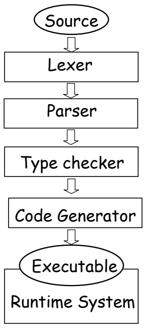
Exceptions.
Language Design and Implementation Issues

Lecture 22

Structure of a Compiler



Source

Lexer

Parser

Type checker

Code Generator

Executable

Runtime System

- We looked at each stage in turn
- A new language feature affects many stages
- We will add exceptions

Lecture Summary

- Why exceptions ?
- Syntax and informal semantics
- Semantic analysis (i.e. type checking rules)
- Code generation
- Runtime system support

Exceptions. Motivation.

- "Classroom" programs are written with optimistic assumptions
- Real-world programs must consider "exceptional" situations:
  - Resource exhaustion (disk full, out of memory, …)
  - Invalid input
  - Errors in the program (null pointer dereference)
- It is usual for solid code to contain 30-50% error handling code !

Exceptions. Motivation

Two ways of dealing with errors:

1. Handle them where you detect them
   - E.g., null pointer dereference → stop execution

2. Let the caller handle the errors:
   - The caller has more contextual information
     E.g. an error when opening a file:
     a) In the context of opening /etc/passwd
     b) In the context of opening a log file
   - But then we must tell the caller about the error !

Exceptions. Error Return Codes.

- The callee can signal the error by returning a special return value:
  - Must not be one of the valid return values
  - Must be agreed upon beforehand
- The caller promises to check the error return and either:
  - Correct the error, or
  - Pass it on to its own caller

Error Return Codes

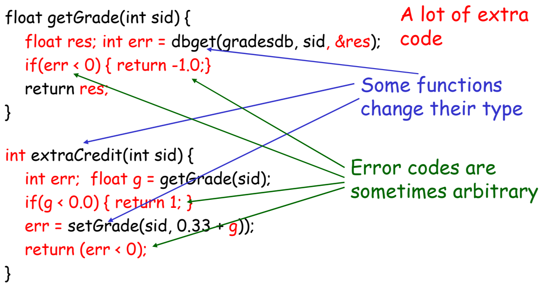
- It is sometimes hard to select return codes
  - What is a good error code for “double divide(…)”?
- How many of you always check errors for:
  - malloc(int) ?
  - open(char *) ?
  - close(int) ?
  - time(struct time_t *) ?
- Easy to forget to check error return codes

Example: Automated Grade Assignment

```
float getGrade(int sid) {   return dbget(gradesdb, sid); }

void setGrade(int sid, float grade) {   dbset(gradesdb, sid, grade); }

void extraCredit(int sid) {
     setGrade(sid, 0.33 + getGrade(sid));
     }

void grade_inflator() {
     while(gpa() < 3.0) {  extraCredit(random());  }
     }
```

- What errors are we ignoring here ?

Example: Automated Grade Assignment



```
float getGrade(int sid) {
   float res; int err = dbget(gradesdb, sid, &res);
   if(err < 0) { return -1.0;}
   return res;
}

int extraCredit(int sid) {
   int err;  float g = getGrade(sid);
   if(g < 0.0) { return 1; }
   err = setGrade(sid, 0.33 + g));
   return (err < 0);
}
```

A lot of extra code

Some functions change their type

Error codes are sometimes arbitrary

Exceptions

- Exceptions are a language mechanism designed to allow:
  - Deferral of error handling to a caller
  - Without (explicit) error codes
  - And without (explicit) error return code checking

Adding Exceptions to Cool

- We extend the language of expressions:

  e ::= throw e | try e catch x : T ⇒ e′

- (Informal) semantics of throw e
  - Signals an exception
  - Interrupts the current evaluation and searches for an exception handler up the activation chain
  - The value of e is an exception parameter and can be used to communicate details about the exception

Adding Exceptions to Cool

(Informal) semantics of try e catch x : T ⇒ e_1

1. e is evaluated first
2. If e’s evaluation terminates normally with v

   then v is the result of the entire expression

   Else (e’s evaluation terminates exceptionally)

   If the exception parameter is of type ≤ T then
   - Evaluate e_1 with x bound to the exception parameter
   - The (normal or exceptional) result of evaluating e_1 becomes the result of the entire expression

   Else
   - The entire expression terminates exceptionally

Example: Automated Grade Assignment

```
float getGrade(int sid) {   return dbget(gradesdb, sid); }
void setGrade(int sid, float grade) {
    if(grade < 0.0 || grade > 4.0) { throw (new NaG); }
   dbset(gradesdb, sid, grade); }
void extraCredit(int sid) {
      setGrade(sid, 0.33 + getGrade(sid)) }
void grade_inflator() {
      while(gpa < 3.0) {
          try extraCredit(random())
          catch x : Object ⇒ print "Nice try! Don't give up.\n"; }
      }
```

Example. Notes.

