An Overview of C++

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C++ Overview

- C++ was designed at AT&T Bell Labs by Bjarne Stroustrup in the early 80's – nearly 30 years ago!
  - The original *cfront* translated C++ into C for portability
    - However, this was difficult to debug and potentially inefficient
  - Many native host machine compilers now exist
    - *e.g., C++ Builder, clang, Comeau C/C++, GCC, Intel C++ Compiler, Microsoft Visual C++, Sun Studio*, etc.
- C++ is a *mostly* upwardly compatible extension of C that provides:

1. *Stronger typechecking*
2. *Support for data abstraction*
3. *Support for object-oriented programming*
4. *Support for generic programming*

C++ Design Goals

- As with C, run-time efficiency is important
  - Unlike other languages (*e.g., Ada, Java, C#, etc.) complicated run-time libraries and virtual machines have not traditionally been required for C++*
    - *Note, that there is no language-specific support for concurrency, persistence, or distribution in C++*
- Compatibility with C libraries & traditional development tools is emphasized, *e.g.,*
  - *Object code reuse*
    - *The storage layout of structures is compatible with C*
    - e.g., support for X-windows, standard ANSI C library, & UNIX/WIN32 system calls via `extern` block
  - *C++ works with the* `make` *recompilation utility*

C++ Design Goals (cont'd)

- "As close to C as possible, but no closer"
  - *i.e., C++ is not a proper superset of C → backwards compatibility is not entirely maintained*
    - *Typically not a problem in practice...*
- Note, certain C++ design goals conflict with modern techniques for:
  1. *Compiler optimization*
     - *e.g., pointers to arbitrary memory locations complicate register allocation & garbage collection*
  2. *Software engineering*
     - *e.g., separate compilation complicates inlining due to difficulty of interprocedural analysis*
     - *Dynamic memory management is error-prone*

Major C++ Enhancements

1. C++ supports data abstraction & encapsulation
   - *e.g., the class mechanism & name spaces*
2. C++ supports object-oriented programming features
   - *e.g., abstract classes, inheritance, & virtual methods*
3. C++ supports generic programming
   - *e.g., parameterized types*
4. C++ supports sophisticated error handling
   - *e.g., exception handling*
5. C++ supports identifying an object's type at runtime
   - *e.g., Run-Time Type Identification (RTTI)*

Important Minor C++ Enhancements

- C++ enforces type checking via *function prototypes*
- Provides type-safe linkage
- Provides inline function expansion
- Declare constants that can be used to define static array bounds with the `const` type qualifier
- Built-in dynamic memory management via `new` & `delete` operators
- Namespace control

Useful Minor C++ Enhancements

- The name of a `struct`, `class`, `enum`, or `union` is a type name
- References allow "call-by-reference" parameter modes
- New type-secure extensible *iostreams* I/O mechanism
- "Function call"-style cast notation
- Several different commenting styles
- New `mutable` type qualifier
- New `bool` boolean type

Questionable C++ Features

- Default values for function parameters
- Operator & function overloading
- Variable declarations may occur anywhere statements may appear within a block
- Allows user-defined conversion operators
- Static data initializers may be arbitrary expressions

Language Features Not Part of C++

1. *Concurrency*
   - "Concurrent C" by Gehani
   - Actor++ model by Lavender & Kafura
2. *Persistence*
   - Object Store, Versant, Objectivity
   - Exodus system & E programming language
3. *Garbage Collection*
   - USENIX C++ 1994 paper by Ellis & Detlefs
   - GNU *g++*
4. *Distribution*
   - CORBA, DDS, COM+, SOAP, etc.

Strategies for Learning C++

- Focus on concepts & programming techniques
  - Don't get lost in language features
- Learn C++ to become a better programmer
  - More effective at designing & implementing
  - Design Patterns
- C++ supports many different programming styles
- Learn C++ gradually
  - Don't have to know every detail of C++ to write a good C++ program

Stack Example

- The following slides examine several alterative methods of implementing a Stack
  - Begin with C & evolve up to various C++ implementations
- First, consider the "bare-bones" implementation:

```
typedef int T;
#define MAX_STACK 100 /* const int MAX_STACK = 100; */
T stack[MAX_STACK];
int top = 0;
T item = 10;
stack[top++] = item; // push
...
item = stack[--top]; // pop
```

- Obviously not very abstract...

