CPSC 427
Video Game Programming

Entity Component System (ECS)

ECS is used in Minecraft and many other commercial games

Learning Goals & Outline

- core game design principles
- Entity component systems (ECS)

First half:

- issues with inheritance
- understanding the ECS concept

Second half:

- implementing ECS
- taking the perspective of the inventor of ECS

Orga

- ***A0 released today***
  - *play yourself, but 'peer grading' is the only submission*
- ***Deadlines***
  - *assignments: on MTA*
  - *milestones: on lecture schedule (will likely add to MTA)* https://docs.google.com/document/d/e/2PACX-1vRZmo-ue-YY-wC9QTdvCm7ujAU-t1GHmRMGpAdKrhU_dnk9bz0BHeGdjpepe2YrskLW_FObnTWRJhQz/pub

  Do you want them on Canvas too?

- ***MTA participation***
  - *use MTA to answer my questions; raise hand to ask your questions*

Team Milestones

19-Sep: Oral pitch slides
https://docs.google.com/presentation/d/1h9wt4b-rBJ27OtjOcObe102B3uc59O6lhWNWGSBSibc/edit?usp=sharing

20-Sep: 1 minute oral pitch
20-Sep: 2-page written pitch

25-Sep: game proposal

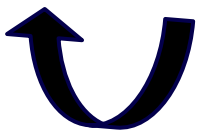
12-Oct: milestone 1
30-Oct: milestone 2
20-Nov: milestone 3
4-Dec: milestone 4

The game loop

Can you imagine a game without?

A game is a simulator

1. ***AI and user input***
2. ***Environment reaction***
3. ***Numerical integration***
   - compute acceleration, update positions and velocities
4. ***Collision detection & resolution***



We will have a separate lecture on physics simulation!

Our game loop (A1, main.cpp)

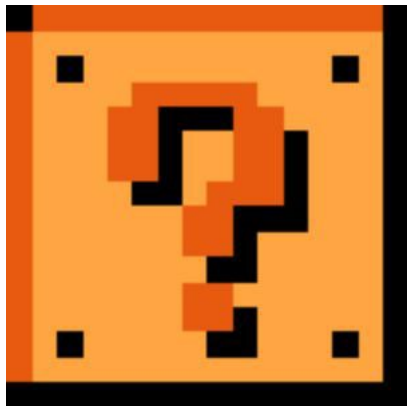
```
// Set all states to default
world.restart();
auto t = Clock::now();
// Variable timestep loop
while (!world.is_over())
{
    // Processes system messages, if this wasn't present the window would become unresponsive
    glfwPollEvents();

    // Calculating elapsed times in milliseconds from the previous iteration
    auto now = Clock::now();
    float elapsed_ms = static_cast<float>((std::chrono::duration_cast<std::chrono::microseconds>(now - t)).count()) / 1000.f;
    t = now;

    DebugSystem::clearDebugComponents();
    ai.step(elapsed_ms, window_size_in_game_units);
    world.step(elapsed_ms, window_size_in_game_units);
    physics.step(elapsed_ms, window_size_in_game_units);
    world.handle_collisions();

    renderer.draw(window_size_in_game_units);
}

return EXIT_SUCCESS;
```

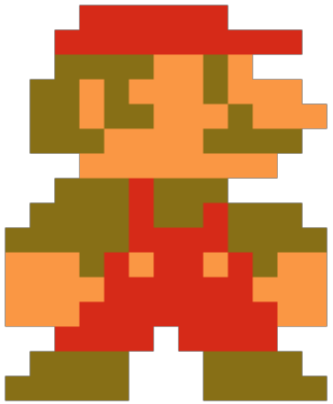
How to represent the parts of your world?

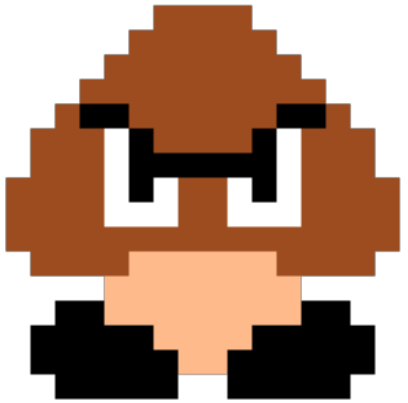
- *for chess?*
- *a platformer?*

What are Entities?

- **Entities:** things that exist in your game world

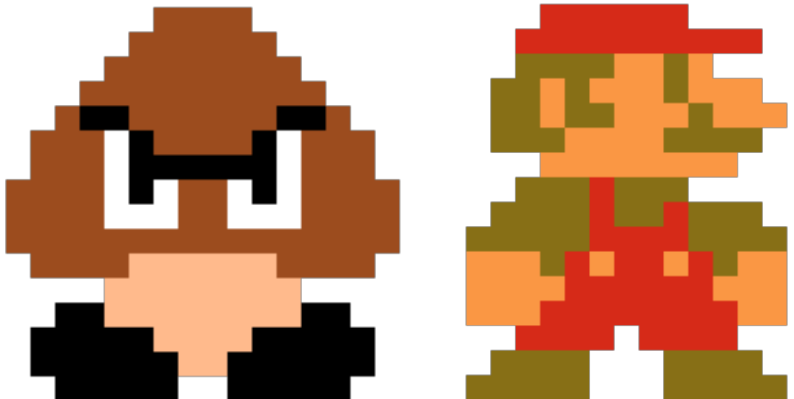


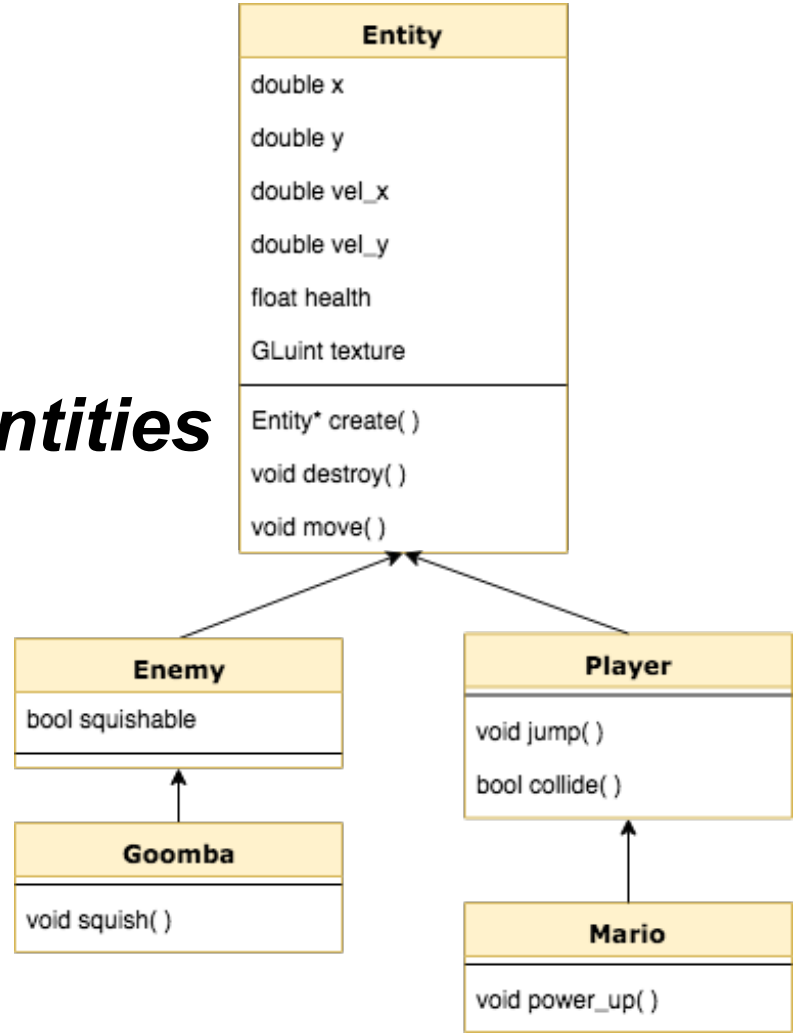




Entities in Traditional Game Programming

- **Object-Oriented Programming**
  - ***Entities as objects***
    - Contains data, behaviors, etc.
  - ***Entity Hierarchy: Entities extend other Entities***



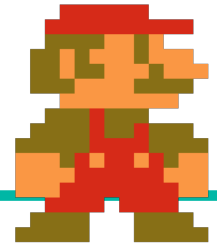


Entity Hierarchy (object oriented design)

```
class Entity {

public:
    void create();
    void destroy();
    void move();

private:
    double x;
    double y;
    double vel_x;
    double vel_y;
    vec2 bbox;
    float health;
    GLuint texture;
}
```

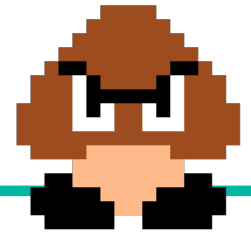
```
class Player : public Entity {

public:
    void jump();
    bool collide();
}
```

```
class Mario : public Player {

public:
    void power_up();
}
```



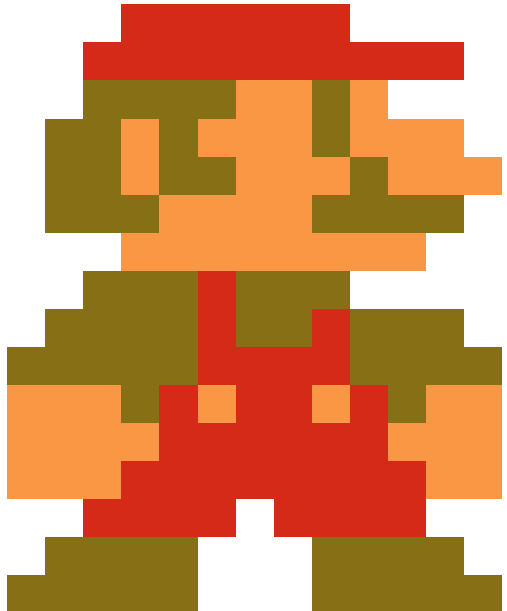
```
class Enemy : public Entity {

private:
    bool squishable;
}
```

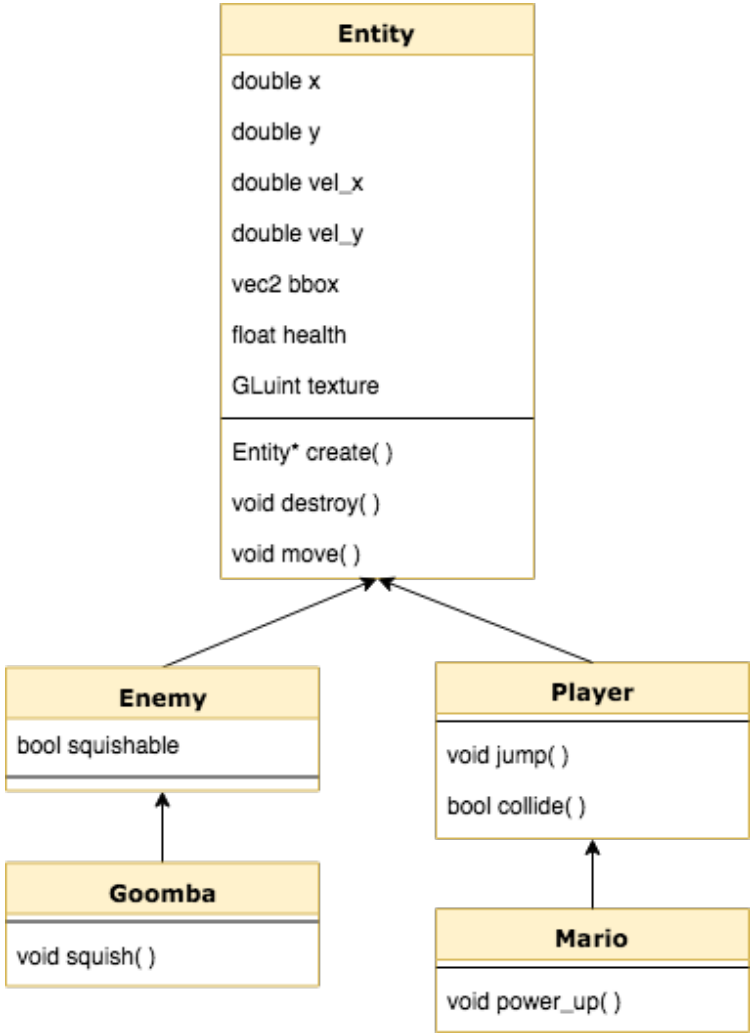
```
class Goomba : public Goomba {

public:
    void squish();
}
```



Issues with Object-Oriented Approach

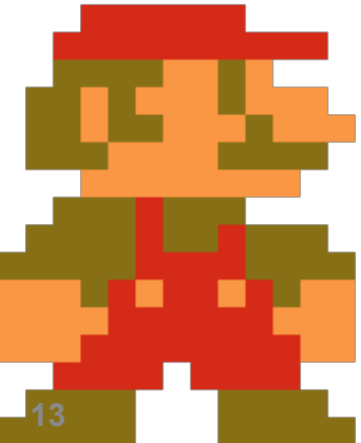
What if we want Mario to be able to be squished?

