X_1 \text{ and } X_2 \text{ are independent.} \tag{22}$$

□

(d) When X_1 and X_2 have one-to-one mapping, $\rho = 1$.

Proof.

$$\rho = 1 - \frac{H(X_2|X_1)}{H(X_1)} = 1 \Longrightarrow H(X_2|X_1) = 0 \Longleftrightarrow X_2 \text{ is a function of } X_1. \tag{23}$$

Accordingly,

$$\rho = \frac{H(X_1) - H(X_2|X_1)}{H(X_2)} = \frac{H(X_2) - H(X_1|X_2)}{H(X_2)} = 0 \Rightarrow H(X_2|X_1) = 0 \Longrightarrow X_1 \text{ is a function of } X_2. \tag{24}$$

Therefore, X_1 and X_2 have one-to-one mapping. □

□

Problem 6 (2.12 Example of entropy.) Score: ________. Let $p(x, y)$ be given by

$X \backslash Y$	0	1
0	$\frac{1}{3}$	$\frac{1}{3}$
1	0	$\frac{1}{3}$

Find:

(a) $H(X)$, $H(Y)$.

(b) $H(X|Y)$, $H(Y|X)$.

(c) $H(X, Y)$.

(d) $H(Y) - H(Y|X)$.

(e) $I(X;Y)$.

(f) Draw a Venn diagram for the quantities in parts (a) through e.

Solution: (a) The PMF of X is

$$P(X = 0) = P(X = 0, Y = 0) + P(X = 0, Y = 1) = \frac{1}{3} + \frac{1}{3} = \frac{2}{3}, \tag{25}$$

$$P(X = 1) = P(X = 1, Y = 0) + P(X = 1, Y = 1) = 0 + \frac{1}{3} = \frac{1}{3}. \tag{26}$$

The PMF of Y is

$$P(Y = 0) = P(X = 0, Y = 0) + P(X = 1, Y = 0) = \frac{1}{3} + 0 = \frac{1}{3}, \tag{27}$$

$$P(Y=1)=P(X=0,Y=1)+P(X=1,Y=1)=\frac{1}{3}+\frac{1}{3}=\frac{2}{3}. \tag{28}$$

The entropy of X is

$$H(X)=-P(X=0)\log_2 P(X=0)-P(X=1)\log_2 P(X=1)=-\frac{2}{3}\log_2\frac{2}{3}-\frac{1}{3}\log_2\frac{1}{3}=0.918 \text{ (bits)}. \tag{29}$$

The entropy of Y is

$$H(Y)=-P(Y=0)\log_2 P(Y=0)-P(Y=1)\log_2 P(Y=1)=-\frac{1}{3}\log_2\frac{1}{3}-\frac{2}{3}\log_2\frac{2}{3}=0.918 \text{ (bits)}. \tag{30}$$

(b) The conditional PMF of $X|Y$ is

$$P(X=0|Y=0)=1, \tag{31}$$
$$P(X=1|Y=0)=0, \tag{32}$$
$$P(X=0|Y=1)=\frac{1}{2}, \tag{33}$$
$$P(X=1|Y=1)=\frac{1}{2}. \tag{34}$$

The conditional PMF of $X|Y$ is

$$P(Y=0|X=0)=\frac{1}{2}, \tag{35}$$
$$P(Y=1|X=0)=\frac{1}{2}, \tag{36}$$
$$P(Y=0|X=1)=0, \tag{37}$$
$$P(Y=1|X=1)=1. \tag{38}$$

The conditional entropy of $X|Y$

$$\begin{aligned}H(X|Y)=&-P(X=0,Y=0)\log_2 P(X=0|Y=0)-P(X=1,Y=0)\log_2 P(X=1|Y=0)\\&-P(X=0,Y=1)\log_2 P(X=0|Y=1)-P(X=1,Y=1)\log_2 P(X=1|Y=1)\\=&-\frac{1}{3}\log_2 1-0-\frac{1}{3}\log_2\frac{1}{2}-\frac{1}{3}\log_2\frac{1}{2}\\=&\frac{2}{3}\text{ (bits)}.\end{aligned} \tag{39}$$

