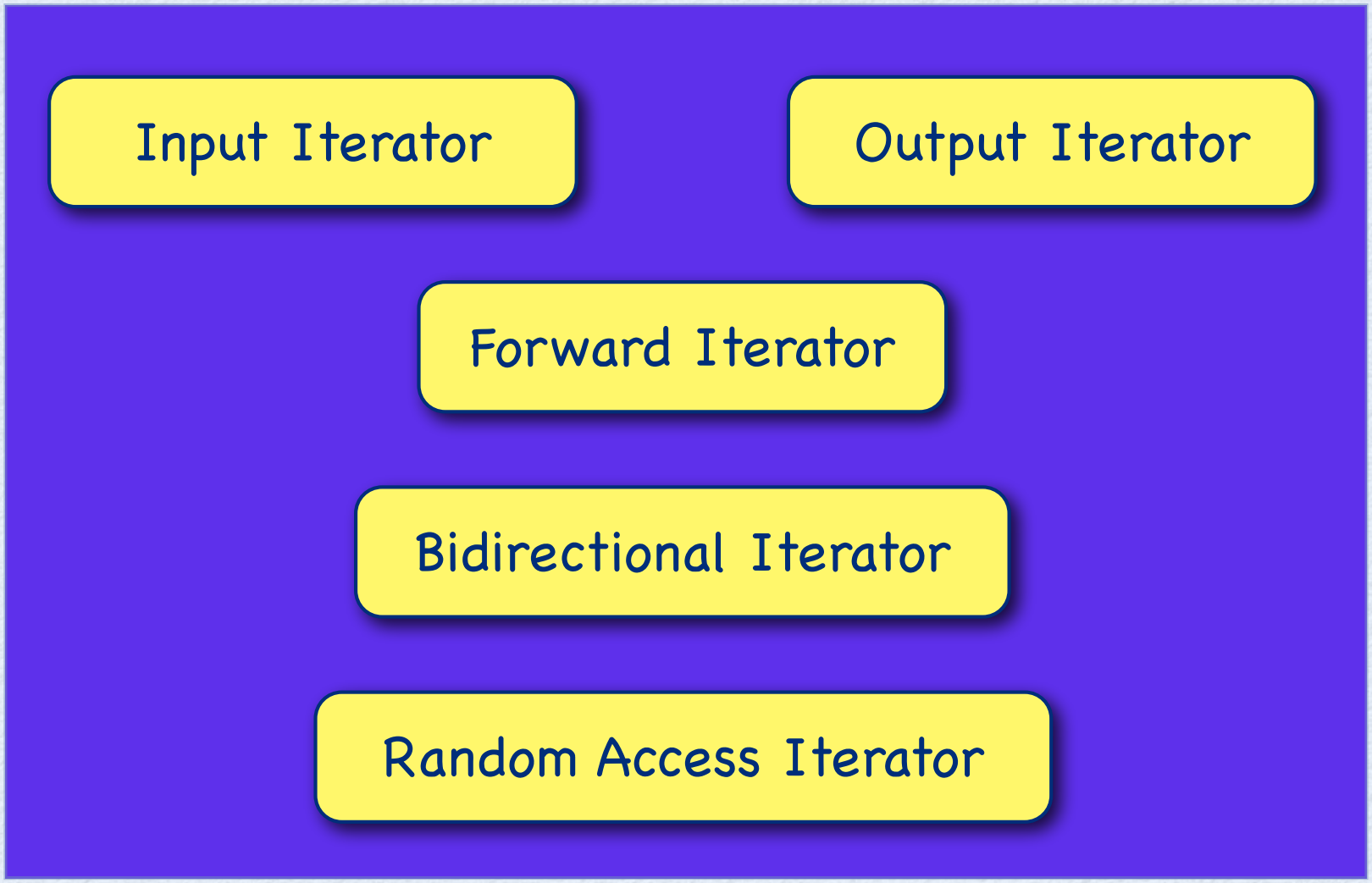
Systematic Traversal of Sets

Iterators

- We can use a loop statement and a loop counter to travers all elements of an array in sequence.
- However, not all data types are arrays and simple indexing may not suffice.
- Iterators offer programmers a suitable alternative to define traversal in a data type agnostic way.
- Conceptually, iterators are objects that implement the necessary infrastructure to iterate over elements of a sequence. They do this via a common interface.
- The C++ ecosystem has popularized and uses five types of iterators. Iterator objects have the look-and-feel of pointers, and advancing an iterator means to increment/decrement a pointer-like object.

