

Notes for ECE 36800 - Data Structures and Algorithms

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These are lecture notes for spring 2024 ECE 36800 at Purdue. Modify, use, and distribute as you please.

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Course Introduction

Provides insight into the use of data structures. Topics include stacks, queues and lists, trees, graphs, sorting, searching, and hashing. The learning outcomes are:

- Advanced programming ideas, in practice and in theory
- Data structures and their abstractions: Stacks, lists, trees, and graphs
- Fundamentals of algorithms and their complexities: Sorting, searching, hashing, and graph algorithms
- Problem-Solving

Introduction to Data Structures & Algorithms

Data Structures are methods of organizing information for ease of manipulation. Examples:

1. Dictionary
2. Check-out line or queues
3. Spring-loaded plate dispenser or stacked
4. Organizational Chart or tree

These are associated with methods known as algorithms to be manipulated

Algorithms are methods of doing something. Examples:

1. Multiplying two numbers
2. Making a sandwich
3. Getting dressed

The topics of interest within them are:

- Correctness
- Efficiency in time and space

Time Complexity Analysis

The questions to be asked about an algorithm are the following:

- Is it correct?
- Is it as fast as possible?
- How many machine instructions (in terms of n) does it take?

Let us take the following algorithm to add the numbers from 1 to n :

```
total = 0;
for (i=1:n)
    total = total + i;
return total
```

The cost will be:

| Cost | Frequency | Function |
|-------|-----------|------------------------------|
| C_1 | 1 | Assign initial value |
| C_2 | $n+1$ | For loop iterations and exit |
| C_3 | n | Number additions |
| C_4 | 1 | Return value |

The total is then:

$$C_1 * 1 + C_2(n + 1) + C_3(n) + C_4(1) = (C_2 + C_3)n + (C_1 + C_2) + C_4$$

However the $O(n)$ will only be n , as the constants and coefficients of these will be deprecated, as we will come to understand in more detail as this topic continues.

Let us take another example of some code that has a

$$\begin{aligned}
 T(n) &= n^2 + 10^7 n + 10^{10} \\
 T(10^{11}) &= 10^{22} + 10^{18} + 10^{10} \\
 T(2 * 10^{11}) &= 4 * 10^{22} + 2 * 10^{18} + 10^{10} \\
 \Rightarrow \frac{T(2 * 10^{11})}{T(10^{11})} &\approx 4 = \left(\frac{2 * 10^{11}}{10^{11}} \right)^2
 \end{aligned}$$

This goes to show that this algorithm has an $O(n) = n^2$, and all coefficients and lower order terms that are a part of the complexity are largely irrelevant for large n values. This is why this is called **asymptotic notation**.

Another example of a simple algorithm is

```

total = 0;
for (i=1:n):
    if (((i*i%3)==0) || ((i*i%7)==0)):
        total = total+i*i;
return total;

```

Which has a cost table that looks like the following:

| Cost | Frequency | Function |
|-------|--|------------------------------|
| C_1 | 1 | Assign initial value |
| C_2 | $n+1$ | For loop iterations and exit |
| C_3 | n | Number of $i\%3$ comparisons |
| C_4 | $n - \lfloor \frac{n}{3} \rfloor$ | Number of $i\%7$ comparisons |
| C_5 | $\lfloor \frac{n}{3} \rfloor + \lfloor \frac{n}{7} \rfloor - \lfloor \frac{n}{21} \rfloor$ | Number of additions |
| C_6 | 1 | Returning value |

It can be noted that $O(n) = n$ for this function, despite all the other complexities in the algorithm. However, it is important to know how to calculate $T(n)$ as well.

Now, let us look at something more complicated, matrix multiplication of two lower triangular matrices.

```

for (i=1:n):
    for (j=1:i):
        C_ij = 0;
        for (k=j:i):
            C_ij = C_ij+A_ik*B_kj
return C

```

This has a cost table that looks like the following: Finally, we can

| Cost | Frequency | Function |
|-------|--|-----------------------------|
| C_1 | $n+1$ | First loop |
| C_2 | $\sum_{i=1}^n (i+1)$ | Second loop |
| C_3 | $\sum_{i=1}^n \sum_{j=1}^i 1$ | Number of assigns |
| C_4 | $\sum_{i=1}^n \sum_{j=1}^i (i-j+2)$ | Third loop |
| C_5 | $\sum_{i=1}^n \sum_{j=1}^i \sum_{k=j}^i 1$ | Number of assigns to matrix |
| C_6 | 1 | Returning value |

analyze an example that has logarithmic complexities.

```

i=2;
k=0;
while (i<n){
    i=i*i;
    k=k+1;
}
return i;

