14VIRTUAL

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1 CMakeLists.txt

cmake_minimum_required(VERSION 3.3)
project(lec14 CXX)
include(.cs211/cmake/CMakeLists.txt)

add_program(animals1 src/animals1.cxx)
add_program(animals2 src/animals2.cxx)
add_program(animals3 src/animals3.cxx)

add_test_program(sprite_tree_test
test/mock_sprite_set.cxx)
(* Some examples of parametric polymorphism in OCaml. *)

(* Reverses a list. *)
let reverse xs0 =  
  let rec loop acc xs =  
    match xs with  
    | [] -> acc  
    | x :: xs' -> loop (x :: acc) xs'  
  in loop [] xs0  

(* Inferred type scheme:  
  reverse : 'a list -> 'a list *)

(* Sums a list of ints. *)
let sum xs0 =  
  let rec loop acc = function  
  | [] -> acc  
  | x :: xs -> loop (x + acc) xs  
  in loop 0 xs0  

(* Inferred type scheme:  
  sum : int list -> int *)

(* Sums a list of floats. *)
let sum_float xs0 =  
  let rec loop acc = function  
  | [] -> acc  
  | x :: xs -> loop (x +. acc) xs  
  in loop 0.0 xs0  

(* Inferred type scheme:  
  sum_float : float list -> float *)

(* Reduces a list, left associatively. *)
let foldl (plus, zero, xs0) =  
  let rec loop acc = function  
  | [] -> acc  
  | x :: xs -> loop (plus (x, acc)) xs  
  in loop zero xs0  

(* Inferred type scheme:  
  foldl : ('a, 'b) list -> 'a -> ('a, 'b) list -> 'a -> 'b list -> 'b *)
foldl : ('a * 'b -> 'b) * 'b * 'a list -> 'b *)

(* Reduces a list, left associatively. *)
let foldl_curried plus zero xs0 =
  let rec loop acc = function
    | [] -> acc
    | x :: xs -> loop (plus x acc) xs
  in loop zero xs0

(* Inferred type scheme: *
foldl : ('a -> 'b -> 'b) -> 'b -> 'a list -> 'b *)

(* Sorts a list according to the given binary predicate. *)
let rec merge_sort (<) xs0 =

let split =
  foldl_curried (fun x (xs1, xs2) -> (x :: xs2, xs1)) ([], []) in

let rec merge xs1 xs2 = match xs1, xs2 with
  | x1 :: xs1', x2 :: xs2' ->
    if x1 < x2
      then x1 :: merge xs1' xs2
      else x2 :: merge xs1 xs2'
  | [], _ -> xs2
  | _, [] -> xs1 in

let rec sort xs =
  match xs with
  | [] | [_] -> xs
  | _ ->
    let (xs1, xs2) = split xs in
    merge (sort xs1) (sort xs2) in

sort xs0

(* Inferred type scheme: *
merge_sort : ('a -> 'a -> bool) -> 'a list -> 'a list *)
C++ provides a mechanism for defining families of classes that are similar in some ways and different in others. For example, suppose we want classes to represent different kinds of pet animal, which have operations like sleeping and playing. We can combine their common behavior into a base class and then derive the specific animal classes from that.

Let’s call the base class Animal. We’ll initially define it as follows:

```cpp
class Animal
{
    public:
        Animal(const std::string& name, unsigned int weight);
        void eat(unsigned int amount);
        void play();
        const std::string& get_name() const { return name_; }
        unsigned int get_weight() const { return weight_; }

    private:
        std::string name_;  
        unsigned int weight_; 
};
```

That is, every animal has a name and a weight, and has operations to eat and to play. The implementations of the operations are in animals1.cpp.

