7 Text Compression

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Learning Outcomes

Unit 7: *Text Compression*

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 a specific type of data.

Outline

7   Text Compression

7.1 Context

Overview

- ▶ Unit 6 & 13: How to *work* with strings
  - ▶ finding substrings
  - ▶ finding approximate matches ⤳ Unit 13
  - ▶ finding repeated parts ⤳ Unit 13
  - ▶ . . .
  - ▶ 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 ⤳ Unit 8

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

- ▶ **decoding:** algorithm mapping coded texts back to original source text

- ▶ **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
  ▶ security (encryption)
  ▶ integrity (detect modifications made by third parties)
  ▶ 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 . . .)

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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!**
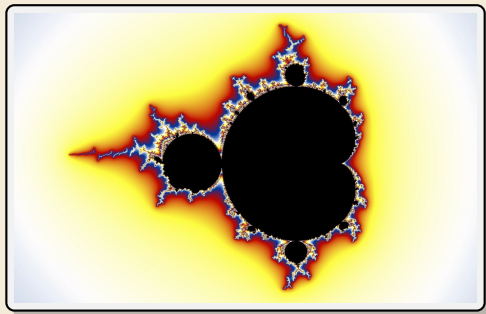
- ⤳ *Kolmogorov complexity*
  - ► *C = any program* that outputs *S*

    self-extracting archives!   needs fixed machine model, but compilers transfer results
  - ► 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 → Part I

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

There is no such thing as a free lunch!

Not *everything* is compressible (→ tutorials)
⤳ 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

⤳ encoding function $E : \Sigma_S \rightarrow \Sigma_C^\star$

    ▶ 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**

International Morse Code

1. The length of a dot is one unit.
2. A dash is three units.
3. The space between parts of the same letter is one unit.
4. The space between letters is three units.
5. The space between words is seven units.

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

https://commons.wikimedia.org/wiki/File:Morse-code-tree.svg
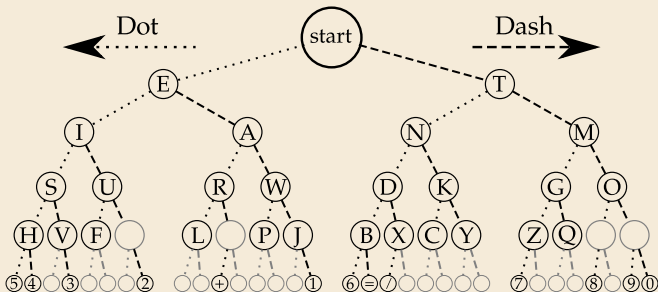
Variable-length codes – UTF-8

▶ Modern example: UTF-8 encoding of Unicode:

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

- ▶ Encodes any Unicode character   (154 998 as of Nov 2024, 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 characters 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
$\underset{\text{b a n a n a}}{\underline{\text{1100100100}}}$

⚡ C = 1100100100 decodes **both** to banana and to bass: $\underset{\text{b a s s}}{\underline{\text{1100100100}}}$

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

but how should we have known?

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

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

⤳ Usually require a *prefix-free* code: No codeword is a prefix of another.

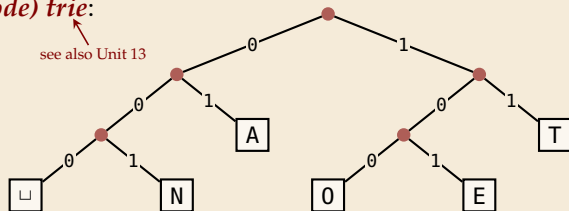prefix-free $\implies$ instantaneously decodable $\implies$ uniquely decodable

Code tries

▶ From now on only consider prefix-free codes E:
$E(c)$ is not a proper 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*:

see also Unit 13

▶ binary tree
▶ one **leaf** for each characters of Σ_S
▶ path from root to leave = codeword
left child = 0; right child = 1

▶ Example for using the code trie:
▶ Encode AN␣ANT → 010010000100111
▶ Decode 111000001010111 → TO␣EAT

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The Codeword Supermarket

total symbol codeword budget

- ▶ Can "spend" at most budget of 1 across all codewords
  - ▶ Codeword with ℓ bits costs $2^{-\ell}$

- ▶ *Kraft-McMillan inequality:* any uniquely decodable code with codeword lengths $\ell_1, \ldots, \ell_\sigma$ satisfies

$$\sum_{i=1}^{\sigma} 2^{-\ell_i} \leq 1$$

and for any such lengths there is a prefix-free code
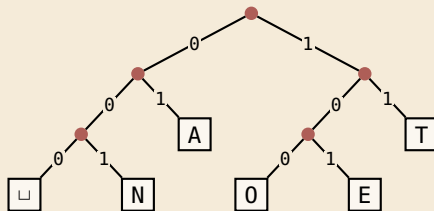
Who decodes the decoder?

