Welcome back! Attendance form below

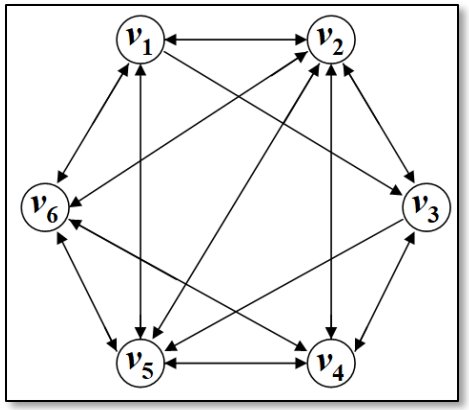
[Link to form]

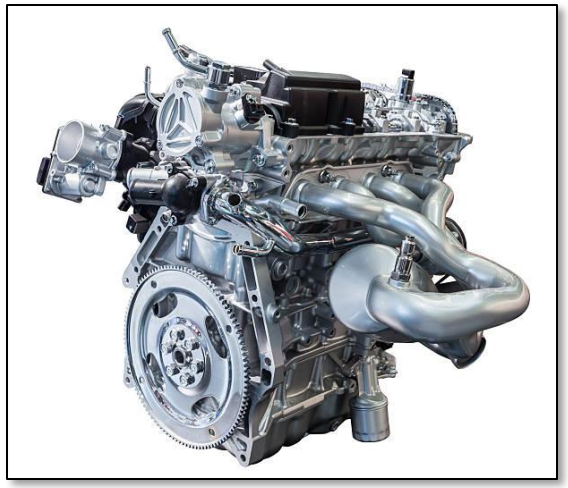
A class as a concept in a program

- You can think of classes as a **concept** in a program
  - Vectors
  - Matrices
  - Graph
  - Valve
  - Thermometer
  - Clock
  - Engine

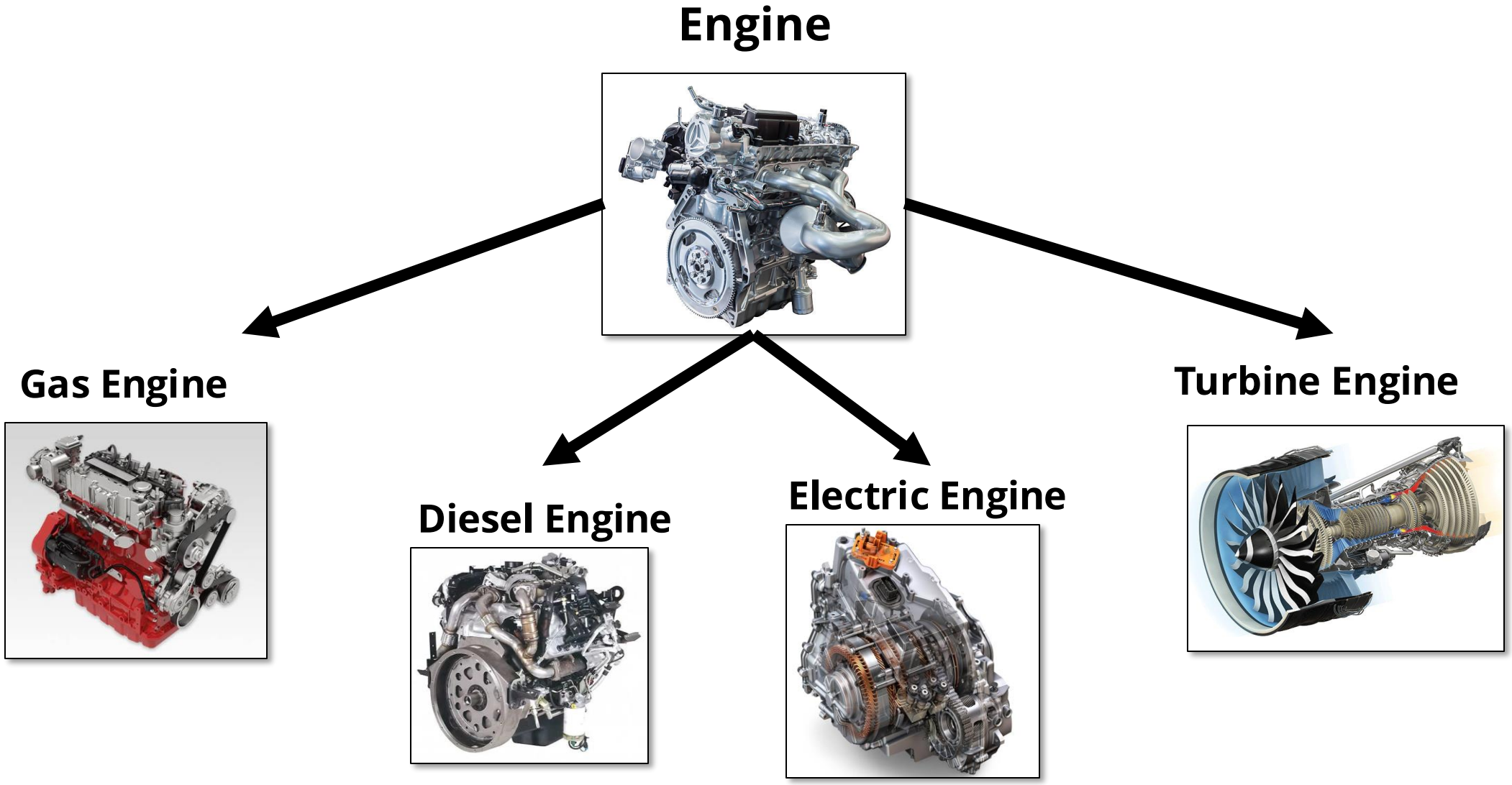
std::vector<int>

$$\begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ a_{m1} & a_{m2} & \cdots & a_{mn} \end{bmatrix}$$





How do we extend classes?



Lecture 9: Inheritance

CS106L, Spring 2025

Today's Agenda

- A Recap on Classes
  - And more on how they work behind the scenes
- Inheritance
  - Inheritance allows us to reuse features from a parent class
- Virtual Functions
  - Defining function interfaces that can be overridden in sub-classes
- Closing Thoughts
  - Should you always use inheritance?

What questions do you have?

bjarne_about_to_raise_hand

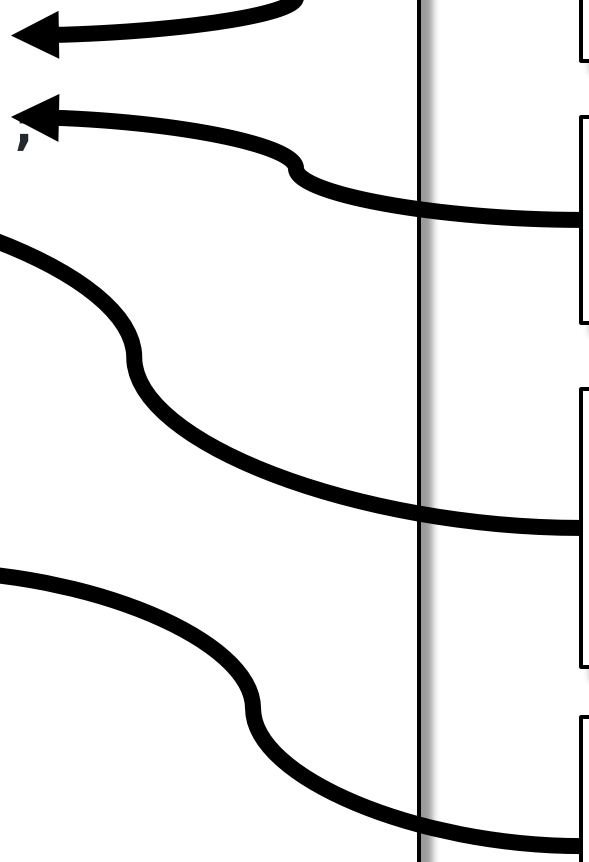
A Recap on Classes

Last Time: Classes

- What are classes?
  - Turn to the person next to you and think of one thing you remember from last Thursday's lecture!
- A class bundles data and methods for an object together

A `Point` on classes

```
class Point {
public:
    Point(int x, int y);
    ~Point();
    int getX();
    int getY();
    void setX();
    void setY();

private:
    int x;
    int y;
};
```



`public:`

Accessible by everyone!

`constructor`

Initializes this class

`destructor`

Cleans up this class

Usually don’t need this

`private:`

Only visible to us!
Implementation details

A Point on classes

```
class Point {
public:
    Point(int x, int y);
    ~Point();
    int getX();
    int getY();

private:
    int x;
    int y;
    std::string color;
}
```

```
#include “Point.h”

Point::Point(int x, int y)
    : x(x), y(y) {}

int Point::getX() {
    return x;
}

int Point::getY() {
    return y;
}
```

Point.h (header file)

Contains **interface, declarations**

Point.cpp

Contains **implementation, definitions**

Classes: Python vs. C++

```python
class Point:
    def __init__(self, x, y):
        self._x = x
        self._y = y

    def getX(self):
        return self._x
    def getY(self):
        return self
```

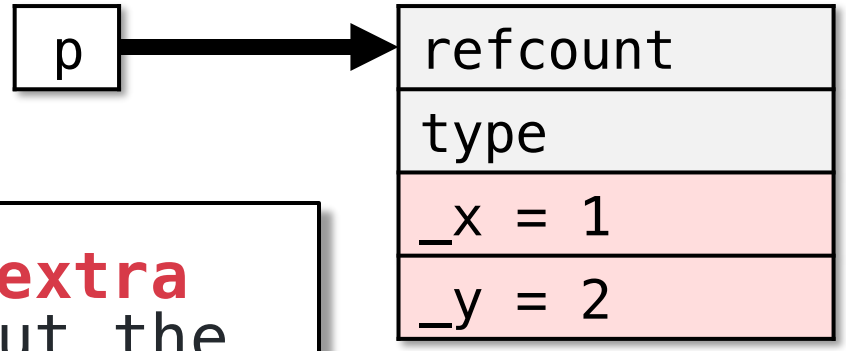
```cpp
class Point {
private:
    int x;
    int y;
public:
    Point(int x, int y)
        : x{x}, y{y} {}
    int getX() { return x; }
    int getY() { return y; }
```

What does a **Point** look like in memory?

Classes: Memory Layout (Python)

```
class Point:
    def __init__(self, x, y):
        self._x = x
        self._y = y

    def getX(self):
        return self.
    def getY(self)
        return self.
```

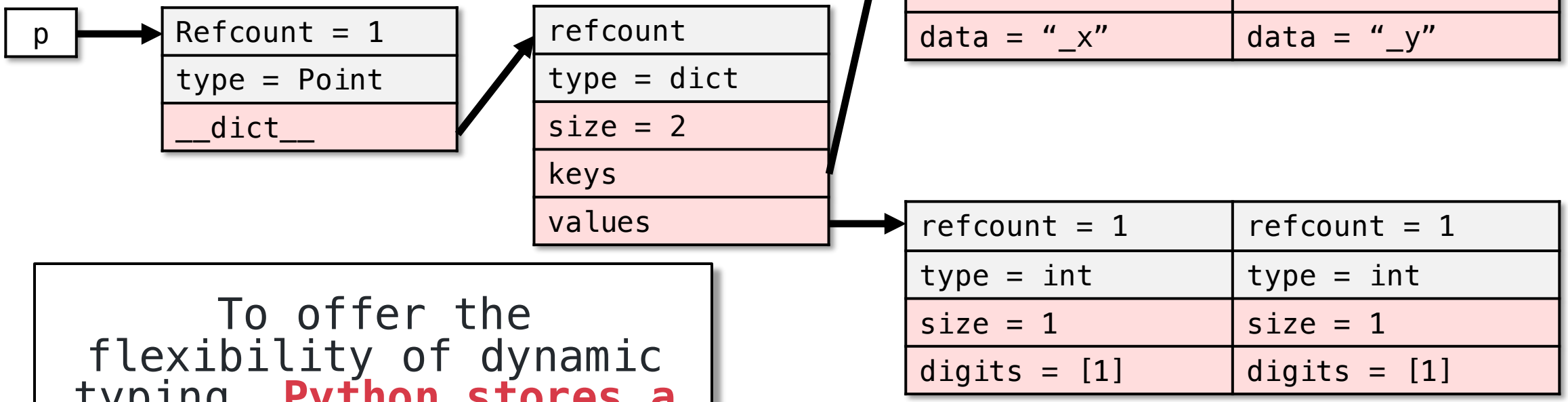
```
p = Point(1, 2)
```



Python **stores extra information** about the type of the object in its memory footprint! This enables runtime type checking.