Data Hiding Implementation in C

- Define the interface to a Stack of integers in C in Stack.h:

```
/* Type of Stack element. */
typedef int T;

/* Stack interface. */
int create (int size);
int destroy (void);
void push (T new_item);
void pop (T *old_top);
void top (T *cur_top);
int is_empty (void);
int is_full (void);
```

Data Hiding Implementation in C (cont'd)

- /* File stack.c */

```
#include "stack.h"
static int top_, size_; /* Hidden within this file. */
static T *stack_;
int create (int size) {
  top_ = 0; size_ = size;
  stack_ = malloc (size * sizeof (T));
  return stack_ == 0 ? -1 : 0;
}
void destroy (void) { free ((void *) stack_); }
void push (T item) { stack_[top_++] = item;}
void pop (T *item) { *item = stack_[--top_]; }
void top (T *item) { *item = stack_[top_ - 1]; }
int is_empty (void) { return top_ == 0; }
int is_full (void) { return top_ == size_; }
```


Data Hiding Implementation in C (cont'd)

- Use case

```
#include "stack.h"
void foo (void) {
  T i;
  push (10); /* Oops, forgot to call create! */
  push (20);
  pop (&i);
  destroy ();
}
```

- Main problems:

1. The programmer must call `create()` first & `destroy()` last!
2. There is only *one* stack & only *one* type of stack
3. Name space pollution...
4. Non-reentrant

Data Abstraction Implementation in C

- An ADT Stack interface in C:

```
typedef int T;
typedef struct { size_t top_, size_; T *stack_; } Stack;

int Stack_create (Stack *s, size_t size);
void Stack_destroy (Stack *s);
void Stack_push (Stack *s, T item);
void Stack_pop (Stack *, T *item);
/* Must call before pop'ing */
int Stack_is_empty (Stack *);
/* Must call before push'ing */
int Stack_is_full (Stack *);
/* ... */
```


Data Abstraction Implementation in C (cont'd)

- An ADT Stack implementation in C:

```
#include "stack.h"
int Stack_create (Stack *s, size_t size) {
  s->top_ = 0; s->size_ = size;
  s->stack_ = malloc (size * sizeof (T));
  return s->stack_ == 0 ? -1 : 0;
}
void Stack_destroy (Stack *s) {
  free ((void *) s->stack_); s->top_ = 0; s->size_ = 0; s->stack_ = 0;
}
void Stack_push (Stack *s, T item)
{ s->stack_[s->top_++] = item; }
void Stack_pop (Stack *s, T *item)
{ *item = s->stack_[--s->top_]; }
int Stack_is_empty (Stack *s) { return s->top_ == 0; }
```

Data Abstraction Implementation in C (cont'd)

- Use case

```
void foo (void) {
  Stack s1, s2, s3; /* Multiple stacks! */
  T item;

  Stack_pop (&s2, &item); /* Pop'd empty stack */

  /* Forgot to call Stack_create! */
  Stack_push (&s3, 10);

  s2 = s3; /* Disaster due to aliasing!!! */

  /* Destroy uninitialized stacks! */
  Stack_destroy (&s1); Stack_destroy (&s2);
}
```


Main problems with Data Abstraction in C

1. No guaranteed initialization, termination, or assignment
2. Still only one type of stack supported
3. Too much overhead due to function calls
4. No generalized error handling...
5. The C compiler does not enforce information hiding *e.g.*,

```
s1.top_ = s2.stack_[0]; /* Violate abstraction */
s2.size_ = s3.top_; /* Violate abstraction */
```

