the gamedesigninitiative at cornell university

Lecture 10

Memory Management: The Details

Sizing Up Memory

Primitive Data Types

- **byte**: basic value (8 bits)
- **char**: 1 byte
- **short**: 2 bytes
- **int**: 4 bytes
- **long**: 8 bytes
- **float**: 4 bytes
- **double**: 8 bytes

Not standard
May change

IEEE standard
Won't change

Complex Data Types

- **Pointer**: platform dependent
  - 4 bytes on 32 bit machine
  - 8 bytes on 64 bit machine
  - Java reference is a pointer
- **Array**: data size * length
  - Strings same (w/ trailing null)
- **Struct**: sum of fields
  - Same rule for classes
  - Structs = classes w/o methods

Memory Example

class Date {	
short year;	2 byte
byte day;	1 byte
byte month;	1 bytes
}	4 bytes
class Student {	
int id;	4 bytes
Date birthdate;	4 bytes
Student* roommate;	4 or 8 bytes (32 or 64 bit)
}	12 or 16 bytes

Memory and Pointer Casting

- C++ allows **ANY** cast
  - Is not “strongly typed”
  - Assumes you know best
  - But must be **explicit** cast
- **Safe** = aligns properly
  - Type should be same size
  - Or if array, multiple of size
- **Unsafe** = data corruption
  - It is all your fault
  - Large cause of seg faults

```
// Floats for OpenGL
float[] lineseg = {0.0f, 0.0f,
                   2.0f, 1.0f};

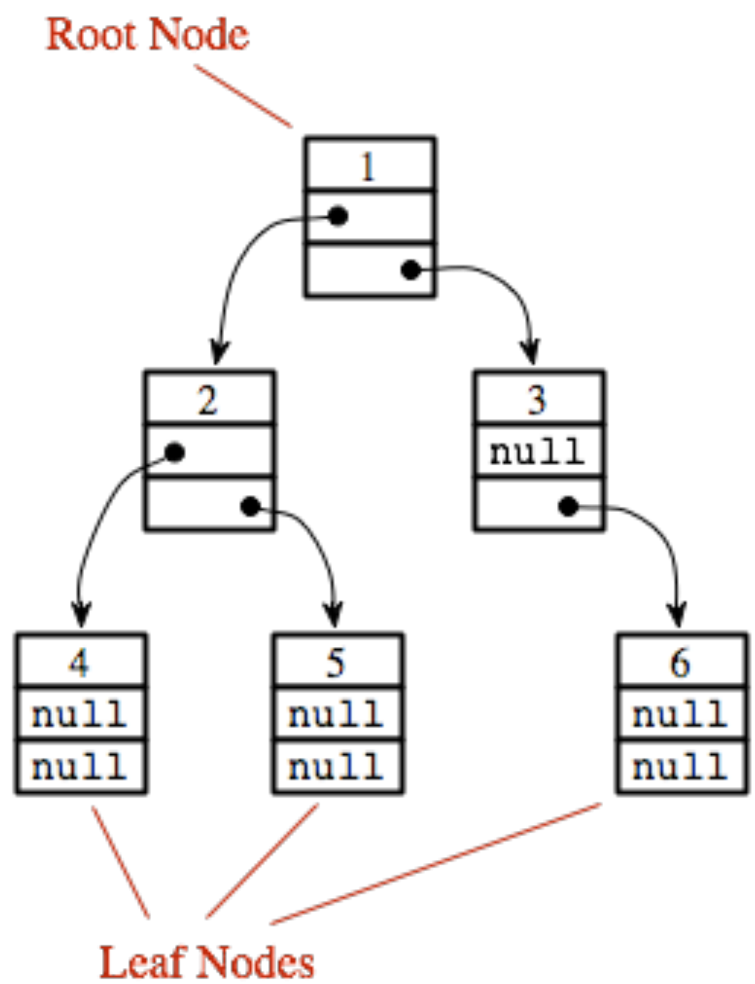
// Points for calculation
Vec2* points

// Convert to the other type
points = (Vec2*)lineseg;

for(int ii = 0; ii < 2; ii++) {
  CCLOG("Point %4.2, %4.2",
        points[ii].x, points[ii].y);
}
```

Data Structures and Memory

- Collection types are **costly**
  - Even null pointers use memory
  - Common for pointers to use as much memory as the pointees
  - Unbalanced trees are very bad
- Even true of (pointer) arrays
  - Array uses additional memory
- Not so in **array of structs**
  - Objects stored directly in array
  - But memory alignment!