It's actually *much* worse than this!

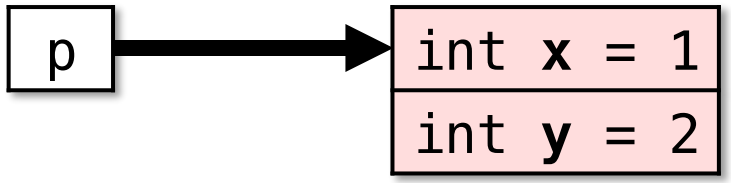
```
p = Point(1, 2)
```



To offer the flexibility of dynamic typing, **Python stores a lot of extra info**!

Classes: Memory Layout (C++)

```
Point p {1, 2};
```



C++ **just stores the data** in the object! The compiler does all of the type checking at compile time!

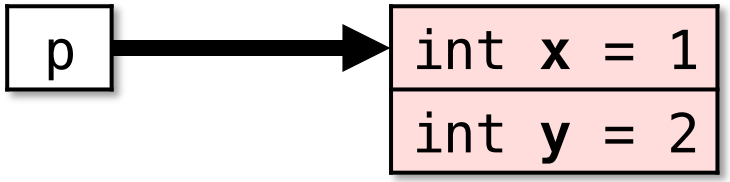
```
class Point {
private:
   int x;
   int y;
public:
   Point(int x, int y)
      : x{x}, y{y} {}
   int getX() { return x; }
   int getY() { return y; }
```

Classes: Memory Layout

C++

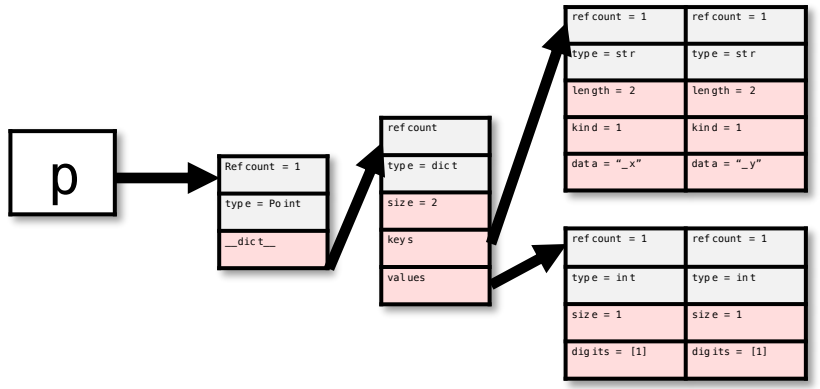
```
p = Point(1, 2)
```

```
Point p {1, 2};
```



Python

```
p = Point(1, 2)
```



C++ **stores less data** in classes! This is one reason why C++ is more memory-efficient than Python

What questions do you have?

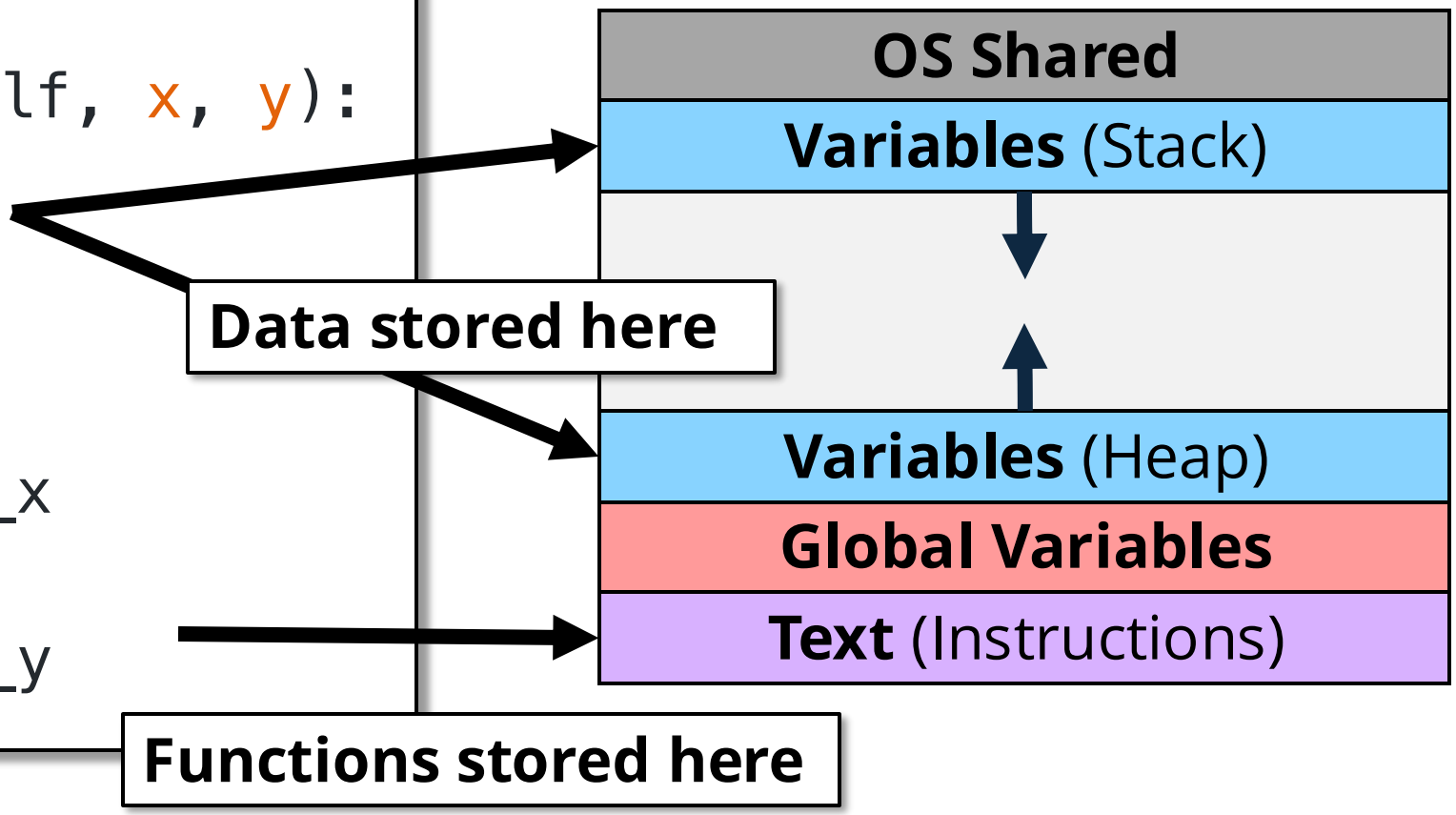
bjarne_about_to_raise_hand

Where are the functions?

Where are the functions?

Functions are not stored in the object itself, but separately

```
class Point:
   def __init__(self, x, y):
      self._x = x
      self._y = y

   def getX(self):
      return self._x
   def getY(self):
      return self._y
```



Where are the functions?

Functions are stored separately from the object

```
class Point:
   def __init__(self, x, y):
      self._x = x
      self._y = y

   def getX(self):
      return self._x
   def getY(self):
      return self._y
```

```
p = Point(1, 2)
px = p.getX()

# ...is the same as...

p = Point(1, 2)
getX(p)
```

Passing `self` as parameter

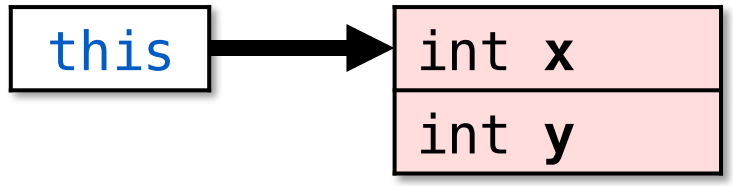
Q: Do we have a `self` in C++?

A: Yes! It's called `this`

`this` in C++

`this` is a pointer to the current class

```
int Point::getX() {
   return this->x;
}
```



The importance of `this`

Are these two snippets of code the same?

```
int Point::getX() {
   return x;
}
```

```
int Point::getX() {
   return this->x;
}
```

✅ These are the same

The importance of `this`

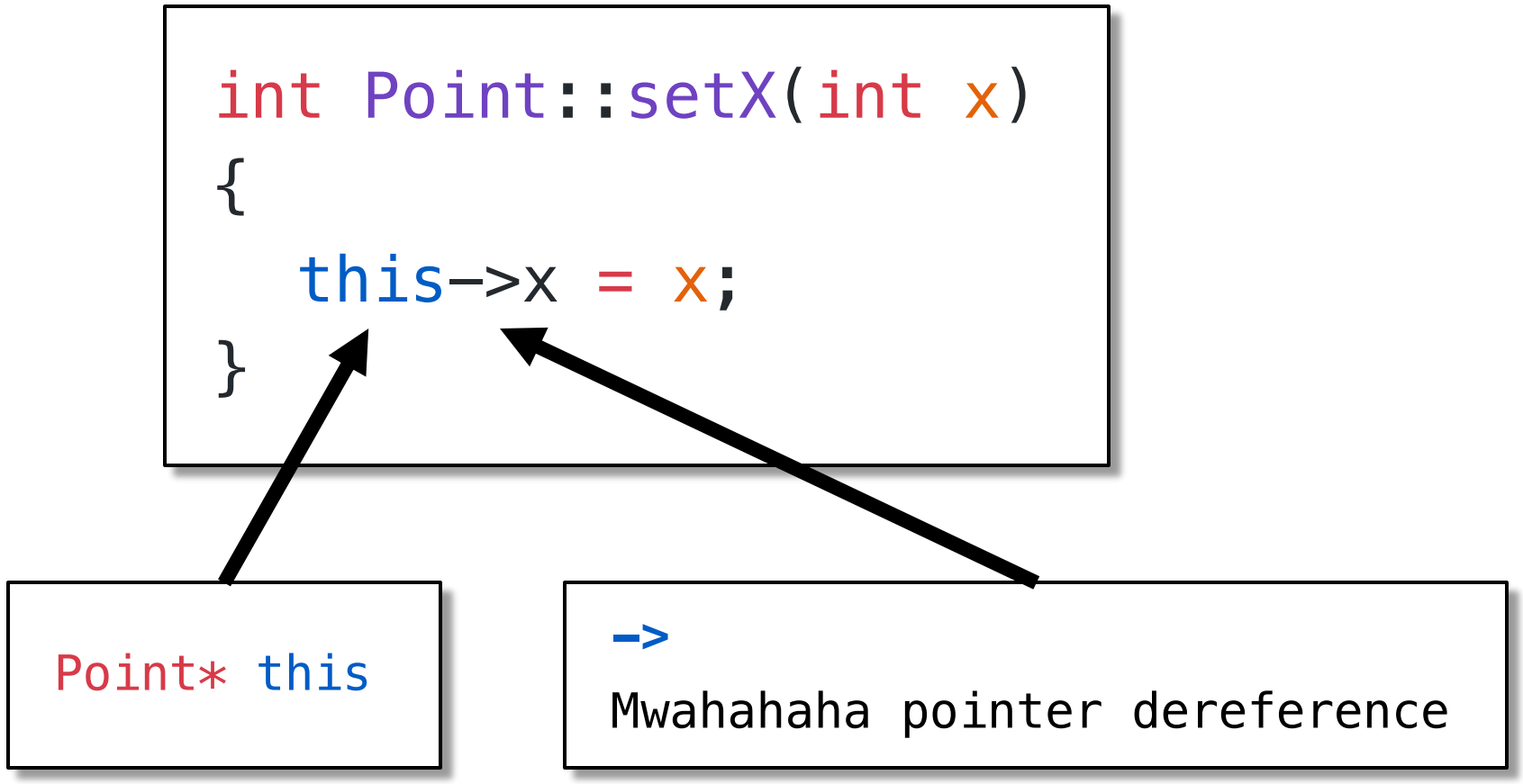
Are these two snippets of code the same?

```
void Point::setX(int x)
{
   x = x;
}
```

```
void Point::setX(int x)
{
   this->x = x;
}
```