C++ Iterators



Abilities of Iterators

Iterator Category	Ability	Provider
Input Iterator	Read forward	istream
Output Iterator	Write forward	ostream, inserter
Forward Iterator	Read and write forward	
Bidirectional Iterator	Read and write forward and backward	list, set, multiset, map, multimap, vector, deque, string, array
Random Access Iterator	Read and write with random access	

Input Iterator

Expression	Effect
*iter	Provides read access to the actual element
iter->member	Provides read access to a member of the actual element
++iter	Steps forward (returns new position)
iter++	Steps forward (returns old position)
iter1 == iter2	Returns whether iter1 and iter2 are equal
iter1 != iter2	Returns whether iter1 and iter2 are not equal

Output Iterator

Expression	Effect
*iter = value	Provides write access to the actual element
++iter	Steps forward (returns new position)
iter++	Steps forward (returns old position)

An output iterator is like a "black hole."

Forward Iterator

Expression	Effect
*iter	Provides read access to the actual element
iter->member	Provides read access to a member of the actual element
++iter	Steps forward (returns new position)
iter++	Steps forward (returns old position)
iter1 == iter2	Returns whether iter1 and iter2 are equal
iter1 != iter2	Returns whether iter1 and iter2 are not equal
iter1 = iter2	Assigns an iterator

Bidirectional Iterator

Expression	Effect
*iter	Provides read access to the actual element
iter->member	Provides read access to a member of the actual element
++iter	Steps forward (returns new position)
iter++	Steps forward (returns old position)
--iter	Steps backward (returns new position)
iter--	Steps backward (returns old position)
iter1 == iter2	Returns whether iter1 and iter2 are equal
iter1 != iter2	Returns whether iter1 and iter2 are not equal
iter1 = iter2	Assigns an iterator

Random Access Iterator

Expression	Effect
iter[n]	Provides read access to the element at index n
iter += n	Steps n elements forward or backward
iter -= n	Steps n elements forward or backward
n+iter	Returns the iterator of the nth next element
n-iter	Returns the iterator of the nth previous element
iter - iter2	Returns disjoint distance between iter1 and iter2
iter1 < iter2	Returns whether iter1 is before iter2
iter1 > iter2	Returns whether iter1 is after iter2
iter1 <= iter2	Returns whether iter1 is not after iter2
iter1 >= iter2	Returns whether iter1 is not before iter2

A Read-Only Forward Iterator

ArrayIterator.h

```
4  class IntArrayIterator
5  {
6  private:
7    const int* fArrayElements;
8    const int fLength;
9    int fIndex;
10
11 public:
12   IntArrayIterator( const int aArray[], const int aLength, int aStart = 0 );
13
14   const int& operator*() const;
15   IntArrayIterator& operator++();       // prefix
16   IntArrayIterator operator++( int );   // postfix (extra unused argument)
17   bool operator==( const IntArrayIterator& aOther ) const;
18   bool operator!=( const IntArrayIterator& aOther) const;
19
20   IntArrayIterator begin() const;
21   IntArrayIterator end() const;
22 };
```

Line: 1 Column: 14 C++ Tab Size: 4

Forward Iterator Constructor

Arrays are passed as pointers to the first element to functions in C++.

We must not repeat the default value.

ArrayIterator.cpp

```
1  #include <iostream>
2  #include "ArrayIterator.h"
3
4  using namespace std;
5
6  IntArrayIterator::IntArrayIterator( const int aArray[], const int aLength, int aStart ) :
7      fArrayElements(aArray), fLength(aLength)
8  {
9      fIndex = aStart;
10 }
11
```

Line: 48 Column: 28 C++

We must use member initializer to initialize const instance variables!