Data Abstraction Implementation in C++

- We can get encapsulation *and* more than one stack:

```
typedef int T;
class Stack {
public:
  Stack (size_t size);
  Stack (const Stack &s);
  void operator= (const Stack &);
  ~Stack (void);
  void push (const T &item);
  void pop (T &item);
  bool is_empty (void) const;
  bool is_full (void) const;
private:
  size_t top_, size_; T *stack_;
};
```


Data Abstraction Implementation in C++ (cont'd)

- Manager operations

```
Stack::Stack (size_t s): top_ (0), size_ (s), stack_ (new T[s]) {}

Stack::Stack (const Stack &s)
  : top_ (s.top_), size_ (s.size_), stack_ (new T[s.size_])
{ for (size_t i = 0; i < s.size_; ++i) stack_[i] = s.stack_[i]; }

void Stack::operator= (const Stack &s) {
  if (this == &s) return;
  T *temp_stack = new T[s.size_]; delete [] stack_; stack_ = 0;
  for (size_t i = 0; i < s.size_; ++i) temp_stack[i] = s.stack_[i];
  stack_ = temp_stack; top_ = s.top_; size_ = s.size_;
}

Stack::~Stack (void) { delete [] stack_; }
```

Data Abstraction Implementation in C++ (cont'd)

- Accessor & worker operations

```
bool Stack::is_empty (void) const { return top_ == 0; }

bool Stack::is_full (void) const { return top_ == size_; }

void Stack::push (const T &item) { stack_[top_++] = item; }

void Stack::pop (T &item) { item = stack_[--top_]; }
```


Data Abstraction Implementation in C++ (cont'd)

- Use case

```
#include "Stack.h"
void foo (void) {
  Stack s1 (1), s2 (100);
  T item;
  if (!s1.is_full ())
    s1.push (473);
  if (!s2.is_full ())
    s2.push (2112);
  if (!s2.is_empty ())
    s2.pop (item);
  // Access violation caught at compile-time!
  s2.top_ = 10;
  // Termination is handled automatically.
}
```

Benefits of C++ Data Abstraction Implemenation

1. Data hiding & data abstraction, *e.g.*,

```
Stack s1 (200);
s1.top_ = 10 // Error flagged by compiler!
```

2. *The ability to declare multiple stack objects*

```
Stack s1 (10), s2 (20), s3 (30);
```

3. *Automatic initialization & termination*

```
{
  Stack s1 (1000); // constructor called automatically.
  // ...
  // Destructor called automatically
}
```


Drawbacks with C++ Data Abstraction Implementation

1. Error handling is obtrusive
   - Use exception handling to solve this (but be careful)!
2. The example is limited to a single type of stack element (int in this case)
   - We can use C++ "parameterized types" to remove this limitation
3. Function call overhead
   - We can use C++ inline functions to remove this overhead

Exception Handling Implementation in C++ (cont'd)

- C++ exceptions separate error handling from normal processing

```
typedef .... T; // Where "...." is a placeholder for any C++ type.
class Stack {
public:
  class Underflow { /* ... */ }; // WARNING: be cautious when using
  class Overflow { /* ... */ };  //          exception specifiers...
  Stack (size_t size);
  Stack (const Stack &rhs);
  void operator= (const Stack &rhs);
  ~Stack (void);
  void push (const T &item) throw (Overflow);
  void pop (T &item) throw (Underflow);
  // ...
private:
  size_t top_, size_; T *stack_;
};
```


Exception Handling Implementation in C++ (cont'd)

- Stack.cpp

```
Stack::Stack (size_t s): top_ (s), size_ (s), stack_ (new T[s]) {}

Stack::~Stack () { delete [] stack_; }

void Stack::push (const T &item) throw (Stack::Overflow) {
  if (is_full ()) throw Stack::Overflow ();
  stack_[top_++] = item;
}

void Stack::pop (T &item) throw (Stack::Underflow) {
  if (is_empty ()) throw Stack::Underflow ();
  item = stack_[--top_];
}
```

Exception Handling Implementation in C++ (cont'd)

