Generic Programming

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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#
Variable, Type, & Function Templates

- Several different constructs can be templated...
Variable, Type, & Function Templates

```cpp
template< typename T >
constexpr T PI = T(3.14159265358979323846)
```
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Variable, Type, & Function Templates

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

float radius = ...
float area = PI<float> * radius * radius;
template<typename T>
struct pair {
    pair(const T& first, const T& second) :
        first{first},
        second{second}
    {}

    T first;
    T second;
};
Variable, Type, & Function Templates

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

    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

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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const T&
min(const T& first, const T& second) {
  if (first < second) {
    return first;
  }
  return second;
};

int smaller = min<int>(1,2);

But *something* about this should feel odd! (Apart from min already existing)
Variable, Type, & Function Templates

- Several different constructs can be templated...
  - Variables
  - Classes
  - Functions
Several different constructs can be templated...

- Variables
- Classes
- Functions
- Type aliases (using)
Several different constructs can be templated...

- Variables
- Classes
- Functions
- Type aliases (*using*)
- Member functions
Variable, Type, & Function Templates

- Several different constructs can be templated...
  - Variables
  - Classes
  - Functions
  - Type aliases (using)
  - Member functions
  - All of the above inside another template...
In many places, template arguments can be deduced from context.
Template Argument Deduction

• In many places, template arguments can be deduced from context.

```cpp
pair<Kitten> kittens = {
    Kitten{"Pawsley"}, Kitten{"Steven"}
};
```
In many places, template arguments can be deduced from context.

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

Requires C++17
Template Argument Deduction

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  pair<Kitten> kittens = {
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  };
  pair moreKittens = {Kitten{"Lionel"}, Kitten{"J"}};
  ```
  Requires C++17

- Uses the constructor as a guide for deduction.
Template Argument Deduction

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

int smaller = min<int>(1,2);
int smaller = min(1,2);
```
In many places, template arguments can be deduced from context.

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pair<Kitten> kittens = {
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Can only deduce based on function arguments
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int smaller = \textcolor{red}{\texttt{min}(1,2)};

- Can only deduce based on function arguments

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

int smaller = min<int>(1,2);
int smaller = min(1,2);

vector from = {0, 1, 2, 3, 4, 5};
vector to   = {0, 0, 0, 0, 0, 0};
copy(from.begin(), from.end(), to.begin());
```
Template Argument Deduction

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int smaller = min(1, 2);

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

- If types cannot be exactly deduced, they must be given

Requires C++17
Parameters: Types, Literals, Templates

- Templates may parameterized on more than types!
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  - Literals: integers, (function) pointers, references, enums
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```cpp
tuple<Kitten, Age, Lethality> kittenRecord = {
    Kitten{"Bitey McBiterson"}, 10, Lethality::TOTAL
};
```
Templates may parameterized on more than types!

- Literals: integers, (function) pointers, references, enums

```cpp
tuple<Kitten, Age, Lethality> kittenRecord = {
    Kitten{"Bitey McBiterson"}, 10, Lethality::TOTAL
};
auto lethality = std::get<2>(kittenRecord);
```
Templates may parameterized on more than types!

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tuple<Kitten, Age, Lethality> kittenRecord = {
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array<Kitten, 10> kittens;
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```

```cpp
array<Kitten, 10> kittens;
```

What do you think the declaration of std::array looks like?
Templates may parameterized on more than types!

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tuple<Kitten, Age, Lethality> kittenRecord = {
    Kitten{"Bitey McBiterson"}, 10, Lethality::TOTAL
};
auto lethality = std::get<2>(kittenRecord);

array<Kitten, 10> kittens;
```

```cpp
template<class T, std::size_t N>
struct array {
    T data[N];
};
```
Templates may parameterized on more than types!
- Literals: integers, (function) pointers, references, enums
- Templates (less common in practice)

```cpp
template<template <class> class CreationPolicy>
struct WidgetLab {
    ...
};
```
Templates may parameterized on more than types!
  – Literals: integers, (function) pointers, references, enums
  – Templates (less common in practice)

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

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

- The complete definition of a template must be available before a template is instantiated.
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  - Having uses of your templates to test them is important
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```cpp
template<class T=std::string,
         class C=std::vector<T>,
         auto size=10>
class SmallRoster { ... };
```
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```cpp
template<class T=std::string,  
        class C=std::vector<T>,  
        auto size=10>
class SmallRoster { ... };

SmallRoster<Kitten> teamKittens;
SmallRoster<> teamStrings;
```
Pragmatic Usage Issues

- The complete definition of a template must be available before a template is instantiated.
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- Methods (& constructors) can be templated
  - You saw this on the first day!
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- Templates can have default arguments
- Methods (& constructors) can be templated
  - You saw this on the first day!
  - You may need to specify explicit templates

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

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- Templates are not type checked until instantiated.
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- Templates can have default arguments
- Methods (& constructors) can be templated
  - You saw this on the first day!
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- Some ambiguous nested types must be specified w/ typename

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

- Sometimes you want a type to behave differently for different parameters
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  - Generic implementation with guides where necessary
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Specialization

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

Specialization

<functional>
This doesn’t implement hashing for custom types. What if I want to add a **Cat** to an **unordered_set**?
This doesn’t implement hashing for custom types. What if I want to add a Cat to an unordered_set?
Specialization

<functional>

```cpp
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

<functional>

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

<Cats.h>

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

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

- Things start to get strange.
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```cpp
template <unsigned N>
struct Fib {
    static constexpr unsigned value =
        Fib<N-1>::value + Fib<N-2>::value;
};

template <>
struct Fib<1> {
    static constexpr unsigned value = 1;
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template <>
struct Fib<0> {
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cout << Fib<7>::value << "\n";
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This prints 13.
The value is computed at compile time!

