

Sorting

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Fall 2025

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One problem, many solutions

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One problem, many solutions

The problem of sorting a collection of objects, as with any problem, has many¹ potential solutions to it.

As such, we will investigate a number of different solutions to this problem.

we will start with an intuitive solution to sorting a collection of entities — *insertion sort*.

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Playing Cards

Since we have stated that insertion sort is an intuitive solution, we will start with an example in which one may instinctively perform it.

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Imagine you are playing a card game with friends with a standard 52-card deck of French-suited playing cards. The game you are playing is a trick-taking game in which it makes sense to sort your cards by their rank from lowest to highest.

You are allowed to pick up each cards as your friend deals them out, so each time your friend deals you a card you add it to your hand. Let's examine what one might do as they are dealt their cards!

Being dealt a hand

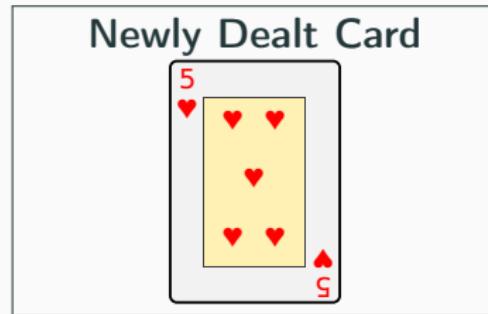
To start with your hand is empty, and you are waiting for your friend to deal you any cards.

Newly Dealt Card

Your Hand So Far

Being dealt a hand

You are now dealt a five of hearts.

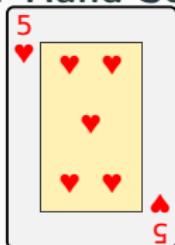


Being dealt a hand

Since you have no other cards in your hand to consider, you simply pick up the five of hearts.

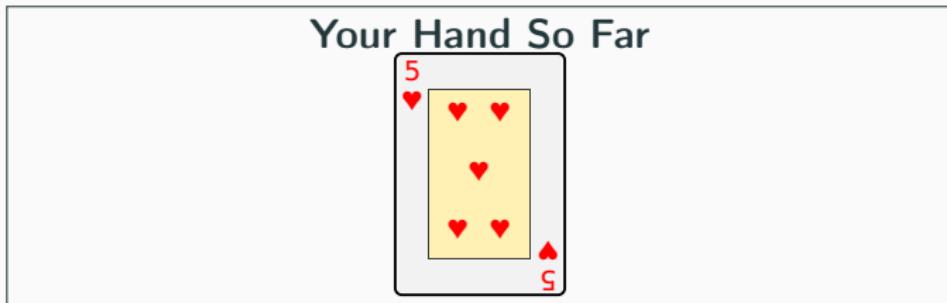
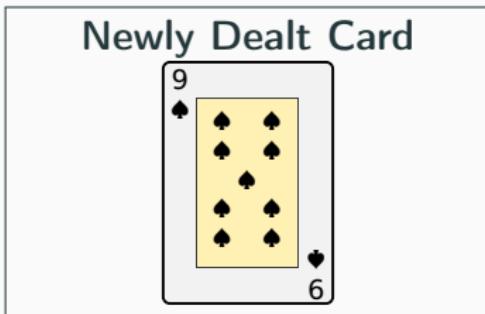
Newly Dealt Card

Your Hand So Far



Being dealt a hand

Next you are dealt the nine of spades.

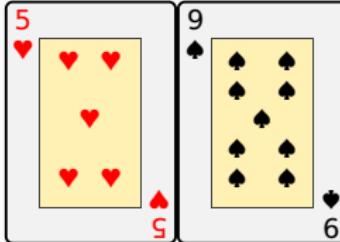


Being dealt a hand

Not being one to procrastinate, you decide there is no better time to sort your hand than as it is dealt. So you place the newly dealt nine of spades to the right of your five of hearts, since nine is larger than five.

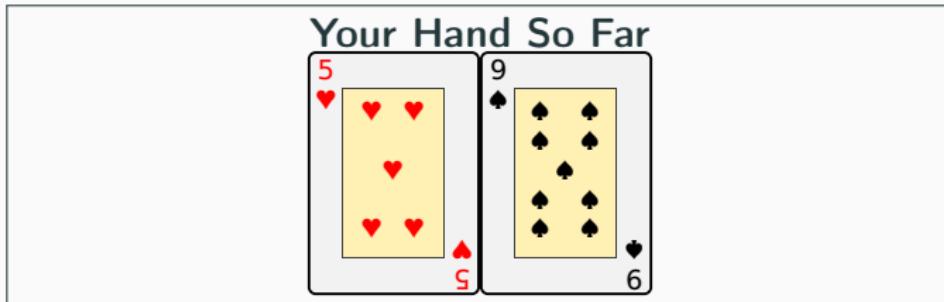
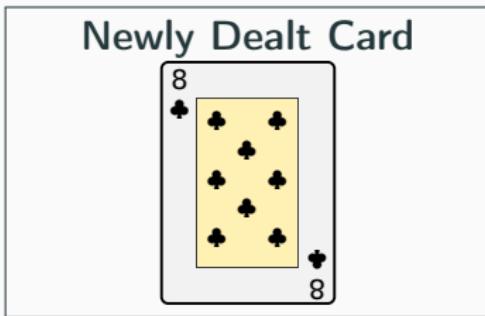
Newly Dealt Card

Your Hand So Far



Being dealt a hand

Next you are dealt the eight of clubs.

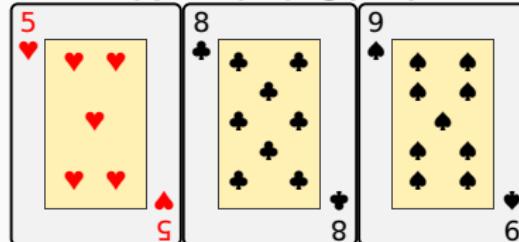


Being dealt a hand

Once again, you sort your cards as they are received, so you place your newly dealt eight in-between your five and your nine.

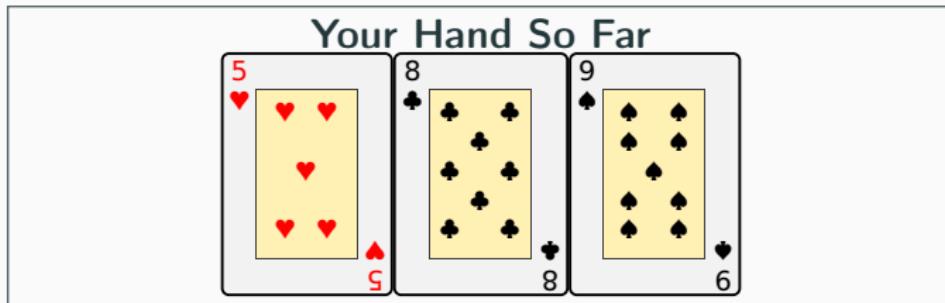
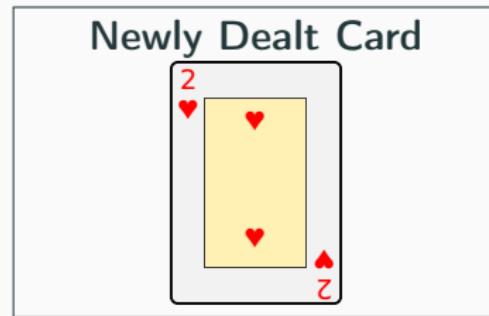
Newly Dealt Card

Your Hand So Far



Being dealt a hand

Lastly you are dealt a two of hearts.

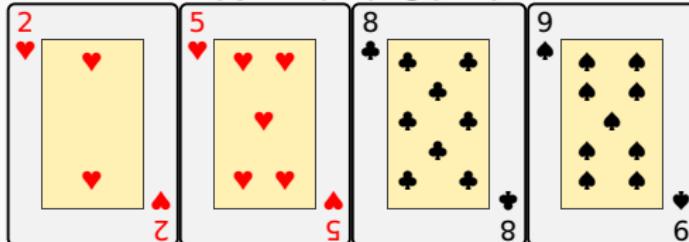


Being dealt a hand

The two is smaller than your five, and as such you place it before the five in your hand.

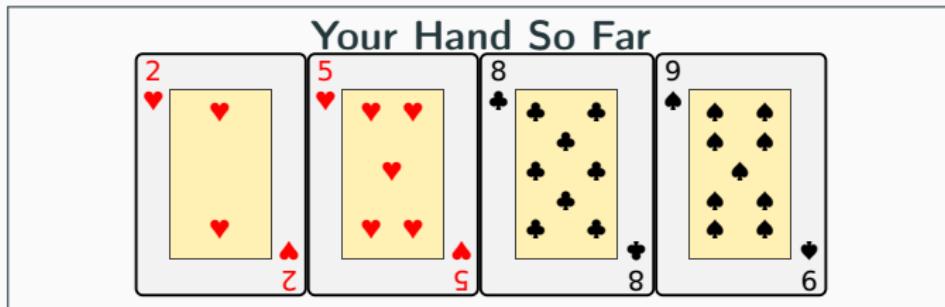
Newly Dealt Card

Your Hand So Far



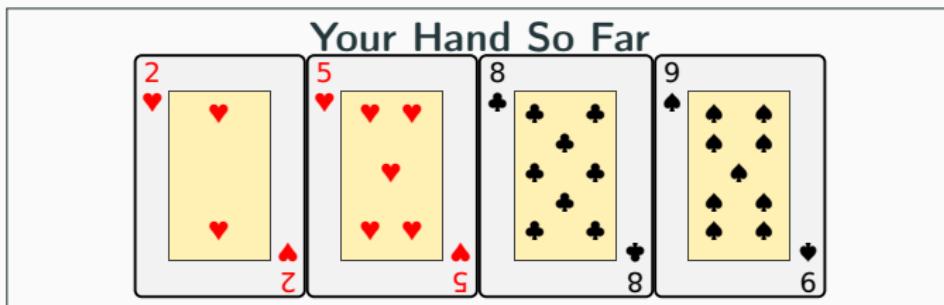
Being dealt a hand

Once the last card is dealt to you, your hand is already sorted!



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So what exactly was the algorithm we followed to sort our hand of cards?

The procedure of insertion sort

The procedure we followed for sorting our hand of cards may be so intuitive it seems there is not much to say about what was done. How might we define the procedure we followed?

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We may simply say “Whenever we were dealt a card we immediately placed in its correct location”.

The procedure of insertion sort

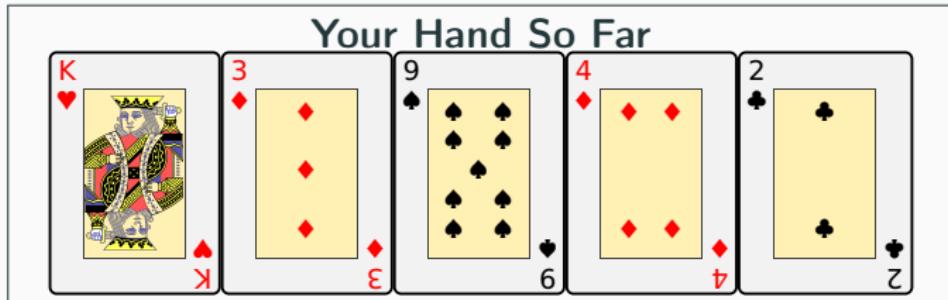
The procedure we followed for sorting our hand of cards may be so intuitive it seems there is not much to say about what was done. How might we define the procedure we followed?

We may simply say “Whenever we were dealt a card we immediately placed in its correct location”.

