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C++ Language Support for Generic Programming

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What is Generic Programming?

- Paradigm for software development
- Express algorithms (and data structures) in terms of abstract requirements
  - Applicable to many data types
  - Runtime performance of concrete implementations
  - Alternative implementations for special-case data structures
- Distinct from template metaprogramming

Outline

- Introduction to GP extensions for C++
  - Generic functions & types
  - Concepts
  - Models
- Existing practice & the Standard Library
- Impact on the C++ community

Introduction to Generic Programming Extensions for C++

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Vector equality

- `std::vector` has this equality operator:

```
template<typename T, typename Alloc>
  bool operator==(const vector<T, Alloc>& x,
                  const vector<T, Alloc>& y);
```

- When can we instantiate this function?
  - Need to be able to compare `T` objects.
  - This requirement is **implicit** in the source code

Explicit requirements

- Make the requirement explicit:

```
template<typename T, typename Alloc>
  where { EqualityComparable<T> }
  bool operator==(const vector<T, Alloc>& x,
                  const vector<T, Alloc>& y);
```

- `where` clause states requirements
  - `EqualityComparable` is a **concept**
  - "`T` must be `EqualityComparable`"

Equality Comparable concept

```
template<typeid T>
concept EqualityComparable
{
  bool operator==(const T&, const T&);
  bool operator!=(const T&, const T&);

  // == is an equivalence relation
  // != is the complement of ==
};
```

- A **concept** gives a name to a set of requirements
  - Syntax
  - Semantics
- A type **models** the concept if it satisfies the requirements

Type-checking calls

- We can now type-check calls to :

```
template<typename T, typename Alloc>
  where { EqualityComparable<T> }
  bool operator==(const vector<T, Alloc>& x,
                  const vector<T, Alloc>& y);

vector<int> iv1, iv2;
if (iv1 == iv2) { … }
vector<my_type> mv1, mv2;
if (mv1 == mv2) { … }
```

- We need to ensure that `int` and `my_type` model `EqualityComparable`

Models of EqualityComparable

- `int` models `EqualityComparable`
  - The Standard Library asserts this
- Does `my_type` model `EqualityComparable`?
  - Only if syntax and semantics match
  - If yes, write a **model definition**:

```
model EqualityComparable<my_type> { };
```

Opaque template parameters

- Let’s add the implementation:

```
template<typeid T, typeid Alloc>
  where { EqualityComparable<T> }
  bool operator==(const vector<T, Alloc>& x,
                  const vector<T, Alloc>& y)
  {
    return x.size() == y.size()
           && equal(x.begin(), x.end(), y.begin());
  }
```

- `typename` eliminates type checking: you can do anything to `typename` types
- `typeid` enables type checking: you can do nothing but what you require
- Two-phase type checking: like C++ already has!

What about the call to `equal`?

- `equal` has this signature with concepts:

```
template<typeid Iter1, typeid Iter2>
  where { EqualityComparable2<
              InputIterator<Iter1>::value_type,
              InputIterator<Iter2>::value_type> }
  bool
  equal(Iter1 first1, Iter1 last1, Iter2 first2);
```

- `EqualityComparable2` is a new concept:

```
template<typeid T, typeid U>
concept EqualityComparable2
{
  bool operator==(const T&, const U&);
  bool operator!=(const T&, const U&);
};
```

What about the call to `equal`?

- `equal` has this signature with concepts:

```
template<typeid Iter1, typeid Iter2>
  where { EqualityComparable2<
              InputIterator<Iter1>::value_type,
              InputIterator<Iter2>::value_type> }
  bool
  equal(Iter1 first1, Iter1 last1, Iter2 first2);
```

- Both `Iter1` and `Iter2` must model the `InputIterator` concept.

What about the call to `equal`?

- `equal` has this signature with concepts:

```
template<typeid Iter1, typeid Iter2>
  where { EqualityComparable2<
              InputIterator<Iter1>::value_type,
              InputIterator<Iter2>::value_type> }
  bool
  equal(Iter1 first1, Iter1 last1, Iter2 first2);
```

- `InputIterator` concept has **associated types**
  - Supersede the use of traits
  - Note: no `typename`!

