Information Theory. 3rd Chapter Slides

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Agenda

1. Universal coding task
2. Useful combinatorial formulas
3. Two pass encoding
4. Enumerative coding
5. Asymptotic bounds of redundancy
6. Adaptive coding
7. Algorithm comparison

- *Encoding redundancy* for a model class Ω is

$$r_n(\Omega) = \sup_{\omega \in \Omega} \left[\bar{R}_n(\omega) - H_\omega \right] . \qquad (1)$$

- Coding is called *Universal* if for algorithm holds

$$\lim_{n \to \infty} r_n(\Omega) = 0,$$

- Consider sequences $\boldsymbol{x} = (x_1, ..., x_n)$, where x_i has one of M_i values, $i = 1, ..., n$. Number of different $\boldsymbol{x}$ is

$$|\{\boldsymbol{x} = (x_1, ..., x_n) : x_i \in \{0, ..., M_i - 1\}, i = 1, ...n\}| = \prod_{i=1}^{n} M_i. \tag{2}$$

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$$A_M^n = M(M-1) \times ... \times (M-n+1) = \frac{M!}{(M-n)!}. \tag{3}$$

Useful combinatorial formulas

- Number of combinations

$$C_M^n = \binom{M}{n} = \frac{A_M^n}{P_n} = $$
$$= \frac{M(M-1)\times \ldots \times (M-n+1)}{n!} = $$
$$= \frac{M!}{n!(M-n)!}. \tag{4}$$

- Number of combinations

$$\binom{n}{k} = \begin{cases} \frac{n!}{k!(n-k)!}, & \text{if } n \geq k \geq 0 \\ 1, & \text{if } n \geq 0 \text{ and } k = 0 \text{ or } k = n \\ 0, & \text{if } k < 0 \text{ or } k > n \end{cases} \tag{5}$$

Useful combinatorial formulas

- binomial coefficient

$$(a+b)^n = \sum_{k=0}^{n} \binom{n}{k} a^k b^{n-k}.$$

- Number os binary sequences of length n, which contain τ_1 ones and $\tau_0 = n - \tau_1$ zeros.

$$N(\tau_0, \tau_1) = \binom{n}{\tau_0} = \frac{n}{\tau_0! \tau_1!}. \qquad (6)$$

- Composition of sequence $\boldsymbol{x}$ is vector $\boldsymbol{\tau}(\boldsymbol{x}) = (\tau_0(\boldsymbol{x}), ..., \tau_{M-1}(\boldsymbol{x}))$, where $\tau_i(\boldsymbol{x})$ denotes number of elements $x_t = i$ in sequence $\boldsymbol{x} = (x_1, ..., x_n)$.

Useful combinatorial formulas

- For arbitrary M

$$N(\boldsymbol{\tau}) = \frac{n!}{\tau_0! \ldots \tau_{M-1}!}. \qquad (7)$$

- Newton formula generalization

$$(a_0 + \ldots + a_{M-1})^n = \sum_{\boldsymbol{\tau}:\ \tau_0 + \ldots + \tau_{M-1} = n} N(\boldsymbol{\tau}) \prod_{i=0}^{M-1} a_i^{\tau_i}.$$

- Consider the following lemma:

Lemma

$n \in$ mathbbN can be written as sum of M non-negative integer terms in $\binom{n+M-1}{M-1}$ ways.

- Number of different compositions of sequence of length n over M-size alphabet is

$$N_\tau(n, M) = \binom{n+M-1}{M-1} \tag{8}$$

- Stirling formula

$$\sqrt{2\pi n} n^n e^{-n} \exp\left\{\frac{1}{12n+1}\right\} < n! < \sqrt{2\pi n} n^n e^{-n} \exp\left\{\frac{1}{12n}\right\}. \tag{9}$$

- Consider

$$N(\boldsymbol{\tau}) < (2\pi n)^{-\frac{M-1}{2}} 2^{n \log n - \sum_i \tau_i \log \tau_i} \left(\prod_i \frac{n}{\tau_i} \right)^{1/2} \times$$

$$\times \exp \left\{ \frac{1}{12n} - \sum_i \frac{1}{12\tau_i + 1} \right\}. \qquad (10)$$

