Department I - C Plus Plus

Modern and Lucid C++ Advanced for Professional Programmers

Week 7 – Advanced Templates

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Recap Week 6

Cevelop
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Memory Allocation (with `new`)

- **Explicit heap memory allocation**
  - new expression
- **Syntax**

```
new <type> <initializer>
```

- **Allocates memory for an instance of `<type>`**
- **Returns a pointer to the object or array created (on the heap)**
  - of type `<type> *`
- **The arguments in the `<initializer>` are passed to the constructor of `<type>`**

```
struct Point {
  Point(int x, int y) :
        x {x}, y {y}{}
  int const x, y;
};

Point * createPoint(int x, int y) {
  return new Point{x, y}; //constructor
}

Point * createCorners(int x, int y) {
  return new Point[2]{{0, 0}, {x, y}};
}
```

Memory Deallocation (with **delete**)

- **Explicit heap memory deallocation**
  - `delete` expression
- **Syntax**

```
delete <pointer>
```

- **Deallocates the memory (of a single object) pointed to by the <pointer>**
- **Calls the Destructor of the destroyed type**
- **`delete nullptr` is well defined**
  - it does nothing
- **Deleting the same object twice is Undefined Behavior!**

```cpp
struct Point {
  Point(int x, int y) :
       x {x}, y {y} {}
  int const x, y;
}

void funWithPoint(int x, int y) {
  Point * pp = new Point{x, y};
  //pp member access with pp->
  //pp is the pointer value
  delete pp; //destructor
}
```

Resource Aquisition Is Initialization (RAII)

- **Alternative to allocating and deallocating a resource explicitly**
  - Wrap allocation and deallocation in a class
  - Constructor for allocation
  - Destructor for deallocation
- **The automatic destruction at the end of a scope will take care of the resource deallocation**
- **Works with exceptions**
  - No `finally` required
- **STL classes for heap memory**
  - `std::unique_ptr` / `std::shared_ptr`

```
struct Resource {
  Resource() {
    //Allocate Resource
  }
  ~Resource() {
    //Deallocate Resource
  }
  //API for accessing the resource
  //Don't leak the resource!
private:
  WrappedResource * wrappedResource;
};
```

```
void workWithResource() {
  Resource item{};
  functionThatMightThrow();
  //Resource is released automatically
}
```

- **Topics:**
  - Static vs. Dynamic Polymorphism
  - Templates Recap
  - Tags for Dispatching
    - Iterators (with Boost)

Static vs. Dynamic Polymorphism

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Pros of static polymorphism

- Happens at compile-time
- Faster execution time
  - No dynamic dispatch required
  - Easier to optimize (inline)
- Type checks at compile-time

Cons of static polymorphism

- Longer compile-times
- Template code has to be known when used
- Larger binary size
  - Copy of the used parts for each (template) instance

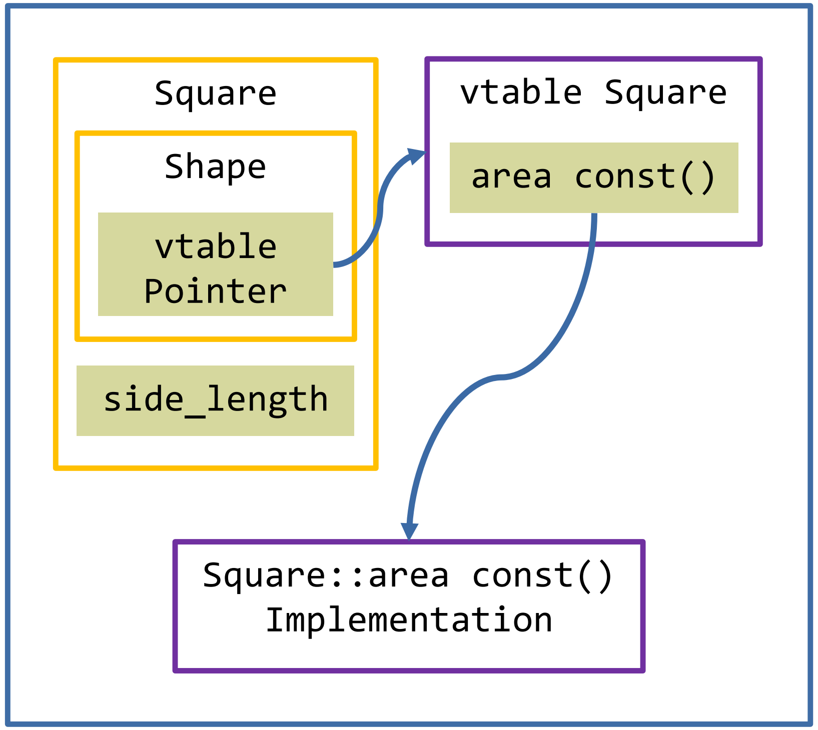
Overhead of Dynamic Dispatching (1/2)

