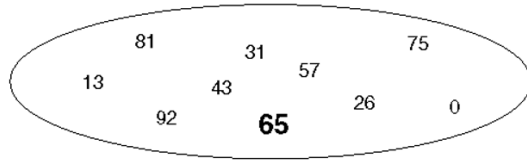
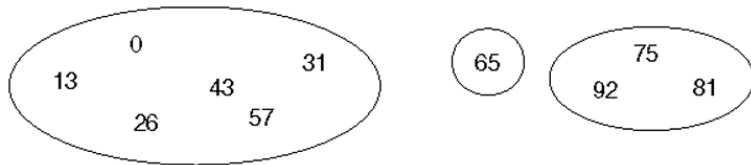


↓ Select pivot



↓ Partition



CSSE 230

Quicksort algorithm Average case analysis

After today, you should be able to...
...implement quicksort
...derive the average case runtime of
quick sort and similar algorithms

Announcements

Review: The Master Theorem works for divide-and-conquer recurrence relations only ... but works well!

For any recurrence relation *in the form*:

$$T(N) = aT\left(\frac{N}{b}\right) + \theta(N^k), \text{ with } a \geq 1, b > 1$$

The solution is:

$$T(N) = \begin{cases} \theta(N^{\log_b a}) & \text{if } a > b^k \\ \theta(N^k \log N) & \text{if } a = b^k \\ \theta(N^k) & \text{if } a < b^k \end{cases}$$

Sorting Demos

▶ Check out now:

- www.sorting-algorithms.com
- <https://www.youtube.com/watch?v=kPRA0W1kECg>
- <http://www.cs.ubc.ca/~harrison/Java/sorting-demo.html>

INEFFECTIVE SORTS

```
DEFINE HALFHEARTEDMERGESORT(LIST):  
  IF LENGTH(LIST) < 2:  
    RETURN LIST  
  PIVOT = INT(LENGTH(LIST) / 2)  
  A = HALFHEARTEDMERGESORT(LIST[:PIVOT])  
  B = HALFHEARTEDMERGESORT(LIST[PIVOT:])  
  // UMMMMM  
  RETURN [A, B] // HERE. SORRY.
```

```
DEFINE FASTBOGOSORT(LIST):  
  // AN OPTIMIZED BOGOSORT  
  // RUNS IN O(N LOG N)  
  FOR N FROM 1 TO LOG(LENGTH(LIST)):  
    SHUFFLE(LIST):  
    IF ISSORTED(LIST):  
      RETURN LIST  
  RETURN "KERNEL PAGE FAULT (ERROR CODE: 2)"
```

```
DEFINE JOBITERVIEWQUICKSORT(LIST):  
  OK SO YOU CHOOSE A PIVOT  
  THEN DIVIDE THE LIST IN HALF  
  FOR EACH HALF:  
    CHECK TO SEE IF IT'S SORTED  
    NO, WAIT, IT DOESN'T MATTER  
    COMPARE EACH ELEMENT TO THE PIVOT  
    THE BIGGER ONES GO IN A NEW LIST  
    THE EQUAL ONES GO INTO, UH  
    THE SECOND LIST FROM BEFORE  
  HANG ON, LET ME NAME THE LISTS  
  THIS IS LIST A  
  THE NEW ONE IS LIST B  
  PUT THE BIG ONES INTO LIST B  
  NOW TAKE THE SECOND LIST  
  CALL IT LIST, UH, A2  
  WHICH ONE WAS THE PIVOT IN?  
  SCRATCH ALL THAT  
  IT JUST RECURSIVELY CALLS ITSELF  
  UNTIL BOTH LISTS ARE EMPTY  
  RIGHT?  
  NOT EMPTY, BUT YOU KNOW WHAT I MEAN  
  AM I ALLOWED TO USE THE STANDARD LIBRARIES?
```

```
DEFINE PANICSORT(LIST):  
  IF ISSORTED(LIST):  
    RETURN LIST  
  FOR N FROM 1 TO 10000:  
    PIVOT = RANDOM(0, LENGTH(LIST))  
    LIST = LIST[PIVOT:] + LIST[:PIVOT]  
    IF ISSORTED(LIST):  
      RETURN LIST  
  IF ISSORTED(LIST):  
    RETURN LIST  
  IF ISSORTED(LIST): // THIS CAN'T BE HAPPENING  
    RETURN LIST  
  IF ISSORTED(LIST): // COME ON COME ON  
    RETURN LIST  
  // OH JEEZ  
  // I'M GONNA BE IN SO MUCH TROUBLE  
  LIST = [ ]  
  SYSTEM("SHUTDOWN -H +5")  
  SYSTEM("RM -RF ./")  
  SYSTEM("RM -RF ~/*")  
  SYSTEM("RM -RF /")  
  SYSTEM("RD /S /Q C:\*") // PORTABILITY  
  RETURN [1, 2, 3, 4, 5]
```

