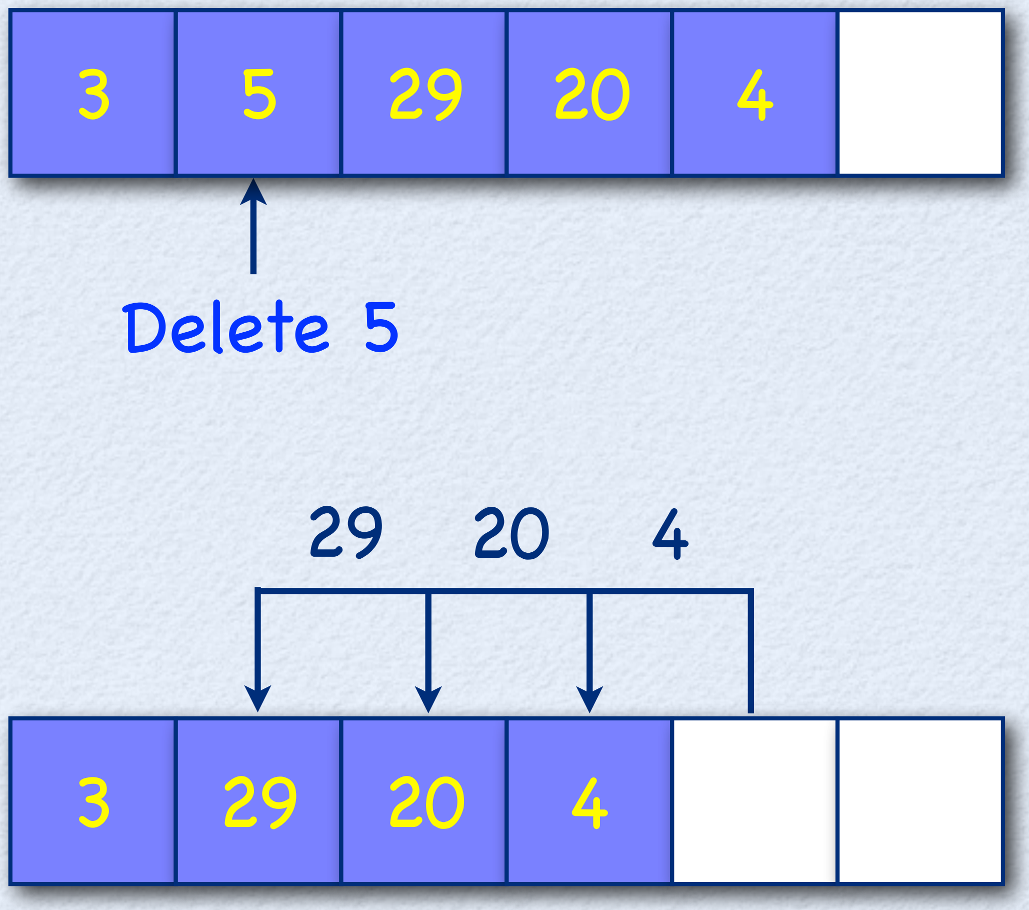
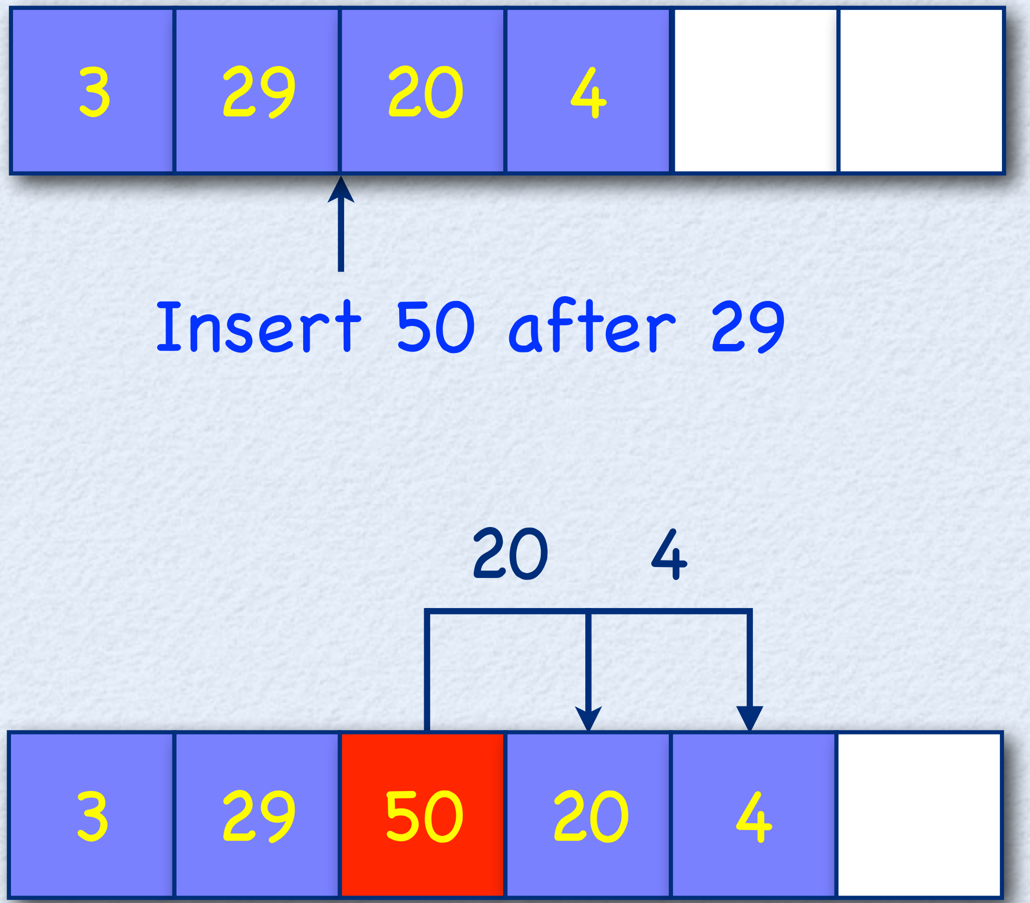
Problems with Arrays