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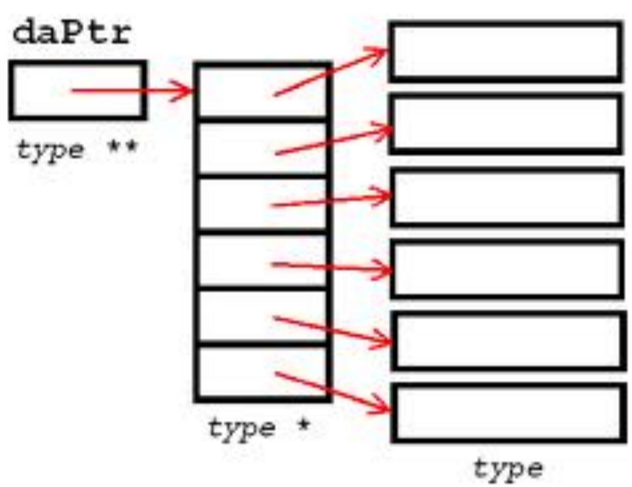


Two Main Concerns with Memory

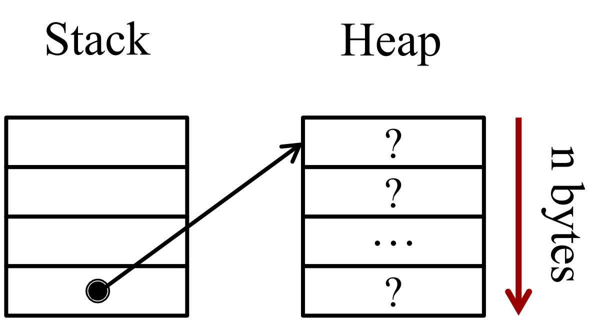
- *Allocating Memory*
  - With OS support: **standard allocation**
  - Reserved memory: **memory pools**
- *Getting rid of memory* you no longer want
  - Doing it yourself: **deallocation**
  - Runtime support: **garbage collection**

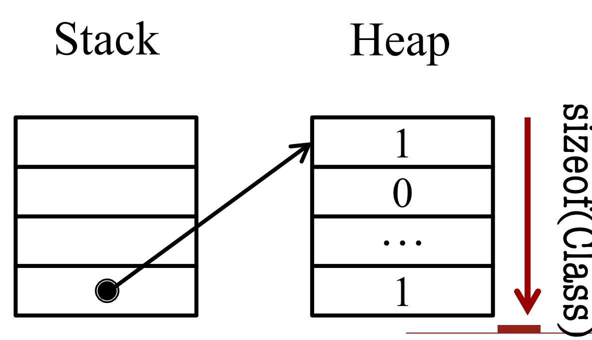
C/C++: Allocation Process

malloc	**new**

- Based on memory size
  - Give it number of **bytes**
  - Typecast result to assign it
  - No initialization at all
	- Based on data type
	  - Give it a data type
	  - If a class, calls constructor
	  - Else no default initialization

- **Example**: `char* p = (char*)malloc(4)`	- **Example**: `Point* p = new Point();`





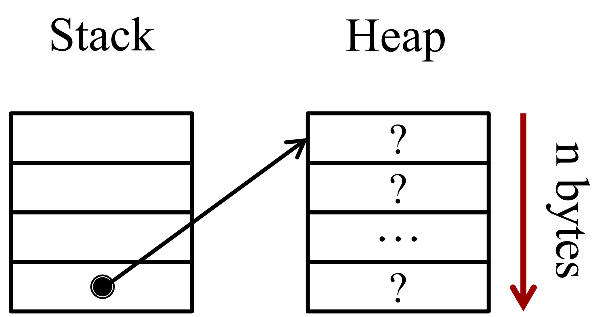
C/C++: Allocation Process

malloc

- Based on memory size
  - Give it number of **bytes**
  - Typecast result ... it
  - ...
- **E**...

char* p = (char*)malloc(4)

Preferred in C

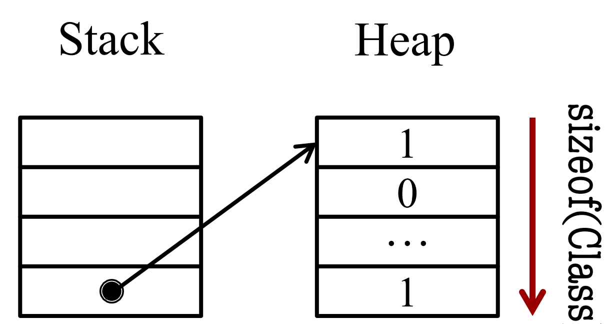


new

- Based on data type
  - Give it a data type
  - If a class, call... tor
  - ...ion
- **E**...

Point* p = new Point();

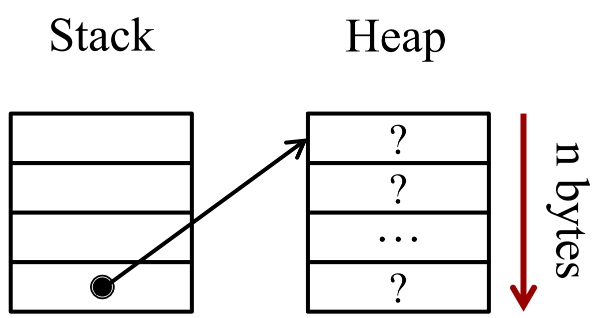
Preferred in C++



C/C++: Allocation Process

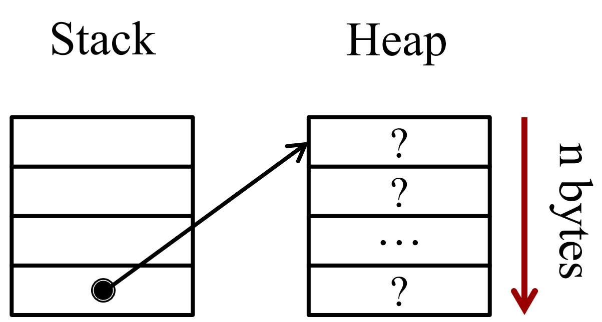
malloc

- Based on memory size
  - Give it number of **bytes**
  - Typecast result to assign it
  - No initialization at all
- **Example**:
  `char* p = (char*)malloc(4)`