EqualityComparable vs. EqualityComparable2

- vector == requires EqualityComparable
- std::equal requires EqualityComparable2
- How are they related?

EqualityComparable vs. EqualityComparable2

- vector == requires EqualityComparable
- std::equal requires EqualityComparable2
- How are they related?
  - EqualityComparable2 is more general
  - We call EqualityComparable a **refinement** of EqualityComparable2.

Refinement

- A concept `B` **refines** concept `A` if `B` includes all of the requirements of `A`.
  - Akin to inheritance of abstract classes
  - `RandomAccessIterator` refines `BidirectionalIterator`
- A better way to define `EqualityComparable`:

```
template<typename T>
concept EqualityComparable : EqualityComparable2<T, T>
{ };
```

`InputIterator` Concept

```
template<typeid Iter>
concept InputIterator : EqualityComparable<Iter>,
                        Assignable<Iter>,
                        CopyConstructible<Iter>
{
  typename value_type;
  typename difference_type;
  require Integral<difference_type>;
  const value_type& operator*(const Iter&);
  Iter& operator++(Iter&);
};
```

“Make the hard things possible”

```
template<typeid X>
concept Sequence : Container<X>
{
  typename value_type;
  typename iterator;
  require ForwardIterator<iterator>,
    ForwardIterator<iterator>::value_type == value_type;

  template<typeid Iter>
    where {
      Convertible<InputIterator<Iter>::value_type,
                  value_type> }
    X::X(Iter first, Iter last);
};
```

Summary of features

- Concepts
  - Refinement
  - Associated types
  - Pseudo-signatures
- Explicit models of concepts
- Where clauses describe requirements
  - Concept
  - Same-type
- Concept-based function selection

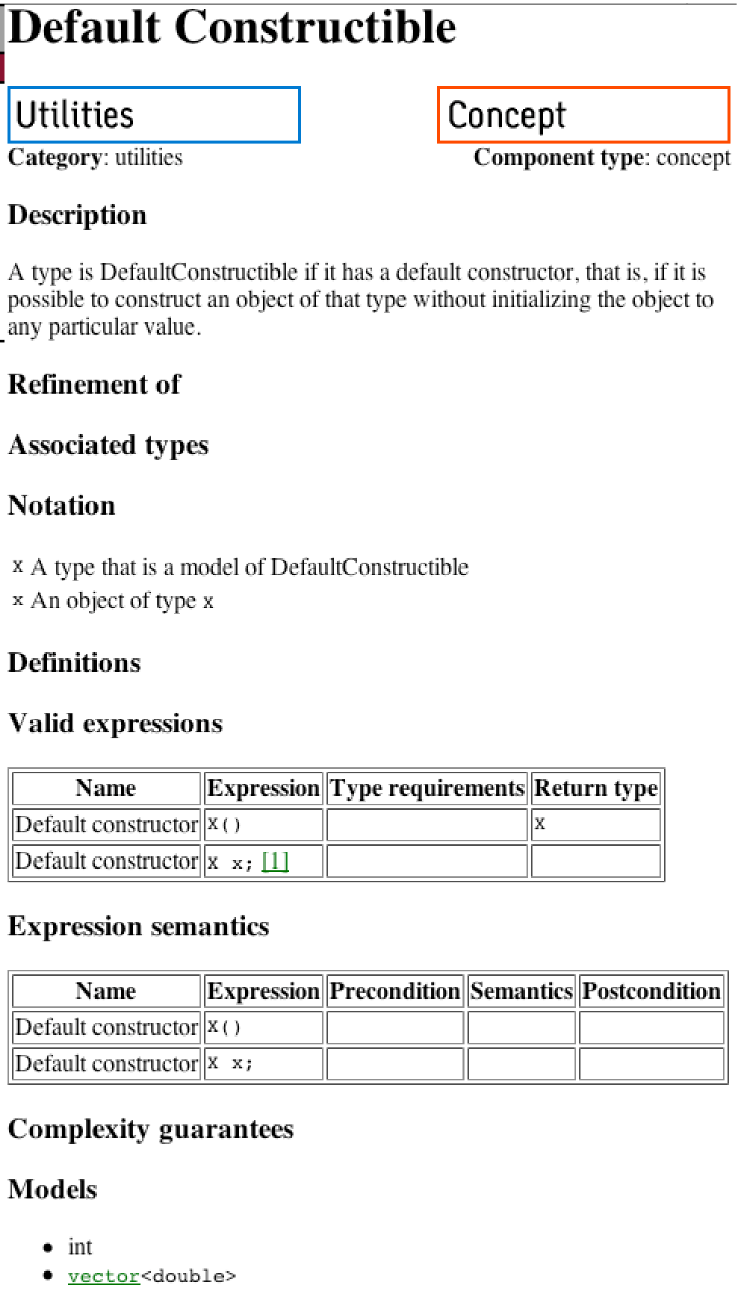
Existing practice and the Standard Library

