Lecture 13
Generics and STL

CS211 – Fundamentals of Computer Programming II

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Administrivia

- Homework 4 due tonight
  - Remember you need to write tests for you code AND play your game
  - Both parts are important
- Exercise 6 is available
  - Last one. Not too long
- Homework 5 should be released tonight
- Project details will be released in next few days
  - First part will be proposing a project idea

Today's Goals

- Explore an Access Control example

- Introduce concept of generic functions/classes
  - How they are made
  - How we used them

- Discuss major use case for generics
  - C++ Standard Template Library

- Understand how iterators allow generic traversal of a container

Getting the code for today

- Download code in a zip file from here:
  https://nu-cs211.github.io/cs211-files/lec/13_generics_stl.zip

- Extract code wherever

- Open with CLion
  - Make sure you open the folder with the CMakeLists.txt
  - Details on CLion in Lab05

Outline

- **Encapsulation Example**
- Generics
- Standard Template Library
- Homework 5 Overview
- Iterators

Encapsulation

- Goal: protect the rules of your data so it remains consistent

- Policy:
  1. Make the data `private`

  2. Add `public` member functions to let clients do useful things

  3. Don't add public member functions that let clients do bad things (like break the rules of the data)

Live coding: update `String_Holder` access control

string_holder.cxx
string_holder-access.cxx

- Data members should be private
  - Convention: private members end with "_"
- Functions should be public
  - And functions should never allow the rules to be broken

Encapsulation cuts off direct access to data members

- Problem: functions outside of the class can never access data members, even to just read from them

- Options:
    1. Include the function as a member function instead
    2. Add “getters” for data variables, example: `String_Holder::size()`
    3. Declare function as a `friend`

Allowing specific things access to private members

- `friend` keyword declares another thing that can access private members from this class

- Example overloaded operator! `operator<<()`
  - Needs to access the private members of String_Holder
  - Inside the `String_Holder` class definition, add:

```
friend std::ostream& operator<<(std::ostream&, const String_Holder&);
```

Welcome to Encapsulation

- Software engineering principle:
  1. Bundle your data and operations together
  2. Don’t let non-bundled operations mess with your bundled data

- Benefits
  - Correctness
    - Data will never become inconsistent
  - Flexibility
    - Implementation details can change without modifying the API

- Warning: does NOT improve security
  - Data can still be accessed, just not by accident

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Overloading functions to support multiple types

- Suppose you want a function that can compare any two things
  - Implement for `int` and implement for `float`

```
// returns 0 if equal, 1 if value1 is bigger, -1 otherwise
int compare(const int& value1, const int& value2) {
  if (value1 < value2){ return -1;}
  if (value2 < value1){ return  1;}
  return 0;
}

// returns 0 if equal, 1 if value1 is bigger, -1 otherwise
int compare(const float& value1, const float& value2) {
  if (value1 < value2){ return -1;}
  if (value2 < value1){ return  1;}
  return 0;
}
```

We want to avoid duplicated code

- The two implementations of `compare()` are nearly identical
  - Seems wasteful

- What if we want to extend `compare()` for other things?
  - `char`, `short`, `long`, `string`, `Position`, `String_Holder`, etc.
  - Impossible to get everything…

“Generic” version of the function

```
// returns 0 if equal, 1 if value1 is bigger, -1 otherwise
int compare(const ???& value1, const ???& value2) {
  if (value1 < value2){ return -1;}
  if (value2 < value1){ return  1;}
  return 0;
}
```

- What we would prefer is one “generic” version of the function
  - Code will be independent of what the real type is
  - One implementation works for everything!
    - Condition here: must implement `operator<()`

C++ Generics

- C++ implements generics through a concept called "templates"

- A template is a function or class that accepts a type as a parameter
  - You write the function code once in a type-agnostic way
  - When you invoke the function or instantiate the class, you specify the type as an argument to it

