Elements of Programming Languages

Lecture 16: Exceptions and Control Abstractions

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Exceptions Tail recursion Continuations

Overview

- We have been considering several high-level aspects of language design:
  - Type soundness
  - References
  - Evaluation order
- Today we complete this tour and examine:
  - Exceptions
  - Tail recursion
  - Other control abstractions

Exceptions Tail recursion Continuations

Exceptions

- In earlier lectures, we considered several approaches to *error handling*
- *Exceptions* are another popular approach (supported by Java, C++, Scala, ML, Python, etc.)
- The `throw e` statement *raises an exception* e
- A try/catch block runs a statement; if an exception is raised, control transfers to the corresponding *handler*

```
try { ... do something ... }
catch (IOException e)
  {... handle exception e ...}
catch (NullPointerException e)
  {... handle another exception...}
```

Exceptions Tail recursion Continuations

`finally` and resource cleanup

- What if the `try` block allocated some resources?
- We should make sure they get deallocated!
- `finally` clause: gets run at the end whether or not exception is thrown

```
InputStream in = null;
try { in = new FileInputStream(fname);
      ... do something with in ... }
catch (IOException exn) {...}
finally { if(in != null)
              in.close(); }
```

- Java 7: "try-with-resources" encapsulates this pattern, for resources implementing `AutoCloseable` interface

throws clauses

- In Java, potentially unhandled exceptions typically need to be *declared* in the types of methods

```
void writeFile(String filename)
    throws IOException {
  InputStream in = new FileInputStream(filename);
  ... write to file ...
  in.close();
}
```

- This means programmers using such methods know that certain exceptions need to be handled
- Failure to handle or declare an exception is a type error!
  - (however, certain *unchecked exceptions* / errors do not need to be declared, e.g. `NullPointerException`)

Exceptions in Scala

- As you might expect, Scala supports a similar mechanism:

```
try { ... do something ... }
catch {
  case exn: IOException =>
    ... handle IO exception...
  case exn: NullPointerException =>
    ... handle null pointer exception...
} finally { ... cleanup ...}
```

- Main difference: The `catch` block is just a Scala pattern match on exceptions
  - Scala allows pattern matching on *types* (via `isInstanceOf`/`asInstanceOf`)
- Also: `throws` clauses not required

Exceptions for shortcutting

- We can also use exceptions for "normal" computation

```
def product(l: List[Int]) = {
  object Zero extends Throwable
  def go(l: List[Int]): Int = l match {
    case Nil => 1
    case x::xs =>
      if (x == 0) {throw Zero} else {x * go(xs)}
  }
  try { go(l) }
  catch { case Zero => 0 }
}
```

- potentially saving a lot of effort if the list contains 0

Exceptions in practice

- Java:
  - Exceptions are subclasses of `java.lang.Throwable`
  - Method types must declare (most) possible exceptions in `throws` clause
  - compile-time error if an exception can be raised and not caught or declared
  - multiple "catch" blocks; "finally" clause to allow cleanup
- Scala:
  - doesn't require declaring thrown exceptions: this becomes especially painful in a higher-order language...
  - "catch" does pattern matching

Modeling exceptions

- We will formalize a simple model of exceptions:

$$e ::= \cdots \mid \texttt{raise}\ e \mid e_1\ \texttt{handle}\ \{x \Rightarrow e_2\}$$

- Here, raise e throws an arbitrary value as an "exception"
- while e_1 handle $\{x \Rightarrow e_2\}$ evaluates e_1 and, if an exception is thrown during evaluation, binds the value v to x and evaluates e.
- Define L_{Exn} as L_{Rec} extended with exceptions

Exceptions and types

- Exception constructs are straightforward to typecheck:

$$\tau ::= \cdots \mid \texttt{exn}$$

- Usually, the exn type is extensible (e.g. by subclassing)

$\Gamma \vdash e : \tau$ for L_{Exn}

$$\frac{\Gamma \vdash e : \texttt{exn}}{\Gamma \vdash \texttt{raise}\ e : \tau} \qquad \frac{\Gamma \vdash e_1 : \tau \quad \Gamma, x : \texttt{exn} \vdash e_2 : \tau}{\Gamma \vdash e_1\ \texttt{handle}\ \{x \Rightarrow e_2\} : \tau}$$

- Note: raise e can have any type! (because raise e never returns)
- The return types of e_1 and e_2 in handler must match.

