Creative Software Design

Exception Handling

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Today's Topics

- What are Exceptions & How to deal with Exceptions?
- C++ Exceptions: Basics
- `try`, `catch`, and `throw`
- Matching Catch Handlers
- Uncaught Exceptions
- Cleaning Up
- Unwinding the stack

Exceptions

- Exceptions are anomalous or ***exceptional situations*** requiring special processing – often changing the normal flow of program execution[wikipedia]
  - Memory allocation error
    - out of memory space
  - Divide by zero

```
double x = 2.;
double y = -2.;
double harmonic_mean = 2.0 * (x * y) / (x + y);
```

  - File IO error
    - Try to open an unavailable file

How to Deal with Exceptions?

- Ignore them
  - Wrong thing to do for all but demo programs
- Abort processing
  - Detect but don’t try to recover
  - A little bit better, but still wrong for all but demo programs

```
double harmonic_mean(double a, double b)
{
    if (a == -b)
    {
        std::cout << "wrong arguments\n";
        std::abort();
    }
    return 2.0 * a * b / (a + b);
}
```

```
$ ./harmonic_mean
wrong arguments
Aborted (core dumped)
```

How to Deal with Exceptions?

- **Returning error values**

```
ret = PerformTask()
If ret is 0 (or some error codes)
    Perform error processing

ret2 = PerformTask2()
If ret2 is 0 (or some error codes)
    Perform error processing
```

  - Traditional approach
    - e.g. malloc(), fopen() of C
  - Difficult to read, modify, maintain and debug
    - Easy to miss a check

```
bool harmonic_mean(double a, double b,
                   double *ans){
    if (a == -b){
        *ans = DBL_MAX;
        return false;
    }
    else{
        *ans = 2.0 * a * b / (a + b);
        return true;
    }
}
```

How to Deal with Exceptions?

- **Use C++ Exceptions**

```
try{
    // protected code
}
catch (ExceptionName e1){
    // catch block
}
```

  - More maintainable
  - Modern approach
    - e.g. new, ifstream::open() of C++
  - Reasonably efficient: zero-cost model (popular strategy for major compilers):
    - if no exceptions are thrown, there’s NO overhead.
    - if exceptions are thrown, there’s more overhead to process them.

C++ Exceptions: Basic

```
#include <iostream>
using namespace std;
double divide(int a, int b){
    if (b == 0){
        throw "divide by zero condition!";
    }
    return (a / b);
}
int main(){
    int x, y;
    double z;
    cin >> x >> y;

    try{
        z = divide(x, y);
        cout << z << endl;
    }
    catch (const char *msg){
        cerr << msg << endl;
    }
    return 0;
}
```

C++ Exceptions: Basic

```
#include <iostream>
using namespace std;
double divide(int a, int b){
    if (b == 0){
        throw "divide by zero condition!";
    }
    return (a / b);
}
int main(){
    int x, y;
    double z;
    cin >> x >> y;

    try{
        z = divide(x, y);
        cout << z << endl;
    }
    catch (const char *msg){
        cerr << msg << endl;
    }
    return 0;
}
```

- For a normal case (e.g. y!= 0),
  1. All code in the try block is executed.
  2. Catch block is skipped.
  3. Computation resumes after the catch block.

C++ Exceptions: Basic

```
#include <iostream>
using namespace std;
double divide(int a, int b){
    if (b == 0){
        throw "divide by zero condition!";
    }
    return (a / b);
}
int main(){
    int x, y;
    double z;
    cin >> x >> y;

    try{
        z = divide(x, y);
        cout << z << endl;
    }
    catch (const char *msg){
        cerr << msg << endl;
    }
    return 0;
}
```

- For an exceptional case (e.g. y==0),
  1. **"Throw"** an exception.
  2. Remaining code in the try block is **skipped**.
  3. **Based on the type of the exception,** the matching catch block is executed, if found.
  4. Computation resumes after the last catch block.