```

Which has a cost table that looks like the following:

| Cost | Frequency | Function |
|-------|---------------------------------------|---------------------------------|
| C_1 | 1 | Assign i |
| C_2 | 1 | Assign k |
| C_3 | $\lceil \log_2(\log_2(n)) \rceil + 1$ | Number of while loop iterations |
| C_4 | $\lceil \log_2(\log_2(n)) \rceil$ | number of assigns of i |
| C_5 | $\lceil \log_2(\log_2(n)) \rceil$ | Number of k assigns |
| C_6 | 1 | Returning value |

It can be noted that if line three was instead changed to

```
while (i<=n){
```

The table will instead be:

| Cost | Frequency | Function |
|-------|---|---------------------------------|
| C_1 | 1 | Assign i |
| C_2 | 1 | Assign k |
| C_3 | $\lceil \log_2(\log_2(n+1)) \rceil + 1$ | Number of while loop iterations |
| C_4 | $\lceil \log_2(\log_2(n+1)) \rceil$ | number of assigns of i |
| C_5 | $\lceil \log_2(\log_2(n+1)) \rceil$ | Number of k assigns |
| C_6 | 1 | Returning value |

As the loop break condition changed from $i \geq n$ to $i \geq n + 1$ by simply changing.

Insertion and Shell Sort

Sorting is necessary to process items in sorted order. It speeds up the location of items, finding identical items, etc.

It is good to know that in real life, what is sorted is in fact the pointers of these structs, as the movement of structs have higher memory requirements.

Insertion Sort

Inserts an item into a sorted array. Compares the item with items in the sorted array, and if they are in the incorrect order, they are swapped. This is continued until everything has been successfully sorted.

The code to sort n integers in an array r looks like this:

```

for (j=1:n-1){
    for (i=j:1){
        if (r[i-1]>r[i]){
            swap(r[i-1], r[i]);
        }
        else {
            break;
        }
    }
}

```

This is suboptimally inefficient due to the restriction of only swapping with neighbors, directly. However, it can be made even more efficient using the following algorithm:

```

for (j=1:n-1){
    temp = r[j];
    for (i=j:1){
        if (r[i-1]>temp_r){

```

```

        r[i] = r[i-1];
    }
    else {
        break;
    }
}
r[i] = temp_r;
}

```

This allows us to "move" items down without constant comparisons, saving us some assignments.

This can also be implemented using while loops, and thus avoiding break:

```

for (j=1:n-1){
    temp=r[j];
    i=j;
    while (i>0 and r[i-1]>temp){
        r[i] = r[i-1];
        i -=1;
    }
    r[i]=temp_r;
}

```

This has the following cost table in the best case: Which has a com-

| Cost | Frequency | Function |
|-------|-----------|----------------------------------|
| C_1 | n | For loop iterations |
| C_2 | $n-1$ | Assign temp |
| C_3 | $n-1$ | Assign i |
| C_4 | $n-1$ | It is checked once per iteration |
| C_5 | 0 | |
| C_6 | 0 | |
| C_7 | $n-1$ | |

plexity $O(n) = n$ And the following in the worst case: Now, we will

| Cost | Frequency | Function |
|-------|------------------------|--|
| C_1 | n | For loop iterations |
| C_2 | $n-1$ | Assign temp |
| C_3 | $n-1$ | Assign i |
| C_4 | $\frac{(n+2)(n-1)}{2}$ | Number of time the while loop is checked |
| C_5 | $\frac{(n)(n-1)}{2}$ | |
| C_6 | $\frac{(n)(n-1)}{2}$ | |
| C_7 | $n-1$ | |

learn how to calculate the average performance of an algorithm like insertion sort.

Let us take a random j^{th} item. The probability of it not needing to be moved is $\frac{1}{j+1}$. And it will need a certain some number between 0 and j exchanges to get to its rightful position if not. This leads the expected total number of exchanges to be $\sum_{i=0}^j \frac{i}{j+1} = \frac{j}{2}$. Once we reach the $(n-1)^{\text{th}}$ element, this is $\frac{1}{2} \frac{n(n-1)}{2} \approx \frac{n^2}{4}$.