We then *derive* other classes from the `Animal` class. Deriving makes the new class like the old class, but then lets us add to or change it. Here’s `Cat`:

```cpp
class Cat : public Animal
{   
```
public:
    Cat(const std::string& name);
    void speak();
};

/*
 * The notation `: public Animal` means that `Cat` starts out as a copy
 * of `Animal`, with all of `Animal`'s public members public in `Cat` as
 * well. We then define a constructor, which takes a name and passes it
 * on to the base class's constructor, along with a fixed weight of 10.
 *
 * `Cat` also has a new member function, `speak`, that `Animal` does not
 * have.
 *
 * We also define `Dog` by deriving from `Animal`, but unlike `Cat`,
 * `Dog`'s playing behavior is a bit more complicated. In particular,
 * each `Dog` has some number of bones, and each time we play the dog
 * gets a new bone. And then when the dog speaks, it says "woof"
 * repeatedly, once for each of its bones. Here's the definition of the
 * `Dog` class:
 */

class Dog : public Animal
{
    public:
        Dog(const std::string& name);
        void speak();
        void play();

    private:
        unsigned int nbones_;
};

/*
 * As you can see, `Dog` adds a member variable `nbones_` to `Animal`,
 * adds a member function `speak`, and replaces the base class's
 * `Animal::play` function with a `Dog`-specific `play` function. The
 * `Dog::play` function delegates to `Animal::play` to do the playing
 * and also increments `nbones_`.
 *
 * Now we can write a program involving cats and dogs. See the bottom of
 * animals1.cpp for main and an introduction to inheritance polymorphism.
 */
// The implementations are here, but the implementations aren't very interesting.

#include "animals1.hxx"
#include <iostream>

Animal::Animal(const std::string& name, unsigned int weight)
    : name_(name), weight_(weight)
{}

void Animal::eat(unsigned int amount)
{
    weight_ += amount;
}

void Animal::play()
{
    std::cout << get_name() << " plays."
}

// The `Cat` constructor passes its the name to the `Animal` constructor along with a starting cat weight.
Cat::Cat(const std::string& name) : Animal(name, 10)
{}

void Cat::speak()
{
    std::cout << get_name() << " says meow!"
}

// The `Dog` constructor has to initialize both the base class `Animal` and its own member `nbones_`.
Dog::Dog(const std::string& name)
    : Animal{name, 50}, nbones_{1}
{}

void Dog::speak()
```cpp
4 src/animals1.cxx

{ std::cout << get_name() << " says";
  for (size_t i = 0; i < nbones_; ++i)
    std::cout << " woof";
  std::cout << "!
";
}

// `Dog`'s `play` behavior is different from the base `Animal`'s.
void Dog::play()
{
  Animal::play();
  ++nbones_;  
}

// Forward declaration, in case we want to call `play_twice` from `main`.
void play_twice(Animal&);

int main()
{
  // My mom has four cats and two dogs.
  Dog willie("Willie");
  Cat vinny("Vinny");
  Cat francie("Francie");

  willie.play();
  vinny.play();
  francie.eat(2);
}

/*
 * An additional feature of inheritance is a form of polymorphism.
 * Polymorphism is when the same variable (or more abstractly, entity)
 * can come in different forms. In this case, the polymorphism is that
 * a reference or pointer whose type says it's of the base class can
 * actually refer to an object of any derived class. Here we have a
 * function that takes an `Animal` reference:
 */

void play_twice(Animal& an)
{
  an.play();
  an.play();
}

/*

7
```
* We can use the reference according to the public interface of *
* `Animal`, but at run time, the actual object the reference points to *
* is allowed to be any derived class of `Animal`:
* *
* `play_twice(willie);`
* `play_twice(vinny);`
* *
* There are two problems with this, however:
* *
* Because we made `speak` different for the two derived classes and
* didn’t include it in the base class, we can’t call it via a base
* class (`Animal`) reference.
* *
* When we call a function on the base class reference, it uses the
* base class version of the function. That is, when we say `an.play()`,
* it uses the `Animal::play` member function rather than `Dog::play`,
* even when `an` is a `Dog`. In particular, the `nbones_` member
* variable won’t be incremented when we call `play_twice` on the `Dog`
* `willie`, even though `Dog::play` increments `nbones_`.
* *
* For the solution to these problems, see animals2.h.
*/

