# ECE 2400 Computer Systems Programming
# Fall 2021

# Topic 13: Object-Oriented Programming

School of Electrical and Computer Engineering
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## Object-oriented programming

- Programming is organized around defining, instantiating, and manipulating *objects* which contain data (i.e., fields, attributes) and code (i.e., methods)
- Classes are the "types" of objects, objects are instances of classes
- Classes are nouns, methods are verbs/actions
- Classes are organized according to various relationships
  - composition relationship ("Class X has a Y")
  - generalization relationship ("Class X is a Y")
  - association relationship ("Class X acts on Y")

## Example class diagram for animals

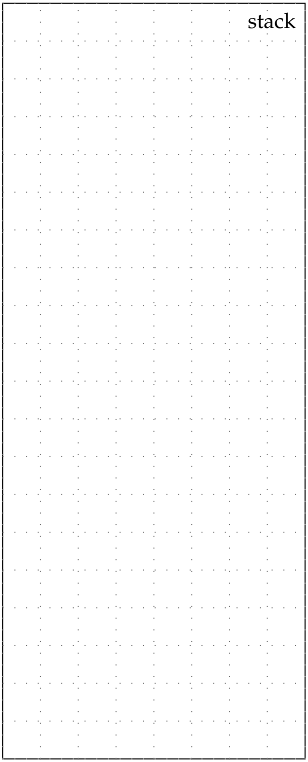
## Example class diagram for shapes and drawings

# 1. C++ Classes

- Perfectly possible to use object-oriented programming in C

```
typedef struct
{
  double x;
  double y;
}
point_t;

void point_translate( point_t* this,
                      double x_offset, double y_offset )
{
  this->x += x_offset; this->y += y_offset;
}

void point_scale( point_t* this, double factor )
{
  this->x *= factor; this->y *= factor;
}

void point_rotate( point_t* this, double angle )
{
  const double pi = 3.14159265358979323846;
  double s = std::sin((angle*pi)/180);
  double c = std::cos((angle*pi)/180);

  double x_new = (c * this->x) - (s * this->y);
  double y_new = (s * this->x) + (c * this->y);

  this->x = x_new; this->y = y_new;
}

void point_print( point_t* this )
{
  std::printf("(%.2f,%.2f)", this->x, this->y );
}
```

```
int main( void )
{
  point_t pt;
  pt.x = 0;
  pt.y = 0;

  point_translate( &pt, 1, 0 );
  point_scale    ( &pt, 2 );
  return 0;
}
```



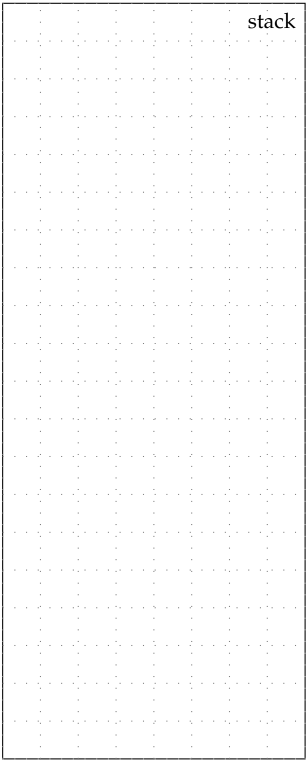
## 1.1. C++ Member Functions

- C++ allows functions to be defined *within* the `struct` namespace
- C++ `struct` has both member fields and member functions
- Member functions have an implicit `this` pointer
- Member functions which do not modify fields are `const`

```
struct Point
{
  double x; // member fields
  double y; //

  // member functions

  void point_translate( double x_offset, double y_offset )
  {
    this->x += x_offset; this->y += y_offset;
  }

  void point_scale( double factor )
  {
    this->x *= factor; this->y *= factor;
  }

  void point_rotate( double angle )
  {
    ...
    double x_new = (c * this->x) - (s * this->y);
    double y_new = (s * this->x) + (c * this->y);
    this->x = x_new; this->y = y_new;
  }

  void point_print() const
  {
    std::printf("(%.2f,%.2f)", this->x, this->y );
  }
};
```

- Non-static member functions are accessed using the dot (.) operator in the same way we access fields

```
int main( void )
{
  Point pt;
  pt.x = 0;
  pt.y = 0;

  pt.point_translate( 1, 0 );
  pt.point_scale( 2 );
  return 0;
}
```



- Recall object-oriented prog in C

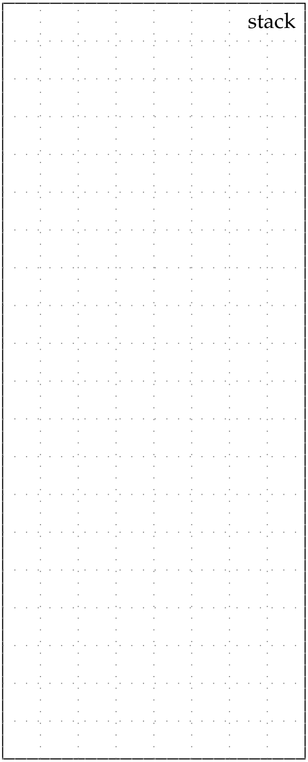
```
int main( void )
{
  point_t pt;
  pt.x = 0;
  pt.y = 0;

  point_translate( &pt, 1, 2 );
  point_scale    ( &pt, 2 );
  return 0;
}
```

```
point_translate( &pt, 1, 0 ) ↔ pt.point_translate( 1, 0 )
           foo( &bar, ...  ) ↔ bar.foo( ...  )
```

- Member functions are in struct namespace
- No need to use the `point_` prefix
- Member fields are in scope within every member function
- No need to explicitly use `this` pointer

```
struct Point
{
  double x; // member fields
  double y; //

  // member functions

  void translate( double x_offset, double y_offset )
  {
    x += x_offset; y += y_offset;
  }

  void scale( double factor )
  {
    x *= factor; y *= factor;
  }

  void rotate( double angle )
  {
    ...
    double x_new = (c * x) - (s * y);
    double y_new = (s * x) + (c * y);
    x = x_new; y = y_new;
  }

  void print() const
  {
    std::printf("(%.2f,%.2f)", x, y );
  }
};
```

```
int main( void )
{
  Point pt;
  pt.x = 0;
  pt.y = 0;

  pt.translate( 1, 2 );
  pt.scale( 2 );
  return 0;
}
```



- A class is just a struct with member functions
- An object is just an instance of a struct with member functions

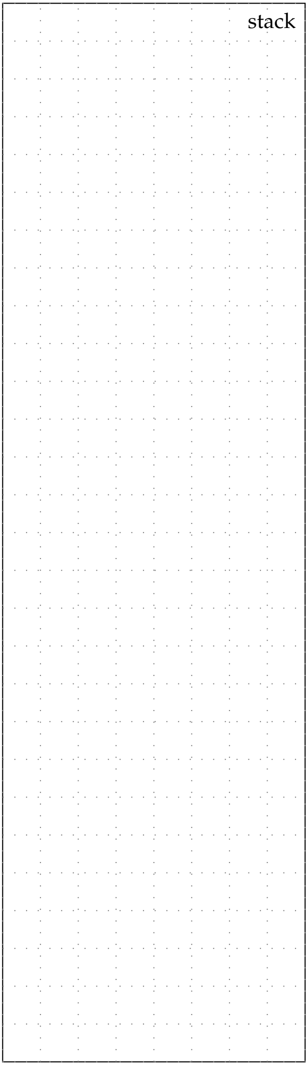
## 1.2. C++ Constructors

- We want to avoid the user from directly accessing member fields
- We want to ensure an object is always initialized to a known state
- In C, we used `foo_construct`
- In C++, we could add a `construct` member function

```
int main( void )
{
  Point pt;
  pt.construct();
  pt.translate( 1, 2 );
  pt.scale( 2 );
  return 0;
}
```

