CMPUT 350 - ECS
Entity Component Systems

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October 28, 2024

Change Log

Motivation

Suppose we want to create a video game which has the following:

- Different classes of characters types (monsters, humans, etc.)
- Each class has different races (goblin and spiders are monsters)
- All characters need to be drawn on screen and has various behaviours

What techniques have we learned to structure our code logic to reduce code complexity and promote code reuse?

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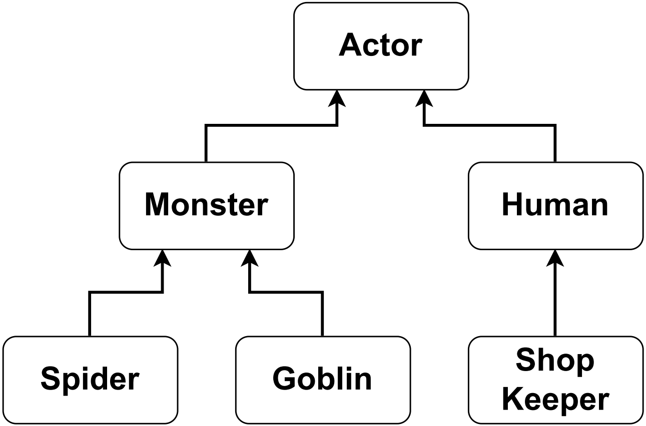
What techniques have we learned to structure our code logic to reduce code complexity and promote code reuse?

Inheritance!

Motivation



Motivation

```cpp
struct Actor {
    virtual void Render() const = 0;
    virtual void Act() = 0;
};

// Monsters
struct Monster : public Actor { };
struct Spider : public Monster {
    void Render() const override;
    void Act() override;
};
struct Goblin : public Monster {
    void Render() const override;
    void Act() override;
};

// Humans
struct Human : public Actor { };
struct ShopKeeper : public Human {
    void Render() const override;
    void Act() override;
};
```

Motivation

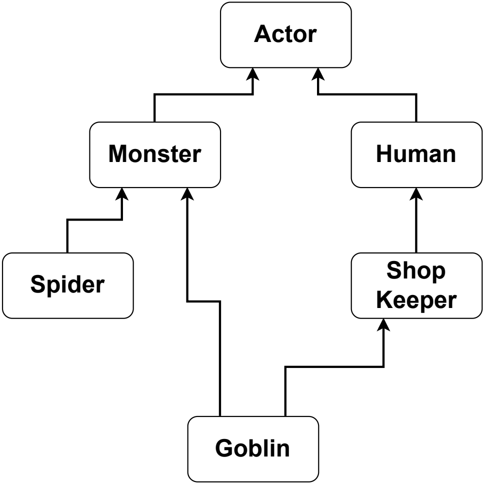
We can call the correct class behaviour through virtual functions:

```
void Render(const std::vector<Actor*> &actors) {
    for (const auto & actor : actors) {
        actor->Render();
    }
}

void Act(std::vector<Actor*> &actors) {
    for (const auto & actor : actors) {
        actor->Act();
    }
}
```

Inheritance Problems

Suppose Goblins can also be Shop-Keepers... Do they also now become Humans?

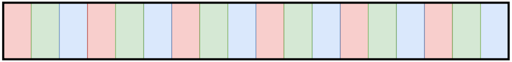


Cache Efficiency

Suppose Actors have the following data:

```
struct Actor {
    std::pair<int, int> pos;    // pos.x = red, pos.y = green
    double velocity;            // blue
};
void update_velocity(std::vector<Actor*> &actors) {
    for (const auto & actor : actors) {
        update(actor.velocity);
    }
}
```

If we many Actors (Goblins, Spiders, Shop Keepers, etc.) allocated contiguously, a function which operates on the actors will fetch them into cache lines:



Since only one data member is being operated on in this function, we are wasting 2/3 of our cache with unrelated data!

Motivation

Benefits:

- Code reuse
- Works well for tree-based dependencies

Downsides:

- How do we deal with multiple inheritance
  - Are Goblins now Humans?
- Need to use virtual function tables + pointers → object data not in cache (SLOW!)

