CSU22012: Data Structures and Algorithms II

Strings

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Outline of String algorithms

- String sorting algorithms
  - Exploit properties of strings to speed up sorting
  - Radix sort
- Tries
  - Data structures for searching with string keys – more efficient than general purpose ones previously discussed, eg hashtables, search trees
- Substring search
  - Interesting problem- multiple approaches illustrating different algorithm design techniques
- Regular expressions
  - Searching for incomplete patterns rather than exact substrings
- Data compression
  - Save storage, faster network transfer
  - Run length encoding, Huffman compression

What are strings?

- Sequences of characters
  - Text
  - Genome sequences
- What are characters then?
  - In C – char data type is 8 bit integer, 7-bit ascii, 256 characters max
  - In Java – char data type, 16 bit unsigned int, range '\u0000' to '\uffff' (0 to 65,535)

java.lang.String

- Immutable sequence of characters
- Implements Comparable
- Implements CharSequences
  - Methods length() – number of characters
  - charAt(i) – returns the i-th character

  - Concatenation- concatenate one string to the end of another java.lang.String
  - Substring – extract a subsequence of characters

Immutable?

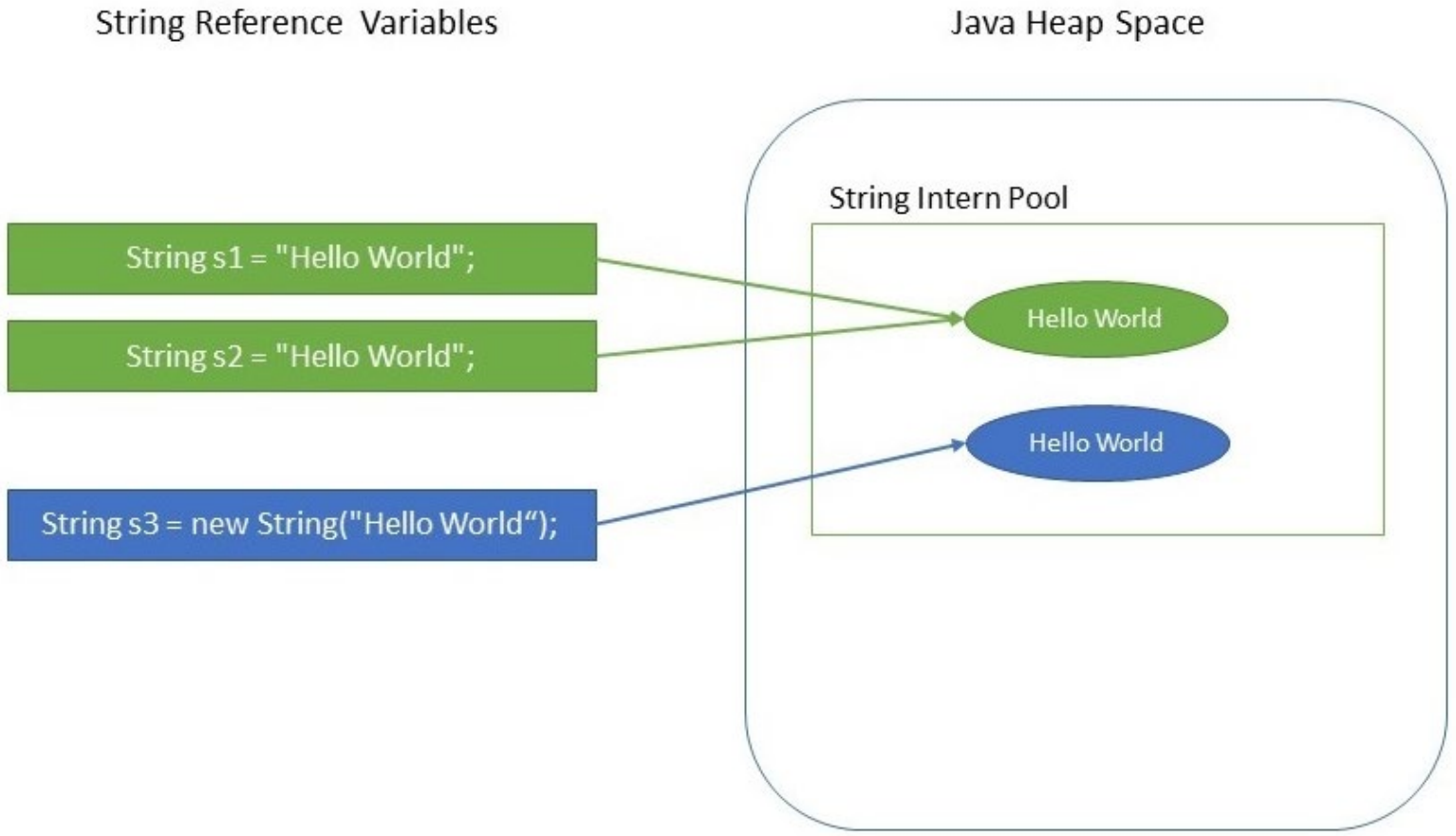
› String cannot be modified
› What happens here then?

```
String test = “blah”;
test = “meh”;
System.out.println(test); //what does this print?
```

New string is created and reference test now points to it instead of the old one – reference to “blah” text has been lost, it’s still unchanged somewhere in memory

Memory leaks/garbage collection

String pool



https://www.baeldung.com/java-string-immutable

Other implications of immutability

- Security
  - Parameters in many methods which could introduce vulnerability – security threats, eg network connection is passed a string – it could be modified to connect to a different machine, or a modified file name can be passed in etc
- Thread-safe
  - No need for synchronisation if shared between threads – no thread can modify it
- Can be used as keys in symbol tables
- Can calculate and save hashcode – efficiency
- https://www.baeldung.com/java-string-immutable

String implementation

char [] value

int length - saved for efficiency so it doesn't have to be calculated every time we need it

int hash - calculated as s[0]*31^(n-1) + s[1]*31^(n-2) + … + s[n-1]

Cost of String operations

› How long does it take to reverse a String?

```
public static String reverse(String s)
{
   String rev = "";
   for (int i = s.length() - 1; i >= 0; i--)
      rev += s.charAt(i);
   return rev;
}
```

quadratic time

› Alternative – mutable sequence of characters, StringBuilder

```
public static String reverse(String s)
{
   StringBuilder rev = new StringBuilder();
   for (int i = s.length() - 1; i >= 0; i--)
      rev.append(s.charAt(i));
   return rev.toString();
}
```

linear time

Substring operation

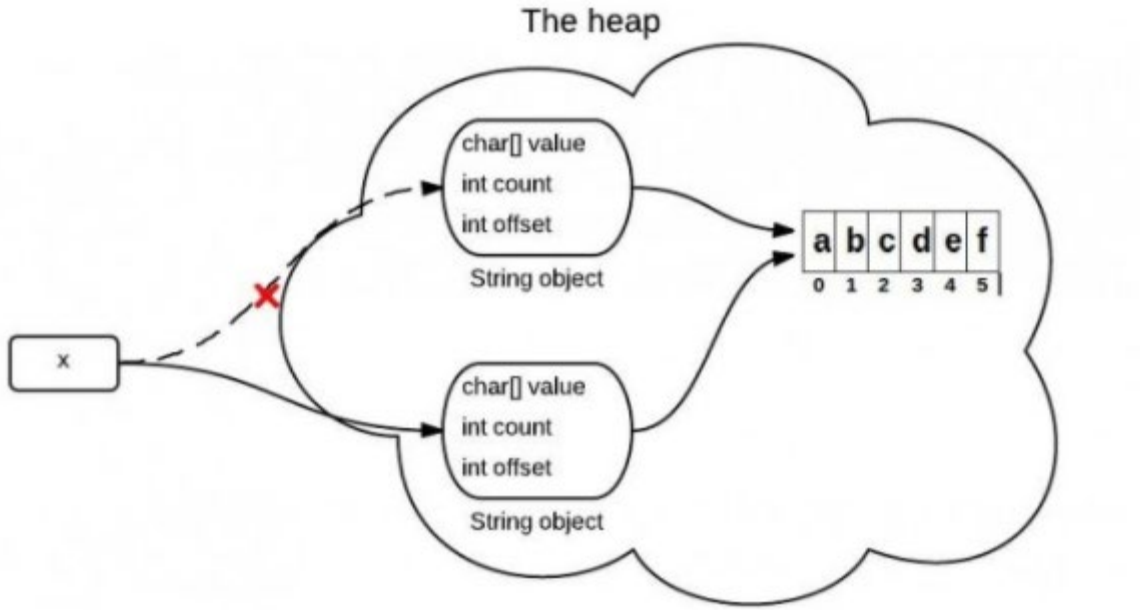
› Java 6 vs Java 7 (and up)

```
String x = "abcdef";
x = x.substring(1,3);
System.out.println(x);
```