- At compile time, the compiler will generate the "specialized" code from your template that uses the type provided
  - The template definition is NOT runnable code
  - The compiler creates runnable code given a concrete type
    - A little like macro substitution

Generic functions

- Template to `compare()` any two things

```
// returns 0 if equal, 1 if value1 is bigger, -1 otherwise
template <typename T>   // <...> can also be written <class T>
int compare(const T& value1, const T& value2) {
  if (value1 < value2) return -1;
  if (value2 < value1) return  1;
  return 0;
}
```

Generic functions

- Template to `compare()` any two things

```
// returns 0 if equal, 1 if value1 is bigger, -1 otherwise
template <typename T>    // <...> can also be written <class T>
int compare(const T& value1, const T& value2) {
  if (value1 < value2) return -1;
  if (value2 < value1) return  1;
  return 0;
}
```

- Declares the following function a template
  - The "generic" type is called `T`

Generic functions

- Template to `compare()` any two things

```
// returns 0 if equal, 1 if value1 is bigger, -1 otherwise
template <typename T>   // <...> can also be written <class T>
int compare(const T& value1, const T& value2) {
  if (value1 < value2) return -1;
  if (value2 < value1) return  1;
  return 0;
}
```

- Declares the following function a template
  - The "generic" type is called `T`
- Code inside the template can use `T` like a type

Generic functions

- Template to `compare()` any two things

```
// returns 0 if equal, 1 if value1 is bigger, -1 otherwise
template <typename COMPARE_TYPE>
int compare(const COMPARE_TYPE& value1, const COMPARE_TYPE& value2) {
  if (value1 < value2) return -1;
  if (value2 < value1) return  1;
  return 0;
}
```

- We didn't have to name the type `T`
  - Could name it anything we want
  - Named in all capital letters by convention

Using generic functions

generic_compare.cxx

- Actual type being used goes in angle brackets after function name
  - `compare<COMPARE_TYPE>`

```
int main() {
  std::cout << compare<int>(10, 20) << "\n";
  std::cout << compare<double>(50.5, 50.6) << "\n";
  std::cout << compare<std::string>("hello", "world") << "\n";
  return 0;
}
```

Using generic functions

- The compiler can sometimes guess the correct type for you based on the arguments provided
  - This is known as "type inference"

- Can occasionally lead to unexpected results though…

```
int main() {
  std::cout << compare(10, 20) << "\n";           // OK
  std::cout << compare(50.5, 50.6) << "\n";       // OK
  std::cout << compare("hello", "world") << "\n"; // FAILS!
  return 0;
}
```

Using generic functions

- The compiler can sometimes guess the correct type for you based on the arguments provided
  - This is known as “type inference”

- Can occasionally lead to unexpected results though…
  - Third example below ends up calling `compare<char*>()`

```
int main() {
  std::cout << compare(10, 20) << “\n”;          // OK
  std::cout << compare(50.5, 50.6) << “\n”;      // OK
  std::cout << compare(“hello”, “world”) << “\n”; // FAILS!
  return 0;
}
```

Generic classes

- Templates are most commonly used for classes (similarly structs)

- Entire class definition is templated
  - Template type can be used for any data member or member functions

Example of generic classes

- Let’s create a class called Pair that holds two “things”
  - The things do NOT have to be the same type
  - Like a tuple in python, but limited to two

- Operations
  - Set the value of the first thing
  - Set the value of the second thing
  - Get the value of the first thing
  - Get the value of the second thing
  - Print the pair of things

- Useful for the ability to return two things at once from a function!

Live coding: implement pair

generic_pair-starter.cxx
generic_pair-complete.cxx

- Operations
  - Set the value of the first thing
  - Set the value of the second thing
  - Get the value of the first thing
  - Get the value of the second thing
  - Print the pair of things

- Real Pair implementation available in the C++ <utility> library
  - https://www.cplusplus.com/reference/utility/pair/pair/

Dangers of templates

generic_pair_compare.cxx

- Doing tricky things with compilers results in tricky errors
- Compiler error when you misuse a generic function (usually unintentionally!) can get really bad
  - Example: try calling `compare()` with something invalid

- Working with templates in general gets complicated and messy
- Need to implement all template code inside headers
  - Needs to be imported into each C++ file that uses it so the generated definitions are available

Generics in GE211

- You’ve already been using them!
  - Posn<int>, Posn<float>, Dims<int>, etc.