Entity Component Systems (ECS)

Entity Component Systems are comprised of three parts:

- **Entity**: An identifier for each entity
- **Components**: Characterizes an entity as possessing a particular aspect, and holds the data to represent that.
- **Systems**: A process which acts on all entities with the desired components

ECS Example

	Entity 1	Entity 2	Entity 3
Component 1	[Data]		
Component 2	[Data]	[Data]	[Data]
Component 3		[Data]	[Data]

[1]

[1] https://en.wikipedia.org/wiki/Entity_component_system

ECS - Entity

Entities are very simple: An unqiue ID which we can use to index various groups of data

```
// size_t is often used to index contiguous data structures
using Entity = std::size_t;

// Our engine can at most handle 5000 entities
const std::size_t MAX_ENTITIES = 5000;
```

ECS - Components

Components represent a collection of data related to a particular aspect

```cpp
template <typename T>
struct Heading2D {       // 2D vector heading
    T x;
    T y;
};

template <typename T>
struct Position {        // 2D grid position
    T x;
    T y;
};

template <typename T>
struct Health {          // All units have health
    T health;
};

template <typename T>
struct Radius {          // All units have a radius
    T radius;
};
```

ECS - Components

To refer to components later, we will assign each a unique ID to it

```
// size_t is often used to index contiguous data structures
using ComponentType = std::size_t;

// Our engine can at most handle 32 components
const std::size_t MAX_COMPONENTS = 32;
```

ECS - Components

Systems will want to refer to a collection of components which define some aspect:

- Our collision system will want to update all entities which have a `Position`, `Radius`, and `Heading2D` component (non-inclusive)

As such, we need a way track which components belong to which entities (which is just an integer). We can do so by using a collection of N bits to represent which of the N components are required (either for a system or for which an entity has):

```
// Signature represents MAX_COMPONENTS bits, like our Set from Assignment 1
using Signature = std::bitset<MAX_COMPONENTS>;
```

ECS - Entity Manager

The `EntityManager` is responsible for distributing Entity IDs and tracking what is the signature of each Entity (what components does it have):

```
class EntityManager {
public:
    EntityManager();

    // Take ID from front of the queue
    //  if we have not handed out all our entities
    auto create_entity() -> Entity;

    // Take back the entity to give out later again
    void destroy_entity(Entity entity);

    void set_entity_signature(Entity entity, Signature signature);

    auto get_entity_signature(Entity entity) -> Signature;

private:
    std::queue<Entity> available_entities;
    std::array<Signature, MAX_ENTITIES> entity_signatures;
};
```

ECS - Component Array

For each component, we can store the data in a contiguous array (FAST!)

```
template <typename T>
struct ComponentArray {
    std::array<T, MAX_COMPONENTS> component_array;
};

ComponentArray<Position> position_components;
```

Entities are just indices, but:

- If entities are created and destroyed, some indices may not be valid
- Not all entities have all components

Thus, this array will have gaps if we naively implement this ...

ECS - Component Array

We can use a map to track which Entity to packed index mappings.
Example: Position Component Array

```
Array: [

]
EntityToIndex: [

]
IndexToEntity: [

]
Size: 0
```

ECS - Component Array

We can use a map to track which Entity to packed index mappings:
Example: Position Component Array

```
Add Position {0, 1} to Entity 0

Array: [
    {0, 1}
]
EntityToIndex: [
    {0:0}
]
IndexToEntity: [
    {0:0}
]
Size: 1
```

ECS - Component Array

We can use a map to track which Entity to packed index mappings:
Example: Position Component Array

```
Add Position {1, 2} to Entity 2

Array: [
    {0, 1}, {1, 2}
]
EntityToIndex: [
    {0:0}, {2:1}
]
IndexToEntity: [
    {0:0}, {1:2}
]
Size: 2
```