The Dereference Operator

ArrayIterator.cpp

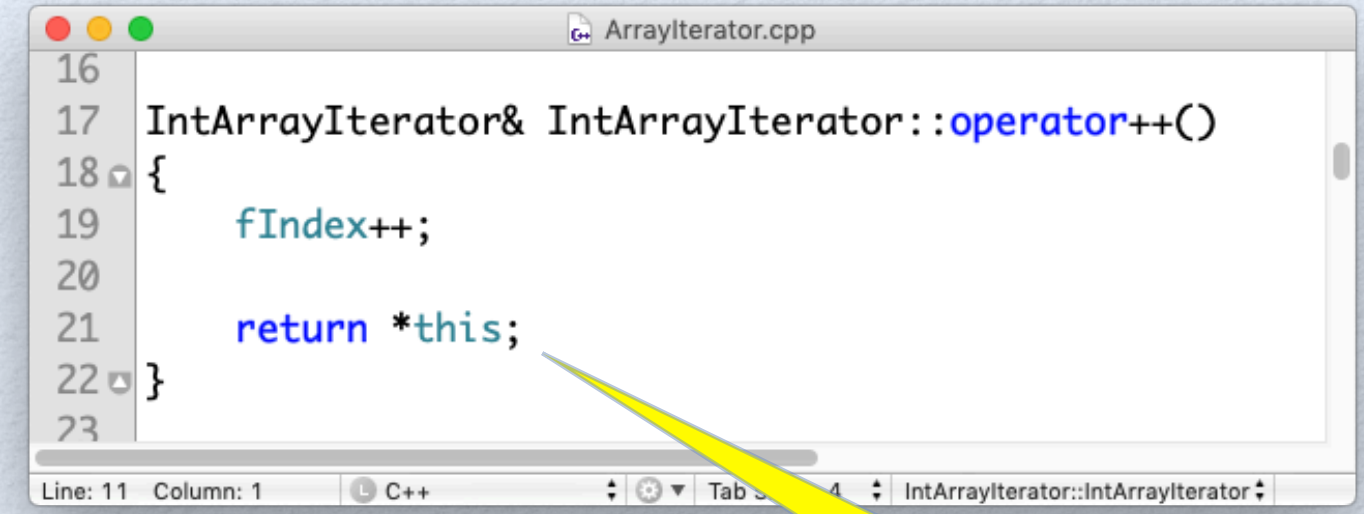
```
11
12  const int& IntArrayIterator::operator*() const
13  {
14      return fArrayElements[fIndex];
15  }
16
```

Line: 20 Column: 1 C++ Tab Size: 4 IntArrayIterator::IntArrayIt...

- The deference operator returns the element the iterator is currently positioned on.
- The dereference operator is a const operation, that is, it does not change any instance variables of the iterator.
- We use a const reference to avoid copying the original value stored in the underlying collection.
- No range check is required. The operator*() should only be called if the iterator has not yet reached the end of the underlying collection.

Prefix Increment

- The prefix increment operator advances the iterator and returns a reference of this iterator.



Postfix Increment

- The postfix increment operator advances the iterator and returns a copy of the old iterator.

ArrayIterator.cpp

```
24  IntArrayIterator IntArrayIterator::operator++( int )
25  {
26      IntArrayIterator temp = *this;
27
28      ++(*this);  // reuse implementation
29
30      return temp;
31  }
```

Line: 20 Column: 1 C++ Tab IntArrayIterator::IntArrayIterator

Return a copy of the old iterator (position unchanged).

Iterator Equivalence

ArrayIterator.cpp

```
33  bool IntArrayIterator::operator==( const IntArrayIterator& aOther) const
34  {
35      return (fIndex == aOther.fIndex) &&
36             (fArrayElements == aOther.fArrayElements);
37  }
```

Line: 20 Column: 1 C++ Tab Size: 4 IntArrayIterator::IntArrayIterator

Two iterators are equal if and only if they refer to the same element (this may require considering the context of ==):

- fIndex is the current index into the array
- Arrays are passed as a pointer to the first element (arrays decay to pointers) that is constant throughout runtime.

Iterator Inequality

ArrayIterator.cpp

```
39  bool IntArrayIterator::operator!=( const IntArrayIterator& aOther) const
40  {
41      return !(*this == aOther);
42  }
```

Line: 20 Column: 1 C++ Tab Size: 4 IntArrayIterator::IntArrayIterator

We implement != in terms of ==.