But that definition ignores some important details of the procedure! For one, it assumes that a “correct location” always exists — is that always true?

Counterexample

Imagine you are dealt the seven of hearts, and your current hand looks as it does below — where would you insert the newly dealt card?



Fixing our procedure

The issue in the counterexample shown was that the instructions of our procedure had a flaw.

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Fixing our procedure

The issue in the counterexample shown was that the instructions of our procedure had a flaw.

“Whenever we were dealt a card we immediately placed in its correct location” fails when no such correct location exists, as in our example! How can we guarantee a correct location exists?

A correct location exists when we are placing a card in a hand that is already sorted. So, instead we will adjust our procedure with that constraint in mind.

Updated insertion sort procedure

Our new updated procedure for insertion sort is as follows

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“Given we have a sorted hand of cards, whenever we are dealt a card immediately insert it into the location in our hand where it is in sorted order”

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"Given we have a sorted hand of cards, whenever we are dealt a card immediately insert it into the location in our hand where it is in sorted order"

However, this new assumption may seem to defeat the purpose of our exercise. If we already have a sorted hand of cards we wouldn't need to sort it! How does this help us build a sorted list from an arbitrary one?

The insert function

The process we defined on the previous slide is *not* the definition of insertion sort, rather it is the *step* that must be followed for each item of the collection to sort.

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The process we've defined is that of *inserting* a single element into a sorted list to build a new sorted list one element larger. Let us first define this function `insert` and then see how this can be used to build a solution to sorting an arbitrary list.

Writing insert

We now define insert

```
def insert(elem, sl):
```

```
    ...
```

insert produces a new list sorted in non-decreasing order, the result of inserting elem into sl

elem - X

sl - LList of X, sorted in non-decreasing order

returns - LList of X

Example:

insert(5, LL(-1, 4, 10, 20)) -> LL(-1, 4, 5, 10, 20)

```
    ...
```

Writing insert

We must find the correct location to insert `elem`. As such we will need to look at multiple values in our `LList`. Recursion over our `LList` will be necessary.

```
def insert(elem, sl):
```

Writing insert

So, we start with a base case, when is it trivial to know where to insert a card in sorted order? Thinking back on our card example there was no decision to be made when we were dealt our first card and our hand was empty!

```
def insert(elem, sl):
```

Writing insert

Therefore when our LList is empty then we of course know where to insert elem, as there is only one choice.

```
def insert(elem, sl):
    if isEmpty(sl):
        return cons(elem, empty())
```

Writing insert

Now, we must consider our recursive case. As always we consider our “current item” and what must be done with it. So what is relevant about the first of our LList?

```
def insert(elem, sl):
    if isEmpty(sl):
        return cons(elem, empty())
```

Writing insert

Since our LList is sorted in non-decreasing order that means everything after `first(sl)` is guaranteed to be greater than or equal to it. So if `elem` is *smaller* than `first(sl)` then `elem` should become the first of our new LList!

```
def insert(elem, sl):
    if isEmpty(sl):
        return cons(elem, empty())
    if elem < first(sl):
        return cons(elem, sl)
```

Writing insert

On the other hand, if `elem` is not smaller than `first(sl)` then inserting it *after* `first(sl)` in our new LList cannot be incorrect. So we should insert `elem` into the rest of `sl`, making sure not to forget to include `first(sl)` in our newly created LList.

```
def insert(elem, sl):
    if isEmpty(sl):
        return cons(elem, empty())
    if elem < first(sl):
        return cons(elem, sl)
    return cons(first(sl), insert(elem, sl))
```

Writing insert

Our `insert` function is now complete, and can now be used to solve the problem of sorting an arbitrary `LList`.

```
def insert(elem, sl):
    if isEmpty(sl):
        return cons(elem, empty())
    if elem < first(sl):
        return cons(elem, sl)
    return cons(first(sl), insert(elem, sl))
```

Writing insertionSort

Now we will write `insertionSort`.

```
def insertionSort(l):
```

```
    '''
```

*insertionSort sorts the given LList in non-decreasing
order.*

l - LList of X, X is comparable.

returns - LList of X

Examples:

insertionSort(LL(5, 9, 8, 2)) -> LL(2, 5, 8, 9)

insertionSort(LL(13, 3, 9, 4, 2)) -> LL(2, 3, 4, 9, 13)

```
'''
```

Writing insertionSort

Not sure where to begin, we think back to how we sorted our hand. To begin with we had an empty hand, and each time we were given an item we inserted it in sorted order. That *is* our algorithm for insertion sort, so we start the same — with an empty LList as our base case.

```
def insertionSort(l):
```

Writing insertionSort

Since an empty collection is trivially sorted, our function correctly sorts an empty LList. What to do if `l` is *not* empty?

```
def insertionSort(l):  
    if isEmpty(l):  
        return empty()
```

Writing insertionSort

When l is not empty then we aim to build our answer up from the recursive result combined with our current element. So we call `insertionSort` recursively on the rest of l .

```
def insertionSort(l):
    if isEmpty(l):
        return empty()
    ror = insertionSort(rest(l))
```

Writing insertionSort

insertionSort is a function that promises us to return the sorted version of a given LList. That means that our result of recursion is the sorted version of the rest of our LList!

Given a sorted version of the rest of l the only work that remains to be completed is that of inserting the first of l into that sorted LList!

```
def insertionSort(l):
    if isEmpty(l):
        return empty()
    ror = insertionSort(rest(l))
```

Writing insertionSort

Since our recursive result is the sorted LList with everything except the first of l then simply inserting the first of l into that result is the sorted LList with *all* the elements of l!

```
def insertionSort(l):
    if isEmpty(l):
        return empty()
    ror = insertionSort(rest(l))
    return insert(first(l), ror)
```

Runtime of insertion sort

What is the runtime of `insertionSort`?

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- Then for each of the n calls the work performed is a constant amount of work by `insertionSort` plus the work performed by the call to `insert`
- So, the runtime of `insertionSort` will be nx where x is the runtime of `insert`, so we must determine the runtime of `insert`

Runtime of insert

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 - If the element should be inserted as the first element, then `insert` is never recursively called and it does a constant amount of work!
 - If the element should be inserted as the last element, then `insert` must walk the entire `LList` recursively, so it performs n recursive calls (each doing constant work).

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 - If the element should be inserted as the first element, then `insert` is never recursively called and it does a constant amount of work!
 - If the element should be inserted as the last element, then `insert` must walk the entire `LList` recursively, so it performs n recursive calls (each doing constant work).
- So best-case `insert` is $\Theta(1)$ and worst-case it is $\Theta(n)$. We will worry only about worst-case runtime.

Completed runtime of insertion sort

Now that we know the work done by `insert` is linear relative to the length of its `LList` parameter we can calculate the work performed by `insertionSort`

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The amount of work performed by `insertionSort` is then $n \times \Theta(n) \rightarrow \Theta(n^2)$.

So considered worst case `insertionSort` takes quadratic time — as such, it cannot be used to write `findPairs` faster than $\Theta(n^2)$.

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Higher Order Sorting

Another sorting algorithm

Sometimes when playing a card game a player is not allowed to pick up their cards until the entire hand is dealt. As such, they pick up their entire hand that is dealt and then may want to sort it².

²Technically, they could choose to pick up their hand one card at a time and perform insertion sort. However, we will consider that they pick it up all at once and then want to sort it.

Another sorting algorithm

Sometimes when playing a card game a player is not allowed to pick up their cards until the entire hand is dealt. As such, they pick up their entire hand that is dealt and then may want to sort it².

If you have ever played such a game, and attempted to sort your hand after picking up all the cards, you may have in the past fumbled around swapping the cards around in your hand until you reach a sorted order. The algorithm we are about to describe is a formalized order of that fumbling sort.

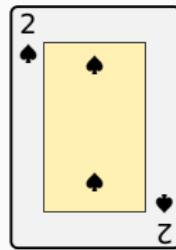
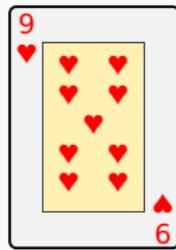
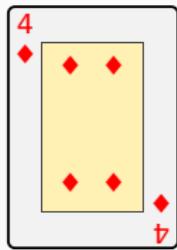
²Technically, they could choose to pick up their hand one card at a time and perform insertion sort. However, we will consider that they pick it up all at once and then want to sort it.

Bubble sorting a hand of cards

The process of *bubble sort* is the process one may undergo when they pick up a hand of unsorted cards and attempt to sort it by swapping pairs of cards around in their hand. We will consider how this algorithm may unfold in a particular example before defining the algorithm itself.

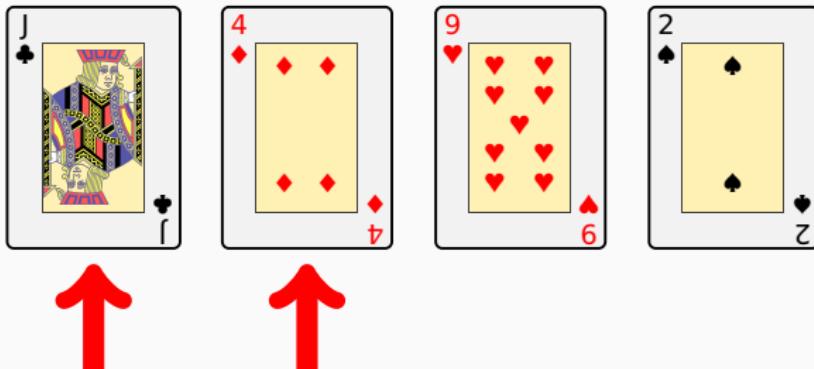
Bubble sorting a hand of cards

You pick up your hand as it is dealt to you, completely unorganized.



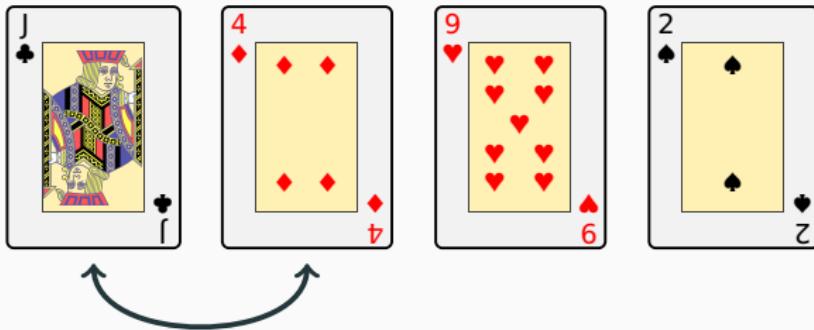
Bubble sorting a hand of cards

You begin a process of repeatedly comparing adjacent pairs of cards in your hand to determine if you should swap them. You start with the pair of your first card and the card to the right of it.



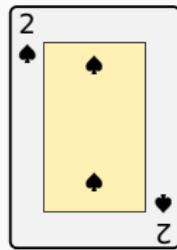
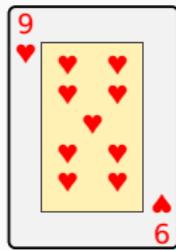
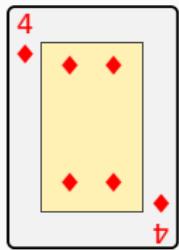
Bubble sorting a hand of cards

Looking at the first card, and the card right of it, you decide a swap must be made as a Jack is a higher rank than a four.



