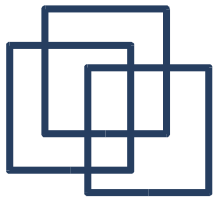
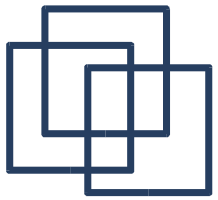
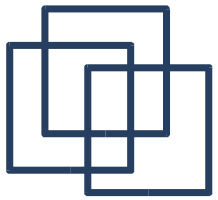


Sorting



The Problem

- **Input**: a sequence of n numbers $\langle a_1, a_2 .. a_n \rangle$
- **Output**: a permutation (reordering) $\langle a_1', a_2' .. a_n' \rangle$ of the input sequence such that $a_1' \leq a_2' \leq .. \leq a_n'$
- Numbers to sort are also known as the **keys**



Sorting Algorithms

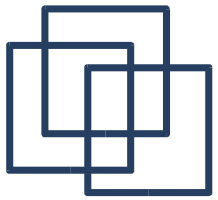
- Bubble sort
- Selection sort
- Insertion sort

n^2

- Merge sort
- Quick sort
- Heap sort

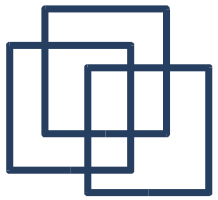
$nlog_2(n)$

  - application: priority queues



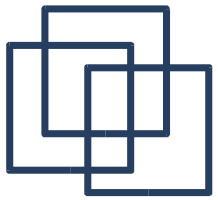
Bubble Sort

- *Pseudo* code, array from *1* to *n*, pb 2-2 p38
- **for** i:=1 **to** n-1 **do**
  for j:=n **downto** i+1 **do**
  if a[j]<a[j-1] **then** swap(a[j],a[j-1])
- Loop invariant: sub-array a[1..i] is sorted before loop (on *i)*.
- Running time: n-1+n-2+…+1=n*(n-1)/2
  $\Theta(n^2)$



Selection Sort

- Exercise 2.2-2 p27
- **for** i:=1 **to** n-1 **do**
  for j:=i+1 **to** n **do**
  if a[i]>a[j] **then** *swap(a[i],a[j])*
- Loop invariant: sub-array a[1..i] is sorted before loop (on *i)*.
- Running time: n-1+n-2+…+1=n*(n-1)/2
  $\Theta(n^2)$



Insertion Sort

- **for** j:=2 **to** n **do**

  key:=a[j]

  i:=j-1

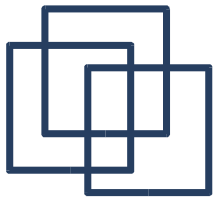
  while i>0 and a[i]>key **do**

    a[i+1]:=a[i]

    i:=i-1

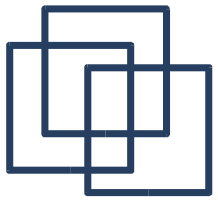
  a[i+1]:=key

- Loop invariant: sub-array a[1..j-1] is sorted before loop (on *j)*.
- Running time: $\Theta(n^2)$



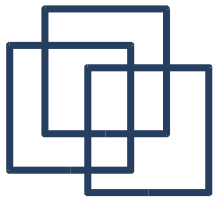
Analysis of Insertion Sort

- Count executions of loops
  - test n times, execute $n-1$ times (outer loop)
  - test t_j times, execute t_j-1 times (inner loop)
  - $c_1+c_2 n+c_3\sum_{j=2}^{n} t_j$
- Analysis
  - best case: $t_j=1$, $T(n)=\Omega(n)$
  - worst case: $t_j=j$, $T(n)=O(n^2)$
  - average case: $t_j=j/2$, $E[T(n)]=O(n^2)$



Merge Sort

- Divide-and-conquer approach
  - apply to algorithm that are *recursive*
  - **divide** main problem into sub-problems
  - **conquer** the sub-problems (solve recursively)
  - **combine** the solutions of the sub-problems
- Merge sort:
  - divide array n into 2 arrays of size $n/2$
  - sort 2 smaller arrays with merge sort
  - combine smaller arrays



Merge Sort

- Key: merge sorted sub-arrays *A[p..q]* and *A[q+1..r]*. For *n* elements merged $T(n)=\Theta(n)$.
- **Merge-sort**(a,p,r):

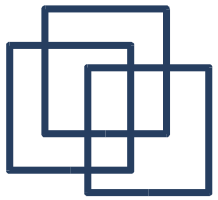
  if p<r **then**

  q:=(p+r)/2

  Merge-sort(a,p,q)

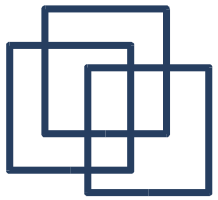
  Merge-sort(a,q+1,r)

  Merge(a,p,q,r)
- **Merge** described using copies and sentinel values



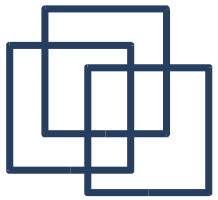
Analysis of Merge Sort

- Running time $T(n)$ given as a recurrence. In general for divide-and-conquer algorithms: $T(n)=\Theta(1)$ if $n \leq c$ (c: small enough) otherwise $T(n)=aT(n/b)+D(n)+C(n)$.
- You are masters in recurrences, easy!
- Merge-sort: $c=1$, $D(n)=1$, $C(n)=\Theta(n)$ (combine), divide: $a=2$ and $b=2$. $T(n)=\Theta(n\lg n)$



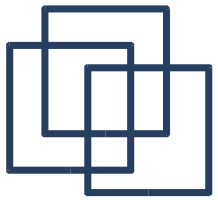
Quick Sort

- Divide-and-conquer algorithm. Worst case $\Theta(n^2)$ but average case $\Theta(n\lg n)$ and in practice ***VERY*** efficient.
- In place algorithm with small constants for the complexity. Fastest sort in practice except for "almost-sorted" inputs.
- We will check it in the exercises.