- Logarithm of number of sequences with specified composition

$$\log N(\boldsymbol{\tau}) < nH(\hat{\boldsymbol{p}}) - \frac{M-1}{2} \log(2\pi n) - \frac{1}{2} \sum_i \log(\hat{p}_i), \qquad (11)$$

- More compact estimation

$$\log N(\boldsymbol{\tau}) < nH(\hat{\boldsymbol{p}}) - \frac{M-1}{2}\log(2\pi n) + \frac{1}{2}\log\frac{n}{n-M+1}. \tag{12}$$

- Recurrent formula holds

$$\binom{n+1}{w} = \binom{n}{w} + \binom{n}{w-1}. \tag{13}$$

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$$\binom{n+1}{w} = \binom{n}{w} + \binom{n-1}{w-1} + \ldots + \binom{n-w+1}{1}. \tag{14}$$

Two pass encoding

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IF_WE_CANNOT_DO_AS_WE_WOULD_WE_SHOULD_DO_AS_WE_CAN
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(15)

-

$$l_2 = 6 + 6 + 12 \times 2 + 5 \times 3 + ... + 6 = 178.$$

    - 00010000010100110111101101111.

Two pass encoding

- $$l_1 = 29 + 8 \times 15 = 149 \text{ bit.}$$

- $$l = l_1 + l_2 = 149 + 178 = 327 \text{ bit.} \qquad (16)$$

Table: Huffman code for text (15)

Character	Number of iterations	Codeword length	Codeword
I	1	6	010000
F	1	6	010001
_	12	2	00
W	5	3	100
E	4	4	0101
C	2	5	01001
A	4	4	1010
N	3	4	1011
O	5	3	110
T	1	6	011110
D	4	4	0110
S	3	4	1110
U	2	4	1111
L	2	5	01110
H	1	6	011111

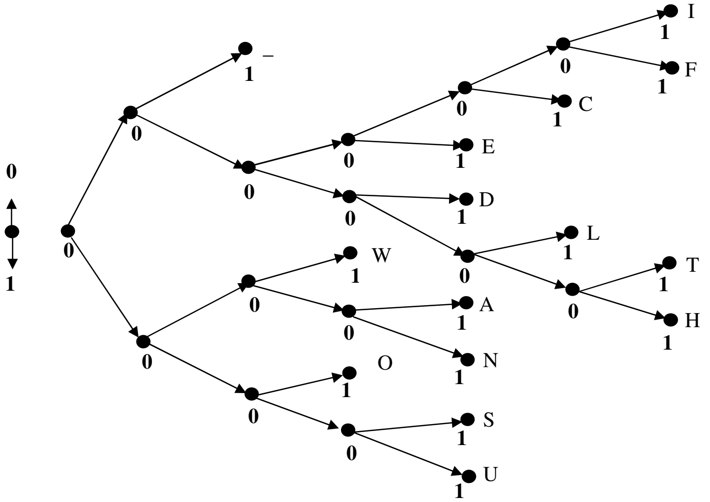

Figure: Huffman codetree for (15)

Table: Regular Huffman code

Character	Codeword length	Codeword
_	2	00
O	3	010
W	3	011
A	4	1000
D	4	1001
E	4	1010
N	4	1011
S	4	1100
U	4	1101
C	5	11100
L	5	11101
F	6	111100
H	6	111101
I	6	111110
T	6	111111

Two pass encoding

Table: Number of bits for regular code tree transmitting

Level	Number of nodes	Number of leaves n_i	Range of values n_i	Expenses in bits
0	1	0	$0 \dots 1$	1
1	2	0	$0 \dots 2$	2
2	4	1	$0 \dots 4$	3
3	6	2	$0 \dots 6$	3
4	8	6	$0 \dots 8$	4
5	4	2	$0 \dots 4$	3
6	4	4	$0 \dots 4$	3
Total				19