- An array is a contiguous storage that provides insufficient abstractions for handling addition and deletion of elements.
- Addition and deletion require $n/2$ shifts on average.
- The computation time is $O(n)$.
- Resizing affects performance.

Deletion Requires Relocation

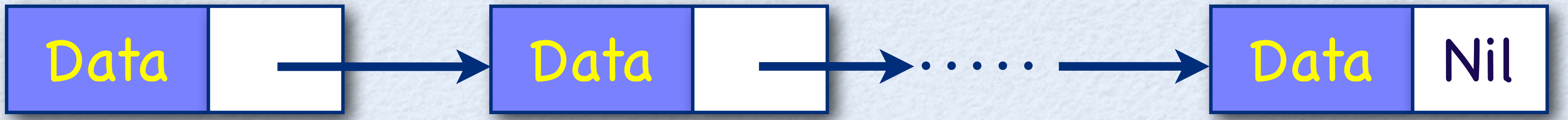


Insertion Requires Relocation



Singly-Linked Lists

- A singly-linked list is a sequence of data items, each connected to the next by a pointer called next.



- A data item may be a primitive value, a composite value, or even another pointer.
- A singly-linked list is a recursive data structure whose nodes refers to nodes of the same type.

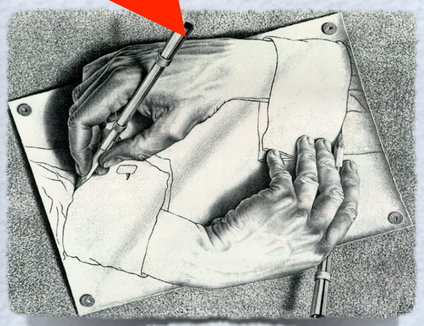
Impossible Singly-Linked List Structure in C++:

SinglyLinkedList.h

```cpp
// impossible singly-linked list

struct SinglyLinkedList
{
    DataType fData;
    SinglyLinkedList fNext;

    SinglyLinkedList( const DataType& aData,
                      const SinglyLinkedList& aNext ) :
        fData(aData),
        fNext(aNext)
    {}
};
```

Line: 4 Column: 22 C++ Tab Size: 4

$X = X \rightarrow X \rightarrow X \rightarrow X \rightarrow \ldots$



Field fNext has incomplete type.

Singly-Linked List Using Pointers

SinglyLinkedList.h

```cpp
struct SinglyLinkedList
{
    DataType fData;
    SinglyLinkedList* fNext;

    SinglyLinkedList( const DataType& aData,
                      SinglyLinkedList* aNext = nullptr ) :
        fData(aData),
        fNext(aNext)
    {}
};
```

Line: 9 Column: 2 C++ Tab Size: 4 SinglyLinkedList

DataType is application-specific

We need to use pointers

- A list manages a collection of elements.
- The class SinglyLinkedList defines a value-based sequence container for values of type DataType.
- To break infinite recursion, we have to use pointers to the next elements. This way, the compiler can deduce the size of a singly-linked list element and compile the definition.

Singly-Linked List with R-Values

SinglyLinkedList.h

```
struct SinglyLinkedList
{
    DataType fData;
    SinglyLinkedList* fNext;

    SinglyLinkedList( const DataType& aData, SinglyLinkedList* aNext = nullptr ) :
        fData(aData),
        fNext(aNext)
    {}

    SinglyLinkedList( DataType&& aData, SinglyLinkedList* aNext = nullptr ) :
        fData(std::move(aData)),
        fNext(aNext)
    {}
};
```

l-value constructor

r-value constructor

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

- The r-value constructor can "steal" the memory of the argument aData to initialize the payload fData. To use this constructor, the parameter aData must be a temporary of literal value.

R-Value References (C++-11)

L-Values and L-Value References &

- The references that we have seen so far are l-value references, that is, references to l-values.
- The term l-value refers to a thing that can occur on the left side of an assignment, named objects that have a defined storage location (i.e., an address). L-value references can only be bound to l-values (exception: we can bind an r-value to a const l-value reference):

```
int var = 42;             // l-value: initialized variable declaration
int& ref = var;           // l-value reference to an l-value
int& ref2 = 42;           // error: non-const l-value reference cannot bind to temporary
const int& ref3 = 42;     // const l-value reference to an r-value
```

R-Values and R-Value References &&

- The term r-value refers to things that can occur on the right side of an assignment, literals and temporaries that do **not** have a defined storage locations.

