COS 301

Exception Handling

Exceptions

- Some assorted definitions
  - An exception is any unusual event, either erroneous or not, detectable by either hardware or software, that may require special processing
  - An exception an error condition which occurs in an operation that cannot be resolved by the operation itself
  - An exception is an event, which occurs during the execution of a program, that disrupts the normal flow of the program's instructions.
  - An error condition that changes the normal flow of control in a program.
- The special processing that may be required after detection of an exception is called exception handling
- The exception handling code unit is called an exception handler

Exception Handling

- Exception handling is a flow control mechanism that alters the normal operation of program
  - Control can be passed to code in the same module or unit, passed up the call stack, or passed to an entirely different modfile
  - By design it it to be used as an error handling mechanism
- Most people agree that exception handling should be used primarily for error handling and not as a flow control mechanism
- Why not use it for control flow?
  - The usual reasons involving readability, writability and difficulty of maintenance

Robust Programs

- Applications are *robust* when they continue to operate correctly under all conceivable error conditions.
  - We don't want the computer controlling the engine in a car to stop operating with a cryptic error message when an error occurs.
  - We also don't want it to accelerate to 100mph and disable the brakes when an error occurs.

Example of Non-Robust Code

```
(* Pascal *)
reset(file, name);  (* open *)
sum := 0.0;
count := 0;
while (not eof(file)) do begin
   read(file, number);
   sum := sum + number;
   count := count + 1;
end;
avg := sum / count;
```

- What can go wrong?
  - If whitespace occurs after last number EOF will be false
  - Number is not in a valid format
  - Open fails
  - No data in file and count is 0

Hardware Errors

- Hardware errors
  - Disk read failure
  - Storage full
  - Memory parity error
  - Network device failure
  - Page fault
  - Null pointer access (if detected by hardware)
  - Illegal memory access
- Errors such as these are detected and handled by low-level OS code that checks device status registers or responds to hardware signals
- The errors are handled by the operating system but passed back to the application in some form

Levels of Abstraction in Errors

- OS Level - errors that occur when operating systems services fail
  - Some hardware errors
  - EOF on input
  - Communications failure
  - File not found
- Programming language level
  - Array access out of bounds, run-time type errors, data not in expected format
- Programmer defined
  - Stack full, pop an empty stack

Exception And Error Handling

- Without exception or error handling
  - When an exception or error occurs at the OS level, the program is terminated and the OS displays a message
  - Errors at the application level such as buffer overflow, index out of bounds, type error etc may allow the program to continue to operate erratically or crash spectacularly
- With exception handling
  - Programs can trap some exceptions and/or test for errors
  - Goal is to either fix the problem and continue or at least die gracefully
  - Essential for operating systems

Exception Handling Alternatives

- An exception is raised when its associated event occurs
- A language that does not have exception handling capabilities can still define, detect, raise, and handle exceptions (user defined, software detected)
- Alternatives are various error handling techniques:
  - Send an auxiliary parameter or use the return value to indicate the return status of a subprogram
  - Pass a label parameter to all subprograms (error return is to the passed label)
  - Pass an exception handling subprogram to all subprograms

Error Handling Strategies

- Many languages do not support exception handling
- A number of strategies for handling errors:
  - Return illegal value from function as error indicator (example: IndexOf for array returns -1)
  - Write functions that return boolean success indicators
  - Add error parameter to a void function
  - Try to anticipate possible errors and add conditional guards to statement blocks

Built-in Exception Handling

- Error detection code is tedious to write and it clutters the program
- Exception handling encourages programmers to consider many different possible errors
- Exception propagation allows a high level of reuse of exception handling code
- Exceptions can be handled in some other unit of dynamic or static scope so that error handling is centralized and encapsulated rather than being strewn throughout the code

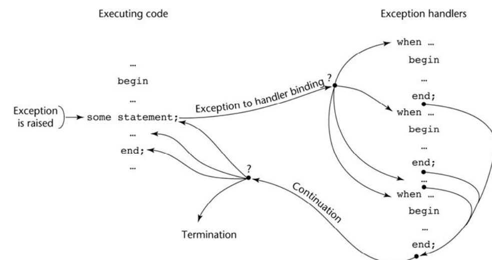
Design Issues

- How are user-defined exceptions specified?
- Should there be default exception handlers for programs that do not provide their own?
- Can built-in exceptions be explicitly raised?
- Are hardware-detectable errors treated as exceptions that can be handled?
- Are there any built-in exceptions?
- How can exceptions be disabled, if at all?

