# Data Compression

Some of these lecture slides have been adapted from:

- *Algorithms in C, 2nd Edition*, Robert Sedgewick.
- *Introduction to Data Compression*, Guy Blelloch.

# Data Compression

Compression reduces the size of a file:

- To save TIME when transmitting it.
- To save SPACE when storing it.
- Most files have lots of redundancy.

Who needs compression?

- Moore's law: # transistors on a chip doubles every 18-24 months.
- Parkinson's law: data expands to fill space available.
- Text, images, sound, video, . . .

Basic concepts ancient (1950s), best technology recently developed.

# Applications of Data Compression

## Generic file compression.

- Files: GZIP, BZIP, BOA.
- Archivers: PKZIP.
- File systems: NTFS.

## Multimedia.

- Images: GIF, JPEG, CorelDraw.
- Sound: MP3.
- Video: MPEG, DivX™, HDTV.


## Communication.

- ITU-T T4 Group 3 Fax.
- V.42bis modem.

## Databases.

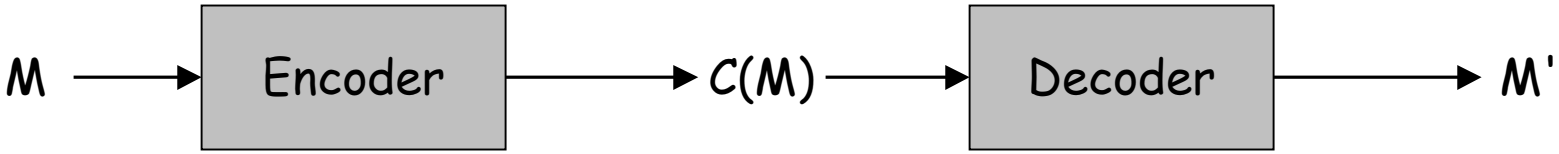
- Google.

# Encoding and Decoding

Message. Binary data M we want to compress.

Encode. Generate a "compressed" representation C(M) that hopefully uses fewer bits.

Decode. Reconstruct original message or some approximation M'.




Compression ratio: bits in C(M) / bits in M.

Lossless. M = M', 50-75% or lower.

Ex: C source code, executables.

Lossy. M ~ M', 10% or lower.

Ex: images, sound, video.

# Simple Ideas

## Ancient ideas.

- Human language.
- Morse code.
- Braille.

## Fixed length coding.

- Use same number of bits for each symbol.
- N symbols $\Rightarrow \lceil \log N \rceil$ bits per symbol.
- 7-bit ASCII code for text.

ASCII coding

| char | dec | binary |
|---|---|---|
| NUL | 0 | 0000000 |
| ... | ... | ... |
| > | 62 | 0111110 |
| ? | 63 | 0111111 |
| @ | 64 | 1000000 |
| A | 65 | 1000001 |
| B | 66 | 1000010 |
| C | 67 | 1000011 |
| ... | ... | ... |
| ~ | 126 | 1111110 |
| DEL | 127 | 1111111 |

| a | b | r | a | c | a | d | a | b | r | a |
|---|---|---|---|---|---|---|---|---|---|---|
| 1100001 | 1100010 | 1110010 | 1100001 | 1100011 | 1100001 | 1110100 | 1100001 | 1100010 | 1110010 | 1100001 |

$7 \times 11 = 77$ bits

# Run-Length Encoding

Natural encoding: $51 \times 19 + 6 = 975$ bits.

Run-length encoding: $63 \times 6 = 378$ bits.

| Raster of letter 'q', lying on its side | RLE |
|---|---|
| 000000000000000000000000000011111111111111000000000 | 28 14 9 |
| 000000000000000000000000001111111111111111110000000 | 26 18 7 |
| 000000000000000000000001111111111111111111111110000 | 23 24 4 |
| 000000000000000000000011111111111111111111111111000 | 22 26 3 |
| 000000000000000000001111111111111111111111111111110 | 20 30 1 |
| 000000000000000000011111110000000000000000001111111 | 19 7 18 7 |
| 000000000000000000111110000000000000000000000011111 | 19 5 22 5 |
| 000000000000000001110000000000000000000000000000111 | 19 3 26 3 |
| 000000000000000001110000000000000000000000000000111 | 19 3 26 3 |
| 000000000000000001110000000000000000000000000000111 | 19 3 26 3 |
| 000000000000000001110000000000000000000000000000111 | 19 3 26 3 |
| 000000000000000001110000000000000000000000000001110 | 20 4 23 3 1 |
| 000000000000000000011100000000000000000000000111000 | 22 3 20 3 3 |
| 011111111111111111111111111111111111111111111111111 | 1 50 |
| 011111111111111111111111111111111111111111111111111 | 1 50 |
| 011111111111111111111111111111111111111111111111111 | 1 50 |
| 011111111111111111111111111111111111111111111111111 | 1 50 |
| 011111111111111111111111111111111111111111111111111 | 1 50 |
| 011000000000000000000000000000000000000000000000011 | 1 2 46 2 |

