Elements of Programming Languages

Lecture 15: Evaluation strategies and laziness

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Overview

- Final few lectures: cross-cutting language design issues
- So far:
  - Type safety
  - References, arrays, resources
- Today:
  - Evaluation strategies (by-value, by-name, by-need)
  - Impact on language design (particularly handling *effects*)

Evaluation order

- We've noted already that some aspects of small-step semantics seem arbitrary
  - For example, left-to-right or right-to-left evaluation
- Consider the rules for $+, \times$. There are two kinds: *computational* rules that actually do something:

$$\frac{}{v_1 + v_2 \mapsto v_1 +_{\mathbb{N}} v_2} \qquad \frac{}{v_1 \times v_2 \mapsto v_1 \times_{\mathbb{N}} v_2}$$

- and *administrative* rules that say how to evaluate inside subexpressions:

$$\frac{e_1 \mapsto e_1'}{e_1 \oplus e_2 \mapsto e_1' \oplus e_2} \qquad \frac{e_2 \mapsto e_2'}{v_1 \oplus e_2 \mapsto v_1 \oplus e_2'}$$

Evaluation order

- We can vary the *evaluation order* by changing the administrative rules.
- To evaluate right-to-left:

$$\frac{e_2 \mapsto e_2'}{e_1 \oplus e_2 \mapsto e_1 \oplus e_2'} \qquad \frac{e_1 \mapsto e_1'}{e_1 \oplus v_2 \mapsto e_1' \oplus v_2}$$

- To leave the evaluation order *unspecified*:

$$\frac{e_1 \mapsto e_1'}{e_1 \oplus e_2 \mapsto e_1' \oplus e_2} \qquad \frac{e_2 \mapsto e_2'}{e_1 \oplus e_2 \mapsto e_1 \oplus e_2'}$$

by lifting the constraint that the other side has to be a value.

Call-by-value

- So far, function calls evaluate arguments to values *before* binding them to variables

$$\frac{e_1 \mapsto e_1'}{e_1\ e_2 \mapsto e_1'\ e_2} \qquad \frac{e_2 \mapsto e_2'}{v_1\ e_2 \mapsto v_1\ e_2'} \qquad \frac{}{(\lambda x.\ e)\ v \mapsto e[v/x]}$$

- This *evaluation strategy* is called *call-by-value*.
  - Sometimes also called *strict* or *eager*
- "Call-by-value" historically refers to the fact that expressions are evaluated before being passed as parameters
- It is the default in most languages

Example

- Consider $(\lambda x.x \times x)\ (1 + 2 \times 3)$
- Then we can derive:

$$\cfrac{\cfrac{2 \times 3 \mapsto 6}{1 + 2 \times 3 \mapsto 1 + 6}}{(\lambda x.x \times x)\ (1 + 2 \times 3) \mapsto (\lambda x.x \times x)\ (1 + 6)}$$

- Next:

$$\frac{1 + 6 \mapsto 7}{(\lambda x.x \times x)\ (1 + 6) \mapsto (\lambda x.x \times x)\ 7}$$

- Finally:

$$\frac{}{(\lambda x.x \times x)\ 7 \mapsto 7 \times 7 \mapsto 49}$$

Interpreting call-by-value

We evaluate subexpressions fully before substituting them for variables:

```
  def eval (e: Expr): Value = e match {
  ...
  case Let(x,e1,e2) => eval(subst(e2,eval(e1),x))
  ...
  case Lambda(x,ty,e) => Lambda(x,ty,e)

  case Apply(e1,e2)   => eval(e1) match {
    case Lambda(x,_,e) => apply(subst(e,eval(e2),x))
  }
}
```


Call-by-name

- Call-by-value may evaluate expressions unnecessarily (leading to nontermination in the worst case)

$$(\lambda x.42)\ \mathit{loop} \mapsto (\lambda x.42)\ \mathit{loop} \mapsto \cdots$$

- An alternative: substitute expressions *before* evaluating

$$(\lambda x.42)\ \mathit{loop} \mapsto 42$$

- To do this, *remove* second administrative rule, and *generalize* the computational rule

$$\frac{e_1 \mapsto e_1'}{e_1\ e_2 \mapsto e_1'\ e_2} \qquad \frac{}{(\lambda x.\ e_1)\ e_2 \mapsto e_1[e_2/x]}$$

