Dynamic Memory Management

Process Memory Layout (1)

Each Linux process runs within its own virtual address space

- The kernel pretends that each process has access to a (huge) continuous range of addresses ($\approx$ 256 TiB on x86-64)
- Virtual addresses are mapped to physical addresses by the kernel using page tables and the MMU (if available)
- Greatly simplifies memory management code in the kernel and improves security due to memory isolation
- Allows for useful “tricks” such as memory-mapping files

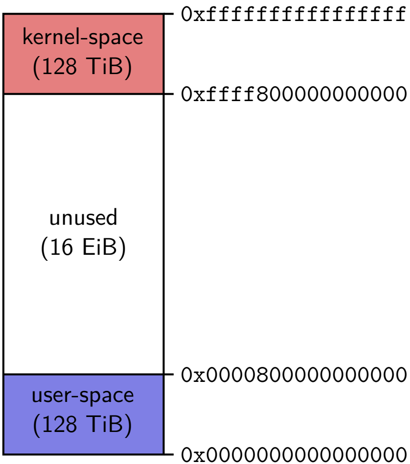
Process Memory Layout (2)

The kernel also uses virtual memory

- Part of the address space has to be reserved for kernel memory
- This kernel-space memory is mapped to the same physical addresses for each process
- Access to this memory is restricted

Most of the address space is unused

- MMUs on x86-64 platforms only support 48 bit pointers at the moment
- Might change in the future (Linux already supports 56 bit pointers)



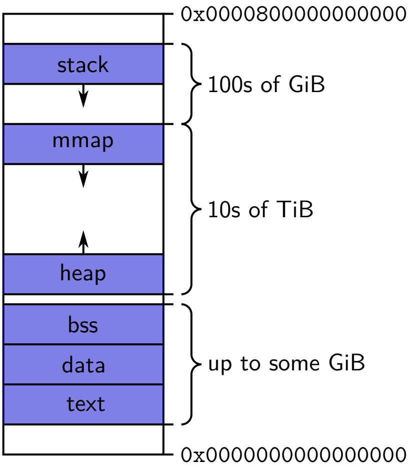
Process Memory Layout (3)

User-space memory is organized in segments

- Stack segment
- Memory mapping segment
- Heap segment
- BSS, data and text segments

Segments can grow

- Stack and memory mapping segments usually grow down (i.e. addresses decrease)
- Heap segment usually grows up (i.e. addresses increase)



Stack Segment (1)

Stack memory is typically used for objects with automatic storage duration

- The compiler can statically decide when allocations and deallocations must happen
- The memory layout is known at compile-time
- Allows for highly optimized code (allocations and deallocations simply increase/decrease a pointer)

Fast, but inflexible memory

- Array sizes must be known at compile-time
- No dynamic data structures are possible (trees, graphs, etc.)

Stack Segment (2)

Example

foo.cpp

```cpp
int foo() {
    int c = 2;
    int d = 21;

    return c * d;
}

int main() {
    int a[100];
    int b = foo();

    return b;
}
```

foo.o

```
foo():
    pushq   %rbp
    movq    %rsp, %rbp
    movl    $2, -4(%rbp)
    movl    $21, -8(%rbp)
    movl    -4(%rbp), %eax
    imull   -8(%rbp), %eax
    popq    %rbp
    ret
main:
    pushq   %rbp
    movq    %rsp, %rbp
    subq    $416, %rsp
    call    foo()
    movl    %eax, -4(%rbp)
    movl    -4(%rbp), %eax
    leave
    ret
```

Heap Segment

The heap is typically used for objects with dynamic storage duration

- The *programmer* must explicitly manage allocations and deallocations
- Allows much more flexible programs

Disadvantages

- Performance impact due to non-trivial implementation of heap-based memory allocation
- Memory fragmentation
- Dynamic memory allocation is error-prone
  - Memory leaks
  - Double free (deallocation)
  - Make use of debugging tools (GDB, ASAN (!))