Auxiliary Methods

We use the default value 0 for aStart here.

ArrayIterator.cpp

```
44  IntArrayIterator IntArrayIterator::begin() const
45  {
46      return IntArrayIterator( fArrayElements, fLength );
47  }
48
49  IntArrayIterator IntArrayIterator::end() const
50  {
51      return IntArrayIterator( fArrayElements, fLength, fLength );
52  }
```

Line: 20 Column: 1 C++ Tab Size: 4 IntArrayIterator::IntArrayIterator

- The methods begin() and end() return fresh iterators set to the first element and past-the-end element, respectively.
- The names and implementation of these auxiliary methods follow standard practices. The compiler may look for them when you use a for-each loop.

Auxiliary Methods: Copy This Object

ArrayIterator.cpp

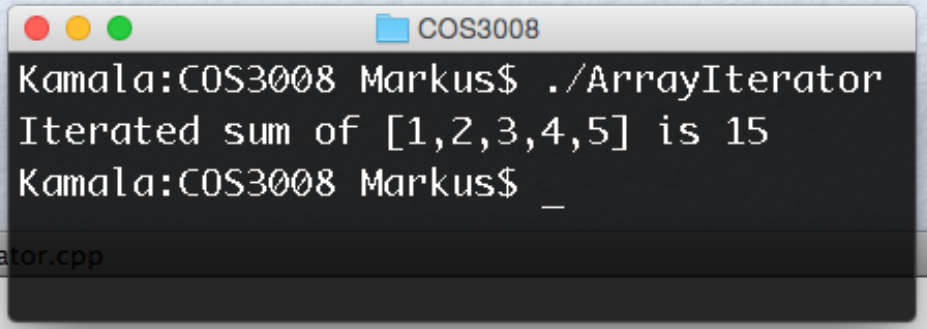
```
54  IntArrayIterator IntArrayIterator::begin() const
55  {
56      IntArrayIterator Result = *this;
57
58      Result.fIndex = 0;
59
60      return Result;
61  }
62
63  IntArrayIterator IntArrayIterator::end() const
64  {
65      IntArrayIterator Result = *this;
66
67      Result.fIndex = fLength;
68
69      return Result;
70  }
```

Line: 51 Column: 33 C++ Tab Size: 4 IntArrayIterator::end

"clone" this object

- The methods "clone" this iterator object and set the position accordingly.

Putting Everything Together



ArrayIterator.cpp

```
53  int main()
54  {
55      int a[] = { 1, 2, 3, 4, 5 };
56      int Sum = 0;
57
58      for ( IntArrayIterator iter( a, 5 ); iter != iter.end(); iter++ )
59          Sum += *iter;
60
61      cout << "Iterated sum of [1,2,3,4,5] is " << Sum << endl;
62
63      return 0;
64  }
65
```

Line: 45 Column: 1 C++ Tab Size: 4 IntArrayIterator::begin

Can we do better?

C++11: For-Each-Loop

- The traditional for statement in C++ reads:

  for (init-statement; condition; expression)

  statement

  This form uses explicit loop variables, conditions, and increments over loop variables.

- C++11 introduces a simpler form, called range for statement, to iterate through the elements of a container or other sequence:

  for (declaration : expression)

  statement

  This form is called for-each, and expression must denote a sequence and declaration defines a variable, set in each step of the iteration.

Understanding C++11's range loop

for (declaration : expression) statement

- According to the standard, this is equivalent to the following plain for loop:

```
auto&& __range = expression;                  // C++11 forwarding (move)
for ( auto __begin = begin-expression,        // begin()
           __end = end-expression;            // end()
           __begin != __end;
           ++__begin )
{
   declaration = *__begin;
   statement;
}
```

Compare with page 188

Using C++11's For-Each-Loop

Main.cpp

```
    // using for-each

    for ( int i : a )
    {
        cout << hex << &i << ", " << sizeof(i) << endl;
    }

    for ( const int& i : a )
    {
        cout << hex << &i << ", " << sizeof(i) << endl;
    }

    for ( auto i : a )
    {
        cout << hex << &i << ", " << sizeof(i) << endl;
    }

    for ( const auto& i : a )
    {
        cout << hex << &i << ", " << sizeof(i) << endl;
    }
```

