CS 240 – Data Structures and Data Management

Module 10: Compression

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Based on lecture notes by many previous cs240 instructors

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Outline

1. Compression
   - Encoding Basics
   - Huffman Codes
   - Run-Length Encoding
   - Lempel-Ziv-Welch
   - bzip2
   - Burrows-Wheeler Transform
Outline

1 Compression

- Encoding Basics
  - Huffman Codes
  - Run-Length Encoding
  - Lempel-Ziv-Welch
  - bzip2
  - Burrows-Wheeler Transform
Data Storage and Transmission

**The problem**: How to store and transmit data?

**Source text** The original data, string $S$ of characters from the **source alphabet** $\Sigma_S$

**Coded text** The encoded data, string $C$ of characters from the **coded alphabet** $\Sigma_C$

**Encoding** An algorithm mapping source texts to coded texts

**Decoding** An algorithm mapping coded texts back to their original source text

**Note**: Source “text” can be any sort of data (not always text!)

Usually the coded alphabet $\Sigma_C$ is just binary: $\{0, 1\}$.

Usually $S$ and $C$ are stored as streams (read/write only one character at a time), which is convenient for handling huge texts.
Judging Encoding Schemes

We can always measure efficiency of encoding/decoding algorithms.

What other goals might there be?
Judging Encoding Schemes

We can always measure efficiency of encoding/decoding algorithms.

What other goals might there be?

- Processing speed
- Reliability (e.g. error-correcting codes)
- Security (e.g. encryption)
- Size
Judging Encoding Schemes

We can always measure efficiency of encoding/decoding algorithms.

What other goals might there be?

- Processing speed
- Reliability (e.g. error-correcting codes)
- Security (e.g. encryption)
- Size *(main objective here)*

Encoding schemes that try to minimize the size of the coded text perform **data compression**. We will measure the **compression ratio**:

\[
\frac{|C| \cdot \log |\Sigma_C|}{|S| \cdot \log |\Sigma_S|}
\]
Types of Data Compression

**Logical vs. Physical**
- **Logical Compression** uses the meaning of the data and only applies to a certain domain (e.g. sound recordings)
- **Physical Compression** only knows the physical bits in the data, not the meaning behind them

**Lossy vs. Lossless**
- **Lossy Compression** achieves better compression ratios, but the decoding is approximate; the exact source text $S$ is not recoverable
- **Lossless Compression** always decodes $S$ exactly

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

We will concentrate on *physical, lossless* compression algorithms. These techniques can safely be used for any application.
A **character encoding** (or more precisely **character-by-character encoding**) maps each character in the source alphabet to a string in coded alphabet.

\[ E : \Sigma_S \rightarrow \Sigma_C^* \]

For \( c \in \Sigma_S \), we call \( E(c) \) the **codeword** of \( c \)

**Two possibilities:**

- **Fixed-length code**: All codewords have the same length.
- **Variable-length code**: Codewords may have different lengths.
Fixed-length codes

ASCII (American Standard Code for Information Interchange), 1963:

<table>
<thead>
<tr>
<th>char code</th>
<th>null</th>
<th>start of heading</th>
<th>start of text</th>
<th>end of text</th>
<th>...</th>
<th>0</th>
<th>1</th>
<th>...</th>
<th>A</th>
<th>B</th>
<th>...</th>
<th>~</th>
<th>delete</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>...</td>
<td>48</td>
<td>49</td>
<td>...</td>
<td>65</td>
<td>66</td>
<td>...</td>
<td>126</td>
<td>127</td>
<td></td>
</tr>
</tbody>
</table>

- 7 bits to encode 128 possible characters:
  - “control codes”, spaces, letters, digits, punctuation

  \[ A \cdot P \cdot P \cdot L \cdot E \rightarrow (65, 80, 80, 76, 69) \rightarrow 1000001 \ 1010000 \ 1010000 \ 1001100 \ 1000101 \]

- Standard in all computers and often our source alphabet.
- Not well-suited for non-English text:
  ISO-8859 extends to 8 bits, handles most Western languages

Other (earlier) examples: Caesar shift, Baudot code, Murray code

To decode a fixed-length code (say codewords have \( k \) bits), we look up each \( k \)-bit pattern in a table.
Variable-Length Codes

**Overall goal**: Find an encoding that is short.

**Observation**: Some letters in $\Sigma$ occur more often than others. So let’s use shorter codes for more frequent characters.

For example, the frequency of letters in typical English text is:

<table>
<thead>
<tr>
<th>Letter</th>
<th>Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>e</td>
<td>12.70%</td>
</tr>
<tr>
<td>t</td>
<td>9.06%</td>
</tr>
<tr>
<td>a</td>
<td>8.17%</td>
</tr>
<tr>
<td>o</td>
<td>7.51%</td>
</tr>
<tr>
<td>i</td>
<td>6.97%</td>
</tr>
<tr>
<td>n</td>
<td>6.75%</td>
</tr>
<tr>
<td>s</td>
<td>6.33%</td>
</tr>
<tr>
<td>h</td>
<td>6.09%</td>
</tr>
<tr>
<td>r</td>
<td>5.99%</td>
</tr>
<tr>
<td>d</td>
<td>4.25%</td>
</tr>
<tr>
<td>l</td>
<td>4.03%</td>
</tr>
<tr>
<td>c</td>
<td>2.78%</td>
</tr>
<tr>
<td>u</td>
<td>2.76%</td>
</tr>
<tr>
<td>m</td>
<td>2.41%</td>
</tr>
<tr>
<td>w</td>
<td>2.36%</td>
</tr>
<tr>
<td>f</td>
<td>2.23%</td>
</tr>
<tr>
<td>g</td>
<td>2.02%</td>
</tr>
<tr>
<td>y</td>
<td>1.97%</td>
</tr>
<tr>
<td>p</td>
<td>1.93%</td>
</tr>
<tr>
<td>b</td>
<td>1.49%</td>
</tr>
<tr>
<td>v</td>
<td>0.98%</td>
</tr>
<tr>
<td>k</td>
<td>0.77%</td>
</tr>
<tr>
<td>j</td>
<td>0.15%</td>
</tr>
<tr>
<td>x</td>
<td>0.15%</td>
</tr>
<tr>
<td>q</td>
<td>0.10%</td>
</tr>
<tr>
<td>z</td>
<td>0.07%</td>
</tr>
</tbody>
</table>
Variable-Length Codes

**Example 1:** Morse code.

- 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 ••

**Example 2:** UTF-8 encoding of Unicode:

- Encodes any Unicode character (more than 107,000 characters) using 1-4 bytes
Encoding

Assume we have some character encoding $E : \Sigma_S \rightarrow \Sigma_C^*$. 
- Note that $E$ is a dictionary with keys in $\Sigma_S$.
- Typically $E$ would be stored as array indexed by $\Sigma_S$.

```markdown
charByChar::encoding(E, S, C)
E : the encoding dictionary
S: input-stream with characters in $\Sigma_S$, C: output-stream
1. while S is non-empty
2. $x \leftarrow E.search(S.pop())$
3. C.append($x$)
```

Example: encode text “WATT” with Morse code:

• •
\[-----------\]
W

• •
\[----------\]
A

• •
\[-------\]
T

• •
\[-------\]
T
Decoding

The **decoding algorithm** must map $\Sigma_C^*$ to $\Sigma_S^*$.

- The code must be *uniquely decodable*.
  - This is false for Morse code as described!
    - `●-● ●-●-●` decodes to WATT and ANO and WJ.
      (Morse code uses ‘end of character’ pause to avoid ambiguity.)

- From now on only consider **prefix-free** codes $E$: no codeword is a prefix of another.

- This corresponds to a **trie** with characters of $\Sigma_S$ only at the leaves.