❌ Not the same

What is this?


int Point::setX(int x)
{
this->x = x;
}
Point* this
->
Mwahahaha pointer dereference

`this` in C++

`this` is passed as a parameter to class function behind the scenes

```
int Point::getX() {
   return this->x;
}

// ...gets turned into...

int Point_getX(Point* this)
{ return this->x; }
```

```
Point p {1,2};
int x = p.getX();


// ...gets turned into...

Point p {1,2};
int x = Point_getX(&p);
```

Passing `this` as parameter

What questions do you have?

bjarne_about_to_raise_hand

Inheritance

A mechanism for one class to inherit properties from another

Many kinds of cars

Car

Many kinds of cars, but they all inherit

- An engine
- Wheels
- A steering wheel

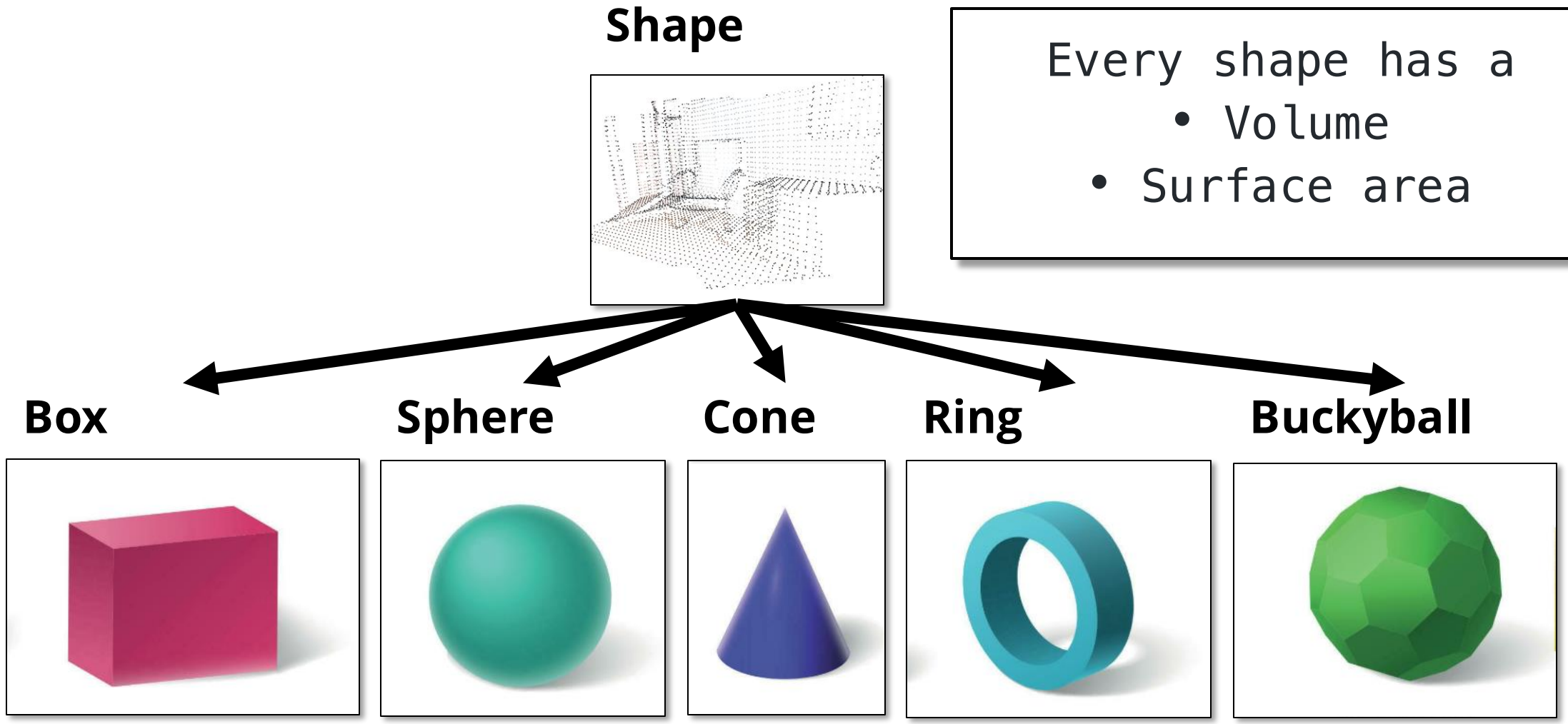
Toyota Camry

Honda Civic

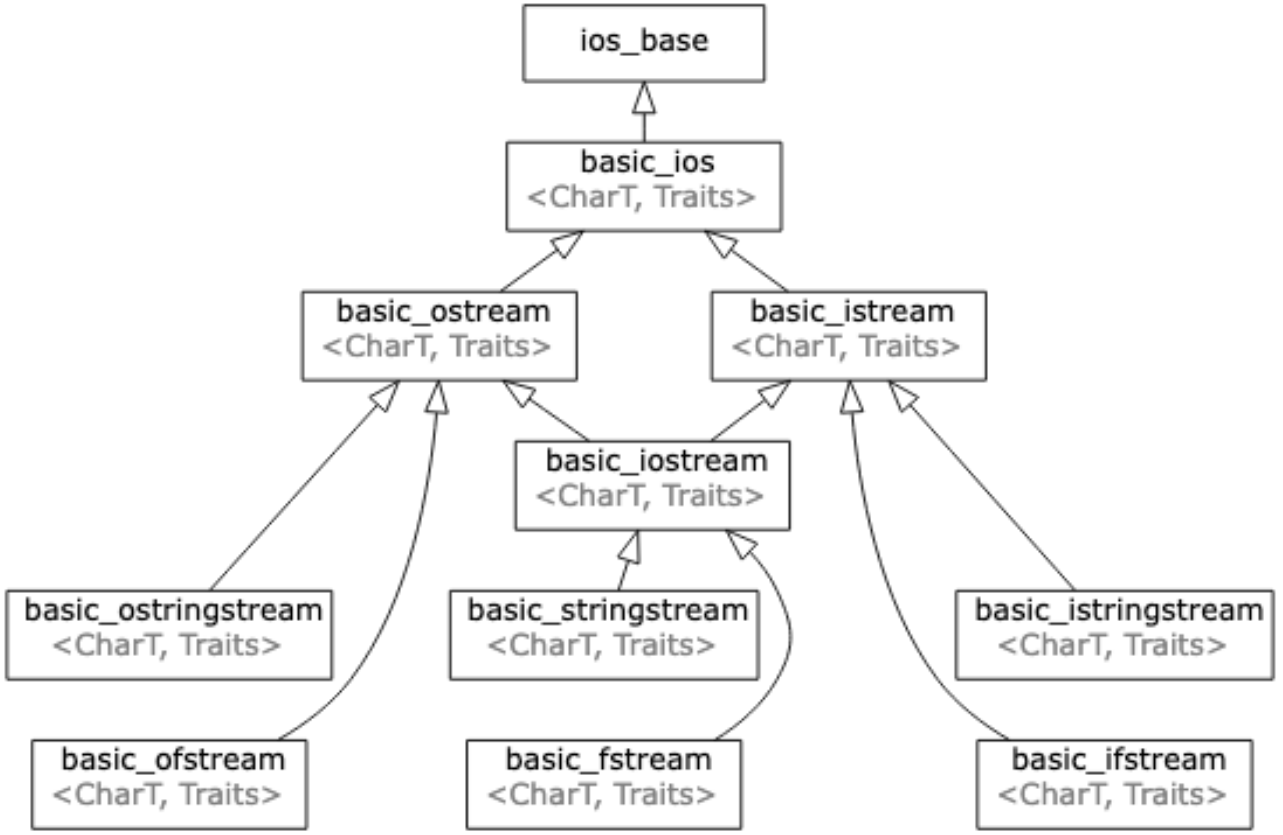
Ford Mustang

Jeep Gladiator

Many kinds of shapes

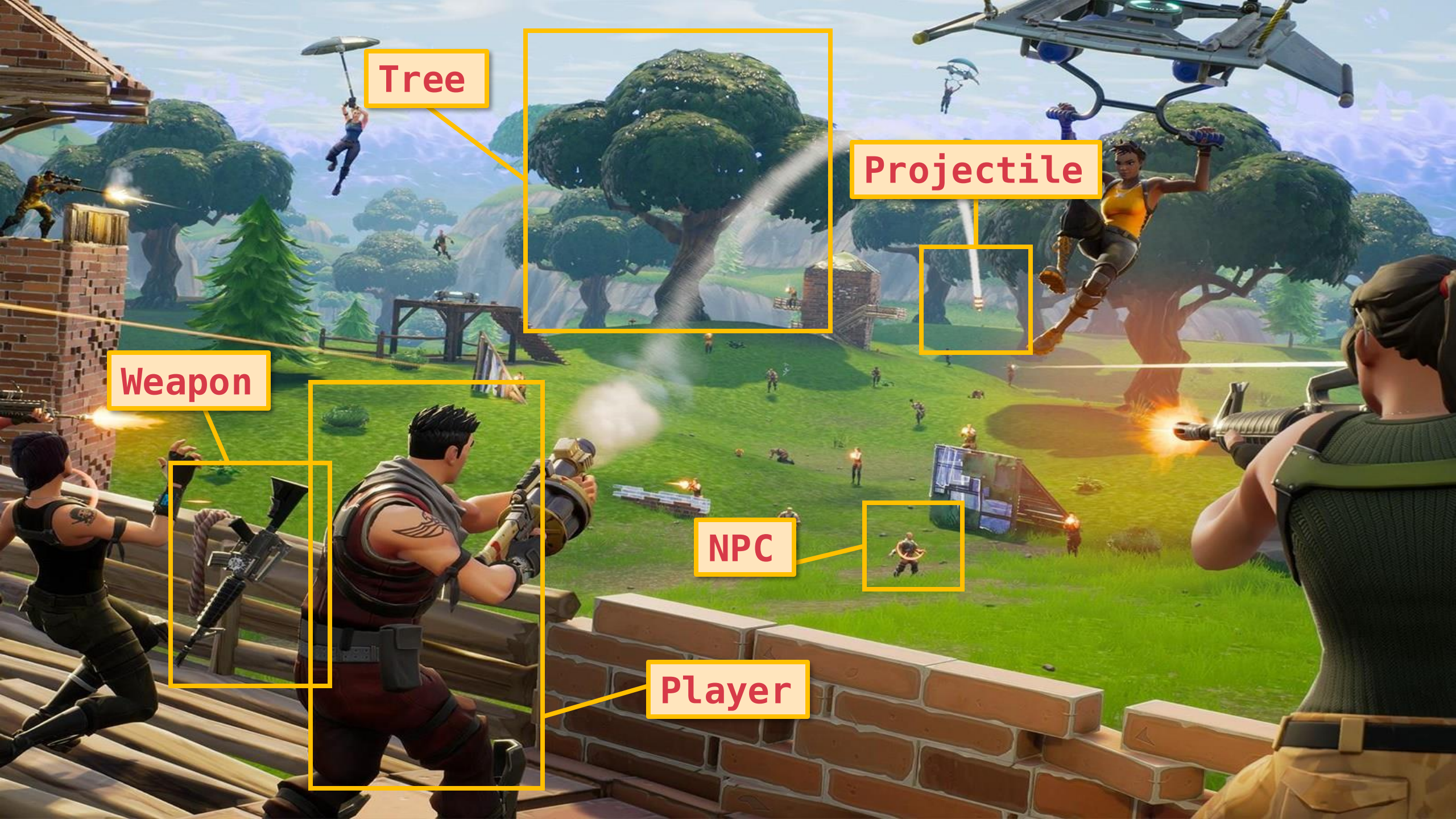


We've seen this before: streams!