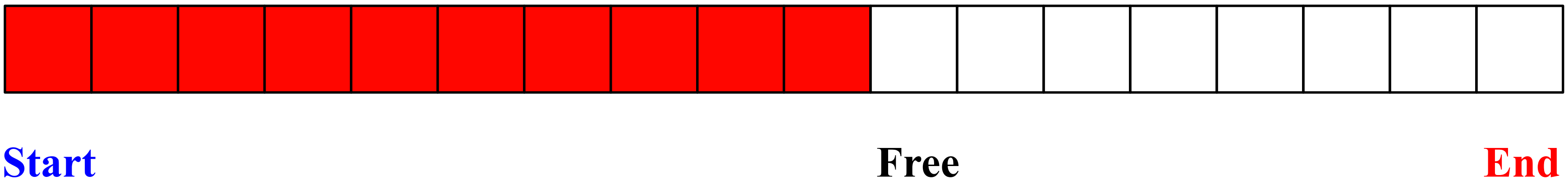
new

- **Can emulate malloc**
  - Create a char (byte) array
  - Arrays not initialized
  - Typecast after creation
- **Example**:
  `Point* p = (Point*)(new char[8])`



Custom Allocators

Pre-allocated Array (called **Object Pool**)



- **Idea**: Instead of `new`, get object from array
  - Just reassign all of the fields
  - Use **Factory pattern** for constructor
  - See `alloc()` method in CUGL objects
- **Problem**: Running out of objects
  - We want to reuse the older objects
  - Easy if deletion is FIFO, but often isn't

Easy if only one object **type** to allocate

Allocation Patterns in CUGL

```
class PolygonNode : public Node {
public:
    /** Creates, but does not initialize node */
    Sprite();
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
    /** Initializes a node with an image filename. */
    virtual bool initWithFile(const string& filename);

    /** Initializes a node with a texture. */
    virtual bool initWithTexture(const shared_ptr<Texture>& texture);
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
    /** Creates a node with an image filename. */
    static shared_ptr<Sprite> allocWithFile(const string& filename);

    /** Creates a node with a Texture object. */
    static shared_ptr<Sprite> allocWithTexture(const shared_ptr<Texture>& texture);

};
```

Allocation only

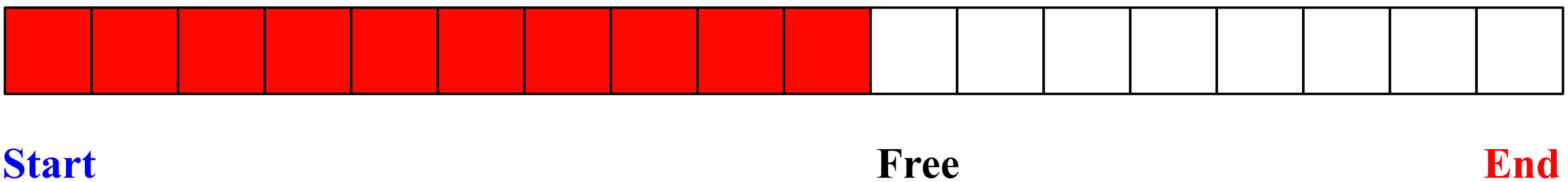
Initialization only

Allocation & initialization

Separating Allocation and Initialization

Pre-allocated Array

These are not pointers!



- Array contains *objects*, not pointers
  - Allocating the array will allocate objects
  - No initialization until user grabs an object
- Makes it easy to implement factory pattern
  - Hides choice of underlying allocation
  - Uses standard initialization independent of allocation

Allocation Patterns in CUGL

```
class PolygonNode : public Node {
public:
    /** Creat
    Sprite();
```

Standard allocation

Allocation only

```
    /** Initializes a node with an image filename. */
    virtual bool initWithFile(const string& filename);

    /** Initializes a node with a texture. */
    virtual bool initWithTexture(const shared_ptr<Texture>& texture);
```

Initialization only

```
    /** Creates a node with an image filename. */
    static shar                          string& filename);

    /** Creates
    static shared_ptr<Sprite> allocWithTexture(const shared_ptr<Texture>& texture);

};
```

