Memory Management and Copy Control

Overview

- Types of memory
- Copy constructor, assignment operator, and destructor
- Reference counting with smart pointers

References

- Stanley B. Lippman, Josée Lajoie, and Barbara E. Moo: C++ Primer. 5th Edition. Addison-Wesley (2013)
- Bruno R. Preiss: Data Structures and Algorithms with Object-Oriented Design Patterns in C++. John Wiley & Sons, Inc. (1999)
- Andrew W. Appel with Jens Palsberg: Modern Compiler Implementation in Java. 2nd Edition, Cambridge University Press (2002).
- Alfred V. Aho, Ravi Sethi, and Jeffrey D. Ullman: Compilers - Principles, Techniques, and Tools. Addison-Wesley (1988)

Static Read-Write Memory

- C++ allows for two forms of global variables:
  - Static non-class variables,
  - Static class variables.
- Static variables are mapped to the global memory. Access to them depends on the visibility specifiers.
- We can find a program's global memory in the so-called read-write .data segment.

The Keyword static

- The keyword static can be used to
  - mark the linkage of a variable or function internal,
  - retain the value of a local variable between function calls,
  - declare a class instance variable,
  - define a class method.

Read-Write Static Variables

Statics.cpp

```
int gCounter = 1;

static int gLocalCounter = 0;

class A
{
private:
    static int ClassACounter;
};

int A::ClassACounter = 1;
```

Static class variables must be initialized outside the class.

Static Read-Only Memory

- In combination with the const specifier we can also define read-only global variables or class variables:

Statics.cpp

```cpp

const int gCounter = 1;

static const int gLocalCounter = 0;

class A
{
private:
    static const int ClassACounter;
};

const int A::ClassACounter = 1;

