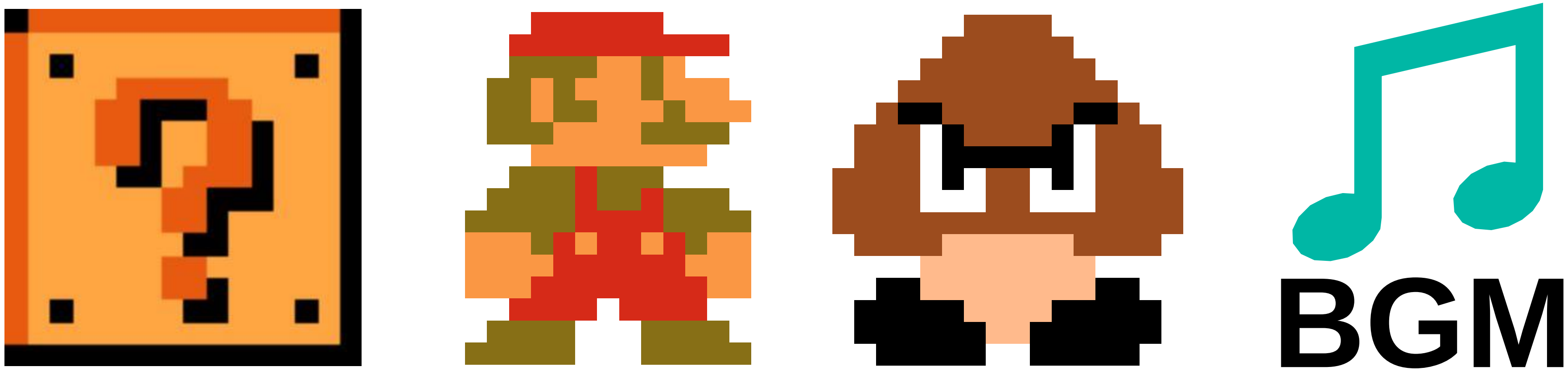
CPSC 427
Video Game Programming

Entity Component System (ECS)

ECS is used in Minecraft and many other commercial games

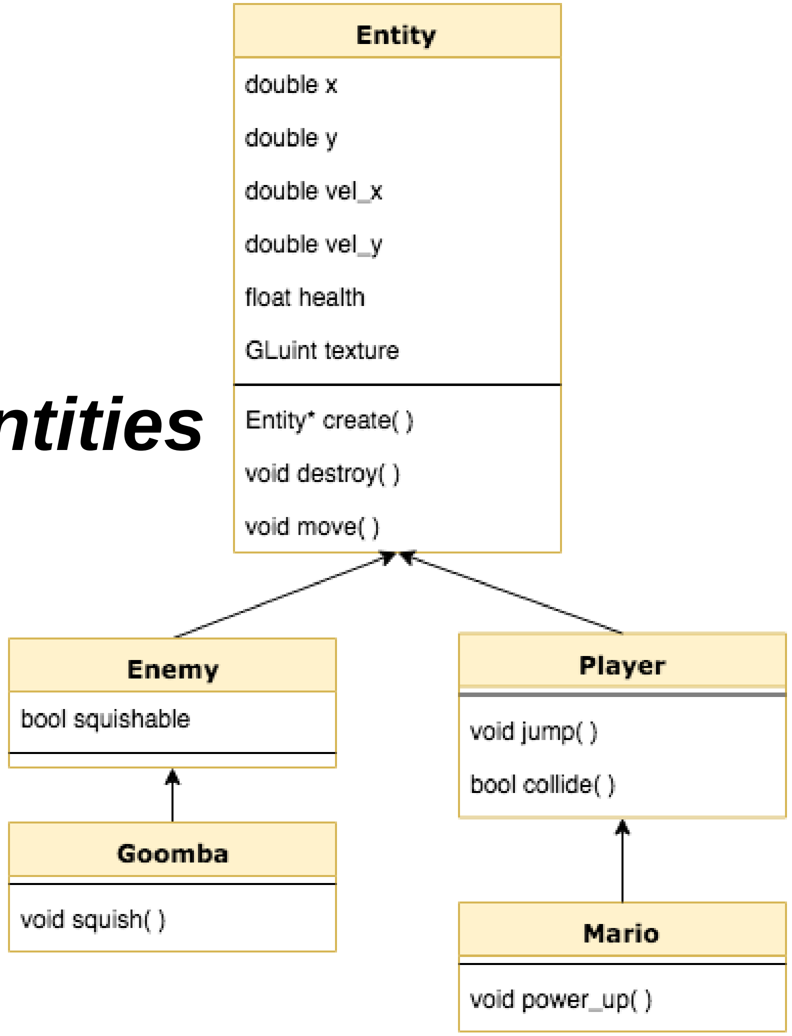
What are Entities?

- **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

double x

double y

double vel_x

double vel_y

float health

GLuint texture

Entity* create( )

void destroy( )

void move( )

Enemy

bool squishable

Goomba

void squish( )

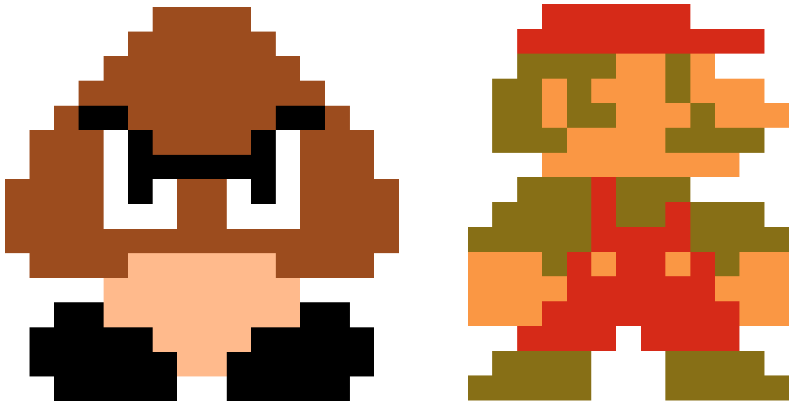
Player

void jump( )

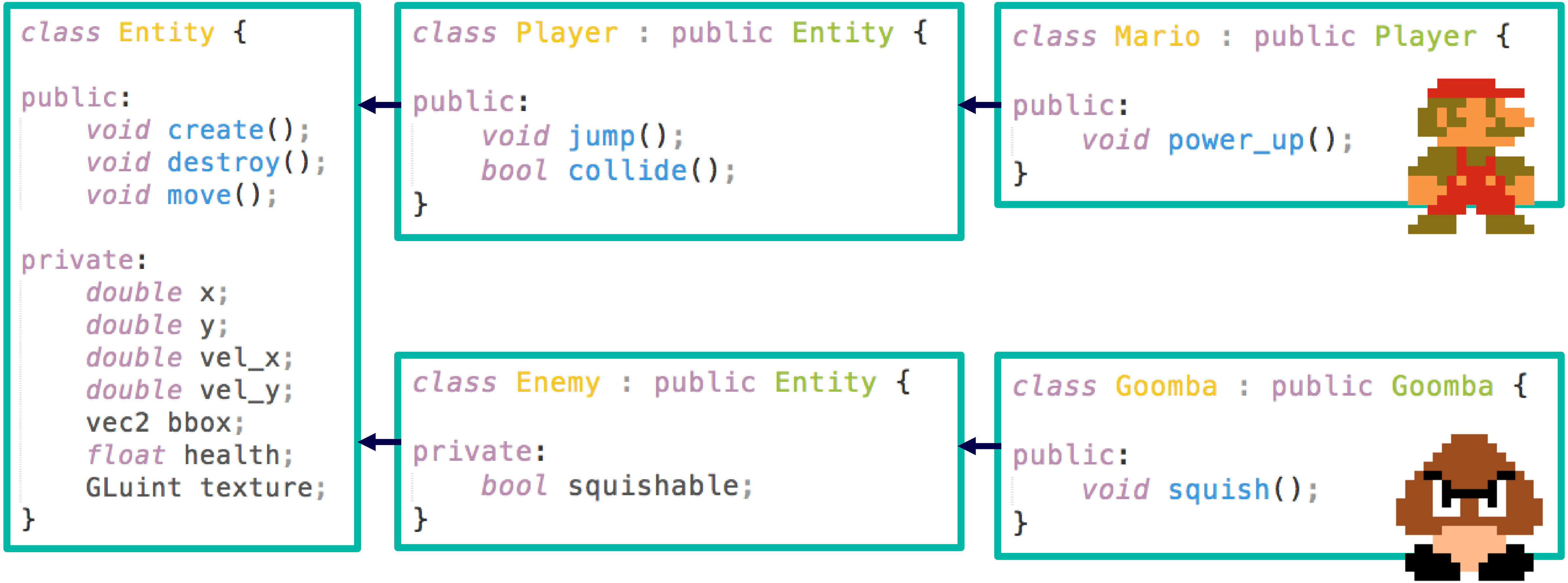
bool collide( )

Mario

void power_up( )



