Complexity Analysis of Algorithms

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Estimating runtime

What is the runtime of g(n)?

```c
void g(int n) {
    for (int i = 0; i < n; ++i) f();
}
```

Runtime(g(n)) ≈ n \cdot \text{Runtime}(f())

```c
void g(int n) {
    for (int i = 0; i < n; ++i)
        for (int j = 0; j < n; ++j) f();
}
```

Runtime(g(n)) ≈ n^2 \cdot \text{Runtime}(f())
Estimating runtime

What is the runtime of \( g(n) \)?

```c
void g(int n) {
    for (int i = 0; i < n; ++i)
        for (int j = 0; j <= i; ++j) f();
}
```

\[
\text{Runtime}(g(n)) \approx (1 + 2 + 3 + \cdots + n) \cdot \text{Runtime}(f())
\]

\[
\approx \frac{n^2 + n}{2} \cdot \text{Runtime}(f())
\]
Complexity analysis

• A technique to characterize the execution time of an algorithm independently from the machine, the language and the compiler.

• Useful for:
  – evaluating the variations of execution time with regard to the input data
  – comparing algorithms

• We are typically interested in the execution time of large instances of a problem, e.g., when $n \to \infty$, (asymptotic complexity).
Big O

• A method to characterize the execution time of an algorithm:
  – Adding two square matrices is $O(n^2)$
  – Searching in a dictionary is $O(\log n)$
  – Sorting a vector is $O(n \log n)$
  – Solving Towers of Hanoi is $O(2^n)$
  – Multiplying two square matrices is $O(n^3)$
  – ... 

• The $O$ notation only uses the dominating terms of the execution time. Constants are disregarded.
Big O: formal definition

- Let $T(n)$ be the execution time of an algorithm when the size of input data is $n$.
- $T(n)$ is $O(f(n))$ if there are positive constants $c$ and $n_0$ such that $T(n) \leq c \cdot f(n)$ when $n \geq n_0$. 
Big O: example

• Let \( T(n) = 3n^2 + 100n + 5 \), then \( T(n) = O(n^2) \)

• Proof:
  – Let \( c = 4 \) and \( n_0 = 100.05 \)
  – For \( n \geq 100.05 \), we have that \( 4n^2 \geq 3n^2 + 100n + 5 \)

• \( T(n) \) is also \( O(n^3), O(n^4) \), etc. Typically, the smallest complexity is used.
## Big O: examples

<table>
<thead>
<tr>
<th>$T(n)$</th>
<th>Complexity</th>
</tr>
</thead>
<tbody>
<tr>
<td>$5n^3 + 200n^2 + 15$</td>
<td>$O(n^3)$</td>
</tr>
<tr>
<td>$3n^2 + 2^{300}$</td>
<td>$O(n^2)$</td>
</tr>
<tr>
<td>$5 \log_2 n + 15 \ln n$</td>
<td>$O(\log n)$</td>
</tr>
<tr>
<td>$2 \log n^3$</td>
<td>$O(\log n)$</td>
</tr>
<tr>
<td>$4n + \log n$</td>
<td>$O(n)$</td>
</tr>
<tr>
<td>$2^{64}$</td>
<td>$O(1)$</td>
</tr>
<tr>
<td>$\log n^{10} + 2\sqrt{n}$</td>
<td>$O(\sqrt{n})$</td>
</tr>
<tr>
<td>$2^n + n^{1000}$</td>
<td>$O(2^n)$</td>
</tr>
</tbody>
</table>
## Complexity ranking

<table>
<thead>
<tr>
<th>Function</th>
<th>Common name</th>
</tr>
</thead>
<tbody>
<tr>
<td>$n!$</td>
<td>factorial</td>
</tr>
<tr>
<td>$2^n$</td>
<td>exponential</td>
</tr>
<tr>
<td>$n^d$, $d &gt; 3$</td>
<td>polynomial</td>
</tr>
<tr>
<td>$n^3$</td>
<td>cubic</td>
</tr>
<tr>
<td>$n^2$</td>
<td>quadratic</td>
</tr>
<tr>
<td>$n \sqrt{n}$</td>
<td></td>
</tr>
<tr>
<td>$n \log n$</td>
<td>quasi-linear</td>
</tr>
<tr>
<td>$n$</td>
<td>linear</td>
</tr>
<tr>
<td>$\sqrt{n}$</td>
<td>root - $n$</td>
</tr>
<tr>
<td>$\log n$</td>
<td>logarithmic</td>
</tr>
<tr>
<td>$1$</td>
<td>constant</td>
</tr>
</tbody>
</table>
Complexity analysis: examples