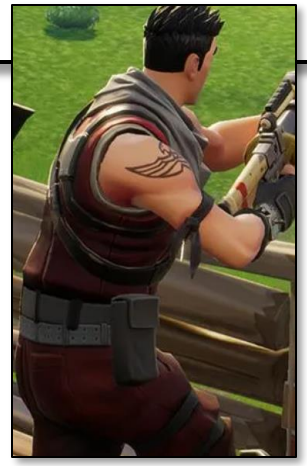
Is-A relationship: An `std::ifstream` **is a** `std::istream` **is a** `std::ios`

How do we model inheritance in C++?

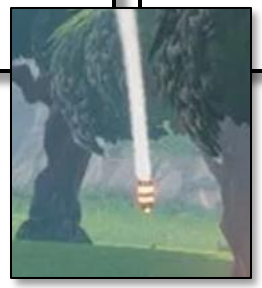

Tree
Projectile
Weapon
NPC
Player

Fortnite as classes

```
class Player {
    double x, y, z;
    HitBox hitbox;
    double hitpoints;
public:
    void damage(double hp);
    void update();
    void render();
};
```



```
class Projectile {
    double x, y, z;
    HitBox hitbox;
    double vx, vy, vz;
public:
    void update();
    void render();
};
```



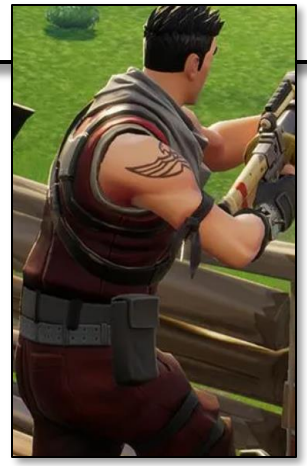
```
class NPC {
    double x, y, z;
    HitBox hitbox;
    double hitpoints;
public:
    void damage(double hp);
    void update();
    void render();
};
```

```
class Weapon {
    double x, y, z;
    HitBox hitbox;
    size_t ammo;
public:
    void fire();
    void update();
    void render();
```

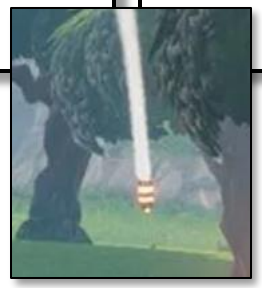
```
class Tree {
    double x, y, z;
    HitBox hitbox;
public:
    void update();
    void render();
};
```

There's a lot of redundancy here!

```
class Player {
    double x, y, z;
    HitBox hitbox;
    double hitpoints;
public:
    void damage(double hp);
    void update();
    void render();
};
```



```
class Projectile {
    double x, y, z;
    HitBox hitbox;
    double vx, vy, vz;
public:
    void update();
    void render();
};
```



```
class NPC {
    double x, y, z;
    HitBox hitbox;
    double hitpoints;
public:
    void damage(double hp);
    void update();
    void render();
};
```

```
class Weapon {
    double x, y, z;
    HitBox hitbox;
    size_t ammo;
public:
    void fire();
    void update();
    void render();
```

```
class Tree {
    double x, y, z;
    HitBox hitbox;
public:
    void update();
    void render();
};
```

This model is also a pain to modify

Imagine we wanted to add an `overlapsWith` method to each object that checks if it overlaps in space with another object

```
class Player {
   /* ... */
public:
   bool overlapsWith(const Player& other);
   bool overlapsWith(const NPC& other);
   bool overlapsWith(const Tree& other);
   bool overlapsWith(const Projectile& other);
   bool overlapsWith(const Weapon& other);
};

// And we'd do the same for NPC, Tree, Projectile, Weapon!
```

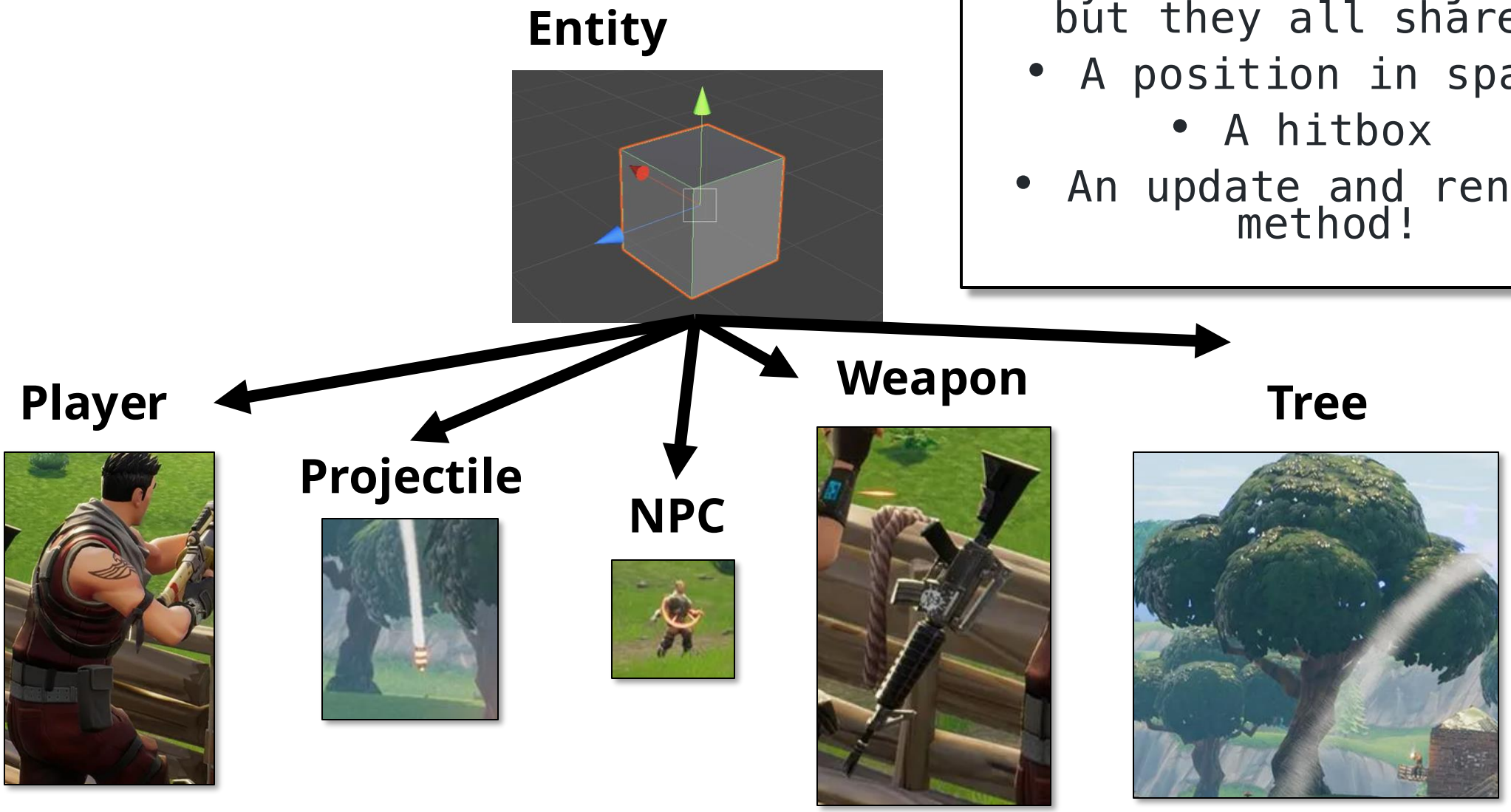
This doesn't scale!

What if we add more object types!

Taking a step back

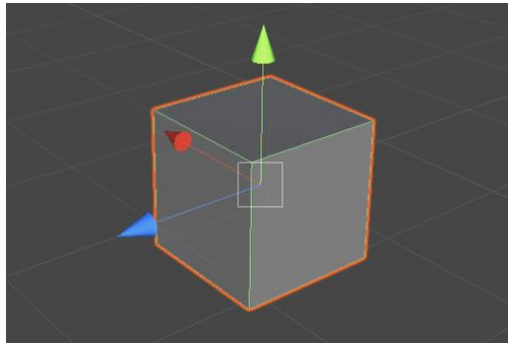
Many different objects, but they all share:

- A position in space
- A hitbox
- An update and render method!



Introducing a common base class: Entity

Entity



```
class Entity {
   double x, y, z;
   HitBox hitbox;
public:
   void update();
   void render();
};
```

Introducing a common base class: Entity

```
class Player {
    double x, y, z;
    HitBox hitbox;
    double hitpoints;
public:
    void damage(double hp);
    void update();
    void render();
};
```

```
class Projectile {
    double x, y, z;
    HitBox hitbox;
    double vx, vy, v
public:
    void update();
    void render();
```

```
class Weapon {
    double x, y, z;
    HitBox hitbo
    size_t ammo;
public:
    void fire();
    void update(
    void render(
};
```

```
class Tree {
    double x, y, z;
    HitBox hi
public:
    void upda
    void rend
};
```

```
class NPC {
    double x, y, z;
    HitBox hitbox;
    double hitpoints;
public:
    void damage(double hp);
    void update();
    void render();
};
```

```
class Entity {
    double x, y, z;
    HitBox hitbox;
public:
    void update();
    void render();
};
```

Now we inherit!


```
class Player : Entity {
    double hitpoints;
public:
    void damage(double hp);
};
```

```
class Projectile : Entity
{
    double vx, vy, v
};
```

```
class Weapon : Entity
{
    size_t ammo;
public:
    void fire();
};
```

```
class Tree : Entity
 {};
```

```
class NPC : Entity {
    double hitpoints;
public:
    void damage(double hp);
};
```

```
class Entity {
   double x, y, z;
   HitBox hitbox;
public:
   void update();
   void render();
};
```

Now we inherit!

```
class Player : Entity {
    double hitpoints;
public:
    void damage(double hp);
};
```

```
class Projectile : Entity
{
    double vx, vy, v
};
```

```
class Weapon : Entity
{
    size_t ammo;
public:
    void fire();
};
```

```
class Tree : Entity
 {};
```

```
class NPC {
    double hitpoints;
public:
    void damage(double hp);
};
```

```
class Entity {
   double x, y, z;
   HitBox hitbox;
public:
   void update();
   void render();
};
```

Notice: there is still some redundancy!