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();
}
```

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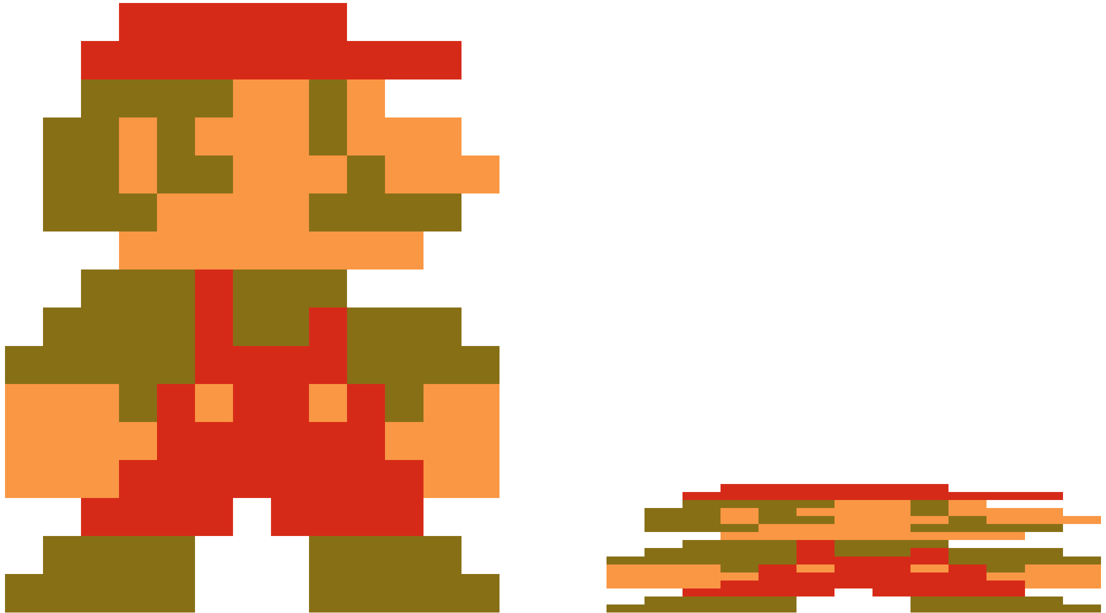
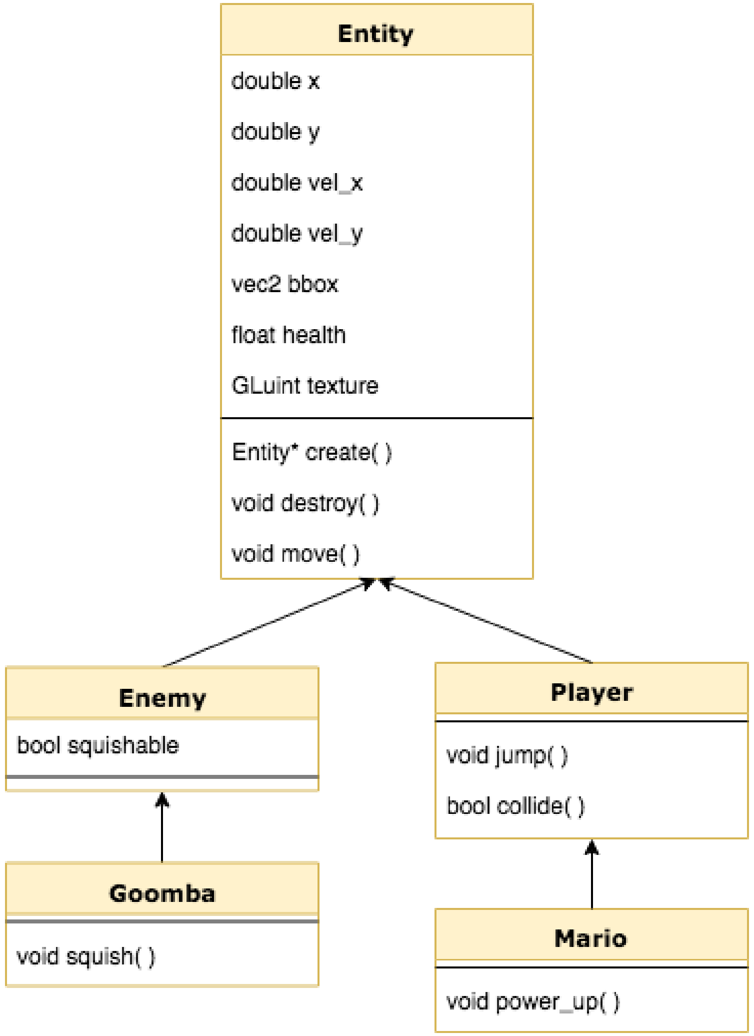
Issues with Object-Oriented Approach

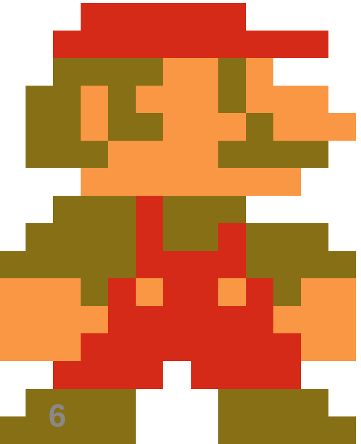
What if we want Mario to be able to be squished?

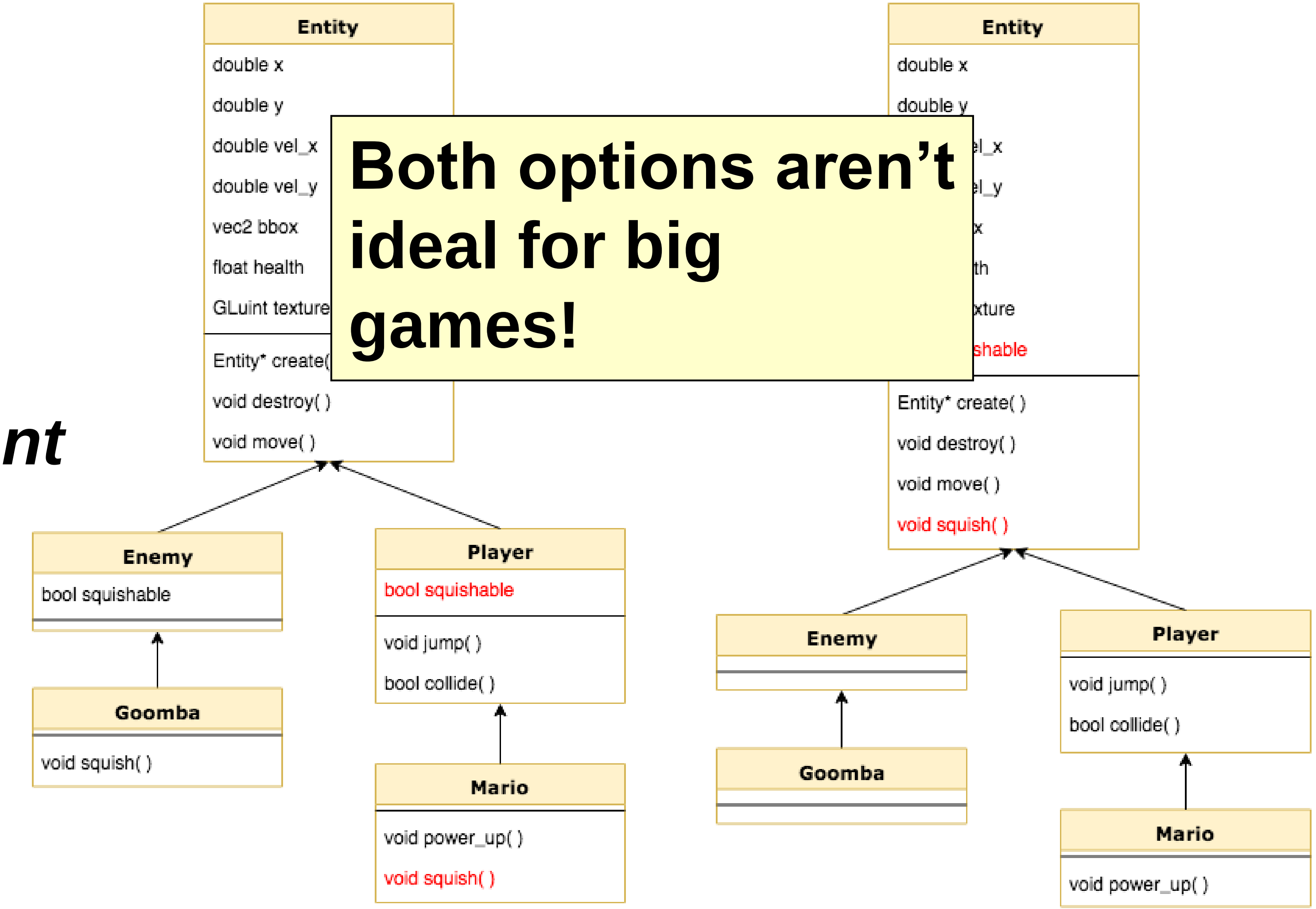




Issues with Object-Oriented Approach

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





Entity
double x
double y
double vel_x
double vel_y
vec2 bbox
float health
GLuint texture
Entity* create(
void destroy( )
void move( )

Enemy
bool squishable

Goomba
void squish( )

Player
bool squishable
void jump( )
bool collide( )

Mario
void power_up( )
void squish( )

Entity
double x
double y
l_x
l_y
x
th
xture
shable
Entity* create( )
void destroy( )
void move( )
void squish( )

Enemy

Goomba

Player
void jump( )
bool collide( )

Mario
void power_up( )

Both options aren’t ideal for big games!

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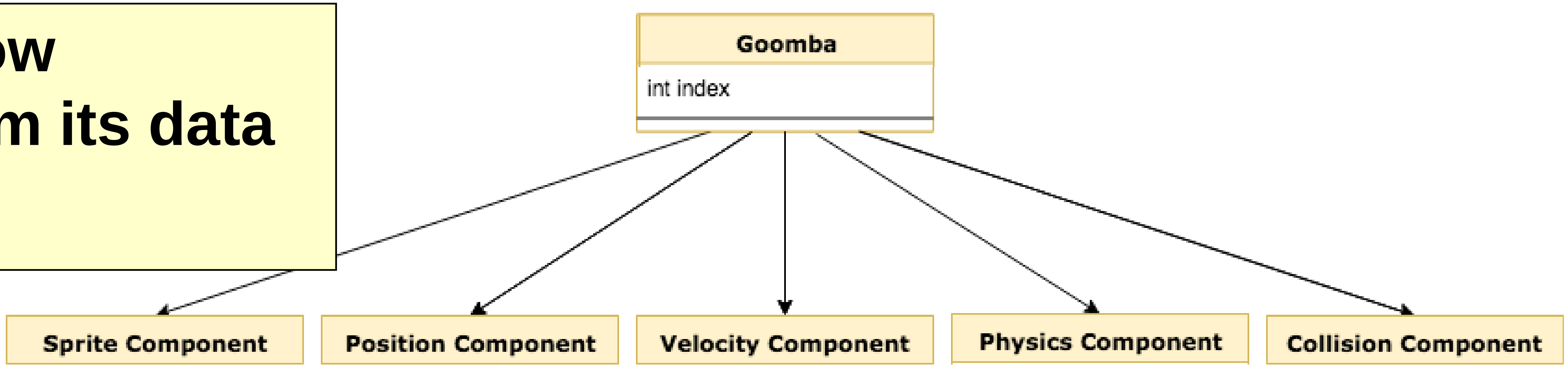
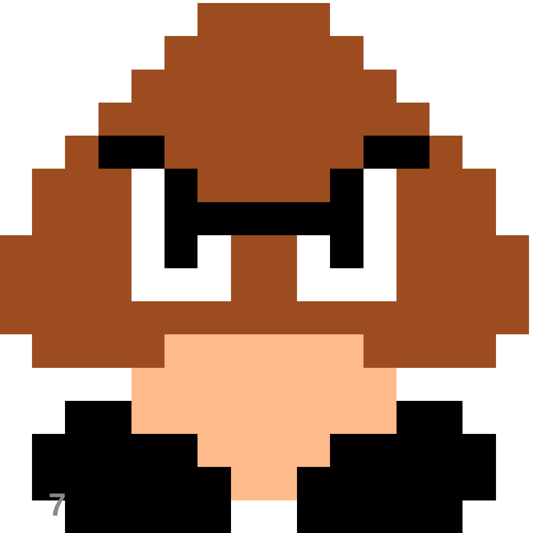
Example ECS Diagram

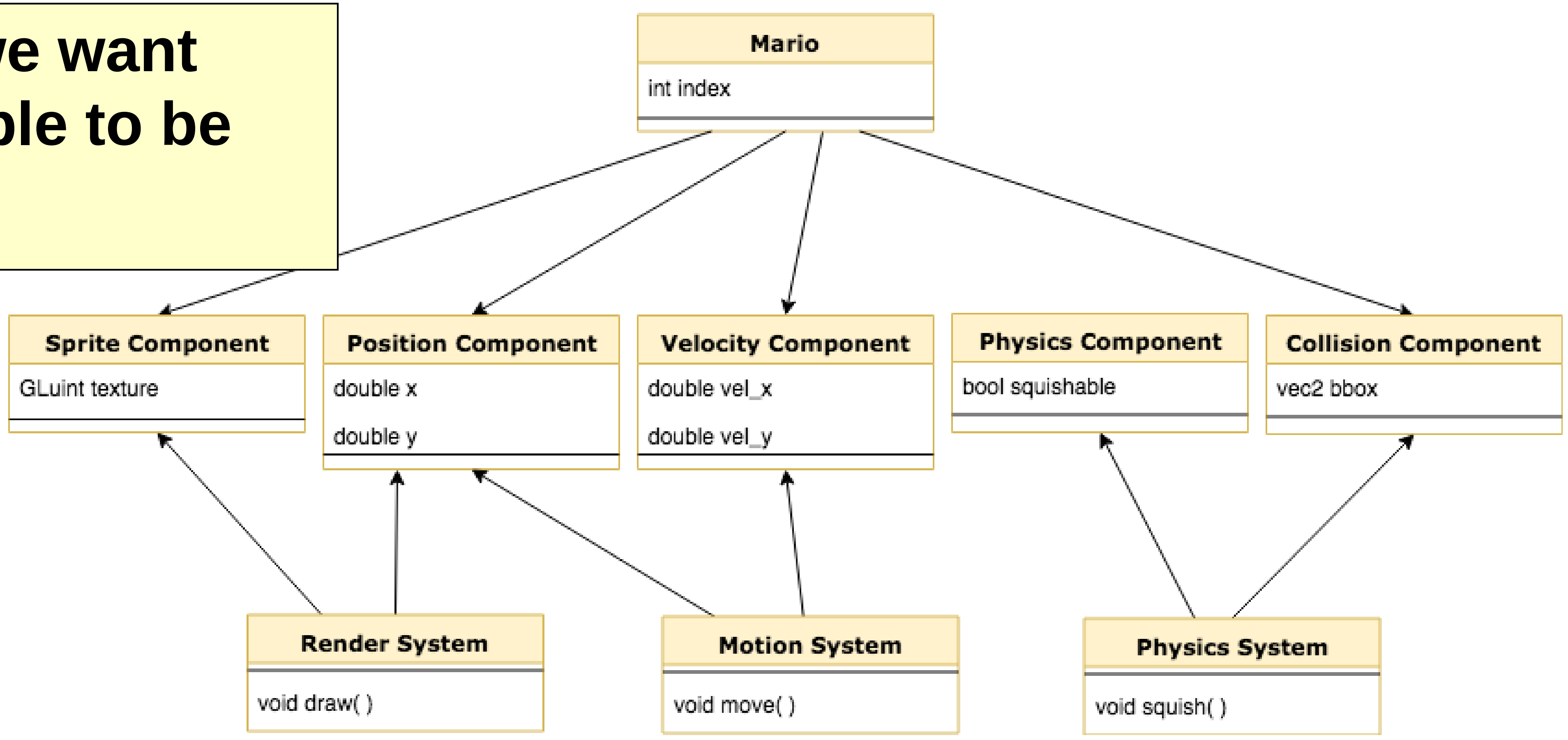
Goomba is now separated from its data & methods





Example ECS Diagram

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



Mario
int index

Sprite Component
GLuint texture

Position Component
double x
double y

Velocity Component
double vel_x
double vel_y

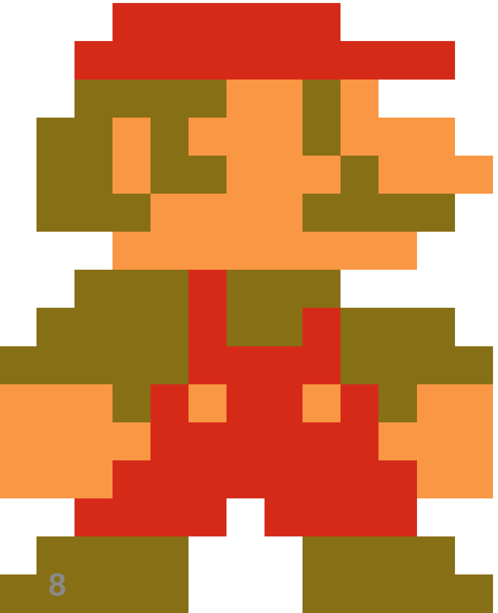
Physics Component
bool squishable

Collision Component
vec2 bbox

Render System
void draw( )

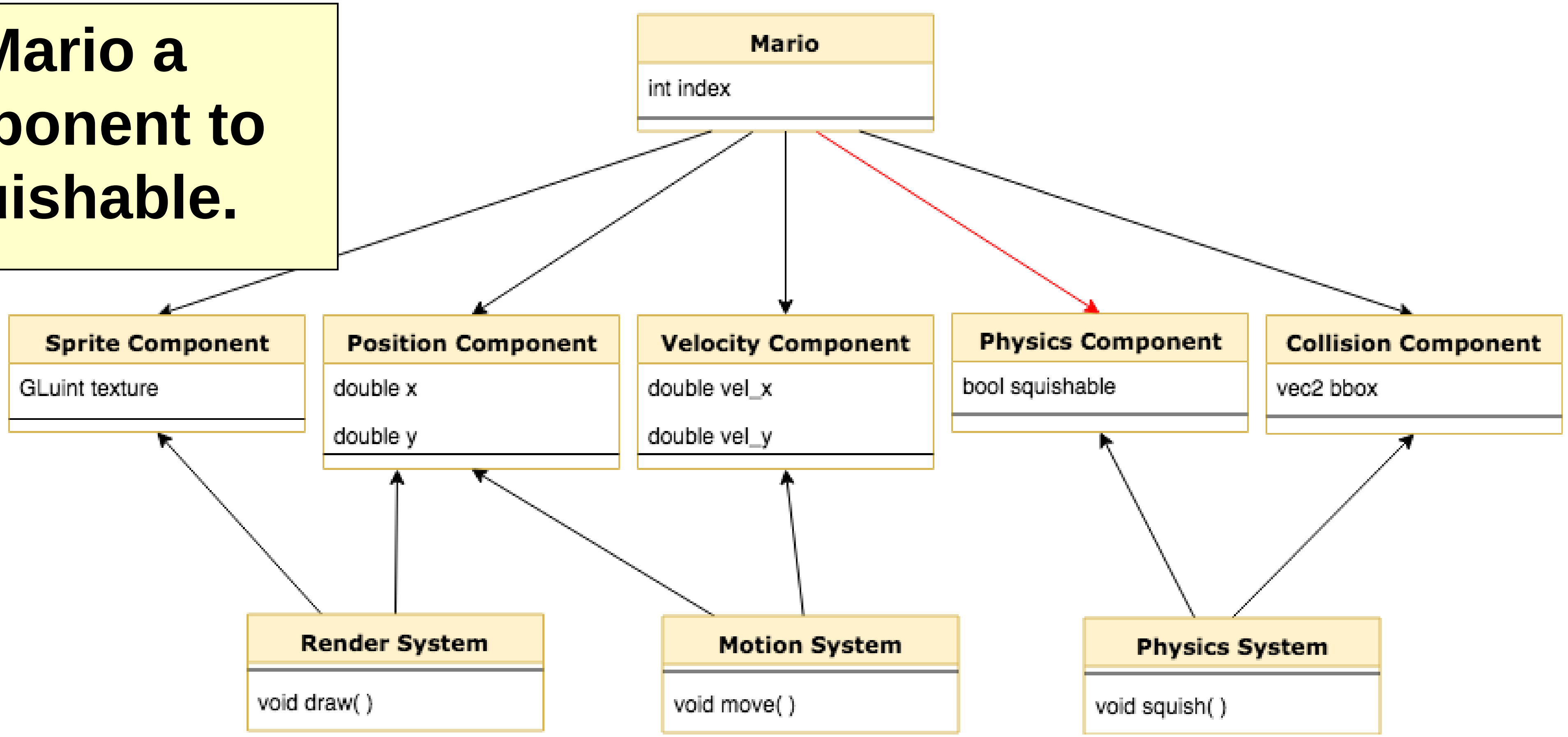
Motion System
void move( )

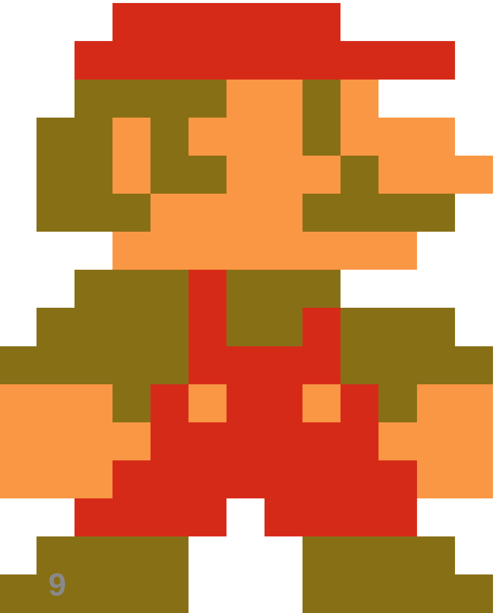
Physics System
void squish( )