C++ Exceptions: Basic

```
void someFunc1(){
    …
    throw SomeException(); // when an exception occurs
    …
}

void someFunc2(){
    try{
        // some code that may throw an exception  someFunc1();
    }
    catch (SomeException &e){
        // some processing to attempt to recover from error
    }
}
```

Quiz #1

- What is the advantage of C++ exception handling ?

try, catch, and throw

```
#include <iostream>
using namespace std;
double divide(int a, int b){
    if (b == 0){
        throw "divide by zero condition!";
    }
    return (a / b);
}
int main(){
    int x, y;
    double z;
    cin >> x >> y;

    try{
        z = divide(x, y);
        cout << z << endl;
    }
    catch (const char *msg){
        cerr << msg << endl;
    }
    return 0;
}
```

- **try {…}:**
  - Consists of codes that may “throw” exceptions
  - Groups one or more statements (that may throw exceptions) with one or more catch blocks

try, catch, and throw

```
#include <iostream>
using namespace std;
double divide(int a, int b){
    if (b == 0){
        throw "divide by zero condition!";
    }
    return (a / b);
}
int main(){
    int x, y;
    double z;
    cin >> x >> y;

    try{
        z = divide(x, y);
        cout << z << endl;
    }
    catch (const char *msg){
        cerr << msg << endl;
    }
    return 0;
}
```

- **catch(E e) {…}:**
  - Catchs the exception of the given type, thrown from a *throw* statement inside try block
  - Exception type can be any built-in type or user-defined class
  - Exceptions are handled inside the catch block

try, catch, and throw

```
#include <iostream>
using namespace std;
double divide(int a, int b){
    if (b == 0){
        throw "divide by zero condition!";
    }
    return (a / b);
}
int main(){
    int x, y;
    double z;
    cin >> x >> y;

    try{
        z = divide(x, y);
        cout << z << endl;
    }
    catch (const char *msg){
        cerr << msg << endl;
    }
    return 0;
}
```

- throw e:
  - “Throw” an exception
  - Exception type can be any built-in type or user-defined class
  - Program immediately jumps to the matching catch block

Matching Catch Handlers

- A catch handler matches an exception based on its type.
- A try block can be followed by multiple catch blocks.
    - Matching attempts are performed **in the order of catch handler declaration.**

```
try{
    // some code that may throw an exception
}
catch (T1 t1){
    // processing for type T1
}
catch (T2 t2){
    // processing for type T2
}
```

Matching Catch Handlers

```
#include <iostream>
#include <string>
using namespace std;

double divide(int a, int b){
    if (b == 0){
        throw -1;                       // "catch int"
        //throw "exception";            // "catch const char*"
        //throw string("exception"); // "catch string&"
    }
    return (a / b);
}
```

```
int main()
{
    int x = 2, y = 0;
    double z;

    try{
        z = divide(x, y);
        cout << z << endl;
    }
    catch (int e){
        cout << "catch int " << e << endl;
    }
    catch (const char *e){
        cout << "catch const char* " << e << endl;
    }
    catch (string &e){
        cout << "catch string& " << e << endl;
    }
    return 0;
}
```

