Solutions to Exercise Sheet 4

Exercise 1.

(a) The encoding procedure is given by the table below:

Position	Substring	Output	Encoded Output
1.	A	(0,A)	(00,000)
2.	A_	(1,_)	(01,011)
3.	AB	(1,B)	(01,001)
4.	ABB	(3,B)	(11,001)
5.	ABC	(3,C)	(11,010)
6.	_	(0,_)	(00,011)
7.	ABA	(3,A)	(11,000)
8.	B	(0,B)	(00,001)
9.	C	(0,C)	(00,010)
10.	.	(0,.)	(00,100)

Table 1: The Lempel-Ziv encoding/decoding table.

The alphabet of the source reads $\mathcal{A} = \{\mathtt{A}, \mathtt{B}, \mathtt{C}, \_\}$. To encode the position 2 bits are sufficient. Furthermore, 3 bits are needed to encode the alphabet (taking into account the extra "." signifying end of the string). Therefore, 5 bits are needed per substring, which gives a total of 50 bits. In a naive way we needs $3 \times 18 = 54$ bits to send the sequence.

The elements A,B and C of the last ABC appear in different substrings in the first example. For the second example, ABC is part of the substring that contains the last character.

(b) The encoding procedure is given by the table below:

Position	Substring	Output	Encoded Output
1.	A	(0,A)	(000,00)
2.	B	(0,B)	(000,01)
3.	AA	(1,A)	(001,00)
4.	AAA	(3,A)	(011,00)
5.	AAAA	(4,A)	(100,00)
6.	AAAAA	(5,A)	(101,00)
7.	BB	(2,B)	(010,01)
8.	.	(0,.)	(000,11)

Table 2: The Lempel-Ziv encoding/decoding table.

The alphabet of the source reads $\mathcal{A} = \{\mathtt{A}, \mathtt{B}\}$.
Lempel-Ziv: $5 * 8 = 40$ bits
Naive encoding: $2 * 19 = 38$ bits

(c) The encoding procedure is given by the table below:

The alphabet of the source reads $\mathcal{A} = \{\mathtt{A}, \mathtt{B}\}$.
Lempel-Ziv: $5 * 8 = 40$ bits
Naive encoding: $2 * 23 = 46$ bits

Position	Substring	Output	Encoded Output
1.	A	(0,A)	(000,00)
2.	B	(0,B)	(000,01)
3.	AA	(1,A)	(001,00)
4.	AAA	(3,A)	(011,00)
5.	AAAA	(4,A)	(100,00)
6.	AAAAA	(5,A)	(101,00)
7.	AAAAAA	(6,A)	(110,00)
8.	.	(0,.)	(000,11)

Table 3: The Lempel-Ziv encoding/decoding table.

(d) The original sequence is: AABABC_ ABBBBBBBB.

Exercise 2.

(a) The optimal method of asking questions can be found by considering the Huffman code applied to the source $X_1 X_2 ... X_n$.

In order to apply this code one needs to define a new random variable Y which has an alphabet that contains all outcomes of the sequence $X_1 X_2 ... X_n$ That is,

$$\begin{aligned}\mathcal{Y} = \{ & \underbrace{111...111}_{\text{"All objects are faulty"}}, \underbrace{111...110}_{\text{"The first } n-1 \text{ objects are faulty, the last one is not"}}, \\ & \underbrace{111...100}_{\text{"The first } n-2 \text{ objects are faulty, the last two are not"}}, \\ & \underbrace{111...101}_{\text{"The first } n-2 \text{ objects and the last one are faulty, the } (n-1)\text{th object is not faulty"}}, \\ & ..., \underbrace{000...000}_{\text{"No object is faulty."}} \}.\end{aligned}$$

In total there are 2^n possible sequences and we allocate to them the following probability distribution

$$\begin{aligned}q(y) = \{ & p_1 p_2 p_3 \cdots p_n, p_1 p_2 p_3 \cdots p_{n-2} p_{n-1}(1-p_n), \\ & p_1 p_2 p_3 \cdots p_{n-2}(1-p_{n-1})(1-p_n), \\ & p_1 p_2 p_3 \cdots p_{n-2}(1-p_{n-1}) p_n, \\ & ..., (1-p_1)(1-p_2) \cdots (1-p_n)\}.\end{aligned}$$

For given p_1, p_2 etc., we construct the priority queue of Y using the probabilities $q(y)$ ($q(y)$ has to be normalized) and then construct the Huffman code.