- What if we call `translate` before `construct`?
- What if we call `construct` multiple times?
- We want a way to specify a special “constructor” member function
  - *always* called when you create an object
  - cannot be called directly, can *only* be called during object creation
- C++ adds support for language-level constructors (i.e., special member functions)
  - no return type
  - same name as the class
- Can use function overloading to have many different constructors

```
struct Point
{
  double x;
  double y;

  // default constructor
  Point()
  {
    x = 0.0;
    y = 0.0;
  }

  // non-default constructor
  Point( double x_, double y_ )
  {
    x = x_;
    y = y_;
  }

  ...
};

int main( void )
{
  Point pt0;
  Point pt1( 1, 2 );
  pt0 = pt1;
  pt0.translate( 1, 0 );
  return 0;
}
```



- Constructors automatically called with `new`

```
Point* pt0_p = new Point;     // constructor called
Point* pt1_p = new Point[4];  // constructor called 4 times
```

- Initialization lists initialize members before body of constructor
  - Avoids creating a temporary default object
  - Required for initializing reference members
  - Prefer initialization lists when possible

```
struct Point
{
  double x;
  double y;

  // default constructor
  Point()
  { x = 0.0; y = 0.0; }

  // non-default constructor
  Point( double x_, double y_ )
  { x = x_; y = y_; }

  ...
};
```

```
struct Point
{
  double x;
  double y;

  // default constructor
  Point()
   : x(0.0), y(0.0) { }

  // non-default constructor
  Point( double x_, double y_ )
   : x(x_), y(y_) { }

  ...
};
```

## 1.3. C++ Operator Overloading

- C++ operator overloading enables using built-in operators (e.g., +, -, *, /) with user-defined types
- Applying an operator to a user-defined type essentially calls a function (either a member function or an overloaded free function)

```
Point operator+( const Point& pt0,
                 const Point& pt1 )
{
  Point tmp = pt0;
  tmp.translate( pt1.x, pt1.y );
  return tmp;
}

int main( void )
{
  Point ptA(1,2);
  Point ptB(3,4);
  Point ptC = ptA + ptB;
  return 0;
}
```

stack

stack

```
Point operator*( const Point& pt, double factor )
{
  Point tmp = pt;
  tmp.scale( factor );
  return tmp;
}

Point operator*( double factor, const Point& pt )
{
  Point tmp = pt;
  tmp.scale( factor );
  return tmp;
}

Point operator%( const Point& pt, double angle )
{
  Point tmp = pt;
  tmp.rotate( angle );
  return tmp;
}

Point operator%( double angle, const Point& pt )
{
  Point tmp = pt;
  tmp.rotate( angle );
  return tmp;
}
```

- Operator overloading enables elegant syntax for user-defined types

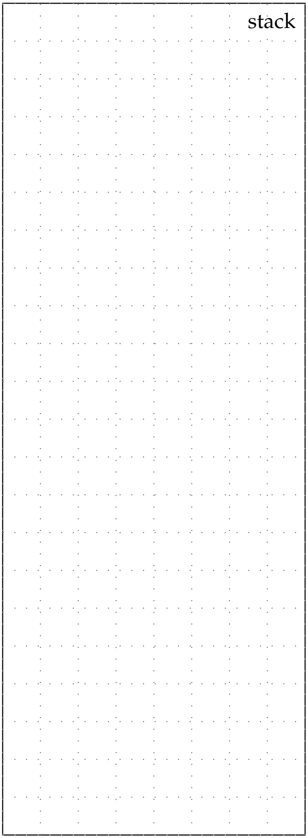
```
Point pt0(1,2);
pt0.translate(5,3);
pt0.rotate(45);
pt0.scale(1.5);
Point pt1 = pt0;
```

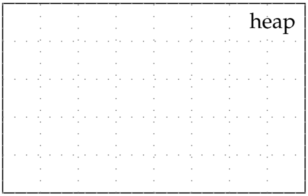
```
Point pt0(1,2);
Point pt1 = 1.5 * ( ( pt0 + Point(5,3) ) % 45 );
```

## 1.4. C++ Rule of Three

- What if point coordinates are allocated on the heap?

```
struct DPoint
{
  double* x_p;
  double* y_p;

  DPoint() {
    x_p = new double;
    y_p = new double;
    *x_p = 0.0;
    *y_p = 0.0;
  }

  void translate( double x_offset,
                  double y_offset )
  {
    *x_p += x_offset;
    *y_p += y_offset;
  }
  ...
};

int main( void )
{
  DPoint pt0;
  pt0.translate( 1, 0 );
  return 0;
}
```

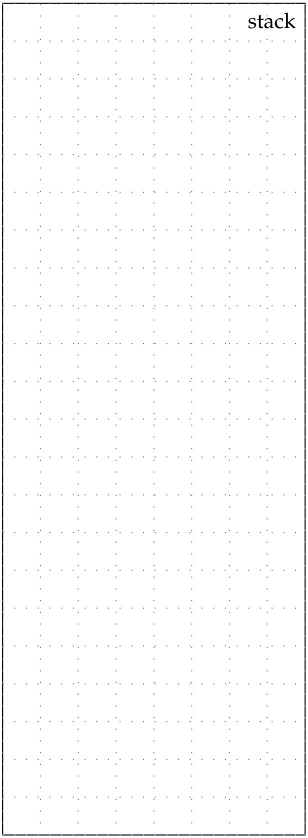


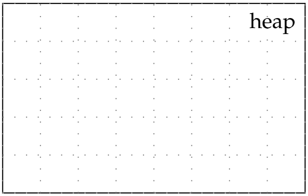


## C++ Destructors

- Destructors are special member functions for destroying an object

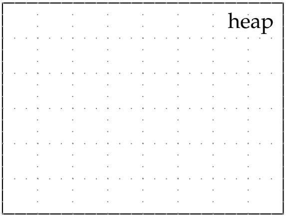
```
struct DPoint
{
  double* x_p;
  double* y_p;

  DPoint() {
    x_p = new double;
    y_p = new double;
    *x_p = 0.0;
    *y_p = 0.0;
  }

  ~DPoint() {
    delete x_p;
    delete y_p;
  }
  ...
};

int main( void )
{
  DPoint pt0;
  pt0.translate( 1, 0 );
  return 0;
}
```

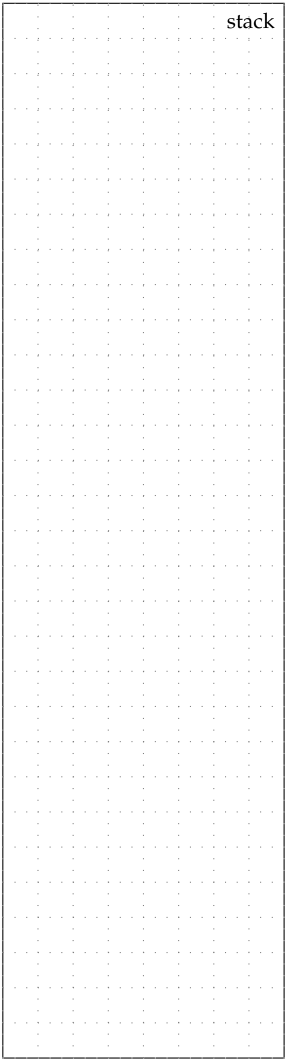




- What if we copy an object with dynamically allocated memory?

```
struct DPoint
{
  double* x_p;
  double* y_p;

  DPoint() {
    x_p = new double;
    y_p = new double;
    *x_p = 0.0;
    *y_p = 0.0;
  }

  ~DPoint() {
    delete x_p; delete y_p;
  }
  ...
};

int main( void )
{
  DPoint pt0;
  DPoint pt1 = pt0;
  pt0.translate( 1, 0 );
  return 0;
}
```