Standard Library ⇔ Concepts

Requirements tables	⇔	Concepts
Template type parameter names	⇔	Where clauses
Loose syntactic requirements	⇔	Concepts + where clauses
Traits	⇔	Associated types, model declarations

Existing practice

- ☐ Excerpt from SGI STL documentation:



Default Constructible

Utilities

Concept

Category: utilities

Component type: concept

Description

A type is DefaultConstructible if it has a default constructor, that is, if it is possible to construct an object of that type without initializing the object to any particular value.

Refinement of

Associated types

Notation

`X` A type that is a model of DefaultConstructible

`x` An object of type x

Definitions

Valid expressions

Name	Expression	Type requirements	Return type
Default constructor	`X()`		`X`
Default constructor	`X x;` [1]		

Expression semantics

Name	Expression	Precondition	Semantics	Postcondition
Default constructor	`X()`			
Default constructor	`X x;`			

Complexity guarantees

Models

- int
- `vector<double>`

- ☐ As written with our proposal:

```
template<typeid X>
concept DefaultConstructible
{
  X::X();
};

model DefaultConstructible<int>  {};
model DefaultConstructible<vector<double> >
{ };

template<typename T>
  model DefaultConstructible<vector<T> >
{ };
```

Requirements tables

[20.1.3/1] In the following Table 30, T is a type to be supplied by a C++ program instantiating a template, t is a value of type T, and u is a value of type const T.

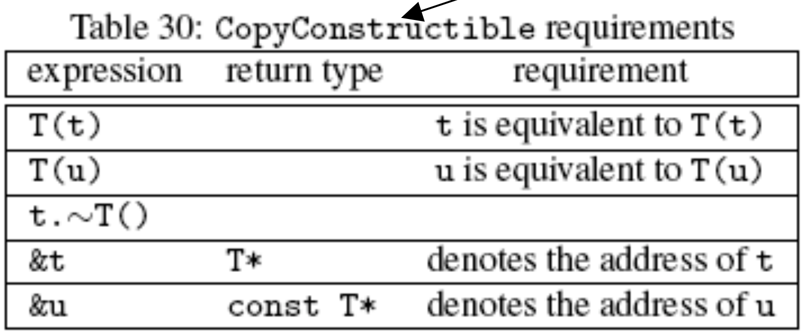


Table 30: `CopyConstructible` requirements

expression	return type	requirement
`T(t)`		`t` is equivalent to `T(t)`
`T(u)`		`u` is equivalent to `T(u)`
`t.~T()`		
`&t`	`T*`	denotes the address of `t`
`&u`	`const T*`	denotes the address of `u`

```
template<typeid T>
concept CopyConstructible
{
  T::T(T&);
  T::T(const T&);
  T::~T();
  T* operator&(T&);

  const T*
  operator&(const T&);
};
```

Impact on the C++ community

Impact on users

- Vast majority of code still works, unchanged
- Generic Programming becomes easier
  - Stronger typing for generic functions
  - Clean, concise error messages
  - Replace learning template tricks with learning Generic Programming
- Application code will need explicit model definitions
  - Not very often: the Standard Library handles most of them
  - Similar effort to inheriting abstract base classes

