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1. Why C++?

- A **programming paradigm** is a way of thinking about software construction based on some fundamental, defining principles

- Different programming paradigms can potentially enable programmers to tell new stories in possibly more elegant ways

- C supports a limited set of programming paradigms, and this can significantly constrain the kind of stories a programmer can tell

- C++ is (mostly) a superset of C that enables new programming paradigms; C++ is a “multi-paradigm programming language”

- C++ enables programmers to tell richer and more elegant stories

1.1. Procedural Programming

- Programming is organized around defining and calling *procedures* (i.e., routines, subroutines, functions)

- C primarily supports procedural programming

- Almost all of the C syntax and semantics you have learned so far can be used in C++; thus C++ also supports procedural programming

```c
int avg( int x, int y )
{
  int sum = x + y;
  return sum / 2;
}

int main( void )
{
  int c = avg(2,3);
  return 0;
}
```
1.2. T13: Object-Oriented Programming

- Programming is organized around defining, instantiating, and manipulating objects which contain data (i.e., fields, attributes) and code (i.e., methods)

- C can (partially) support object-oriented programming through careful policies on using structs and functions

- C++ adds new syntax and semantics to elegantly support object-oriented programming

```c
typedef struct
{
    // implementation specific
}
list_int_t;

void list_int_construct ( list_int_t* this );
void list_int_destruct ( list_int_t* this );
void list_int_push_front ( list_int_t* this, int v );
void list_int_reverse ( list_int_t* this );
```

1.3. T14: Generic Programming

- Programming is organized around algorithms and data structures where generic types are specified upon instantiation as opposed to definition

- C can (partially) support generic programming through awkward use of the preprocessor and/or void* pointers

- C++ adds new syntax and semantics to elegantly support generic programming
1. Why C++?

1.4. T15: Functional Programming

• Programming is organized around pure functions (i.e., function output depends only on the parameters) as first-class primitives that can be manipulated just like other values

• C can (partially) support functional programming through the use of function pointers

• C++ adds new syntax and semantics to elegantly support functional programming

```c
typedef int (*cmp_ptr_t) ( int, int );
int lt( int x, int y ) { return x < y; }

int main( void )
{
    cmp_ptr_t cmp_ptr = &lt;
    int result = (*cmp_ptr)( 3, 4 );
    return 0;
}
```
1.5. T16: Concurrent Programming

- Programming is organized around computations that execute *concurrently* (i.e., computations execute overlapped in time) instead of *sequentially* (i.e., computations execute one at a time)
- C can support concurrent programming through the use of a standard library (e.g., `pthreads`)
- C++ adds new syntax and semantics to elegantly support concurrent programming

1.6. C vs. C++

- 1972: C development started by Dennis Ritchie and Ken Thompson
- 1979: C++ development started by Bjarne Stroustrup
- C90: First ANSI C standard
- C++98: First ISO C++ standard
- C99: Modern C standard *(this course)*
- C++11: Major C++ revision with many new features *(this course)*
- C++14: Small C++ revision mostly for bug fixes
- C++17: Medium C++ revision with some new features
2. C++ Namespaces

• Large C projects can include tens or hundreds of files and libraries
• Very easy for two files or libraries to define a function with the same name causing a namespace collision

```c
// contents of foo.h
// this avg rounds down
int avg( int x, int y )
{
    int sum = x + y;
    return sum / 2;
}

#include "foo.h"
#include "bar.h"
#include <stdio.h>

int main( void )
{
    printf("avg(2,3) = %d\n", avg(2,3));
    return 0;
}
```

• Unclear which version of avg to use
• Causes compile-time “redefinition” error
• Traditional approach in C is to use prefixes
• Can create cumbersome syntactic overhead

```cpp
// contents of foo.h
// this avg rounds down
int foo_avg( int x, int y )
{
    int sum = x + y;
    return sum / 2;
}

#include "foo.h"
#include "bar.h"
#include <stdio.h>

int main( void )
{
    printf("avg(2,3) = %d (rnd down)\n", foo_avg(2,3) );
    printf("avg(2,3) = %d (rnd up)\n", bar_avg(2,3) );
    return 0;
}
```

```cpp
// contents of bar.h
// this avg rounds up
int bar_avg( int x, int y )
{
    int sum = x + y;
    return (sum + 1) / 2;
}
```