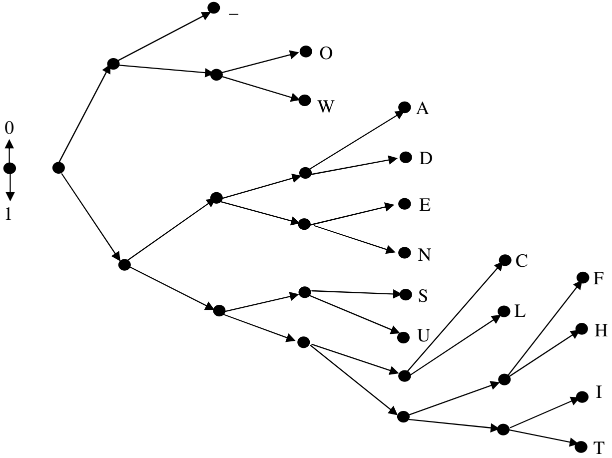

Figure: Codetree for regular Huffman code

Two pass encoding

- Enough for transmitting information about letters that are associated with regular codetree nodes:

$$\left\lceil \log \binom{256}{1} \right\rceil + \left\lceil \log \binom{255}{2} \right\rceil + \left\lceil \log \binom{253}{6} \right\rceil +$$

$$+ \left\lceil \log \binom{247}{2} \right\rceil + \left\lceil \log \binom{245}{4} \right\rceil = 105 \text{ bits}$$

- More precise

$$I = 178 + 19 + 105 = 302 \text{ bits.} \tag{17}$$

Theorem

For two pass coding with Huffman code of Discrete Memoryless Source with alphabet size M and entropy H, average code rate satisfies

$$\bar{R} \leq H + 1 + \frac{1}{n}\left(M \log M + 3M - 1\right). \tag{18}$$

Proof.

- $l_1(\boldsymbol{x}) \le 2M - 1 + M\lceil \log M \rceil \le M \log M + 3M - 1.$
-

$$\begin{aligned} l_2(\boldsymbol{x}) &\overset{(a)}{=} \sum_{i=1}^{n} l(x_i) = \\ &\overset{(b)}{=} \sum_{x \in X} \tau_n(x) l(x) = \\ &\overset{(c)}{=} n \sum_{x \in X} \frac{\tau_n(x)}{n} l(x) = \\ &\overset{(d)}{=} n \sum_{x \in X} \hat{p}_n(x) l(x) = \\ &\overset{(e)}{=} n\mathbf{M}_{\hat{\boldsymbol{p}}_n}\left[l(x)\right] \le \\ &\overset{(f)}{\le} n(H(\hat{\boldsymbol{p}}_n) + 1). \end{aligned} \tag{19}$$

Proof.

- $$\bar{R}(\boldsymbol{x}) = \frac{l(\boldsymbol{x})}{n} = \frac{l_1(\boldsymbol{x}) + l_2(\boldsymbol{x})}{n} \le \tag{20}$$
  $$\le H(\hat{\boldsymbol{p}}_n) + 1 + \frac{1}{n}\left(M \log M + 3M - 1\right). \tag{21}$$

- $$\mathbf{M}\left[H(\hat{\boldsymbol{p}}_n)\right] \overset{\text{(a)}}{\le} H\left(\mathbf{M}\left[\hat{\boldsymbol{p}}_n\right]\right) \overset{\text{(b)}}{=} H(\boldsymbol{p}) = H. \tag{22}$$

- $$\mathbf{M}\left[\hat{\boldsymbol{p}}_n\right] = \boldsymbol{p}, \tag{23}$$

- $$\mathbf{M}\left[\frac{\tau_n(a)}{n}\right] = p(a), \;\; a \in X.$$

Proof.

- $$\chi_a(x) = \begin{cases} 1, & \text{if } x = a, \\ 0, & \text{if } x \neq a. \end{cases}$$

- $$\mathbf{M}\left[\chi_a(x)\right] = 1 \times p(a) + 0 \times (1 - p(a)) = p(a).$$

- $$\begin{aligned} \mathbf{M}\left[\frac{\tau_n(a)}{n}\right] &= \frac{1}{n}\mathbf{M}\left[\sum_{i=1}^{n} \chi_a(x_i)\right] = \\ &= \frac{1}{n}\sum_{i=1}^{n} \mathbf{M}\left[\chi_a(x_i)\right] = \\ &= p(a), \ a \in X. \end{aligned}$$

- Note, that coding redundancy satisfies

$$r = \bar{R} - H \leq 1 + \frac{K}{n}, \tag{24}$$

- When using arithmetic coding, the redundancy can be achieved:

$$r(n) = \frac{M-1}{n} \log n + \frac{K}{n}, \tag{25}$$

where M alphabet size, K is a constant.