- R-value references only bind to r-values:

```
int&& ref = 42;        // r-value reference to an r-value
int val = 42;          // l-value: initialized variable declaration
int&& ref2 = val;      // error: r-value reference cannot bind to l-value
```

Move Semantics (std::move)

- R-values are typically temporary and so can be freely modified: if you know that your function parameter is an r-value, you can use it as temporary storage, or "steal" its contents without affecting program correctness.
- This means that rather than copying the contents (expensive) of an r-value, you can move the contents (cheap).

SinglyLinkedList.h — Programs

```cpp
struct SinglyLinkedList
{
    DataType fData;
    SinglyLinkedList* fNext;

    SinglyLinkedList( const DataType& aData, SinglyLinkedList* aNext = nullptr ) :
        fData(aData),
        fNext(aNext)
    {}

    SinglyLinkedList( DataType&& aData, SinglyLinkedList* aNext = nullptr ) :
        fData(std::move(aData)),
        fNext(aNext)
    {}
};
```

Line: 18 C++ Tab Size: 4 fNext

copy l-value

move r-value

std::move is a function that performs a type cast of its argument to an r-value.

Using L-Values and R-Values

SinglyLinkedList.h — Programs

```cpp
struct SinglyLinkedList
{
    DataType fData;
    SinglyLinkedList* fNext;

    SinglyLinkedList( const DataType& aData, SinglyLinkedList* aNext = nullptr ) :
        fData(aData),
        fNext(aNext)
    {}

    SinglyLinkedList( DataType&& aData, SinglyLinkedList* aNext = nullptr ) :
        fData(std::move(aData)),
        fNext(aNext)
    {}
};
```

Line: 18 | C++ | Tab Size: 4 | fNext

- Using the different constructors, we can write:

```cpp
string lValue = "COS30008";

SinglyLinkedList lNodeWithCopy( lValue );

SinglyLinkedList lNodeWithMove( "COS30008" );
```

copy
l-value

move
r-value

Using L-Values and R-Values: No Move

SinglyLinkedList.h — Programs

```cpp
struct SinglyLinkedListCopyOnly
{
    DataType fData;
    SinglyLinkedListCopyOnly* fNext;

    SinglyLinkedListCopyOnly( const DataType& aData, SinglyLinkedList* aNext = nullptr ) :
        fData(aData),
        fNext(aNext)
    {}
};
```

Line: 15:19 | C++ | Tab Size: 4 | SinglyLinkedList

- If a class does not support move semantics, then the compiler will use copy semantics. That is, an r-value decays to an l-value.

```cpp
string lValue = "COS30008";

SinglyLinkedListCopyOnly lNodeWithLValue( lValue );

SinglyLinkedListCopyOnly lNodeWithRValue( "COS30008" );
```

copy l-value

copy
r-value

We discuss more details later when we study memory management.

A Simple List of Integers

Main.cpp — Programs

```cpp
#include <iostream>
#include <string>

using namespace std;

using DataType = string;

#include "SinglyLinkedList.h"

int main()
{
    string lA = "AAAA";
    string lC = "CCCC";

    SinglyLinkedList One( lA );
    SinglyLinkedList Two( "BBBB", &One );
    SinglyLinkedList Three( lC, &Two );

    SinglyLinkedList* lTop = &Three;

    for ( ; lTop != nullptr; lTop = lTop->fNext )
    {
        cout << "Value: " << lTop->fData << endl;
    }

    return 0;
}
```

Line: 36:2 C++ Tab Size: 4 main

define DataType a synonym for string

Microsoft Visual Studio Deb...

```
Value: CCCC
Value: BBBB
Value: AAAA
```

Using Declaration — C++11 Type Aliases

- A type alias is a name that refers to a previously defined type.

```
using identifier = type;
```

- Type aliases are commonly used for three purposes:
  - To hide the implementation of a given type.
  - To streamline complex type definitions making them easier to understand, and
  - To allow a single type to be used in different contexts under different names.
- Type aliases establish a nominal equivalence between types.
- Type aliases are similar to **typedef**. However, type aliases are better suited when creating alias templates.

Can we do better?

Templates - C++'s Generic Types

- Templates are blueprints from which classes and/or functions are automatically generated by the compiler based on a set of parameters.
- Note, every time a given template is being instantiated with type parameters that have not been used before, a new version of the class or function is generated.
- A new version of a class or function is called specialization of the template. Specializations are not mutually compatible.

Class Template

```
template<typename T1, ..., typename Tn>
class AClassTemplate
{
    // class specification
};
```

- A template is a parameterized abstraction over a class.
- From the language-theoretical perspective, templates are 2nd order functions from types to classes/functions.
- To instantiate a class template we supply the desired types, as actual template parameters, so that the C++ compiler can synthesize a specialized class for the template.