- ▶ 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 → next)

  - ▶ **adaptive coding:** code depends on message and changes during encoding; implicitly stored withing the message (e. g., LZW → 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%	ı
n	6.75%	▬▬▬	**w**	2.36%	■	**x**	0.15%	ı
s	6.33%	▬▬	**f**	2.23%	■	**q**	0.10%	ı
h	6.09%	▬▬	**g**	2.02%	■	**z**	0.07%	ı
r	5.99%	▬▬	**y**	1.97%	■			

⤳ Want shorter codes for more frequent characters!

Huffman coding

▶ **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 $\displaystyle \sum_{c \in \Sigma} w(c) \cdot |E(c)|$

▶ Let's abbreviate $|S|_c$ = #occurrences of c in S

▶ If we use $w(c) = |S|_c$,
   this is the character encoding with smallest possible $|C|$

   ⤳ **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 a, b with lowest weights.
   ▶ We will encode them with the same prefix, plus one distinguishing bit,
     i. e., $E(a) = u0$ and $E(b) = u1$ for a bitstring $u \in \{0, 1\}^\star$ (u to be determined)

2. (Conceptually) replace a and b by a single character "ab"
   with $w(\text{ab}) = w(a) + w(b)$.

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

▶ 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: $S = \text{LOSSLESS}$ ⇝ $\Sigma_S = \{\text{E}, \text{L}, \text{O}, \text{S}\}$

▶ Character frequencies: E : 1, L : 2, O : 1, S : 4
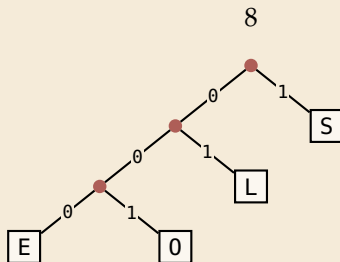
⇝ *Huffman tree* (code trie for Huffman code)

LOSSLESS → 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 CS 566: 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.

  ⤳ practice in tutorials

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. ◀

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

- ▶ 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 a, b in x, y
  (that can only make ℓ smaller, so still optimal)

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

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

◀

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

$$\mathcal{H}(p_1, \ldots, p_n) \;=\; -\sum_{i=1}^{n} p_i \lg p_i \;=\; \sum_{i=1}^{n} p_i \lg\!\left(\frac{1}{p_i}\right)$$

◄

▶ entropy is a **measure** of **information** content of a distribution

    ▶ *"20 Questions on $[0, 1)$":* Land inside my interval by halving.

$p_i = \frac{3}{4} - \frac{11}{16} = \frac{1}{16}$
$\rightsquigarrow \lg(1/p_i) = 4$
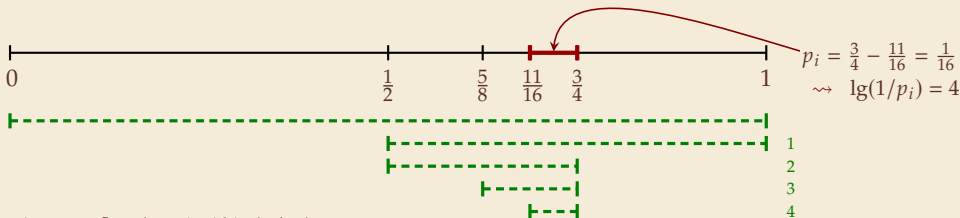
$\rightsquigarrow$ Need to cut $[0, 1)$ in half $\lg(1/p_i)$ times

▶ 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 as length of single codeword that is; but can be possible *on average*!

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

Theorem 7.3 (Entropy bounds for Huffman codes)

For any probabilities $p_1, \ldots, p_\sigma$ for $\Sigma = \{a_1, \ldots, a_\sigma\}$, the Huffman code E for Σ with weights

$p(a_i) = p_i$ satisfies $\boxed{\mathcal{H} \leq \ell(E) \leq \mathcal{H} + 1}$ where $\mathcal{H} = \mathcal{H}(p_1, \ldots, p_\sigma)$.   ◄

Proof sketch:

▶ $\ell(E) \geq \mathcal{H}$

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

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

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

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

Entropy and Huffman codes [2]

Proof sketch (continued):

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

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

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

  - If $\sigma = 2$, E' uses a single bit each.
    Here, $q_i \leq 1/2$, so $\lg(1/q_i) \geq 1 = |E'(a_i)|$ ✓

  - If $\sigma \geq 3$, 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
    $q_2 + q_2 + \cdots + q_\sigma \leq 1$.