- Stack.cpp

```
Stack::Stack (const Stack &s):
  : top_ (s.top_), size_ (s.size_), stack_ (0) {
  scoped_array<T> temp_stack (new T[s.size_]);
  for (size_t i = 0; i < s.size_; ++i) temp_stack[i] = s.stack_[i];
  temp_stack.swap (stack_);
}

void Stack::operator= (const Stack &s) {
  if (this == &s) return; // Check for self-assignment
  scoped_array<T> temp_stack (new T[s.size_]);
  for (size_t i = 0; i < s.size_; ++i) temp_stack[i] = s.stack_[i];
  top_ = s.top_; size_ = s.size_;
  temp_stack.swap (stack_);
}
```


Exception Handling Implementation in C++ (cont'd)

- scoped_array extends auto_ptr to destroy built-in arrays

```
template <typename T> class scoped_array {
public:
  explicit scoped_array (T *p = 0) : ptr_ (p) {}
  ~scoped_array () { delete [] ptr_; }
  T &operator[](std::ptrdiff_t i) const { return ptr_[i]; }
  T *get() const { return ptr_; }
  void swap (T *&b) { T *tmp = b; b = ptr_; ptr_ = tmp; }
  void swap (scoped_array<T> &b)
  { T *tmp = b.ptr_; b.ptr_ = this->ptr_; this->ptr_ = tmp; }
private:
  T *ptr_;
  scoped_array (const scoped_array<T> &);
  scoped_array &operator=(const scoped_array<T> &);
};
```

Exception Handling Implementation in C++ (cont'd)

- There's a better way to implement `operator=()`:

```
void Stack::operator= (const Stack &s) {
  if (this == &s) return; // Check for self-assignment
  Stack t (s);
  std::swap (t.top_, top_); std::swap (t.size_, size_);
  std::swap (t.stack_, stack_);
}
// Old way:
void Stack::operator= (const Stack &s) {
  if (this == &s) return; // Check for self-assignment
  scoped_array<T> temp_stack (new T[s.size_]);
  for (size_t i = 0; i < s.size_; ++i) temp_stack[i] = s.stack_[i];
  top_ = s.top_; size_ = s.size_;
  temp_stack.swap (stack_);
}
```


Exception Handling Implementation in C++ (cont'd)

- And yet an even better way to implement exception-safe `Stack`:

```
class Stack { // ...
private: // ...
  scoped_array<T> stack_;
  void swap (Stack &);
};
// ...
Stack::Stack (const Stack &s)
  : top_ (s.top_), size_ (s.size_), stack_ (new T[s.size_]) {
  for (size_t i = 0; i < s.size_; ++i) stack_[i] = s.stack_[i];
}

Stack::~Stack () { /* no-op! */ }
```

Exception Handling Implementation in C++ (cont'd)

- And yet an even better way to implement operator=():

```
void Stack::operator= (const Stack &s) {
  if (this == &s) return; // Check for self-assignment
  Stack temp_stack (s);
  swap (temp_stack);
}

void Stack::swap (Stack &t) {
  std::swap (t.top_, top_);
  std::swap (t.size_, size_);
  t.stack_.swap (stack_);
}
```

- This solution is easy to generalize!

Exception Handling Implementation in C++ (cont'd)

- Use case

```
#include "Stack.h"
void foo (void) {
  Stack s1 (1), s2 (100);
  try {
    T item;
    s1.push (473);
    s1.push (42); // Exception, push'd full stack!
    s2.pop (item); // Exception, pop'd empty stack!
    s2.top_ = 10; // Access violation caught!
  } catch (Stack::Underflow) { /* Handle underflow... */ }
  catch (Stack::Overflow) { /* Handle overflow... */ }
  catch (...) { /* Catch anything else... */ throw; }
  } // Termination is handled automatically.
}
```

Template Implementation in C++

- A parameterized type Stack class interface using C++

```
template <typename T> class Stack {
public:
  Stack (size_t size);
  Stack (const Stack<T> &rhs);
  void operator= (const Stack<T> &rhs);
  ~Stack (void)
  void push (const T &item);
  void pop (T &item);
  bool is_empty (void) const;
  bool is_full (void) const;
private:
  size_t top_, size_; scoped_array<T> stack_;
  void swap (scoped_array<T> &t);
};
```