Singly-Linked List Class Template

The typename parameter
binds all occurrences of DataType in
SinglyLinkedList

```cpp
template <typename DataType>
struct SinglyLinkedList
{
    DataType fData;
    SinglyLinkedList* fNext;

    SinglyLinkedList( const DataType& aData, SinglyLinkedList* aNext = nullptr ) :
        fData(aData),
        fNext(aNext)
    {}

    SinglyLinkedList( DataType&& aData, SinglyLinkedList* aNext = nullptr ) :
        fData(std::move(aData)),
        fNext(aNext)
    {}
};
```

The New Main

Main.cpp — Programs

```cpp
#include <iostream>
#include <string>

using namespace std;

#include "SinglyLinkedListTemplate.h"

int main()
{
    using StringList = SinglyLinkedList<string>;

    string lA = "AAAA";
    string lC = "CCCC";

    StringList One( lA );
    StringList Two( "BBBB", &One );
    StringList Three( lC, &Two );

    StringList* lTop = &Three;

    for ( ; lTop != nullptr; lTop = lTop->fNext )
    {
        cout << "Value: " << lTop->fData << endl;
    }

    return 0;
}
```

Line: 37:19 C++ Tab Size: 4 main

We instantiate the template SinglyLinkedList to SinglyLinkedList<string>.

Class Template Instantiation

```
using IntegerList = SinglyLinkedList<int>;

using ListOfIntegerLists = SinglyLinkedList<IntegerList>;
```

- Types used as arguments cannot be classes with local scope.
- Once instantiated, a class template can be used as any other class.

List Iterator Template

SinglyLinkedList Iterator Specification

SinglyLinkedListIterator SPEC.h — Programs

```cpp
#pragma once

#include "SinglyLinkedListTemplate.h"

template <typename T>
class SinglyLinkedListIterator
{
private:

    using ListNode = SinglyLinkedList<T>;

    const ListNode* fList;
    const ListNode* fIndex;

public:

    using Iterator = SinglyLinkedListIterator<T>;

    SinglyLinkedListIterator( const ListNode* aList );

    const T& operator*() const;
    Iterator& operator++();      // prefix
    Iterator operator++(int);    // postfix
    bool operator==( const Iterator& aRHS ) const;
    bool operator!=( const Iterator& aRHS ) const;

    Iterator begin();            // for-range feature
    Iterator end();              // for-range feature
};
```

Line: 32 C++ Tab Size: 4 end

We maintain a pointer to read-only list elements

Notes on Templates

- When using templates, the C++ compiler must have access not only the specification of a template class but also to all method implementations in order to properly instantiate the template.
- Templates are not to be confused with library classes. Templates are blueprint that have to be instantiated for each separate type application.
- Think of templates as special forms of macros.
- When defining a template class, we need to implement, like in Java, all methods within the class definition, usually in a header file.

Templates have no .cpp file!

Constructor & Deference

SinglyLinkedListIterator.h

```
using Iterator = SinglyLinkedListIterator<T>;

SinglyLinkedListIterator( const ListNode* aList ) :
    fList(aList),
    fIndex(aList)
{}

const T& operator*() const
{
    return fIndex->fData;
}
```

Line: 15 Column: 1 C++ Tab Size: 4 SinglyLinke

For iterator implementation in header file.

Increments

SinglyLinkedListIterator.h

```cpp
    Iterator& operator++()      // prefix
    {
        fIndex = fIndex->fNext;

        return *this;
    }

    Iterator operator++(int)   // postfix
    {
        Iterator old = *this;

        ++(*this);

        return old;
    }
```

Line: 15 Column: 1 C++ Tab Size: 4 SinglyLinkedListIterator

Equivalence

SinglyLinkedListIterator.h

```cpp
    bool operator==( const Iterator& aRHS ) const
    {
        return
            fList == aRHS.fList &&
            fIndex == aRHS.fIndex;
    }

    bool operator!=( const Iterator& aRHS ) const
    {
        return !(*this == aRHS);
    }
```

Auxiliaries (For-Range)

SinglyLinkedListIterator.h

```
    Iterator begin()        // for-range feature
    {
        Iterator iter = *this;

        iter.fIndex = iter.fList;

        return iter;
    }

    Iterator end()          // for-range feature
    {
        Iterator iter = *this;

        iter.fIndex = nullptr;

        return iter;
    }
```

Line: 15 Column: 1 C++ Tab Size: 4 SinglyLinkedListIterator

SinglyLinkedList Iterator Test

Main.cpp — Programs

```cpp
#include <iostream>
#include <string>

using namespace std;

#include "SinglyLinkedListIterator.h"

int main()
{
    using StringList = SinglyLinkedList<string>;
    using StringListIterator = SinglyLinkedListIterator<string>;

    string lA = "AAAA";
    string lC = "CCCC";

    StringList One( lA );
    StringList Two( "BBBB", &One );
    StringList Three( lC, &Two );

    for ( const string& i : StringListIterator( &Three ) )
    {
        cout << "Value: " << i << endl;
    }

    return 0;
}
```

Line: 37:19 C++ Tab Size: 4 main

For iterator implementation see Canvas

address of Three

SinglyLinkedList Iterator: Specification B

SinglyLinkedListIteratorB SPEC.h — Programs

```cpp
#include "SinglyLinkedListTemplate.h"

template <typename T>
class SinglyLinkedListIterator
{
private:

    using ListNode = SinglyLinkedList<T>;

    const ListNode& fList;
    const ListNode* fIndex;

public:

    using Iterator = SinglyLinkedListIterator<T>;

    SinglyLinkedListIterator( const ListNode& aList );

    const T& operator*() const;
    Iterator& operator++();      // prefix
    Iterator operator++(int);    // postfix
    bool operator==( const Iterator& aRHS ) const;
    bool operator!=( const Iterator& aRHS ) const;

    Iterator begin();            // for-range feature
    Iterator end();              // for-range feature
};
```

Line: 31 C++ Tab Size: 4 end

We maintain a read-only reference to list elements

Reference Data Members

```
class ClassWithRefMember
{
private:
    SomeType& fRef;
public:
    ClassWithRefMember( SomeType& aRef ) : fRef(aRef)
    { … }
};
```

Reference data members must be initialized before the contructor body is entered!