ECS - Component Array

We can use a map to track which Entity to packed index mappings:
Example: Position Component Array

```
Add Position {3, 0} to Entity 5

Array: [
    {0, 1}, {1, 2}, {3, 0}
]
EntityToIndex: [
    {0:0}, {2:1}, {5:2}
]
IndexToEntity: [
    {0:0}, {1:2}, {2:5}
]
Size: 3
```

ECS - Component Array

We can use a map to track which Entity to packed index mappings:
Example: Position Component Array

```
Add Position {4, 4} to Entity 8

Array: [
    {0, 1}, {1, 2}, {3, 0}, {4, 4}
]
EntityToIndex: [
    {0:0}, {2:1}, {5:2}, {8:3}
]
IndexToEntity: [
    {0:0}, {1:2}, {2:5}, {3:8}
]
Size: 4
```

ECS - Component Array

We can use a map to track which Entity to packed index mappings:
Example: Position Component Array

```
Remove Entity 2 (swap array element to end)

Array: [
    {0, 1}, {1, 2}, {3, 0}, {4, 4}
]
EntityToIndex: [
    {0:0}, {2:1}, {5:2}, {8:3}
]
IndexToEntity: [
    {0:0}, {1:2}, {2:5}, {3:8}
]
Size: 4
```

ECS - Component Array

We can use a map to track which Entity to packed index mappings:
Example: Position Component Array

```
Remove Entity 2 (swap array element to end)
                ----------------
Array: [        |               |
    {0, 1}, {4, 4}, {3, 0}, {1, 2}
]
EntityToIndex: [
    {0:0}, {2:3}, {5:2}, {8:1}
]
IndexToEntity: [
    {0:0}, {1:8}, {2:5}, {3:2}
]
Size: 4
```

ECS - Component Array

We can use a map to track which Entity to packed index mappings:
Example: Position Component Array

```
Remove Entity 2 (swap array element to end)

Array: [
    {0, 1}, {4, 4}, {3, 0}
]
EntityToIndex: [
    {0:0}, {5:2}, {8:1}
]
IndexToEntity: [
    {0:0}, {2:5}, {3:2}
]
Size: 3
```

ECS - Component Array

```cpp
// Will need to call interface on list of multiple tempalted types
struct BaseComponentArray {
    virtual ~BaseComponentArray() = default;
    virtual void entity_destroyed(Entity entity) = 0;
};

template <typename T>
struct ComponentArray : public BaseComponentArray {
    // Insert entity with component data
    void insert(Entity entity, T component);

    // Remove component data from entity
    void remove(Entity entity);

    // Get the entities component data
    auto get_entity_data(Entity entity) -> T&;

    // Signal an entity destroyed and needs to update mappings
    void entity_destroyed(Entity entity) override;

    std::array<T, MAX_ENTITIES> component_array;
    std::unordered_map<Entity, std::size_t> entity_to_index;
    std::unordered_map<std::size_t, Entity> index_to_entity;
};
```

ECS - Component Manager

The `ComponentManager` is responsible managing each of the `ComponentArrays` such as adding or removing a component from an Entity.

Since we are tracking which components belong to which entities using N bits, each component will need a unique ID which maps to the bit index.

```
class component_type_counter {
    static inline ComponentType current_index = 0;

public:
    template <typename T>
    static inline const ComponentType index_of = current_index++;
};
```

ECS - Component Manager

```
struct ComponentManager {
    template <typename T>
    void register_component();

    // Same index into bitset
    template <typename T>
    auto get_component_type() -> ComponentType;

    // Add component to entity
    template <typename T>
    void add_component(Entity entity, T component);

    // Remove component from entity
    template <typename T>
    void remove_component(Entity entity);

    // Notify each component array than an entity has been destroyed
    void entity_destroyed(Entity);

    std::unordered_map<ComponentType, std::shared_ptr<BaseComponentArray>>
    ↪  component_arrays;
};
```

