7 Compression

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COMP526 (Fall 2022)
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Learning Outcomes

1. Understand the necessity for encodings and know *ASCII* and *UTF-8 character encodings*.
2. Understand (qualitatively) the *limits of compressibility*.
3. Know and understand the algorithms (encoding and decoding) for *Huffman codes*, *RLE*, *Elias codes*, *LZW*, *MTF*, and *BWT*, including their *properties* like running time complexity.
4. Select and *adapt* (slightly) a *compression* pipeline for specific type of data.

Unit 7: ***Compression***

Outline

7 Compression

7.1 Context

Overview

- Unit 4–6: How to *work* with strings
  - finding substrings
  - finding approximate matches
  - finding repeated parts
  - . . .
  - assumed character array (random access)!
- Unit 7–8: How to *store/transmit* strings
  - computer memory: must be binary
  - how to compress strings (save space)
  - how to robustly transmit over noisy channels $\rightsquigarrow$ Unit 8

Clicker Question

What compression methods do you know?

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Terminology

- **source text:** string $S \in \Sigma_S^\star$ to be stored / transmitted
  Σ_S is some alphabet
- **coded text:** encoded data $C \in \Sigma_C^\star$ that is actually stored / transmitted
  usually use $\Sigma_C = \{0, 1\}$
- **encoding:** algorithm mapping source texts to coded texts $S \rightsquigarrow C$
- **decoding:** algorithm mapping coded texts back to original source text $C \rightsquigarrow S$

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- **Lossy vs. Lossless**
  - **lossy compression** can only decode **approximately**;
    the exact source text S is lost
  - **lossless compression** always decodes S exactly

- For media files, lossy, logical compression is useful (e. g. JPEG, MPEG)

- We will concentrate on *lossless* compression algorithms.
  These techniques can be used for any application.

What is a good encoding scheme?

- Depending on the application, goals can be
  - efficiency of encoding/decoding
  - resilience to errors/noise in transmission → Unit 8
  - security (encryption)
  - integrity (detect modifications made by third parties)
  - size

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  - size

- Focus in this unit: **size** of coded text

  Encoding schemes that (try to) minimize the size of coded texts perform *data compression*.

- We will measure the *compression ratio*: $\dfrac{|C| \cdot \lg |\Sigma_C|}{|S| \cdot \lg |\Sigma_S|} \overset{\Sigma_C = \{0,1\}}{=} \dfrac{|C|}{|S| \cdot \lg |\Sigma_S|}$

  < 1 means successful compression

  $= 1$ means no compression

  > 1 means "compression" made it bigger!? (yes, that happens ...)

Clicker Question

Do you know what uncomputable problems (halting problem, Post's correspondence problem, . . .) are?

- **A** Sure, I could explain what it is.
- **B** Heard that in a lecture, but don't quite remember
- **C** No, never heard of it

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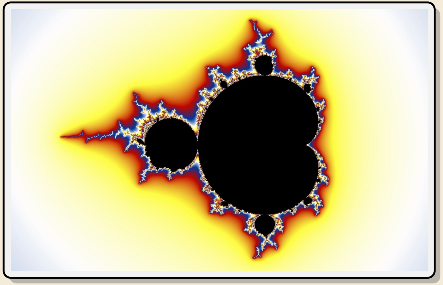
Limits of algorithmic compression

Is this image compressible?

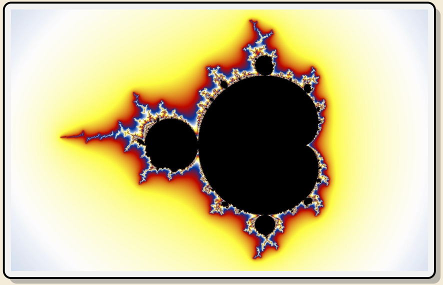


Limits of algorithmic compression

Is this image compressible?

visualization of Mandelbrot set

- Clearly a complex shape!
- Will not compress (too) well using, say, PNG.
- but:
  - completely defined by mathematical formula
  - ⇝ **can be generated by a very small program!**



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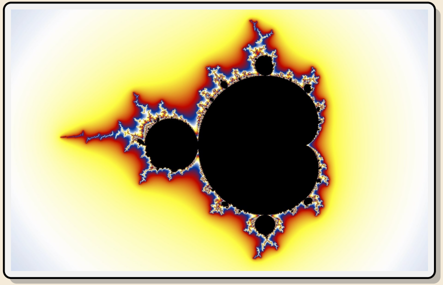

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⇝ ***Kolmogorov complexity***

- C = *any program* that outputs S

  self-extracting archives!
- Kolmogorov complexity = length of smallest such program

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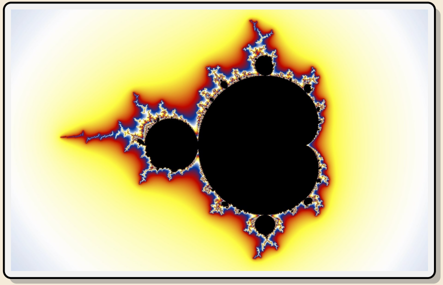

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⇝ ***Kolmogorov complexity***

- C = *any program* that outputs S

  self-extracting archives!
- Kolmogorov complexity = length of smallest such program
- **Problem:** finding smallest such program is *uncomputable*.
- ⇝ No optimal encoding algorithm is possible!
- ⇝ must be inventive to get efficient methods

What makes data compressible?

- Lossless compression methods mainly exploit two types of redundancies in source texts:

  1. **uneven character frequencies**
     some characters occur more often than others $\longrightarrow$ Part I

  2. **repetitive texts**
     different parts in the text are (almost) identical $\longrightarrow$ Part II

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  1. **uneven character frequencies**
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  2. **repetitive texts**
     different parts in the text are (almost) identical $\rightarrow$ Part II

There is no such thing as a free lunch!

Not *everything* is compressible ($\rightarrow$ tutorials)
$\rightsquigarrow$ focus on versatile methods that often work

Part I

Exploiting character frequencies

7.2 Character Encodings

Character encodings

- Simplest form of encoding: Encode each source character individually

$\leadsto$ encoding function $E : \Sigma_S \to \Sigma_C^\star$

  - typically, $|\Sigma_S| \gg |\Sigma_C|$, so need several bits per character
  - for $c \in \Sigma_S$, we call $E(c)$ the *codeword* of c

- **fixed-length code:** $|E(c)|$ is the same for all $c \in \Sigma_C$
- **variable-length code:** not all codewords of same length

Fixed-length codes

- fixed-length codes are the simplest type of character encodings
- Example: **ASCII** (American Standard Code for Information Interchange, 1963)

0000000	NUL	0010000	DLE	0100000		0110000	0	1000000	@	1010000	P	1100000	‘	1110000	p
0000001	SOH	0010001	DC1	0100001	!	0110001	1	1000001	A	1010001	Q	1100001	a	1110001	q
0000010	STX	0010010	DC2	0100010	"	0110010	2	1000010	B	1010010	R	1100010	b	1110010	r
0000011	ETX	0010011	DC3	0100011	#	0110011	3	1000011	C	1010011	S	1100011	c	1110011	s
0000100	EOT	0010100	DC4	0100100	$	0110100	4	1000100	D	1010100	T	1100100	d	1110100	t
0000101	ENQ	0010101	NAK	0100101	%	0110101	5	1000101	E	1010101	U	1100101	e	1110101	u
0000110	ACK	0010110	SYN	0100110	&	0110110	6	1000110	F	1010110	V	1100110	f	1110110	v
0000111	BEL	0010111	ETB	0100111	’	0110111	7	1000111	G	1010111	W	1100111	g	1110111	w
0001000	BS	0011000	CAN	0101000	(	0111000	8	1001000	H	1011000	X	1101000	h	1111000	x
0001001	HT	0011001	EM	0101001	)	0111001	9	1001001	I	1011001	Y	1101001	i	1111001	y
0001010	LF	0011010	SUB	0101010	*	0111010	:	1001010	J	1011010	Z	1101010	j	1111010	z
0001011	VT	0011011	ESC	0101011	+	0111011	;	1001011	K	1011011	[	1101011	k	1111011	{
0001100	FF	0011100	FS	0101100	,	0111100	<	1001100	L	1011100	\	1101100	l	1111100	|
0001101	CR	0011101	GS	0101101	-	0111101	=	1001101	M	1011101	]	1101101	m	1111101	}
0001110	SO	0011110	RS	0101110	.	0111110	>	1001110	N	1011110	^	1101110	n	1111110	~
0001111	SI	0011111	US	0101111	/	0111111	?	1001111	O	1011111	_	1101111	o	1111111	DEL

- 7 bit per character
- just enough for English letters and a few symbols (plus control characters)

Fixed-length codes – Discussion

👍 Encoding & Decoding as fast as it gets

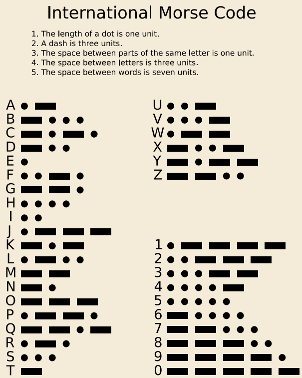
👎 Unless all characters equally likely, it wastes a lot of space

👎 inflexible (how to support adding a new character?)

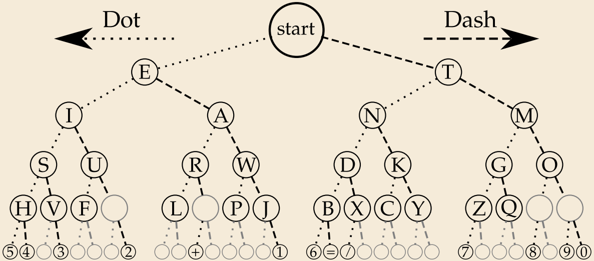
Variable-length codes

- to gain more flexibility, have to allow different lengths for codewords

- actually an old idea: **Morse Code**



https://commons.wikimedia.org/wiki/File:International_Morse_Code.svg



https://commons.wikimedia.org/wiki/File:Morse-code-tree.svg

Clicker Question

How many characters are there in the alphabet of the coded text in Morse Code, i. e., what is $|\Sigma_C|$?

A 1

B 2

C 3

D 4

E 26

F 36

G 256

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Clicker Question

How many characters are there in the alphabet of the coded text in Morse Code, i. e., what is $|\Sigma_C|$?

- **A** ~~1~~
- **B** ~~2~~
- **C** 3 ✓
- **D** ~~4~~
- **E** ~~26~~
- **F** ~~36~~
- **G** ~~256~~

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Variable-length codes – UTF-8

- Modern example: UTF-8 encoding of Unicode:

  default encoding for text-files, XML, HTML since 2009

  - Encodes any Unicode character (137 994 as of May 2019, and counting)
  - uses 1–4 bytes (codeword lengths: 8, 16, 24, or 32 bits)
  - Every ASCII character is encoded in 1 byte with leading bit `0`, followed by the 7 bits for ASCII
  - Non-ASCII charactters start with 1–4 `1`s indicating the total number of bytes, followed by a `0` and 3–5 bits.
    The remaining bytes each start with `10` followed by 6 bits.

Char. number range (hexadecimal)	UTF-8 octet sequence (binary)
`0000 0000 – 0000 007F`	`0xxxxxxx`
`0000 0080 – 0000 07FF`	`110xxxxx 10xxxxxx`
`0000 0800 – 0000 FFFF`	`1110xxxx 10xxxxxx 10xxxxxx`
`0001 0000 – 0010 FFFF`	`11110xxx 10xxxxxx 10xxxxxx 10xxxxxx`

For English text, most characters use only 8 bit,
but we can include any Unicode character, as well.

Pitfall in variable-length codes

- Suppose we have the following code:

c	a	n	b	s
$E(c)$	0	10	110	100

- Happily encode text S = banana with the coded text C = 1100100100

b a n a n a

Pitfall in variable-length codes

- Suppose we have the following code:

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↯ C = 1100100100 decodes **both** to banana and to bass: $\underbrace{\texttt{110}}_{\texttt{b}}\underbrace{\texttt{0}}_{\texttt{a}}\underbrace{\texttt{100}}_{\texttt{s}}\underbrace{\texttt{100}}_{\texttt{s}}$

⇝ not a valid code . . . (cannot tolerate ambiguity)

but how should we have known?

Pitfall in variable-length codes

- Suppose we have the following code:

c	a	n	b	s
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- Happily encode text S = `banana` with the coded text C = `1100100100`
  `b a n a n a`

ϟ C = `1100100100` decodes **both** to `banana` and to `bass`: `1100100100`
  `b a s s`

⇝ not a valid code . . . (cannot tolerate ambiguity)

but how should we have known?

$E(\mathtt{n}) = \mathtt{10}$ is a (proper) **prefix** of $E(\mathtt{s}) = \mathtt{100}$

⇝ Leaves decoder wondering whether to stop after reading `10` or continue!

⇝ Require a ***prefix-free*** code: No codeword is a prefix of another.

prefix-free $\Longrightarrow$ instantaneously decodable $\Longrightarrow$ uniquely decodable

Code tries

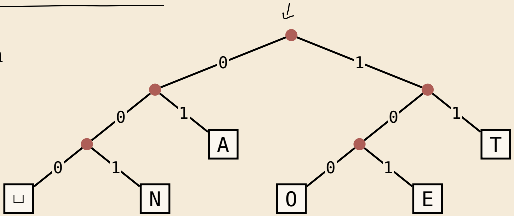
- From now on only consider prefix-free codes E: $E(c)$ is not a prefix of $E(c')$ for any $c, c' \in \Sigma_S$.