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

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

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

Empirical Entropy

▶ Theorem **??** works for *any* character *probabilities* $p_1, \ldots, p_\sigma$

   . . . but we only have a string S! (nothing random about it!)

🔆 use relative frequencies: $p_i = \dfrac{|S|_{a_i}}{|S|} = \dfrac{\#\text{occurences of } a_i \text{ in string } S}{\text{length of } S}$

▶ Recall: For $S[0..n)$ over $\Sigma = \{a_1, \ldots, a_\sigma\}$,
   length of Huffman-coded text is

$$|C| = \sum_{i=1}^{\sigma} |S|_{a_i} \cdot |E(a_i)| = n \sum_{i=1}^{\sigma} \overset{=p_i}{\boxed{\frac{|S|_{a_i}}{n}}} \cdot |E(a_i)| = n\ell(E)$$

⇝ Theorem **??** tells us rather precisely how well Huffman compresses:
   $\mathcal{H}_0(S) \cdot n \leq |C| \leq (\mathcal{H}_0(S) + 1)n$

▶ $\mathcal{H}_0(S) = \mathcal{H}\left(\dfrac{|S|_{a_1}}{n}, \ldots, \dfrac{|S|_{a_\sigma}}{n}\right) = \sum_{i=1}^{\sigma} \dfrac{n}{|S|_{a_i}} \log_2\left(\dfrac{|S|_{a_i}}{n}\right)$ is called the *empirical entropy* of S

zero-th order empirical entropy

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, . . .)

👍 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
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 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 Jack a dull boy.  All work and no play makes Jack a dull boy.
```

▶ character-by-character encoding will **not** capture such repetitions
  ↝ 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

```
00000000000000000000000000000000000000000
00000000000000000000000000000000000000000
00000000000000000000000000000000000000000
00010110010000000001111000000000011111000
00111111111000000011111110000000111111100
00111101101000001110000000000000111000000
00110000000000111000000000000111000000000
00110000000001110000000000000111000000000
00110000000011100000000000011100000000000
00110110000001100111110000011001111100000
00111111110000111111111100000111111111000
00111011110001111100111100011110011111100
00000000111001110000001110011100000011100
00000000011100110000001100111100000001100
00000000011000110000001110001100000001100
00000000011001110000001100111100000001100
00000000110001110000001110000110000001100
00110111110000011111111100001111111111000
01111111110000011111111100001111111111000
00010110110000000010010000000000100100000
00010110110000000010010000000000100100000
00000000000000000000000000000000000000000
00000000000000000000000000000000000000000
```

▶ here: only consider $\Sigma_S = \{0, 1\}$ (work on a binary representation)
  ▶ can be extended for larger alphabets

⤳ **run-length encoding (RLE)**:
  use runs as phrases: $S = \underbrace{00000}\ \underbrace{111}\ \underbrace{0000}$

⤳ We have to store
  ▶ the first bit of S (either 0 or 1)
  ▶ the length of each subsequent run
  ▶ Note: don't have to store bit for later runs since they must alternate.

▶ Example becomes: $0, 5, 3, 4$

▶ **Question**: How to encode a run length k in binary?   (k can be arbitrarily large!)

Elias codes

- ▶ Need a *prefix-free encoding* for $\mathbb{N} = \{1, 2, 3, \ldots, \}$
    - ▶ must allow arbitrarily large integers
    - ▶ must know when to stop reading

- ▶ But that's simple!   Just use *unary* **encoding**!
  $7 \mapsto$ 00000001 $3 \mapsto$ 0001 $0 \mapsto$ 1 $30 \mapsto$ 0000000000000000000000000000001

    🖓 Much too long
    - ▶ (wasn't the whole point of RLE to get rid of long runs??)

- ▶ Refinement: *Elias gamma code*
    - ▶ Store the **length** ℓ of the binary representation in **unary**
    - ▶ Followed by the binary digits themselves
    - ▶ little tricks:
        - ▶ always have $\ell \geq 1$, so store $\ell - 1$ instead
        - ▶ binary representation always starts with 1 ⤳ don't need terminating 1 in unary
    - ⤳ Elias gamma code = $\ell - 1$ zeros, followed by binary representation

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

Run-length encoding – Examples

► Encoding:
$S = $ 11111110010000000000000000000000011111111111

$C = $ 100111010100001010000001011

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

► Decoding:
$C = $ 00001101001001010
$b = $
$\ell = $
$k = $
$S = $ 00000000000001111011

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

Peas por idg h t,
cold,
in the p
Nine days

Some like t

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/>`"

- ▶ **Lempel-Ziv** stands for family of *adaptive* compression algorithms.

    - ▶ **Idea:** store repeated parts by reference!
    - ↝ each codeword refers to
        - ▶ either a single character in Σ_S,
        - ▶ or a *substring* of S (that both encoder and decoder have seen before).

    - ▶ Variants of Lempel-Ziv compression
        - ▶ **"LZ77"** Original version (sliding window, overlapping phrases)
          Derivatives: LZSS, LZFG, LZRW, LZP, DEFLATE, . . .
          DEFLATE used in (`pk`)`zip`, `gzip`, PNG
        - ▶ **"LZ78"** Second version (whole-phrase references)
          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: $k = 12$) $\rightsquigarrow$ 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.

add xc = bana to dictionary
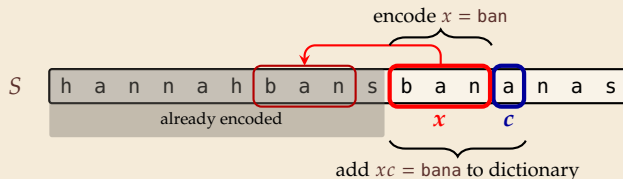
- $\rightsquigarrow$ new codeword in D
- D actually stores codewords for x and c, not the expanded string

LZW encoding – Example

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

	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!

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

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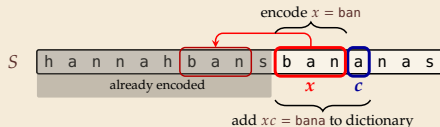
LZW encoding – Code