ECS - System

A System implements some functionality upon a lit of entities with a certain signature of components.

```cpp
// Forward declare to avoid recursive includes
// Acts as a coordinator between Entities, Components, and Systems
//  to pass information between
class Coordinator;

// Iterated over a collection of entities of a particular signature
// Meant to be subclassed
class System {
public:
    virtual ~System() = default;

    // Update the system after step_seconds has passed since the past update
    virtual void update(Coordinator &world, double step_seconds);

    // What entities belong to the system
    std::set<Entity> entities;
};
```

ECS - System Example

Consider the collision handler from Assignment 2. We can create a `System` which implements that behaviour on the set of entities which have a `CollisionComponent`.

```
class CollisionSystem : public System {
public:
    void update(Coordinator &world, double step_seconds) override {
        for (const auto &entity : entities) {
            auto &collisions =
                world.get_component<CollisionComponent>(entity);
            auto &heading = world.get_component<HeadingComponent>(entity);
            if (collisions[LEFT] || collisions[RIGHT]) {
                heading.x = -heading.x;
            }
            if (collisions[TOP] || collisions[BOTTOM]) {
                heading.y = -heading.y;
            }
            collisions.reset();
        }
    }
};
```

ECS - System Manager

The `SystemManager` is responsible managing each system.

Again, we use the same *trick* to track system types to indices in our data structures:

```
class system_type_counter {
    static inline std::size_t current_index = 0;

public:
    template <typename T>
    static inline const std::size_t index_of = current_index++;
};
```

ECS - System Manager

```
class SystemManager {
    // Register (create) a new system constructing with the passed args
    // The priority lets us control which systems are updated in what order
    template <typename T, typename ...Args>
    auto register_sytem(int priority, Args ... args) -> std::shared_ptr<T>;

    // Set the signature for collection of components the system T
    //  will operate on
    template <typename T>
    void set_signature(Signature signature);

    // Remove entity from all systems
    void entity_destroyed(Entity entity);

    // Update entity signature for all systems
    void entity_signature_changed(Entity entity, Signature signature);

    // Call the update method for each system
    void update_all(Coordinator &world, double step_seconds);

    std::unordered_map<std::size_t, Signature> signatures;
    std::unordered_map<std::size_t, std::shared_ptr<System>> systems;
    std::map<int, std::vector<std::shared_ptr<System>>> systems_by_priority;
};
```

ECS - Coordinator

The `Coordinator` is a single object which we will use to interface between the entities, components, and systems.

```cpp
class Coordinator {
public:
    Coordinator()
        : component_manager(std::make_unique<ComponentManager>()),
          entity_manager(std::make_unique<EntityManager>()),
          system_manager(std::make_unique<SystemManager>()) {}
    // ...
private:
    std::unique_ptr<ComponentManager> component_manager;
    std::unique_ptr<EntityManager> entity_manager;
    std::unique_ptr<SystemManager> system_manager;
    std::unordered_map<std::string, std::any> data;
};
```

ECS - Coordinator

Entity methods:

```
class Coordinator {
public:
    auto create_entity() -> Entity {
        return entity_manager->create_entity();
    }

    void destroy_entity(Entity entity) {
        entity_manager->destroy_entity(entity);
        component_manager->entity_destroyed(entity);
        system_manager->entity_dstroyed(entity);
    }
};

Entity player1 = coordinator.create_entity();
coordinator.destroy_entity(player1);
```

ECS - Coordinator

Component methods:

```
class Coordinator {
public:
    template <typename T>
    void register_component() {
        component_manager->register_component<T>();
    }

    template <typename T> // Add component to an entity
    void add_component(Entity entity, T component);

    template <typename T>  // Remove component from an entity
    void remove_component(Entity entity);

    template <typename T>  // Get component data for the entity
    auto get_component(Entity entity) -> T &;

    template <typename T>
    auto get_component_type() -> ComponentType;
};

coordinator.register_component<Position>()
coordinator.add_component<Position>(player1, {10, 20});
```

ECS - Coordinator

System methods:

```
class Coordinator {
public:
    // System methods
    template <typename T, typename... Args>
    auto register_system(int priority, Args... args) -> std::shared_ptr<T> {
        return system_manager->register_system<T>(priority, args...);
    }

    template <typename T>
    void set_system_signature(Signature signature);

    void update_all_standard_systems(double step_seconds);

    void update_all_render_systems(double step_seconds);

    // Misc
    void store_data(const std::string &name, std::any value);

    template <typename T>
    auto get_data(const std::string &name) -> T &;
};
```

Game Loop

All game loops look something like the following:

```
while (true) {
    process_input();
    update_world();
    render();
}
```

Every loop iteration (*tick*), we process input from users, update entities in the world, then render the current state of the world.