- The codewords need no end-of-string symbol $\$$ if $E$ is prefix-free.
Decoding of Prefix-Free Codes

Any prefix-free code is uniquely decodable (why?)

```
prefixFree::decoding(T, C, S)
T : trie of a prefix-free code
C: input-stream with characters in \( \Sigma_C \), S: output-stream
1.   while C is non-empty
2.     r ← T.root
3.     while r is not a leaf
4.        if C is empty or r has no child labelled C.top()
5.           return “invalid encoding”
6.     r ← child of r that is labelled with C.pop()
7.     S.append(character stored at r)
```

Run-time: \( O(|C|) \).
Encoding from the Trie

We can also encode directly from the trie.

\[
\text{prefixFree::encoding}(T, S, C)
\]

\(T\): trie of a prefix-free code
\(S\): input-stream with characters in \(\Sigma_S\), \(C\): output-stream

1. \(E \leftarrow\) array of nodes in \(T\) indexed by \(\Sigma_S\)
2. \(\text{for all leaves } \ell \text{ in } T\)
3. \(E[\text{character at } \ell] \leftarrow \ell\)
4. \(\text{while } S \text{ is non-empty}\)
5. \(w \leftarrow\) empty string
6. \(v \leftarrow E[S.pop()]\)
7. \(\text{while } v \text{ is not the root}\)
8. \(w.prepend(\text{character from } v \text{ to its parent})\)
9. \(\text{// Now } w \text{ is the encoding of character from } S.\)
10. \(C.append(w)\)

Run-time: \(O(|T| + |C|) = O(|\Sigma_S| + |C|)\) if \(T\) has no nodes with 1 child)
Example: Prefix-free Encoding/Decoding

Code as table:

<table>
<thead>
<tr>
<th>$c \in \Sigma$</th>
<th>$\sqcup$</th>
<th>A</th>
<th>E</th>
<th>N</th>
<th>O</th>
<th>T</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E(c)$</td>
<td>000</td>
<td>01</td>
<td>101</td>
<td>001</td>
<td>100</td>
<td>11</td>
</tr>
</tbody>
</table>

Code as trie:

- Encode AN\sqcupANT
- Decode 111000001010111
Example: Prefix-free Encoding/Decoding

Code as table:

<table>
<thead>
<tr>
<th>$c \in \Sigma_S$</th>
<th>$\bot$</th>
<th>A</th>
<th>E</th>
<th>N</th>
<th>O</th>
<th>T</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E(c)$</td>
<td>000</td>
<td>01</td>
<td>101</td>
<td>001</td>
<td>100</td>
<td>11</td>
</tr>
</tbody>
</table>

Code as trie:

- Encode $\text{AN} \rightarrow 010010000100111$
- Decode $1110000001010111 \rightarrow \text{TO}_\bot\text{EAT}$
Outline

Compression

- Encoding Basics
- **Huffman Codes**
- Run-Length Encoding
- Lempel-Ziv-Welch
- bzip2
- Burrows-Wheeler Transform
Huffman’s Algorithm: Building the best trie

For a given source text $S$, how to determine the “best” trie that minimizes the length of $C$?

1. Determine frequency of each character $c \in \Sigma$ in $S$
2. For each $c \in \Sigma$, create “[c]” (height-0 trie holding $c$).
3. Our tries have a weight: sum of frequencies of all letters in trie. Initially, these are just the character frequencies.
4. Find the two tries with the minimum weight.
5. Merge these tries with new interior node; new weight is the sum. (Corresponds to adding one bit to the encoding of each character.)
6. Repeat last two steps until there is only one trie left

What data structure should we store the tries in to make this efficient?
Huffman’s Algorithm: Building the best trie

For a given source text $S$, how to determine the “best” trie that minimizes the length of $C$?

1. Determine frequency of each character $c \in \Sigma$ in $S$
2. For each $c \in \Sigma$, create “$\overline{c}$” (height-0 trie holding $c$).
3. Our tries have a weight: sum of frequencies of all letters in trie. Initially, these are just the character frequencies.
4. Find the two tries with the minimum weight.
5. Merge these tries with new interior node; new weight is the sum. (Corresponds to adding one bit to the encoding of each character.)
6. Repeat last two steps until there is only one trie left

What data structure should we store the tries in to make this efficient?
A min-ordered heap! Step 4 is two delete-mins, Step 5 is insert
Example: Huffman tree construction

Example text: GREENENERGY, $\Sigma_S = \{G, R, E, N, Y\}$

Character frequencies: $G: 2, \quad R: 2, \quad E: 4, \quad N: 2, \quad Y: 1$
Example: Huffman tree construction

Example text: GREENENERGY, $\Sigma_S = \{G, R, E, N, Y\}$

Character frequencies: $G : 2$, $R : 2$, $E : 4$, $N : 2$, $Y : 1$

```
  3
 G  1

  2
 R

  4
 E

  2
 N
```

$GREENENERGY \rightarrow 0001001011101110110000001$

Compression ratio: $25 \frac{1}{11} \cdot \log_2 5 \approx 97\%$

(These frequencies are not skewed enough to lead to good compression.)
Example: Huffman tree construction

Example text: $\text{GREENENERGY}$, $\Sigma_S = \{G, R, E, N, Y\}$

Character frequencies: $G : 2, \quad R : 2, \quad E : 4, \quad N : 2, \quad Y : 1$

```
GREENENERGY → 0001001011101110110000001
```

Compression ratio: $\frac{11}{25} \cdot \log_2 5 \approx 97\%$

(These frequencies are not skewed enough to lead to good compression.)
Example: Huffman tree construction

Example text: GREENENERGY, $\Sigma_s = \{G, R, E, N, Y\}$

Character frequencies: $G : 2$, $R : 2$, $E : 4$, $N : 2$, $Y : 1$

![Huffman tree diagram]
Example: Huffman tree construction

Example text: GREENENERGY, \( \Sigma_S = \{G, R, E, N, Y\} \)

Character frequencies: \( G: 2, \quad R: 2, \quad E: 4, \quad N: 2, \quad Y: 1 \)

\[
\begin{align*}
\text{G} & \quad \text{0} \quad \text{1} \\
\text{E} & \quad 0 \quad 1 \\
\text{R} & \quad 1 \quad 0 \\
\text{N} & \quad 1 \quad 0 \\
\text{Y} & \quad 0 \quad 1 \\
\text{11} & \quad \text{0} \quad \text{1} \\
\end{align*}
\]

GREENENERGY \rightarrow
Example: Huffman tree construction

Example text: GREENENERGY, $\Sigma_S = \{G, R, E, N, Y\}$

Character frequencies: $G : 2, \quad R : 2, \quad E : 4, \quad N : 2, \quad Y : 1$

![Huffman tree diagram]

GREENENERGY → 000 10 01 01 11 01 11 01 10 000 001

Compression ratio: $\frac{25}{11 \cdot \log 5} \approx 97%$

(These frequencies are not skewed enough to lead to good compression.)
Huffman’s Algorithm: Pseudocode

**Huffman::encoding**\((S, C)\)

\(S\): input-stream with characters in \(\Sigma_S\), \(C\): output-stream

1. \(f \leftarrow \text{array indexed by } \Sigma_S, \text{ initially all-0} \) \hspace{1cm} // frequencies
2. **while** \(S\) is non-empty **do** increase \(f[S.pop()]\) by 1
3. \(Q \leftarrow \text{min-oriented priority queue that stores tries} \) \hspace{1cm} // initialize PQ
4. **for** all \(c \in \Sigma_S\) with \(f[c] > 0\) **do**
   5. \(Q.insert(\text{single-node trie for } c \text{ with weight } f[c])\)
6. **while** \(Q.size > 1\) **do** \hspace{1cm} // build decoding trie
   7. \(T_1 \leftarrow Q.deleteMin(), f_1 \leftarrow \text{weight of } T_1\)
   8. \(T_2 \leftarrow Q.deleteMin(), f_2 \leftarrow \text{weight of } T_2\)
   9. \(Q.insert(\text{trie with } T_1, T_2 \text{ as subtries and weight } f_1+f_2)\)
10. \(T \leftarrow Q.deleteMin\)
11. \(C.append(\text{encoding trie } T)\)
12. **Re-set input-stream** \(S\) \hspace{1cm} // actual encoding
13. **prefixFree::encoding**\((T, S, C)\)
Huffman Coding Evaluation

- Note: constructed trie is *not unique* (why?)
  So decoding trie must be transmitted along with the coded text.
- This may make encoding bigger than source text!
- Encoding must pass through text twice (to compute frequencies and to encode). Cannot use a stream unless it can be re-set.
- Encoding run-time: $O(|\Sigma_S| \log |\Sigma_S| + |C|)$
- Decoding run-time: $O(|C|)$
- The constructed trie is *optimal* in the sense that coded text is shortest (among all prefix-free character-encodings with $\Sigma_C = \{0, 1\}$).
  We will not go through the proof.
- Many variations (give tie-breaking rules, estimate frequencies, adaptively change encoding, ....)
Outline

1 Compression

- Encoding Basics
- Huffman Codes
- Run-Length Encoding
- Lempel-Ziv-Welch
- bzip2
- Burrows-Wheeler Transform
Run-Length Encoding

- Variable-length code
- Example of **multi-character encoding**: multiple source-text characters receive one code-word.
- The source alphabet and coded alphabet are both binary: \( \{0, 1\} \).
- Decoding dictionary is uniquely defined and not explicitly stored.

**When to use**: if \( S \) has long runs: \( 00000 \ 111 \ 0000 \)

**Encoding idea:**
- Give the first bit of \( S \) (either 0 or 1)
- Then give a sequence of integers indicating run lengths.
- We don’t have to give the bit for runs since they alternate.