- This evaluation strategy is called *call-by-name* (the "name" is the expression)

Example, revisited

- Consider $(\lambda x.x \times x)\ (1 + 2 \times 3)$
- Then in call-by-name we can derive:

$$\frac{}{(\lambda x.x \times x)\ (1 + 2 \times 3) \mapsto (1 + (2 \times 3)) \times (1 + (2 \times 3))}$$

- The rest is standard:

$$\begin{aligned}(1 + (2 \times 3)) \times (1 + (2 \times 3)) &\mapsto (1 + 6) \times (1 + (2 \times 3)) \\ &\mapsto 7 \times (1 + (2 \times 3)) \\ &\mapsto 7 \times (1 + 6) \\ &\mapsto 7 \times 7 \mapsto 49\end{aligned}$$

- Notice that we recompute the argument twice!

Interpreting call-by-name

We substitute expressions for variables *before* evaluating.

```
def eval (e: Expr): Value = e match {
...
case Let(x,e1,e2 ) => eval(subst(e2,e1,x))
...
case Lambda(x,ty,e) => Lambda(x,ty,e)

case Apply(e1,e2) => eval(e1) match {
  case Lambda(x,_,e) => eval(subst(e,e2,x))
}
}
```


Call-by-name in Scala

- In Scala, can flag an argument as being passed by name by writing => in front of its type
- Such arguments are evaluated only when needed (but may be evaluated many times)

```
scala> def byName(x : => Int) = x + x
byName: (x: => Int)Int
scala> byName({ println("Hi␣there!"); 42})
Hi there!
Hi there!
res1: Int = 84
```

- This can be useful; sometimes we actually want to re-evaluate an expression (see next week's tutorial)

Simulating call-by-name

- Using functions, we can simulate passing $e : \tau$ by name in a call-by-value language
- Simply pass it as a "delayed" expression $\lambda().e : \mathtt{unit} \to \tau$.
- When its value is needed, apply to ().
- Scala's "by name" argument passing is basically syntactic sugar for this (using annotations on types to decide when to silently apply to ())

Comparison

- Call-by-value evaluates every expression at most once
  - ... whether or not its value is needed
  - Performance tends to be more predictable
  - Side-effects happen predictably
- Call-by-name only evaluates an expression if its value is *needed*
  - Can be faster (or even avoid infinite loop), if not needed
  - But may evaluate multiple times if needed more than once
  - Reasoning about performance requires understanding when expressions are needed
  - Side-effects may happen multiple times or not at all!

Best of both worlds?

- A third strategy: evaluate each expression when it is needed, but then *save the result*
- If an expression's value is never needed, it never gets evaluated
- If it is needed many times, it's still only evaluated once.
- This is called *call-by-need* (or sometimes *lazy*) evaluation.

Laziness in Scala

- Scala provides a `lazy` keyword
- Variables declared `lazy` are not evaluated until needed
- When they are evaluated, the value is *memoized* (that is, we store it in case of later reuse).

```
scala> lazy val x = {println("Hello"); 42}
x: Int = <lazy>
scala> x + x
Hello
res0: Int = 84
```


Laziness in Scala

- Actually, laziness can also be *emulated* using references and variant types:

```
class Lazy[A](a: => A) {
  private var r: Either[A,() => A] = Right{() => a}
  def force = r match {
    case Left(a) => a
    case Right(f) => {
      val a = f()
      r = Left(a)
      a
    }
  }
}
```

Call-by-need

- The semantics of call-by-need is a little more complicated.
- We want to *share* expressions to avoid recomputation of needed subexpressions
- We can do this using a "memo table" $\sigma : Loc \to Expr$
  - (similar to the *store* we used for references)
- Idea: When an expression e is bound to a variable, replace it with a *label* ℓ bound to e in σ
  - The labels are *not* regarded as values, though.
  - When we try to evaluate the label, look up the expression in the store and evaluate it