5 src/animals2.hxx

```cpp
#include <string>

///
/// Polymorphism
///

/*
* The solution to the problem at the end of animals2.cpp is a *virtual*
* function. Declaring a function `virtual` in the base class means
* that we expect the derived classes to *override* it, and we want to
* get the overridden derived class behavior, even with working with a
* base class reference. To do this, we change the declaration of
* `Animal::play` to be virtual:
*/

class Animal {
    public:
        Animal(const std::string& name, unsigned int weight);
```
```cpp
void eat(unsigned int amount);
virtual void play(); // <<< CHANGE IS HERE

const std::string& get_name() const { return name_; }
unsigned int get_weight() const { return weight_; }

// When using inheritance, the base class *must* have a virtual
// destructor, even if it doesn’t have to do anything.
virtual ~Animal() { }

private:
    std::string name_;  
    unsigned int weight_; 
};

/*
* The `Cat` class remains the same as before because we want `Cat` to have
* the default `play` behavior inherited from `Animal`.
*/
class Cat : public Animal
{
public:
    Cat(const std::string& name);  
    void speak();
};

/*
* Then in `Dog`, we redefine `play` and indicate that we are overriding
* the base definition of `play`:
*/
class Dog : public Animal
{
public:
    Dog(const std::string& name);  
    void speak();
    void play() override; // <<< OTHER CHANGE IS HERE

private:
    unsigned int nbones_; 
};

/*
* Now when we use a `Dog` object via an `Animal&` reference, it uses
* `Dog::play` rather than `Animal::play`.
*/
```
* This is polymorphic because the `Animal&` does not necessarily refer
  to an `Animal` object, but different kinds of derived classes with
  potentially different behaviors.

* Continue in animals3.h.

/*

6 src/animals2.cxx

// The implementations are here, but the implementations aren't very
// interesting, since they're the same as in animals1.cpp. You probably
// want animals2.h or if you've been there already, animals3.h.

#include "animals2.hxx"
#include <iostream>

Animal::Animal(const std::string& name, unsigned int weight)
  : name_(name), weight_(weight)
{
}

void Animal::eat(unsigned int amount)
{
  weight_ += amount;
}

void Animal::play()
{
  std::cout << get_name() << " plays.\n";
}

Cat::Cat(const std::string& name) : Animal(name, 10)
{
}

void Cat::speak()
{
  std::cout << get_name() << " says meow!\n";
}

Dog::Dog(const std::string& name)
  : Animal{name, 50}
    , nbones_{1}
{
}
void Dog::speak()
{
    std::cout << get_name() << " says";
    for (size_t i = 0; i < nbones_; ++i)
        std::cout << " woof";
    std::cout << "!
";
}

void Dog::play()
{
    Animal::play();
    ++nbones_;  
}

// This function uses inheritance polymorphism, since it takes an `Animal`
// reference that might refer to a derived class of `Animal` such as `Dog` or
// `Cat`. Further, because `Animal::play` is virtual, it will use the derived
// class’s version of `play` if the derived class overrides it.

void play_twice(Animal& an)
{
    an.play();
    an.play();
}

/* We can’t do the same for `speak` because `Animal` doesn’t define a `speak`
* function, so there’s no guarantee that a particular `Animal&` will be from
* a class that defines `speak`.
* */

void speak_twice(Animal& an)
{
    an.speak();
    an.speak();
}

int main()
{
    Dog willie("Willie");
    Cat vinny("Vinny");
    Cat francie("Francie");

    play_twice(willie);
    play_twice(vinny);
```cpp
#include <string>

///
/// Pure virtual functions
///

/*
 * We did not define a `speak` function in the `Animal` class, since
 * that function is different for the derived classes, and so there was
 * no sharing to be had. But this prevents us from calling `speak` on an
 * `Animal&`, even if the object referred to is actually a `Cat` or
 * `Dog`. It has to be this way because there's no guarantee of every
 * derived class of `Animal` will define `speak`. We can fix this by
 * declaring in `Animal` that every derived class of `Animal` must
 * define `speak`. We do this by declaring `speak` to be *pure virtual*.
 */

class Animal
{
public:
    Animal(const std::string& name, unsigned int weight);

    void eat(unsigned int amount);
    virtual void play();
    virtual void speak() = 0; // << NEW LINE HERE

    const std::string& get_name() const { return name_; }
};
```
unsigned int get_weight() const { return weight_; }

// When using inheritance, the base class *must* have a virtual
// destructor, even if it doesn't have to do anything.
virtual ~Animal() { }

private:
  std::string name_;  // << ADDED override HERE
  unsigned int weight_;  // << ADDED override HERE
};