Unfortunately, we have no control over the speed at which the game progresses:

- *Light weight* games will run too fast for the users to interpret what is going on.

Game Loop - Target FPS

We can modify the previous game loop by using a target frames-per-second (FPS). If we can process input, update the game state, and render in under the FPS target, our game will run at a smooth consistent framerate:

```cpp
const double FPS = 60;
const double MS_PER_SECOND = 1000;
const double MS_PER_FRAME = MS_PER_SECOND / FPS;

while (true) {
    double start_time = get_current_time();
    process_input();
    update_world();
    render();
    double end_time = get_current_time();
    double sleep_time = (start_time - end_time) + MS_PER_FRAME;
    std::this_thread::sleep_for(sleep_time);
}
```

What happens if we cannot process the game state fast enough for our target FPS? Are there any other downsides?

Game Loop - Syncing The Clocks

There are two clocks we need to be aware of:

1. Each world update advances the game clock by a certain amount
2. It takes a certain amount of *real* time to process that

If step 2 takes longer than step 1 (i.e. it takes more than 16ms of processing to advance the game world clock by 16ms) then the game slows down.

If we can update the game by *more* than 16ms of game time in a single step, then we can update less frequently and still keepup:

- Choose a time step to advance based on how much *real* time has passed since the last frame
- Longer frame times results in bigger steps taken when updating the game forward
- We always stay in sync with real time, as we change our world step size based on the real clock

Game Loop - Syncing The Clocks

Choose a time step for the game world to update that matches how long its taken for the real clock to process the last step (i.e. always play catchup)

```
double prev_time = get_current_time();

while (true) {
    double curr_time = get_current_time();
    double elapsed_time = curr_time - prev_time;
    process_input();
    update_world(elapsed_time);
    render();
    prev_time = curr_time;
}
```

Game Loop - Syncing The Clocks

Pros:

- Game plays at consistent rate on different hardware
- Faster hardware will result in more engine updates (with smaller step sizes), but also with more render steps (i.e. higher frame rate)

Cons:

- Engine is non-deterministic (update step size is determined by hardware speed)!
- Many smaller game step updates can result in math stability issues:
  - Floating point math has rounding errors and will accumulate with more updates
  - More updates with smaller delta values can lead to more rounding errors

Game Loop - Playing Catchup

Ideally, we should use a fixed timestep to update the game state.

- Deterministic game engine
- Can control amount of accumulation errors

Once insight is that rendering is not affected by our time steps:

- The renderer captures an instant in time and draws that on screen
- It doesn't matter how much time has advanced in the engine, it just grabs the current state of the world

Solution:

- Update the game engine at fixed intervals of time (game engine tick rate)
- Continue to update until we catch up to the amount of *real time* has passed since the last frame
- Once we are caught up, draw the frame

Game Loop - Playing Catchup

We use the variable `lag` to represent how much *real* time has passed since the last frame. This measures how much time the engine is behind the real world clock.

The inner loop then runs until we have *caught up*:

```
double prev_time = get_current_time();
double lag = 0;

while (true) {
    double curr_time = get_current_time();
    double elapsed_time = curr_time - prev_time;
    prev_time = curr_time;
    lag += elapsed;
    process_input();

    while (lag >= MS_PER_UPDATE) {
        update_world(elapsed_time);
        lag -= MS_PER_UPDATE;
    }
    render();
}
```

References

[1] A. Morlan, "A Simple Entity Component System (SCS)"
`http://austinmorlan.com/posts/entity_component_system`

[2] R. Nystrom, "Game Programming Patterns", Genever Benning, 201