Dynamic Memory Management in C++

C++ provides several mechanisms for dynamic memory management

- Through `new` and `delete` expressions (discouraged)
- Through the C functions `malloc` and `free` (discouraged)
- Through smart pointers and ownership semantics (preferred)

Mechanisms give control over the storage duration and possibly lifetime of objects

- Level of control varies by method
- In all cases: Manual intervention required

The new Expression

Creates and initializes objects with dynamic storage duration

- Syntax: `new` *`type initializer`*
- *`type`* must be a type
- *`type`* can be an array type
- *`initializer`* can be omitted

Explanation

- Allocates heap storage for a single object or an array of objects
- Constructs and initializes a single object or an array of objects in the newly allocated storage
- If *`initializer`* is absent, the object is default-initialized
- Returns a pointer to the object or the initial element of the array

The `delete` Expression

Every object allocated through `new` must be destroyed through `delete`

- Syntax (single object): `delete expression`
- *`expression`* must be a pointer created by the single-object form of the `new` expression
- Syntax (array): `delete[] expression`
- *`expression`* must be a pointer created by the array form of the `new` expression
- In both cases *`expression`* may be `nullptr`

Explanation

- If *`expression`* is `nullptr` nothing is done
- Invokes the destructor of the object that is being destroyed, or of every object in the array that is being destroyed
- Deallocates the memory previously occupied by the object(s)

new & delete Example

```
class IntList {
    struct Node {
        int value;
        Node* next;
    };

    Node* first;
    Node* last;

    public:
    ~IntList() {
        while (first != nullptr) {
            Node* next = first->next;
            delete first;
            first = next;
        }
    }

    void push_back(int i) {
        Node* node = new Node{i, nullptr};
        if (!last)
            first = node;
        else
            last->next = node;
        last = node;
    }
};
```

Memory Leaks

Memory leaks can happen easily

```
int foo(unsigned length) {
    int* buffer = new int[length];

    /* ... do something ... */

    if (condition)
        return 42;  // MEMORY LEAK

    /* ... do something else ... */

    delete[] buffer;
    return 123;
}
```

Avoid explicit memory management through `new` and `delete` whenever possible

Placement new (1)

Constructs objects in already allocated storage

- Syntax: `new` (*placement_params*) *type initializer*
- *placement_params* must be a pointer to a region of storage large enough to hold an object of type *type*
- The strict aliasing rule must not be violated
- Alignment must be ensured manually
- Only rarely required (e.g. for custom memory management)
- Requires that the <new> standard header is included

Placement new (2)

Example

```
#include <cstddef>
#include <new>

struct A { };

int main() {
        std::byte* buffer = new std::byte[sizeof(A)];
        A* a = new (buffer) A();
        /* ... do something with a ... */
        a->~A();  // we must explicitly call the destructor
        delete[] buffer;
}
```

Lifetimes and Storage Duration (1)

The lifetime of an object is equal to or nested within the lifetime of its storage

- Equal for regular `new` and `delete`
- Possibly nested for placement `new`

Example

```
struct A { };

int main() {
    A* a1 = new A();        // lifetime of a1 begins, storage begins
    a1->~A();               // lifetime of a1 ends
    A* a2 = new (a1) A();   // lifetime of a2 begins
    delete a2;              // lifetime of a2 ends, storage ends
}
```

Lifetimes and Storage Duration (2)

Lifetime and storage duration of objects have real-world implications

- Accessing objects outside of their lifetime is undefined behavior and will often lead to segmentation faults
- Important to always keep track of lifetimes (if necessary through suitable comments)
- Use debugging tools (in particular ASAN) to find such bugs!

Examples of common bugs

- Returning pointers/references to local variables from functions
- Using a pointer/reference to access memory that has already been freed
- Using a pointer/reference to access an object that has already been destructed
- Maintaining pointers/references to objects in an `std::vector` after its internal storage has been reallocated (e.g. through a call to push_back)
- ...

std::memcpy (1)

std::memcpy copies bytes between non-overlapping memory regions

- Defined in <cstring> standard header
- Syntax: `void* memcpy(void* dest, const void* src, std::size_t count);`
- Copies count bytes from the object pointed to by src to the object pointed to by dest
- Can be used to work around strict aliasing rules without causing undefined behavior

Restrictions (undefined behavior if violated)

- Objects must not overlap
- src and dest must not be nullptr
- Objects must be *trivially copyable*
- dest must be aligned suitably

std::memcpy (2)

Example (straightforward copy)

```
#include <cstring>
#include <vector>

int main() {
    std::vector<int> buffer = {1, 2, 3, 4};
    buffer.resize(8);
    std::memcpy(&buffer[4], &buffer[0], 4 * sizeof(int));
}
```

