Week 9: String Algorithms, Approximation

Strings

Strings

A *string* is a sequence of characters.

An *alphabet* Σ is the set of possible characters in strings.

Examples of strings:

- C program
- HTML document
- DNA sequence
- Digitised image

Examples of alphabets:

- ASCII
- Unicode
- {0,1}
- {A,C,G,T}

... Strings

Notation:

- *length(P)* … #characters in *P*
- *λ* … *empty* string   (*length(λ)* = 0)
- Σ^m … set of all strings of length *m* over alphabet Σ
- Σ^* … set of all strings over alphabet Σ

νω denotes the *concatenation* of strings ν and ω

Note: length(νω) = length(ν)+length(ω)   λω = ω = ωλ

... Strings

Notation:

- *substring* of *P* … any string *Q* such that *P* = *νQω*, for some $\nu,\omega \in \Sigma^*$
- *prefix* of *P* … any string *Q* such that *P* = *Qω*, for some $\omega \in \Sigma^*$
- *suffix* of *P* … any string *Q* such that *P* = *ωQ*, for some $\omega \in \Sigma^*$

Exercise #1: Strings

The string `a/a` of length 3 over the ASCII alphabet has

- how many prefixes?
- how many suffixes?
- how many substrings?

- 4 prefixes: `""` `"a"` `"a/"` `"a/a"`
- 4 suffixes: `"a/a"` `"/a"` `"a"` `""`
- 6 substrings: `""` `"a"` `"/"` `"a/"` `"/a"` `"a/a"`

Note:
`""` means the same as λ (= empty string)

... Strings

ASCII (American Standard Code for Information Interchange)

- Specifies mapping of 128 characters to integers 0..127
- The characters encoded include:
  - upper and lower case English letters: A-Z and a-z
  - digits: 0-9
  - common punctuation symbols
  - special non-printing characters: e.g. *newline* and *space*

Ascii	Char	Ascii	Char	Ascii	Char	Ascii	Char
0	Null	32	Space	64	@	96	`
1	Start of heading	33	!	65	A	97	a
2	Start of text	34	"	66	B	98	b
3	End of text	35	#	67	C	99	c
4	End of transmit	36	$	68	D	100	d
5	Enquiry	37	%	69	E	101	e
6	Acknowledge	38	&	70	F	102	f
7	Audible bell	39	'	71	G	103	g
8	Backspace	40	(	72	H	104	h
9	Horizontal tab	41	)	73	I	105	i
10	Line feed	42	*	74	J	106	j
11	Vertical tab	43	+	75	K	107	k
12	Form feed	44	,	76	L	108	l
13	Carriage return	45	-	77	M	109	m
14	Shift in	46	.	78	N	110	n
15	Shift out	47	/	79	O	111	o
16	Data link escape	48	0	80	P	112	p
17	Device control 1	49	1	81	Q	113	q
18	Device control 2	50	2	82	R	114	r
19	Device control 3	51	3	83	S	115	s
20	Device control 4	52	4	84	T	116	t
21	Neg. acknowledge	53	5	85	U	117	u
22	Synchronous idle	54	6	86	V	118	v
23	End trans. block	55	7	87	W	119	w
24	Cancel	56	8	88	X	120	x
25	End of medium	57	9	89	Y	121	y
26	Substitution	58	:	90	Z	122	z
27	Escape	59	;	91	[	123	{
28	File separator	60	<	92	\	124	|
29	Group separator	61	=	93	]	125	}
30	Record separator	62	>	94	^	126	~
31	Unit separator	63	?	95	_	127	Forward del.

Pattern Matching

Pattern Matching

Example (pattern checked *backwards*):

- *Text* … `abacaab`
- *Pattern* … `abacab`

... Pattern Matching

Given two strings *T* (text) and *P* (pattern),
the *pattern matching problem* consists of finding a substring of *T* equal to *P*

Applications:

- Text editors
- Search engines
- Biological research

... Pattern Matching

Naive pattern matching algorithm

- checks for each possible shift of *P* relative to *T*
  - until a match is found, or
  - all placements of the pattern have been tried

```
NaiveMatching(T,P):
|  Input  text T of length n, pattern P of length m
|  Output starting index of a substring of T equal to P
|         -1 if no such substring exists
|
|  for all i=0..n-m do
|  |  j=0                        // check from left to right
|  |  while j<m and T[i+j]=P[j] do  // test ith shift of pattern
|  |  |  j=j+1
|  |  |  if j=m then
|  |  |     return i            // entire pattern checked
|  |  |  end if
|  |  end while
|  end for
|  return -1                    // no match found
```

Analysis of Naive Pattern Matching

Naive pattern matching runs in O(n·m)

Examples of worst case (forward checking):

- *T* = aaa…ah
- *P* = aaah
- may occur in DNA sequences
- unlikely in English text

Exercise #2: Naive Matching

Suppose all characters in *P* are different.