- **A polymorphic call of a virtual function requires lookup of the target function**

```
struct Shape {
  virtual unsigned area() const = 0;
  virtual ~Shape();
};

struct Square : Shape {
  Square(unsigned side_length)
    : side_length{side_length} {}
  unsigned area() const {
    return side_length * side_length;
  }
  unsigned const side_length;
};
```

```
decltype(auto) amountOfSeeds(Shape const & shape) {
  auto area = shape.area();
  return area * seedsPerSquareMeter;
};
```



- **Article on this topic:** http://eli.thegreenplace.net/2013/12/05/the-cost-of-dynamic-virtual-calls-vs-static-crtp-dispatch-in-c

Overhead of Dynamic Dispatching (2/2)

- **Non-virtual calls directly call the target function**

Argument Type

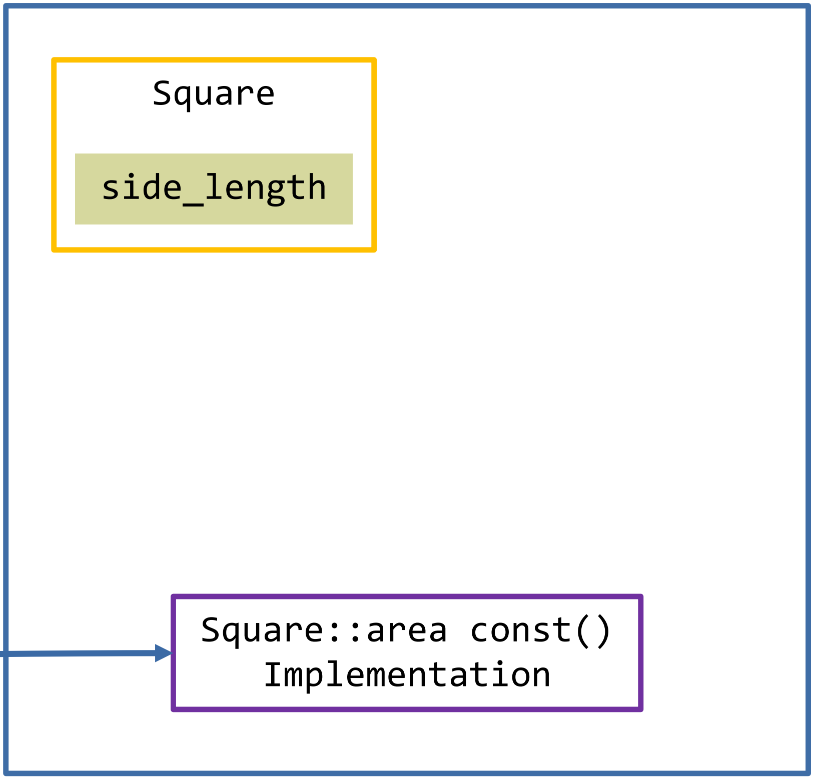
```
struct Square {
  Square(unsigned side_length)
    : side_length{side_length} {}
  unsigned area() const {
    return side_length * side_length;
  }
  unsigned const side_length;
};
```

Template

```
template<typename ShapeType>
decltype(auto) amountOfSeeds(ShapeType const & shape) {
  auto area = shape.area();
  return area * seedsPerSquareMeter;
};
```

Instance

```
decltype(auto) amountOfSeeds(Square const & shape) {
  auto area = shape.area();
  return area * seedsPerSquareMeter;
};
```



Object Layout (Visual Studio)

- **Object is smaller**
  - No vtable
- **Compiler flag for (cl.exe)**
  - /d1reportSingleClassLayout<ClassName>
  - /d1reportAllClassLayout

```
class Shape        size(1):
        +---
        +---

class Square       size(4):
        +---
 0      | +--- (base class Shape)
        | +---
 0      | side_length
        +---
```

```
class Shape        size(4):
        +---
 0      | {vfptr}
        +---

Shape::$vftable@:
        | &Shape_meta
        |  0
 0      | &Shape::area
 1      | &Shape::{dtor}

class Square       size(8):
        +---
 0      | +--- (base class Shape)
 0      | | {vfptr}
        | +---
 4      | side_length
        +---

Square::$vftable@:
        | &Square_meta
        |  0
 0      | &Square::area
 1      | &Square::{dtor}
```

