Welcome back! Attendance form below

Lecture 8: Inheritance

CS106L, Fall 2025

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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?

Last Time: Classes

- What are classes?
  - Turn to the person next to you and think of one thing you remember from Tuesday's lecture!

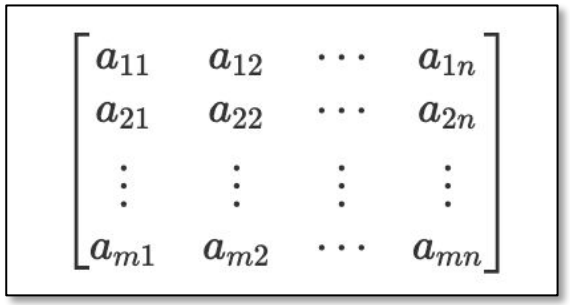
Last Time: Classes

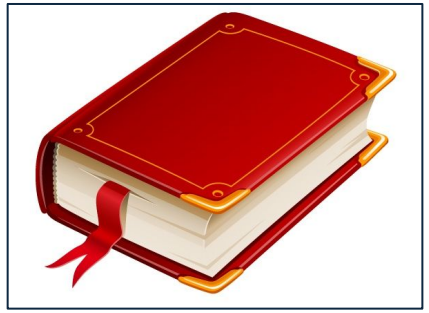
- What are classes?
  - Turn to the person next to you and think of one thing you remember from Tuesday's lecture!
- A class represents an abstraction — it can model a real-world object, a concept, or any entity you want to organize into data and behavior.
- A class bundles data and methods for an object together

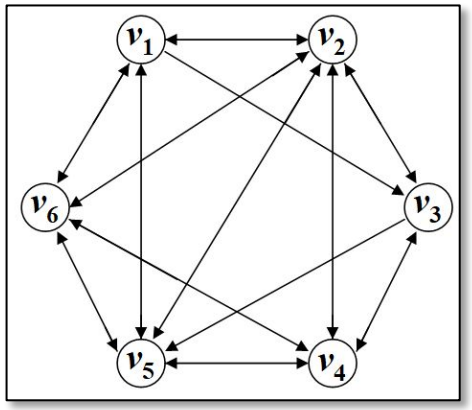
A class as a concept in a program

- You can think of classes as a **real life concept**
  - Car
  - Engine
  - Video Game Character
  - Vectors
  - Graph
  - Book
  - Dog

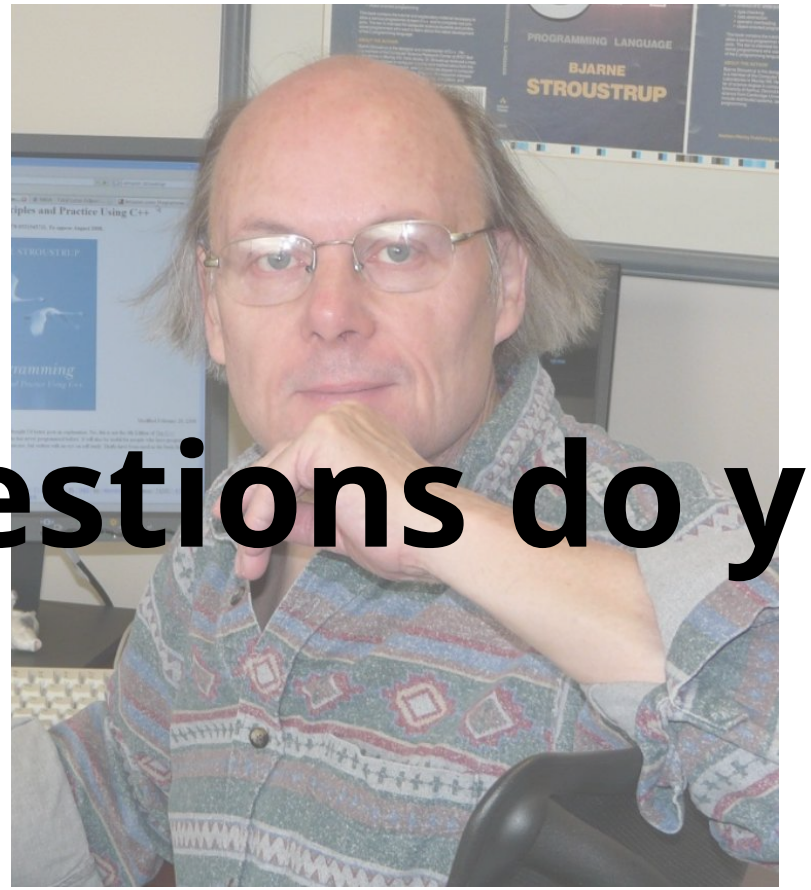
std::vector<int>







What questions do you have?



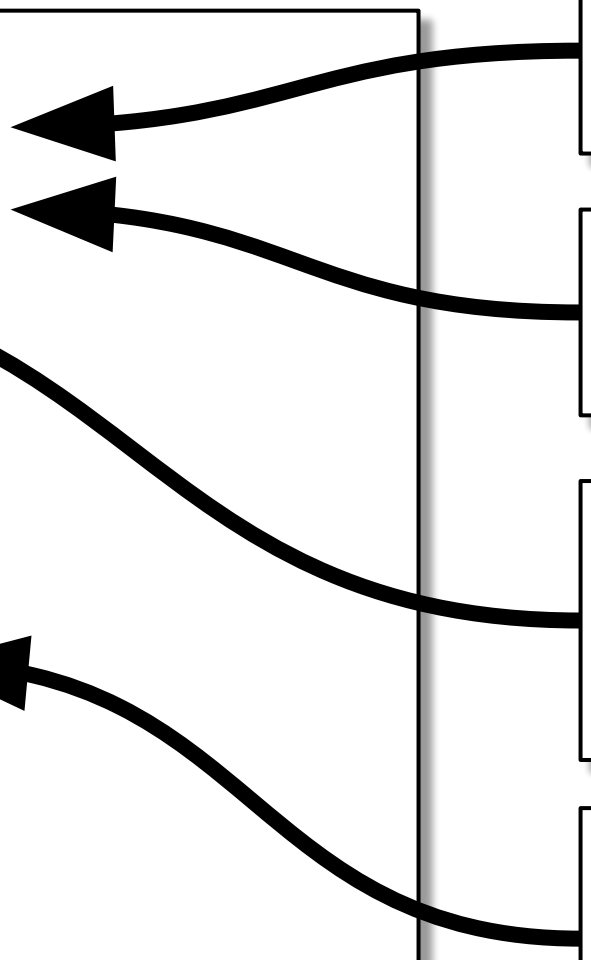
bjarne_about_to_raise_hand

A Recap on Classes

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;
}
```

Point.h (header file)

Contains **interface, declarations**

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._y
```

```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; }
```

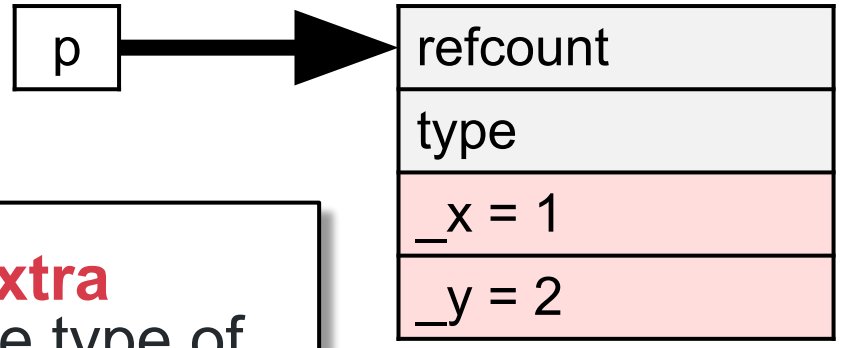
What does a **Point** look like in memory?

Classes: Memory Layout (Python)

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

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

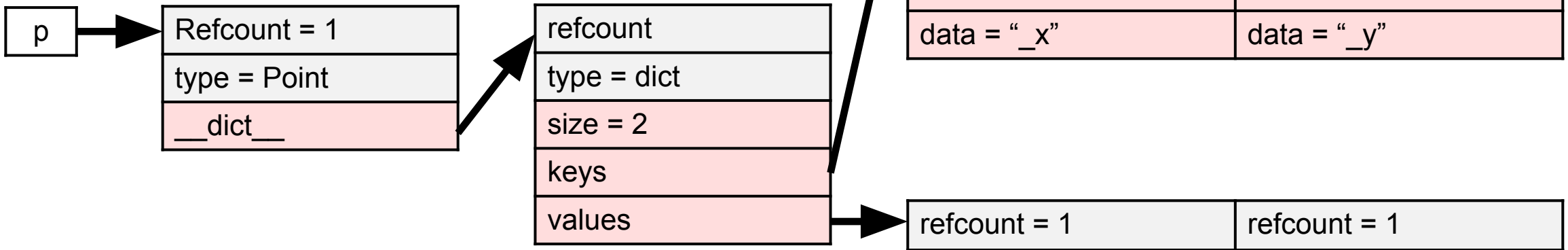
```
p = Point(1, 2)
```



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!

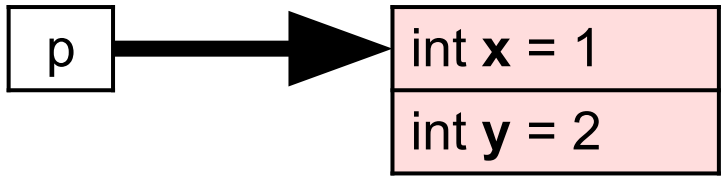
```
p = Point(1, 2)
```



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

Classes: Memory Layout (C++)

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



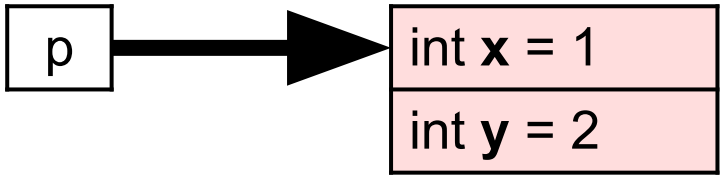
C++ **just stores the data** in the object! The compiler does all of the type checking at compile time!

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

Classes: Memory Layout

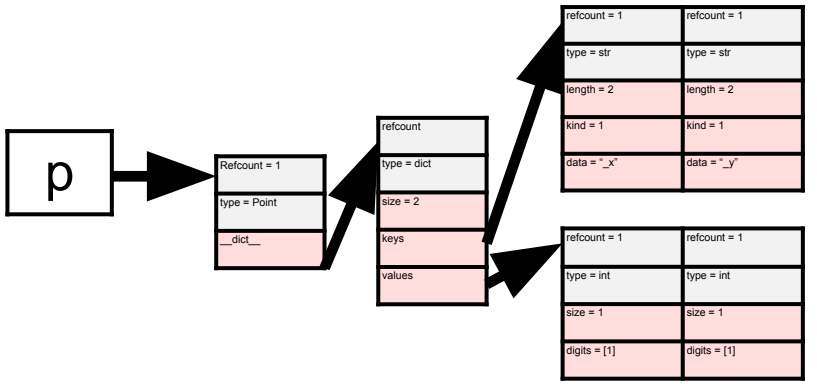
C++

Point p {1, 2};



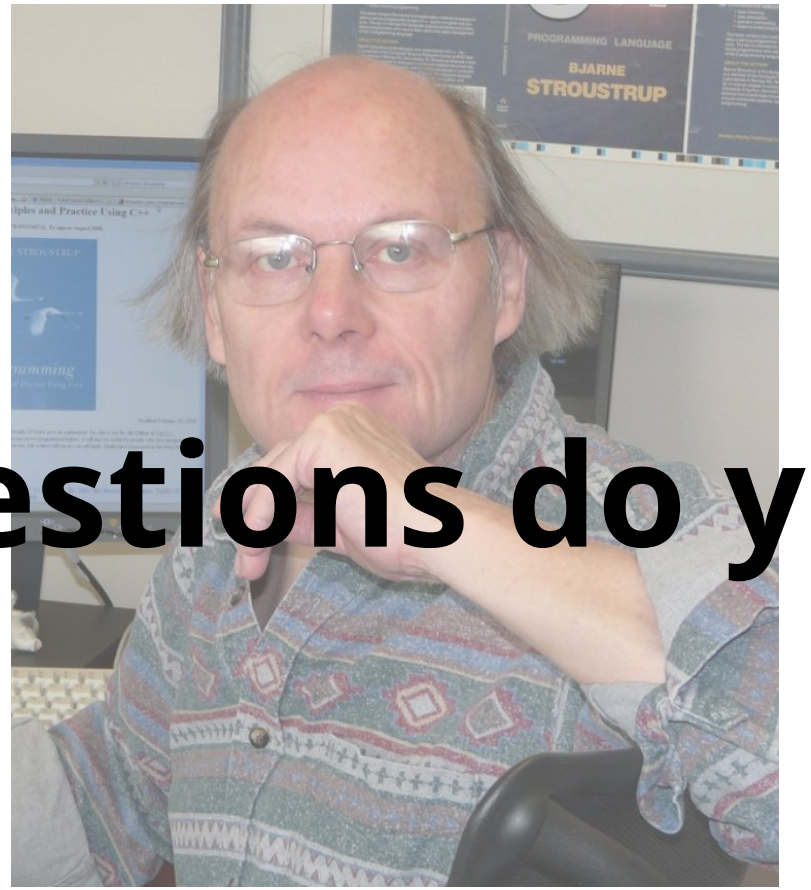
Python

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?



