61A Extra Lecture 4
Announcements
Encoding Strings
Representing Strings: UTF-8 Encoding
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UTF (UCS (Universal Character Set) Transformation Format)
Representing Strings: UTF-8 Encoding

UTF (UCS (Universal Character Set) Transformation Format)

Unicode: Correspondence between characters and integers
Representing Strings: UTF-8 Encoding

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A byte is 8 bits and can encode any integer 0–255.
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```
00000000 0
```

bytes integers
Representing Strings: UTF-8 Encoding

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A byte is 8 bits and can encode any integer 0–255.

\[
\begin{array}{ccc}
00000000 & 0 & \\
00000001 & 1 & \\
\end{array}
\]

<table>
<thead>
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</tr>
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A byte is 8 bits and can encode any integer 0–255.

```
00000000  0
00000001  1
00000010  2
```

bytes    integers
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</tr>
<tr>
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<td>2</td>
</tr>
<tr>
<td>00000011</td>
<td>3</td>
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Variable-length encoding: integers vary in the number of bytes required to encode them.
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Variable-length encoding: integers vary in the number of bytes required to encode them.

In Python: `string` length is measured in characters, `bytes` length in bytes.
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A byte is 8 bits and can encode any integer 0–255.

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00000000  0
00000001  1
00000010  2
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Variable-length encoding: integers vary in the number of bytes required to encode them.

In Python: `string` length is measured in characters, `bytes` length in bytes.

(Demo)
Fixed-Length Encodings
A First Attempt
A First Attempt

- Let’s use an encoding
A First Attempt

• Let’s use an encoding

<table>
<thead>
<tr>
<th>Letter</th>
<th>Binary</th>
<th>Letter</th>
<th>Binary</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>0</td>
<td>n</td>
<td>1</td>
</tr>
<tr>
<td>b</td>
<td>1</td>
<td>o</td>
<td>0</td>
</tr>
<tr>
<td>c</td>
<td>0</td>
<td>p</td>
<td>1</td>
</tr>
<tr>
<td>d</td>
<td>1</td>
<td>q</td>
<td>1</td>
</tr>
<tr>
<td>e</td>
<td>1</td>
<td>r</td>
<td>0</td>
</tr>
<tr>
<td>f</td>
<td>0</td>
<td>s</td>
<td>1</td>
</tr>
<tr>
<td>g</td>
<td>0</td>
<td>t</td>
<td>0</td>
</tr>
<tr>
<td>h</td>
<td>1</td>
<td>u</td>
<td>0</td>
</tr>
<tr>
<td>i</td>
<td>1</td>
<td>v</td>
<td>1</td>
</tr>
<tr>
<td>j</td>
<td>1</td>
<td>w</td>
<td>1</td>
</tr>
<tr>
<td>k</td>
<td>0</td>
<td>x</td>
<td>1</td>
</tr>
<tr>
<td>l</td>
<td>1</td>
<td>y</td>
<td>0</td>
</tr>
<tr>
<td>m</td>
<td>1</td>
<td>z</td>
<td>0</td>
</tr>
</tbody>
</table>
Decoding

• An encoding without a deterministic decoding procedure is not very useful
Decoding

- An encoding without a deterministic decoding procedure is not very useful
- How many bits do we need to encode each letter uniquely?
Decoding

• An encoding without a deterministic decoding procedure is not very useful

• How many bits do we need to encode each letter uniquely?

  • lowercase alphabet
Decoding

• An encoding without a deterministic decoding procedure is not very useful

• How many bits do we need to encode each letter uniquely?

  • lowercase alphabet

  • 5 bits
A Second Attempt
A Second Attempt

• Let’s try another encoding
A Second Attempt

- Let’s try another encoding

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<thead>
<tr>
<th>Letter</th>
<th>Binary</th>
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<tbody>
<tr>
<td>a</td>
<td>00000</td>
<td>n</td>
<td>01101</td>
</tr>
<tr>
<td>b</td>
<td>00001</td>
<td>o</td>
<td>01110</td>
</tr>
<tr>
<td>c</td>
<td>00010</td>
<td>p</td>
<td>01111</td>
</tr>
<tr>
<td>d</td>
<td>00011</td>
<td>q</td>
<td>10000</td>
</tr>
<tr>
<td>e</td>
<td>00100</td>
<td>r</td>
<td>10001</td>
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<td>f</td>
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Analysis
Analysis

Pros
Analysis

Pros

• Encoding was easy
Analysis

Pros

• Encoding was easy

• Decoding was deterministic
Analysis

Pros

- Encoding was easy
- Decoding was deterministic

Cons
Analysis

Pros

• Encoding was easy
• Decoding was deterministic

Cons

• Takes more space...
Analysis

Pros

• Encoding was easy
• Decoding was deterministic

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• Takes more space...
• What restriction did we place that’s unnecessary?
Analysis

Pros

• Encoding was easy

• Decoding was deterministic

Cons

• Takes more space...

• What restriction did we place that’s unnecessary?

• Fixed length
Variable-Length Encodings
Variable Length Encoding
Variable Length Encoding

- Encoding Candidate 1: A: 1, B: 01, C: 10, D: 11, E: 100, F: 101, ...
Variable Length Encoding

- Encoding Candidate 1: A: 1, B: 01, C: 10, D: 11, E: 100, F: 101, ...
  - What does 01111 encode?
Variable Length Encoding

- Encoding Candidate 1: A: 1, B: 01, C: 10, D: 11, E: 100, F: 101, ...
  - What does 01111 encode?

- Encoding Candidate 2: A: 00, B: 01, C: 100, D: 101, E: 1100, F: 1101, ...
Variable Length Encoding

• Encoding Candidate 1: A: 1, B: 01, C: 10, D: 11, E: 100, F: 101, ...
  
  • What does 01111 encode?

• Encoding Candidate 2: A: 00, B: 01, C: 100, D: 101, E: 1100, F: 1101, ...
  
  • What does 0100101 encode? How about 10110011010010011100?
Variable Length Encoding

- Encoding Candidate 1: A: 1, B: 01, C: 10, D: 11, E: 100, F: 101, ...
  - What does 0111 encode?

- Encoding Candidate 2: A: 00, B: 01, C: 100, D: 101, E: 1100, F: 1101, ...
  - What does 0100101 encode? How about 1011001101001001100?

- Deterministic decoding from left to right is possible if the encoding of one character is never a proper prefix of the decoding of another character.
Deterministic Codes Have a Tree Structure
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```
Letter | Binary
-------|-------
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B      | 01    
C      | 1     
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Huffman Encoding
Huffman Encoding

- Let’s pretend we want to come up with the optimal encoding:
Huffman Encoding

- Let’s pretend we want to come up with the optimal encoding:
  - AAAAAAAAAABBBCCCCDDDDDDDDD
Huffman Encoding

• Let’s pretend we want to come up with the optimal encoding:
  • AAAAAAAAAABBBBBCCCCCCDDDDDDDDDD
  • A appears 10 times
Huffman Encoding

- Let’s pretend we want to come up with the optimal encoding:
  - AAAAAAAAAABBBBCCCCDDDDDDDDDD
  - A appears 10 times
  - B appears 5 times
Huffman Encoding

• Let’s pretend we want to come up with the optimal encoding:
  • AAAAAAAAAABBBBBCCCCCCDDDDDDDDDD
  • A appears 10 times
  • B appears 5 times
  • C appears 7 times
Huffman Encoding

• Let’s pretend we want to come up with the optimal encoding:
  • AAAAAAAAAABBBBBCCCCCCCCDDDDDDDD
  • A appears 10 times
  • B appears 5 times
  • C appears 7 times
  • D appears 9 times
Huffman Encoding
Huffman Encoding

- Start with the two smallest frequencies
Huffman Encoding

- Start with the two smallest frequencies
  - A appears 10 times, B appears 5 times, C appears 7 times, D appears 9 times
Huffman Encoding

- Start with the two smallest frequencies

  - A appears 10 times, B appears 5 times, C appears 7 times, D appears 9 times
Huffman Encoding

• Start with the two smallest frequencies
  • A appears 10 times, B appears 5 times, C appears 7 times, D appears 9 times
Huffman Encoding

• Start with the two smallest frequencies
  • A appears 10 times, B appears 5 times, C appears 7 times, D appears 9 times
Huffman Encoding
Huffman Encoding

- Continue…
Huffman Encoding

• Continue…

• A appears 10 times, B & C appear a combined 12 times, D appears 9 times
Huffman Encoding

- Continue...
  - A appears 10 times, B & C appear a combined 12 times, D appears 9 times
Huffman Encoding

- Continue...
  - A appears 10 times, B & C appear a combined 12 times, D appears 9 times
Huffman Encoding

• Continue...
  
  • A appears 10 times, B & C appear a combined 12 times, D appears 9 times