Design Issues

- How and where are exception handlers specified and what is their scope?
- How is an exception occurrence bound to an exception handler?
- Can information about the exception be passed to the handler?
- Where does execution continue, if at all, after an exception handler completes its execution? (terminate or resume?)
- Is some form of finalization provided?

Exception Handling Control Flow



Terminate or Resume?

- Resumption model transfers control back to faulting code after exception has been handled
- Termination model transfers control back to caller
- Either may be appropriate depending on type of exception and resolution of problem.
- Languages such as Ada, Java, C++ all use the termination model
  - If resumption model is needed then an alternate error handling mechanism must be used

Implementation Complexity

- Both terminate and resume models have complex issues
  - Resume: have to restore state of program at time exception was called
  - Terminate: what happens to resources (memory, open files, etc) belonging to the terminated code?

Propagation of exceptions

- Languages that support exceptions associate exceptions with a scope or block of code
  - Java, C++, C# use the Try block
  - Ada allows exception handlers to be defined at both block and subprogram levels of scope
- If no handler is found within current scope, the exception is propagated up the call stack
- If no handler is found then typically the language runtime will handle the exception by terminating the program

Exception Handling Evolution

- COBOL provided very limited exception handling
- PL/I generalized the idea, first language with real exception handling (1970's)
- Ada is usually considered to be the first language with well defined an usable exception handling (1983)
  - But most academic authors fail to mention BASIC with its ON ERROR GOTO statement (early 1980s)
- Mainstream adoption came in 1990's with C++ compilers

Exception Handling in Ada

- The Ada design for exception handling embodies the state-of-the-art in language design in 1980
  - Ada was the only widely used language with exception handling until it was added to C++
  - There are a few technical problems with Ada exceptions especially with object oriented extensions
- The frame of an exception handler in Ada is either a subprogram body, a package body, a task, or a block
- Because exception handlers are usually local to the code in which the exception can be raised, they do not have parameters

Ada Exception Handlers

- Handler form:

  `when` *exception_choice*{|*exception_choice*} `=>` *statement_sequence*
  `...`
  `[when others =>`
  statement_sequence`]`

  exception_choice form:

  exception_name | `others`

- Handlers are placed at the end of the block or unit in which they occur

Example

```
with Ada.Exceptions, Ada.Text_IO;

procedure Foo is
  Some_Error : exception;
begin
  Do_Something_Interesting;
exception -- Start of exception handlers
  when Constraint_Error =>
    ... -- Handle constraint error
  when Storage_Error =>
    -- Propagate Storage_Error as a different exception
    -- with a useful message
    raise Some_Error with "Out of memory";
  when Error : others =>
    -- Handle all others
    Ada.Text_IO.Put("Exception: ");
    Ada.Text_IO.Put_Line(Ada.Exceptions.Exception_Name(Error));
    Ada.Text_IO.Put_Line(Ada.Exceptions.Exception_Message(Error));
end Foo;
```

Binding Exceptions to Handlers

- If the block or unit in which an exception is raised does not have a handler for that exception, the exception is propagated elsewhere to be handled
  - Procedures - propagate it to the caller
  - Blocks - propagate it to the scope in which it appears
  - Package body - propagate it to the declaration part of the unit that declared the package (if it is a library unit, the program is terminated)
  - Task - no propagation; if it has a handler, execute it; in either case, mark it "completed"

Continuation

- The block or unit that raises an exception but does not handle it is always terminated (also any block or unit to which it is propagated that does not handle it)
- Control never returns to the block or unit that raised the exception

Example

```
package Directory_Enquiries is

    procedure Insert (New_Name   : in Name;
                      New_Number : in Number);

    procedure Lookup (Given_Name  : in  Name;
                      Corr_Number : out Number);

    Name_Duplicated : exception;
    Name_Absent     : exception;
    Directory_Full  : exception;

  end Directory_Enquiries;
```