/*
 * Class `Cat` inherits from abstract class `Animal`. In order for `Cat` to
 * be a concrete class (in order to create instances of `Cat`), it has to
 * override `Animal`'s pure virtual function `speak`:
 */
class Cat : public Animal
{
  public:
    Cat(const std::string& name);
    void speak() override;  // << ADDED override HERE
  }

  /*
   * Class `Dog` also has to override `speak` in order to be concrete.
   */
class Dog : public Animal
{
  public:
    Dog(const std::string& name);
    void speak() override;  // << ADDED override HERE
    void play() override;

  private:
    unsigned int nbones_;  // << ADDED override HERE
  }

  /*
   * The function definitions in animals3.cpp remain unchanged. However, see
   * the end of animals3.cpp for how to store `Animal`'s in a collection.
   */
```cpp
#include "animals3.hxx"

#include <iostream>
#include <memory>
#include <vector>

Animal::Animal(const std::string& name, unsigned int weight) : name_(name), weight_(weight)
{
}

void Animal::eat(unsigned int amount)
{
    weight_ += amount;
}

void Animal::play()
{
    std::cout << get_name() << " plays."
}

Cat::Cat(const std::string& name) : Animal(name, 10)
{
}

void Cat::speak()
{
    std::cout << get_name() << " says meow!"
}

Dog::Dog(const std::string& name)
    : Animal{name, 50}, nbones_{1}
{
}

void Dog::speak()
{
    std::cout << get_name() << " says";
    for (size_t i = 0; i < nbones_; ++i)
        std::cout << " woof";
    std::cout << "!
"
}

void Dog::play()
```
8 src/animals3.cxx

```cpp
43 {
44   Animal::play();
45   ++nbones_; 
46 }
47
void play_twice(Animal& an)
48 {
49   an.play();
50   an.play();
51 }
52
/*
4/* In C++, inheritance polymorphism works only through references and
5 * pointers, because base classes and derived classes may have different
6 * sizes. That is, you cannot have an `Animal` variable that actual contains
7 * a `Cat` or `Dog` objects. (Actually, because `Animal` is abstract now, you
8 * cannot have `Animal` variable at all.) However, you can have an `Animal&`
9 * that actually refers to a `Dog` or a `Cat`, and similarly for pointer types.
*/
10
11 using animal_ptr = std::shared_ptr<Animal>;
12 using Animal_vec = std::vector<animal_ptr>;
13
Animal_vec get_animals()
14 {
15   Animal_vec animals;
16   animals.push_back(std::make_shared<Dog>("Willie"));
17   animals.push_back(std::make_shared<Cat>("Vinny"));
18   animals.push_back(std::make_shared<Cat>("Francie"));
19   return animals;
20 }
21
/*
22 * We can `push_back` a `shared_ptr<Cat>` into a vector of
23 * `shared_ptr<Animal>` because `shared_ptr` is specially designed to work
24 * with inheritance. If we have a vector of shared pointers to `Animal`'s, we
25 * can use the pointers, even though we don't know what kind of `Animal` each
26 * pointer points to.
*/
```
```cpp
void example1()
{
    Animal_vec animals = get_animals();
    for (animal_ptr an : animals) an->speak();
    for (animal_ptr an : animals) play_twice(*an);
    for (animal_ptr an : animals) an->speak();
}

/*/ 
* It's possible to convert in the other direction, from a shared pointer to 
* a base class into a shared pointer to a derived class, but the conversion 
* is partial, because it can only happen if the pointer actually is pointing 
* to the desired derived class. Below, we show how to attempt to convert a 
* `shared_ptr<Animal>` into a `shared_ptr<Cat>` using 
* `std::dynamic_pointer_cast`. The cast returns `nullptr` if the shared 
* pointer doesn't actually point to a `Cat`.
*/

void feed_only_cats(const Animal_vec& animals, unsigned int amount)
{
    std::cout << "Feeding " << amount << " to each cat.\n";
    for (animal_ptr an : animals) {
        std::shared_ptr<Cat> cat = std::dynamic_pointer_cast<Cat>(an);
        if (cat != nullptr) cat->eat(amount);
    }
}

void census(const Animal_vec& animals)
{
    for (animal_ptr an : animals)
        std::cout << an->get_name() << " weighs " << an->get_weight() << " .\n";
}

void example2()
{
    Animal_vec animals = get_animals();
    census(animals);
    feed_only_cats(animals, 1);
    census(animals);
}

int main()
```
```cpp
namespace widget
{
namespace detail
{
struct ISprite_set
{
    virtual void add_sprite(ge211::Sprite const&,
                            ge211::Position,
                            int,
                            ge211::Transform) = 0;
};

class Sprite_set_adapter : ISprite_set
{
    ge211::Sprite_set& base_
;

public:
    explicit Sprite_set_adapter(ge211::Sprite_set& base)
        : base_(base)
    {
    }

private:
    void add_sprite(ge211::Sprite const&,
                    ge211::Position,
                    int z,
                    ge211::Transform) override;
};
```
struct Sprite_tree_link
{
    virtual int do_draw(ISprite_set&, int z) = 0;
    virtual ~Sprite_tree_link() = default;
};