# Run-Length Encoding

## Run-length encoding (RLE).

- Exploit long runs of repeated characters.
- Replace run by count followed by repeated character, but don't bother if run is less than 3.
  - AAAABBBAABBBBBCCCCCCCCDABCBAAABBBBCCCD
  - 4A3BAA5B8CDABCB3A4B3CD
- Annoyance: how to represent counts.
- Runs in binary file alternate between 0 and 1, so output count only.
- "File inflation" if runs are short.

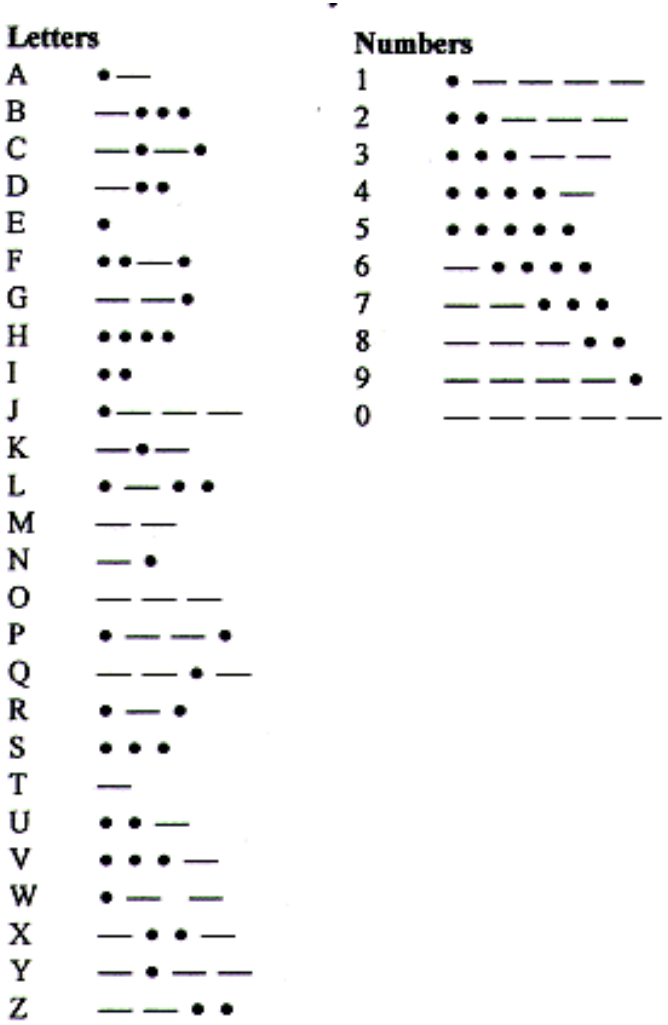
## Applications.

- Black and white graphics.
  - compression ratio improves with resolution!
- JPEG (Joint Photographic Experts Group).

# Variable Length Encoding

## Variable-length encoding.

- Use DIFFERENT number of bits to encode different character.



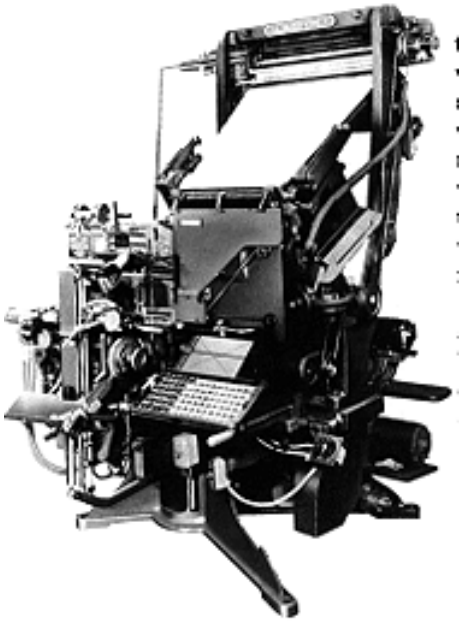
| Letters | | Numbers | |
|---|---|---|---|
| A | •— | 1 | •————— |
| B | —••• | 2 | ••——— |
| C | —•—• | 3 | •••—— |
| D | —•• | 4 | ••••— |
| E | • | 5 | ••••• |
| F | ••—• | 6 | —•••• |
| G | ——• | 7 | ——••• |
| H | •••• | 8 | ———•• |
| I | •• | 9 | ————• |
| J | •——— | 0 | ————— |
| K | —•— | | |
| L | •—•• | | |
| M | —— | | |
| N | —• | | |
| O | ——— | | |
| P | •——• | | |
| Q | ——•— | | |
| R | •—• | | |
| S | ••• | | |
| T | — | | |
| U | ••— | | |
| V | •••— | | |
| W | •—— | | |
| X | —••— | | |
| Y | —•—— | | |
| Z | ——•• | | |