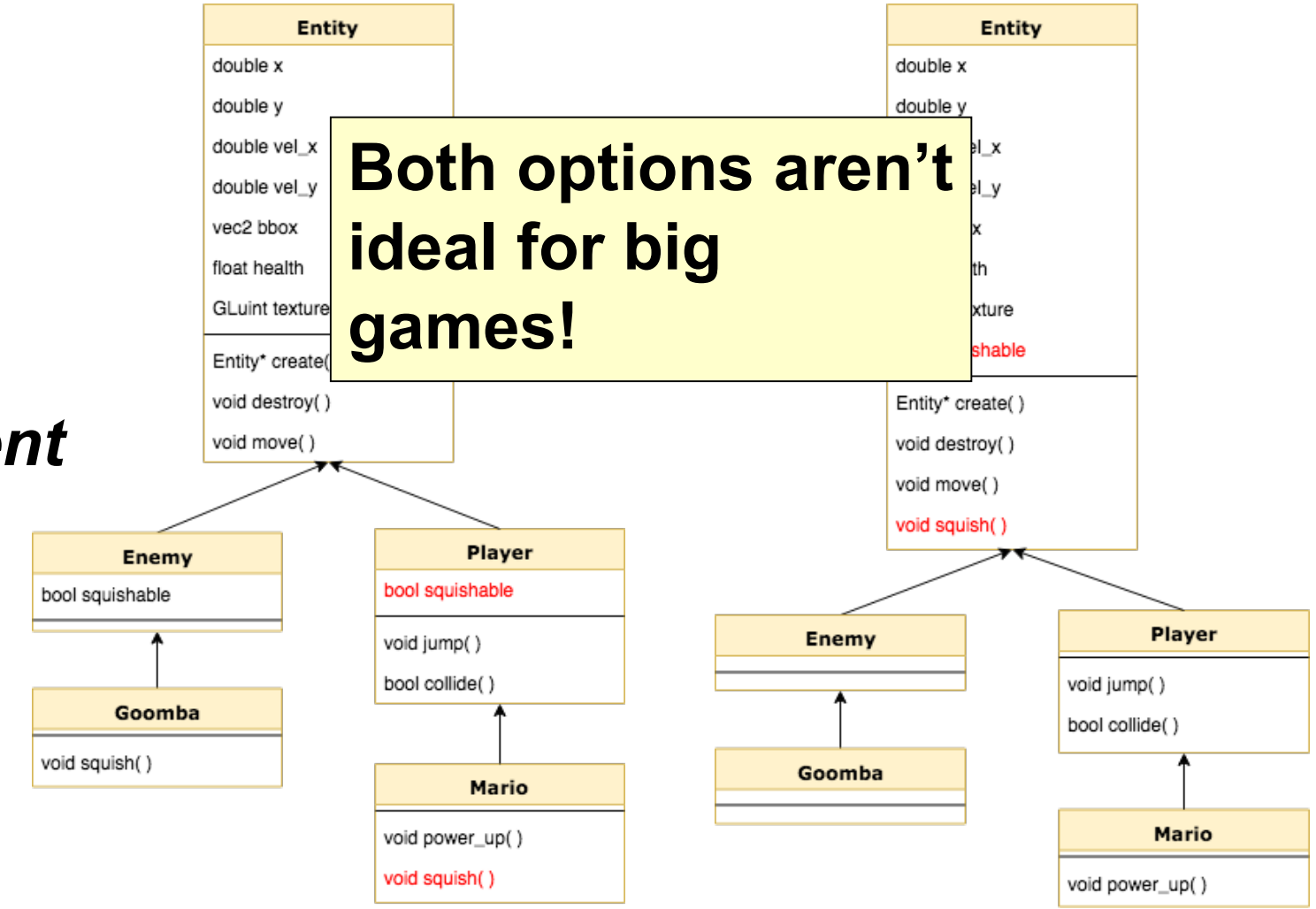




Issues with Object-Oriented Approach

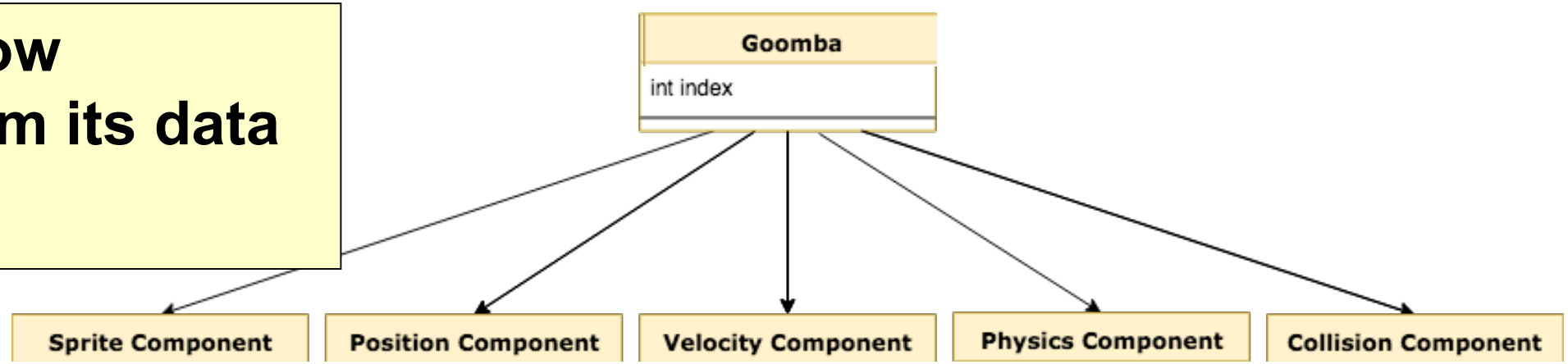
- **Difficult to add new behaviors**
  - ***Choice between replicating code or***
  - ***MONSTER SIZE parent classes***

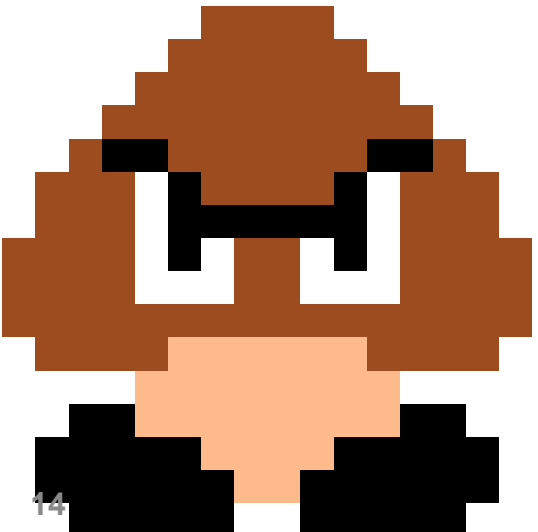




Example ECS Diagram

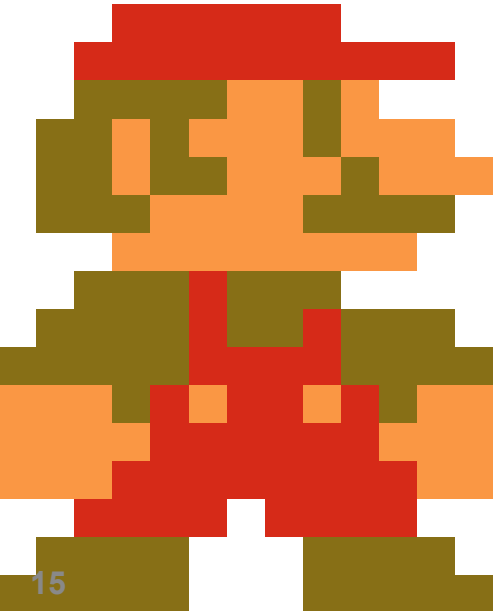
Goomba is now separated from its data & methods

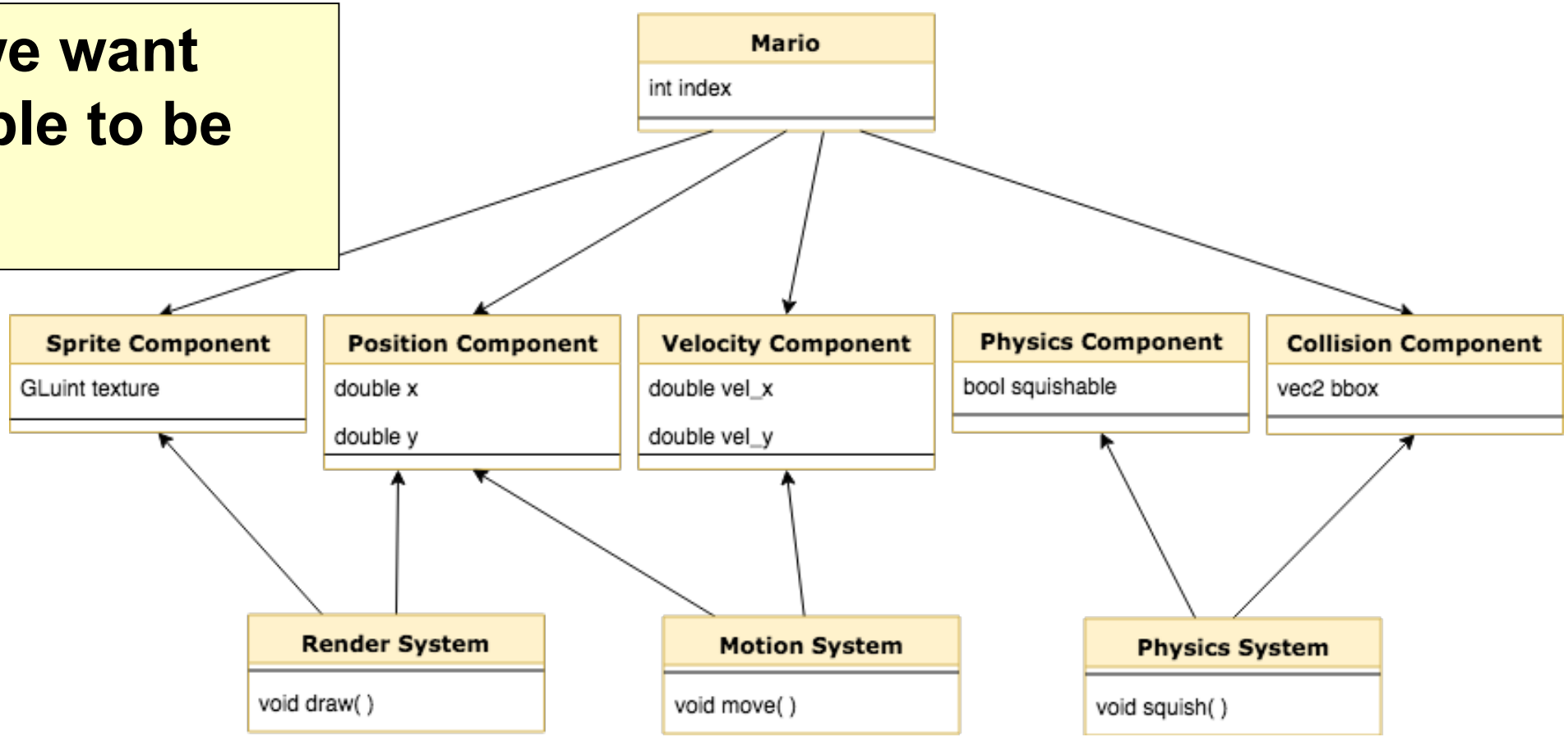




Example ECS Diagram

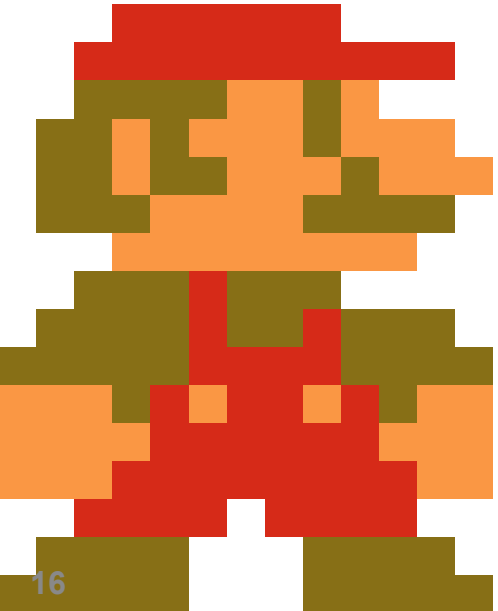
Now what if we want Mario to be able to be squished?

