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

int, long: Not standard
May change

float, double: 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

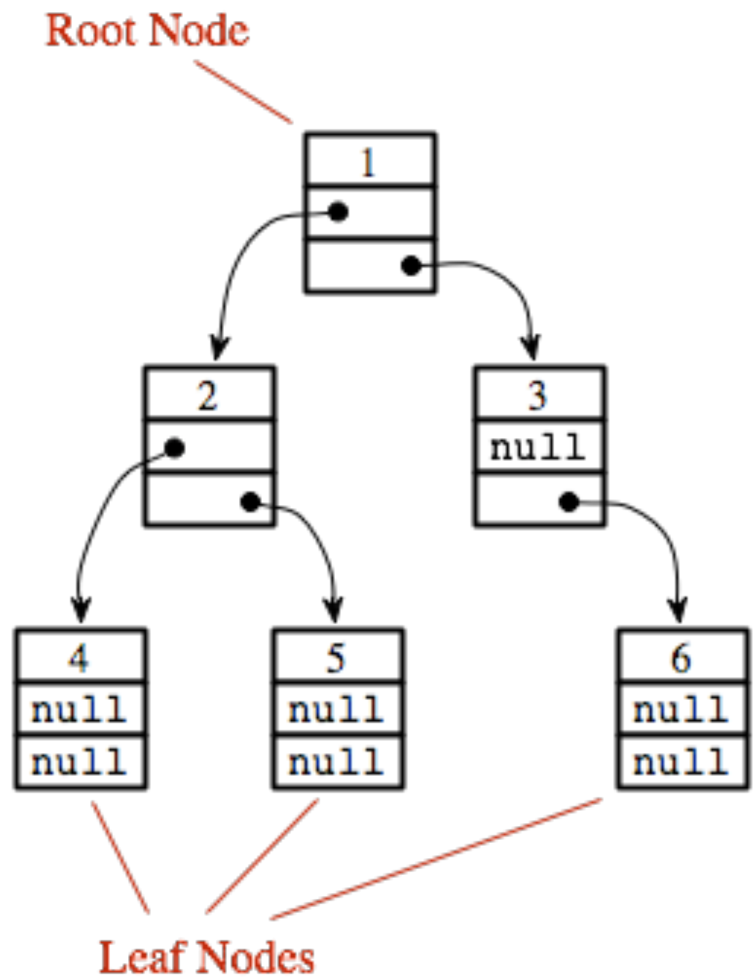
Memory and Pointer Casting

- 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!



Data Structures and Memory

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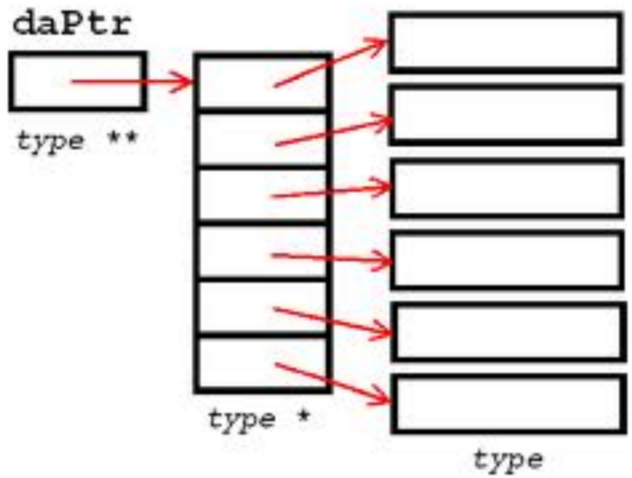