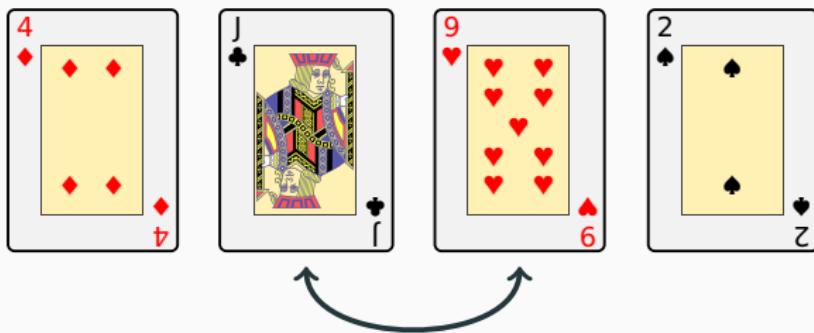
Bubble sorting a hand of cards

As you have already looked at the first card you now look at the second card and the card to the right of it.



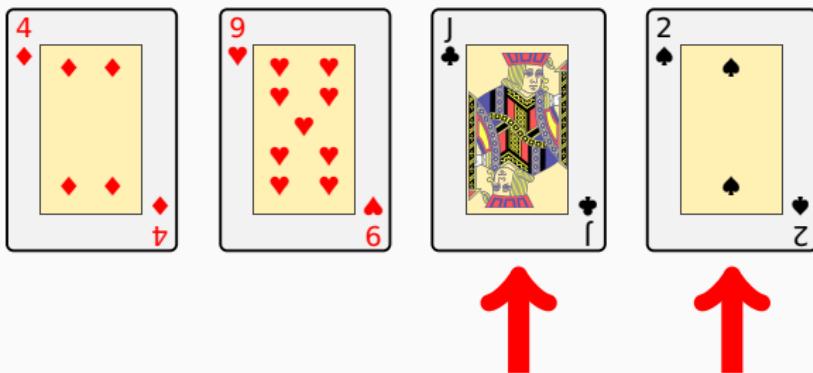
Bubble sorting a hand of cards

As the left card is a Jack and the card to the right of it is a nine you again determine a swap should be made.



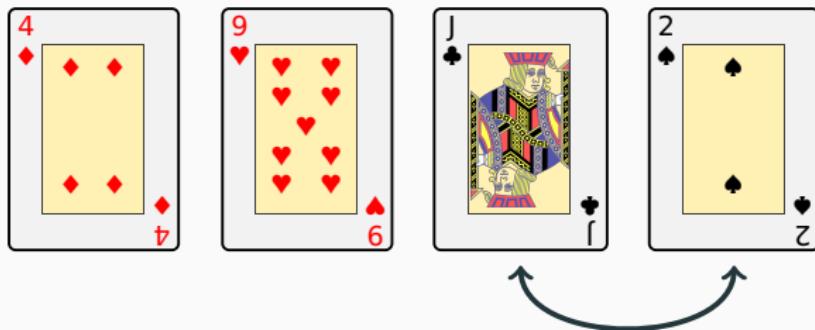
Bubble sorting a hand of cards

Now you consider the third card, and the card next to it.



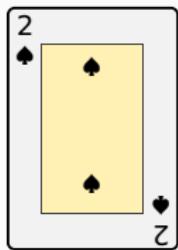
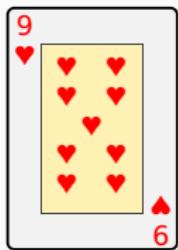
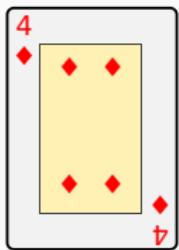
Bubble sorting a hand of cards

Once again you determine a swap must take place, because Jack is a higher rank than two.



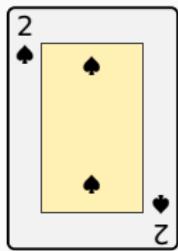
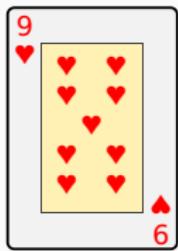
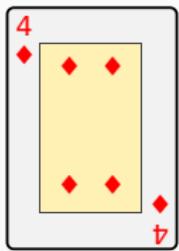
Bubble sorting a hand of cards

Now you have considered all but the last card, but there is no card to the right of the last card to consider swapping it with, you are content that the last card is in the right place.



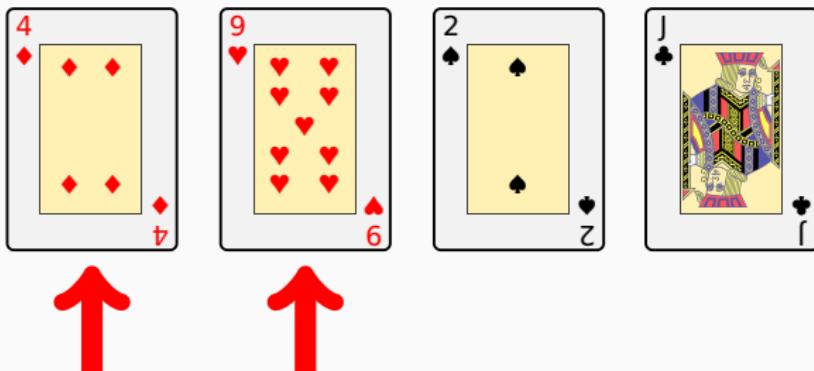
Bubble sorting a hand of cards

However, nothing can be said for the rest of your hand besides the last card!



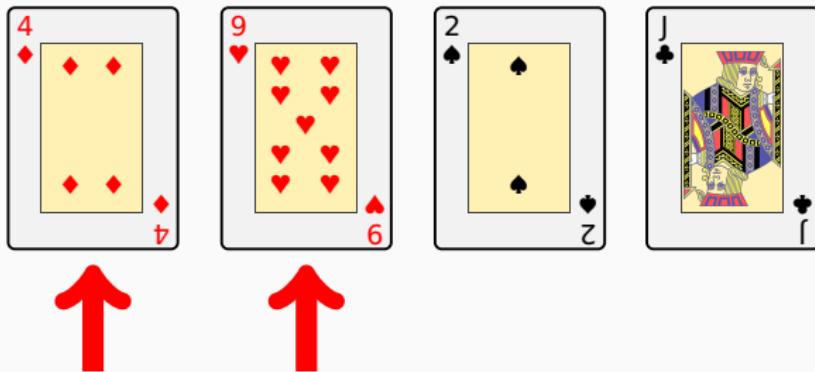
Bubble sorting a hand of cards

We repeat this process of comparing pairs starting with the first card and the card to the right of it again.



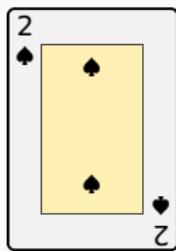
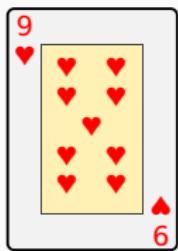
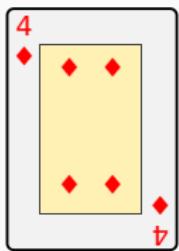
Bubble sorting a hand of cards

This time we determine that no swap should take place, as four is a smaller rank than nine.



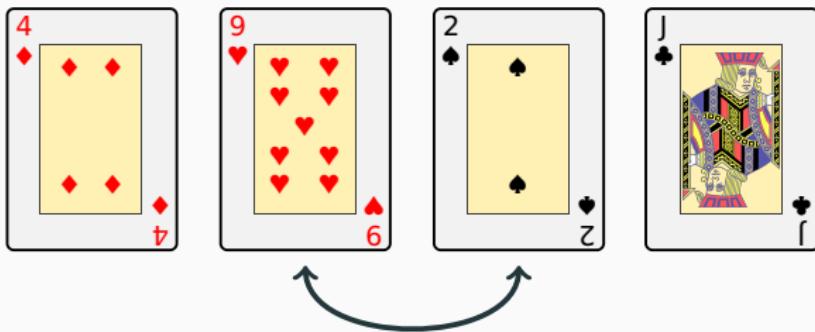
Bubble sorting a hand of cards

So, we move on to the pair starting at the second card and the card to the right of it.



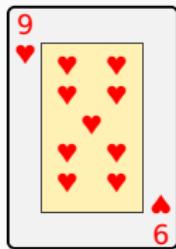
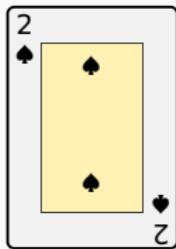
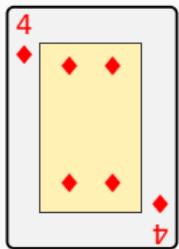
Bubble sorting a hand of cards

This time we determine the cards should swap positions because Nine is a larger rank than Two



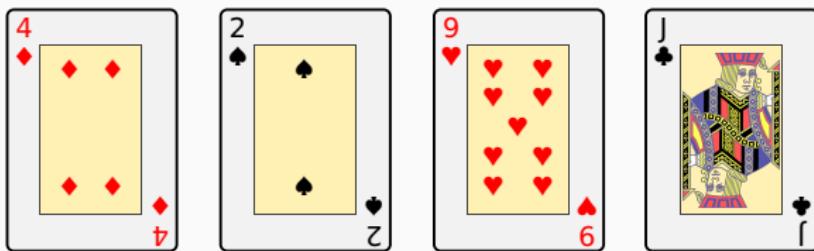
Bubble sorting a hand of cards

As we have now considered the second card and the card to the right of it we could now continue to consider the third card and the card to the right of it.



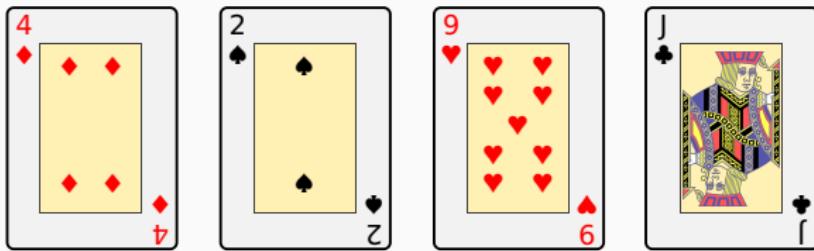
Bubble sorting a hand of cards

However, since we have already applied this process once the rightmost card is guaranteed to be the largest card. So the third card is our last “unsorted” card, and as such there is no unsorted card to the right of it to compare it to, so we are finished for this step.



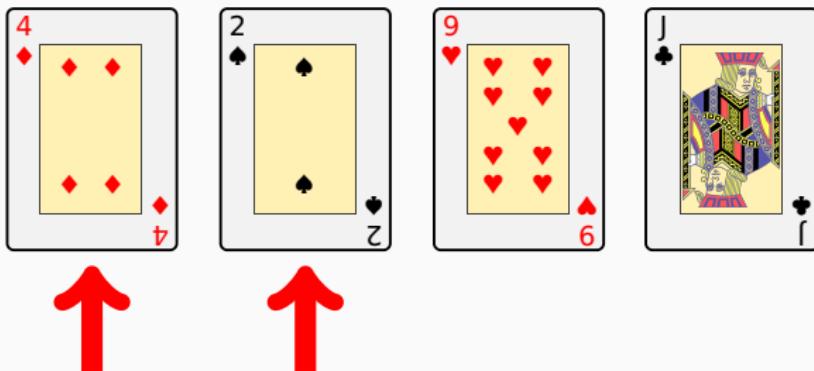
Bubble sorting a hand of cards

Now our last *two* cards are guaranteed to be in right place, but nothing for the cards before them.