class Sprite_tree : private Sprite_tree_link
{
public:
    Sprite_tree&
    add_branch(Sprite_tree&& branch,
               int z = 0) &;

    Sprite_tree&
    add_leaf(ge211::Sprite const&,
             ge211::Position,
             int z = 0,
             ge211::Transform const& = ge211::Transform()) &;

    Sprite_tree&&
    add_branch(Sprite_tree&& branch,
               int z = 0) &&;

    Sprite_tree&&
    add_leaf(ge211::Sprite const&,
             ge211::Position,
             int z = 0,
             ge211::Transform const& = ge211::Transform()) &&;

    int draw(ISprite_set&, int);

protected:
    int do_draw(ISprite_set&, int) override;

private:
    std::multimap<int, std::unique_ptr<Sprite_tree_link>>
        children_;
#include "Sprite_tree.hxx"
#include <limits>

using namespace ge211;

namespace widget
{
    namespace detail
    {

        struct Sprite_tree_leaf : Sprite_tree_link
        {
            Sprite_tree_leaf(Sprite const& sprite,
                             Position pos,
                             Transform const& transform);

            int do_draw(ISprite_set&, int) override;

            Sprite const& sprite_; // Sprite
            Position     pos_;     // Position
            Transform    transform_; // Transform
        };

        void Sprite_set_adapter::add_sprite(ge211::Sprite const& sprite,
                                             ge211::Position pos,
                                             int           z,
                                             ge211::Transform transform)
        {
            base_.add_sprite(sprite, pos, z, transform);
        }

        Sprite_tree&
        Sprite_tree::add_branch(Sprite_tree&& branch, int z) &
        {
            std::unique_ptr<Sprite_tree_link>
            new_node(new Sprite_tree(std::move(branch)));
            children_.insert({z, std::move(new_node)}); // Insert TreeNode
            return *this;
        }

    }
}

Sprite_tree&
10 src/Sprite_tree.cxx

Sprite_tree::add_leaf(Sprite const& sprite,
            Position pos,
            int z,
            Transform const& transform) &
{
    std::unique_ptr<Sprite_tree_link>
    new_node(new Sprite_tree_leaf(sprite, pos, transform));
    children_.emplace(z, std::move(new_node));
    return *this;
}

Sprite_tree&& Sprite_tree::add_branch(Sprite_tree&& branch, int z) &&
{
    ((Sprite_tree*)(this))->add_branch(std::move(branch), z);
    return std::move(*this);
}

Sprite_tree&& Sprite_tree::add_leaf(ge211::Sprite const& sprite,
            ge211::Position xy, int z,
            ge211::Transform const& transform) &&
{
    ((Sprite_tree*)(this))->add_leaf(sprite, xy, z, transform);
    return std::move(*this);
}

int Sprite_tree::do_draw(ISprite_set& set, int z)
{
    if (children_.empty())
        return z;
    int max_z = z;
    int previous = children_.begin()->first;
    for (auto const& child : children_) {
        if (child.first != previous) {
            z = max_z + 1;
            previous = child.first;
        }
        max_z = std::max(max_z, child.second->do_draw(set, z));
    }
    return max_z;
Sprite_tree_leaf::Sprite_tree_leaf(
    Sprite const& sprite,
    Position pos,
    Transform const& transform)
    : sprite_(sprite)
        , pos_(pos)
        , transform_(transform)
{ }

int Sprite_tree_leaf::do_draw(ISprite_set& set, int z)
{
    set.add_sprite(sprite_, pos_, z, transform_);
    return z;
}

int Sprite_tree::draw(ISprite_set& set, int z)
{
    return do_draw(set, z);
}

} // end namespace detail

} // end namespace widget

#include "Sprite_tree.hxx"