Example becomes: 0, 5, 3, 4

**Question**: How to encode a run length \( k \) in binary?
Prefix-free Encoding for Positive Integers

Use **Elias gamma coding** to encode \( k \):

- \( \lfloor \log k \rfloor \) copies of 0, followed by
- binary representation of \( k \) (always starts with 1)

<table>
<thead>
<tr>
<th>( k )</th>
<th>( \lfloor \log k \rfloor )</th>
<th>( k ) in binary</th>
<th>encoding</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>10</td>
<td>010</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>11</td>
<td>011</td>
</tr>
<tr>
<td>4</td>
<td>2</td>
<td>100</td>
<td>00100</td>
</tr>
<tr>
<td>5</td>
<td>2</td>
<td>101</td>
<td>00101</td>
</tr>
<tr>
<td>6</td>
<td>2</td>
<td>110</td>
<td>00110</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
</tbody>
</table>
RLE Encoding

\[ \text{RLE::encoding}(S, C) \]

\( S \): input-stream of bits, \( C \): output-stream

1. \( b \leftarrow S\.top() \); \( C\.append(b) \)
2. \( \text{while } S \text{ is non-empty } \text{ do} \)
3. \( k \leftarrow 1 \) \hspace{1cm} \text{// length of run} 
4. \( \text{while } (S \text{ is non-empty and } S\.top() = b) \text{ do} \)
5. \( k++; S\.pop() \)
6. \( K \leftarrow \text{empty string} \)
7. \( \text{while } k > 1 \)
8. \( C\.append(0) \)
9. \( K\.prepend(k \mod 2) \)
10. \( k \leftarrow \lfloor k/2 \rfloor \)
11. \( K\.prepend(1) \) \hspace{1cm} \text{// } K \text{ is binary encoding of } k 
12. \( C\.append(K) \)
13. \( b \leftarrow 1 - b \)
RLE Decoding

\[ \text{RLE::decoding}(C, S) \]
\[ C: \text{input-stream of bits} \quad S: \text{output-stream} \]
1. \( b \leftarrow C.\text{pop()} \quad \text{// bit-value for the current run} \)
2. \textbf{while} \( C \) is non-empty
3. \( \ell \leftarrow 0 \quad \text{// length of base-2 number } -1 \)
4. \textbf{while} \( C.\text{pop()} = 0 \) \textbf{do} \( \ell++ \)
5. \( k \leftarrow 1 \quad \text{// base-2 number converted} \)
6. \textbf{for} (\( j \leftarrow 1 \text{ to } \ell \)) \textbf{do} \( k \leftarrow k \times 2 + C.\text{pop()} \)
7. \textbf{for} (\( j \leftarrow 1 \text{ to } k \)) \textbf{do} \( S.\text{append}(b) \)
8. \( b \leftarrow 1 - b \)

If \( C.\text{pop()} \) is called when there are no bits left, then \( C \) was not valid input.
RLE Example

Encoding:
\[ S = 11111110010000000000000000000011111111111 \]
\[ C = 1 \]

Decoding:
\[ C = 00001101001001010 \]
\[ S = 0000000000000 \]

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RLE Example

Encoding:
\[ S = 111111100100000000000000000011111111111 \]
\[ k = 7 \]
\[ C = 100111 \]

Decoding:
\[ C = 00001101001001010 \]
\[ B = \ell = k = 7 \]
\[ S = 000000000000011110111 \]
RLE Example

Encoding:
S = 11111110010000000000000000000011111111111
k = 2
C = 100111010

Decoding:
C = 00001101001001010

S =
RLE Example

Encoding:
\[ S = 1111111001000000000000000011111111111 \]
\[ k = 1 \]
\[ C = 1001110101 \]

Decoding:
\[ C = 00001101001001010 \]
\[ b = \ell = k = 1 \]
\[ S = 000000000000001111011 \]
RLE Example

Encoding:
\[ S = 11111110010000000000000000000011111111111 \]
\[ k = 20 \]
\[ C = 1001110101000010100 \]

Decoding:
\[ C = 00001101001001010 \]
\[ \ell = k = 20 \]
\[ S = 000000000000011110100010011 \]
RLE Example

Encoding:
\[ S = 111111100100000000000000000000000011111111111 \]
\[ k = 11 \]
\[ C = 1001110101000010100001011 \]

Decoding:
\[ C = 00001101001001010 \]
\[ S = \]

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RLE Example

Encoding:
\[ S = 11111110010000000000000000000011111111111 \]

\[ C = 10011101010000101000001011 \]

Compression ratio: \( 26/41 \approx 63\% \)

Decoding:
\[ C = 00001101001001010 \]

\[ S = \]
RLE Example

Encoding:
$S = 1111111001000000000000000000011111111111$

$C = 10011101010000101000001011$

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

Decoding:
$C = 00001101001001010$

$S =$
RLE Example

Encoding:
\[ S = 111111100100000000000000000000011111111111 \]
\[ C = 10011101010000101000001011 \]

Compression ratio: \( 26/41 \approx 63\% \)

Decoding:
\[ C = 00001101001001010 \]
\[ b = 0 \]
\[ S = \]

S =
RLE Example

Encoding:
\[ S = 111111100100000000000000000000011111111111 \]
\[ C = 10011101010000101000001011 \]

Compression ratio: \( \frac{26}{41} \approx 63\% \)

Decoding:
\[ C = 00001101001001010 \]
\[ b = 0 \]
\[ \ell = 3 \]
\[ S = \]
RLE Example

Encoding:
\( S = 1111111001000000000000000000000011111111111 \)

\( C = 10011101010000101000001011 \)

Compression ratio: \( 26/41 \approx 63\% \)

Decoding:
\( C = 00001101001001010 \)
\( b = 0 \)
\( \ell = 3 \)
\( k = 13 \)
\( S = 00000000000000 \)
RLE Example

Encoding:
\[ S = 11111110010000000000000000000011111111111 \]
\[ C = 10011101010000101000001011 \]

Compression ratio: \( \frac{26}{41} \approx 63\% \)

Decoding:
\[ C = 00001101001001010 \]
\[ b = 1 \]
\[ l = 2 \]
\[ k = \]
\[ S = 00000000000000 \]
RLE Example

Encoding:
\[ S = 11111110010000000000000000000011111111111 \]
\[ C = 10011101010000101000001011 \]

Compression ratio: \( 26/41 \approx 63\% \)

Decoding:
\[ C = 00001101001001010 \]
\[ b = 1 \]
\[ \ell = 2 \]
\[ k = 4 \]
\[ S = 000000000000001111 \]
RLE Example

Encoding:
\[ S = 11111110010000000000000000000011111111111 \]

\[ C = 10011101010000101000001011 \]

Compression ratio: \( 26/41 \approx 63\% \)

Decoding:
\[ C = 00001101001001010 \]
\[ b = 0 \]
\[ \ell = 0 \]
\[ k = \]
\[ S = 00000000000001111 \]
RLE Example

Encoding:
\[ S = 111111100100000000000000000011111111111 \]
\[ C = 10011101010000101000001011 \]

Compression ratio: \( 26/41 \approx 63\% \)

Decoding:
\[ C = 00001101001001010 \]
\[ b = 0 \]
\[ \ell = 0 \]
\[ k = 1 \]
\[ S = 000000000000011110 \]
RLE Example

Encoding:
\[ S = 1111111100100000000000000000000011111111111 \]

\[ C = 10011101010000101000001011 \]

Compression ratio: \( 26/41 \approx 63\% \)

Decoding:
\[ C = 00001101001001010 \]
\[ b = 1 \]
\[ \ell = 1 \]
\[ k = \]
\[ S = 000000000000011110 \]
RLE Example

Encoding:
$S = 11111110010000000000000000000011111111111$

$C = 10011101010000101000001011$

Compression ratio: $\frac{26}{41} \approx 63\%$

Decoding:
$C = 00001101001001010$

$b = 1$

$\ell = 1$

$k = 2$

$S = 000000000000001111011$
An all-0 string of length $n$ would be compressed to $2\lceil \log n \rceil + 2 \in o(n)$ bits.

Usually, we are not that lucky:

- No compression until run-length $k \geq 6$
- *Expansion* when run-length $k = 2$ or $4$

Used in some image formats (e.g. TIFF)

Method can be adapted to larger alphabet sizes (but then the encoding of each run must also store the character)

Method can be adapted to encode *only* runs of 0 (we will need this soon)
Outline

1 Compression
   - Encoding Basics
   - Huffman Codes
   - Run-Length Encoding
   - Lempel-Ziv-Welch
   - bzip2
   - Burrows-Wheeler Transform
Longer Patterns in Input

Huffman and RLE take advantage of frequent/repeated *single characters*.

**Observation**: Certain *substrings* are much more frequent than others.

- English text:
  Most frequent digraphs: TH, ER, ON, AN, RE, HE, IN, ED, ND, HA
  Most frequent trigraphs: THE, AND, THA, ENT, ION, TIO, FOR, NDE

- HTML: “<a href”, “<img src”, “<br>”

- Video: repeated background between frames, shifted sub-image

**Ingredient 1** for Lempel-Ziv-Welch compression: take advantage of such substrings *without* needing to know beforehand what they are.
Adaptive Dictionaries

ASCII, UTF-8, and RLE use *fixed* dictionaries.

In Huffman, the dictionary is not fixed, but it is *static*: the dictionary is the same for the entire encoding/decoding.