- **Copy-pasting at compile-time**
  - Instances for `Square`, `Circle` and `Triangle`
  - The optimizer might get rid of them

```
template<typename ShapeType>
decltype(auto) amountOfSeeds(ShapeType const & shape) {
  auto area = shape.area();
  return area * seedsPerSquareMeter;
};
```

```
unsigned amountOfSeeds(Square const & shape) {
  auto area = shape.area();
  return area * seedsPerSquareMeter;
};
```

```
Circle const & shape) {
a();
rSquareMeter;
};
```

```
Triangle const & shape) {
a();
rSquareMeter;
};
```

Templates Recap

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Function Templates (Recap)

- **Template declaration**
  - `template` Keyword
  - Template Parameters
- **Function is implicitly inline**

template Keyword

Template Parameters

```
template<typename ShapeType>
decltype(auto) amountOfSeeds(ShapeType const & shape) {
  auto area = shape.area();
  return area * seedsPerSquareMeter;
};
```

- **Template arguments might be deduced from the function call arguments**

ShapeType is deduced to be `Rectangle`

```
Rectangle r{5, 8};
auto seeds = amountOfSeeds(r);
```

Explicitly specified to be `Rectangle`

```
Rectangle r{5, 8};
auto seeds = amountOfSeeds<Rectangle>(r);
```

Template Template Parameter

Template Type Parameter

Template Non-Type Parameter

```
template<template<typename, unsigned> class Container, typename Target, std::size_t N>
Target extractMiddleElement(Container<Target, N> & container) {
  Target middleElement{};
  std::swap(container.at(N / 2), middleElement);
  return middleElement;
}
```

```
std::array<int, 3> values{1, 2, 3};
extractMiddleElement(values);
```

```
Container => std::array
Target    => int
N         => 3
```

```
BoundedBuffer<int, 3> values{1, 2, 3};
extractMiddleElement(values);
```

```
Container => BoundedBuffer
Target    => int
N         => 3
```

- **Since C++17 `template <...> typename` is allowed for template template parameters**
  - Cevelop does not recognize it yet, `class` is ok

- **We could also implement `extractMiddleElement` differently**
  - Instead of `N` we might use `size()`
  - Instead of `Target` we have the member type `value_type` of `Container`
- **That changes the Concept of the parameter. How?**

Container must have:
- member type `value_type`
- `size()` member function

It does not need to be a template with type and unsigned parameter anymore.

- **The member type `value_type` is a dependent type**
  - The compiler does not know whether `Container::value_type` is a member type, function or variable
  - To tell the compiler that it is a type the `typename` keyword is required (there is also a template keyword for cases where the member is a template)

```
template<typename Container>
auto extractMiddleElement(Container & container) {
  typename Container::value_type middleElement{};
  std::swap(container.at(container.size() / 2), middleElement);
  return middleElement;
}
```

- **In specific cases the number of template parameters might not be fix/known upfront**
- **Thus the template shall take an arbitrary number of parameters**
- **Example:**

```
template<typename First, typename...Types>
void printAll(First const & first, Types const &...rest) {
  std::cout << first;
  if (sizeof...(Types)) {
    std::cout << ", ";
  }
  printAll(rest...);
}
```

- **Syntax (ellipses everywhere): `...`**
  - `...` in template parameter list for an arbitrary number of template parameters (Template Parameter Pack)
  - `...` in function parameter list for an arbitrary number of function arguments (Function Parameter Pack)
  - `...` after `sizeof` to access the number of elements in template parameter pack
  - `...` in the variadic template implementation after a pattern (Pack Expansion)

- **Templates allow generic programming in C++**
- **A template is instantiated for a specific set of template arguments**

Type Parameter

Non-Type Parameter

```
template<typename Freight, unsigned Space>
struct Carriage {
  std::array<Freight, Space> cargo{};
};

decltype(auto) createSmallTankWagon() {
  return Carriage<Oil, 1>{};
}
```

Creates Template Instance

```
struct Carriage {
  std::array<Oil, 1> cargo{};
};
```

