

ECE 2400 Computer Systems Programming

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Topic 14: Generic Programming

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- 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  #define SPECIALIZE_LIST_T( T )           \
2                                          \
3  typedef struct                          \
4  {                                        \
5      /* implementation specific */      \
6  }                                        \
7  list_ ## T ## _t;                      \
8                                          \
9  void list_ ## T ## _construct ( list_ ## T ## _t* this ); \
10 void list_ ## T ## _destruct  ( list_ ## T ## _t* this ); \
11 void list_ ## T ## _push_front ( list_ ## T ## _t* this, T v ); \
12 void list_ ## T ## _reverse   ( list_ ## T ## _t* this ); \
13                                          \
14 SPECIALIZE_LIST_T( int   ) \
15 SPECIALIZE_LIST_T( float )
```

1. C++ Function Templates

- Two implementations of avg

```
1 int avg_int( int x, int y )      1 float avg_float( float x, float y )
2 {                                2 {
3     int sum = x + y;            3     float sum = x + y;
4     return sum / 2;            4     return sum / 2;
5 }                                5 }
```

- These implementations are identical except for the types
- Use dynamic polymorphism? but dynamic polymorphism is slow
- Instead we can use **templates** to implement **static polymorphism**

```
1 template < typename T >
2 T avg( T x, T y )
3 {
4     T sum = x + y;
5     return sum / 2;
6 }
```

```
1 template <>                    1 template <>
2 int avg<int>( int x, int y )   2 float avg<float>( float x, float y )
3 {                                3 {
4     int sum = x + y;            4     float sum = x + y;
5     return sum / 2;            5     return sum / 2;
6 }                                6 }
```

- Does not implement a function, implements a **function template**
- We can **instantiate** the template to create a **template specialization**

```
0001 template < typename T >
0002 T avg( T x, T y )
0003 {
0004     T sum = x + y;
0005     return sum / 2;
0006 }
0007
0008 template <>
0009 int avg<int>( int x, int y )
0010 {
0011     int sum = x + y;
0012     return sum / 2;
0013 }
0014
0015 template <>
0016 float avg<float>( float x,
0017                  float y )
0018 {
0019     float sum = x + y;
0020     return sum / 2;
0021 }
0022
0023 int main( void )
0024 {
0025     int    a = avg<int>(5,10);
0026     float  b = avg<float>(5,10);
0027     return 0;
0028 }
```

stack

- Compiler can infer the template specialization from parameter types
- ... but be careful!

```
1 int main( void )
2 {
3     int a = avg( 5, 10 ); // will call avg<int>
4     float b = avg( 5, 10 ); // will call avg<int>
5     float c = avg( 5.0f, 10.0f ); // will call avg<float>
6     return 0;
7 }
```

- Can have a list of template arguments

```
1 template < typename T, typename U, typename V >
2 T avg( U x, V y )
3 {
4     T sum = x + y;
5     return sum / 2;
6 }
7
8 int main( void )
9 {
10    float a = avg<float,int,int>(5,1);
11    float b = avg<float>(5,1); // cannot infer from return type
12    return 0;
13 }
```

- Template arguments can also be values

```
1 template < int v >          1 int main( void )
2 int incr( int x )          2 {
3 {                             3     int a = 1;
4     return x + v;           4     int b = incr<1>(a); // legal
5 }                             5     int c = 0;
                                6     for ( int i = 0; i < 5; i++ )
                                7         c += incr<i>(1); // illegal!
                                8     return 0;
                                9 }
```

2. C++ Class Templates

- A class to generically store two values of potentially different types

```
1  struct PairFloatFloat
2  {
3      PairFloatFloat( float a, float b )
4          : first(a), second(b) { }
5      float first;
6      float second;
7  }
8
9  struct PairCharInt
10 {
11     PairCharInt( char a, int b )
12         : first(a), second(b) { }
13     char first;
14     int second;
15 }
```

- Class templates enable static polymorphism for classes

```
1  template < typename T, typename U >
2  struct Pair
3  {
4      Pair( const T& a, const U& b )
5          : first(a), second(b) { }
6      T first;
7      U second;
8  }
9
10 int main( void )
11 {
12     Pair<float,float> pair( 5.5, 7.5 );
13     Pair<char,int>    pair( 'a', 1 );
14     return 0;
15 }
```


3. Dynamic vs. Static Polymorphism

Dynamic Polymorphism