- You know enough to understand the entire implementation of Posn
  - Take a look at it when you get a chance
  - https://github.com/tov/ge211/blob/2d7d3a1bd762c3b6d6fac791b0da2fc6c2013d3c/include/ge211/geometry.hxx#L264

Break + Question

- What syntax would you use to create a Pair where both the values are a `Posn` object with coordinates of type `int`?

Pair<**???**> pair({0, 0}, {3, 3});

Break + Question

- What syntax would you use to create a Pair where both the values are a `Posn` object with coordinates of type `int`?

Pair<**Posn<int>, Posn<int>**> pair({0, 0}, {3, 3});

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- **Standard Template Library**
- Homework 5 Overview
- Iterators

C++ Standard Library

- Four major pieces

1. The entire C standard library

2. C++ input/output stream library
   - std::cin, std::cout, etc.

3. C++ Standard Template Library (STL)
   - Containers, iterators, algorithms, etc.

4. Miscellaneous other stuff
   - Strings, exceptions, memory allocation, localization

STL Containers

- Standard Template Library
  - Contains various useful functionality created as templates!
  - Apply for any type you want

- A container is an object that stores a collection of other objects
  - Like arrays or linked lists

- We already covered one of these: `std::vector`

STL std::list

- http://www.cplusplus.com/reference/list/list/

- A generic doubly-linked list
  - Next pointers and previous pointers allow movement in either direction

  - Can be more or less efficient than std::vector
    - See CS214

STL std::unordered_map

- https://www.cplusplus.com/reference/unordered_map/unordered_map/

- Generic map from key to value
  - For any type of key and type of value

  - Can store a value by its key
  - Can retrieve a value by its key

  - Works just like a python `dict`

Live coding: unordered_map example

unordered_map_example.cxx

```
int main() {
  std::unordered_map<std::string, int> map;

  map["CS211"] = 176;
  map["CE346"] = 0;
  std::cout << "map at CS211 = "
            << map["CS211"]
            << "\n";

  return 0;
}
```

Other STL containers https://www.cplusplus.com/reference/stl/

- Map
  - Key->Value in sorted order by key
- Set
  - Ordered list of unique elements
- Unordered_set
  - Unique elements in no particular order
- Array
  - Fixed size list of elements (like vector, but not resizable)
- And various others
  - Stack, Queue, etc.