Example (work around strict aliasing)

```
#include <cstring>
#include <cstdint>

int main() {
    int64_t i = 42;
    double j;
    std::memcpy(&j, &i, sizeof(double)); // OK
}
```

std::memmove (1)

std::memmove copies bytes between possibly overlapping memory regions

- Defined in <cstring> standard header
- Syntax: `void* memmove(void* dest, const void* src, std::size_t count);`
- Copies count bytes from the object pointed to by src to the object pointed to by dest
- Acts as if the bytes were copied to a temporary buffer

Restrictions (undefined behavior if violated)

- src and dest must not be nullptr
- Objects must be *trivially copyable*
- dest must be suitably aligned

std::memmove (2)

Example (straightforward copy)

```
#include <cstring>
#include <vector>

int main() {
    std::vector<int> buffer = {1, 2, 3, 4};
    buffer.resize(6);
    std::memmove(&buffer[2], &buffer[0], 4 * sizeof(int));
    // buffer is now {1, 2, 1, 2, 3, 4}
}
```

Copy and Move Semantics

Copy Semantics

Assignment and construction of classes employs *copy semantics* in most cases

- By default, a shallow copy is created
- Usually not particularly relevant for fundamental types
- Very relevant for user-defined class types

Considerations for user-defined class types

- Copying may be expensive
- Copying may be unnecessary or even unwanted
- An object on the left-hand side of an assignment might manage dynamic resources

Copy Constructor (1)

Invoked whenever an object is initialized from an object of the same type

- Syntax: `class_name ( const class_name& )`
- `class_name` must be the name of the current class

For a class type `T` and objects `a`, `b`, the copy constructor is invoked on

- Copy initialization: `T a = b;`
- Direct initialization: `T a(b);`
- Function argument passing: `f(a);` where `f` is `void f(T t);`
- Function return: `return a;` inside a function `T f();` if `T` has no move constructor (more details next)

Copy Constructor (2)

Example

```
class A {
    private:
    int v;

    public:
    explicit A(int v) : v(v) { }
    A(const A& other) : v(other.v) { }
};

int main() {
    A a1(42);    // calls A(int)

    A a2(a1);    // calls copy constructor
    A a3 = a2;   // calls copy constructor
}
```

Copy Assignment (1)

Typically invoked if an object appears on the left-hand side of an assignment with an lvalue on the right-hand side

- Syntax (1): `class_name& operator=( class_name )`
- Syntax (2): `class_name& operator=( const class_name& )`
- *`class_name`* must be the name of the current class
- Usually, option (2) is preferred unless the *copy-and-swap* idiom is used (more details next)

Explanation

- Called whenever selected by overload resolution
- Returns a reference to the object itself (i.e. `*this`) to allow for chaining assignments

Copy Assignment (2)

Example

```
class A {
    private:
    int v;

    public:
    explicit A(int v) : v(v) { }
    A(const A& other) : v(other.v) { }

    A& operator=(const A& other) {
        v = other.v;
        return *this;
    }
};

int main() {
    A a1(42);   // calls A(int)
    A a2 = a1;  // calls copy constructor

    a1 = a2;    // calls copy assignment operator
}
```

Implicit Declaration (1)

The compiler will implicitly declare a copy constructor if no user-defined copy constructor is provided

- The implicitly declared copy constructor will be a `public` member of the class
- The implicitly declared copy constructor may or may not be defined

The implicitly declared copy constructor is defined as *deleted* if one of the following is true

- The class has non-static data members that cannot be copy-constructed
- The class has a base class which cannot be copy-constructed
- The class has a base class with a deleted or inaccessible destructor
- The class has a user-defined move constructor or assignment operator
- See the reference documentation for more details

In some cases, this can be circumvented by explicitly defaulting the constructor.

Implicit Declaration (2)

The compiler will implicitly declare a copy assignment operator if no user-defined copy assignment operator is provided

- The implicitly declared copy assignment operator will be a `public` member of the class
- The implicitly declared copy assignment operator may or may not be defined

The implicitly declared copy assignment operator is defined as *deleted* if one of the following is true

- The class has non-static data members that cannot be copy-assigned
- The class has a base class which cannot be copy-assigned
- The class has a non-static data member of reference type
- The class has a user-defined move constructor or assignment operator
- See the reference documentation for more details

In some cases, this can be circumvented by explicitly defaulting the assignment operator.