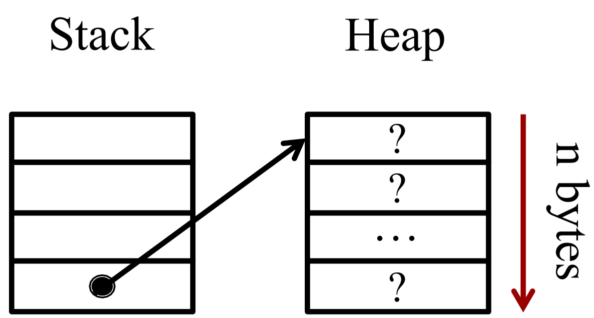
Two Main Concerns with Memory

- *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

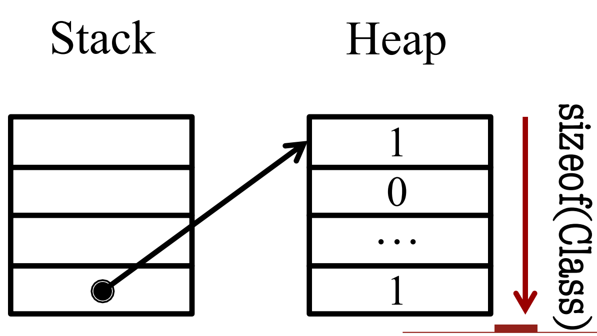
malloc

- 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

- Based on data type
  - Give it a data type
  - If a class, calls constructor
  - Else no default initialization
- **Example**:
  `Point* p = new Point();`



C/C++: Allocation Process

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  -
- E...

Preferred in C

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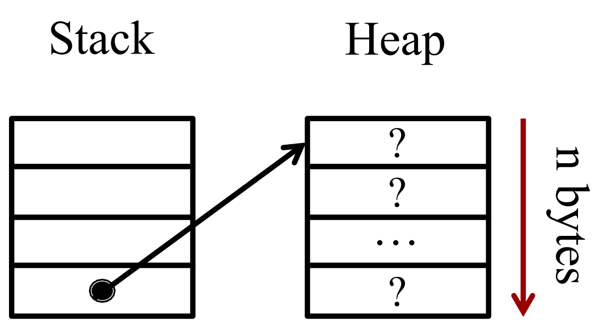

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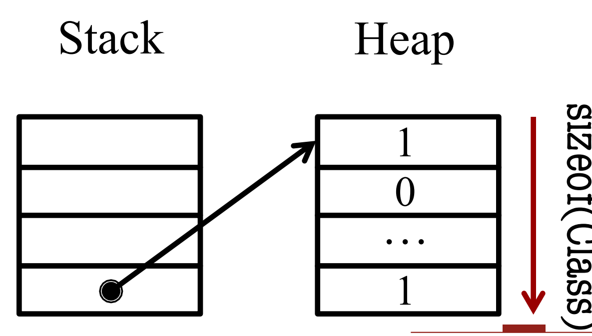

C/C++: Allocation Process

malloc

- Based on memory size
  - Give it number of **bytes**
  - Typecast result to assign it
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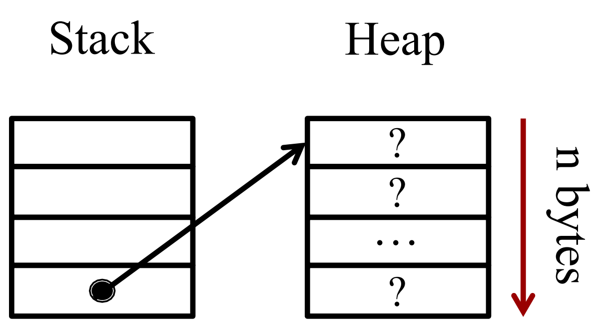
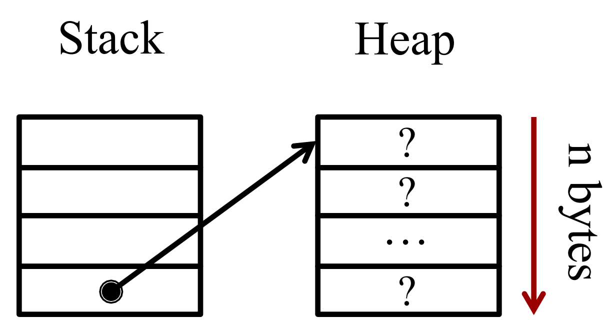


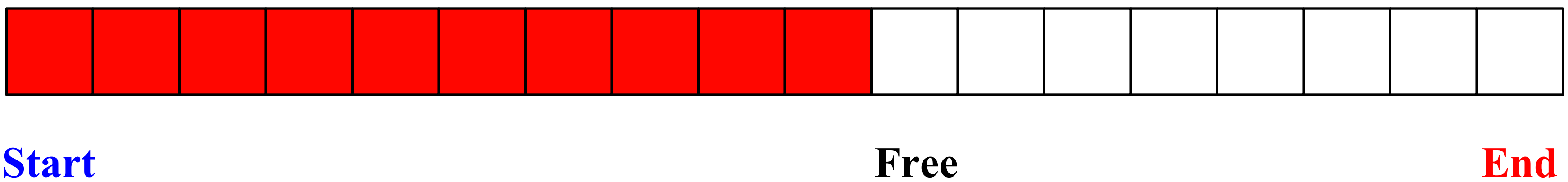
new

- **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 `create()` method in Cocos2D-x 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