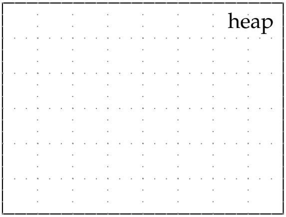


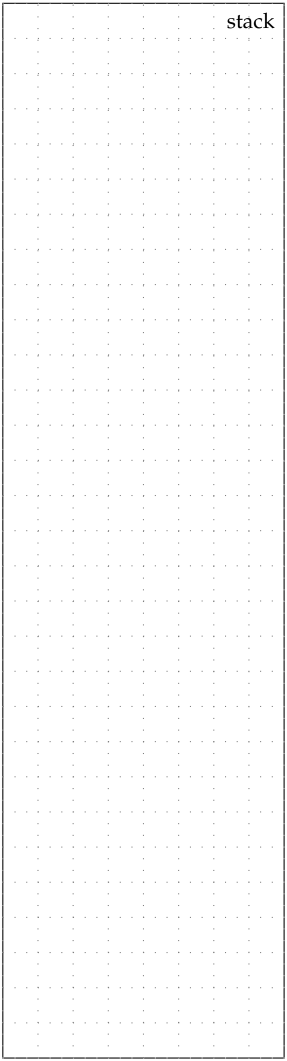


## C++ Copy Constructors

- Copy constructors are special member functions for constructing a new object from an old object

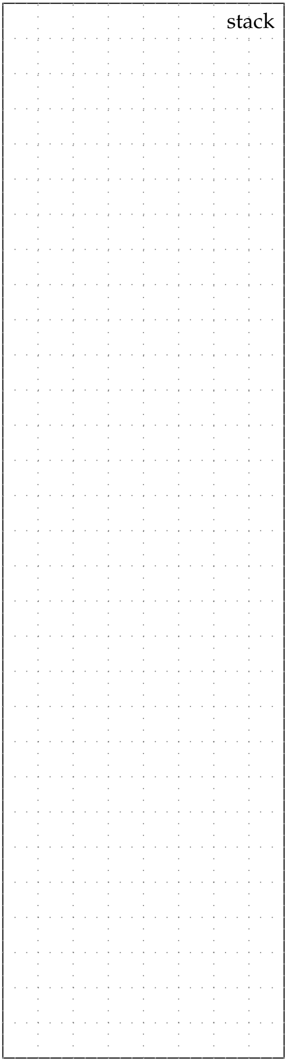
```
struct DPoint
{
  double* x_p;
  double* y_p;

  DPoint( const DPoint& pt ) {
    x_p = new double;
    y_p = new double;
    *x_p = *pt.x_p;
    *y_p = *pt.y_p;
  }

  ~DPoint() {
    delete x_p; delete y_p;
  }
  ...
};

int main( void )
{
  DPoint pt0;
  DPoint pt1 = pt0;
  pt0.translate( 1, 0 );
  return 0;
}
```

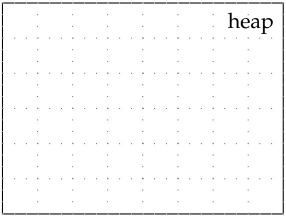




- What if we assign to an object with dynamically allocated memory?

```
struct DPoint
{
  double* x_p;
  double* y_p;

  DPoint() {
    x_p = new double;
    y_p = new double;
    *x_p = 0.0;
    *y_p = 0.0;
  }

  ~DPoint() {
    delete x_p; delete y_p;
  }
  ...
};

int main( void )
{
  DPoint pt0;
  DPoint pt1;
  pt1 = pt0;
  pt0.translate( 1, 0 );
  return 0;
}
```

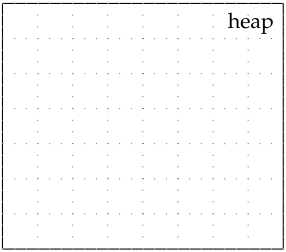


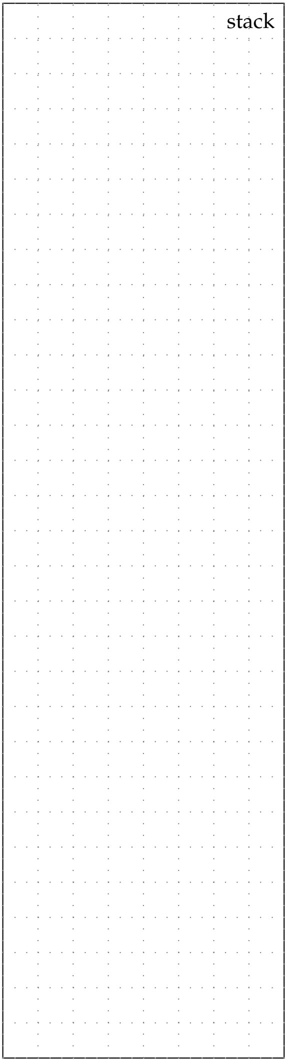


## C++ Assignment Operators

- An overloaded assignment operator will be called for assignment

```
struct DPoint
{
  double* x_p;
  double* y_p;

  DPoint&
  operator=( const DPoint& pt )
  {
    if ( this != &pt ) {
      *x_p = *pt.x_p;
      *y_p = *pt.y_p;
    }
    return *this;
  }
  ...
};

int main( void )
{
  DPoint pt0;
  DPoint pt1;
  pt1 = pt0;
  pt0.translate( 1, 0 );
  return 0;
}
```





### C++ Rule of Three

- Default destructor, copy constructor, and assignment operator will work fine for simple classes
- For a more complex class may need to define one of these ...
- ... and if you define one, then you probably need to define all three!
- Be very careful about self assignment

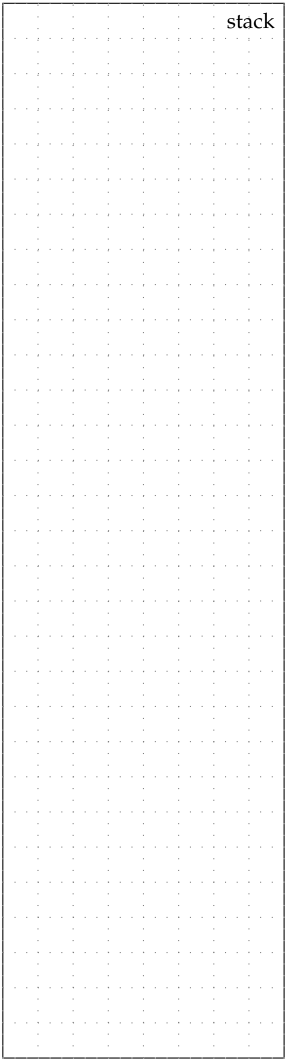
```
struct DPoint
{
  double* x_p;
  double* y_p;

  DPoint()
  {
    x_p = new double;
    y_p = new double;
    *x_p = 0.0;
    *y_p = 0.0;
  }

  DPoint( double x, double y )
  {
    x_p = new double;
    y_p = new double;
    *x_p = x;
    *y_p = y;
  }
```

```
  DPoint( const DPoint& pt )
  {
    x_p = new double;
    y_p = new double;
    *x_p = *pt.x_p;
    *y_p = *pt.y_p;
  }

  ~DPoint()
  {
    delete x_p;
    delete y_p;
  }

  DPoint&
  operator=( const DPoint& pt )
  {
    if ( this != &pt ) {
      *x_p = *pt.x_p;
      *y_p = *pt.y_p;
    }
    return *this;
  }

  ...
};
```

## C++ Exceptions and Destructors

- Destructors called automatically for all objects in scope when exception thrown

```
struct DPoint
{
  double* x_p;
  double* y_p;

  ~DPoint() {
    delete x_p;
    delete y_p;
  }

  void translate( double x_offset,
                  double y_offset )
  {
    if (     (x_offset > 100)
          || (y_offset > 100) )
      throw 42;
    *x_p += x_offset;
    *y_p += y_offset;
  }

  ...
};

int main( void )
{
  try {
    DPoint pt0;
    pt0.translate( 1e9, 0 );
  }
  catch ( int e ) {
    return e;
  }
  return 0;
}
```