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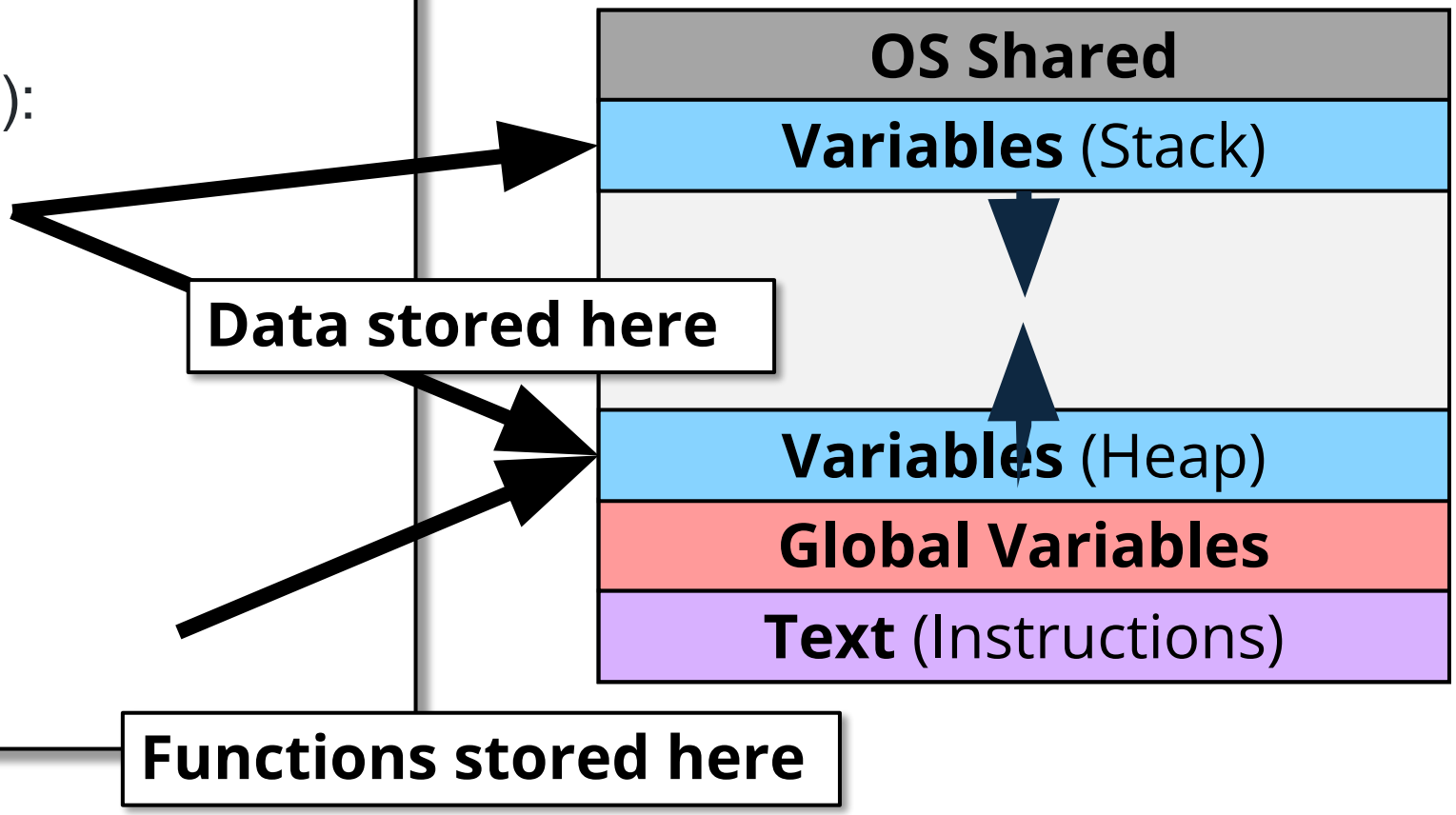
Where are the functions?

Where are the functions in Python?

Functions are not stored in the object dictionary itself, but separately in a dictionary associated with the class.

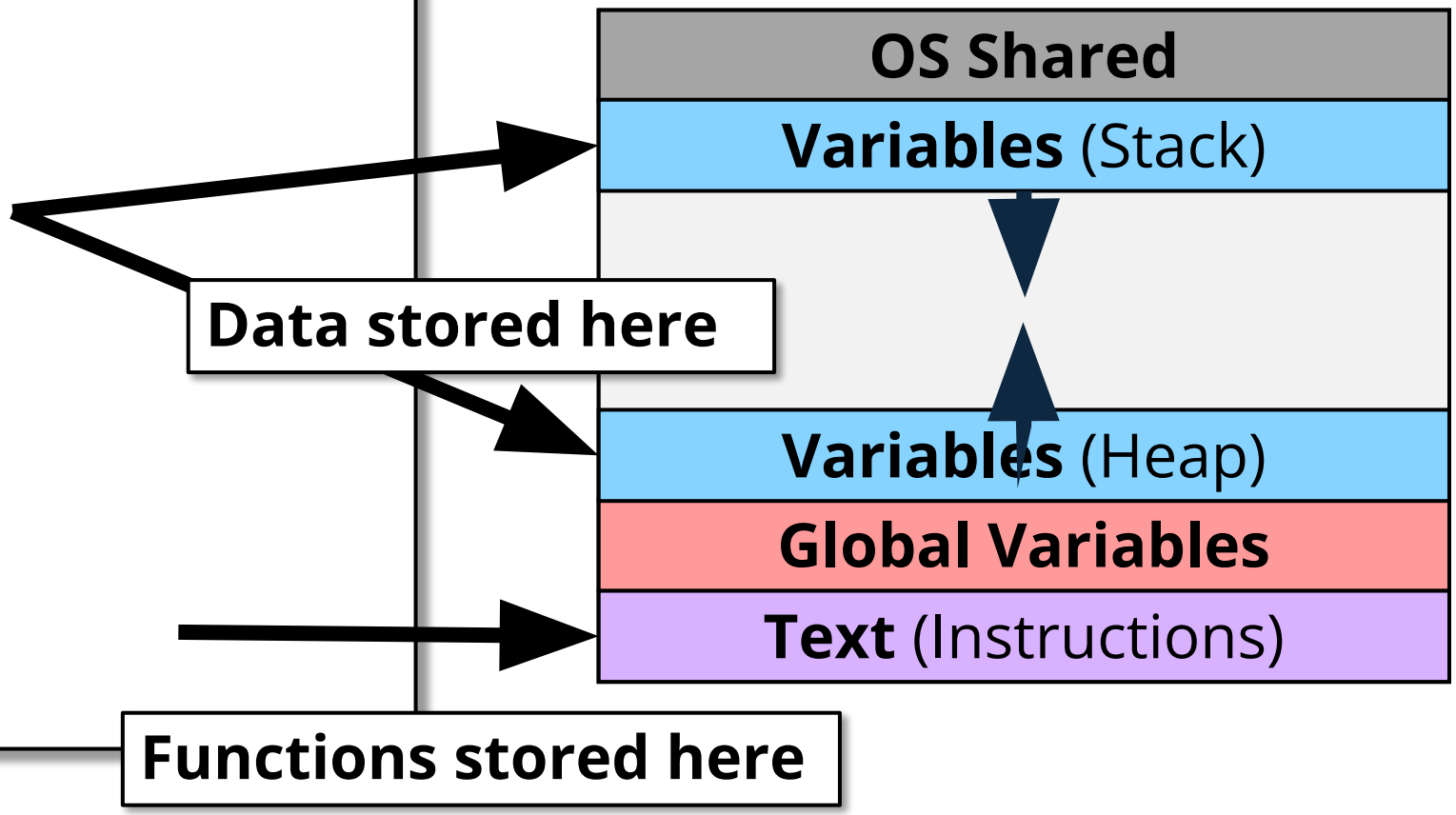
```
class Point:
    def __init__(self, x, y):
        self._x = x
        self._y = y

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



Where are the functions in C++?

Functions are not stored in the object itself, but separately

```
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; }
};
```



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
```

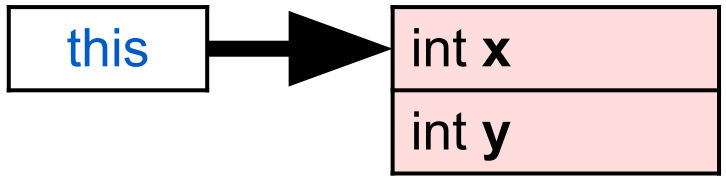
```
p = Point(1, 2)
px = p.getX()

# ...is the same as...

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

Passing self as parameter

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

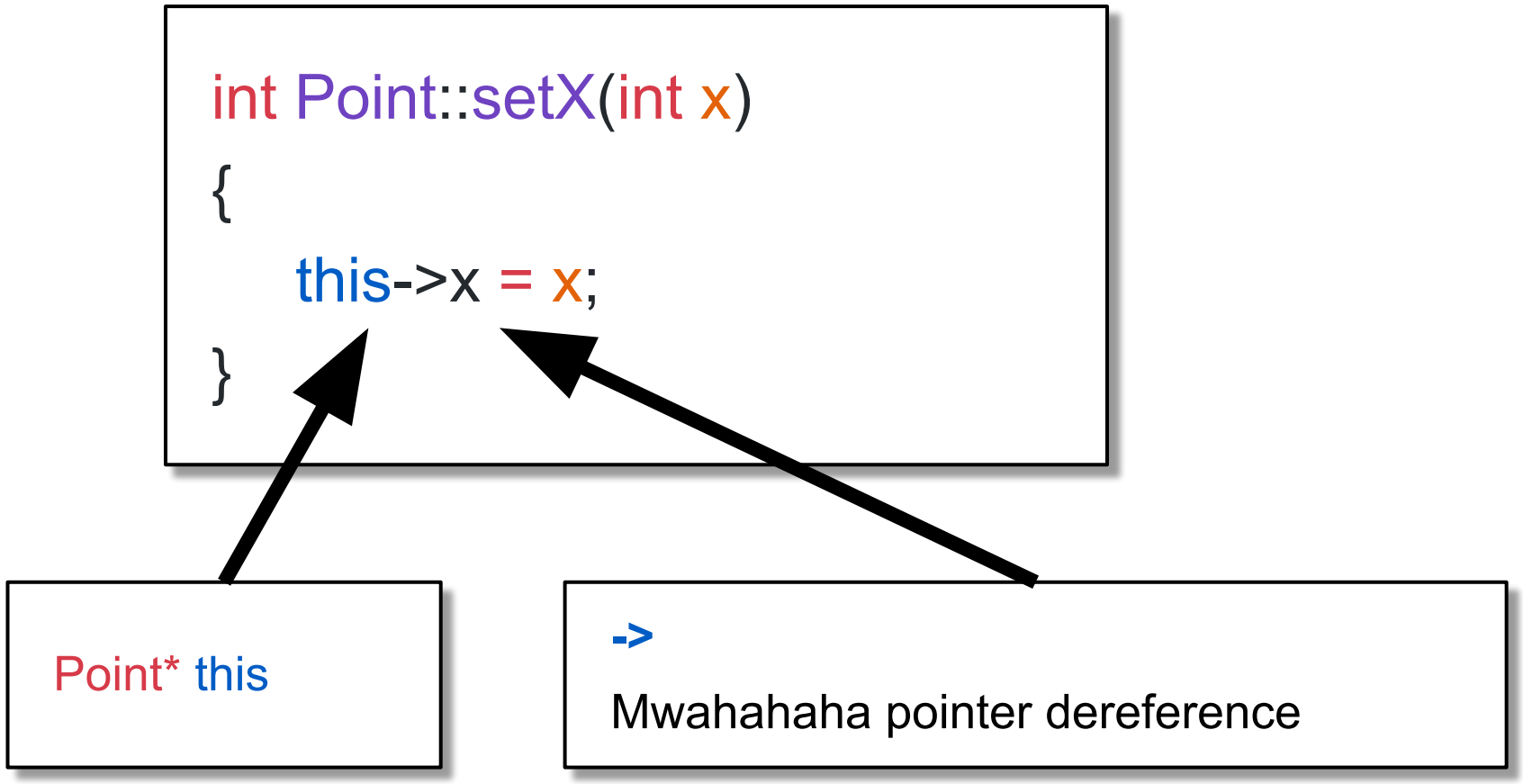
Are these two snippets of code the same?

