

Code Theory

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1. Memoryless resources

1.1. Sources and average word length

Definition 1: a **source** is a finite set \mathcal{S} together with a set of random variables (X_1, X_2, \dots) whose range is \mathcal{S} .

If $P(X_n = \mathcal{S}_i)$ only depends on i and not on n then we say the source is **stationary** and if the X_n are independent then it's **memoryless**.

Insert example here

Definition 2: Let \mathcal{T} be a finite set called **alphabet**. A map $\mathfrak{C} : \mathbb{S} \longrightarrow \mathbb{U}_{n \geq 1} T^n$ is called a **code**.

If $|\mathcal{T}| = r$ then \mathfrak{C} is a **r -ary code**.

A code extends from \mathbb{S} to $T \cup T^2 \cup \dots$ to $\mathbb{S} \cup \mathbb{S}^2 \cup \dots$ to $T \cup T^2 \cup \dots$ in obvious way.

insert example here

Definition 3: The **average word-length** of a code \mathfrak{C} is $L(\mathfrak{C}) := \sum_{i=1}^n p_i l_i$ where l_i is the length of the image of the symbol of \mathbb{S} , which is emitted with probability p_i .

For now, we write \mathfrak{C} to be the image of \mathfrak{C} .

1.2. Uniquely decodeable codes

Definition 4: If for any sequences $u_1 \dots u_n = v_1 \dots v_m$ in \mathfrak{C} implies $m = n$ and $u_i = v_i$ for $i = 1, \dots, n$ then we say that \mathfrak{C} is **uniquely decodeable**.

insert example here

insert example here

insert example here

Let $\mathfrak{C}_0 = \mathfrak{C}$:

- $\mathfrak{C}_n := \{\omega \in T \cup T^2 \cup \dots \mid u\omega = v \text{ for some } u \in \mathfrak{C}_{n-1}, v \in \mathfrak{C} \text{ or } u\omega = v \text{ for some } u \in \mathfrak{C}, v \in \mathfrak{C}_{n-1}\}$
- $\mathfrak{C}_\infty := \bigcup_{k \geq 1} \mathfrak{C}_k$

Since everythig is finite either $\mathfrak{C}_m = \emptyset$ for some m and then $\mathfrak{C}_n = \emptyset$ for $n \geq m$ or it will be periodic and start repeating.

Theorem 1: \mathfrak{C} is uniquely decodeable $\iff \mathfrak{C} \cap \mathfrak{C}_\infty = \emptyset$.

proof: Insert proof here

insert example here

insert example here

insert example here

Definition 5: A code is a **prefix-code** if no codeword is prefix of another (ie. $\mathfrak{C}_1 = \emptyset$).

A prefix code is uniquely decodeable.

Theorem 2: (Kraft's inequality) $\exists r$ -ary prefix code with word lengths $l_1, l_2, \dots, l_q \iff$

$$\sum_{i=1}^q r^{-l_i} \leq 1$$

proof: Insert proof here

insert example here

Theorem 3: (McMillan's inequality) $\exists r$ -ary uniquely decodeable code with word lengths $l_1, l_2, \dots, l_q \iff$

$$\sum_{i=1}^q r^{-l_i} \leq 1$$

proof: Insert proof here

1.3. Optimal codes

Let be \mathcal{S} a source with symbols s_1, \dots, s_q emitted with probabilities p_1, \dots, p_q and \mathfrak{C} is a code which encodes s_i with a codeword length l_i . Recall $L(\mathfrak{C}) = \sum_{i=1}^q p_i l_i$.

Definition 6: An **optimal code** for \mathcal{S} is an uniquely decodeable code \mathfrak{D} such that $L(\mathfrak{C}) \geq L(\mathfrak{D})$ for all unique decodeable code \mathfrak{C} .

inset example here

insert example here

Definition 7: A code constructed in this way is called a **Huffman code**.

insert example here

Construct the r -arg Huffman code we sum together (at each step) the r smallest probabilities.