```
1
2
3 int calc_pts( const IPiece& p0,
4               const IPiece& p1 )
5 {
6     int pts0 = p0.get_pts();
7     int pts1 = p1.get_pts();
8     return pts0 + pts1;
9 }
10
11 int main( void )
12 {
13     Pawn p('a',2);
14     Rook r('h',3);
15     int sum = calc_pts( p, r );
16     return 0;
17 }
```

- Only a single version of `calc_pts` is compiled
- State diagram includes run-time type information (implicit type fields)
- Run-time type information used for dynamic dispatch
- Slower performance, more space usage

Static Polymorphism

```
1 template < typename T,
2           typename U >
3 int calc_pts( const T& p0,
4               const U& p1 )
5 {
6     int pts0 = p0.get_pts();
7     int pts1 = p1.get_pts();
8     return pts0 + pts1;
9 }
10
11 int main( void )
12 {
13     Pawn p('a',2);
14     Rook r('h',3);
15     int sum = calc_pts( p, r );
16     return 0;
17 }
```

- Many versions (template specializations) of `calc_pts` are compiled
- State diagram does not include any run-time type information
- Compile-time type information used for static dispatch
- Faster performance, less space usage

Flexibility of Dynamic Polymorphism

```
1
2 int calc_pts( IPiece** pieces,
3               int n )
4 {
5     int sum = 0;
6     for ( int i=0; i<n; i++ )
7         sum += pieces[i]->get_pts();
8     return sum;
9 }
10
11 int main( void )
12 {
13     Pawn p('a',2);
14     Rook r('h',3);
15
16     IPiece* pieces[2];
17     pieces[0] = &p;
18     pieces[1] = &r;
19
20     int sum
21         = calc_pts( pieces, 2 );
22     return 0;
23 }
```

- Types must inherit from an abstract base class
- Does not work well with primitive types
- Can easily mix *different* concrete types
- In general, more flexible

Flexibility of Static Polymorphism

```
1     template < typename T >
2     int calc_pts( T** pieces,
3                   int n )
4     {
5         int sum = 0;
6         for ( int i=0; i<n; i++ )
7             sum += pieces[i]->get_pts();
8         return sum;
9     }
10
11 int main( void )
12 {
13     Pawn p0('a',2);
14     Pawn p1('h',3);
15
16     Pawn* pieces[2];
17     pieces[0] = &p0;
18     pieces[1] = &p1;
19
20     int sum
21         = calc_pts( pieces, 2 );
22     return 0;
23 }
```

- Types must adhere to a given “concept”
- Works well with primitive types (if they adhere to concept)
- Cannot easily mix *different* concrete types
- In general, less flexible

4. Generic Lists

- Dynamic polymorphic list can store any type derived from `IObject`
- Cannot store primitive types (e.g., `int`, `float`)
- Cannot store other types that do not derive from `IObject`
- Dynamic memory allocation is slow

4.1. Singly Linked List Interface

- Object-oriented list which stores ints

```
1 class SListInt
2 {
3     public:
4         SListInt();           // constructor
5         ~SListInt();         // destructor
6         void push_front( int v ); // member function
7         void reverse();      // member function
8
9         // implementation specific
10 };
```

- Generic list which stores objects of type `T`

```
1 template < typename T >
2 class SList
3 {
4     public:
5         SList();           // constructor
6         ~SList();         // destructor
7         void push_front( const T& v ); // member function
8         void reverse();    // member function
9
10        // implementation specific
11 };
```

- C++ rule of three means we also need to declare and define a copy constructor and an overloaded assignment operator

4.2. Singly Linked List Implementation

- Corresponding implementation for an object-oriented list
- Corresponding implementation for a generic list

```
1
2 class SListInt
3 {
4     public:
5         SListInt();
6         ~SListInt();
7         void push_front( int v );
8         void reverse();
9
10        struct Node
11        {
12            int    value;
13            Node* next_p;
14        };
15
16        Node* m_head_p;
17    };
```

```
1 template < typename T >
2 class SList
3 {
4     public:
5         SList();
6         ~SList();
7         void push_front( const T& v );
8         void reverse();
9
10        struct Node
11        {
12            T    value;
13            Node* next_p;
14        };
15
16        Node* m_head_p;
17    };
```

- Implementation for an object-oriented list