```
1  procedure LZWencode(S[0..n]):
2      x := ε // previous phrase, initially empty
3      C := ε // output, initially empty
4      D := dictionary, initialized with codes for c ∈ Σ_S // stored as trie (⤳ Unit 13)
5      k := |Σ_S| // next free codeword
6      for i := 0, . . . , n − 1 do
7          c := S[i]
8          if D.containsKey(xc) then
9              x := xc
10         else
11             C := C · D.get(x) // append codeword for x
12             D.put(xc, k) // add xc to D, assigning next free codeword
13             k := k + 1; x := c
14     end for
15     C := C · D.get(x)
16     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)

decode y = an

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

already decoded x y

add xc = bana to dictionary
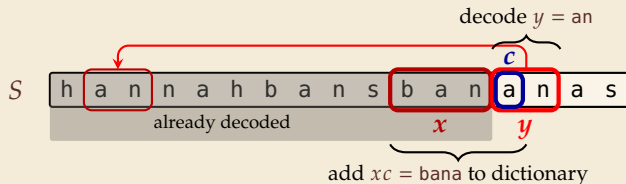
⤳ Note: only start adding to D after *second* substring of S is decoded

LZW decoding – Example

▶ Same idea: build dictionary while reading string.

▶ Example: 67 65 78 32 66 129 133

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

$D =$

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 – 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 $y = D[k] = xc$.
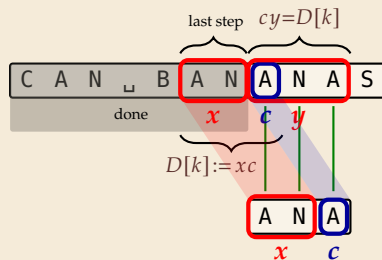
1. en/decode x.

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

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

LZW decoding – Code

```
1  procedure LZWdecode(C[0..m]):
2      D := dictionary [0..2^d] → Σ_S^+, initialized with codes for c ∈ Σ_S // stored as array
3      k := |Σ_S| // next unused codeword
4      q := C[0] // first codeword
5      y := D[q] // lookup meaning of q in D
6      S := y // output, initially first phrase
7      for j := 1, . . . , m − 1 do
8          x := y // remember last decoded phrase
9          q := C[j] // next codeword
10         if q == k then
11             y := x · x[0] // bootstrap case
12         else
13             y := D[q]
14         S := S · y // append decoded phrase
15         D[k] := x · y[0] // store new phrase
16         k := k + 1
17     end for
18     return S
```

LZW decoding – Example continued

▶ Example: 67 65 78 32 66 129 133 83

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

$D =$

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
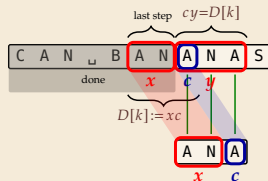
1. en/decode x.