```
  0  1
 B   C
```

```
  0  1
 A   D
```

```
  0  1
 B   C
```

```
  0  1
 A   D
```
Huffman Encoding
Huffman Encoding

• And finally…
Huffman Encoding

- And finally…
Huffman Encoding

• And finally…
Huffman Encoding

• And finally…
Huffman Encoding
Huffman Encoding

- Another example...
Huffman Encoding

- Another example...
  
  - AAAAAAAAAAABCCD
Huffman Encoding

• Another example...

  • AAAAAAAAAABCCD

  • A appears 10 times
Huffman Encoding

• Another example...
  • AAAAAAAAAABCCD
  • A appears 10 times
  • B appears 1 time
Huffman Encoding

- Another example...
  - AAAAAAAAAABBCCD
  - A appears 10 times
  - B appears 1 time
  - C appears 2 times
Huffman Encoding

• Another example...
  • AAAAAAAAAABCCD
  • A appears 10 times
  • B appears 1 time
  • C appears 2 times
  • D appears 1 time
Huffman Encoding
Huffman Encoding

- Start with the two smallest frequencies
Huffman Encoding

• Start with the two smallest frequencies
  • A appears 10 times, B appears 1 time, C appears 2 times, D appears 1 time
Huffman Encoding

- Start with the two smallest frequencies
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Huffman Encoding
Huffman Encoding

- Start with the two smallest frequencies
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• Start with the two smallest frequencies
  • A appears 10 times, B & D appear a combined 2 times, C appears 2 times
Huffman Encoding

• Start with the two smallest frequencies
  • A appears 10 times, B & D appear a combined 2 times, C appears 2 times
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- Start with the two smallest frequencies
  - A appears 10 times, B & D appear a combined 2 times, C appears 2 times
Huffman Encoding

- Start with the two smallest frequencies
  - A appears 10 times, B & D appear a combined 2 times, C appears 2 times
Huffman Encoding
Huffman Encoding

- And finally…
Huffman Encoding

• And finally…

```
        1
       / 
      0   1
     /   / 
    C   B   D
    /   /   /
   0   0   1
  /     /   /
 A     B   D
```
Huffman Encoding

- And finally...
Huffman Encoding

- And finally...