CMPT 373
Software Development Methods

Generic Programming & Templates

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- This should immediately make you think: “Polymorphism”
  - We already called this ***parametric polymorphism***
- In C++, this is done through templates
  - Generics in Java, C#, TypeScript, Swift, Python, …
  - Parameterized types in ML, Haskell, (Python again), …

Variable, Type, & Function Templates

- Several different constructs can be templated…

Variable, Type, & Function Templates

```
template<typename T>
constexpr T PI = T(3.14159265358979323846)
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template<typename T>
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```

```
float radius = ...
float area = PI<float> * radius * radius;
```

Variable, Type, & Function Templates

```
template<typename T>
struct pair {
  pair(const T& first, const T& second)
    : first{first},
      second{second}
      { }

  T first;
  T second;
};
```

Variable, Type, & Function Templates

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struct pair {
  pair(const T& first, const T& second)
    : first{first},
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      { }

  T first;
  T second;
};
```

```
pair<Kitten> kittenPair = {
  Kitten{"Pawsley"}, Kitten{"Steven"}
};
```

Variable, Type, & Function Templates

```
template<typename T>
const T&
min(const T& first, const T& second) {
  if (first < second) {
    return first;
  }
  return second;
};
```

Variable, Type, & Function Templates

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template<typename T>
const T&
min(const T& first, const T& second) {
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```
int smaller = min<int>(1,2);
```

Variable, Type, & Function Templates

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template<typename T>
const T&
min(const T& first, const T& second) {
  if (first < second) {
    return first;
  }
  return second;
};
```

But *something* about this should feel odd!
(Apart from min already existing)

```
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  - Variables
  - Classes
  - Functions

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Variable, Type, & Function Templates

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  - Variables
  - Classes
  - Functions
  - Type aliases (`using`)
  - Member functions
  - All of the above inside another template…

Template Argument Deduction

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```
pair<Kitten> kittens = {
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pair moreKittens = {Kitten{"Lionel"}, Kitten{"J"}};
```

Requires C++17

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- Uses the constructor as a guide for deduction.

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int smaller = min<int>(1,2);
int smaller = min(1,2);
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```
vector from = {0, 1, 2, 3, 4, 5};
vector to   = {0, 0, 0, 0, 0, 0};
copy(from.begin(), from.end(), to.begin());
```

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int smaller = min<int>(1,2);
int smaller = min(1,2);
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```
vector from = {0, 1, 2, 3, 4, 5};
vector to   = {0, 0, 0, 0, 0, 0};
copy(from.begin(), from.end(), to.begin());
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- If types cannot be exactly deduced, they must be given

Parameters: Types, Literals, Templates

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```
tuple<Kitten,Age,Lethality>  kittenRecord = {
  Kitten{"Bitey McBiterson"}, 10, Lethality::TOTAL
};
```

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```
tuple<Kitten,Age,Lethality>  kittenRecord = {
  Kitten{"Bitey McBiterson"}, 10, Lethality::TOTAL
};
auto lethality = std::get<2>(kittenRecord);
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array<Kitten,10> kittens;
kittens[5] = Kitten{"Notadog"};
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```

What do you think the declaration of std::array looks like?

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auto lethality = std::get<2>(kittenRecord);
```

```
array<Kitten,10> kittens;
kittens[5] = Kitten{"Notadog"};
```

```
template<class T, std::size_t N>
struct array {
  T data[N];
};
```

Parameters: Types, Literals, Templates

- Templates may parameterized on more than types!
  - Literals: integers, (function) pointers, references, enums
  - Templates (less common in practice)

```
template<template <class> class CreationPolicy>
struct WidgetLab {
  ...
};
```

Parameters: Types, Literals, Templates

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```
template<template <class> class CreationPolicy>
struct WidgetLab {
  ...
};
```

Suppose WidgetLab uses & creates Widgets.
Why is the CreationPolicy a template?

Parameters: Types, Literals, Templates

- Templates may parameterized on more than types!
  - Literals: integers, (function) pointers, references, enums
  - Templates (less common in practice)
- Thought experiment:
  How do I write a function that takes a lambda?