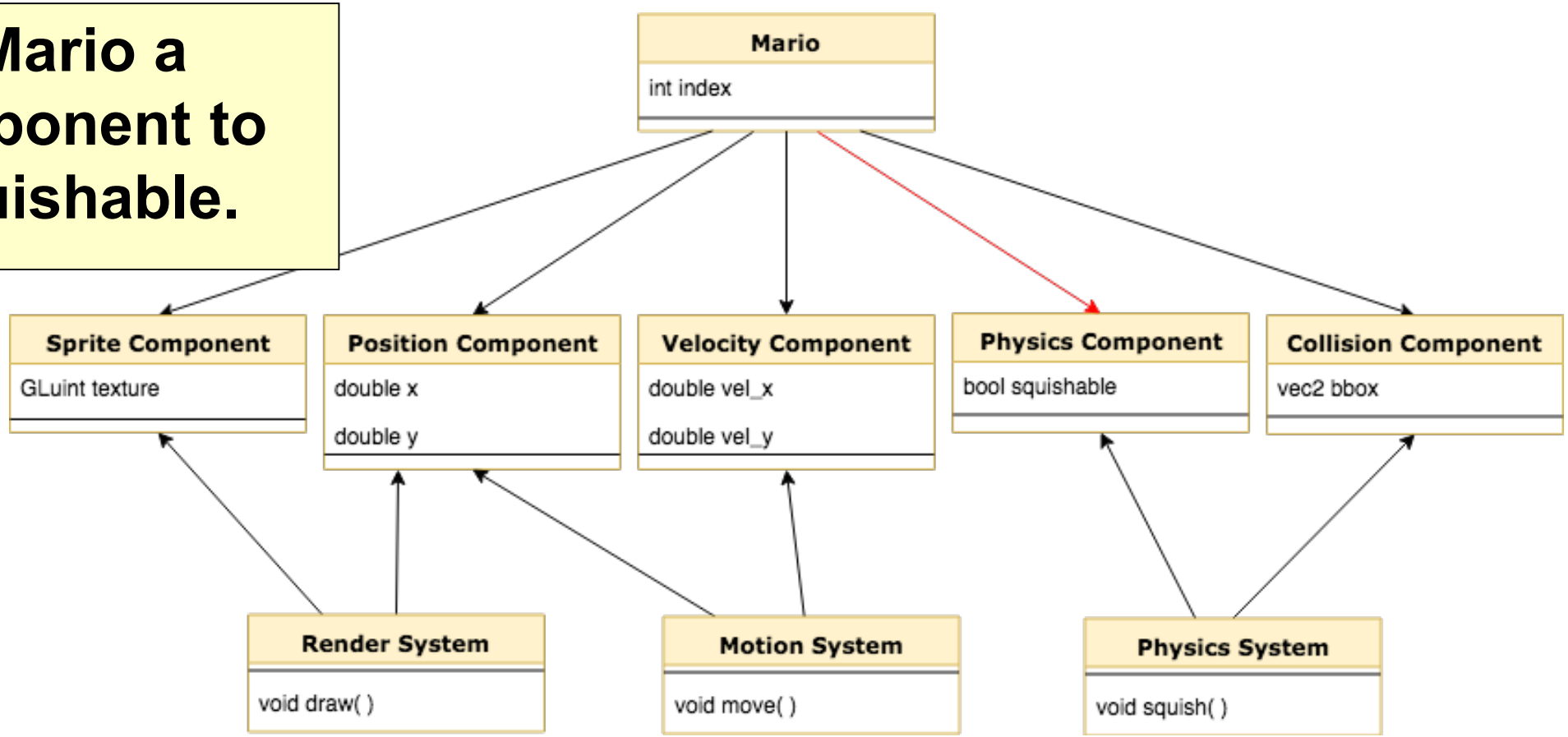




Example ECS Diagram

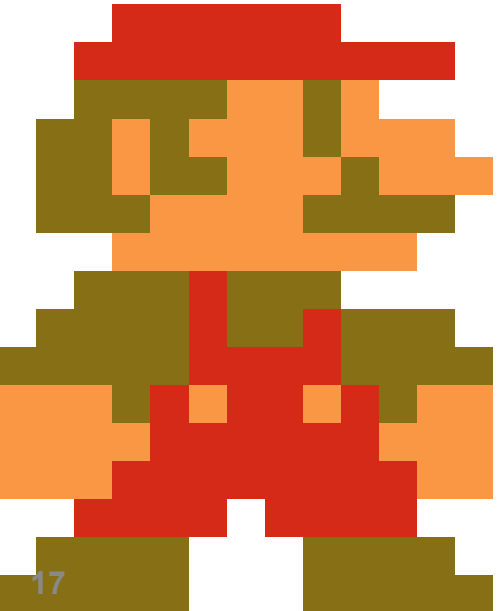
We can give Mario a Physics Component to make him squishable.

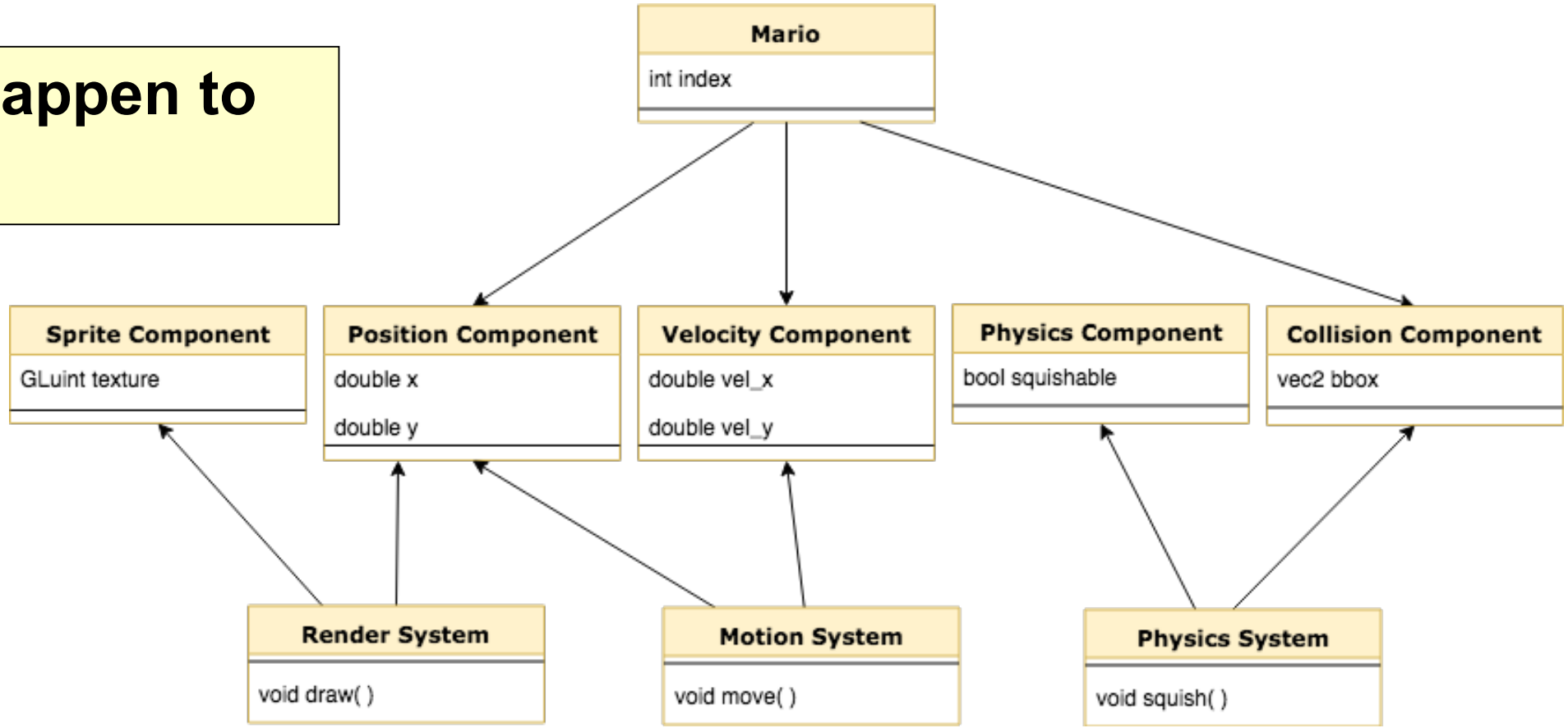




Example ECS Diagram

What would happen to Mario here?





What is ECS?

- Alternative to object-oriented programming
- Data is self-contained & modular
  - *Similar concept to building blocks*
  - *Entities no longer "own" data*
  - *Entities pick & choose*

What is ECS?

- **Entities actions determined only by their data**
  - ***Update loop doesn't need references to Entities***
  - ***Systems search for Entities with right parts (data) & update***
    - For Mario to move he needs a position & velocity

What is ECS?

- **Composition over hierarchy**

- **Entities are collections of Components**
- **Components contain game data**
  - *Position, velocity, input, etc.*
- **Systems are collections of actions**
  - *Render system, motion system, etc.*

Component

- Contains **only** game data
- Describes **one** aspect of an Entity
  - *ex. a trumpet Entity will likely have an audio Component*

Sprite Component
GLuint texture

Position Component
double x
double y

Velocity Component
double vel_x
double vel_y

Physics Component
bool squishable

Collision Component
vec2 bounding_box

Input Component
bool left
bool right
bool jump
bool attack

AI Component
bool do_left
bool do_right
bool do_jump
bool do_shoot

Health Component
float health

Audio Component
mp3 sound

Component

- **Typically implemented with structs.**

```
struct SpriteComponent {
    GLuint texture;
}
```

```
struct PositionComponent {
    double x;
    double y;
}
```

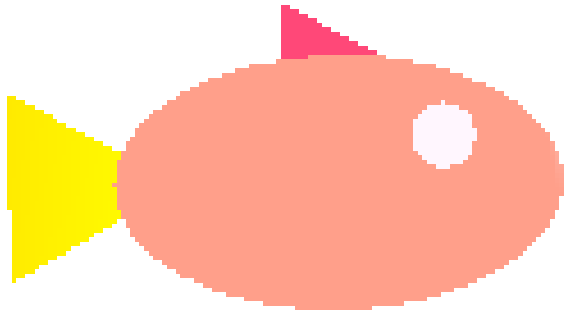
```
struct VelocityComponent {
    double vel_x;
    double vel_y;
}
```

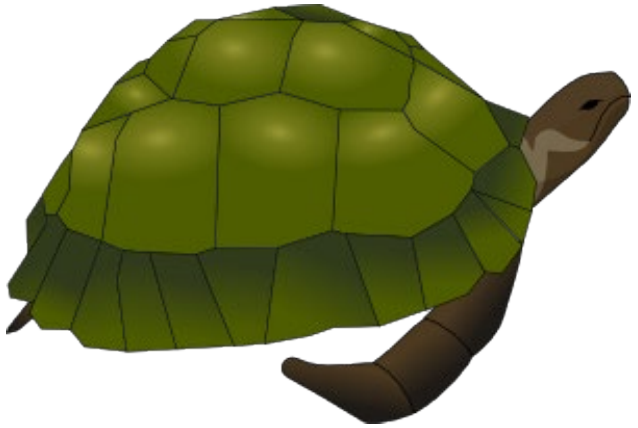
```
struct PhysicsComponent {
    bool squishable;
}
```

```
struct CollisionComponent {
    vec2 bbox;
}
```

What Components to Make?