```

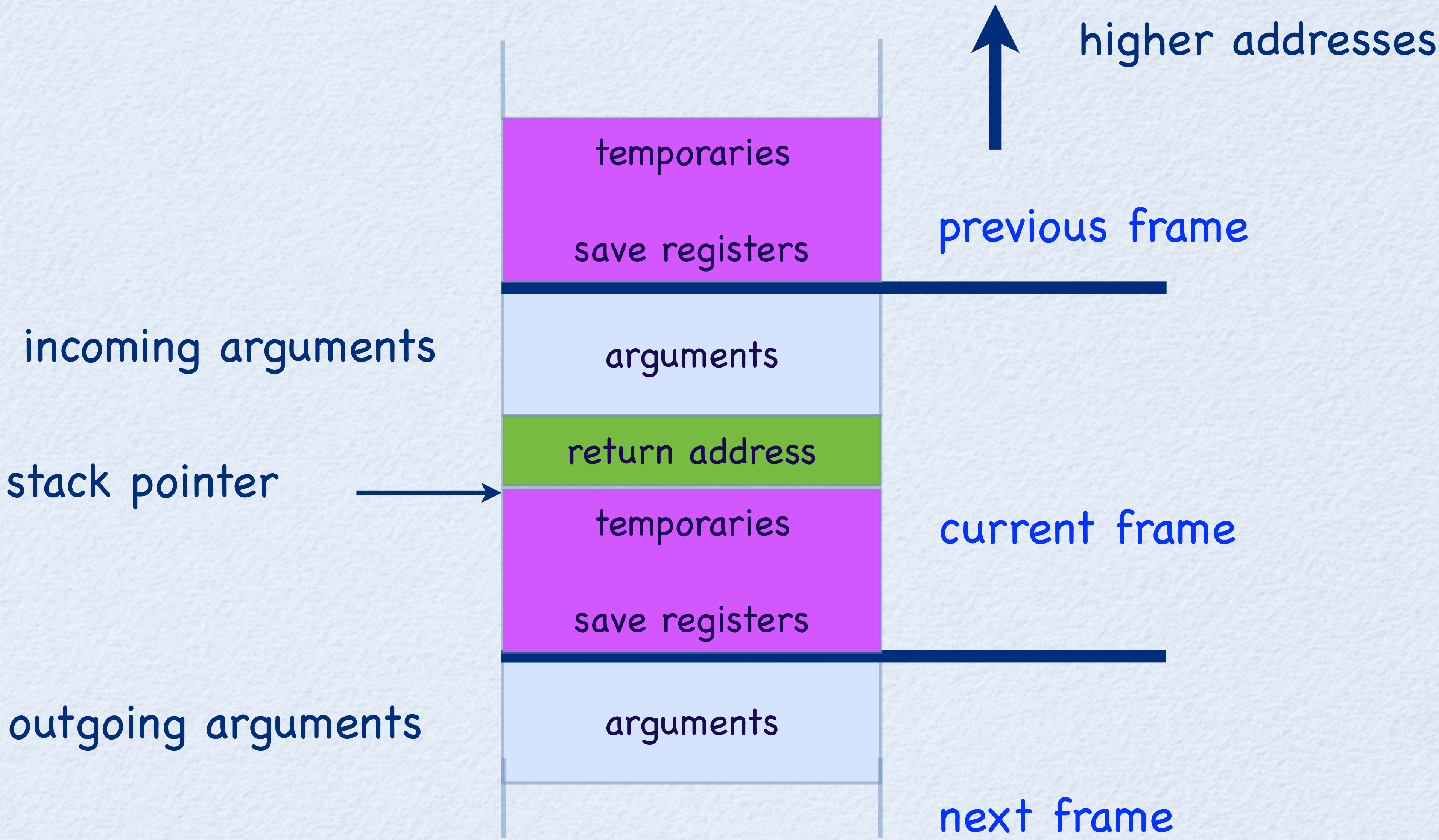
Line: 15 Column: 1 C++ Tab Size: 4 A

Const variables are often stored in the program's read-only .text segment.

Program Memory: Stack

- All value-based objects are stored in the program's stack.
- The program stack is automatically allocated and freed.
- References to stack locations are only valid when passed to a callee. References to stack locations cannot be returned from a function.

Stack Frames (C)



Program Memory: Heap

- Every program maintains a heap for dynamically allocated objects.
- Each heap object is accessed through a pointer.
- Heap objects are not automatically freed when pointer variables become inaccessible (i.e., go out of scope).
- Memory management becomes essential in C++ to reclaim memory and to prevent the occurrences of so-called memory leaks.

List::~List()

```
~List()                                                          // destructor - frees all nodes
{
    while ( fRoot != nullptr )
    {
        if ( fRoot != &fRoot->getPrevious() )                    // more than one element
        {
            Node* lTemp = const_cast<Node*>(&fRoot->getPrevious()); // select last

            lTemp->isolate();                                    // remove from list
            delete lTemp;                                        // free
        }
        else
        {
            delete fRoot;                                        // free last
            break;                                               // stop loop
        }
    }
}
```

Line: 68 Column: 9 C++ Tab Size: 4 fCount

Release memory associated with list node object on the heap.

The Dominion Over Objects

- Alias control is one of the most difficult problems to master in object-oriented programming.
- Aliases are the default in reference-based object models used, for example, in Java and C#.
- To guarantee uniqueness of value-based objects in C++, we are required to define copy constructors.

The Copy Constructor

- Whenever one defines a new type, one needs to specify implicitly or explicitly what has to happen when objects of that that type are copied, assigned, and destroyed.
- The copy constructor is a special member, taking just a single parameter that is a const reference to an object of the class itself.

A simple String class

SimpleString

SimpleString.h

```cpp
class SimpleString
{
private:
    char * fCharacters;

public:
    SimpleString();
    ~SimpleString();

    SimpleString& operator+( const char aCharacter );
    const char* operator*() const;
};
```

SimpleString: Constructor & Destructor

SimpleString.cpp

```cpp
#include <iostream>
#include "SimpleString.h"

using namespace std;

SimpleString::SimpleString()
{
    fCharacters = new char[1];
    *fCharacters = '\0';
}

SimpleString::~SimpleString()
{
    delete fCharacters;
}
```

Line: 20 Column: 1 C++ Tab Size: 4 SimpleString::~SimpleString

SimpleString: The Operators

SimpleString.cpp

```cpp
SimpleString& SimpleString::operator+( const char aCharacter )
{
    char *Temp = new char[strlen(fCharacters) + 2];
    unsigned int i = 0;

    for ( ; i < strlen( fCharacters ); i++ )
        Temp[i] = fCharacters[i];

    Temp[i++] = aCharacter;
    Temp[i] = '\0';

    delete fCharacters;
    fCharacters = Temp;
    return *this;
}

const char* SimpleString::operator*() const
{
  return fCharacters;
}
```