For this to work we need $q \equiv 1(r-1)$. Recall q is the number of symbols in the source. If not, then we add symbols with probabilities zero so that it is.

insert example here

Lemma 1: Every source \mathcal{S} has an optimal binary code \mathfrak{D} in which two of the longest codewords are **siblings**, ie. $\exists x$ (a string) such that $x_0, x_1 \in \mathfrak{D}$.

proof: Insert proof here

Theorem 4: The Huffman code is an optimal code.

proof: Insert proof here

1.4. Extension of sources

Given a source \mathcal{S} we define \mathcal{S}^n the source with $|\mathcal{S}|^n$ symbols, typically s_1, \dots, s_n , emitted with p_1, \dots, p_n probabilities.

insert example here

2. Information and entropy

2.1. Definitions

Definition 1: the **information** conveyed by a source is a function $I : S \rightarrow [0, \infty)$ where S is a **source**¹ with the properties:

- $I(s_i)$ is a decreasing function of the probability p_i , with $I(s_i) = 0$ if $p_i = 1$.
- $I(s_i s_j) = I(s_i) + I(s_j)$, ie. the information gained by two symbols is the sum of the information obtained from each where the source has symbols s_1, \dots, s_q emitted with probabilities p_1, \dots, p_q .

Lemma 1: $I(s_i) = -\log_r p_i$ for some r .

proof: Insert proof here

Definition 2: The r -ary **entropy** $H_r(S)$ of a source S is the average information conveyed by S .

$$H_r(S) := - \sum_{i=1}^q p_i \log_r p_i$$

, by convention $x \log_r x$ evaluated at 0 is 0.

Insert five examples

2.2. Properties of the entropy function

Theorem 1: $H_r(S) \leq \log_r q$ with equality if and only iff S is the source where each symbol is emitted with probability $1/q$.

proof: Insert proof here

Theorem 2: $H_r(S) \leq L(C)$ for unique decodeable code C .

proof: Insert proof here

2.3. Shannon-Fano Code

Let S be the source with symbols s_i and probabilities p_i . Let $l_i := \lceil \log_r 1/p_i \rceil$.

Then: $\sum_{i=1}^q r^{-l_i} \leq \sum r^{-\log_r 1/p_i} = \sum p_i = 1$

¹A **source** is a finite set S together with a sequence of random variables X_i whose range is S

Definition 3: by Kraft exists a prefix code with word length l_1, l_2, \dots, l_1 . This code is called **Shannon-Fano code**.

Inert example here

Lemma 2: For the Shannon-Fano code C : $H_r(S) \leq L(C) < H_r(S) + 1$.

proof: Insert proof here

2.4. Product of sources

Let S and T be two memoryless sources, S with symbols s_i and probabilities p_i and T with symbols t_j and probabilities q_j .

Definition 4: The **product source** $S \times T$ is a source with symbols $s_i t_j$ and probabilities $p_i q_j$.

Theorem 3: $H_r(S \times T) = H_r(S) + H_r(T)$.

proof: Insert proof here

Corollary 1: $H_r(S^n) = nH_r(S)$.

Theorem 4: Noiseless Coding The average word length L_n of an optimal code of S^n satisfies:

$$\frac{L_n}{n} \rightarrow H_r(S), n \rightarrow \infty$$

proof: Insert proof here

some examples

2.5. Markov Chains

Definition 4: A **Markov Chain** is a sequence of random variables where X_{n+1} depends only for X_n .

$$P(X_{n+1} = s_j | X_n = s_i) = p_{i,j}$$

This can be represented in a direct graph and also by a matrix $P := (p)_{i,j}$.

Suppose u_0 is the vector which describes the initial distribution, ie. the i -th coordinate of u_0 is probability we start at s_i . Probability of being in the i -th state after r steps is the i -th coordinate of $u_0 P^r$.

Theorem 5: if $\exists r \in \mathbb{N}$ such that P^r has no zero entries, then $u_0 P^r \rightarrow u$, as $n \rightarrow \infty$.

Definition 5: This vector u is called the **stationary distribution**. It is normalised eigenvector of P^t with eigenvalue 1, ie. $u_j = \sum_i p_{i,j} u_i$ and $\sum_j u_j = 1$.

Definition 6: If P is the matrix of a Markov Chain and $\exists r$ such that P^r has non zero entries then we say that the Markov Chain is **regular**.