Custom Allocators in Cocos2d-x

```
class Sprite : public Node, public TextureProtocol {
public:
    /** Creates a sprite with an image filename. */
    static Sprite* create(const string& filename);

    /** Creates a sprite with a Texture2D object. */
    static Sprite* createWithTexture(Texture2D *texture);

private:
    /** Creates, but does not initialize sprite */
    Sprite();

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

    /** Initializes a sprite with a texture. */
    virtual bool initWithTexture(Texture2D *texture);
};
```

Allocation & initialization

Allocation only

Initialization only

Custom Allocators in Cocos2d-x

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};
```

Customizable allocation

Standard allocation

Allocation & initialization

Allocation only

Initialization only

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);

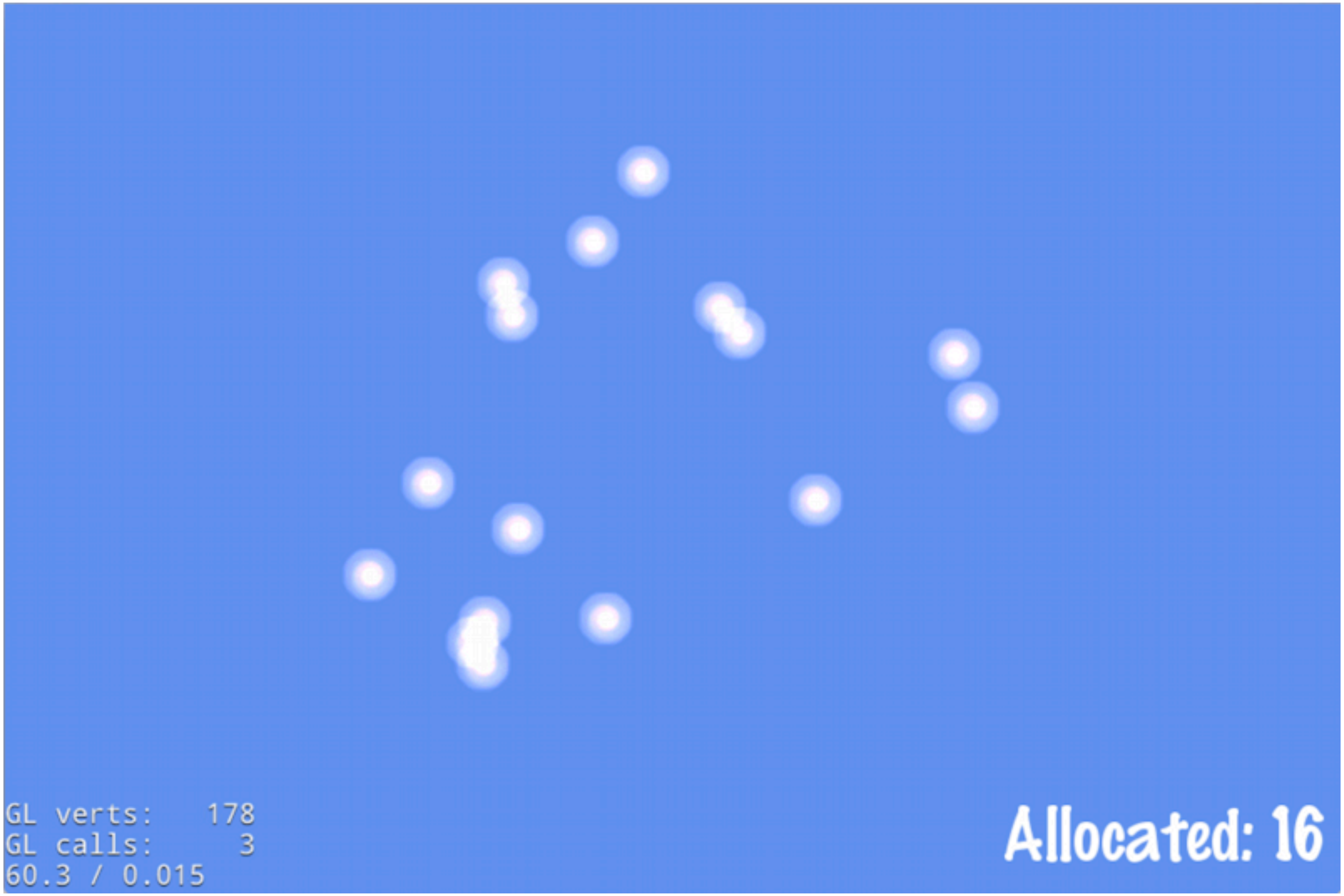
...

// 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++

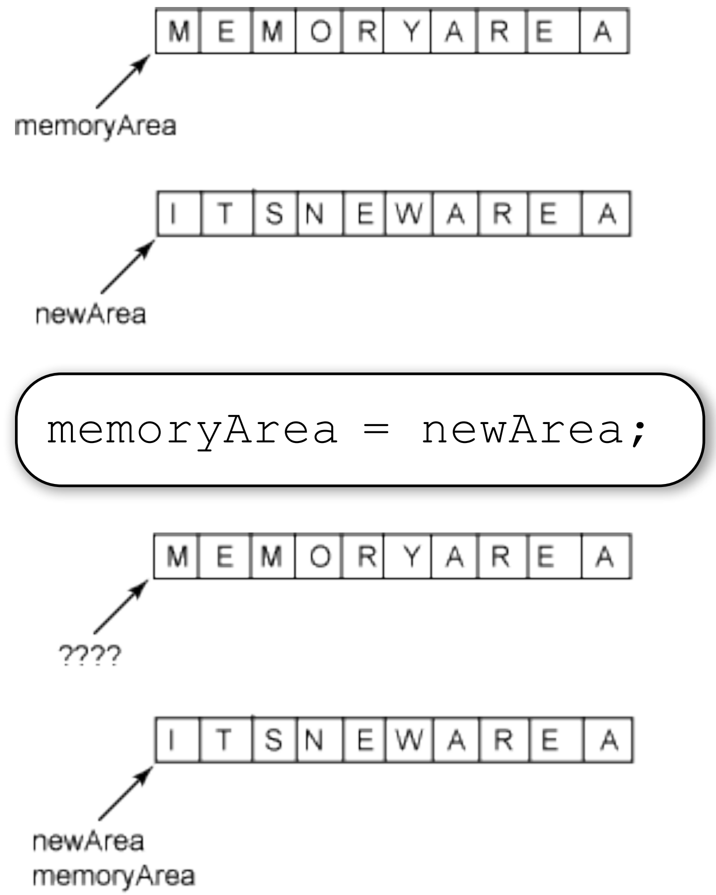