Example

```
package body Directory_Enquiries is
     procedure Insert (New_Name   : in Name;
                       New_Number : in Number)
     is
     begin
        …
        if New_Name = Old_Entry.A_Name then
           raise Name_Duplicated;
        end if;
        …
        New_Entry :=  new Dir_Node'(New_Name, New_Number,…);
        …
     exception
        when Storage_Error => raise Directory_Full;
     end Insert;
     procedure Lookup (Given_Name  : in  Name;
                       Corr_Number : out Number)
     is
    begin
        …
        if not Found then
           raise Name_Absent;
        end if;
    end Lookup;
  end Directory_Enquiries;
```

Other Design Choices

- User-defined Exceptions form:

  `exception_name_list : exception;`
- Raising Exceptions form:

  `raise [exception_name]`
  - (the exception name is not required if it is in a handler--in this case, it propagates the same exception)
- Exception conditions can be disabled with:

  `pragma SUPPRESS(exception_list)`

Predefined Exceptions

- **CONSTRAINT_ERROR** - index constraints, range constraints, etc.
- **NUMERIC_ERROR** - numeric operation cannot return a correct value (overflow, division by zero, etc.)
- **PROGRAM_ERROR** - call to a subprogram whose body has not been elaborated
- **STORAGE_ERROR** - system runs out of heap
- **TASKING_ERROR** - an error associated with tasks

Exception Handling in C++

- Added to C++ ANSI Standard in 1990
  - Design is based on that of CLU, Ada, and ML
  - But C++ has no standard exceptions: all are user/library defined
- Scope of C++ exception handler is a try block rather than a program unit

C++ Exception Handlers

- Try block

```
  try {
    /* code that is expected to raise an
  exception */
  }
  catch (formal parameter) {
    // handler code
  }
  ...
  catch (formal parameter) {
    // handler code
  }
catch (...) {
    // catch anything handler code
  }
```

The Catch Function

- `catch` is the name of all handlers--it is an overloaded name, so the formal parameter of each must be unique
- The formal parameter can be a bare type name instead of a variable
  - Provides a signature to distinguish the handler from others
- With a variable name the formal parameter can be used to transfer information to the handler
- An exception raised in a try block causes immediate transfer of control to catch handlers
  - Catch blocks are searched sequentially so the convention is is to place more specific handlers at the top of the catch block and more generic ones below
  - The formal parameter can be an ellipsis, in which case it handles all exceptions not yet handled and guarantees that all exceptions will be caught

C++ Catch Clause

- From a C++ manual:

```
catch(T)
catch(const T)
catch(T&)
catch(const T&)

Such handlers can catch exception objects of type E if:

1. T and E are the same type, or
2. T is an accessible base class of E at the throw point,
   or
3. T and E are pointer types and there exists a standard
   pointer conversion from E to T at the throw point. T is
   an accessible base class of E if there is an
   inheritance path from E to T with all derivations
   public.
```

Throwing Exceptions

- Exceptions are all raised explicitly by the statement:
  `throw expression;`
- `throw` without an operand can only appear in a handler
  - when it appears, it simply re-raises the exception, which then must be handled elsewhere
- The type of the expression disambiguates the intended handler

Unhandled Exceptions

- An unhandled exception is propagated to the caller of the function in which it is raised
- This propagation continues to the main function
- If no handler is found, the default handler is called

Continuation

- After a handler completes its execution, control flows to the first statement after the last handler in the sequence of handlers of which it is an element
- Other design choices
  - All exceptions are user-defined
  - Exceptions are neither specified nor declared
  - The default handler, `unexpected`, simply terminates the program; `unexpected` can be redefined by the user
  - Functions can list the exceptions they may raise
  - Without a specification, a function can raise any exception (the `throw` clause)

C++ Example 1

```
#include <iostream.h>
int main () {
  char A[10];
  cin >> n;
  try {
    for (int i=0; i<n; i++){
      if (i>9) throw "array index error";
      A[i]=getchar();
    }
  }
  catch (char* s)
  { cout << "Exception: " << s << endl; }
  return 0;
}
```

Example

```
/* this example computes a frequency distribution
   for a set of grades read from cin and terminated
   by the appearance of a grade < 0 */

#include <iostream>
int main() {
  int new_grade, index, limit1, limit2;
  int freq[10] = {0,0,0,0,0,0,0,0,0,0};

class NegativeInputException(){
  public:
  NegativeInputException(){  // constructor
    cout << "End of input data reached << endl;
  }
}
```