- **Example:**

c	A	E	N	O	T	␣
$E(c)$	01	101	001	100	11	000

Any prefix-free code corresponds to a ***(code) trie*** (trie of codewords) with characters of Σ_S at **leaves**.

no need for end-of-string symbols $ here (already prefix-free!)



- Encode AN␣ANT   01001
- Decode 11|100|000|101|01|11
  T O ␣ E A T

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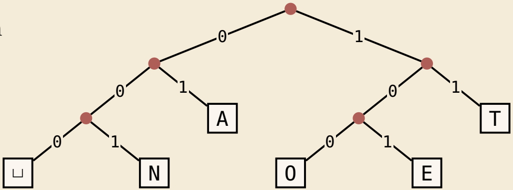

- Encode `AN␣ANT` $\rightarrow$ `010010000100111`
- Decode `111000001010111` $\rightarrow$ `TO␣EAT`

Who decodes the decoder?

- Depending on the application, we have to **store/transmit** the **used code**!
- We distinguish:
  - **fixed coding:** code agreed upon in advance, not transmitted (e. g., Morse, UTF-8)
  - **static coding:** code depends on message, but stays same for entire message; it must be transmitted (e. g., Huffman codes $\rightarrow$ next)
  - **adaptive coding:** code depends on message and changes during encoding; implicitly stored withing the message (e. g., LZW $\rightarrow$ below)

7.3 Huffman Codes

Character frequencies

- **Goal:** Find character encoding that produces short coded text
- Convention here: fix $\Sigma_C = \{0, 1\}$ (binary codes), abbreviate $\Sigma = \Sigma_S$,
- **Observation:** Some letters occur more often than others.

Typical English prose:

e	12.70%	**d**	4.25%	**p**	1.93%
t	9.06%	**l**	4.03%	**b**	1.49%
a	8.17%	**c**	2.78%	**v**	0.98%
o	7.51%	**u**	2.76%	**k**	0.77%
i	6.97%	**m**	2.41%	**j**	0.15%
n	6.75%	**w**	2.36%	**x**	0.15%
s	6.33%	**f**	2.23%	**q**	0.10%
h	6.09%	**g**	2.02%	**z**	0.07%
r	5.99%	**y**	1.97%		

$\rightsquigarrow$ Want shorter codes for more frequent characters!

Huffman coding

e. g. frequencies / probabilities

- **Given:** Σ and weights $w : \Sigma \to \mathbb{R}_{\geq 0}$
- **Goal:** prefix-free code E (= code trie) for Σ that minimizes coded text length

  i. e., a code trie minimizing $\displaystyle\sum_{c \in \Sigma} w(c) \cdot |E(c)|$

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- If we use $w(c)$ = #occurrences of c in S,
  this is the character encoding with smallest possible $|C|$

  $\rightsquigarrow$ best possible character-wise encoding

- Quite ambitious! *Is this efficiently possible?*

Huffman's algorithm

- Actually, yes! A greedy/myopic approach succeeds here.

Huffman's algorithm:

1. Find two characters $\mathtt{a}$, $\mathtt{b}$ with lowest weights.
   - We will encode them with the same prefix, plus one distinguishing bit, i. e., $E(\mathtt{a}) = u\mathtt{0}$ and $E(\mathtt{b}) = u\mathtt{1}$ for a bitstring $u \in \{0,1\}^\star$ (u to be determined)
2. (Conceptually) replace $\mathtt{a}$ and $\mathtt{b}$ by a single character "$\boxed{\mathtt{ab}}$" with $w(\boxed{\mathtt{ab}}) = w(\mathtt{a}) + w(\mathtt{b})$.
3. Recursively apply Huffman's algorithm on the smaller alphabet. This in particular determines $u = E(\boxed{\mathtt{ab}})$.

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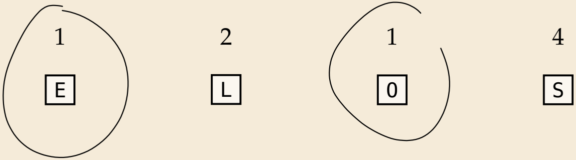
3. Recursively apply Huffman's algorithm on the smaller alphabet. This in particular determines $u = E(\boxed{\mathtt{ab}})$.

   $\sim \sigma$ iterations

- efficient implementation using a (min-oriented) ***priority queue***
  - start by inserting all characters with their weight as key
  - step 1 uses two `deleteMin` calls
  - step 2 inserts a new character with the sum of old weights as key

Huffman's algorithm – Example

- Example text: S = LOSSLESS $\rightsquigarrow$ $\Sigma_S = \{$E, L, O, S$\}$
- Character frequencies: E : 1, L : 2, O : 1, S : 4



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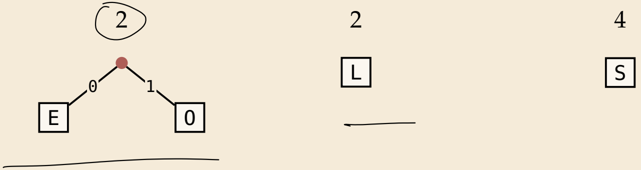

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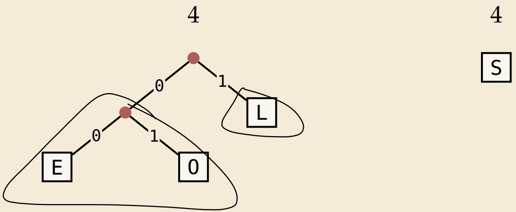

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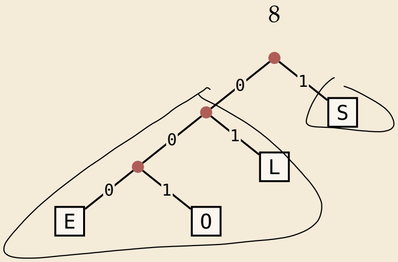

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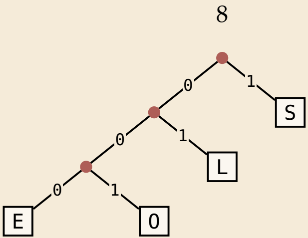

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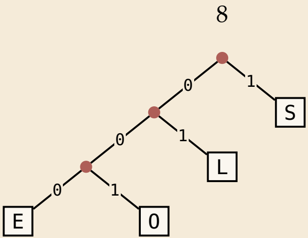

$\rightsquigarrow$ *Huffman tree* (code trie for Huffman code)

LOSSLESS $\to$ 01001110100011 compression ratio: $\frac{14}{8 \cdot \log 4} = \frac{14}{16} \approx 88\%$

Huffman tree – tie breaking

- The above procedure is ambiguous:
  - which characters to choose when weights are equal?
  - which subtree goes left, which goes right?

- For COMP 526: always use the following rule:

1. To break ties when selecting the two characters,
   first use the smallest letter according to the alphabetical order,
   or the tree containing the smallest alphabetical letter.
2. When combining two trees of different values,
   place the lower-valued tree on the left (corresponding to a `0`-bit).
3. When combining trees of equal value,
   place the one containing the smallest letter to the left.

Encoding with Huffman code

- The overall encoding procedure is as follows:
  - Pass 1: Count character frequencies in S
  - Construct Huffman code E (as above)
  - Store the Huffman code in C (details omitted)
  - Pass 2: Encode each character in S using E and append result to C

- Decoding works as follows:
  - Decode the Huffman code E from C. (details omitted)
  - Decode S character by character from C using the code trie.

- Note: Decoding is much simpler/faster!

Huffman code – Optimality

Theorem 7.1 (Optimality of Huffman's Algorithm)
Given Σ and $w : \Sigma \to \mathbb{R}_{\geq 0}$, Huffman's Algorithm computes codewords $E : \Sigma \to \{0,1\}^\star$ with minimal expected codeword length $\ell(E) = \sum_{c \in \Sigma} w(c) \cdot |E(c)|$ among all prefix-free codes for Σ. ◀

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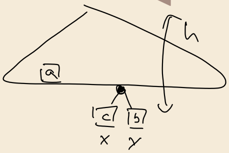
Proof sketch: by induction over $\sigma = |\Sigma| \geq 2$



- Given any optimal prefix-free code E^* (as its code trie).
- code trie $\rightsquigarrow$ $\exists$ two sibling leaves x, y at largest depth D
- swap characters in leaves to have two lowest-weight characters $\mathtt{a}$, $\mathtt{b}$ in x, y (that can only make ℓ smaller, so still optimal)

- any optimal code for $\Sigma' = \Sigma \setminus \{\mathtt{a}, \mathtt{b}\} \cup \{\boxed{\mathtt{ab}}\}$ yields optimal code for Σ by replacing leaf $\boxed{\mathtt{ab}}$ by internal node with children $\mathtt{a}$ and $\mathtt{b}$.

$\rightsquigarrow$ recursive call yields optimal code for Σ' by inductive hypothesis, so Huffman's algorithm finds optimal code for Σ. $\square$

7.4 Entropy

Entropy

Definition 7.2 (Entropy)

Given probabilities $p_1, \ldots, p_n$ (for outcomes $1, \ldots, n$ of a random variable), the *entropy* of the distribution is defined as

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$n = 6$ standard fair die $p_1 = p_2 = \cdots = p_6 = \frac{1}{6}$

$$\mathcal{H}(p_1, \ldots, p_6) = 6 \cdot \frac{1}{6} \cdot \lg(6) = \lg(6)$$

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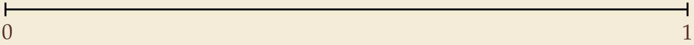
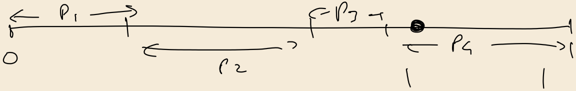


Entropy



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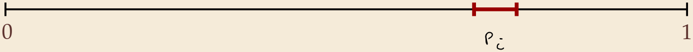

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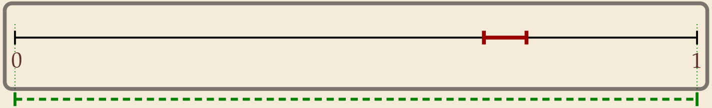

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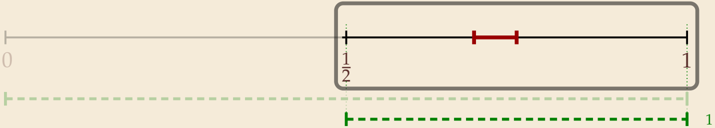

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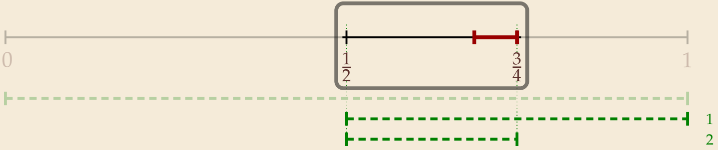

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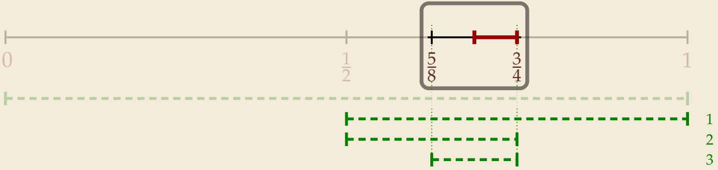

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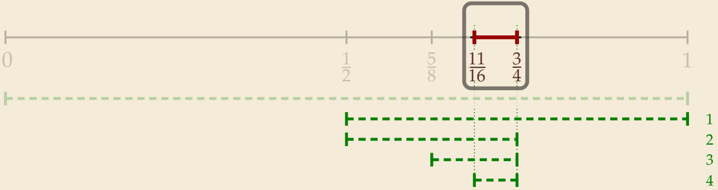

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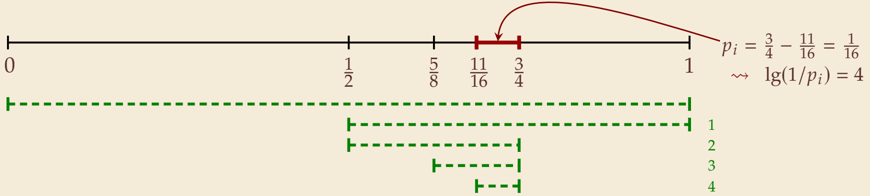

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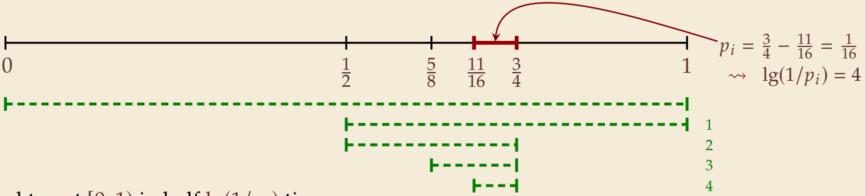

$\rightsquigarrow$ Need to cut $[0,1)$ in half $\lg(1/p_i)$ times

- more precisely: the expected number of bits (Yes/No questions) required to nail down the random value

Entropy and Huffman codes

- would ideally encode value i using $\lg(1/p_i)$ bits

  not always possible; cannot use codeword of 1.5 bits . . .

not as length of single codeword that is;
but can be possible *on average*!

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Theorem 7.3 (Entropy bounds for Huffman codes)

For any $\Sigma = \{a_1, \ldots, a_\sigma\}$ and $w : \Sigma \to \mathbb{R}_{>0}$ and its Huffman code E, we have

$$\boxed{\mathcal{H} \ \le\ \ell(E) \ \le\ \mathcal{H} + 1} \quad \text{where } \mathcal{H} = \mathcal{H}\left(\frac{w(a_1)}{W}, \ldots, \frac{w(a_\sigma)}{W}\right) \text{ and } W = w(a_1) + \cdots + w(a_\sigma).$$

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Proof sketch:

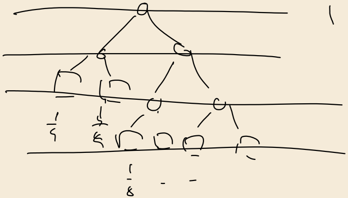
- $\ell(E) \ge \mathcal{H}$

  Any prefix-free code E induces weights $q_i = 2^{-|E(a_i)|}$.