Average performance is seldom calculated for the intents and purposes of this course.

There are still some inefficiencies in insertion sort that can be improved by using sentinels.

```

for (j=n-1:1){
    if (r[j]<r[j-1]){
        swap(r[j], r[j-1]);
    }
}
for (j=2:n-1){
    temp=r[j];
    i=j;
    while (r[i-1]>temp){
        r[i] = r[i-1];
        i -= 1;
    }
    r[i]=temp;
}

```

By moving the smallest item to the beginning, we can avoid the $(i>0)$ condition, slightly increasing efficiency.

Shell Sort

This improves insertion sort by allowing for swaps along larger distances between elements.

If we did 7-sorting and 3-sorting:

We would start with 7 subarrays with at most $\lceil \frac{n}{7} \rceil$ elements. These subarrays would need to be sorted within themselves.

We would then go over to having 3 subarrays with at most $\lceil \frac{n}{3} \rceil$ elements. These subarrays would once again need to be sorted within themselves.

Finally, we would conduct regular insertion sort. The complexity of shell sort changes based on the selected sequence.

- $1, 3, 7, 15, \dots, 2^k - 1, \dots$ has a complexity of $O(n^{1.5})$
- $1, 4, 13, \dots, 3h(h-1), \dots$ also has a complexity of $O(n^{1.5})$
- $2^p 3^q$ has a complexity $O(n(\log(n))^2)$

The algorithm of shell sort is the following:

```

for (j=k:n-1){
    temp=r[j];
    i=j;
    while (i>=k and r[i-k]>temp){
        r[i]=r[i-k];
        i=i-k;
    }
    r[i]=temp;
}

```

To prove the complexity of the $2^p 3^q$ complexity, we can visualize the following triangle:

```

      1
     2 3
    4 6 9
   8 12 18 27

```

which holds the values of k from the above algorithm the height and base of the triangle both have complexities of $\log(n)$, while the sorting of the subset made by each k has a complexity of n , which results in a total complexity of $n(\log(n))^2$.

Let us consider a triangle of the following form:

```

      a
     2a 3a

```

If one were to start with the largest and go to the smallest, that is, if one were to $3a$ -sort, and then $2a$ -sort, all numbers in the array would be at most a positions away from their correct positions.

This can be semi-trivially proven under the assumption that if an array is $3a$ -sorted and then $2a$ -sorted, it will still be $3a$ -sorted. This will not be solved in this document as it is a homework assignment.

Asymptotic Notation

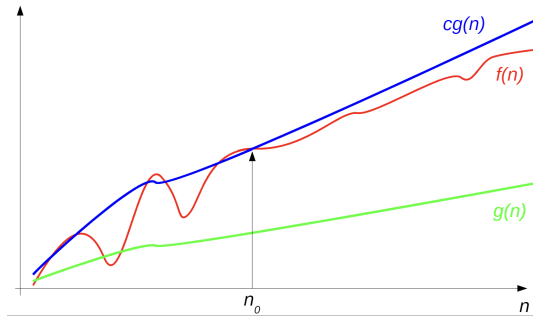
The number of instructions executed is dependent on the number of inputs. As it gets larger, the number of instructions increases too.

This has been generalized and classified using asymptotic notation.

$$f(n) = O(g(n)) \iff \exists(c, n_0) \text{ such that } f(n) \leq cg(n) \quad \forall(n \geq n_0)$$

Note: If the space complexity is $O(g)$, the time complexity will be at least $O(g)$.

The graphical representation of the above definition $O(n)$ is :



The values of c and n_0 can be variable, and have any value, as long as the condition is fulfilled.

However, we are searching for $g(n)$ such that it refers to the smallest and simplest possible function of n to allow for the existence of the values of c and n_0 that will make the condition true.

A good strategy to select c is the sum of the absolute values of all the coefficients in $f(n)$.

Note: $f(n)$ is equivalent to the $T(n)$ in the Time Complexity Analysis section.

Another proof of $f(n) = O(g(n))$ is $\lim_{n \rightarrow \infty} \frac{f(n)}{g(n)} \neq \infty$.