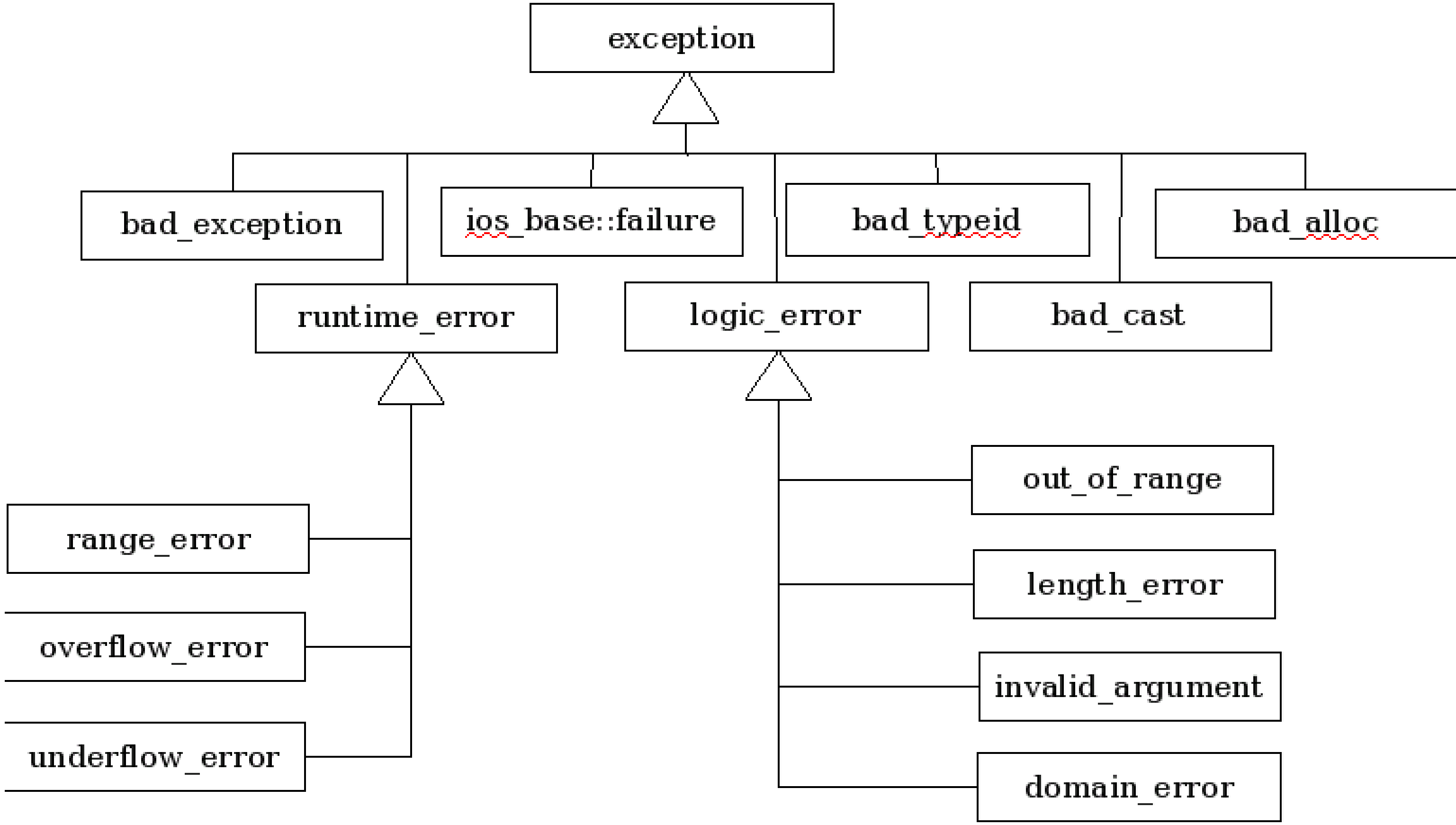
Matching Catch Handlers

- The conventional way to throw and catch exceptions is:
  - throw an exception **object**
  - catch it by **reference** (or const reference)

- A **derived class object** can be caught by **base class reference**.
  - But the opposite does not work.
  - Caution: If a derived class object is passed **by value of base class type**, *object slicing* occurs.

Matching Catch Handlers

- **std::exception** : Base class for standard exceptions.
  - All exceptions thrown by C++ standard library are derived from this class.
  - Therefore, all standard exceptions can be caught by catching this type by reference (`catch(std::exception & e)`).



Matching Catch Handlers

```cpp
#include <iostream>
using namespace std;
class ExceptionA : public std::exception {};
class ExceptionB : public ExceptionA {};
double divide(int a, int b){
    if (b == 0){
        throw ExceptionA();        // "catch ExceptionA&"
        //throw ExceptionB();      // "catch ExceptionA&"
        //throw std::exception();  // "catch std::exception&"
    }
    return (a / b);
}
```

```cpp
int main(){
    int x = 2, y = 0;
    double z;

    try{
        z = divide(x, y);
        cout << z << endl;
    }
    catch (ExceptionA &e){
        cout << "catch ExceptionA&" << endl;
    }
    catch (std::exception &e){
        cout << "catch std::exception&" << endl;
    }

    return 0;
}
```

Matching Catch Handlers

```
class ExceptionA : public std::exception
{
    …
};
class ExceptionB : public ExceptionA
{
    …
};
```

To catch each exception types in a hierarchy:

- Most-derived type should be caught first
- Most-base type should be caught last

```
int main()
{
    try{
        // This may throw
        // ...
    }
    catch (ExceptionB &e){
        // ...
    }
    catch (ExceptionA &e){
        // ...
    }
    catch (std::exception &e){
        // ...
    }
    return 0;
}
```

Quiz #2

- What is the expected output? (including compile/runtime error)

```
#include<iostream>
using namespace std;

class Base {};
class Derived: public Base {};
int main()
{
    Derived d;
    try {
        throw d;
    }
    catch(Base b) {
         cout<<"Caught Base Exception";
    }
    catch(Derived d) {
         cout<<"Caught Derived Exception";
    }
    return 0;
}
```

Nested Try Blocks

- Try blocks can be nested.
- If a throw occurs in an inner try block, the exception moves outward through the nested try blocks until the first matching catch block is found.
  - If one of the inner catch blocks catches the exception, it will not get caught by the outer catch blocks.
  - else, it will try to find a matching one in the outer catch blocks.