Example ECS Diagram

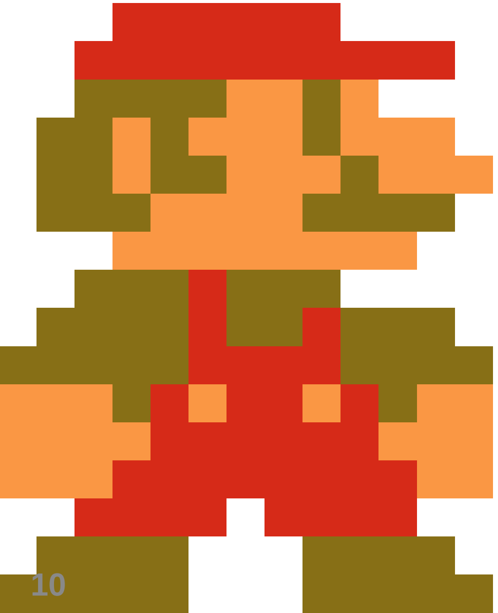
We can give Mario a Physics Component to make him squishable.

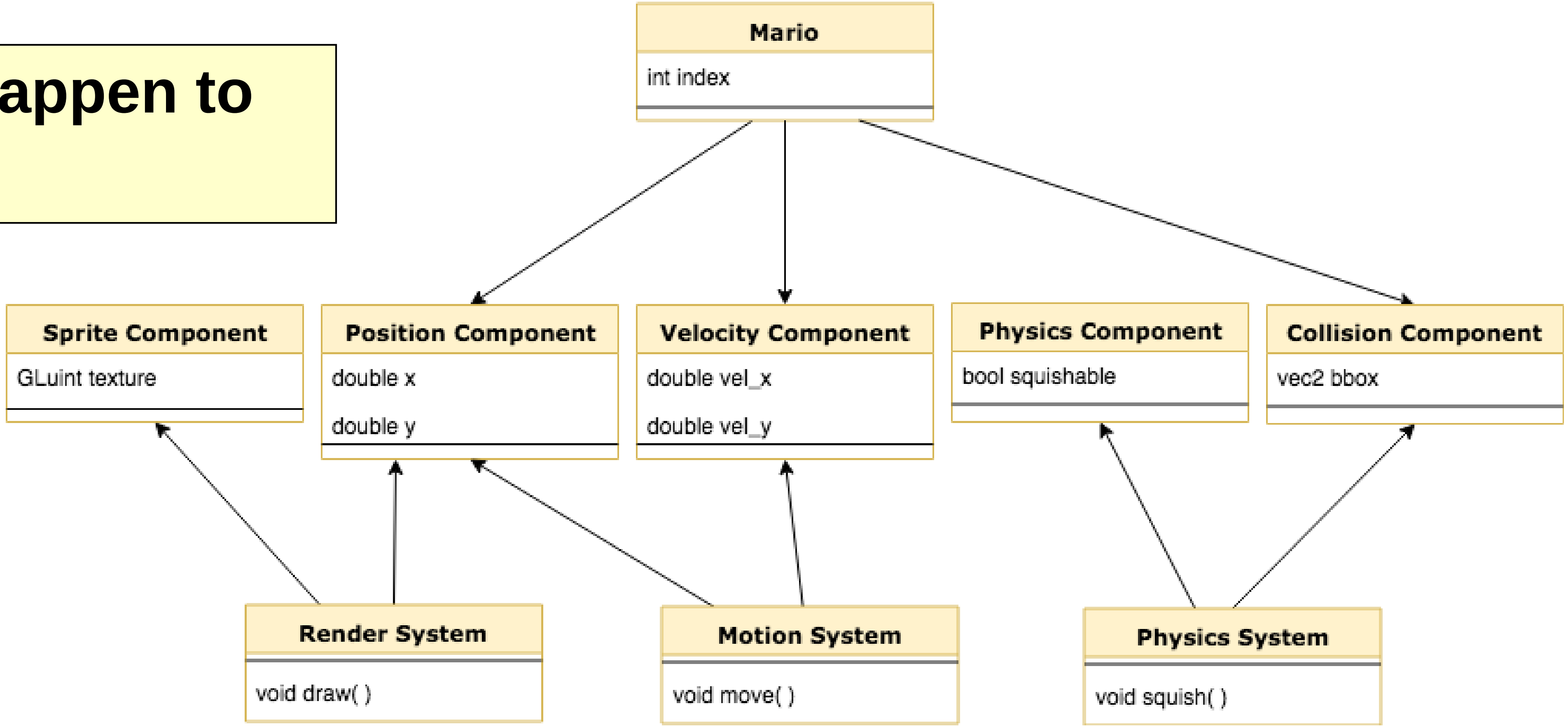




Example ECS Diagram

What would happen to Mario here?





Mario
int index

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 bbox

Render System
void draw( )

Motion System
void move( )

Physics System
void squish( )

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

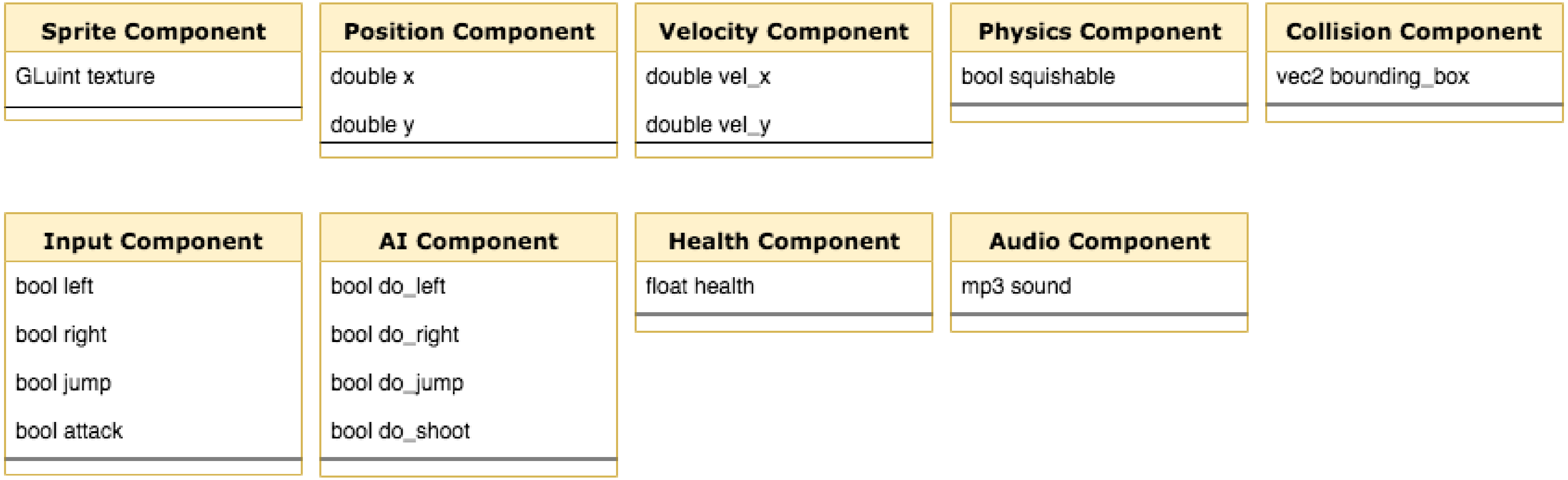
What is ECS?

- 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

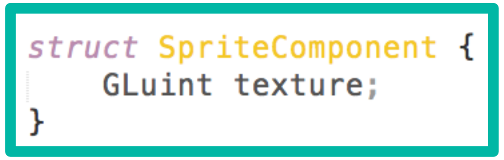
AI Component
bool do_left
bool do_right
bool do_jump
bool do_shoot

Health Component
float health

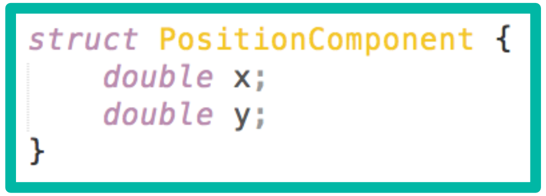
Audio Component
mp3 sound

Component

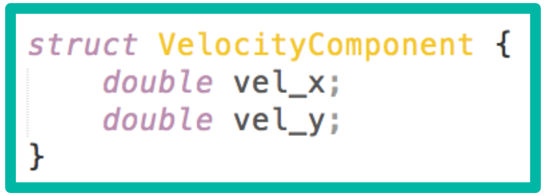
- **Typically implemented with structs.**



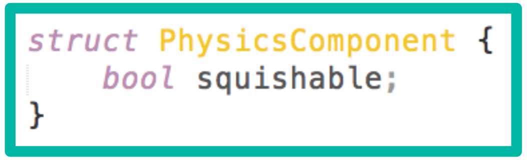
```
struct SpriteComponent {
    GLuint texture;
}
```



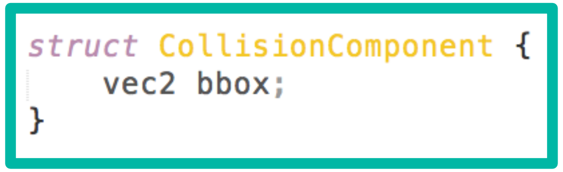
```
struct PositionComponent {
    double x;
    double y;
}
```



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



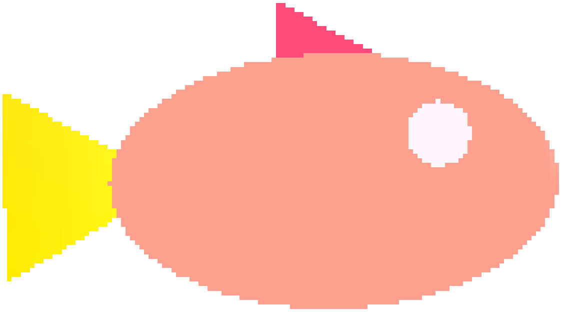
```
struct PhysicsComponent {
    bool squishable;
}
```



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

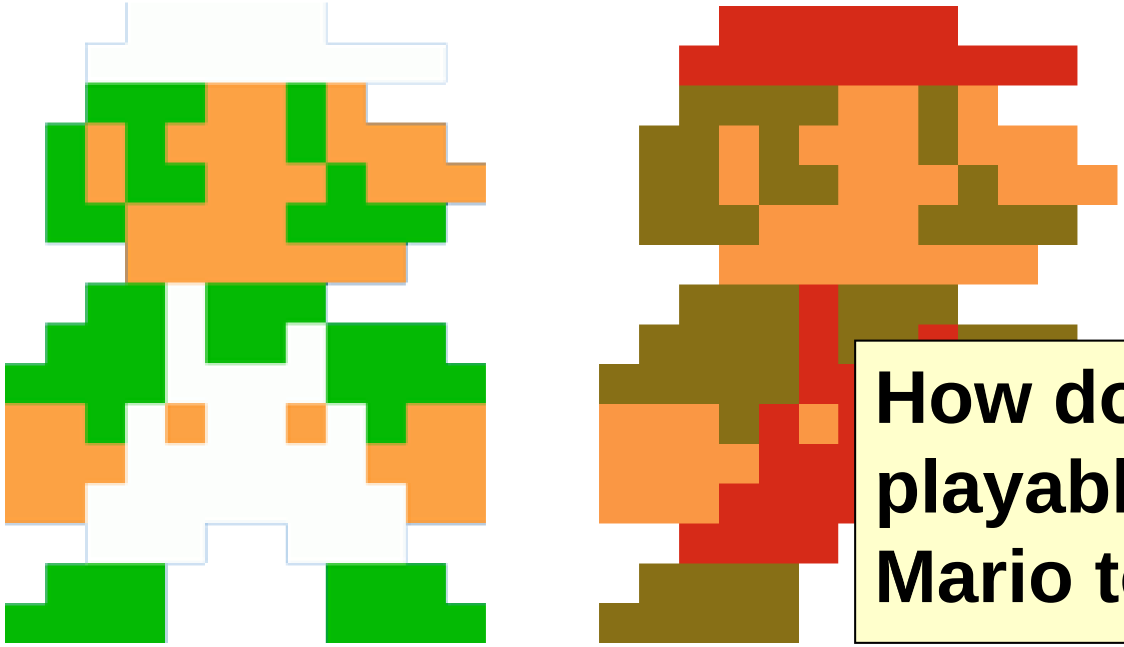
What Components to Make?

- What Components would we give to the following Entities?



Components

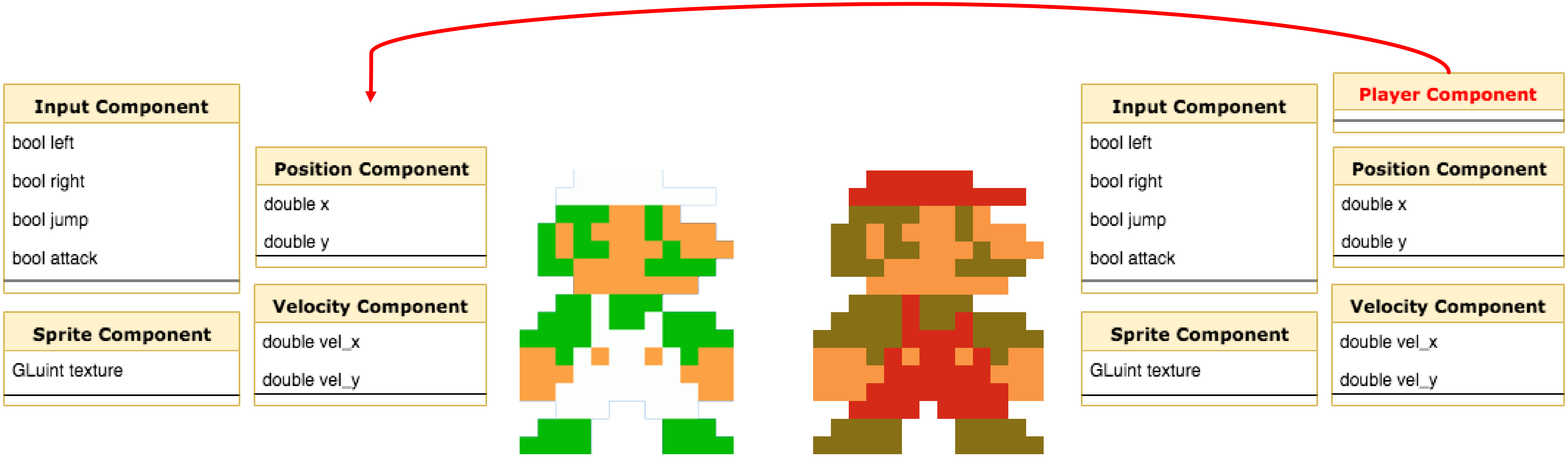
- **Easy to add new Entity characteristics**
  - ***Just create the desired Component & give to Entity***



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

Components

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



Input Component
