

ECE 2400 Computer Systems Programming

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Topic 13: 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

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

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

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**

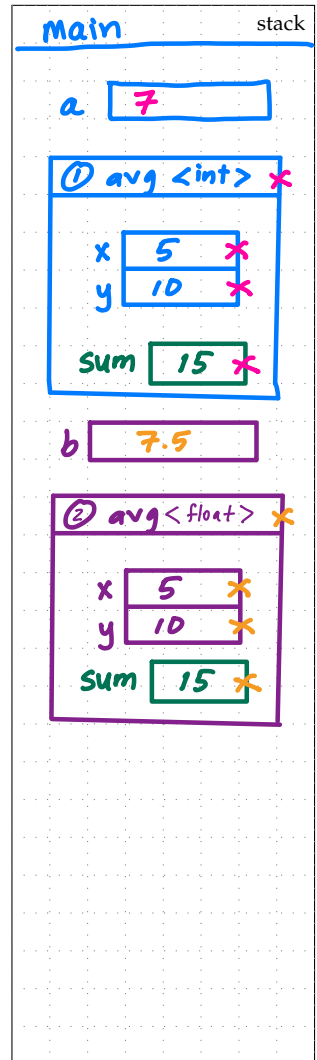
```
1 template < typename T >
2 T avg( T x, T y )
3 {
4     T sum = x + y;
5     return sum / 2;
6 }
```

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

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

1. C++ Function Templates

```
01 template < typename T >
02 T avg( T x, T y )
03 {
04     T sum = x + y;
05     return sum / 2;
06 }
07
08 template <>
09 int avg<int>( int x, int y )
10 {
11     int sum = x + y;
12     return sum / 2;
13 }
14
15 template <>
16 float avg<float>( float x,
17                  float y )
18 {
19     float sum = x + y;
20     return sum / 2;
21 }
22
23 int main( void )
24 {
25     int a = avg<int>(5,10); ①
26     float b = avg<float>(5,10); ②
27     return 0;
28 }
```



Develop a generic `contains` algorithm

Develop a generic `contains` function that takes as input an array (`x`), the size of that array (`n`), and a value (`v`) to search for in the array. It should return `true` if the value is contained in the array and `false` otherwise. The function should be generic across the type of values stored in the array. In other words, the function should work for arrays of `ints`, arrays of `doubles`, etc. *Hint: Develop a version of the algorithm specialized for `ints` and then make it generic.*

- 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 Data Structures with Static Polymorphism

- 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      ...
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      ...
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          ...
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          ...
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 ( m_head_p != nullptr ) {
21         Node* temp_p
22             = m_head_p->next_p;
23         delete m_head_p;
24         m_head_p = temp_p;
25     }
26 }

```

- Implementation for a generic list

```

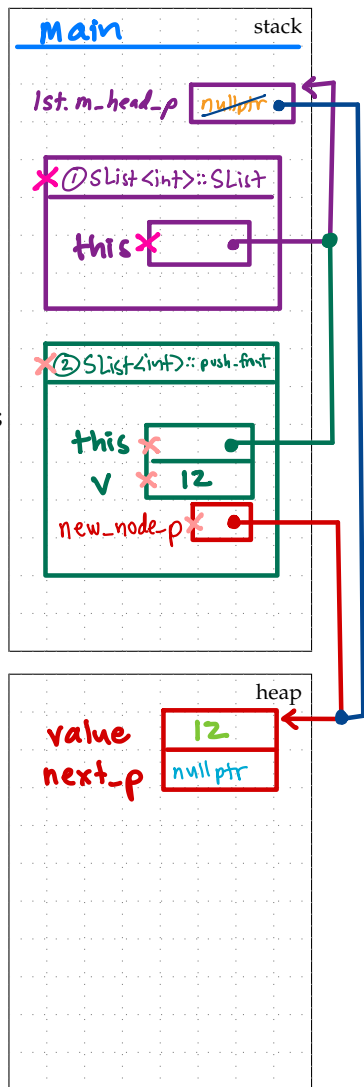
1  template < typename T >
2  SList<T>::SList()
3  {
4      m_head_p = nullptr;
5  }
6
7  template < typename T >
8  void SList<T>::push_front( const T& v )
9  {
10     Node* new_node_p
11         = new Node;
12     new_node_p->value = v;
13     new_node_p->next_p = m_head_p;
14     m_head_p
15         = new_node_p;
16 }
17
18 template < typename T >
19 SList<T>::~~SList()
20 {
21     while ( m_head_p != nullptr ) {
22         Node* temp_p
23             = m_head_p->next_p;
24         delete m_head_p;
25         m_head_p = temp_p;
26     }
27 }

```

```

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 = new_node_p;
16 }
17
18 int main( void )
19 {
20     SList<int> lst; ①
21     lst.push_front( 12 ); ②
22     lst.push_front( 11 );
23     lst.push_front( 10 );
24
25     Node* node_p = lst.m_head_p;
26     while ( node_p != nullptr ) {
27         int value = node_p->value
28         node_p = node_p->next_p;
29     }
30
31     return 0;
32 }

```



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

- Recall generic contains for an array storing elements of any type