- Reference member variables store references to data outside an object. These references are established upon object creation via a member initializer.
- In case of iterators this might be an attractive option to avoid coping the underlying collection.
- Important: Reference data members require a constructor initializer.

Constructor & Deference B

SinglyLinkedListIteratorB.h

```cpp
    using Iterator = SinglyLinkedListIterator<T>;

    SinglyLinkedListIterator( const ListNode& aList ) :
        fList(aList),
        fIndex(&aList)
    {}

    const T& operator*() const
    {
        return fIndex->fData;
    }
```

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

Establish reference

fIndex is a pointer

Increments B

SinglyLinkedListIteratorB.h

```cpp
    Iterator& operator++()      // prefix
    {
        fIndex = fIndex->fNext;

        return *this;
    }

    Iterator operator++(int)    // postfix
    {
        Iterator old = *this;

        ++(*this);

        return old;
    }
```

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

unchanged

Equivalence B

SinglyLinkedListIteratorB.h

```cpp
    bool operator==( const Iterator& aRHS ) const
    {
        return
            &fList == &aRHS.fList &&
            fIndex == aRHS.fIndex;
    }

    bool operator!=( const Iterator& aRHS ) const
    {
        return !(*this == aRHS);
    }
```

compare addresses

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

Auxiliaries (For-Range) B

SinglyLinkedListIteratorB.h

```
    Iterator begin()        // for-range feature
    {
        Iterator iter = *this;

        iter.fIndex = &iter.fList;

        return iter;
    }

    Iterator end()           // for-range feature
    {
        Iterator iter = *this;

        iter.fIndex = nullptr;

        return iter;
    }
```

use address

Line: 1 Column: 1 C++ Tab Size: 4 —

SinglyLinkedList Iterator Test B

Main.cpp — Programs

```
#include <iostream>
#include <string>

using namespace std;

#include "SinglyLinkedListIteratorB.h"

int main()
{
    using StringList = SinglyLinkedList<string>;
    using StringListIterator = SinglyLinkedListIterator<string>;

    string lA = "AAAA";
    string lC = "CCCC";

    StringList One( lA );
    StringList Two( "BBBB", &One );
    StringList Three( lC, &Two );

    for ( const string& i : StringListIterator( Three ) )
    {
        cout << "Value: " << i << endl;
    }

    return 0;
}
```

Line: 30 | C++ | Tab Size: 4 | main

For iterator implementation see Canvas

Three passed as l-value reference

Pointers

The Need for Pointers

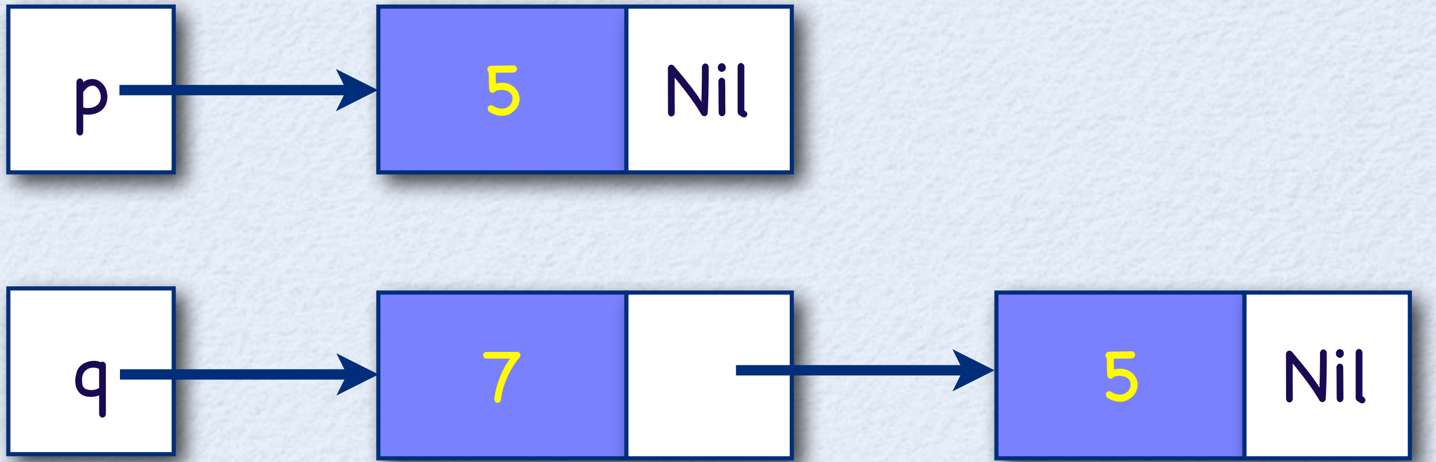
- A linked-list is a dynamic data structure with a varying number of nodes.
- Access to a linked-list is through a pointer variable in which the base type is the same as the node type:

```
IntegerList<int>* pListOfIntegers = &Three;

IntegerList<int>* Nil = nullptr;
```

Nil means “empty list.”