Example

```
try {
  while (true) {
    cout << "please enter a grade" << endl;
    if ((cin >> newgrade) < 0) // end of data
      throw NegativeInputException();
    index = new_grade / 10;
    {
      try {
        if (index > 9)
           throw new_grade;
        freq[index]++;
      }
      catch (int grade) {
         if (grade == 100){
           freq[9]++;
         else
           cout << "Error: new grade " << grade
                << " out of range." << endl;
      }
    }
  }
}
```

Example

```
catch (NegativeInputException& e)
  cout << "From\tTo\tFrequency" << endl;
  for (index  = 0; index < 10; index++){
     limit1 = index * 10;
     limit2 = index == 9 ? 100 : limit1 + 9;
     cout << limit1 << '\t' << limit2 << '\t' <<
  freq[index] << endl;

  }
}
} // end main
```

- This example illustrates a perhaps inappropriate use of exception handling as a control structure

Remarks on C++ design

- C++ exception handling design has some peculiarities
  - exceptions are not named
  - hardware- and system software-detectable exceptions cannot be handled
  - Exceptions are bound to handlers by type of parameter rather than type of error

Exception Handling in Java

- Based on that of C++, but more in line with OOP philosophy
- Includes some predefined exceptions that can be implicitly raised by the JVM

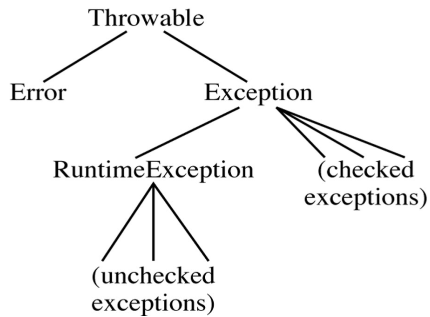
Classes of Exceptions

- All exceptions are objects of classes that are descendants of the `Throwable` class
- The Java library includes two subclasses of `Throwable` :
  - `Error`
    - Thrown by the Java interpreter for events such as heap overflow
    - Never handled by user programs
  - `Exception`
    - User-defined exceptions are usually subclasses of this
    - Has two predefined subclasses, `IOException` and `RuntimeException` (e.g., `ArrayIndexOutOfBoundsException` and `NullPointerException`

Java Exception Handlers

- Like those of C++, except every `catch` requires a named parameter and all parameters must be descendants of `Throwable`
- Syntax of `try` clause is exactly that of C++
- Exceptions are thrown with `throw`, as in C++, but often the `throw` includes the `new` operator to create the object, as in: `throw new MyException();`

Java Exception Class Hierarchy



Binding Exceptions to Handlers

- When an exception is thrown an instance of the exception class is the operand of the throw statement

```
class MyException extends Exception {
  public MyException() {}
  public MyException (String msg){
    super (msg);
  }
}
 . . .
throw new MyException();
throw new MyException("A weird error occurred.");
```

Binding Exceptions to Handlers

- Binding an exception to a handler is similar to C++
  - An exception is bound to the first handler with a parameter is the same class as the thrown object or an ancestor of it
- The generic exception handler that handles anything is

```
catch(Exception genericObj){
}
```

- An exception can be handled and rethrown by including a `throw` in the handler (a handler could also throw a different exception)

Continuation

- If no handler is found in the `try` construct, the search is continued in the nearest enclosing `try` construct, etc.
- If no handler is found in the method, the exception is propagated to the method's caller
- If no handler is found (all the way to `main`), the program is terminated
- To insure that all exceptions are caught, a generic handler can be included in any `try` construct that catches all exceptions
  - Like C++ it must be the last in the `try` construct

Java throws Clause

- Specifies what exceptions might be raised

```
public void methodA() throws SomeException,
   AnotherException  {
     //methodbody
}
public void methodB() throws CustomException {
     //Methodbody
}
public void methodC() {
  try
    methodB();
    methodA();
  catch (Exception e){
   ...
  }
  finally {
    // clean up ...
  }
}
```

Checked and Unchecked Exceptions

- Exceptions of class **`Error`** and **`RunTimeException`** and all of their descendants are called unchecked exceptions
- All other exceptions are called checked exceptions
- Checked exceptions that may be thrown by a method must be either:
  - Listed in the `throws` clause, or
  - Handled in the method
- Checked at compile time