<http://www.xkcd.com/1185/>

Stacksort connects to StackOverflow, searches for "sort a list", and downloads and runs code snippets until the list is sorted. For real: <https://gkoberger.github.io/stacksort/>

QuickSort (a.k.a. “partition–exchange sort”)

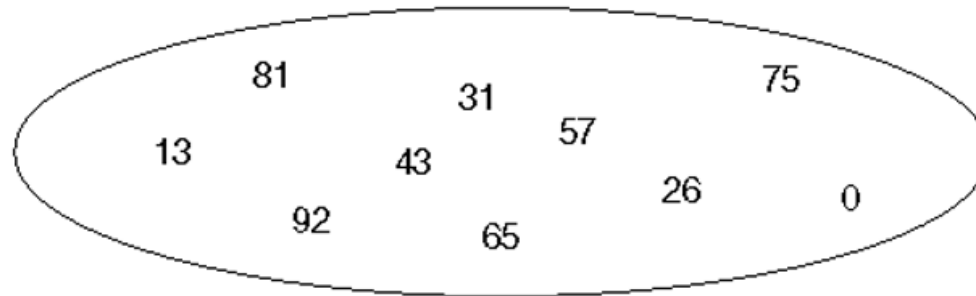
- ▶ Invented by C.A.R. “Tony” Hoare in 1961*
- ▶ Very widely used
- ▶ Somewhat complex, but fairly easy to understand
 - Like in basketball, it’s all about planting a good pivot.

A quote from Tony Hoare:

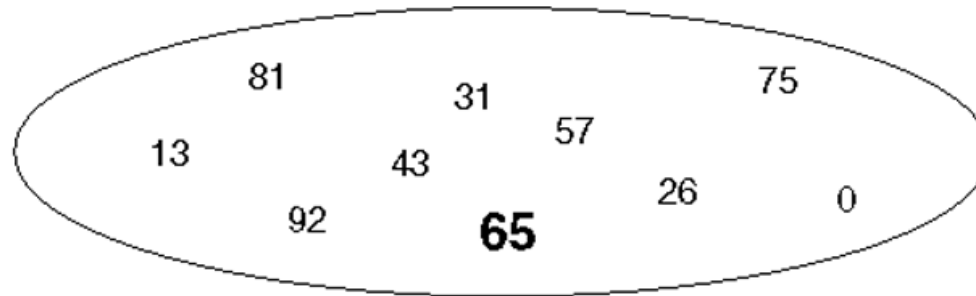
There are two ways of constructing a software design: One way is to make it so simple that there are obviously no deficiencies, and the other way is to make it so complicated that there are no obvious deficiencies. The first method is far more difficult.



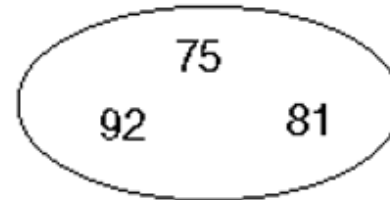
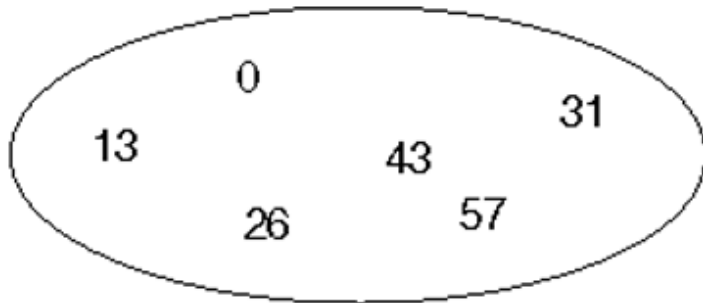
Partition: split the array into 2 parts:
smaller than pivot and greater than pivot