Let us assume that $f()$ has complexity $O(1)$

```
for (int i = 0; i < n; ++i) f();  \rightarrow O(n)
```

```
for (int i = 0; i < n; ++i)
    for (int j = 0; j < n; ++j) f();  \rightarrow O(n^2)
```

```
for (int i = 0; i < n; ++i)
    for (int j = 0; j <= i; ++j) f();  \rightarrow O(n^2)
```

```
for (int i = 0; i < n; ++i)
    for (int j = 0; j < n; ++j)
        for (int k = 0; k < n; ++k) f();  \rightarrow O(n^3)
```

```
for (int i = 0; i < m; ++i)
    for (int j = 0; j < n; ++j)
        for (int k = 0; k < p; ++k) f();  \rightarrow O(mnp)
```
Complexity analysis: recursion

```
void f(int n) {
    if (n > 0) {
        DoSomething(n); // O(n)
        f(n/2);
    }
}
```

\[
T(n) = n + T\left(\frac{n}{2}\right)
\]

\[
T(n) = n + \frac{n}{2} + \frac{n}{4} + \frac{n}{8} + \cdots + 2 + 1
\]

\[
2 \cdot T(n) = 2n + n + \frac{n}{2} + \frac{n}{4} + \frac{n}{8} + \cdots + 4 + 2
\]

\[
2 \cdot T(n) - T(n) = T(n) = 2n - 1
\]

\[
T(n) \text{ is } \mathcal{O}(n)
\]
void f(int n) {
    if (n > 0) {
        DoSomething(n); // O(n)
        f(n/2); f(n/2);
    }
}

\[
T(n) = n + 2 \cdot T(n/2)
\]
\[
= n + 2 \cdot \frac{n}{2} + 4 \cdot \frac{n}{4} + 8 \cdot \frac{n}{8} + \cdots
\]
\[
= n + n + n + \cdots + n = n \log_2 n
\]

\(T(n)\) is \(O(n \log n)\)
Complexity analysis: recursion

```c
void f(int n) {
    if (n > 0) {
        DoSomething(n); // O(n)
        f(n-1);
    }
}
```

\[
T(n) = n + T(n - 1)
\]

\[
T(n) = n + (n - 1) + (n - 2) + \cdots + 2 + 1
\]

\[
T(n) = \frac{n^2 + n}{2}
\]

\(T(n)\) is \(O(n^2)\)
Complexity analysis: recursion

```c
void f(int n) {
    if (n > 0) {
        DoSomething(); // O(1)
        f(n-1); f(n-1);
    }
}
```

\[
T(n) = 1 + 2 \cdot T(n - 1) \\
= 1 + 2 + 4 \cdot T(n - 2) \\
= 1 + 2 + 4 + 8 \cdot T(n - 3) \\
\vdots \\
= 1 + 2 + 4 + 8 + \cdots + 2^{n-1} \\
= \sum_{i=0}^{n-1} 2^i = 2^n - 1
\]

\( T(n) \) is \( O(2^n) \)
Asymptotic complexity (small values)
Asymptotic complexity (larger values)
Let us consider that every operation can be executed in 1 ns ($10^{-9}$ s).