  By *Kraft's Inequality*, we have $q_1 + \cdots + q_\sigma \le 1$.

  Hence we can apply *Gibb's Inequality* to get

$$\mathcal{H} \;=\; \sum_{i=1}^{\sigma} p_i \lg\left(\frac{1}{p_i}\right) \;\le\; \sum_{i=1}^{\sigma} p_i \lg\left(\frac{1}{q_i}\right) \;=\; \ell(E).$$



Entropy and Huffman codes [2]

Proof sketch (continued):

- $\ell(E) \le \mathcal{H} + 1$

  Set $q_i = 2^{-\lceil \lg(1/p_i) \rceil}$. We have $\displaystyle\sum_{i=1}^{\sigma} p_i \lg\left(\frac{1}{q_i}\right) = \sum_{i=1}^{\sigma} p_i \lceil \lg(1/p_i) \rceil \le \mathcal{H} + 1.$

We construct a code E' for Σ with $|E'(a_i)| \le \lg(1/q_i)$ as follows; w.l.o.g. assume $q_1 \le q_2 \le \cdots \le q_\sigma$

not covered in detail

- If $\sigma = 2$, E' uses a single bit each.
  Here, $q_i \le 1/2$, so $\lceil \lg(1/q_i) \rceil \ge 1 = |E'(a_i)|$ ✓
- If $\sigma \ge 3$, we merge a_1 and a_2 to $\boxed{a_1 a_2}$, assign it weight $2q_2$ and recurse.
  If $q_1 = q_2$, this is like Huffman; otherwise, q_1 is a unique smallest value and $q_2 + q_2 + \cdots + q_\sigma \le 1$.

  By the inductive hypothesis, we have $\left|E'(\boxed{a_1 a_2})\right| \le \lg\left(\frac{1}{2q_2}\right) = \lg\left(\frac{1}{q_2}\right) - 1.$

  By construction, $|E'(a_1)| = |E'(a_2)| = \left|E'(\boxed{a_1 a_2})\right| + 1$, so $|E'(a_1)| \le \lg(\frac{1}{q_1})$ and $|E'(a_2)| \le \lg(\frac{1}{q_2})$.

By optimality of E, we have $\displaystyle \ell(E) \le \ell(E') \le \sum_{i=1}^{\sigma} p_i \lg\left(\frac{1}{q_i}\right) \le \mathcal{H} + 1.$

Clicker Question

When does Huffman coding yield more efficient compression than a fixed-length character encoding?

A always

B when $\mathcal{H} \approx \lg(\sigma)$

C when $\mathcal{H} < \lg(\sigma)$

D when $\mathcal{H} < \lg(\sigma) - 1$

E when $\mathcal{H} \approx 1$

→ `sli.do/comp526`

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When does Huffman coding yield more efficient compression than a fixed-length character encoding?

- **A** always ✓
- **B** ~~when $\mathcal{H} \approx \lg(\sigma)$~~
- **C** ~~when $\mathcal{H} < \lg(\sigma)$~~
- **D** when $\mathcal{H} < \lg(\sigma) - 1$ ✓
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→ `sli.do/comp526`

Huffman coding – Discussion

- running time complexity: $O(\sigma \log \sigma)$ to construct code
  - build PQ + $\sigma \cdot$ (2 deleteMins and 1 insert)
  - can do $\Theta(\sigma)$ time when characters already sorted by weight
  - time for encoding text (after Huffman code done): $O(n + |C|)$
- many variations in use (tie-breaking rules, estimated frequencies, adaptive encoding, . . .)

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- many variations in use (tie-breaking rules, estimated frequencies, adaptive encoding, ...)

👍 optimal prefix-free character encoding

👍 very fast decoding

👎 needs 2 passes over source text for encoding
  - one-pass variants possible, but more complicated

👎 have to store code alongside with coded text

Part II

Compressing repetitive texts

Beyond Character Encoding

- Many "natural" texts show repetitive redundancy

```
All work and no play makes Jack a dull boy.  All work and no play makes Jack a dull
boy.  All work and no play makes Jack a dull boy.  All work and no play makes Jack
a dull boy.  All work and no play makes Jack a dull boy.  All work and no play makes
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  - ⇝ Huffman won't compression this very much

⇝ Have to encode whole ***phrases*** of S by a single codeword

7.5 Run-Length Encoding

Run-Length encoding

- simplest form of repetition: ***runs*** of characters
  same character repeated

```
0000000000000000000000000000000000000000
0000000000000000000000000000000000000000
0000000000000000000000000000000000000000
0001011001000001111110000000000011111000
0011111111100011111111110000001111111000
0011110110100011100011110000011100000000
0011000000000000000000111000111000000000
0011000000000000000000011001110000000000
0011000000000000000000011001110000000000
0011011000000000000000111001100111110000
0011111111000000000000111001111111111000
0011101111100000000001110001111100111100
0000000001110000000111000001110000001110
0000000001110000000110000001110000001100
0000000000110000000110000000110000001110
0000000000110000011100000001110000001100
0000000001110001110000000000110000001110
0000000001100001110000000000111000011100
0011011111100011110111010000111111111000
0111111111100011111111111100001111110000
0001011000000010100110010000001001000000
0000000000000000000000000000000000000000
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- here: only consider $\Sigma_S = \{0, 1\}$ (work on a binary representation)
  - can be extended for larger alphabets

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001101100000000000000111001100111110000
001111111100000000000111001111111111000
001110111110000000001110001111100111100
000000000111000000011100001110000001110
000000000111000000011000001110000001100
000000000011000000110000001100000001110
000000000011000001110000001110000001100
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$\rightsquigarrow$ **run-length encoding (RLE)**:
use runs as phrases: $S = \underbrace{\texttt{00000}}\;\underbrace{\texttt{111}}\;\underbrace{\texttt{0000}}$

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0011101111100000000001110001111100111100
0000000001110000000011100001110000001110
0000000001110000000011000001110000001100
0000000000110000000110000000110000001110
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- Example becomes: $0, 5, 3, 4$

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001110111110000000001110001111100111100
000000000111000000011100001110000001110
000000000111000000011000001110000001100
000000000011000000110000001100000001110
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- **Question**: How to encode a run length k in binary? (k can be arbitrarily large!)

Clicker Question

How would you encode a string that can we arbitrarily long?

→ `sli.do/comp526`

Elias codes

- Need a *prefix-free encoding* for $\mathbb{N} = \{1, 2, 3, \ldots, \}$
  - must allow arbitrarily large integers
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- Refinement: ***Elias gamma code***
  - Store the **length** ℓ of the binary representation in **unary**
  - Followed by the binary digits themselves
  - little tricks:
    - always $\ell \geq 1$, so store $\ell - 1$ instead
    - binary representation always starts with `1` $\rightsquigarrow$ don't need terminating `1` in unary

  $\rightsquigarrow$ Elias gamma code = $\ell - 1$ zeros, followed by binary representation

Examples: $1 \mapsto$ `1`, $3 \mapsto$ `011`, $5 \mapsto$ `00101`, $30 \mapsto$ `000011110`

Clicker Question

Decode the **first** number in Elias gamma code (at the beginning) of the following bitstream:

$$\underbrace{\underline{000}}_{\Rightarrow 4\ \text{bit}}\underbrace{1101}_{13\,=\,1101_2}11011100110.$$

→ sli.do/comp526

Run-length encoding – Examples

- Encoding:

  S = `1111111001000000000000000000011111111111`

  C = `1`

- Decoding:

  C = `00001101001001010`

  S =

Run-length encoding – Examples

- Encoding:

  S = `11111110010000000000000000000011111111111`

  $k = 7$

  C = `100111`

- Decoding:

  C = `00001101001001010`

  S =

Run-length encoding – Examples

- Encoding:

  S = `11111110010000000000000000000011111111111`

  $k = 2$

  C = `100111010`

- Decoding:

  C = `00001101001001010`

  S =

Run-length encoding – Examples

- Encoding:

  S = `11111110010000000000000000000011111111111`

  $k = 1$

  C = `1001110101`

- Decoding:

  C = `00001101001001010`

  S =

Run-length encoding – Examples

- Encoding:

  S = `1111111001``00000000000000000000``11111111111`

  $k = 20$

  C = `1001110101``000010100`

- Decoding:

  C = `00001101001001010`

  S =

Run-length encoding – Examples

- Encoding:
  $S =$ `111111100100000000000000000000011111111111`
  $k = 11$
  $C =$ `10011101010000101000001011`
- Decoding:
  $C =$ `00001101001001010`

  $S =$

Run-length encoding – Examples

- Encoding:
  S = `11111110010000000000000000000011111111111`

  C = `10011101010000101000001011`

  Compression ratio: $26/41 \approx 63\%$

- Decoding:
  C = `00001101001001010`

  S =

Run-length encoding – Examples

- Encoding:
  $S =$ `11111110010000000000000000000011111111111`

  $C =$ `1001110101000010100000101 1`

  Compression ratio: $26/41 \approx 63\%$

- Decoding:
  $C =$ `00001101001001010`

  $S =$

Run-length encoding – Examples

- Encoding:

  $S =$ `11111110010000000000000000000011111111111`

  $C =$ `10011101010000101000001011`

  Compression ratio: $26/41 \approx 63\%$

- Decoding:

  $C =$ `00001101001001010`

  $b = 0$

  $S =$

Run-length encoding – Examples

- Encoding:

  $S =$ `11111110010000000000000000000011111111111`

  $C =$ `10011101010000101000001011`

  Compression ratio: $26/41 \approx 63\%$

- Decoding:

  $C =$ `0000110100100101 0`

  $b = 0$

  $\ell = 3 + 1$

  $S =$

Run-length encoding – Examples

- Encoding:

  $S = $ `11111110010000000000000000000011111111111`

  $C = $ `10011101010000101000001011`

  Compression ratio: $26/41 \approx 63\%$

- Decoding:

  $C = $ `0000110100100101 0`

  $b = 0$

  $\ell = 3 + 1$

  $k = 13$

  $S = $ `0000000000000`

Run-length encoding – Examples

- Encoding:

  S = `11111110010000000000000000000011111111111`

  C = `10011101010000101000001011`

  Compression ratio: $26/41 \approx 63\%$

- Decoding:

  C = `00001101001001010`

  $b = 1$

  $\ell = 2 + 1$

  $k =$

  S = `0000000000000`

Run-length encoding – Examples

- Encoding:

  S = `11111110010000000000000000000011111111111`

  C = `10011101010000101000001011`

  Compression ratio: $26/41 \approx 63\%$

- Decoding:

  C = `00001101001001010`

  $b = 1$

  $\ell = 2 + 1$

  $k = 4$

  S = `00000000000001111`

Run-length encoding – Examples

- Encoding:

  $S = $ `11111110010000000000000000000011111111111`

  $C = $ `10011101010000101000001011`

  Compression ratio: $26/41 \approx 63\%$

- Decoding:

  $C = $ `00001101001001010`

  $b = 0$

  $\ell = 0 + 1$

  $k =$

  $S = $ `00000000000001111`

Run-length encoding – Examples

- Encoding:

  S = `11111110010000000000000000000011111111111`

  C = `10011101010000101000001011`

  Compression ratio: $26/41 \approx 63\%$

- Decoding:

  C = `00001101001001010`

  $b = 0$

  $\ell = 0 + 1$

  $k = 1$

  S = `000000000000011110`

Run-length encoding – Examples

- Encoding:

  $S =$ `11111110010000000000000000000001111111111`

  $C =$ `10011101010000101000001011`

  Compression ratio: $26/41 \approx 63\%$

- Decoding:

  $C =$ `00001101001001010`

  $b = 1$

  $\ell = 1 + 1$

  $k =$

  $S =$ `000000000000011110`

Run-length encoding – Examples

- Encoding:

  S = `11111110010000000000000000000011111111111`

  C = `10011101010000101000001011`

  Compression ratio: $26/41 \approx 63\%$

- Decoding:

  C = `000011010010010`$\color{red}{\texttt{10}}$

  $b = 1$

  $\ell = 1 + 1$

  $k = 2$

  S = `0000000000000111101`$\color{red}{\texttt{1}}$

Run-length encoding – Discussion

- extensions to larger alphabets possible (must store next character then)
- used in some image formats (e. g. TIFF)

Run-length encoding – Discussion

- extensions to larger alphabets possible (must store next character then)
- used in some image formats (e. g. TIFF)

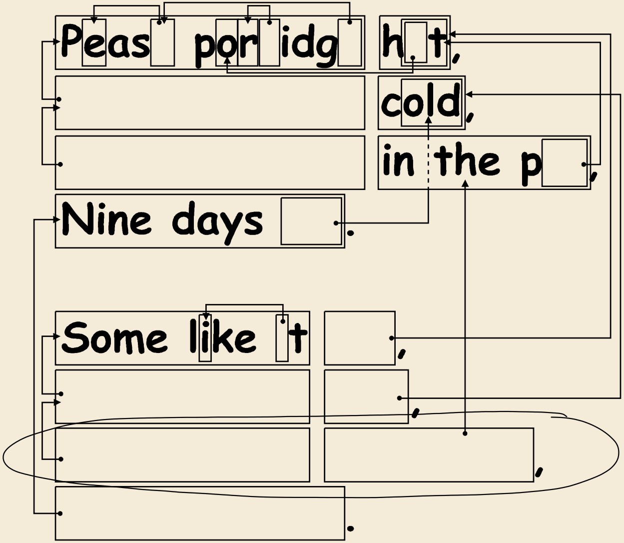
👍 fairly simple and fast

👍 can compress n bits to $\Theta(\log n)$!
for extreme case of constant number of runs

👎 negligible compression for many common types of data
- No compression until run lengths $k \geq 6$
- **expansion** for run length $k = 2$ or 6

7.6 Lempel-Ziv-Welch

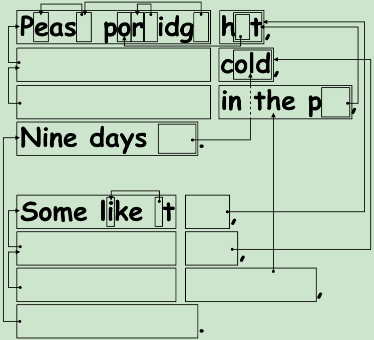
Warmup



https://classic.csunplugged.org/text-compression/

https://www.flickr.com/photos/quintanaroo/2742726346

Clicker Question



What is the **second-to-last line** of the poem to the left?