Nested Try Blocks

```cpp
#include <iostream>
using namespace std;
class ExceptionA : public std::exception {};
class ExceptionB : public ExceptionA {};

double divide(int a, int b){
    if (b == 0){
        throw ExceptionA();   // "catch std::exception&"
        //throw ExceptionB(); // "catch ExceptionB&"
    }
    return (a / b);
}
```

```cpp
int main(){
    int x = 2, y = 0;
    double z;
    try{
        try{
            z = divide(x, y);
        }
        catch (ExceptionB &e){
            cout << "catch ExceptionB&" << endl;
        }
        cout << z << endl;
    }
    catch (std::exception &e){
        cout << "catch std::exception&" << endl;
    }

    return 0;
}
```

Re-throw Exceptions

- If your catch handler does not completely handle an exception, you may **re-throw** it to the next outer catch blocks.

```
catch (E e)
{
     // if the processing to handle e is incomplete,
     throw;
}
```

Re-throw Exceptions

```
#include <iostream>  using namespace std;
class ExceptionA : public std::exception { };
class ExceptionB : public ExceptionA { };
double divide(int a, int b)
{
    if (b == 0){
        // "catch ExceptionB&", "catch std::exception&"
        throw ExceptionB();
    }
    return (a / b);
}
```

```
int main()
{
    int x = 2, y = 0;
    double z;
    try
    {
        try
        {
            z = divide(x, y);
        }
        catch (ExceptionB &e)
        {
            cout << "catch ExceptionB&" << endl;
            throw;
        }
        cout << z << endl;
    }
    catch (std::exception &e)
    {
        cout << "catch std::exception&" << endl;
    }
    return 0;
}
```

Uncaught Exceptions

- If there is ***no matching catch handler*** in all of the nested try block,
  - Exception is ***uncaught***
  - If an exception is uncaught, the special function **terminate**() is called

```
$ ./test
terminate called after throwing an instance of
'std::exception'
what(): std::exception Aborted (core dumped)
```

- Use "**catch(...)**", an *ellipsis* handler, to avoid uncaught exceptions.
  - It catches any exception not caught earlier.

Uncaught Exceptions: Example

- If none of the catch handlers matches,
  - – Exception moves to the next enclosing try block

```
void ThrowsException(){
    throw string("Exception!");
}
void CallsOne(){
    ThrowsException();
}
void CallsTwo(){
    try{
        CallsOne();
    }
    catch (const char *e){
        cout << "Caught in CallsTwo\n";
    }
}
```

```
int main()
{
    try
    {
        CallsTwo();
    }
    catch (string e)
    {
        cout << "Caught an exception in main\n";
    }
    return 0;
}
```

Output:

```
Caught an exception in main
```

Uncaught Exceptions: Example

- If an exception is uncaught,
    - – The special function **terminate**() is called

```
void ThrowsException(){
    throw string("Exception!");
}
void CallsOne(){
    ThrowsException();
}
void CallsTwo(){
    try{
        CallsOne();
    }
    catch (const char *e){
        cout << "Caught in CallsTwo\n";
    }
}
```

```
int main()
{
    try
    {
        CallsTwo();
    }
    catch (const char *e)
    {
        cout << "Caught an exception in main\n";
    }
    return 0;
}
```

Output:

```
terminate called after throwing an instance of
'std::string'
```

Uncaught Exceptions: Example

- An ellipsis handler catches all uncaught exceptions

```
void ThrowsException(){
    throw string("Exception!");
}
void CallsOne(){
    ThrowsException();
}
void CallsTwo(){
    try{
        CallsOne();
    }
    catch (const char *e){
        cout << "Caught in CallsTwo\n";
    }
}
```

```
int main(){
    try{
        try{
            CallsTwo();
        }
        catch (const char *e){
            cout << "Caught an exception in main\n";
        }
        catch (...){
            cout << "An ellipsis handler catches all
                uncaught exceptions " << endl;
        }
    }
    return 0;
}
```

Output:

```
An ellipsis handler catches all uncaught

exceptions
```

Quiz #3

- What is the expected output? (including compile/runtime error)

```cpp
#include <iostream>
using namespace std;

int main()
{
    try{
       throw 10;
    }
    catch (...){
        cout << "default exception\n";
    }
    catch (int param){
        cout << "int exception\n";
    }

    return 0;
}
```

Cleaning Up

- When an exception is thrown and leaves a scope, ***destructors*** of all the objects in that scope will be called.