Other Design Choices

- A method cannot declare more exceptions in its `throws` clause than the method it overrides
- A method that calls a method that lists a particular checked exception in its `throws` clause has three alternatives for dealing with that exception:
  - Catch and handle the exception
  - Catch the exception and throw an exception that is listed in its own `throws` clause
  - Declare it in its `throws` clause and do not handle it

The `finally` Clause

- The finally clause can appear at the end of a try construct
- Form:

```
finally {
...
}
```

- Specifies code that is to be executed, regardless of what happens in the `try` construct
  - Typical uses are freeing resources such as an open file or database connection that must be closed regardless of error conditions

The Finally Block

- Java and C# support the finally block – a major omission in C++

```
try {
  // The guarded region:
  // Errors might throw A, B, or C
} catch (A a1) {
  // Handle A
} catch (B b1) {
  // Handle B
} catch (C c1) {
  // Handle C
} finally {
   // Executed whether or not there was an exception
}
```

Example

- A try construct with a finally clause can be used outside exception handling
- The finally clause will be executed even if the return statements terminates the loop

```
try {
    for (index = 0; index < 100; index++) {
          …
          if (…) {
                 return;
          }
}  // end try
finally {
    …
}  //
```

Assertions

- Primarily used during program development
- Statements in the program declaring a boolean expression regarding the current state of the computation
  - When evaluated to true nothing happens
  - When evaluated to false an `AssertionError` exception is thrown
  - Can be disabled during runtime without program modification or recompilation
- Two forms
  - `assert` *condition;*
  - `assert` *condition*: *expression;*

Assertion or Exception?

- From Programming with Assertions

http://download.oracle.com/javase/1.4.2/docs/guide/lang/assert.html

- By convention, preconditions on public methods are enforced by explicit checks that throw particular, specified exceptions. For example:

```
/**  Sets the refresh rate.
     * @param  rate refresh rate, in frames per second.
     * @throws IllegalArgumentException if rate <= 0 or
     *          rate > MAX_REFRESH_RATE.   */
     public void setRefreshRate(int rate) {
         // Enforce specified precondition in public method
         if (rate <= 0 || rate > MAX_REFRESH_RATE)
             throw new IllegalArgumentException
                       ("Illegal rate: " + rate);
         setRefreshInterval(1000/rate);
     }
```

- This convention is unaffected by the addition of the assert construct.
- Do not use assertions to check the parameters of a public method.
- An assert is inappropriate because the method guarantees that it will always enforce the argument checks. It must check its arguments whether or not assertions are enabled. Further, the assert construct does not throw an exception of the specified type. It can throw only an AssertionError.

Assertion or Exception?

- You can, however, use an assertion to test a nonpublic method's precondition that you believe will be true no matter what a client does with the class. For example, an assertion is appropriate in the following "helper method" that is invoked by the previous method:

```
/**
   * Sets the refresh interval (which must correspond
   * to a legal frame rate).
   * @param  interval refresh interval in milliseconds.*/
   private void setRefreshInterval(int interval) {
       // Confirm adherence to precondition
       //in nonpublic method
       assert interval > 0 &&
           interval <= 1000/MAX_REFRESH_RATE : interval;
       ... // Set the refresh interval
   }
```

Exceptions in Scripting Languages

- Most modern scripting languages implement some form of try … catch block even though they use dynamic typing

JavaScript

```
try {
  // run some code here
} catch(error) {
  // a javascript error object with
  //properties such as error.message
} finally {
  // Statements that execute afterward either way
}
```

- JavaScript also has a throw statement
- Many error object properties are vendor specific

PHP

```
<?php
function inverse($x) {
    if (!$x) {
        throw new Exception('Division by zero.');
    }
    else return 1/$x;
}

try {
    echo inverse(5) . "\n";
    echo inverse(0) . "\n";
} catch (Exception $e) {
    echo 'Caught exception: ',  $e->getMessage(), "\n";
}

// Continue execution
echo 'Hello World';
?>
{
```