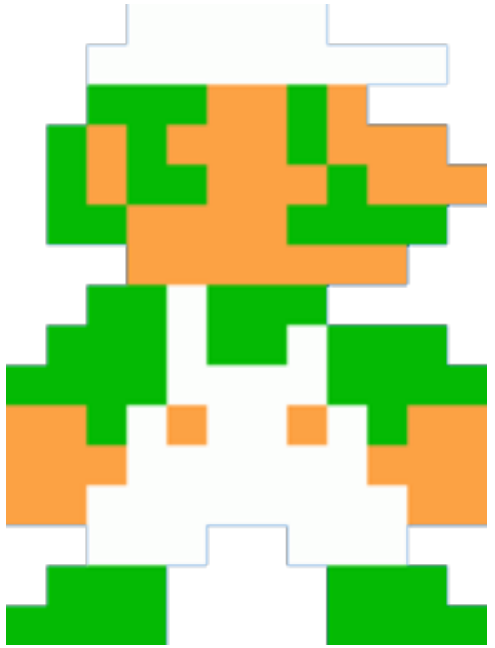
- **What Components would we give to the following Entities?**





Components

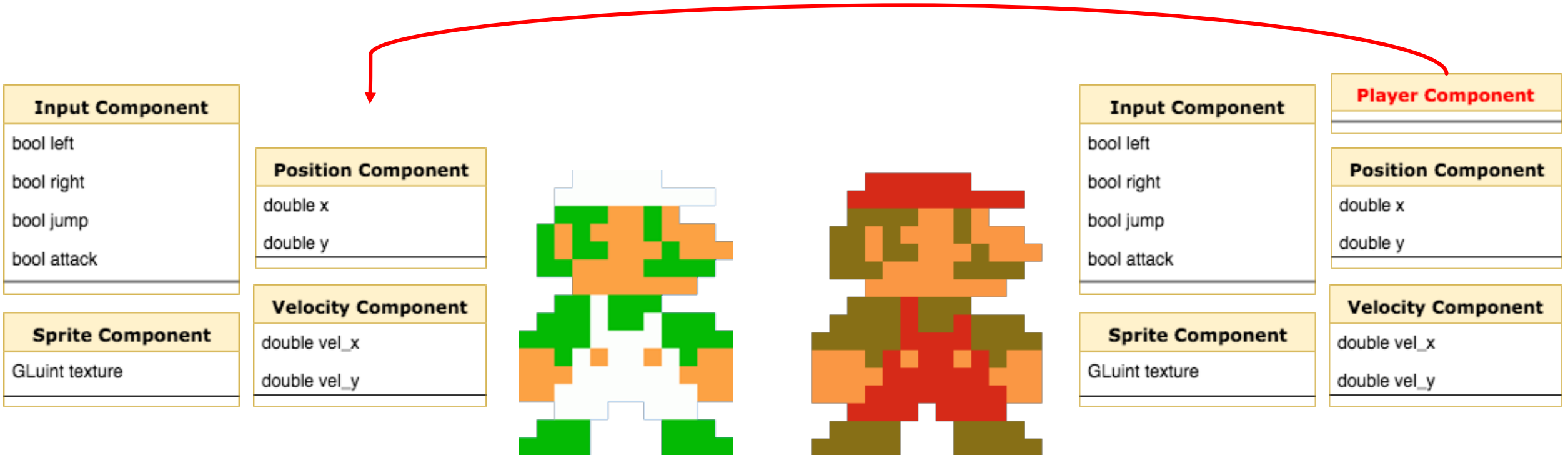
- **Easy to add new Entity characteristics**
  - ***Just create the desired Component & give to Entity***



How do we change our playable hero from Mario to Luigi?

Components

- **Empty Components can be used to tag Entities**



Empty components are useful, a flag indicating an ability!

Components

- **Empty Components can be used to tag Entities**

Input Component
bool left
bool right
bool jump
bool attack

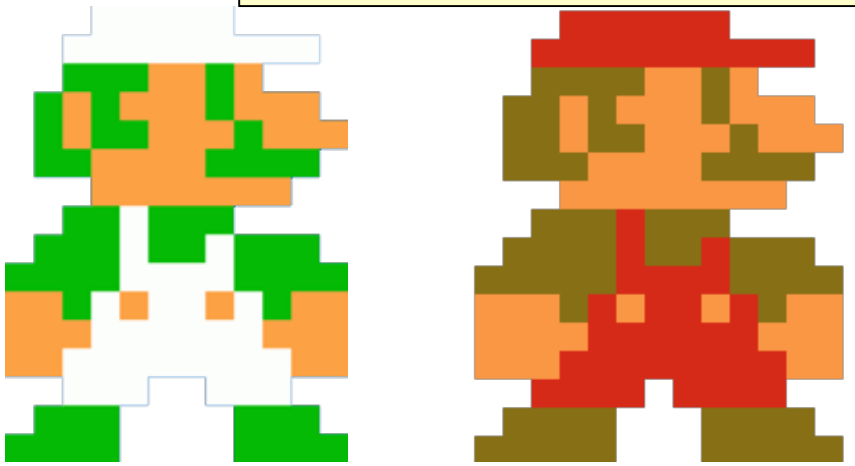
Player Component

Position Component
double x
double y

Velocity Component
double vel_x
double vel_y

Sprite Component
GLuint texture

Now Luigi can be identified as the active player



nent
bool attack

Position Component
double x
double y

Velocity Component
double vel_x
double vel_y

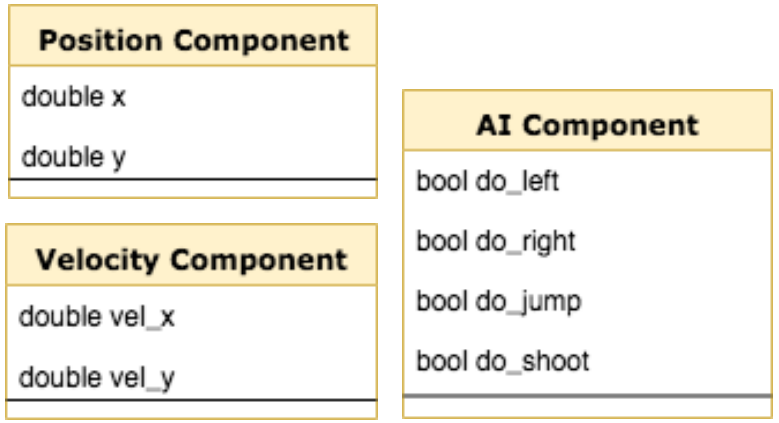
Sprite Component
GLuint texture

Systems

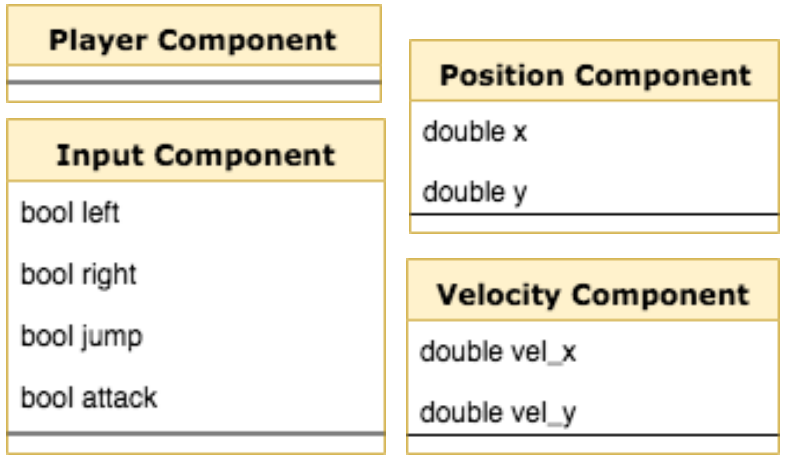
- Groups of Components describe behavior/action
  - *ex. bounding box, position & velocity describe collisions*
- Systems code behaviors/actions
- Operate on Entities with related groups of components
  - *Related: describe same (type of) behavior/action*
  - *ex. render all Entities with sprite & position*
- Entity behavior can be dynamic
  - *Add/remove components on the fly*

System Example

- **What systems might these related groups of components describe?**



Enemy Motion System



Player Motion System

System Examples

Physics System … iterates over all components of type velocity

```
for(Velocity& velocity : velocity_components)
    velocity += 9.81 * dt
```

The physics system may not care about entities at all!

Game loop

```
Entity player;
    if(! alive_components.has(player) ) exit();
```

Simple checks

Motion System … iterates over all entities that have velocity and position

```
for(int entity : velocity_entities)
     if (position_components.has(entity))
          position_components.get(entity)+= velocity_components.get(entity);
```

Need to know all entities that have component X
Need to retrieve a component X from an entity

Break

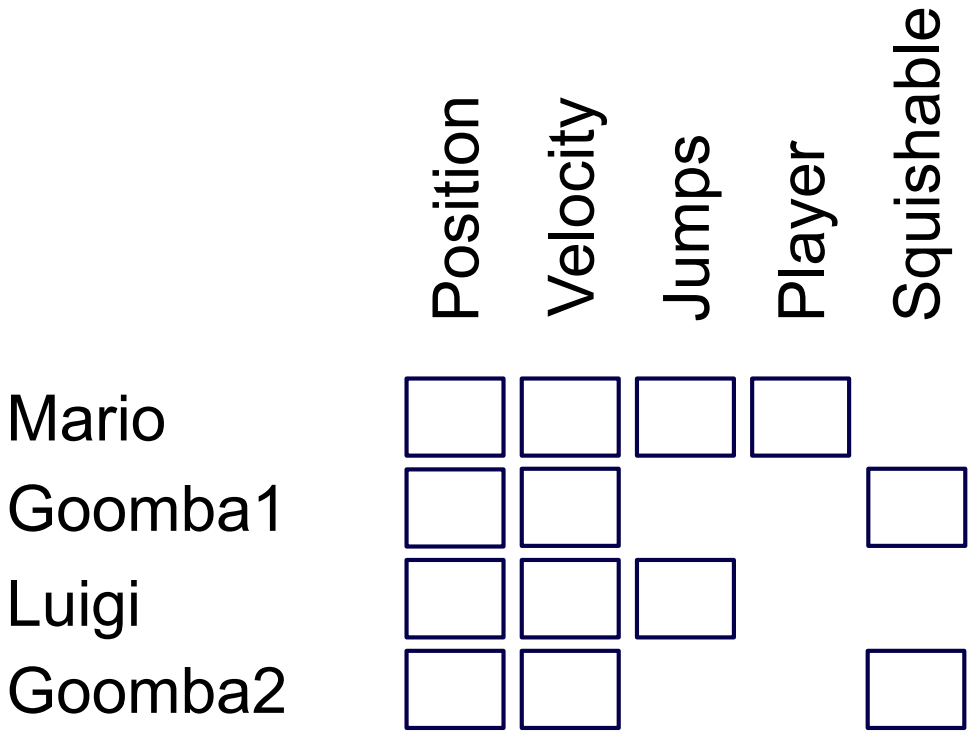
ECS implementations

Where do we store our Components?

Where/How do we store components?