Pragmatic Usage Issues

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template<class T=std::string,
         class C=std::vector<T>,
         auto size=10>
class SmallRoster { ... };
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template<class T=std::string,
         class C=std::vector<T>,
         auto size=10>
class SmallRoster { ... };

SmallRoster<Kitten> teamKittens;
SmallRoster<> teamStrings;
```

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- Methods (& constructors) can be templated
  - You saw this on the first day!

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- Methods (& constructors) can be templated
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  - You may need to specify explicit templates

```
template<typename T>
void foo() {
  Object<T> foo;
  foo.template someMethod<int>();
}
```

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  - You may need to specify explicit templates
- Some ambiguous nested types must be specified w/ typename

```
T::iterator * p;
typename T::iterator * p;
```

Specialization

- Sometimes you want a type to behave differently for different parameters

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- This is achieved through ***template specialization***
  - Declaring a special variant of a template for known parameters

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- This is achieved through ***template specialization***
  - Declaring a special variant of a template for known parameters

Consider having **`std::hash`**
do the right thing custom types.

Specialization

<functional>

```
namespace std {
  template< class Key >
  struct hash;
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This doesn't implement hashing for custom types.
What if I want to add a **`Cat`** to an **`unordered_set`**?

Specialization

<functional>

```
namespace std {
  template< class Key >
  struct hash;
}
```

<unordered_set>

```
template<
  class Key,
  class Hash = std::hash<Key>,
  class KeyEqual = std::equal_to<Key>,
  class Allocator = std::allocator<Key>
> class unordered_set;
```

This doesn’t implement hashing for custom types.
What if I want to add a `Cat` to an `unordered_set`?

Specialization

<functional>

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namespace std {
  template< class Key >
  struct hash;
}
```

<Cats.h>

```
namespace std {
  template<>
  struct hash<Cat> {
    std::size_t
    operator()(Cat const& s) const noexcept {
      return ...;
    }
  };
}
```

Specialization

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  template<>
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    }
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}
```

```
std::unordered_set<Cat> bigBagOfCats;
```

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struct Fib {
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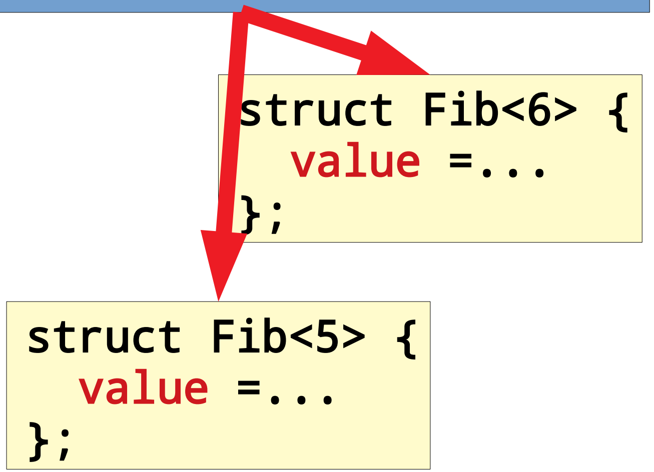

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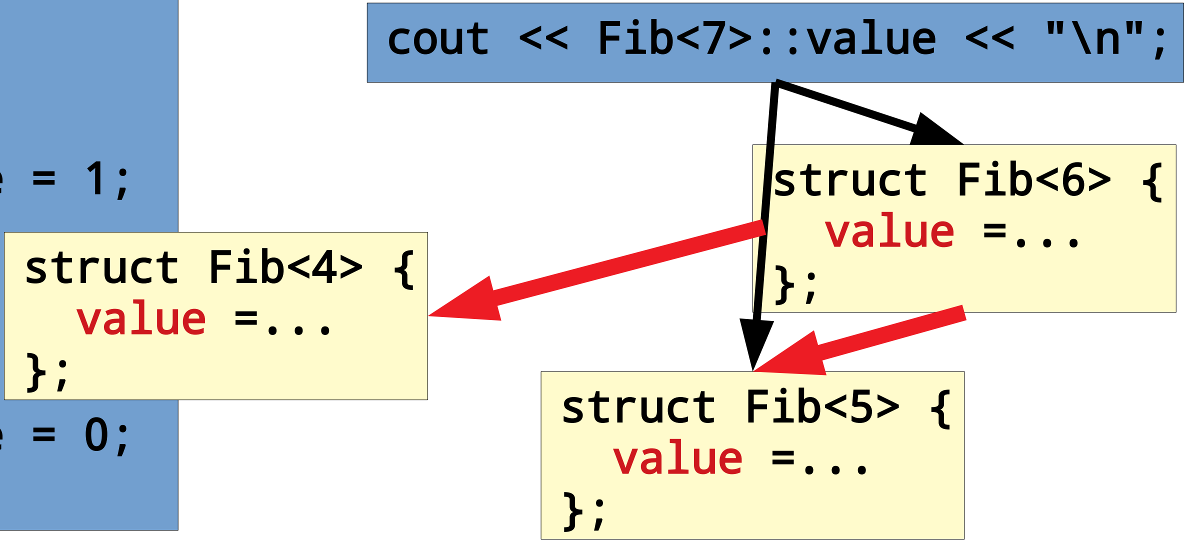