Customizable allocation

Allocation & initialization

Free Lists

- Create an object **queue**
  - Separate from preallocation
  - Stores objects when "freed"
- To allocate an object…
  - Look at front of free list
  - If object there take it
  - Otherwise make new object
- Preallocation unnecessary
  - Queue wins in long term
  - Main performance hit is deletion/fragmentation

```
// Free the new particle
freelist.push_back(p);

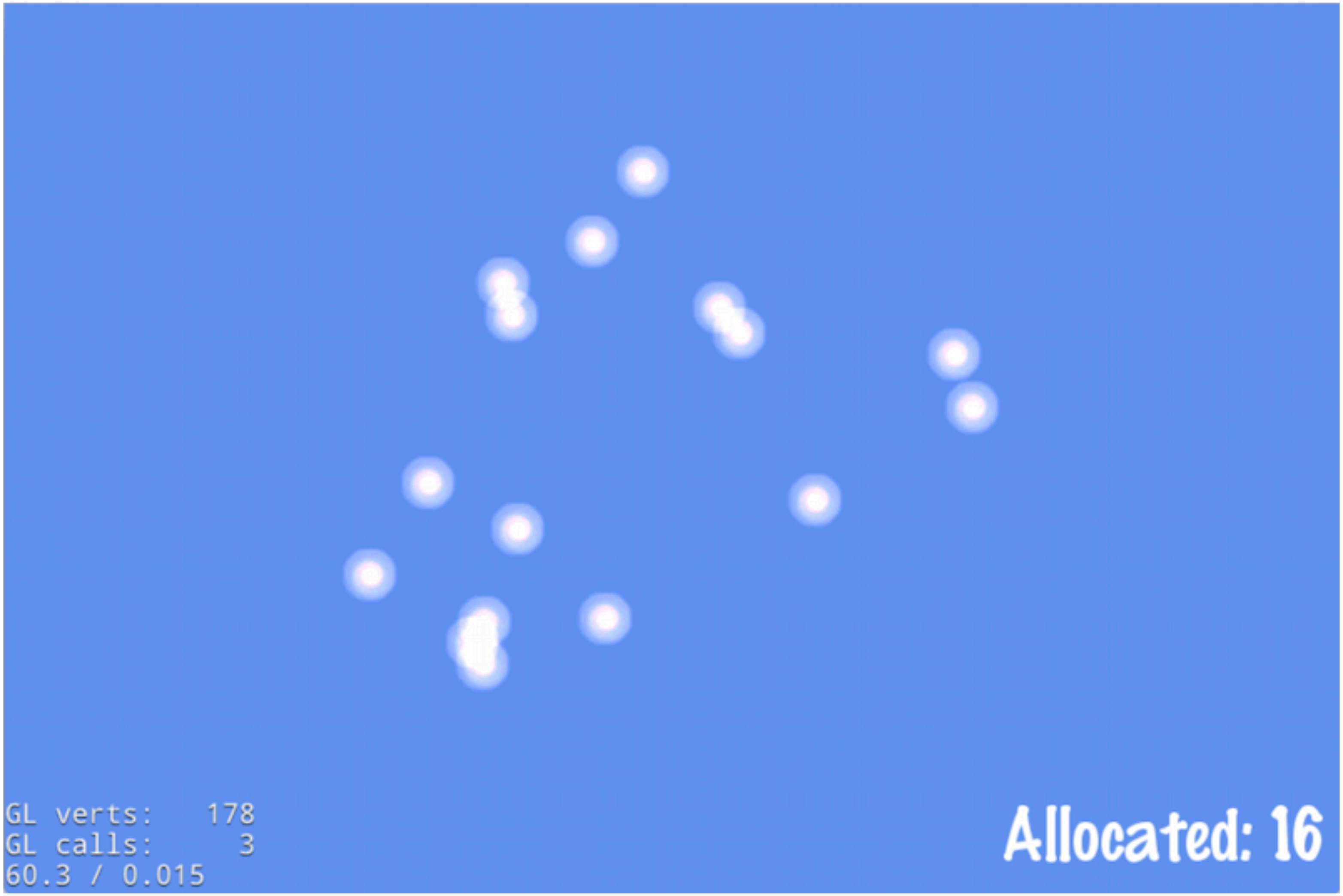
...

// Allocate a new particle
Particle* q;

if (!freelist.isEmpty()) {
    q = freelist.pop();
} else {
    q = new Particle();
}

q.set(...)
```

Particle Pool Example



Particle Pool Example

```
class ParticlePool {
public:
  /** Creates a ParticlePool with the given capacity. */
  ParticlePool(int capacity);
  /** Returns a new OR reused object from this pool. */
  Particle* obtain();
  /** Marks object as eligible for reuse. */
  void free (Particle* object) ;
private:
  /** Allocates a new object from the pool.  */
  Particle* alloc();
};
```