bool left
bool right
bool jump
bool attack

Sprite Component
GLuint texture

Position Component
double x
double y

Velocity Component
double vel_x
double vel_y

Input Component
bool left
bool right
bool jump
bool attack

Sprite Component
GLuint texture

Player Component

Position Component
double x
double y

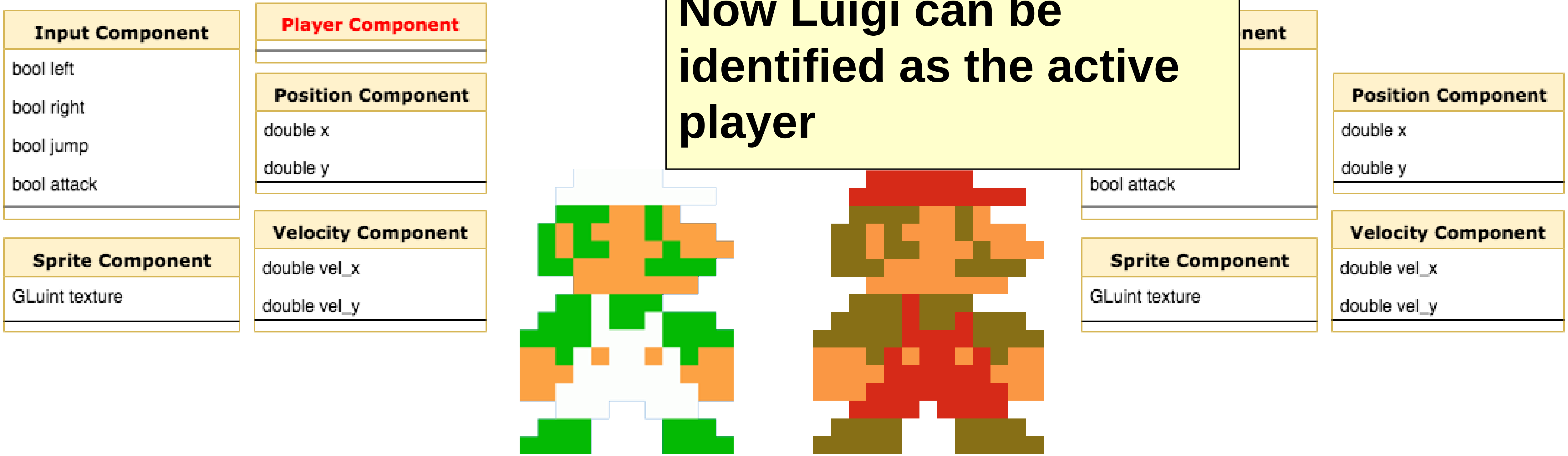
Velocity Component
double vel_x
double vel_y

Empty components are useful, a flag indicating an ability!

Components

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

Now Luigi can be identified as the active player



Input Component

bool left

bool right

bool jump

bool attack

Sprite Component

GLuint texture

Player Component

Position Component

double x

double y

Velocity Component

double vel_x

double vel_y

nent

bool attack

Sprite Component

GLuint texture

Position Component

double x

double y

Velocity Component

double vel_x

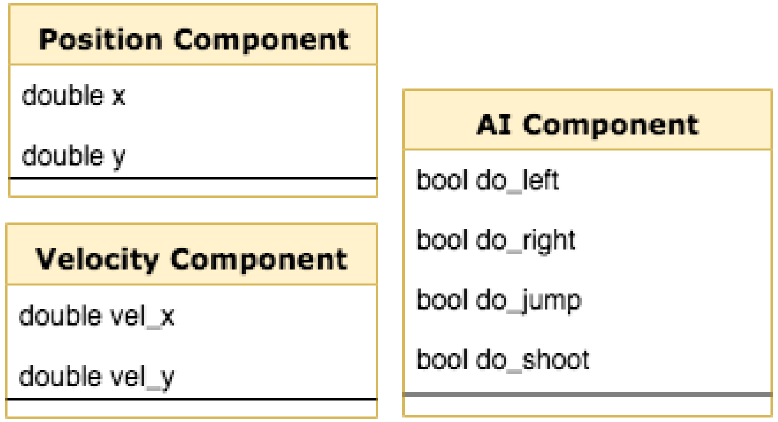
double vel_y

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?**



Position Component

double x

double y

Velocity Component

double vel_x

double vel_y

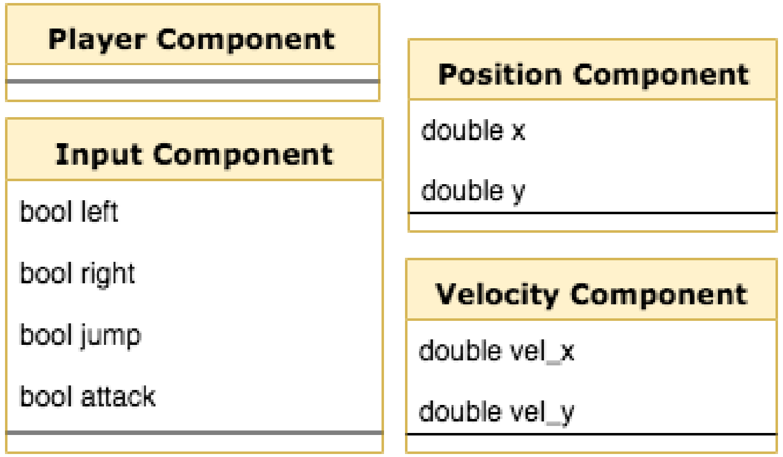
AI Component

bool do_left

bool do_right

bool do_jump

bool do_shoot



Player Component

Input Component

bool left

bool right

bool jump

bool attack

Position Component

double x

double y

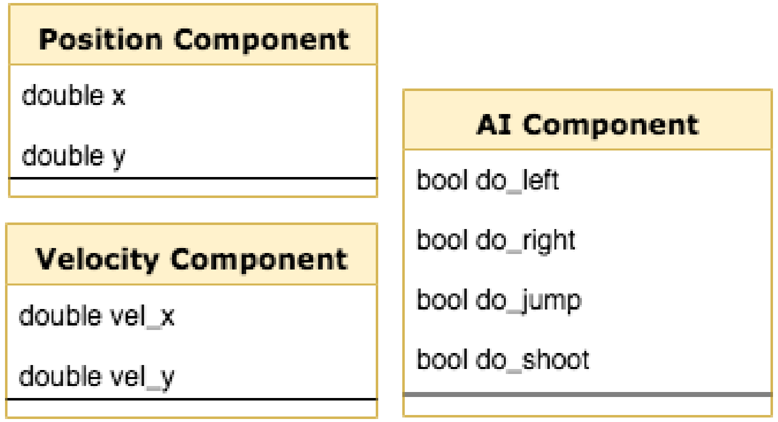
Velocity Component

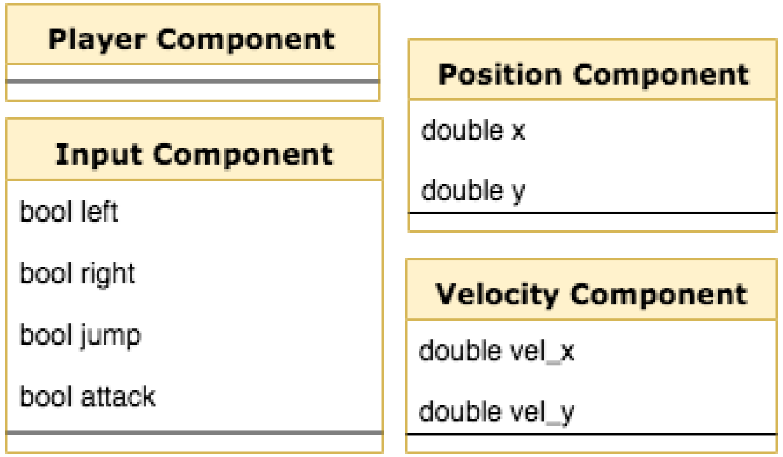
double vel_x

double vel_y

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 does not care about entities at all!

Game loop

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

Single boolean check

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