Quick Sort

- **Divide:** partition $A[p..r]$ into $A'[p..q-1]$ and $A'[q+1..r]$ s.t. $a'_{p..q-1} \leq a'_q \leq a'_{q+1..r}$. Compute q.
- **Conquer:** sort $A'[p..q-1]$ and $A'[q+1..r]$ by recursive calls to quicksort.
- **Combine:** $A[p..r]$ is sorted, nothing to do!
- **Key:** partitioning. We can choose a'_q arbitrarily.

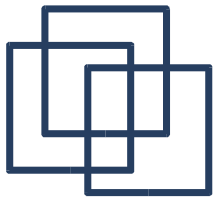


Quick Sort Partitioning

- **Partition**(A,p,r)

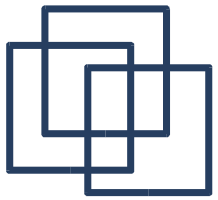
```
x:=A[r]                    // pivot element
i:=p-1
for j:=p to r-1 do
    if A[j]≤x then
        i:=i+1
        swap(A[i],A[j])
swap(A[i+1],A[r])
return i+1
```

- Equivalent to selection-sort for worst case.



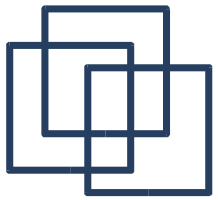
Performance of Quick Sort

- Depends on the input (balanced array or not) and the choice of the pivot.
- Worst-case (sorted, reversed, or equal elements): $\Theta(n^2)$.
- Best-case (balanced): $T(n) \leq 2T(n/2) + \theta(n)$, *i.e*, $T(n) = O(n \lg n)$.
- Average case?
  - remark: case 1/10 – 9/10 is still in $n \lg n$.
  - it is $O(n \lg n)$.



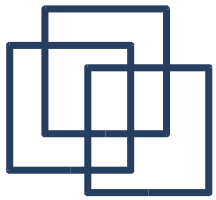
More Quick Sort

- Randomized quicksort
  - There is no worst-case input, but an unlucky run may result in $T(n)=n^2$.
  - Choose the pivot randomly, i.e., swap a random element with *A[r]*.
- Hoare partitioning (pb 7-1)
  - possibly fewer swaps
  - common *pivot*:=*A[(p+r)/2]*



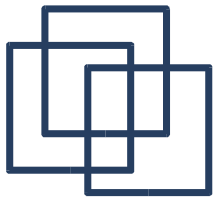
Heap Data Structure

- See it as a binary tree
- **root**=*A[1]* (root of the tree)
- **parent(i)**=i/2 (for a node i)
- **left(i)**=2i (left child)
- **right(i)**=2i+1 (right child)
- **max-heap** property: A[parent(i)]≥A[i]
- or **min-heap** property: A[parent(i)]≤A[i]
- **height** is Θ*(lgn)*.



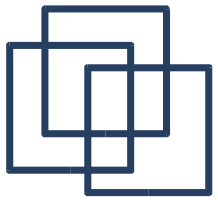
Heap Sort

- Max-heap for sorting (ascending).
- Basic proceedures:
  - **max-heapify**: maintains max-heap property $O(\lg n)$.
  - **build-max-heap**: computes a max-heap $O(n)$.
  - **heapsort**: sorts an array in place $O(n \lg n)$.
  - others for priority queues (later).



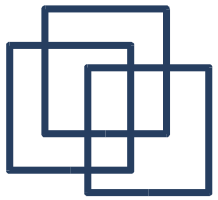
Maintaining a Heap

- **max-heapify(A,i)**
  - assume that **left(i)** and **right(i)** are max-heaps.
  - *A[i]* may be smaller than its children.
  - (simplified) algorithm:
    child:=A[left(i)] > A[right(i)] ? left(i) : right(i)
    if A[i]<A[child] **then**
        swap(A[i],A[child])
        max-heapify(A,child)
  - when the algorithm terminates, the max-heap property is restored. Clearly $O(\lg n)$.



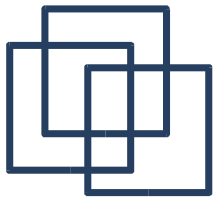
Building a Heap

- We can use **max-heapify** in a bottom-up manner: build the tree incrementally.
- **build-max-heap(A):**
  heap_size[A]:=length(A)
  for i:=length[A]/2 **downto** 1 **do**
    max-heapify(A,i)
- Clearly $O(n\lg n)$.
- Why do we start from length[A]/2?



Heap Sort

- Build a max-heap, put the root element at the end of the heap, max-heapify with a smaller heap, repeat.
- **heap-sort(A):**
  build-max-heap(A)
  for i:=length(A) **downto** 2 **do**
    swap(A[1],A[i])
    heap_size(A)--
    max-heapify(A,1)
- Clearly $O(n\lg n)$, but also $\Omega(n\lg n)$ (bad).



Priority Queues

- Heaps are useful for priority queues because of the max(or min)-heap property.
- Operations:
  - insert an element
  - get the max (or the min) element
  - remove the max (or the min) element
  - increase key of an element
- Used in the STL