https://www.programcreek.com/2013/09/the-substring-method-in-jdk-6-and-jdk-7/

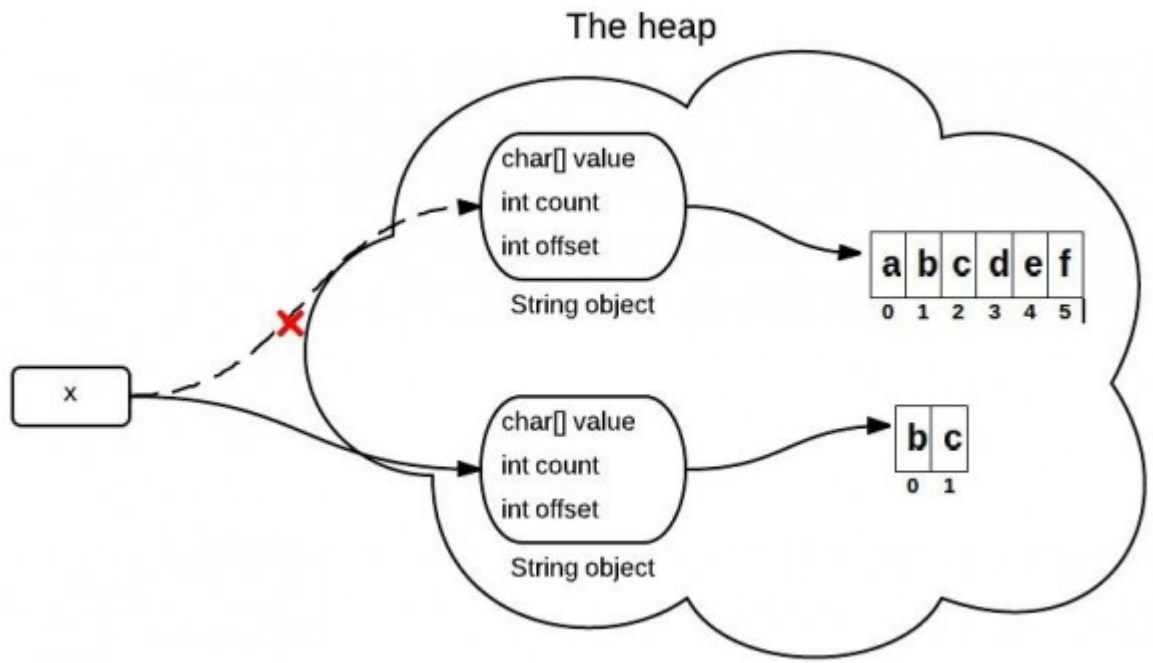
Substring operation in Java 6

- Cheap (cost of 1)
- Memory leaks – unused portion of the string cant be garbage collected
- Points to same value
- Count modified
- Offset modified



Substring operation in Java 7 (now)

- Cost of N, new string needs to be created- characters copied into it
- Old string can be garbage collected



Comparing 2 Strings

Q. How many character compares to compare two strings of length W ?

p	r	e	f	e	t	c	h
0	1	2	3	4	5	6	7
p	r	e	f	i	x	e	s

Running time. Proportional to length of longest common prefix.

- Proportional to W in the worst case.
- But, often sublinear in W.

Different Alphabets

› Performance depends on the size of the alphabet (i.e., unique characters)

Digital key. Sequence of digits over fixed alphabet.

Radix. Number of digits R in alphabet.

name	R()	lgR()	characters
BINARY	2	1	01
OCTAL	8	3	01234567
DECIMAL	10	4	0123456789
HEXADECIMAL	16	4	0123456789ABCDEF
DNA	4	2	ACTG
LOWERCASE	26	5	abcdefghijklmnopqrstuvwxyz
UPPERCASE	26	5	ABCDEFGHIJKLMNOPQRSTUVWXYZ
PROTEIN	20	5	ACDEFGHIKLMNPQRSTVWY
BASE64	64	6	ABCDEFGHIJKLMNOPQRSTUVWXYZabcdef ghijklmnopqrstuvwxyz0123456789+/
ASCII	128	7	*ASCII characters*
EXTENDED_ASCII	256	8	*extended ASCII characters*
UNICODE16	65536	16	*Unicode characters*

Key-Indexed Counting

Review: summary of the performance of sorting algorithms

Frequency of operations.

algorithm	guarantee	random	extra space	stable?	operations on keys
insertion sort	$\frac{1}{2} N^2$	$\frac{1}{4} N^2$	1	✔	compareTo()
mergesort	$N \lg N$	$N \lg N$	N	✔	compareTo()
quicksort	$1.39 N \lg N$ *	$1.39 N \lg N$	$c \lg N$		compareTo()
heapsort	$2 N \lg N$	$2 N \lg N$	1		compareTo()

* probabilistic

Lower bound. ~ $N \lg N$ compares required by any compare-based algorithm.

Q. Can we do better (despite the lower bound)?

A. Yes, if we don't depend on key compares. ← use array accesses to make R-way decisions (instead of binary decisions)

Key-indexed counting

- Basis for other more complex sorting algorithms
  - LSD and MSD (least and most significant digit)
- Specialized sorting algorithm which works best when the following conditions are met:
  - Input consists of collection of n items
  - Maximum possible value of each of the individual item is K

Key-indexed counting: assumptions about keys

Assumption. Keys are integers between 0 and $R - 1$.

Implication. Can use key as an array index.

Applications.

- Sort string by first letter.
- Sort class roster by section.
- Sort phone numbers by area code.
- Subroutine in a sorting algorithm. [stay tuned]

Remark. Keys may have associated data ⇒ can't just count up number of keys of each value.

input		sorted result (by section)	
name	*section*		
Anderson	2	Harris	1
Brown	3	Martin	1
Davis	3	Moore	1
Garcia	4	Anderson	2
Harris	1	Martinez	2
Jackson	3	Miller	2
Johnson	4	Robinson	2
Jones	3	White	2
Martin	1	Brown	3
Martinez	2	Davis	3
Miller	2	Jackson	3
Moore	1	Jones	3
Robinson	2	Taylor	3
Smith	4	Williams	3
Taylor	3	Garcia	4
Thomas	4	Johnson	4
Thompson	4	Smith	4
White	2	Thomas	4
Williams	3	Thompson	4
Wilson	4	Wilson	4