→ sli.do/comp526

Lempel-Ziv Compression

- Huffman and RLE mostly take advantage of frequent or repeated *single characters*.
- **Observation**: Certain *substrings* are much more frequent than others.
  - in English text: the, be, to, of, and, a, in, that, have, I
  - in HTML: "`<a href`", "`<img src`", "`<br/>`"

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- Huffman and RLE mostly take advantage of frequent or repeated *single characters*.
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  - in English text: the, be, to, of, and, a, in, that, have, I
  - in HTML: "`<a href`", "`<img src`", "`<br/>`"
- **Lempel-Ziv** stands for family of *adaptive* compression algorithms.
  - **Idea:** store repeated parts by reference!

  $\rightsquigarrow$ each codeword refers to
    - either a single character in Σ_S,
    - or a *substring* of S (that both encoder and decoder have already seen).

Lempel-Ziv Compression

- Huffman and RLE mostly take advantage of frequent or repeated *single characters*.
- **Observation**: Certain *substrings* are much more frequent than others.
  - in English text: the, be, to, of, and, a, in, that, have, I
  - in HTML: “<a href”, “<img src”, “
”
- **Lempel-Ziv** stands for family of *adaptive* compression algorithms.
  - **Idea:** store repeated parts by reference!

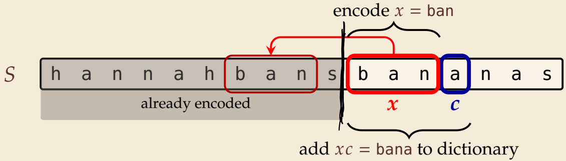
  $\leadsto$ each codeword refers to
    - either a single character in Σ_S,
    - or a *substring* of S (that both encoder and decoder have already seen).
  - Variants of Lempel-Ziv compression
    - “LZ77” Original version (“sliding window”)
      Derivatives: LZSS, LZFG, LZRW, LZP, DEFLATE, ...
      DEFLATE used in (pk)zip, gzip, PNG
    - “LZ78” Second (slightly improved) version
      Derivatives: LZW, LZMW, LZAP, LZY, ...
      LZW used in compress, GIF

Lempel-Ziv-Welch

- here: ***Lempel-Ziv-Welch (LZW)*** (arguably the "cleanest" variant of Lempel-Ziv)
- ***variable-to-fixed*** **encoding**
  - all codewords have k bits (typical: $k = 12$) $\leadsto$ fixed-length
  - but they represent a variable portion of the source text!

Lempel-Ziv-Welch

- here: ***Lempel-Ziv-Welch (LZW)*** (arguably the "cleanest" variant of Lempel-Ziv)
- ***variable-to-fixed* encoding**
  - all codewords have k bits (typical: $k = 12$) $\rightsquigarrow$ fixed-length
  - but they represent a variable portion of the source text!
- maintain a **dictionary** D with 2^k entries $\rightsquigarrow$ codewords = indices in dictionary
  - initially, first $|\Sigma_S|$ entries encode single characters (rest is empty)
  - **add** a new entry to D **after each step**:
  - **Encoding:** after encoding a substring x of S,
    add xc to D where c is the character that follows x in S.



$\rightsquigarrow$ new codeword in D

- D actually stores codewords for x and c, not the expanded string

LZW encoding – Example

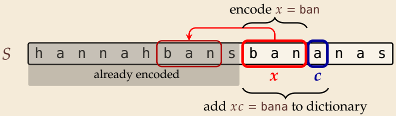
Input: `YO!␣YOU!␣YOUR␣YOYO!` Σ_S = ASCII character set (0–127)

$C =$

$D =$

Code	String
. . .	
32	␣
33	!
. . .	
79	O
. . .	
82	R
. . .	
85	U
. . .	
89	Y
. . .	

Code	String
128	
129	
130	
131	
132	
133	
134	
135	
136	
137	
138	
139	



LZW encoding – Example

Input: `YO!␣YOU!␣YOUR␣YOYO!` Σ_S = ASCII character set (0–127)

Y

$C = 89$

$D =$

Code	String
...	
32	␣
33	!
...	
79	O
...	
82	R
...	
85	U
...	
89	Y
...	

Code	String
128	
129	
130	
131	
132	
133	
134	
135	
136	
137	
138	
139	

encode x = ban

S h a n n a h b a n s b a n a n a s

already encoded

x c

add xc = bana to dictionary

LZW encoding – Example

Input: Y0!␣Y0U!␣Y0UR␣Y0Y0! Σ_S = ASCII character set (0–127)

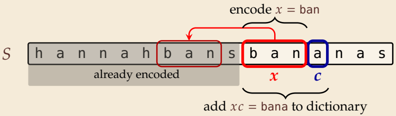
Y

C = 89

D =

Code	String
...	
32	␣
33	!
...	
79	0
...	
82	R
...	
85	U
...	
89	Y
...	

Code	String
128	Y0
129	
130	
131	
132	
133	
134	
135	
136	
137	
138	
139	



LZW encoding – Example

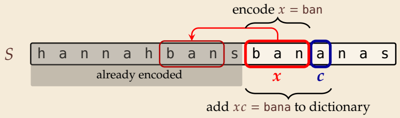
Input: `YO!␣YOU!␣YOUR␣YOYO!` Σ_S = ASCII character set (0–127)

	Y	O
$C =$	89	79

$D =$

Code	String
...	
32	␣
33	!
...	
79	O
...	
82	R
...	
85	U
...	
89	Y
...	

Code	String
128	YO
129	
130	
131	
132	
133	
134	
135	
136	
137	
138	
139	



LZW encoding – Example

Input: `YO!␣YOU!␣YOUR␣YOYO!`

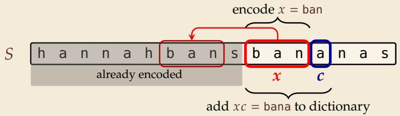
Σ_S = ASCII character set (0–127)

	Y	O
$C =$	89	79

$D =$

Code	String
...	
32	␣
33	!
...	
79	O
...	
82	R
...	
85	U
...	
89	Y
...	

Code	String
128	YO
129	O!
130	
131	
132	
133	
134	
135	
136	
137	
138	
139	



LZW encoding – Example

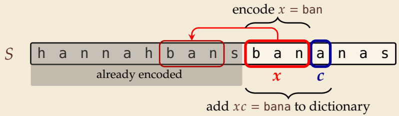
Input: `YO!␣YOU!␣YOUR␣YOYO!` Σ_S = ASCII character set (0–127)

	Y	O	!
C =	89	79	33

D =

Code	String
...	
32	␣
33	!
...	
79	O
...	
82	R
...	
85	U
...	
89	Y
...	

Code	String
128	YO
129	O!
130	
131	
132	
133	
134	
135	
136	
137	
138	
139	



LZW encoding – Example

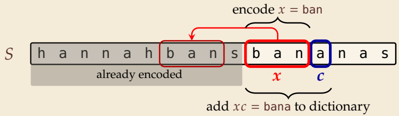
Input: `YO!␣YOU!␣YOUR␣YOYO!` Σ_S = ASCII character set (0–127)

	Y	O	!
C =	89	79	33

D =

Code	String
...	
32	␣
33	!
...	
79	O
...	
82	R
...	
85	U
...	
89	Y
...	

Code	String
128	YO
129	O!
130	!␣
131	
132	
133	
134	
135	
136	
137	
138	
139	



LZW encoding – Example

Input: `YO!␣YOU!␣YOUR␣YOYO!`

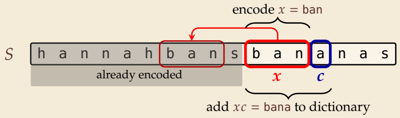
Σ_S = ASCII character set (0–127)

	Y	O	!	␣
$C =$	89	79	33	32

$D =$

Code	String
. . .	
32	␣
33	!
. . .	
79	O
. . .	
82	R
. . .	
85	U
. . .	
89	Y
. . .	

Code	String
128	YO
129	O!
130	!␣
131	
132	
133	
134	
135	
136	
137	
138	
139	



LZW encoding – Example

Input: YO!␣YOU!␣YOUR␣YOYO!

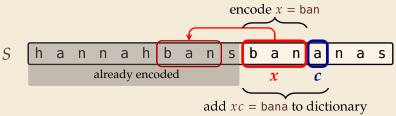
Σ_S = ASCII character set (0–127)

	Y	O	!	␣
$C =$	89	79	33	32

$D =$

Code	String
...	
32	␣
33	!
...	
79	O
...	
82	R
...	
85	U
...	
89	Y
...	

Code	String
128	YO
129	O!
130	!␣
131	␣Y
132	
133	
134	
135	
136	
137	
138	
139	



LZW encoding – Example

Input: `YO!␣YOU!␣YOUR␣YOYO!`

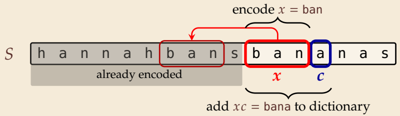
Σ_S = ASCII character set (0–127)

	Y	O	!	␣	YO
$C =$	89	79	33	32	128

$D =$

Code	String
. . .	
32	␣
33	!
. . .	
79	O
. . .	
82	R
. . .	
85	U
. . .	
89	Y
. . .	

Code	String
128	YO
129	O!
130	!␣
131	␣Y
132	
133	
134	
135	
136	
137	
138	
139	



LZW encoding – Example

Input: `YO!␣YOU!␣YOUR␣YOYO!`

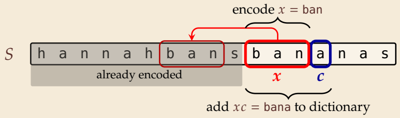
Σ_S = ASCII character set (0–127)

	Y	O	!	␣	YO
$C =$	89	79	33	32	128

$D =$

Code	String
...	
32	␣
33	!
...	
79	O
...	
82	R
...	
85	U
...	
89	Y
...	

Code	String
128	YO
129	O!
130	!␣
131	␣Y
132	YOU
133	
134	
135	
136	
137	
138	
139	



LZW encoding – Example

Input: `YO!␣YOU!␣YOUR␣YOYO!`

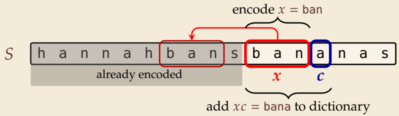
Σ_S = ASCII character set (0–127)

	Y	O	!	␣	YO	U
$C =$	89	79	33	32	128	85

$D =$

Code	String
...	
32	␣
33	!
...	
79	O
...	
82	R
...	
85	U
...	
89	Y
...	

Code	String
128	YO
129	O!
130	!␣
131	␣Y
132	YOU
133	
134	
135	
136	
137	
138	
139	



LZW encoding – Example

Input: `YO!␣YOU!␣YOUR␣YOYO!`

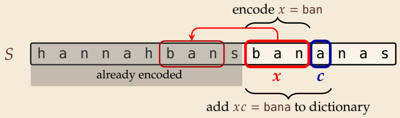
Σ_S = ASCII character set (0–127)

	Y	O	!	␣	YO	U
$C =$	89	79	33	32	128	85

$D =$

Code	String
. . .	
32	␣
33	!
. . .	
79	O
. . .	
82	R
. . .	
85	U
. . .	
89	Y
. . .	

Code	String
128	YO
129	O!
130	!␣
131	␣Y
132	YOU
133	U!
134	
135	
136	
137	
138	
139	



LZW encoding – Example

Input: `YO!␣YOU!␣YOUR␣YOYO!`

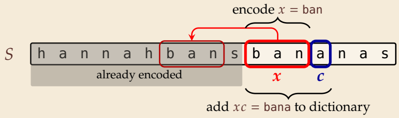
Σ_S = ASCII character set (0–127)

	Y	O	!	␣	YO	U	!␣
C =	89	79	33	32	128	85	130

D =

Code	String
...	
32	␣
33	!
...	
79	O
...	
82	R
...	
85	U
...	
89	Y
...	

Code	String
128	YO
129	O!
130	!␣
131	␣Y
132	YOU
133	U!
134	
135	
136	
137	
138	
139	



LZW encoding – Example

Input: `YO!␣YOU!␣YOUR␣YOYO!`

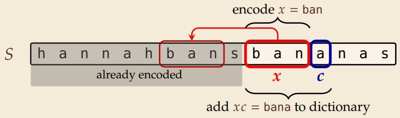
Σ_S = ASCII character set (0–127)

	Y	O	!	␣	YO	U	!␣
$C =$	89	79	33	32	128	85	130

$D =$

Code	String
...	
32	␣
33	!
...	
79	O
...	
82	R
...	
85	U
...	
89	Y
...	