```
for(int entity : velocity_entities)
     if (position_entities.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

ECS implementations

Memory & ECS

Where do we store our Components?

- **RAM, harddrive, or chache?**
- **Inside Systems?**
    - ***Better, but could be improved***
    - ***Different Systems may need the same Component types***
        - How do we decide who owns what?
        - Messaging can get overly complex between systems

Problem: associating entities and components

	Position	Velocity	Jumps	Player	Squishable
Mario	□	□	□	□	
Goomba1	□	□			□
Luigi	□	□	□		
Goomba2	□	□			□

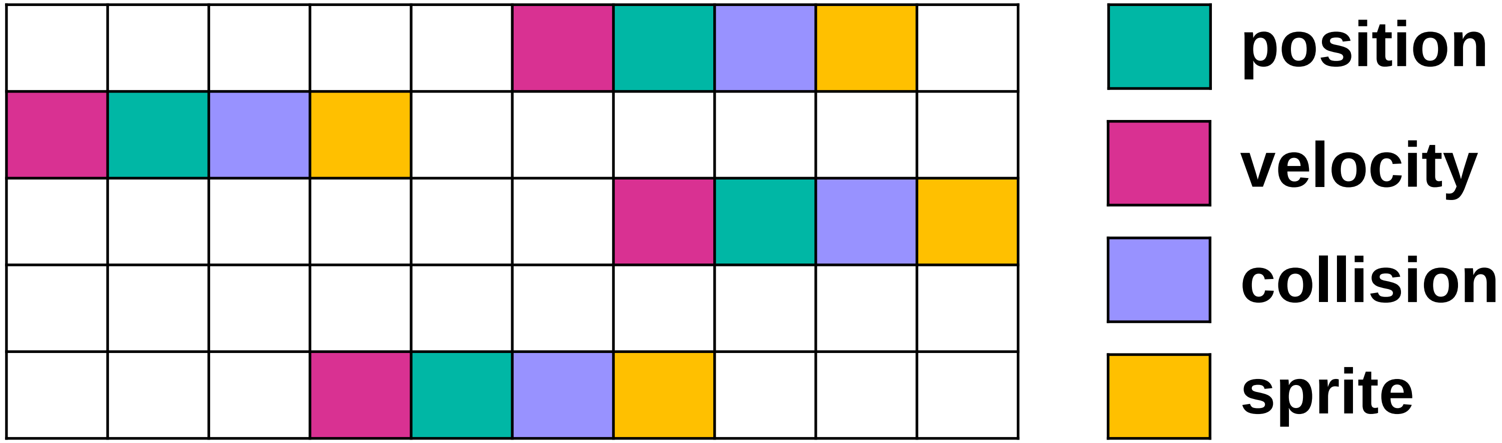
Object-oriented-programming (OOP)?

ECS = containers of components?

Memory & ECS

Where do we store our Components?

- Inside Entities?

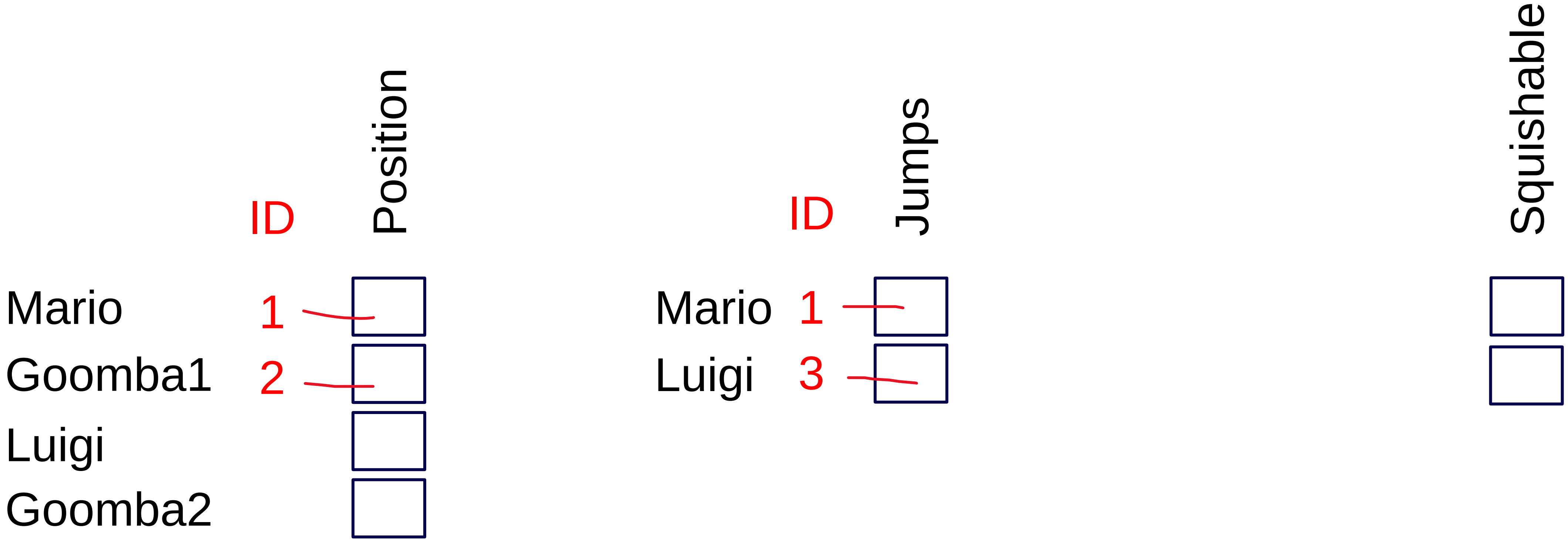


Memory Blocks

Update loop has to access non-contiguous memory repeatedly!

Slow memory access!

The Map Approach (entity ID to component address)



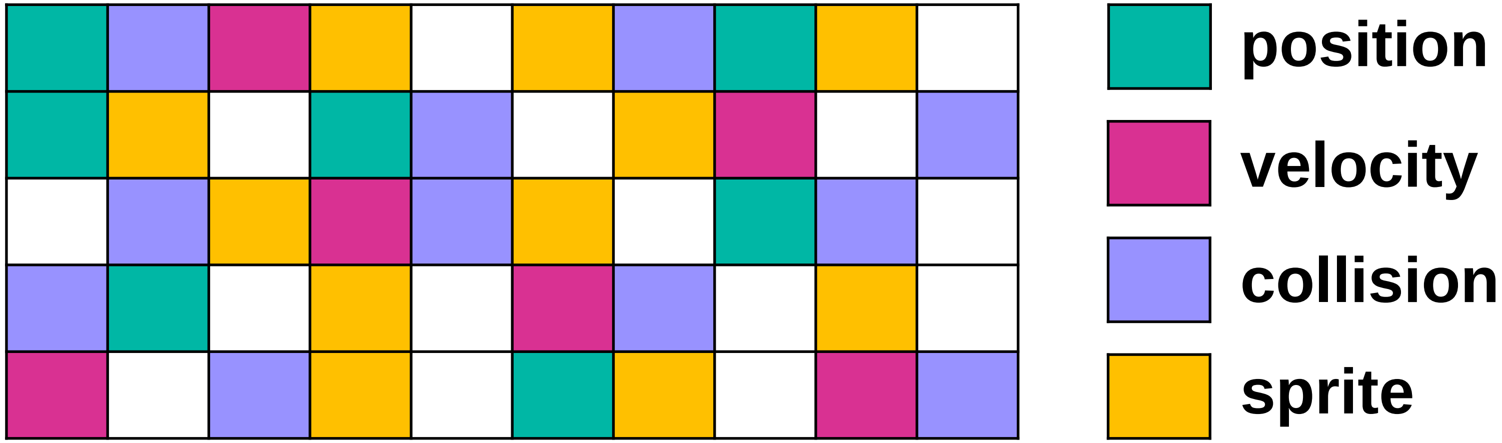
Concept: A (hierarchical) acceleration structure to lookup components
Implementation: std:map<Entity,Position>

Memory & ECS

Where do we store our Components?

- In a map?

Update loop has to access non-contiguous memory repeatedly!



Memory Blocks

Slow memory access!

The (giant) Sparse Array

	ID	Position	Velocity	Jumps	Player	Squishable
Mario	1	□	□	□	□	
Goomba1	2	□	□			□
Luigi		□	□	□		
Goomba2		□	□			□

Issues?