keys are small integers

ASCII TABLE

Decimal	Hex	Char	Decimal	Hex	Char	Decimal	Hex	Char	Decimal	Hex	Char
0	0	[NULL]	32	20	[SPACE]	64	40	@	96	60	`
1	1	[START OF HEADING]	33	21	!	65	41	A	97	61	a
2	2	[START OF TEXT]	34	22	"	66	42	B	98	62	b
3	3	[END OF TEXT]	35	23	#	67	43	C	99	63	c
4	4	[END OF TRANSMISSION]	36	24	$	68	44	D	100	64	d
5	5	[ENQUIRY]	37	25	%	69	45	E	101	65	e
6	6	[ACKNOWLEDGE]	38	26	&	70	46	F	102	66	f
7	7	[BELL]	39	27	'	71	47	G	103	67	g
8	8	[BACKSPACE]	40	28	(	72	48	H	104	68	h
9	9	[HORIZONTAL TAB]	41	29	)	73	49	I	105	69	i
10	A	[LINE FEED]	42	2A	*	74	4A	J	106	6A	j
11	B	[VERTICAL TAB]	43	2B	+	75	4B	K	107	6B	k
12	C	[FORM FEED]	44	2C	,	76	4C	L	108	6C	l
13	D	[CARRIAGE RETURN]	45	2D	-	77	4D	M	109	6D	m
14	E	[SHIFT OUT]	46	2E	.	78	4E	N	110	6E	n
15	F	[SHIFT IN]	47	2F	/	79	4F	O	111	6F	o
16	10	[DATA LINK ESCAPE]	48	30	0	80	50	P	112	70	p
17	11	[DEVICE CONTROL 1]	49	31	1	81	51	Q	113	71	q
18	12	[DEVICE CONTROL 2]	50	32	2	82	52	R	114	72	r
19	13	[DEVICE CONTROL 3]	51	33	3	83	53	S	115	73	s
20	14	[DEVICE CONTROL 4]	52	34	4	84	54	T	116	74	t
21	15	[NEGATIVE ACKNOWLEDGE]	53	35	5	85	55	U	117	75	u
22	16	[SYNCHRONOUS IDLE]	54	36	6	86	56	V	118	76	v
23	17	[ENG OF TRANS. BLOCK]	55	37	7	87	57	W	119	77	w
24	18	[CANCEL]	56	38	8	88	58	X	120	78	x
25	19	[END OF MEDIUM]	57	39	9	89	59	Y	121	79	y
26	1A	[SUBSTITUTE]	58	3A	:	90	5A	Z	122	7A	z
27	1B	[ESCAPE]	59	3B	;	91	5B	[	123	7B	{
28	1C	[FILE SEPARATOR]	60	3C	<	92	5C	\	124	7C	|
29	1D	[GROUP SEPARATOR]	61	3D	=	93	5D	]	125	7D	}
30	1E	[RECORD SEPARATOR]	62	3E	>	94	5E	^	126	7E	~
31	1F	[UNIT SEPARATOR]	63	3F	?	95	5F	_	127	7F	[DEL]

Key-indexed counting demo

Goal. Sort an array `a[]` of N integers between 0 and $R - 1$.

- Count frequencies of each letter using key as index.
- Compute frequency cumulates which specify destinations.
- Access cumulates using key as index to move items.
- Copy back into original array.

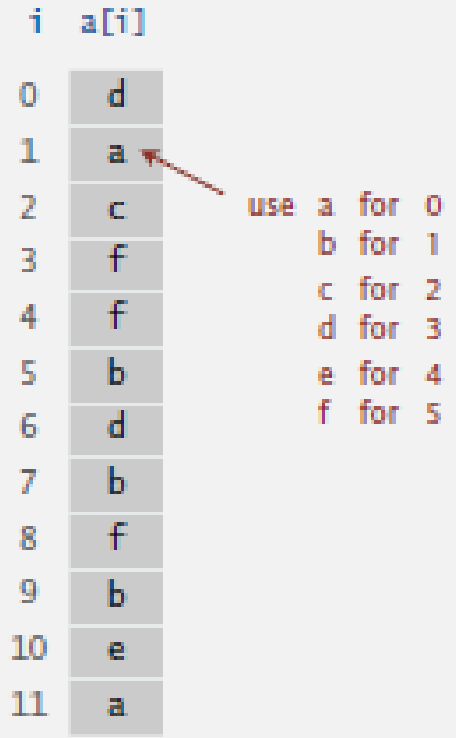
```
int N = a.length;
int[] count = new int[R+1];

for (int i = 0; i < N; i++)
   count[a[i]+1]++;

for (int r = 0; r < R; r++)
   count[r+1] += count[r];

for (int i = 0; i < N; i++)
   aux[count[a[i]]++] = a[i];

for (int i = 0; i < N; i++)
   a[i] = aux[i];
```



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- Compute frequency cumulates which specify destinations.
- Access cumulates using key as index to move items.
- Copy back into original array.

count frequencies

```
int N = a.length;
int[] count = new int[R+1];

for (int i = 0; i < N; i++)
   count[a[i]+1]++;

for (int r = 0; r < R; r++)
   count[r+1] += count[r];

for (int i = 0; i < N; i++)
   aux[count[a[i]]++] = a[i];

for (int i = 0; i < N; i++)
   a[i] = aux[i];
```

i	a[i]
0	d
1	a
2	c
3	f
4	f
5	b
6	d
7	b
8	f
9	b
10	e
11	a

offset by 1
[stay tuned]

r	count[r]
a	0
b	2
c	3
d	1
e	2
f	1
-	3

Key-indexed counting demo

Goal. Sort an array a[] of N integers between 0 and $R - 1$.

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- Access cumulates using key as index to move items.
- Copy back into original array.

```
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int[] count = new int[R+1];

for (int i = 0; i < N; i++)
   count[a[i]+1]++;

for (int r = 0; r < R; r++)
   count[r+1] += count[r];

for (int i = 0; i < N; i++)
   aux[count[a[i]]++] = a[i];

for (int i = 0; i < N; i++)
   a[i] = aux[i];
```
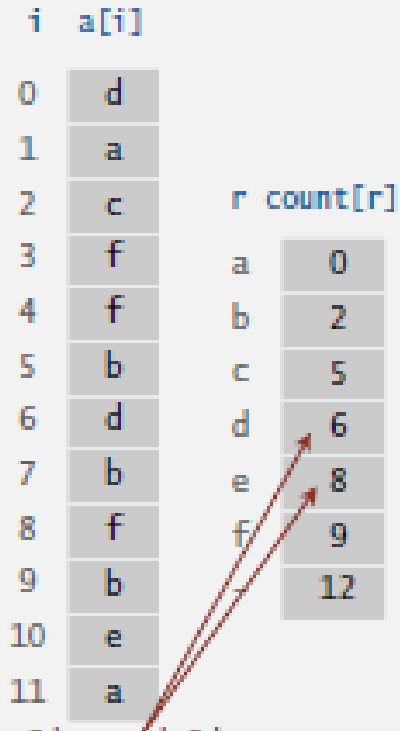

compute cumulates



6 keys < d, 8 keys < e
so d's go in a[6] and a[7]

Key-indexed counting demo

Goal. Sort an array `a[]` of N integers between 0 and $R - 1$.

- Count frequencies of each letter using key as index.
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- Copy back into original array.

```
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int[] count = new int[R+1];

for (int i = 0; i < N; i++)
   count[a[i]+1]++;

for (int r = 0; r < R; r++)
   count[r+1] += count[r];

for (int i = 0; i < N; i++)
   aux[count[a[i]]++] = a[i];

for (int i = 0; i < N; i++)
   a[i] = aux[i];
```

move items

i	a[i]
0	d
1	a
2	c
3	f
4	f
5	b
6	d
7	b
8	f
9	b
10	e
11	a

r	count[r]
a	2
b	5
c	6
d	8
e	9
f	12
-	12

i	aux[i]
0	a
1	a
2	b
3	b
4	b
5	c
6	d
7	d
8	e
9	f
10	f
11	f

Key-indexed counting demo

Goal. Sort an array `a[]` of N integers between 0 and $R - 1$.