Specializations

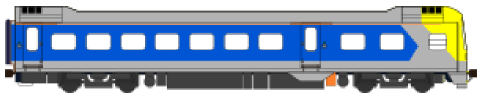
- **Templates can be (partially) specialized**
- **Liskov's Substitution Principle does not apply for specializations, i.e. a specialized template does not need to satisfy the interface of the base template!**

```
template<typename Freight, unsigned Space>
struct Carriage;

template<unsigned Space>
struct Carriage<Passenger, Space> {
  unsigned const doors{4};
}

decltype(auto) createPassengerWagon() {
  return Carriage<Passenger, 100>{};
}
```

```
struct Carriage {
  unsigned const doors{4};
}
```

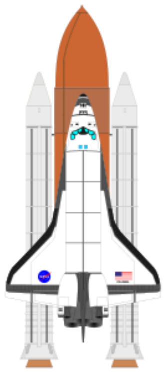


- **When a template is instantiated the compiler has to decide whether to use the base template or one of its specializations**

Tags for Dispatching

- **Template parameters don't require a specified type hierarchy**
  - but they expect an argument to satisfy a concept
- **If the same operation can be implemented more/less efficiently depending on the capabilities of the argument, tags can be used to find the "best" implementation**
- **Let's have a look at a hypothetical example**
  - Different types of space ships have different means of travel (API)

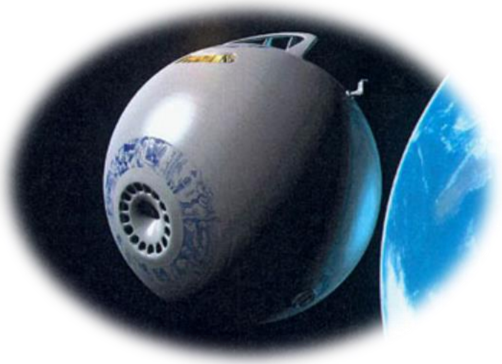
```
template<typename SpaceShip>
void travelTo(Galaxy destination, SpaceShip & ship) {
  ship.$functionUsedToTravel$(destination);
}
```



```
struct MultiPurposeCrewVehicle {
  void travelThroughSpace(Galaxy destination);
};
```

```
struct GalaxyClassShip {
  void travelThroughSpace(Galaxy destination);
  void travelThroughHyperspace(Galaxy destination);
};
```

```
struct HeartOfGold {
  void travelThroughSpace(Galaxy destination);
  Galaxy travelImprobably();
};
```



Heart of Gold Image from: http://hitchhikers.wikia.com/wiki/File:Heartofgold_exterior1.jpg

Tags for Dispatching: Drive Technology Tags

```
//Provides travelThroughSpace
struct SpaceDriveTag {};

//Provides travelThroughSpace and travelThroughHyperspace
struct HyperspaceDriveTag : SpaceDriveTag {};

//Provides travelThroughSpace and travelImprobably
struct InfniteProbabilityDriveTag : SpaceDriveTag {};
```

- **Tag types are used mark capabilities of associated types**
- **Such tag types do not contain any members**
- **It is possible to derive tag types from each other to "inherit" the capabilities**
- **Space ship example: Every space ship can somehow travel through space, but some space ships have more advanced technology**

Tags for Dispatching: Space Ship and Drive Association

```
struct SpaceDriveTag {};

struct HyperspaceDriveTag : SpaceDriveTag {};

struct InfniteProbabilityDriveTag : SpaceDriveTag {};
```

```
struct MultiPurposeCrewVehicle;

struct GalaxyClassShip;

struct HeartOfGoldPrototype;
```

- **Approach 1: Derive space ship from the associated tag typ**
  - This is not applicable for all types (e.g. for primitive types)
  - This is not extensible (i.e. you cannot specify new kinds of tag kinds as a user of the API)
- **Approach 2: `SpaceshipTraits` template**

```
template<typename>
struct SpaceshipTraits {
  using Drive = SpaceDriveTag;
};
```

```
template<>
struct SpaceshipTraits<GalaxyClassShip> {
  using Drive = HyperspaceDriveTag;
};
```

```
template<typename Spaceship>
void travelToDispatched(Galaxy destination, Spaceship & ship, SpaceDriveTag) {
  ship.travelThroughSpace();
}

template<typename Spaceship>
void travelToDispatched(Galaxy destination, Spaceship & ship, InfniteProbabilityDriveTag) {
  while(destination != ship.travelImprobably());
}

template<typename Spaceship>
void travelTo(Galaxy destination, Spaceship & ship) {
  typename SpaceShipTraits<SpaceShip>::Drive drive{};  //instance of the spaceship's Drive
  travelToDispatched(destination, ship, drive);        //call overloaded function
}
```

- **A call of `travelTo` with a `HeartOfGold` space ship instance as argument will use the `travelImprobably` function**
- **A call of `travelTo` with any other space ship with the `SpaceDriveTag` in the `SpaceshipTraits` template will use `travelThroughSpace`**