Rules for call-by-need

$\sigma, e \mapsto \sigma', e'$

$$\frac{}{\sigma, (\lambda x.e_1)\ e_2 \mapsto \sigma[\ell := e_2], e_1[\ell/x]}$$

$$\frac{}{\sigma, \texttt{let}\ x = e_1\ \texttt{in}\ e_2 \mapsto \sigma[\ell := e_1], e_2[\ell/x]}$$

$$\frac{}{\sigma[\ell := v], \ell \mapsto \sigma[\ell := v], v} \qquad \frac{\sigma, e \mapsto \sigma', e'}{\sigma[\ell := e], \ell \mapsto \sigma'[\ell := e'], \ell}$$

- When we reduce a function application or `let`, add expression to the memo table and replace with label
- When we encounter the label, look up its value or evaluate it (if not yet evaluated)

Rules for call-by-need

As with L_{Ref}, we also need to adjust all of the rules to handle σ.

$\sigma, e \mapsto \sigma', e'$

$$\frac{\sigma, e_1 \mapsto \sigma', e_1'}{\sigma, e_1 \oplus e_2 \mapsto \sigma', e_1' \oplus e_2} \qquad \frac{\sigma, e_2 \mapsto \sigma', e_2'}{\sigma, v_1 \oplus e_2 \mapsto \sigma', v_1 \oplus e_2'}$$

$$\frac{}{\sigma, v_1 + v_2 \mapsto \sigma, v_1 +_{\mathbb{N}} v_2} \qquad \frac{}{\sigma, v_1 \times v_2 \mapsto \sigma, v_1 \times_{\mathbb{N}} v_2}$$

$$\vdots$$

Example, revisited again

- Consider $(\lambda x.x \times x)\ (1 + 2 \times 3)$
- Then we can derive:

$$\frac{}{[], (\lambda x.x \times x)\ (1 + 2 \times 3) \mapsto [\ell = 1 + (2 \times 3)], \ell \times \ell}$$

- Next, we have:

$$[\ell = 1 + (2 \times 3)], \ell \times \ell \mapsto [\ell = 1 + 6], \ell \times \ell \mapsto [\ell = 7], \ell \times \ell$$

- Finally, we can fill in the ℓ labels:

$$[\ell = 7], \ell \times \ell \mapsto [\ell = 7], 7 \times \ell \mapsto [\ell = 7], 7 \times 7 \mapsto [\ell = 7], 49$$

- Notice that we compute the argument only once (but only when its value is needed).

Pure functional programming

- Call-by-name/call-by-need interact *badly* with side-effects
- On the other hand, they support very strong *equational* reasoning about programs
- Haskell (and some other languages) are *pure*: they adopt lazy evaluation, and forbid **any** side-effects!
- This has strengths and weaknesses:
  - (+) Easier to optimize, parallelize because side-effects are forbidden
  - (+) Can be faster
  - (-) but memoization has overhead (e.g. memory leaks) and performance is less predictable
  - (-) Dealing with I/O, exceptions etc. requires major rethink

I/O in Haskell

- Dealing with I/O and other side-effects in Haskell was a long-standing challenge
- Today's solution: use a type constructor `IO a` to "encapsulate" side-effecting computations

```
do { x <- readLn::IO Int ; print x }
123
123
```

- Note: `do`-notation is also a form of *comprehension*
- Haskell's *monads* provide (equivalents of) the `map` and `flatMap` operations

Lazy data structures

- We have (so far) assumed eager evaluation for data structures (pairs, variants)
  - e.g. a pair is fully evaluated to a value, even if both components are not needed
- However, alternative (lazy) evaluation strategies can be considered for data structures too
  - e.g. could consider a pair (e_1, e_2) to be a value; we only evaluate e_1 if it is "needed" by applying `fst`:

    ```
    ghci> fst (42, undefined) == 42
    ```
- An example: *streams* (see next week's tutorial)

```
ghci> let ones = 1::ones
ghci> take 10 ones
```


Summary

- We are continuing our tour of language-design issues
- Today we covered:
  - Call-by-value (the default)
  - Call-by-name
  - Call-by-need and lazy evaluation
- Next time:
  - Guest lecture on Rust