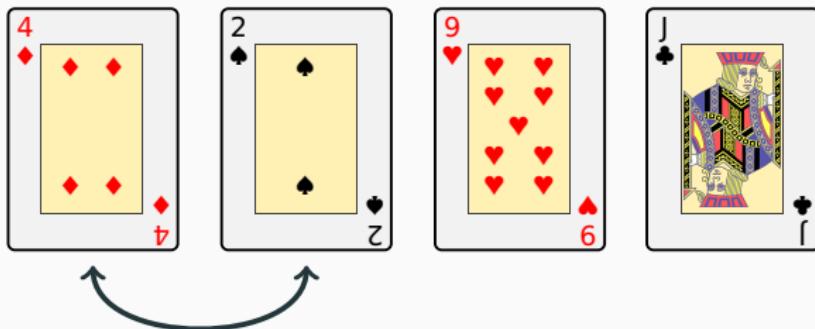
Bubble sorting a hand of cards

We begin this process again, starting with the pair of the first card and the card to the right of it.



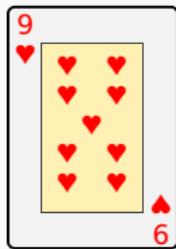
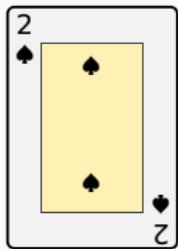
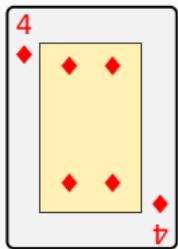
Bubble sorting a hand of cards

We determine that a swap should take place as four is a higher rank than two.



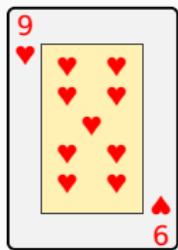
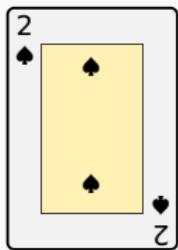
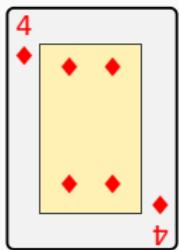
Bubble sorting a hand of cards

Now as we have looked at the pair situated at the first card and the card to the right of it we would move on to consider pair that is the second card and the card to the right of it.



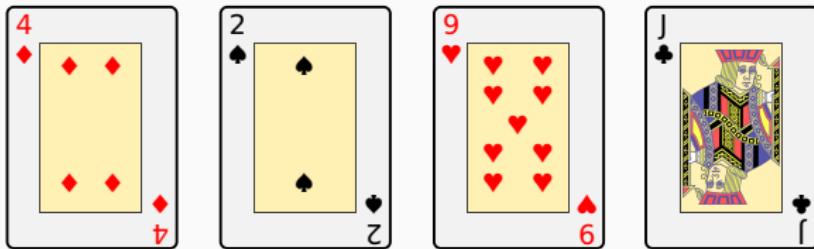
Bubble sorting a hand of cards

However, since all the cards after our second card are already known to be in the right position then we do not need to consider this pair at all.



Bubble sorting a hand of cards

Now the last three cards are guaranteed to be in the correct position. Since our hand is only four cards long this means that *all* cards are in the correct position and our algorithm is finished!



Bubble sort algorithm

Bubble sort's name comes from the fact procedure of repeated comparisons of adjacent pairs, which "bubbles" the largest value to the end of our sequence. So this process, the process of comparing the first n adjacent pairs to each other, we will call one single "bubbling". Then the algorithm for Bubble sort becomes quite simple.

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- Perform a "bubbling" of the sequence
- If you have completed n bubblings, where n is the length of the sequence, then return the result of that bubbling
- If you have not completed n bubblings, then begin at step one again but operating on the sequence that was produced by the previous bubbling

Implementing bubble

We will now implement bubble which takes a single LList parameter and performs a single “bubbling” procedure on that LList.

```
def bubble(l):
```

Implementing bubble

As with any of our functions we will determine our base case.
When is the result of “bubbling” a LList trivial to know?

If the LList contains zero or one value then the result is simply the LList itself

```
def bubble(l):  
    if len(l) <= 1:  
        return l
```

Implementing bubble

Now what needs to be done if the LList is not empty or one element large? The bubbling process works by comparing each set of adjacent pairs and swapping them if necessary.

The adjacent pair we can easily access is the first pair, so that is the pair on which we operate.

```
def bubble(l):
    if len(l) <= 1:
        return l
    if first(l) > second(l):
```

Implementing bubble

If the first item in our LList in our pair is greater than the second then their positions should swap in our resultant LList!

So our result should be the LList that has the first and second item swapped.

```
def bubble(l):
    if len(l) <= 1:
        return l
    if first(l) > second(l):
        newFirst = second(l)
        newRest = cons(first(l), rest(rest(l)))
```

Implementing bubble

However this has only compared the *first* adjacent pair. We must compare each adjacent pair in our whole LList to complete one bubbling, so we recursively call bubble on the (new) rest of our LList and build our final answer from its result!

```
def bubble(l):
    if len(l) <= 1:
        return l
    if first(l) > second(l):
        newFirst = second(l)
        newRest = cons(first(l), rest(rest(l)))
    return cons(newFirst, bubble(newRest))
```

Implementing bubble

This only handles the recursive case where we *should* swap the current adjacent pair we're looking at. If we should *not* perform such a swap then the result should simply be the recursive result combined with our current first element.

```
def bubble(l):
    if len(l) <= 1:
        return l
    if first(l) > second(l):
        newFirst = second(l)
        newRest = cons(first(l), rest(rest(l)))
        return cons(newFirst, bubble(newRest))
    return cons(first(l), bubble(rest(l)))
```

Implementing bubble

Now we have the function `bubble` that returns the result of applying the “bubbling” procedure to a `LList` once. Now to implement `bubbleSort` we simply need to call this function multiple times.

```
def bubble(l):
    if len(l) <= 1:
        return l
    if first(l) > second(l):
        newFirst = second(l)
        newRest = cons(first(l), rest(rest(l)))
        return cons(newFirst, bubble(newRest))
    return cons(first(l), bubble(rest(l)))
```

Implementing bubbleSort

We will now implement bubbleSort which takes a single LList parameter and returns the result of sorting that LList in non-decreasing order using the bubble sort algorithm.

```
def bubbleSort(l):
```

Implementing bubbleSort

We note that we want to call `bubble` a number of times equal to the length of the given `LList`. In order to repeat our process that many times we need to write a recursion on that number. So we write a helper function that takes a `LList` and an integer that represents the number of times to perform `bubble`.

```
def bubbleSort(l):  
    def repeatBubble(bl, n):
```

Implementing bubbleSort

If n is zero, then bubble does not need to be applied to the parameter bl at all. As such, the answer is just bl .

```
def bubbleSort(l):
    def repeatBubble(bl, n):
        if n == 0:
            return bl
```

Implementing bubbleSort

If n is non-zero then we want to apply bubble that many times. We observe that three result of applying bubble to b_1 n times is the same thing as applying bubble to $\text{bubble}(b_1)$ $n - 1$ times. As such, our recursion becomes obvious.

```
def bubbleSort(l):
    def repeatBubble(bl, n):
        if n == 0:
            return bl
        return repeatBubble(bubble(bl), n-1)
```

Implementing bubbleSort

The last thing left to do is to have bubbleSort return the result of n bubblings.

```
def bubbleSort(l):
    def repeatBubble(bl, n):
        if n == 0:
            return bl
        return repeatBubble(bubble(bl), n-1)
    return repeatBubble(l, len(l))
```

Runtime of bubble sort

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- There is one recursive call for each non-base case application of `repeatBubble`, each applied to the $n - 1$, so there will be n recursive calls to `repeatBubble` for a `LList` of length n .
- Then for each of the n calls the work performed is a constant amount of work by `repeatBubble` plus the work performed by the call to `bubble`
- So, the runtime of `repeatBubble` will be nx where x is the runtime of `bubble`, so we must determine the runtime of `bubble`

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- bubble performs only basic operations, except for its recursive call.
- bubble recursively calls itself until the LList is empty or length one, and each recursive application of bubble is to a LList with one less element in it so there will be $n - 1$ recursive calls.
- So bubble performs only basic operations each call, and recursively calls itself $n - 1$ times, as such it does $\Theta(n)$ work.

Completed runtime of bubble sort

Now that we know that the work done by `bubble` is linear relative to the length of the `LList` parameter we can calculate the work performed by `repeatBubble` and thus the work performed by `bubbleSort`.

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Completed runtime of bubble sort

Now that we know that the work done by bubble is linear relative to the length of the LList parameter we can calculate the work performed by repeatBubble and thus the work performed by bubbleSort.

The amount of work performed by repeatBubble is then
 $n \times \Theta(n) \rightarrow \Theta(n^2)$

So bubbleSort also has a quadratic runtime and also cannot be used to write findPairs faster than $\Theta(n^2)$.

Some improvements on our bubbleSort implementation

There are some notes to be made on our bubbleSort implementation, which can be observed from our card example.

- We do not need to perform n bubblings but rather $n - 1$ bubblings
- Each bubbling does not need to bubble *every* adjacent pair, because after k bubblings the last k items are already guaranteed to be in their sorted position

Neither of these changes will change the asymptotic runtime of bubbleSort but they will improve our implementation!

Practice Question: Update our implementation of bubbleSort with the improvements noted above.

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Higher Order Sorting

An observation from a *different* problem

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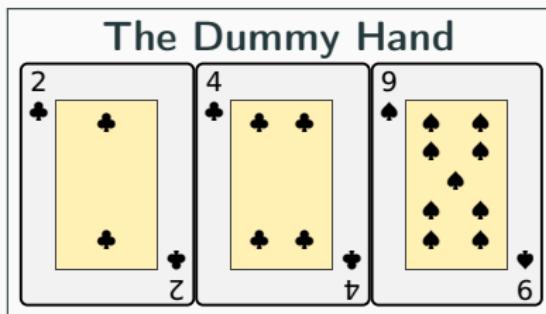
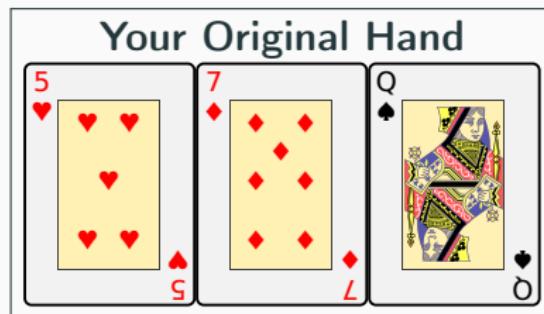
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Example combining two sorted hands

To begin with your newly combined hand has zero cards in it.

Combined Hand

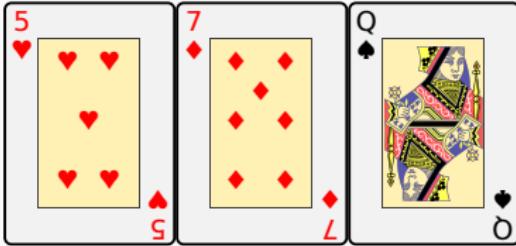


Example combining two sorted hands

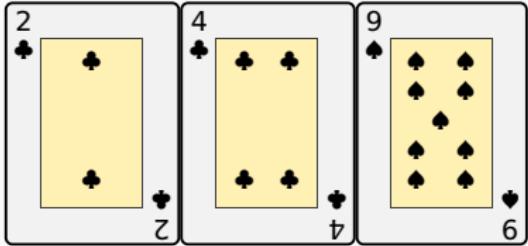
Since both hands are sorted you need only compare the first of each hand to decide which to add to your hand first.