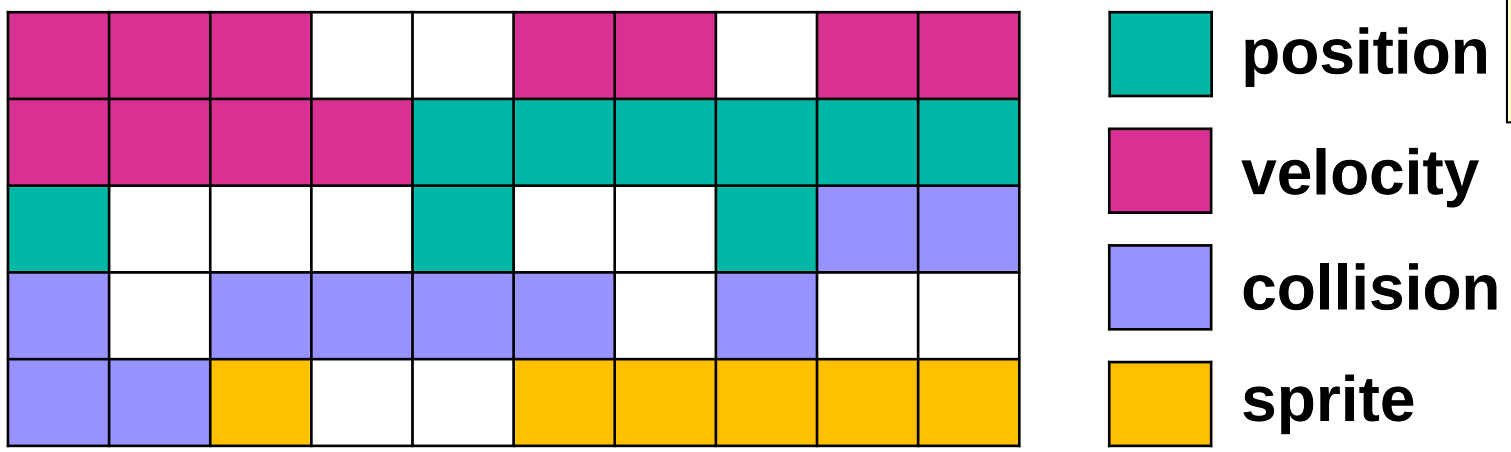
Concept: A huge data matrix of size Nr. Entities x Nr. components

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

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

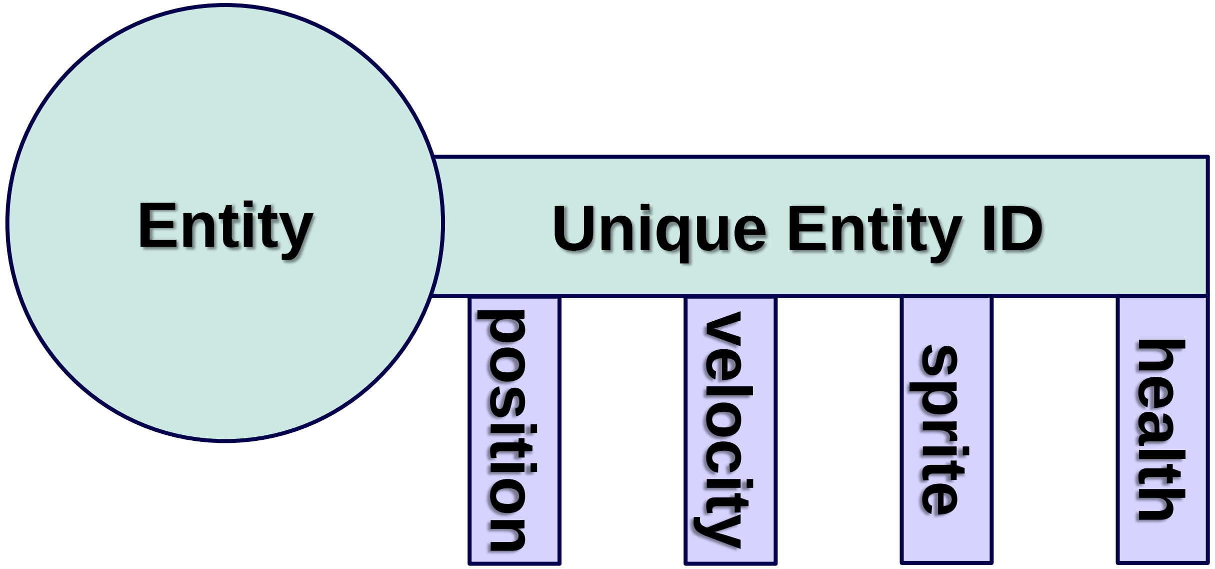
Issues?

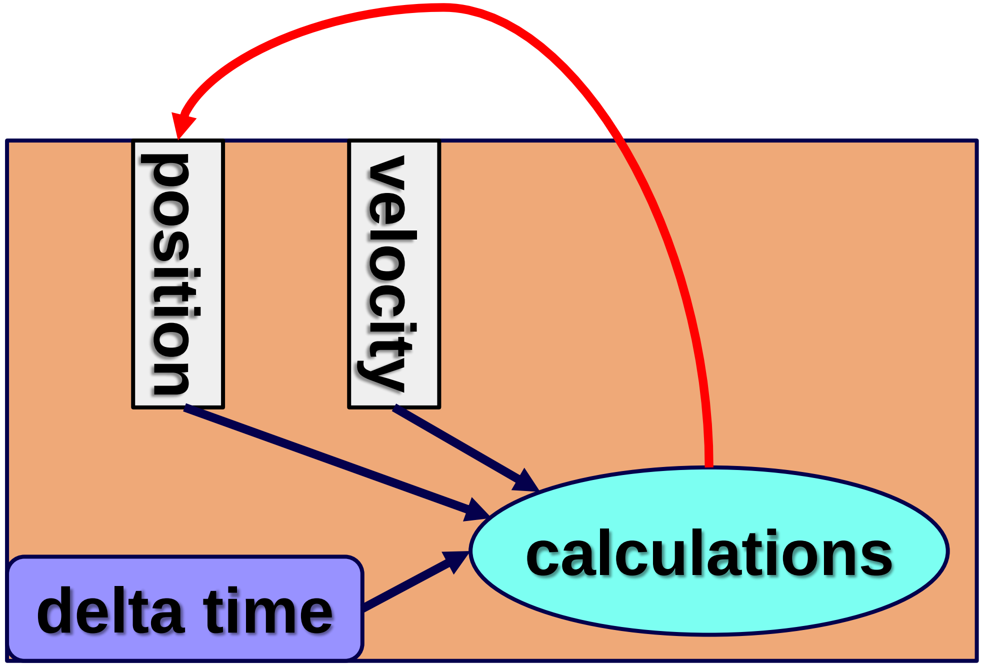
Concept: Each entity has a bitset that is true for its ‘owned’ components

Implementation: long bitset; // how many components can we support?

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

Key & Lock Metaphor



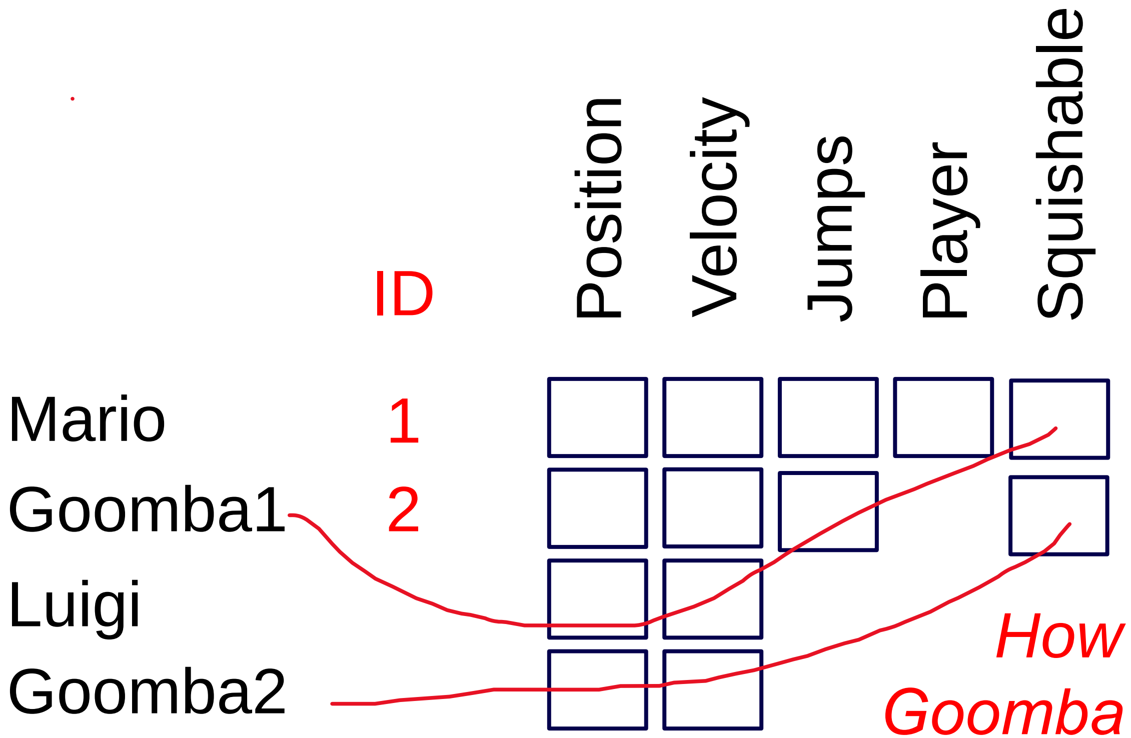


Systems will only operate on Entities with the required Components

Motion System

Further Improvements

Dense Component Vectors (an attempt, needs more)



	ID	Position	Velocity	Jumps	Player	Squishable
Mario	1	□	□	□	□	□
Goomba1	2	□	□	□		□
Luigi		□	□			
Goomba2		□	□			

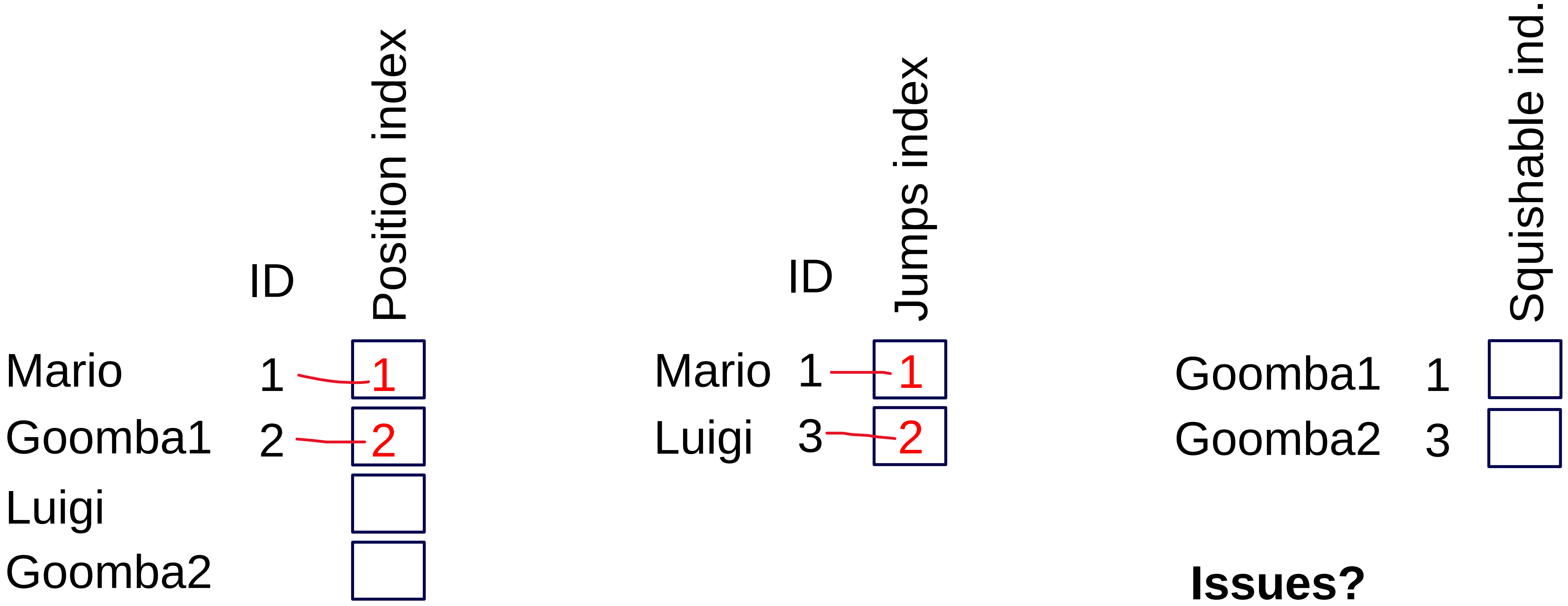
Issues?