- Make sure that all allocated members in each object should be deallocated in its destructors.

Cleaning Up: Example

```
class CleaningUp{
private:
    string word;

public:
    CleaningUp(const string &str){
        word = str;
        cout << "Created word:" << word << endl;
    }
    ~CleaningUp(){
        cout << "Destroyed word:" << word << endl;
    }
};
void ThrowsException(){
    CleaningUp hi("HI");
    int *pi = new int;
    throw "Exception";
    delete pi; // memory leak
    CleaningUp bye("BYE");
}
```

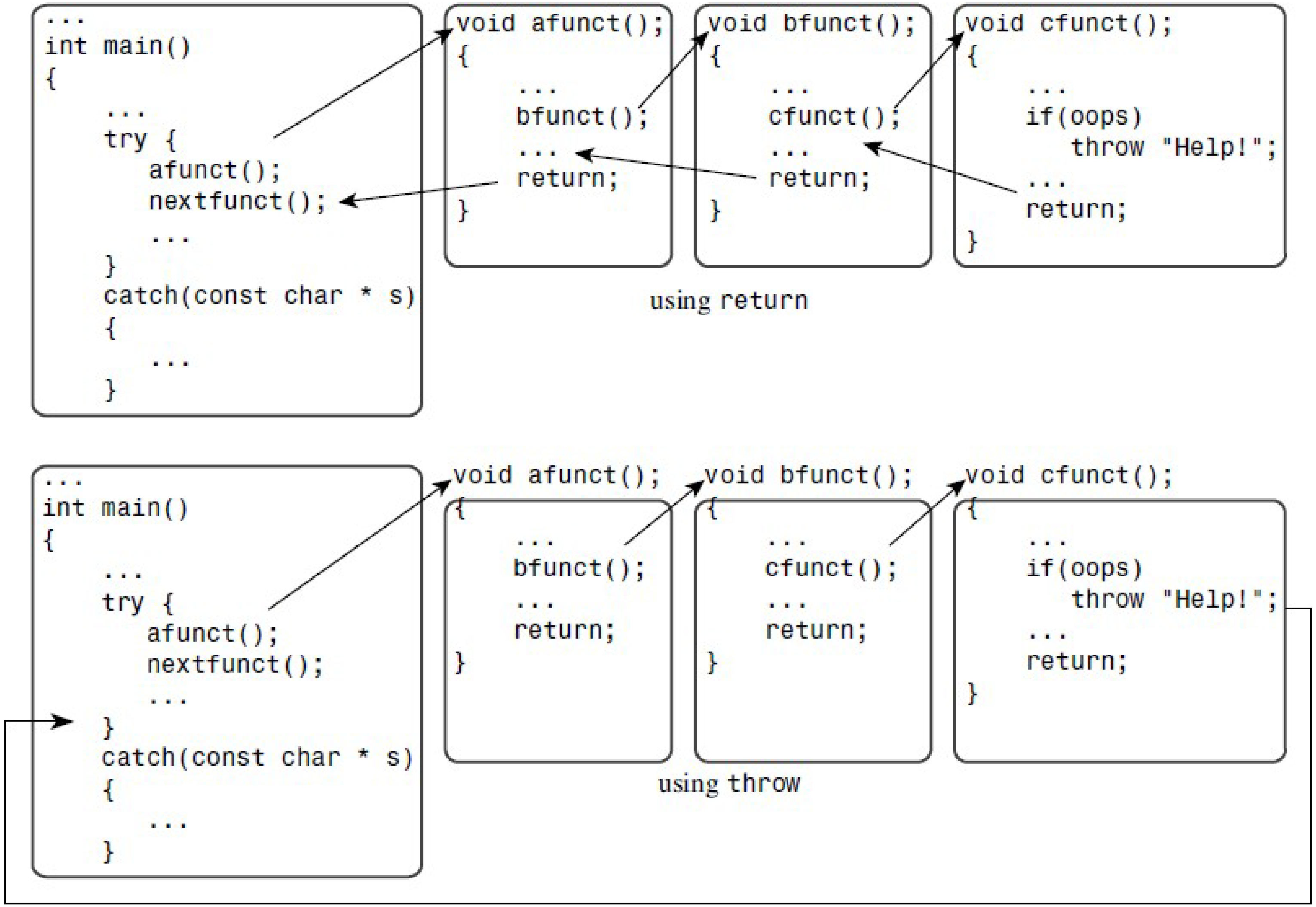
```
int main()
{
    try
    {
        ThrowsException();
    }
    catch (const char *e)
    {
        cout << "Caught an exception" << endl;
    }
    return 0;
```