```

1
2 SListInt::SListInt()
3 {
4     m_head_p = nullptr;
5 }
6
7
8 void SListInt::push_front( int v )
9 {
10     Node* new_node_p
11         = new Node;
12     new_node_p->value = v;
13     new_node_p->next_p = m_head_p;
14     m_head_p
15         = new_node_p;
16
17
18 SListInt::~SListInt()
19 {
20     while ( head_p != nullptr ) {
21         Node* temp_p
22             = head_p->next_p;
23         delete head_p;
24         head_p = temp_p;
25     }
26 }

```

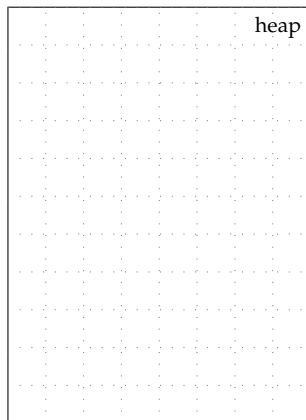
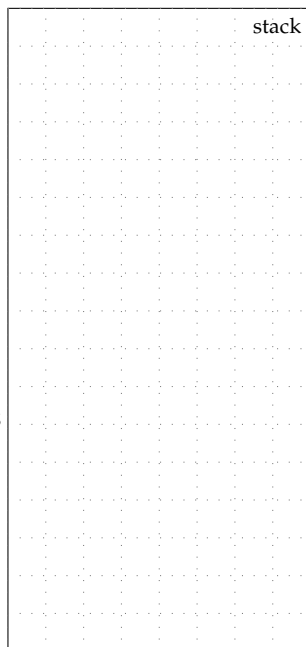
- Implementation for a generic list

```

1 template < typename T >
2 SList<T>::SList()
3 {
4     m_head_p = nullptr;
5 }
6
7 template < typename T >
8 void SList<T>::push_front( const T& v )
9 {
10     Node* new_node_p
11         = new Node;
12     new_node_p->value = v;
13     new_node_p->next_p = m_head_p;
14     m_head_p
15         = new_node_p;
16
17 template < typename T >
18 SList<T>::~SList()
19 {
20     while ( head_p != nullptr ) {
21         Node* temp_p
22             = head_p->next_p;
23         delete head_p;
24         head_p = temp_p;
25     }
26 }

```

```
01 template <>
02 SList<int>::SList()
03 {
04     m_head_p = nullptr;
05 }
06
07 template <>
08 void SList<int>::push_front(
09     const int& v )
10 {
11     Node* new_node_p
12         = new Node;
13     new_node_p->value = v;
14     new_node_p->next_p = m_head_p;
15     m_head_p
16         = new_node_p;
17 }
18
19 int main( void )
20 {
21     SList<int> lst;
22     lst.push_front( 12 );
23     lst.push_front( 11 );
24     lst.push_front( 10 );
25
26     Node* node_p = lst.m_head_p;
27     while ( node_p != nullptr ) {
28         int value = node_p->value
29         node_p = node_p->next_p;
30     }
31
32     return 0;
33 }
```



4.3. 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

```
1  template < typename T >
2  class SList
3  {
4  public:
5
6      class Itr
7      {
8      public:
9          Itr( Node* node_p );
10         void next();
11         T&  get();
12         bool eq( Itr itr ) const;
13
14     private:
15         Node* m_node_p;
16     };
17
18     Itr begin();
19     Itr end();
20     ...
21
22 private:
23
24     struct Node
25     {
26         T      value;
27         Node* next_p;
28     };
29
30     Node* m_head_p;
31 };
```

```
1  template < typename T >
2  SList<T>::Itr::Itr( Node* node_p )
3      : m_node_p(node_p)
4  { }
5
6  template < typename T >
7  void SList<T>::Itr::next()
8  {
9      assert( m_node_p != nullptr );
10     m_node_p = m_node_p->next_p;
11 }
12
13 template < typename T >
14 T& SList<T>::Itr::get()
15 {
16     assert( m_node_p != nullptr );
17     return m_node_p->value;
18 }
19
20 template < typename T >
21 bool SList::Itr::eq( Itr itr ) const
22 {
23     return ( m_node_p == itr.m_node_p );
24 }
25
26 SList::Itr SList::begin() { return Itr(m_head_p); }
27 SList::Itr SList::end()  { return Itr(nullptr); }
```

- Same overloaded operators as before for ++, *, !=