- Depends on **allocation**
  - `malloc`: `free`
  - `new`: `delete`
- What does deletion do?
  - Marks memory as available
  - Does **not** erase contents
  - Does **not** reset pointer
- Only crashes if pointer bad
  - Pointer is currently NULL
  - Pointer is illegal address

```
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	Thread 2

“Owners” of obj

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

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

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**
  - Active as long as allocator is
  - But allocated on heap (why?)

Object-Based

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

Reference Strength

Strong Reference

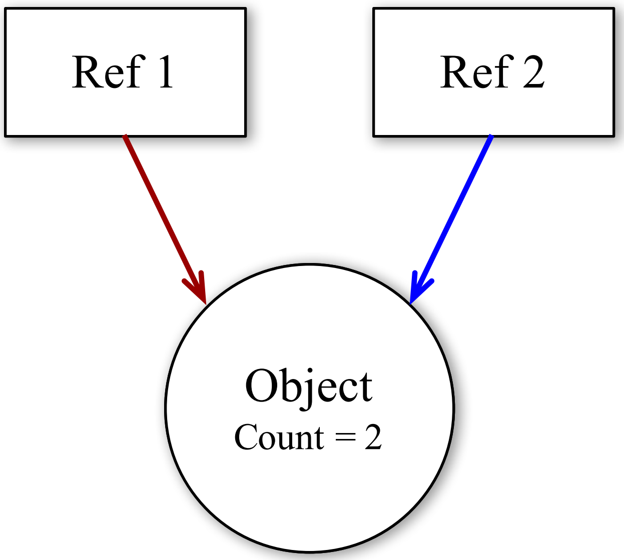
- Reference asserts ownership
  - Cannot delete referred object
  - Assign to NULL to release
  - Else assign to another object
- Can use reference **directly**
  - No need to copy reference
  - Treat like a normal object
- Standard type of reference