```
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++

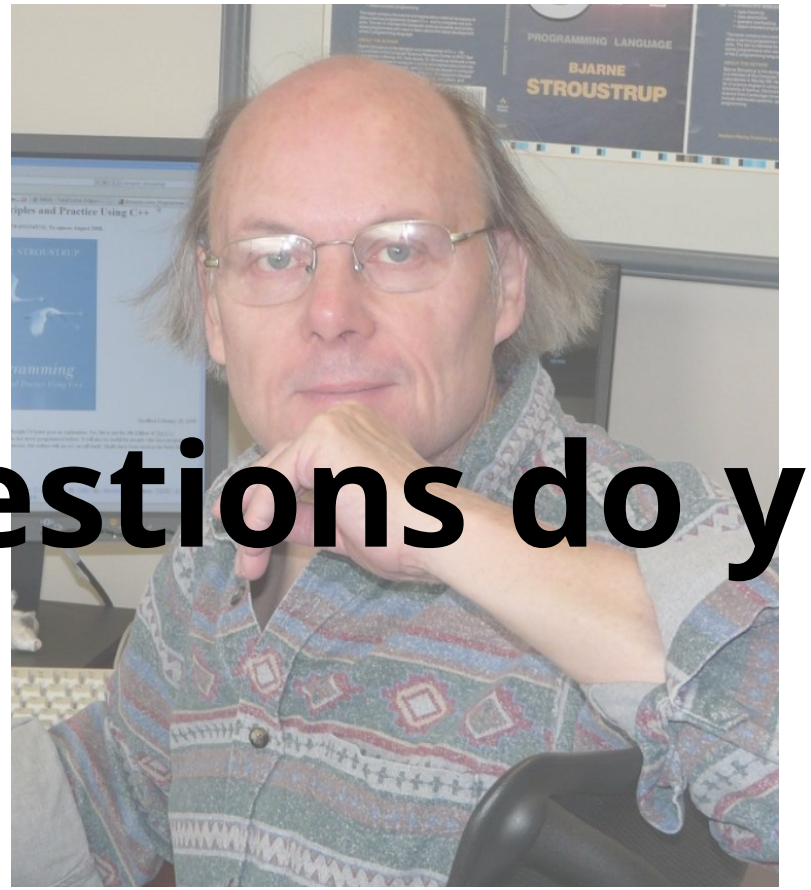
this is passed as a parameter to class function behind the scenes

```
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?



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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

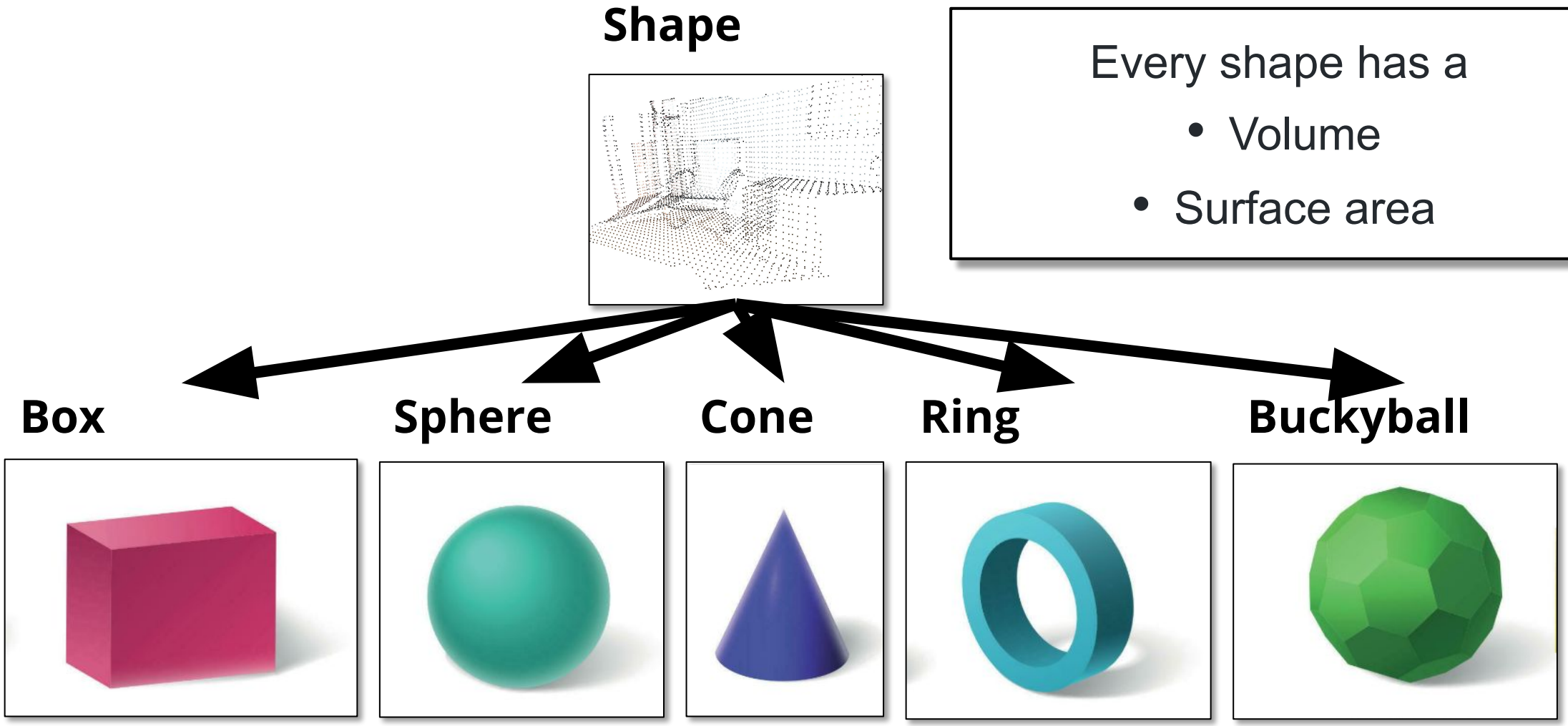
Toyota Camry

Honda Civic

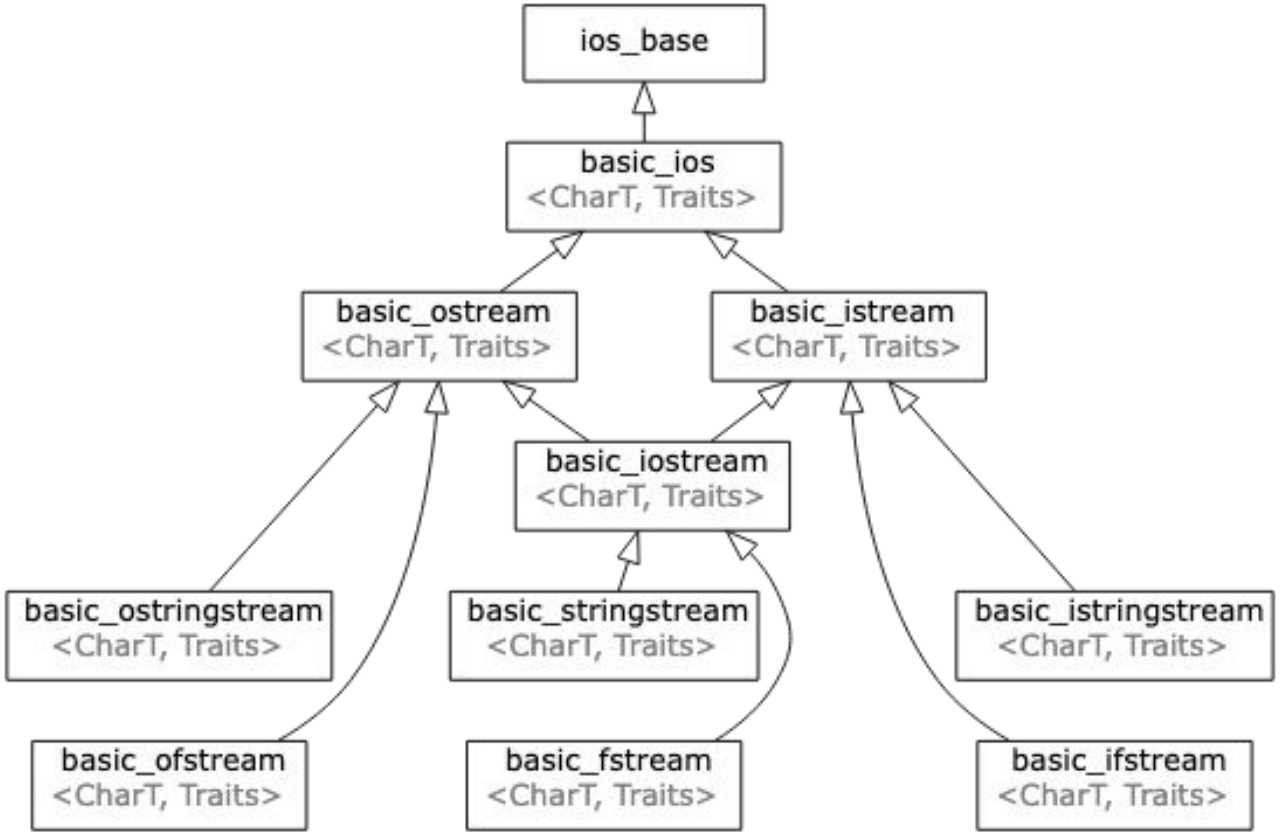
Ford Mustang

Jeep Gladiator

Many kinds of shapes

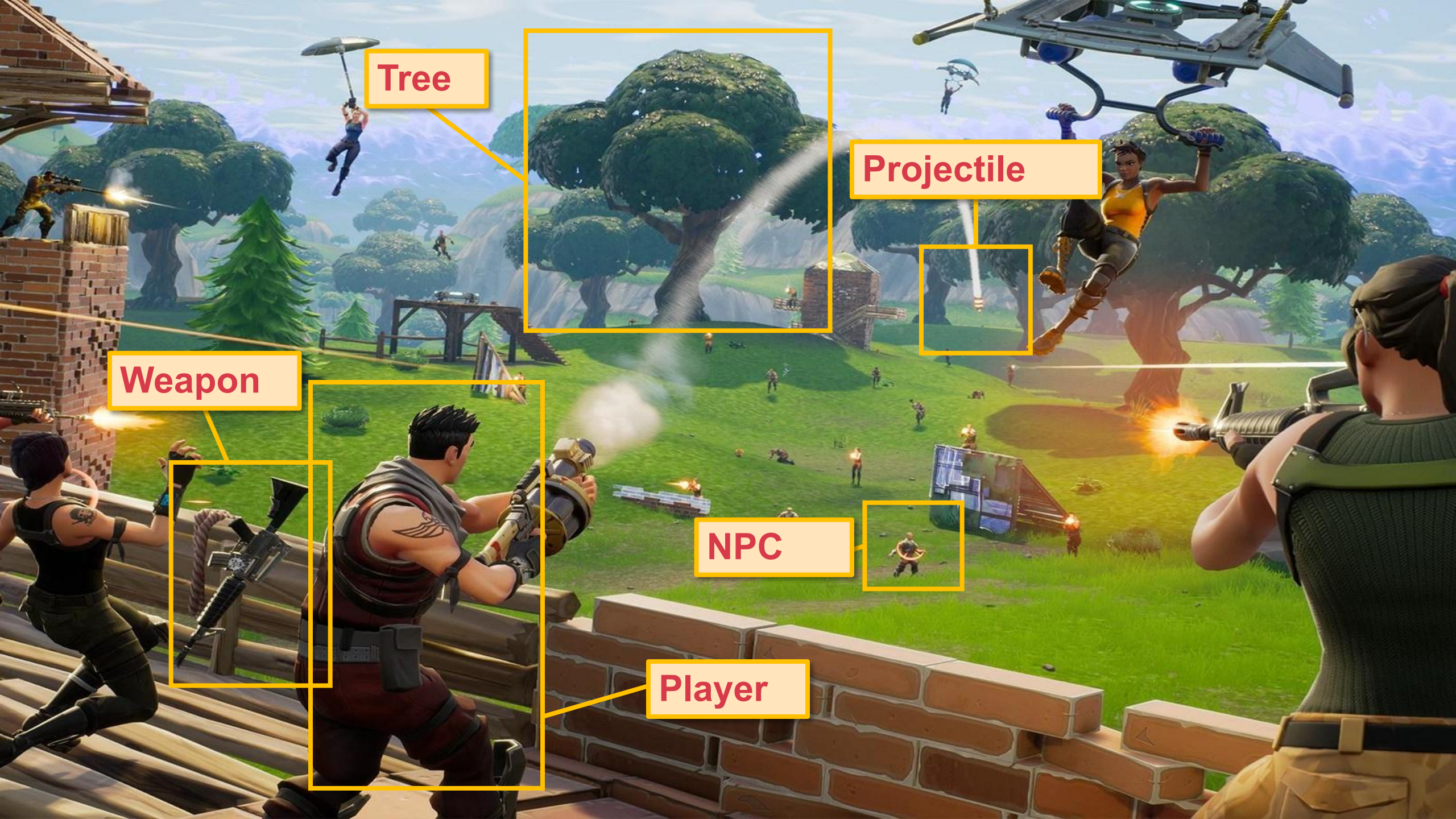


We've seen this before: streams!



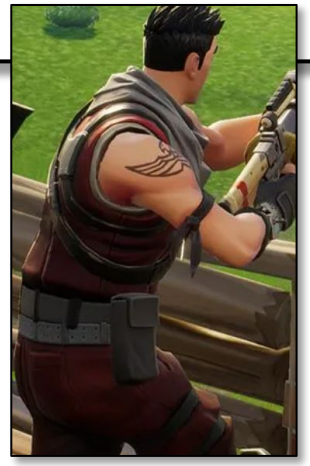
Is-A relationship: An std::ifstream **is a** std::istream **is a** std::ios

How do we model inheritance in C++?

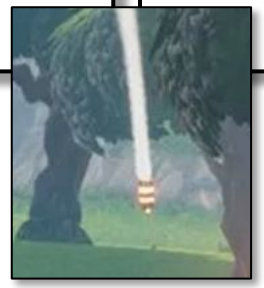

Tree
Projectile
Weapon
NPC
Player

Fortnite as classes

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

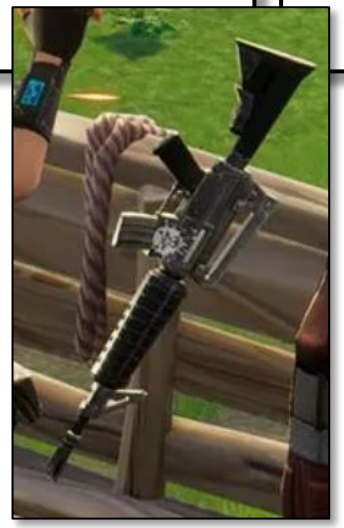