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

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

LZW – Discussion

▶ As presented, LZW uses coded alphabet $\Sigma_C = [0..2^d)$.

   ⇝ use another encoding for   code numbers $\mapsto$ binary,   e. g., Huffman

▶ need a rule when dictionary is full; different options:

   ▶ increment d ⇝ longer codewords

   ▶ "flush" dictionary and start from scratch ⇝ 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 if we have one the following:
    - ▶ long runs ⇝ RLE
    - ▶ frequently used characters ⇝ Huffman
    - ▶ many (locally) repeated substrings ⇝ LZW
- ▶ but methods can be frustratingly "blind" to other "obvious" redundancies
    - ▶ LZW: repetition too distant ⚡ dictionary already flushed
    - ▶ Huffman: changing probabilities (local clusters) ⚡ averaged out globally
    - ▶ RLE: run of alternating pairs of characters ⚡ not a run
- ▶ Enter: **text transformations**
    - ▶ invertible functions of text
    - ▶ do not by themselves reduce the space usage
    - ▶ but help compressors "see" existing redundancy
    - ⇝ use as pre-/postprocessing in a 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)
  ⇝ list "learns" probabilities of access to objects
    makes access to frequently requested objects 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
  ⇝ codewords are integers, i. e., $\Sigma_C = [0..\sigma)$

⇝ clusters of few characters ⇝ many small numbers

MTF – Code

▶ **Transform (encode):**

```
1  procedure MTF−encode(S[0..n)):
2      L := list containing Σ_S (sorted order)
3      C := ε
4      for i := 0, . . . , n − 1 do
5          c := S[i]
6          p := position of c in L
7          C := C · p
8          Move c to front of L
9      end for
10     return C
```

▶ **Inverse transform (decode):**

```
1  procedure MTF−decode(C[0..m)):
2      L := list containing Σ_S (sorted order)
3      S := ε
4      for j := 0, . . . , m − 1 do
5          p := C[j]
6          c := character at position p in L
7          S := S · c
8          Move c to front of L
9      end for
10     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
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

$$S = \text{I N E F F I C I E N C I E S}$$
$$C = 8\ 13\ 6\ 7\ 0\ 3\ 6\ 1\ 3\ 4\ 3\ 3\ 3\ 18$$

► 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)

   ↝ used as part of longer pipeline

▶ Intuitively effect:
   MTF converts locally low empirical entropy to globally low empirical entropy(!)

   ↝ makes Huffman coding much more effective!

   ▶ cheaper option: Elias gamma code

      ↝ smaller numbers gets shorter codewords
         works well for text with small "local effective" alphabet

👎 many natural texts do not have locally low empirical entropy

👍 but we can often make it so . . . stay tuned ($\rightarrow$ BWT)

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 (local char frequencies)

- ▶ Encoding algorithm needs **all** of S (no streaming possible).
    - ↝ 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   # original
      1191071 bible.txt.gz   # gzip   (0.2s)
       888604 bible.txt.7z   # 7z   (2s)
       845635 bible.txt.bz2   # bzip2   (0.3s)

       632634 bible.txt.paq8l   # paq8l -8 (6min!)

BWT – Definitions

▶ *cyclic shift* of a string: $T = $ time␣flies␣quickly␣

flies␣quickly␣time␣

▶ add *end-of-word character* $ to *S* (always assumed in this section!)

⤳ cyclic shift

⤳ can **recover** original string

▶ The Burrows-Wheeler Transform proceeds in three steps:

  0. Append end-of-word character $ to *S*.

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

  2. Sort the strings in *L* lexicographically

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

BWT – Example

$S = \texttt{alf\_eats\_alfalfa\$}$

1. Take all cyclic shifts of S

2. Sort cyclic shifts

3. Extract last column

$B = \texttt{asff\$f\_e\_lllaaata}$