- Count frequencies of each letter using key as index.
- Compute frequency cumulates which specify destinations.
- Access cumulates using key as index to move items.
- Copy back into original array.

```
int N = a.length;
int[] count = new int[R+1];

for (int i = 0; i < N; i++)
   count[a[i]+1]++;

for (int r = 0; r < R; r++)
   count[r+1] += count[r];

for (int i = 0; i < N; i++)
   aux[count[a[i]]++] = a[i];

for (int i = 0; i < N; i++)
   a[i] = aux[i];
```

copy back →

i	a[i]
0	a
1	a
2	b
3	b
4	b
5	c
6	d
7	d
8	e
9	f
10	f
11	f

r	count[r]
a	2
b	5
c	6
d	8
e	9
f	12
-	12

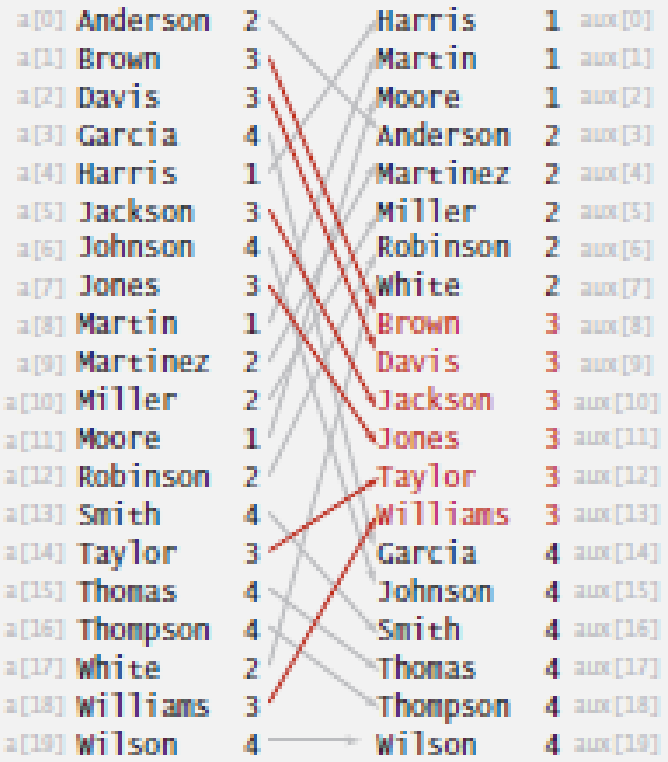
i	aux[i]
0	a
1	a
2	b
3	b
4	b
5	c
6	d
7	d
8	e
9	f
10	f
11	f

Key-indexed counting: analysis

Proposition. Key-indexed takes time proportional to $N + R$.

Proposition. Key-indexed counting uses extra space proportional to $N + R$.

Stable? ✔



Radix Sorts – LSD and MSD

Radix sorts

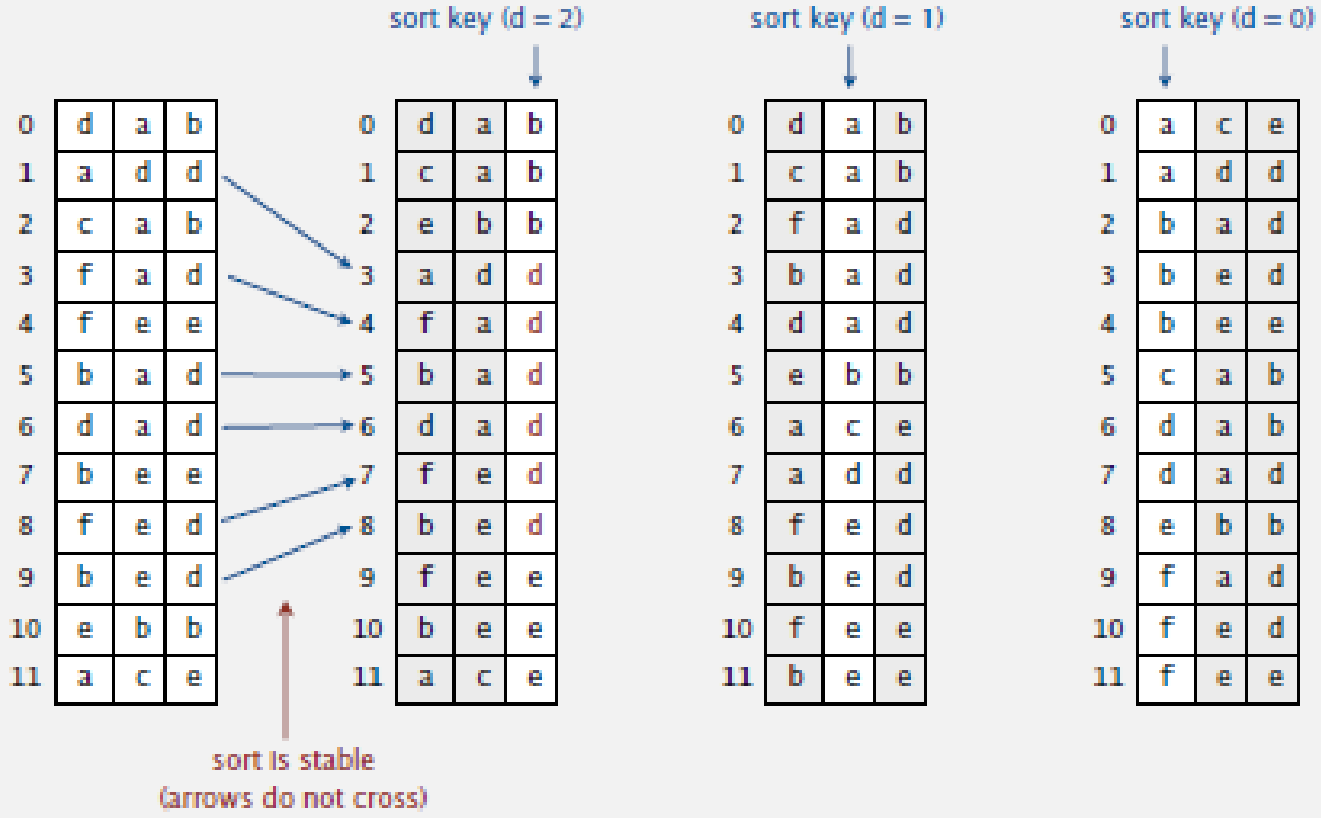
- Non-comparative integer sorting algorithm
- Sorts data with integer keys by grouping keys by the individual digits which share the same significant position and value.
- LSD radix sort
  - short keys come before longer keys
  - keys of the same length are sorted lexicographically
  - Ie, normal order of integer representations, such as the sequence 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11
- MSD radix sort
  - lexicographic order, which is suitable for sorting strings, such as words, or fixed-length integer representations
  - A sequence such as "b, c, d, e, f, g, h, i, j, ba" would be lexicographically sorted as "b, ba, c, d, e, f, g, h, i, j"
  - (1 to 10 would be output as 1, 10, 2, 3, 4, 5, 6, 7, 8, 9,)

LSD Sort

LSD Sort – Sort by Least Significant Digit first

LSD string (radix) sort.

- Consider characters from right to left.
- Stably sort using d^{th} character as the key (using key-indexed counting).



0	d	a	b
1	a	d	d
2	c	a	b
3	f	a	d
4	f	e	e
5	b	a	d
6	d	a	d
7	b	e	e
8	f	e	d
9	b	e	d
10	e	b	b
11	a	c	e

0	d	a	b
1	c	a	b
2	e	b	b
3	a	d	d
4	f	a	d
5	b	a	d
6	d	a	d
7	f	e	d
8	b	e	d
9	f	e	e
10	b	e	e
11	a	c	e

0	d	a	b
1	c	a	b
2	f	a	d
3	b	a	d
4	d	a	d
5	e	b	b
6	a	c	e
7	a	d	d
8	f	e	d
9	b	e	d
10	f	e	e
11	b	e	e

0	a	c	e
1	a	d	d
2	b	a	d
3	b	e	d
4	b	e	e
5	c	a	b
6	d	a	b
7	d	a	d
8	e	b	b
9	f	a	d
10	f	e	d
11	f	e	e

LSD exercise

Provide the trace of sorting the array of strings given in a table below using LSD sort, providing an equivalent table for each of the 3 passes of the algorithm.