Code	String
128	YO
129	O!
130	!␣
131	␣Y
132	YOU
133	U!
134	!␣Y
135	
136	
137	
138	
139	



LZW encoding – Example

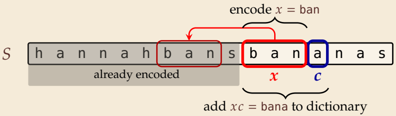
Input: `YO!␣YOU!␣YOUR␣YOYO!` $\qquad \Sigma_S$ = ASCII character set (0–127)

	Y	O	!	␣	YO	U	!␣	YOU
$C =$	89	79	33	32	128	85	130	132

$D =$

Code	String
...	
32	␣
33	!
...	
79	O
...	
82	R
...	
85	U
...	
89	Y
...	

Code	String
128	YO
129	O!
130	!␣
131	␣Y
132	YOU
133	U!
134	!␣Y
135	
136	
137	
138	
139	



LZW encoding – Example

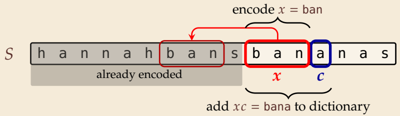
Input: `YO!␣YOU!␣YOUR␣YOYO!` $\qquad \Sigma_S$ = ASCII character set (0–127)

	Y	O	!	␣	YO	U	!␣	YOU
$C =$	89	79	33	32	128	85	130	132

$D =$

Code	String
...	
32	␣
33	!
...	
79	O
...	
82	R
...	
85	U
...	
89	Y
...	

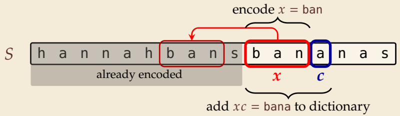
Code	String
128	YO
129	O!
130	!␣
131	␣Y
132	YOU
133	U!
134	!␣Y
135	YOUR
136	
137	
138	
139	



LZW encoding – Example

Input: `YO!␣YOU!␣YOUR␣YOYO!` Σ_S = ASCII character set (0–127)

	Y	O	!	␣	YO	U	!␣	YOU	R
$C =$	89	79	33	32	128	85	130	132	82



$D =$

Code	String
...	
32	␣
33	!
...	
79	O
...	
82	R
...	
85	U
...	
89	Y
...	

Code	String
128	YO
129	O!
130	!␣
131	␣Y
132	YOU
133	U!
134	!␣Y
135	YOUR
136	
137	
138	
139	

LZW encoding – Example

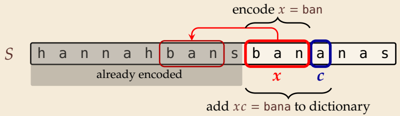
Input: `YO!␣YOU!␣YOUR␣YOYO!` Σ_S = ASCII character set (0–127)

	Y	O	!	␣	YO	U	!␣	YOU	R
$C =$	89	79	33	32	128	85	130	132	82

$D =$

Code	String
...	
32	␣
33	!
...	
79	O
...	
82	R
...	
85	U
...	
89	Y
...	

Code	String
128	YO
129	O!
130	!␣
131	␣Y
132	YOU
133	U!
134	!␣Y
135	YOUR
136	R␣
137	
138	
139	



LZW encoding – Example

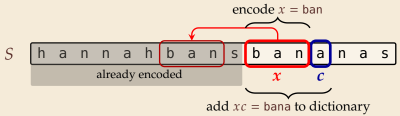
Input: `YO!␣YOU!␣YOUR␣YOYO!` $\qquad \Sigma_S$ = ASCII character set (0–127)

	Y	O	!	␣	YO	U	!␣	YOU	R	␣Y
$C =$	89	79	33	32	128	85	130	132	82	131

$D =$

Code	String
...	
32	␣
33	!
...	
79	O
...	
82	R
...	
85	U
...	
89	Y
...	

Code	String
128	YO
129	O!
130	!␣
131	␣Y
132	YOU
133	U!
134	!␣Y
135	YOUR
136	R␣
137	
138	
139	



LZW encoding – Example

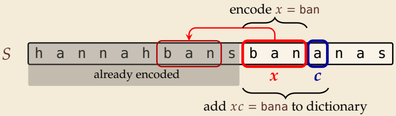
Input: `YO!␣YOU!␣YOUR␣YOYO!` Σ_S = ASCII character set (0–127)

	Y	O	!	␣	YO	U	!␣	YOU	R	␣Y
$C =$	89	79	33	32	128	85	130	132	82	131

$D =$

Code	String
...	
32	␣
33	!
...	
79	O
...	
82	R
...	
85	U
...	
89	Y
...	

Code	String
128	YO
129	O!
130	!␣
131	␣Y
132	YOU
133	U!
134	!␣Y
135	YOUR
136	R␣
137	␣YO
138	
139	



LZW encoding – Example

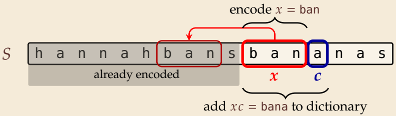
Input: `YO!␣YOU!␣YOUR␣YOYO!` Σ_S = ASCII character set (0–127)

	Y	O	!	␣	YO	U	!␣	YOU	R	␣Y	O
$C =$	89	79	33	32	128	85	130	132	82	131	79

$D =$

Code	String
...	
32	␣
33	!
...	
79	O
...	
82	R
...	
85	U
...	
89	Y
...	

Code	String
128	YO
129	O!
130	!␣
131	␣Y
132	YOU
133	U!
134	!␣Y
135	YOUR
136	R␣
137	␣YO
138	
139	



LZW encoding – Example

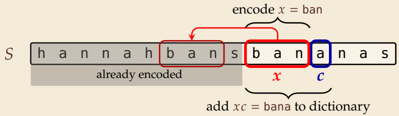
Input: `YO!␣YOU!␣YOUR␣YOYO!` Σ_S = ASCII character set (0–127)

	Y	O	!	␣	YO	U	!␣	YOU	R	␣Y	O
$C =$	89	79	33	32	128	85	130	132	82	131	79

$D =$

Code	String
...	
32	␣
33	!
...	
79	O
...	
82	R
...	
85	U
...	
89	Y
...	

Code	String
128	YO
129	O!
130	!␣
131	␣Y
132	YOU
133	U!
134	!␣Y
135	YOUR
136	R␣
137	␣YO
138	OY
139	



LZW encoding – Example

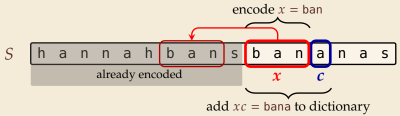
Input: `YO!␣YOU!␣YOUR␣YOYO!` Σ_S = ASCII character set (0–127)

	Y	O	!	␣	YO	U	!␣	YOU	R	␣Y	O	YO
$C =$	89	79	33	32	128	85	130	132	82	131	79	128

$D =$

Code	String
...	
32	␣
33	!
...	
79	O
...	
82	R
...	
85	U
...	
89	Y
...	

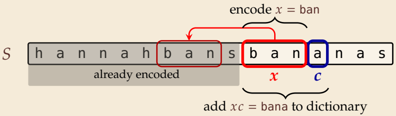
Code	String
128	YO
129	O!
130	!␣
131	␣Y
132	YOU
133	U!
134	!␣Y
135	YOUR
136	R␣
137	␣YO
138	OY
139	



LZW encoding – Example

Input: `YO!␣YOU!␣YOUR␣YOYO!` $\quad \Sigma_S$ = ASCII character set (0–127)

	Y	O	!	␣	YO	U	!␣	YOU	R	␣Y	O	YO
$C =$	89	79	33	32	128	85	130	132	82	131	79	128



$D =$

Code	String
...	
32	␣
33	!
...	
79	O
...	
82	R
...	
85	U
...	
89	Y
...	

Code	String
128	YO
129	O!
130	!␣
131	␣Y
132	YOU
133	U!
134	!␣Y
135	YOUR
136	R␣
137	␣YO
138	OY
139	YO!

LZW encoding – Example

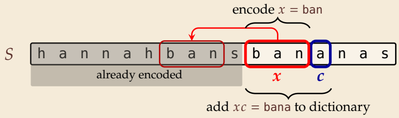
Input: `YO!␣YOU!␣YOUR␣YOYO!` Σ_S = ASCII character set (0–127)

	Y	O	!	␣	YO	U	!␣	YOU	R	␣Y	O	YO	!
$C =$	89	79	33	32	128	85	130	132	82	131	79	128	33

$D =$

Code	String
. . .	
32	␣
33	!
. . .	
79	O
. . .	
82	R
. . .	
85	U
. . .	
89	Y
. . .	

Code	String
128	YO
129	O!
130	!␣
131	␣Y
132	YOU
133	U!
134	!␣Y
135	YOUR
136	R␣
137	␣YO
138	OY
139	YO!



LZW encoding – Code

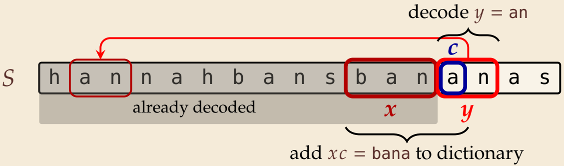
```
procedure LZWencode(S[0..n))
    x := ε // previous phrase, initially empty
    C := ε // output, initially empty
    D := dictionary, initialized with codes for c ∈ Σ_S // stored as trie
    k := |Σ_S| // next free codeword
    for i := 0, . . . , n − 1 do
        c := S[i]
        if D.containsKey(xc) then
            x := xc
        else
            C := C · D.get(x) // append codeword for x
            D.put(xc, k) // add xc to D, assigning next free codeword
            k := k + 1;  x := c
    end for
    C := C · D.get(x)
    return C
```

7.7 Lempel-Ziv-Welch Decoding

LZW decoding

- Decoder has to replay the process of growing the dictionary!

⇝ **Decoding:**
after decoding a substring y of S, add xc to D,
where x is previously encoded/decoded substring of S,
and $c = y[0]$ (first character of y)



⇝ Note: only start adding to D after *second* substring of S is decoded

LZW decoding – Example

- Same idea: build dictionary while reading string.
- Example: 67 65 78 32 66 129 133

$D =$

Code #	String
...	
32	␣
...	
...	
65	A
66	B
67	C
...	
78	N
...	
83	S
...	

input	decodes to	Code #	String (human)	String (computer)

LZW decoding – Example

- Same idea: build dictionary while reading string.
- Example: 67 65 78 32 66 129 133

$D =$

Code #	String
...	
32	␣
...	
...	
65	A
66	B
67	C
...	
78	N
...	
83	S
...	

input	decodes to	Code #	String (human)	String (computer)
67	C			

LZW decoding – Example

- Same idea: build dictionary while reading string.
- Example: 67 65 78 32 66 129 133

$x = C \quad y = A \quad x\,y[0] = CA$

$D =$

Code #	String
...	
32	␣
...	
...	
65	A
66	B
67	C
...	
78	N
...	
83	S
...	

input	decodes to	Code #	String (human)	String (computer)
67	C			
65	A	128	CA	67, A

LZW decoding – Example

- Same idea: build dictionary while reading string.
- Example: 67 65 78 32 66 129 133

$x = A \quad y = N \quad \leadsto AN$

$D =$

Code #	String
...	
32	␣
...	
...	
65	A
66	B
67	C
...	
78	N
...	
83	S
...	

input	decodes to	Code #	String (human)	String (computer)
67	C			
65	A	128	CA	67, A
78	N	129	AN	65, N

LZW decoding – Example

- Same idea: build dictionary while reading string.
- Example: 67 65 78 32 66 129 133

$D =$

Code #	String
. . .	
32	␣
. . .	
. . .	
65	A
66	B
67	C
. . .	
78	N
. . .	
83	S
. . .	

input	decodes to	Code #	String (human)	String (computer)
67	C			
65	A	128	CA	67, A
78	N	129	AN	65, N
32	␣	130	N␣	78, ␣

LZW decoding – Example

- Same idea: build dictionary while reading string.
- Example: 67 65 78 32 66 129 133

$D =$

Code #	String
...	
32	␣
...	
...	
65	A
66	B
67	C
...	
78	N
...	
83	S
...	

input	decodes to	Code #	String (human)	String (computer)
67	C			
65	A	128	CA	67, A
78	N	129	AN	65, N
32	␣	130	N␣	78, ␣
66	B	131	␣B	32, B

LZW decoding – Example

- Same idea: build dictionary while reading string.
- Example: 67 65 78 32 66 129 133

$x = B \quad y = AN \quad BA$

$D =$

Code #	String
...	
32	␣
...	
...	
65	A
66	B
67	C
...	
78	N
...	
83	S
...	

input	decodes to	Code #	String (human)	String (computer)
67	C			
65	A	128	CA	67, A
78	N	129	AN	65, N
32	␣	130	N␣	78, ␣
66	B	131	␣B	32, B
129	AN	132	BA	66, A

LZW decoding – Example

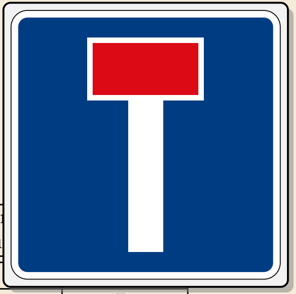
- Same idea: build dictionary while reading string.
- Example: 67 65 78 32 66 129 133

$D =$

Code #	String
...	
32	␣
...	
...	
65	A
66	B
67	C
...	
78	N
...	
83	S
...	

input	decodes to	Code #	String (human)	String (computer)
67	C			
65	A	128	CA	67, A
78	N	129	AN	65, N
32	␣	130	N␣	78, ␣
66	B	131	␣B	32, B
129	AN	132	BA	66, A
133	???	133		

LZW decoding – Example



- Same idea: build dictionary while reading string.
- Example: 67 65 78 32 66 129 133

$D =$

Code #	String
...	
32	␣
...	
...	
65	A
66	B
67	C
...	
78	N
...	
83	S
...	

input	decodes to	Code #	St (hu	
67	C			
65	A	128	CA	67, A
78	N	129	AN	65, N
32	␣	130	N␣	78, ␣
66	B	131	␣B	32, B
129	AN	132	BA	66, A
133	???	133		

LZW decoding – Bootstrapping

- example: Want to decode 133, but not yet in dictionary!