2.6. Sources with memory

Suppose S is a Markov Chain source with random variables X_1, X_2, \dots such that

$$P(X_{n+1} = s_j | X_n = s_j) = p_{i,j}$$

Definition 7: S is **not memoryless**, but it is stationary.

Theorem 6: suppose S is a regular Markov Chain source with stationary distribution $u = (u_1, \dots, u_n)$. Let S' be the stationary memoryless source with the same source elements as S (where s_i is emitted with probability w_i). Then:

$$H_r(S) \leq H_r(S')$$

proof: Insert proof here

3. Information channels

3.1. Channel matrix

Let \mathcal{A} be a stationary memoryless source with random variables X_1, X_2, \dots where $P(X_n = a_i) = p_i$ for $a_i \in \mathcal{A}$.

Suppose we transmit \mathcal{A} through a channel Γ .

Let \mathcal{B} be a source with random variables Y_1, Y_2, \dots where $P(Y_n = b_j) = q_j$

For b_j emerging from the channel:

$$\mathcal{A} \xrightarrow{\Gamma} \mathcal{B}$$

Definition 1: The **channel** is defined by a matrix (p_{ij}) where $p_{ij} = P(X_n = b_j | X_n = a_i)$ the probability we receive b_j given that a_i was sent, p_{ij} -**forward probabilities**. The **backwards probabilities** are $q_{ij} = P(X_n = a_i | Y_n = b_j)$ and **joint probabilities** $r_{ij} = P(X_n = a_i, Y_n = b_j)$

insert example here

inser example here (binary erasure channel)

3.2. System Entropies and mutual information

Definition 2: We define the **input entropy** as:

$$H(\mathcal{A}) := - \sum_i p_i \log(p_i)$$

Definition 3: We define the **output entropy** as:

$$H(\mathcal{B}) := - \sum_j q_j \log(q_j)$$

We suppress the r (base) in the \log_r but it's always the same for every one.

Given that we have received $b_j \in \mathcal{B}$, $H(\mathcal{A} | Y_n = b_j) = - \sum_i q_{ij} \log(q_{ij})$.

This is telling us the average information of \mathcal{A} knowing that $Y_n = b_j$.

If $H(\mathcal{A} | Y_n = b_j) = 0$ then $\exists m$ such that $q_{ij} = 0$ for all $i \neq m$ and $q_{ij} = 1$ if $i = m$, ie. $P(X_n = a_m | Y_n = b_j) = 1$, ie. if we receive b_j then we know that a_m was sent.

If $H(\mathcal{A} | Y_n = b_j) = H(\mathcal{A})$ then we learn nothing about \mathcal{A} when we receive b_j and this occurs when $q_{ij} = P(X_n = a_i | Y_n = b_j) = P(X_n = a_i) = p_i$.

Definition 4: Averaging over $b_j \in \mathcal{B}$ we get the **condicional entropy**:

$$H(\mathcal{A} | \mathcal{B}) := - \sum_j P(Y_n = b_j) H(\mathcal{A} | Y_n = b_j) = - \sum_{i,j} q_j q_{ij} \log q_{ij}$$

Similary:

$$H(\mathcal{B}|\mathcal{A}) := - \sum_{i,j} p_i p_{ij} \log p_{ij}$$

Definition 5: The **joint entropy**:

$$H(\mathcal{A}, \mathcal{B}) := - \sum_{i,j} r_{ij} \log r_{ij}$$

insert example here

Theorem 1: For sources \mathcal{A} and \mathcal{B} :

$$H(\mathcal{A}, \mathcal{B}) = H(\mathcal{A}|\mathcal{B}) + H(\mathcal{B}) = H(\mathcal{B}|\mathcal{A}) + H(\mathcal{A})$$

proof: Insert proof here

Definition 6: We define the **mutual information** as the amount of information about \mathcal{A} we have learnt from \mathcal{B} and vice-versa:

$$I(\mathcal{A}, \mathcal{B}) := H(\mathcal{B}) - H(\mathcal{B}|\mathcal{A}) = H(\mathcal{A}) - H(\mathcal{A}|\mathcal{B})$$

If $H(\mathcal{A}) = H(\mathcal{A}|\mathcal{B})$ then \mathcal{B} tells us nothing about \mathcal{A} , so $I(\mathcal{A}, \mathcal{B}) = 0$. This is an unrialiable channel and useless as a mean of communication.