Can you accelerate `NaiveMatching` to run in *O(n)* on an *n*-character text *T*?

When a mismatch occurs between *P[j]* and *T[i+j]*, shift the pattern all the way to align *P[0]* with *T[i+j]*

⇒ each character in *T* checked at most twice

Example:

```
abcdabcdeabcc   abcdabcdeabcc
abcde               abcde
```

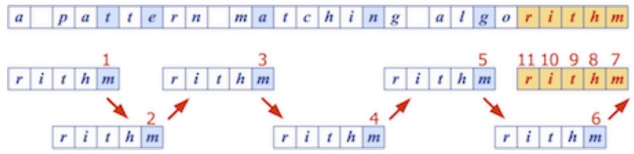
Boyer-Moore Algorithm

The *Boyer-Moore* pattern matching algorithm is based on two heuristics:

- *Looking-glass heuristic*: Compare *P* with subsequence of *T* moving *backwards*
- *Character-jump heuristic*: When a mismatch occurs at *T[i]*=`c`
  - if *P* contains `c` ⇒ shift *P* so as to align the last occurrence of `c` in *P* with *T[i]*
  - otherwise ⇒ shift *P* so as to align *P[0]* with *T[i+1]* (a.k.a. "big jump")

... Boyer-Moore Algorithm

Example:



... Boyer-Moore Algorithm

Boyer-Moore algorithm preprocesses pattern *P* and alphabet Σ to build

- *last-occurrence function L*
  - *L* maps Σ to integers such that *L(c)* is defined as
    - the largest index *i* such that *P[i]=c*, or
    - -1 if no such index exists

Example: Σ = {`a`,`b`,`c`,`d`}, *P* = `acab`

c	a	b	c	d
L(c)	2	3	1	-1

- *L* can be represented by an array indexed by the numeric codes of the characters
- *L* can be computed in *O(m+s)* time (*m* … length of pattern, *s* … size of Σ)

... Boyer-Moore Algorithm

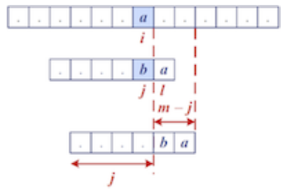

```
BoyerMooreMatch(T,P,Σ):
|  Input  text T of length n, pattern P of length m, alphabet Σ
|  Output starting index of a substring of T equal to P
|         -1 if no such substring exists
|
|  L=lastOccurenceFunction(P,Σ)
|  i=m-1, j=m-1                // start at end of pattern
|  repeat
|  |  if T[i]=P[j] then
|  |  |  if j=0 then
```

```
|   |   |      return i           // match found at i
|   |   |   else
|   |   |      i=i-1, j=j-1       // keep comparing
|   |   |   end if
|   |   else                      // character-jump
|   |   |   i=i+m-min(j,1+L[T[i]])
|   |   |   j=m-1
|   |   end if
|   until i≥n
|   return -1                     // no match
```

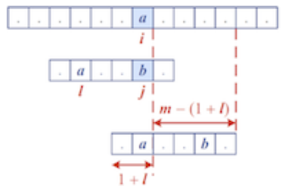
- Biggest jump (m characters ahead) occurs when *L[T[i]]* = -1

... Boyer-Moore Algorithm

Case 1: $j \le 1+L[c]$



Case 2: $1+L[c] < j$



Exercise #3: Boyer-Moore algorithm

For the alphabet Σ = {a,b,c,d}

1. compute last-occurrence function *L* for pattern *P* = **abacab**
2. trace Boyer-More on *P* and text *T* = abacaabadcabacabaabb
   - how many comparisons are needed?