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struct Fib<6> {
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```
struct Fib<5> {
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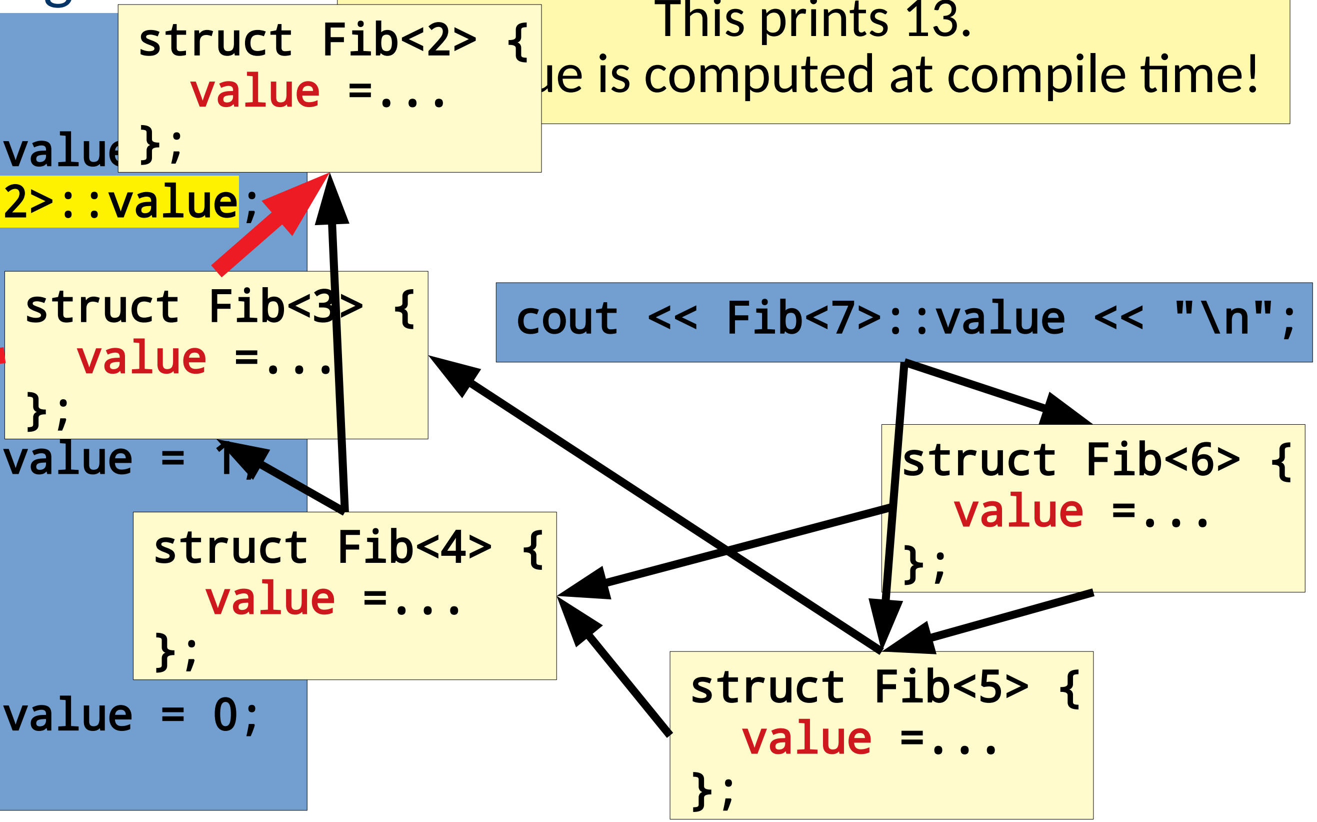