If $H(\mathcal{A}|\mathcal{B}) = 0$ then knowing \mathcal{B} we know everythin about \mathcal{A} , so $I(\mathcal{A}, \mathcal{B}) = H(\mathcal{A})$. This is the perfect situation because when we recive something, we know exactly what was sent.

insert example here

3.3. Extension of noiseless coding theorem to information channels

We have proved that given a source \mathcal{A} we can find an encoding of \mathcal{A}^n such that the average word lenglht L_n satisfies $\frac{L_n}{n} \rightarrow H(\mathcal{A})$.

$\mathcal{A} \rightarrow \mathcal{B}$, imagine we know \mathcal{B} .

Lemma 1: $H(\mathcal{A}^n|\mathcal{B}^n) = nH(\mathcal{A}|\mathcal{B})$

proof: EXERCISE

Theorem 2: if \mathcal{B} is know then we can find encodings of \mathcal{A}^n such that the average word length L_n satisfies $\frac{L_n}{n} \rightarrow H(\mathcal{A}|\mathcal{B})$.

proof: Insert proof here

3.4. Decision rules

$$\mathcal{A} \xrightarrow{\Gamma} \mathcal{B}$$

Where \mathcal{A} is the **input**, \mathcal{B} is the **output** and Γ is the **channel**.

The channel is given by a matrix (p_{ij}) , $p_{ij} = P(Y_n = b_j | X_n = a_i)$. We defined $r_{ij} = P(X_n = a_i | X_n = b_j)$.

So if we recive b_j we should “decode” b_j as a_{j*} where $r_{j*j} \geq r_{ij}$ for all i .

Definition 7: We would define our decision $\Delta : \mathcal{B} \rightarrow \mathcal{A}$ as $\Delta(b_j) := a_{j*}$, this is called the **ideal observer rule**.

Howecer, most likely we only know p_{ij} ’s.

Definition 8: In **maximun likelihood decoding** we use the decision rule $\Delta(b_j) := a_{j*}$, where $p_{j*j} \geq p_{ij}$ for all i .

Definition 9: The **average probability of a correct decoding** is:

$$P_{cor} := \sum_j q_j q_{j*j} - \sum_j r_{j*j}$$

Remind $q_{ij} = P(X_n = a_i | Y_n = b_j)$. Given that we received b_j if we dcode it as a_{j*} then the probability we have decoded correctly is $P(X_n = a_{j*} | Y_n = b_j) = q_{j*j}$

3.5. Improving reliability

Suposse Γ is the binary symmetrical channel $\begin{pmatrix} \phi & 1-\phi \\ 1-\phi & \phi \end{pmatrix}$ (and assume $\phi > \frac{1}{2}$).

If we extends the source $\mathcal{A} = \{0, 1\}$ to $\{000, 001\}$ then the outpout source if $\{000, 001, 010, 100, 110, 101, 011, 111\}$. Now we have the channel matrix:

$$\begin{pmatrix} \phi^3 & \phi^2(1-\phi) & \phi^2(1-\phi) & \phi^2(1-\phi) & \phi^2(1-\phi) & \phi^2(1-\phi) & \phi^2(1-\phi) & (1-\phi)^3 \\ (1-\phi)^3 & \phi^2(1-\phi) & \phi^2(1-\phi) & \phi^2(1-\phi) & \phi^2(1-\phi) & \phi^2(1-\phi) & \phi^2(1-\phi) & \phi^3 \end{pmatrix}$$

if we decode $\Delta(000) = \Delta(001) = \Delta(010) = \Delta(100) = 0$ and $\Delta(111) = \Delta(110) = \Delta(101) = \Delta(011) = 1$.

effectively we have the channel:

$$\begin{pmatrix} \phi^3 + 3\phi^2(1-\phi) & 3\phi^2(1-\phi) + (1-\phi)^3 \\ 3\phi^2(1-\phi) + (1-\phi)^3 & \phi^3 + 3\phi^2(1-\phi) \end{pmatrix}$$

since $\phi > 1 - \phi$ we have $\phi^3 + 3\phi^2(1 - \phi) > \phi$.