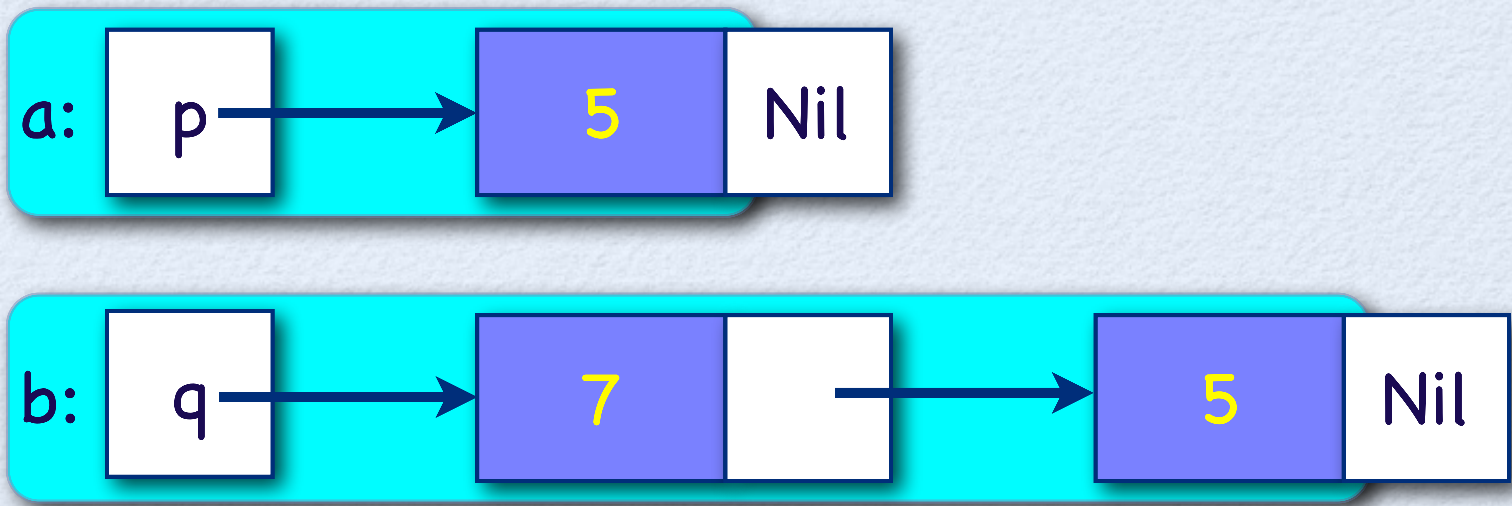
Node Construction

```
IntegerList *p, *q;

p = new IntegerList( 5 );

q = new IntegerList( 7, p );
```