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- Case 1: read-write variable
- Case 2: constant reference
- Case 3: auto variable
- Case 4: constant auto reference

For-Each-Loop Behavior

Main.cpp

```
30      // using for-each
31
32      for ( int i : a )
33      {
34          cout << hex << &i << ", " << sizeof(i) << endl;
35      }
36
37      for ( const int& i : a )
38      {
39          cout << hex << &i << ", " << sizeof(i) << endl;
40      }
41
42      for ( auto i : a )
43      {
44          cout << hex << &i << ", " << sizeof(i) << endl;
45      }
46
47      for ( const auto& i : a )
48      {
49          cout << hex << &i << ", " << sizeof(i) << endl;
50      }
51
```

Line: 1 Column: 1 C++ Tab Size: 4

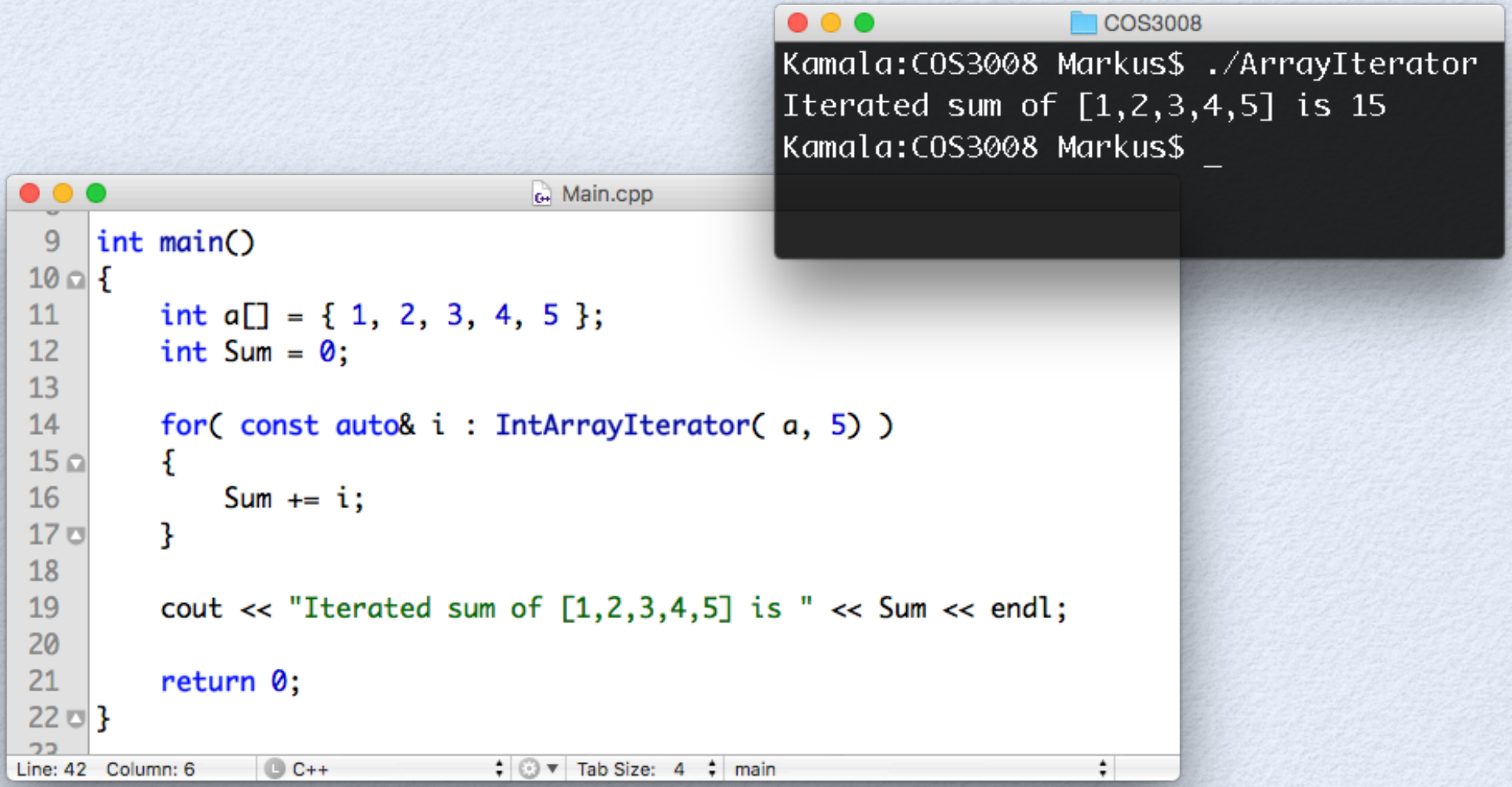
Debug

```
./ArrayIterator
0x7fff5a95e5dc, 4
0x7fff5a95e5dc, 4
0x7fff5a95e5dc, 4
0x7fff5a95e5dc, 4
0x7fff5a95e5dc, 4
0x7fff5a95e6f0, 4
0x7fff5a95e6f4, 4
0x7fff5a95e6f8, 4
0x7fff5a95e6fc, 4
0x7fff5a95e700, 4
0x7fff5a95e59c, 4
0x7fff5a95e59c, 4
0x7fff5a95e59c, 4
0x7fff5a95e59c, 4
0x7fff5a95e59c, 4
0x7fff5a95e6f0, 4
0x7fff5a95e6f4, 4
0x7fff5a95e6f8, 4
0x7fff5a95e6fc, 4
0x7fff5a95e700, 4
```