Line: 13 Column: 11 C++ Tab Size: 4 SimpleString::~SimpleString

Implicit Copy Constructor

```cpp
int main()
{
    SimpleString s1;
    s1 + 'A';
    SimpleString s2 = s1;
    s2 + 'B';

    cout << "S1: " << *s1 << endl;
    cout << "S2: " << *s2 << endl;

    return 0;
}
```

```
Kamala:COS30008 Markus$ ./SimpleString
S1: A
S2: AB
SimpleString(17203,0x7fff7167d300) malloc: *** error
for object 0x7fef2a404be0: pointer being freed was no
t allocated
*** set a breakpoint in malloc_error_break to debug
Abort trap: 6
Kamala:COS30008 Markus$
```

On Windows you may not see anything.

What Has Happened?

SimpleString.cpp

```cpp
int main()
{
    SimpleString s1;
    s1 + 'A';
    SimpleString s2 = s1;
    s2 + 'B';

    cout << "S1: " << *s1 << endl;
    cout << "S2: " << *s2 << endl;

    <delete s1;>
    <delete s2;>

    return 0;
}
```

Line: 44 Column: 26 C++ Tab Size: 4 main

Shallow copy:
s2.fCharacters == s1.fCharacters

Double free:
delete s2.fCharacters, which was called in s2 + 'B'.

We need an explicit copy constructor!

SimpleString.h

```cpp
class SimpleString
{
private:
    char * fCharacters;

public:
    SimpleString();
    ~SimpleString();
    SimpleString( const SimpleString& aOtherString );

    SimpleString& operator+( const char aCharacter );
    const char* operator*() const;
};
```

Line: 2 Column: 18 C++ Tab Size: 4 SIMPLESTRING_H_

The Explicit Copy Constructor

SimpleString.cpp

```cpp
SimpleString::SimpleString( const SimpleString& aOtherString )
{
    int lLength = strlen(aOtherString.fCharacters) + 1;
    fCharacters = new char[lLength];

    for ( unsigned int i = 0; i < lLength; i++ )
        fCharacters[i] = aOtherString.fCharacters[i];
}
```

Line: 39 Column: 24 C++ Tab Size: 4 SimpleString::SimpleString

- When a copy constructor is called, then all instance variables are uninitialized in the beginning.

Explicit Copy Constructor in Use

SimpleString.cpp

```cpp
int main()
{
    SimpleString s1;
    s1 + 'A';
    SimpleString s2 = s1;
    s2 + 'B';

    cout << "S1: " << *s1 << endl;
    cout << "S2: " << *s2 << endl;

    return 0;
}
```

Line: 13 Column: 11 C++ Tab Size: 4 SimpleString::~Sim...

COS30008

```
Kamala:COS30008 Markus$ ./SimpleString
S1: A
S2: AB
Kamala:COS30008 Markus$ _
```

What Has Happened?

SimpleString.cpp

```
int main()
{
    SimpleString s1;
    s1 + 'A';
    SimpleString s2 = s1;
    s2 + 'B';

    cout << "S1: " << *s1 << endl;
    cout << "S2: " << *s2 << endl;

    <delete s1;>
    <delete s2;>

    return 0;
}
```

Line: 44 Column: 26 C++ Tab Size: 4 main

Deep copy:
s2.fCharacters != s1.fCharacters

That's it. No more problems, or?

A Simple Assignment

```
Kamala:COS30008 Markus$ ./SimpleString
S1: AB
S2: AB
SimpleString(17245,0x7fff7167d300) malloc: *** error for obj
ect 0x7ff97ac04bf0: pointer being freed was not allocated
*** set a breakpoint in malloc_error_break to debug
Abort trap: 6
Kamala:COS30008 Markus$
```

SimpleString.cpp

```cpp
int main()
{
    SimpleString s1;
    s1 + 'A';
    SimpleString s2 = s1;
    s2 + 'B';

    s1 = s2;
    cout << "S1: " << *s1 << endl;
    cout << "S2: " << *s2 << endl;

    return 0;
}
```

Line: 56 Column: 13 C++ Tab Size: 4 main

What Has Happened?