```
class Projectile {
        double x, y, z;
        HitBox hitbox;
        double vx, vy, vz;
public:
        void update();
        void render();
};
```



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

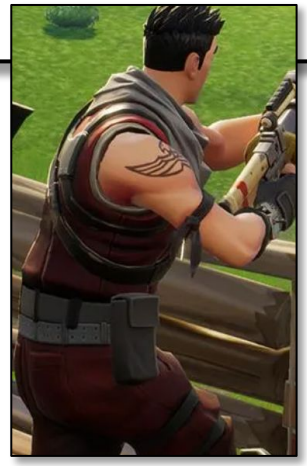
```
class Weapon {
        double x, y, z;
        HitBox hitbox;
        size_t ammo;
public:
        void fire();
        void update();
        void render();
```



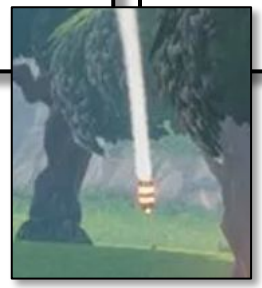
```
class Tree {
        double x, y, z;
        HitBox hitbox;
public:
        void update();
        void render();
};
```

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();
};
```

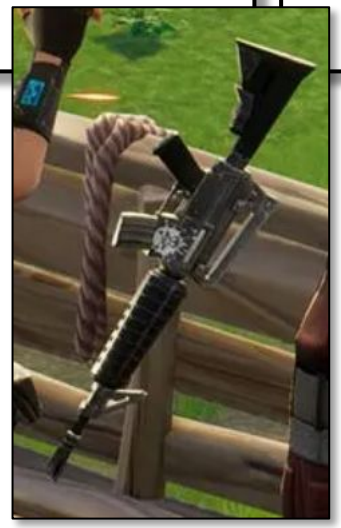


```
class Projectile {
        double x, y, z;
        HitBox hitbox;
        double vx, vy, vz;
public:
        void update();
        void render();
};
```



```
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!

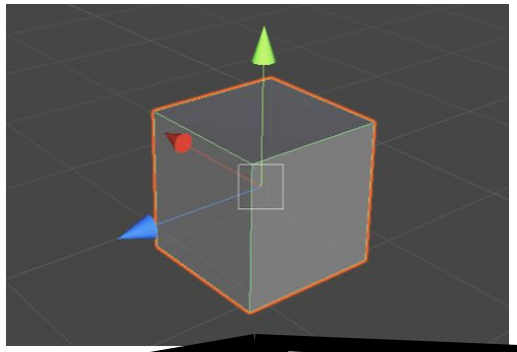
What if we add more object types!

Taking a step back

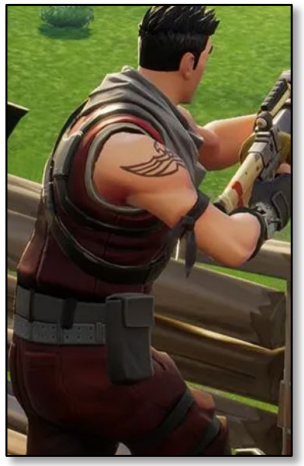
Many different objects, but they all share:

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

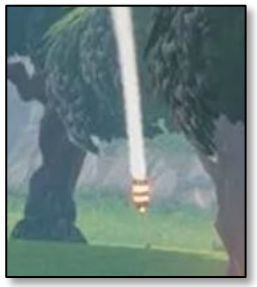
Entity



Player



Projectile



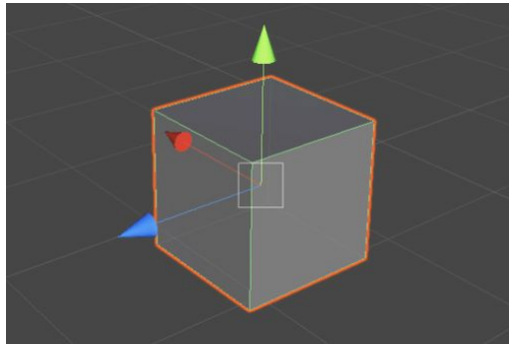
NPC

Weapon

Tree

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, vz;
public:
        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 hitb
public:
        void updat
        void rende
};
```

```
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, vz;
};
```

```
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, vz;
};
```

```
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();
};
```

Notice: there is still some redundancy!

More layers of inheritance...

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

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

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

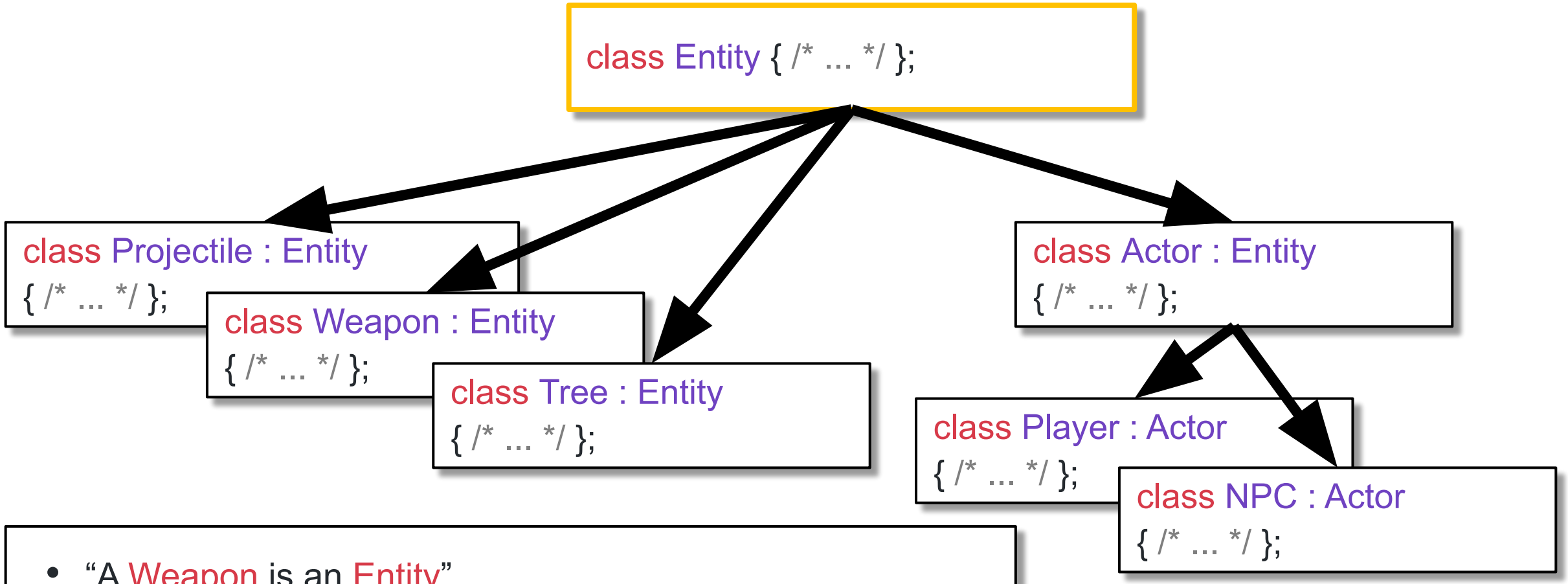
```
class Tree : Entity
 {};
```

```
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!

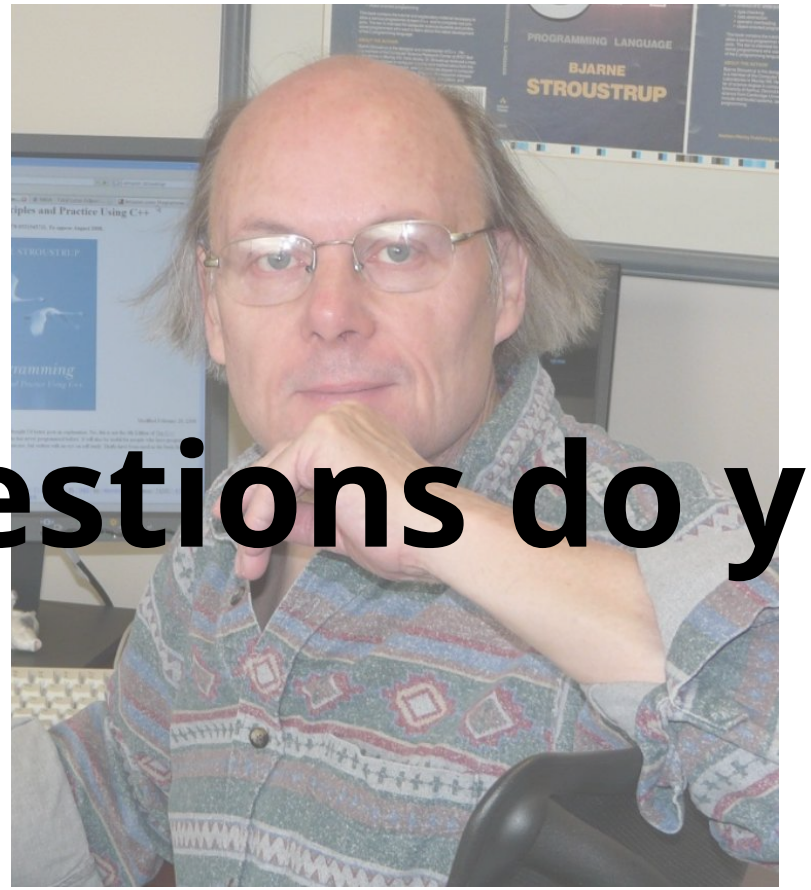
Now we can check if two Entity's overlap, no matter what kind it is!

```
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);
```

What questions do you have?



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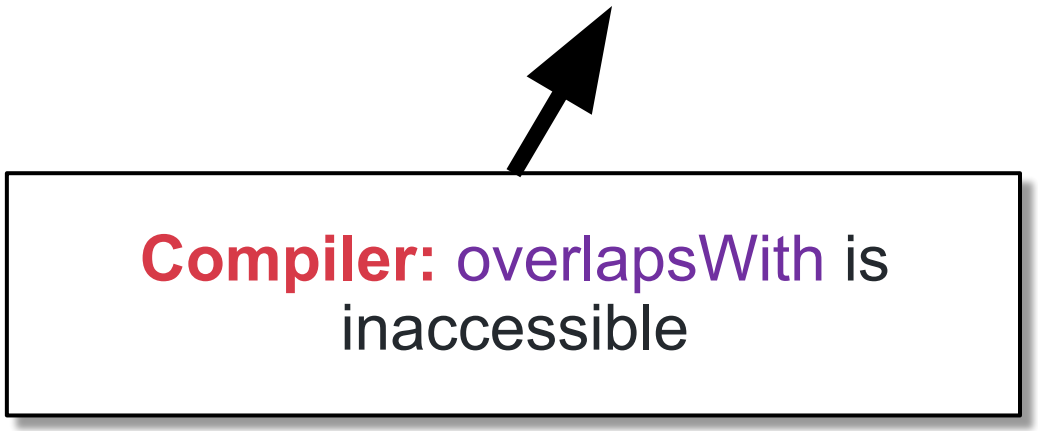
Note: access modifiers

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

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



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();
    voi
};
```

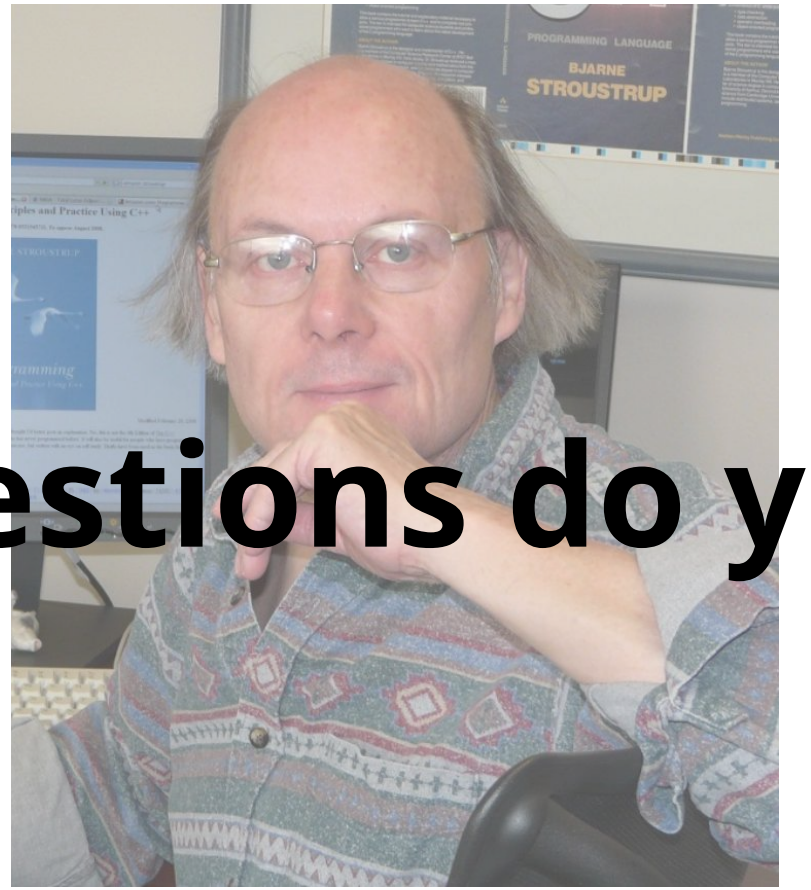
private by default

We need to mark them protected inside Entity

```
class Projectile
ity {
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?



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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
}
```