#include <vector>
#include <initializer_list>
#include <iostream>

struct Pos_sprite
{
    ge211::Sprite const& sprite;
    ge211::Position xy;
    int z;
};

struct Mock_sprite_set : widget::detail::ISprite_set
{
    Mock_sprite_set() = default;
    Mock_sprite_set(std::initializer_list<Pos_sprite>);
12 test/mock_sprite_set.cxx

    std::vector<Pos_sprite> sprites;
    
    void add_sprite(ge211::Sprite const&,
                    ge211::Position, int, ge211::Transform) override;
    
bool operator==(Pos_sprite const& a, Pos_sprite const& b);
bool operator==(Mock_sprite_set const& a, Mock_sprite_set const& b);

std::ostream& operator<<(std::ostream&, Pos_sprite const&);
std::ostream& operator<<(std::ostream&, Mock_sprite_set const&);

12 test/mock_sprite_set.cxx

#include "mock_sprite_set.hxx"

bool operator==(Pos_sprite const& a, Pos_sprite const& b)
{
    return &a.sprite == &b.sprite &&
           a.xy == b.xy &&
           a.z == b.z;
}

std::ostream& operator<<(std::ostream& os, Pos_sprite const& ps)
{
    return os
           << "Pos_sprite{" << &ps.sprite << " @ (" << ps.xy.x << ", " << ps.xy.y << ", " << ps.z << "}";
}

Mock_sprite_set::Mock_sprite_set(std::initializer_list<Pos_sprite> elts)
{
    std::move(elts.begin(), elts.end(), std::back_inserter(sprites));
}

void Mock_sprite_set::add_sprite(ge211::Sprite const& sprite,
                                 ge211::Position xy, int z, ge211::Transform)
{
    sprites.push_back(Pos_sprite{sprite, xy, z});
}

bool operator==(Mock_sprite_set const& a, Mock_sprite_set const& b)


```cpp
30
31
32
33
34
35
36
37
38
39
40
41
```

```
13 test/sprite_tree_test.cxx

```cpp
#include "Sprite_tree.hxx"
#include "mock_sprite_set.hxx"

#include <catch.hxx>

using namespace ge211;
using namespace widget::detail;

TEST_CASE("Sprite_tree::draw")
{
    Circle_sprite sprite1(5);
    Rectangle_sprite sprite2({10, 15});
    Sprite_tree tree;

    tree.add_leaf(sprite1, {0, 0}, 0);
    tree.add_leaf(sprite2, {10, 0}, 0);

    Sprite_tree child1;
    child1.add_leaf(sprite1, {0, 5}, -6);
    child1.add_leaf(sprite2, {10, 5}, -4);
    tree.add_branch(std::move(child1), 1);

    tree.add_leaf(sprite1, {0, 15}, 0);

    Mock_sprite_set set;
    CHECK( tree.draw(set, 5) == 7 );
    CHECK( set == Mock_sprite_set{

```
{sprite1, {0, 0}, 5},
{sprite2, {10, 0}, 5},
{sprite1, {0, 15}, 5},
{sprite1, {0, 5}, 6},
    {sprite2, {10, 5}, 7},
   });
}

TEST_CASE("fluent")
{
    Circle_sprite sprite0(5);

    auto tree = Sprite_tree()
        .add_leaf(sprite0, {0, 0}, 8)
        .add_leaf(sprite0, {1, 0}, 7)
        .add_branch(Sprite_tree()
            .add_leaf(sprite0, {2, 0}, 6)
            .add_leaf(sprite0, {3, 0}, 5),
        4)
        .add_leaf(sprite0, {4, 0}, 3);

    Mock_sprite_set set;
    CHECK( tree.draw(set, 0) == 4 );
    CHECK( set == Mock_sprite_set{
        {sprite0, {4, 0}, 0},
        {sprite0, {3, 0}, 1},
        {sprite0, {2, 0}, 2},
        {sprite0, {1, 0}, 3},
        {sprite0, {0, 0}, 4},
    } );
}