Iterators

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Recap: Iterator Categories

- **Different algorithms require different strengths of iterators**
  - InputIterator - read sequence once
    - `operator *` returns const lvalue reference, or rvalue
  - OutputIterator - write results, without designating an end
    - `operator *` returns lvalue reference
  - ForwardIterator - read/write sequence, multiple passes
    - const version: `operator *` returns const lvalue reference or rvalue
    - non-const: `operator *` returns lvalue
  - BidirectionalIterator - read/write sequence, back-forth
  - RandomAccessIterator - read/write/indexed sequence
- **More versatile iterators can be used for more efficient algorithm (like space ships)**
- **Iterator's capabilities can be determined at compile time (with tag types)**

- **Pre C++17: Inherit from `std::iterator<tag, value_type>`**
  - Now deprecated
- **Provide member types**

Member	Description
`iterator_category`	Specifies the iterator category by tag
`value_type`	Specifies the type of the elements the iterator iterates over
`difference_type`	Specifies the type used to specify iterator distance (ususally `ptrdiff_t`)
`pointer`	Specifies the pointer type for the elements the iterator iterates over
`reference`	Specifies the reference type for the elements the iterator iterates

- **Example:**

```
struct IntIterator {
  using iterator_category = std::input_iterator_tag;
  using value_type = int;
  using difference_type = ptrdiff_t;
  using pointer = int *;
  using reference = int &;
};
```

- **Implement members required by your `?_iterator_tag`**
- **Example: InputIterator (Concept)**

```
struct IntIterator {
  using iterator_category = std::input_iterator_tag;
  using value_type = int;
  using difference_type = ptrdiff_t;
  using pointer = int *;
  using reference = int &;

  //operator *
  //operator ->
  //operator ++ (prefix)
  //operator ++ (postfix)
  //operator ==
  //operator !=
};
```

Example DIY Iterator for Integers


```
struct IntIterator { /* Member Types Omitted */
  explicit IntIterator(int const start = 0) :
    value { start } {}
  bool operator==(IntIterator const & r) const {
    return value == r.value;
  }
  bool operator!=(IntIterator const & r) const {
    return !(*this == r);
  }
  value_type operator*() const {
    return value;
  }
  IntIterator & operator++() {
    ++value;
    return *this;
  }
  IntIterator operator++(int) {
    auto old = *this;
    ++(*this);
    return old;
  }
private:
  value_type value;
};
```

Explicit constructor

Implement != through operator ==

Implement postfix through prefix operators

Reuse pre-defined type

```
struct input_iterator_tag{};
struct output_iterator_tag{};
struct forward_iterator_tag : public input_iterator_tag{};
struct bidirectional_iterator_tag : public forward_iterator_tag{};
struct random_access_iterator_tag : public bidirectional_iterator_tag{};
```

- **Iterators define type aliases for common usage**
- **`std::iterator<>` base class provides defaults (Pre C++17)**

C++03 Style with typedef

```
template<typename Category, typename Tp, typename Distance = ptrdiff_t,
         typename Pointer = Tp *, typename Reference = Tp &>
  struct iterator {
    /// One of the iterator_tags tag types.
    typedef Category  iterator_category;
    /// The type "pointed to" by the iterator.
    typedef Tp        value_type;
    /// Distance between iterators is represented as this type.
    typedef Distance  difference_type;
    /// This type represents a pointer-to-value_type.
    typedef Pointer   pointer;
    /// This type represents a reference-to-value_type.
    typedef Reference reference;
};
```

```
using iterator_category = Category
```

```
using value_type = Tp
```

What Are `iterator_traits<>`?

```
template<typename InputIterator, typename Tp>
typename iterator_traits<InputIterator>::difference_type
  count(InputIterator first, InputIterator last, const Tp& value) {
    ...
```

- **STL algorithms often want to determine the type of some specific thing related to an iterator -> use optimal solution!**
- **However, not all iterator types are actually classes, i.e., subclasses of `std::iterator<>`.**
- **Default `iterator_traits` just pick the type aliases from those provided by base class `std::iterator`**
- **Specialization of `iterator_traits` also allows "naked pointers" to be used as iterators in algorithms (that is the main reason for the separate traits mechanism)**

```
template<typename _Tp>
struct iterator_traits<_Tp*> {
  typedef random_access_iterator_tag  iterator_category;
  typedef _Tp                         value_type;
  typedef ptrdiff_t                   difference_type;
  typedef _Tp *                       pointer;
  typedef _Tp &                       reference;
};
```