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cout << Fib<7>::value << "\n";
```

`constexpr` functions make this less common.

Specialization

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```
constexpr unsigned
fibonacci(unsigned target) {
  if (target < 2) {
    return target;
  }

  unsigned fib_back_2 = 0;
  unsigned fib_back_1 = 1;
  for (unsigned pos = 2; pos <= target; ++pos) {
    unsigned latest = fib_back_2 + fib_back_1;
    fib_back_2 = fib_back_1;
    fib_back_1 = latest;
  }

  return fib_back_1;
}
```

This prints 13.
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cout << Fib<7>::value << "\n";
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```
constexpr auto result = fibonacci(40);
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`constexpr` functions make this less common.

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Where would you use it?
look up tables, efficient data structures, bare metal, …

Specialization

- Specialization can help build efficient, decoupled interfaces through ***type traits***.

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template<typename GraphKind>
struct GraphTraits {
  static_assert(false, "Not specialized");
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```
template<typename GraphKind>
struct GraphTraits {
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```

```
template<>
struct GraphTraits<SocialNetwork> {
  using NodeRef = ...;
  using ChildIterator = ...;
  NodeRef getEntryNode(SocialNetwork&) {...}
  ChildIterator child_begin(NodeRef&) {...}
  ChildIterator child_end(NodeRef&) {...}
};
```

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- Specialization can help build efficient, decoupled interfaces through ***type traits***.

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```

We can define custom types & behavior related to the type parameter.

Specialization

- Specialization can help build efficient, decoupled interfaces through ***type traits***.

```
template<typename GraphKind>
struct GraphTraits {
  static_assert(false, "Not specialized");
};
```

```
template<>
struct GraphTraits<SocialNetwork> {
...
};
```

```
template<>
struct GraphTraits<RoadMap> {
  using NodeRef = ...;
  using ChildIterator = ...;
  NodeRef getEntryNode(RoadMap&) {...}
  ChildIterator child_begin(NodeRef&) {...}
  ChildIterator child_end(NodeRef&) {...}
};
```

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  ChildIterator child_begin(NodeRef&) {...}
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};
```

```
template<class Kind, class GT=GraphTraits<Kind>>
void
printGraph(const& Kind graph) { ... }

...

  RoadMap roadMap;
  printGraph(roadMap);

  SocialNetwork socialGraph;
  printGraph(socialGraph);
```

Specialization

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  type traits.

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template<typename GraphKind>
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template<class Kind, class GT=GraphTraits<Kind>>
void
printGraph(const& Kind graph) { ... }

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  RoadM
  printGraph(roadMap);

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  printGraph(socialGraph);
```

We can use GT to provide a graph interface to an arbitrary Kind *and write the function only once.*

Specialization

- Specialization can help
  type traits.

```
template<typename GraphKind>
struct GraphTraits {
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```
template<>
struct GraphTraits<SocialN
};
```

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template<>
struct GraphTraits<RoadMap> {
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  NodeRef getEntryNode(RoadMap&) {...}
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};
```

```
template<class Kind, class GT=GraphTraits<Kind>>
void
printGraph(const& Kind graph) { ... }

...

  RoadMap roadMap;
  printGraph(roadMap);

  SocialNetwork socialGraph;
  printGraph(socialGraph);