A	R	M
C	A	T
C	A	B
A	R	T
B	U	G
B	U	S

LSD stability and correctness

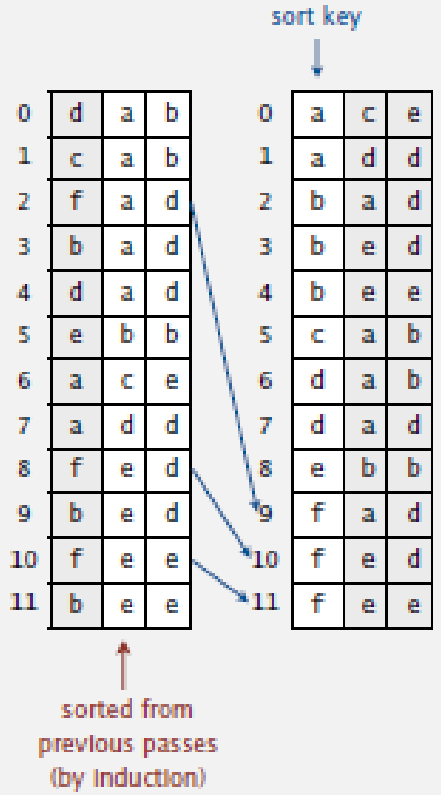
LSD string sort: correctness proof

Proposition. LSD sorts fixed-length strings in ascending order.

Pf. [by induction on i]

After pass *i*, strings are sorted by last *i* characters.

- If two strings differ on sort key, key-indexed sort puts them in proper relative order.
- If two strings agree on sort key, stability keeps them in proper relative order.



Proposition. LSD sort is stable.

Pf. Key-indexed counting is stable.

LSD in Java

```
public class LSD
{
   public static void sort(String[] a, int W)
   {
      int R = 256;
      int N = a.length;
      String[] aux = new String[N];

      for (int d = W-1; d >= 0; d--)
      {
         int[] count = new int[R+1];
         for (int i = 0; i < N; i++)
            count[a[i].charAt(d) + 1]++;
         for (int r = 0; r < R; r++)
            count[r+1] += count[r];
         for (int i = 0; i < N; i++)
            aux[count[a[i].charAt(d)]++] = a[i];
         for (int i = 0; i < N; i++)
            a[i] = aux[i];
      }
   }
}
```

fixed-length W strings

radix R

do key-indexed counting
for each digit from right to left

key-indexed counting

Performance wrt other sorting algorithms

Frequency of operations.

algorithm	guarantee	random	extra space	stable?	operations on keys
insertion sort	$\frac{1}{2} N^2$	$\frac{1}{4} N^2$	1	✔	compareTo()
mergesort	$N \lg N$	$N \lg N$	N	✔	compareTo()
quicksort	$1.39 N \lg N$ *	$1.39 N \lg N$	$c \lg N$		compareTo()
heapsort	$2 N \lg N$	$2 N \lg N$	1		compareTo()
LSD sort †	$2 W (N + R)$	$2 W (N + R)$	$N + R$	✔	charAt()

* probabilistic
† fixed-length W keys

LSD Performance

- Key indexed counting
  - 11n+4R+1
    - Initialize arrays n+R+1
    - First loop 3n
    - Second loop 3R
    - Third loop 5n
    - Fourth loop 2n
- LSD
  - 10wn+n+WR
  - W x LSD apart from third loop which is just 1 x rather than LSD x
  - R usually much smaller than N, so proportional to wn – linear!

Example - sorting large integer arrays

String sorting interview question

Problem. Sort one million 32-bit integers.

Ex. Google (or presidential) interview.

Which sorting method to use?

- Insertion sort.
- Mergesort.
- Quicksort.
- Heapsort.
- LSD string sort.

LSD Sorting large integer arrays

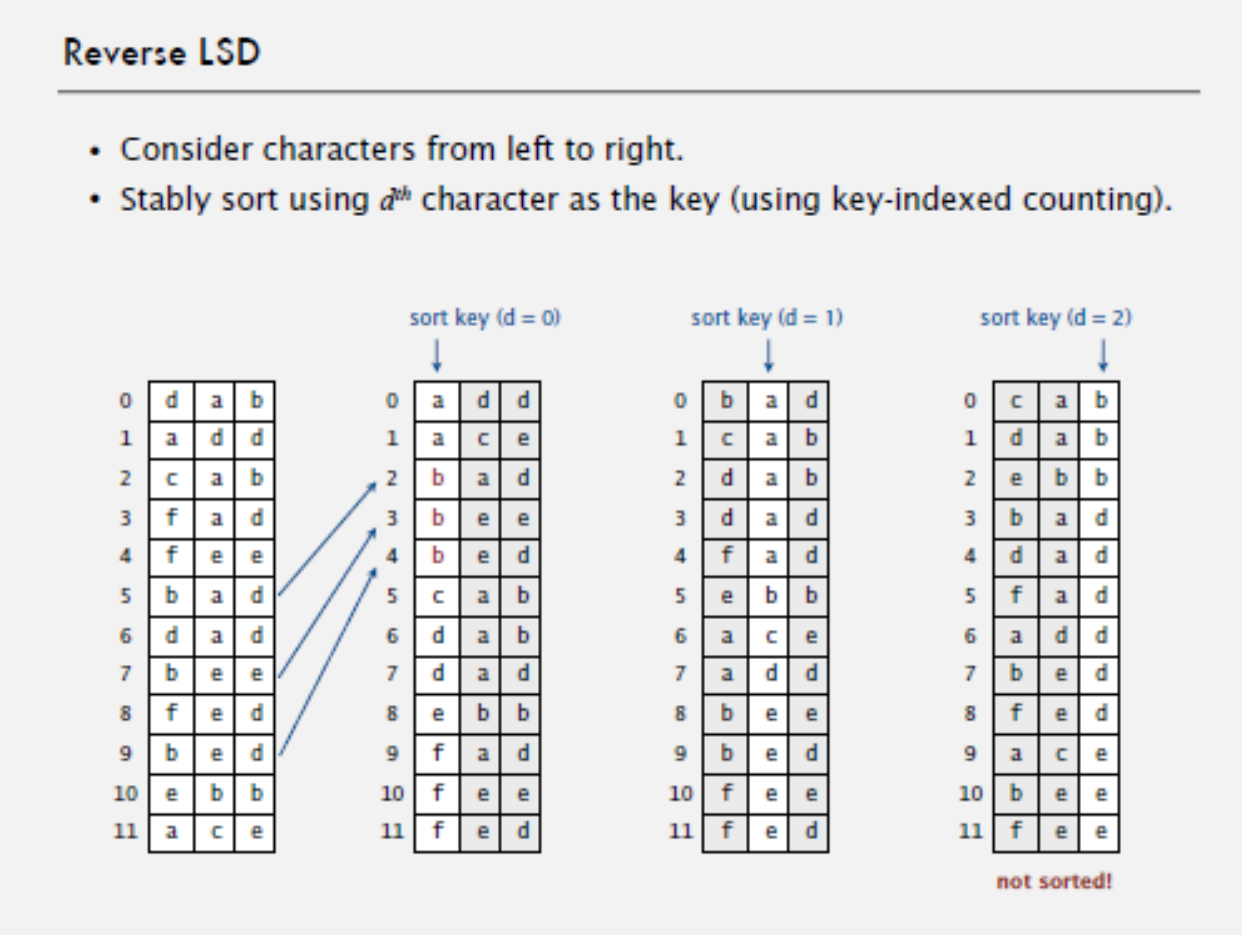
- https://algs4.cs.princeton.edu/51radix/LSD.java.html
- Break up 32-bit integer in 4 8-bit characters
- Use bit shifting and masking to isolate characters to sort by

- What if strings are not same length? MSD!