- Inside Systems?
  - *NO!*
    - Component may be used by different systems

Problem: associating entities and components



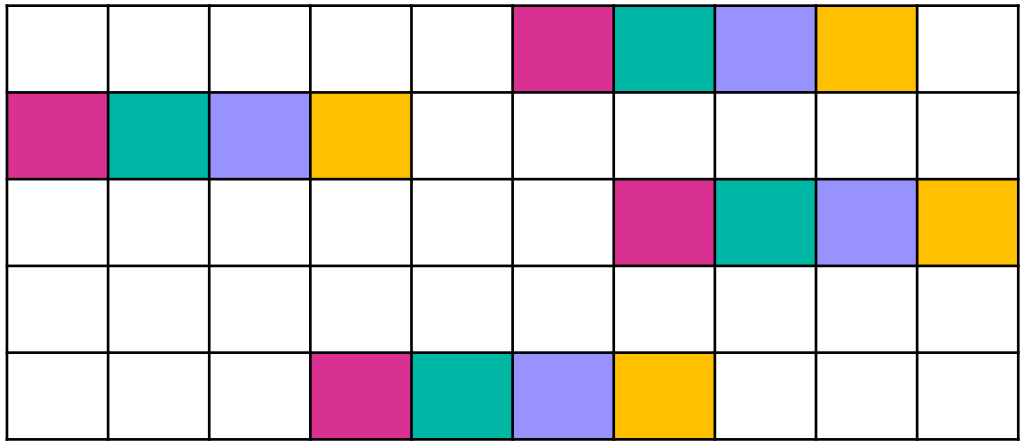
Object-oriented-programming (OOP)?

ECS = containers of components?

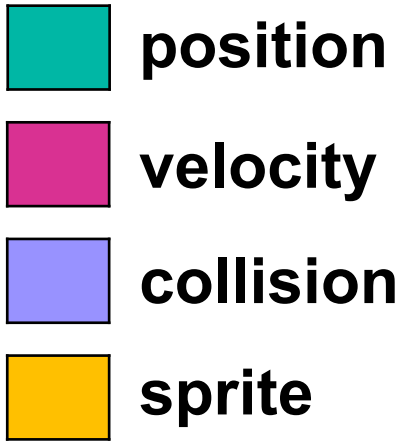
Memory & ECS

Where do we store our Components?

- Inside Entities?



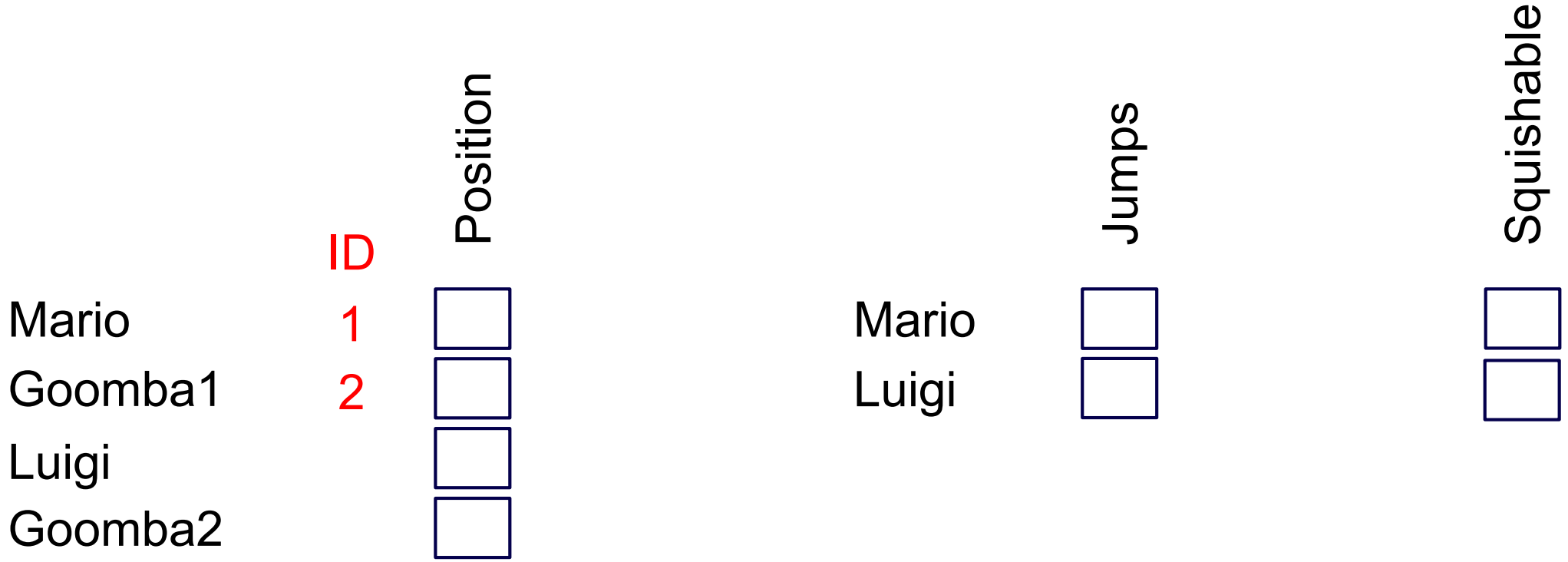
Memory Blocks



Update loop has to access non-contiguous memory repeatedly!

Slow memory access!

The Map Approach (entity ID to component address)



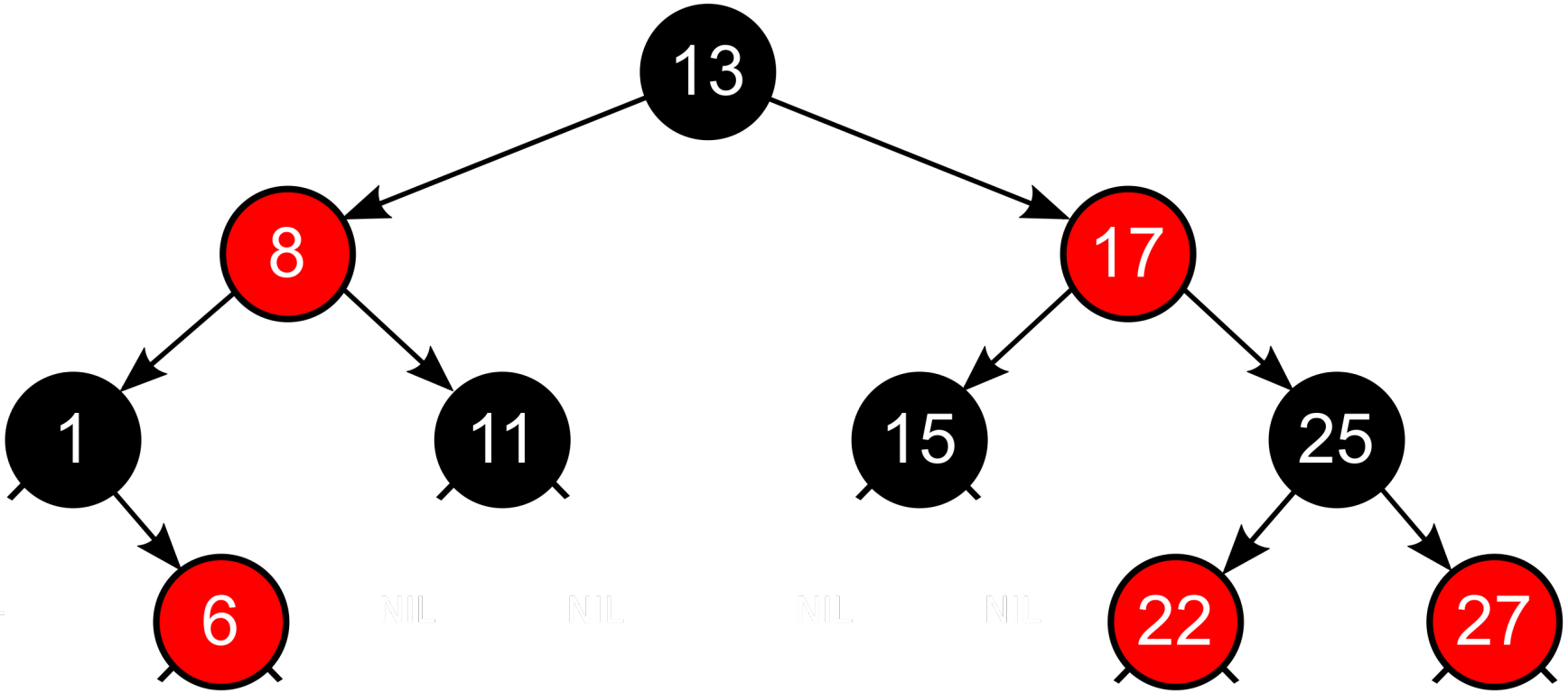
Concept:

- A map to lookup components (fast if implemented correctly)

Implementation: std:map<Entity, Component>

Recall: Red-black trees

- Usually used for std::map
- A type of self-balancing binary search trees
- Hash map could be used too



Assignment 0 (A0)

- ***Released today***
  - *You have to grade ECS implementations*
  - *Suggested: Implement your own ECS using std::map (see previous slides)*

- ***Simple and complex versions***

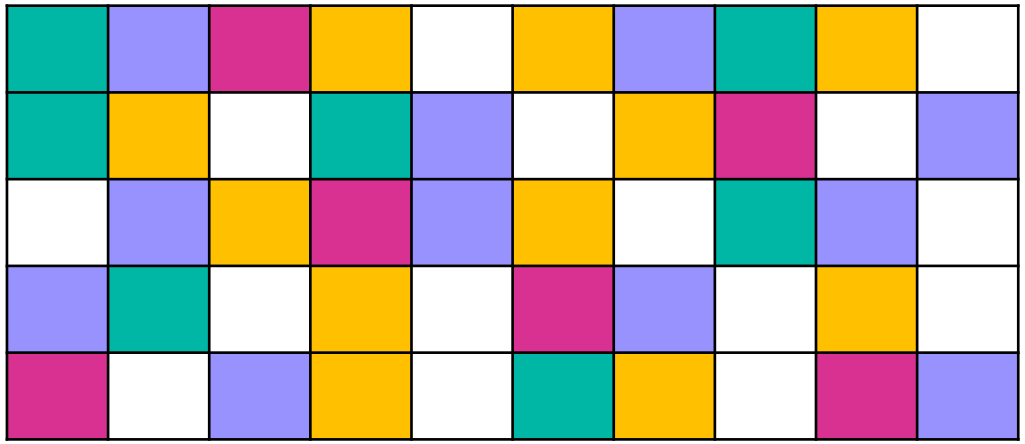
- ***Requires C++:***
  - *pointer, reference, value*
  - *templates (simple template classes)*

Attend tutorial if rusty!

Memory & ECS

Where do we store our Components?

- In a map?



Memory Blocks

position

velocity

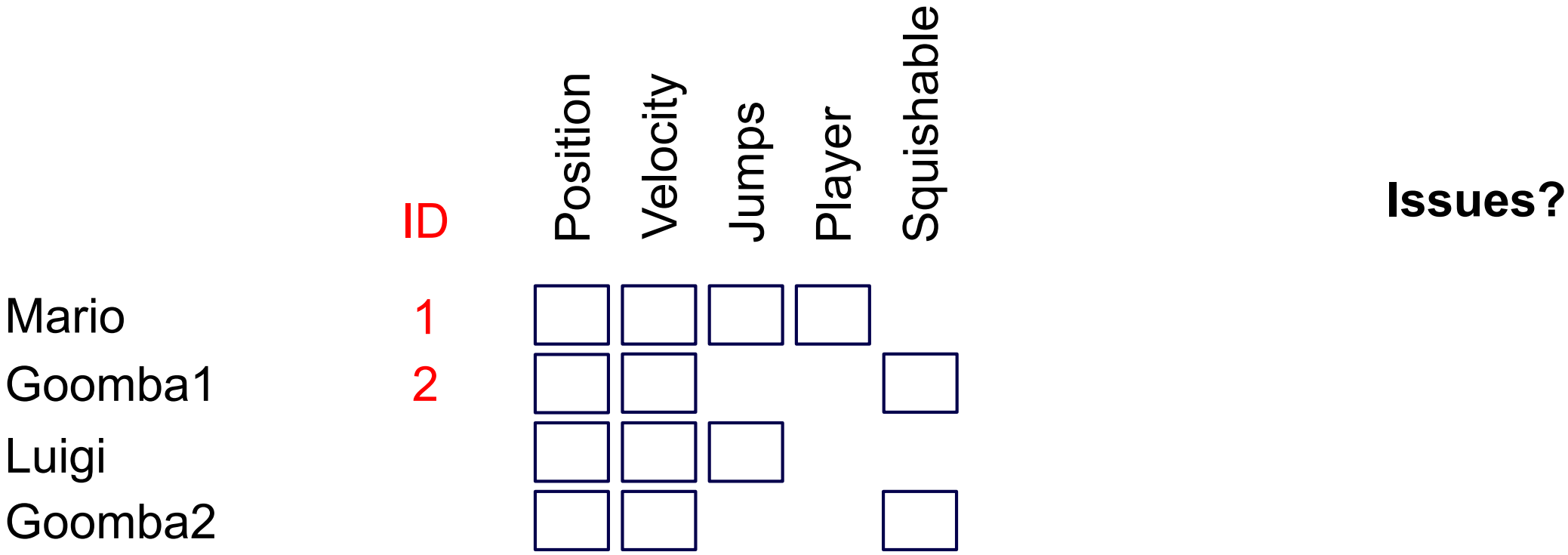
collision

sprite

Update loop has to access non-contiguous memory repeatedly!