⚠ decoder is "one step behind" in creating dictionary

LZW decoding – Bootstrapping

- example: Want to decode 133, but not yet in dictionary!

⚠ decoder is "one step behind" in creating dictionary

⇝ problem occurs if *we want to use a code* that we are *just about to build*.

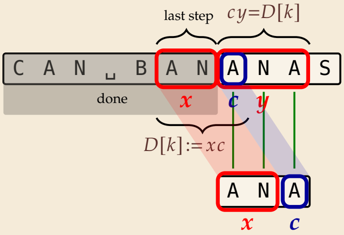
LZW decoding – Bootstrapping

- example: Want to decode 133, but not yet in dictionary!

⚠ decoder is "one step behind" in creating dictionary

⇝ problem occurs if *we want to use a code* that we are *just about to build*.

- But then we actually know what is going on:
  - Situation: decode using k in the step that will define k.
  - decoder knows last phrase x, needs phrase $y = D[k] = xc$.



1. en/decode x.

2. store $D[k] := xc$

3. next phrase y equals $D[k]$

⇝ $D[k] = xc = x \cdot \underline{x[0]}$ (all known)

LZW decoding – Code

procedure LZWdecode($C[0..m)$)
  D := dictionary $[0..2^d) \to \Sigma_S^+$, initialized with codes for $c \in \Sigma_S$ *// stored as array*
  $k := |\Sigma_S|$ *// next unused codeword*
  $q := C[0]$ *// first codeword*
  $y := D[q]$ *// lookup meaning of q in D*
  $S := y$ *// output, initially first phrase*
  for $j := 1, \ldots, m-1$ **do**
    $x := y$ *// remember last decoded phrase*
    $q := C[j]$ *// next codeword*
    if $q == k$ **then**
      $y := x \cdot x[0]$ *// bootstrap case*
    else
      $y := D[q]$
    $S := S \cdot y$ *// append decoded phrase*
    $D[k] := x \cdot y[0]$ *// store new phrase*
    $k := k + 1$
  end for
  return S

LZW decoding – Example continued

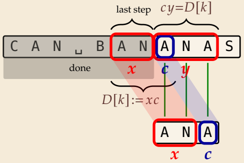
- Example: 67 65 78 32 66 129 133 83

$x = AN$ ANA new codeword

$D =$

Code #	String
...	
32	␣
...	
...	
65	A
66	B
67	C
...	
78	N
...	
83	S
...	

input	decodes to	Code #	String (human)	String (computer)
67	C			
65	A	128	CA	67, A
78	N	129	AN	65, N
32	␣	130	N␣	78, ␣
66	B	131	␣B	32, B
129	AN	132	BA	66, A
133	ANA	133	ANA	129, A



1. en/decode x.
2. store $D[k] := xc$
3. next phrase y equals $D[k]$

$\rightsquigarrow D[k] = xc = x \cdot x[0]$ (all known)

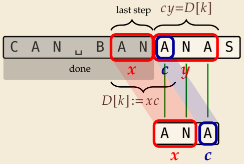
LZW decoding – Example continued

- Example: 67 65 78 32 66 129 133 83

$D =$

Code #	String
...	
32	␣
...	
...	
65	A
66	B
67	C
...	
78	N
...	
83	S
...	

input	decodes to	Code #	String (human)	String (computer)
67	C			
65	A	128	CA	67, A
78	N	129	AN	65, N
32	␣	130	N␣	78, ␣
66	B	131	␣B	32, B
129	AN	132	BA	66, A
133	ANA	133	ANA	129, A
83	S	134	ANAS	133, S



1. en/decode x.

2. store $D[k] := xc$

3. next phrase y equals $D[k]$
   $\rightsquigarrow$ $D[k] = xc = x \cdot x[0]$ (all known)

Clicker Question

How many phrases will LZW create on $S = \texttt{a}^n$, a run of n copies of $\texttt{a}$s?

A $\sim n$

B $\sim n/2$

C $\sim n/4$

D $\Theta(n/\log n)$

E $\Theta(\sqrt{n})$

F $\Theta(\log n)$

G $\Theta(\log\log n)$

H 2

I 1

→ sli.do/comp526

Clicker Question

$$\frac{k^2}{2} \sim \sum_{i=1}^{k} i \geq n$$

a a a a a a a a a a a a a

How many phrases will LZW create on $S = \mathtt{a}^n$, a run of n copies of as?

- **A** ~~$\sim n$~~
- **B** ~~$\sim n/2$~~
- **C** ~~$\sim n/4$~~
- **D** ~~$\Theta(n/\log n)$~~
- **E** $\Theta(\sqrt{n})$ ✓
- **F** ~~$\Theta(\log n)$~~
- **G** ~~$\Theta(\log\log n)$~~
- **H** ~~2~~
- **I** ~~1~~

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LZW – Discussion

- As presented, LZW uses coded alphabet $\Sigma_C = [0..2^d)$.
  - $\rightsquigarrow$ use another encoding for code numbers $\mapsto$ binary, e. g., Huffman
- need a rule when dictionary is full; different options:
  - increment d $\rightsquigarrow$ longer codewords
  - "flush" dictionary and start from scratch $\rightsquigarrow$ limits extra space usage
  - often: reserve a codeword to trigger flush at any time
- encoding and decoding both run in linear time (assuming $|\Sigma_S|$ constant)

LZW – Discussion

- As presented, LZW uses coded alphabet $\Sigma_C = [0..2^d)$.
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  - increment d $\rightsquigarrow$ longer codewords
  - "flush" dictionary and start from scratch $\rightsquigarrow$ limits extra space usage
  - often: reserve a codeword to trigger flush at any time
- encoding and decoding both run in linear time (assuming $|\Sigma_S|$ constant)

👍 fast encoding & decoding

👍 works in streaming model (no random access, no backtrack on input needed)

👍 significant compression for many types of data

👎 captures only local repetitions (with bounded dictionary)

Compression summary

Huffman codes	Run-length encoding	Lempel-Ziv-Welch
fixed-to-variable	variable-to-variable	variable-to-fixed
2-pass	1-pass	1-pass
must send dictionary	can be worse than ASCII	can be worse than ASCII
60% compression on English text	bad on text	45% compression on English text
optimal binary character encopding	good on long runs (e.g., pictures)	good on English text
rarely used directly	rarely used directly	frequently used
part of pkzip, JPEG, MP3	fax machines, old picture-formats	GIF, part of PDF, Unix compress

Part III

Text Transforms

Text transformations

- compression is effective is we have one the following:
  - long runs $\rightsquigarrow$ RLE
  - frequently used characters $\rightsquigarrow$ Huffman
  - many (local) repeated substrings $\rightsquigarrow$ LZW

Text transformations

- compression is effective is we have one the following:
  - long runs $\rightsquigarrow$ RLE
  - frequently used characters $\rightsquigarrow$ Huffman
  - many (local) repeated substrings $\rightsquigarrow$ LZW
- but methods can be frustratingly "blind" to other "obvious" redundancies
  - LZW: repetition too distant ϟ dictionary already flushed
  - Huffman: changing probabilities (local clusters) ϟ averaged out globally
  - RLE: run of alternating pairs of characters ϟ not a run

Text transformations

- compression is effective is we have one the following:
  - long runs $\leadsto$ RLE
  - frequently used characters $\leadsto$ Huffman
  - many (local) repeated substrings $\leadsto$ LZW
- but methods can be frustratingly "blind" to other "obvious" redundancies
  - LZW: repetition too distant $\lightning$ dictionary already flushed
  - Huffman: changing probabilities (local clusters) $\lightning$ averaged out globally
  - RLE: run of alternating pairs of characters $\lightning$ not a run
- Enter: **text transformations**
  - invertible functions of text
  - do not by themselves reduce the space usage
  - but help compressors "see" existing redundancy

$\leadsto$ use as pre-/postprocessing in compression pipeline

7.8 Move-to-Front Transformation

Move to Front

- ***Move to Front (MTF)*** is a heuristic for *self-adjusting linked lists*
  - unsorted linked list of objects
  - whenever an element is accessed, it is moved to the front of the list (leaving the relative order of other elements unchanged)
  - $\rightsquigarrow$ list "learns" probabilities of access to objects makes access to frequently requested ones cheaper

Move to Front

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  - $\rightsquigarrow$ list "learns" probabilities of access to objects makes access to frequently requested ones cheaper

- Here: use such a list for storing source alphabet Σ_S
  - to encode c, access it in list
  - encode c using its (old) position in list
  - then apply MTF to the list
  - $\rightsquigarrow$ codewords are integers, i. e., $\Sigma_C = [0..\sigma)$

Move to Front

- ***Move to Front (MTF)*** is a heuristic for *self-adjusting linked lists*
  - unsorted linked list of objects
  - whenever an element is accessed, it is moved to the front of the list (leaving the relative order of other elements unchanged)

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- Here: use such a list for storing source alphabet Σ_S
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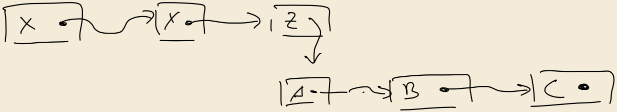
  - encode c using its (old) position in list
  - then apply MTF to the list

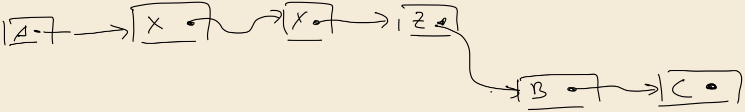
  $\rightsquigarrow$ codewords are integers, i. e., $\Sigma_C = [0..\sigma)$

$\rightsquigarrow$ clusters of few characters $\rightsquigarrow$ many small numbers

Clicker Question



Assume a MTF list currently contains the items `X Y Z A B C`, and we now access `A`. What is the list content after the MTF rule has been applied?



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MTF – Code

- **Transform (encode):**

procedure MTF–encode($S[0..n)$)
    L := list containing Σ_S (sorted order)
    $C := \varepsilon$
    for $i := 0, \ldots, n-1$ **do**
        $c := S[i]$
        p := position of c **in** L
        $C := C \cdot p$
        Move c to front of L
    end for
    return C

- **Inverse transform (decode):**

procedure MTF–decode($C[0..m)$)
    L := list containing Σ_S (sorted order)
    $S := \varepsilon$
    for $j := 0, \ldots, m-1$ **do**
        $p := C[j]$
        c := character at position p **in** L
        $S := S \cdot c$
        Move c to front of L
    end for
    return S

- Important: encoding and decoding produce same accesses to list

MTF – Example

0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z

$S =$ `INEFFICIENCIES`

$C =$

MTF – Example

0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z

S = INEFFICIENCIES

C = 8

MTF – Example

0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
I	A	B	C	D	E	F	G	H	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z

S = `INEFFICIENCIES`

$C = 8\ 13$

MTF – Example

0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
N	I	A	B	C	D	E	F	G	H	J	K	L	M	O	P	Q	R	S	T	U	V	W	X	Y	Z

S = INEFFICIENCIES

$C = 8\ 13\ 6$

MTF – Example

0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
E	N	I	A	B	C	D	F	G	H	J	K	L	M	O	P	Q	R	S	T	U	V	W	X	Y	Z

S = `INEFFICIENCIES`

$C = 8\ 13\ 6\ 7$

MTF – Example

0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
F	E	N	I	A	B	C	D	G	H	J	K	L	M	O	P	Q	R	S	T	U	V	W	X	Y	Z

S = `INEFFICIENCIES`

C = 8 13 6 7 0

MTF – Example

0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
F	E	N	I	A	B	C	D	G	H	J	K	L	M	O	P	Q	R	S	T	U	V	W	X	Y	Z

S = `INEFFICIENCIES`

$C = 8\ 13\ 6\ 7\ 0\ 3$

MTF – Example

0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
I	F	E	N	A	B	C	D	G	H	J	K	L	M	O	P	Q	R	S	T	U	V	W	X	Y	Z

S = INEFFICIENCIES

C = 8 13 6 7 0 3 6

MTF – Example

0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
C	I	F	E	N	A	B	D	G	H	J	K	L	M	O	P	Q	R	S	T	U	V	W	X	Y	Z

S = `INEFFICIENCIES`

C = 8 13 6 7 0 3 6 1

MTF – Example

0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
S	E	I	C	N	F	A	B	D	G	H	J	K	L	M	O	P	Q	R	T	U	V	W	X	Y	Z

$$S = \texttt{INEFFICIENCIES}$$

$$C = 8\ 13\ 6\ 7\ 0\ 3\ 6\ 1\ 3\ 4\ 3\ 3\ 3\ 18$$

- What does a run in S encode to in C?
- What does a run in C mean about the source S?

MTF – Discussion

- MTF itself does not compress text (if we store codewords with fixed length)

⇝ prime use as part of longer pipeline

- two simple ideas for encoding codewords:
  - Elias gamma code ⇝ smaller numbers gets shorter codewords
    works well for text with small "local effective" alphabet
  - Huffman code (better compression, but need 2 passes)

- but: most effective after BWT (→ next)

A A A A A A A C C C C C C C C

? 0 0 0 ? 0 0 0 0

7.9 Burrows-Wheeler Transform

Burrows-Wheeler Transform

- Burrows-Wheeler Transform (BWT) is a sophisticated text-transformation technique.
  - coded text has same letters as source, just in a different order
  - But: coded text is (typically) more compressible with MTF(!)