**Ingredient 2** for LZW: *adaptive encoding*:
- There is a fixed initial dictionary $D_0$. (Usually ASCII.)
- For $i \geq 0$, $D_i$ is used to determine the $i$th output character
- After writing the $i$th character to output, both encoder and decoder update $D_i$ to $D_{i+1}$

Encoder and decoder must both know how the dictionary changes.
LZW Overview

- Start with dictionary $D_0$ for $|\Sigma_S|$. Usually $\Sigma_S = ASCII$, then this uses codenumbers 0,\ldots, 127.
- Every step adds to dictionary a multi-character string, using codenumbers 128, 129,\ldots.
- Encoding:
  - Store current dictionary $D_i$ as a trie.
  - Parse trie to find longest prefix $w$ already in $D_i$. So all of $w$ can be encoded with one number.
  - Add to dictionary the substring that would have been useful: add $wK$ where $K$ is the character that follows $w$ in $S$.
  - This creates one child in trie at the leaf where we stopped.
- Output is a list of numbers. This is usually converted to bit-string with fixed-width encoding using 12 bits.
  - This limits the codenumbers to 4096.
LZW Example

Text: A N A N A S A N N A A

Dictionary:

Dictionary:

65
A

N 78
S

83
LZW Example

Text: A N A N A S A N N N A

Dictionary:

```
A
\-- 65

N
\-- 78
  \-- S
    \-- 83

128
```

Final output: 000001000001000011100000000000001000000100011000000000000000100000000000000000000001000000000000000000000010000000000000000000000128
LZW Example

Text: A N A N A S A N N A A

Dictionary:

Dictionary: 000001000001 000001001110 000010000000 000001000001 000001000001 000001000001 000010000000 000010000001 000010000001
LZW Example

Text:

<table>
<thead>
<tr>
<th>A</th>
<th>N</th>
<th>A</th>
<th>N</th>
<th>A</th>
<th>S</th>
<th>A</th>
<th>N</th>
<th>N</th>
<th>A</th>
</tr>
</thead>
<tbody>
<tr>
<td>65</td>
<td>78</td>
<td>128</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Dictionary:

<table>
<thead>
<tr>
<th>A</th>
<th>N</th>
<th>130</th>
</tr>
</thead>
<tbody>
<tr>
<td>65</td>
<td>128</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>A</th>
<th>129</th>
</tr>
</thead>
<tbody>
<tr>
<td>78</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>S</th>
<th>83</th>
</tr>
</thead>
</table>
LZW Example

Text: A N A N A S A N N A A

65 78 128 65

Dictionary:

A 130
N 128
S 131
78 A 129
83
LZW Example

Text: A  N  A  N  A  S  A  N  N  A

65  78  128  65  83

Dictionary:

A  130
128
N
65
A  129
131
S
78
83  A  132
LZW Example

Text:  

\[
\begin{array}{cccccccc}
65 & 78 & 128 & 65 & 83 & 128 & & \\
& & & & 65 & & & \\
& & & & 83 & & & \\
& & & & 128 & & & \\
& & & & 129 & & & \\
& & & & 130 & & & \\
& & & & 131 & & & \\
& & & & 132 & & & \\
\end{array}
\]

Dictionary:

\[
\begin{array}{cccc}
A & S & 78 & 129 \\
& & 83 & 132 \\
& & 131 & 133 \\
\end{array}
\]
LZW Example

Text: A N A N A S A N N A

65 78 128 65 83 128 129

Dictionary:

Biedl, Schost, Veksler (SCS, UW)
LZW Example

Text:  
A  N  A  N  A  S  A  N  N  A  

65  78  128  65  83  128  129  

Dictionary:  

Final output:  

Biedl, Schost, Veksler (SCS, UW)  
CS240 – Module 10  
Winter 2021  
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### LZW encoding pseudocode

**LZW::encoding**\((S, C)\)

\(S\) : input-stream of characters, \(C\) : output-stream

1. Initialize dictionary \(D\) with ASCII in a trie
2. \(idx \leftarrow 128\)
3. while \(S\) is non-empty do
4. \(v \leftarrow \) root of trie \(D\)
5. while \((S\) is non-empty and \(v\) has a child \(c\) labelled \(S.top())\)
6. \(v \leftarrow c; S.pop()\)
7. \(C.append\)(codenumber stored at \(v\))
8. if \(S\) is non-empty
9. create child of \(v\) labelled \(S.top()\) with codenumber \(idx\)
10. \(idx++\)
LZW decoding

- Build dictionary while reading string by imitating encoder.
- We are one step behind.

Example:

<table>
<thead>
<tr>
<th>ASCII</th>
</tr>
</thead>
<tbody>
<tr>
<td>...</td>
</tr>
<tr>
<td>32</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>...</td>
</tr>
<tr>
<td>65</td>
</tr>
<tr>
<td>A</td>
</tr>
<tr>
<td>66</td>
</tr>
<tr>
<td>B</td>
</tr>
<tr>
<td>67</td>
</tr>
<tr>
<td>C</td>
</tr>
<tr>
<td>...</td>
</tr>
<tr>
<td>78</td>
</tr>
<tr>
<td>N</td>
</tr>
<tr>
<td>...</td>
</tr>
<tr>
<td>83</td>
</tr>
<tr>
<td>S</td>
</tr>
<tr>
<td>...</td>
</tr>
</tbody>
</table>

What encoder did:

```
32
.
65
.
66
.
B
67
.
C
78
.
N
83
.
S
```
LZW decoding

- Build dictionary while reading string by imitating encoder.
- We are one step behind.
- Example: \( \text{67} \) 
  
\[ \begin{array}{c|c}
\text{ASCII} & \text{dictionary} \\
0 & \text{...} \\
32 & \text{...} \\
65 & \text{A} \\
66 & \text{B} \\
67 & \text{C} \\
78 & \text{N} \\
83 & \text{S} \\
\end{array} \]

What encoder did: 

\[ \begin{array}{c|c}
0 & \text{...} \\
32 & \text{...} \\
65 & \text{A} \\
66 & \text{B} \\
67 & \text{C} \\
78 & \text{N} \\
83 & \text{S} \\
\end{array} \]
LZW decoding

- Build dictionary while reading string by imitating encoder.
- We are one step behind.
- Example:

```
67  65
C   A
```

<table>
<thead>
<tr>
<th>ASCII</th>
</tr>
</thead>
<tbody>
<tr>
<td>...</td>
</tr>
<tr>
<td>32</td>
</tr>
<tr>
<td>...</td>
</tr>
<tr>
<td>...</td>
</tr>
<tr>
<td>65 A</td>
</tr>
<tr>
<td>66 B</td>
</tr>
<tr>
<td>67 C</td>
</tr>
<tr>
<td>...</td>
</tr>
<tr>
<td>78 N</td>
</tr>
<tr>
<td>...</td>
</tr>
<tr>
<td>83 S</td>
</tr>
<tr>
<td>...</td>
</tr>
</tbody>
</table>

What encoder did:

Deduced one step later:
LZW decoding

- Build dictionary while reading string by imitating encoder.
- We are one step behind.
- Example: 67  65  78
  C   A   N

<table>
<thead>
<tr>
<th>ASCII</th>
</tr>
</thead>
<tbody>
<tr>
<td>...</td>
</tr>
<tr>
<td>...</td>
</tr>
<tr>
<td>...</td>
</tr>
<tr>
<td>32</td>
</tr>
<tr>
<td>...</td>
</tr>
<tr>
<td>...</td>
</tr>
<tr>
<td>65</td>
</tr>
<tr>
<td>A</td>
</tr>
<tr>
<td>66</td>
</tr>
<tr>
<td>B</td>
</tr>
<tr>
<td>67</td>
</tr>
<tr>
<td>C</td>
</tr>
<tr>
<td>...</td>
</tr>
<tr>
<td>78</td>
</tr>
<tr>
<td>N</td>
</tr>
<tr>
<td>...</td>
</tr>
<tr>
<td>83</td>
</tr>
<tr>
<td>S</td>
</tr>
<tr>
<td>...</td>
</tr>
</tbody>
</table>

What encoder did:

Deduced one step later:
LZW decoding

- Build dictionary while reading string by imitating encoder.
- We are one step behind.
- Example: 67 65 78 32

<table>
<thead>
<tr>
<th>ASCII</th>
</tr>
</thead>
<tbody>
<tr>
<td>...</td>
</tr>
<tr>
<td>32 □</td>
</tr>
<tr>
<td>...</td>
</tr>
<tr>
<td>...</td>
</tr>
<tr>
<td>65 A</td>
</tr>
<tr>
<td>66 B</td>
</tr>
<tr>
<td>67 C</td>
</tr>
<tr>
<td>...</td>
</tr>
<tr>
<td>78 N</td>
</tr>
<tr>
<td>...</td>
</tr>
<tr>
<td>83 S</td>
</tr>
</tbody>
</table>

What encoder did:

Deduced one step later:
LZW decoding

- Build dictionary while reading string by imitating encoder.
- We are one step behind.
- Example: 67 65 78 32 66
  C A N □ B

<table>
<thead>
<tr>
<th>ASCII</th>
</tr>
</thead>
<tbody>
<tr>
<td>...</td>
</tr>
<tr>
<td>32 □</td>
</tr>
<tr>
<td>...</td>
</tr>
<tr>
<td>65 A</td>
</tr>
<tr>
<td>66 B</td>
</tr>
<tr>
<td>67 C</td>
</tr>
<tr>
<td>...</td>
</tr>
<tr>
<td>78 N</td>
</tr>
<tr>
<td>...</td>
</tr>
<tr>
<td>83 S</td>
</tr>
<tr>
<td>...</td>
</tr>
</tbody>
</table>

What encoder did:

Deduced one step later:
LZW decoding

- Build dictionary while reading string by imitating encoder.
- We are one step behind.
- Example: 67 65 78 32 66 129

<table>
<thead>
<tr>
<th>ASCII</th>
</tr>
</thead>
<tbody>
<tr>
<td>...</td>
</tr>
<tr>
<td>32</td>
</tr>
<tr>
<td>...</td>
</tr>
<tr>
<td>65</td>
</tr>
<tr>
<td>66</td>
</tr>
<tr>
<td>67</td>
</tr>
<tr>
<td>...</td>
</tr>
<tr>
<td>78</td>
</tr>
<tr>
<td>...</td>
</tr>
<tr>
<td>83</td>
</tr>
<tr>
<td>...</td>
</tr>
</tbody>
</table>

What encoder did:

Deduced one step later:
LZW decoding

- Build dictionary while reading string by imitating encoder.
- We are one step behind.
- Example: \[67 \ 65 \ 78 \ 32 \ 66 \ 129 \ 133\]
  \[\text{C A N } \square \text{B AN } ???\]

What encoder did:

Deduced one step later:
LZW decoding: the catch

- In this example: Want to decode 133, but incomplete in dictionary!

Dictionary (parts omitted):

<table>
<thead>
<tr>
<th>65</th>
</tr>
</thead>
<tbody>
<tr>
<td>129</td>
</tr>
<tr>
<td>133</td>
</tr>
</tbody>
</table>

We know: 133 encodes AN

We know: Next step uses 133 = AN

So $x_1 = A$ and 133 encodes ANA

Generally: If code number is about to be added to D, then it encodes "previous string + first character of previous string"
LZW decoding: the catch

- In this example: Want to decode 133, but incomplete in dictionary!
- What happened during the corresponding encoding?

Text: \[\text{C A N } \underline{B A N} x_1 \quad x_2 \quad \ldots\]

\[\begin{array}{cccccccc}
67 & 65 & 78 & 33 & 66 & 129 & \ldots
\end{array}\]

Dictionary

(parts omitted):

\[\begin{array}{c}
A \\ B
\end{array}\]

\[\begin{array}{c}
65 \quad N \quad 129 \quad x_1 \quad 133
\end{array}\]

\[\begin{array}{c}
66 \quad A \quad 132
\end{array}\]
**LZW decoding: the catch**

- In this example: Want to decode 133, but incomplete in dictionary!
- What happened during the corresponding encoding?

<table>
<thead>
<tr>
<th>Text:</th>
<th>C</th>
<th>A</th>
<th>N</th>
<th>B</th>
<th>A</th>
<th>N</th>
<th>x₁</th>
<th>x₂</th>
<th>...</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>67</td>
<td>65</td>
<td>78</td>
<td>33</td>
<td>66</td>
<td>129</td>
<td>133</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Dictionary**

(parts omitted):

- We know: 133 encodes $ANx_1$ (for unknown $x_1$)
LZW decoding: the catch

- In this example: Want to decode 133, but incomplete in dictionary!
- What happened during the corresponding encoding?

Text: C A N [B A N x₁ x₂ ... ]

67 65 78 33 66 129 133

Dictionary

(parts omitted):

- We know: 133 encodes ANx₁ (for unknown x₁)
- We know: Next step uses 133 = ANx₁
LZW decoding: the catch

- In this example: Want to decode 133, but incomplete in dictionary!
- What happened during the corresponding encoding?

| Text: C A N _ B A N x₁ x₂ ... |
|---|---|---|---|
| 67 65 78 33 66 129 A N x₁ |

Dictionary

(parts omitted):

- We know: 133 encodes ANx₁ (for unknown x₁)
- We know: Next step uses 133 = ANx₁
- So x₁ = A and 133 encodes ANA
LZW decoding: the catch

- In this example: Want to decode 133, but incomplete in dictionary!
- What happened during the corresponding encoding?

Text:

```
C  A  N  □  B  A  N  x₁  x₂  ...  
67  65  78  33  66  129  A  N  x₁
```

Dictionary

(parts omitted):

```
A
B
```

- We know: 133 encodes ANx₁ (for unknown x₁)
- We know: Next step uses 133 = ANx₁
- So x₁ = A and 133 encodes ANA

Generally: If code number is about to be added to D, then it encodes

“previous string + first character of previous string”
LZW decoding pseudocode

\[ \text{LZW::decoding}(C, S) \]
C: input-stream of integers, S: output-stream
1. \( D \leftarrow \text{dictionary that maps \{0, \ldots, 127\} to ASCII} \)
2. \( idx \leftarrow 128 \)
3. \( code \leftarrow C.pop(); s \leftarrow D(code); S.append(s) \)
4. \textbf{while} there are more codes in \( C \) \textbf{do}
5. \( s_{prev} \leftarrow s; code \leftarrow C.pop() \)
6. \textbf{if} \( code < idx \)
7. \( s \leftarrow D(code) \)
8. \textbf{else if} \( code = idx \) // special situation!
9. \( s \leftarrow s_{prev} + s_{prev}[0] \)
10. \textbf{else} FAIL // Encoding was invalid
11. \( S.append(s) \)
12. \( D.insert(idx, s_{prev} + s[0]) \)
13. \( idx++ \)
LZW decoding example revisited

67 65 78 32 66 129 133
C AN □ B AN ANA

What encoder did:

Deduced one step later:
LZW decoding example revisited

What encoder did:

Deduced one step later:
LZW decoding - second example

98  97  114  128  114  97
b  a  r  ba  r  a

- No need to build a trie; store dictionary as array.

<table>
<thead>
<tr>
<th>ASCII</th>
<th>input</th>
<th>decodes to</th>
<th>Code #</th>
<th>String (human)</th>
<th>String (computer)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>98</td>
<td>b</td>
<td></td>
<td></td>
<td>98, a</td>
</tr>
<tr>
<td>...</td>
<td>97</td>
<td>a</td>
<td>128</td>
<td>ba</td>
<td>97, r</td>
</tr>
<tr>
<td>97</td>
<td>114</td>
<td>r</td>
<td>129</td>
<td>ar</td>
<td></td>
</tr>
<tr>
<td>98</td>
<td>128</td>
<td>ba</td>
<td>130</td>
<td>rb</td>
<td>114, b</td>
</tr>
<tr>
<td>...</td>
<td>101</td>
<td>e</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>101</td>
<td>114</td>
<td>r</td>
<td>131</td>
<td>bar</td>
<td>128, r</td>
</tr>
<tr>
<td>...</td>
<td>97</td>
<td>a</td>
<td>132</td>
<td>ra</td>
<td>114, a</td>
</tr>
<tr>
<td>97</td>
<td>133</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>...</td>
<td>110</td>
<td>n</td>
<td>134</td>
<td></td>
<td></td>
</tr>
<tr>
<td>110</td>
<td>135</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>...</td>
<td>114</td>
<td>r</td>
<td>136</td>
<td></td>
<td></td>
</tr>
<tr>
<td>114</td>
<td></td>
<td></td>
<td>137</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- To save space, store string as code of prefix + one character.
- Can still look up $s$ in $O(|s|)$ time.
LZW decoding - second example

98 97 114 128 114 97 131
b a r b a r a bar

- No need to build a trie; store dictionary as array.

<table>
<thead>
<tr>
<th>ASCII</th>
<th>input</th>
<th>decodes to</th>
<th>Code #</th>
<th>String (human)</th>
<th>String (computer)</th>
</tr>
</thead>
<tbody>
<tr>
<td>...</td>
<td>98 b</td>
<td>b</td>
<td>98, a</td>
<td></td>
<td></td>
</tr>
<tr>
<td>97 a</td>
<td>97 a</td>
<td>a</td>
<td>128 ba</td>
<td>ba</td>
<td>98, a</td>
</tr>
<tr>
<td>98 b</td>
<td>114 r</td>
<td>r</td>
<td>129 ar</td>
<td>ar</td>
<td>97, r</td>
</tr>
<tr>
<td>...</td>
<td>128 ba</td>
<td>ba</td>
<td>130 rb</td>
<td>rb</td>
<td>114, b</td>
</tr>
<tr>
<td>101 e</td>
<td>114 r</td>
<td>r</td>
<td>131 bar</td>
<td>bar</td>
<td>128, r</td>
</tr>
<tr>
<td>...</td>
<td>97 a</td>
<td>a</td>
<td>132 ra</td>
<td>ra</td>
<td>114, a</td>
</tr>
<tr>
<td>110 n</td>
<td>131 bar</td>
<td>bar</td>
<td>133 ab</td>
<td>ab</td>
<td>97, b</td>
</tr>
<tr>
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- To save space, store string as code of prefix + one character.
- Can still look up $s$ in $O(|s|)$ time.
LZW decoding - second example

98 97 114 128 114 97 131 134
b a r b a r a r a bar barb

- No need to build a trie; store dictionary as array.