So we have proved the reliability of the channel, because $P_{cor} = \sum_j r_{j*j} = p(\phi^3 + 3\phi^2(1 - \phi)) + (1 - p)(\phi^3 + 3\phi^2(1 - \phi)) = \phi^3 + 3\phi^2(1 - \phi)$.

Observe if we do not extend the sorce $P_{cor} = \phi$.

3.6. Rates of transmission and Hamming distance

noindent Suppose \mathcal{A} is a source with r symbols. By extending the source, consider \mathcal{C} to be a subset of \mathcal{A}^n .

Definition 10: The **(transmission) rate of \mathcal{C}** is:

$$R := \frac{\log_r |\mathcal{C}|}{n}$$

By increasing n in the previous exercise we can make $P_{cor} \rightarrow 1$. However $R \rightarrow 0$ since $|\mathcal{C}| = \frac{\log_2 2}{n} \rightarrow 0$.

Definition 11: The **capacity of a channel Γ** is:

$$\Lambda = \max_{\mathcal{A}, \mathcal{B}} I(\mathcal{A}, \mathcal{B})$$

Maximising over \mathcal{A}, \mathcal{B} means we can vary p_i 's and q_j 's.

Since \mathcal{C} is a subset of \mathcal{A}^n the rate tell us how many bits of information we can send in n bits (it is Rn).

Lemma 2: The capacity of a binary symmetric channel $\begin{pmatrix} \phi & 1-\phi \\ 1-\phi & \phi \end{pmatrix}$ is $\Lambda = 1 + \phi \log_2 \phi + (1-\phi) \log_2 (1-\phi)$.

proof: Insert proof here

Definition 12: For any $u, v \in \mathcal{A}^n$, the **Hamming distance** is $d(u, v) :=$ number of coordinates where u and v differ.

Lemma 3: The Hamming distance satisfies the triangle inequality $d(u, v) \leq d(u, w) + d(w, v)$

proof: Insert proof here

Lemma 4: For the binary symmetric channel, maximum likelihood decoding is $\Delta(v) = u$, where u is the closest element of \mathcal{C} with respect to the Hamming distance.

proof: Insert proof here

Definition 13: in general this decoding is called **nearest neighbour decoding**.

Lemma 5: For $0 < \lambda < \frac{1}{2}$:

$$\sum_{i=0}^{\lambda n} \binom{n}{i} \leq 2^{n(-\lambda \log(\lambda) - (1-\lambda) \log(1-\lambda))}$$

proof: Insert proof here

Theorem 2: (Shannon) Let $\delta, \varepsilon > 0$. For all sufficiently large n there is a code of length n and rate R satisfying $\Lambda - \varepsilon < R < \Lambda$ together with a decision rule Δ such that $P_{cor} \rightarrow 1 - \delta$.

proof: Insert proof here (ONLY FOR BINARY SYMMETRIC CHANNEL)

Lemma 6: For an input source \mathcal{A} and output source \mathcal{B} and decision rule $\Delta(b_j) = a_{j*}$.

$$H(\mathcal{A}|\mathcal{B}) \leq -P_{cor} \log(P_{cor}) - (1 - P_{cor}) \log(1 - P_{cor}) + (1 - P_{cor})(\log |\mathcal{C}| - 1)$$

where \mathcal{C} is the set of input source elements emitted with non zero probability.

Theorem 3: If $\Lambda' > \Lambda$ and we fix the input probability distribution is uniform then there is no sequence of codes C_n of rate R satisfying $\Lambda' - \varepsilon < R < \Lambda'$ such that $P_{cor} \rightarrow 1$ as $n \rightarrow \infty$.

proof: Insert proof here

4. Finite fields

4.1. Basic definitions

Definition 1: A **field** is a commutable ring in which every non-zero element has a multiplicative inverse.

insert example here

inse example here

Notation 1: We denote as (f) with $f \in \mathbb{F}_p[X]$, the **ideal consisiting of all multiples of f**.

Theorem 1: if f is an irreducible polynomial of degree h then $\mathbb{F}_p[X]/(f)$ is a finite field with p^h elements.

proof: Insert proof here

insert examples here

Exercise : construct a field wih 9 elements.