https://repl.it/@cbatten/ece2400-T12-ex2
• **C++ namespaces** extend the language to support named scopes
• Namespaces provide flexible ways to use specific scopes

```cpp
// contents of foo.h
namespace foo {
    // this avg rounds down
    int avg( int x, int y )
    {
        int sum = x + y;
        return sum / 2;
    }
}

// Other code in namespace uses "avg"

// contents of bar.h
namespace bar {
    // this avg rounds up
    int avg( int x, int y )
    {
        int sum = x + y;
        return (sum + 1) / 2;
    }
}

// Other code in namespace uses "avg"

#include "foo.h"
#include "bar.h"
#include <stdio.h>

int main( void )
{
    printf("avg(2,3) = %d (rnd down)\n", foo::avg(2,3) );
    printf("avg(2,3) = %d (rnd up)\n", bar::avg(2,3) );
    return 0;
}
```

```cpp
int main( void )
{
    using namespace foo;
    printf("avg(2,3) = %d (rnd down)\n", avg(2,3) );
    printf("avg(2,3) = %d (rnd up)\n", bar::avg(2,3) );
    return 0;
}
```
2. C++ Namespaces

- Namespaces are just syntactic sugar
- Useful way to group related struct and function definitions

```c++
namespace ListInt {
    typedef struct _node_t {
        int value;
        struct _node_t* next_p;
    } node_t;
}
```

```c++
namespace ListInt {
    void construct ( list_t* this );
    void destruct ( list_t* this );
    void push_front( list_t* this, int v );
    ...
}
```

```c++
int main( void )
{
    ListInt::list_t list;
    ListInt::construct ( &list );
    ListInt::push_front( &list, 12 );
    ListInt::push_front( &list, 11 );
    ListInt::push_front( &list, 10 );
    ListInt::destruct ( &list );
    return 0;
}
```
• Can rename namespaces and import one namespace into another
• All of the C standard library is placed in the std namespace
• Use the C++ version of the C standard library headers

```cpp
#include "foo.h"
#include "bar.h"
#include <cstdio>

int main( void )
{
    std::printf("avg(2,3) = %d (rnd down)\n", foo::avg(2,3) );
    std::printf("avg(2,3) = %d (rnd up)\n", bar::avg(2,3) );
    return 0;
}
```

<assert.h> <cassert> conditionally compiled macro
<errno.h> <cerrno> macro containing last error num
<fenv.h> <cfenv> floating-point access functions
<float.h> <cfloat> limits of float types
<inttypes.h> <cinttypes> formatting macros for int types
<limits.h> <climits> limits of integral types
<locale.h> <clocale> localization utilities
<math.h> <cmath> common mathematics functions
<setjmp.h> <csetjmp> for saving and jumping to execution context
<signal.h> <csignal> signal management
<stdarg.h> <cstdarg> handling variable length arg lists
<stddef.h> <cstddef> standard macros and typedefs
<stdio.h> <cstdio> input/output functions
<string.h> <cstring> narrow character string handling
<time.h> <ctime> time utilities
<ctype.h> <cctype> types for narrow characters
<uchar.h> <cuchar> unicode character conversions
<wchar.h> <cwchar> wide and multibyte character string handling
<wctype.h> <cwctype> types for wide characters
3. C++ Functions

- C only allows a single definition for any given function name

```cpp
int avg ( int x, int y );
int avg3( int x, int y, int z );
```

- C++ function overloading allows multiple def per function name
- Each definition must have a unique function signature (e.g., number of parameters)

```cpp
int avg( int x, int y )
{
    int sum = x + y;
    return sum / 2;
}

int avg( int x, int y, int z )
{
    int sum = x + y + z;
    return sum / 3;
}

int main()
{
    // Will call definition of avg with 2 parameters
    int a = avg( 10, 20 );

    // Will call definition of avg with 3 parameters
    int b = avg( 10, 20, 25 );

    return 0;
}
```
• C only allows a single definition for any given function name

```c
int avg ( int x, int y );
double favg( double x, double y );
```

• Function overloading also enables multiple definitions with the same number of arguments but different argument types

```c
int avg( int x, int y )
{
    int sum = x + y;
    return sum / 2;
}

double avg( double x, double y )
{
    double sum = x + y;
    return sum / 2;
}

int main()
{
    // Will call definition of avg with int parameters
    int a = avg( 10, 20 );

    // Will call definition of avg with double parameters
    double b = avg( 7.5, 20 );

    return 0;
}
```
• **Default parameters** can allow the caller to *optionally* specify specific parameters at the *end* of the parameter list

```c
#include <cstdio>

enum round_mode_t
{
    ROUND_MODE_FLOOR,
    ROUND_MODE_CEIL,
};

int avg( int a, int b,
    round_mode_t round_mode = ROUND_MODE_FLOOR )
{
    int sum = a + b;
    if ( round_mode == ROUND_MODE_CEIL )
        sum += 1;
    return sum / 2;
}

int main( void )
{
    std::printf("avg( 5, 10 ) = %d\n", avg( 5, 10 ) );
    return 0;
}  
```