Enumerative coding

- Codeword length

$$
\begin{aligned}
l(\boldsymbol{x}) &= l_1(\boldsymbol{x}) + l_2(\boldsymbol{x}) = \\
&= \lceil \log N_\tau(M) \rceil + \lceil \log N(\boldsymbol{\tau}) \rceil = \\
&= \left\lceil \log \binom{n+M-1}{M-1} \right\rceil + \left\lceil \log \frac{n!}{\prod_{i=0}^{M-1} \tau_i(\boldsymbol{x})!} \right\rceil \qquad (26)
\end{aligned}
$$

- `IF_WE_CANNOT_DO_AS_WE_WOULD_WE_SHOULD_DO_AS_WE_CAN`
-

$$
\begin{aligned}
l_1 &= \left\lceil \log \binom{50+255}{255} \right\rceil = 190 \text{ bits}, \\
l_2 &= \left\lceil \log \left(\frac{50!}{12!5!^2 4!^3 3!^2 2!^3} \right) \right\rceil = 150 \text{ bits}.
\end{aligned}
$$

- $\tilde{\boldsymbol{\tau}} = (\tilde{\tau}_0, \ldots, \tilde{\tau}_{M-1})$=(12, 5, 5, 4, 4, 4, 3, 3, 2, 2, 2, 1, 1, 1, 1, 0,. . . ., 0).
- $$1 \le \tilde{\tau}_0 \le n, \quad \tilde{\tau}_{j+1} \le \tilde{\tau}_j, \quad j \ge 0.$$
- It's possible to transmit number of composition, no more than
$$\left\lceil \log \left(n \prod_{j:\tau_j>0} \tau_j \right) \right\rceil \text{ bits} \tag{27}$$
- To transmit the composition $\boldsymbol{\tau}' = (1, 2, 3, 2, 3, 4, 241)$
$$l_1 = \left\lceil \log \left(n \prod_{j:\tau_j>0} \tau_j \right) \right\rceil + \left\lceil \log \left(\frac{M!}{\prod_j \tau_j'!} \right) \right\rceil = 25 + 108 = 133 \text{ bits.} \tag{28}$$

- $$l = l_1 + l_2 = 283 \text{ bits}$$

- $$\begin{aligned} l(\boldsymbol{x}) &= l_1(\boldsymbol{x}) + l_2(\boldsymbol{x}) = \\ &= \lceil \log N_\tau(M) \rceil + \lceil \log N(\boldsymbol{\tau}) \rceil \le \\ &\le nH(\hat{\mathbf{p}}) - \frac{M-1}{2}\log(2\pi n) - \\ &\quad -\frac{1}{2}\sum_i \log(\hat{p}_i) + (M-1)\log(n+1) + 1. \end{aligned}$$

Theorem

For enumerate coding of discrete memoryless source with alphabet size M and entropy H, the average code rate is.

$$\bar{R} \leq H + \frac{M-1}{2}\frac{\log(n+1)+K}{n}, \qquad (29)$$

where K does not depend on sequence length n.

Example

- Let $n = 10$, $\boldsymbol{\tau} = (2, 5, 3)$, $\boldsymbol{x} = (2011021211)$. Probability distribution on first step $\boldsymbol{\tau}/n = (2/10, 5/10, 3/10)$ $G = 0.3$.
- Probability distribution after first step: $(2, 5, 2)/9 = (2/9, 5/9, 2/9)$.
- After second step: $G = 3/10 \times 2/9$.
- After 10 steps:

$$G = \frac{3}{10} \times \frac{2}{9} \times \frac{5}{8} \times \frac{4}{7} \times \frac{1}{6} \times \frac{2}{5} \times \frac{3}{4} \times \frac{1}{3} \times \frac{2}{2} \times \frac{1}{1} \quad .$$

- Codeword length for this example:

$$l = \lceil - \log G \rceil = \left\lceil - \log \frac{10!}{2!5!3!} \right\rceil$$

Asymptotic bounds of redundancy

- Redundancy

$$r_n(\Omega) = \sup_{\omega \in \Omega} \left[\bar{R}_n(\omega) - H_\omega \right]. \qquad (30)$$

- For a given $\boldsymbol{\theta}$

$$p(\boldsymbol{x}|\boldsymbol{\theta}) = \prod_{i=0}^{M-1} \theta_i^{\tau_i(\boldsymbol{x})},$$

where $\boldsymbol{\tau}(\boldsymbol{x}) = (\tau_0(\boldsymbol{x}), \ldots, \tau_{M-1}(\boldsymbol{x}))$ composition of sequence $\boldsymbol{x}$.