# Variable Length Encoding

## Variable-length encoding.

- Use DIFFERENT number of bits to encode different character.
  - use fewer bits for more frequent letters (ETAONIS)
  - use more bits for rarer letters (ZQJXKVB)

| Char | Freq | Char | Freq |
|---|---|---|---|
| E | 12.51 | M | 2.53 |
| T | 9.25 | F | 2.30 |
| A | 8.04 | P | 2.00 |
| O | 7.60 | G | 1.96 |
| I | 7.26 | W | 1.92 |
| N | 7.09 | Y | 1.73 |
| S | 6.54 | B | 1.54 |
| R | 6.12 | V | 0.99 |
| H | 5.49 | K | 0.67 |
| L | 4.14 | X | 0.19 |
| D | 3.99 | J | 0.16 |
| C | 3.06 | Q | 0.11 |
| U | 2.71 | Z | 0.09 |



Linotype machine, 1886

# Variable Length Encoding

Variable-length encoding.

- Use DIFFERENT number of bits to encode different character.

| a | | | b | | | r | | | a | | | c | | | a | | | d | | | a | | | b | | | r | | | a | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 0 | 0 |

3-bit fixed length coding: $3 \times 11 = 33$ bits

| a | b | | | r | | a | c | | | a | d | | | a | b | | | r | | a |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 0 | 0 | 1 | 0 | 1 | 1 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 1 | 0 | 1 | 1 |

variable length coding: 23 bits

| char | encoding |
|---|---|
| a | 1 |
| b | 001 |
| c | 0000 |
| d | 0001 |
| r | 01 |

# Variable Length Decoding

## But, then how do we decode?

- Variable length codes can be ambiguous.

| a | b | r | | a | c | | a | d | | a | b | r | | a |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 0 | 0 | 0 | 1 | 1 | 0 | 1 | 0 | 1 | 1 | 0 | 0 | 0 | 1 |
| c | | r | | a | a | | d | b | a | c | | r | | a |

| char | encoding |
|---|---|
| a | 1 |
| b | 0 |
| c | 10 |
| d | 01 |
| r | 00 |

## How do we avoid ambiguity?

- One solution: ensure no encoding is a PREFIX of another.
- Ex: 00 is a prefix of 0001.

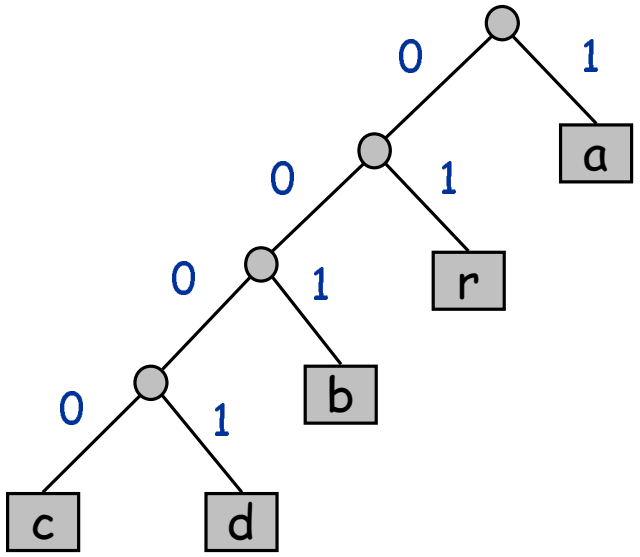
| a | b | | | r | | a | c | | | | a | d | | | | a | b | | | r | | a |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 0 | 0 | 1 | 0 | 1 | 1 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 1 | 0 | 1 | 1 |

| char | encoding |
|---|---|
| a | 1 |
| b | 001 |
| c | 0000 |
| d | 0001 |
| r | 01 |

# Implementing Prefix-Free Codes

## How to represent?

- Use a binary trie.
  - symbols are stored in leaves
  - encoding is path to leaf




## Encoding.

- Start at leaf of trie corresponding to symbol s.
- Follow path up to the root.
- Print bits in reverse order.

| char | encoding |
|---|---|
| a | 1 |
| b | 001 |
| c | 0000 |
| d | 0001 |
| r | 01 |

## Decoding.

- Start at root of tree.
- Take right branch if bit is 0; left branch if 1.
- When at a leaf node, print symbol and return to root.