• Function overloading and default parameters are just syntactic sugar
• Enable elegantly writing more complicated code, but must also be more careful about which function definition is actually associated with any given function call
4. C++ References

• C provides pointers to indirectly refer to a variable

```cpp
int a = 3; // stack
int* const b = &a;
*b = 5;
int c = *b;
int* d = &(*b);
```

Aside:

```cpp
// cannot change value
const int a;

// cannot change pointed-to value
const int* b = &a;

// cannot change pointer
int* const b = &a;

// cannot change pointer or pointed-to value
const int* const b = &a;
```

• Pointer syntax can sometimes be cumbersome (we will see this later with operator overloading)
• C++ references are an alternative way to indirectly refer to variable
• References require introducing new types
• Every type \( T \) has a corresponding reference type \( T \& \)
• A variable of type \( T \& \) contains a reference to a variable of type \( T \)

```cpp
int& a // reference to a variable of type int
char& b // reference to a variable of type char
float& c // reference to a variable of type float
```
4. C++ References

- Cannot declare and then assign to reference in separate statements
- Must always use an initialization statement
- Do not use address-of operator (&) to initialize reference

1. `int a = 42;`
2. `int& b; // reference to a variable (illegal)`
3. `b = &a; // assign to reference (illegal)`
4. `int& c = &a; // initialize ref with address of (illegal)`
5. `int& c = a; // initialize reference (legal)`

- For the most part, references act like syntactic sugar for pointers
- References must use an initialization statement (cannot be NULL)
- Cannot change reference after initialization
- References are automatically dereferenced
- References are a synonym for the referenced variable

```
01 int a = 3;  // int a = 3;
02 int& b = a; // int* const b = &a;
03 b = 5;      // *b = 5;
04 int c = b;  // int c = *b;
05 int* d = &b; // int* d = &(*b);
```
4. C++ References

- Using pointers for call-by-reference

```c++
void sort( int* x_ptr,
          int* y_ptr )
{
    if ( (*x_ptr) > (*y_ptr) ) {
        int temp = *x_ptr;
        *x_ptr = *y_ptr;
        *y_ptr = temp;
    }
}
```

- Using references for call-by-reference

```c++
void sort( int& x, int& y )
{
    if ( x > y ) {
        int temp = x;
        x = y;
        y = temp;
    }
}

int main( void )
{
    int a = 9;
    int b = 5;
    sort( a, b );
    return 0;
}
```

https://repl.it/@cbatten/ece2400-T12-ex5
Draw a state diagram corresponding to the execution of this program

```cpp
void avg( int& result, int x, int y )
{
    int sum = x + y;
    result = sum / 2;
}

int main( void )
{
    int a = 10;
    int b = 20;
    int c;
    avg( c, a, b );
    return 0;
}
```

- Our coding conventions prefer using pointers for return values
- Makes it obvious to caller that the parameter can be changed
- Const references useful for passing in large values

```cpp
void blur( image_t* out, const image_t& in );

int main( void )
{
    image_t in = /* initialize */
    image_t out = /* initialize */
    blur( &out, in );
    return 0;
}
```
5. C++ Exceptions

• When handling errors in C we can return an invalid value

```c
int days_in_month( int month )
{
    int x;
    switch ( month )
    {
        case 1: x = 31; break;
        ...
        case 12: x = 31; break;
        default: x = -1;
    }
    return x;
}
```

• When handling errors in C we can assert

```c
int days_in_month( int month )
{
    assert( (month >= 1) && (month <= 12 ) );
    ...
}

int main()
{
    int result = days_in_month( 13 );
    // Indicate success to the system
    return 0;
}
```
5. C++ Exceptions

- C++ exceptions enable global non-linear control flow

```cpp
int x = 1;

try {
    int y = 10;
    if ( x )
        throw -1;
    y = 11;
    x = 2;
}
catch ( int e ) {
    x = e;
}
```

```cpp
int x = 0;

try {
    int y = 10;
    if ( x )
        throw -1;
    y = 11;
    x = 2;
}
catch ( int e ) {
    x = e;
}
```
• **C++ exceptions** enable cleanly throwing and catching errors

```cpp
#include <cstdio>

int days_in_month( int month )
{
    int x;
    switch ( month )
    {
        case 1: x = 31; break;
        case 2: x = 28; break;
        ...
        case 12: x = 31; break;
        default:
            throw -1;
    }
    return x;
}

int main()
{
    try {
        int month = 13;
        int days = days_in_month( month );
        std::printf( "month %d has %d days\n", month, days );
    }
    catch ( int e ) {
        std::printf( "ERROR: %d\n", e );
        return e;
    }
    // Indicate success to the system
    return 0;
}
https://repl.it/@cbatten/ece2400-T12-ex6
```
• Can throw variable of any type (e.g., integers, structs)
• Can catch and rethrow exceptions
• Uncaught exceptions will terminate the program