Asymptotic bounds of redundancy

- $$r_n(\Theta) \le \frac{M-1}{2}\frac{\log(n+1)+K}{n}, \qquad (31)$$
  where K does not depend on n.

- $$r_n(\Theta) = \inf \sup_{\theta \in \Theta} \left[\bar{R}_n(\boldsymbol{\theta}) - H(X|\boldsymbol{\theta})\right], \qquad (32)$$
  where $H(X|\boldsymbol{\theta})$ is entropy of X.

Asymptotic bounds of redundancy

Theorem

For a discrete memoryless source with alphabet size M, with redundancy of universal code $r_n(\Theta)$ per message of length n holds:

$$r_n(\Theta) \geq \frac{M-1}{2}\frac{\log n + C}{n}, \qquad (33)$$

where C does not depend on n.

Proof of theorem.

- Consider $\Theta = \{\boldsymbol{\theta}\}$, $f(\boldsymbol{\theta})$. Required redundancy:

$$r_n(\Theta) = \inf_{f(\boldsymbol{\theta})} \sup \mathbf{M}_f \left[\bar{R}_n(\boldsymbol{\theta}) - H(X|\boldsymbol{\theta}) \right], \quad (34)$$

-

$$r_n(\Theta) \geq \sup_{f(\boldsymbol{\theta})} \inf \mathbf{M}_f \left[\bar{R}_n(\boldsymbol{\theta}) - H(X|\boldsymbol{\theta}) \right], \quad (35)$$

-

$$\sum_{\boldsymbol{x} \in X^n} 2^{-l(\boldsymbol{x})} \leq 1.$$

Proof of theorem

- $$q(\boldsymbol{x}) = 2^{-l(\boldsymbol{x})},$$
- $$-\sum_{\boldsymbol{x}\in X^n} p(\boldsymbol{x}|\boldsymbol{\theta}) \log q(\boldsymbol{x}) \le \bar{l}_n(q,\boldsymbol{\theta}) \le -\sum_{\boldsymbol{x}\in X^n} p(\boldsymbol{x}|\boldsymbol{\theta}) \log q(\boldsymbol{x}) + 1.$$
- $$\bar{l}_n(q,\boldsymbol{\theta}) = -\sum_{\boldsymbol{x}\in X^n} p(\boldsymbol{x}|\boldsymbol{\theta}) \log q(\boldsymbol{x}). \tag{36}$$

Proof of theorem

- $$\bar{I}_n(q) = -\sum_{\boldsymbol{x} \in X^n} p(\boldsymbol{x}) \log q(\boldsymbol{x}), \qquad (37)$$

- $$p(\boldsymbol{x}) = \mathbf{M}_f \left[p(\boldsymbol{x}|\boldsymbol{\theta}) \right] = \int_{\boldsymbol{\theta}} f(\boldsymbol{\theta}) p(\boldsymbol{x}|\boldsymbol{\theta}) d\boldsymbol{\theta}. \qquad (38)$$

Proof of theorem

- Minimum at right is achieved, when $p(\boldsymbol{x}) = q(\boldsymbol{x})$.

$$-\sum_{\boldsymbol{x}\in X^n} p(\boldsymbol{x}) \log p(\boldsymbol{x}) + \sum_{\boldsymbol{x}\in X^n} p(\boldsymbol{x}) \log q(\boldsymbol{x}) = -L(p||q) \le 0$$

-

$$r_n(\Theta) \ge \frac{1}{n} \sup_{f(\boldsymbol{\theta})} \mathbf{M}_f \sum_{\boldsymbol{x}\in X^n} p(\boldsymbol{x}|\boldsymbol{\theta}) \log \frac{p(\boldsymbol{x}|\boldsymbol{\theta})}{p(\boldsymbol{x})} \quad . \qquad (39)$$

Proof of theorem

- Dirichlet distribution:

$$f_{\boldsymbol{\lambda}}(\boldsymbol{\theta}) = \Gamma\left(\sum_{i=0}^{M-1} \lambda_i\right) \prod_{i=0}^{M-1} \frac{\theta_i^{\lambda_i - 1}}{\Gamma(\lambda_i)}, \tag{40}$$

  where $\boldsymbol{\lambda} = (\lambda_0, ..., \lambda_{M-1})$ is vector of distribution parameters, $\lambda_i \geq 0$, $i = 0, ..., M-1$, $\Gamma(z)$ is Gamma function.

