CS 242

Control in Sequential Languages

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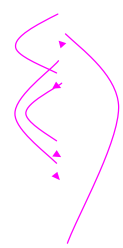
Topics

- Structured Programming
  - Go to considered harmful
- Exceptions
  - "structured" jumps that may return a value
  - dynamic scoping of exception handler
- Continuations
  - Function representing the rest of the program
  - Generalized form of tail recursion
- Control of evaluation order (force and delay)
  - Will skip this. You can look at reader if interested.

Fortran Control Structure

```
10 IF (X .GT. 0.000001) GO TO 20
11 X = -X
   IF (X .LT. 0.000001) GO TO 50
20 IF (X*Y .LT. 0.00001) GO TO 30
   X = X-Y-Y
30  X = X+Y
   ...
50 CONTINUE
   X = A
   Y = B-A
   GO TO 11
   ...
```



Historical Debate

- Dijkstra, Go To Statement Considered Harmful
  - Letter to Editor, *C ACM*, March 1968
  - Now on web: http://www.acm.org/classics/oct95/
- Knuth, Structured Prog. with go to Statements
  - You can use goto, but do so in structured way …
- Continued discussion
  - Welch, GOTO (Considered Harmful)^n, n is Odd
- General questions
  - Do syntactic rules force good programming style?
  - Can they help?

Advance in Computer Science

- Standard constructs that structure jumps
  - if … then … else … end
  - while … do … end
  - for … { … }
  - case …
- Modern style
  - Group code in logical blocks
  - Avoid explicit jumps except for function return
  - Cannot jump *into* middle of block or function body

Exceptions: Structured Exit

- Terminate part of computation
  - Jump out of construct
  - Pass data as part of jump
  - Return to most recent site set up to handle exception
  - Unnecessary activation records may be deallocated
    - May need to free heap space, other resources
- Two main language constructs
  - Declaration to establish exception *handler*
  - Statement or expression to *raise* or *throw* exception

Often used for unusual or exceptional condition, but not necessarily.

ML Example

```
exception Determinant;  (* declare exception name *)
fun invert (M) =        (* function to invert matrix *)
      ...
      if ...
          then raise Determinant    (* exit if Det=0 *)
          else ...
 end;
...
invert (myMatrix) handle Determinant => ... ;
```

Value for expression if determinant of myMatrix is 0

C++ Example

```
Matrix invert(Matrix m) {
   if ... throw Determinant;
   ...
};

try { ... invert(myMatrix); ...
}
catch (Determinant) { ...
   // recover from error
}
```

C++ vs ML Exceptions

- C++ exceptions
  - Can throw any type
  - Stroustrup: "I prefer to define types with no other purpose than exception handling. This minimizes confusion about their purpose. In particular, I never use a built-in type, such as int, as an exception." -- The C++ Programming Language, 3rd ed.
- ML exceptions
  - Exceptions are a different kind of entity than types.
  - Declare exceptions before use

Similar, but ML requires the recommended C++ style.

ML Exceptions

- Declaration

  exception ⟨name⟩ of ⟨type⟩

  gives name of exception and type of data passed when raised
- Raise

  raise ⟨name⟩ ⟨parameters⟩

  expression form to raise and exception and pass data
- Handler

  ⟨exp1⟩ handle ⟨pattern⟩ => ⟨exp2⟩

  evaluate first expression

  if exception that matches pattern is raised,

  then evaluate second expression instead

General form allows multiple patterns.

Which handler is used?

```
exception Ovflw;
fun reciprocal(x) =
    if x<min  then raise Ovflw  else 1/x;
(reciprocal(x) handle Ovflw=>0)  /  (reciprocal(y) handle Ovflw=>1);
```

- Dynamic scoping of handlers
  - First call handles exception one way
  - Second call handles exception another
  - General dynamic scoping rule

    Jump to most recently established handler on run-time stack
- Dynamic scoping is not an accident
  - User knows how to handler error
  - Author of library function does not

Exception for Error Condition

```
- datatype 'a tree = LF of  'a | ND of  ('a tree)*('a tree)
- exception No_Subtree;
- fun lsub (LF x) = raise No_Subtree
  |    lsub (ND(x,y)) = x;
> val lsub = fn : 'a tree -> 'a tree
```

- This function raises an exception when there is no reasonable value to return
- We'll look at typing later.