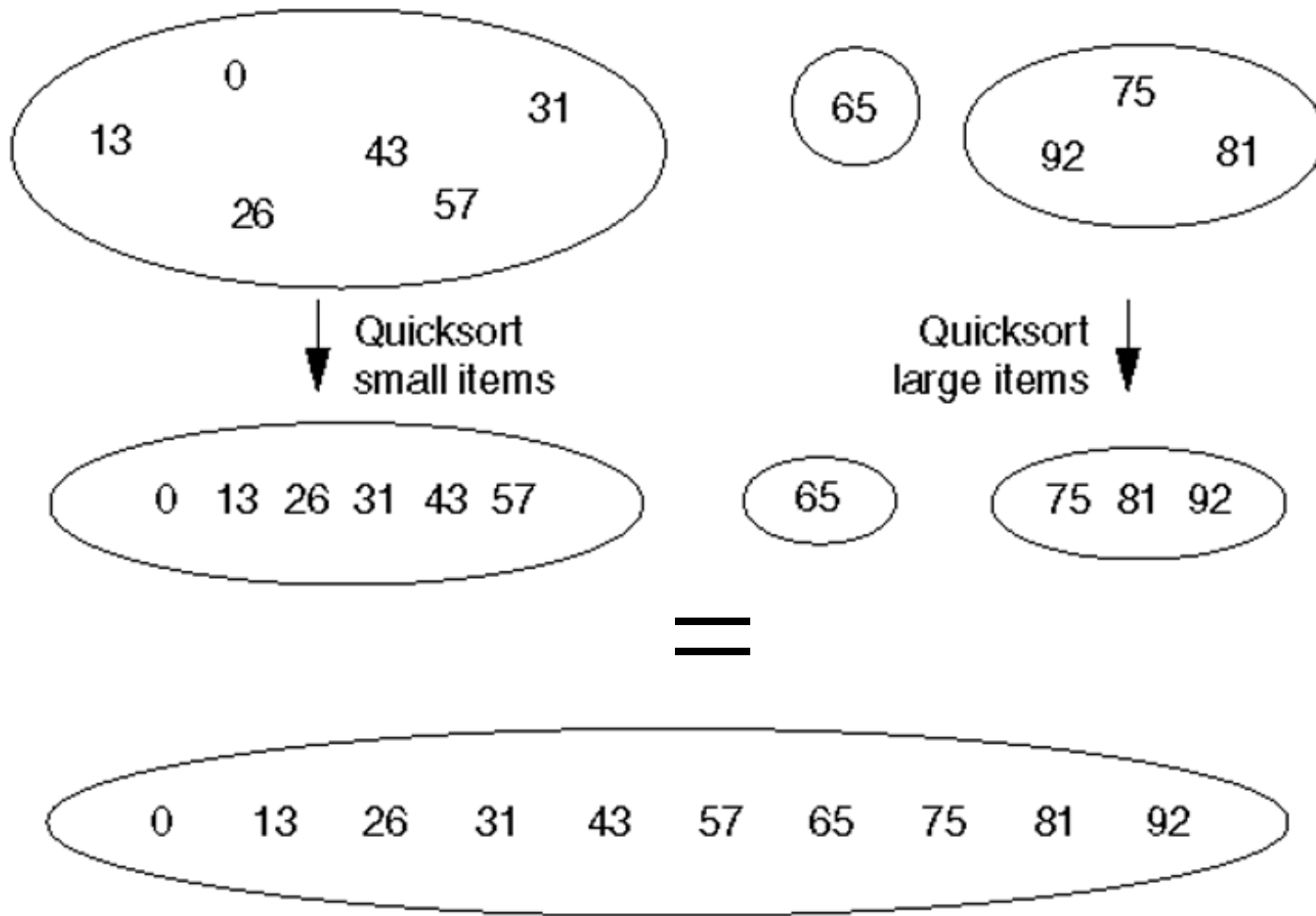
↓ Select pivot



↓ Partition



Quicksort then recursively calls itself on the partitions



Partition: efficiently move small elements to the left of the pivot and greater ones to the right

```
// Assume min and max indices are low and high
pivot = a[low] // can do better
i = low+1, j = high
while (true) {
    while (a[i] < pivot) i++
    while (a[j] > pivot) j--
    if (i >= j) break
    swap(a, i, j)
}
swap(a, low, j) // moves the pivot to the
                // correct place
return j
```