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Use instead of new

Use instead of delete

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};
```

Use instead of new

Use instead of delete

What to do if nothing free

Two Main Concerns with Memory

- *Allocating Memory*
  - With OS support: **standard allocation**
  - Reserved memory: **memory pools**
- *Getting rid of memory* you no longer want
  - Doing it yourself: **deallocation**
  - Runtime support: **garbage collection**

Manual Deletion in C/C++

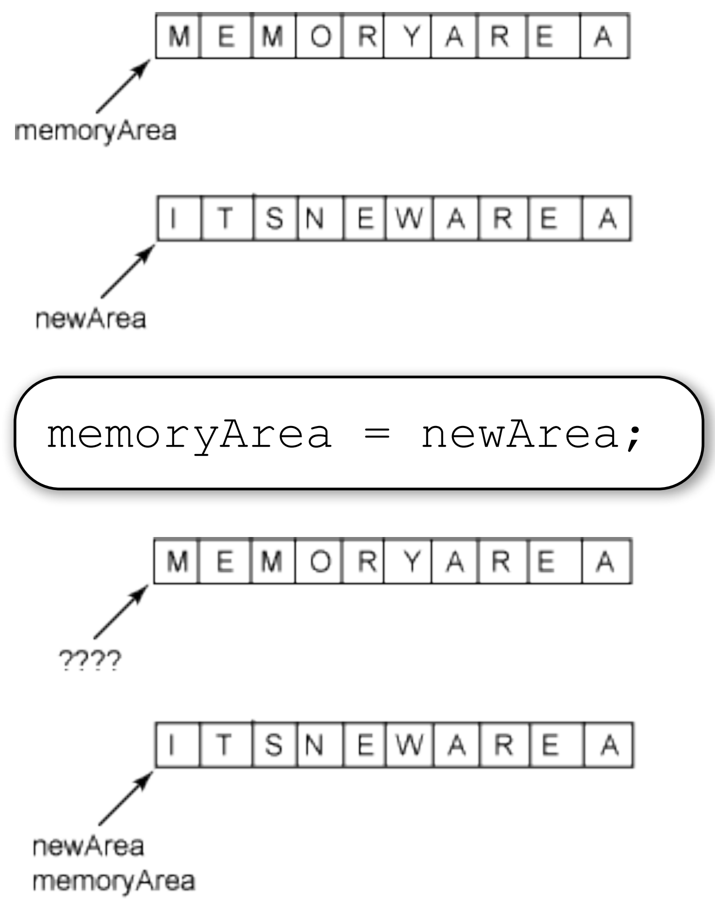
- Depends on **allocation**
  - malloc: free
  - new: delete
- What does deletion do?
  - Marks memory as available
  - Does **not** erase contents
  - Does **not** reset pointer
- Only crashes if pointer bad
  - Pointer is currently NULL
  - Pointer is illegal address

```
int main() {
    cout << "Program started" << endl;
    int* a = new int[LENGTH];


    delete a;
    for(int ii = 0; ii < LENGTH; ii++) {
        cout << "a[" << ii << "]="
              << a[ii] << endl;
    }
    cout << "Program done" << endl;
}
```

Memory Leaks

- **Leak**: Cannot release memory
  - Object allocated on heap
  - Only reference is moved
- Consumes memory fast!
- Can even happen in Java
  - JNI supports native libraries
  - Method may allocate memory
  - Need another method to free
  - **Example**: dispose() in JOGL



A Question of Ownership

```
void foo() {
    MyObject* o =
        new MyObject();
    o.doSomething();
    o = null;
    return;
}
```

Memory Leak

```
void foo(int key) {
    MyObject* o =
        table.get(key);
    o.doSomething();
    o = null;
    return;
}
```

Not a Leak

A Question of Ownership

```
void foo() {
    MyObject* o =
        table.get(key);
    table.remove(key);
    o = null;
    return;
}
```

Memory Leak?

```
void foo(int key) {
    MyObject* o =
        table.get(key);
    table.remove(key);
    ntable.put(key,o);
    o = null;
    return;
}
```

Not a Leak

A Question of Ownership

Thread 1