SimpleString.cpp

```cpp
int main()
{
    SimpleString s1;
    s1 + 'A';
    SimpleString s2 = s1;
    s2 + 'B';

    s1 = s2;
    cout << "S1: " << *s1 << endl;
    cout << "S2: " << *s2 << endl;

    <delete s1;>
    <delete s2;>

    return 0;
}
```

Line: 56 Column: 13 C++ Tab Size: 4 main

Shallow copy:
s2.fCharacters == s1.fCharacters

Double free:
delete s2.fCharacters, which is the same as s1.fCharacters.

Rule Of Thumb

- Copy control in C++ requires three elements:
  - a copy constructor
  - an assignment operator
  - a destructor
- Whenever one defines a copy constructor, one must also define an assignment operator and a destructor.
- C++ also supports move constructor and move assignment operator. They work similarly, but steal the memory for its r-value source. Moreover, while the compiler still synthesizes missing l-value copy constructors and assignment operators, their r-value counterparts are not synthesized if the programmer does specify either but not both.

We need an explicit assignment operator!

SimpleString.h

```cpp
class SimpleString
{
private:
    char * fCharacters;

public:
    SimpleString();
    ~SimpleString();
    SimpleString( const SimpleString& aOtherString );

    SimpleString& operator=( const SimpleString& aOtherString );

    SimpleString& operator+( const char aCharacter );
    const char* operator*() const;
};
```

Line: 2 Column: 15 C++ Tab Size: 4 SIMPLESTRING_H_

The Explicit Assignment Operator

SimpleString.cpp

```
SimpleString& SimpleString::operator=( const SimpleString& aOtherString )
{
    if ( &aOtherString != this )
    {
        delete fCharacters;

        int lLength = strlen(aOtherString.fCharacters) + 1;
        fCharacters = new char[lLength];

        for ( unsigned int i = 0; i < lLength; i++ )
            fCharacters[i] = aOtherString.fCharacters[i];
    }

    return *this;
}
```

Line: 17 Column: 2 C++ Tab Size: 4 SimpleString::~SimpleString

protection against accidental suicide

- When the assignment operator is invoked, then all instance variables are initialized in the beginning. We need to release the memory first!

Explicit Assignment Operator in Use

SimpleString.cpp

```cpp
int main()
{
    SimpleString s1;
    s1 + 'A';
    SimpleString s2 = s1;
    s2 + 'B';

    s1 = s2;
    cout << "S1: " << *s1 << endl;
    cout << "S2: " << *s2 << endl;

    return 0;
}
```

COS30008

```
Kamala:COS30008 Markus$ ./SimpleString
S1: AB
S2: AB
Kamala:COS30008 Markus$ _
```

What Has Happened?

SimpleString.cpp

```
int main()
{
    SimpleString s1;
    s1 + 'A';
    SimpleString s2 = s1;
    s2 + 'B';

    s1 = s2;
    cout << "S1: " << *s1 << endl;
    cout << "S2: " << *s2 << endl;

    <delete s1;>
    <delete s2;>

    return 0;
}
```

Line: 56 Column: 13 C++ Tab Size: 4 main

Deep copy:
s2.fCharacters != s1.fCharacters

Cloning: Alias Control for References

Copying Pointers

SimpleString.cpp

```cpp

int main()
{
    SimpleString* ps1 = new SimpleString();
    (*ps1) + 'A';
    SimpleString* ps2 = ps1;
    (*ps2) + 'B';

    cout << "S1: " << **ps1 << endl;
    cout << "S2: " << **ps2 << endl;

    delete ps1;
    delete ps2;

    return 0;
}
```

Line: 50 Column: 24 C++

COS30008

```
Kamala:COS30008 Markus$ ./SimpleString
S1: AB
S2: AB
SimpleString(17284,0x7fff7167d300) malloc: *** error for obj
ect 0x7fc7cac04be0: pointer being freed was not allocated
*** set a breakpoint in malloc_error_break to debug
Abort trap: 6
Kamala:COS30008 Markus$ _
```

What Has Happened?