Combined Hand

Your Original Hand



The Dummy Hand

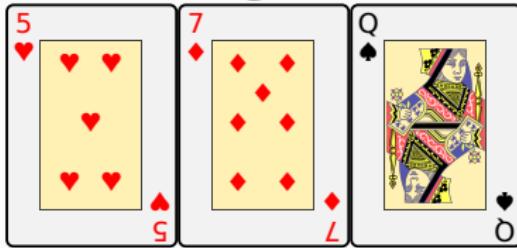


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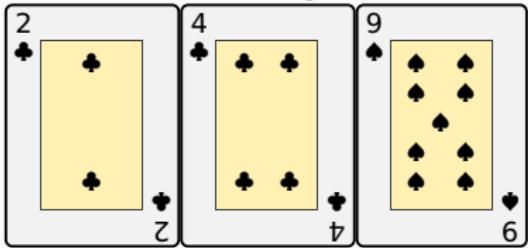
The dummy hand has a two which is smaller than a five, so the two should be the first card of your new hand.

Combined Hand

Your Original Hand



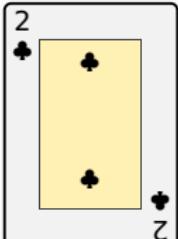
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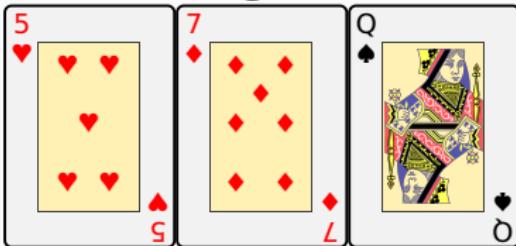
Example combining two sorted hands

So, you take the two of clubs from the dummy hand and place it in your newly combined hand.

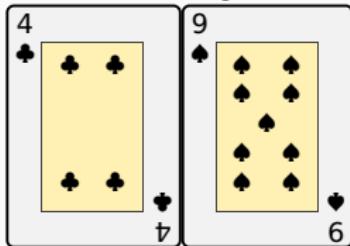
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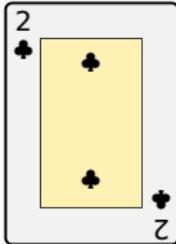
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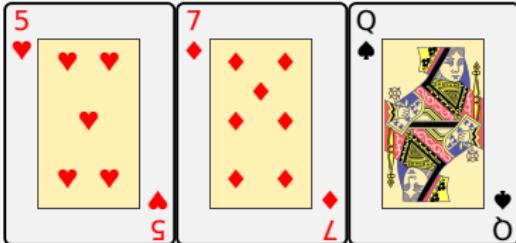
Example combining two sorted hands

Once again you need only compare the first of each hand. In this case the dummy hand's four is the next smallest card, so it should be the second card in your newly combined hand.

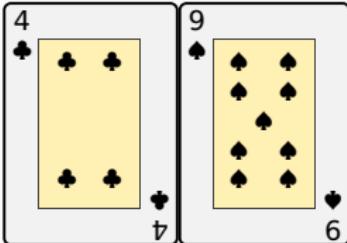
Combined Hand



Your Original Hand

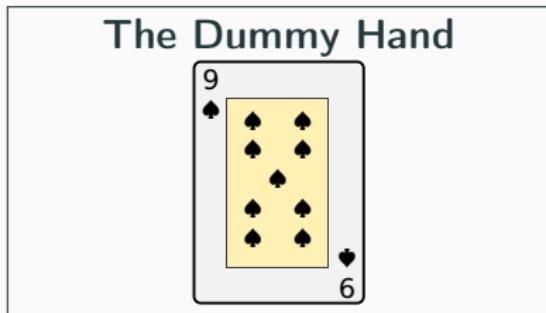
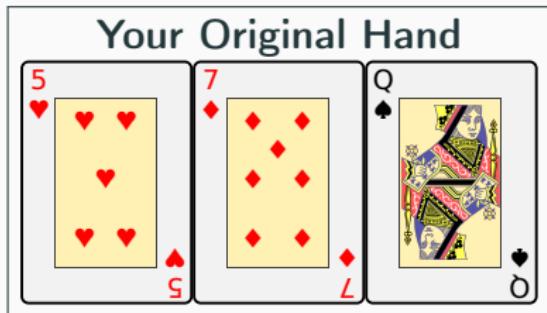
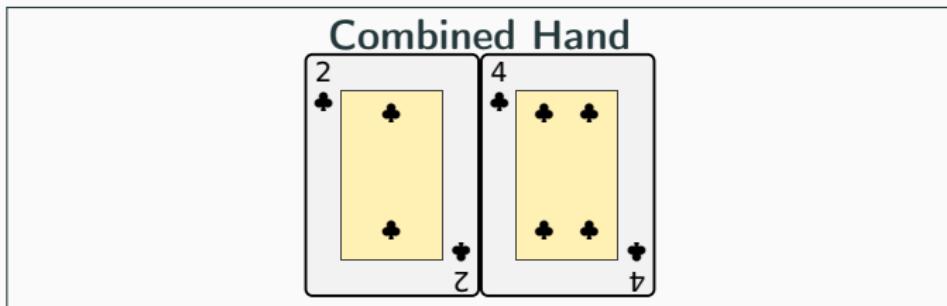


The Dummy Hand



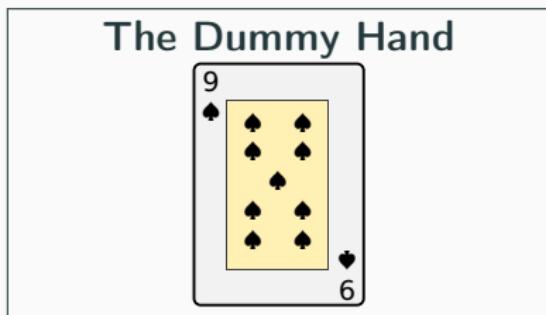
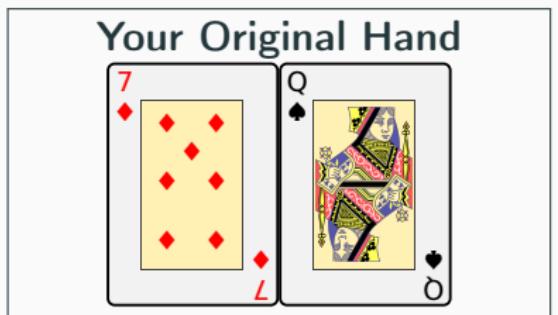
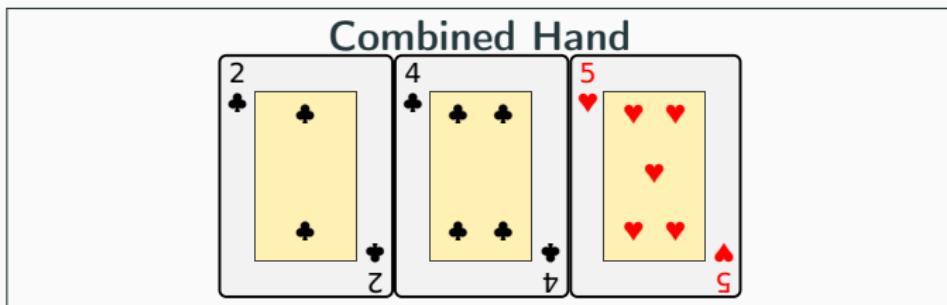
Example combining two sorted hands

Repeat the process comparing the first of each hand and always taking the smaller.



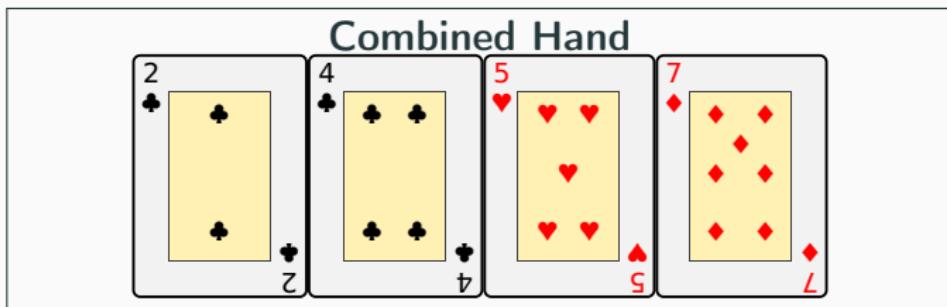
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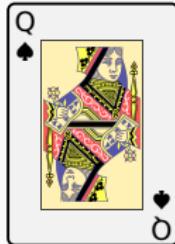


Example combining two sorted hands

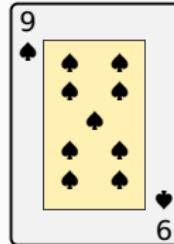
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Your Original Hand

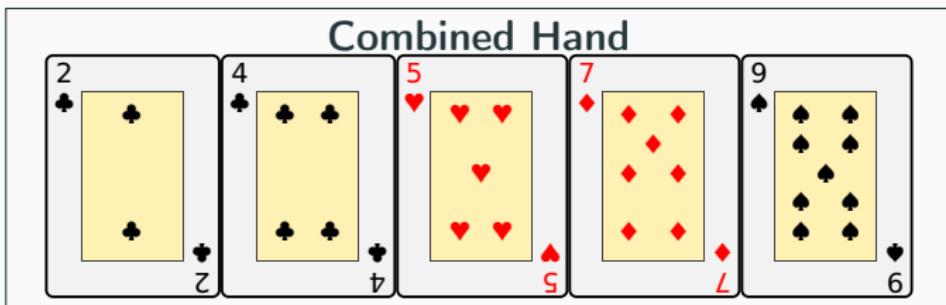


The Dummy Hand

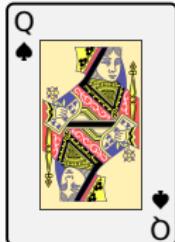


Example combining two sorted hands

Since one hand is empty now, the remaining hand can simply be picked up and placed on the end of your newly sorted hand.



Your Original Hand

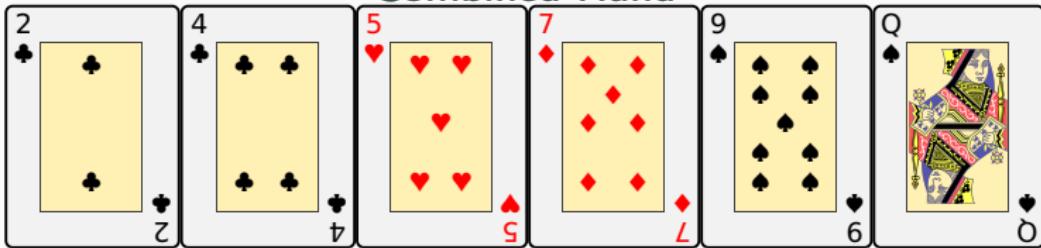


The Dummy Hand

Example combining two sorted hands

Now, you are left with a new combined hand which is the sorted result of combining the sorted dummy hand with your original sorted hand.

Combined Hand



Your Original Hand

The Dummy Hand

The merge algorithm

The algorithm we employed on our two sorted hands of cards can more generally be applied to any two sorted sequences to produce a combined sorted sequence. We'll call this function the `merge` function and write it in Python for two LLists

The merge function

Our merge function operates the same as our example did on our two hands of cards, comparing the first of each LList and determining which should go in the resultant LList first.

```
def merge(s1, s2):
    if first(s1) < first(s2):
        return cons(first(s1), ...)
    else:
        return cons(first(s2), ...)
```

The merge function

But what LList should the selected item be the first of?

```
def merge(s11, s12):
    if first(s11) < first(s12):
        return cons(first(s11), ...)
    else:
        return cons(first(s12), ...)
```

The merge function

But what LList should the selected item be the first of?