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
  - Often an explicit method call
  - Historically called `retain()`
- Decrement when remove reference
  - Method call is `release()`
  - If makes count 0, delete it



When to Adjust the Count?

- On object **allocation**
  - Initial allocator is an owner
  - Even if in a local variable
- When **added** to an object
  - Often handled by setter
  - Part of class invariant
- When **removed** from object
  - Also handled by the setter
  - Release before reassign
- Any other time?

```
class Container {
public:
    RCObject* object;

    Container() {
        // Initial allocation; ownership
        object = new RCObject();
        object->retain();
    }

    void setObject(RCObject o) {
        if (object != null) {
            object->release();
        }
        o->retain();
        object = o;
    }
};
```

Reference Counting in Cocos2d-X

```
// create a new instance
Sprite* sprite = Sprite::create();
sprite->retain();

// Add the sprite to scene graph
rootnode->addChild(sprite);

// Release the local reference
sprite->release();

// Remove from scene graph
scene->removeChild(sprite);
```

Custom allocator

Reference count 1

Reference count 2

Reference count 1

Reference count 0

sprite is deleted

Reference Counting in Cocos2d-X

```
// create a new instance
Sprite* sprite = Sprite::create();
sprite->retain();

// Add the sprite to scene graph
rootnode->addChild(sprite);

// Do not release the local reference

// Remove from scene graph
scene->removeChild(sprite);
```

Custom allocator

Reference count 1

Reference count 2

Reference count 1

Memory Leak!

Which Is Correct?

```
Sprite* foo(float x, float y) {

    // create a new instance
    Sprite* sp = Sprite::create();
    sp->retain();
    sp->initWithFile("image.png");

    // set the position
    sp.setPosition(Vec2(x,y));

    // free memory
    sp->release();

    // return it
    return sp;
}
```

```
Sprite* foo(float x, float y) {

    // create a new instance
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    sp->retain();
    sp->initWithFile("image.png");

    // set the position
    sp.setPosition(Vec2(x,y));

    // DO NOTHING


    // return it
    return sp;
}
```

Which Is Correct?

```
Sprite* foo(float x, float y) {

    // create a new instance
    Sprite* sp = Sprite::create();
    sp->initWithFile("image.png");

    // set the position
    sp.setPositi

    // free me
    sp->release(

    // return it
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}
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                             on
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    // DO NOTHING


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}
```

Trick Question!

Which Is Correct?

```
Sprite* foo(float x, float y) {

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    // return it
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}
```

Object freed.
Nothing left to return.

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Sprite* foo(float x, float y) {

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    // DO NOTHING

    // return it
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```

Reference kept.
Who will release this?

Which Is Correct?

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Object freed.
Nothing left to return.

```
Sprite* foo(float x, float y

    // create a new instance
                                ();
                                g");

    // DO NOTHING

    // return it
    return sp;
}
```

One possibility: make **ownership transfer** part of the specification

Reference kept.
Who will release this?

Ownership in Specifications

```
/**
 * Creates a sprite at (x,y)
 *
 * @release object ownership
 *          passes to the caller
 *
 * @return a new sprite
 */
Sprite* foo(float x, float y) {
   …
}
```

```
/**
 * Stores the given sprite
 *
 * @retain container acquires
 *          ownership of sprite
 *
 * @param sp  sprite to store
 */
void foo(const Sprite* sp) {
   …
}
```

An Alternate Solution

```
Sprite* foo(float x, float y) {
    // create a new instance
    Sprite* sp = Sprite::create();
    sp->initWithFile("image.png");

    // set the position
    sp.setPosition(Vec2(x,y));

    // free memory
    sp->autorelease();

    // return it
    return sp;
}
```

Delay release until later.