⋮

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

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

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

⋮

```
// 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();
};
```

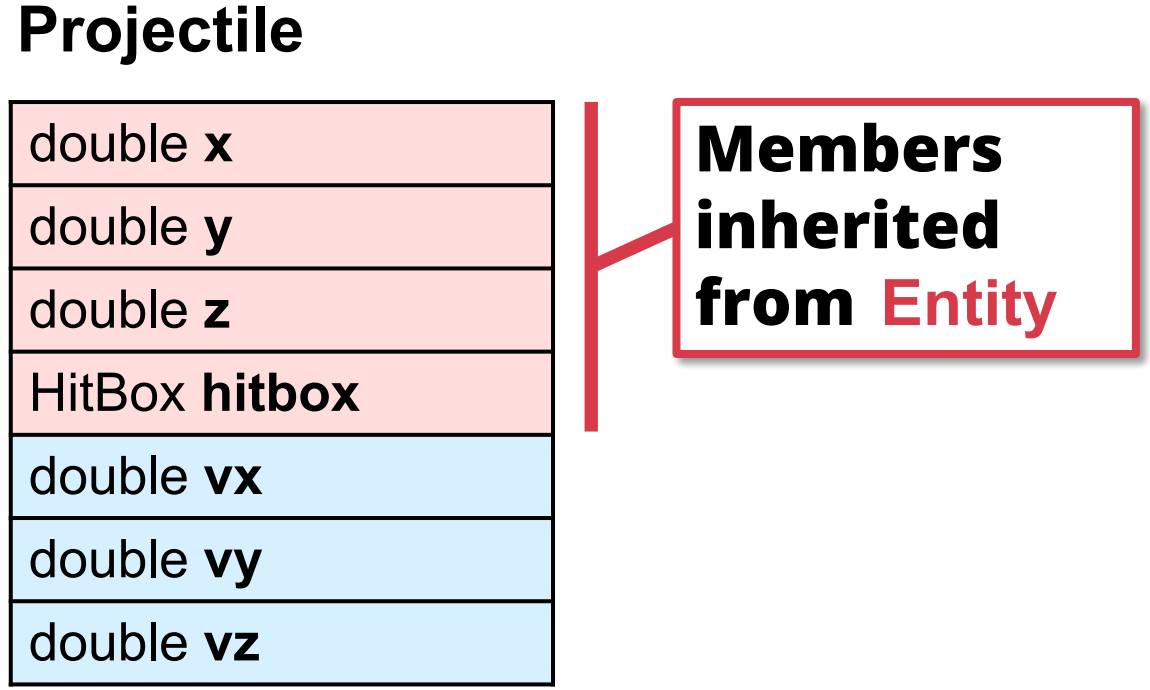
Entity

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**

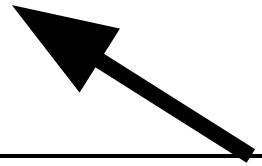
Issue: every element in the vector is an Entity, so the compiler calls Entity::update() (which does nothing) instead of Player::update(), Tree::update(), Projectile::update, etc.

A Projectile doesn't "fit" into an Entity

Solution: Use an Entity* instead

Object slicing only happens when a copy is made!

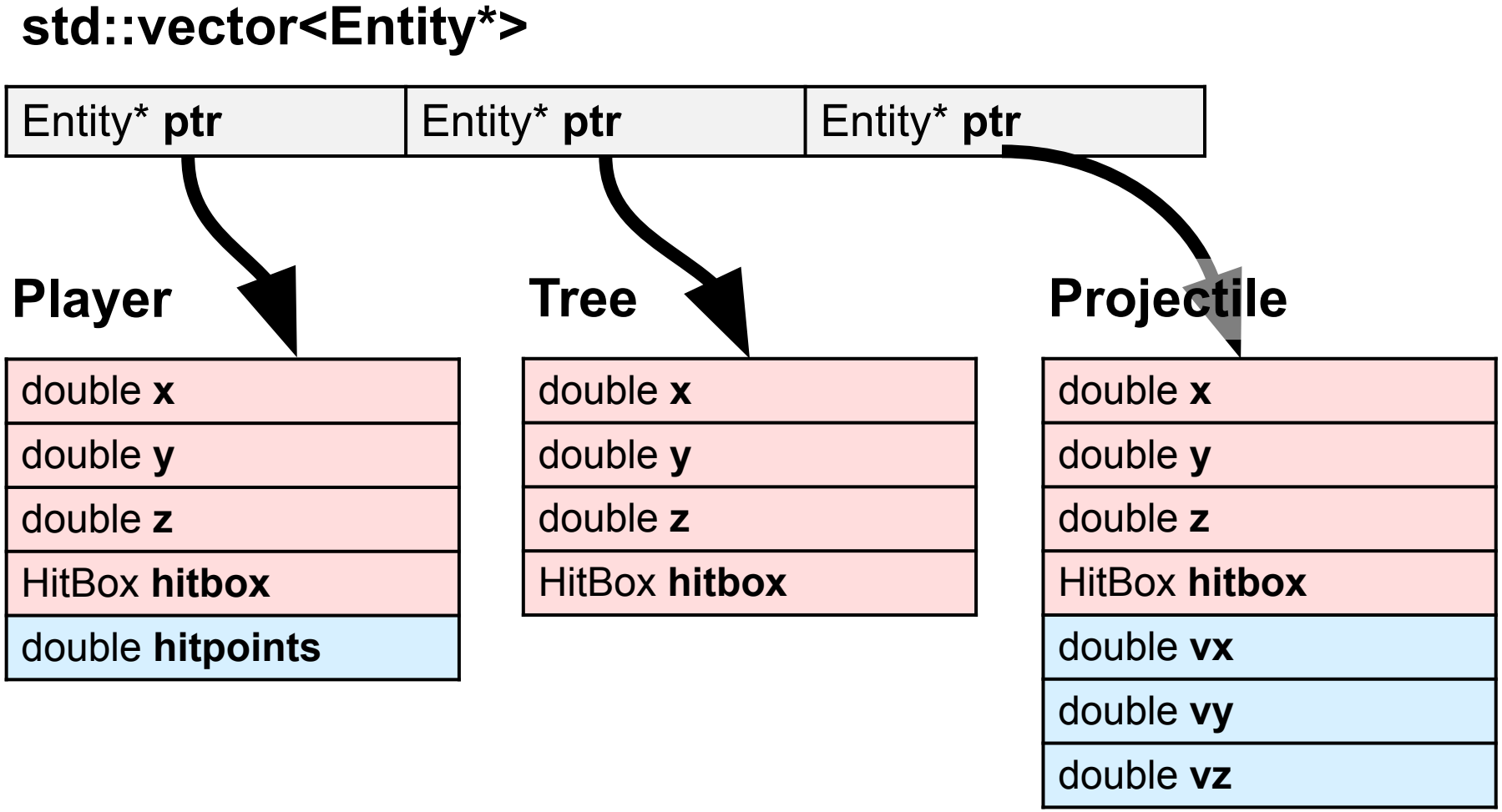
```
int main() {
    Player p; Tree t; Projectile b;

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



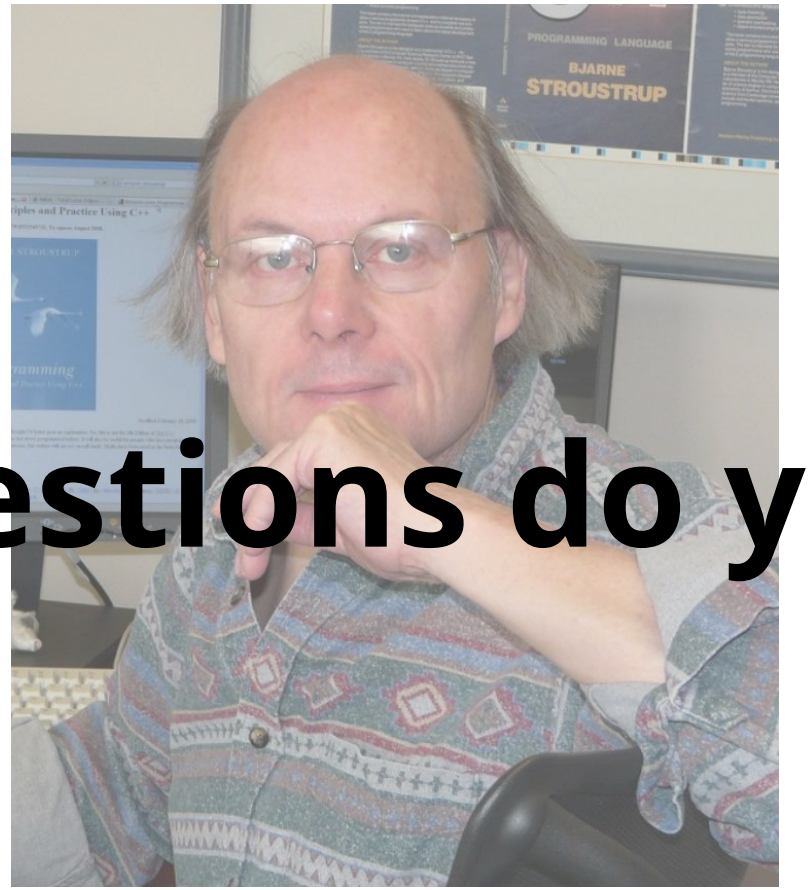
Storing pointers to entities here, not the entities themselves!

Solution: Use an Entity* instead

Pointers retain the details of the subclass by avoiding copies



What questions do you have?



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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 9:30-10:30am Mon, 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();
```

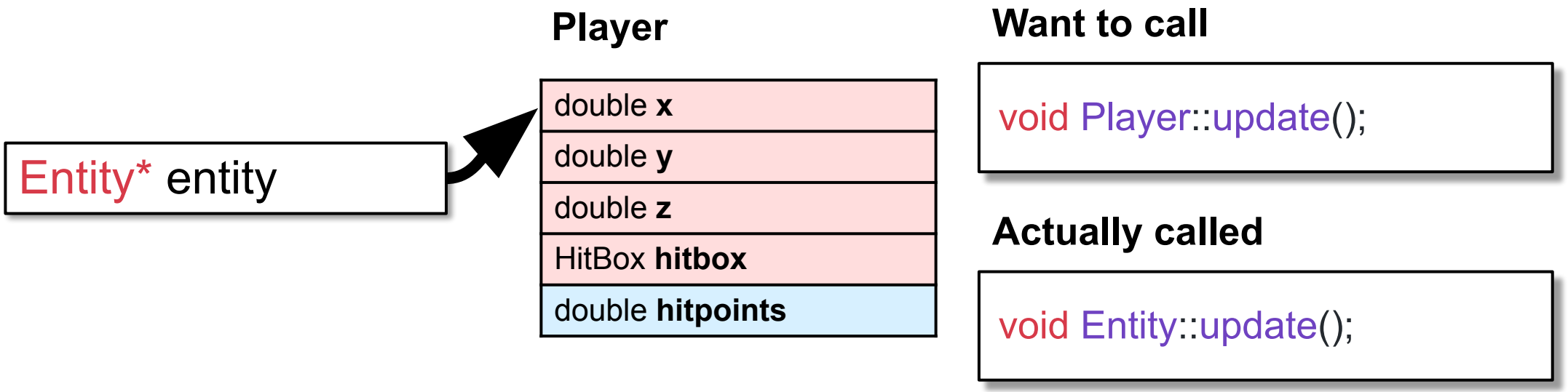
```
void Entity::update();
```

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

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

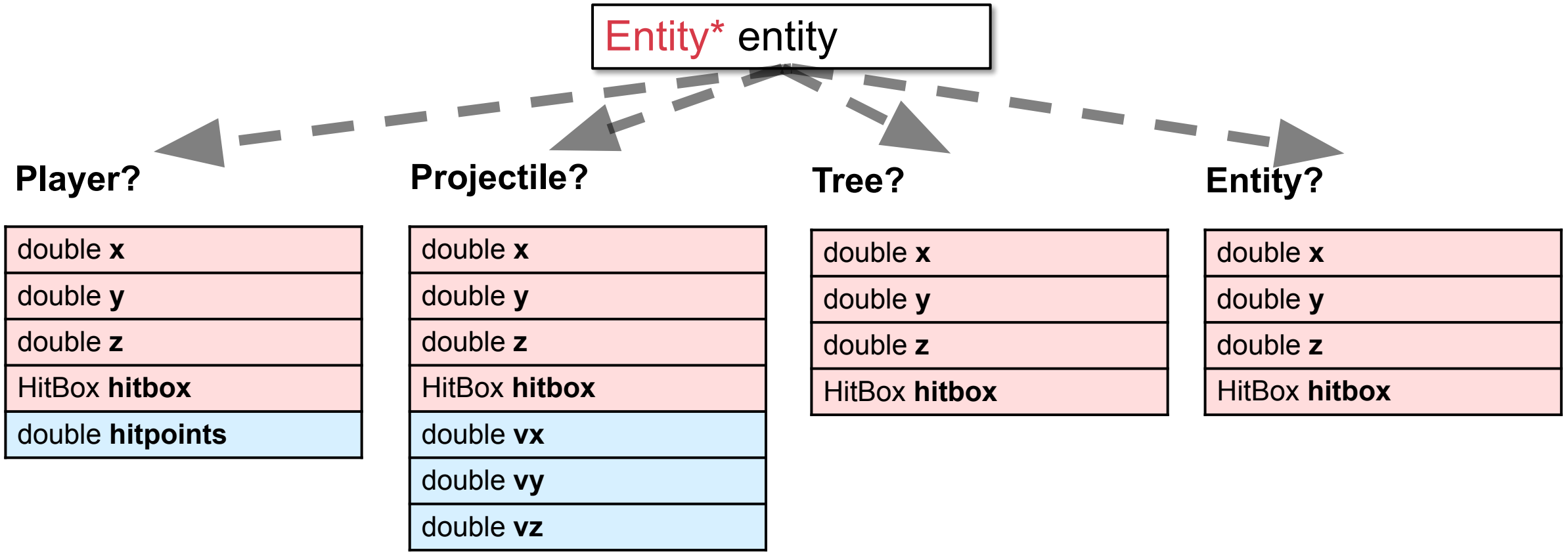
Problem: Which one is called?

