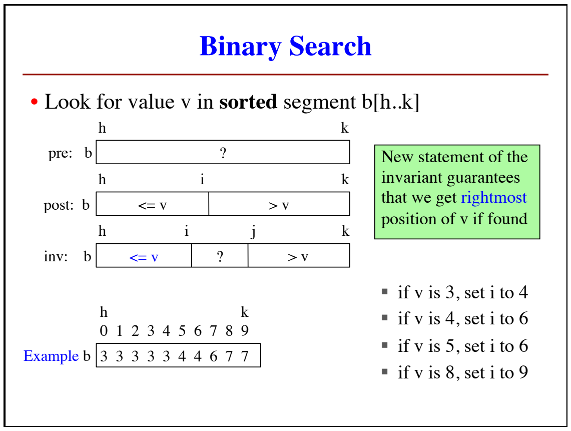


Binary Search

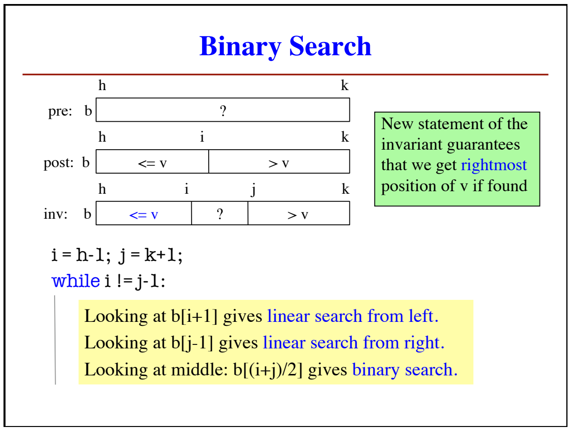
- Look for value v in **sorted** segment b[h..k]

```
           h                          k
pre:  b   [             ?              ]
           h           i              k
post: b   [    <= v    |      > v      ]
           h        i      j          k
inv:  b   [  <= v   |  ?   |   > v     ]
```

New statement of the invariant guarantees that we get rightmost position of v if found

```
          h                 k
          0 1 2 3 4 5 6 7 8 9
Example b 3 3 3 3 3 4 4 6 7 7
```

- if v is 3, set i to 4
- if v is 4, set i to 6
- if v is 5, set i to 6
- if v is 8, set i to 9

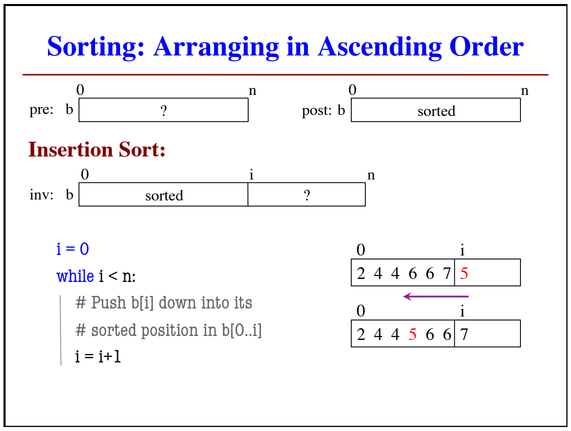


Binary Search

```
           h                          k
pre:  b   [             ?              ]
           h           i              k
post: b   [    <= v    |      > v      ]
           h        i      j          k
inv:  b   [  <= v   |  ?   |   > v     ]
```

New statement of the invariant guarantees that we get rightmost position of v if found

```
i = h-1; j = k+1;
while i != j-1:
    Looking at b[i+1] gives linear search from left.
    Looking at b[j-1] gives linear search from right.
    Looking at middle: b[(i+j)/2] gives binary search.
```