Template Implementation in C++ (cont'd)

- A parameterized type Stack class implementation using C++

```
template <typename T> inline
Stack<T>::Stack (size_t size)
  : top_ (0), size_ (size), stack_ (new T[size]) { }

template <typename T> inline
Stack<T>::~Stack (void) { /* no-op! */ }

template <typename T> inline void
Stack<T>::push (const T &item) { stack_[top_++] = item; }

template <typename T> inline void
Stack<T>::pop (T &item) { item = stack_[--top_]; }
// ...
```

Template Implementation in C++ (cont'd)

- Note minor changes to accommodate parameterized types

```
#include "Stack.h"

void foo (void) {
  Stack<int> s1 (1000);
  Stack<float> s2;
  Stack< Stack <Activation_Record> *> s3;

  s1.push (-291);
  s2.top_ = 3.1416; // Access violation caught!
  s3.push (new Stack<Activation_Record>);
  Stack <Activation_Record> *sar;
  s3.pop (sar);
  delete sar; // Termination of s1, s2, & s3 handled automatically
}
```


Template Implementation in C++ (cont'd)

- Another parameterized type Stack class

```
template <typename T, size_t SIZE> class Stack {
public:
  Stack (void);
  ~Stack (void)
  void push (const T &item);
  void pop (T &item);
private:
  size_t top_, size_;
  T stack_[SIZE];
};
```

- No need for dynamic memory, though SIZE must be const, *e.g.*,

```
Stack<int, 200> s1;
```

Object-Oriented Implementation in C++

- Problems with previous examples:
  - Changes to the implementation will require recompilation & relinking of clients
  - Extensions will require access to the source code
- Solutions
  - Combine inheritance with dynamic binding to *completely* decouple interface from implementation & binding time
  - This requires the use of C++ *abstract base classes*

Object-Oriented Implementation in C++ (cont'd)

- Defining an abstract base class in C++

```
template <typename T>
class Stack {
public:
  virtual ~Stack (void) = 0; // Need implementation!
  virtual void push (const T &item) = 0;
  virtual void pop (T &item) = 0;
  virtual bool is_empty (void) const = 0;
  virtual bool is_full (void) const = 0;
  void top (T &item) { /* Template Method */ pop (item); push (item); }
};
```

- By using "pure virtual methods," we can guarantee that the compiler won't allow instantiation!

Object-Oriented Implementation in C++ (cont'd)

- Inherit to create a specialized stack implemented via an STL vector:

```
#include "Stack.h"
#include <vector>

template <typename T> class V_Stack : public Stack<T> {
public:
  enum { DEFAULT_SIZE = 100 };
  V_Stack (size_t size = DEFAULT_SIZE);
  V_Stack (const V_Stack &rhs);
  virtual void push (const T &item);
  virtual void pop (T &item);
  virtual bool is_empty (void) const;
  virtual bool is_full (void) const;
private:
  size_t top_; std::vector<T> stack_;
};
```


Object-Oriented Implementation in C++ (cont'd)

- class V_Stack implementation

```
template <typename T>
V_Stack<T>::V_Stack (size_t size): top_ (0), stack_ (size) {}

template <typename T>
V_Stack<T>::V_Stack (const V_Stack &rhs): top_ (rhs.top_), stack_ (rhs.stack_) {}

template <typename T> void
V_Stack<T>::push (const T &item) { stack_[top_++] = item; }

template <typename T> void
V_Stack<T>::pop (T &item) { item = stack_[--top_]; }

template <typename T> int
V_Stack<T>::is_full (void) const { return top_ >= stack_.size (); }
```

Object-Oriented Implementation in C++ (cont'd)