- 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!



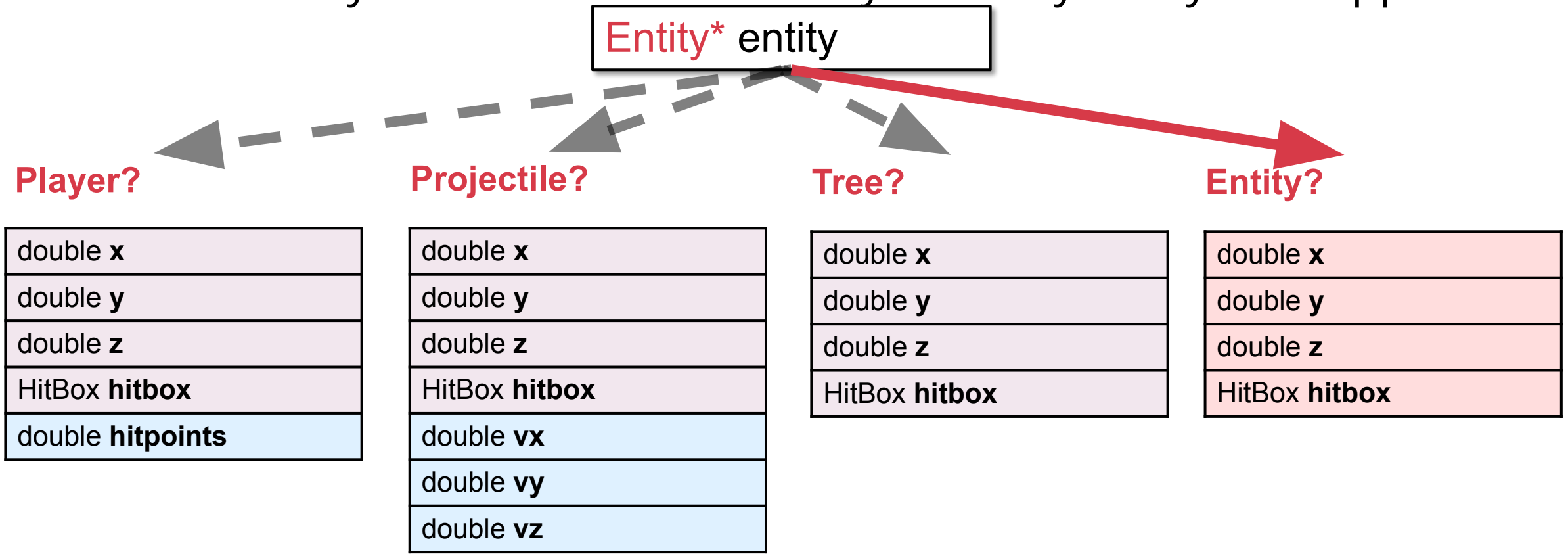
Problem: Which one is called?

- 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



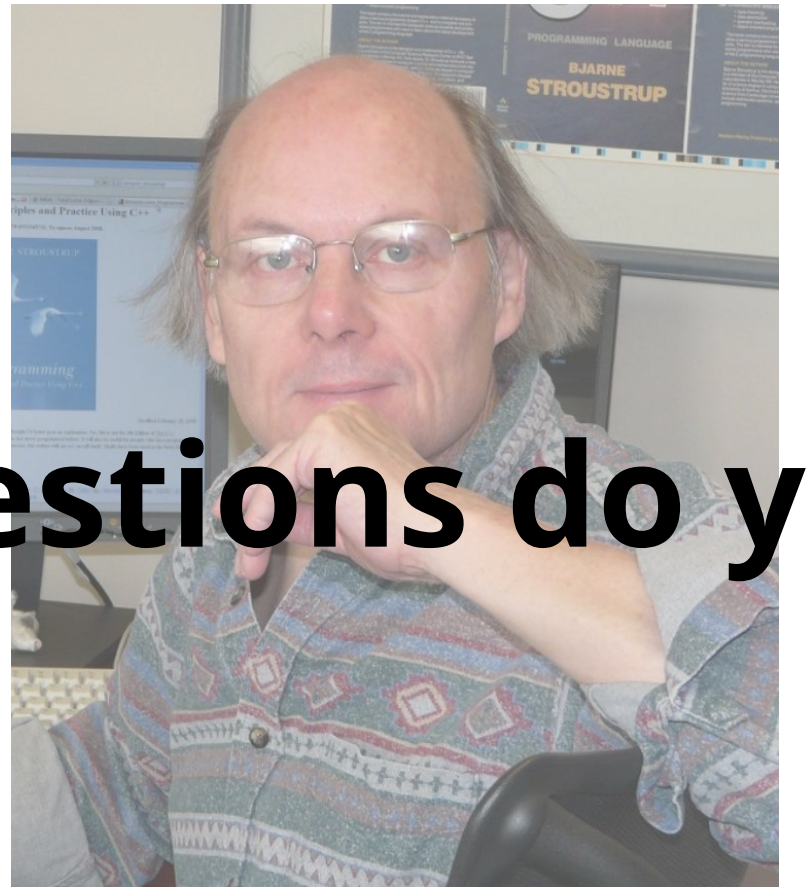
Using Entity* comes at a cost:

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?



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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() {}
};
```

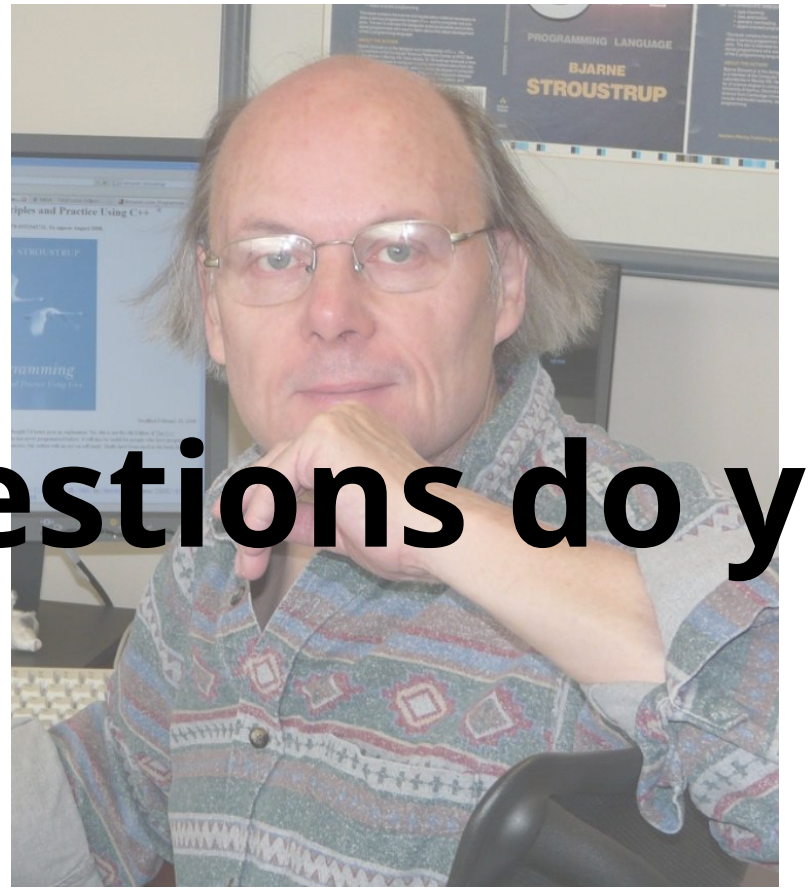
```
class Projectile : public Entity {
public:
    void update() override {};
};
```

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?



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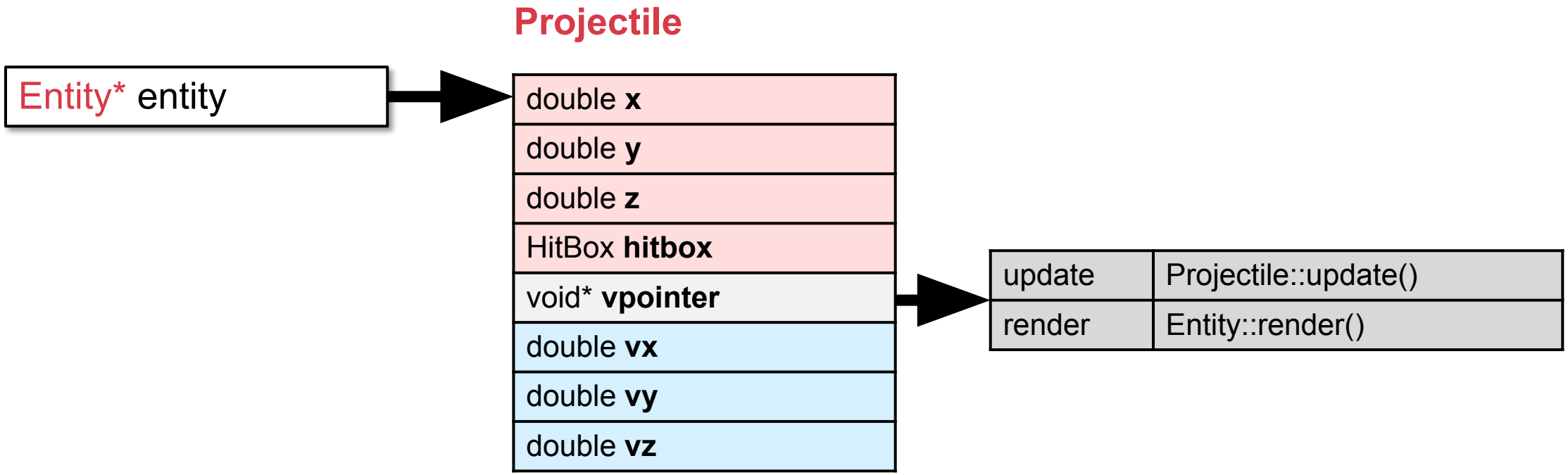
How does it work?

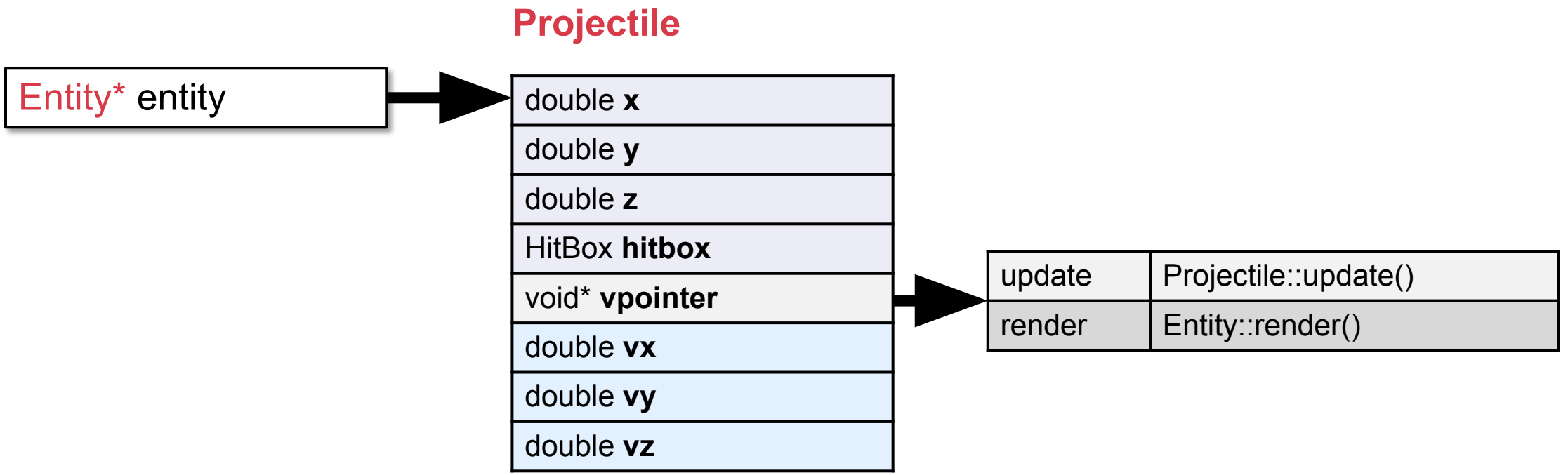
Behind the Scenes

- 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();
```