## 1.5. C++ Resource Acquisition Is Initialization

- What if we forget to call `delete`? What if there is an exception?
- RAII is a design pattern that ties a resource to object lifetime (also known as scope-bound resource management)
- Use `new` in constructors and `delete` in destructors
- Elegantly ensures `delete` is called for every `new` even if an exception is thrown; can completely eliminate memory leaks

```
char* get_first_word( const char* str )
{
  // Determine how many characters are in first word
  int len = 0;
  while ( (str[len] != ' ') && (str[len] != '\0') )
    len++;

  // Dynamically allocate space for first word
  char* first_word = new char[len+1];

  // Copy the first word to the new allocated string
  for ( int i = 0; i < len; i++ )
    first_word[i] = str[i];
  first_word[len] = '\0';

  return first_word;
}

int main( void )
{
  char* x = get_first_word( "foo bar" );
  char* y = get_first_word( "foo" );
  char* z = get_first_word( "foo bar baz" );
  return 0;
};
```

```
struct String
{
  String()                          { m_str = nullptr;        }
  String( int size )                { m_str = new char[size]; }
  char& operator[]( int idx ) { return m_str[idx];      }
  ~String()                         { delete[] m_str;         }
  String( const String& str ) { copy( str.m_str );      }
  const char* c_str() const   { return m_str;           }

  String& operator=( const String& str )
  {
    if ( this != &str ) {
      delete[] m_str;
      copy( str.m_str );
    }
    return *this;
  }

  void copy( const char* s )
  {
    // Determine how many characters are in given string
    int len = 0;
    while ( s[len] != '\0' )
      len++;

    // Dynamically allocate space for copy
    m_str = new char[len+1];

    // Copy the given string to the newly allocated string
    for ( int i = 0; i < len+1; i++ )
      m_str[i] = s[i];
  }

  char* m_str;
};
```

```
String get_first_word( const char* str )
{
  int len = 0;
  while ( (str[len] != ' ') && (str[len] != '\0') )
    len++;

  String first_word(len+1);

  for ( int i = 0; i < len; i++ )
    first_word[i] = str[i];

  first_word[len] = '\0';
  return first_word;
}

int main( void )
{
  String x = get_first_word( "foo bar" );
  String y = get_first_word( "foo" );
  String z = get_first_word( "foo bar baz" );
  return 0;
};
```

- Every time you use a `new` think critically ...
- ... who is in charge of calling delete?
- ... what happens if there is an exception through?

- Every use of `new`/`delete` needs to be purposeful and only if absolutely necessary!

## 1.6. C++ Data Encapsulation

- Recall the importance of separating interface from implementation
- This is an example of abstraction
- In this context, also called information hiding, data encapsulation
  - Hides implementation complexity
  - Can change implementation without impacting users

- So far, we have relied on a *policy* to enforce data encapsulation
  - Users of a struct could still directly access member fields

```
int main( void )
{
  Point pt(1,2);
  pt.x = 13; // direct access to member fields
  return 0;
}
```

- In C++, we can *enforce* data encapsulation at compile time
  - By default all member fields and functions of a `struct` are public
  - Member fields and functions can be explicitly labeled as public or private
  - Externally accessing an internal private field causes a compile time error

```
struct Point
{
 private:
  double x; double y;

 public:
  // default constructor
  Point() { x = 0.0; y = 0.0; }

  // non-default constructor
  Point( double x_, double y_ ) { x = x_; y = y_; }
  ...
};
```

- In C++, we usually use `class` instead of `struct`
  - By default all member fields and functions of a `struct` are public
  - By default all member fields and functions of a `class` are private
  - We should almost always use `class` and explicitly use public and private

```
class Point // almost always use class instead of struct
{
 public:    // always explicitly use public ...
 private:   // ... or private
};
```

- We are free to change how we store the point
- We could change point to store coordinates on the stack or heap
- Statically guaranteed that others cannot access this private implementation

## 1.7. C++ I/O Streams

- `printf` does not support user-defined types
- Need to encapsulate printing in a member function ...
- ... but this leads to very awkward syntax

```
int main( void )
{
  Point pt0(1,2);
  Point pt1 = pt0;
  pt1.translate(2.0,2.0);

  std::printf("initial point = ");
  pt0.print();
  std::printf("\n");
  std::printf("translate by %.2f,%.2f\n", 2.0, 2.0 );
  std::printf("new point = ");
  pt1.print();
  std::printf("\n");
}
```

- Clever use of operator overloading can provide cleaner syntax

```
struct ostream
{
  // internal stream state
};

ostream cout;

ostream& operator<<( ostream& os, int i )
{
  std::printf("%d",i); return os;
}

ostream& operator<<( ostream& os, double d )
{
  std::printf("%.2f",d); return os;
}

ostream& operator<<( ostream& os, const char* str )
{
  std::printf("%s",str); return os;
}

ostream& operator<<( ostream& os, const Point& pt )
{
  pt.print(); return os;
}

struct EndOfLine
{ };

EndOfLine endl;

ostream& operator<<( ostream& os, const EndOfLine& endl )
{
  std::printf("\n"); return os;
}
```

```
int main( void )
{
  Point pt0(1,2);
  Point pt1 = pt0;
  pt1.translate(2.0,2.0);

  cout << "initial point = " << pt0 << endl;
  cout << "translate by " << 2.0 << "," << 2.0 << endl;
  cout << "new point = " << pt1 << endl;
}
```

- The standard C++ library provides powerful streams
  - `iostream` : write/read standard I/O as streams
  - `fstream` : write/read files as streams
  - `sstream` : write/read strings as streams

# 2. Basic Object-Oriented Lists

- Object-oriented programming can enable elegant interfaces and implementations for data structures

## 2.1. Singly Linked List Interface

- Recall the interface for a C singly linked list

```
typedef struct
{
  // implementation specific
}
slist_int_t;

void slist_int_construct  ( slist_int_t* this );
void slist_int_destruct   ( slist_int_t* this );
void slist_int_push_front ( slist_int_t* this, int v );
void slist_int_reverse    ( slist_int_t* this );
```

- Corresponding interface for a C++ singly linked list data structure

```
class SListInt
{
 public:
  SListInt();                   // constructor
  ~SListInt();                  // destructor
  void push_front( int v );     // member function
  void reverse();               // member function

  // implementation specific
};
```

- C-based list could not be easily copied or assigned
- C++ rule of three means we also need to declare and define a copy constructor and an overloaded assignment operator

## 2.2. Singly Linked List Implementation

- Recall the implementation for a C singly linked list data structure

```
typedef struct _slist_int_node_t
{
  int                        value;
  struct _slist_int_node_t* next_p;
}
slist_int_node_t;

typedef struct
{
  slist_int_node_t* head_p;
}
list_int_t;
```

- Corresponding implementation for a C++ singly linked list data structure

```
class SListInt
{
 public:
  SListInt();                  // constructor
  ~SListInt();                 // destructor
  void push_front( int v );    // member function
  void reverse();              // member function

  struct Node                  // nested struct declaration
  {
    int   value;
    Node* next_p;
  };

  Node* m_head_p;              // member field
};
```

- Implementation for a C singly linked list data structure

```c
void slist_int_construct(
  slist_int_t* this )
{
  this->head_p = NULL;
}

void slist_int_push_front(
  slist_int_t* this, int v )
{
  slist_int_node_t* new_node_p
   = malloc(sizeof(slist_int_node_t));
  new_node_p->value  = v;
  new_node_p->next_p = this->head_p;
  this->head_p       = new_node_p;
}

void slist_int_destruct(
  slist_int_t* this )
{
  while ( this->head_p != NULL ) {
    list_int_node_t* temp_p
      = this->head_p->next_p;
    free( this->head_p );
    this->head_p = temp_p;
  }
}
```