We want it to be the first in our newly sorted LList, so the LList we should cons it onto is the result of merging the *rest* of our values.

```
def merge(sl1, sl2):
    if first(sl1) < first(sl2):
        return cons(first(sl1), ...)
    else:
        return cons(first(sl2), ...)
```

The merge function

In this case the “rest of our values” refers to the values we have not yet included in our final answer, which is all of them except for the one selected.

```
def merge(sl1, sl2):
    if first(sl1) < first(sl2):
        return cons(first(sl1), merge(rest(sl1), sl2))
    else:
        return cons(first(sl2), merge(sl1, rest(sl2)))
```

The merge function

In this case the “rest of our values” refers to the values we have not yet included in our final answer, which is all of them except for the one selected.

For this reason in each case we do not change the LList we did not take an item from when passing it as a recursive argument, just as only the hand which we took a card from changed in each step.

```
def merge(s1, s2):
    if first(s1) < first(s2):
        return cons(first(s1), merge(rest(s1), s2))
    else:
        return cons(first(s2), merge(s1, rest(s2)))
```

The merge function

We have written our recursive cases, but now must write our base case! Since in each recursion we are making either `s11` or `s12` smaller we must have a base case for each LList.

```
def merge(s11, s12):
    if first(s11) < first(s12):
        return cons(first(s11), merge(rest(s11), s12))
    else:
        return cons(first(s12), merge(s11, rest(s12)))
```

The merge function

We have written our recursive cases, but now must write our base case! Since in each recursion we are making either $s1$ or $s2$ smaller we must have a base case for each LList.

If one of our LLists is empty then the result of merging a non-empty LList with an empty LList is simply the non-empty LList!

```
def merge(s1, s2):
    if first(s1) < first(s2):
        return cons(first(s1), merge(rest(s1), s2))
    else:
        return cons(first(s2), merge(s1, rest(s2)))
```

The merge function

With our base cases complete our `merge` function is now finished.

```
def merge(sl1, sl2):
    if isEmpty(sl1):
        return sl2
    if isEmpty(sl2):
        return sl1
    if first(sl1) < first(sl2):
        return cons(first(sl1), merge(rest(sl1), sl2))
    else:
        return cons(first(sl2), merge(sl1, rest(sl2)))
```

Considering the runtime of `merge`

How many basic operations does `merge` perform? Since `merge` has two inputs which both affect its execution we must specify in terms of both.

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How many basic operations does `merge` perform? Since `merge` has two inputs which both affect its execution we must specify in terms of both.

If we consider the length of `s11` to be h and the length of `s12` to be d then how many basic operations are performed by `merge`?

`merge` only performs basic operations other than its recursive call, and only executes one recursive call each time it executes, so we simply need to determine how many times `merge` recursively calls itself.

Considering the runtime of merge

`merge` reaches a base case when *one* of the LLists is empty. How many items must be looked at is determined by the values within the LLists.

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Imagine that s11 is values v_0, v_1, \dots, v_h and s12 is values w_0, w_1, \dots, w_d , and that v_0 is larger than w_d . How many times does merge run?

Considering the runtime of `merge`

`merge` reaches a base case when *one* of the LLists is empty. How many items must be looked at is determined by the values within the LLists.

Imagine that `s11` is values v_0, v_1, \dots, v_h and `s12` is values w_0, w_1, \dots, w_d , and that v_0 is larger than w_d . How many times does `merge` run?

In that case `merge` is called d times, because every item in `s12` is smaller than even the smallest item in `s11`. After `merge` is called d times then `s12` is empty and a base case is reached.

Considering the runtime of merge

So, in the best case `merge` runs as many times as the length of *one* of it's input LLists, and for truly best case that length is the smaller one. So in the best case `merge` is $\Theta(\min(h, d))$

Considering the runtime of `merge`

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However, we know we are interested in the worst case. So what is it the worst case?

Imagine that $s/1$ and $s/2$ are the first twenty even and the first twenty odd non-zero naturals. So $s1$ is the LList $2, 4, \dots, 40$ and $s2$ is $1, 3, \dots, 39$

Considering the runtime of merge

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Imagine that $s/1$ and $s/2$ are the first twenty even and the first twenty odd non-zero naturals. So $s1$ is the LList $2, 4, \dots, 40$ and $s2$ is $1, 3, \dots, 39$

In this case we have to repeatedly switch which LList we make smaller each recursion, and so we will actually look at *every* value in each LList.

Considering the runtime of `merge`

Our `merge` function can't do worse than calling itself once for each value, since it removes that value from the recursion each time it chooses it. So since we've found a case where it is called for every value in our two input LLists, and it can't do worse than that, we have found our worst case.

So the worst-case asymptotic runtime for `merge` is $\Theta(h + d)$. We also note that $h + d$ is the length of the resultant LList, so this is linear in the length of the result.

What use is merge?

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But how does this help us to sort an arbitrary LList?

Well with the recursive way of thinking we've developed throughout this course it actually helps us quite a lot!

Writing mergeSort

We will now write a sorting algorithm that uses `merge` and the power of recursion to sort a LList.

```
def mergeSort(l):
```

Writing mergeSort

As with most of our recursions we will start with our base case.
Once again we note that an empty LList or a LList of one element is trivially sorted.

```
def mergeSort(l):  
    if len(l) <= 1:  
        return l
```

Writing mergeSort

Next we must decide how to recursively call ourselves. If our goal is to use `merge` to help us solve the problem then we must end up with *two* sorted LLists.

```
def mergeSort(l):
    if len(l) <= 1:
        return l
```

Writing mergeSort

Next we must decide how to recursively call ourselves. If our goal is to use `merge` to help us solve the problem then we must end up with *two* sorted LLists.

Since `mergeSort` is a function that promises it will return the sorted version of a LList, and we need two sorted LLists to provide to `merge` we can recursively call `mergeSort` to produce the arguments for `merge`!

```
def mergeSort(l):
    if len(l) <= 1:
        return l
```

Writing mergeSort

Which LLists should we recursively call `mergeSort` on? The elements we provide to each call must be distinct from those provided to the other, so that we do not duplicate elements in our final result.

```
def mergeSort(l):
    if len(l) <= 1:
        return l
    return merge(mergeSort(????) , mergeSort(????))
```

Writing mergeSort

Which LLists should we recursively call `mergeSort` on? The elements we provide to each call must be distinct from those provided to the other, so that we do not duplicate elements in our final result.

So we need to somehow split up `l` into two LLists to sort. In order to help us do so we'll write two helper functions `skipN` and `takeN`

```
def mergeSort(l):
    if len(l) <= 1:
        return l
    return merge(mergeSort(????) , mergeSort(????))
```

Writing mergeSort

takeN and skipN are shown below, simple recursive functions.

```
def takeN(l, n):
    # Returns a LList of the first n items of l
    if n == 0:
        return empty()
    return cons(first(l), takeN(rest(l), n-1))

def skipN(l, n):
    # Returns a LList of all except the first n items of l
    if n == 0:
        return l
    return skipN(rest(l), n-1)
```

Writing mergeSort

With skipN and takeN we can easily produce two portions of our parameter l to call mergeSort on. The question now is how many elements to take for each recursive call?

```
def mergeSort(l):
    if len(l) <= 1:
        return l
    return merge(mergeSort(????) , mergeSort(????))
```

Writing mergeSort

With skipN and takeN we can easily produce two portions of our parameter l to call mergeSort on. The question now is how many elements to take for each recursive call?

A natural choice is to split the LList in *half* each recursion.

```
def mergeSort(l):
    if len(l) <= 1:
        return l
    return merge(mergeSort(????) , mergeSort(????))
```

Writing mergeSort

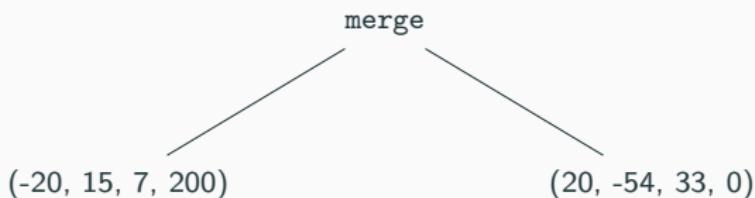
Below is shown our completed `mergeSort`.

```
def mergeSort(l):
    if len(l) <= 1:
        return l
    leftHalf = takeN(l, len(l)//2)
    rightHalf = skipN(l, len(l)//2)
    return merge(mergeSort(leftHalf), mergeSort(rightHalf))
```

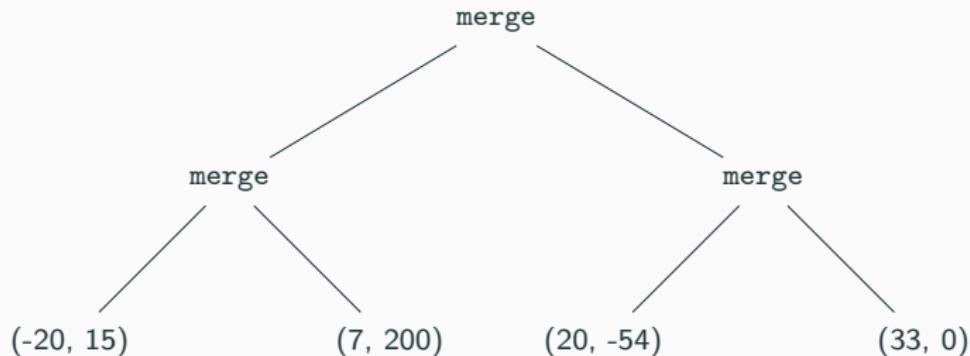
Example application of mergeSort

(-20, 15, 7, 200, 20, -54, 33, 0)