Impact on Standard Libraries

- Add `where` clauses as specified by the standard
- Option: conditionally enable `where` clauses for a single C++03/C++0x library
  - Tag dispatching & associated types a little harder
- Option: leave template parameters as `typename`
  - Checks uses of templates
  - … but not definitions!
  - Allows clever optimizations in library implementations

Impact on compilers

- Several parts to implementation
  - Concepts, refinement, pseudo-signatures similar to class templates
  - Models similar to class template specializations
  - Type-checking is still two-phase lookup
  - Where clauses are quite simple
- We’re addressing this on several fronts
  - Nontrivial portion of STL implemented in $\mathscr{G}$
  - Prototype in GCC

Summary of the proposal

- We propose complete support for Generic Programming in C++ that:
  - Makes Generic Programming accessible
  - Reflects existing practice
  - Is expressive enough for the **entire** C++ Standard Library
  - Is implementable in current C++ compilers

Explicit vs. Implicit Model Declarations

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Definitions Recap

- A **model declaration** states that a type or set of types meet the syntactic and semantic requirements of a concept.
- With **implicit** model declarations, the compiler performs **structural matches** to determine if a set of types model a concept.
- With **explicit** model declarations, the **user states** that a set of types model a concept.

Implicit Model Declarations

Benefits

- User need not fully understand concepts
- Backward compatibility
- Matches what we do now in C++ (sometimes [*])

Problems

- Accidental conformance [*]
- Implementation complexity [*]

[*] Indicates that we have examples for these points.

Accidental Conformance

- Occurs when the semantics assumed due to a structural match are incorrect.
- Consider `istream_iterator`:
  - Structurally matches `ForwardIterator`.
  - Semantically matches `InputIterator`.
  - With implicit models, compiler can't catch this error.
-
  ```
  vector<int> v(istream_iterator<int>(cin),
                istream_iterator<int>());
  ```

Accidental Conformance

- Occurs when the semantics assumed due to a structural match are incorrect.
- Consider `istream_iterator`:
  - Structurally matches `ForwardIterator`.
  - Semantically matches `InputIterator`.
  - With implicit models, compiler can't catch this error.

-
  ```
  vector<int> v(istream_iterator<int>(cin),
                istream_iterator<int>());
  ```
- Why doesn't this problem happen now?

Accidental Conformance

- Occurs when the semantics assumed due to a structural match are incorrect.
- Consider `istream_iterator`:
  - Structurally matches `ForwardIterator`.
  - Semantically matches `InputIterator`.
  - With implicit models, compiler can't catch this error.
-
  ```
  vector<int> v(istream_iterator<int>(cin),
                istream_iterator<int>());
  ```
- Why doesn't this problem happen now?
  - `iterator_category` is an explicit model declaration!

Nominal conformance in N1782

- The refinement hierarchy uses nominal conformance
- Overloading is not structural (see Section 6.3 of N1782)

Implementation Complexity

- Structural matching requires SFINAE-like behavior
  - For arbitrary types & expressions
  - Compiler must quietly “back out” if structural match fails
  - Compiler initiates search for structural matches
- Implementors have claimed this is difficult

Explicit Model Declarations

Benefits

- Strong semantic guarantees
  - No accidental conformance
  - Better optimization [*]
- Matches what we do now in C++ (sometimes)

Problems

- Not fully backward-compatible [*]
- Users must understand concepts [*]
- Users must write model declarations

[*] Indicates that we have examples for these points.

Backward Compatibility

- User will need to add model declarations
- Some ways to avoid these:
  - Where model declarations already exist as traits, we can create model templates (e.g., in the standard library)
  - Falling back to (weak) structural matching can be accomplished with model templates and metaprogramming.
  - Some concepts (e.g., DefaultConstructible) may be so basic that the compiler should add the models.