Burrows-Wheeler Transform

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- Encoding algorithm needs **all** of S (no streaming possible).
  - $\rightsquigarrow$ BWT is a *block compression method*.

Burrows-Wheeler Transform

- Burrows-Wheeler Transform (BWT) is a sophisticated text-transformation technique.
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  - But: coded text is (typically) more compressible with MTF(!)

- Encoding algorithm needs **all** of S (no streaming possible).
  $\rightsquigarrow$ BWT is a *block compression method*.

- BWT followed by MTF, RLE, and Huffman is the algorithm used by the `bzip2` program.
  achieves best compression on English text of any algorithm we have seen:

```
4047392 bible.txt
1191071 bible.txt.gz
 888604 bible.txt.7z
 845635 bible.txt.bz2
```

BWT transform

- *cyclic shift* of a string: $T =$ `time␣flies␣quickly␣` ⇝ cyclic shift `flies␣quickly␣time␣`

BWT transform

- *cyclic shift* of a string:
- add *end-of-word character* $ to S (as in Unit 6)

⇝ can recover original string

$T =$ `time␣flies␣quickly␣`

⇝ cyclic shift

`flies␣quickly␣time␣`

BWT transform

- *cyclic shift* of a string:

T = `time␣flies␣quickly␣`

⇝ cyclic shift

`flies␣quickly␣time␣`

- add *end-of-word character* \$ to S (as in Unit 6)

⇝ can recover original string

- The Burrows-Wheeler Transform proceeds in three steps:

  1. Place *all cyclic shifts* of S in a list L

  2. Sort the strings in L lexicographically using $\$ < a$ for $a \in \Sigma$

  3. B is the *list of trailing characters* (last column, top-down) of each string in L

BWT transform – Example

$S =$ `alf␣eats␣alfalfa$`

1. Write all cyclic shifts

```
alf␣eats␣alfalfa$
lf␣eats␣alfalfa$a
f␣eats␣alfalfa$al
␣eats␣alfalfa$alf
eats␣alfalfa$alf␣
ats␣alfalfa$alf␣e
ts␣alfalfa$alf␣ea
s␣alfalfa$alf␣eat
␣alfalfa$alf␣eats
alfalfa$alf␣eats␣
lfalfa$alf␣eats␣a
falfa$alf␣eats␣al
alfa$alf␣eats␣alf
lfa$alf␣eats␣alfa
fa$alf␣eats␣alfal
a$alf␣eats␣alfalf
$alf␣eats␣alfalfa
```

$\rightsquigarrow$ sort

BWT transform – Example

$S =$ `alf␣eats␣alfalfa$`

1. Write all cyclic shifts
2. Sort cyclic shifts

```
alf␣eats␣alfalfa$
lf␣eats␣alfalfa$a
f␣eats␣alfalfa$al
␣eats␣alfalfa$alf
eats␣alfalfa$alf␣
ats␣alfalfa$alf␣e
ts␣alfalfa$alf␣ea
s␣alfalfa$alf␣eat
␣alfalfa$alf␣eats
alfalfa$alf␣eats␣
lfalfa$alf␣eats␣a
falfa$alf␣eats␣al
alfa$alf␣eats␣alf
lfa$alf␣eats␣alfa
fa$alf␣eats␣alfal
a$alf␣eats␣alfalf
$alf␣eats␣alfalfa
```

$\rightsquigarrow$ sort

```
$alf␣eats␣alfalfa
␣alfalfa$alf␣eats
␣eats␣alfalfa$alf
a$alf␣eats␣alfalf
alf␣eats␣alfalfa$
alfa$alf␣eats␣alf
alfalfa$alf␣eats␣
ats␣alfalfa$alf␣e
eats␣alfalfa$alf␣
f␣eats␣alfalfa$al
fa$alf␣eats␣alfal
falfa$alf␣eats␣al
lf␣eats␣alfalfa$a
lfa$alf␣eats␣alfa
lfalfa$alf␣eats␣a
s␣alfalfa$alf␣eat
ts␣alfalfa$alf␣ea
```

BWT transform – Example

$S =$ `alf␣eats␣alfalfa$`

1. Write all cyclic shifts
2. Sort cyclic shifts
3. Extract last column

$B =$ `asff$f␣e␣lllaaata`

```
alf␣eats␣alfalfa$
lf␣eats␣alfalfa$a
f␣eats␣alfalfa$al
␣eats␣alfalfa$alf
eats␣alfalfa$alf␣
ats␣alfalfa$alf␣e
ts␣alfalfa$alf␣ea
s␣alfalfa$alf␣eat
␣alfalfa$alf␣eats
alfalfa$alf␣eats␣
lfalfa$alf␣eats␣a
falfa$alf␣eats␣al
alfa$alf␣eats␣alf
lfa$alf␣eats␣alfa
fa$alf␣eats␣alfal
a$alf␣eats␣alfalf
$alf␣eats␣alfalfa
```

⇝ sort

BWT ↓

```
$alf␣eats␣alfalfa
␣alfalfa$alf␣eats
␣eats␣alfalfa$alf
a$alf␣eats␣alfalf
alf␣eats␣alfalfa$
alfa$alf␣eats␣alf
alfalfa$alf␣eats␣
ats␣alfalfa$alf␣e
eats␣alfalfa$alf␣
f␣eats␣alfalfa$al
fa$alf␣eats␣alfal
falfa$alf␣eats␣al
lf␣eats␣alfalfa$a
lfa$alf␣eats␣alfa
lfalfa$alf␣eats␣a
s␣alfalfa$alf␣eat
ts␣alfalfa$alf␣ea
```

Clicker Question

What is the relation between suffix array $L[0..n]$ and BWT $B[0..n]$ of a string $T[0..n)\$$?

- **A** L can be very easily computed from B and T
- **B** B can be very easily computed from L and T
- **C** Both A and B
- **D** Neither A nor B

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Clicker Question

What is the relation between suffix array $L[0..n]$ and BWT $B[0..n]$ of a string $T[0..n)\$$?

- **A** ~~L can be very easily computed from B and T~~
- **B** B can be very easily computed from L and T ✓
- **C** ~~Both A and B~~
- **D** ~~Neither A nor B~~

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BWT – Implementation & Properties

Compute BWT efficiently:

- cyclic shifts $S \quad \widehat{=} \quad$ suffixes of S
- BWT is essentially suffix sorting!
  - $B[i] = S[L[i] - 1]$ $\qquad$ (L = suffix array!)
    (if $L[i] = 0$, $B[i] = \$$)
  - $\rightsquigarrow$ Can compute B in $O(n)$ time

	r		$\downarrow$ $L[r]$
alf␣eats␣alfalfa$	0	$alf␣eats␣alfalf**a**	16
lf␣eats␣alfalfa$a	1	␣alfalfa$alf␣eat**s**	8
f␣eats␣alfalfa$al	2	␣eats␣alfalfa$al**f**	3
␣eats␣alfalfa$alf	3	a$alf␣eats␣alfal**f**	15
eats␣alfalfa$alf␣	4	alf␣eats␣alfalfa**$**	0
ats␣alfalfa$alf␣e	5	alfa$alf␣eats␣al**f**	12
ts␣alfalfa$alf␣ea	6	alfalfa$alf␣eats**␣**	9
s␣alfalfa$alf␣eat	7	ats␣alfalfa$alf␣**e**	5
␣alfalfa$alf␣eats	8	eats␣alfalfa$alf**␣**	4
alfalfa$alf␣eats␣	9	f␣eats␣alfalfa$a**l**	2
lfalfa$alf␣eats␣a	10	fa$alf␣eats␣alfa**l**	14
falfa$alf␣eats␣al	11	falfa$alf␣eats␣a**l**	11
alfa$alf␣eats␣alf	12	lf␣eats␣alfalfa$**a**	1
lfa$alf␣eats␣alfa	13	lfa$alf␣eats␣alf**a**	13
fa$alf␣eats␣alfal	14	lfalfa$alf␣eats␣**a**	10
a$alf␣eats␣alfalf	15	s␣alfalfa$alf␣ea**t**	7
$alf␣eats␣alfalfa	16	ts␣alfalfa$alf␣e**a**	6

BWT – Implementation & Properties

Compute BWT efficiently:

- cyclic shifts S $\widehat{=}$ suffixes of S
- BWT is essentially suffix sorting!
  - $B[i] = S[L[i] - 1]$ $\quad$ (L = suffix array!)
    (if $L[i] = 0$, $B[i] = \$$)
  - $\rightsquigarrow$ Can compute B in $O(n)$ time

	r		$\downarrow$ $L[r]$
alf␣eats␣alfalfa$	0	$alf␣eats␣alfalf**a**	16
lf␣eats␣alfalfa$a	1	␣alfalfa$alf␣eat**s**	8
f␣eats␣alfalfa$al	2	␣eats␣alfalfa$al**f**	3
␣eats␣alfalfa$alf	3	a$alf␣eats␣alfal**f**	15
eats␣alfalfa$alf␣	4	alf␣eats␣alfalfa**$**	0
ats␣alfalfa$alf␣e	5	alfa$alf␣eats␣al**f**	12
ts␣alfalfa$alf␣ea	6	alfalfa$alf␣eats**␣**	9
s␣alfalfa$alf␣eat	7	ats␣alfalfa$alf␣**e**	5
␣alfalfa$alf␣eats	8	eats␣alfalfa$alf**␣**	4
alfalfa$alf␣eats␣	9	f␣eats␣alfalfa$a**l**	2
lfalfa$alf␣eats␣a	10	fa$alf␣eats␣alfa**l**	14
falfa$alf␣eats␣al	11	falfa$alf␣eats␣a**l**	11
alfa$alf␣eats␣alf	12	lf␣eats␣alfalfa$**a**	1
lfa$alf␣eats␣alfa	13	lfa$alf␣eats␣alf**a**	13
fa$alf␣eats␣alfal	14	lfalfa$alf␣eats␣**a**	10
a$alf␣eats␣alfalf	15	s␣alfalfa$alf␣ea**t**	7
$alf␣eats␣alfalfa	16	ts␣alfalfa$alf␣e**a**	6

Why does BWT help?

- sorting groups characters *by what follows*
  - Example: `lf` always preceded by `a`

$\rightsquigarrow$ B has local clusters of characters
  - that makes MTF effective

- repeated substring in S $\rightsquigarrow$ *runs* of characters in B
  - picked up by RLE

Bigger Example

```
have␣had␣hadnt␣hasnt␣havent␣has␣what$
ave␣had␣hadnt␣hasnt␣havent␣has␣what$h
ve␣had␣hadnt␣hasnt␣havent␣has␣what$ha
e␣had␣hadnt␣hasnt␣havent␣has␣what$hav
␣had␣hadnt␣hasnt␣havent␣has␣what$have
had␣hadnt␣hasnt␣havent␣has␣what$have␣
ad␣hadnt␣hasnt␣havent␣has␣what$have␣h
d␣hadnt␣hasnt␣havent␣has␣what$have␣ha
␣hadnt␣hasnt␣havent␣has␣what$have␣had
hadnt␣hasnt␣havent␣has␣what$have␣had␣
adnt␣hasnt␣havent␣has␣what$have␣had␣h
dnt␣hasnt␣havent␣has␣what$have␣had␣ha
nt␣hasnt␣havent␣has␣what$have␣had␣had
t␣hasnt␣havent␣has␣what$have␣had␣hadn
␣hasnt␣havent␣has␣what$have␣had␣hadnt
hasnt␣havent␣has␣what$have␣had␣hadnt␣
asnt␣havent␣has␣what$have␣had␣hadnt␣h
snt␣havent␣has␣what$have␣had␣hadnt␣ha
nt␣havent␣has␣what$have␣had␣hadnt␣has
t␣havent␣has␣what$have␣had␣hadnt␣hasn
␣havent␣has␣what$have␣had␣hadnt␣hasnt
havent␣has␣what$have␣had␣hadnt␣hasnt␣
avent␣has␣what$have␣had␣hadnt␣hasnt␣h
vent␣has␣what$have␣had␣hadnt␣hasnt␣ha
ent␣has␣what$have␣had␣hadnt␣hasnt␣hav
nt␣has␣what$have␣had␣hadnt␣hasnt␣have
t␣has␣what$have␣had␣hadnt␣hasnt␣haven
␣has␣what$have␣had␣hadnt␣hasnt␣havent
has␣what$have␣had␣hadnt␣hasnt␣havent␣
as␣what$have␣had␣hadnt␣hasnt␣havent␣h
s␣what$have␣had␣hadnt␣hasnt␣havent␣ha
␣what$have␣had␣hadnt␣hasnt␣havent␣has
what$have␣had␣hadnt␣hasnt␣havent␣has␣
hat$have␣had␣hadnt␣hasnt␣havent␣has␣w
at$have␣had␣hadnt␣hasnt␣havent␣has␣wh
t$have␣had␣hadnt␣hasnt␣havent␣has␣wha
$have␣had␣hadnt␣hasnt␣havent␣has␣what
```

```
$have␣had␣hadnt␣hasnt␣havent␣has␣what
␣had␣hadnt␣hasnt␣havent␣has␣what$have
␣hadnt␣hasnt␣havent␣has␣what$have␣had
␣has␣what$have␣had␣hadnt␣hasnt␣havent
␣hasnt␣havent␣has␣what$have␣had␣hadnt
␣havent␣has␣what$have␣had␣hadnt␣hasnt
␣what$have␣had␣hadnt␣hasnt␣havent␣has
ad␣hadnt␣hasnt␣havent␣has␣what$have␣h
adnt␣hasnt␣havent␣has␣what$have␣had␣h
as␣what$have␣had␣hadnt␣hasnt␣havent␣h
asnt␣havent␣has␣what$have␣had␣hadnt␣h
at$have␣had␣hadnt␣hasnt␣havent␣has␣wh
ave␣had␣hadnt␣hasnt␣havent␣has␣what$h
avent␣has␣what$have␣had␣hadnt␣hasnt␣h
d␣hadnt␣hasnt␣havent␣has␣what$have␣ha
dnt␣hasnt␣havent␣has␣what$have␣had␣ha
e␣had␣hadnt␣hasnt␣havent␣has␣what$hav
ent␣has␣what$have␣had␣hadnt␣hasnt␣hav
had␣hadnt␣hasnt␣havent␣has␣what$have␣
hadnt␣hasnt␣havent␣has␣what$have␣had␣
has␣what$have␣had␣hadnt␣hasnt␣havent␣
hasnt␣havent␣has␣what$have␣had␣hadnt␣
hat$have␣had␣hadnt␣hasnt␣havent␣has␣w
have␣had␣hadnt␣hasnt␣havent␣has␣what$
havent␣has␣what$have␣had␣hadnt␣hasnt␣
nt␣has␣what$have␣had␣hadnt␣hasnt␣have
nt␣hasnt␣havent␣has␣what$have␣had␣had
nt␣havent␣has␣what$have␣had␣hadnt␣has
s␣what$have␣had␣hadnt␣hasnt␣havent␣ha
snt␣havent␣has␣what$have␣had␣hadnt␣ha
t$have␣had␣hadnt␣hasnt␣havent␣has␣wha
t␣has␣what$have␣had␣hadnt␣hasnt␣haven
t␣hasnt␣havent␣has␣what$have␣had␣hadn
t␣havent␣has␣what$have␣had␣hadnt␣hasn
ve␣had␣hadnt␣hasnt␣havent␣has␣what$ha
vent␣has␣what$have␣had␣hadnt␣hasnt␣ha
what$have␣had␣hadnt␣hasnt␣havent␣has␣
```