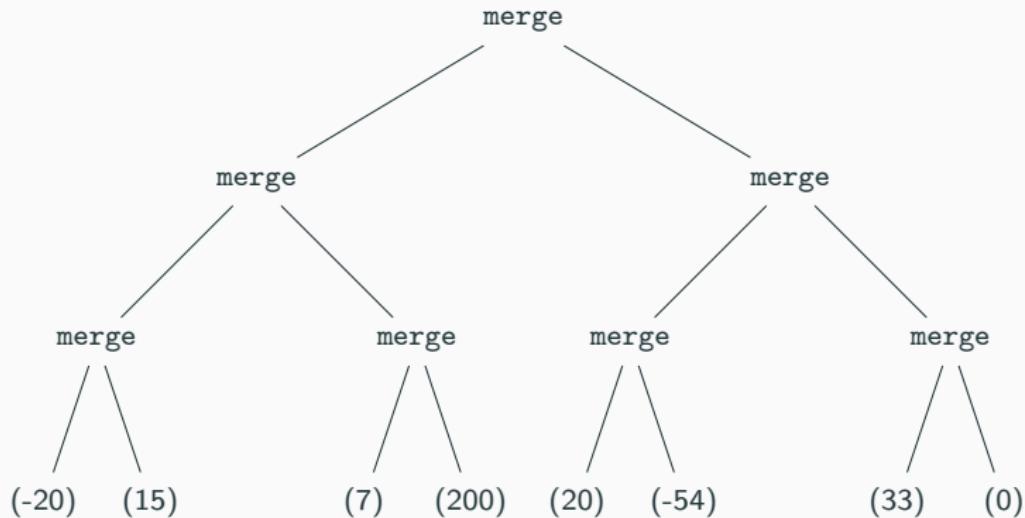
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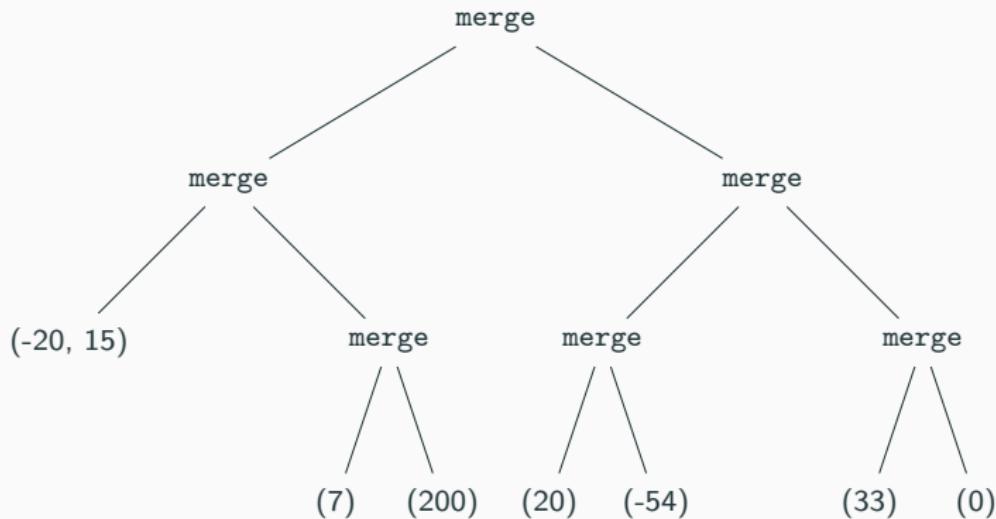
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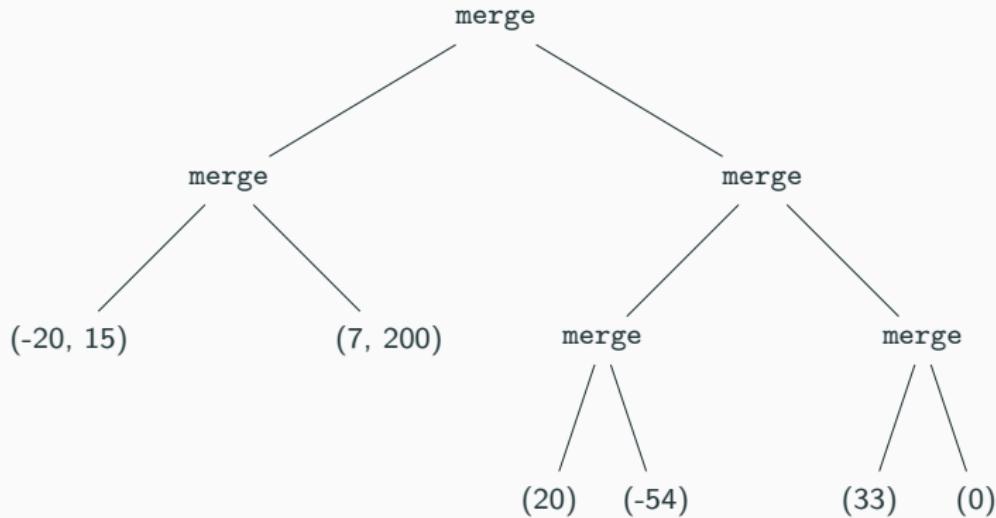
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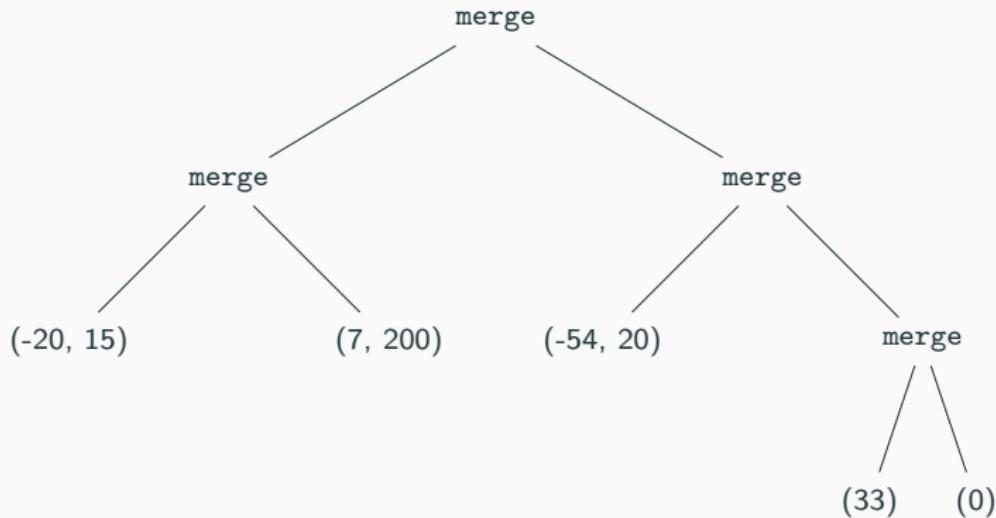
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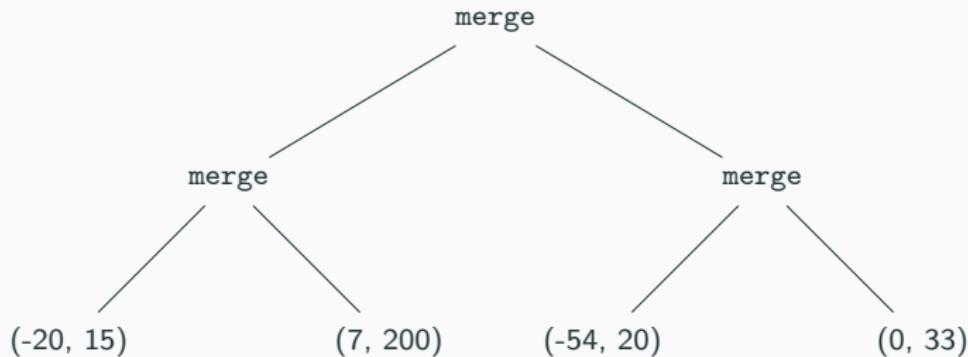
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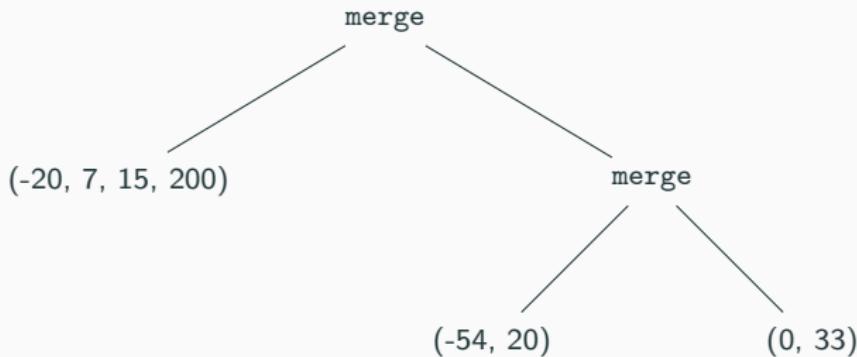
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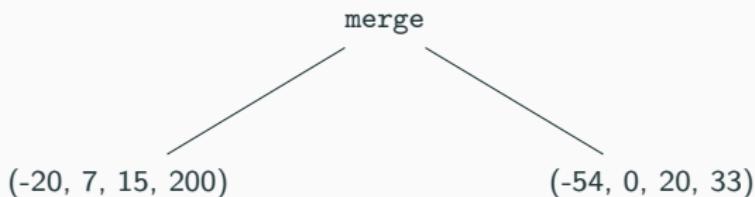
Example application of mergeSort



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Example application of mergeSort

(-54, -20, 0, 7, 15, 20, 33, 200)

Runtime of mergeSort

What then is the asymptotic runtime of `mergeSort`?

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First we must think about how much work each application of `mergeSort` does in terms of its input length.

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Each call to `mergeSort` calls `skipN`, `takeN`, and `merge` once. If the length of the `LList` given to `mergeSort` is n then:

- The calls to `skipN` and `takeN` both do $\frac{n}{2}$ work
- The call to `merge` does n work
- Therefore each call to `mergeSort` does $2n$ work

The call to `merge` does So each call to `mergeSort` is doing a linear amount of work relative to the input size.

Runtime of mergeSort

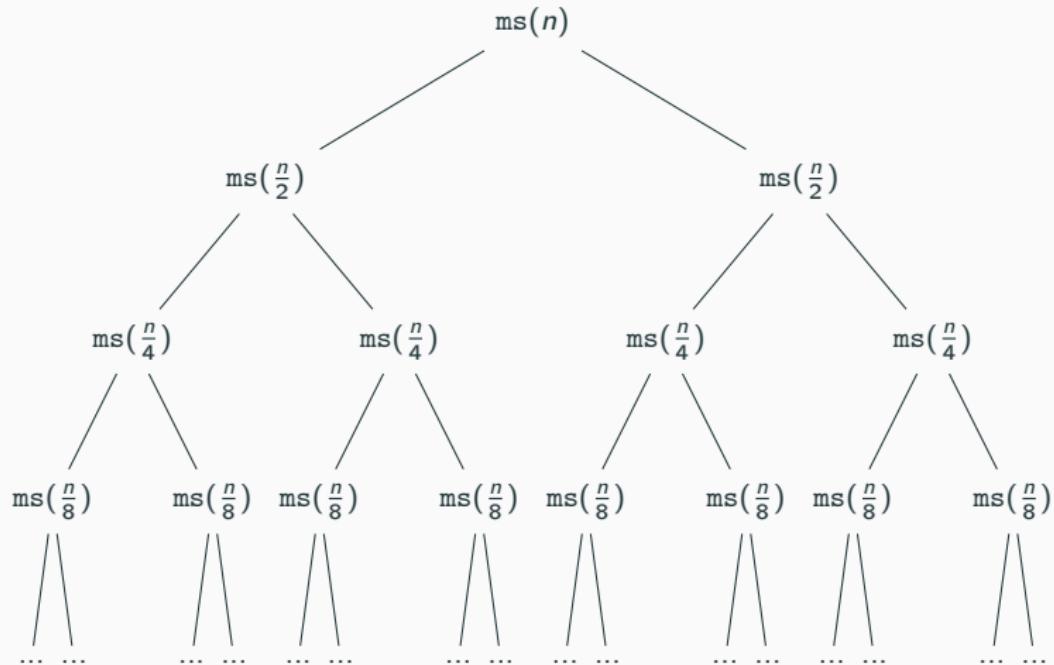
However, unlike our previous functions we cannot simply calculate how many times we call `mergeSort` and multiply by that by n because each call to `mergeSort` isn't doing an amount of work relative to our original input n but their own very different argument!

Runtime of `mergeSort`

However, unlike our previous functions we cannot simply calculate how many times we call `mergeSort` and multiply by that by n because each call to `mergeSort` isn't doing an amount of work relative to our original input n but their own very different argument!

To understand how much work `mergeSort` does we will draw a diagram and interpret it. Remember that each call to `mergeSort` is doing an amount of work linearly relative to its input size.

Analyzing mergeSort



Look at each “row” of our diagram. How much work is actually being done in each row?

Analyzing mergeSort

If we number our rows starting at zero and increasing by one each row we go down then the number of calls to `mergeSort` performed in row i is 2^i . That's a lot of calls very quickly!