- **Simple function overload resolution determines which implementation to use**

```
template<typename InputIter, typename Distance>
void advanceImpl(InputIter & i, Distance d, std::input_iterator_tag) {
  while (d--) { i++; }
}

template<typename RandomAccessIter, typename Distance>
void advanceImpl(RandomAccessIter & i, Distance d, std::random_access_iterator_tag) {
  i += d;
}

template<typename InputIter, typename Distance>
void advance(InputIter & i, Distance n) {
  typename std::iterator_traits<InputIter>::difference_type d = n;
  advanceImpl(i, d, typename std::iterator_traits<InputIter>::iterator_category{});
}
```

```
::advance(iter, 15);
```

Boost Iterator Library Provides More


```
#include <boost/iterator/counting_iterator.hpp>
#include <boost/iterator/filter_iterator.hpp>
#include <boost/iterator/transform_iterator.hpp>
```

- **Several pre-defined adapters with factory functions, for example**
  - Counting
  - Filtering
  - Transforming
- **See also**
  - http://www.boost.org/doc/libs/1_66_0/libs/iterator/doc/index.html

Example: Using Boost Iterator

```
struct odd {
  bool operator()(int n) const {
    return n % 2;
  }
};

int main() {
  using counter = boost::counting_iterator<int>;
  std::vector<int> v(counter{ 1 }, counter{ 11 });
  std::ostream_iterator<int> out { std::cout, ", " };
  copy(v.begin(), v.end(), out);
  std::cout << '\n';

  copy(boost:: make_filter_iterator(odd{}, v.begin(), v.end()),
       boost::make_filter_iterator(odd{}, v.end(), v.end()), out);
  std::cout << '\n';

  auto sq = [](auto i) {return i * i;};
  copy(boost::make_transform_iterator(v.begin(), sq),
       boost::make_transform_iterator(v.end(), sq), out);
}
```

Functor for filtering

Counting iterator

Filter iterator only odd values provided

transform iterator applies function/functor/lambda for each value

Boost Operators' Iterator Helpers

`#include <boost/operators.hpp>`

- **Inherit and provide own iterator**
  - Class as first template argument
  - Second argument for `value_type`
  - Other template arguments are usually defaulted and OK
- **`input_iterator_helper<T, V>`**
- **`forward_iterator_helper<T, V>`**
- **`bidirectional_iterator_helper<T, V>`**
- **`random_access_iterator_helper<T, V>`**
- **`output_iterator_helper<T>`**
  - Output only is special, no value type, special requirements!

- **Using boost/operators.hpp shortens definition**

```
struct IntIteratorBoost
  : boost::input_iterator_helper<IntIteratorBoost, int> {

  explicit IntIteratorBoost(int start = 0)
    : value { start } {}

  bool operator==(IntIteratorBoost const & r) const {
    return value == r.value;
  }

  value_type operator*() const { return value; }

  IntIteratorBoost & operator ++() {
    ++value;
    return *this;
  }

private:
  value_type value;
};
```

Pass own type
CRTP = Curiously Recurring Template Parameter

Explicit Constructor

Inherit to obtain types and operations (through CRTP)

Reuse predefined type

operator== required

Deduction Guides

Synthesized Deduction Guides

- **Class template arguments can usually be determined by the compiler**

```
template <typename T>
struct Box {
    Box(T content)
      : content{content}{}
    T content;
};

int main() {
  Box<int> b0{0}; //Before C++17
  Box      b1{1}; //Since C++17
}
```

- **The behavior is similar to pretending as if there was a factory function for each constructor**

```
template <typename T>
Box<T> make_box(T content) {
  return Box<T>{content};
}
```

```
auto gift = make_box(teddy);
```

- **In the following example the only template parameter is `T`, which can be deduced from `std::initializer_list<T>`**

```
template <typename T>
class Sack {
  //...
  Sack(std::initializer_list<T> values)
      : theSack(values) {
  }
  //...
};
```

```
void testImplicitDeductionGuide () {
  Sack charSack{'a', 'b', 'c'};
  ASSERT_EQUAL(3, charSack.size());
}
```

```
std::initializer_list<char>
```