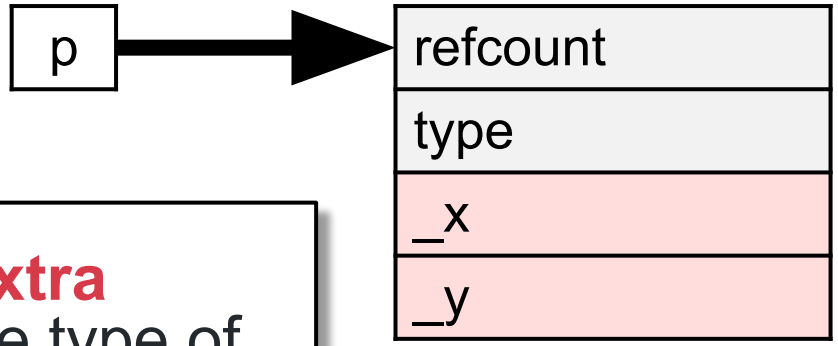


Recall: Classes in Python

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

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

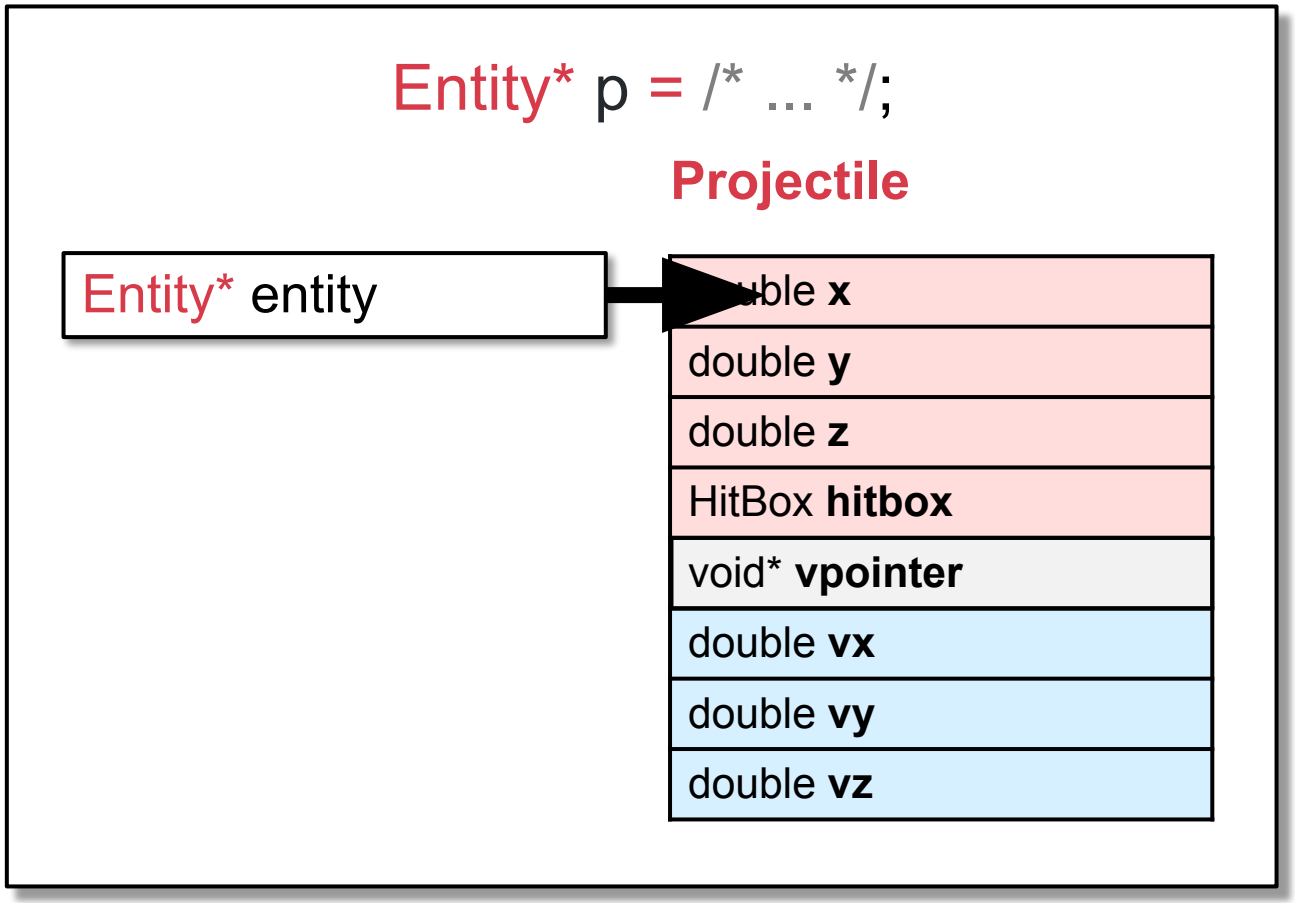
```
p = Point(1, 2)
```

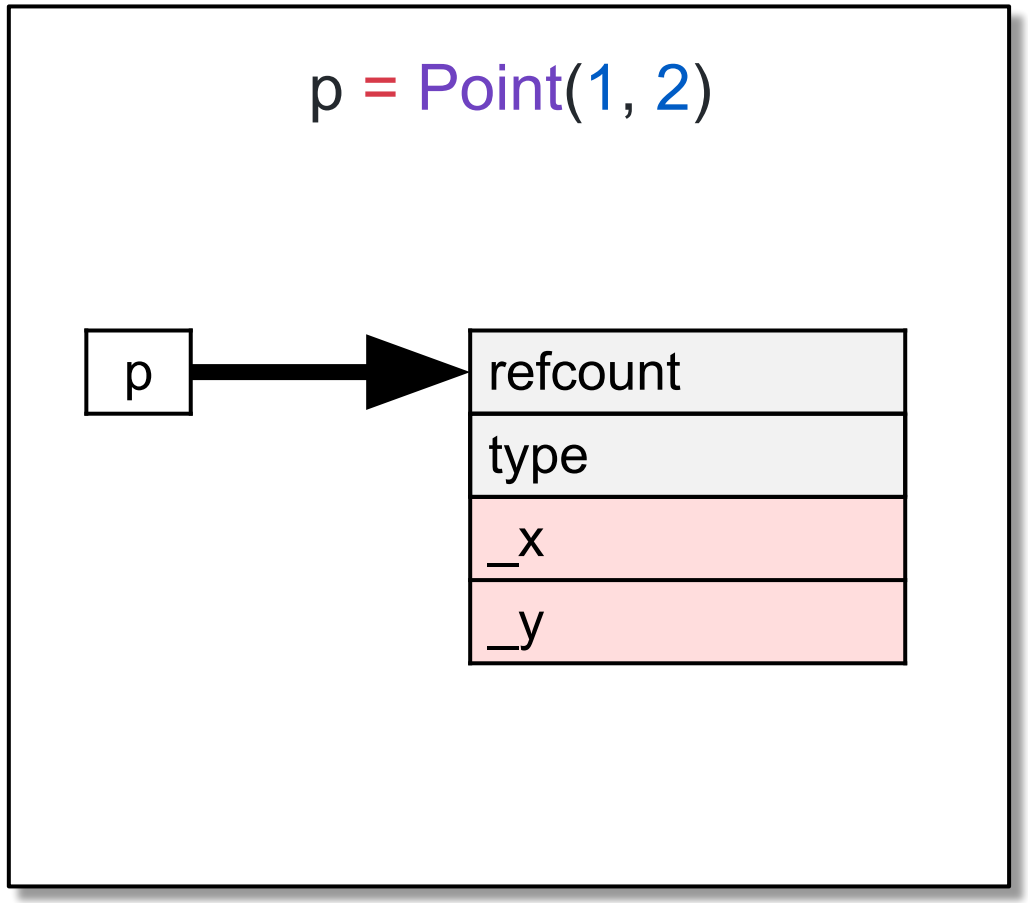


Python **stores extra information** about the type of the object in its memory footprint! This enables runtime type checking.

virtual is kind of like Python

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





Quick check: pros/cons of virtual functions?

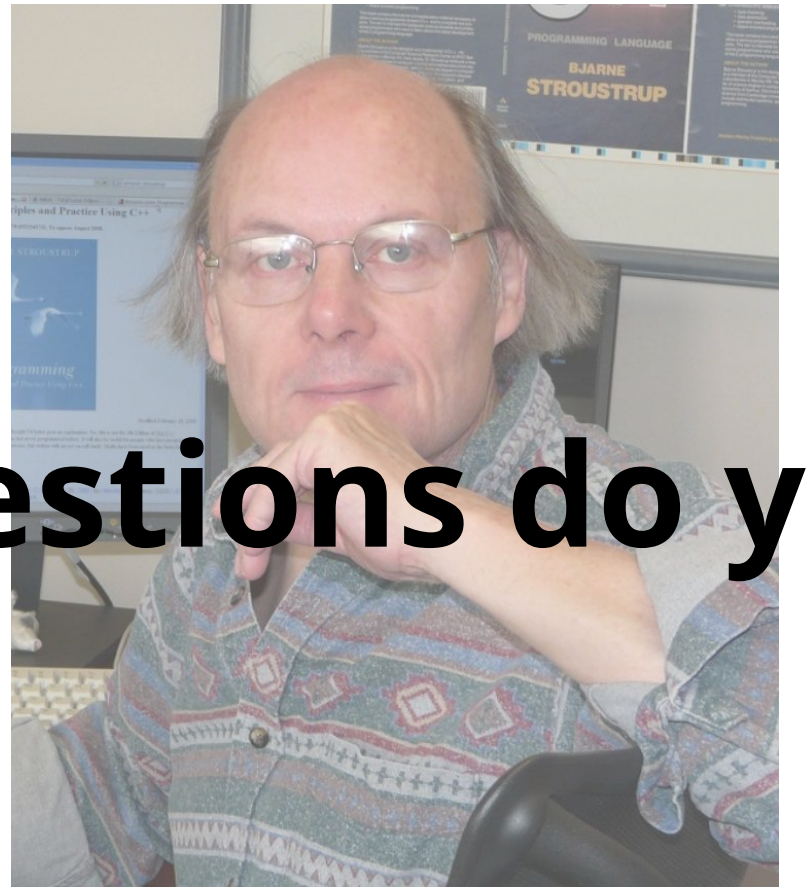
- Turn to a partner and talk about:
  - When might you want to use a virtual function?
  - When might you **not** want to use a virtual function?

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?



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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

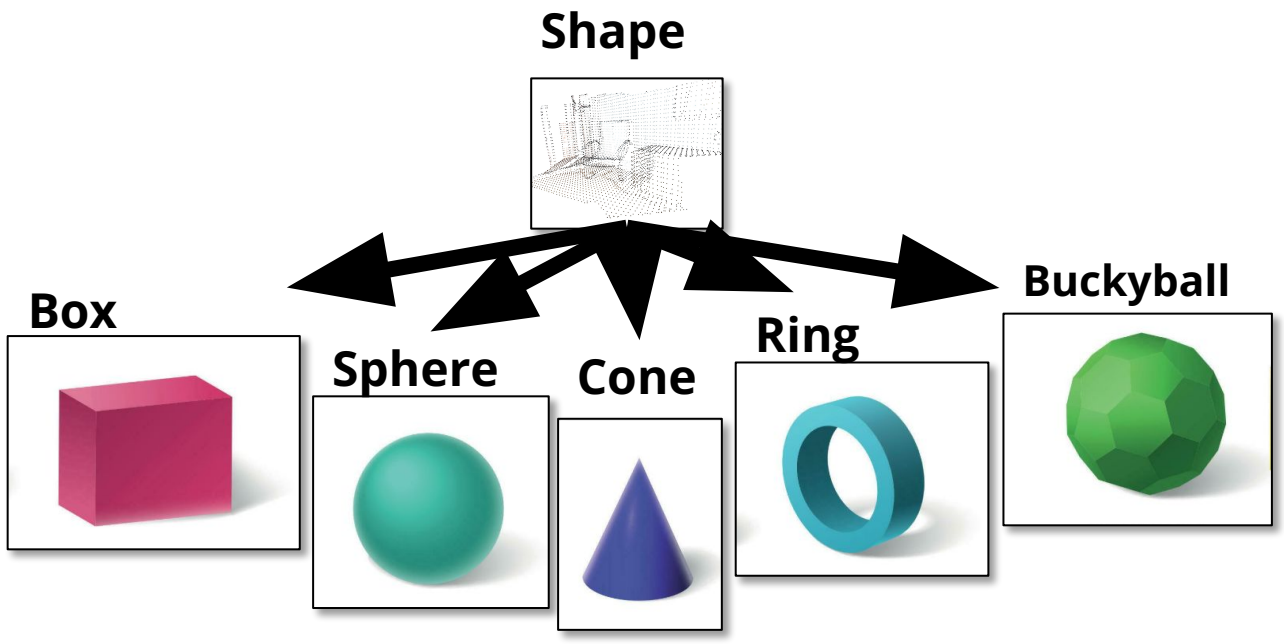
- A class with one or more pure virtual functions is an **abstract** class, it can't be instantiated!
- Overriding all of the pure virtual functions makes the class **concrete**!

```
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

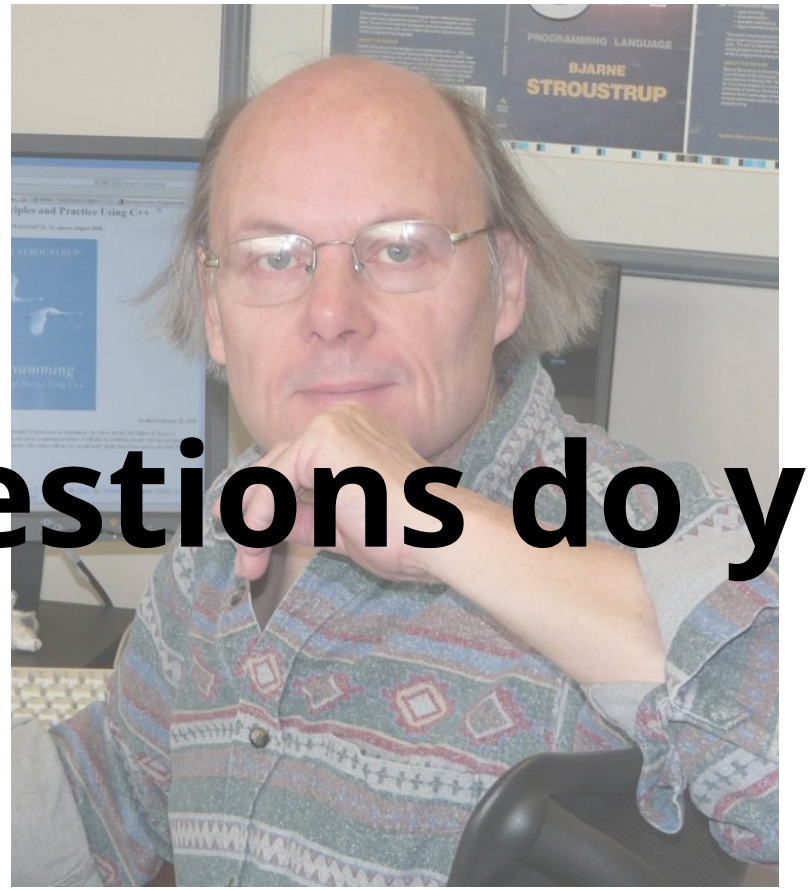
Pure virtual functions are useful when there's **no clear default implementation**!