```
alf_eats_alfalfa$              $alf_eats_alfalfa
lf_eats_alfalfa$a              _alfalfa$alf_eats
f_eats_alfalfa$al              _eats_alfalfa$alf
_eats_alfalfa$alf              a$alf_eats_alfalf
eats_alfalfa$alf_              alf_eats_alfalfa$
ats_alfalfa$alf_e              alfalfa$alf_eats_alf
ts_alfalfa$alf_ea    ⤳⤳→      alfalfa$alf_eats_
s_alfalfa$alf_eat    sort      ats_alfalfa$alf_e
_alfalfa$alf_eats              eats_alfalfa$alf_
alfalfa$alf_eats_              f_eats_alfalfa$al
lfalfa$alf_eats_a              fa$alf_eats_alfal
falfa$alf_eats_al              falfa$alf_eats_al
alfa$alf_eats_alf              lf_eats_alfalfa$a
lfa$alf_eats_alfa              lfa$alf_eats_alfa
fa$alf_eats_alfal              lfalfa$alf_eats_a
a$alf_eats_alfalf              s_alfalfa$alf_eat
$alf_eats_alfalfa              ts_alfalfa$alf_ea
```

▶ BWT can be computed in $O(n)$ time!

  ▶ totally non-obvious from definition (naive sorting could take $\Omega(n^2)$ time in worst case!)

  ▶ will use one of the most sophisticated algorithms we cover ⤳ Unit 13!

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BWT – Properties

Why does BWT help for compression?

- sorting *groups* characters *by what follows*
    - Example: lf always preceded by a
    - more generally: BWT can be partitioned into letters following a given context

$\leadsto$ repeated substring in S $\leadsto$ *runs* in B

- Example: alf $\leadsto$ run of as
- picked up by RLE

(formally: low higher-order empirical entropy)

$\leadsto$ *If S allows predicting symbols from context, B has locally low entropy of characters.*

- that makes MTF effective!

		r		$\downarrow$ $L[r]$	
alf␣eats␣alfalfa$		0	$alf␣eats␣alfal**a**	16
lf␣eats␣alfalfa$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

A 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_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_
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_
```

For T some English text, $MTF(B)$ has typically around 50% zeroes!

$T =$ 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 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

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Run-length BWT Compression

- ► amazingly, just run-length compressing the BWT is already powerful!

- ► r = number of runs in BWT

- ► $r = O(z \log^2(n))$, z number of LZ77 phrases
  proven in 2019 (!)

Example:

$S = \text{alf}_\sqcup\text{eats}_\sqcup\text{alfalfa\$}$

$B = \text{asff\$f}_\sqcup\text{e}_\sqcup\text{lllaaata}$

$RL(B) = \begin{bmatrix}a\\1\end{bmatrix}\begin{bmatrix}s\\1\end{bmatrix}\begin{bmatrix}f\\2\end{bmatrix}\begin{bmatrix}\$\\1\end{bmatrix}\begin{bmatrix}f\\1\end{bmatrix}\begin{bmatrix}\sqcup\\1\end{bmatrix}\begin{bmatrix}e\\1\end{bmatrix}\begin{bmatrix}\sqcup\\1\end{bmatrix}\begin{bmatrix}l\\3\end{bmatrix}\begin{bmatrix}a\\3\end{bmatrix}\begin{bmatrix}t\\1\end{bmatrix}\begin{bmatrix}a\\1\end{bmatrix}$

$\leadsto \quad r = |RL(B)| = 12; \quad n = 17$

Larger Example:

$S = \text{have}_\sqcup\text{had}_\sqcup\text{hadnt}_\sqcup\text{hasnt}_\sqcup\text{havent}_\sqcup\text{has}_\sqcup\text{what\$}$

$\leadsto \quad r = 19; \quad n = 36$

7.10 Inverse BWT

Inverse BWT

► Great, can compute BWT efficiently and it helps compression. *But how can we decode it?*

	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)

► **"Magic" solution:**

   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 = $ abracadabra\$

Inverse BWT – The magic revealed

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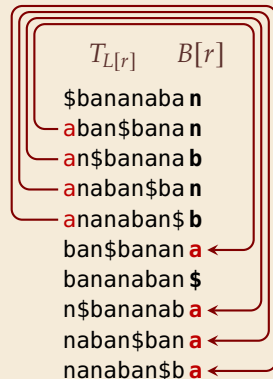 - $\rightsquigarrow O(n)$ with counting sort

- ▶ *but why does this work!?*
- ▶ 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
  - ⤳ decoding much simpler & faster (but same Θ-class)

👎 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