Deducing Element Type for Iterators

- **There is no direct relation from `Iter` to `T` (constructor parameters to template parameter)**

```
template <typename T>
struct BoundedBuffer {
  //...
  template <typename Iter>
  BoundedBuffer(Iter begin, Iter end);
  //...
};
```

```
void testDeductionFromIterators() {
  std::vector values{3, 1, 4, 1, 5, 9, 2, 6};
  BoundedBuffer buffer{begin(values), end(values)};
  ASSERT_EQUAL(values.size(), buffer.size());
}
```

```
error: class template argument deduction failed:
  Sack aSack(begin(values), end(values));
```

User Provided Deduction Guides

- **User-defined deduction guides can be specified in the same scope as the template**
  - Usually, after the template definition itself

```
TemplateName(ConstructorParameters) -> TemplateID;
```

- **Might be necessary for complex cases, e.g. template constructors if the constructor template parameters do not map directly to the class template parameters**
- **The deduction guide can be (and usually is) a template itself**
- **It looks similar to a free-standing constructor**
- **Unfortunately,** Cevelop **does not recognize the deduction guides yet**

Template declaration for `Iter`

```
template <typename Iter>
BoundedBuffer(Iter begin, Iter end) -> BoundedBuffer<typename std::iterator_traits<Iter>::value_type>;
```

Constructor signature

Deduced template instance

- **Test for deducing template argument from iterator works**

```
void testDeductionFromIterators() {
  std::vector values{3, 1, 4, 1, 5, 9, 2, 6};
  BoundedBuffer buffer{begin(values), end(values)};
  ASSERT_EQUAL(values.size(), buffer.size());
}
```

Summary

- **Function calls resolved at compile-time can be much faster**
- **Tag types can be used for static dispatching (For example in iterators)**
- **DIY Iterators are used much less often than functors for parameterizing the standard library algorithm**
  - Try one of the boost adapters first
- **They need pre-defined member types to work with the standard algorithms**
  - as well as a set of operators
  - if DIY `<boost/operators.hpp>` provides boilerplate code

Self-Study

Variadic Template Instances Unfolded (Recap)

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- **Template declaration:**

```
template<typename First, typename...Types>
void printAll(First const & first, Types const &...rest);
```

- **Implicit instantiation:**

```
int i{42}; double d{1.25}; std::string book{"Lucid C++"};
printAll(i, f, book);
```

- **Template instance:**

```
void printAll(int const & first, double const & __rest0,
                                 std::string const & __rest1) {
  std::cout << first;
  if (2) { //sizeof...(Types) - Number of arguments in the pack
    std::cout << ", ";
  }
  printAll(__rest0, __rest1); //rest... expansion
}
```

- `sizeof...(<PACK>)` **will be replaced by the number of arguments in the pack parameter**
  - `0, 1, 2, ...`

Pack Expansion of `printAll(rest...);`

```
template<typename First, typename...Types>
void printAll(First const & first, Types const &...rest) {
 //...
 printAll(rest...);
}
```

- **Pattern: `rest`**
- **The pattern must contain at least one pack parameter**
- **An expansion is a coma-separated list of instances of the pattern**
- **For each argument in that pack an instance of the pattern is created**
- **In an instance of the pattern the parameter pack name is replaced by an argument of the pack**

```
void printAll(int const & first, double const & __rest0, std::string const & __rest1) {
  //...
  printAll(__rest0, __rest1); //rest...
}
```

- **For the call `printAll(__rest0, __rest1)`: `printAll<double, std::string>`**

```
void printAll(double const & first, std::string const & __rest0) {
  std::cout << first;
  if (1) { //sizeof...(Types) – Number of arguments in the pack
    std::cout << ", ";
  }
  printAll(__rest0); //rest... expansion
}
```

- **For the call `printAll(<rest0>)`: `printAll<std::string>`**

```
void printAll(std::string const & first) {
  std::cout << first;
  if (0) { //sizeof...(Types) – Number of arguments in the pack
    std::cout << ", ";
  }
  printAll(); //rest... expansion
}
```

- **What about `printAll()`?**

- **What about `printAll()`?**
  - The variadic template `printAll` is not viable, as it requires at least one parameter
- **We need a base case for the recursion**

```
void printAll() {
}
```

- **Wouldn't it be feasible to just rearange the code in the variadic template?**

```
template<typename First, typename...Types>
void printAll(First const & first, Types const &...rest) {
  std::cout << first;
  if (sizeof...(Types)) {
    std::cout << ", ";
    printAll(rest...);
  }
}
```

?