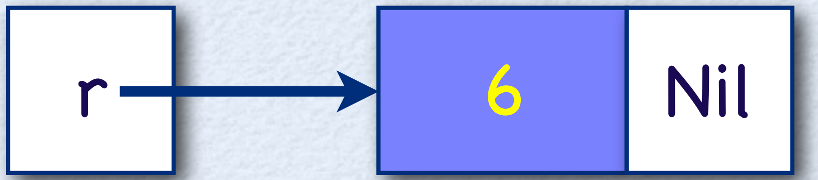


Node Access

```
int a = p->fData;

int b = q->fNext->fData;
```

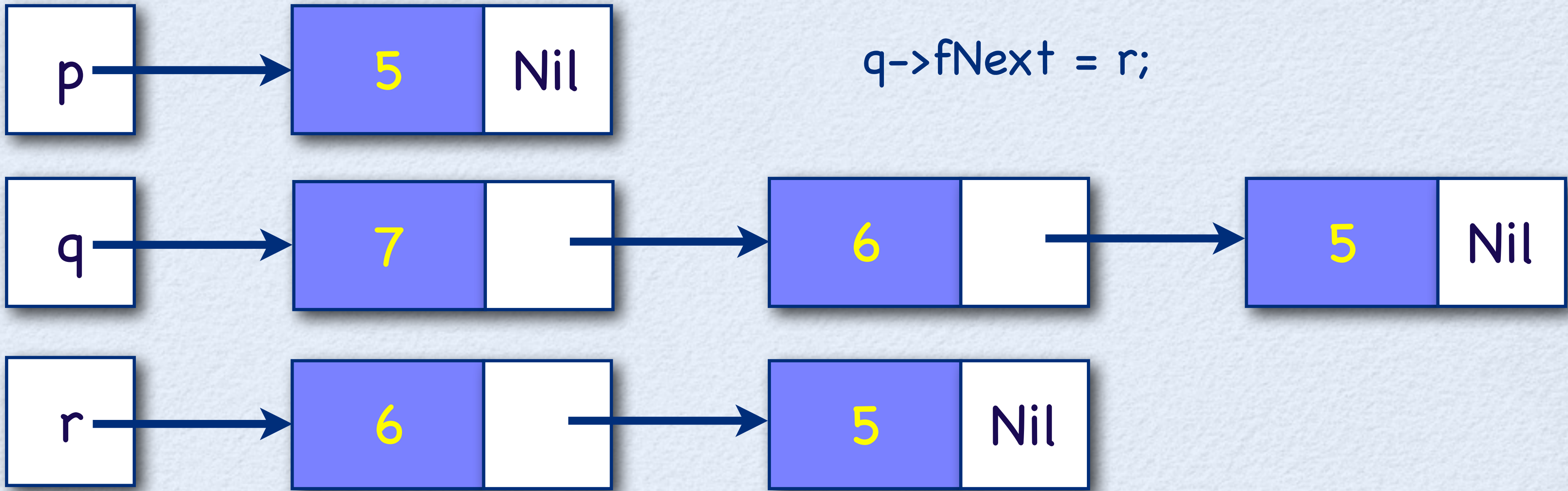


Inserting a Node

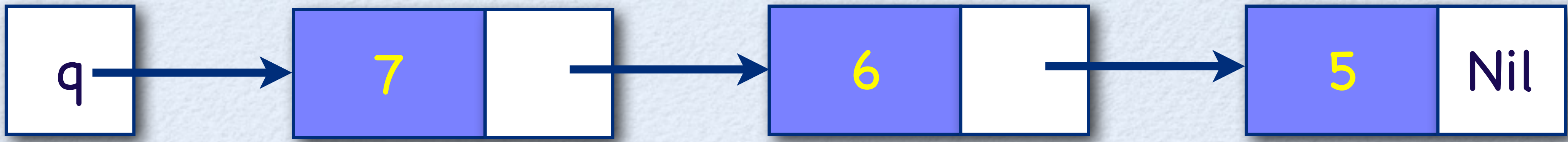



```
IntegerList *r;

r = new IntegerList( 6 );
```

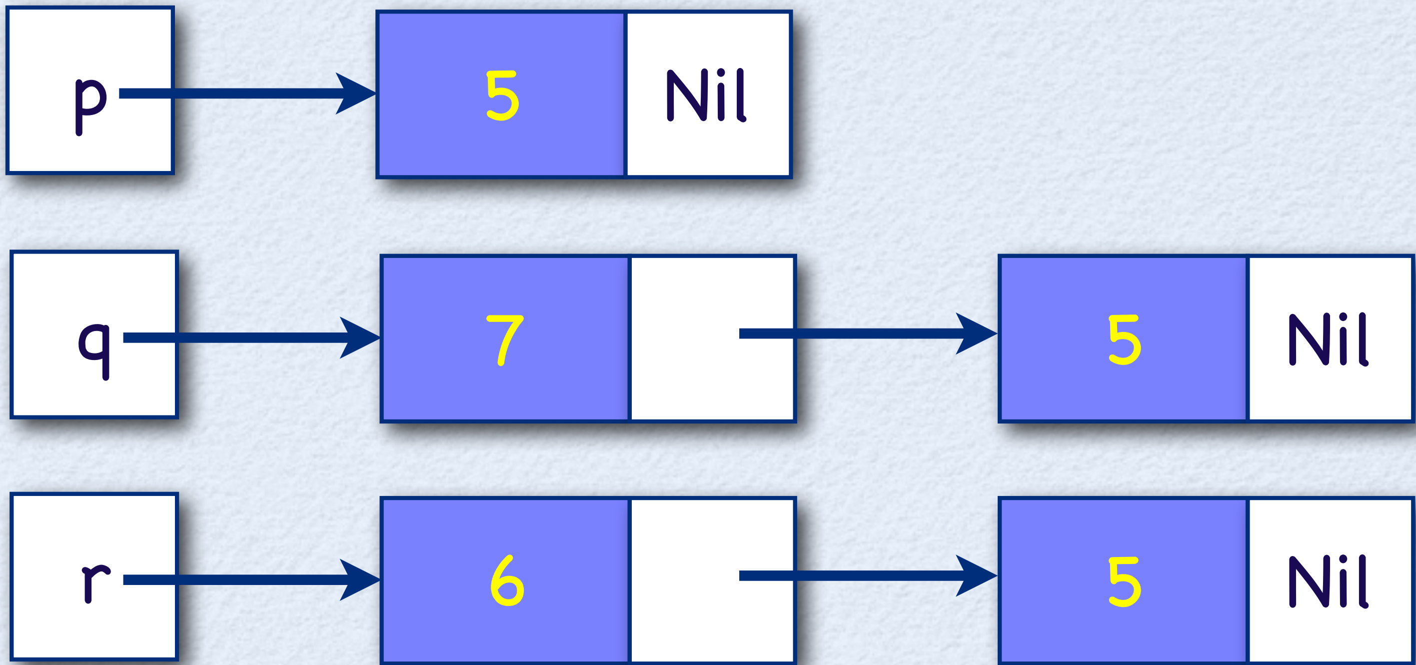
```
r->fNext = p;

q->fNext = r;
```



Deleting a Node



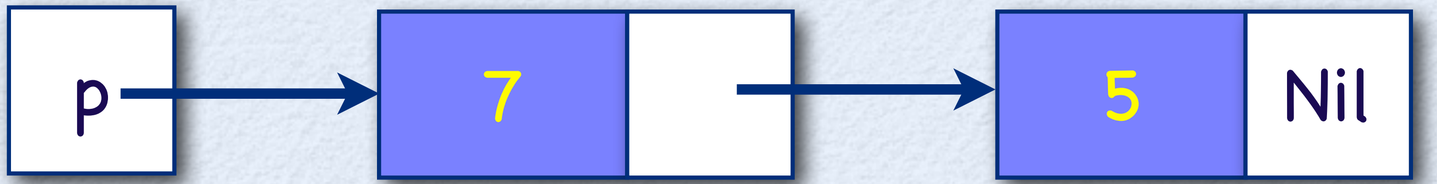

```
q->fNext = q->fNext->fNext;
```



Insert at the Top

```
IntegerList *p = nullptr;

p = new IntegerList( 5, p );
```


```
p = new IntegerList( 7, p );
```