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)



	ID	Position index
Mario	1	1
Goomba1	2	2
Luigi		
Goomba2		

	ID	Jumps index
Mario	1	1
Luigi	3	2

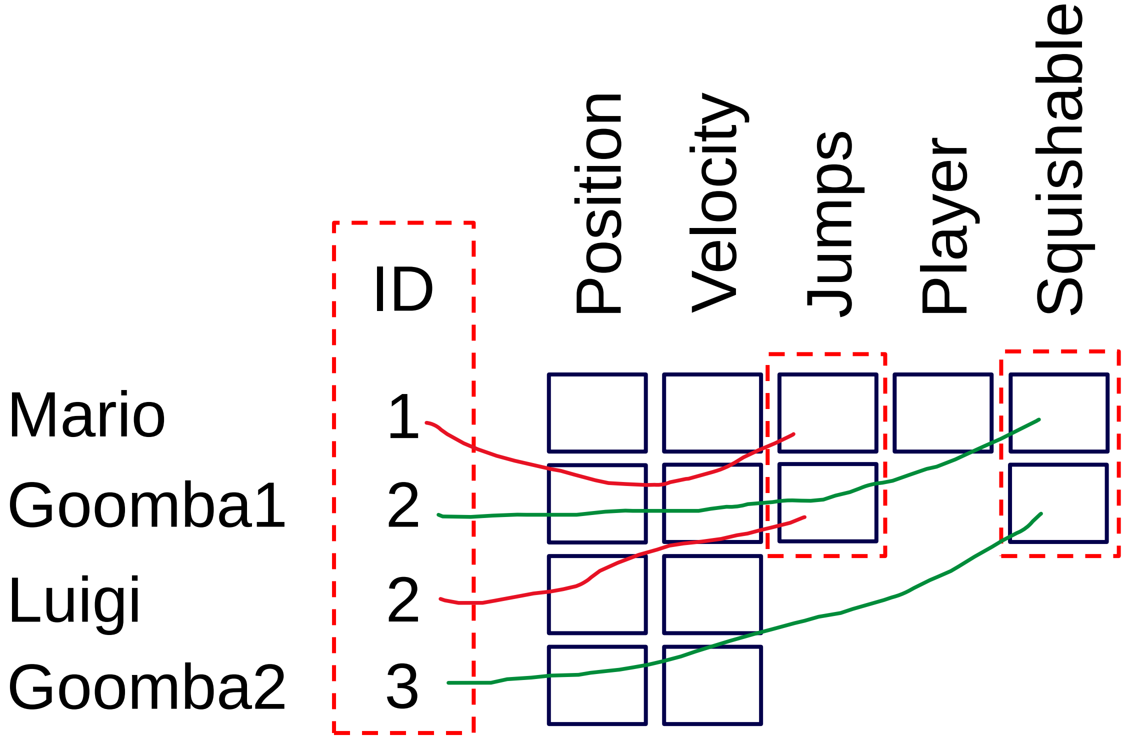
		Squishable ind.
Goomba1	1	
Goomba2	3	

Issues?

Concept: Combine dense vectors with a map

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

Map + Dense Vector (different visualization)