More layers of inheritance...

```
class Player : Actor {};
```

```
class Projectile : Entity
{
    double vx, vy, v
};
```

```
class Weapon : Entity
{
    size_t ammo;
public:
    void fire();
```

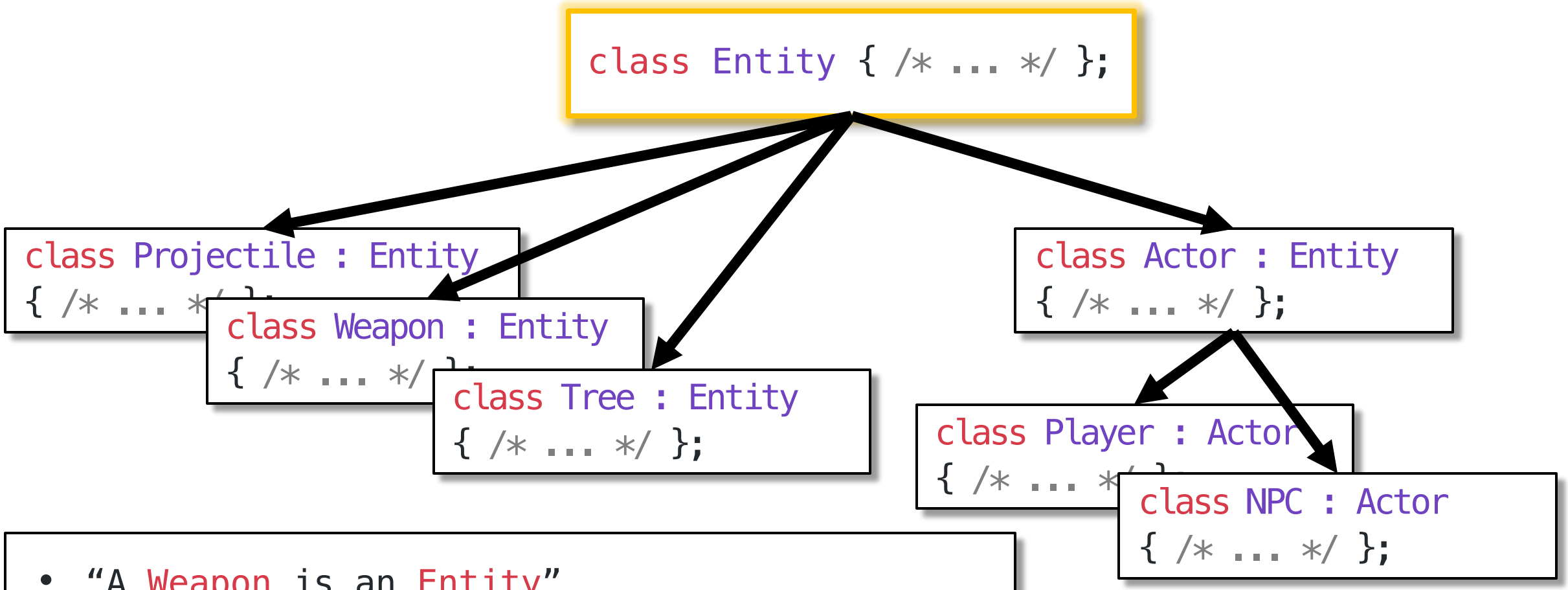
```
class Tree : Entity
 {};
```

```
class Entity {
   double x, y, z;
   HitBox hitbox;
public:
   void update();
   void render();
};
```

```
class Actor : Entity
{
   double hitpoints;
public:
   void damage(double hp);
};
```

```
class NPC : Actor {};
```

An inheritance tree defines is-a relationships

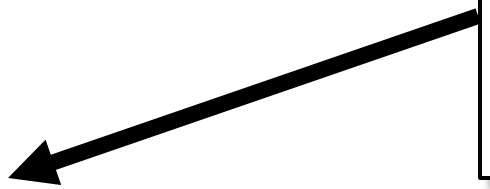


- "A Weapon is an Entity"
- "An NPC is an Actor, and is also an Entity"

Defining common functionality is trivial!

Now we can check if two `Entity`'s overlap, no matter what kind it is!

```
class Entity {
   double x, y, z;
   HitBox hitbox;

public:
   void update();
   void render();
   bool overlapsWith(const Entity& other);
};

Player player { /* ... */ };
Projectile bullet { /* ... */ };
bool isHit = player.overlapsWith(bullet);
```



To implement, check `x`,`y`,`z` and `hitbox` to see if there was an overlap

What questions do you have?

bjarne_about_to_raise_hand

Note: access modifiers

That last line won't actually work due to access modifiers!

```
Player player { /* ... */ };
Projectile bullet { /* ... */ };
bool isHit = player.overlapsWith(bullet);
```

Compiler: overlapsWith is inaccessible

Note: access modifiers

By default, classes are inherited privately.

```
class Entity {
public:
   bool overlapsWith(const Entity& other);
};

class Player : /* private */ Entity {
   // Private inheritance:
   // - private members of Entity are inaccessible to all
   // - public members become private (inaccessible to outside)
};
```

Note: access modifiers

We can fix this issue by inheriting `Entity` publicly!

```
class Entity {
public:
   bool overlapsWith(const Entity& other);
};

class Player : public Entity {
   // Public inheritance:
   // - private members of Entity are still inaccessible
   // - public members become public (accessible to outside)
};
```

Note: access modifiers

`private` inheritance (default)

```
class Child : private Parent
```

`private` in parent	→	`inaccessible` in child
`public` in parent		`private` in child

`public` inheritance

```
class Child : public Parent
```

`private` in parent	→	`inaccessible` in child
`public` in parent		`public` in child

Note: public inheritance better models **is-a** relationships! A `Player` really *is* an `Entity` because it exposes all of `Entity`'s functionality publicly

Note: `protected` access modifier

Protected members are visible to subclasses, but not the outside!

- Remember, class members are *`private` by default*

```
class Entity {
protected:
   double x, y, z;
   HitBox hitbox;
public:
   void update();
   vo
};
```

`private` by default

We need to mark them `protected` inside `Entity`

```
class Projectile
   Entity {
private:
   double vx, vy, vz;
public:
   void move() {
      x += vx;
      y += vy;
      z += vz;
   }
}
```

In order to access `x`, `y`, and `z` inside `Projectile`

What questions do you have?

bjarne_about_to_raise_hand

Let’s build a game!

Let’s build a game!

```
class Entity {
    double x, y, z;
    HitBox hitbox;
public:
    void update();
    void render();
};
```

We’ll implement the logic for our game by overriding `update` and `render` for each kind of `Entity`.

Let's build a game!

Let's **override** the `update` and `render` function for each `Entity` type!

```
void Player::update() {
   // Handle controller input
}
```

```
void Projectile::update() {
   // Move the projectile
}
```

```
void Player::render() {
   // Draw the player!
}
```

```
void Projectile::render() {
   // Cool particle effects!
}
```

```
// By default, do nothing!
void Entity::update() {}
```

```
// By default, do nothing!
void Entity::render() {}
```

Let’s build a game!

A game is basically a collection of entities updated and rendered every frame!

```
int main() {
    std::vector<Entity> entities { Player(), Tree(), Projectile() };
    while (true) {
        for (auto& entity : entities) {
            entity.update();
            entity.render();
        }
    }
}
```

Game event loop
(runs every frame)

Let’s try it out!

It didn’t work! What’s going on!?

Behind the scenes

Recall that C++ lays out the fields of an object sequentially

```
class Entity {
protected:
   double x, y, z;
   HitBox hitbox;
public:
   void update();
   void render();
};
```

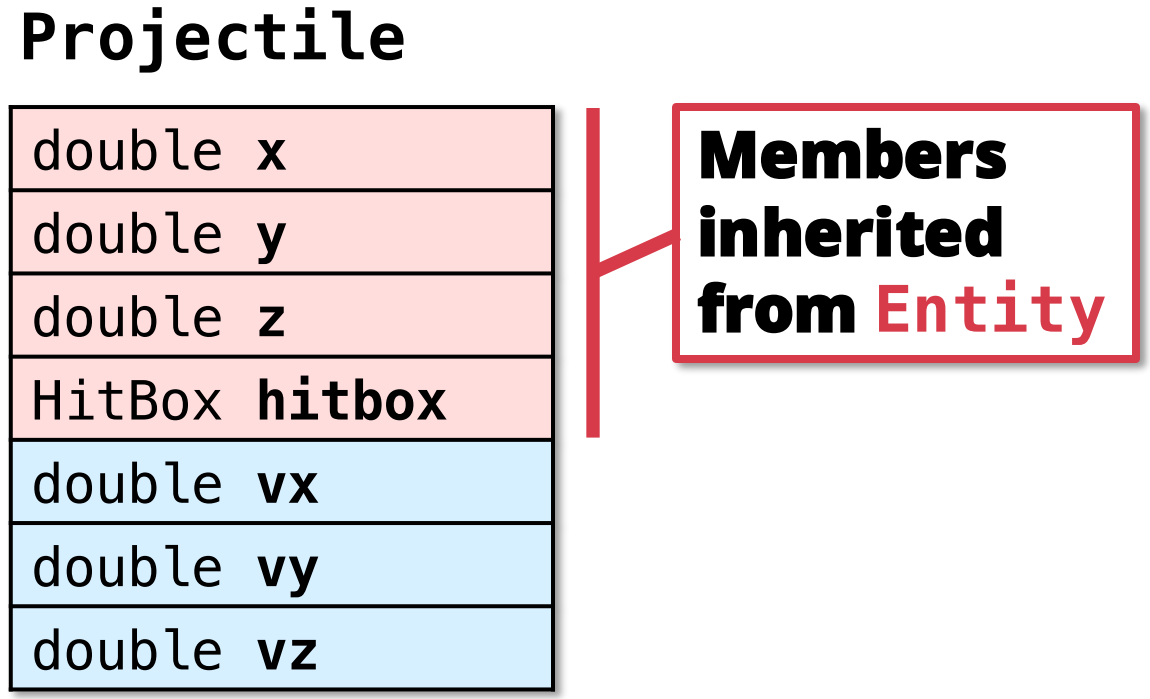
Entity

double **x**
double **y**
double **z**
HitBox **hitbox**

Behind the scenes

C++ stacks the subclass's members below the inherited ones!

```
class Projectile
   : public Entity {
private:
   double vx, vy, vz;
public:
   void move();
}
```



Behind the scenes

Be careful: when you assign a derived class to a base class, it gets sliced!

`Projectile`

`double x`
`double y`
`double z`
`HitBox hitbox`
`double vx`
`double vy`
`double vz`

`std::vector<Entity>`

`double x`	`double x`	`double x`
`double y`	`double y`	`double y`
`double z`	`double z`	`double z`
`HitBox hitbox`	`HitBox hitbox`	`HitBox hitbox`

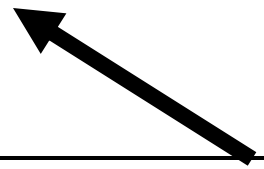
Issue: every element in the vector is an `Entity`, so the compiler calls `Entity::update()` (which does nothing) instead of `Player::update()`, `Tree::update()`, `Projectile::update`, etc.

A `Projectile` doesn't "fit" into an `Entity`

Solution: Use an `Entity*` instead

Object slicing only happens when a copy is made!

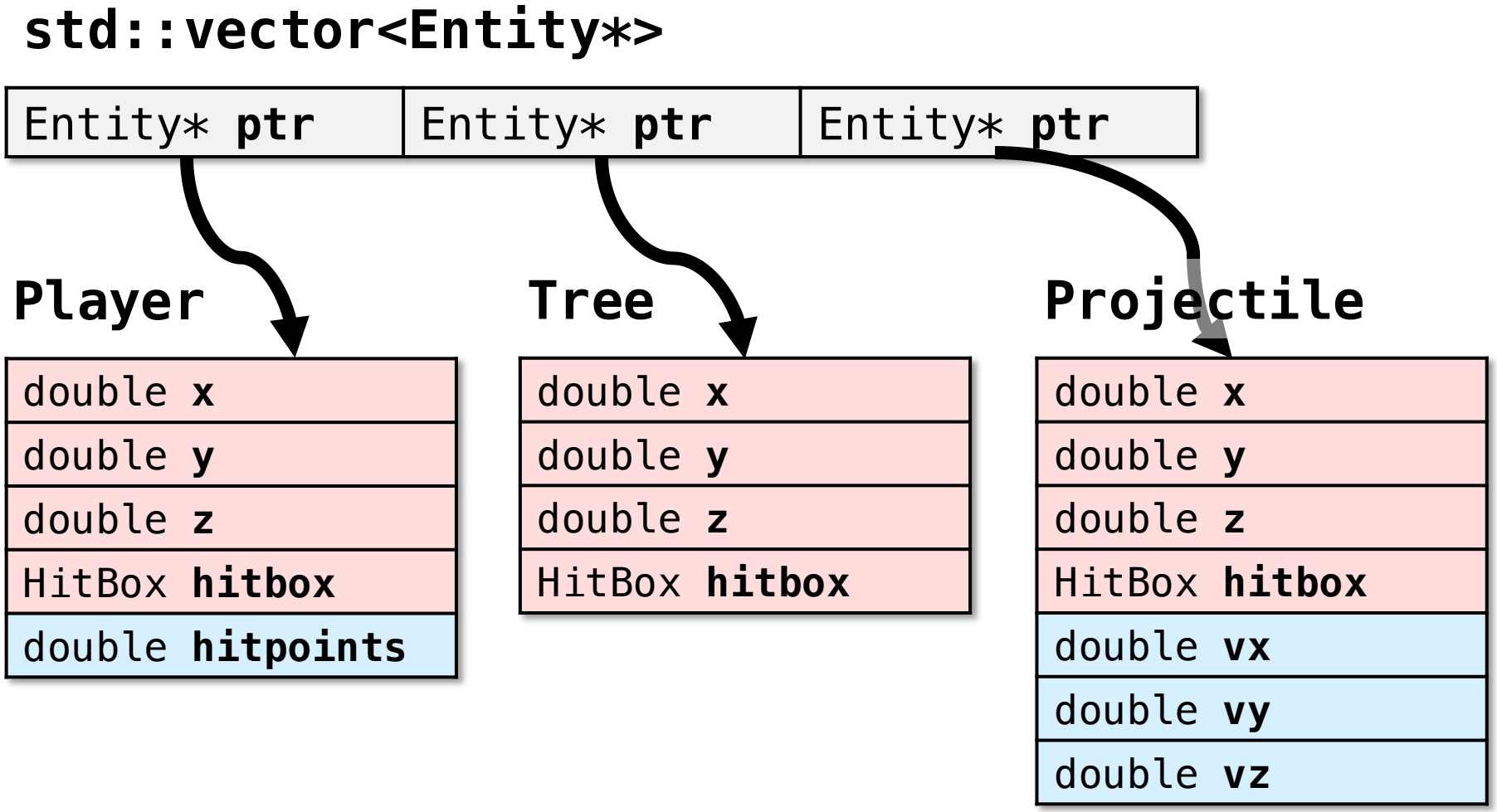
```
int main() {
   Player p; Tree t; Projectile b;

   std::vector<Entity*> entities { &p, &t, &b };
   while (true) {
      for (auto& ent : entities) {
         ent->update();
         ent->render();
      }
   }
}
```



Storing pointers to entities here, not the entities themselves!