MSD Sort

MSD – Sort by Most Significant Digit first

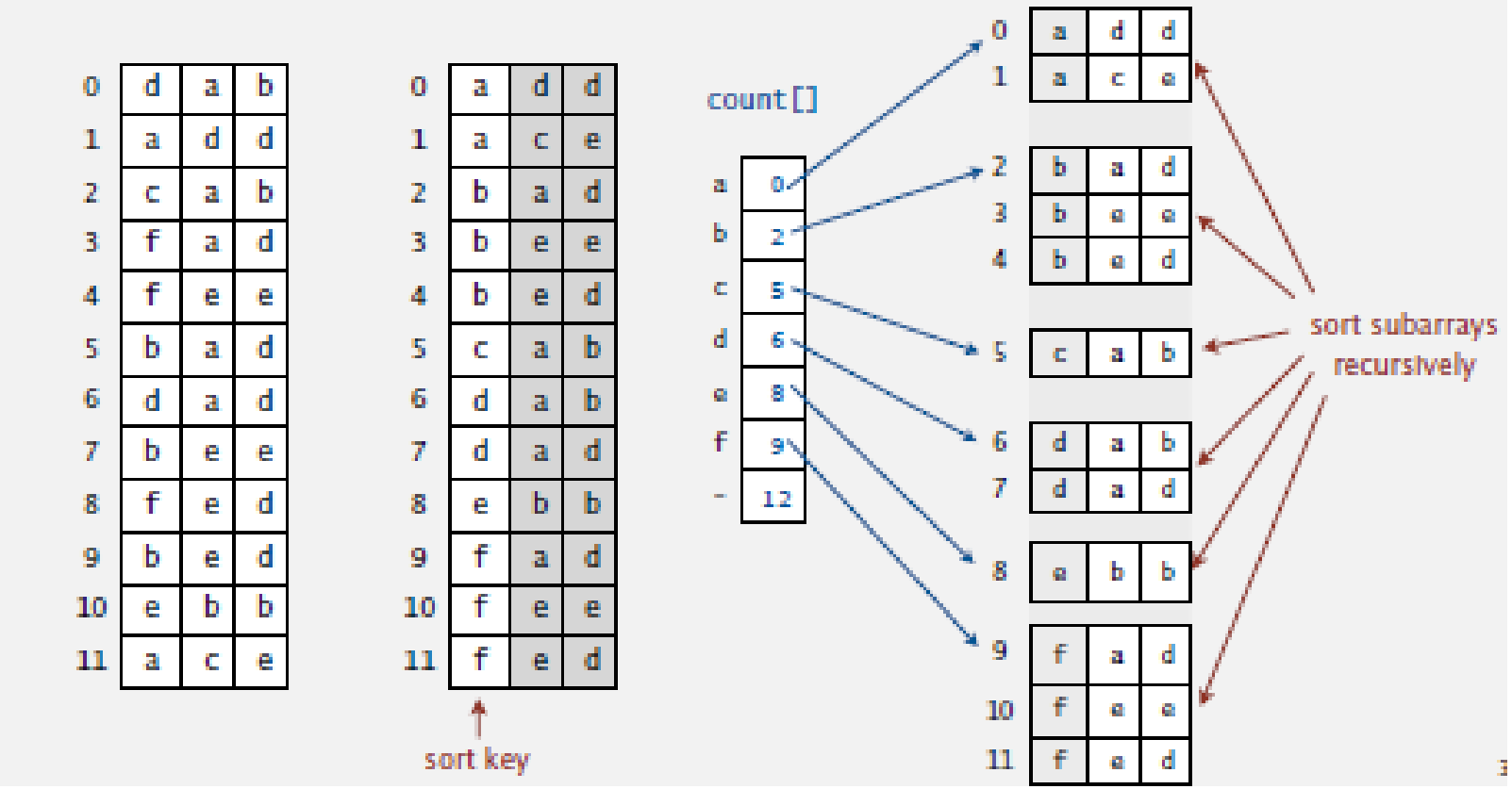
› Does simply reversing LSD work?



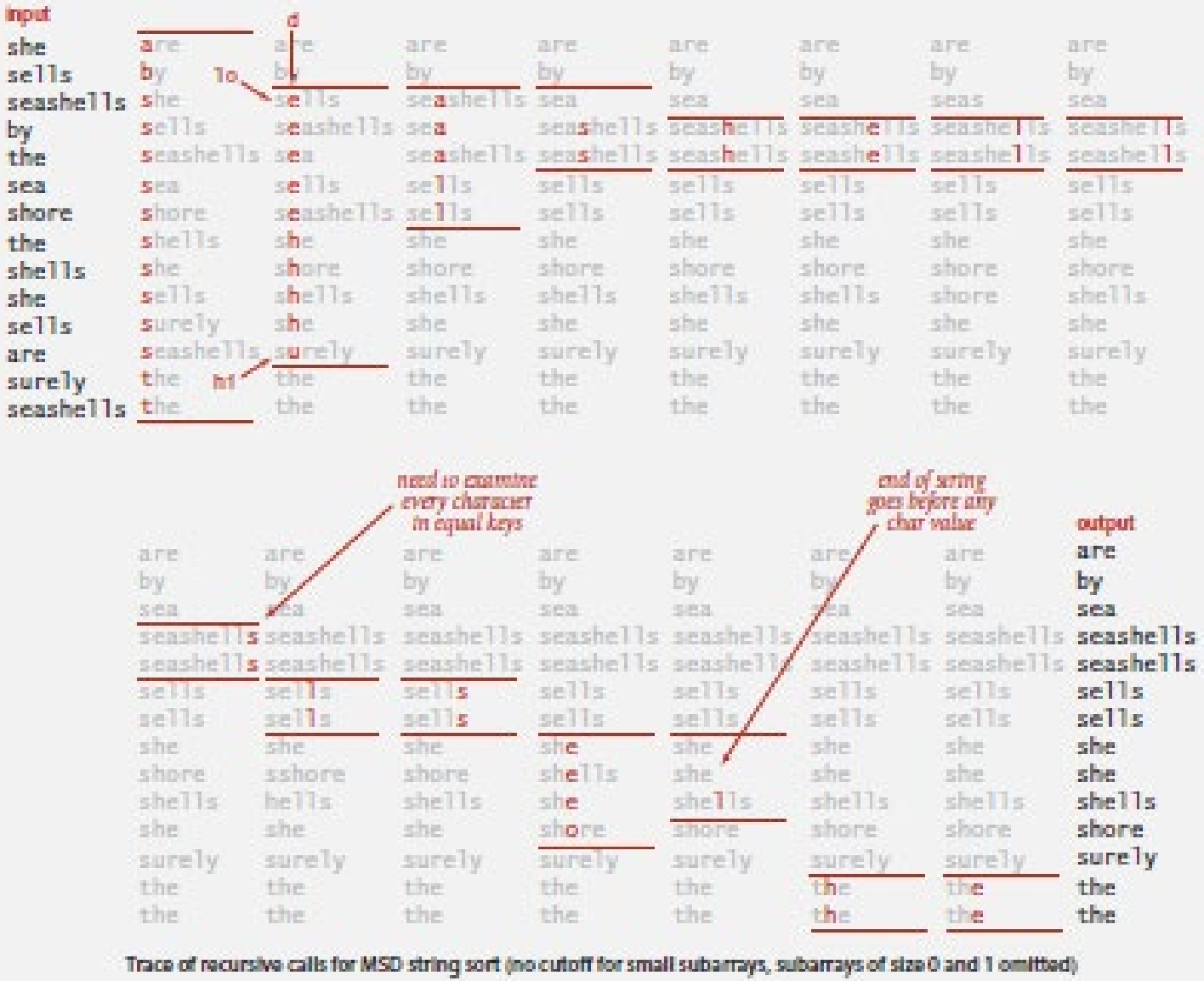
MSD string sort

- Similar to quicksort
- Partition array into R (radix) pieces according to the first character (most significant digit) using key-indexed counting
- Recursively sort all strings that start with each character (key-indexed counts delineate subarrays to sort)