“Porting” `iterator_traits`

```
template<typename OldIter>
  where { Convertible<typename std::iterator_traits<OldIter>::category,
                      std::input_iterator_tag> }
  model InputIterator<OldIter> {};

template<typename OldIter>
  where { Convertible<typename std::iterator_traits<OldIter>::category,
                      std::output_iterator_tag> }
  model OutputIterator<OldIter> {};

template<typename OldIter>
  where { Convertible<typename std::iterator_traits<OldIter>::category,
                      std::forward_iterator_tag> }
  model ForwardIterator<OldIter> {};

template<typename OldIter>
  where { Convertible<typename std::iterator_traits<OldIter>::category,
          Convertible<std::forward_iterator_tag>,
         is_same<typename std::iterator_traits<OldIter>::reference,
                 typename std::iterator_traits<OldIter>::value_type&>::value
  model MutableForwardIterator<OldIter> {};
```

Better Optimization

- Explicit models are semantic guarantees
  - Needed by generic functions
  - Usable by compilers & optimizers
- Examples:
  - `CopyConstructible`/`Assignable` copy propagation
  - Parallelize `RandomAccessIterator` loops
  - `VectorSpace` loop fusion
- Is this feasible?
  - It’s still somewhat of a research topic, but…
  - Could find some important optimization opportunities

Users must understand concepts

- What if the user forgets a model declaration?
  - Compiler provides message like “type Foo does not model the InputIterator concept.”
  - User needs to know what that means.
- Mitigating factor: the compiler can suggest model declarations.

```
sort_list.cpp:7: error: no matching function for call to 'sort(std::_List_iterator<int>,
     std::_List_iterator<int>)'
/…/bits/stl_algo.h:2559: note: candidates are: void std::sort(_RandomAccessIterator,
     _RandomAccessIterator) [with _RandomAccessIterator = std::_List_iterator<int>]
     <failed requirements>
sort_list.cpp:7: note:   unable to locate a model
     'std::MutableRandomAccessIterator<std::_List_iterator<int> >'
sort_list.cpp:7: note:   for concept requirement
'std::MutableRandomAccessIterator<_RandomAccessIterator>' (you may need to write a model
     definition)
```

Our View

- Concepts have semantic requirements
  - We need users to state that their types meet these requirements
  - It’s common practice to do so (e.g., iterators)
  - Optimization, simpler implementation just side benefits
- Backward compatibility is one-time hit
  - Big benefits once the jump is made
  - Compilers, libraries, and tools can help bridge the gap.

Pseudo-signatures vs. Usage Patterns

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Definitions recap

- **Pseudo-signatures** look like function declarations or definitions, but match a class of functions.
- **Usage patterns** illustrate the syntax that generic functions will use, but match a class of functions.

Semantics are the same

- One-sided leniency for both syntax kinds
  - Strict checking of concept uses in generic functions
  - “Convertible-to” okay in models (implicit and explicit)
  - Misunderstandings and prior issues obscure this
- Can both express concepts in the Standard Library
  - `->` operator gives usage patterns some trouble
  - `OutputIterator` is hard on both syntax kinds

Pseudo-signatures

- Declarations look like function declarations:

```
bool operator==(const T&, const U&);
bool operator!=(const T&, const U&);

template<typeid Iter>
    where {
      Convertible<InputIterator<Iter>::value_type,
                  value_type> }
    X::X(Iter first, Iter last);
```

Usage patterns

- Declare variables to be used in expressions:

```
T t;
U u;
Input_Iterator Iter;
Iter i, j;
static_assert
  Convertible<Iter::value_type, value_type> {};
```

- Write expressions describing how objects can be used:

```
(bool)(t == u);
(bool)(t != u);
X(i, j);
```

`operator->`

- Not possible in general for usage patterns (see N1782)
- Pseudo-signatures use, e.g.,:
  `T* operator->(const X&);`
- Impact: Probably need a built-in `Arrow` concept to support usage patterns

Compound expressions

- Usage patterns can represent compound expressions:

```
 T a, b, c;
 (T)(a * b + c);
```

  - Internal type of `a * b` is unknown/irrelevant
- Pseudo-signatures require naming the type:

```
typename mul_type;
mul_type operator*(T, T);
T operator+(mul_type, T);
```

  - `mul_type` can use a `decltype` default to save the user some effort

Compound expressions: Impact

- Input and output iterator postincrement is specified as a compound expression
  - Just list the expression with usage patterns
  - Requires introduction of a hidden type for each concept
    - See N1758 for details

Should models look like concepts?