- Only error handling code remains
- But no error propagation code
  - The compiler handles the error propagation
  - No way to forget about it
  - And also much more efficient (we'll see)
- Two kinds of evaluation outcomes:
  - Normal return (with a return value)
  - Exceptional "return" (with an exception parameter)
  - No way to get confused which is which

Overview

✓ Why exceptions ?

✓ Syntax and informal semantics

- Semantic analysis (i.e. type checking rules)
- Code generation
- Runtime system support

Typing Exceptions

- We must extend the Cool typing judgment

$$O, M, C \vdash e : T$$

  - Type T refers to the normal return !
- We'll start with the rule for try:
  - Parameter "x" is bound in the catch expression
  - try is like a conditional

$$\frac{O, M, C \vdash e : T_1 \qquad O[T/x], M, C \vdash e' : T_2}{O, M, C \vdash \text{try } e \text{ catch } x : T \Rightarrow e' : T_1 \sqcup T_2}$$

Typing Exceptions

- What is the type of "throw e" ?
- The type of an expression:
  - Is a description of the possible return values, and
  - Is used to decide in what contexts we can use the expression
- "throw" does not return to its immediate context but directly to the exception handler !
- The same "throw e" is valid in any context:

  if throw e then (throw e) + 1 else (throw e).foo()
- As if "throw e" has any type !

Typing Exceptions

$$\frac{O, M, C \vdash e : T_1}{O, M, C \vdash \text{throw } e : T_2}$$

- As long as "e" is well typed, "throw e" is well typed with any type needed in the context
- This is convenient because we want to be able to signal errors from any context

Overview

- ✓ Why exceptions ?
- ✓ Syntax and informal semantics
- ✓ Semantic analysis (i.e. type checking rules)
- Code generation
- Runtime system support

Operational Semantics of Exceptions

- Several ways to model the behavior of exceptions
- A generalized value is
  - Either a normal termination value, or
  - An exception with a parameter value

    g ::= Norm(v) | Exc(v)
- Thus given a generalized value we can:
  - Tell if it is normal or exceptional return, and
  - Extract the return value or the exception parameter

Operational Semantics of Exceptions (1)

- The existing rules are modified to use Norm(v) :

$$\frac{\begin{array}{c}\text{so, E, S} \vdash e_1 : \text{Norm}(\text{Int}(n_1)), S_1 \\ \text{so, E, } S_1 \vdash e_2 : \text{Norm}(\text{Int}(n_2)), S_2\end{array}}{\text{so, E, S} \vdash e_1 + e_2 : \text{Norm}(\text{Int}(n_1 + n_2)), S_2}$$

$$\frac{\begin{array}{c}E(id) = l_{id} \\ S(l_{id}) = v\end{array}}{\text{so, E, S} \vdash \text{id} : \text{Norm}(v), S} \qquad \frac{}{\text{so, E, S} \vdash \text{self} : \text{Norm}(\text{so}), S}$$

Operational Semantics of Exceptions (2)

- "throw" returns exceptionally:

$$\frac{\text{so, E , S} \vdash e : v, S_1}{\text{so, E, S} \vdash \text{throw } e : \text{Exc}(v), S_1}$$

- The rule above is not well formed! Why?

$$\frac{\text{so, E , S} \vdash e : \text{Norm}(v), S_1}{\text{so, E, S} \vdash \text{throw } e : \text{Exc}(v), S_1}$$

Operational Semantics of Exceptions (3)

- "throw e" returns exceptionally:

$$\frac{\text{so, E , S} \vdash e : \text{Norm}(v), S_1}{\text{so, E, S} \vdash \text{throw } e : \text{Exc}(v), S_1}$$

- What if the evaluation of e itself throws an exception?
  - E.g. "throw (1 + (throw 2))" is like "throw 2"
  - Formally:

$$\frac{\text{so, E , S} \vdash e : \text{Exc}(v), S_1}{\text{so, E, S} \vdash \text{throw } e : \text{Exc}(v), S_1}$$

Operational Semantics of Exceptions (4)