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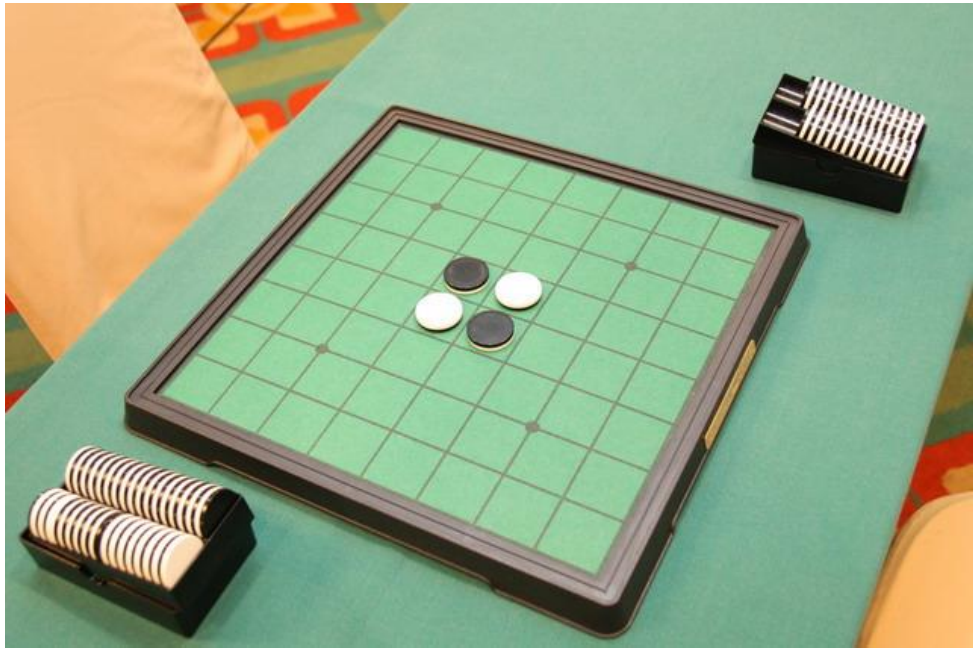
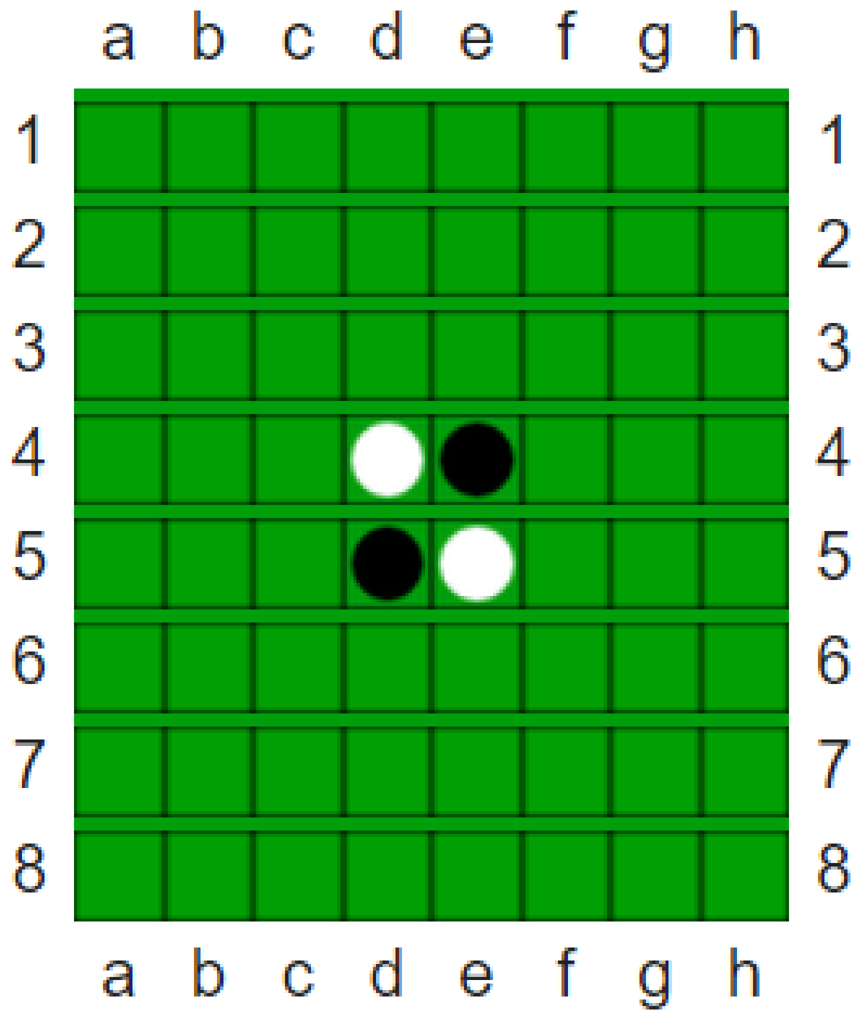
Reversi



- Also known as Othello
- Light player and dark player take turns placing pieces
- A valid placed piece must be in a line with any number of opposing pieces followed by one piece of the current player
  - All opposing pieces in that bounded line are flipped to belong to the current player