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However, how much work is actually being performed in each of these rows? We know each `mergeSort` does work linear to its input size other than its recursive calls which are depicted in the lower rows, so the recursive work is calculated separately.

In each row we have 2^i calls, but each call in that row is only doing $\frac{n}{2^i}$ work! So each row is doing an amount of work equal to $2^i \cdot \frac{n}{2^i} \rightarrow \frac{2^i n}{2^i} \rightarrow n$

Analyzing mergeSort

Since we now know each row is really only performing n work, where n is the size of our original input we need only to find how many rows there will be for a LList of length n and multiply!

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Since we now know each row is really only performing n work, where n is the size of our original input we need only to find how many rows there will be for a LList of length n and multiply!

Each time we recursively call ourselves we divide n by two, and we stop when our LList is empty or length one. So since the input to each row has half the length of the previous row we simply need to answer the question “How many times can we divide n by two before it becomes one?”

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The logarithm function is exactly the function that answers that question! As such, the number of rows we will have when mergeSort is called on a LList of length n is then $\log_2 n$

Analyzing mergeSort

This means the runtime of `mergeSort` is then $\Theta(n \log_2 n)$ — which is much better than the $\Theta(n^2)$ of bubble sort and insertion sort!

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Remember our `findPairs` function which had a runtime of n^2 for the naive solution on an arbitrary `LList`, but a runtime of n for a sorted `LList`.

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This means the runtime of `mergeSort` is then $\Theta(n \log_2 n)$ — which is much better than the $\Theta(n^2)$ of bubble sort and insertion sort!

Remember our `findPairs` function which had a runtime of n^2 for the naive solution on an arbitrary `LList`, but a runtime of n for a sorted `LList`.

Now with `mergeSort` we could write `findPairs` that takes only $n \log_2 n$ time on an arbitrary `LList`!

Improving findPairs

The algorithm to write `findPairs` on an arbitrary `LList` in $n \log_2 n$ time becomes quite simple, and is as follows.

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1. Call `mergeSort` to sort the `LList`, this takes $n \log_2 n$ time

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The algorithm to write `findPairs` on an arbitrary `LList` in $n \log_2 n$ time becomes quite simple, and is as follows.

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4. So, this algorithm is $\Theta(n \log_2 n)$

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Changing sort comparator

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Changing sort comparator

So far all the sorting algorithms we've written have sorted in non-decreasing order. What if we wanted to sort in a different order — for example non-increasing?

As it stands now, we'd have to write a whole new function to sort differently. Consider the two implementations of merge sort on the following slides.

Merge sort in non-decreasing order

```
def mergeSort(l):
    def merge(sl1, sl2):
        if isEmpty(sl1):
            return sl2
        if isEmpty(sl2):
            return sl1
        if first(sl1) < first(sl2):
            return cons(first(sl1), merge(rest(sl1), sl2))
        return cons(first(sl2), merge(sl1, rest(sl2)))
    if len(l) <= 1:
        return l
    leftHalf = mergeSort(takeN(l, len(l)//2))
    rightHalf = mergeSort(skipN(l, len(l)//2))
    return merge(leftHalf, rightHalf)
```

Merge sort in non-increasing order

```
def mergeSort(l):
    def merge(sl1, sl2):
        if isEmpty(sl1):
            return sl2
        if isEmpty(sl2):
            return sl1
        if first(sl1) > first(sl2):
            return cons(first(sl1), merge(rest(sl1), sl2))
        return cons(first(sl2), merge(sl1, rest(sl2)))
    if len(l) <= 1:
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The difference in sorts

How did the two implementations of `mergeSort` differ?

They differed in only *one* way! They differed in how they compared two elements of the LList.

One version compared `first(s11) > first(s12)` while the other compared `first(s11) < first(s12)`

As we did when writing other higher order functions we can abstract out the differences of these two implementations by simply adding a parameter to represent this process.

Parameterized mergeSort

We simply add a second parameter `cmp` to `mergeSort`. The parameter `cmp` should be the function that takes two parameters `a` and `b` and returns `True` if `a` should come before `b` in a sorted sequence and `False` otherwise.

Such a function is called a *comparator* function as it *compares* elements of the sequence.

Parameterized mergeSort

```
def mergeSort(l, cmp):
    def merge(sl1, sl2):
        if isEmpty(sl1):
            return sl2
        if isEmpty(sl2):
            return sl1
        if cmp(first(sl1), first(sl2)):
            return cons(first(sl1), merge(rest(sl1), sl2))
        return cons(first(sl2), merge(sl1, rest(sl2)))
    if len(l) <= 1:
        return l
    leftHalf = mergeSort(takeN(l, len(l)//2), cmp)
    rightHalf = mergeSort(skipN(l, len(l)//2), cmp)
    return merge(leftHalf, rightHalf)
```

Improved sorting

The benefit of adding a comparator function parameter to our sorting functions is that we can specify how we would like our elements sorted each time we call the function without having to write a whole new sorting function.

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Being able to specify the comparator function doesn't only help us to change the order in which we sort. Previously when we only used the `<` operator we could only sort `Lists` of data for which the `<` operator was defined.

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Being able to specify the comparator function doesn't only help us to change the order in which we sort. Previously when we only used the `<` operator we could only sort `LLists` of data for which the `<` operator was defined.

As we now provided the comparator function we can define it to work on whatever type we have stored within our `LList`. For example, we might want to store cards.

Representing playing cards

How can we represent playing cards in our Python program?

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We start by identifying that a playing card is nothing more than two pieces of data — a rank and a suit.

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How can we represent playing cards in our Python program?

We start by identifying that a playing card is nothing more than two pieces of data — a rank and a suit.

Our possible ranks, in order, are the numbers 2 – 10 as well as the Jack, Queen, King, and Ace.

Our suits, in order, are Diamonds, Clubs, Hearts, and Spades.

Storing cards

So, we define a data type to represent cards as shown below.

...

A Card is a

- $LL(Rank, Suit)$

A Rank is

- *An integer in the range [2, 14]*

A suit is

- *An integer in the range [0, 3]*

...

Storing cards

Why are our ranks the numbers 2 – 14 when they should be 2 – 10 as well as Jack, Queen, King, and Ace?

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Why are our ranks the numbers 2 – 14 when they should be 2 – 10 as well as Jack, Queen, King, and Ace?

Even stranger why are our suits 0 – 3 when they should be Diamonds, Clubs, Hearts, and Spades?

We need to be able to compare our ranks to each other as well as our suits to each other. The strings that represent our suits or ranks are not easily comparable.

Storing cards

Why are our ranks the numbers 2 – 14 when they should be 2 – 10 as well as Jack, Queen, King, and Ace?

Even stranger why are our suits 0 – 3 when they should be Diamonds, Clubs, Hearts, and Spades?

We need to be able to compare our ranks to each other as well as our suits to each other. The strings that represent our suits or ranks are not easily comparable.

So, we use our functional way of thinking to propose a mapping between integers and ranks as well as integers and suits.

Storing cards

The mapping we propose for our ranks is as follows:

$$2 \longleftrightarrow 2$$

$$3 \longleftrightarrow 3$$

$$4 \longleftrightarrow 4$$

$$5 \longleftrightarrow 5$$

$$6 \longleftrightarrow 6$$

$$7 \longleftrightarrow 7$$

$$8 \longleftrightarrow 8$$

$$9 \longleftrightarrow 9$$

$$10 \longleftrightarrow 10$$

$$11 \longleftrightarrow Jack$$

$$12 \longleftrightarrow Queen$$

$$13 \longleftrightarrow King$$

$$14 \longleftrightarrow Ace$$

Storing cards

The mapping we propose for our suits is as follows:

$$0 \longleftrightarrow \textit{Diamonds}$$

$$1 \longleftrightarrow \textit{Clubs}$$

$$2 \longleftrightarrow \textit{Hearts}$$

$$3 \longleftrightarrow \textit{Spades}$$

Both of these mappings are chosen such that the integer representing any rank A is higher than another rank B 's integer if A should appear to the right of B in a sorted hand. The same is true for our mapping of ranks.

Suited ordering

Quite often in card games we sort not only based on card rank, but also on card suit. In this sorting the card suit first determines order, and only if two cards have the same suit is rank used to determine which should come first.

Suited ordering

Quite often in card games we sort not only based on card rank, but also on card suit. In this sorting the card suit first determines order, and only if two cards have the same suit is rank used to determine which should come first.

That is, imagine you are given a hand of cards and you want to sort it so that all diamonds come first, then clubs, then hearts, then spades. Within each collection of suits you want the card sorted by rank in non-decreasing order.

Suited ordering

Quite often in card games we sort not only based on card rank, but also on card suit. In this sorting the card suit first determines order, and only if two cards have the same suit is rank used to determine which should come first.

That is, imagine you are given a hand of cards and you want to sort it so that all diamonds come first, then clubs, then hearts, then spades. Within each collection of suits you want the card sorted by rank in non-decreasing order.

Given that a Card is a LL(Rank, Suit) can you write a comparator function that compares two cards c_1 and c_2 and returns True if c_1 should appear before c_2 in the sorted order described above?

Suited ordering comparator function

The comparator function for two cards becomes quite easy to write, as we have defined our data in such a way that it is natural to work with.

```
def suitOrder(c1, c2):
    if second(c1) < second(c2):
        return True
    if second(c1) > second(c2):
        return False
    return first(c1) < first(c2)
```

Sorting a LList of Cards

Then sorting a LList of Cards in suited ordering is as simple as calling `mergeSort` on the LList and passing the correct comparator function.

```
hand = LL(LL(13, 2), LL(2, 3), LL(7, 1),
          LL(14, 0), LL(4, 3), LL(10, 0))
```

```
mergeSort(hand, suitOrder)
-> LL(LL(10, 0), LL(14, 0), LL(7, 1),
      LL(13, 2), LL(2, 3), LL(4, 3))
```

The sort is correct, but now our data doesn't really resemble *cards* because of how we've mapped between ranks, suits and integers.

Internal representation versus presentation

Using numbers to represent our suits and all of our ranks is the *internal representation* or the *implementation* we've chosen for our data. The internal representation of data should be chosen in such a way that it aids in the work we need to perform, which is why we chose the mapping we did.

However, when it comes to actually displaying data we often want to show something other than the internal representation. We may choose to call this the *presentation* of the data. This can be achieved simply by constructing a function that takes a particular type of data and returns whatever we want to display it as (e.g. a nice string).

Displaying Cards nicely

To improve the presentation of our cards we'll write a function `cardToStr` which can be called whenever we want to actually display a hand of cards. This function should take a `Card` as we've defined them and produce a string. The string should be the rank of the card followed by the suit character which is one of ♦, ♣, ♥, or ♠. For the ranks Jack, Queen, King, and Ace the character J, Q, K, and A should be used.

The cardToStr function

```
def cardToStr(c):
    suits = ('♦', '♣', '♥', '♠')
    ranks = ("2", "3", "4", "5", "6", "7", "8", "9",
             "10", "J", "Q", "K", "A")
    return ranks[first(c)-2] + suits[second(c)]
```

Now we can simply map this function onto a LList of cards in order to produce a LList of the string representation of those cards!

New kinds of data

Considering Cards as a data type we've now investigated how we can easily use functions to map between internal representations and presentations we'd like to display.

However, our hand of cards actually demonstrates another concept we have not discussed in detail. If we think of our hand as simply being a `LList` of `Cards` then it is easy to reason about. However, in reality our hand of cards is a `LList` of `LLists`.

When we have collection data types that themselves can contain collections as their elements we call it *multi-dimensional* data. Next we will investigate some of the many use cases of this data.