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- Can still look up $s$ in $O(|s|)$ time.
LZW decoding - second example

98 97 114 128 114 97 131 134 129
b a r ba r a bar barb ar

- No need to build a trie; store dictionary as array.

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LZW decoding - second example

98  97  114  128  114  97  131  134  129  101
b    a   r    b   a   r   a   b   a   r   e

- No need to build a trie; store dictionary as array.

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LZW decoding - second example

98 97 114 128 114 97 131 134 129 101 110
b a r b a r a  b a r b a r b a r e n

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- To save space, store string as code of prefix + one character.
- Can still look up s in $O(|s|)$ time.
Lempel-Ziv-Welch discussion

- **Encoding**: $O(|S|)$ time, uses a trie of encoded substrings to store the dictionary.
- **Decoding**: $O(|S|)$ time, uses an array indexed by code numbers to store the dictionary.
- **Encoding and decoding** need to go through the string only *once* and do not need to see the whole string.
  - ⇒ can do compression while streaming the text.
- **Compresses quite well** ($\approx 45\%$ on English text).

**Brief history:**

- **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 (patent issues!)
Outline

1 Compression
   - Encoding Basics
   - Huffman Codes
   - Run-Length Encoding
   - Lempel-Ziv-Welch
   - bzip2
   - Burrows-Wheeler Transform
**bzip2 overview**

To achieve even better compression, bzip2 uses *text transform*: Change input into a different text that is not necessarily shorter, but that has other desirable qualities.

```
    text $T_0$
    ↓ Burrows-Wheeler transform
    text $T_1$
    ↓ Move-to-front transform
    text $T_2$
    ↓ Modified RLE
    text $T_3$
    ↓ Huffman encoding
    text $T_4$
```

- **$T_0$**: If $T_0$ has repeated substrings, then $T_1$ has long runs of characters.
- **$T_1$**: If $T_1$ has long runs of characters, then $T_2$ has long runs of zeros and skewed frequencies.
- **$T_2$**: If $T_2$ has long runs of zeroes, then $T_3$ is shorter. Skewed frequencies remain.
- **$T_3$**: Compresses well since frequencies are skewed.
Move-to-Front transform

Recall the MTF heuristic for self-organizing search:

- Dictionary $L$ is stored as an unsorted array or linked list
- After an element is accessed, move it to the front of the dictionary

How can we use this idea for transforming a text with repeat characters?

Encode each character of source text $S$ by its index in $L$.

After each encoding, update $L$ with Move-To-Front heuristic.

Example:

$S = \text{GOOD}$ becomes $C = 1, 2, 0, 2$

$0 1 2 \rightarrow G O D$ $2 0 1 2 \rightarrow O G D$ $0 1 2 \rightarrow O G D$ $2 0 1 2 \rightarrow D O G$

Observe:

A character in $S$ repeats $k$ times $\iff C$ has run of $k - 1$ zeroes.

Observe:

$C$ contains lots of small numbers and few big ones.

$C$ has the same length as $S$, but better properties.
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**Example:** $S = \text{GOOD}$ becomes $C = 1, 2, 0, 2$

\[
\begin{align*}
D & \rightarrow G & 0 & \rightarrow 1 & 1 & \rightarrow G & 0 & \rightarrow 1 & 2 & \rightarrow 0 & 0 & \rightarrow 1 & 2 & \rightarrow 0 & 0 & \rightarrow 1 & 2 & \rightarrow 2 & \rightarrow 0 & 1 & 2 & \rightarrow D & \rightarrow O & \rightarrow G
\end{align*}
\]
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- After each encoding, update $L$ with Move-To-Front heuristic.
- **Example**: $S = \text{GOOD}$ becomes $C = 1, 2, 0, 2$

\[
\begin{array}{cccc}
0 & 1 & 2 & 0 \\
D & G & O & D \\
\end{array} \quad \xrightarrow{g} \quad 
\begin{array}{cccc}
0 & 1 & 2 & 0 \\
G & D & O & D \\
\end{array} \quad \xrightarrow{0} \quad 
\begin{array}{cccc}
0 & 1 & 2 & 0 \\
O & G & D & D \\
\end{array} \quad \xrightarrow{0} \quad 
\begin{array}{cccc}
0 & 1 & 2 & 0 \\
O & G & D & D \\
\end{array} \quad \xrightarrow{2} \quad 
\begin{array}{cccc}
0 & 1 & 2 & 0 \\
D & O & G & D \\
\end{array}
\]

**Observe**: A character in $S$ repeats $k$ times $\iff$ $C$ has run of $k-1$ zeroes

**Observe**: $C$ contains lots of small numbers and few big ones. $C$ has the same length as $S$, but better properties.
Move-to-Front Encoding/Decoding

**MTF::encoding**(S, C)
1. \( L \leftarrow \) array with \( \Sigma_S \) in some pre-agreed, fixed order (usually ASCII)
2. **while** S is not empty **do**
3. \( c \leftarrow S.pop() \)
4. \( i \leftarrow \) index such that \( L[i] = c \)
5. \( C.append(i) \)
6. **for** \( j = i - 1 \) down to 0
   7. swap \( L[j] \) and \( L[j + 1] \)

Decoding works in *exactly* the same way:

**MTF::decoding**(C, S)
1. \( L \leftarrow \) array with \( \Sigma_S \) in some pre-agreed, fixed order (usually ASCII)
2. **while** C is not empty **do**
3. \( i \leftarrow \) next integer from C
4. \( S.append(L[i]) \)
5. **for** \( j = i - 1 \) down to 0
   6. swap \( L[j] \) and \( L[j + 1] \)
Outline

1. Compression
   - Encoding Basics
   - Huffman Codes
   - Run-Length Encoding
   - Lempel-Ziv-Welch
   - bzip2
   - Burrows-Wheeler Transform
Burrows-Wheeler Transform

**Idea:**

- **Permute** the source text $S$: the coded text $C$ has the exact same letters (and the same length), but in a different order.
- **Goal:** If $S$ has repeated substrings, then $C$ should have long runs of characters.
- We need to choose the permutation carefully, so that we can **decode** correctly.

**Details:**

- Assume that the source text $S$ ends with end-of-word character $\$\$ that occurs nowhere else in $S$.
- A cyclic shift of $S$ is the concatenation of $S[i+1..n-1]$ and $S[0..i]$, for $0 \leq i < n$.
- The encoded text $C$ consists of the last characters of the cyclic shifts of $S$ after sorting them.
BWT Encoding Example

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

1. Write all cyclic shifts

$\text{alf} \text{eats} \text{alfalfa}\$
$\text{lf} \text{eats} \text{alfalfa}\$
$\text{f} \text{eats} \text{alfalfa}\$
$\text{alf} \text{eats} \text{alfalfa}\$
$\text{a} \text{lf} \text{eats} \text{alfalfa}\$
$\text{f} \text{alfa}\$
$\text{e} \text{ats} \text{alfalfa}\$
$\text{a} \text{lf} \text{eats} \text{alfalfa}\$
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Observe:
Substring $\text{alf}$ occurs three times and causes runs $\text{lll}$ and $\text{aaa}$ in $C$ (why?)
BWT Encoding Example

\[ S = \text{alf} \text{eats} \text{alfalfa} $ \]

1. Write all cyclic shifts
2. Sort cyclic shifts

Observe:
Substring \text{alf} occurs three times and causes runs \text{lll} and \text{aaa} in \text{C} (why?)
BWT Encoding Example

\[ S = \text{alf} \text{eats} \text{ alfalfa}$ \]

1. Write all cyclic shifts
2. Sort cyclic shifts
3. Extract last characters from sorted shifts

\[ C = \text{asff}\text{f e lllaata} \]

Observe:
Substring alf occurs three times and causes runs lll and aaa in C (why?)
BWT Encoding Example

\[ S = \text{alf\textunderscore eats\underline{\text{alfalfa}}$} \]

1. Write all cyclic shifts
2. Sort cyclic shifts
3. Extract last characters from sorted shifts

\[ C = \text{asff$\underline{f\text{e}}\underline{lll\text{aaaata}}}} \]

Observe: Substring \text{alf} occurs three times and causes runs \underline{lll} and \underline{aaa} in \( C \) (why?)
Fast Burrows-Wheeler Encoding

