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More terminology: expressions like `x` and `a[n+1]` that refer to memory locations are called *lvalues*, as you can put them on the left side of an assignment: `a[n+1] = 42;`

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Exercise Some languages allow expressions on the left, as long as they evaluate to an lvalue (memory location). Read about this

Evaluation

Call by Reference

An rvalue does not (necessarily) have an associated memory location

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So things like `42 = n;` and `(2*m)++;` do not make sense

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So things like `42 = n;` and `(2*m)++;` do not make sense

Call by reference works on lvalues only

Evaluation

Behind the Scenes

In reality, call by reference is implemented by use of pointers, thus if you wrote code like

```
void f(int& a) {
    a = a + 3;
}
```

and called it with `f(n)` this is transformed behind the scenes by the compiler to the equivalent of

```
void f(int *a) {
    *a = *a + 3;
}
```

and the function call is rewritten to `f(&n)`

Evaluation

Behind the Scenes

The advantage is that you write the simpler code without the proliferation of ∗s and &s, and the compiler does the pointer chasing for you

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Exercise Work though the code carefully to explain to yourself that it works as an implementation of call by reference

Evaluation

Exercise Fortran is call by reference, but *does* allow things like `inc(2*m)`. Find out what is happening here

Advanced Exercise Read about how lvalues are implicitly coerced/dereferenced/converted to rvalues on the right of an assignment

Advanced Exercise Read about Algol 68

Advanced Exercise Read about *rvalue references* in C++

Evaluation

References are a sharp tool and there are roughly three different approaches to sharp tools.

- *1. Don't give programmers sharp tools. They may make mistakes and cut their fingers off. This is the Java/Python/Perl/Ruby/PHP... approach.*
- *2. Give programmers all the sharp tools they want. They are professionals and if they cut their fingers off it's their own fault. This is the C/C++ approach.*
- *3. Give programmers sharp tools, but put guards on them so they can't accidentally cut their fingers off. This is Rust's approach.*

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Evaluation

Call by Name

Call by name takes this a bit further, lifting the restriction that the arguments are lvalues (memory locations)

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For example the function in Algol 60:

```
integer procedure sumsq(n, m)
integer n, m;
begin
  sumsq := (n + m)*(n + m);
end;
```

that squares the sum of the arguments

Evaluation

Call by Name

Then

```
sumsq(x+1, y+2)
```

is effectively evaluated as

```
begin
  ((x+1) + (y+2)) * ((x+1) + (y+2))
end
```

i.e., the whole *expressions* in the call are substituted into the function body, which is then evaluated

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Exercise For hackers. Compare with *inlining* code

Evaluation

Implementations avoid name clashes so that local variables in the function body will never coincide with variables passed in

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```
integer procedure foo(n)
integer n;
begin integer m;
  m := 1;
  foo := n + m;
end;
```

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And then `foo(m + 1)` is *not* evaluated as

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end;
```

And then `foo(m + 1)` is *not* evaluated as

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  m := 1;
  foo := (m + 1) + m;
end;
```

as here there is inadvertent *capture* of the outer `m` by the local `m`

Evaluation

Call by Name

Rather, something more like

```
begin integer m001;
  m001 := 1;
  foo := (m + 1) + m001;
end;
```

where the local `m` is renamed

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begin integer m001;
  m001 := 1;
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```

where the local `m` is renamed

Advanced Exercise Compare with name capture in the Lambda Calculus, and read about *alpha renaming*

Exercise Read about Algol 60 and its mechanism for implementing call by name

Evaluation

Call by Name

Exercise Read about *Jensen's Device*

Exercise Read about *fexprs* in Lisp

Exercise Does call by reference need local variables to be renamed?

Evaluation

Call by Name

CBN is an interesting evaluation strategy that is occasionally more efficient than call by value:

```
integer procedure k(x, y)
integer x, y;
begin
  k := x;
end
...
n = k(1+1, 1+2+3+4+5+6+7);
```

Evaluation

Call by Name

CBN is an interesting evaluation strategy that is occasionally more efficient than call by value:

```
integer procedure k(x, y)
integer x, y;
begin
  k := x;
end
...
n = k(1+1, 1+2+3+4+5+6+7);
```

Here the second argument is not used in the function body, so will not be substituted in, and therefore not evaluated

Evaluation

Call by Name

The evaluation is essentially