6. C++ Types

Small changes to two types, one new type, one new literal, and a new way to do type inference

• struct types
• bool type
• void* type
• nullptr literal
• auto type inference

6.1. struct Types

• C++ supports a simpler syntax for declaring struct types

```cpp
typedef struct {
  double real;
  double imag;
}
complex_t;

int main( void ) {
  complex_t complex;
  complex.real = 1.5;
  complex.imag = 3.5;
  return 0;
}
```

• C coding convention uses _t suffix for user defined types
• C++ coding convention uses CamelCase for user defined types
6.2. bool Type

- C used int types to represent boolean values
- C++ has an actual bool type which is part of the language
- C++ provides two new literals: true and false
- C++ still accepts integers where a boolean value is expected

```c
1 int eq( int a, int b )
2 {
3     int a_eq_b = ( a == b );
4     return a_eq_b;
5 }
```

```c
1 bool eq( int a, int b )
2 {
3     bool a_eq_b = ( a == b );
4     return a_eq_b;
5 }
```

6.3. void* Type

- C allows automatic type conversion of void* to any pointer type
- C++ requires explicit type casting of void*

```c
1 int main( void )
2 {
3     int* x = malloc( 4 * sizeof(int) );
4     free(x);
5     return 0;
6 }
```

```c
1 int main( void )
2 {
3     int* x = (int*) malloc( 4 * sizeof(int) );
4     free(x);
5     return 0;
6 }
```
6.4. nullptr Literal

- C used the constant NULL to indicate a null pointer
- Part of the C standard library, not part of the language
- C++ includes a new nullptr literal for pointers

6.5. auto Type Inference

- C requires explicitly specifying the type in every variable declaration
- C++ includes the auto keyword for automatic type inference

```
int avg( int x, int y )
{
    int sum = x + y;
    return sum / 2;
}

int main()
{
    auto a = 1.0 + 2.5;    // type of a is double
    auto b = 1.0f + 2.5f;  // type of b is float
    auto c = avg( 10, 20 ); // type of c is int
    return 0;
}
```

- Do not overuse auto! Only use for complicated types!
- The above example, is not a good use of auto
- auto is completely handled by the compiler, nothing to do with dynamic polymorphism
7. C++ Range-Based For Loop

• Iterating over arrays is very common and error prone
• C++ includes range-based for loops to simplify this common pattern
• Only works if compiler can figure out the size of the array

```cpp
int a[] = { 10, 20, 30, 40 };
ext int sum = 0;
for ( int v : a ) // v is a new temporary
    sum += v; // for each iteration of loop
int avg = sum / 4;
```

• Syntactic sugar for ...

```cpp
int a[] = { 10, 20, 30, 40 };
ext int sum = 0;
for ( int i = 0; i < 4; i++ ) {
    int v = a[i];
    sum += v;
}
int avg = sum / 4;
```
8. C++ Dynamic Allocation

- C dynamic allocation was handled by `malloc/free`
- Part of the C standard library, not part of the language
- C++ includes two new operators as part of the language
- The `new` operator is used to dynamically allocate variables
- The `delete` operator is used to deallocate variables
- These operators are “type safe” and are critical for object oriented programming

```cpp
int* a_p = new int;
*a_p = 42;
delete a_p;

int* b_p = new int[4];
b_p[0] = 1;
b_p[1] = 2;
b_p[2] = 3;
b_p[3] = 4;
delete[] b_p;

// struct Complex
// {
//   double real;
//   double imag;
// };;
Complex* complex_p = new Complex;
complex_p->real = 1.5;
complex_p->imag = 3.5;
delete complex_p;
```
8. C++ Dynamic Allocation

- Revisiting earlier example for a function that appends a dynamically allocated node to a chain of nodes

```c
#include <cstddef>

struct Node
{
    int value;
    Node* next_p;
};

Node* append( Node* node_p, int value )
{
    Node* new_node_p = // Node* new_node_p =
        new Node; // malloc( sizeof(Node) );
    new_node_p->value = value;
    new_node_p->next_p = node_p;
    return new_node_p;
}

int main( void )
{
    Node* node_p = NULL;
    node_p = append( node_p, 3 );
    node_p = append( node_p, 4 );
    delete node_p->next_p; // free( node_p->next_pt );
    delete node_p; // free( node_p );
    return 0;
}
```