Sorting: Arranging in Ascending Order

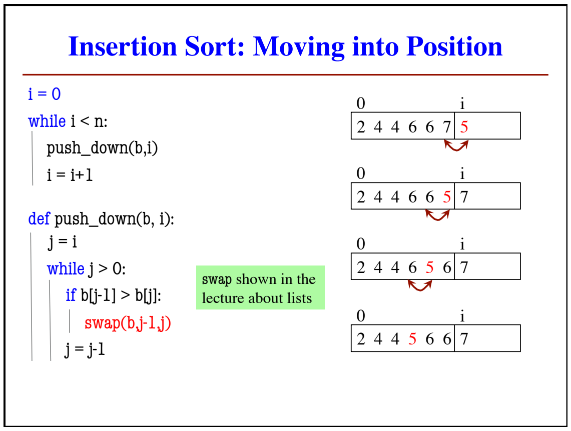
```
           0                n             0                n
pre:  b   [        ?         ]   post: b [     sorted       ]
```

Insertion Sort:

```
           0                i            n
inv:  b   [     sorted      |      ?     ]
```

```
i = 0
while i < n:
    # Push b[i] down into its
    # sorted position in b[0..i]
    i = i+1
```

```
0          i
2 4 4 6 6 7|5
0          i
2 4 4 5 6 6|7
```



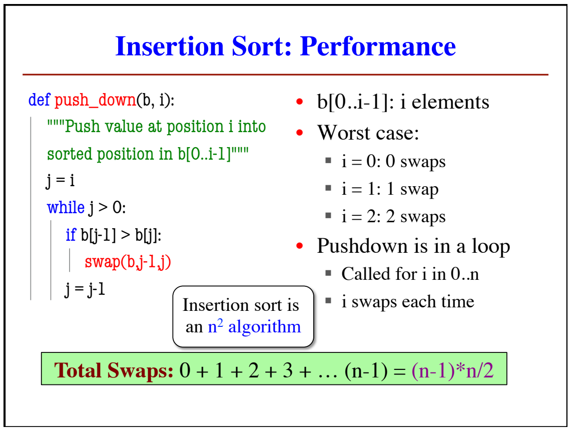
Insertion Sort: Moving into Position

```
i = 0
while i < n:
    push_down(b,i)
    i = i+1

def push_down(b, i):
    j = i
    while j > 0:
        if b[j-1] > b[j]:
            swap(b,j-1,j)
        j = j-1
```

swap shown in the lecture about lists

```
0          i
2 4 4 6 6 7|5
0          i
2 4 4 6 6 5|7
0          i
2 4 4 6 5 6|7
0          i
2 4 4 5 6 6|7
```



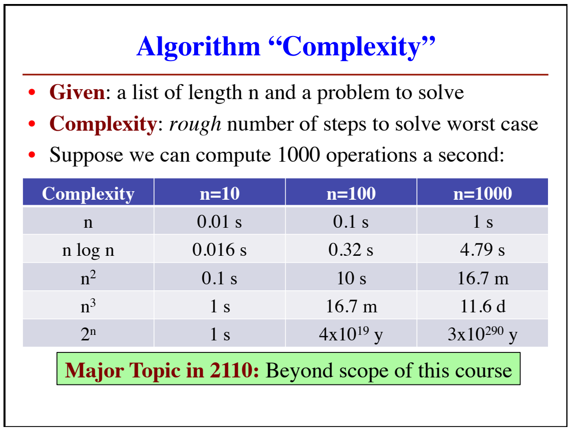
Insertion Sort: Performance

```
def push_down(b, i):
    """Push value at position i into
    sorted position in b[0..i-1]"""
    j = i
    while j > 0:
        if b[j-1] > b[j]:
            swap(b,j-1,j)
        j = j-1
```

- b[0..i-1]: i elements
- Worst case:
  - i = 0: 0 swaps
  - i = 1: 1 swap
  - i = 2: 2 swaps
- Pushdown is in a loop
  - Called for i in 0..n
  - i swaps each time

Insertion sort is an n^2 algorithm

Total Swaps: 0 + 1 + 2 + 3 + … (n-1) = (n-1)*n/2

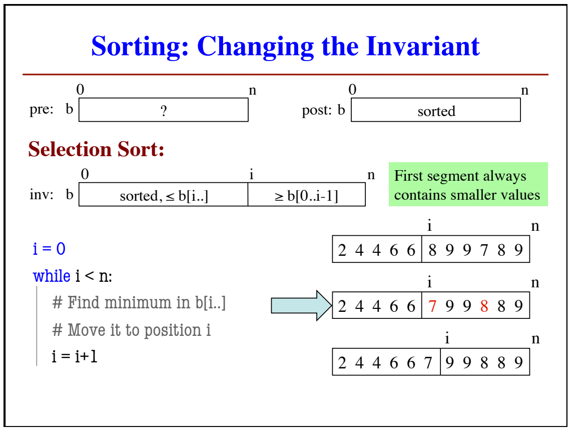


Algorithm "Complexity"