Self-Study

Output Iterators

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Defining Your Own Output Iterator

- **Rarely needed, special tricks required**
- **`operator*` just returns `this`, `operator++` is a no-op**
- **`operator=` defines output of value**
- **`*out++ = 42;` // works**

```
struct MyIntOutIter {

  using iterator_category = std::output_iterator_tag;
  using value_type = int;
  /* Other Member Types Omitted */

  MyIntOutIter & operator++() {
    return *this;
  }
  MyIntOutIter operator++(int) {
    return *this;
  }
  MyIntOutIter const & operator*() const {
    return *this;
  }
  void operator=(value_type val) const {
    std::cout << "val = " << val << '\n';
  }
};
```

Defining Your Own Output Iterator (with Boost)

- **Even simpler with Boost**
- **`operator=` defines output of value**
- **`*out++ = 42;` // works**

```
struct MyIntOutIterBoost : boost::output_iterator_helper<MyIntOutIterBoost> {
  void operator=(int val) const {
   std::cout << "value = " << val << '\n';
  }
};
```

- **An output iterator for summing and averaging**

```
struct SummingIter {
  using iterator_category = std::output_iterator_tag;
  using value_type = int;
  /* Other Member Types Omitted */

  void operator++() { ++counter; }
  SummingIter & operator*() {
    return *this;
  }
  void operator=(int val) {
    sum += val;
  }
  double average() const {
    return sum / coutner;
  }
  double sum{};
  size_t counter{};
};
```

```
std::vector<int> v {3, 1, 4, 1, 5, 9, 2};
auto res = copy(v.begin(), v.end(), SummingIter{});
std::cout << res.sum << " average: "<< res.average();
```

Self-Study

Stream Iterators

```
struct IntInputter {
  using iterator_category = std::input_iterator_tag;
  using value_type = int;
  /* Other Member Types Omitted */

  IntInputter();
  explicit IntInputter(std::istream & in)
    : input { in } {}
  value_type operator*();
  IntInputter & operator++() {
    return *this;
  }
  IntInputter operator++(int) {
    IntInputter old{*this};
    ++(*this);
    return old;
  }
  bool operator==(IntInputter const & other) const;
  bool operator!=(IntInputter const & other) const {
    return !(*this == other);
  }
private:
  std::istream & input;
};
```

Default Constructor for EOF

++ does nothing

Equal only if both EOF

Caller must guarantee survival of object, otherwise "dangling" reference!

Problems with Stream Input Iterator

```
IntInputter();
value_type operator*();
bool operator==(IntInputter const & other) const;
```

- **How do we initialize the reference in the default constructor?**
- **What should happen in `operator*()`?**
- **How can we compare iterators to guarantee equality for EOF-condition?**

```
IntInputter();
```

- **We need a dirty trick: A global variable to initialize the reference!**
  - Put it into an anonymous namespace to hide it
  - Not good for multi-threading -> bad for production code

```
namespace {
  // a global helper needed...
  std::istringstream empty{};
}
IntInputter::IntInputter()
    : input { empty } {
  // guarantee the empty stream is not good()
  input.clear(std::ios_base::eofbit);
}
```

```
value_type operator*();
bool operator==(IntInputter const & other) const;
```

- **Just input**

```
IntInputter::value_type IntInputter::operator*() {
  value_type value{};
  input >> value;
  return value;
}
```

- **And Compare. Only equal if both are `!good()`**
  - Both `eof()` would result in problems on failing input when using standard algorithms

```
bool IntInputter::operator==(const IntInputter & other) const {
    return !input.good() && !other.input.good();
}
```

- **Alternative to global variable: Naked pointer that might point to "nothing"**
  - A pointer can be empty, which requires a check
- **Boost can be used for brevity**

```
struct IntInputterPtrBoost
    : boost::input_iterator_helper<IntInputterPtrBoost, int> {
  IntInputterPtrBoost() = default;
  explicit IntInputterPtrBoost(std::istream & in)
    : input {&in} {}
  IntInputterPtrBoost::value_type operator*();
  IntInputterPtrBoost & operator++() {
    return *this;
  }
  bool operator==(IntInputterPtrBoost const & other) const;
private:
  std::istream * input{};
};
```

Caller must guarantee survival of object, otherwise "dangling" reference!

Initialized with `nullptr`

```
value_type operator*();
bool operator==(IntInputter const & other) const;
```

- **Input only if defined**

```
IntInputterPtrBoost::value_type IntInputterPtrBoost::operator*() {
  value_type value{};
  if (input) (*input) >> value;
  return value;
}
```

- **And Compare. Only equal if both are either `nullptr` or `!good()`**

```
bool IntInputterPtrBoost::operator==(IntInputterPtrBoost const & other) const {
   return (!input || !input->good()) && (!other.input || !other.input->good());
}
```