Recurrences for Quicksort

- ▶ Let $T(N)$ be the average # of comparisons of array elements needed to quicksort N elements.
- ▶ What is $T(1)$?
- ▶ Otherwise $T(N)$ is the sum of
 - time for partition
 - time to quicksort left part: $T(N_L)$
 - time to quicksort right part: $T(N_R)$
- ▶ $T(N) = N + T(N_L) + T(N_R)$
- ▶ What's the best case? What's the worst case?
- ▶ Write and solve each now!

Quicksort Runtimes

- ▶ Running time for **partition** of **N** elements is $\Theta(N)$
- ▶ Quicksort Running time:
 - call partition. Get two subarrays of sizes N_L and N_R (what is the relationship between N_L , N_R , and N ?)
 - Then Quicksort the smaller parts
 - $T(N) = N + T(N_L) + T(N_R)$
- ▶ Quicksort Best case: **write and solve the recurrence**
- ▶ Quicksort Worst case: **write and solve the recurrence**
- ▶ average: **a little bit trickier**
 - We have to be careful how we measure

Average time for Quicksort

- ▶ Let $T(N)$ be the average # of comparisons of array elements needed to quicksort N elements.
- ▶ What is $T(0)$? $T(1)$?
- ▶ Otherwise $T(N)$ is the sum of
 - time for partition
 - **average** time to quicksort left part: $T(N_L)$
 - **average** time to quicksort right part: $T(N_R)$
- ▶ $T(N) = N + T(N_L) + T(N_R)$

We need to figure out for each case, and average all of the cases

- ▶ Harder than just a single case...

We assume that all positions for the pivot are equally likely

- ▶ We always need to make some kind of “distribution” assumptions when we figure out Average case
- ▶ Assume that when we execute `k = partition(pivot, i, j)`, all positions `i..j` are **equally likely** places for the pivot to end up
- ▶ Thus N_L is equally likely to have each of the values $0, 1, 2, \dots, N-1$
- ▶ $N_L + N_R = N-1$; thus N_R is also equally likely to have each of the values $0, 1, 2, \dots, N-1$
- ▶ Thus $T(N_L) = T(N_R) =$

Continue the calculation

- ▶ $T(N) =$
- ▶ Multiply both sides by N
- ▶ Rewrite, substituting $N-1$ for N
- ▶ Subtract the equations and forget the insignificant (in terms of big-oh) -1 :
 - $NT(N) = (N+1)T(N-1) + 2N$
- ▶ Can we rearrange so that we can telescope?

Continue continuing the calculation

- ▶ $NT(N) = (N+1)T(N-1) + 2N$
- ▶ Solve using telescoping and iteration:
 - Divide both sides by $N(N+1)$
 - Write formulas for $T(N)$, $T(N-1)$, $T(N-2) \dots T(2)$.
 - Add the terms and rearrange.
 - Notice the familiar series
 - Multiply both sides by $N+1$.

Recap

- ▶ Best, worst, average time for Quicksort
- ▶ What causes the worst case?

- ▶ We can guarantee we never hit the worst case
 - How?
 - But this makes quicksort slower than merge sort in practice.

Improvements to QuickSort

- ▶ Avoid the worst case
 - Select pivot from the middle
 - Randomly select pivot
 - **Median of 3 pivot selection. (You'll want this.)**
 - Median of k pivot selection
- ▶ "Switch over" to a simpler sorting method (insertion) when the subarray size gets small

Weiss's code does Median of 3 and switchover to insertion sort at 10.

- [Linked from schedule page](#)

What does the official Java Quicksort do? See the source code!

Final notes

The partition code I gave you has 2 bugs:

1. It can walk off the end of the array
2. If the chosen pivot is duplicated, it can go into an infinite recursion (stack overflow)

```
// Assume min and max indices are low and high
pivot = a[low] // can do better
i = low+1, j = high
while (true) {
    while (a[i] < pivot) i++
    while (a[j] > pivot) j--
    if (i >= j) break
    swap(a, i, j)
}
swap(a, low, j) // moves the pivot to the
                // correct place
return j
```