Solution: Use an `Entity*` instead

Pointers retain the details of the subclass by avoiding copies



What questions do you have?

bjarne_about_to_raise_hand

Let’s try it again!

It still didn’t work… 😭 😭 😭

Announcements

- Assignment 2 due this Friday
- A note on assignment workload!
  - We want you guys to spend ~1 hour on each assignment!
  - If you consistently spend more time than this, come to OH!
- OH is 4-5pm Wed, 3-4pm Friday... we are so lonely, please come!!

Virtual Functions

Problem: Which one is called?

- We have many different `update` methods

```
void Projectile::update();
```

```
void Player::update();
```

```
void NPC::update();
```

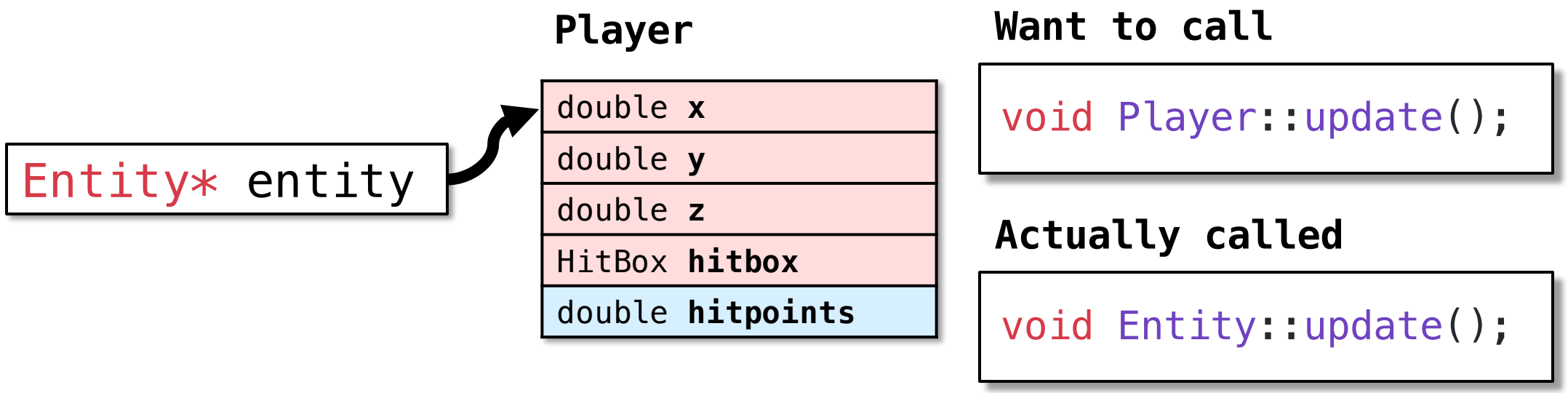
```
void Entity::update();
```

- Given a pointer to an `Entity`, how does the compiler know which method to call?

```
Entity* entity = entities[0];
entity->update();
```

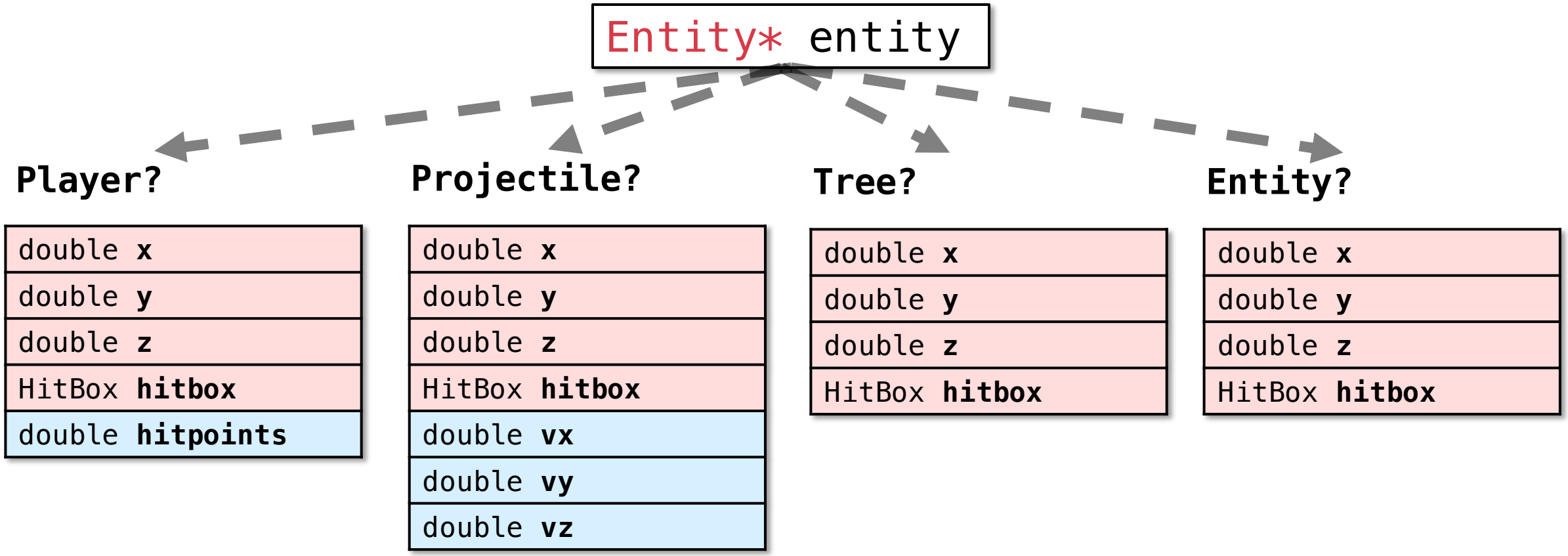
Problem: Which one is called?

- We should call the update method which matches the type of the object that `entity` points to
  - If entity points to a `Player`, we should call `Player::update()`
  - If it points to a `Projectile`, we should call `Projectile::update()` and so on
- But an `Entity*` alone doesn't tell us any information about the type!



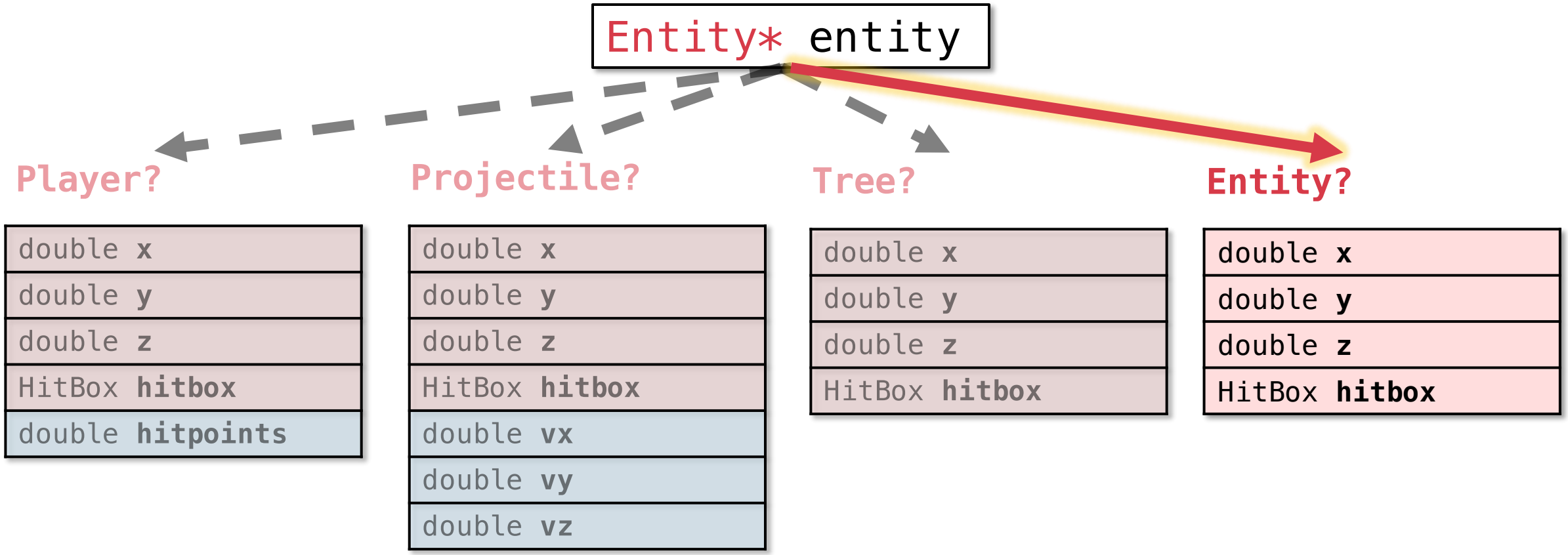
Problem: Which one is called?

- Given an `Entity*`, does it point to:



Problem: Which one is called?

- The compiler defaults to assuming `entity` points to an `Entity`
- This is the only one it can be absolutely sure any entity will support



Using `Entity*` comes at a cost:

We “forget” which type the object actually is

This is not what we wanted!

- Notice: there is a difference between the **compile-time** vs. **runtime** type of the object!
  - At compile time, it is treated as an `Entity`
  - At runtime, it could be an `Entity` or any subclass, e.g. `Projectile`, `Player`, etc.
- What we need is **dynamic dispatch**
- Depending on the runtime (dynamic) type of the object, a different method should be called (dispatched)!

What questions do you have?

bjarne_about_to_raise_hand

Introducing virtual functions

Virtual functions

- Marking a function as `virtual` enables dynamic dispatch
- Subclasses can `override` this method

```
class Entity {
public:
   virtual void update() {}
   virtual void render() {}
};
```

```
class Projectile : public
Entity {
public:
   void update() override {};
};
```

`override` isn't required but is good for readability! It will check that you are overriding a `virtual` method instead of creating a new one.

Does it work?