- Gamma function:

$$\Gamma(z) = \int_0^\infty t^{z-1} e^{-t} dt.$$

-

$$\Gamma(x) = (x-1)\Gamma(x-1), \quad \Gamma\left(\frac{1}{2}\right) = \sqrt{\pi}.$$

Proof of theorem

- $$\Gamma(n) = (n-1)! \quad .$$
- $$\Gamma(z) \approx \sqrt{2\pi} z^{z-1/2} e^{-z}, \quad z \to \infty.$$
- For some K_1
$$|\log \Gamma(z) + z \log e - (z - 1/2) \log z| \leq K_1. \tag{41}$$

Asymptotic bounds of redundancy

Proof of theorem

- Dirichlet integral: $\forall \alpha_i$, $i = 1, ..., n$ and a continuous function f:

$$\int_{\boldsymbol{x}:\sum_i x_i=1} f\left(\sum_{i=1}^n x_i\right) \prod_{i=1}^n x_i^{\alpha_i-1} dx_1 ... dx_n =$$

$$= \frac{\prod_{i=1}^n \Gamma(\alpha_i)}{\Gamma(\sum_{i=1}^n \alpha_i)} \int_0^1 f(\tau) \tau^{\left(\sum_{i=1}^n \alpha_i\right)-1} d\tau. \quad (42)$$

- Consider parameter $\lambda_i = 1/2$, $i = 1, ..., M$,

$$f(\boldsymbol{\theta}) = \frac{\Gamma(M/2)}{\pi^{M/2}} \prod_{i=0}^{M-1} \theta_i^{-1/2}. \quad (43)$$

Asymptotic bounds of redundancy

Proof of theorem

- $$p(\boldsymbol{x}) = \frac{\Gamma(M/2)}{\pi^{M/2}} \int_{\boldsymbol{\theta}} \prod_{i=0}^{M-1} \theta_i^{\tau_i(\boldsymbol{x})-1/2} d\boldsymbol{\theta}.$$

- $$p(\boldsymbol{x}) = \frac{\Gamma(M/2)}{\pi^{M/2}} \quad \frac{\prod_{i=0}^{M-1} \Gamma(\tau_i(\boldsymbol{x}) + 1/2)}{\Gamma(n + M/2)}. \quad (44)$$

- $$-\log p(\boldsymbol{x}) = nH\left(\frac{\boldsymbol{\tau}(\boldsymbol{x})}{n}\right) + \frac{M-1}{2}\log n + K(n), \quad (45)$$

  where $K(n)$ is bounded

Lemma

For a given parameters θ, the average "empirical entropy" $H\left(\frac{\tau(x)}{n}\right)$ $\forall\theta$ is connected to it's entropy $H_{\theta}(X)$ by inequalities:

$$-\frac{K_1}{n} \leq \sum_{x} p(x|\theta)H\left(\frac{\tau(x)}{n}\right) - H_{\theta}(X) \leq 0 \quad , \tag{46}$$

where K_1 is a constant, $H_{\theta}(X) = -\sum_{i=0}^{M-1} \theta_i \log \theta_i$ is entropy of the source

Proof of Lemma

- $$\sum_{\boldsymbol{x}} p(\boldsymbol{x}|\boldsymbol{\theta})\tau_i(\boldsymbol{x}) = n\theta_i \quad , \tag{47}$$

- $$\sum_{\boldsymbol{x}} p(\boldsymbol{x}|\boldsymbol{\theta})\tau_i^2(\boldsymbol{x}) = n^2\theta_i^2 + n\theta_i(1-\theta_i) \quad . \tag{48}$$