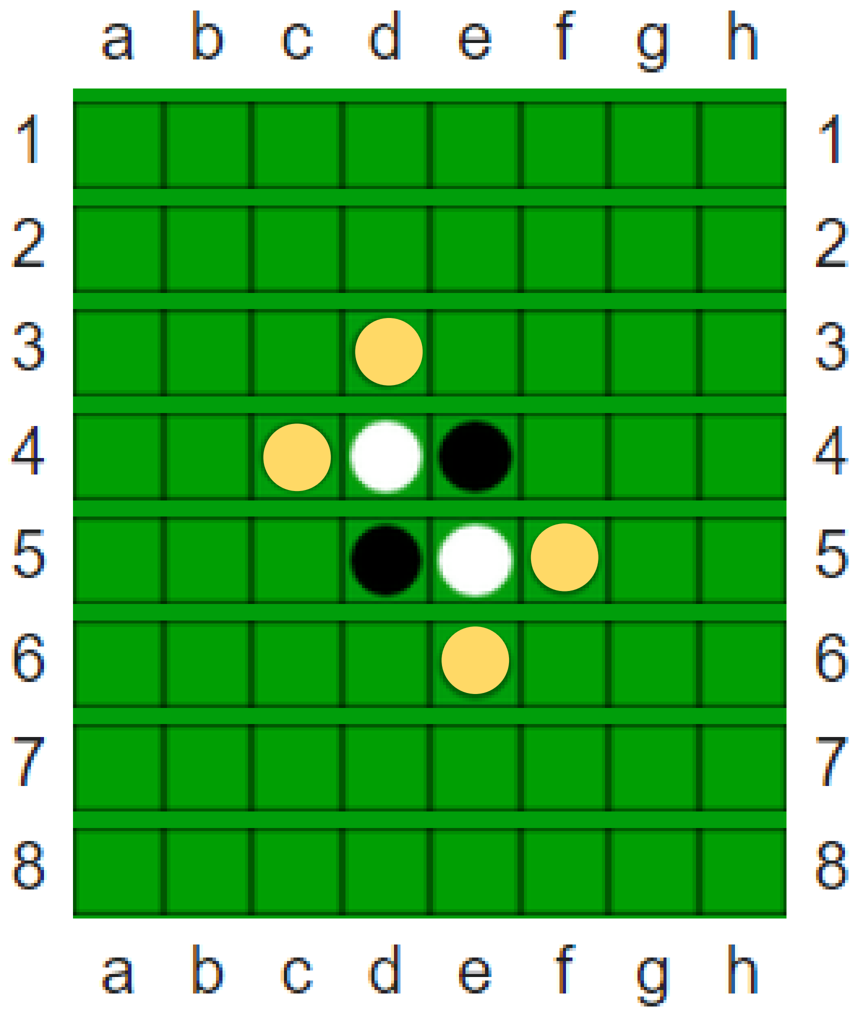
Example move in reversi

- First, must place pieces in the central four squares
  - These don't follow the normal rules