- Implementation for a C++ singly linked list data structure

```cpp
SListInt::SListInt()

{
  m_head_p = nullptr;
}

void SListInt::push_front( int v )

{
  Node* new_node_p
    = new Node;
  new_node_p->value  = v;
  new_node_p->next_p = m_head_p;
  m_head_p           = new_node_p;
}

SListInt::~SListInt()

{
  while ( m_head_p != nullptr ) {
    Node* temp_p
      = m_head_p->next_p;
    delete m_head_p;
    m_head_p = temp_p;
  }
}
```

- Notice the syntax used for separating member function *declarations* from member function *definitions*

```
SListInt::SListInt()
{
  m_head_p = nullptr;
}

void SListInt::push_front( int v )
{
  Node* new_node_p
    = new Node;
  new_node_p->value = v;
  new_node_p->next_p = m_head_p;
  m_head_p = new_node_p;
}

int main( void )
{
  SListInt lst;
  lst.push_front(12);
  lst.push_front(11);
  lst.push_front(10);

  SListInt::Node* node_p
    = lst.m_head_p;
  while ( node_p != nullptr ) {
    int value = node_p->value;
    node_p = node_p->next_p;
  }

  return 0;
}
```

stack

heap

## 2.3. Iterator-Based List Interface and Implementation

- We can use iterators to improve data encapsulation yet still enable the user to cleanly iterate through a sequence

```
class SListInt
{
  ...

 private:

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

  Node* m_head_p;

 public:

  class Itr
  {
   public:
    Itr( Node* node_p );
    void next();
    int& get();
    bool eq( Itr itr ) const;

   private:
    Node* m_node_p;
  };

  Itr begin();
  Itr end();

};
```

```
SListInt::Itr::Itr( Node* node_p )
 : m_node_p(node_p)
{ }

void SListInt::Itr::next()
{
  assert( m_node_p != nullptr );
  m_node_p = m_node_p->next_p;
}

int& SListInt::Itr::get()
{
  assert( m_node_p != nullptr );
  return m_node_p->value;
}

bool SListInt::Itr::eq( Itr itr ) const
{
  return ( m_node_p == itr.m_node_p );
}

SListInt::Itr SListInt::begin()
{
  return Itr(m_head_p);
}

SListInt::Itr SListInt::end()
{
  return Itr(nullptr);
}
```

```
SListInt::Node* node_p
  = list.m_head_p;
while ( node_p != nullptr ) {
  int value = node_p->value
  printf( "%d\n", value );
  node_p = node_p->next_p;
}
```

```
SListInt::Itr itr
  = list.begin();
while ( !itr.eq(list.end()) ) {
  int value = itr.get();
  printf( "%d\n", value );
  itr.next();
}
```

- We can use operator overloading to improve iterator syntax

```
// postfix increment operator (itr++)
SListInt::Itr operator++( SListInt::Itr& itr, int )
{
  SListInt::Itr itr_tmp = itr; itr.next(); return itr_tmp;
}

// prefix increment operator (++itr)
SListInt::Itr& operator++( SListInt::Itr& itr )
{
  itr.next(); return itr;
}

// dereference operator (*itr)
int& operator*( SListInt::Itr& itr )
{
  return itr.get();
}

// not-equal operator (itr0 != itr1)
bool operator!=( const SListInt::Itr& itr0,
                 const SListInt::Itr& itr1  )
{
  return !itr0.eq( itr1 );
}
```

```
SListInt::Itr itr = lst.begin();
while ( !itr.eq(lst.end()) ) {
  int value = itr.get();
  printf( "%d\n", value );
  itr.next();
}
```

```
SListInt::Itr itr = lst.begin();
while ( itr != lst.end() ) {
  int value = *itr;
  printf( "%d\n", value );
  ++itr;
}
```

```
for ( SListInt::Itr itr = lst.begin(); itr != lst.end(); ++itr ) {
  printf( "%d\n", *itr );
}
```

- We can use `auto` and range-based loops with user-defined data structures to enable elegant syntax
- C++11 `auto` keyword will automatically infer type from initializer

```
for ( auto itr = lst.begin(); itr != lst.end(); ++itr ) {
  printf( "%d\n", *itr );
}
```

- C++11 range-based loops are syntactic sugar for above

```
for ( int v : lst ) {
  printf( "%d\n", v );
}
```

# 3. C++ Inheritance

```cpp
class Pawn
{
 public:
  Pawn( char col, int row )
    : m_col(col), m_row(row)
  { }

  int get_pts() const
  {
    return 1;
  }

  char get_col() const
  {
   return m_col;
  }

  int get_row() const
  {
   return m_row;
  }

  void move( char col, int row )
  {
   if (     (col != m_col)
        || (row != (m_row + 1)) )
    throw 42;

   m_col = col;
   m_row = row;
  }

  void print() const
  {
    std::printf( "pawn@%c%d",
                 m_col, m_row );
  }

 private:
  char m_col;
  int  m_row;
};
```

```cpp
class Rook
{
 public:
  Rook( char col, int row )
    : m_col(col), m_row(row)
  { }

  int get_pts() const
  {
    return 5;
  }

  char get_col() const
  {
   return m_col;
  }

  int get_row() const
  {
   return m_row;
  }

  void move( char col, int row )
  {
   if (     (col != m_col)
        && (row != m_row) )
    throw 42;

   m_col = col;
   m_row = row;
  }

  void print() const
  {
    std::printf( "rook@%c%d",
                 m_col, m_row );
  }

 private:
  char m_col;
  int  m_row;
};
```

- Object-oriented design without inheritance

- We want to be able to ...

... create algorithms and data structures that work for all pieces
... easily reuse implementation code across pieces

- Inheritance enables declaring a derived class that automatically includes the interface and implementation of a different base class
  - Derived class also called the child class or subclass
  - Base class also called the parent class or superclass

- We will take an incremental approach
  - Implementation inheritance
  - From implementation to interface inheritance
  - Interface inheritance

## 3.1. C++ Implementation Inheritance

- Object-oriented design with implementation inheritance

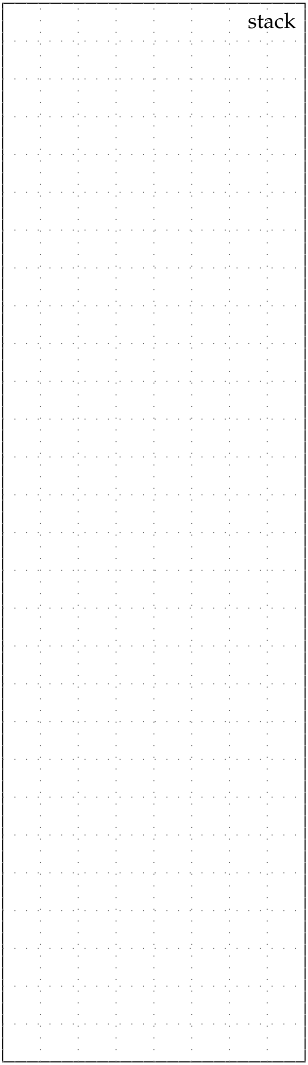
```cpp
class Piece
{
 public:

  Piece( char col, int row )
    : m_col(col), m_row(row)
  { }

  char get_col() const
  {
   return m_col;
  }

  int get_row() const
  {
   return m_row;
  }






  void move( char col, int row )
  {
    m_col = col;
    m_row = row;
  }







 // derived classes cannot
 // access private data in
 // base class
 protected:

  char m_col;
  int  m_row;

};
```

```cpp
class Rook : public Piece
{
 public:

  Rook( char col, int row )
   : Piece( col, row )
  { }











  int get_pts() const
  {
    return 5;
  }

  void move( char col, int row )
  {
   if (     (col != m_col)
        && (row != m_row) )
    throw 42;

   Piece::move( col, row );
  }

  void print() const
  {
    std::printf( "rook@%c%d",
                 m_col, m_row );
  }






};
```

```cpp
class Piece
{
  Piece( char col, int row )
    : m_col(col), m_row(row)
  { }

  char get_col() const
  {
    return m_col;
  }

  int get_row() const
  {
    return m_row;
  }
  ...
};

class Pawn : public Piece
{
  Pawn( char col, int row )
   : Piece( col, row )
  { }

  int get_pts() const
  {
    return 1;
  }
  ...
};

int main( void )
{
  Pawn p('a',2);
  char col = p.get_col();
  return 0;
}
```

stack

```
class Piece
{
  Piece( char col, int row )
    : m_col(col), m_row(row)
  { }

  char get_col() const
  {
    return m_col;
  }

  int get_row() const
  {
    return m_row;
  }
  ...
};

class Pawn : public Piece
{
  int get_pts() const { return 1; }
  ...
};

class Rook : public Piece
{
  int get_pts() const { return 5; }
  ...
};

int main( void )
{
  Pawn p('a',2);
  Rook r('h',3);
  int pts0 = p.get_pts();
  int pts1 = r.get_pts();
  int sum  = pts0 + pts1;
  return 0;
}
```