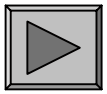
# Huffman Coding

OK, but how do I find a good prefix-free coding scheme?

- Greed.

To compute Huffman prefix-free code:

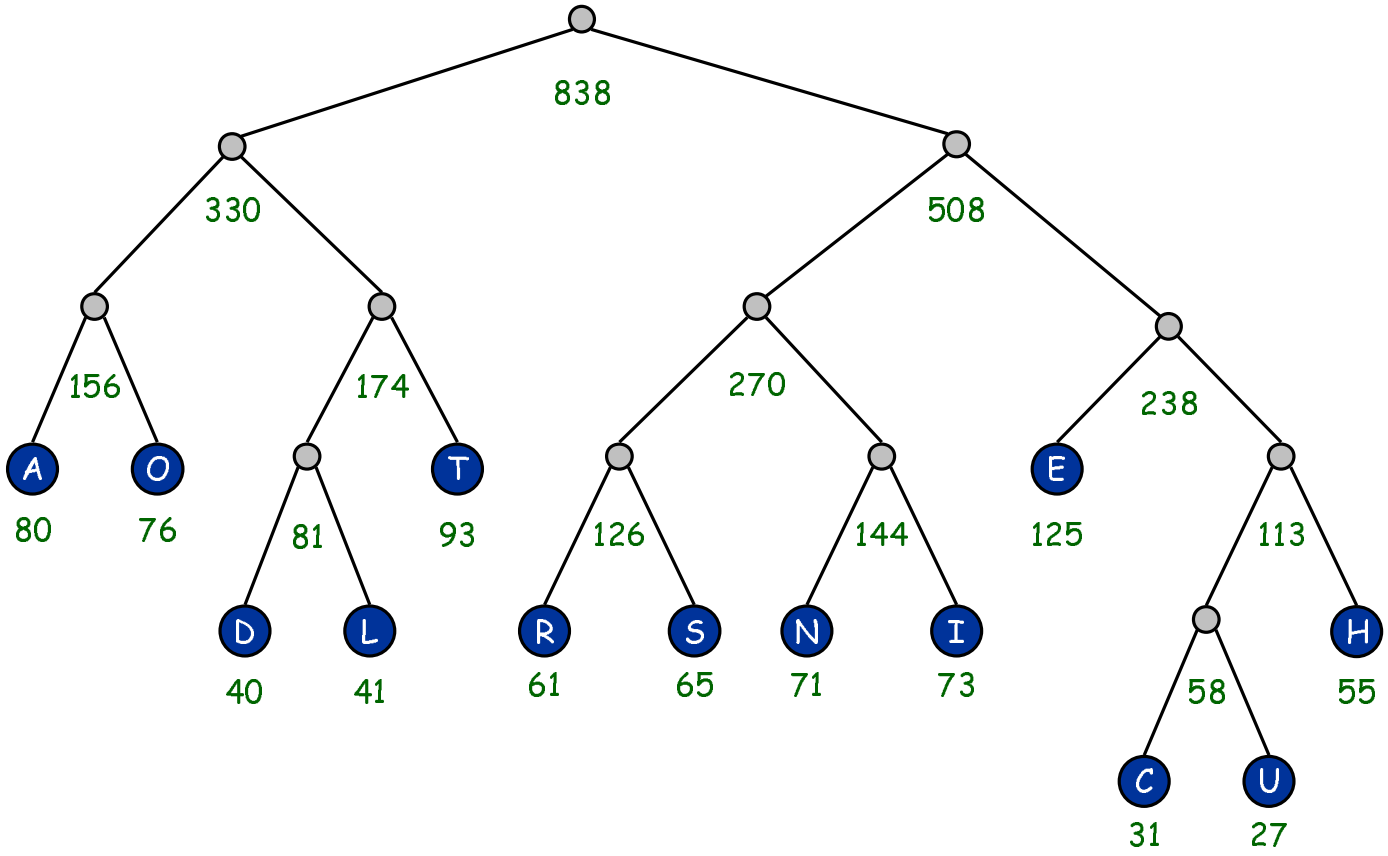
- Count character frequencies $p_s$ for each symbol s in file.
- Start with a forest of trees, each consisting of a single vertex corresponding to each symbol s with weight $p_s$.
- Repeat:
  - select two trees with min weight $p_1$ and $p_2$
  - merge into single tree with weight $p_1 + p_2$



Applications: JPEG, MP3, MPEG, PKZIP.