However, it is not really necessary to go to this extent to find c as there are several easier ways to find valid values. This method is an unnecessary complication for most cases.

For $g(n)$ to be useful, it should be simpler than $f(n)$ such as $1, n, n^2, n \log(n), 2^n, n!$.

However, once we go to exponential functions or above, the algorithms cease to be useful.

Some properties of asymptotic notation are:

$$f(n) = O(f(n))$$

$$f(n) = O(g(n)) \quad \& \quad g(n) = O(h(n)) \implies f(n) = O(h(n))$$

$$f(n) = O(g(n)) \quad \& \quad g(n) = O(h(n)) \implies f(n) + g(n) = O(h(n))$$

$$f_1(n) = O(g_1(n)) \quad \& \quad f_2(n) = O(g_2(n)) \implies f_1(n) * f_2(n) = O(g_1(n) * g_2(n))$$

Hierarchy of $O(n)$ (in this section, we will show what possible asymptotic notations functions can have.):

1. $k = O(1)$
2. $k = O(\log_m(n))$

3. $k \log_m(n) = O(\log(n))$
4. $k(\log_m(n))^i = O(n)$
5. $kn = O(n)$
6. $kn \log_m(n) = O(n \log(n))$
7. $kn \log(n) = O(n^2)$
8. $kn^i = O(n^l) \quad \forall (j \geq i)$
9. $kn^j = O(d^n \quad \forall (d > 1))$
10. $kd^n = O(d^n) \quad \forall (d > 1)$
11. $kd_1^n = O(d_2^n) \quad \forall (d_1 > 1 \quad \& \quad d_1 < d_2)$
12. $kd^n = O(n!)$
13. $kn! = O(n!)$
14. $kn! = O(n^n)$
15. $kn^n = O(n^n)$

There is a notation that goes hand in hand with $O(n)$:

$$\begin{aligned}
 f(n) = O(g(n)) &\implies g(n) = \Omega(f(n)) \\
 \exists c, n_0 \mid f(n) \leq g(n) &\implies \exists c', n'_0 \mid g(n) \geq f(n) \\
 &\implies \lim_{n \rightarrow \infty} \frac{f(n)}{g(n)} = 0
 \end{aligned}$$

And another, the Theta Notation:

$$\begin{aligned}
 f(n) = \Theta(g(n)) &\iff \exists (c_1, c_2, n_0) \quad c_1 g(n) \leq f(n) \leq c_2 g(n) \\
 &\iff \lim_{n \rightarrow \infty} \frac{f(n)}{g(n)} \neq 0, \infty \\
 &\iff [f(n) = O(g(n))] \wedge [g(n) = O(f(n))]
 \end{aligned}$$

And finally the little-o notation:

$$\begin{aligned}
 f(n) = o(g(n)) &\iff \lim_{n \rightarrow \infty} \frac{f(n)}{g(n)} = 0 \\
 &\iff \forall c, \exists n_0 \mid f(n) \leq c g(n) \quad \forall n \geq n_0
 \end{aligned}$$

Which leads to the little-omega notation:

$$\begin{aligned}
 g(n) = \omega(f(n)) &\iff f(n) = o(g(n)) \\
 &\iff \lim_{n \rightarrow \infty} \frac{g(n)}{f(n)} = \infty
 \end{aligned}$$

For most cases, if f is $O(g)$, but not $\Theta(g)$, it is $o(g)$. Exceptional cases would be like $f(n) = n^{|\sin(n)|}$, which seldom exist.

Linked Lists

A list is a linear collection of items that can be inserted and removed at any position.

Arrays have $O(1)$ access and overwrite, although insertion or removal may be more than $O(1)$. The size of the array is necessary to program correctly.

A linked list has the followings structure defining it:

```
typedef int Info_t;
typedef struct _Node
{
    Info_t data;
    struct _Node *next;
} Node;
```

```
typedef struct _Header
{
    Node *head;
    Node *tail;
} Header;
```

Need to have Head, without it, we cannot do anything.

One can also have the tail, if we so wanted.

The header may contain the addresses of the head, tail, and other useful information for easy access.

They have primitive operations:

- Empty: return true/false
- First: return address to first node
- Last: return address to last node
- Insert at head: insert as the first node of the list
- Insert at tail: insert as last node
- Remove at head
- etc.