```
1 int main( void )
2 {
3     SList<int> lst;
4     lst.push_front( 12 );
5     lst.push_front( 11 );
6     lst.push_front( 10 );
7
8     for ( int v : lst )
9         std::printf( "%d\n", v );
10    return 0;
11 }
```

```
1 int main( void )
2 {
3     SList<float> lst;
4     lst.push_front( 12.5 );
5     lst.push_front( 11.5 );
6     lst.push_front( 10.5 );
7
8     for ( float v : lst )
9         std::printf( "%f\n", v );
10    return 0;
11 }
```

```
1 int main( void )
2 {
3     typedef Pair<int,float> PairIF;
4     SList< PairIF > lst;
5     lst.push_front( PairIF(3,12.5) );
6     lst.push_front( PairIF(4,11.5) );
7     lst.push_front( PairIF(5,10.5) );
8
9     for ( PairIF v : lst )
10        std::printf( "%d,%f\n", v.first, v.second );
11    return 0;
12 }
```

5. More Complex Generic Programming

- We could add a `contains` member function to our generic list
- Would only be generic across any type stored in the list
- Need to add `contains` member function to every data structure
- We can use generic programming to create a stand-alone algorithm to work across *any* data structure (and *any* types stored in those data structures) that adheres the concept of a sequence
 - sequences have `begin`, `end`, iterators
- Generic `contains` algorithm for *any* sequence

```
1  template < typename S,  
2          typename T >  
3  bool contains( const S& seq,  
4                const T& v )  
5  {  
6  {  
7      auto itr = seq.begin();  
8      while ( itr != seq.end() ) {  
9          if ( *itr == v )  
10             return true;  
11         ++itr;  
12     }  
13     return false;  
14 }
```

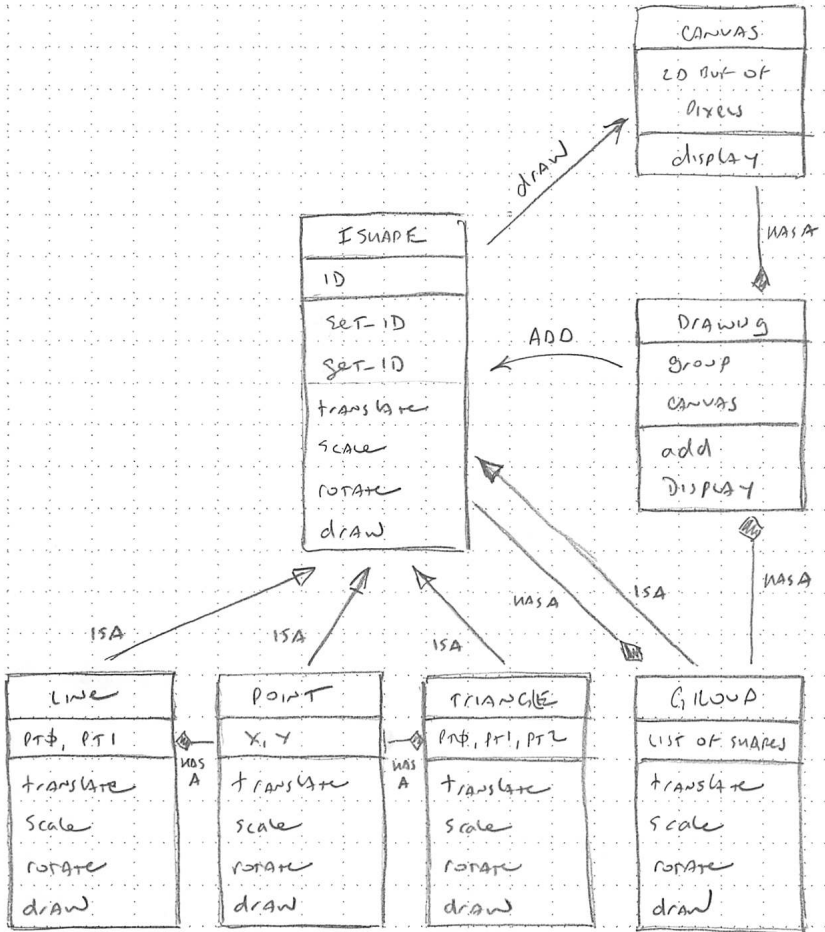
```
1  template < typename Itr,  
2          typename T >  
3  bool contains( Itr begin,  
4                Itr end,  
5                const T& v )  
6  {  
7      auto itr = begin;  
8      while ( itr != end ) {  
9          if ( *itr == v )  
10             return true;  
11         ++itr;  
12     }  
13     return false;  
14 }
```

- Using generic algorithms that operate on data structures
- Using generic algorithms that operate on iterators