# Huffman Coding Example

| Char | Freq | Huff |
|---|---|---|
| E | 125 | 110 |
| T | 93 | 000 |
| A | 80 | 000 |
| O | 76 | 011 |
| I | 73 | 1011 |
| N | 71 | 1010 |
| S | 65 | 1001 |
| R | 61 | 1000 |
| H | 55 | 1111 |
| L | 41 | 0101 |
| D | 40 | 0100 |
| C | 31 | 11100 |
| U | 27 | 11101 |
| Total | 838 | 3.62 |



# Huffman Encoding Implementation

## Huffman Encoding

```
#define SYMBOLS 256

char *lookup[SYMBOLS];           // lookup[c] = codeword for c
unsigned char text[MAXN + 1];    // input text

typedef struct node *link;       // Huffman trie node
struct node {
   unsigned char c;              // symbol
   int freq;                     // symbol frequency
   link l, r;                    // subtries
};

int main(void) {
...
   while((c = getchar()) != EOF) {    // read input
      text[N++] = c;                  // save input text
      freq[c]++;                      // compute frequencies
   }
...
```

# Huffman Encoding Implementation

## Huffman Encoding (build trie and print codewords)

```
PQinit(SYMBOLS);                          // init PQ
for (i = 0; i < SYMBOLS; i++)
   if (freq[i] > 0)
      PQinsert(NEWnode(i, freq[i], NULL, NULL));

while (PQsize() > 1) {                    // build trie
   x = PQdelmin();                        // smallest
   y = PQdelmin();                        // next smallest
   parent = NEWnode('*', x->freq + y->freq, x, y);
   PQinsert(parent);
}
trie = PQdelmin();

makeLookupTable(tree, 0);
for (i = 0; i < N; i++)
   printf("%s", lookup[text[i]]);
```

| char | lookup |
|---|---|
| a | 11 |
| b | 001 |
| . . . | . . . |

# Huffman Decoding Implementation

Huffman decoding: recall COS 126.

**Huffman Decoding**

```
typedef struct node *link;              // Huffman trie node
struct node {
   unsigned char c;                     // symbol in leaf
   link l, r;                           // subtries
};

. . .

x = trie = maketrie();                  // reconstruct trie
while ((c = getbit()) != EOF) {         // read in bit
   if      (c == 0) x = x->l;           // go left
   else if (c == 1) x = x->r;           // go right
   if (x->l == NULL) {                  // no more trie
      putchar(x->c);                    // print symbol
      x = trie;                         // restart
   }
}
```

# Huffman Encoding

Theorem (Huffman, 1952). Huffman coding is optimal prefix-free code.

- No variable length code uses fewer bits.

Corollary. Greed is good.

Implementation.

- Two passes.
  - tabulate symbol frequencies and build trie
  - encode file by traversing trie or lookup table
- Use priority queue for delete min and insert.
- O(M + N log N).

M = file size
N = # distinct symbols

Difficulties.

- Have to transmit encoding (trie).
- Not optimal!

# What Data Can be Compressed?

US Patent 5,533,051 on "Methods for Data Compression."

- Capable of compressing all files.

Slashdot reports of the Zero Space Tuner™ and BinaryAccelerator™.

- "ZeoSync has announced a breakthrough in data compression that allows for 100:1 lossless compression of random data. If this is true, our bandwidth problems just got a lot smaller. . . ."

Impossible claims for lossless compression.

- Consider all 1000 bit messages.
- $2^{1000}$ possible messages.
- Only $2^{999} + 2^{998} + \ldots + 1$ can be encoded with $\leq 999$ bits.
- Only 1 in $2^{499}$ can even be encoded with $\leq 500$ bits!