MSD String sort



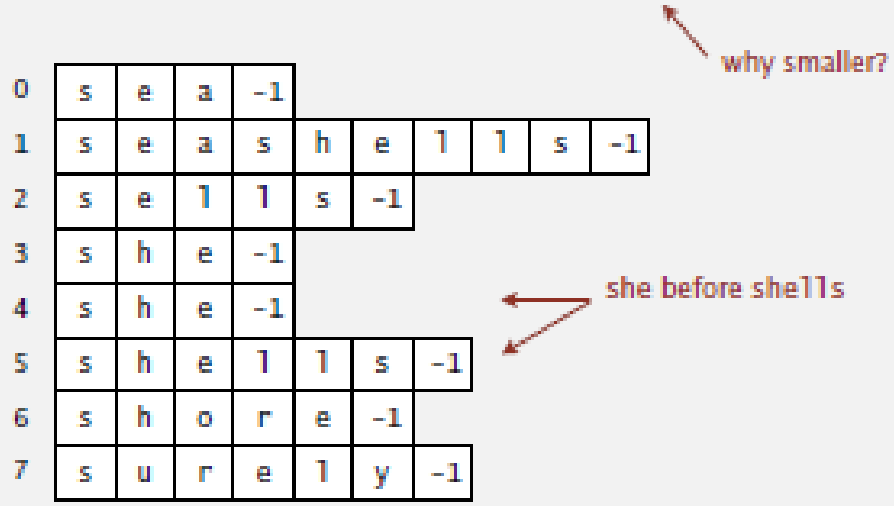
MSD string sort: example



Trace of recursive calls for MSD string sort (no cutoff for small subarrays, subarrays of size 0 and 1 omitted)

Variable length Strings

Treat strings as if they had an extra char at end (smaller than any char).




```
private static int charAt(String s, int d)
{
   if (d < s.length()) return s.charAt(d);
   else return -1;
}
```

C strings. Have extra char '\0' at end ⇒ no extra work needed.

MSD String sort – Java Implementation

```
public static void sort(String[] a)
{
   aux = new String[a.length];
   sort(a, aux, 0, a.length - 1, 0);
}

private static void sort(String[] a, String[] aux, int lo, int hi, int d)
{
   if (hi <= lo) return;
   int[] count = new int[R+2];
   for (int i = lo; i <= hi; i++)
      count[charAt(a[i], d) + 2]++;
   for (int r = 0; r < R+1; r++)
      count[r+1] += count[r];
   for (int i = lo; i <= hi; i++)
      aux[count[charAt(a[i], d) + 1]++] = a[i];
   for (int i = lo; i <= hi; i++)
      a[i] = aux[i - lo];

   for (int r = 0; r < R; r++)
      sort(a, aux, lo + count[r], lo + count[r+1] - 1, d+1);
}
```

recycles aux[] array
but not count[] array

key-indexed counting

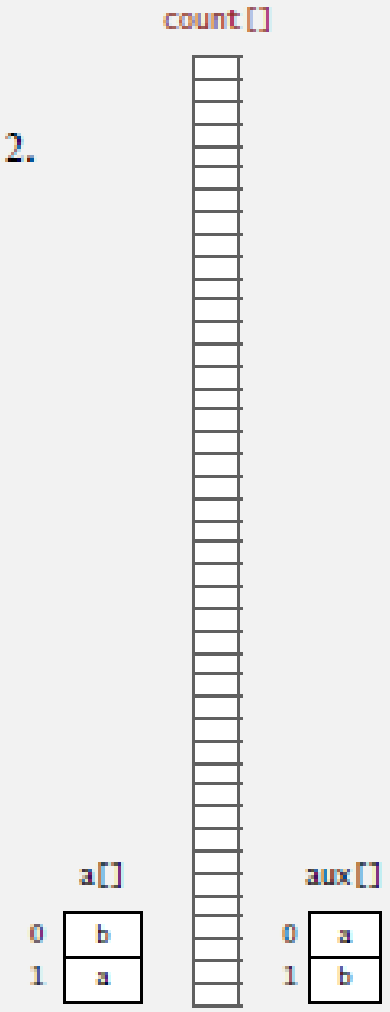
sort R subarrays recursively

MSD – improvements

Observation 1. Much too slow for small subarrays.

- Each function call needs its own `count[]` array.
- ASCII (256 counts): 100x slower than copy pass for $N = 2$.
- Unicode (65,536 counts): 32,000x slower for $N = 2$.

Observation 2. Huge number of small subarrays because of recursion.



Yep, you guessed it – cutoff to Insertion sort

Cutoff to insertion sort

Solution. Cutoff to insertion sort for small subarrays.

- Insertion sort, but start at d^{th} character.

```
private static void sort(String[] a, int lo, int hi, int d)
{
   for (int i = lo; i <= hi; i++)
      for (int j = i; j > lo && less(a[j], a[j-1], d); j--)
         exch(a, j, j-1);
}
```

- Implement `less()` so that it compares starting at d^{th} character.

```
private static boolean less(String v, String w, int d)
 {
   for (int i = d; i < Math.min(v.length(), w.length()); i++)
   {
      if (v.charAt(i) < w.charAt(i)) return true;
      if (v.charAt(i) > w.charAt(i)) return false;
   }
   return v.length() < w.length();
 }
```

MSD Performance

Frequency of operations.

algorithm	guarantee	random	extra space	stable?	operations on keys
insertion sort	$\frac{1}{2} N^2$	$\frac{1}{4} N^2$	1	✔	compareTo()
mergesort	$N \lg N$	$N \lg N$	N	✔	compareTo()
quicksort	$1.39 N \lg N$ *	$1.39 N \lg N$	$c \lg N$		compareTo()
heapsort	$2 N \lg N$	$2 N \lg N$	1		compareTo()
LSD sort †	$2 W (N + R)$	$2 W (N + R)$	$N + R$	✔	charAt()
MSD sort ‡	$2 W (N + R)$	$N \log_R N$	$N + D R$	✔	charAt()

D = function-call stack depth
(length of longest prefix match)

* probabilistic
† fixed-length W keys
‡ average-length W keys

MSD improvements - American flag sort

- Analogy to Dutch national flag, partition array into many “stripes”
- In-place variant of radix sort that distributes items into hundreds of buckets
- How?
- Cut off to insertion sort
- Replaces recursion with explicit stack
- In-place, eliminate auxiliary array (no stability)

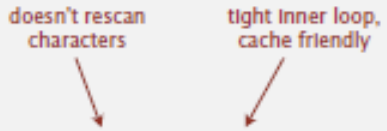
MSD vs Quicksort for String sorting

Disadvantages of MSD string sort.

- Extra space for `aux[]`.
- Extra space for `count[]`.
- Inner loop has a lot of instructions.
- Accesses memory "randomly" (cache inefficient).

Disadvantage of quicksort.

- Linearithmic number of string compares (not linear).
- Has to rescan many characters in keys with long prefix matches.



Goal. Combine advantages of MSD and quicksort.