```
begin
  k := 1+1;
end
```

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Thus using CBN is more efficient than CBV in this example

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begin
  k := 1+1;
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Exercise How many functions that you have written have had unused arguments?

Evaluation

Call by Name

More interestingly, call by name can evaluate some expressions that call by value cannot:

```
n = k(1 + 1, infiniteloop());
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n = k(1 + 1, infiniteloop());
```

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Thus CBN is a more powerful evaluation mechanism than CBV, in the sense that it can evaluate a larger class of expressions

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Call by Name

On the other hand, the call by name substitution mechanism is usually relatively expensive, so we don’t often win overall

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And in the `sumsq` example above, the `x+1` and `y+2` are both evaluated in the body *twice*, less efficient than a call by value:
`((x+1) + (y+2)) * ((x+1) + (y+2))`

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Algol 60 defaults to CBN, but also allows CBV, for this reason

Exercise Compare with *applicative order reduction* and *normal order reduction* in the Lambda Calculus

Evaluation

Call by Need

Next: *call by need*, or *lazy evaluation*

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Now

```
sumsq(x+1, y+2)
```

would evaluate as call by name, but now the `x+1` and the `y+2` are only evaluated *at most once* each

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Call by Need

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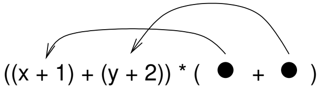
The trade-off here is single evaluation of the arguments against a more complicated evaluation mechanism

Evaluation

Call by Need

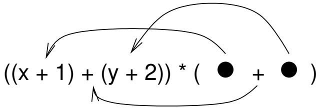


((x + 1) + (y + 2)) * (● + ●)

Memoisation of expressions

Evaluation

Call by Need



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Memoisation of expressions

The memoisation will even notice the outer addition, and not re-evaluate that

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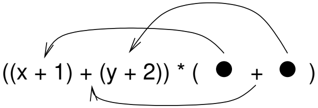

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The memoisation will even notice the outer addition, and not re-evaluate that

Examples. Haskell and Miranda; also see special forms like `delay` and similar in some languages, e.g., Scheme

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Exercise Read about *referential transparency*

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Mostly, that compiler was never created

Evaluation

Call by Need

Perhaps, in the last few years, such compilers are just about beginning to appear

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But we have still a long way to go to as people keep inventing new ideas that need clever compiler support

Evaluation

Laziness

Perhaps surprisingly, laziness is a feature that has been supported in many languages (in a small way) for a long time: called *short-circuit evaluation*

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For example, `x == 0.0` $||$ `1.0/x == 2.0` is evaluated lazily

Evaluate the `x == 0.0` first. If true, the whole expression is true, and the `1.0/x == 2.0` never gets evaluated

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For example, `x == 0.0 || 1.0/x == 2.0` is evaluated lazily

Evaluate the `x == 0.0` first. If true, the whole expression is true, and the `1.0/x == 2.0` never gets evaluated

Only if `x == 0.0` returns false does the `1.0/x == 2.0` get evaluated

Evaluation

Laziness

So this is lazy evaluation

Evaluation

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Of course this is done in many languages as it is a useful thing

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If `x == 0.0 || 1.0/x == 2.0` is evaluated eagerly, there will be problems when `x` is `0.0`

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If `x == 0.0` || `1.0/x == 2.0` is evaluated eagerly, there will be problems when `x` is `0.0`

It means, though, that `&&` and || are not like other operators, such as + and `&`, which are evaluated normally. And so they have to be treated differently in the compiler

Evaluation

Laziness

Exercise Make sure you understand the difference between the `&` and the `&&` operators

Exercise For C++ geeks: you can overload `&&` and so on in C++. What happens to the evaluation?

Exercise What happens in `foo()` || `bar()` if the functions have side-effects?

Exercise Investigate *extended boolean* operators, such as in Python and JavaScript

Evaluation

More examples to compare call by whatever. Suppose we have