# A Difficult File To Compress

## One million pseudo-random characters (a - p)

```
fclkkacifobjofmkgdcoiicnfmcpcjfccabckjamolnihkbgobcjbngjiceeelpfgcjiihppenefllhglfemdemgahlb
piggmllmnefnhjelmgjncjcidlhkglhceninidmmgnobkeglpnadanfbecoonbiehglmpnhkkamdffpacjmgojmcaabp
cjcecplfbgamlidceklhfkkmioljdnoaagiheiapaimlcnlljniggpeanbmojgkccogpmkmoifioeikefjidbadgdcep
nhdpfjaeeapdjeofklpdeghidbgcaiemajllhnndigeihbebifemacfadnknhlbgincpmimdogimgeeomgeljfjgklkd
gnhafohonpjbmlkapddhmepdnckeajebmeknmeejnmenbmnnfefdbhpmigbbjknjmobimamjjaaaffhlhiggaljbaijn
ebidpaeigdgoghcihodnlhahllhhoojdfacnhadhgkfahmeaebccacgeojgikcoapknlomfignanedmajinlompjoaif
iaejbcjcdibpkofcbmjiobbpdhfilfajkhfmppcngdneeinpnfafaeladbhhifechinknpdnplamackphekokigpddmm
jnbngklhibohdfeaggmclllmdhafkldmimdbplggbbejkcmhlkjocjjlcngckfpfakmnpiaanffdjdlleiniilaenbni
kgfnjfcophbgkhdgmfpoehfmkbpiaignphogbkelphobonmfghpdgmkfedkfkchceeldkcofaldinljjcgafimaanelm
fkokcjekefkbmegcgjifjcpjppnabldjoaafpbdafifgcoibbcmoffbbgigmngefpkmbhbghlbdjngenldhgnfbdlcmj
dmoflhcogfjoldfjpaokepndejmnbiealkaofifekdjkgedgdlgbioacflfjlafbcaemgpjlagbdgilhcfdcamhfmppf
gohjphlmhegjechgdpkkljpndphfcnnganmbmnggpphnckbieknjhilafkegboilajdppcodpeoddldjfcpialoalfeo
mjbphkmhnpdmcpgkgeaohfdmcnegmibjkajcdcpjcpgjminhhakihfgiiachfepffnilcooiciepoapmdjniimfbolch
kibkbmhbkgconimkdchahcnhapfdkiapikencegcjapkjkfljgdlmgncpbakhjidapbldcgeekkjaoihbnbigmhboeng
pmedliofgioofdcphelapijcegejgcldcfodikalehbccpbbcfakkblmoobdmdgdkafbbkjnidoikfakjclbchambcpa
epfeinmenmpoodadoecbgbmfkkeabilaoeoggghoekamaibhjibefmoppbhfbhffapjnodlofeihmjahmeipejlfhloe
fgmjhjnlomapjakhhjpncomippeanbikkhekpcfgbgkmklipfbiikdkdcbolofhelipbkbjmjfoempccneaebklibmca
ddlmjdcajpmhhaeedbbfpjafcndianlfcjmmbfncpdcccodeldhmnbdjmeajmboclkggojghlohlbhgjkhkmclohkgja
mfmcchkchmiadjgjhjehflcbklfifackbecgjoggpbkhlcmfhipflhmnmifpjmcoldbeghpcekhgmnahijpabnomnokl
djcpppbcpgcjofngmbdcpeeeiiiclmbbmfjkhlanckidhmbeanmlabncnccpbhoafajjicnfeenppoekmlddholnbdja
pbfcajblbooiaepfmmeoafedflmdcbaodgeahimcgpcammjljoebpfmghogfckgmomecdipmodbcempidfnlcggpgbff
oncajpncomalgoiikeolmigliikjkolgolfkdgiijjiooiokdihjbbofiooibakadjnedlodeeiijkliicnioimablfd
pjiafcfineecbafaamheiipegegibioocmlmhjekfikfeffmddhoakllnifdhckmbonbchfhhclecjamjildonjjdpif
ngbojianpljahpkindkdoanlldcbmlmhjfomifhmncikoljjhebidjdphpdepibfgdonjljfgifimniipogockpidamn
kcpipglafmlmoacjibognbplejnikdoefccdpfkomkimffgjgielocdemnblimfmbkfbhkelkpfoheokfofochbmifle
ecbglmnfbnfncjmefnihdcoeiefllemnohlfdcmbdfebdmbeebbalggfbajdamplphdgiimehglpikbipnkkecekhilc
hhhfaeafbbfdmcjojfhpponglkfdmhjpcieofcnjgkpibcbiblfpnjlejkcppbhopohdghljlcokhdoahfmlglbdklia
jbmnkkfcoklhlelhjhoiginaimgcabcfebmjdnbfhohkjphnklcbhcjpgbadakoecbkjcaebbanhnfhpnfkfbfpohmnk
ligpgfkjadomdjjnhlnfailfpcmnololdjekeolhdkebiffebajjpclghllmemegncknmkkeoogilijmmkomllbkkabe
lmodcohdhppdakbelmlejdnmbfmcjdebefnjihnejmnogeeafldabjcgfoaehldcmkbnbafpciefhlopicifadbppgmf
ngecjhefnkbjmliodhelhicnfoongngemddepchkokdjafegnpgledakmbcpcmkckhbffeihpkajginfhdolfnlgnade
famlfocdibhfkiaofeegppcjilndepleihkpkkgkphbnkggjiaolnolbjpobjdcehglelckbhjilafccfipgebpc....
```

# A Difficult File To Compress

## 170 characters

```
#include <stdio.h>
#include <stdlib.h>
#define N 1000000
int main(void) {
   int i;
   for (i = 0; i < N; i++)
      putchar('a' + rand() % 16);
   return 0;
}
```

Easy to store two 8-bit characters per byte for 50% compression.