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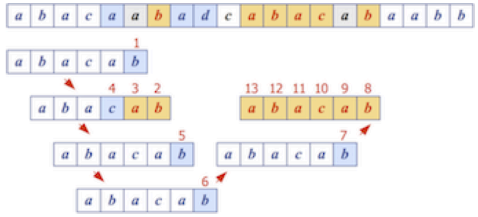
c	a	b	c	d
L(c)	4	5	3	-1



13 comparisons in total

... Boyer-Moore Algorithm

Analysis of Boyer-Moore algorithm:

- Runs in $O(nm+s)$ time
  - *m* … length of pattern   *n* … length of text   *s* … size of alphabet
- Example of worst case:
  - *T* = aaa … a
  - *P* = baaa
- Worst case may occur in images and DNA sequences but unlikely in English texts
  ⇒ Boyer-Moore significantly faster than naive matching on English text

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Knuth-Morris-Pratt Algorithm

The *Knuth-Morris-Pratt* algorithm …

- compares the pattern to the text *left-to-right*
- but shifts the pattern more intelligently than the naive algorithm

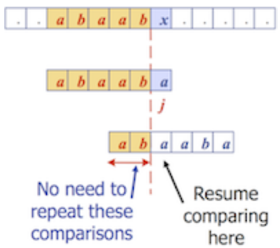
Reminder:

- *Q* is a *prefix* of *P*   … $P = Q\omega$, for some $\omega \in \Sigma^*$
- *Q* is a *suffix* of *P*   … $P = \omega Q$, for some $\omega \in \Sigma^*$

... Knuth-Morris-Pratt Algorithm

When a mismatch occurs …

- what is the most we can shift the pattern to avoid redundant comparisons?
- Answer: the largest *prefix* of *P[0..j]* that is a *suffix* of *P[1..j]*



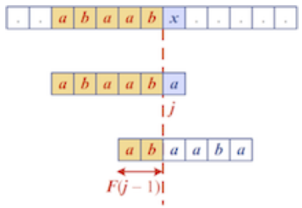
... Knuth-Morris-Pratt Algorithm

KMP preprocesses the pattern *P[0..m-1]* to find matches of its prefixes with itself

- *Failure function F(j)* defined as
  - the size of the *largest prefix* of *P[0..j]* that is also a *suffix* of *P[1..j]*
    - for each position *j*=0..*m-1*
- if mismatch occurs at P_j ⇒ advance *j* to *F(j-1)*

Example: *P* = abaaba

j	0	1	2	3	4	5
P_j	a	b	a	a	b	a
F(j)	0	0	1	1	2	3



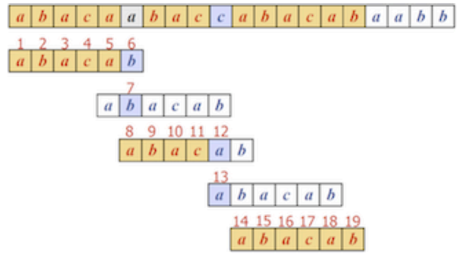
... Knuth-Morris-Pratt Algorithm


```
KMPMatch(T,P):
|  Input  text T of length n, pattern P of length m
|  Output starting index of a substring of T equal to P
|         -1 if no such substring exists
|
|  F=failureFunction(P)
|  i=0, j=0                 // start from left
|  while i<n do
|  |  if T[i]=P[j] then
|  |  |  if j=m-1 then
|  |  |     return i-j       // match found at i-j
|  |  |  else
|  |  |     i=i+1, j=j+1    // keep comparing
|  |  |  end if
|  |  else if j>0 then      // mismatch and j>0?
|  |  |  j=F[j-1]           //  → advance j to F[j-1]
|  |  else                  // mismtach and j still 0?
|  |  |  i=i+1              //  → begin at next text character
|  |  end if
|  end while
|  return -1                // no match
```

Exercise #4: KMP-Algorithm

1. compute failure function *F* for pattern *P* = **abacab**
2. trace Knuth-Morris-Pratt on *P* and text *T* = abacaabaccabacabaabb
   - how many comparisons are needed?

j	0	1	2	3	4	5
P_j	a	b	a	c	a	b
F(j)	0	0	1	0	1	2



19 comparisons in total

... Knuth-Morris-Pratt Algorithm

Analysis of Knuth-Morris-Pratt algorithm:

- Failure function can be computed in *O(m)* time (→ next slide)
- At each iteration of the while-loop, either
  - *i* increases by one, or
  - the "shift amount" *i-j* increases by at least one (observe that always F(j-1)<j)
- Hence, there are no more than 2·*n* iterations of the while-loop