(b) The longest sequence of in the set of questions is associated with least probable the case. Since $p_i > \frac{1}{2}$ the least probable case is when no object is faulty. The second least probable case is when only the last object is faulty. These two cases are the leaves of the longest paths in the Huffman tree. The last question is thus: "Is the last object faulty?".

Exercise 3. We know Bob uses the optimal code. We also know that he needs to ask 35 questions on average ("bits") to identify the object. This implies the inequality

$$\begin{aligned} H(X) \leq 35 < H(X) + 1 \\ \Rightarrow 34 < H(X) \end{aligned}$$

For a fixed number of objects, the distribution of objects of Alice which gives the highest entropy is the uniform distribution. Conversely, if the entropy is fixed then the uniform distribution minimizes the number of objects. The uniform distribution offers a possibility to calculate a lower bound on the number of objects:

$$34 < \log_2 m.$$

We conclude that there are at least $2^{34} \simeq 1.7 \times 10^{10}$ objects in the ensemble.

Exercise 4.

(a) The probability distribution that maximizes the Shannon entropy is the one where all possible elements have the same probability to occur. There are $n+1$ possible elements: n where one of the coins is counterfeit and one element taking into account the possibility that no coin is counterfeit. The probability distribution of this case is $p_i = \frac{1}{n+1}$, and the Shannon entropy is $H(X) = \log_2(n+1)$ bits.

(b) With the optimal code, one needs on average k weighs with k such that

$$H(X) \leq k < H(X) + 1.$$

For the case of maximal entropy, we have

$$\log_2(n+1) \leq k < \log_2(n+1) + 1.$$

(c) With the help of (b) one deduces that $n+1 \leq 2^k < 2(n+1)$, thus, $n \leq 2^k - 1$.

(d) The probability distribution attains the bound, if $n = 2^k - 1$ and thus $p_i = \frac{1}{2^k}$ (probability distribution which is 2-adic).

Weigh	Max. coins
1	1
2	3
3	7
4	15

The bound is attained if one has a number of coins equal to $1, 3, 7, 15, \ldots$.

Exercise 5. 1. We are given $L - H_5(X) = 0$

$$L - H_5(X) = \sum_{i=1}^{m} p_i l_i + \sum_{i=1}^{m} p_i \log_5 p_i = 0,$$

but $l_i = -\log_5 5^{-l_i}$, so we can rewrite

$$L - H_5(X) = -\sum_{i=1}^{m} p_i \log_5 5^{-l_i} + \sum_{i=1}^{m} p_i \log_5 p_i = 0.$$

Defining $r_i = \frac{5^{-l_i}}{\sum_j 5^{-l_j}}$ and $R = \sum_i 5^{-l_i}$, we have

$$-\sum_i p_i \log_5 (r_i \cdot \sum_j 5^{-l_j}) + \sum_{i=1}^{m} p_i \log_5 p_i = 0,$$

$$-\sum_i p_i \log_5 r_i - \log_5 \sum_j 5^{-l_j} + \sum_{i=1}^{m} p_i \log_5 p_i = 0,$$

which can be simplified into

$$L - H_5(X) = \sum_i p_i \log_5 \frac{p_i}{r_i} - \log_5 R = 0.$$

The Kraft inequality tells us that $R \leq 1$. Also note that r_i is a probability distribution, since $r_i \geq 0$ and $\sum_i r_i = 1$. So we can rewrite the previous expression using the definition of the relative entropy $D(x||y)$:

$$L - H_5(X) = D(p||r) + \log_5 \frac{1}{R} = 0.$$

We know that $D(p||r) \geq 0$ and $\log_5 \frac{1}{R} \geq 0$ since $R \leq 1$. The non-negativity of the inequalities implies $R = 1$ and $p_i = r_i = 5^{-l_i}$.

2. Since $L = H_5(X)$ we know that the 5-adic code is optimal. Thus, we can construct it using the Huffman code. For each step of this encoding one groups 5 elements into one, thus the number of elements is decreased by 4 at each step. If at the beginning one had m elements, at the end of the encoding, i.e. after k steps, only one element remains ($m - 4k = 1$). Thus, $m = 4k + 1$.