  printGraph<SocialNetwork,CustomView>(socialGraph
```

And we *can* even customize
how the interface is bound if so desired.

Specialization

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  RoadMap roadMap;
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```

Regardless of the actual graph data structure,
or even its API,
traits allow generic algorithms to work!

Let's see it in action…

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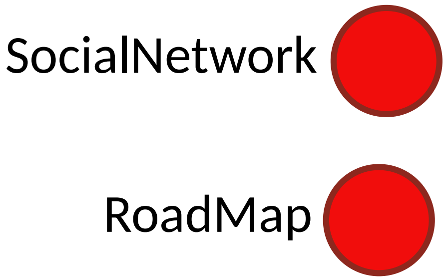

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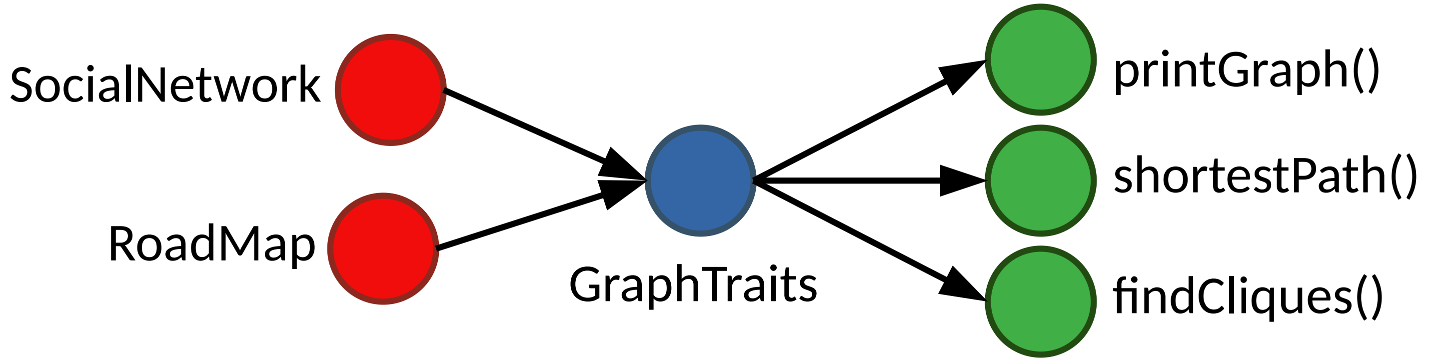

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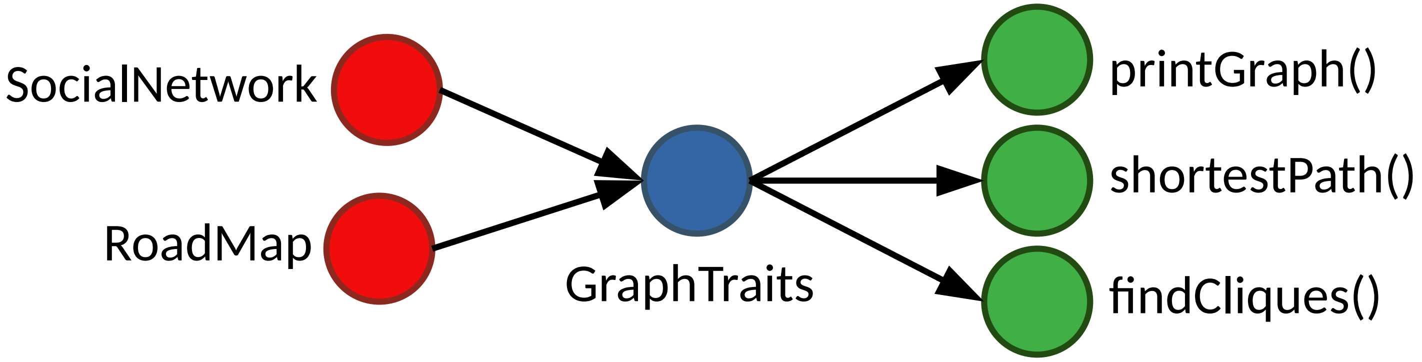

Information & behavior can be added to data types regardless of original APIs

Partial Specialization

- Maybe you do not want to *fully specialize* the type
  - A set of types behave similarly but not all

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```
template<class T=std::string, class C=std::vector<T>, auto size=10>
class SmallRoster { ... };

SmallRoster<Kitten> teamKittens;
SmallRoster<> teamStrings;
```

CRTP

- Sometimes information needs to flow from a derived class to a base class.

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```
template<class T>
class Base {
public:
  void print() { getDerived().printImpl(); }
private:
  T& getDerived() { return *static_cast<T*>(this); }
};
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```
class Specific : public Base<Specific> {
public:
  void printImpl() { printf("Yo\n"); }
};
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  void printImpl() { printf("Yo\n"); }
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```

What other approaches could we have used?
What are the trade offs?

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Flexibility vs Efficiency

Policy Based Design

- All of these tools we’ve seen led to ***policy based design*** in the 2000’s.