⇒ KMP's algorithm runs in *optimal time O(m+n)*

... Knuth-Morris-Pratt Algorithm

Construction of the failure function matches pattern against *itself*:

```
failureFunction(P):
|  Input  pattern P of length m
|  Output failure function for P
|
|  F[0]=0                 // F[0] is always 0
|  j=1, len=0
|  while j<m do
|  |  if P[j]=P[len] then
|  |     len=len+1        // we have matched len+1 characters
|  |     F[j]=len         // P[0..len-1] = P[len-1..j]
|  |     j=j+1
|  |  else if len>0 then  // mismatch and len>0?
|  |     len=F[len-1]     //  → use already computed F[len] for new len
|  |  else                // mismatch and len still 0?
```

```
|  |     F[j]=0            //  → no prefix of P[0..j] is also suffix of P[1..j]
|  |     j=j+1             //  → continue with next pattern character
|  |  end if
|  end while
|  return F
```

Exercise #5:

Trace the `failureFunction` algorithm for pattern P = **`abaaba`**

```
                         ⇒          F[0]=0
j=1, len=0, P[1]≠P[0] ⇒          F[1]=0
j=2, len=0, P[2]=P[0] ⇒ len=1, F[2]=1
j=3, len=1, P[3]≠P[1] ⇒ len=F[0]=0
j=3, len=0, P[3]=P[0] ⇒ len=1, F[3]=1
j=4, len=1, P[4]=P[1] ⇒ len=2, F[4]=2
j=5, len=2, P[5]=P[2] ⇒ len=3, F[5]=3
```

... Knuth-Morris-Pratt Algorithm

Analysis of failure function computation:

- At each iteration of the while-loop, either
  - i increases by one, or
  - the "shift amount" i-j increases by at least one (remember that always F(j-1)<j)
- Hence, there are no more than 2·m iterations of the while-loop

⇒ failure function can be computed in $O(m)$ time

Boyer-Moore vs KMP

Boyer-Moore algorithm

- decides how far to jump ahead based on the mismatched character in the text
- works best on large alphabets and natural language texts (e.g. English)

Knuth-Morris-Pratt algorithm

- uses information embodied in the pattern to determine where the next match could begin
- works best on small alphabets (e.g. `A,C,G,T`)

For the keen: The article "Average running time of the Boyer-Moore-Horspool algorithm" shows that the time is inversely proportional to size of alphabet

Word Matching With Tries

Preprocessing Strings

Preprocessing the *pattern* speeds up pattern matching queries

- After preprocessing P, KMP algorithm performs pattern matching in time proportional to the text length

If the text is large, immutable and searched for often (e.g., works by Shakespeare)

- we can preprocess the *text* instead of the pattern

... Preprocessing Strings

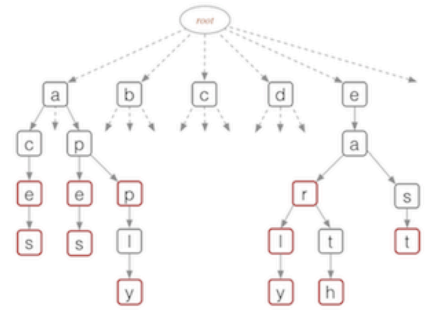
A *trie* …

- is a compact data structure for representing a set of strings
  - e.g. all the words in a text, a dictionary etc.
- supports pattern matching queries in time proportional to the pattern size

Note: Trie comes from *retrieval*, but is pronounced like "try" to distinguish it from "tree"

Tries

Tries are trees organised using parts of keys (rather than whole keys)



... Tries

Each node in a trie …

- contains one part of a key (typically one character)
- may have up to 26 children
- may be tagged as a "finishing" node
- but even "finishing" nodes may have children

Depth d of trie = length of longest key value

Cost of searching $O(d)$ (independent of n)

... Tries

Possible trie representation:

```
#define ALPHABET_SIZE 26

typedef struct Node *Trie;
```

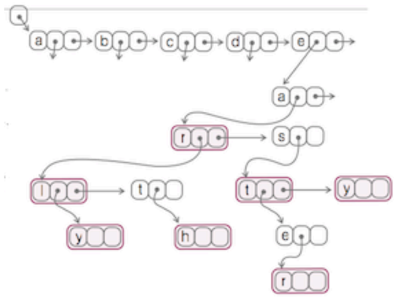
```
typedef struct Node {
   bool finish;      // last char in key?
   Item data;        // no Item if !finish
   Trie child[ALPHABET_SIZE];
} Node;

typedef char *Key;
```