SimpleString.cpp

```cpp

int main()
{
    SimpleString* ps1 = new SimpleString();
    (*ps1) + 'A';
    SimpleString* ps2 = ps1;
    (*ps2) + 'B';

    cout << "S1: " << **ps1 << endl;
    cout << "S2: " << **ps2 << endl;

    delete ps1;
    delete ps2;

    return 0;
}
```

Line: 50 Column: 24 C++ Tab Size: 4 Simpl

Shallow copy:
ps2. == ps1

Double free:
delete ps2, which is the same as ps1.

Solution: A clone() Method

SimpleString.h

```cpp
class SimpleString
{
private:
    char * fCharacters;

public:
    SimpleString();
    virtual ~SimpleString();
    SimpleString( const SimpleString& aOtherString );

    SimpleString& operator=( const SimpleString& aOtherString );

    virtual SimpleString* clone();

    SimpleString& operator+( const char aCharacter );
    const char* operator*() const;
};
```

Line: 2 Column: 12 C++ Tab Size: 4 SIMPLESTRING_H_

Destructor
must be virtual!

- It is best to define the destructor of a class virtual always in order to avoid problems later.

The Use of clone()

SimpleString.cpp

```
SimpleString* SimpleString::clone()
{
    return new SimpleString( *this );
}
```

COS30008

```
Kamala:COS30008 Markus$ ./SimpleString
S1: A
S2: AB
Kamala:COS30008 Markus$
```

SimpleString.cpp

```
int main()
{
    SimpleString* ps1 = new SimpleString();
    (*ps1) + 'A';
    SimpleString* ps2 = ps1->clone();
    (*ps2) + 'B';

    cout << "S1: " << **ps1 << endl;
    cout << "S2: " << **ps2 << endl;

    delete ps1;
    delete ps2;

    return 0;
}
```

Problems With Cloning

- The member function clone() must be defined virtual to allow for proper redefinition in subtypes.
- Whenever a class contains a virtual function, then its destructor is required to be defined virtual as well.
- The member function clone() can only return one type. When a subtype redefines clone(), only the super type can be returned.

Non-virtual Cloning Does Not Work!

- One could define clone() non-virtual and use overloading. But this does not work as method selection starts at the static type of the pointer.

```
SimpleString* pToString = new SubtypeOfSimpleString();
SimpleString* c1 = pToString->clone(); // SimpleString::clone()
```

Reference-based Semantics: When Do We Destroy Objects?

Reference Counting

- A simple technique to record the number of active uses of an object is reference counting.
- Each time a heap-based object is assigned to a variable the object's reference count is incremented and the reference count of what the variable previously pointed to is decremented.
- Some compilers emit the necessary code, but in case of C++ reference counting must be defined (semi-)manually.

Smart Pointers: Handle

Handle.h

```
template<class T>
class Handle
{
private:
    T* fPointer;
    int* fCount;

    void addRef();
    void releaseRef();

public:
    Handle( T* aPointer = (T*)0 );
    Handle( const Handle<T>& aOtherHandle );
    ~Handle();

    Handle& operator=( Handle<T>& aOtherHandle );
    T& operator*();
    T* operator->();
};
```

Line: 2 Column: 12 C++ Tab Size: 4 HANDLE_H_

The Use of Handle

- The template class Handle provides a pointer-like behavior:
  - Copying a Handle will create a shared alias of the underlying object.
  - To create a Handle, the user will be expected to pass a fresh, dynamically allocated object of the type managed by the Handle.
  - The Handle will own the underlying object. In particular, the Handle assumes responsibility for deleting the owned object once there are no longer any Handles attached to it.

Handle: Constructor & Destructor

Handle.h

```
    Handle( T* aPointer = (T*)0 )
    {
        fPointer = aPointer;
        fCount = new int;
        *fCount = 1;
    }

    ~Handle()
    {
        releaseRef();
    }
```

Create a shared counter

Decrement reference count

Handle: addRef & releaseRef

Handle.h

```cpp
    void addRef()
    {
        ++*fCount;
    }

    void releaseRef()
    {
        if ( --*fCount == 0 )
        {
            delete fPointer;
            delete fCount;
        }
    }
```

Increment reference count

Decrement reference count and delete object if it is no longer referenced anywhere.