Slow memory access!

The (giant) Sparse Array



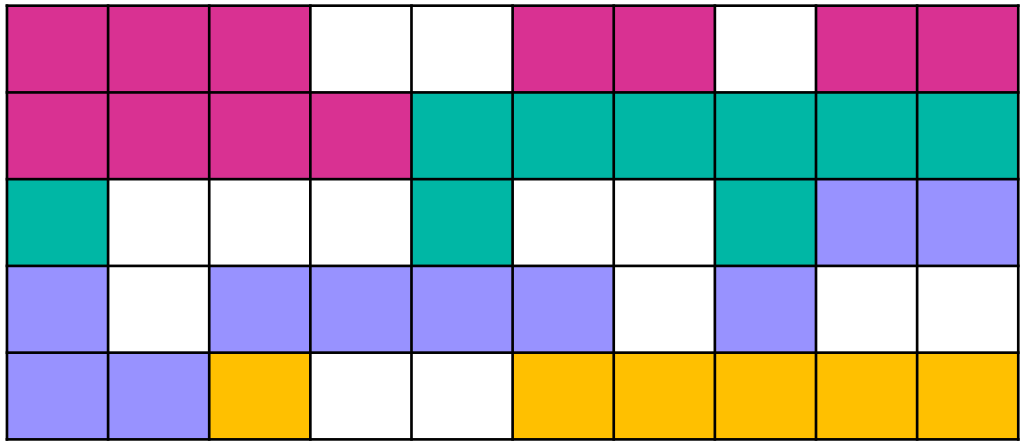
Issues?

Concept: A huge data matrix of size Nr. Entities x Nr. components
Implementation: std:vector<Position>; std:vector<Velocity>

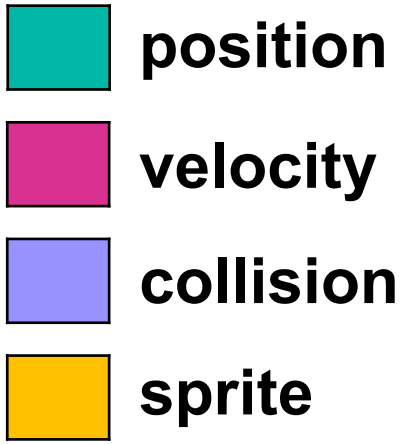
Memory & ECS

Where do we store our Components?

- Array with holes?



Memory Blocks



Better cache utilization!

Not memory efficient!

Bitset / Bitmap

Problem: How to know that an entity has a component?

	ID	Bitset	Position	Velocity	Jumps	Player	Squishable
Mario	1	11110	☐	☐	☐	☐	
Goomba1	2	11001	☐	☐			☐
Luigi	3		☐	☐	☐		
Goomba2	4		☐	☐			☐

Issues?

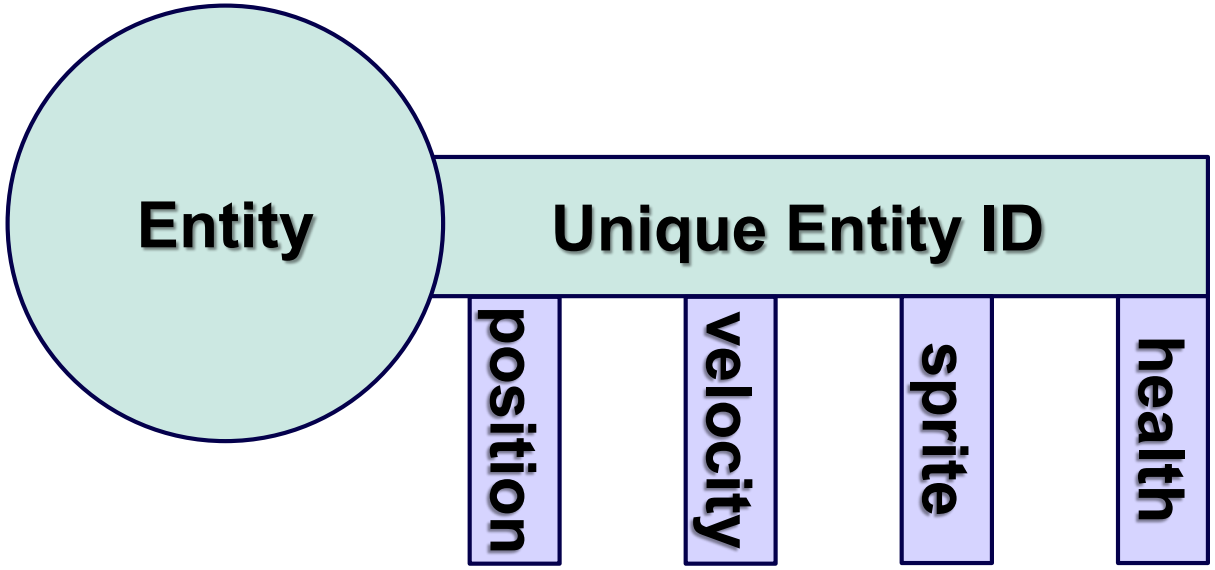
Concept: Each entity has a bitset that is true for its 'owned' components

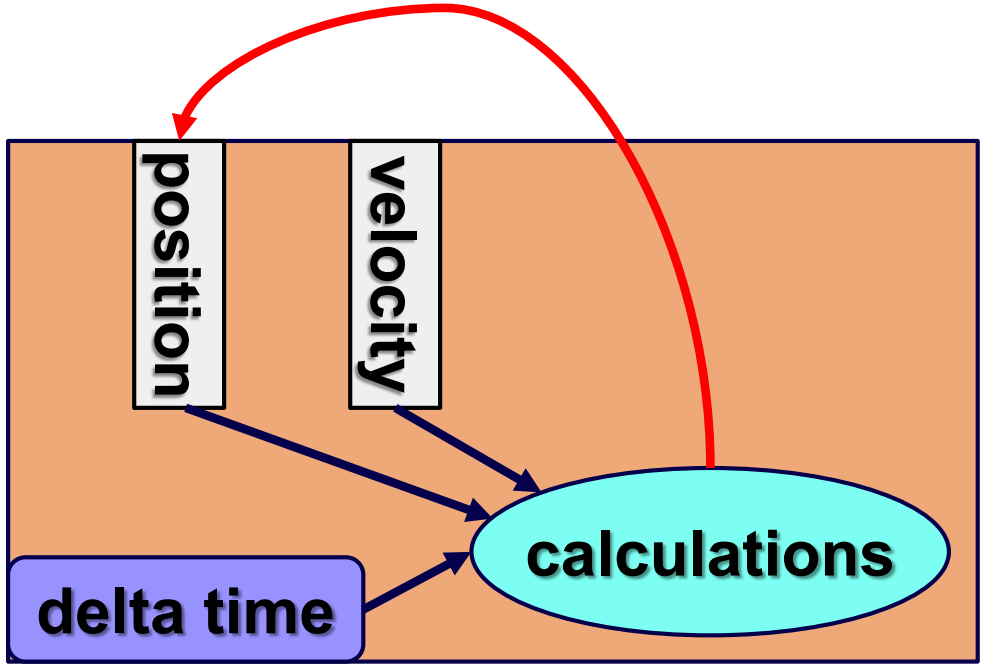
Implementation: long bitset;

How many components can we support?

```
If(bitset & query == query)  // has the entity all query components?
```

Key & Lock Metaphor



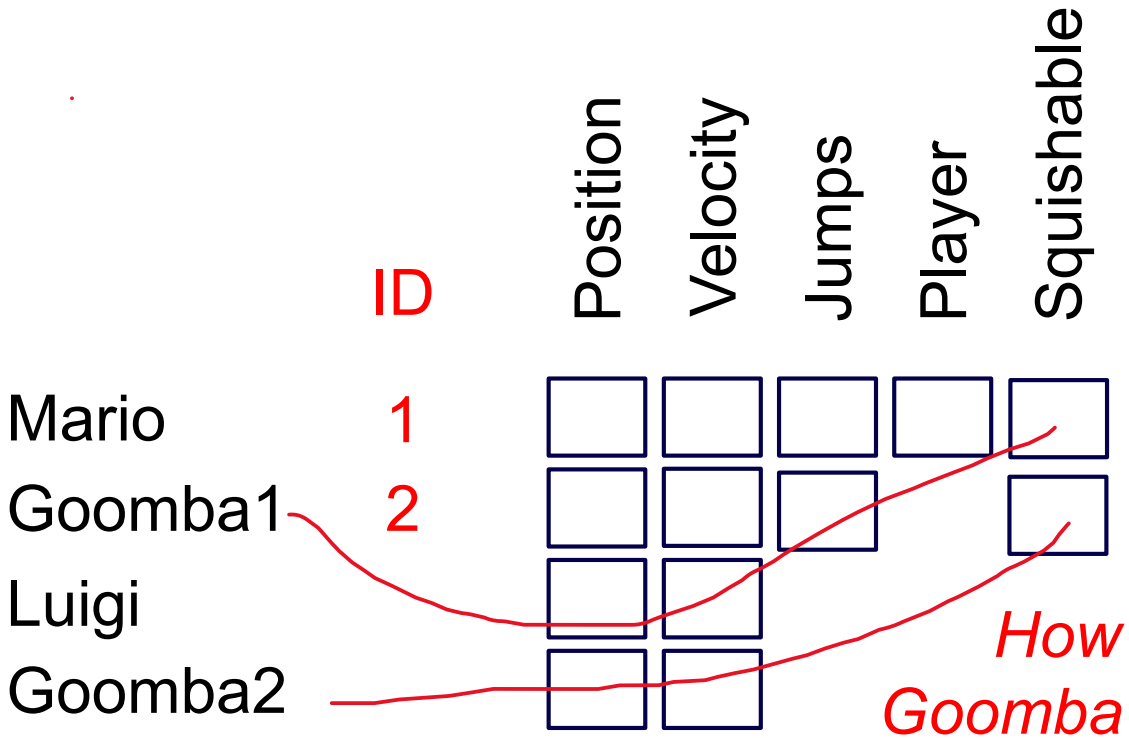


Motion System

Systems will only operate on Entities with the required Components

Further Improvements

Dense Component Vectors (an attempt, needs more)

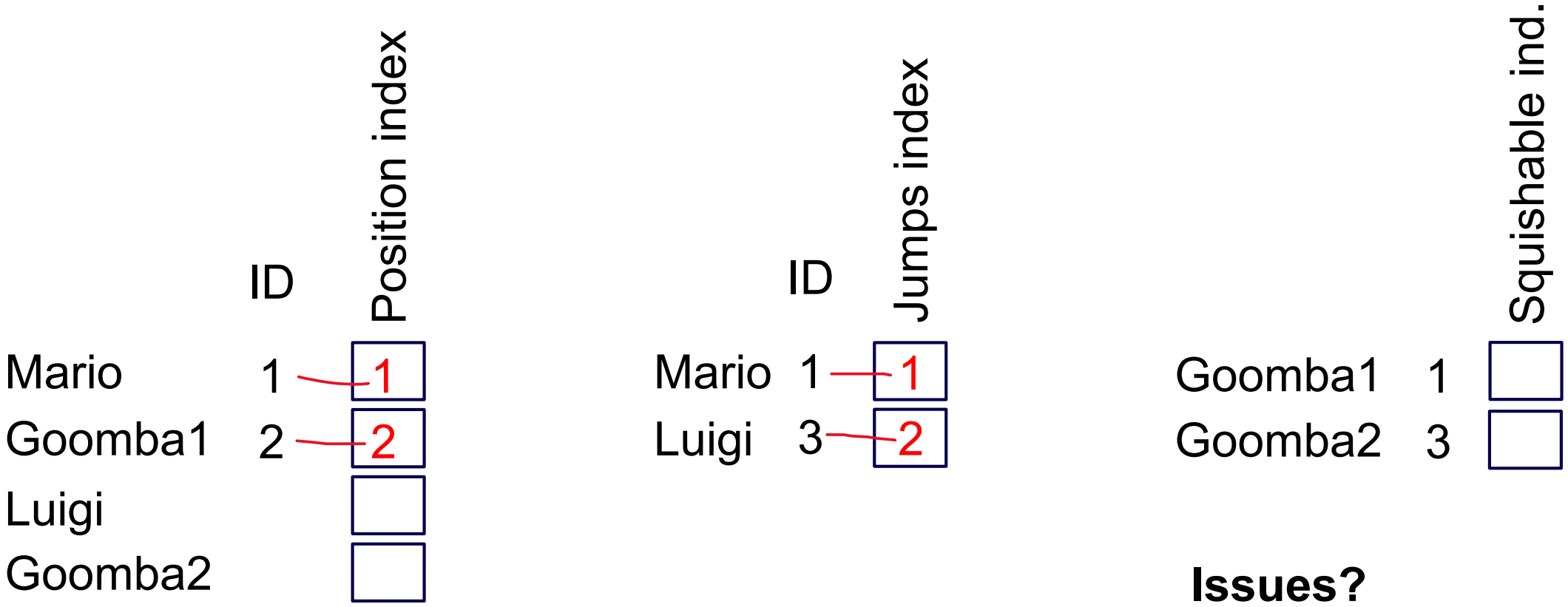


Issues?