## Compression Achieved

```
% gcc rand.c
% a.out > temp.txt
% compress –c < temp.txt > temp.Z
% gzip –c < temp.txt > temp.gz
% bzip2 –c < temp.txt > temp.bz2
```

## Resulting Files

```
% ls –lr temp*
    170 rand.c
1000000 temp.txt
 576861 temp.Z
 570872 temp.gz
 499329 temp.bz2
```

# Information Theory

Intrinsic difficulty of compression.

- Short program generates large data file.
- Optimal compression algorithm has to discover program!
- Undecidable problem.

So how do we know if our algorithm is doing well?

- Want lower bound on # bits required by ANY compression scheme.

# Language Model

How compression algorithms work?

- Exploit bias on input messages.
- Word "Princeton" occurs more frequently than "Yale."
- White patches occur in typical images.

Compression is all about probability.

- Formulate probabilistic model to predict symbols.
  - simple: character counts, repeated strings
  - complex: models of a human face
- Use model to encode message.
- Use same model to decode message.

Example. Order 0 Markov model.

- Each symbol s generated randomly with fixed probability p(s), independently.

# Entropy

Entropy. (Shannon 1948) $$H(S) = \sum_{s \in S} p(s) \log_2 \frac{1}{p(s)}$$

- Information content of symbol s is proportional to $\log_2 \frac{1}{p(s)}$
- Weighted average of information content over all symbols.
- Interface between coding and model.

| | p(a) | p(b) | H(S) |
|---|---|---|---|
| Model 1 | 1/2 | 1/2 | 1 |
| Model 2 | 0.900 | 0.100 | 0.469 |
| Model 3 | 0.990 | 0.010 | 0.0808 |
| Model 4 | 1 | 0 | 0 |

| | p(a) | p(b) | p(c) | p(d) | p(e) | H(S) |
|---|---|---|---|---|---|---|
| Model 5 | 1/5 | 1/5 | 1/5 | 1/5 | 1/5 | 2.322 |

# Entropy and Compression

Shannon's theorem (1948). Avg # bits per symbol ≥ entropy.

- If data source S is an order 0 Markov model, then ANY compression scheme must use ≥ H(S) bits per symbol on average.
- Cornerstone result of information theory.

Huffman's coding theorem (1952). Huffman code is optimal.

- If data source S is an order 0 Markov mode, then H(S) ≤ avg # bits per symbol ≤ H(S) + 1.

Is there any hope of doing better?

- Yes. Huffman wastes up to 1 bit per symbol.
  - if H(S) is close to 0, this matters
  - can do better with "arithmetic coding"
- Yes. Source may not be order 0 Markov model.

# Entropy of the English Language

How much information is in each character of English language?

- Model = English text.

How can we measure it? Shannon's experiment (1951).

- Asked humans to predict next character given previous text.
- The number of guesses required for right answer:

| # of guesses | 1 | 2 | 3 | 4 | 5 | ≥ 6 |
|---|---|---|---|---|---|---|
| Probability | 0.79 | 0.08 | 0.03 | 0.02 | 0.02 | 0.05 |

- Shannon's estimate = 0.6 - 1.3.

# Lossless Compression Ratio for Calgary Corpus

| Year | Scheme | Bits / char |
|---|---|---|
| ---- | ASCII | 7.00 |
| 1950 | Huffman | 4.70 |
| 1977 | LZ77 | 3.94 |
| 1984 | LZMW | 3.32 |
| 1987 | LZH | 3.30 |
| 1987 | Move-to-front | 3.24 |
| 1987 | LZB | 3.18 |
| 1987 | Gzip | 2.71 |
| 1988 | PPMC | 2.48 |
| 1988 | SAKDC | 2.47 |
| 1994 | PPM | 2.34 |
| 1995 | Burrows-Wheeler | 2.29 |
| 1997 | BOA | 1.99 |
| 1999 | RK | 1.89 |

| Entropy | Bits/char |
|---|---|
| Char by char | 4.5 |
| 8 chars at a time | 2.4 |
| Asymptotic | 1.3 |

# Statistical Methods

Estimate symbol frequencies and assign codewords based on this.

Static model. Same distribution for all texts.

- Fast.
- Not optimal since different texts exhibit different distributions.
- Ex: ASCII, Morse code, Huffman "Etaoin Shrdlu" code.

Dynamic model. Generate model based on text.