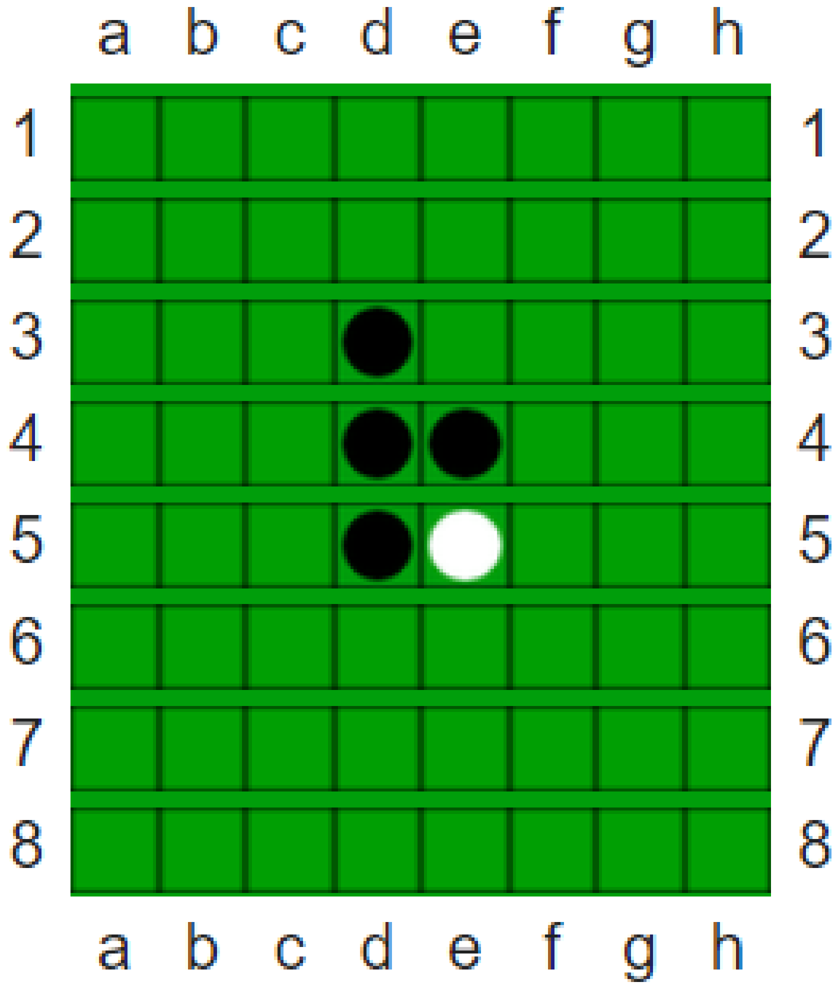
Example move in reversi

- It is the dark player's turn
- They may play in any of the four locations indicated
  - Must form a line with a light piece in the middle



Example move in reversi

- Once the dark player places a piece, all opposing pieces in that line are flipped



Game demo

- https://www.mathsisfun.com/games/reversi.html

- Warning: the game setup rules are slightly different from ours
  - We let players play out the first two moves, which must be in the center

Project layout

- Model, View, Controller
  - Same as with prior homework
  - **View** is responsible for drawing things
  - **Controller** gets inputs from the user
  - **Model** contains the game logic

- Model interacts with several other components
  - Board
  - Player
  - Move
    - Position_set
    - Move_map

Player

- Represents a Player
  - Either in terms who owns a piece
  - Or whose turn it currently is

```
enum class Player {
  dark,
  light,
  neither
};
```

Enums

- Define a new type with a fixed list of possible values

```
enum class Player {
  dark,
  light,
  neither
};
```

  - New type: Player
  - Possible values: Player::dark, Player::light, Player::neither

- Enums are in C as well as many other languages!

Board

- Stores state for the game
  - The board at each `Posn<int>` contains a Player
    - `Player::light`, `Player::dark`, or `Player::neither`
  - Valid positions are the rows/columns on the board
    - An 8x8 board goes from {0,0} to {7,7}
    - We might change the size of the board in tests though
  - Can ask the board which piece is in a certain position
  - Can tell the board to set a piece in a certain position

Move

- A `std::pair` of:
  - A position on the board
  - All pieces that would flip if the current player played in that position
    - Stored as a `Position_set`

- Move_map
  - An `std::unordered_map`
    - Holds Moves

  - Key is a position on the board
  - Value is the corresponding position set for the Move

What do you have to do?