## 3.2. From Implementation to Interface Inheritance

- Implementation Inheritance
  - really more of the composition relationship (“has a”)
  - focuses on refactoring implementation code into the base class
  - still only instantiate and manipulate derived “implementation” classes
  - need to know all type information at compile time
- Interface Inheritance
  - the key to leveraging the generalization relationship (“is a”)
  - focuses on enabling dynamic polymorphism (i.e., subtype polymorphism)
  - can manipulate objects using the base “interface” class
  - do not need to know implementation type information at compile time
  - can use run-time type information

### Type conversion and casting in class hierarchies

```
Rook rook('h',3);

// implicit type conversion
Piece* piece_p = &rook;

// can only call methods defined in Piece
piece_p->get_col();

// explicit type casting to correct type
Rook* rook_p = (Rook*) piece_p;

// can call methods defined in Piece or Rook
rook_p->get_pts();

// explicit type casting to wrong type (segfault)
Pawn* pawn_p = (Pawn*) piece_p;

// ptr == nullptr if piece_p is not pointer to a Rook
Rook* ptr = dynamic_cast<Rook*>(piece_p);
```

## Dynamic Polymorphism

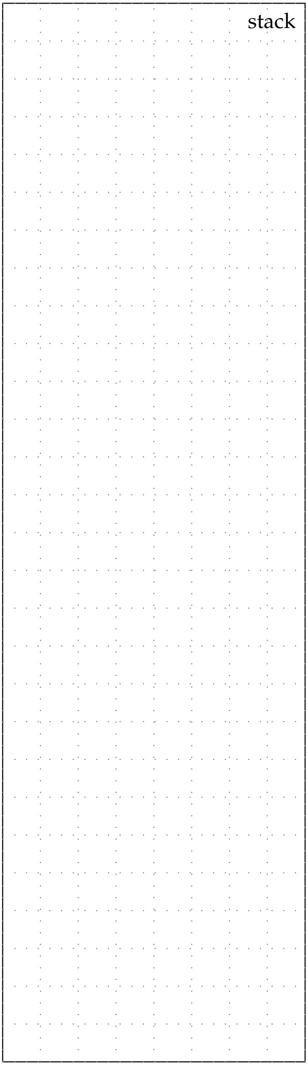
- Consider the following code snippet from previous example

```
int pts0 = p.get_pts();
int pts1 = r.get_pts();
int sum  = pts0 + pts1;
```

- Consider refactoring this code into a separate function
  - we want our function to be able to work with any type of chess piece
  - this function exhibits dynamic polymorphism
  - polymorphism = condition of occurring in several different forms
  - dynamic = run-time

```
int calc_pts( Piece* p0, Piece* p1 )
{
  int pts0 = p0->get_pts();
  int pts1 = p1->get_pts();
  return pts0 + pts1;
}
```

```
class Piece
{
  Piece( char col, int row )      { ...
  char get_col() const            { ...
  int  get_row() const            { ...
  void move( char col, int row ) { ...
  ...
};

class Pawn : public Piece
{
  int get_pts() const { return 1; }
  ...
};

class Rook : public Piece
{
  int get_pts() const { return 5; }
  ...
};

int calc_pts( Piece* p0, Piece* p1 )
{
  int pts0 = p0->get_pts();
  int pts1 = p1->get_pts();
  return pts0 + pts1;
}

int main( void )
{
  Pawn p('a',2);
  Rook r('h',3);
  int sum = calc_pts( &p, &r );
  return 0;
}
```

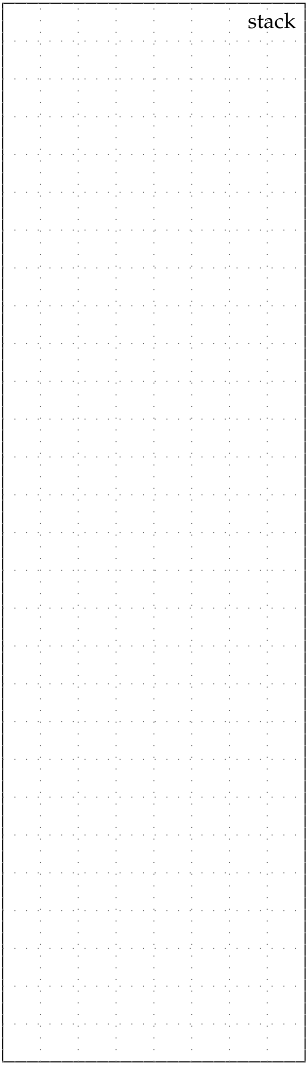


```
// enum for all possible
// implementation types
enum PieceType { PAWN, ROOK };

class Piece
{
 public:

  Piece( PieceType type,
         char col, int row )
   : m_type(type),
     m_col(col), m_row(row)
  { }

  PieceType get_type() const
  {
    return m_type;
  }

  char get_col() const
  {
    return m_col;
  }

  int get_row() const
  {
    return m_row;
  }

  void move( char col, int row )
  {
    m_col = col;
    m_row = row;
  }

 protected:

  // explicit type field
  PieceType m_type;

  char      m_col;
  int       m_row;

};
```

- Add type field to base class
- Use type field to determine implementation type
- Cast a pointer from the base class to a pointer to the appropriate derived type
- Call the corresponding member function

```
class Rook : public Piece
{
 public:

  Rook( char col, int row )
   : Piece( ROOK, col, row )
  { }

  int get_pts() const
  {
    return 5;
  }

  void move( char col, int row )
  {
   if (    (col != m_col)
        && (row != m_row) )
    throw 42;

   Piece::move( col, row );
  }

  void print() const
  {
    std::printf( "rook@%c%d",
                 m_col, m_row );
  }
};
```

```
class Pawn : public Piece
{
  int get_pts() const { return 1; }
  ...
};

int calc_pts( Piece* p0, Piece* p1 )
{
  int pts0;
  if ( p0->get_type() == PAWN ) {
    Pawn* pawn_p = (Pawn*) p0;
    pts0 = pawn_p->get_pts();
  }
  else if ( p0->get_type() == ROOK ) {
    Rook* rook_p = (Rook*) p0;
    pts0 = rook_p->get_pts();
  }

  int pts1;
  if ( p1->get_type() == PAWN ) {
    Pawn* pawn_p = (Pawn*) p1;
    pts1 = pawn_p->get_pts();
  }
  else if ( p1->get_type() == ROOK ) {
    Rook* rook_p = (Rook*) p1;
    pts1 = rook_p->get_pts();
  }

  return pts0 + pts1;
}

int main( void )
{
  Pawn p('a',2);
  Rook r('h',3);
  int sum = calc_pts( &p, &r );
  return 0;
}
```