Proof of Lemma

$$
\begin{aligned}
& -\sum_{\boldsymbol{x}} p(\boldsymbol{x}|\boldsymbol{\theta}) \sum_{i=0}^{M-1} \frac{\tau_i(\boldsymbol{x})}{n} \log \frac{\tau_i(\boldsymbol{x})}{n} + \sum_{i=0}^{M-1} \theta_i \log \theta_i = \\
\overset{(a)}{=} \quad & -\sum_{\boldsymbol{x}} p(\boldsymbol{x}|\boldsymbol{\theta}) \sum_{i=0}^{M-1} \frac{\tau_i(\boldsymbol{x})}{n} \log \frac{\tau_i(\boldsymbol{x})}{n} + \sum_{\boldsymbol{x}} \sum_{i=0}^{M-1} p(\boldsymbol{x}|\boldsymbol{\theta}) \frac{\tau_i(\boldsymbol{x})}{n} \log \theta_i = \\
= \quad & -\sum_{\boldsymbol{x}} p(\boldsymbol{x}|\boldsymbol{\theta}) \sum_{i=0}^{M-1} \frac{\tau_i(\boldsymbol{x})}{n} \log \frac{\tau_i(\boldsymbol{x})}{n\theta_i} \geq \\
\overset{(b)}{\geq} \quad & -\log \sum_{\boldsymbol{x}} \sum_{i=0}^{M-1} p(\boldsymbol{x}|\boldsymbol{\theta}) \frac{\tau_i^2(\boldsymbol{x})}{n^2\theta_i} = \\
\overset{(c)}{=} \quad & = -\log \sum_{i=0}^{M-1} \frac{n^2\theta_i^2 + \theta_i(1-\theta_i)}{n^2\theta_i} = \\
= \quad & -\log\left(1 + \frac{M-1}{n}\right) \geq \frac{M-1}{n} \log e.
\end{aligned}
$$

Proof of theorem

- $$-\sum_{\boldsymbol{x}\in X^n} p(\boldsymbol{x}|\boldsymbol{\theta})\log p(\boldsymbol{x}|\boldsymbol{\theta}) = H(X^n|\boldsymbol{\theta}) = nH_{\boldsymbol{\theta}}(X).$$

- $$\sum_{\boldsymbol{x}\in X^n} p(\boldsymbol{x}|\boldsymbol{\theta})\log \frac{p(\boldsymbol{x}|\boldsymbol{\theta})}{p(\boldsymbol{x})} \geq \frac{M-1}{2}\log n + K(n) - \frac{K_1}{n}.$$

Proof of theorem

- $$\begin{aligned} -\log p(\boldsymbol{x}) &= -\sum_{i=0}^{M-1} \tau_i(\boldsymbol{x}) \log\left(\tau_i(\boldsymbol{x}) + \frac{1}{2}\right) + \\ &\quad + \left(n + \frac{M-1}{2}\right) \log\left(n + \frac{M}{2}\right) + K_2 = \\ &= -\sum_{i=0}^{M-1} \tau_i(\boldsymbol{x}) \log\left[\frac{\tau_i(\boldsymbol{x})}{n}\left(1 + \frac{1}{2\tau_i(\boldsymbol{x})}\right)\right] - n\log n + \\ &\quad + \left(n + \frac{M-1}{2}\right) \log n + \\ &\quad + \left(n + \frac{M-1}{2}\right) \log\left(1 + \frac{M}{2n}\right) + K_2, \end{aligned}$$

- $$0 \le \log(1+\epsilon) \le \epsilon \log e,$$

Example 1

- IF_WE_CANNOT_DO_AS_WE_WOULD_WE_SHOULD_DO_AS_WE_CAN
- $$G = 1 \cdot \frac{1}{256} \cdot \frac{1}{257} \cdot \frac{1}{258} \cdot \frac{1}{259} \cdot \frac{1}{260} \cdot \frac{2}{261} \cdot \ldots =$$
$$= \frac{12!(5!)^2(4!)^3(3!)^2(2!)^3}{256 \cdot \ldots \cdot 305}.$$
- $$I = \lceil -\log G \rceil + 1 = 342 \text{ bits.} \tag{49}$$
- $$\hat{p}_n(a) = \frac{\tau_n(a) + 1/2}{n + M/2} = \frac{2\tau_n(a) + 1}{2n + M}. \tag{50}$$