$S = \text{alf} \underline{e} \underline{a} \underline{t} \underline{s} \underline{a} \underline{l} \underline{f} \underline{a} \underline{l} \underline{f} \underline{a} \$ 

<table>
<thead>
<tr>
<th>$i$</th>
<th>$i$th cyclic shift</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>16 $\text{alf} \underline{e} \underline{a} \underline{t} \underline{s} \underline{a} \underline{l} \underline{f} \underline{a} \underline{l} \underline{f} \underline{a}$</td>
</tr>
<tr>
<td>1</td>
<td>9 $\text{alf} \underline{a} \underline{f} \underline{a} $ $\text{alf} \underline{e} \underline{a} \underline{t} \underline{s}$</td>
</tr>
<tr>
<td>2</td>
<td>4 $\underline{e} \underline{a} \underline{t} \underline{s} \underline{a} \underline{l} \underline{f} \underline{a}$ $\underline{a} \underline{l} \underline{f} \underline{a}$</td>
</tr>
<tr>
<td>3</td>
<td>16 $\text{a}$ $\text{alf} \underline{e} \underline{a} \underline{t} \underline{s} \underline{a} \underline{l} \underline{f} \underline{a} \underline{l} \underline{f} \underline{a}$</td>
</tr>
<tr>
<td>4</td>
<td>1 $\text{alf} \underline{e} \underline{a} \underline{t} \underline{s} \underline{a} \underline{l} \underline{f} \underline{a} \underline{l} \underline{f} \underline{a}$</td>
</tr>
<tr>
<td>5</td>
<td>13 $\text{a} \underline{f} \underline{a}$ $\underline{a} \underline{f} \underline{e} \underline{a} \underline{t} \underline{s}$</td>
</tr>
<tr>
<td>6</td>
<td>10 $\text{a} \underline{f} \underline{a}$ $\underline{a} \underline{f} \underline{e} \underline{a} \underline{t} \underline{s}$</td>
</tr>
<tr>
<td>7</td>
<td>6 $\underline{a} \underline{t} \underline{s} \underline{a} \underline{l} \underline{f} \underline{a}$ $\underline{a} \underline{f} \underline{e} \underline{a}$</td>
</tr>
<tr>
<td>8</td>
<td>5 $\underline{e} \underline{a} \underline{t} \underline{s} \underline{a} \underline{l} \underline{f} \underline{a}$ $\underline{a} \underline{f} \underline{e} \underline{a}$</td>
</tr>
<tr>
<td>9</td>
<td>3 $\underline{f} \underline{e} \underline{a} \underline{t} \underline{s} \underline{a} \underline{l} \underline{f} \underline{a}$ $\underline{a} \underline{f} \underline{e} \underline{a}$</td>
</tr>
<tr>
<td>10</td>
<td>15 $\underline{f} \underline{a}$ $\underline{a} \underline{f} \underline{e} \underline{a} \underline{t} \underline{s}$</td>
</tr>
<tr>
<td>11</td>
<td>12 $\underline{f} \underline{a}$ $\underline{a} \underline{f} \underline{e} \underline{a} \underline{t} \underline{s}$</td>
</tr>
<tr>
<td>12</td>
<td>2 $\underline{f} \underline{a}$ $\underline{a} \underline{f} \underline{e} \underline{a} \underline{t} \underline{s}$</td>
</tr>
<tr>
<td>13</td>
<td>14 $\underline{f} \underline{a}$ $\underline{a} \underline{f} \underline{e} \underline{a} \underline{t} \underline{s}$</td>
</tr>
<tr>
<td>14</td>
<td>11 $\underline{f} \underline{a}$ $\underline{a} \underline{f} \underline{e} \underline{a} \underline{t} \underline{s}$</td>
</tr>
<tr>
<td>15</td>
<td>8 $\underline{s} \underline{a} \underline{l} \underline{f} \underline{e} \underline{a} \underline{t}$</td>
</tr>
<tr>
<td>16</td>
<td>7 $\underline{t} \underline{s} \underline{a} \underline{l} \underline{f} \underline{e} \underline{a} \underline{t}$</td>
</tr>
</tbody>
</table>

- Need: sorting permutation of cyclic shifts.
Fast Burrows-Wheeler Encoding

\[
S = \textit{alf\_eats\_alfalfa}\$
\]

\[
\begin{array}{|c|c|}
\hline
i & ith \text{ cyclic shift} \\
\hline
0 & 16 \text{ alf\_eats\_alfalfa} \\
1 & 9 \text{ alf\_eats\_alfalfa\$} \\
2 & 4 \text{ alfa\$alf\_eats\_alf} \\
3 & 16 \text{ a$alf\_eats\_alfalfa} \\
4 & 1 \text{ alf\_eats\_alfalfa\$} \\
5 & 13 \text{ alfa\$alf\_eats\_alf} \\
6 & 10 \text{ alfalfa\$alf\_eats\_} \\
7 & 6 \text{ ats\_alfalfa\$alf\_e} \\
8 & 5 \text{ eats\_alfalfa\$alf\_} \\
9 & 3 \text{ f$eats\_alfalfa\$a} \\
10 & 15 \text{ fa$alf\_eats\_alf} \\
11 & 12 \text{ alfa$alf\_eats\_a} \\
12 & 2 \text{ lf\_eats\_alfalfa\$a} \\
13 & 14 \text{ lfa$alf\_eats\_alf} \\
14 & 11 \text{ lalfa$alf\_eats\_a} \\
15 & 8 \text{ s$alfalfa\$alf\_e} \\
16 & 7 \text{ ts$alfalfa\$alf\_e} \\
\hline
\end{array}
\]

\[
\begin{array}{|c|c|}
\hline
A_s & \text{corresponding suffix} \\
\hline
0 & 16 \text{ alf\_eats\_alfalfa} \\
1 & 9 \text{ alf\_eats\_alfalfa\$} \\
2 & 4 \text{ alfa\$alf\_eats\_alf} \\
3 & 16 \text{ a$alf\_eats\_alfalfa} \\
4 & 1 \text{ alf\_eats\_alfalfa\$} \\
5 & 13 \text{ alfa\$alf\_eats\_alf} \\
6 & 10 \text{ alfalfa\$alf\_eats\_} \\
7 & 6 \text{ ats\_alfalfa\$alf\_e} \\
8 & 5 \text{ eats\_alfalfa\$alf\_} \\
9 & 3 \text{ f$eats\_alfalfa\$a} \\
10 & 15 \text{ fa$alf\_eats\_alf} \\
11 & 12 \text{ alfa$alf\_eats\_a} \\
12 & 2 \text{ lf\_eats\_alfalfa\$a} \\
13 & 14 \text{ lfa$alf\_eats\_alf} \\
14 & 11 \text{ lalfa$alf\_eats\_a} \\
15 & 8 \text{ s$alfalfa\$alf\_e} \\
16 & 7 \text{ ts$alfalfa\$alf\_e} \\
\hline
\end{array}
\]

- Need: sorting permutation of cyclic shifts.
- Observe: This is the same as the sorting permutation of the suffixes.
**Fast Burrows-Wheeler Encoding**

\[ S = \text{alf} \text{eats} \text{alfalfa} \$

<table>
<thead>
<tr>
<th>( i )</th>
<th>( \text{i}^{\text{th}} ) cyclic shift</th>
<th>( A_s ) corresponding suffix</th>
</tr>
</thead>
</table>
|  0     | $\text{alf} \text{eats} \text{alfalfa}$ |  0  16 $\text{alf} \text{eats} \text{alfalfa} \$
|  1     | $\text{alfalfa} \text{alf} \text{eats}$   |  1  19 $\text{alf} \text{eats} \text{alfalfa} \$
|  2     | $\text{eats} \text{alfalfa} \text{alf}$   |  2  14 $\text{alf} \text{eats} \text{alfalfa} \$
|  3     | $\text{alf} \text{eats} \text{alfalfa} \text{a}$ |  3  16 $\text{alf} \text{eats} \text{alfalfa} \$
|  4     | $\text{alf} \text{eats} \text{alfalfa}$   |  4  11 $\text{alf} \text{eats} \text{alfalfa} \$
|  5     | $\text{alf} \text{eats} \text{alfalfa} \text{a}$ |  5  13 $\text{alf} \text{eats} \text{alfalfa} \$
|  6     | $\text{alf} \text{eats} \text{alfalfa} \text{a}$ |  6  10 $\text{alf} \text{eats} \text{alfalfa} \$
|  7     | $\text{eats} \text{alfalfa} \text{alf}$   |  7  03 $\text{alf} \text{eats} \text{alfalfa} \$
|  8     | $\text{eats} \text{alfalfa} \text{alf}$   |  8  09 $\text{alf} \text{eats} \text{alfalfa} \$
|  9     | $\text{eats} \text{alfalfa} \text{alf}$   |  9  02 $\text{alf} \text{eats} \text{alfalfa} \$
| 10    | $\text{alf} \text{eats} \text{alfalfa} \text{a}$ | 10  05 $\text{alf} \text{eats} \text{alfalfa} \$
| 11    | $\text{alf} \text{eats} \text{alfalfa} \text{a}$ | 11  07 $\text{alf} \text{eats} \text{alfalfa} \$
| 12    | $\text{alf} \text{eats} \text{alfalfa} \text{a}$ | 12  08 $\text{alf} \text{eats} \text{alfalfa} \$
| 13    | $\text{alf} \text{eats} \text{alfalfa} \text{a}$ | 13  06 $\text{alf} \text{eats} \text{alfalfa} \$
| 14    | $\text{alf} \text{eats} \text{alfalfa} \text{a}$ | 14  01 $\text{alf} \text{eats} \text{alfalfa} \$
| 15    | $\text{alf} \text{eats} \text{alfalfa} \text{a}$ | 15  15 $\text{alf} \text{eats} \text{alfalfa} \$
| 16    | $\text{alf} \text{eats} \text{alfalfa} \text{a}$ | 16  12 $\text{alf} \text{eats} \text{alfalfa} \$