Implicit Definition

If it is not deleted, the compiler defines the implicitly-declared copy constructor

- Only if it is actually used (odr-used)
- Performs a full member-wise copy of the object's bases and members in their initialization order
- Uses direct initialization

If it is not deleted, the compiler defines the implicitly-declared copy assignment operator

- Only if it is actually used (odr-used)
- Performs a full member-wise copy assignment of the object's bases and members in their initialization order
- Uses built-in assignment for scalar types and copy assignment for class types

Example: Implicit Declaration & Definition

Example

```
struct A {
    const int v;

    explicit A(int v) : v(v) { }
};

int main() {
    A a1(42);

    A a2(a1);  // OK: calls the generated copy constructor
    a1 = a2;   // ERROR: the implicitly-declared copy assignment
               //        operator is deleted
}
```

Trivial Copy Constructor and Assignment Operator (1)

The copy constructor/assignment operator may be *trivial*

- It must not be user-provided (explicitily defaulting does not count as user-provided)
- The class has no virtual member functions
- The copy constructor/assignment operator for all direct bases and non-static data members of class type is trivial

A trivial copy constructor/assignment operator behaves similar to `std::memcpy`

- Every scalar subobject is copied recursively and no further action is performed
- The object representation of the copied object is not necessarily identical to the source object
- Trivially copyable objects may legally be copied using `std::memcpy`
- All data types compatible with C are trivially copyable

Trivial Copy Constructor and Assignment Operator (2)

Example

```
#include <vector>

struct A {
    int b;
    double c;
};

int main() {
    std::vector<A> buffer1;
    buffer1.resize(10);

    std::vector<A> buffer2;     // copy buffer1 using copy-constructor
    for (const A& a : buffer1)
        buffer2.push_back(a);

    std::vector<A> buffer3;     // copy buffer1 using memcpy
    buffer3.resize(10);
    std::memcpy(&buffer3[0], &buffer1[0], 10 * sizeof(A));
}
```

Implementing Custom Copy Operations (1)

Custom copy constructors/assignment operators are only **occasionally** necessary

- Often, a class should not be copyable anyway if the implicitly generated versions do not make sense
- Exceptions include classes which manage some kind of resource (e.g. dynamic memory)

Guidelines for implementing custom copy operations

- The programmer should either provide neither a copy constructor nor a copy assignment operator, or both
- The copy assignment operator should usually include a check to detect self-assignment
- If possible, resources should be reused
- If resources cannot be reused, they have to be cleaned up properly

Implementing Custom Copy Operations (2)

Example

```
struct A {
    unsigned capacity;
    int* memory;

    explicit A(unsigned capacity) : capacity(capacity), memory(new int[capacity]) { }
    A(const A& other) : A(other.capacity) {
        std::memcpy(memory, other.memory, capacity * sizeof(int));
    }
    ~A() { delete[] memory; }

    A& operator=(const A& other) {
        if (this == &other)                 // check for self-assignment
            return *this;

        if (capacity != other.capacity) {  // attempt to reuse resources
            delete[] memory;
            capacity = other.capacity;
            memory = new int[capacity];
        }

        std::memcpy(memory, other.memory, capacity * sizeof(int));

        return *this;
    }
};
```

Move Semantics

Copy semantics often incur unnecessary overhead or are unwanted

- An object may be immediately destroyed after it is copied
- An object might not want to share a resource it is holding

Move semantics provide a solution to such issues

- Move constructors/assignment operators typically "steal" the resources of the argument
- Leave the argument in a valid but indeterminate state
- Greatly enhances performance in some cases

Move Construction (1)

Typically called when an object is initialized from an rvalue of the same type

- Syntax: `class_name ( class_name&& ) noexcept`
- *`class_name`* must be the name of the current class
- The `noexcept` keyword should be added to indicate that the constructor never throws an exception

Explanation

- Overload resolution decides if the copy or move constructor of an object should be called
- Temporary values and calls to functions that return an object are rvalues
- The `std::move` function in the `<utility>` header may be used to convert an lvalue to an rvalue
- We know that the argument does not need its resources anymore, so we can simply steal them

Move Construction (2)

For a class type `T` and objects `a`, `b`, the move constructor is invoked on

- Direct initialization: `T a(std::move(b));`
- Copy initialization: `T a = std::move(b);`
- Function argument passing: `f(std::move(b));` with `void f(T t);`
- Function return: `return a;` inside `T f();`

