Foundations of Computer Science: Lecture 2

Recursion and Complexity

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The Practical Classes

https://www.cl.cam.ac.uk/teaching/2324/OCaml/

- Executed online in the hub.cl.cam.ac.uk server
- There are 5 ticks, each of which have a deadline for submission 10 days after they are issued *(except last tick, which goes into Lent term)*.

Tick 1: released 2023-10-06 due 2023-10-16

Tick 2: released 2023-10-13 due 2023-10-23

Tick 3: released 2023-10-20 due 2023-10-30

Tick 4: released 2023-10-27 due 2023-11-06

Tick 5: released 2023-11-03 due 2024-01-19

Expression Evaluation

$$E_0 \to E_1 \to \dots \to E_n \to v$$

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$$E_0 \rightarrow E_1 \rightarrow \ldots \rightarrow E_n \rightarrow v$$

Focus on *expressions;*
ignore *side-effects* for now.

This discipline of separating expression
from effects is often known as
functional programming

We will return to side effects later in the
course to make useful programs!

Expression Evaluation

$$E_0 \to E_1 \to \dots \to E_n \to v$$

```
# let rec power x n =
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```

$\text{power}(2, 12) \Rightarrow$

$\text{power}(4, 6) \Rightarrow$

$\text{power}(16, 3) \Rightarrow$

$16 \times \text{power}(256, 1) \Rightarrow$

$16 \times 256 \Rightarrow$

4096

Summing first *n* integers

```
# let rec nsum n =
    if n = 0 then
      0
    else
      n + nsum (n - 1)
```

$$
\begin{aligned}
nsum\ 3 &\Rightarrow 3 + (nsum\ 2) \\
&\Rightarrow 3 + (2 + (nsum\ 1)) \\
&\Rightarrow 3 + (2 + (1 + nsum\ 0)) \\
&\Rightarrow 3 + (2 + (1 + 0))
\end{aligned}
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Nothing can progress
until the final expression
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Nothing can progress until the final expression is calculated!

Two types of storage:
heap is a **global area** where the memory storing values bound to names are tracked
stack is a list where function call arguments are **pushed** and return values **popped.**

Iteratively summing

```
# let rec summing n total =
    if n = 0 then
      total
    else
      summing (n - 1) (n + total)
```

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# let rec nsum n =
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$$\begin{aligned} \mathit{summing}\ 3\ 0 &\Rightarrow \mathit{summing}\ 2\ 3 \\ &\Rightarrow \mathit{summing}\ 1\ 5 \\ &\Rightarrow \mathit{summing}\ 0\ 6 \\ &\Rightarrow 6 \end{aligned}$$

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Iteratively summing

```
# let rec summing n total =
    if n = 0 then
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```

Extra argument `total` acts as the *accumulator* to keep track explicitly instead of using the stack

$$\begin{aligned} \mathit{summing}\ 3\ 0 &\Rightarrow \mathit{summing}\ 2\ 3 \\ &\Rightarrow \mathit{summing}\ 1\ 5 \\ &\Rightarrow \mathit{summing}\ 0\ 6 \\ &\Rightarrow 6 \end{aligned}$$

Algorithms like this are known as *iterative* or *tail recursive*

Recursion *vs* iteration

- Why two terms *iterative* and *tail recursive*?
  - “Iterative” normally refers to a loop: e.g. coded using `while`.
  - “Tail-recursion” involves the recursive function call being the last thing that expression does.
- Tail-recursion is efficient only if the compiler detects it.
  - Mainly it saves space, though iterative code can run faster.
- Do not make programs iterative unless you determine the gain is significant.

How can we analyse our programs for efficiency?

Silly summing first *n* integers

```
# let rec sillySum n =
    if n = 0 then
      0
    else
      n + (sillySum (n-1) + sillySum (n-1)) / 2
```

Recursively calls itself
twice for every invocation

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Should **assign** the result to a local variable to prevent evaluating it twice

```
# let x = 2.0 in
  let y = Float.pow x 20.0 in
  y *. (x /. y)
```

Asymptotic complexity refers to how program costs grow with increasing inputs

Usually **space** or **time**, with the latter usually being larger than the former.

Question: if we double our processing power, how much does our computation capability increase?

Time Complexity

complexity	*1 second*	*1 minute*	*1 hour*	**gain**
n	1000	60,000	3,600,000	$\times 60$
$n \lg n$	140	4,893	200,000	$\times 41$
n^2	31	244	1,897	$\times 8$
n^3	10	39	153	$\times 4$
2^n	9	15	21	$+6$

complexity = milliseconds of runtime given an input of size n

Comparing Algorithms with O(n)

Formally, define $f(n) = O(g(n))$

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Intuitively, consider the *most significant term* and ignore constant or smaller factors

E.g. simplify $3n^2 + 34n + 433 \quad \rightarrow \quad n^2$

Facts about O notation

$O(2g(n))$ **is the same as** $O(g(n))$

$O(\log_{10} n)$ **is the same as** $O(\ln n)$

$O(n^2 + 50n + 36)$ **is the same as** $O(n^2)$

$O(n^2)$ **is contained in** $O(n^3)$

$O(2^n)$ **is contained in** $O(3^n)$

$O(\log n)$ **is contained in** $O(\sqrt{n})$

Common complexity classes

$O(1)$	*constant*
$O(\log n)$	*logarithmic*
$O(n)$	*linear*
$O(n \log n)$	*quasi-linear*
$O(n^2)$	*quadratic*
$O(n^3)$	*cubic*
$O(a^n)$	*exponential (for fixed a)*

Sample costs in O-notation

Function	Time	Space
npower, nsum	$O(n)$	$O(n)$
summing	$O(n)$	$O(1)$
$n(n+1)/2$	$O(1)$	$O(1)$
power	$O(\log n)$	$O(\log n)$
sillySum	$O(2^n)$	$O(n)$

Simple recurrence relations

$T(n)$: a cost we want to bound using O notation

Typical *base case*: $T(1) = 1$

Some *recurrences*:

$$T(n+1) = T(n) + 1 \qquad O(n)$$

$$T(n+1) = T(n) + n \qquad O(n^2)$$

$$T(n) = T(n/2) + 1 \qquad O(\log n)$$

$$T(n) = 2T(n/2) + n \qquad O(n \log n)$$

Mapping this to OCaml

```
# let rec nsum n =
    if n = 0 then
      0
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```

Given (n+1), does a constant amount of work

Then calls itself with n

Mapping this to OCaml

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$$O(n)$$

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Calls itself recursively once

Calls nsum which takes O(n)

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$$O(n^2)$$

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Always divides iteration count by 2

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$$O(\log n)$$