	ID
Mario	1
Goomba1	2
Luigi	2
Goomba2	3

Position

Velocity

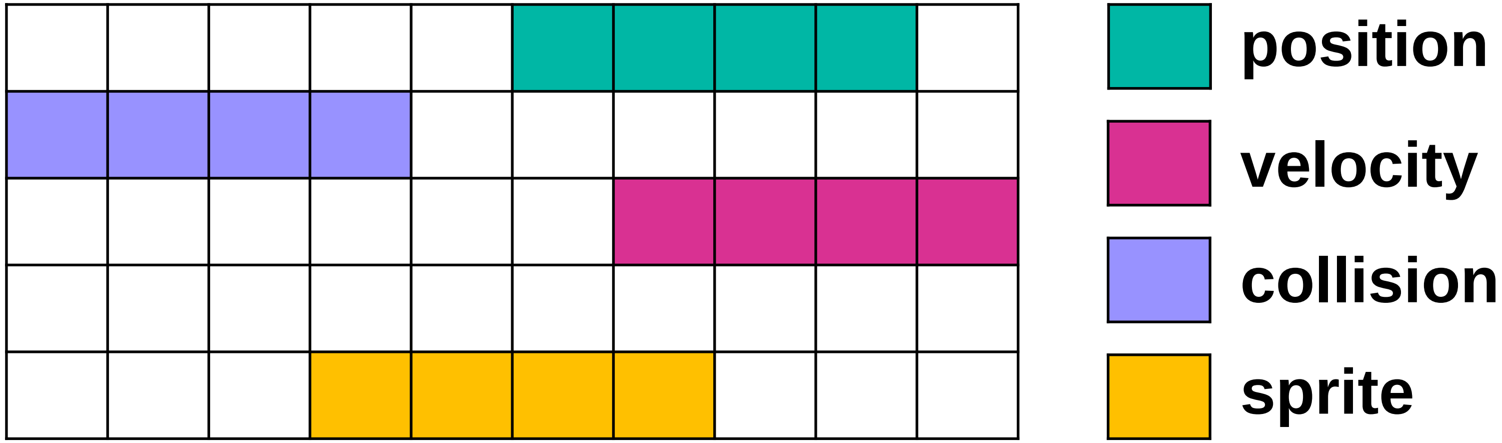
Jumps

Player

Squishable

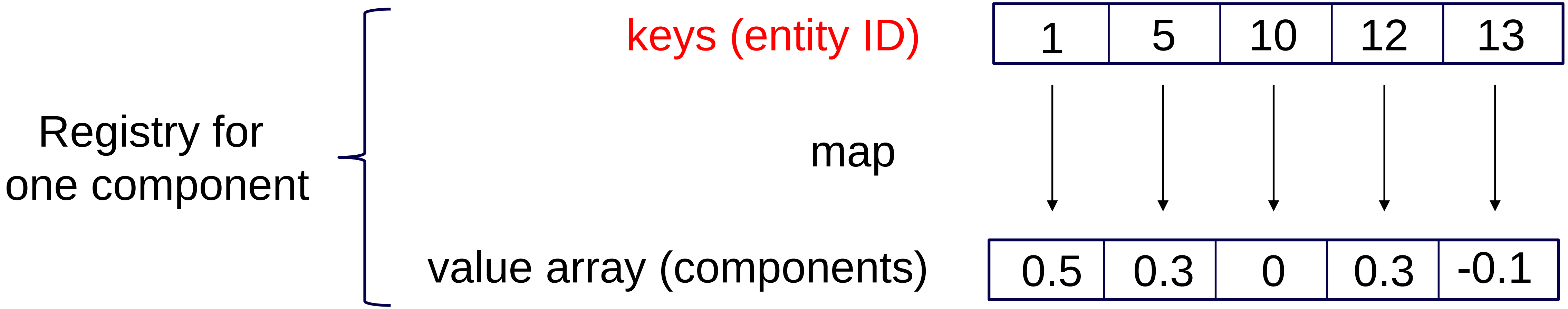
Cache is Key

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



Memory Blocks

Map + Component Vector + Entity Vector



keys (entity ID)	1	5	10	12	13
value array (components)	0.5	0.3	0	0.3	-0.1

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

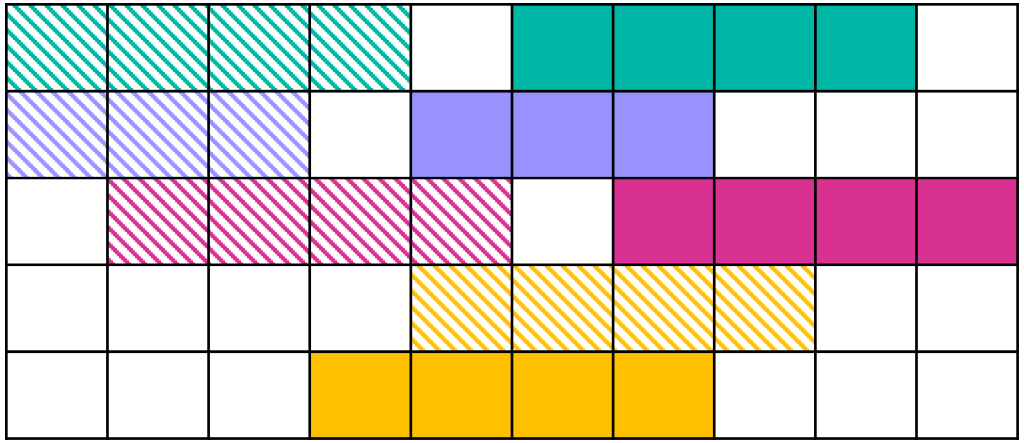
Accessing the velocity map (reg_velocity.map) is an unnecessary indirection

```
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



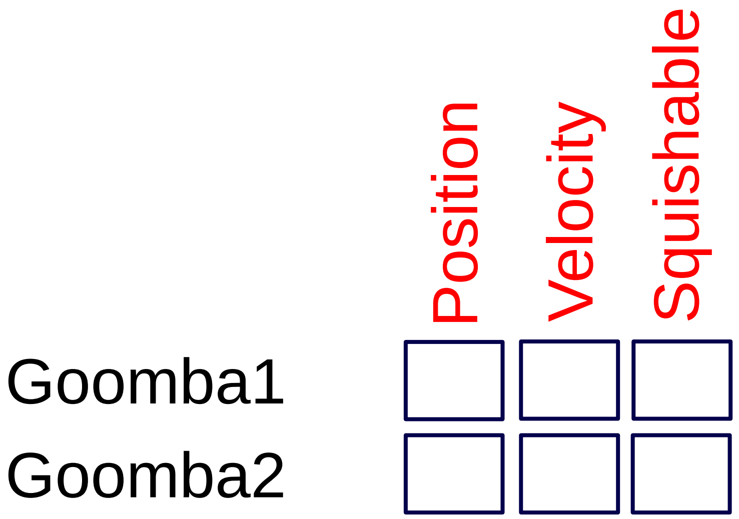
Memory Blocks

- 🟩 position
- 🟪 velocity
- 🟦 collision
- 🟨 sprite
- ▨ position entities
- ▨ velocity entities
- ▨ collision entities
- ▨ sprite entities

Update loop accesses contiguous memory **IDEAL!**

Map access slow

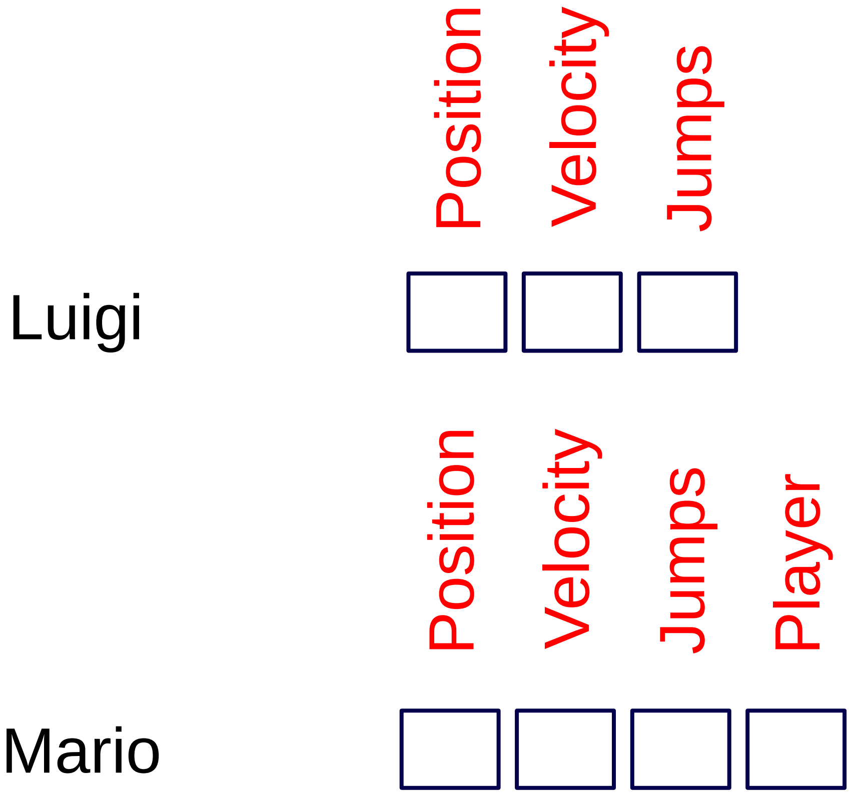
Advanced ECS: Archetypes / prototypes / pools



Position Velocity Squishable

Goomba1

Goomba2



Position Velocity Jumps

Luigi

Position Velocity Jumps Player

Mario

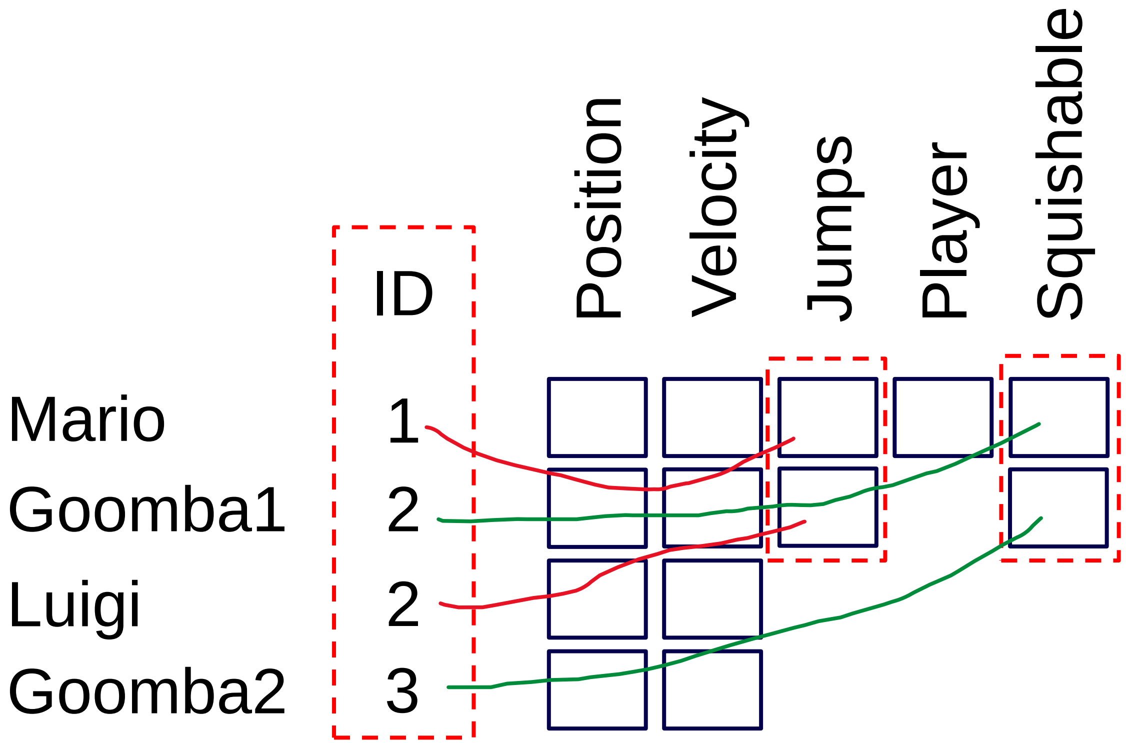
- **Concept:** store all types with the same components in dense arrays
- Used by the Unity ECS system
- Difficult to implement

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



ID

Position

Velocity

Jumps

Player

Squishable

Mario 1

Goomba1 2

Luigi 2

Goomba2 3

Self-study: The ‘Sparse Set’

	ID	Index Pos	Index Vel	Index Jump	Index Player	Index Squish
Mario	1	□	□	1	1	
Goomba1	2	□	□			1
Luigi	3	□	□	2		
Goomba2	4	□	□			2

Position	Velocity	Jumps	Player	Squishable
□	□	□	□	□
□	□	□		□
□	□			
□	□			

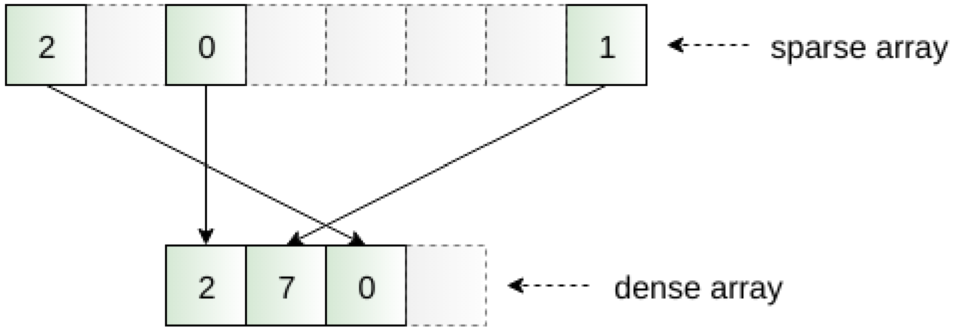
Issues?

Concept: Sparse array + dense array

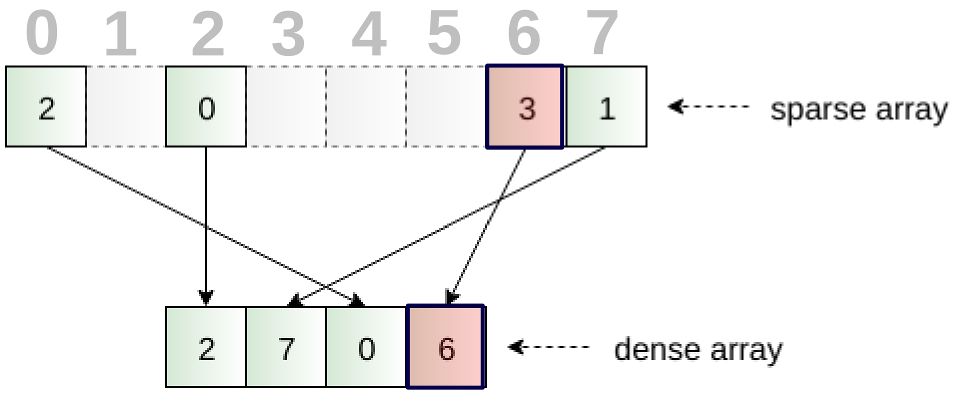
Implementation: std:vector<Entity> entities; std:vector<unsigned int> indices; std:vector<Components> components;

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

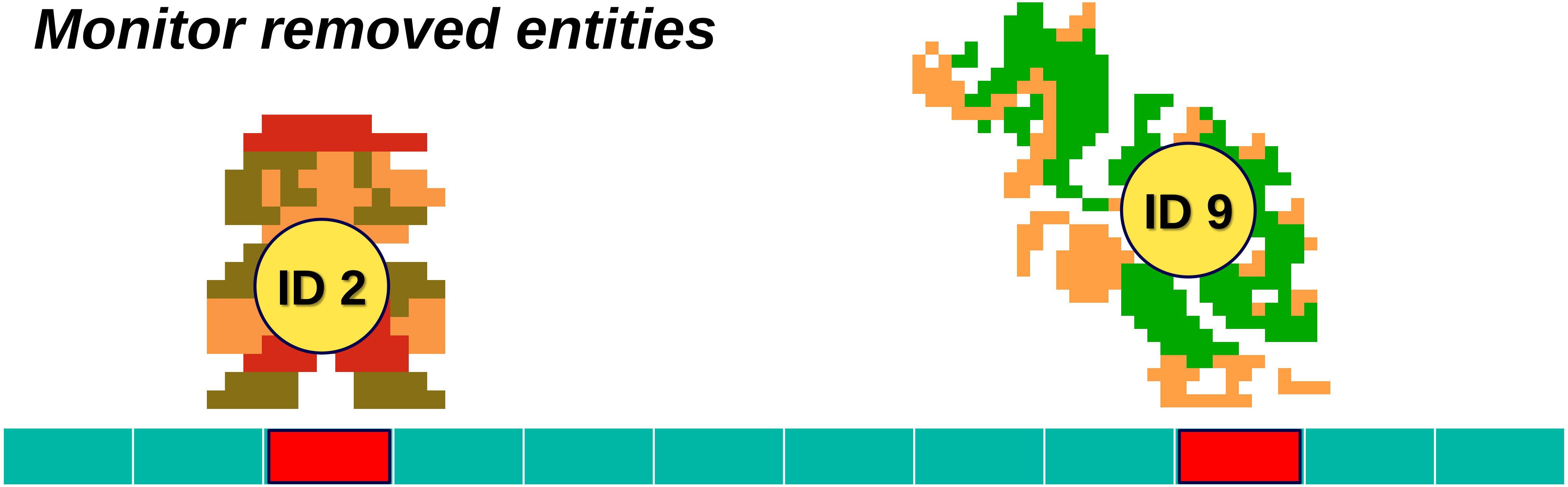
- A hashmap is O(1), but that 1 is big

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*



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!

The game loop

Can you imagine a game without?

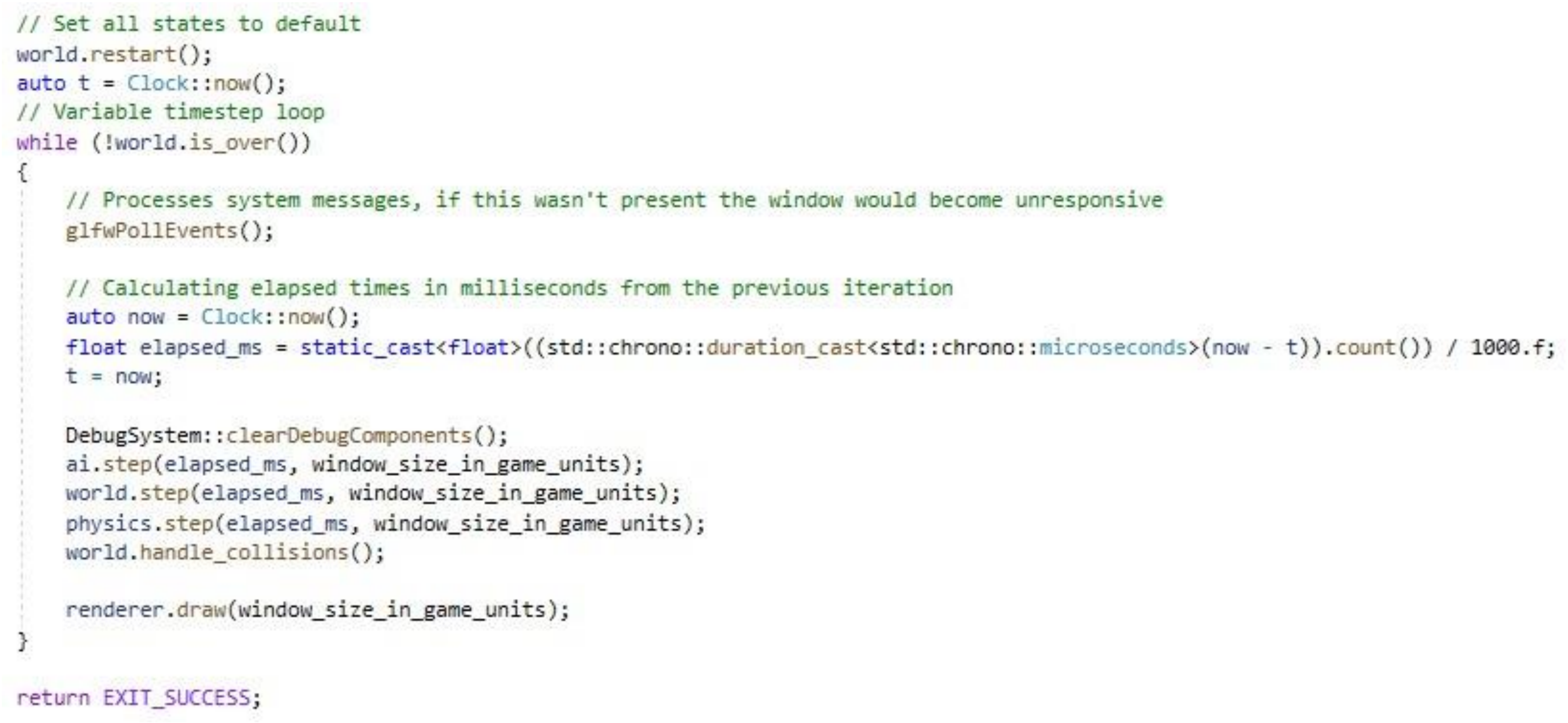
A game is a simulator

1. ***AI and user input***
2. ***Environment reaction***
3. ***Equations of Motion***
   - sum forces & torques, solve for accelerations: $\vec{\boldsymbol{F}} = \boldsymbol{ma}$
4. ***Numerical integration***
   - update positions, velocities
5. ***Collision detection***
6. ***Collision resolution***

← *Also simulation forms!*

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;
```

Backup