- Inheritance can also create an linked list stack:

```
template <typename T> class Node; // forward declaration.
template <typename T> class L_Stack : public Stack<T> {
public:
  enum { DEFAULT_SIZE = 100 };
  L_Stack (size_t hint = DEFAULT_SIZE);
  ~L_Stack (void);
  virtual void push (const T &new_item);
  virtual void pop (T &top_item);
  virtual bool is_empty (void) const { return head_ == 0; }
  virtual bool is_full (void) const { return 0; }
private:
  // Head of linked list of Node<T>'s.
  Node<T> *head_;
};
```


Object-Oriented Implementation in C++ (cont'd)

- class Node implementation

```
template <typename T> class Node {
friend template <typename T> class L_Stack;
public:
  Node (T i, Node<T> *n = 0): item_ (i), next_ (n) {}
private:
  T item_;
  Node<T> *next_;
};
```

- Note that the use of the "Cheshire cat" idiom allows the library writer to completely hide the representation of class V_Stack...

Object-Oriented Implementation in C++ (cont'd)

- class L_Stack implementation:

```
template <typename T> L_Stack<T>::L_Stack (size_t): head_ (0) {}

template <typename T> void L_Stack<T>::push (const T &item) {
  Node<T> *t = new Node<T> (item, head_); head_ = t;
}

template <typename T> void L_Stack<T>::pop (T &top_item) {
  top_item = head_->item_;
  Node<T> *t = head_; head_ = head_->next_;
  delete t;
}

template <typename T> L_Stack<T>::~L_Stack (void)
{ for (T t; head_ != 0; pop (t)) continue; }
```


Object-Oriented Implementation in C++ (cont'd)

- Using our abstract base class, it is possible to write code that does not depend on the stack implementation, *e.g.*,

```
Stack<int> *make_stack (bool use_V_Stack)
{ return use_V_Stack ? new V_Stack<int> : new L_Stack<int>; }

void print_top (Stack<int> *stack) {
  std::cout << "top = " << stack->top () << std::endl;
}

int main (int argc, char **) {
  std::auto_ptr <Stack<int>> sp (make_stack (argc > 1));
  sp->push (10);
  print_top (sp.get ());
}
```

Object-Oriented Implementation in C++ (cont'd)

- Moreover, we can make changes at run-time without modifying, recompiling, or relinking existing code via dynamic linking:

```
char stack_symbol[MAXNAMLEN];
char stack_file[MAXNAMLEN];
cin >> stack_file >> stack_factory;
void *handle = ACE_OS::dlopen (stack_file);
Stack<int> *(*factory)(bool) = ACE_OS::dlsym (handle, stack_factory);
std::auto_ptr <Stack<int>> sp ((*factory) (argc > 1));
sp->push (10);
print_top (sp.get ());
```

- Note, no need to stop, modify, & restart an executing application!
  - Naturally, this requires careful configuration management...

The Road Ahead: C++11

The modifications for C++ involve both the core language and the standard library:

- Prefer introduction of new features through the standard library, rather than extending the core language
- Improve C++ to facilitate systems and library design, rather than to introduce new features only useful to specific applications;
- Increase type safety by providing safer alternatives to current, unsafe techniques;
- Increase performance and the ability to work directly with hardware;
- Implement "zero-overhead" principle (additional support required by some utilities must be used only if the utility is used)
- Make C++ easier to teach and to learn without removing any utility needed by expert programmers.

C++11 Example

```
#include <iostream>
#include <iterator>
#include <vector>
#include <algorithm>

int main () {
  std::vector<int> v ({10, 20, 30, 40});

  for (int &i : v) std::cout << i << std::endl;

  auto total = 0;
  std::for_each (v.begin (), v.end (),
                 [&total](int x) { total += x; });

  std::cout << total << std::endl;
  return 0;
}
```


Summary

- A major contribution of C++ is its support for defining abstract data types (ADTs) & for generic programming
  - *e.g.*, classes, parameterized types, & exception handling
- For some systems, C++'s ADT support is more important than using the OO features of the language
- For other systems, the use of C++'s OO features is essential to build highly flexible & extensible software
  - *e.g.*, inheritance, dynamic binding, & RTTI