Example

```
struct A {
    A(const A& other);
    A(A&& other);
};
A getA();
int main() {
    A a1;
    A a2(a1);             // calls copy constructor
    A a3(std::move(a1));  // calls move constructor
    A a4(getA());         // calls move constructor
}
```

Move Assignment (1)

Typically called if an object appears on the left-hand side of an assignment with an rvalue on the right-hand side

- Syntax: `class_name& operator=( class_name&& ) noexcept`
- *`class_name`* must be the name of the current class
- The `noexcept` keyword should be added to indicate that the assignment operator never throws an exception

Explanation

- Overload resolution decides if the copy or move assignment operator of an object should be called
- We know that the argument does not need its resources anymore, so we can simply steal them
- The move assignment operator returns a reference to the object itself (i.e. `*this`) to allow for chaining

Move Assignment (2)

Example

```
struct A {
    A();
    A(const A&);
    A(A&&) noexcept;

    A& operator=(const A&);
    A& operator=(A&&) noexcept;
};

int main() {
    A a1;
    A a2 = a1;              // calls copy-constructor
    A a3 = std::move(a1);   // calls move-constructor

    a3 = a2;                // calls copy-assignment
    a2 = std::move(a3);     // calls move-assignment
}
```

Implicit Declaration (1)

The compiler will implicitly declare a `public` move constructor if all the following conditions hold

- There are no user-declared copy constructors
- There are no user-declared copy assignment operators
- There are no user-declared move assignment operators
- There are no user-declared destructors

The implicitly declared move constructor is defined as *deleted* if one of the following is true

- The class has non-static data members that cannot be moved
- The class has a base class which cannot be moved
- The class has a base class with a deleted or inaccessible destructor
- See the reference documentation for more details

In some cases, this can be circumvented by explicitly defaulting the constructor.

Implicit Declaration (2)

The compiler will implicitly declare a `public` move assignment operator if all the following conditions hold

- There are no user-declared copy constructors
- There are no user-declared copy assignment operators
- There are no user-declared move constructors
- There are no user-declared destructors

The implicitly declared move assignment operator is defined as *deleted* if one of the following is true

- The class has non-static data members that cannot be moved
- The class has non-static data members of reference type
- The class has a base class which cannot be moved
- The class has a base class with a deleted or inaccessible destructor
- See the reference documentation for more details

In some cases, this can be circumvented by explicitly defaulting the assignment operator.

Implicit Definition

If it is not deleted, the compiler defines the implicitly-declared move constructor

- Only if it is actually used (odr-used)
- Performs a full member-wise move of the object's bases and members in their initialization order
- Uses direct initialization

If it is not deleted, the compiler defines the implicitly-declared move assignment operator

- Only if it is actually used (odr-used)
- Performs a full member-wise move assignment of the object's bases and members in their initialization order
- Uses built-in assignment for scalar types and move assignment for class types

Example: Implicit Declaration & Definition

Example

```
struct A {
    const int v;

    explicit A(int v) : v(v) { }
};

int main() {
    A a1(42);

    A a2(std::move(a1));  // OK: calls the generated move constructor
    a1 = std::move(a2);   // ERROR: the implicitly-declared move
                          //        assignment operator is deleted
}
```

Trivial Move Constructor and Assignment Operator

The move constructor/assignment operator may be *trivial*

- It must not be user-provided (explicitily defaulting does not count as user-provided)
- The class has no virtual member functions
- The move constructor/assignment operator for all direct bases and non-static data members of class type is trivial

A trivial move constructor/assignment operator acts similar to `std::memcpy`

- Every scalar subobject is copied recursively and no further action is performed
- The object representation of the copied object is not necessarily identical to the source object
- Trivially movable objects may legally be moved using `std::memcpy`
- All data types compatible with C are trivially movable

Implementing Custom Move Operations (1)

Custom move constructors/assignment operators are **often** necessary

- A class that manages some kind of resource *almost always* requires custom move constructors and assignment operators

Guidelines for implementing custom move operations

- The programmer should either provide neither a move constructor nor a move assignment operator, or both
- The move assignment operator should usually include a check to detect self-assignment
- The move operations should typically not allocate new resources, but steal the resources from the argument
- The move operations should leave the argument in a valid state
- Any previously held resources must be cleaned up properly

Implementing Custom Move Operations (2)