Handle: Copy Control

Handle.h

```cpp
Handle( const Handle<T>& aOtherHandle )
{
    fPointer = aOtherHandle.fPointer;
    fCount = aOtherHandle.fCount;
    addRef();                          // increment use
}

Handle& operator=( Handle<T>& aOtherHandle )
{
    if ( &aOtherHandle != this )
    {
        aOtherHandle.addRef();         // increment use
        releaseRef();                  // release old handle
        fPointer = aOtherHandle.fPointer;
        fCount = aOtherHandle.fCount;
    }

    return *this;
}
```

Line: 20 Column: 1 C++ Tab Size: 4 ~Handle

Handle: Pointer Behavior

Handle.h

```cpp
T& operator*()
{
  if ( fPointer )
    return *fPointer;
  else
    throw std::runtime_error( "Dereference of unbound handle!" );
}

T* operator->()
{
  if ( fPointer )
    return fPointer;
  else
    throw std::runtime_error( "Access through unbound handle!" );
}
```

Line: 39 Column: 22 C++ Tab Size: 4 Handle

Using Handle

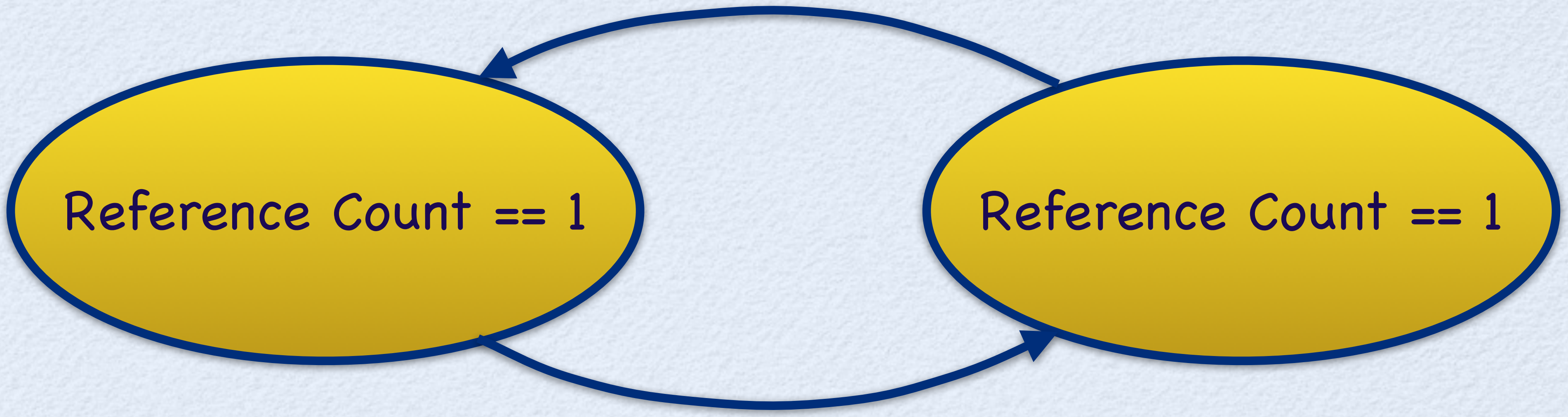
```
Kamala:COS30008 Markus$ ./SimpleString
HS1: A
HS2: AB
HS3: A
Kamala:COS30008 Markus$ _
```

```cpp
int main()
{
    Handle<SimpleString> hs1( new SimpleString() );
    *hs1 + 'A';
    Handle<SimpleString> hs2( hs1->clone() );
    *hs2 + 'B';
    Handle<SimpleString> hs3 = hs1;

    cout << "HS1: " << **hs1 << endl;
    cout << "HS2: " << **hs2 << endl;
    cout << "HS3: " << **hs3 << endl;

    return 0;
}
```

Reference Counting Limits



- Reference counting fails on circular data structures like double-linked lists.
- Circular data structures require extra effort to reclaim allocated memory. Know solution: Mark-and-Sweep