```
1 SList<int> lst0;
2 lst0.push_front( 12 );
3 lst0.push_front( 11 );
4 lst0.push_front( 10 );
5 bool a =
6     contains( lst0, 11 );
7
8
9 SList<float> lst1;
10 lst1.push_front( 12.5 );
11 lst1.push_front( 11.5 );
12 lst1.push_front( 10.5 );
13 bool b =
14     contains( lst1, 11.5 );
15
16
17 BVector<int> vec;
18 vec.push_front( 12 );
19 vec.push_front( 11 );
20 vec.push_front( 10 );
21 bool c =
22     contains( vec, 11 );
23
24
25 // compile time error!
26 bool d =
27     contains( vec, Point(1,2) );
```

```
1 SList<int> lst0;
2 lst0.push_front( 12 );
3 lst0.push_front( 11 );
4 lst0.push_front( 10 );
5 bool a =
6     contains( lst0.begin(),
7               lst0.end(), 11 );
8
9
10 SList<float> lst1;
11 lst1.push_front( 12.5 );
12 lst1.push_front( 11.5 );
13 lst1.push_front( 10.5 );
14 bool b =
15     contains( lst1.begin(),
16               lst1.end(), 11.5 );
17
18
19 BVector<int> vec;
20 vec.push_front( 12 );
21 vec.push_front( 11 );
22 vec.push_front( 10 );
23 bool c =
24     contains( vec.begin(),
25               vec.end(), 11 );
26
27
28 // compile time error!
29 bool d =
30     contains( vec.begin(),
31               vec.end(),
32               Point(1,2) );
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```

6. Drawing Framework Case Study



- Use a statically sized array of IShape pointers
- Group must do all of the dynamic memory management

```
1  class Group : public IShape
2  {
3  public:
4      ...
5
6      ~Group()
7      {
8          for ( int i = 0; i < m_shapes_size; i++ )
9              delete m_shapes[i];
10     }
11
12     void add( const IShape& shape )
13     {
14         assert( m_shapes_size < 16 );
15         m_shapes[m_shapes_size] = shape.clone();
16         m_shapes_size++;
17     }
18
19     void translate( double x_offset, double y_offset )
20     {
21         for ( int i = 0; i < m_shapes_size; i++ )
22             m_shapes[i]->translate( x_offset, y_offset );
23     }
24
25     private:
26         int     m_shapes_size;
27         IShape* m_shapes[16];
28     };
```

Using Dynamic Polymorphic List

- Use a dynamic polymorphic list to store IShapes
- Make sure IShape inherits from IObject
- Group does not do any dynamic memory management

```
1  class Group
2  {
3  public:
4      ...
5
6      ~Group()
7      { }
8
9      void add( const IShape& shape )
10     {
11         m_shapes.push_back( shape );
12     }
13
14     void translate( double x_offset, double y_offset )
15     {
16         for ( IObject* obj_p : m_shapes ) {
17             IShape* shape_p = dynamic_cast<IShape*>(obj_p);
18             shape->translate( x_offset, y_offset );
19         }
20     }
21
22     ...
23
24     private:
25         ListIObj m_shapes;
26     };
```

Using Static Polymorphic List

- Use a static polymorphic list to store IShape pointers
- Group now has to handle some of the dynamic memory management

```
1  class Group
2  {
3  public:
4      ...
5
6      ~Group()
7      {
8          for ( IShape* shape_p : m_shapes )
9              delete shape_p;
10     }
11
12     void add( const IShape& shape )
13     {
14         IShape* shape_p = shape->clone();
15         m_shapes.push_back( shape_p );
16     }
17
18     void translate( double x_offset, double y_offset )
19     {
20         for ( IShape* shape_p : m_shapes )
21             shape_p->translate( x_offset, y_offset );
22     }
23
24     ...
25
26     private:
27         List<IShape*> m_shapes;
28 };
```