Example 2

- $$G = 1 \cdot \frac{1}{256} \cdot \frac{1}{258} \cdot \frac{1}{260} \cdot \frac{1}{262} \cdot \frac{1}{264} \cdot \frac{3}{266} \cdot \ldots =$$
$$= \frac{23!!(9!!)^2(7!!)^3(5!!)^2(3!!)^3}{256 \cdot \ldots \cdot 305}.$$
- $$(2n-1)!! = 1 \times 3 \times \ldots \times (2n-1),$$
$$(2n)!! = 2 \times 4 \times \ldots \times (2n).$$
- $$I = \lceil -\log G \rceil + 1 = 323 \text{ bits.} \tag{51}$$

- $$\hat{p}_n(a) = \frac{\tau_n(a)}{n+1}, \quad \tau_n(a) > 0.$$
- $$\hat{p}_n(esc) = \frac{1}{n+1},$$
- *A-algorithm* formula

$$\hat{p}_n(a) = \begin{cases} \frac{\tau_n(a)}{n+1}, & \text{if } \tau_n(a) > 0; \\ \frac{1}{n+1}\frac{1}{M-M_n}, & \text{if } \tau_n(a) = 0, \end{cases} \tag{52}$$

- IF_WE_CANNOT_DO_AS_WE_WOULD_WE_SHOULD_DO_AS_WE_CAN
- $$G = 1 \cdot \frac{1}{2} \cdot \frac{1}{256} \cdot \frac{1}{3} \cdot \frac{1}{255} \cdots$$
- $$G = \frac{11!(4!)^2(3!)^3(2!)^2}{50!} \cdot \frac{1}{256 \cdot 255 \cdot \ldots \cdot 242}.$$

$$I = \lceil -\log G \rceil + 1 = 291 \text{ bits.} \tag{53}$$

- for a $\boldsymbol{x} = (x_1, ..., x_n)$ with composition $(\tau_1, ..., \tau_M)$

$$
\begin{aligned}
G &= \frac{\prod_{i=1}^{M_n} (\tau_i - 1)!}{n!} \cdot \frac{(M - M_n)!}{M!} = \\
&= \frac{\prod_{i=1}^{M_n} \tau_i!}{n!} \cdot \frac{(M - M_n)!}{M! \prod_{i=1}^{M_n} \tau_i} \geq \\
&\geq \frac{\prod_{i=1}^{M_n} \tau_i!}{n!} M^{-M} (n+1)^{-M}.
\end{aligned}
$$

Theorem

For adaptive arithmetic coding of discrete memoryless source with alphabet size size M and entropy H, average code rate satisfies

$$\bar{R} \leq H + \frac{M}{2} \frac{\log(n+1) + K}{n}, \qquad (54)$$

where K does not depend on n.

Example 4. D-algorithm

- $$\hat{p}_n(a) = \begin{cases} \frac{\tau_n(a)-1/2}{n}, & \text{if } \tau_n(a) > 0; \\ \frac{M_n}{2n}\frac{1}{M-M_n}, & \text{if } \tau_n(a) = 0. \end{cases} \quad (55)$$

- $$G = 1 \cdot \frac{1}{2} \cdot \frac{1}{256} \cdot \frac{2}{4} \cdot \frac{1}{255} \cdot \frac{3}{6} \cdot \frac{1}{254} \frac{4}{8} \cdot \frac{1}{253} \frac{1}{10} \cdot \frac{5}{12} \cdot \frac{1}{252} \ldots$$

Example 4. D-algorithm

- $$(2 \times 4 \times \ldots \times 100) \times (256 \times 255 \times \ldots \times 242).$$

- $$G = \frac{(2 \times 12 - 3)!!((2 \times 5 - 3)!!)^2((2 \times 4 - 3)!!)^3((2 \times 3 - 3)!!)^2}{100!!} \times$$
$$\times \frac{14!}{256 \cdot 255 \cdot \ldots \cdot 242}.$$

- $$I = \lceil -\log G \rceil + 1 = 283 \quad \text{bits.}$$

Table: Universal coding algorithm comparison

Algorithm	Number of traverses	Asymptotic redundancy	codeword length for text (15)
2-traverse coding, Huffman code	2	$1 + K_1/n$	302
Enumerative coding	2	$\frac{M \log n + K_3}{2n}$	283
Adaptive coding (A)	1	$\frac{M \log n + K_4}{2n}$	291
Adaptive coding (D)	1	$\frac{M \log n + K_5}{2n}$	283