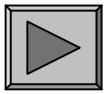
- Preliminary pass needed to generate model.
- Must transmit the model.
- Ex: Huffman code using frequencies from text.

Adaptive models. Progressively learn and update model as you read text.

- More accurate models produce better compression.
- Decoding must start from beginning.
- Ex: LZW.

# LZW Algorithm

Lempel-Ziv-Welch (variant of LZ78).



- Adaptively maintain symbol table of useful strings.
- If input matches word in ST, output index instead of string.

Algorithm.

- Find longest word W in ST that is a prefix of string starting at current index.
- Output index for W followed by x = next symbol.
- Add Wx to dictionary.

Example.

- Dictionary: **a**, **aa**, **ab**, **aba**, **abb**, **abaa**, **abaab**, **abaaa**,
- String starting at current index: . . . **abaab**a**bbb** . . .
- W = **abaab**, x = **a**.
- Output index for W, insert **abaaba** into ST.

# LZW Example

| Input | Send |
|---|---|
| SEND | 256 |
| i | 105 |
| t | 116 |
| t | 116 |
| y | 121 |
| _ | 32 |
| b | 98 |
| i | |
| t | 258 |
| t | |
| y | 260 |
| _ | |
| b | 262 |
| i | |
| t | 258 |
| _ | |
| b | |
| i | 266 |
| n | 110 |
| STOP | 257 |

| Dictionary | | | |
|---|---|---|---|
| Index | Word | Index | Word |
| 0 | | 258 | it |
| … | | 259 | tt |
| 32 | _ | 260 | ty |
| … | | 261 | y_ |
| 97 | a | 262 | _b |
| 98 | b | 263 | bi |
| … | | 264 | itt |
| 122 | z | 265 | ty_ |
| … | | 266 | _bi |
| 256 | SEND | 267 | it_ |
| 257 | STOP | 268 | _bin |

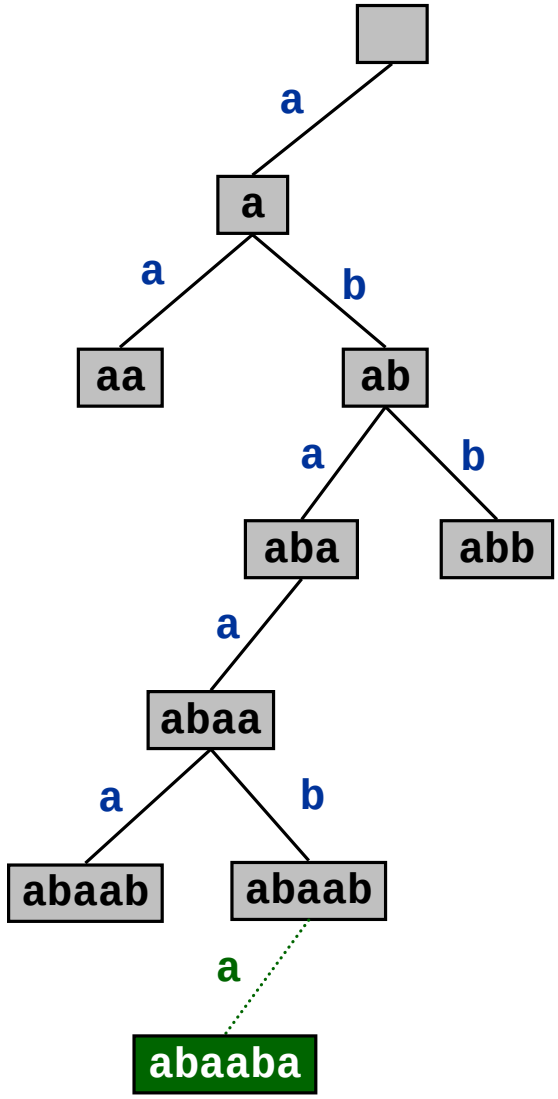
# LZW Implementation

Implementation.

- Use trie to create symbol table on-the-fly.
  - prefix of every word also in ST
- Encode.
  - lookup string suffix in trie
  - output ST index at bottom
  - add new node to bottom of trie
- Decode.
  - lookup string suffix in trie
  - output ST word at bottom
  - add new node to bottom of trie

What to do when ST gets too large?

- Throw away and start over. GIF
- Throw away when not effective. Unix compress



# Summary

Lossless compression.

- Simple approaches.
  - RLE
- Represent fixed length symbols with variable length codes.
  - Huffman
- Represent variable length symbols with fixed length codes.
  - LZW

Lossy compression.

- Algorithms not covered in COS 226.
- Signal processing, wavelets, fractals, . . . .

Limits on compression.

- Entropy.