```
void run() {
    o.doSomething1();
}
```

Thread 2

```
void run() {
    o.doSomething2();
}
```

"Owners" of obj

Who deletes obj?

Understanding Ownership

Function-Based

- Object owned by a function
  - Function allocated object
  - Can delete when function done
- Ownership *never transferred*
  - May pass to other functions
  - But always returns to owner
- Really a **stack-based object**
  - Active as long as allocator is
  - But allocated on heap (why?)

Object-Based

- Owned by another object
  - Referenced by a field
  - Stored in a data structure
- Allows *multiple ownership*
  - No guaranteed relationship between owning objects
  - Call each owner a reference
- When can we deallocate?
  - No more references
  - References "unimportant"

Understanding Ownership

Function-Based

- Object owned by a function
  - Function allocated object
  - Can delete when function done
- Own…
  - …returns to owner

Easy: Will ignore

- Really a **stack-based object**
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- When can we deallocate?
  - No more references
  - References "unimportant"

Reference Strength

Strong Reference

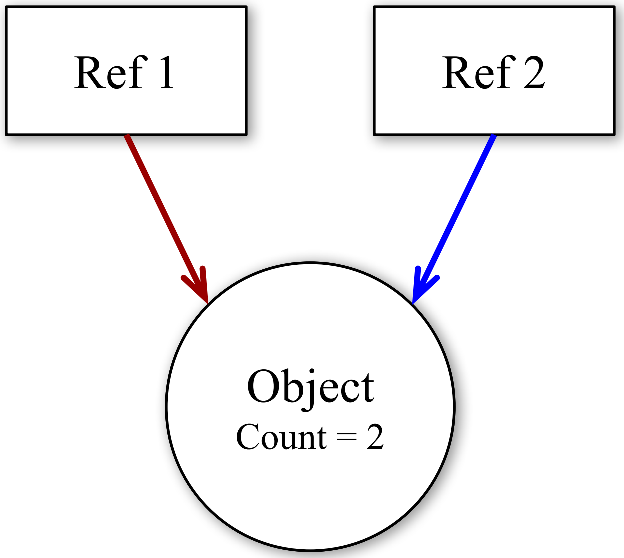
- Reference asserts ownership
  - Cannot delete referred object
  - Assign to NULL to release
  - Else assign to another object
- Can use reference **directly**
  - No need to copy reference
  - Treat like a normal object
- Standard type of reference

Weak Reference

- Reference != ownership
  - Object can be deleted anytime
  - Often for *performance caching*
- Only use **indirect** references
  - Copy to local variable first
  - Compute on local variable
- Be prepared for NULL
  - Reconstruct the object?
  - Abort the computation?

Reference Counting

- Every object has a **counter**
  - Tracks number of "owners"
  - No owners = memory leak
- Increment when assign reference
  - Historically an explicit method call
  - Method often called `retain()`
- Decrement when remove reference
  - Method call is `release()`
  - If makes count 0, delete it



References vs. Garbage Collectors

Reference Counting

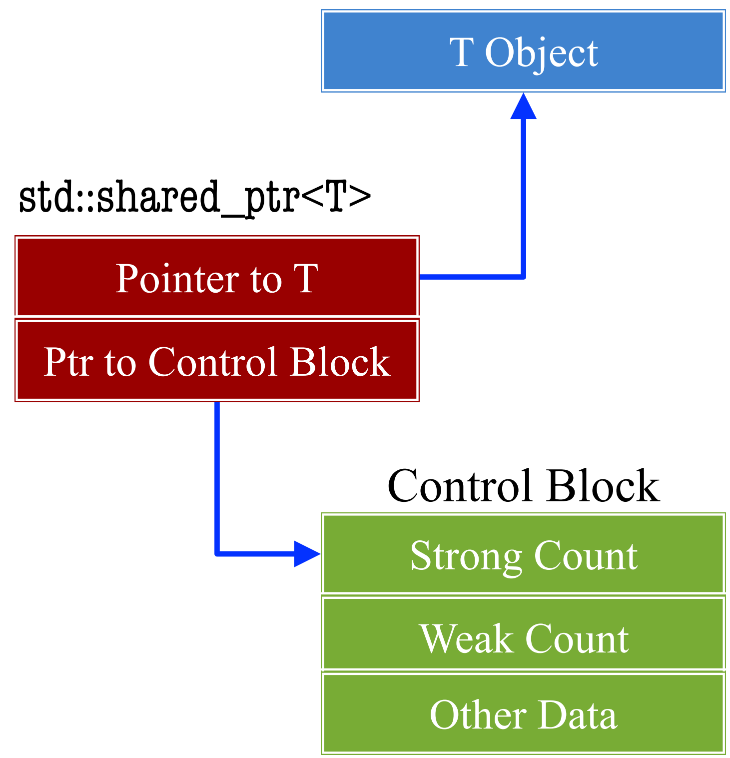
- **Advantages**
  - Deallocation is immediate
  - Works on non-memory objects
  - Ideal for real-time systems
- **Disadvantages**
  - Overhead on every assignment
  - **Cannot easily handle cycles**
    (e.g. object points to itself)
  - May require training to use

Mark-and-Sweep

- **Advantages**
  - No assignment overhead
  - Can handle reference cycles
  - No specialized training to use
- **Disadvantages**
  - Collection can be expensive
  - Hurts performance when runs
  - Usually triggered whenever the memory is close to full

Smart Pointers

- std::shared_ptr<T>
  - Templatized type in C++11
  - Provides reference counting
  - Need to include <memory>
- Counting is automatic
  - Uses overloaded operators
  - Increments at creation/copy
  - Decrements when destroyed
- Smart pointer is on stack!
  - Passing as a parameter copies
  - So often pass by reference



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```
#include <memory>
#include "A.h"
using namespace std;

/** Okay, but inefficient */
void foo(shared_ptr<A> var)
{
   …
}

/** Preferred approach */
void foo(const shared_ptr<A>& var)
{
   …
}
```

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foo claims **ownership**

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foo wants **usage** only

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foo claims **ownership**

foo can change A, **not** smart pointer

foo wants **usage** only

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#include <memory>
#include "A.h"
using namespace std;

/** Good */
shared_ptr<A> foo(void) {
  shared_ptr<A> result
  ...
  return result;
}

/** BAD!!! */
shared_ptr<A>& foo(void) {
  shared_ptr<A> result
  ...
  return result;
}
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Smart Pointers

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#include <memory>
#include "A.h"
using namespace std;

/** Good */
shared_ptr<A> foo(void) {
  shared_ptr<A> result
  …
  return result;   // Copied to caller
}

/** BAD!!! */
shared_ptr<A>& foo(void) {
  shared_ptr<A> result
  …
  return result;   // Deleted with stack
}
```

Recall: Smart Pointers and Allocation

Heap Allocation

```
void func() {
  Point* p = new Point(1,2,3);
  …
  delete p;
}
```

- Must remember to delete
- Otherwise will *memory leak*

Smart Pointer

```
void func() {
  shared_ptr<Point> p;
  p = make_shared<Point>(1,2,3);
  …
}
```

Same arguments as constructor

- Deletion is not necessary
- Sort-of garbage collection

Allocation Patterns in CUGL