- All existing rules are changed to propagate the exception:

$$\frac{\text{so, E, S} \vdash e_1 : \text{Exc}(v), S_1}{\text{so, E, S} \vdash e_1 + e_2 : \text{Exc}(v), S_1}$$

  - Note: the evaluation of e_2 is aborted

$$\frac{\begin{array}{c}\text{so, E, S} \vdash e_1 : \text{Norm}(\text{Int}(n_1)), S_1 \\ \text{so, E, } S_1 \vdash e_2 : \text{Exc}(v), S_2\end{array}}{\text{so, E, S} \vdash e_1 + e_2 : \text{Exc}(v), S_2}$$

Operational Semantics of Exceptions (5)

- The rules for "try" expressions:
  - Multiple rules (just like for a conditional)

$$\frac{so, E, S \vdash e : Norm(v), S_1}{so, E, S \vdash \text{try } e \text{ catch } x : T \Rightarrow e' : Norm(v), S_1}$$

- What if e terminates exceptionally?
  - We must check whether it terminates with an exception parameter of type T or not

Operational Semantics for Exceptions (6)

- If e does not throw the expected exception

$$\frac{\begin{array}{l} so, E, S \vdash e : Exc(v), S_1 \\ v = X(\ldots) \\ \text{not } (X \leq T) \end{array}}{so, E, S \vdash \text{try } e \text{ catch } x : T \Rightarrow e' : Exc(v), S_1}$$

- If e does throw the expected exception

$$\frac{\begin{array}{l} so, E, S \vdash e : Exc(v), S_1 \\ v = X(\ldots) \\ X \leq T \\ l_{new} = newloc(S_1) \\ so, E[l_{new}/x] \text{ , } S_1[v/l_{new}] \vdash e' : g, S_2 \end{array}}{so, E, S \vdash \text{try } e \text{ catch } x : T \Rightarrow e' : g, S_2}$$

Operational Semantics of Exceptions. Notes

- Our semantics is precise
- But is not very clean
  - It has two or more versions of each original rule
- It is not a good recipe for implementation
  - It models exceptions as "compiler-inserted propagation of error return codes"
  - There are much better ways of implementing exceptions
- There are other semantics that are cleaner and model better implementations

Overview

- ✓ Why exceptions ?
- ✓ Syntax and informal semantics
- ✓ Semantic analysis (i.e. type checking rules)
- Code generation
- Runtime system support

Code Generation for Exceptions

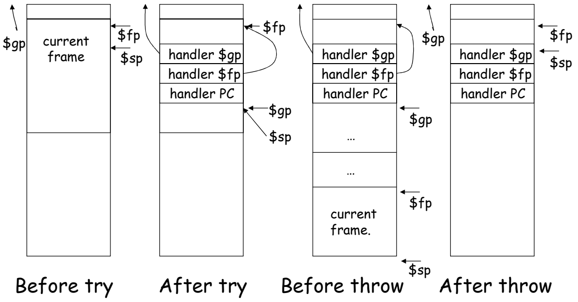
- Propagate a pair of return values:
  - normal+exception
- Simple to implement
- But not very good
  - We pay a cost at each call/return (i.e. often)
  - Even though exceptions are rare (i.e. exceptional)
- A good engineering principle:
  - Don't pay often for something that you use rarely!
  - Optimize the common case !

Implementing Exceptions with Long Jumps (1)

Idea:

- "try" saves on the stack the handler context:
  - The current SP, FP and the label of the catch code
- "throw" jumps to the last saved handler label
  - Called a long jump
- We reserve the MIPS register $gp to hold the most recently saved handler context
- Implement exceptions without parameters

Long Jumps. Example.



Implementing Exceptions with Long Jumps (2)

```
cgen(try e catch e') =
   sw $gp  0($sp)        ; Save old handler context
   sw $fp  -4($sp)        ; Save FP
   sw L_catch -8($sp)     ; Save handler address
   addiu $sp $sp -12     ; Finish the pushes
   mov $gp $sp           ; Set the new handler context
   cgen(e)               ; Try part. Result in $a0
   addiu $sp $sp 12      ; Pop the context
   lw $gp 0($sp)         ; Restore old handler context
   b end_try
L_catch:
   cgen(e')              ; Catch part. Result in $a0
 end_try:
```

Implementing Exceptions with Long Jumps (3)

```
cgen(throw) =
   mov $sp $gp          ; Restore the stack pointer
   addiu $sp $sp 12
   lw $t0 -8($sp)       ; Load the catch PC address
   lw  $fp -4($sp)      ; Load the new FP
   lw  $gp  0($sp)      ; Restore the old handler context
   jr $t0               ; Jump to the exception handler
```