... Tries

41/85

Note: Can also use BST-like nodes for more space-efficient implementation of tries



Trie Operations

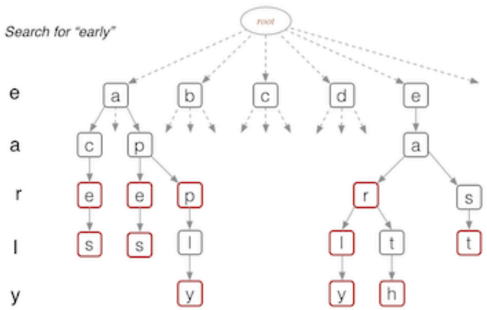
42/85

Basic operations on tries:

1. search for a key
2. insert a key

... Trie Operations

43/85



... Trie Operations

44/85

Traversing a path, using char-by-char from Key:

```
find(trie,key):
|  Input  trie, key
|  Output pointer to element in trie if key found
|         NULL otherwise
|
|  node=trie
|  for each char in key do
|  |  if node.child[char] exists then
|  |     node=node.child[char]  // move down one level
|  |  else
|  |     return NULL
|  |  end if
|  end for
|  if node.finish then           // "finishing" node reached?
|     return node
|  else
|     return NULL
|  end if
```

... Trie Operations

45/85

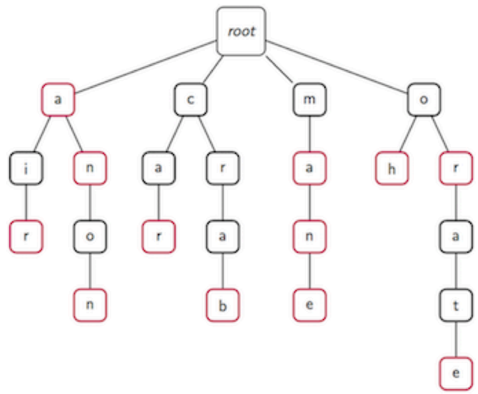
Insertion into Trie:

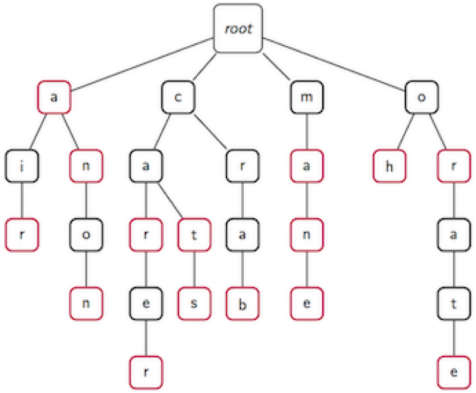
```
insert(trie,item,key):
|  Input  trie, item with key of length m
|  Output trie with item inserted
|
|  if trie is empty then
|     t=new trie node
|  end if
|  if m=0 then
|     t.finish=true, t.data=item
|  else
|     t.child[key[0]]=insert(t.child[key[0]],item,key[1..m-1])
|  end if
|  return t
```

Exercise #6: Trie Insertion

46/85

Insert cat, cats and carer into this trie:





... Trie Operations

48/85

Analysis of standard tries:

- *O(n)* space
- insertion and search in time *O(m)*
  - *n* … total size of text (e.g. sum of lengths of all strings in a given dictionary)
  - *m* … size of the string parameter of the operation (the "key")

Word Matching With Tries

Word Matching with Tries

50/85

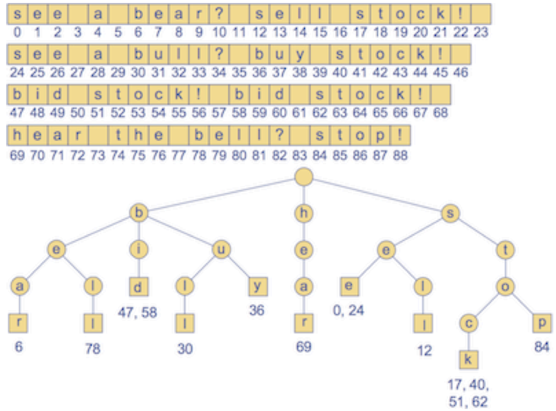
Preprocessing the text:

1. Insert all searchable words of a text into a trie
2. Each leaf stores the occurrence(s) of the associated word in the text

... Word Matching with Tries

51/85

Example text and corresponding trie of searchable words:



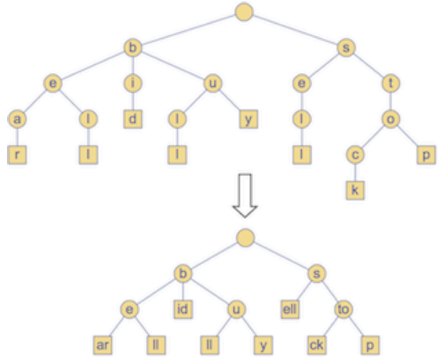
Compressed Tries

52/85

Compressed tries …

- have internal nodes of degree ≥ 2
- are obtained from standard tries by compressing "redundant" chains of nodes

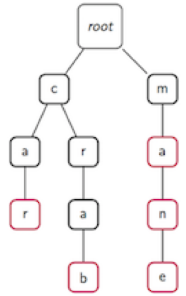
Example:



Exercise #7: Compressed Tries

53/85

Consider this uncompressed trie:



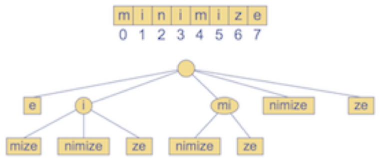
How many nodes (including the root) are needed for the compressed trie?

7

Pattern Matching With Suffix Tries

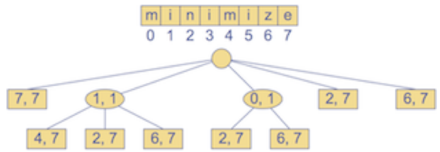
The *suffix trie* of a text *T* is the compressed trie of all the suffixes of *T*

Example:



... Pattern Matching With Suffix Tries

Compact representation:



... Pattern Matching With Suffix Tries

Input:

- compact suffix trie for text *T*
- pattern *P*

Goal:

- find starting index of a substring of *T* equal to *P*

... Pattern Matching With Suffix Tries

```
suffixTrieMatch(trie,P):
|  Input  compact suffix trie for text T, pattern P of length m
|  Output starting index of a substring of T equal to P
|         -1 if no such substring exists
|
|  j=0, v=root of trie
|  repeat
|  |  // we have matched j+1 characters
|  |  if ∃w∈children(v) such that P[j]=T[start(w)] then
|  |  |  i=start(w)              // start(w) is the start index of w
|  |  |  x=end(w)-i+1            // end(w) is the end index of w
|  |  |  if m≤x then    // length of suffix ≤ length of the node label?
|  |  |     if P[j..j+m-1]=T[i..i+m-1] then
|  |  |        return i-j        // match at i-j
|  |  |     else
|  |  |        return -1         // no match
|  |  |  else if P[j..j+x-1]=T[i..i+x-1] then
|  |  |     j=j+x, m=m-x        // update suffix start index and length
|  |  |     v=w                 // move down one level
|  |  |  else return -1         // no match
|  |  |  end if
|  |  else
|  |     return -1
|  |  end if
|  until v is leaf node
|  return -1                    // no match
```


... Pattern Matching With Suffix Tries

Analysis of pattern matching using suffix tries:

Suffix trie for a text of size *n* …

- can be constructed in *O(n)* time
- uses *O(n)* space
- supports pattern matching queries in *O(m)* time
  - *m* … length of the pattern

Text Compression

Text Compression

Problem: Efficiently encode a given string *X* by a smaller string *Y*

Applications:

- Save memory and/or bandwidth

Huffman's algorithm

- computes frequency *f(c)* for each character *c*
- encodes high-frequency characters with short code
- no code word is a prefix of another code word
- uses optimal *encoding tree* to determine the code words

... Text Compression

Code … mapping of each character to a binary code word

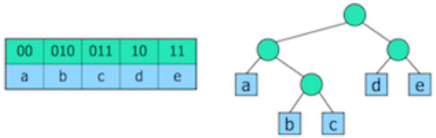
Prefix code … binary code such that no code word is prefix of another code word

Encoding tree …

- represents a prefix code
- each leaf stores a character
- code word given by the path from the root to the leaf (0 for left child, 1 for right child)

... Text Compression

Example:



... Text Compression

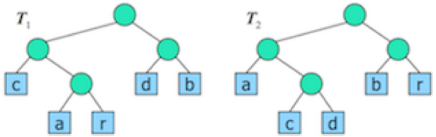
Text compression problem

Given a text T, find a prefix code that yields the shortest encoding of T

- short codewords for frequent characters
- long code words for rare characters

... Text Compression

Example: T = `abracadabra`



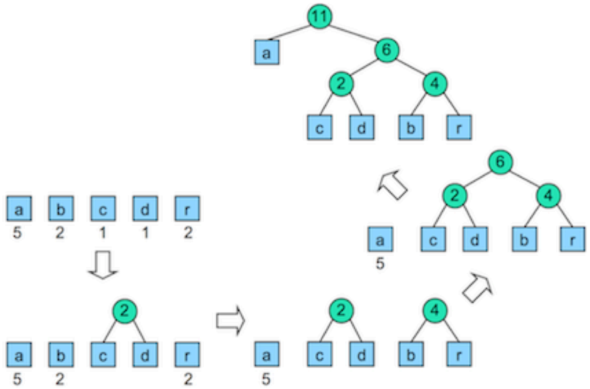
T_1 requires 29 bits to encode text T,
T_2 requires 24 bits

... Text Compression

Huffman's algorithm

- computes frequency $f(c)$ for each character
- successively combines pairs of lowest-frequency characters to build encoding tree "bottom-up"

Example: `abracadabra`



Huffman Code

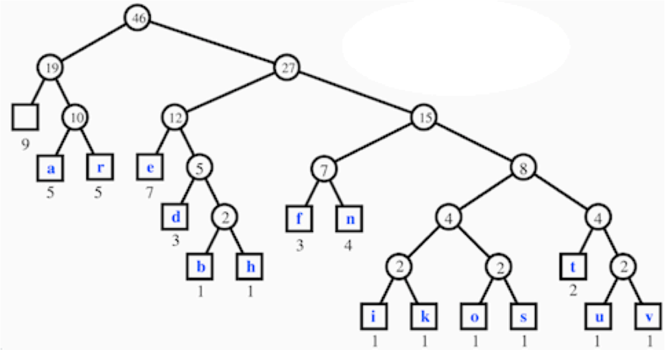
Huffman's algorithm using priority queue:

```
HuffmanCode(T):
|  Input  string T of size n
|  Output optimal encoding tree for T
|
|  compute frequency array
|  Q=new priority queue
|  for all characters c do
|  |  T=new single-node tree storing c
|  |  join(Q,T) with frequency(c) as key
|  end for
|  while |Q|≥2 do
|  |  f1=Q.minKey(), T1=leave(Q)
|  |  f2=Q.minKey(), T2=leave(Q)
|  |  T=new tree node with subtrees T1 and T2
|  |  join(Q,T) with f1+f2 as key
|  end while
|  return leave(Q)
```

Exercise #8: Huffman Code

Construct a Huffman tree for: a fast runner need never be afraid of the dark

Character		a	b	d	e	f	h	i	k	n	o	r	s	t	u	v
Frequency	9	5	1	3	7	3	1	1	1	4	1	5	1	2	1	1



... Huffman Code

70/85

Analysis of Huffman's algorithm:

- *O(n+d·log d)* time
  - *n* … length of the input text *T*
  - *d* … number of distinct characters in *T*

Approximation

Approximation for Numerical Problems

72/85

Approximation is often used to solve numerical problems by

- solving a simpler, but much more easily solved, problem
- where this new problem gives an approximate solution
- and refine the method until it is "accurate enough"

Examples:

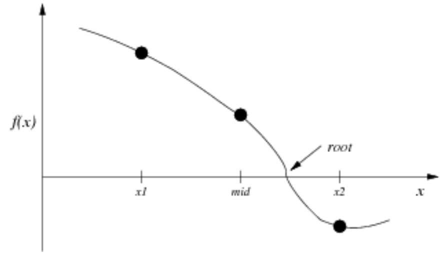
- roots of a function *f*
- length of a curve determined by a function *f*
- … and many more

... Approximation for Numerical Problems

73/85

Example: Finding Roots

Find where a function crosses the x-axis:



Generate and test: move x_1 and x_2 together until "close enough"

... Approximation for Numerical Problems

74/85

A simple approximation algorithm for finding a root in a given interval:

```
bisection(f,x1,x2):
|  Input  function f, interval [x1,x2]
|  Output x∈[x1,x2] with f(x)≅0
|
|  repeat
|  |  mid=(x1+x2)/2
|  |  if f(x1)*f(mid)<0 then
|  |     x2=mid      // root to the left of mid
|  |  else
|  |     x1=mid      // root to the right of mid
|  |  end if
|  until f(mid)=0 or x2-x1<ε   // ε: accuracy
|  end while
|  return mid
```