Exception for Efficiency

- Function to multiply values of tree leaves

```
fun prod(LF x) = x
|    prod(ND(x,y)) = prod(x) * prod(y);
```

- Optimize using exception

```
fun prod(tree) =
    let exception Zero
        fun p(LF x) = if x=0 then (raise Zero) else x
        |    p(ND(x,y)) = p(x) * p(y)
    in
        p(tree) handle Zero=>0
    end;
```

Dynamic Scope of Handler

```
exception X;
(let fun f(y) = raise X
    and g(h) = h(1) handle X => 2
in
    g(f) handle X => 4
end) handle X => 6;
```

scope

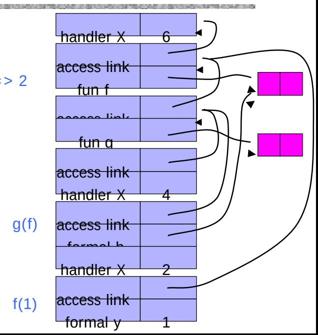
handler

Which handler is used?

Dynamic Scope of Handler

```
exception X;
(let fun f(y) = raise X
    and g(h) = h(1) handle X => 2
in
    g(f) handle X => 4
end) handle X => 6;
```

Dynamic scope: find first X handler, going up the dynamic call chain leading to raise X.



Compare to static scope of variables

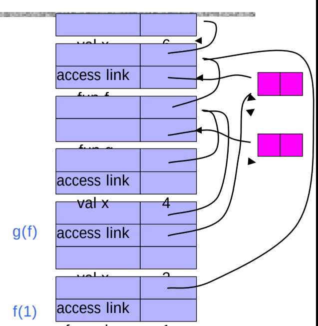
```
exception X;
(let fun f(y) = raise X
    and g(h) = h(1)
            handle X => 2
in
    g(f) handle X => 4
end) handle X => 6;
```

```
val x=6;
(let fun f(y) = x
    and g(h) = let val x=2 in
                    h(1)
 in
    let val x=4 in g(f)
end);
```

Static Scope of Declarations

```
val x=6;
(let fun f(y) = x
    and g(h) = let val x=2 in
                    h(1)
 in
    let val x=4 in g(f)
end);
```

Static scope: find first x, following access links from the reference to X.



Typing of Exceptions

- Typing of raise ⟨exn⟩
  - Recall definition of typing
    - Expression e has type t if normal termination of e produces value of type t
  - Raising exception is not normal termination
    - Example: 1 + raise X
- Typing of handle ⟨exn⟩ => ⟨value⟩
  - Converts exception to normal termination
  - Need type agreement
  - Examples
    - 1 + ((raise X) handle X => e)   Type of e must be int
    - 1 + (e_1 handle X => e_2)   Type of e_1, e_2 must be int

Exceptions and Resource Allocation

```
exception X;
(let
   val x = ref [1,2,3]
 in
   let
       val y = ref [4,5,6]
   in
      … raise X
    end
end);  handle X => …
```

- Resources may be allocated between handler and raise
- May be "garbage" after exception
- Examples
  - Memory
  - Lock on database
  - Threads
  - …

General problem: no obvious solution

Continuations

- General technique using higher-order functions
  - Allows "jump" or "exit" by function call
- Used in compiler optimization
  - Make control flow of program explicit
- General transformation to "tail recursive form"
- Idea:
  - The continuation of an expression is "the remaining work to be done after evaluating the expression"
  - Continuation of *e* is a function applied to *e*