- **Given**: a list of length n and a problem to solve
- **Complexity**: *rough* number of steps to solve worst case
- Suppose we can compute 1000 operations a second:

Complexity	n=10	n=100	n=1000
n	0.01 s	0.1 s	1 s
n log n	0.016 s	0.32 s	4.79 s
n^2	0.1 s	10 s	16.7 m
n^3	1 s	16.7 m	11.6 d
2^n	1 s	$4x10^{19}$ y	$3x10^{290}$ y

Major Topic in 2110: Beyond scope of this course



Sorting: Changing the Invariant

pre: b [0 ? n]   post: b [0 sorted n]

Selection Sort:

inv: b [0 sorted, ≤ b[i..] | i ≥ b[0..i-1] n]

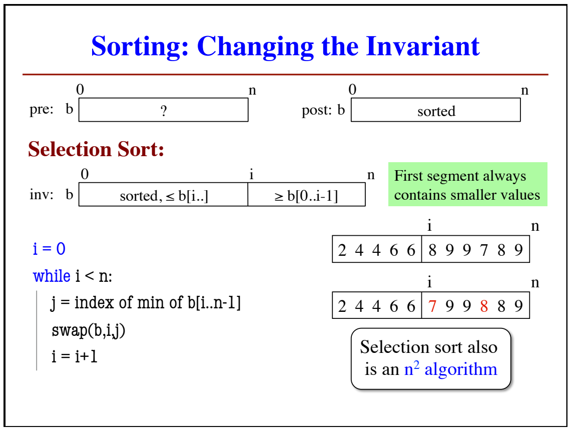
First segment always contains smaller values

```
i = 0
while i < n:
    # Find minimum in b[i..]
    # Move it to position i
    i = i+1
```

i n
2 4 4 6 6 | 8 9 9 7 8 9

i n
2 4 4 6 6 | 7 9 9 8 8 9

i n
2 4 4 6 6 7 | 9 9 8 8 9



Sorting: Changing the Invariant

pre: b [0 ? n]   post: b [0 sorted n]

Selection Sort:

inv: b [0 sorted, ≤ b[i..] | i ≥ b[0..i-1] n]

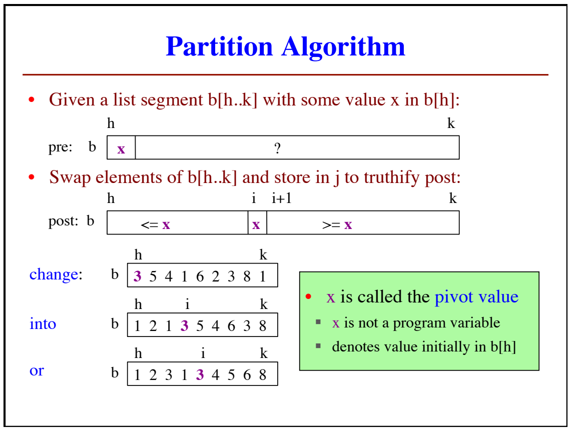
First segment always contains smaller values

```
i = 0
while i < n:
    j = index of min of b[i..n-1]
    swap(b,i,j)
    i = i+1
```

i n
2 4 4 6 6 | 8 9 9 7 8 9

i n
2 4 4 6 6 | 7 9 9 8 8 9

Selection sort also is an n^2 algorithm



Partition Algorithm

- Given a list segment b[h..k] with some value x in b[h]:

pre: b [h x | ? k]

- Swap elements of b[h..k] and store in j to truthify post:

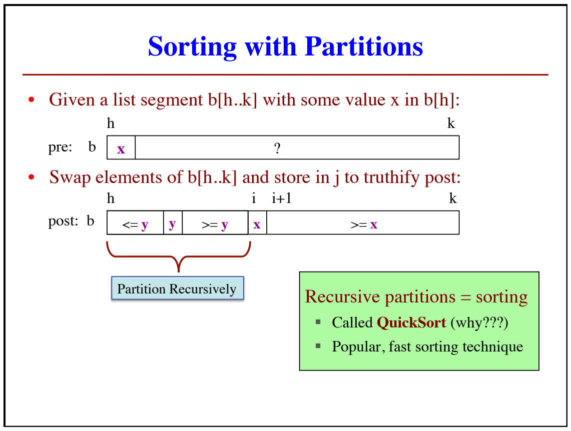
post: b [h <= x | i x | i+1 >= x k]

change: b [h 3 5 4 1 6 2 3 8 1 k]

into b [h 1 2 1 3 5 4 6 3 8 k] (i at 3)

or b [h 1 2 3 1 3 4 5 6 8 k] (i at 3)

- x is called the pivot value
  - x is not a program variable
  - denotes value initially in b[h]



Sorting with Partitions

- Given a list segment b[h..k] with some value x in b[h]:

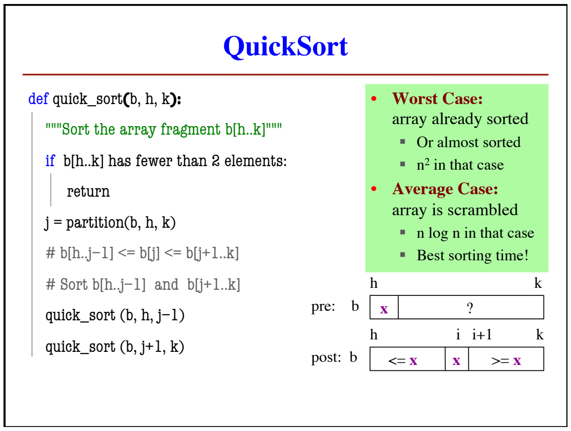
pre: b [h x | ? k]

- Swap elements of b[h..k] and store in j to truthify post:

post: b [h <= y | y | >= y | i x | i+1 >= x k]

Partition Recursively

Recursive partitions = sorting
- Called **QuickSort** (why???)
- Popular, fast sorting technique



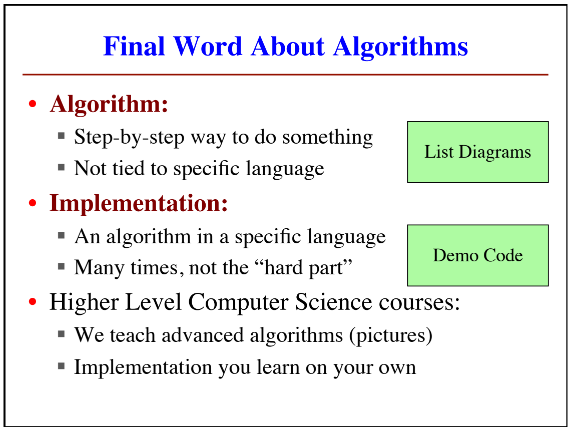
QuickSort

```
def quick_sort(b, h, k):
    """Sort the array fragment b[h..k]"""
    if b[h..k] has fewer than 2 elements:
        return
    j = partition(b, h, k)
    # b[h..j–1] <= b[j] <= b[j+1..k]
    # Sort b[h..j–1]  and  b[j+1..k]
    quick_sort (b, h, j–1)
    quick_sort (b, j+1, k)
```

- **Worst Case:** array already sorted
  - Or almost sorted
  - n^2 in that case
- **Average Case:** array is scrambled
  - n log n in that case
  - Best sorting time!

pre: b [h x | ? k]

post: b [h <= x | i x | i+1 >= x k]



Final Word About Algorithms

- **Algorithm:**
  - Step-by-step way to do something
  - Not tied to specific language
- **Implementation:**
  - An algorithm in a specific language
  - Many times, not the "hard part"
- Higher Level Computer Science courses:
  - We teach advanced algorithms (pictures)
  - Implementation you learn on your own

List Diagrams

Demo Code