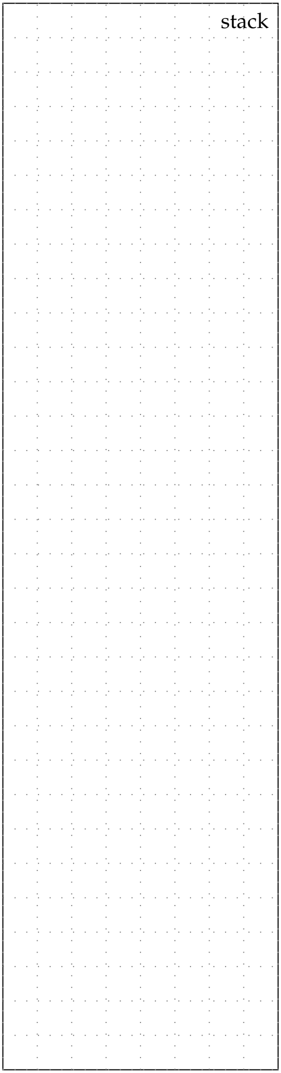


```
enum PieceType { PAWN, ROOK };

class Piece
{
 public:

  Piece( PieceType type,
         char col, int row )
   : m_type(type),
     m_col(col), m_row(row)
  { }

  int get_pts() const
  {
    if ( m_type == PAWN ) {
      Pawn* pawn_p = (Pawn*) this;
      return pawn_p->get_pts();
    }
    else if ( m_type == ROOK ) {
      Rook* rook_p = (Rook*) this;
      return rook_p->get_pts();
    }
  }

  char get_col() const
  {
    return m_col;
  }

  int get_row() const
  {
    return m_row;
  }

  void move( char col, int row )
  {
    m_col = col;
    m_row = row;
  }

 protected:
  PieceType m_type;
  char      m_col;
  int       m_row;
};
```

- Add type field to base class
- Use type field to determine implementation type
- Cast a pointer from the base class to a pointer to the appropriate derived type
- Call the corresponding member function
- Example of dynamic dispatch

```
class Rook : public Piece
{
 public:

  Rook( char col, int row )
   : Piece( ROOK, col, row )
  { }

  int get_pts() const
  {
    return 5;
  }

  void move( char col, int row )
  {
   if (     (col != m_col)
         && (row != m_row) )
    throw 42;

   Piece::move( col, row );
  }

  void print() const
  {
    std::printf( "rook@%c%d",
                 m_col, m_row );
  }
};
```

```cpp
class Piece
{
  ...
  int get_pts() const
  {
    if ( m_type == PAWN ) {
      Pawn* pawn_p = (Pawn*) this;
      return pawn_p->get_pts();
    }
    else if ( m_type == ROOK ) {
      Rook* rook_p = (Rook*) this;
      return rook_p->get_pts();
    }
  }
};

class Pawn : public Piece
{
  int get_pts() const { return 1; }
  ...
};

int calc_pts( Piece* p0, Piece* p1 )
{
  int pts0 = p0->get_pts();
  int pts1 = p1->get_pts();
  return pts0 + pts1;
}

int main( void )
{
  Pawn p('a',2);
  Rook r('h',3);
  int sum = calc_pts( &p, &r );
  return 0;
}
```



## 3.3. C++ Interface Inheritance

- C++ includes language support for dynamic dispatch
- `virtual` keyword can be used with a base class member function
- Calling a virtual member function will dynamically dispatch to the appropriate derived class member function
- At least one virtual function, compiler generates implicit type field
- Compiler generates more optimized version of dynamic dispatch

```
class Piece
{
 public:

  Piece( char col, int row )
   : m_col(col), m_row(row)
  { }

  // pure virtual function
  virtual int get_pts() const = 0;

  char get_col() const
  {
    return m_col;
  }

  int get_row() const
  {
    return m_row;
  }

  void move( char col, int row )
  {
    m_col = col;
    m_row = row;
  }

 protected:
  char      m_col;
  int       m_row;
};
```

```
class Rook : public Piece
{
 public:

  Rook( char col, int row )
   : Piece( col, row )
  { }

  int get_pts() const
  {
    return 5;
  }

  void move( char col, int row )
  {
   if (    (col != m_col)
        && (row != m_row) )
    throw 42;

   Piece::move( col, row );
  }

  void print() const
  {
    std::printf( "rook@%c%d",
                 m_col, m_row );
  }
};
```

```
class Piece
{
  virtual int get_pts() const = 0;
  ...
};

class Pawn : public Piece
{
  int get_pts() const { return 1; }
  ...
};

class Rook : public Piece
{
  int get_pts() const { return 5; }
  ...
};

int calc_pts( Piece* p0, Piece* p1 )
{
  int pts0 = p0->get_pts();
  int pts1 = p1->get_pts();
  return pts0 + pts1;
}

int main( void )
{
  Pawn p('a',2);
  Rook r('h',3);
  int sum = calc_pts( &p, &r );
  return 0;
}
```

stack

## Abstract base classes

- All member functions are pure virtual member functions
- Need to have a non-pure virtual destructor in base class

```
class IPiece
{
 public:
  virtual ~IPiece() { }
  virtual int  get_pts() const = 0;
  virtual char get_col() const = 0;
  virtual int  get_row() const = 0;
  virtual void move( char col, int row ) = 0;
  virtual void print() const  = 0;
};

class Rook : public IPiece
{
 public:
  Rook( char col, int row ) : m_col(col), m_row(row) { }
  ~Rook() { }

  int  get_pts() const { return 5;     }
  char get_col() const { return m_col; }
  int  get_row() const { return m_row; }

  void move( char col, int row )
  {
    if ( (col != m_col) && (row != m_row) )
      throw 42;
    m_col = col;
    m_row = row;
  }

  void print() const
  {
    std::printf( "rook@%c%d", m_col, m_row );
  }

 private:
  char m_col;
  int  m_row;
};
```

## 3.4. Revisiting Composition vs. Generalization

```cpp
class Position
{
 public:
  Position( char col, int row )
    : m_col(col), m_row(row)
  { }

  char get_col() const
  {
    return m_col;
  }

  int get_row() const
  {
    return m_row;
  }

  void move( char col, int row )
  {
    m_col = col;
    m_row = row;
  }

  void print() const
  {
    std::printf( "%c%d",
                 m_col, m_row );
  }

private:
  char m_col;
  int  m_row;
};
```

```cpp
class Pawn : public IPiece
{
 public:

  Pawn( char col, int row )
    : m_pos(col,row)
  { }

  ~Pawn()
  { }

  int get_pts() const
  {
    return 1;
  }

  char get_col() const
  {
    return m_pos.get_col();
  }

  int get_row() const
  {
    return m_pos.get_row();
  }

  void move( char col, int row )
  {
    int curr_col = m_pos.get_col();
    int curr_row = m_pos.get_row();
    if (    (col != curr_col)
         || (row != (curr_row + 1)) )
      throw 42;
    m_pos.move( col, row );
  }

  void print() const
  {
    std::printf("pawn@");
    m_pos.print();
  }

 private:
  Position m_pos;
};
```

# 4. Dynamic Polymorphic Object-Oriented Lists

- So far our list data structure can only store `ints`
- If we want a list of doubles → copy-and-paste
- If we want a list of complex numbers → copy-and-paste
- We have no way to store elements of different types in a list
- We can use dynamic polymorphism to create a polymorphic list