Example

```
struct A {
    unsigned capacity;
    int* memory;

    explicit A(unsigned capacity) : capacity(capacity), memory(new int[capacity]) { }
    A(A&& other) noexcept : capacity(other.capacity), memory(other.memory) {
        other.capacity = 0;
        other.memory = nullptr;
    }
    ~A() { delete[] memory; }

    A& operator=(A&& other) noexcept {
        if (this == &other)          // check for self-assignment
            return *this;

        delete[] memory;
        capacity = other.capacity;
        memory = other.memory;

        other.capacity = 0;
        other.memory = nullptr;

        return *this;
    }
};
```

Copy Elision (1)

Compilers must omit copy and move constructors under certain circumstances

- Objects are instead directly constructed in the storage into which they would be copied/moved
- Results in zero-copy pass-by-value semantics
- Most importantly in return statements and variable initialization from a temporary
- More optimizations allowed, but not required

This is one of very few optimizations which is allowed to change observable side-effects

- Not all compilers perform the same optional optimizations
- Programs that rely on side-effects of copy/move constructors and destructors are not portable

Copy Elision (2)

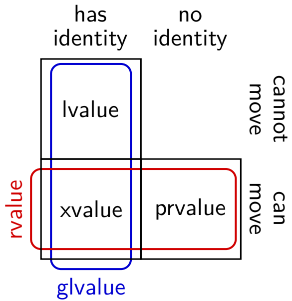
Example

```
#include <iostream>

struct A {
    int a;

    A(int a) : a(a) {
        std::cout << "constructed" << std::endl;
    }

    A(const A& other) : a(other.a) {
        std::cout << "copy-constructed" << std::endl;
    }
};

A foo() {
    return A(42);
}

int main() {
    A a = foo();  // prints only "constructed"
}
```

Value Categories

Move semantics and copy elision require a more sophisticated taxonomy of expressions

- glvalues identify objects
- xvalues identify an object whose resources can be reused
- prvalues compute the value of an operand or initialize an object



In particular, `std::move` just converts its argument to an xvalue expression

- `std::move` is exactly equivalent to a `static_cast` to an rvalue reference
- `std::move` is exclusively syntactic sugar (to guide overload resolution)

Copy-And-Swap (1)

The copy-and-swap idiom is convenient if copy assignment cannot benefit from resource reuse

- The class defines only the `class_type& operator=( class_type )` copy-and-swap assignment operator
- Acts both as copy and move assignment operator depending on the value category of the argument

Implementation

- Exchange the resources between the argument and `*this`;
- Let the destructor clean up the resources of the argument

Copy-And-Swap (2)

Example

```cpp
#include <algorithm>
#include <cstring>

struct A {
    unsigned capacity;
    int* memory;

    explicit A(unsigned capacity) : capacity(capacity), memory(new int[capacity]) { }
    A(const A& other) : A(other.capacity) {
        std::memcpy(memory, other.memory, capacity * sizeof(int));
    }
    ~A() { delete[] memory; }

    A& operator=(A other) { // copy/move constructor is called to create other
        std::swap(capacity, other.capacity);
        std::swap(memory, other.memory);

        return *this;
    }  // destructor cleans up resources formerly held by *this
};
```

Temporarily uses more resources than strictly required

The Rule of Three

If a class requires one of the following, it almost certainly requires all three

- A user-defined destructor
- A user-defined copy constructor
- A user-defined copy assignment operator

Explanation

- Having a user-defined copy constructor usually implies some custom setup logic which needs to be executed by copy assignment and vice-versa
- Having a user-defined destructor usually implies some custom cleanup logic which needs to be executed by copy assignment and vice-versa
- The implicitly-defined versions are usually incorrect if a class manages a resource of non-class type (e.g. a raw pointer, POSIX file descriptor, etc.)

The Rule of Five

If a class follows the rule of three, move operations are defined as deleted

- If move semantics are desired for a class, it has to define all five special member functions
- If only move semantics are desired for a class, it still has to define all five special member functions, but define the copy operations as deleted

Explanation

- Not adhering to the rule of five usually does not lead to incorrect code
- However, many optimization opportunities may be inaccessible to the compiler if no move operations are defined

Resource Acquisition is Initialization (1)

Bind the lifetime of a resource that has to be allocated to the lifetime of an object

- Resources can be allocated heap memory, sockets, files, mutexes, disk space, database connections, etc.
- Guarantees availability of the resource during the lifetime of the object
- Guarantees that resources are released when the lifetime of the object ends
- Object should have automatic storage duration
- Known as the **Resource Acquisition is Initialization (RAII)** idiom

One of the most important and powerful idioms in C++!