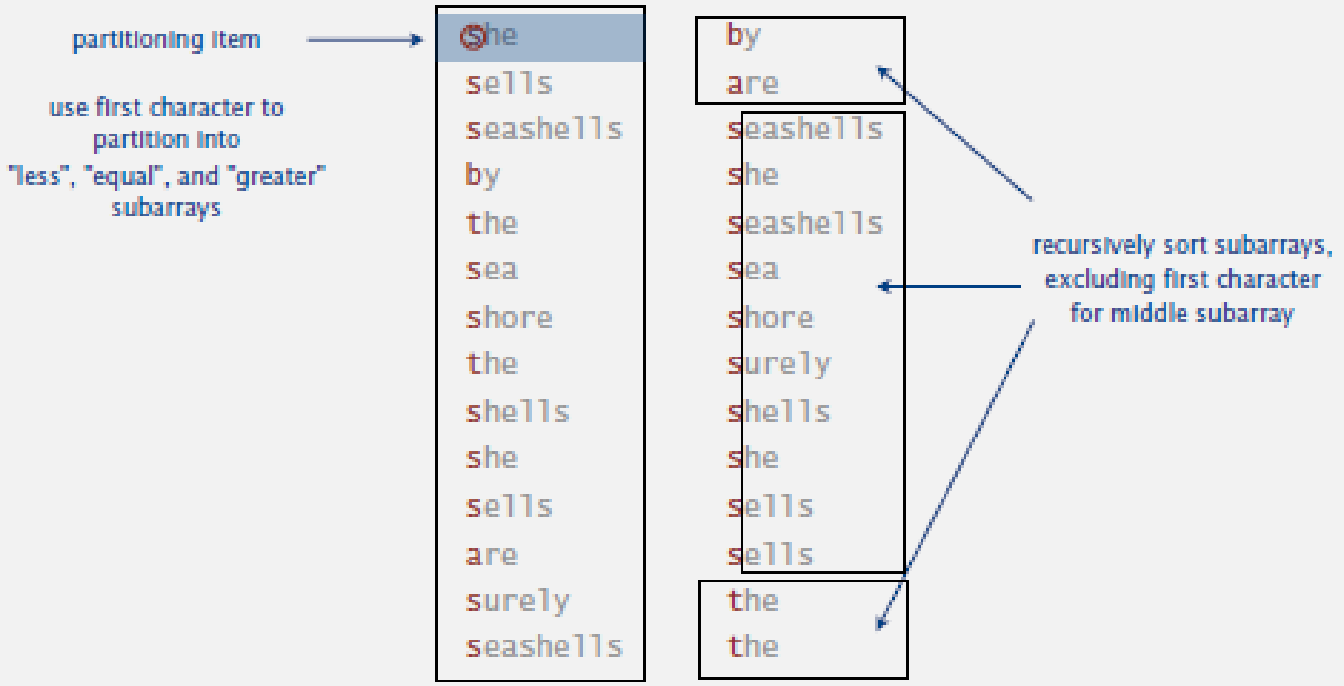
› 3-way string quicksort – addressed inefficiency of both

3-way string quicksort

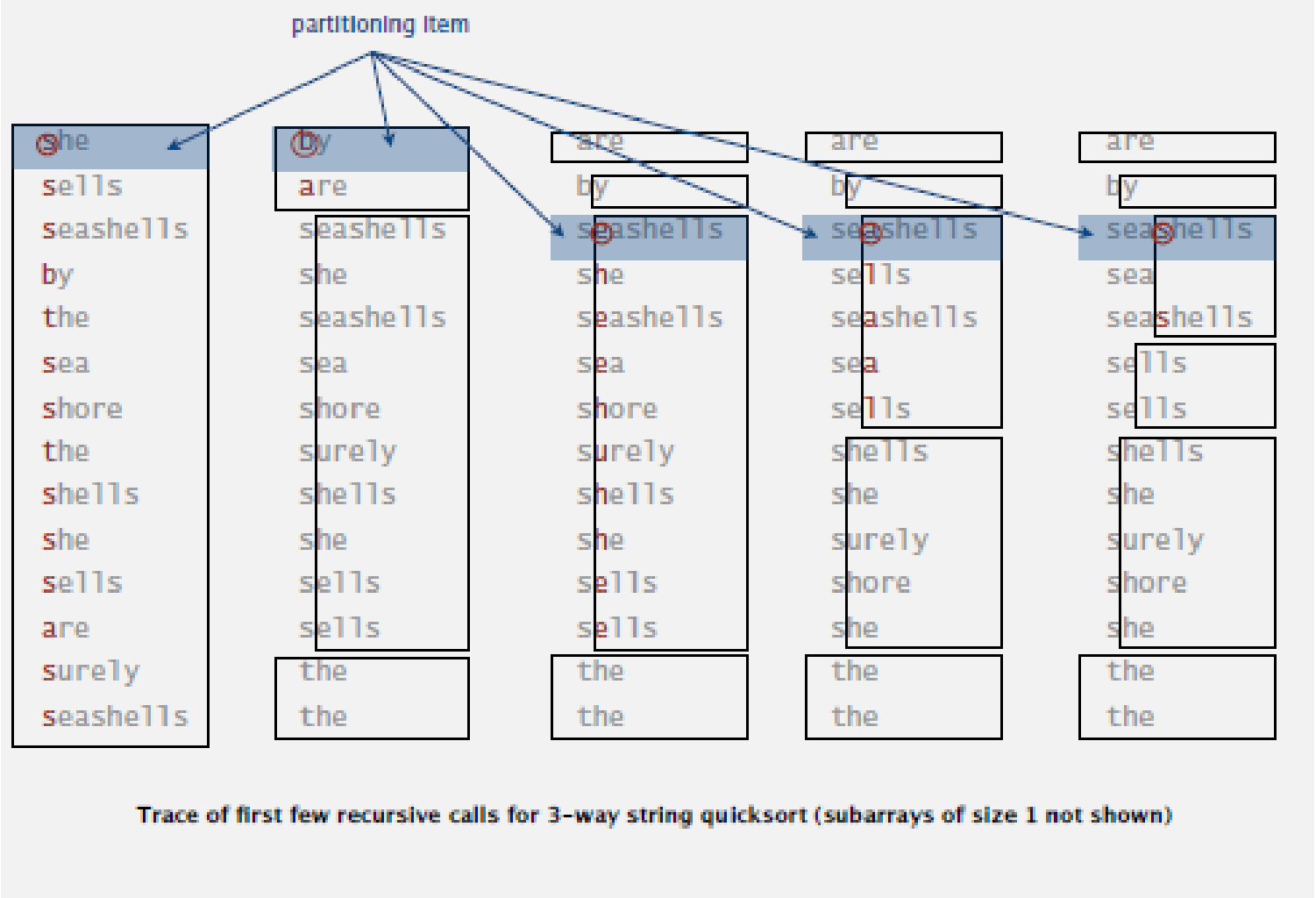
Overview. Do 3-way partitioning on the d^{th} character.

- Less overhead than R-way partitioning in MSD string sort.
- Does not re-examine characters equal to the partitioning char.

  (but does re-examine characters not equal to the partitioning char)



3- way string quicksort



Trace of first few recursive calls for 3-way string quicksort (subarrays of size 1 not shown)

3-way string quicksort in java

› charAt instead of compare

```
private static void sort(String[] a)
{  sort(a, 0, a.length - 1, 0);  }

private static void sort(String[] a, int lo, int hi, int d)
{
   if (hi <= lo) return;
   int lt = lo, gt = hi;
   int v = charAt(a[lo], d);
   int i = lo + 1;
   while (i <= gt)
   {
      int t = charAt(a[i], d);
      if      (t < v) exch(a, lt++, i++);
      else if (t > v) exch(a, i, gt--);
      else            i++;
   }

   sort(a, lo, lt-1, d);
   if (v >= 0) sort(a, lt, gt, d+1);
   sort(a, gt+1, hi, d);
}
```

3-way partitioning (using d^{th} character)

to handle variable-length strings

sort 3 subarrays recursively

Summary of string sorts

Frequency of operations.

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insertion sort	$\frac{1}{2} N^2$	$\frac{1}{4} N^2$	1	✔	compareTo()
mergesort	$N \lg N$	$N \lg N$	N	✔	compareTo()
quicksort	$1.39\, N \lg N$ *	$1.39\, N \lg N$	$c \lg N$		compareTo()
heapsort	$2\, N \lg N$	$2\, N \lg N$	1		compareTo()
LSD sort †	$2\, W\, (N + R)$	$2\, W\, (N + R)$	$N + R$	✔	charAt()
MSD sort †	$2\, W\, (N + R)$	$N \log_R N$	$N + D\, R$	✔	charAt()
3-way string quicksort	$1.39\, W N \lg R$ *	$1.39\, N \lg N$	$\log N + W$		charAt()

String sorting algorithms – when to use which?

- Insertion
  - Small arrays, arrays in (almost)order
- Quick
  - General purpose when space is tight
- Merge
  - General purpose stable
- 3-way quick
  - Large number of equal keys
- LSD
  - Short fixed-length strings
- MSD
  - Random strings
- 3-way string quicksort
  - General purpose, strings with long pre-fix matches

Check if 2 strings are anagrams

- two words are anagrams if they contain the same characters
  - “abc” and “cba” are anagrams