Insert at the End

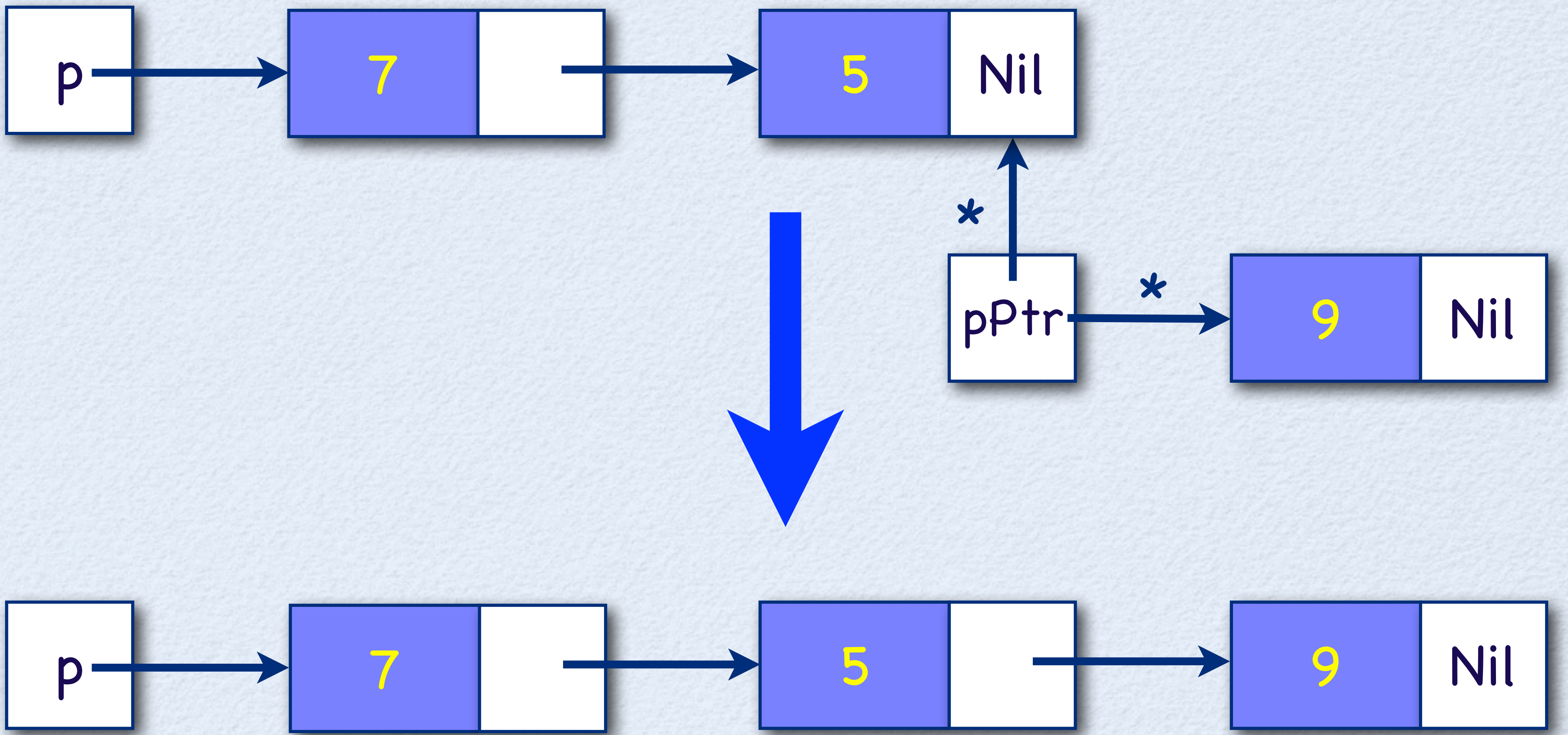
- To insert a new node at the end of a linked list we need to search for the end:

Main.cpp

```
    IntegerList* p = new IntegerList( 5 );
    IntegerList* q = new IntegerList( 7, p );

    IntegerList** pPtr = &q;

    while ( *pPtr != nullptr )
    {
        pPtr = &((*pPtr)->fNext);
    }

    *pPtr = new IntegerList( 9 );
```

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

Insert at the End: The Pointers



Insert at the end preserves the order of list nodes.

Insert at the End with Aliasing

- Rather than using a Pointer-to-Pointer we can just record the last next pointer.

Main.cpp

```cpp
    IntegerList* pList = nullptr;
    IntegerList* pLastNode = nullptr;

    IntegerList* pNewNode = new IntegerList( 5 );

    if ( pList == nullptr )
        pList = pNewNode;
    else
        pLastNode->fNext = pNewNode;

    pLastNode = pNewNode;
```

Complications with Singly-Linked Lists

- The deletion of a node at the end of a list requires a search from the top to find the new last node.