Autorelease

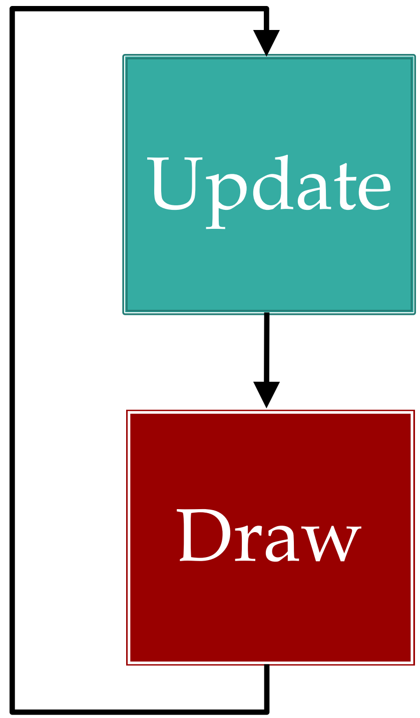
- Places the object in a **pool**
  - Marked for deletion later
  - OS releases all in pool
- When is object deleted?
  - iOS: defined manually
  - Cocos2d: at end of frame?
- Must retain immediately
  - Otherwise, inter-frame obj

Recall: Memory Organization

Inter-Frame Memory

Carries over across frame boundaries

Must retain()



Intra-Frame Memory

Recovered each frame

autorelease() may be ok

Memory Management: **Setters**

```
class GameObject {
private:
    Sprite* _image;
    ...

public:
    ...
    void setSprite(Sprite* s) {
        if (_image != nullptr) _image->release();
        _image = s;
        if (_image != nullptr) _image->retain();
    }
};
```

Protected reference

Release previous

Retain current

Allocation and Memory Management

```
class Sprite : public Node, public TextureProtocol {
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private:
    /** Creates, but does not initialize sprite */
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Allocation and Memory Management

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```
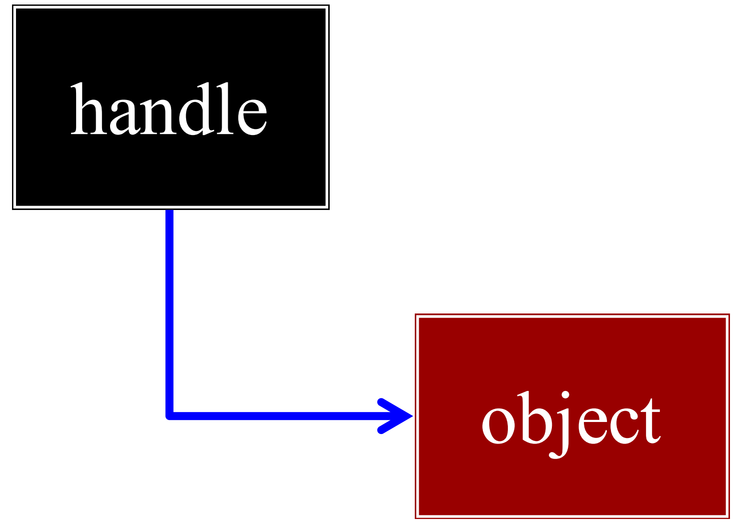

Autorelease

Reference Count 0

C++11 Analogue: Shared Pointers

- C++ can override **anything**
  - Assignment operator =
  - Dereference operator ->
- Use special object as pointer
  - A field to reference object
  - Also a reference counter
  - Assignment increments
- What about decrementing?
  - When smart pointer deleted
  - Delete object if count is 0




```
Foo object = new Class();
shared_ptr<Foo> handle(object);
...
handle->foo();   //object->foo()
```

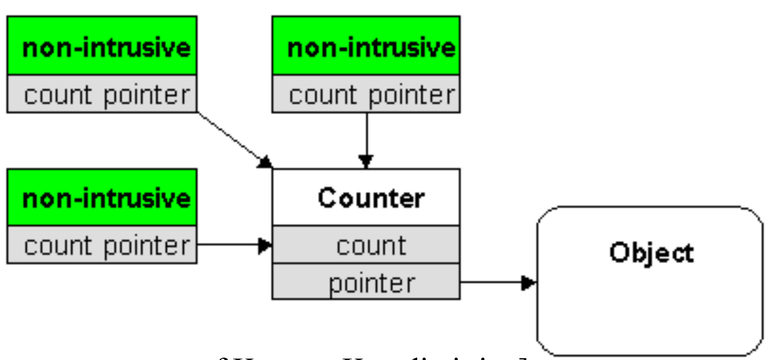
C++11 Analogue: Shared Pointers