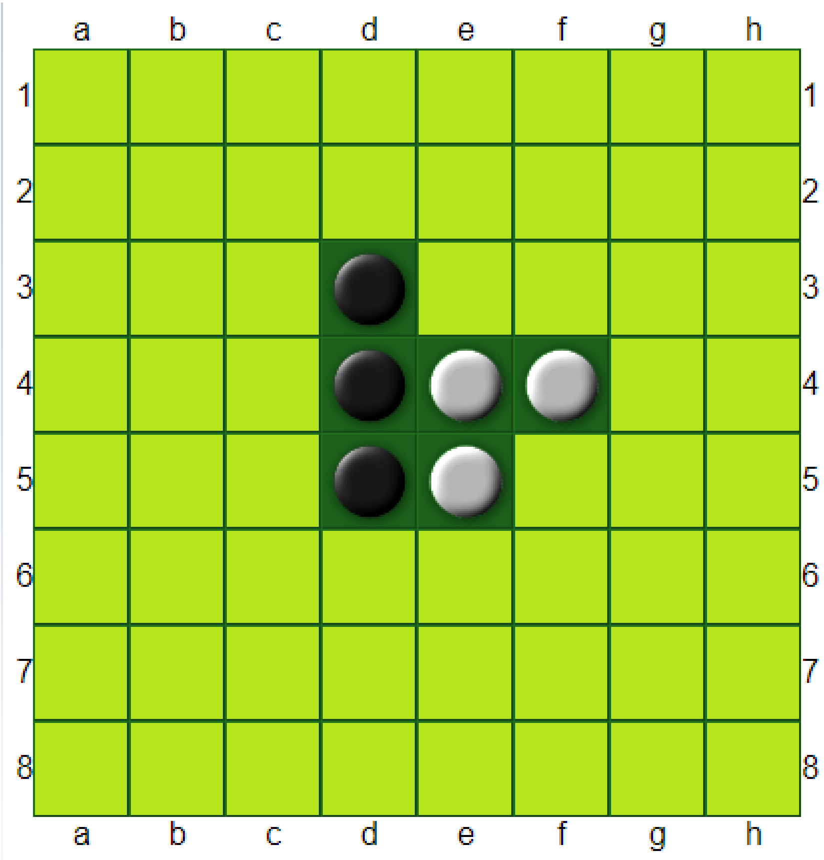
- Interact with a big program with lots of library files you didn't write
  - Board, Move, Player, Position_set
  - You don't need to understand all of the code, but you do need to understand how to use them
    - Look through the .hxx files for them

- Fill the Move_map `next_moves`
  - Contents are each valid Move that the current player could make
  - Need to analyze the board to make that determination

- Eventually, you'll fill in the controller/view too
  - Including hints to the current player about possible places they could play