- PHP also has a throw statement

Python

```
f = None
try:
   f = file("aFileName")
   f.write(could_make_error())
except IOError:
   print "Unable to open file"
except:   # catch all exceptions
   print "Unexpected error"
else:     # executed if no exceptions are raised
   print "File write completed successfully"
finally:  # clean-up actions, always executed
   if f:
      f.close()
```

Ruby

```
begin
  # Do something nifty
  raise SomeError, "This is the error message!"  # Uh-oh!
rescue SomeError
  # This is executed when a SomeError exception
  # is raised
rescue AnotherError => error
  # Here, the exception object is referenced from the
  # `error' variable
rescue
  # This catches all exceptions derived from StandardError
  retry # This executes the begin section again
else
  # This is executed only if no exceptions were raised
ensure
  # This is always executed, exception or not
end
```

Abusing Exception Handling

- From

http://leedumond.com/blog/the-greatest-exception-handling-wtf-of-all-time/

```
public static class NumberHelpers
{
   public static ApplicationException EvenOrOdd(int integer)
   {
      if (integer % 2 == 0)
      {
         return new ApplicationException("The integer is even.");
      }
      else
      {
         return new ApplicationException("The integer is odd.");
      }
   }
}
```

Usage

```
protected void btnTest_Click(object sender,
                                         EventArgs e)
{
   try
   {
      throw NumberHelpers.EvenOrOdd
       (Convert.ToInt32(txtIntToTest.Text));
   }
   catch (ApplicationException ex)
   {
      litResult.Text = ex.Message;
   }
}
```

A light-hearted look at exceptions

- Shamelessly copied from http://www.theregister.co.uk/2006/01/11/exception_handling/page2.html
- **What to do if you get an exception.** Faced with this question, some writers indulge in hand waving. Fortunately I am able to offer specific guidelines, based on standard practice as observed in commercial software, and some informed guesswork.
- If you are running as some sort of web service, the standard approach on handling an exception is to send the user a page of ODBC diagnostics, preferably mashed up with a few suggestions from Apache.

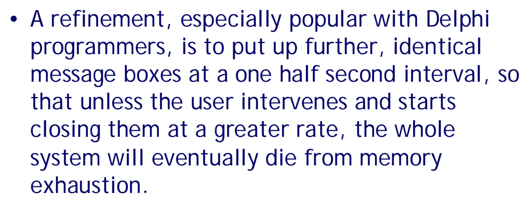
A light-hearted look at exceptions

- But this approach doesn't just work with HTML output. For example some banks have also adopted it, as a novel method of telling you that you aren't going to see your card back from the ATM any time soon.

A light-hearted look at exceptions

- If you are running as a background process with no user interaction, don't just disappear silently. Be sure to do a memory dump, so gifting the user a digital turd - a binary lump of disk space of no use to man or beast. Naturally it won't help you-the-programmer find the cause of the exception, because even if the user troubles to send it to you, like everyone else you don't keep your debug symbol tables in version control, kidding yourself that you can rebuild them identically from the source.

- (By the way, the Windows API call to create this thing, MiniDumpWriteDump(), is one of my faves: as it says in the docs, sometimes you have to throw *another* exception to get it to fire. Neat.)
- If you are GUI program, now's the time to pop up a modal message box. It doesn't really matter what text you put in it, because the user will ignore it.

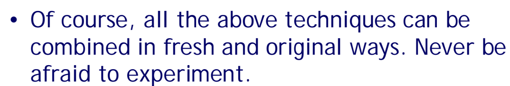


- A refinement, especially popular with Delphi programmers, is to put up further, identical message boxes at a one half second interval, so that unless the user intervenes and starts closing them at a greater rate, the whole system will eventually die from memory exhaustion.

- If you're running under Windows XP, consider converting the exception into a null pointer dereference in the catch handler:

```
catch(...)
  { // now we're really stuffed
      int * p = 0;
     *p = 22;
```

- This has the advantage over an ordinary crash that you will get one of those special OS-supplied dialogs, that asks permission to send log details back to Microsoft. Naive users will interpret this as a Windows fault, and will direct their bile Redmondwards.



- Of course, all the above techniques can be combined in fresh and original ways. Never be afraid to experiment.

- The primary duty of an exception handler is to get the error out of the lap of the programmer and into the surprised face of the user. Provided you keep this cardinal rule in mind, you can't go far wrong.