```
void foo() {
    shared_ptr<Thing> p1(new Thing);    // Allocate new object
    shared_ptr<Thing> p2=p1;            // p1 and p2 share ownership
    shared_ptr<Thing> p3(newThing);     // Allocate another Thing
    …
    p1 = find_some_thing();    // p1 might be new thing
    p3->defrangulate();        // call a member function
    cout <<*p2 << endl;        // dereference pointer
    …
    // "Free" the memory for pointer
    p1.reset();       // decrement count, delete if last
    p2 = nullptr;     // empty pointer and decrement
}
```

Where Does the Count Go?

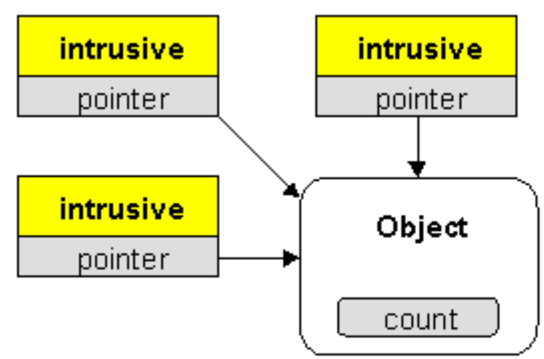
Non-Intruisive Pointers

- Count inside smart pointer
- **Advantage**:
  - Works with any class
- **Disadvantage**:
  - Combining with raw pointers (and hence any stdlib code)



Intruisive Pointers

- Count inside referred object
- Advantage:
  - Easy to mix with raw pointers
- Disadvantage:
  - Requires custom base object



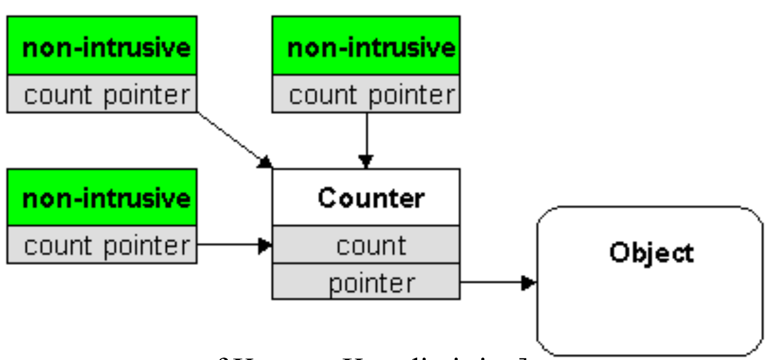
[Images courtesy of Kosmas Karadimitriou]

Where Does the Count Go?

Non-Intruisive Pointers

- Count inside smart pointer
- **Advantag**
- **D**ge:
  - Combining with raw pointers (and hence any stdlib code)

C++11 shared_ptr



Intruisive Pointers

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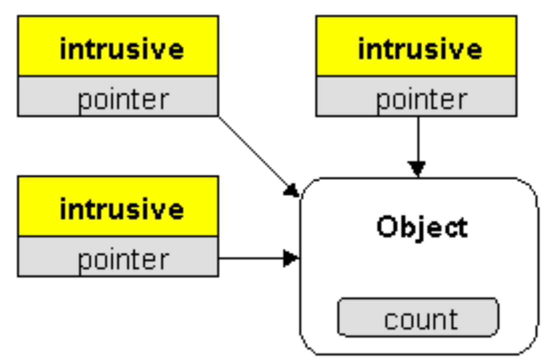
- Advanta
  - s
- ge:
  - Requires custom base object

Cocos2d-X Ref



[Images courtesy of Kosmas Karadimitriou]

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)
  - Requires 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

Summary

- Must control **allocation** of heap objects
  - Preallocate objects when it makes sense
  - Use free-lists to recycle objects when possible
- Must track **ownership** of allocated objects
  - Know who is responsible for deleting
  - True even with Cocos2d reference counting
  - **Rule of Thumb**: Use setters to retain/release