How to find the position of Goomba's squishable component?

Concept: One array/vector per component, but how to associate?
Implementation: std:vector<Position>; std:vector<Velocity> + X?

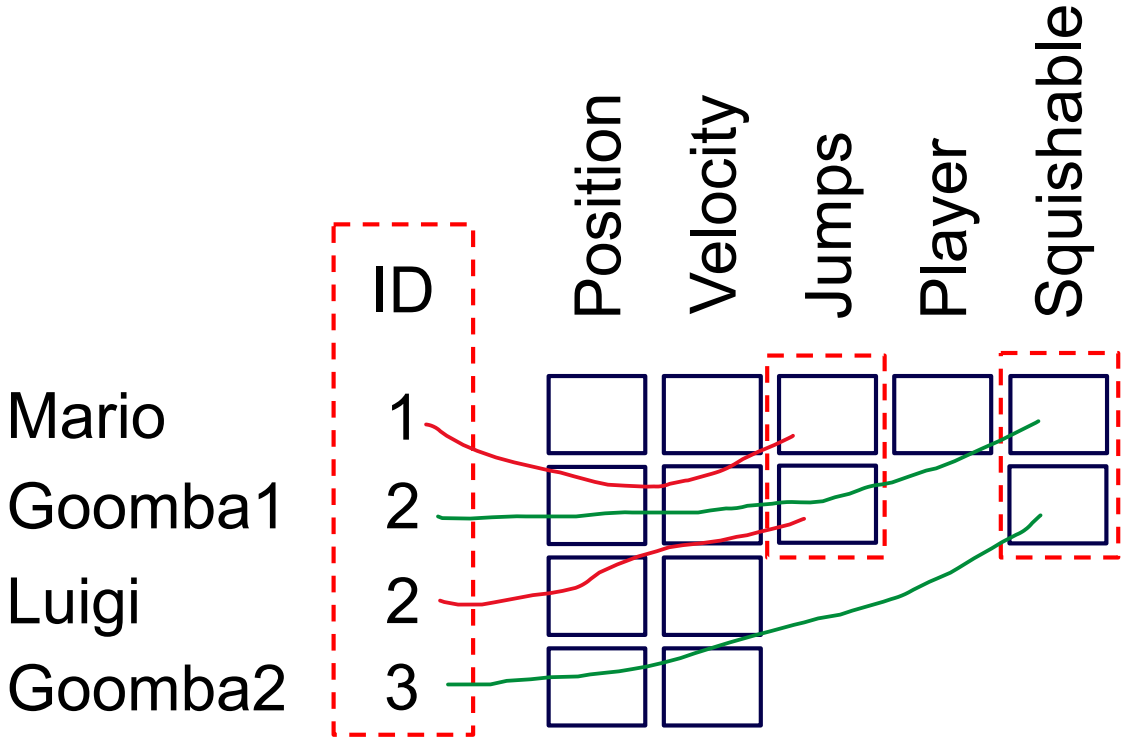
Map + Dense Component Vectors (entity ID to component ~~address~~ index)



Concept: Combine dense vectors with a map

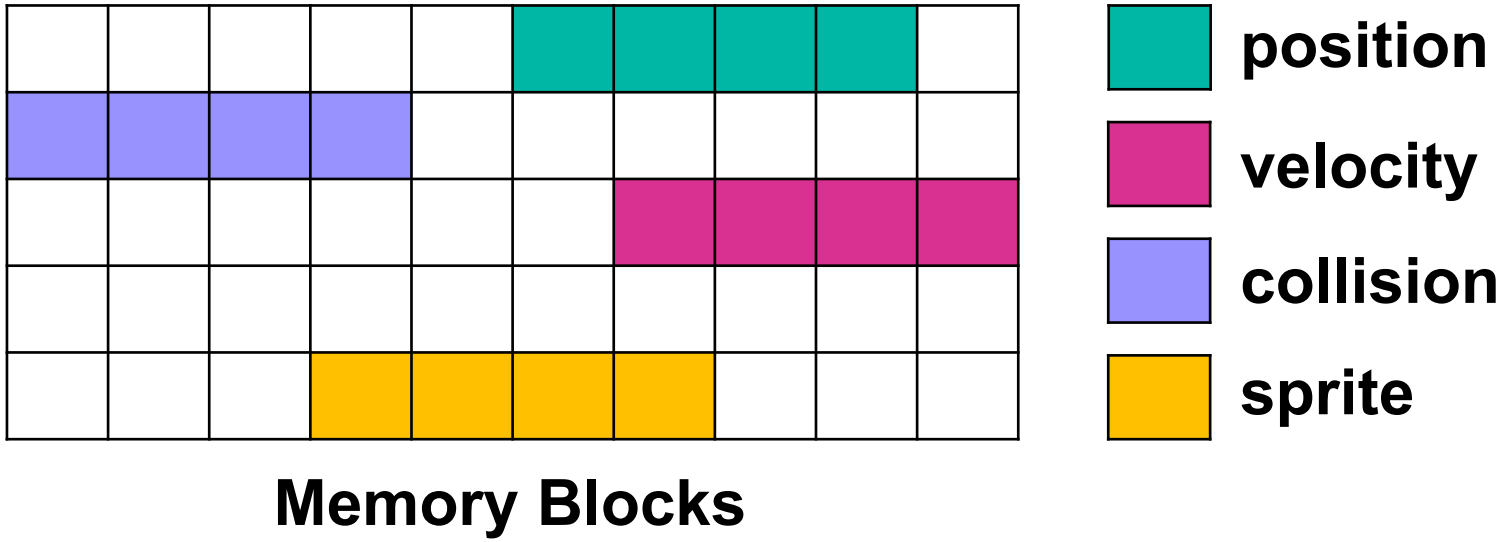
Implementation: std::vector<Component>; std::map<Entity,unsigned int>

Map + Dense Vector (different visualization)



Cache is Key

- Each Component type has a statically allocated array
- Minimizes costly cache misses
  - *Keeps components we access around the same time close to each other*



Map + Component Vector + Entity Vector

Concept: Add a dense vector of entities to facilitate quick iteration over entities
Implementation: std::vector<Entities>; std::vector<Component>; std::map<Entity,unsigned int>

Easy to iterate over all velocity components that belong to an entity with a position

```
for(int entity : velocity_entities) // using the key array
    if (position_entity_map.has(entity)) // using the map
        position_entity_map.get(entity) += velocity_entity_map.get(entity); // using component array
```

Faster iteration via entity and component array

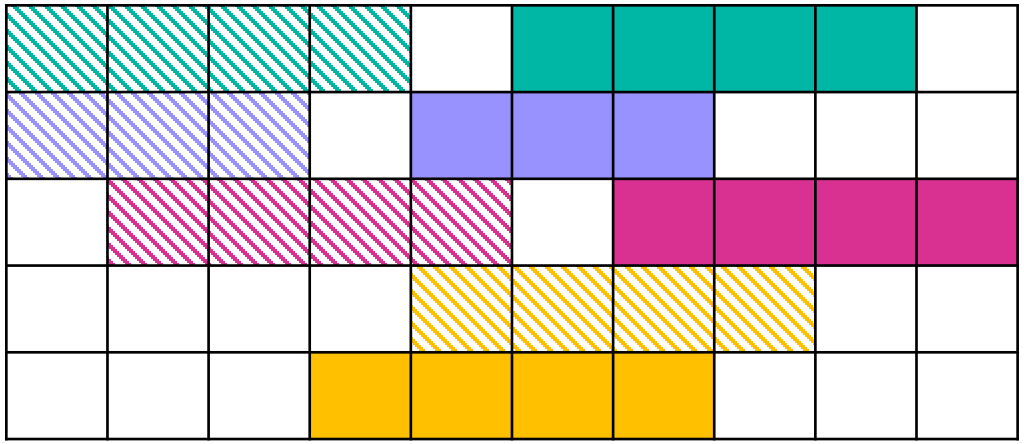
Accessing the velocity map (reg_velocity.map) is an unnecessary indirection

```
for(int entity : velocity_entities) // efficient
    if (position_entity_map.has(entity)) // inefficient lookup
            position_entity_map.get(entity)+= velocity_entity_map.get(entity); // 2x inefficient lookup
```

We can access the velocity components in linear fashion

```
for(int vel_i = 0; vel_i < velocity_entities.size(); vel_i++) // efficient
    Entity entity : velocity_entities[vel_i]; // efficient
    int pos_i = position_entity_map.getIndex(entity); // inefficient lookup
    if (pos_i)
            position_components[pos_i]+= reg_velocity_components[vel_i]; // efficient
```

Map + Component Vectors + Entity Vector Cache is Key



Memory Blocks

position

velocity

collision

sprite

position entity IDs

velocity entity IDs

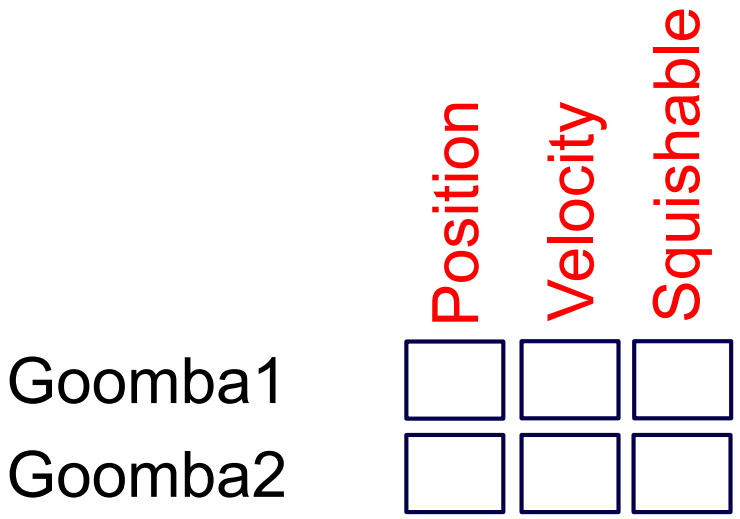
collision entity IDs

sprite entity IDs

Update loop accesses contiguous memory IDEAL?