- Need: sorting permutation of cyclic shifts.
- Observe: This is the same as the sorting permutation of the suffixes.
- That’s the suffix array! Can compute this in \( O(n \log n) \) time.
- Can read BWT encoding from suffix array in linear time.
Idea: Given $C$, we can reconstruct the first and last column of the array of cyclic shifts by sorting.

$C = ard$rcaaaabb

1. Last column: $C$

<p>| | | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
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<tbody>
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<td></td>
</tr>
<tr>
<td>a</td>
<td>r</td>
<td>d</td>
<td>$</td>
<td>r</td>
<td>c</td>
<td>a</td>
</tr>
<tr>
<td></td>
<td>b</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
BWT Decoding

**Idea:** Given $C$, we can reconstruct the *first* and *last column* of the array of cyclic shifts by sorting.

$C = \text{ard}$rcaaaabb

1. Last column: $C$
2. First column: $C$ sorted

\begin{align*}
\text{First column: } C & \quad \text{sorted} \\
\text{Last column: } C & \quad \text{ard}$rcaaaabb
\end{align*}
BWT Decoding

**Idea:** Given $C$, we can reconstruct the *first* and *last column* of the array of cyclic shifts by sorting.

$C = \text{ard}\$rcaaaabb

1. Last column: $C$
2. First column: $C$ sorted
3. Disambiguate by row-index
   Can argue: Repeated characters are in the same order in the first and the last column (the sort was *stable*).
BWT Decoding

**Idea:** Given $C$, we can reconstruct the *first* and *last column* of the array of cyclic shifts by sorting.

$C = \text{ard}$rcaaaaabb

1. Last column: $C$
2. First column: $C$ sorted
3. Disambiguate by row-index
   Can argue: Repeated characters are in the same order in the first and the last column (the sort was *stable*).
4. Starting from $\$$, recover $S$

\[
\begin{align*}
  &,3\ldots\ldots\ldots\ldots\text{a},0 \\
  \text{a},0\ldots\ldots\ldots\text{r},1 \\
  \text{a},6\ldots\ldots\ldots\text{d},2 \\
  \text{a},7\ldots\ldots\ldots\$$,3 \\
  \text{a},8\ldots\ldots\ldots\text{r},4 \\
  \text{a},9\ldots\ldots\ldots\text{c},5 \\
  \text{b},10\ldots\ldots\ldots\text{a},6 \\
  \text{b},11\ldots\ldots\ldots\text{a},7 \\
  \text{c},5\ldots\ldots\ldots\text{a},8 \\
  \text{d},2\ldots\ldots\ldots\text{a},9 \\
  \text{r},1\ldots\ldots\ldots\text{b},10 \\
  \text{r},4\ldots\ldots\ldots\text{b},11
\end{align*}
\]
BWT Decoding

**Idea:** Given $C$, we can reconstruct the *first* and *last column* of the array of cyclic shifts by sorting.

$C = \text{ard}$rcaaaaabb

1. Last column: $C$
2. First column: $C$ sorted
3. Disambiguate by row-index
   Can argue: Repeated characters are in the same order in the first and the last column (the sort was *stable*).
4. Starting from $\$, recover $S$

$S = a$

$\$,3...........a,0
a,0...........r,1
a,6...........d,2
a,7...........$,3
a,8...........r,4
a,9...........c,5
b,10..........a,6
b,11..........a,7
c,5..........a,8
d,2..........a,9
r,1..........b,10
r,4..........b,11
**BWT Decoding**

**Idea:** Given $C$, we can reconstruct the *first* and *last column* of the array of cyclic shifts by sorting.

$C = ard$rcaaaabb

1. Last column: $C$
2. First column: $C$ sorted
3. Disambiguate by row-index
   - Can argue: Repeated characters are in the same order in the first and the last column (the sort was *stable*).
4. Starting from $\$, recover $S$

$S = ab$

$\$,3...........a,0
a,0...........r,1
a,6...........d,2
a,7...........\$,3
a,8...........r,4
a,9...........c,5
b,10...........a,6
b,11...........a,7
c,5...........a,8
d,2...........a,9
r,1...........b,10
r,4...........b,11
BWT Decoding

Idea: Given $C$, we can reconstruct the first and last column of the array of cyclic shifts by sorting.

$C = \text{ard}$r$\text{aaaaabb}$

1. Last column: $C$
2. First column: $C$ sorted
3. Disambiguate by row-index
   Can argue: Repeated characters are in the same order in the first and the last column (the sort was stable).
4. Starting from $\$$, recover $S$

$S = \text{abr}$
BWT Decoding

**Idea:** Given $C$, we can reconstruct the *first* and *last column* of the array of cyclic shifts by sorting.

$C = \text{ard}$rcaaaabb

1. Last column: $C$
2. First column: $C$ sorted
3. Disambiguate by row-index
   Can argue: Repeated characters are in the same order in the first and the last column (the sort was *stable*).
4. Starting from $\$, recover $S$

$S = \text{abracadabra}$
BWT Decoding

\[ BWT::decoding(C[0..n-1], S) \]

\( C \) : string of characters over alphabet \( \Sigma_S \), \( S \) : output-stream

1. \( A \leftarrow \) array of size \( n \) \hspace{1em} // leftmost column
2. \( \text{for } i = 0 \text{ to } n - 1 \)
3. \( A[i] \leftarrow (C[i], i) \) \hspace{1em} // store character and index
4. \( \text{Stably sort } A \text{ by character} \)
5. \( \text{for } j = 0 \text{ to } n - 1 \) \hspace{1em} // where is the $-char?
6. \( \text{if } C[j] = $ \hspace{1em} \text{break} \)

7. \( \text{repeat} \)
8. \( S.append(\text{character stored in } A[j]) \)
9. \( j \leftarrow \text{index stored in } A[j] \)
10. \( \text{until we have appended } $ \)
BWT Overview

**Encoding cost**: $O(n \log n)$

- Read encoding from the suffix array.
- In practice MSD radix sort is good enough (but worst-case $\Theta(n^2)$).

**Decoding cost**: $O(n + |\Sigma_S|)$ (faster than encoding)

Encoding and decoding both use $O(n)$ space.

They need *all* of the text (no streaming possible). BWT is a **block compression method**.

BWT tends to be slower than other methods, but (combined with MTF, modified RLE and Huffman) gives better compression.
## Compression summary

<table>
<thead>
<tr>
<th>Huffman</th>
<th>Run-length encoding</th>
<th>Lempel-Ziv-Welch</th>
<th>bzip2 (uses Burrows-Wheeler)</th>
</tr>
</thead>
<tbody>
<tr>
<td>variable-length</td>
<td>variable-length</td>
<td>fixed-length</td>
<td>multi-step</td>
</tr>
<tr>
<td>single-character</td>
<td>multi-character</td>
<td>multi-character</td>
<td>multi-step</td>
</tr>
<tr>
<td>2-pass, must send dictionary</td>
<td>1-pass</td>
<td>1-pass</td>
<td>not streamable</td>
</tr>
<tr>
<td>60% compression on English text</td>
<td>bad on text</td>
<td>45% compression on English text</td>
<td>70% compression on English text</td>
</tr>
<tr>
<td>optimal 01-prefix-code</td>
<td>good on long runs (e.g., pictures)</td>
<td>good on English text</td>
<td>better on English text</td>
</tr>
<tr>
<td>requires uneven frequencies</td>
<td>requires runs</td>
<td>requires repeated substrings</td>
<td>requires repeated substrings</td>
</tr>
<tr>
<td>rarely used directly</td>
<td>rarely used directly</td>
<td>frequently used</td>
<td>used but slow</td>
</tr>
<tr>
<td>part of pkzip, JPEG, MP3</td>
<td>fax machines, old picture-formats</td>
<td>GIF, some variants of PDF, compress</td>
<td>bzip2 and variants</td>
</tr>
</tbody>
</table>