Interpreting exceptions

- We can extend our Scala interpreter for L_{Rec} to manage exceptions as follows:

```
case class ExceptionV(v: Value) extends Throwable
def eval(e: Expr): Value = e match {
  ...
  case Raise(e: Expr) => throw (ExceptionV(eval(e)))
  case Handle(e1: Expr, x: Variable, e2:Expr) =>
    try {
      eval(e1)
    } catch (ExceptionV(v)) {
      eval(subst(e2,v,x))
    }
```

- This might seem a little circular!

Semantics of exceptions

- To formalize the semantics of exceptions, we need an auxiliary judgment e raises v
- Intuitively: this says that expression e does not finish normally but instead raises exception value v

e raises v

$$\frac{}{\texttt{raise}\ v\ \text{raises}\ v} \qquad \frac{e_1\ \text{raises}\ v}{e_1 \oplus e_2\ \text{raises}\ v} \qquad \frac{e_2\ \text{raises}\ v}{v_1 \oplus e_2\ \text{raises}\ v}$$

$$\frac{e\ \text{raises}\ v}{\texttt{if}\ e\ \texttt{then}\ e_1\ \texttt{else}\ e_2\ \text{raises}\ v} \qquad \cdots$$

- The most interesting rule is the first one; the rest are "administrative"

Semantics of exceptions

- We can now define the small-step semantics of `handle` using the following additional rules:

$e \mapsto e'$

$$\frac{e_1 \mapsto e_1'}{e_1 \; \texttt{handle} \; \{x \Rightarrow e_2\} \mapsto e_1' \; \texttt{handle} \; \{x \Rightarrow e_2\}}$$

$$\frac{}{v_1 \; \texttt{handle} \; \{x \Rightarrow e_2\} \mapsto v_1}$$

$$\frac{e_1 \text{ raises } v}{e_1 \; \texttt{handle} \; \{x \Rightarrow e_2\} \mapsto e_2[v/x]}$$

- If e_1 steps normally to e_1', take that step
- If e_1 raises an exception v, substitute it in for x and evaluate e_2

Tail recursion

- A function call is a *tail call* if it is the last action of the calling function. If every recursive call is a tail call, we say `f` is *tail recursive*.
- For example, this version of `fact` is not tail recursive:

```
def fact1(n: Int): Int =
  if (n == 0) {1} else {n * (fact1(n-1))}
```

- But this one is:

```
def fact2(n: Int) = {
  def go(n: Int, r: Int): Int =
    if (n == 0) {r} else {go(n-1,n*r)}
  go(n,1)
}
```


Tail recursion and efficiency

- Tail recursive functions can be compiled more efficiently
- because there is no more "work" to do after the recursive call
- In Scala, there is a (checked) annotation `@tailrec` to mark tail-recursive functions for optimization

```
def fact2(n: Int) = {
  @tailrec
  def go(n: Int, r: Int): Int =
    if (n == 0) {r} else {go(n-1,n*r)}
  go(n,1)
}
```


Continuations [non-examinable]

- Conditionals, while-loops, exceptions, "goto" are all form of *control abstraction*
- *Continuations* are a highly general notion of control abstraction, which can be used to implement exceptions (and much else).
- Material covered from here on is non-examinable.
  - just for fun!
  - (Depends on your definition of fun, I suppose)

Continuations

- A continuation is a function representing "the rest of the computation"
- Any function can be put in "continuation-passing form"
- for example

```
def fact3[A](n: Int, k: Int => A): A =
  if (n == 0) {k(1)}
  else {fact3(n-1, {m => k (n * m)})}
```

- This says: if n is 0, pass 1 to k
- otherwise, recursively call with parameters $n-1$ and $\lambda r.k(n \times r)$
- "when done, multiply the result by n and pass to k"