```
class PolygonNode : public Node {
public:
    /** Creates, but does not initialize node */
    Sprite();
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
    /** Initializes a node with an image filename. */
    virtual bool initWithFile(const string& filename);

    /** Initializes a node with a texture. */
    virtual bool initWithTexture(const shared_ptr<Texture>& texture);
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    /** Creates a node with an image filename. */
    static shared_ptr<Sprite> allocWithFile(const string& filename)

    /** Creates a node with a Texture object. */
    static shared_ptr<Sprite> allocWithTexture(const shared_ptr<Texture>& texture);

};
```

Smart pointer & initialization

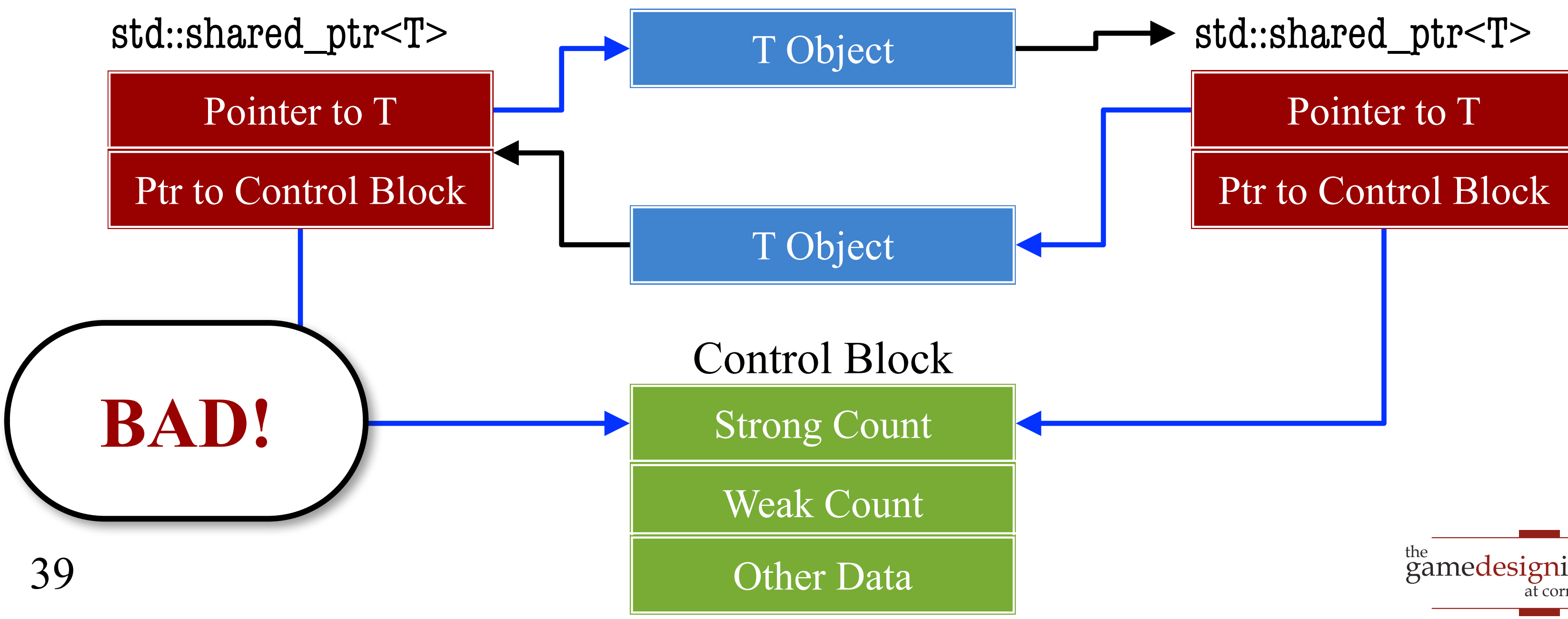
Recall: Reference Strength

Strong Reference

- shared_ptr<A>
  - Always safe to use
  - Held until all deleted

Weak Reference

- weak_ptr<A>
  - Not always safe to use
  - Returns null if deleted



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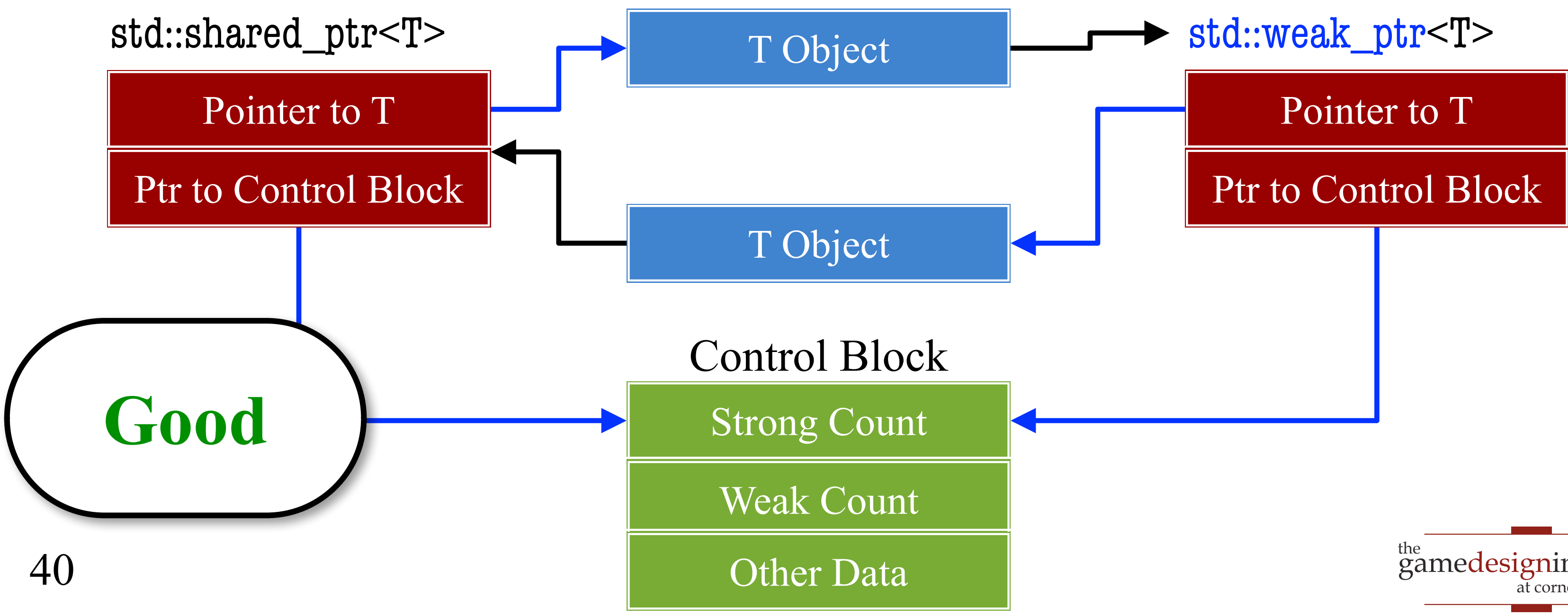

Weak Pointers vs. Raw Pointers

- Weak pointers are still managed!
  - `weak_ptr<A>` and `A*` not the same thing
  - Weak pointer has reference to the control block
  - Will null the base pointer when no longer valid
- But sometimes you want a raw pointer `A*`
  - May be required by 3rd party APIs
  - Can get this from strong, weak pointers: `var.get()`
  - Caching this value past a function call is unsafe

Recall: Typecasting and Smart Pointers

Normal Pointers