```
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?



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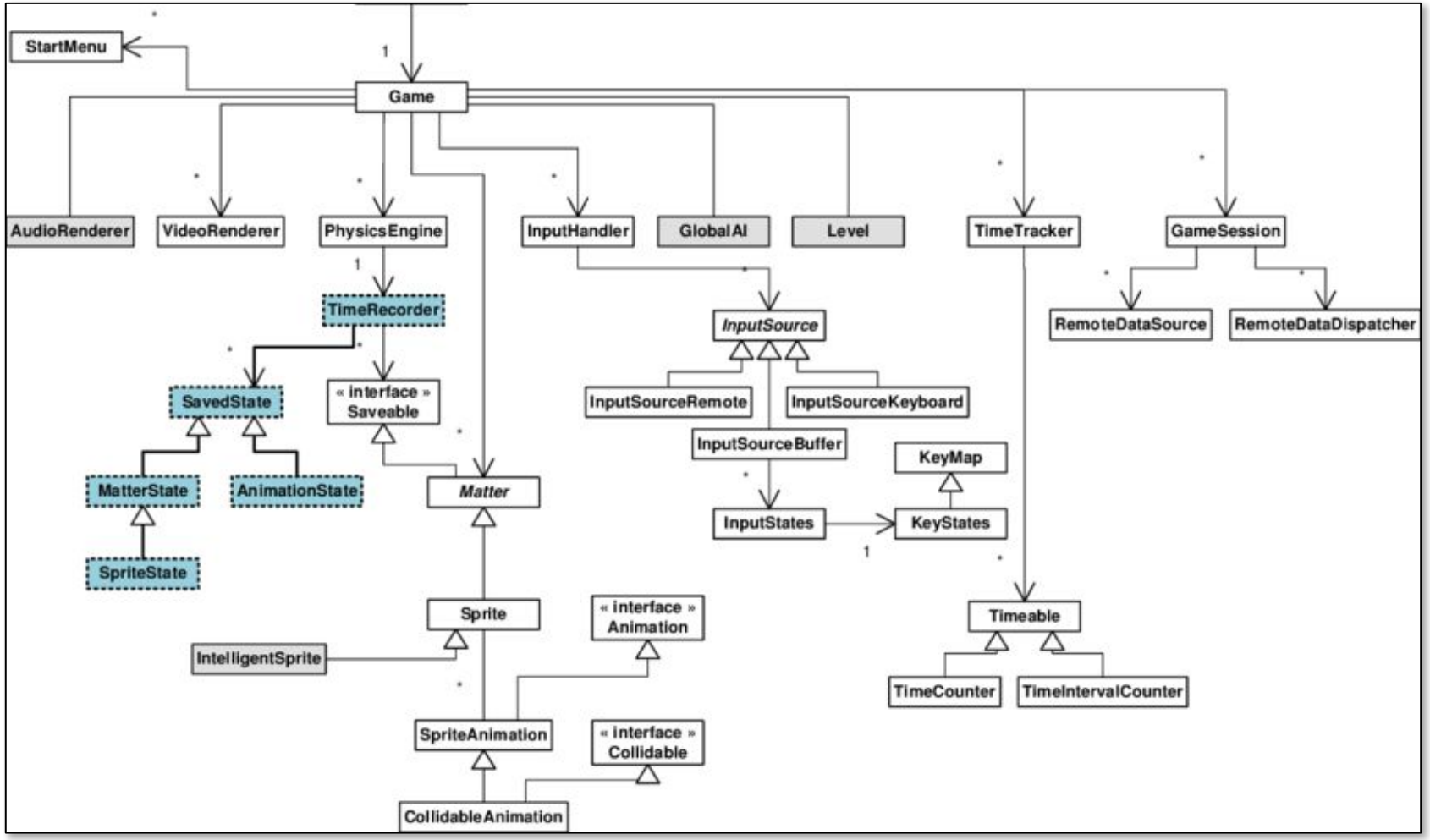
Closing Thoughts

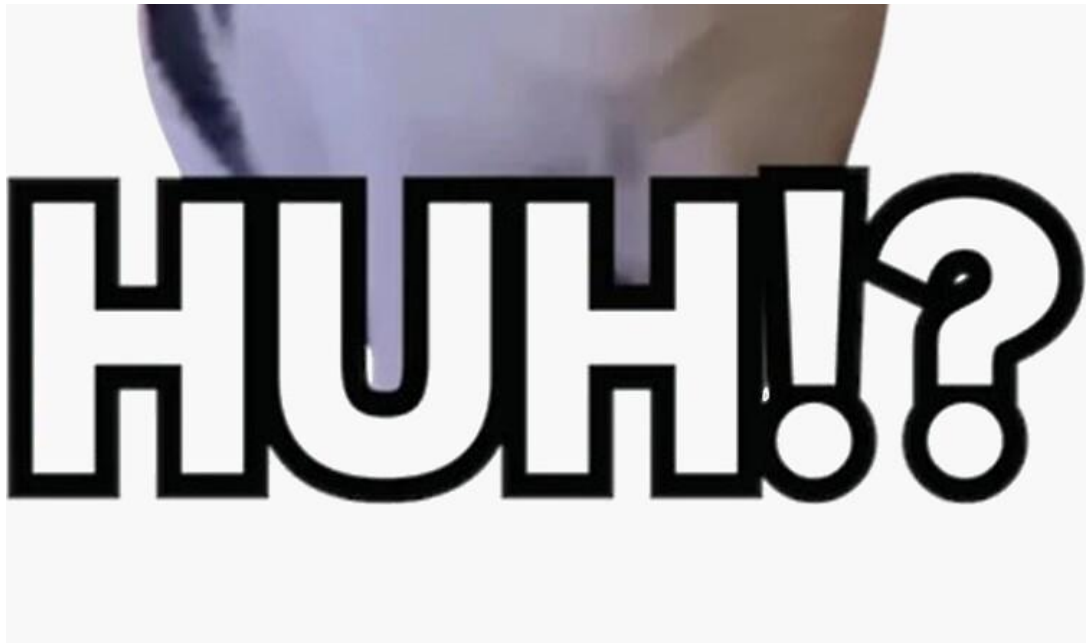
Sometimes inheritance can get out of hand



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”

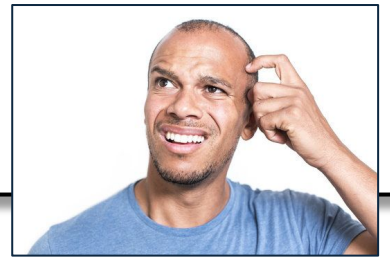


“A car ~~is~~ has an engine”

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

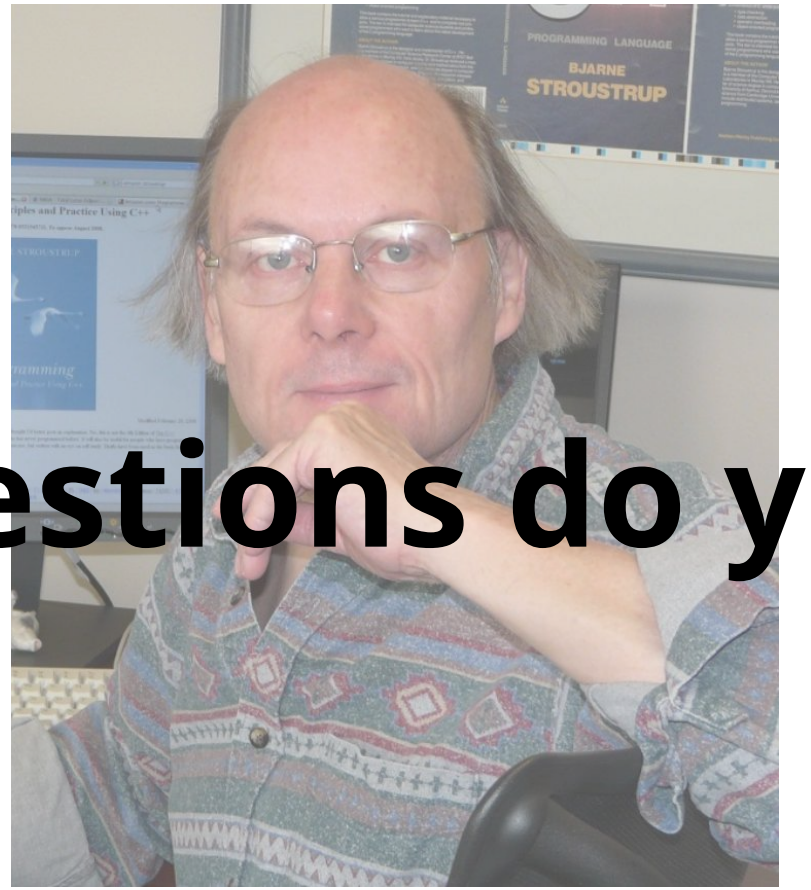
Combining both of these ideas can give the best of both worlds!

```
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?



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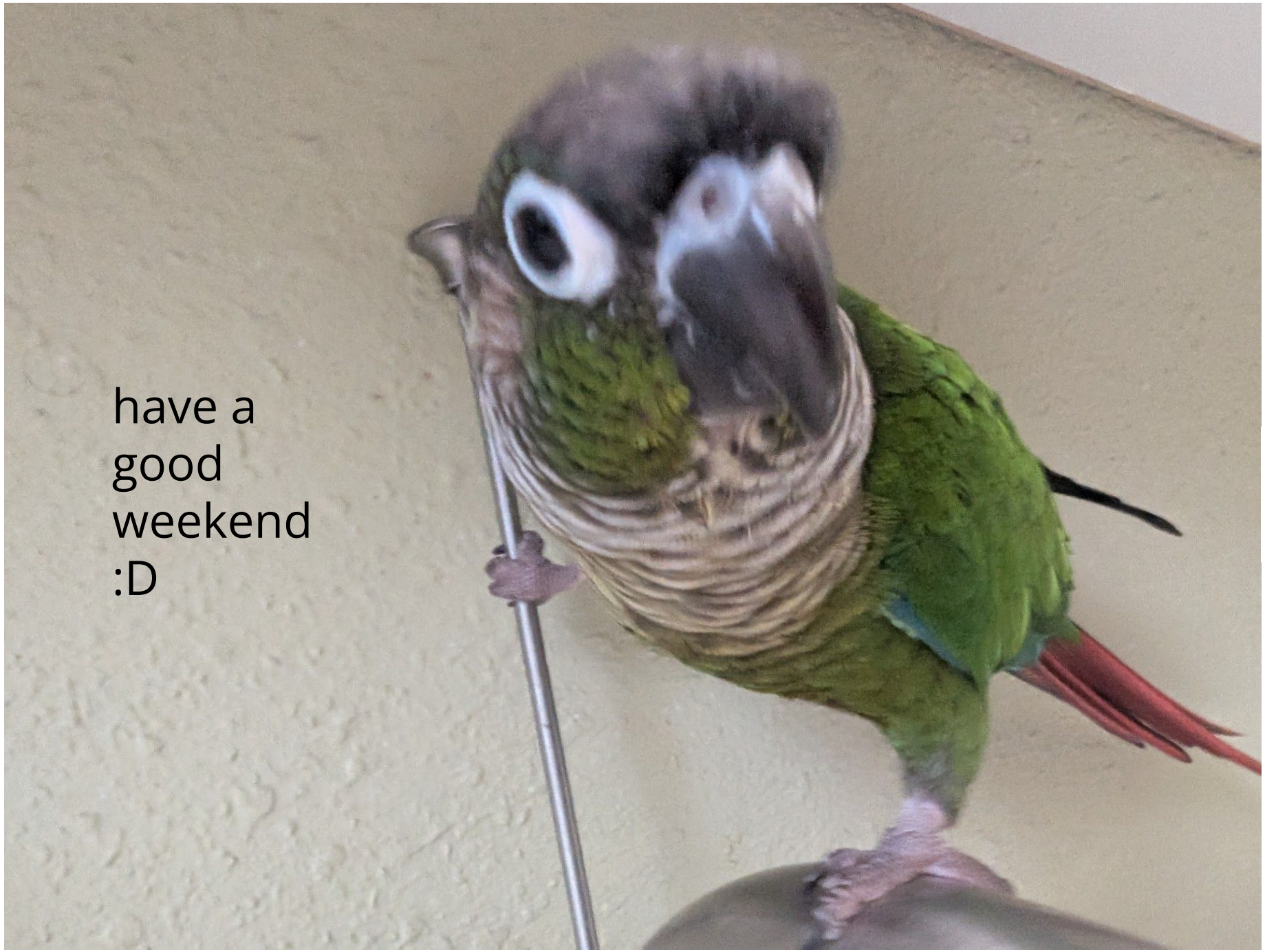
have a
good
weekend
:D