Output:

```
Created word:HI
Destroyed word:HI
Caught an exception
```

Unwinding the stack

- return vs. throw



```
...
int main()
{
    ...
    try {
        afunct();
        nextfunct();
        ...
    }
    catch(const char * s)
    {
        ...
    }
```

```
void afunct();
{
    ...
    bfunct();
    ...
    return;
}
```

```
void bfunct();
{
    ...
    cfunct();
    ...
    return;
}
```

```
void cfunct();
{
    ...
    if(oops)
       throw "Help!";
    ...
    return;
}
```

using return

```
...
int main()
{
    ...
    try {
        afunct();
        nextfunct();
        ...
    }
    catch(const char * s)
    {
        ...
    }
```

```
void afunct();
{
    ...
    bfunct();
    ...
    return;
}
```

```
void bfunct();
{
    ...
    cfunct();
    ...
    return;
}
```

```
void cfunct();
{
    ...
    if(oops)
       throw "Help!";
    ...
    return;
}
```

using throw

Unwinding the stack

- Exceptions can be propagated through several levels of function calls if there is no try-catch block

```
void ThrowsException(){
    throw string("Exception!");
}
void DoSomething(){
    cout << "DoSomething called.\n";
    ThrowsException();
    cout << "DoSomething finished\n";
}
void DoSomethingMore(){
    cout << "DoSomethingMore called.\n";
    DoSomething();
    cout << "error in DoSomethingMore\n";
    throw string("error");
    cout << "DoSomethingMore finished.\n";
}
```

```
int main(){
    try{
        DoSomethingMore();
    }
    catch (string s){
        cout << "Caught an exception"
             << "'" << s << "'" << endl;
    }
    cout << "All done." << endl;
    return 0;
}
```

Output:

```
DoSomethingMore called.
DoSomething called.
Caught an exception 'Exception!’
All done.
```

Best Practices for Exceptions

- Use purpose-designed user-defined types as exceptions (not built-in types)
    - Do not throw built-in types and std::exception
    - https://isocpp.github.io/CppCoreGuidelines/CppCoreGuidelines#e14-use-purpose-designed-user-defined-types-as-exceptions-not-built-in-types

- Throw by value, catch exceptions from a hierarchy by reference
    - https://isocpp.github.io/CppCoreGuidelines/CppCoreGuidelines#e15-throw-by-value-catch-exceptions-from-a-hierarchy-by-reference

- For more best practices for C++ programming, please refer to https://isocpp.github.io/CppCoreGuidelines/CppCoreGuidelines

Exception Safety

- **Exception safety** is the state of code working correctly when exceptions are thrown.

- If your code does not guarantee exception safety, your program may risk resource leaks or enter an invalid state.

Exception Safety

- The C++ standard library provides several levels of exception safety
  - **No-throw guarantee**, :
    - Operations are guaranteed to succeed and satisfy all requirements even in exceptional situations.
  - **Strong exception safety**, :
    - Operations can fail, but failed operations are guaranteed to have no side effects, leaving the original values intact.
  - **Basic exception safety**:
    - Despite partial execution and possible side effects from failed operations, all invariants are maintained, and stored data remains valid, even if altered.
    - Resource leaks are prevented by managing all resources through enforced invariants.
  - **No exception safety**:
    - No guarantees are made.

Debate on C++ Exception

- Some people recommend not using exceptions in C++.
  - E.g., Google C++ Style Guide does not allow using C++ exceptions (https://google.github.io/styleguide/cppguide.html#Exceptions)
- Why?
  - **Transitive Caller Responsibility**:
    - When adding a throw statement, all transitive callers must handle exceptions safely or risk unexpected program termination.
  - **Complex Control Flow**:
    - Exceptions disrupt control flow, making it harder to trace and maintain code as functions may exit unexpectedly.
  - **Exception Safety Complexity**:
    - Writing exception-safe code demands RAII and other practices, often requiring isolated "commit" phases, which can make code more complex and harder to understand.
  - **Increased Binary Size and Compile Time**:
    - Enabling exceptions adds data to binaries, potentially increasing compile time and address space usage.
  - **Encouraging Misuse**:
    - The availability of exceptions may lead developers to use them improperly, like throwing exceptions for invalid user input, necessitating stricter coding guidelines.