```
B* b;    // The super class
A* a;    // The subclass
```

Acceptable:

```
b = new B();
a = (A*)b;
```

Better:

```
b = new B();
a = dynamic_cast<A*>(b);
```

Smart Pointers

```
shared_ptr<B> b;    // Contains B*
shared_ptr<A> a;    // Contains A*
```

Bad:

```
b = make_shared<B>();
a = (shared_ptr<A>)b;
```

Good:

```
b = make_shared<B>();
a = dynamic_pointer_cast<A>(b);
```

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```

Good:

Must acquire control block!

```
b = make_shared<B>();
a = dynamic_pointer_cast<A>(b);
```

Platform Specific Issues

- **Android**: JNI interface issues
  - May need to call Java method from C++
  - Doing so requires pointers/references to Java
  - This requires a special allocator/deallocator
- **Apple**: Reference counting issues
  - Objective C has its own reference counting
  - Works with normal raw pointers so easier to use
  - But this requires specialized compiler support
  - Obj-C++ does not enable this support!

Android: Calling Java from inside C++

```
// Retrieve the JNI environment.
JNIEnv* env = (JNIEnv*)SDL_AndroidGetJNIEnv();

// Retrieve the Java instance of the SDLActivity and get its class
jobject activity = (jobject)SDL_AndroidGetActivity();
jclass clazz(env->GetObjectClass(activity));

// Find the identifier of the method to call
jmethodID method_id;
method_id = env->GetMethodID(clazz, "myMethod", "()V");

// Effectively call the Java method
env->CallVoidMethod(activity, method_id);

// Clean up the local references.
env->DeleteLocalRef(activity);
env->DeleteLocalRef(clazz);
```

See SDL API for more info

Memory leak if forget this

Apple: Reference Issues in Obj-C++

```
// Note Objective separates allocation, initialization
// Reference var has reference count of 1
A* var = [[A alloc] init];

// Increments reference count to 2
[var retain];

// Decrements reference count to 1
[var release];

// Decrements reference count to 0 AND deletes
[var release];
```

Apple: Reference Issues in Obj-C++

```
// Note Objective separates allocation, initialization
// Reference var has reference count of 1
A* var = [[A alloc] init];

// Increments reference count to 2
[var retain];

// Decrements reference count to 1
[var release];

// Decrements ref                          AND deletes
[var release];
```

Do this instead of free or delete

Summary

- Must control **allocation** of heap objects
  - Preallocate objects when it makes sense
  - Use free-lists to recycle objects when possible
  - Use the CUGL factory pattern to support these
- Must track **ownership** of allocated objects
  - Know who is responsible for deleting
  - True even when using smart pointers
  - Pay attention to platform specific issues