$T =$ h a v e ␣ h a d ␣ h a d n t ␣ h a s n t ␣ h a v e n t ␣ h a s ␣ w h a t $

$B =$ t e d t t t s h h h h h h h a a v v ␣ ␣ ␣ ␣ w $ ␣ e d s a a a n n n a a ␣

$MTF(B) =$ 8 5 5 2 **0** **0** 8 7 **0** **0** **0** **0** **0** **0** 7 **0** 9 **0** 8 **0** **0** **0** 10 9 2 9 9 8 7 **0** **0** 10 **0** **0** 1 **0** 5

Clicker Question

Consider T = `have␣had␣hadnt␣hasnt␣havent␣has␣what$`.
The BWT is B = `tedttts`<u>`hhhhhh`</u>`aavv␣␣␣␣w$␣edsaaannnaa␣`.
How can we explain the long run of `h`s in B?

A `h` is the most frequent character

B `h` always appears at the beginning of a word

C almost all words start with `h`

D `h` is always followed by `a`

E all `a`s are preceded by `h`

F `h` is the 4th character in the alphabet

→ *sli.do/comp526*

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- **B** ~~`h` always appears at the beginning of a word~~
- **C** ~~almost all words start with `h`~~
- **D** ~~`h` is always followed by `a`~~
- **E** all `a`s are preceded by `h` ✓
- **F** ~~`h` is the 4th character in the alphabet~~

→ sli.do/comp526

7.10 Inverse BWT

Inverse BWT

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Example:

$B =$ `ard$rcaaaabb`

$S =$

	D
0	(a, 0)
1	(r, 1)
2	(d, 2)
3	($, 3)
4	(r, 4)
5	(c, 5)
6	(a, 6)
7	(a, 7)
8	(a, 8)
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Example:

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$S =$

	D		sorted D (char, next)
0	(a, 0)	0	($, 3)
1	(r, 1)	1	(a, 0)
2	(d, 2)	2	(a, 6)
3	($, 3)	3	(a, 7)
4	(r, 4)	4	(a, 8)
5	(c, 5)	5	(a, 9)
6	(a, 6)	6	(b, 10)
7	(a, 7)	7	(b, 11)
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Example:

B = `ard$rcaaaabb`

S = `a`

	D		sorted D (char, next)
0	(a, 0)	0	($, 3)
1	(r, 1)	1	(a, 0)
2	(d, 2)	2	(a, 6)
3	($, 3)	3	(a, 7)
4	(r, 4)	4	(a, 8)
5	(c, 5)	5	(a, 9)
6	(a, 6)	6	(b, 10)
7	(a, 7)	7	(b, 11)
8	(a, 8)	8	(c, 5)
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Example:

$B =$ `ard$rcaaaabb`

$S =$ `ab`

	D	sorted D (char, next)
0	(a, 0)	($, 3)
1	(r, 1)	(a, 0)
2	(d, 2)	(a, 6)
3	($, 3)	(a, 7)
4	(r, 4)	(a, 8)
5	(c, 5)	(a, 9)
6	(a, 6)	(b, 10)
7	(a, 7)	(b, 11)
8	(a, 8)	(c, 5)
9	(a, 9)	(d, 2)
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Example:

B = `ard$rcaaaabb`

S = `abr`

	D		sorted D (char, next)
0	(a, 0)	0	($, 3)
1	(r, 1)	1	(a, 0)
2	(d, 2)	2	(a, 6)
3	($, 3)	3	(a, 7)
4	(r, 4)	4	(a, 8)
5	(c, 5)	5	(a, 9)
6	(a, 6)	6	(b, 10)
7	(a, 7)	7	(b, 11)
8	(a, 8)	8	(c, 5)
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11	(b, 11)	11	(r, 4)

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Example:

B = `ard$rcaaaabb`

S = `abra`

	D	sorted D (char, next)
0	(a, 0)	($, 3)
1	(r, 1)	(a, 0)
2	(d, 2)	(a, 6)
3	($, 3)	(a, 7)
4	(r, 4)	(a, 8)
5	(c, 5)	(a, 9)
6	(a, 6)	(b, 10)
7	(a, 7)	(b, 11)
8	(a, 8)	(c, 5)
9	(a, 9)	(d, 2)
10	(b, 10)	(r, 1)
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  1. Create array $D[0..n]$ of pairs: $D[r] = (B[r], r)$.
  2. Sort D *stably* with respect to *first entry*.
  3. Use D as linked list with (char, next entry)

Example:

$B =$ `ard$rcaaaabb`

$S =$ `abrac`

D

0	(a, 0)
1	(r, 1)
2	(d, 2)
3	($, 3)
4	(r, 4)
5	(c, 5)
6	(a, 6)
7	(a, 7)
8	(a, 8)
9	(a, 9)
10	(b, 10)
11	(b, 11)

sorted D

	char	next
0	$	3
1	a	0
2	a	6
3	a	7
4	a	8
5	a	9
6	b	10
7	b	11
8	c	5
9	d	2
10	r	1
11	r	4

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Example:

B = `ard$rcaaaabb`

S = `abraca`

	D		sorted D (char, next)
0	(a, 0)	0	($, 3)
1	(r, 1)	1	(a, 0)
2	(d, 2)	2	(a, 6)
3	($, 3)	3	(a, 7)
4	(r, 4)	4	(a, 8)
5	(c, 5)	5	(a, 9)
6	(a, 6)	6	(b, 10)
7	(a, 7)	7	(b, 11)
8	(a, 8)	8	(c, 5)
9	(a, 9)	9	(d, 2)
10	(b, 10)	10	(r, 1)
11	(b, 11)	11	(r, 4)

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  3. Use D as linked list with $(\text{char}, \text{next entry})$

Example:

B = `ard$rcaaaabb`

S = `abracad`

	D		sorted D (char, next)
0	(a, 0)	0	($, 3)
1	(r, 1)	1	(a, 0)
2	(d, 2)	2	(a, 6)
3	($, 3)	3	(a, 7)
4	(r, 4)	4	(a, 8)
5	(c, 5)	5	(a, 9)
6	(a, 6)	6	(b, 10)
7	(a, 7)	7	(b, 11)
8	(a, 8)	8	(c, 5)
9	(a, 9)	9	(d, 2)
10	(b, 10)	10	(r, 1)
11	(b, 11)	11	(r, 4)

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  2. Sort D *stably* with respect to *first entry*.
  3. Use D as linked list with $(\text{char}, \text{next entry})$

Example:

B = `ard$rcaaaabb`

S = `abracada`

	D		sorted D (char, next)
0	(a, 0)	0	($, 3)
1	(r, 1)	1	(a, 0)
2	(d, 2)	2	(a, 6)
3	($, 3)	3	(a, 7)
4	(r, 4)	4	(a, 8)
5	(c, 5)	5	(a, 9)
6	(a, 6)	6	(b, 10)
7	(a, 7)	7	(b, 11)
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Example:

B = `ard$rcaaaabb`

S = `abracadab`

	D		sorted D (char, next)
0	(a, 0)	0	($, 3)
1	(r, 1)	1	(a, 0)
2	(d, 2)	2	(a, 6)
3	($, 3)	3	(a, 7)
4	(r, 4)	4	(a, 8)
5	(c, 5)	5	(a, 9)
6	(a, 6)	6	(b, 10)
7	(a, 7)	7	(b, 11)
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Example:

B = `ard$rcaaaabb`

S = `abracadabr`

	D		sorted D (char, next)
0	(a, 0)	0	($, 3)
1	(r, 1)	1	(a, 0)
2	(d, 2)	2	(a, 6)
3	($, 3)	3	(a, 7)
4	(r, 4)	4	(a, 8)
5	(c, 5)	5	(a, 9)
6	(a, 6)	6	(b, 10)
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Example:

$B =$ `ard$rcaaaabb`

$S =$ `abracadabra`

D

0	(a, 0)
1	(r, 1)
2	(d, 2)
3	($, 3)
4	(r, 4)
5	(c, 5)
6	(a, 6)
7	(a, 7)
8	(a, 8)
9	(a, 9)
10	(b, 10)
11	(b, 11)

sorted D

	char, next
0	($, 3)
1	(a, 0)
2	(a, 6)
3	(a, 7)
4	(a, 8)
5	(a, 9)
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7	(b, 11)
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Example:

B = `ard$rcaaaabb`

S = `abracadabra$`

D

0	(a, 0)
1	(r, 1)
2	(d, 2)
3	($, 3)
4	(r, 4)
5	(c, 5)
6	(a, 6)
7	(a, 7)
8	(a, 8)
9	(a, 9)
10	(b, 10)
11	(b, 11)

sorted D

	char next
0	($, 3)
1	(a, 0)
2	(a, 6)
3	(a, 7)
4	(a, 8)
5	(a, 9)
6	(b, 10)
7	(b, 11)
8	(c, 5)
9	(d, 2)
10	(r, 1)
11	(r, 4)

Inverse BWT – The magic revealed

- Inverse BWT very easy to compute:
  - only sort individual characters in B (not suffixes)
  - $\rightsquigarrow$ $O(n)$ with counting sort

- *but why does this work!?*

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  - only sort individual characters in B (not suffixes)
  - $\rightsquigarrow$ $O(n)$ with counting sort
- *but why does this work!?*
- decode char by char
  - can find unique \$ $\rightsquigarrow$ starting row
- to get next char, we need
  - (i) char in *first* column of *current row*
  - (ii) find row with that char's copy in BWT
  - $\rightsquigarrow$ then we can walk through and decode

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  - can find unique \$ $\rightsquigarrow$ starting row
- to get next char, we need
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  (ii) find row with that char's copy in BWT
  $\rightsquigarrow$ then we can walk through and decode
- for (i): first column $=$ characters of B in sorted order ✓

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  - only sort individual characters in B (not suffixes)
  - $\rightsquigarrow$ $O(n)$ with counting sort
- *but why does this work!?*
- decode char by char
  - can find unique \$ $\rightsquigarrow$ starting row
- to get next char, we need
  - (i) char in *first* column of *current row*
  - (ii) find row with that char's copy in BWT
  - $\rightsquigarrow$ then we can walk through and decode
- for (i): first column = characters of B in sorted order ✓
- for (ii): relative order of same character stays same:
  ith `a` in first column = ith `a` in BWT
  - $\rightsquigarrow$ stably sorting $(B[r], r)$ by first entry enough ✓

r	$L[r]$	$T_{L[r]}$	$B[r]$
0	9	`$bananaba`	**n**
1	5	`aban$bana`	**n**
2	7	`an$banana`	**b**
3	3	`anaban$ba`	**n**
4	1	`ananaban$`	**b**
5	6	`ban$banan`	**a**
6	0	`bananaban`	**$**
7	8	`n$bananab`	**a**
8	4	`naban$ban`	**a**
9	2	`nanaban$b`	**a**

BWT – Discussion

- Running time: $\Theta(n)$
  - **encoding** uses suffix sorting
  - decoding only needs counting sort
  - $\rightsquigarrow$ decoding much simpler & faster (but same Θ-class)

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- Running time: $\Theta(n)$
  - **encoding** uses suffix sorting
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- typically slower than other methods
- need access to entire text (or apply to blocks independently)
- BWT-MTF-RLE-Huffman (bzip2) pipeline tends to have best compression

Summary of Compression Methods

Huffman	Variable-width, single-character (optimal in this case)
RLE	Variable-width, multiple-character encoding
LZW	Adaptive, fixed-width, multiple-character encoding Augments dictionary with repeated substrings
MTF	Adaptive, transforms to smaller integers should be followed by variable-width integer encoding
BWT	Block compression method, should be followed by MTF