Example

- Expression
  - 2*x + 3*y + 1/x + 2/y
- What is continuation of 1/x?
  - Remaining computation after division

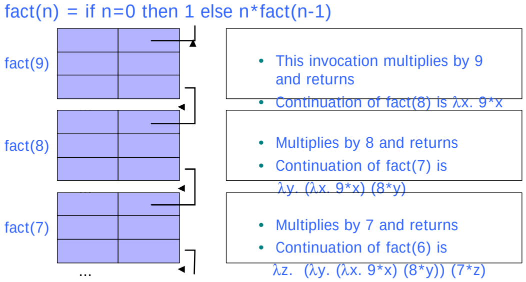
```
let val before = 2*x + 3*y
    fun continue(d) = before + d + 2/y
in
    continue (1/x)
end
```

Example: Tail Recursive Factorial

- Standard recursive function
  - fact(n) = if n=0 then 1 else n*fact(n-1)
- Tail recursive
  - f(n,k) = if n=0 then k else f(n-1, n*k)
  - fact(n) = f(n,1)
- How could we derive this?
  - Transform to continuation-passing form
  - Optimize continuation functions to single integer

Continuation view of factorial

fact(n) = if n=0 then 1 else n*fact(n-1)



Derivation of tail recursive form

- Standard function
  - fact(n) = if n=0 then 1 else n*fact(n-1)
- Continuation form
  - fact(n, k) = if n=0 then k(1) else fact(n-1, λx.k (n*x)) — continuation
  - fact(n, λx.x) computes n!
- Example computation
  - fact(3,λx.x) = fact(2, λy.((λx.x) (3*y)))
  - = fact(1, λx.((λy.3*y)(2*x)))
  - = λx.((λy.3*y)(2*x)) 1 = 6

Tail Recursive Form

- Optimization of continuations

```
fact(n,a) = if n=0 then a
                  else fact(n-1, n*a )
```

Each continuation is effectively λx.(a*x) for some a

- Example computation

```
fact(3,1)  = fact(2, 3)       was  fact(2, λy.3*y)
           = fact(1, 6)       was  fact(1, λx.6*x)
           = 6
```

Other uses for continuations

- Explicit control
  - Normal termination -- call continuation
  - Abnormal termination -- do something else
- Compilation techniques
  - Call to continuation is functional form of "go to"
  - Continuation-passing style makes control flow explicit

MacQueen: "Callcc is the closest thing to a 'come-from' statement I've ever seen."

Capturing Current Continuation

- Language feature (use open SMLofNJ; on Leland)
  - callcc : *call* a function with *current continuation*
  - Can be used to abort subcomputation and go on
- Examples
  - callcc (fn k => 1);

  > val it = 1 : int
    - Current continuation is "fn x => print x"
    - Continuation is not used in expression.
  - 1 + callcc(fn k => 5 + throw k 2);

  > val it = 3 : int
    - Current continuation is "fn x => print 1+x"
    - Subexpression throw k 2 applies continuation to 2

More with callcc

- Example

```
1 + callcc(fn k1=>   ...
        callcc(fn k2 => ...
              if ... then (throw k1 0)
                    else (throw k2 "stuck")
        ))
```

- Intuition
  - Callcc lets you mark a point in program that you can return to
  - Throw lets you jump to that point and continue from there

Continuations in compilation

- SML continuation-based compiler [Appel, Steele]

1) Lexical analysis, parsing, type checking
2) Translation to λ-calculus form
3) Conversion to continuation-passing style (CPS)
4) Optimization of CPS
5) Closure conversion – eliminate free variables
6) Elimination of nested scopes
7) Register spilling – no expression with >n free vars
8) Generation of target assembly language program
9) Assembly to produce target-machine program

Summary

- Structured Programming
  - Go to considered harmful
- Exceptions
  - "structured" jumps that may return a value
  - dynamic scoping of exception handler
- Continuations
  - Function representing the rest of the program
  - Generalized form of tail recursion
  - Used in Lisp, ML compilation