How does this work?

```
def fact3[A](n: Int, k: Int => A): A =
  if (n == 0) {k(1)} else {fact3(n-1, {r => k (n * r)})}
```

$$
\begin{array}{ll}
 & fact3(3, \lambda x.x) \\
\mapsto & fact3(2, \lambda r_1.(\lambda x.x)\ (3 \times r_1)) \\
\mapsto & fact3(1, \lambda r_2.(\lambda r.(\lambda x.x)\ (3 \times r))\ (2 \times r_2)) \\
\mapsto & fact3(0, \lambda r_3.(\lambda r_2.(\lambda r_1.(\lambda x.x)\ (3 \times r_1))\ (2 \times r_2))\ (1 \times r_3)) \\
\mapsto & (\lambda r_3.(\lambda r_2.(\lambda r_1.(\lambda x.x)\ (3 \times r_1))\ (2 \times r_2))\ (1 \times r_3))\ 1 \\
\mapsto & (\lambda r_2.(\lambda r_1.(\lambda x.x)\ (3 \times r_1))\ (2 \times r_2))\ (1 \times 1) \\
\mapsto & (\lambda r_1.(\lambda x.x)\ (3 \times r_1))\ (2 \times 1) \\
\mapsto & (\lambda x.x)\ (3 \times 2) \\
\mapsto & 6
\end{array}
$$

Interpreting L_{Arith} using continuations

```
def eval[A](e: Expr, k: Value => A): A = e match {
  // Arithmetic
  case Num(n) => k(NumV(n))

  case Plus(e1,e2) =>
    eval(e1,{case NumV(v1) =>
      eval(e2,{case NumV(v2) => k(NumV(v1+v2))})})

  case Times(e1,e2) =>
    eval(e1,{case NumV(v1) =>
      eval(e2,{case NumV(v2) => k(NumV(v1*v2))})})
  ...
}
```


Interpreting L_{If} using continuations

```
def eval[A](e: Expr, k: Value => A): A = e match {
  ...
  // Booleans
  case Bool(n) => k(BoolV(n))

  case Eq(e1,e2) =>
    eval(e1,{v1 =>
      eval(e2,{v2 => k(BoolV(v1 == v2))})})

  case IfThenElse(e,e1,e2) =>
    eval(e,{case BoolV(v) =>
      if(v) { eval(e1,k) } else { eval(e2,k) } })
  ...
}
```

Interpreting L_{Let} using continuations

```
def eval[A](e: Expr, k: Value => A): A = e match {
  ...
  // Let-binding
  case Let(e1,x,e2) =>
    eval(e1,{v =>
      eval(subst(e2,v,x),k)})
  ...
}
```


Interpreting L_{Rec} using continuations

```
def eval[A](e: Expr, k: Value => A): A = e match {
  ...
  // Functions
  case Lambda(x,ty,e) => k(LambdaV(x,ty,e))
  case Rec(f,x,ty1,ty2,e) => k(RecV(f,x,ty1,ty2,e))

  case Apply(e1,e2) =>
    eval(e1, {v1 =>
      eval(e2, {v2 => v1 match {
        case LambdaV(x,ty,e) => eval(subst(e,v2,x), k)
        case RecV(f,x,ty1,ty2,e) =>
          eval(subst(subst(e,v2,x),v1,f),k)
      }})})
  ...
}
```


Interpreting L_{Exn} using continuations

To deal with exceptions, we add a second continuation `h` for handling exceptions. (Cases seen so far just pass `h` along.)

```
def eval[A](e: Expr, h: Value => A,
                     k: Value => A): A = e match {
  ...
  // Exceptions
  case Raise(e0) => eval(e0,h,h)

  case Handle(e1,x,e2) =>
    eval(e1,{v => eval(subst(e2,v,x),h,k)},k)
}
```

When raising an exception, we forget `k` and pass to `h`.
When handling, we install new handler using `e2`

Summary

- Today we completed our tour of
  - Type soundness
  - References and resource management
  - Evaluation order
  - Exceptions and control abstractions (today)
- which can interact with each other and other language features in subtle ways
- Next time:
  - review lecture
  - information about exam, reading