The conditional entropy of $Y|X$ is

$$\begin{aligned}H(Y|X)=&-P(X=0,Y=0)\log_2 P(Y=0|X=0)-P(X=0,Y=1)\log_2 P(Y=1|X=0)\\&-P(X=1,Y=0)\log_2 P(Y=0|X=1)-P(X=1,Y=1)\log_2 P(Y=1|X=1)\\=&-\frac{1}{3}\log_2\frac{1}{2}-\frac{1}{3}\log_2\frac{1}{2}-0-\frac{1}{3}\log_2 1\\=&\frac{2}{3}\text{ (bits)}.\end{aligned} \tag{40}$$

(c) The joint entropy of X and Y is

$$\begin{aligned}H(X,Y)=&-P(X=0,Y=0)\log_2 P(X=0,Y=0)-P(X=1,Y=0)\log_2 P(X=1,Y=0)\\&-P(X=0,Y=1)\log_2 P(X=0,Y=1)-P(X=1,Y=1)\log_2 P(X=1,Y=1)\\=&-\frac{1}{3}\log_2\frac{1}{3}-0-\frac{1}{3}\log_2\frac{1}{3}-\frac{1}{3}\log_2\frac{1}{3}\\=&\log_2 3=1.585\text{ (bits)}.\end{aligned} \tag{41}$$

(d)

$$H(Y) - H(Y|X) = 0.251 \text{ (bits)}. \tag{42}$$

(e) The mutual information of X and Y is

$$I(X;Y) = H(Y) - H(Y|X) = 0.251 \text{ (bits)}. \tag{43}$$

(f) As shown in figure 1.

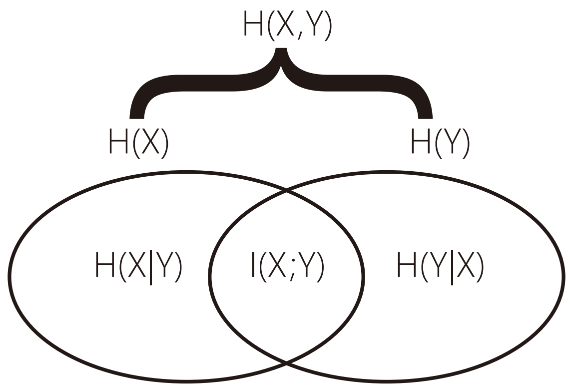

Figure 1: Venn diagram of $H(X)$, $H(Y)$, $H(X|Y)$, $H(Y|X)$, $H(X,Y)$ and $I(X;Y)$

□

Problem 7 (8.1 Diffrential entropy.) Score: ________. Evaluate the differential entropy $h(X) = -\int f \ln f$ for the following:

(a) The exponential density, $f(x) = \lambda e^{-\lambda x}$, $x \geq 0$.

(b) The Laplace density, $f(x) = \frac{1}{2}\lambda e^{-\lambda|x|}$.

(c) The sum of X_1 and X_2, where X_1 and X_2 are independent random variables with means μ_i and variables σ_i^2, $i = 1, 2$.

Solution: (a) The differential entropy of the exponential density is

$$\begin{aligned}
h(f) =& -\int_0^{+\infty} \lambda e^{-\lambda x} \ln[\lambda e^{-\lambda x}] \, \mathrm{d}x \\
=& -\int_0^{+\infty} \lambda e^{-\lambda x} \ln \lambda \, \mathrm{d}x - \int_0^{+\infty} \lambda e^{-\lambda x}(-\lambda x) \, \mathrm{d}x \\
=& \, e^{-\lambda x} \ln \lambda \Big|_0^{+\infty} - \lambda \int_0^{+\infty} x \, \mathrm{d}(e^{-\lambda x}) \\
=& -\ln \lambda - \lambda x e^{-\lambda x} \Big|_0^{+\infty} + \lambda \int_0^{+\infty} e^{-\lambda x} \, \mathrm{d}x \\
=& 1 - \ln \lambda \text{ (nats)} \\
=& \log_2 \frac{e}{\lambda} \text{ (bits)}.
\end{aligned} \tag{44}$$

(b) The differential entropy of the Laplace density is

$$h(f) = -\int_{-\infty}^{+\infty} \frac{1}{2}\lambda e^{-\lambda|x|} = -\int_0^{+\infty} \lambda e^{-\lambda|x|} = \log_2 \frac{e}{\lambda} \text{ (bits)}. \tag{45}$$

(c) $X_1 + X_2 \sim N(\mu_1 + \mu_2, \sigma_1^2 + \sigma_2^2)$, thus

$$h(X_1 + X_2) = \frac{1}{2} \log_2 2\pi e(\sigma_1^2 + \sigma_2^2) \text{ (bits)}. \tag{46}$$

$\square$