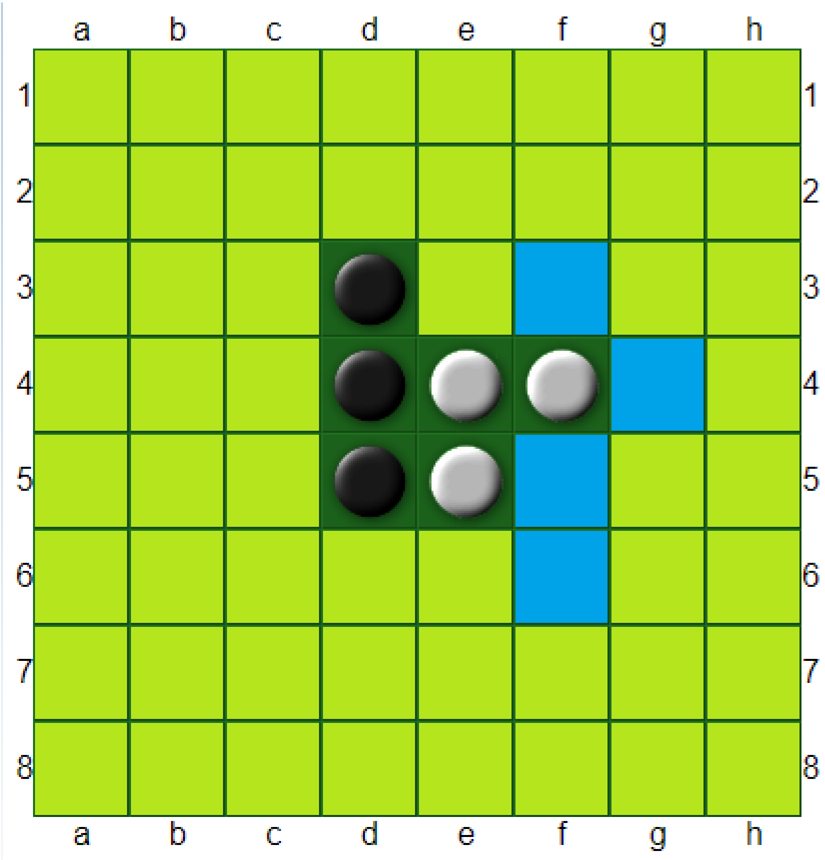
Break + Reversi

- It is Dark's turn. Where may they play?



Break + Reversi

- It is Dark's turn. Where may they play?



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- **Iterators**

How do we make algorithms work on generic containers?

- C++ provides various algorithms in its `<algorithm>` library
    - `find()`, `count()`, `sort()`

- How does it make those work on any container?
    - Algorithm needs to traverse the container. But each container is different

    - Vector:
    ```
    for(i=0; i<vector.size(); i++) {
      vector[i];
    }
    ```

    - List:
    ```
    for(node* curr=head; curr!=NULL; curr=curr->next){
      curr.value;
    }
    ```

Iterators allow generic traversing of containers

- Concept:
  - Create an object that allows you to move through the container
  - Holds a reference to the original object
  - Understands how to move through that specific implementation

- Operations an iterator must support:
  - Construction
  - Getting the value at the current location (* dereference)
  - Moving to the next location in the container (++)
  - Comparison with another iterator (== or !=)
    - Usually get two iterators, start and end, and traverse start until at end

General iterator pattern

```
start_iterator = object.begin();
end_iterator = object.end();

while (start_iterator != end_iterator) {
  value = *start_iterator; // get value
  // do something useful with value
  start_iterator++; // move to next location
}
```

Iterators are modeled after pointers!

iterator_example.cxx

```
int array[5] = {1, 2, 3, 4, 5};

int* start_iterator = &(array[0]);
int* end_iterator = &(array[5]);

while (start_iterator != end_iterator) {
  int value = *start_iterator;
  std::cout << “Value: ” << value << “\n”;
  start_iterator++;
}
```

Same code but for std::vector

iterator_example.cxx

```
std::vector<int> vec{1, 2, 3, 4, 5};

auto start_iterator = vec.begin();
auto end_iterator = vec.end();

while (start_iterator != end_iterator) {
  int value = *start_iterator;
  std::cout << "Value: " << value << "\n";
  start_iterator++;
}
```

`auto` asks the compiler to figure out the type for you

This part didn't have to change at all!

More complicated iterators can support more operations

- Depending on the container, iterators could support many operations

- Forward:
  - construction, equality, increment, get value
- Bidirectional:
  - Everything Forward does, decrement
- Random Access:
  - Everything Bidirectional does, arithmetic, comparison, get value at index

Live coding: use the count algorithm

iterator_example.cxx

- ```
  int count(InputIterator first,
            InputIterator second,
            constT& value)
  ```
  - Counts occurrences of a value in a container
  - Actually returns an `iterator::difference_type`, but we'll ignore that
    - It's just a signed integer in practice

- We can count the number of times a certain value occurs inside a vector or array
  ```

Break + Question

- How would we implement the following code?

```
int array[5] = {1, 1, 1, 2, 2};

// count the number of twos in array
int num_twos = count(???, ???, 2);
```

Break + Question

- How would we implement the following code?
  - Pointers!

```
int array[5] = {1, 1, 1, 2, 2};


// count the number of twos in array
int num_twos = count(&(array[0]), &(array[5]), 2);
```

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