```
1  template < typename T >
2  bool contains( T* x, int n, const T& v )
3  {
4      for ( int i = 0; i < n; i++ ) {
5          if ( x[i] == v )
6              return true;
7      return false;
8  }
```

- How can we apply the contains algorithm to our generic list?
 - Implement different contains algorithm for SList<T>?
 - Implement contains member function for SList<T>?
- We can use generic programming to create a stand-alone algorithm that works across *any* data structure (and *any* types stored in those data structures) that is an iterable sequence ADT
 - Iterable sequence ADTs have begin, end, iterators

```
1  template < typename S,
2              typename T >
3  bool contains( const S& seq,
4
5                const T& v )
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 }
```

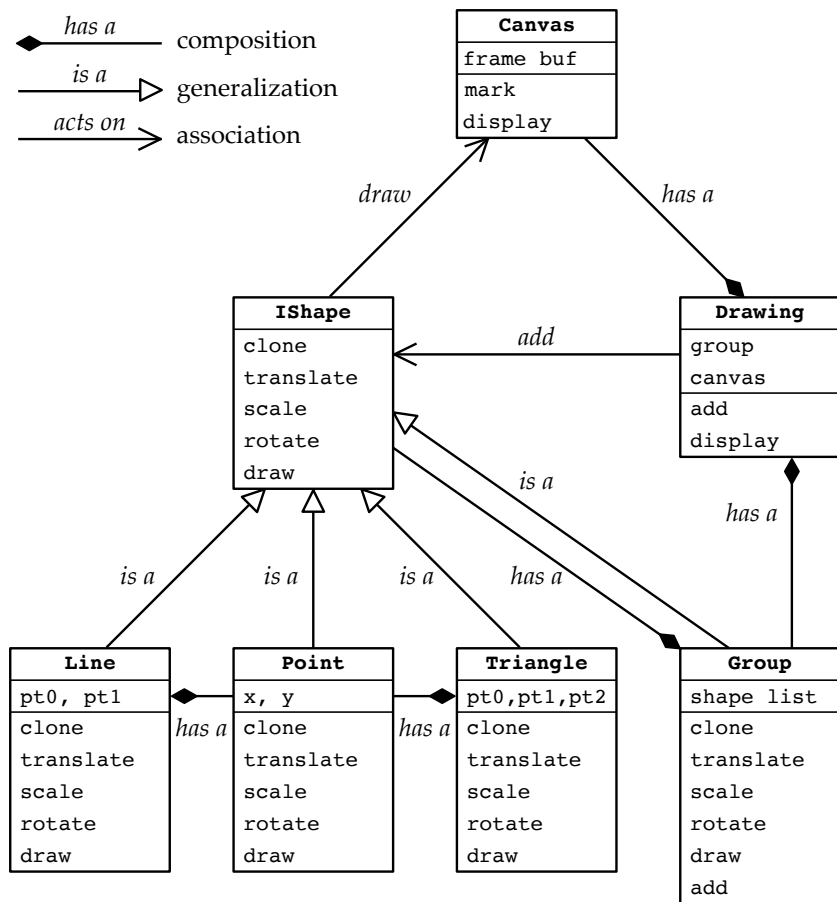
```
1  template < typename Itr,
2              typename T >
3  bool contains( Itr first,
4
5                Itr last,
6                const T& v )
7  {
8      auto itr = first;
9      while ( itr != last ) {
10         if ( *itr == v )
11             return true;
12         ++itr;
13     }
14     return false;
15 }
```

- 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) );
33
34
35 int a[] = { 10, 11, 12 };
36 bool d =
37     contains( a, a+3, 11 );
```

6. Drawing Framework Case Study



Storing shapes using a statically sized array of IShape pointers

- Group handles all of the dynamic memory management

```
1  class Group : public IShape
2  {
3      public:
4          ...
5
6      void add( const IShape& shape ) {
7          assert( m_shapes_size < 16 );
8          m_shapes[m_shapes_size] = shape.clone();
9          m_shapes_size++;
10     }
11
12     private:
13         int      m_shapes_size;
14         IShape*  m_shapes[16];
15     };
```

Storing shapes using a dynamic polymorphic list

- Modify IShape to inherit from IObject
- Group does not handle any of the dynamic memory management

```
1  class Group : public IShape
2  {
3      public:
4          ...
5
6      void add( const IShape& shape ) {
7          m_shapes.push_front( shape );
8      }
9
10     private:
11         SListIObj m_shapes;
12     };
```

Storing shapes using a static polymorphic (generic) list

- Group handles 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_front( 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     void draw( Canvas* canvas ) const
25     {
26         for ( IShape* shape_p : m_shapes )
27             shape_p->draw( canvas );
28     }
29
30     private:
31         SList<IShape*> m_shapes;
32     };
```