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This is essentially dependency injection at the template level!

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template<class T, class Allocator = std::allocator<T>>
class vector;
```

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class vector;
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This addresses the *combinatorial explosion* of hand written types.
We shall see this again in design patterns.

Policy B

- All of t … e 2000's.
  - Ider … nto tem
  - Inve … policies.

```
namespace TF {
class LeakyReluOp
    : public Op<LeakyReluOp,
                OpTrait::OneResult,
                OpTrait::HasNoSideEffect,
                OpTrait::SameOperandsAndResultType,
                OpTrait::OneOperand> {
public:
  static StringRef getOperationName() {
    return "tf.LeakyRelu";
  };
  Value* value() { ... }
  APFloat alpha() const { ... }
  static void build(...) { ... }
  bool verify() const {
    if (...) return emitOpError(
      "requires 32-bit float attribute 'alpha'");
    return false;
  }
};
} // end namespace
```

Lattner, MLIR Primer
Compilers for Machine Learning Workshop, CGO 2019

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  - Invert control so that the user of the algorithm can pass in new policies.
- Originally, policy based design
  - focused on ad hoc, implicit interfaces amongst policies
  - Used multiple inheritance for mixins and flexible policy coordination.
- Lately people have wanted more assurances;
  it can be easy to make an interface *too* flexible.

SFINAE & Correctness

```
void foo(unsigned i) {
  std::cout << "unsigned " << i << "\n";
}

template <typename T>
void foo(const T& t) {
  std::cout << "template " << t << "\n";
}
```

[Eli Bendersky, 2014]

What is printed by `foo(42)`?

SFINAE & Correctness

```
void foo(unsigned i) {
  std::cout << "unsigned " << i << "\n";
}

template <typename T>
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What is printed by `foo(42)`?

`"template 42"`

Why?

SFINAE & Correctness

```
void foo(unsigned i) {
  std::cout << "unsigned " << i << "\n";
}

template <typename T>
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}
```

[Eli Bendersky, 2014]

What is printed by `foo(42)`?

`"template 42"`

Why?

What we want is a way to *bound* where our templates apply…

SFINAE & Correctness

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```
template <typename T, typename U=T::value_type>
void foo(const T& t) {
  std::cout << "template " << t << "\n";
}
```

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template <typename T, typename U=T::value_type>
void foo(const T& t) {
  std::cout << "template " << t << "\n";
}
```

What happens if we try to match an integer?

SFINAE & Correctness

- template<B> enable_if{…};
  - Using the same techniques we've seen, enable_if allows arbitrary condition checking.

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```
template <typename T, typename=std::enable_if_t<std::is_class_v<T>>>
void foo(const T& t) {
  std::cout << "template \n";
}
```

SFINAE & Correctness

- template<B> enable_if{…};
  - Using the same techniques we've seen, enable_if allows arbitrary condition checking.

```
template <typename T, typename=std::enable_if_t<std::is_class_v<T>>>
void foo(const T& t) {
  std::cout << "template \n";
}
```

How would we implement that?

SFINAE & Correctness

- This can also be attacked with **`if constexpr`**:

```
template <typename T>
void foo(const T& t) {
  if constexpr (std::is_class_v<T>) {
    std::cout << "template \n";
  } else if constexpr (std::is_unsigned_v<T>) {
    std::cout << "unsigned " << t << "\n";
  }
}
```

But this may not be exactly the same!

SFINAE & Correctness

- NOTE: Going forward in C++20(+),
  much of this will be simplified via “Concepts”

```
void foo(Sequence auto& s) {
...
}

std::list<int> asLinkedList = ...;
foo(asLinkedList);

std::vector<int> asVector = ...;
foo(asVector);
```

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```
template<typename T>
concept Hashable = requires(T a) {
    { std::hash<T>{}(a) } -> std::convertible_to<std::size_t>;
};
```

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```
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void bar(const Hashable auto& hashable);
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```
foo("Oh bother."s);
bar("Oh bother."s);

foo(32);
bar(32);

Cat kitten;
bar(kitten);

Dog doggo;
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- Can be (partially) specialized to refine behavior
- Can be used in traits for highly efficient decoupling
- Can be made safer using SFINAE and now Concepts based bounds