- One consequence: Never use `new` and `delete` outside of an RAII class
- C++ already defines *smart pointers* that are RAII wrappers for `new` and `delete`
- Thus we almost never need to use `new` and `delete` in our code

Resource Acquisition is Initialization (2)

Implementation of RAII

- Encapsulate each resource into a class whose sole responsibility is managing the resource
- The constructor acquires the resource and establishes all class invariants
- The destructor releases the resource
- Typically, copy operations should be deleted and custom move operations need to be implemented

Usage of RAII classes

- RAII classes should only be used with automatic or temporary storage duration
- Ensures that the compiler manages the lifetime of the RAII object and thus indirectly manages the lifetime of the resource

Resource Acquisition is Initialization (3)

Example

```
class CustomIntBuffer {
private:
    int* memory;
public:
    explicit CustomIntBuffer(unsigned size) : memory(new int[size]) { }
    CustomIntBuffer(const CustomIntBuffer&) = delete;
    CustomIntBuffer(CustomIntBuffer&& other) noexcept : memory(other.memory) {
        other.memory = nullptr;
    }
    ~CustomIntBuffer() { delete[] memory; }

    CustomIntBuffer& operator=(const CustomIntBuffer&) = delete;
    CustomIntBuffer& operator=(CustomIntBuffer&& other) noexcept {
        if (this != &other) {
            delete[] memory;
            memory = other.memory;
            other.memory = nullptr;
        }
        return *this;
    }

    int* getMemory() { return memory; }
    const int* getMemory() const { return memory; }
};
```

Resource Acquisition is Initialization (4)

Example usage of the `CustomIntBuffer` class

```
#include <utility>

bool foo(CustomIntBuffer buffer) {
    /* do something */

    if (condition)
        return false;  // no worries about forgetting to free memory

    /* do something more */

    return true;       // no worries about forgetting to free memory
}

int main() {
    CustomIntBuffer buffer(5);

    return foo(std::move(buffer));
}
```

Ownership

Ownership Semantics

One of the main challenges in manual memory management is tracking ownership

- Traditionally, owners can be, e.g., functions or classes
- Only the owner of some dynamically allocated memory may safely free it
- Multiple objects may have a pointer to the same dynamically allocated memory

The RAII idiom and move semantics together enable *ownership semantics*

- A resource should be "owned", i.e. encapsulated, by exactly one C++ object at all times
- Ownership can only be transferred explicitly by moving the respective object
- E.g., the `CustomIntBuffer` class implements ownership semantics for a dynamically allocated `int`-array

std::unique_ptr (1)

std::unique_ptr is a so-called *smart pointer*

- Essentially implements RAII/ownership semantics for arbitrary pointers
- Assumes unique ownership of another C++ object through a pointer
- Automatically disposes of that object when the std::unique_ptr goes out of scope
- A std::unique_ptr may own no object, in which case it is empty
- Can be used (almost) exactly like a raw pointer
- But: std::unique_ptr can only be moved, not copied

std::unique_ptr is defined in the <memory> standard header

- It is a template class, and can be used for arbitrary types
- Syntax: std::unique_ptr< type > where one would otherwise use type*

std::unique_ptr should *always* be preferred over raw pointers!

std::unique_ptr (2)

Usage of std::unique_ptr (for details: see reference documentation)

Creation

- std::make_unique<type>(arg0, ..., argN), where arg0, ..., argN are passed to the constructor of type

Indirection, subscript, and member access

- The indirection, subscript, and member access operators *, [] and -> can be used in the same way as for raw pointers

Conversion to bool

- std::unique_ptr is contextually convertible to bool, i.e. it can be used in if statements in the same way as raw pointers

Accessing the raw pointer

- The get() member function returns the raw pointer
- The release() member function returns the raw pointer and releases ownership

std::unique_ptr (3)