Map access slow

Advanced ECS: Archetypes / prototypes / pools



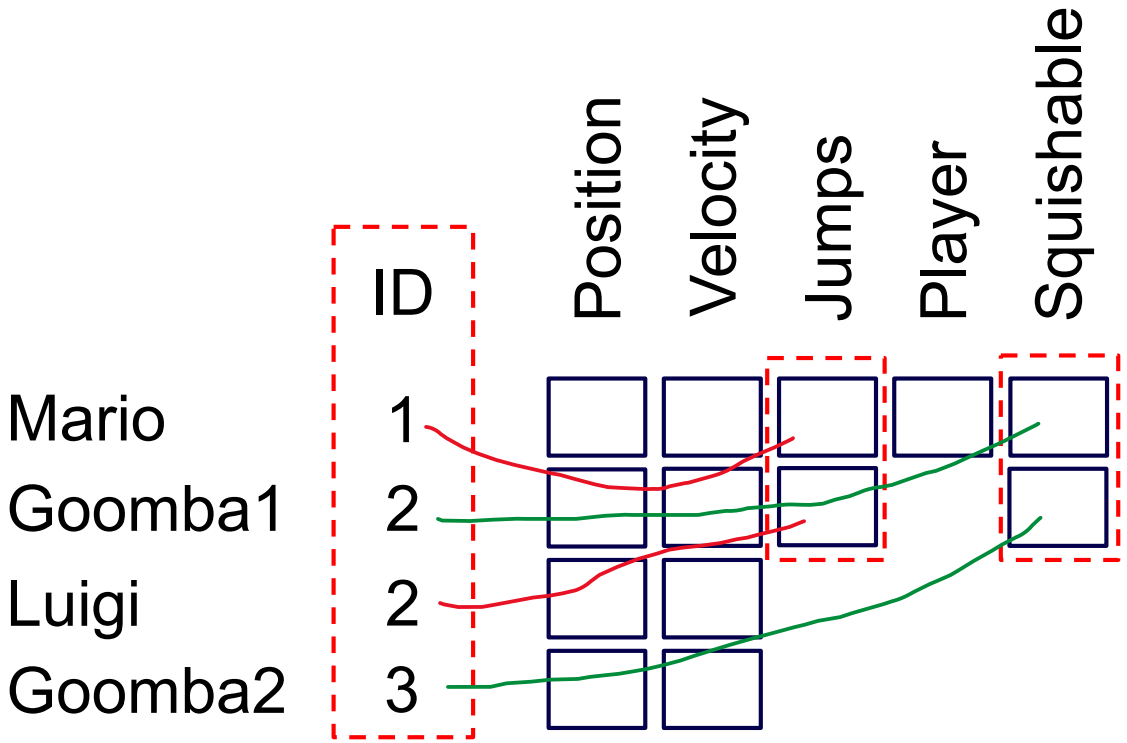
- **Concept:** store all types with the same components in dense arrays
- Used by the Unity ECS system
- Difficult to implement

How Does a System Find its Entities?

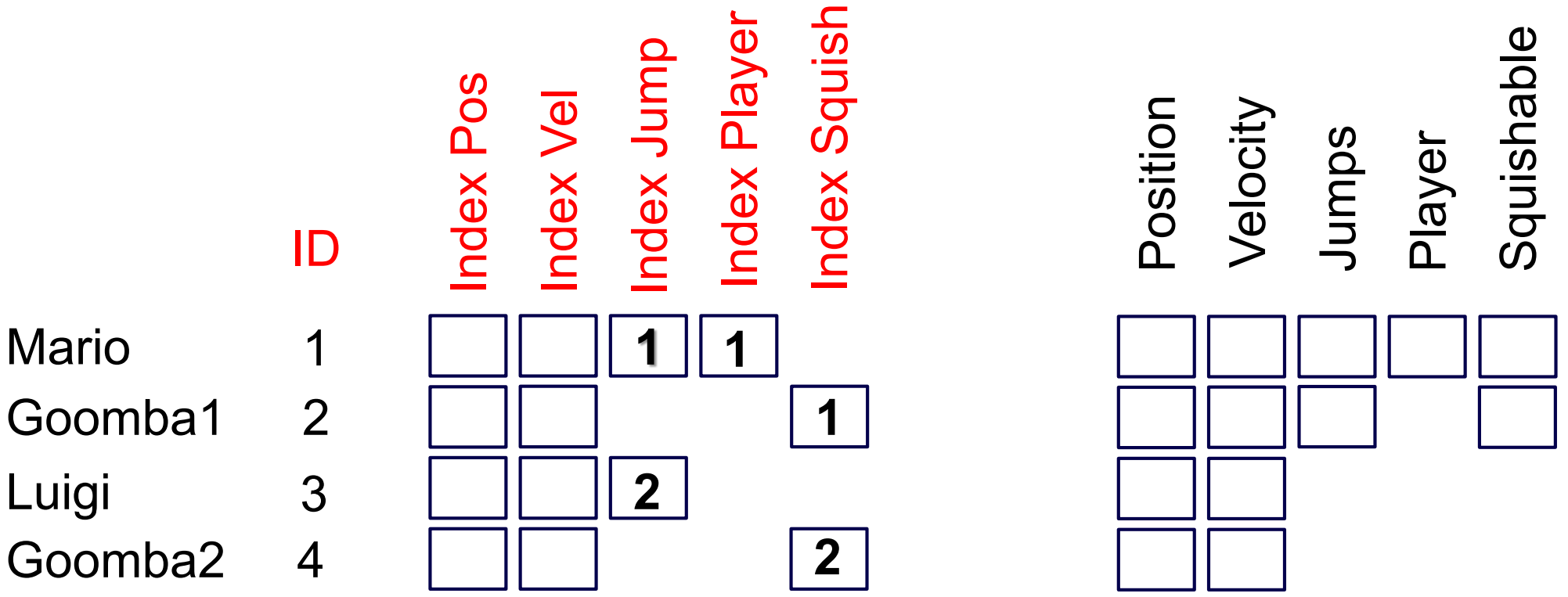
Extension: Entity Manager

- Each system has a list of entity IDs it is interested in
- Systems register their bitsets/bitmaps with the Entity Manager
- Whenever an Entity is added…
  - *Evaluate which systems are interested & update their ID lists*

Self-study: A special map approach



Self-study: The ‘Sparse Set’



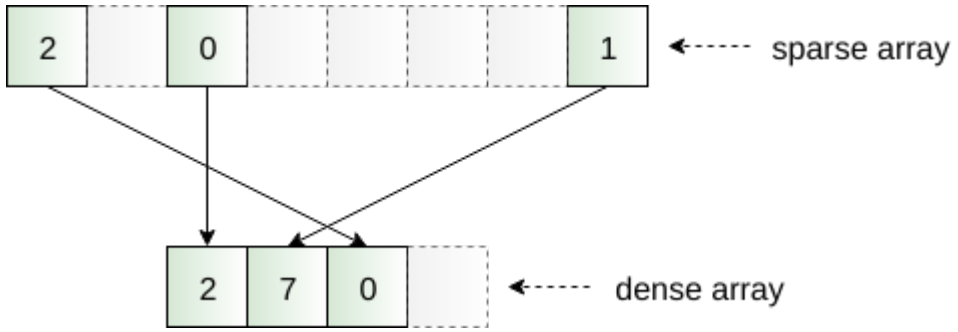
Issues?

Concept: Sparse array + dense array

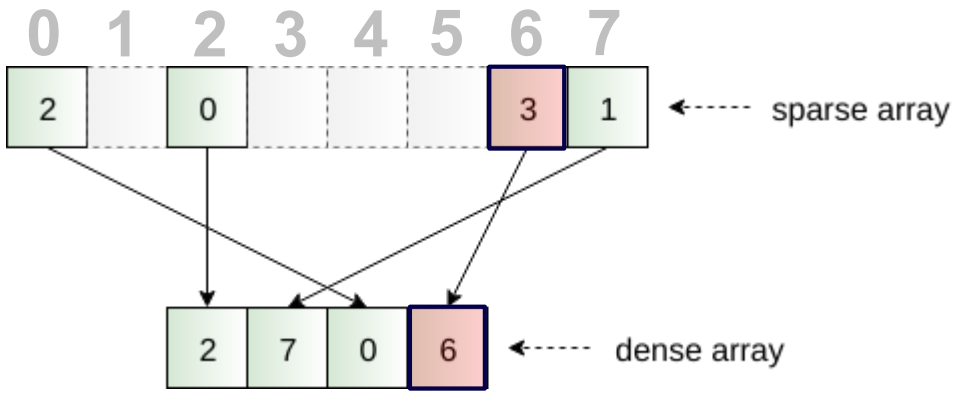
Implementation: std:vector<Entity> entities; std:vector<unsigned int> indices; std:vector<Components> components;

Self-study: Faster Lookup with Sparse Sets

Lookup:



Insert:



[https://skypjack.github.io/2020-08-02-ecs-baf-part-9/]

The map lookup (map.get(entity)) is costly

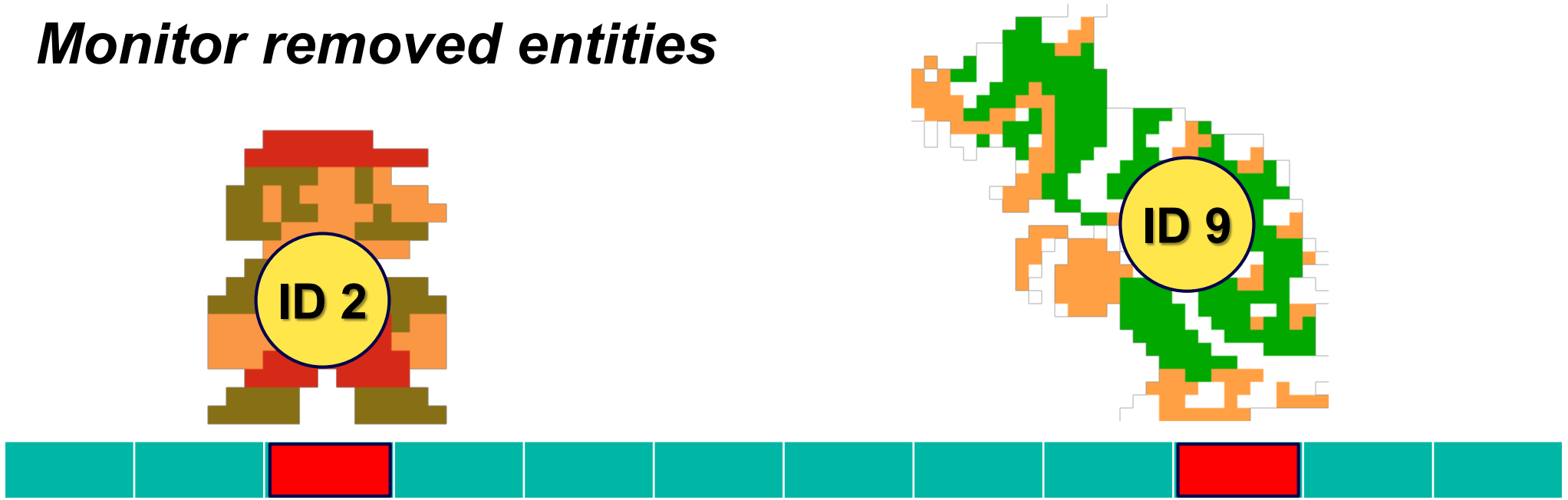
- A hashmap is O(1), but that 1 is big

Sparse set:

- An array as large as the number of entities in the game
  - Crazy waste of memory?!
  - 32 bit integer -> ???
  - a sparsely filled array
- A small dense array of all entities in sequence (as before)
- Extremely fast lookup, insert, & clear

Entity Summary

- Each Entity is typically just a unique identifier to its components
- Store Entities in a big static array in the Entity Manager
  - *Monitor removed entities*



Memory & ECS

Where do we store our Components?

- **Inside a registry!**
  - ***Systems don't own components***
  - ***One big array for each Component type***
  - ***Takes advantage of modular architecture of ECS***

YES!

Cache is Key

- **When we "delete" an entity we must delete corresponding components to.**
- **Different approaches to this,**
  - ***Fill deleted components in arrays with the last entities data***
    - Extra care must be taken when managing indices
  - ***Mark spots in arrays as rewritable***
    - Big systems will suffer from poor memory management

Entity Component Systems: Benefits

- **Complexity**
  - ***Game code tends to grow exponentially***
  - ***Complexity of ECS architecture does not grow with it***
  - **Easy to maintain**
- **Customization**
  - **Games have a lot of dynamic operations**
  - ***Add/remove components to change Entity behavior***
  - ***ECS is highly modular***
- **Can be very memory efficient!**

Backup