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```

This prints 13.
The value is computed at compile time!

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

constexpr functions make this less common.
Things start to get strange.

```cpp
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.
The value is computed at compile time!

```cpp
constexpr auto result = fibonacci(40);
```

`constexpr` functions make this less common.
Specialization can help build efficient, decoupled interfaces through type traits.
Specialization

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```cpp
template<typename GraphKind>
struct GraphTraits {
    static_assert(false, "Not specialized");
};
```
Specialization can help build efficient, decoupled interfaces through type traits.

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

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

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

template<class Kind, class GT=GraphTraits<Kind>>
class dfs_iterator { ... };
```

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

- Specialization can help build efficient, decoupled interfaces through type traits.
- Type traits in C++ are deeply related to type classes in Haskell.
  - Concepts in the next version of C++ make that clearer & cleaner
Partial Specialization

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

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

SmallRoster<Kitten> teamKittens;
SmallRoster<> teamStrings;
```
Sometimes information needs to flow from a derived class to a base class.
CRTP

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```cpp
template<class T>
class Base {
public:
    void print() { getDerived().printImpl(); }
private:
    T& getDerived() { return *static_cast<T*>(this); }
};
```
Sometimes information needs to flow from a derived class to a base class.

template<class T>
class Base {
public:
    void print() { getDerived().printImpl(); }
private:
    T& getDerived() { return *static_cast<T*>(this); }
};

class Specific : public Base<Specific> {
public:
    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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What other approaches could we have used? What are the trade offs?

Flexibility vs Efficiency
Sometimes information needs to flow from a derived class to a base class.

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public:
    void print() { getDerived().printImpl(); }
private:
    T& getDerived() { return *static_cast<T*>(this); }
};

class Specific : public Base<Specific> {
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    void printImpl() { printf("Yo\n"); }
};

We have already seen a pattern this could make safer. How?
Policy Based Design

- All of these tools we’ve seen led to *policy based design* in the 2000’s.
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  - *Identify all of the design decisions* in an algorithm & turn them into template parameters.
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  - Invert control so that the user of the algorithm can pass in new policies.
All of these tools we’ve seen led to policy based design in the 2000’s.
- Identify all of the design decisions in an algorithm & turn them into template parameters.
- Invert control so that the user of the algorithm can pass in new policies.

This is essentially dependency injection at the template level!
All of these tools we’ve seen led to policy based design in the 2000’s.

- Identify all of the design decisions in an algorithm & turn them into template parameters.
- Invert control so that the user of the algorithm can pass in new policies.

```cpp
template<class T, class Allocator = std::allocator<T> >
class vector;
```
Policy Based Design

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  - Identify all of the design decisions in an algorithm & turn them into template parameters.
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template<class T, class Allocator = std::allocator<T>>
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```

This addresses a static variant of the combinatorial explosion. Recall the dynamic form & decorators.
All of these tools we've seen led to policy based design in the 2000's.
- Identify all of the design decisions in an algorithm & turn them into template parameters.
- Invert control so that the user of the algorithm can pass in new policies.

```cpp
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
Policy Based Design

- All of these tools we've seen led to policy based design in the 2000’s.
  - Identify all of the design decisions in an algorithm & turn them into template parameters.
  - Invert control so that the user of the algorithm can pass in new policies.

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We also saw this in 473!

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- 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.
What is printed by foo(42)?

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

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

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

Why?
void foo(unsigned i) {
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template <typename T>
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What is printed by foo(42)?
"template 42"

Why?

What we want is a way to bound where our templates apply...
SFINAЕ & Correctness

- SFINAЕ is one approach to bounded static polymorphism in C++
SFINAE & Correctness

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- **Substitution Failure Is Not An Error**
  - When trying to substitute into the template or function signature, skip errors & keep looking.
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```cpp
template <typename T, typename U=T::value_type>
void foo(const T& t) {
    std::cout << "template " << t << "\n";
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SFINAE & Correctness

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  - When trying to substitute into the template or function signature, skip errors & keep looking.

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template <typename T, typename U=T::value_type>
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    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.
SFINAE & Correctness

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

```cpp
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.

```cpp
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`:

```cpp
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”

```cpp
void foo(Sequence auto& s) {
  ...
}
std::list<int> asLinkedList = ...;
foo(asLinkedList);
std::vector<int> asVector = ...;
foo(asVector);
```
• Enable efficient generic programming in C++
Templates

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- Can be (partially) specialized to refine behavior
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- Can be (partially) specialized to refine behavior
- Can be used in traits similar to Haskell type classes
- Can be made safer using SFINAE based bounds