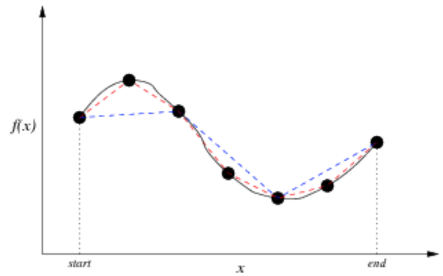
`bisection` guaranteed to converge to a root if *f* continuous on $[x_1,x_2]$ and $f(x_1)$ and $f(x_2)$ have opposite signs

... Approximation for Numerical Problems

75/85

Example: Length of a Curve

Estimate length: approximate curve as sequence of straight lines.




```
length=0, δ=(end-start)/StepSize
for each x∈[start+δ,start+2δ,..,end] do
   length = length + sqrt(δ² + (f(x)-f(x-δ))²)
```

```
end for
```


Approximation for NP-hard Problems

Approximation is often used for NP-hard problems …

- computing a near-optimal solution
- in polynomial time

Examples:

- vertex cover of a graph
- subset-sum problem

Vertex Cover

Reminder: Graph $G = (V,E)$

- set of vertices V
- set of edges E

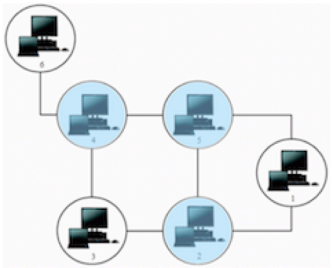
Vertex cover C of G …

- $C \subseteq V$
- for all edges $(u,v) \in E$ either $v \in C$ or $u \in C$ (or both)

⇒ All edges of the graph are "covered" by vertices in C

... Vertex Cover

Example (6 nodes, 7 edges, 3-vertex cover):



Applications:

- Computer Network Security
  - compute minimal set of routers to cover all connections
- Biochemistry

... Vertex Cover

size of vertex cover C … $|C|$ (number of elements in C)

optimal vertex cover … a vertex cover of minimum size

Theorem.
Determining whether a graph has a vertex cover of a given size k is an NP-complete problem.

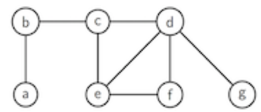
... Vertex Cover

An approximation algorithm for vertex cover:

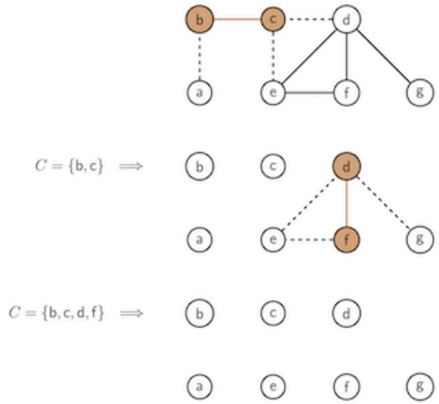
```
approxVertexCover(G):
|  Input  undirected graph G=(V,E)
|  Output vertex cover of G
|
|  C=∅
|  unusedE=E
|  while unusedE≠∅
|  |  choose any (v,w)∈unusedE
|  |  C = C∪{v,w}
|  |  unusedE = unusedE\{all edges incident on v or w}
|  end while
|  return C
```


Exercise #9: Vertex Cover

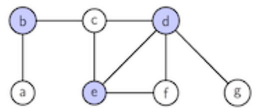
Show how the approximation algorithm produces a vertex cover on:



Possible result:



What would be an optimal vertex cover?



... Vertex Cover

Theorem.
The approximation algorithm returns a vertex cover *at most twice the size* of an optimal cover.

Proof. Any (optimal) cover must include at least one endpoint of each chosen edge.

Cost analysis …

- repeatedly select an edge from E
  - add endpoints to C
  - delete all edges in E covered by endpoints

Time complexity: $O(V+E)$ (adjacency list representation)

Summary

- Alphabets and words
- Pattern matching
  - Boyer-Moore, Knuth-Morris-Pratt
- Tries
- Text compression
  - Huffman code
- Approximation
  - numerical problems
  - vertex cover

- Suggested reading:
  - tries … Sedgewick, Ch. 15.2
  - approximation … Moffat, Ch. 9.4