Which declaration to use?

- In a for-each loop always use a reference variable. This avoids unnecessary copies.
- Prefer auto to explicit type declarations. Iterator types can be quite complex and hard to express. Using auto - automatic type deduction - simplifies things dramatically.
- You still need to understand what type deduction means and what the results are. Code becomes less readable, as fewer explicit detail is available.

Iterator Idiom at Work



A Note on auto

- Using auto saves typing and prevents correctness and performance issues when dealing with complex types.
- Automatic type deduction via auto is no free lunch. The programmer has to guide the compiler to produce the right answer. Failing to do so, can result in a wrong type altogether.
- The use of auto can hamper program comprehension. We may have to perform an in-depth study of the code base to understand what type we are dealing with and which methods can be safely invoked on a given object.
- Using auto can produce undefined behavior. The code still compiles fine, but there is a chance the result will be unpredictable. In this case an explicit type specification is required.

How can we define an iterator in Java?

Iterator Interface - java.util.Iterator

- boolean hasNext():
  - Returns true if the iteration has more elements. In other words, returns true if next() would return an element rather than throwing an exception.
- E next():
  - Returns the next element in the iteration. Calling this method repeatedly until the hasNext() method returns false will return each element in the underlying collection exactly once.
- void remove():
  - Removes the last element returned from the underlying collection. This is an optional operation.

IntArrayIterator in Java

IntArrayIterator.java

```
1  import java.util.*;
2
3  public class IntArrayIterator implements Iterator<Integer>
4  {
5      private int[] fArrayElements;
6      private int fIndex;
7
8      public IntArrayIterator( int[] aArray ) { fArrayElements = aArray; }
9
10     public boolean hasNext() { return fIndex < fArrayElements.length; }
11
12     public Integer next()
13     {
14         if ( hasNext() )
15             return new Integer( fArrayElements[fIndex++] );
16     }
17
18     public void remove() {}     // intentionally empty
19
20     public static void main( String[] args ) { ... }
21 }
```

Line: 24 Column: 1 Java Tab Size: 4 main(String[] args)

The Iterator's main Method

IntArrayIterator.java

```
3  public class IntArrayIterator implements Iterator<Integer>
4  {
5      ...
6
7      public static void main( String[] args )
8      {
9          int[] a = { 1, 2, 3, 4, 5 };
10         IntArrayIterator iter = new IntArrayIterator( a );
11         int Sum = 0;
12
13         while ( iter.hasNext() )
14             Sum += iter.next().intValue();
15
16         System.out.println( "Iterated sum of [1,2,3,4,5] is " + Sum );
17     }
18 }
19
```

Line: 20 Column: 1 Java Tab Size: 4 main(String[] args)