YES!!! 😄

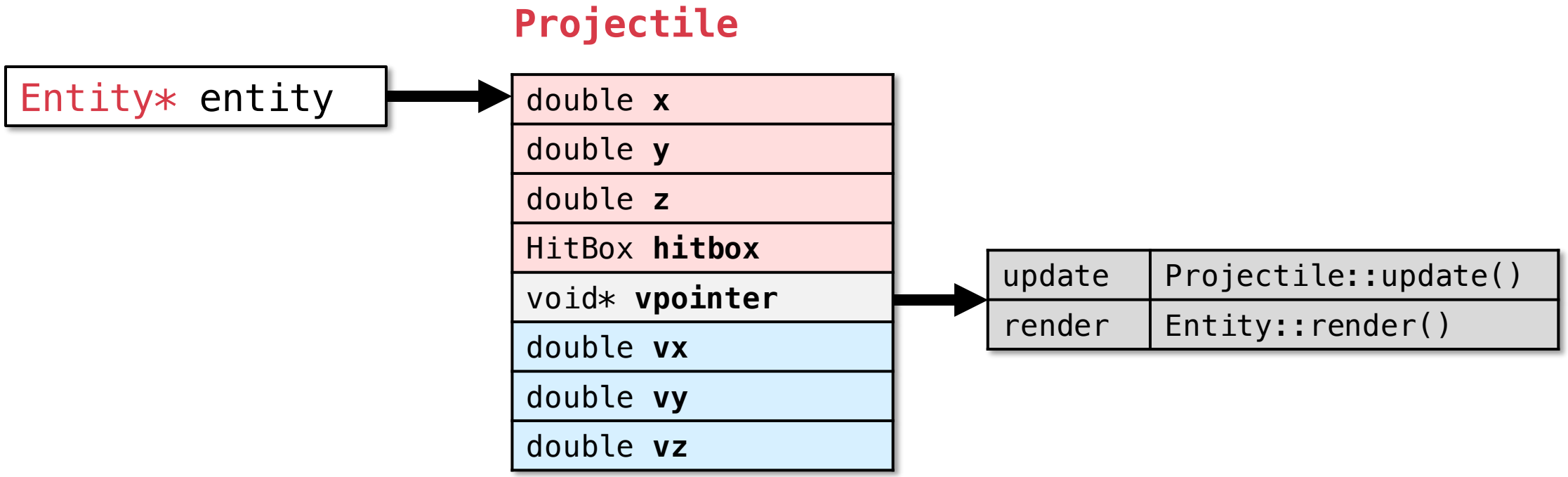
What questions do you have?

bjarne_about_to_raise_hand

How does it work?

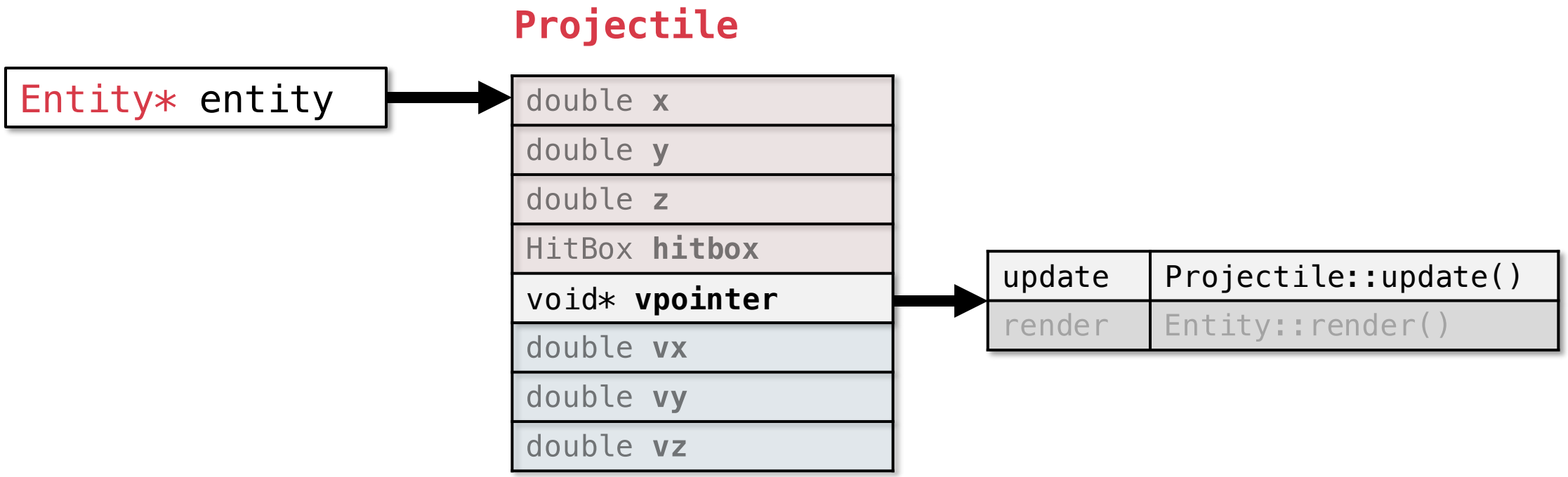
Behind the Scenes

- Adding `virtual` to a function adds some metadata to each object
- Specifically, it adds a pointer (called a `vpointer`) to a table (called a `vtable`) that says, for each `virtual` method, which function should be called for that object



Behind the Scenes

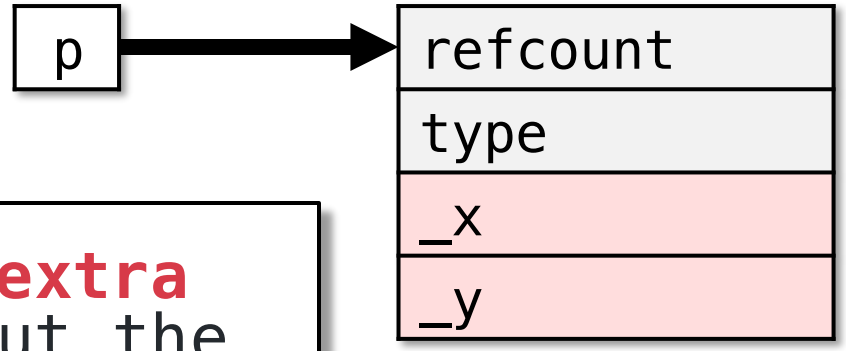
```
Entity* p = new Projectile { /* ... */ };
p->update();
```



Recall: Classes in Python

```
class Point:
    def __init__(self, x, y):
        self._x = x
        self._y = y

    def getX(self):
        return self.
    def getY(self)
        return self.
```

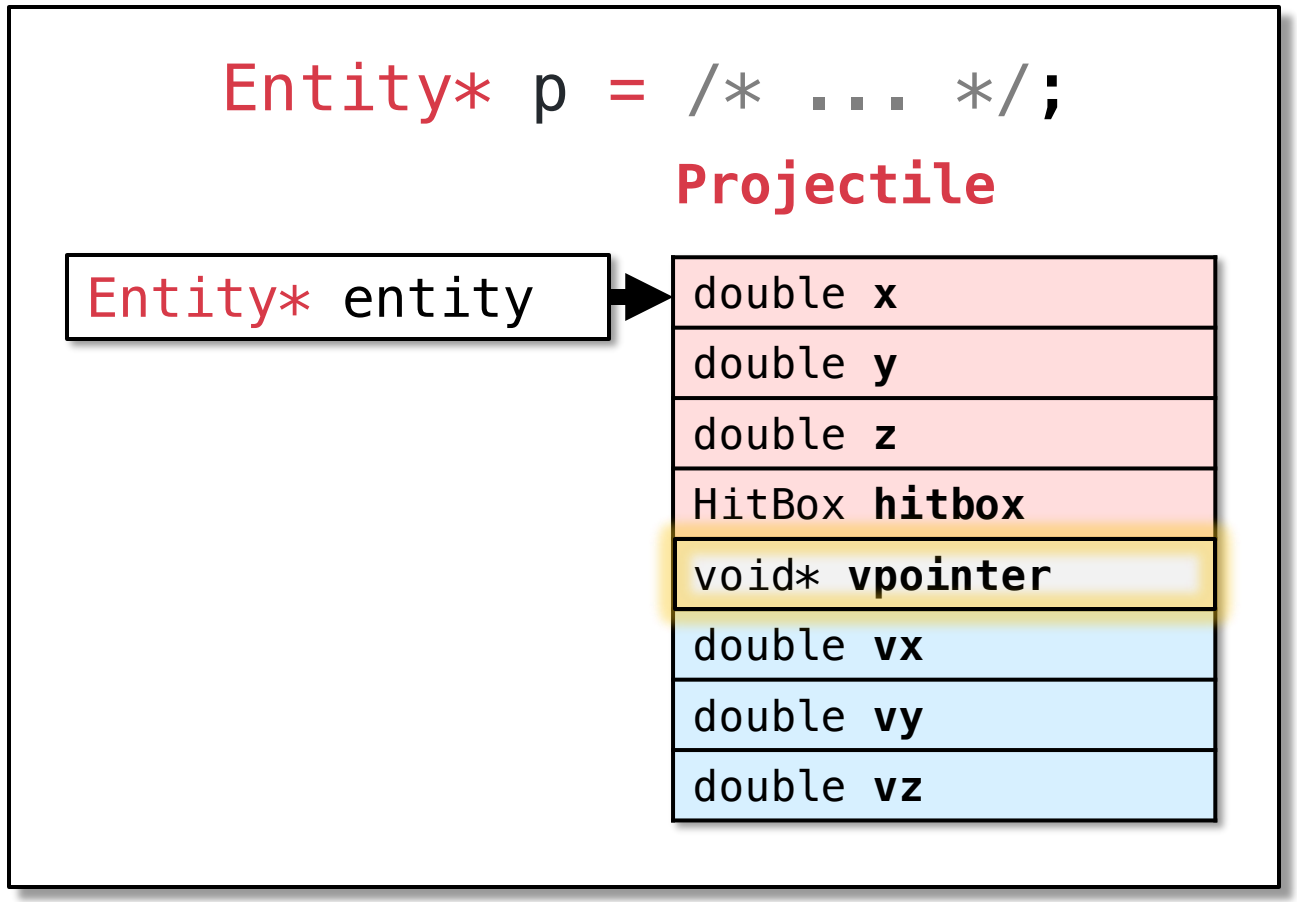
```
p = Point(1, 2)
```

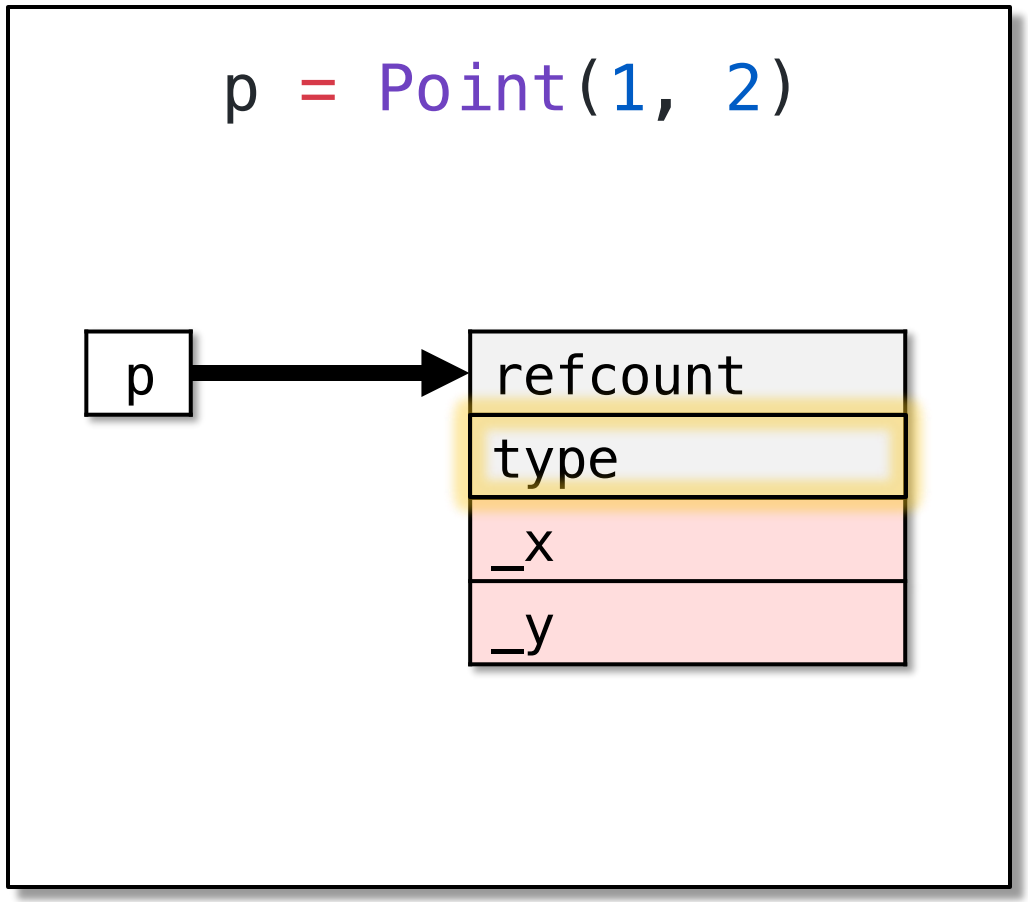


Python **stores extra information** about the type of the object in its memory footprint! This enables runtime type checking.