### Class Hierarchy for Objects

```
class IObject
{
 public:

  virtual ~IObject() { };
  virtual IObject*    clone( )                    const = 0;
  virtual bool        eq( const IObject& rhs ) const = 0;
  virtual bool        lt( const IObject& rhs ) const = 0;
  virtual void        print()                     const = 0;

};

bool operator==( const IObject& lhs, const IObject& rhs )
{
  return lhs.eq(rhs);
}

bool operator!=( const IObject& lhs, const IObject& rhs )
{
  return !lhs.eq(rhs);
}

bool operator<( const IObject& lhs, const IObject& rhs )
{
  return lhs.lt(rhs);
}
```

```
class Integer : public IObject
{
 public:
  Integer()           : m_data(0)        { }
  Integer( int data ) : m_data(data)     { }

  Integer* clone() const
  {
    return new Integer( *this );
  }

  bool eq( const IObject& rhs ) const
  {
    const Integer* rhs_p = dynamic_cast<const Integer*>( &rhs );
    if ( rhs_p == nullptr )
      return false;
    else
      return ( m_data == rhs_p->m_data );
  }

  bool lt( const IObject& rhs ) const
  {
    const Integer* rhs_p = dynamic_cast<const Integer*>( &rhs );
    if ( rhs_p == nullptr )
      return false;
    else
      return ( m_data < rhs_p->m_data );
  }

  void print() const
  {
    std::printf( "%d", m_data );
  }

 private:
  int m_data;
};
```

```
class IObject
{
 public:
   virtual bool
   eq( const IObject& rhs ) const = 0;
  ...
};

bool operator==( const IObject& lhs,
                 const IObject& rhs ) {
  return lhs.eq(rhs);
}

class Integer : public IObject
{
 public:
  Integer( int data ) : m_data(data) { }

  bool eq( const IObject& rhs ) const {
   const Integer* rhs_p
    = dynamic_cast<const Integer*>(&rhs);
   if ( rhs_p == nullptr )
     return false;
   else
     return (m_data == rhs_p->m_data);
  }
  ...
 private:
  int m_data;
};

int main( void )
{
  Integer a(2);
  Integer b(3);
  bool c = ( a == b );
  return 0;
}
```

stack

## 4.1. Singly Linked List Interface

- Object-oriented list which stores `int`s

```
class SListInt
{
 public:
  SListInt();
  ~SListInt();
  void push_front(
    int v );
  void reverse();

  class Itr
  {
   public:
    Itr( Node* node_p );
    void next();
    int& get();
    bool eq( Itr itr ) const;

   private:
    Node* m_node_p;
  };

  Itr begin();
  Itr end();

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

  Node* m_head_p;
};
```

- Object-oriented list which stores `IObject`s

```
class SListIObj
{
 public:
  SListIObj();
  ~SListIObj();
  void push_front(
    const IObject& v );
  void reverse();

  class Itr
  {
   public:
    Itr( Node* node_p );
    void next();
    IObject*& get();
    bool eq( Itr itr ) const;

   private:
    Node* m_node_p;
  };

  Itr begin();
  Itr end();

 private:
  struct Node
  {
    IObject* obj_p;
    Node*    next_p;
  };

  Node* m_head_p;
};
```

## 4.2. Singly Linked List Implementation

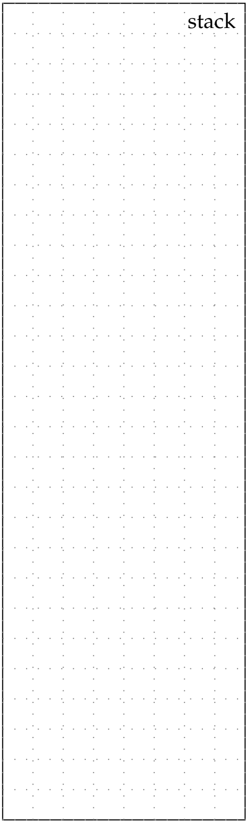
- Implementation for singly linked list to store `ints`

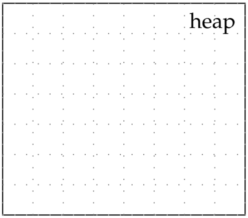
- Implementation for singly linked list to store `IObjects`

```
SListInt::SListInt()
{
  m_head_p = nullptr;
}

void SListInt::push_front( int v )

{
  Node* new_node_p    = new Node;
  new_node_p->value   = v;
  new_node_p->next_p = m_head_p;
  m_head_p            = new_node_p;
}

SListInt::~SListInt()
{
  while ( m_head_p != nullptr ) {
    Node* temp_p = m_head_p->next_p;

    delete m_head_p;
    m_head_p = temp_p;
  }
}
```

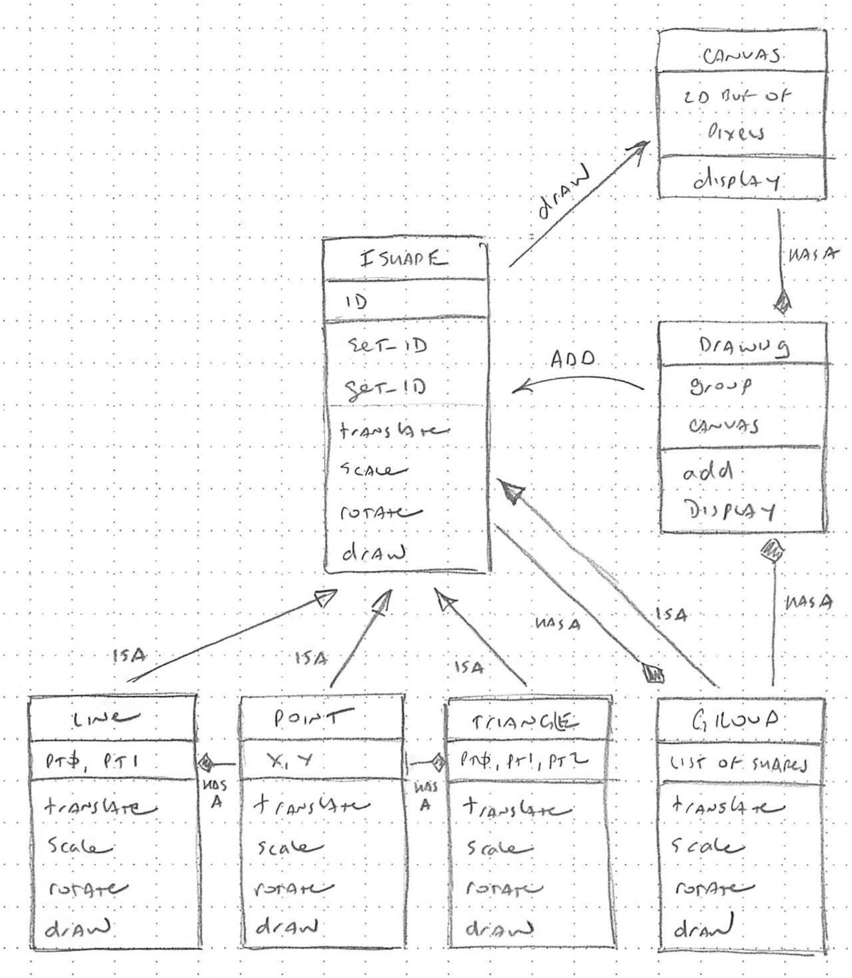
```
SListIObj::SListIObj()
{
  m_head_p = nullptr;
}

void SListIObj::push_front(
                const IObject& v )
{
  Node* new_node_p    = new Node;
  new_node_p->obj_p   = v.clone();
  new_node_p->next_p = m_head_p;
  m_head_p            = new_node_p;
}

SListIObj::~SListIObj()
{
  while ( m_head_p != nullptr ) {
    Node* temp_p = m_head_p->next_p;
    delete m_head_p->obj_p;
    delete m_head_p;
    m_head_p = temp_p;
  }
}
```

```
class IObject
{
 public:
   virtual IObject* clone( ) const = 0;
  ...
};

class Integer : public IObject
{
 public:
  Integer( int data ) : m_data(data) { }
  Integer* clone() const {
    return new Integer( *this );
  }
  ...
 private:
  int m_data;
};

SListIObj::SListIObj() {
  m_head_p = nullptr;
}

void SListIObj::push_front(
                const IObject& v ) {
  Node* new_node_p   = new Node;
  new_node_p->obj_p  = v.clone();
  new_node_p->next_p = m_head_p;
  m_head_p           = new_node_p;
}

int main( void )
{
  SListIObj list;
  Integer a(12);
  list.push_front(a);
  return 0;
}
```





# 5. Drawing Framework Case Study



`https://repl.it/@cbatten/ece2400-T13-ex3`