Example

```
#include <memory>

struct A {
    int a;
    int b;

    A(int a, int b) : a(a), b(b) { }
};
void foo(std::unique_ptr<A> aptr) {  // assumes ownership
    /* do something */
}
void bar(const A& a) { // does not assume ownership
    /* do something */
}
int main() {
    std::unique_ptr<A> aptr = std::make_unique<A>(42, 123);
    int a = aptr->a;
    bar(*aptr);             // retain ownership
    foo(std::move(aptr));   // transfer ownership
}
```

std::unique_ptr (4)

std::unique_ptr can also be used for heap-based arrays

```
std::unique_ptr<int[]> foo(unsigned size) {
    std::unique_ptr<int[]> buffer = std::make_unique<int[]>(size);

    for (unsigned i = 0; i < size; ++i)
        buffer[i] = i;

    return buffer;  // transfer ownership to caller
}

int main() {
    std::unique_ptr<int[]> buffer = foo(42);

    /* do something */
}
```

std::shared_ptr (1)

Rarely, true *shared ownership* is desired

- A resource may be simultaneously have several owners
- The resource should only be released once the last owner releases it
- std::shared_ptr defined in the <memory> standard header can be used for this
- Multiple std::shared_ptr objects may own the same raw pointer (implemented through reference counting)
- std::shared_ptr may be copied and moved

Usage of std::shared_ptr

- Use std::make_shared for creation
- Remaining operations analogous to std::unique_ptr
- For details: See the reference documentation

std::shared_ptr is rather expensive and should be avoided when possible

std::shared_ptr (2)

Example

```
#include <memory>
#include <vector>

struct Node {
    std::vector<std::shared_ptr<Node>> children;

    void addChild(std::shared_ptr<Node> child);
    void removeChild(unsigned index);
};

int main() {
    Node root;
    root.addChild(std::make_shared<Node>());
    root.addChild(std::make_shared<Node>());
    root.children[0]->addChild(root.children[1]);

    root.removeChild(1);  // does not free memory yet
    root.removeChild(0);  // frees memory of both children
}
```

Usage Guidelines: Pointers (1)

`std::unique_ptr` represents ownership

- Used for dynamically allocated objects
  - Frequently required for polymorphic objects
  - Useful to obtain a movable handle to an immovable object
- `std::unique_ptr` as a function parameter or return type indicates a transfer of ownership
- `std::unique_ptr` should almost always be passed *by value*

Raw pointers represent resources

- Should almost always be encapsulated in RAII classes (mostly `std::unique_ptr`)
- Very occasionally, raw pointers are desired as function parameters or return types
  - If ownership is not transferred, but there might be no object (i.e. `nullptr`)
  - If ownership is not transferred, but pointer arithmetic is required

Usage Guidelines: References (2)

References grant temporary access to an object without assuming ownership

- If necessary, a reference can be obtained from a smart pointer through the indirection operator `*`

Ownership can also be relevant for other types (e.g. `std::vector`)

- Moving (i.e. transferring ownership) should always be preferred over copying
- Should be passed *by lvalue-reference* if ownership is not transferred
- Should be passed *by rvalue-reference* if ownership is transferred
- Should be passed *by value* if they should be copied

Rules can be relaxed if an object is not copyable

- Should be passed *by lvalue-reference* if ownership is not transferred
- Should be passed *by value* if ownership is transferred

Usage Guidelines (3)

Example

```
struct A { };

// reads a without assuming ownership
void readA(const A& a);
// may read and modify a but doesn't assme ownership
void readWriteA(A& a);
// assumes ownership of A
void consumeA(A&& a);
// works on a copy of A
void workOnCopyOfA(A a);

int main() {
    A a;

    readA(a);
    readWriteA(a);
    workOnCopyOfA(a);
    consumeA(std::move(a));  // cannot call without std::move
}
```

Usage Guidelines: Function Arguments (1)

When dealing with an object of type T use the following rough guidelines to decide which type to use when passing it as function argument:

Situation	Type to Use
▪ Ownership of object should be transferred to callee ▪ Potential copies are acceptable or T is not copyable ▪ Object is relatively small (at most ≈ one cache line)	`T`
▪ Ownership of object should be transferred to callee ▪ Object is relatively large (more than ≈ one cache line), so it should live on the heap	`std::unique_ptr<T>`

Usage Guidelines: Function Arguments (2)

Situation	Type to Use
▪ Ownership of object should *not* be transferred to callee ▪ Callee should not modify object ▪ Object is larger than a pointer	`const T&`
▪ Ownership of object should *not* be transferred to callee ▪ Callee is expected to modify the object	`T&`
▪ Same as `const T&`, but should be nullable	`const T*`
▪ Same as `T&`, but should be nullable	`T*`