<table>
<thead>
<tr>
<th>Function</th>
<th>$n = 10^3$</th>
<th>$n = 10^4$</th>
<th>$n = 10^5$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\log_2 n$</td>
<td>10 ns</td>
<td>13.3 ns</td>
<td>16.6 ns</td>
</tr>
<tr>
<td>$\sqrt{n}$</td>
<td>31.6 ns</td>
<td>100 ns</td>
<td>316 ns</td>
</tr>
<tr>
<td>$n$</td>
<td>1 µs</td>
<td>10 µs</td>
<td>100 µs</td>
</tr>
<tr>
<td>$n \log_2 n$</td>
<td>10 µs</td>
<td>133 µs</td>
<td>1.7 ms</td>
</tr>
<tr>
<td>$n^2$</td>
<td>1 ms</td>
<td>100 ms</td>
<td>10 s</td>
</tr>
<tr>
<td>$n^3$</td>
<td>1 s</td>
<td>16.7 min</td>
<td>11.6 days</td>
</tr>
<tr>
<td>$n^4$</td>
<td>16.7 min</td>
<td>116 days</td>
<td>3171 yr</td>
</tr>
<tr>
<td>$2^n$</td>
<td>$3.4 \cdot 10^{284}$ yr</td>
<td>$6.3 \cdot 10^{2993}$ yr</td>
<td>$3.2 \cdot 10^{30086}$ yr</td>
</tr>
</tbody>
</table>
How about “big data”? 

**Source:** Jon Kleinberg and Éva Tardos, Algorithm Design, Addison Wesley 2006.

Table 2.1 The running times (rounded up) of different algorithms on inputs of increasing size, for a processor performing a million high-level instructions per second. In cases where the running time exceeds $10^{25}$ years, we simply record the algorithm as taking a very long time.

<table>
<thead>
<tr>
<th>$n$</th>
<th>$n$</th>
<th>$n \log_2 n$</th>
<th>$n^2$</th>
<th>$n^3$</th>
<th>$1.5^n$</th>
<th>$2^n$</th>
<th>$n!$</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>&lt; 1 sec</td>
<td>&lt; 1 sec</td>
<td>&lt; 1 sec</td>
<td>&lt; 1 sec</td>
<td>&lt; 1 sec</td>
<td>&lt; 1 sec</td>
<td>4 sec</td>
</tr>
<tr>
<td>30</td>
<td>&lt; 1 sec</td>
<td>&lt; 1 sec</td>
<td>&lt; 1 sec</td>
<td>&lt; 1 sec</td>
<td>&lt; 1 sec</td>
<td>18 min</td>
<td>$10^{25}$ years</td>
</tr>
<tr>
<td>50</td>
<td>&lt; 1 sec</td>
<td>&lt; 1 sec</td>
<td>&lt; 1 sec</td>
<td>&lt; 1 sec</td>
<td>11 min</td>
<td>36 years</td>
<td>very long</td>
</tr>
<tr>
<td>100</td>
<td>&lt; 1 sec</td>
<td>&lt; 1 sec</td>
<td>&lt; 1 sec</td>
<td>1 sec</td>
<td>12,892 years</td>
<td>10^{17} years</td>
<td>very long</td>
</tr>
<tr>
<td>1,000</td>
<td>&lt; 1 sec</td>
<td>&lt; 1 sec</td>
<td>1 sec</td>
<td>18 min</td>
<td>very long</td>
<td>very long</td>
<td>very long</td>
</tr>
<tr>
<td>10,000</td>
<td>&lt; 1 sec</td>
<td>&lt; 1 sec</td>
<td>2 min</td>
<td>18 min</td>
<td>very long</td>
<td>very long</td>
<td>very long</td>
</tr>
<tr>
<td>100,000</td>
<td>&lt; 1 sec</td>
<td>2 sec</td>
<td>3 hours</td>
<td>12 days</td>
<td>very long</td>
<td>very long</td>
<td>very long</td>
</tr>
<tr>
<td>1,000,000</td>
<td>1 sec</td>
<td>20 sec</td>
<td>12 days</td>
<td>31,710 years</td>
<td>very long</td>
<td>very long</td>
<td>very long</td>
</tr>
</tbody>
</table>

This is often the practical limit for big data.
Summary

- Complexity analysis is a technique to analyze and compare algorithms (not programs).

- It helps to have preliminary back-of-the-envelope estimations of runtime (milliseconds, seconds, minutes, days, years?).

- Worst-case analysis is sometimes overly pessimistic. Average case is also interesting (not covered in this course).

- In many application domains (e.g., big data) quadratic complexity, $O(n^2)$, is not acceptable.

- Recommendation: avoid last-minute surprises by doing complexity analysis before writing code.