Long Jumps

- A long jump is a non-local goto:
  - In one shot you can jump back to a function in the caller chain (bypassing many intermediate frames)
  - A long jump can "return" from many frames at once
- Long jumps are a commonly used implementation scheme for exceptions
- Disadvantage:
  - Minor performance penalty at each try

Implementing Exceptions with Tables (1)

- We do not want to pay for exceptions when executing a "try"
  - Only when executing a "throw"

```
cgen(try e catch e') =
   cgen(e)              ; Code for the try block
   goto end_try
L_catch:
   cgen(e')             ; Code for the catch block
end_try:
   ...
cgen(throw) =
   jr runtime_throw
```

Implementing Exceptions with Tables (2)

- The normal execution proceeds at full speed
- When a throw is executed we use a runtime function that finds the right catch block
- For this to be possible the compiler produces a table saying for each catch block to which instructions it corresponds

Implementing Exceptions with Tables. Example.

- Consider the expression

  e_1 + (try e_2 + (try e_3 catch e_3') catch e_2')

Regular code:

```
$L_1$:  cgen($e_1$)
$L_1'$: $t_1$ = acc
$L_2$:  cgen($e_2$)
$L_2'$: $t_2$ = acc
$L_3$:  cgen($e_3$)
$L_3'$:  acc $\leftarrow$ acc + $t_2$
 $L_4'$:  acc $\leftarrow$ acc + $t_1$
```

Handlers:

```
$C_2$:  cgen($e_2'$)
     goto $L_4'$
$C_3$:  cgen($e_3'$)
     goto $L_3'$
```

Exception Table:

From	To	Handler
L_1	L_1'	caller
L_2	L_2'	C_2
L_3	L_3'	C_3
C_2	C_3	caller
C_3	end	C_2

Implementing Exceptions with Tables. Notes

- runtime_throw looks at the table and figures which catch handler to invoke

- Advantage:
  - No cost, except if an exception is thrown
- Disadvantage:
  - Tables take space (even 30% of binary size)
  - But at least they can be placed out of the way

- Java Virtual Machine uses this scheme

try … finally …

- Another exception-related construct:

  try e_1 finally e_2
  - After the evaluation of e_1 terminates (either normally <u>or</u> exceptionally) it evaluates e_2
  - The whole expression then terminates like e_1
- Used for cleanup code:

```
try
    f = fopen("treasure.directions", "w");
    … compute … fprintf(f, "Go %d paces to the left", paces); …
finally
    fclose(f)
```

Code Generation for try … finally

- Consider the expression: e_1 + try e_2 finally e_2'

Regular code:

```
$L_1$:  cgen($e_1$)
$L_1'$: $t_1$ = acc
$L_2$:  cgen($e_2$)
$L_2'$: $t_2$ = acc
     cgen($e_2'$)      ; Run finally
     acc $\leftarrow$ $t_1$ + $t_2$
```

Handlers:

```
$C_2$:  cgen($e_2'$)
     jr runtime_throw
```

Exception Table:

From	To	Handler
L_1	L_1'	caller
L_2	L_2'	C_2
C_2	end	caller

Code for finally clauses must be duplicated !

Avoiding Code Duplication for try … finally

- The Java Virtual Machine designers wanted to avoid this code duplication

- So they invented a new notion of <u>subroutine</u>
  - Executes within the stack frame of a method
  - Has access to and can modify local variables
  - One of the few true innovations in the JVM

JVML Subroutines Are Complicated

- Subroutines are the most difficult part of the JVML

- And account for the several bugs and inconsistencies in the bytecode verifier

- Complicate the formal proof of correctness:
  - 14 or 26 proof invariants due to subroutines
  - 50 of 120 lemmas due to subroutines
  - 70 of 150 pages of proof due to subroutines

Are JVML Subroutines Worth the Trouble ?

- Subroutines save space?
  - About 200 subroutines in 650,000 lines of Java (mostly in JDK)
  - No subroutines calling other subroutines
  - Subroutines save 2427 bytes of 8.7 Mbytes (0.02%) !
- Changing the name of the language from Java to Oak saves 13 times more space !

Exceptions. Conclusion

- Exceptions are a very useful construct
- A good <u>programming language solution</u> to an important <u>software engineering problem</u>
- But exceptions are complicated:
  - Hard to implement
  - Complicate the optimizer
  - Very hard to debug the implementation (exceptions are exceptionally rare in code)