```
struct Big {
  int stuff[1000];
  int things[1000];
};
```

This structure might occupy 8000 bytes

Aside

“Big values”

Be careful about saying “a big value”: this is ambiguous and can mean two different things

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The array `int v[1000]` is a big value in the sense it occupies a large number of bytes

So always make it clear what you mean

Evaluation

Then if `b` is a `struct Big` we get

call by value
`foo(b);` slow, as it copies 8000 bytes of `b` into the function

Evaluation

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call by value
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So many languages (e.g., C) support pointers:
`bar(&b);` fast, copies 8 (typically) bytes of pointer into the function, and we use this reference in the function

Evaluation

call by reference
`foo(b);` fast, as it copies only (say) 8 bytes of reference to `b` (e.g., a pointer) into the function

Evaluation

call by name
`foo(b);` the expression `b` is substituted into function; cost likely moderately high without a good optimiser

Evaluation

call by need

`foo(b);` as call by name, but with extra complication of the memoisation check

Which is best in real life? It depends

Evaluation

call by need
`foo(b);` as call by name, but with extra complication of the memoisation check

Which is best in real life? It depends

On the language, how it implements stuff, the cleverness of the compiler writers, the data, the computation, and many other things

Evaluation

CBV is fast on values that occupy few bytes; slow on values that occupy many bytes

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CBR is moderately fast on all sizes; but slower than CBR on values that occupy a small number of bytes

And slower as it needs to do pointer chasing to get to the value in the function body

And so on

Evaluation

Exercise Many other evaluation strategies have been thought about. Read about them

Exercise What is the difference between call by reference and using references in a call by value language?

Exercise Is Java call by value or call by reference? Explain (take care: the Java Language Specification differs in its definitions of some terms)

Evaluation

Exercise What is Python's calling mechanism?

Exercise Consider the following Python code

```
>>> x = [1,2,3]
>>> y = x
>>> x.append(4)
>>> x
[1, 2, 3, 4]
>>> y
```

What is the value of `y`? Explain. Then explain the result of doing `x.append(x)`

Evaluation

Exercise For C++ hackers. C++ has native CBR. Read about how to use lambdas to mimic call by name

Exercise Explain if is possible to mimic CBR in Python

Exercise Read about *generators* (more generally, *coroutines*) as a way an eager language can mimic lazy behaviour

Exercise Read about *thunks* as a way an eager language can mimic lazy behaviour

Advanced Exercise How do C++'s rvalue references differ from call by name?

Evaluation

Exercise

```
func foo(n) {
   if (n < 2) { return 1; }
   return n*foo(n-1);
}
```

Trace the evaluation of this function in a call by need language

Exercise Read about how lazy evaluation enables you to describe (effectively) *infinite* datastructures

Exercise Some people regard lazy evaluation as declarative. Do you agree with this?

Exercise Some people regard lazy evaluation as dataflow. Do you agree with this?

Application

Carrying on looking at general features of languages…

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In contrast to the "generic" languages, several applications areas have languages specifically designed for that area

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Example. Maple for doing maths. The basic datatypes are numbers, variables, polynomials, matrices, functions (trig, exp, etc.) and the like. The basic operations are arithmetics of all these things, integration, differentiation, and so on

Application

```
> diff(ln(x), x);
                                      1/x

> int(sin(x), x);
                                    -cos(x)
```

Application

```
> expand((x+1)^100);
     100        99         98           97            96             95
1 + x    + 100 x   + 4950 x   + 161700 x   + 3921225 x   + 75287520 x

                   94                93                 92                  91
     + 1192052400 x   + 16007560800 x   + 186087894300 x   + 1902231808400 x

                       90                    89                     88
     + 17310309456440 x   + 141629804643600 x   + 1050421051106700 x

                         87                      86                       85
     + 7110542499799200 x   + 44186942677323600 x   + 253338471349988640 x

                            84                        83
     + 1345860629046814650 x   + 6650134872937201800 x

                             82                          81
     + 30664510802988208300 x   + 132341572939212267400 x

                              80                           79
     + 535983370403809682970 x   + 2041841411062132125600 x

                               78                            77
     + 7332066885177656269200 x   + 24865270306254660391200 x

                                76                             75
     + 79776075565900368755100 x   + 242519269720337121015504 x

     ...
```

Application

Cobol: business. Data on employees, payroll and so on

Application

Cobol: business. Data on employees, payroll and so on

Fortran: numerical computation. Numbers and almost nothing else

Application

Visual Basic: interfaces, teaching

Application

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Postscript and its compact cousin, PDF: printing and display

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Exercise Go, Rust, Zig, Julia and Swift are new languages presently being developed. Look at them and decide what is new and different in each language (if anything)