Let \mathbb{F} be a finite field. Let n minimal such that adding 1 n times gives 0.

Since $\overbrace{(1 + \dots + 1)}^n = \overbrace{(1 + \dots + 1)}^r \overbrace{(1 + \dots + 1)}^{n/r} = 0$ minimaliy implies that $n = p$ is prime.

Definition 2: In this situation, we say that \mathbb{F} has **characteristic** p . If no such p exists then we say that \mathbb{F} has **characteristic zero**, in which case $\mathbb{F} \supset \mathbb{Z}$ and so $\mathbb{F} \supseteq \mathbb{Q}$.

insert exercise here

4.2. Propierties of finite fields

Theorem 2: Let \mathbb{F} be a field with q elements. For all $x \in \mathbb{F}$. $x^q = x$.

proof: Insert proof here

The finite field with q elements is unique since it is the splitting field of the polynomial $x^q - x \in \mathbb{F}_p[X]$.

Considerer the map $x \mapsto x^p$ in \mathbb{F} ($q = p^h$).

$$(x + y)^p = \sum_{j=0}^p \binom{p}{j} x^j y^{p-j} = x^p + y^p$$

Observe that $\binom{p}{j} = 0$ (modulo p) for $j = 1, \dots, p-1$.

$$(x * y)^p = x^p y^p$$

So this map is partially an automorphism of \mathbb{F}_p since it preserves addition and multiplication.

Definition 3: This is called the **Frobenius automorphism**.

$$x \mapsto x^p \mapsto x^{p^2} \mapsto x^{p^3} \mapsto \dots \mapsto x^{p^{h-1}} \mapsto x$$

4.3. Factorization of polynomials

Let \mathbb{F}_p denote the unique finite field with q elements ($q = p^h$).

Lemma 1: The polynomial $x^{q-1} - 1$ factories into distinct linear factors in $\mathbb{F}_q[X]$.

proof: Insert proof here

Lemma 2: The polynomial $x^q - 1$ factories into distinct irreducible factors whose degree divides h .

proof: Insert proof here

insert example here

insert example here

Observation 1: if q is odd $x^{q-1} - 1 = (x^{\frac{q-1}{2}} - 1)(x^{\frac{q-1}{2}} + 1)$ the zeros of the first factor are on the non-zeros squares in \mathbb{F}_q and vice-versa ($x = y^2$ then $x^{\frac{q-1}{2}} = y^{q-1} = 1$).

Observation 2: if $q^1 = q^r$ then $x^n - 1 = (x^{n/q^r} - 1)^{q^r}$ so if we want to factorise $x^n - 1$ in $\mathbb{F}_p[x]$ we can assume $(n, p) = 1$.

To factorise $x^n - 1$ in $\mathbb{F}_q[X]$, we find an extension field in \mathbb{F}_q which contains n -th roots of 1, ie. find h such that n divides $q^h - 1$ since then $x^{q^n-1} - 1$ is divisible by $x^n - 1$, ie. $q^n = 1 \pmod{1}$, ie. h is the multiplicative order of q in $\mathbb{Z}/n\mathbb{Z}$.

If we let ε be a primitive n -th root of 1 in \mathbb{F}_{q^n} then $(x - \varepsilon)(x - \varepsilon^q)(x - \varepsilon^{q^2})\dots(x - \varepsilon^{q^{h-1}})$ is a polynomial whose coefficients are in \mathbb{F}_q since $(x - \varepsilon)(x - \varepsilon^q)(x - \varepsilon^{q^2})\dots(x - \varepsilon^{q^h})$.

insert example here

insert exercise here

insert example here

5. Block codes

5.1. Minimum distance

5.2. Bounds on block codes

5.3. Asymptotically good codes

6. Linear codes

6.1. Basics

6.2. Syndrom decoding

6.3. Dual code and Mc Williams identities

6.4. The Griesmer bound

7. Cyclic codes

7.1. Introduction

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7.3. BCH Codes

Decision problem, yes/no problem

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10.1. Bipartite graphs with the expander property

10.2. Low density parity check (LDPC) codes

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11.1. P-adic numbers

11.2. Polynomials over \mathbb{Q}_p