`virtual` is kind of like Python

Both Python and C++ `virtual` functions store type-specific information





Quick check: pros/cons of `virtual` functions?

- Turn to a partner and talk about:
  - When might you want to use a virtual function?
  - When might you **not** want to use a virtual function?

- In many other languages, class functions are virtual by default
- **Key idea:** In C++, you have to opt in because they are more expensive
  - Increased **size** of memory layout of the class
  - Takes **longer** to look up `vtable` and call the method
- In quant finance and industries where nanoseconds count, virtual functions are not used!

What questions do you have?

bjarne_about_to_raise_hand

Pure virtual functions

```
class Entity {
public:
   virtual void update() = 0;
   virtual void render() = 0;
};
```

Pure virtual functions

```
class Entity {
public:
   virtual void update() = 0;
   virtual void render() = 0;
};
```

Mark a virtual function as pure virtual by adding `= 0;` instead of an implementation!

Pure virtual functions

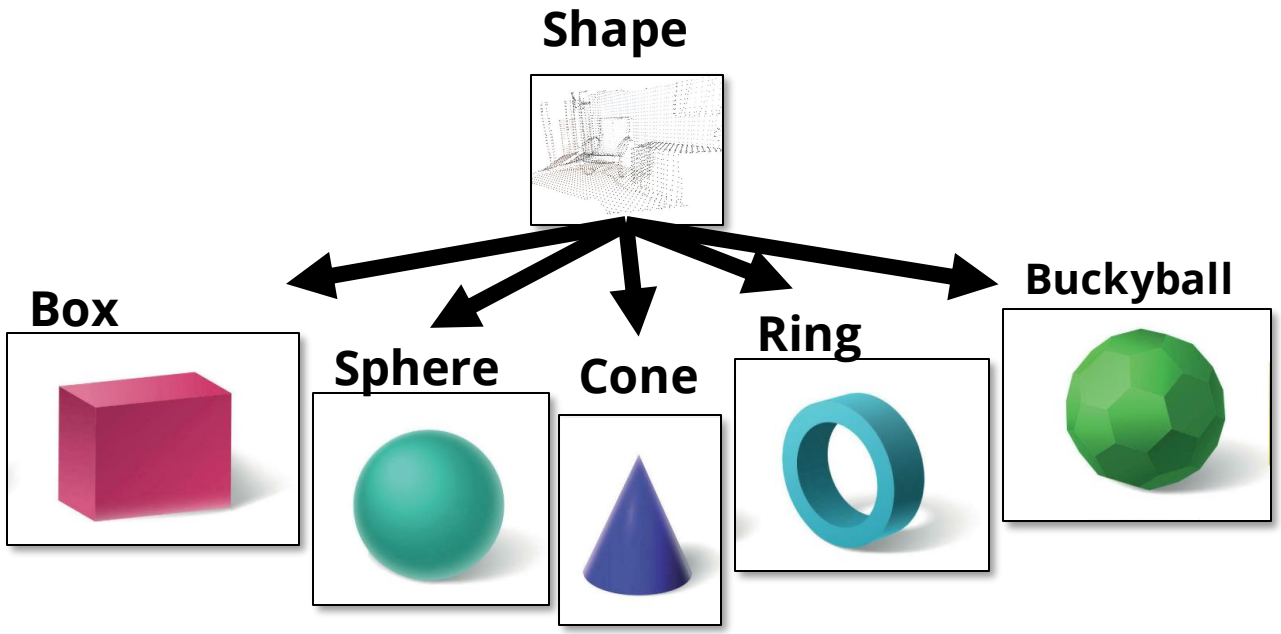
- A class with one or more pure virtual functions is an **abstract** class, it can't be instantiated!
- Overriding all of the pure virtual functions makes the class **concrete**!

```
class Entity {
public:
   virtual void update() = 0;
   virtual void render() = 0;
};

Entity e;
// ❌ Entity is abstract!
```

```
class Projectile
   : public Entity {
public:
   void update() override {};
   void render() override {};
};

Projectile p;
// ✅ Projectile is concrete
```

Pure virtual functions

Pure virtual functions are useful when there's **no clear default implementation**!




```
class Shape {
public:
    virtual double volume() = 0;
};
```

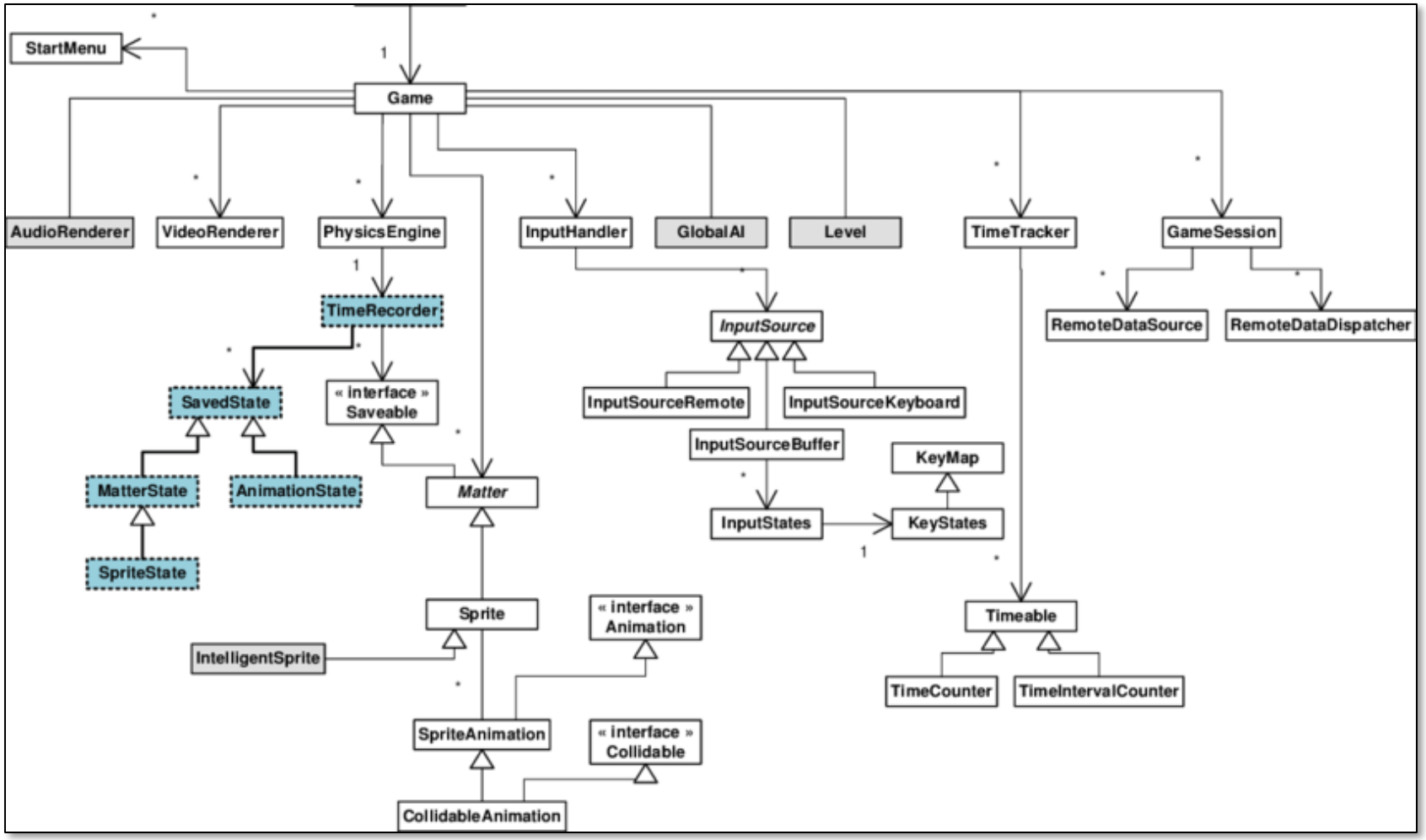
What's the default volume of a Shape? Let's mark it pure virtual and let subclass decide!

What questions do you have?

bjarne_about_to_raise_hand

Closing Thoughts

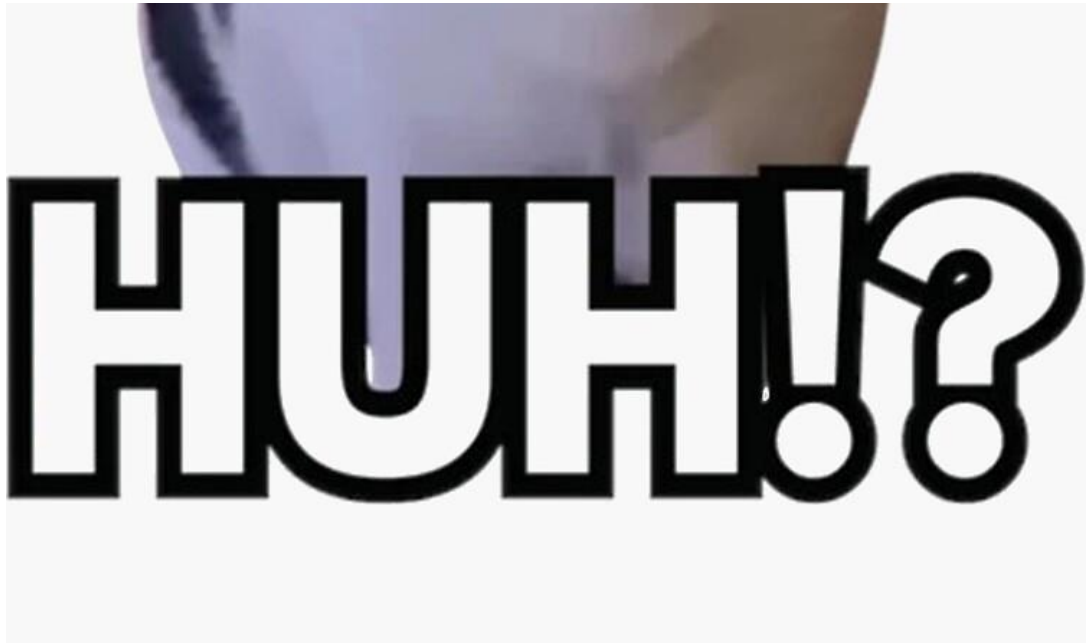
Sometimes inheritance can get out of hand



Sometimes inheritance can get out of hand

- Big inheritance trees tend to be **slower** and **harder to reason about**
  - In video games, approach of subclassing for every different object type is uncommon among modern game engines
  - Composition is often more flexible and just makes sense

“A car is an engine”



“A car ~~is~~ has an engine”

Prefer composition over inheritance

Inheritance is a powerful tool, but sometimes, composition just makes more sense!

```
class Car
   : public Engine
   , public SteeringWheel
   , public Brakes
{
   /* Hmmm... this doesn't
   seem quite right */
};
```

```
class Car {
   Engine engine;
   SteeringWheel wheel;
   Brakes brakes;
};
```

Prefer composition and inheritance

Combining both of these ideas can give the best of both worlds!

```
class Car {
    Engine* engine;
    SteeringWheel* wheel;
    Brakes* brakes;
};

class Engine {};
class CombustionEngine : public Engine {};
class GasEngine : public CombustionEngine {};
class DieselEngine : public CombustionEngine{};
class ElectricEngine : public Engine {};
```

If you want to see one place this technique is used in C++, look up the PIMPL idiom!

What questions do you have?

bjarne_about_to_raise_hand