- If a model looks like one of these:

```
static_assert FG<X> {
  void f(X& a) { a.f(); }
  void X::g() { g(*this); }
};
```

```
model FG<X> {
  void f(X& a) { a.f(); }
  void X::g() { g(*this); }
};
```

- What should the concept look like?

```
concept FG<class T> {
  T a;
  f(a);
  a.g();
};
```

```
template<typeid T>
concept FG {
  void f(X& a);
  void X::g();
};
```

Expression templates

- Expression templates require lots of “hidden” types
  - One for each subexpression
- Impact:
  - Usage patterns: list every expression in the function body as a usage pattern
  - Pseudo-signatures: add pseudo-types for each subexpression
- Distinction between “opaque” and “non-opaque” types in N1758 offers one solution.

Syntax: Pseudo-signatures

- Pros:
  - Match free & member function syntax
  - Model syntax matches concept syntax
  - Concepts resemble abstract classes
  - Very little new parser technology
- Cons:
  - More verbose than usage patterns
  - Compound expressions are more painful
  - Standard Library (and other generic libraries) use usage patterns/valid expressions

Syntax: Usage patterns

- Pros:
  - Concise
  - Similar to existing requirements tables
  - Very little new parser technology
- Cons:
  - Usage patterns look different from the things they describe (no cut ‘n’ paste coding)
  - Need built-in `Arrow` concept
  - Determining which declarations declare values vs. types can be confusing.

Our View

- It’s just a syntax issue
- Which is “more readable”?
  - It’s a toss up: good and bad examples for both
  - We like how pseudo-signatures look like the function declarations they match
    - How does one implement a new model of a concept? Copy ‘n’ paste!
    - No “hidden” template requirements

Associated Types

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Where do associated types live?

- N1758: As associated types of concepts
  - `ForwardIterator<Iter>::value_type`
- N1782: As member types of types involved in concepts
  - `Iter::value_type`

Ambiguity with member types

```
concept Callable1<F,T1> {
  typename F::result_type;
  F f; T1 t1;
  (F::result_type)(f(t1));
};

struct negate {
  template<typename T> operator()(T x) { return -x; }
};

static_assert Callable1<negate, int>
  { typedef int negate::result_type; };

static_assert Callable1<negate, float>
  { typedef float negate::result_type; };
```

// (what is negate::result_type?)

Our View

- Using member types can be awkward
  - Potential ambiguities with syntax
  - Odd to add member types to non-classes
  - There isn't always a "main type" to hang on
- Associated types are naturally part of concepts
  - Multiple types of a concept participate to produce associated types
  - Traits use this same level of indirection

Semi-structured additional slides

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std::distance with concepts

```
template<typeid Iter> where { InputIterator<Iter> }
InputIterator<Iter>::difference_type
distance(Iter first, Iter last)
{
  InputIterator<T>::difference_type result = 0;
  for (; first != last; ++first)
     ++result;
  return result;
}
```

- Things to notice:
  - We’ve added more to the declaration
  - The body really hasn’t changed

std::distance with concepts

```
template<typeid Iter> where { InputIterator<Iter> }
InputIterator<Iter>::difference_type
distance(Iter first, Iter last)
{
  InputIterator<T>::difference_type result = 0;
  for (; first != last; ++first)
     ++result;
  return result;
}
template<typeid Iter>
   where { RandomAccessIterator<Iter> }
RandomAccessIterator<Iter>::difference_type
distance(Iter first, Iter last)
{
  return last - first;
}
```

Concepts

```
template<typeid Iter> where { InputIterator<Iter> }
InputIterator<Iter>::difference_type
distance(Iter first, Iter last)
{
  InputIterator<T>::difference_type result = 0;
  for (; first != last; ++first)
     ++result;
  return result;
}
```

- A **concept** is a set of requirements
  - Syntactic: functions, operators, types
  - Semantic: what functions do, function complexity
  - Like requirements tables in the standard

`InputIterator` Concept

```
template<typeid Iter>
concept InputIterator : EqualityComparable<Iter>,
                        Assignable<Iter>,
                        CopyConstructible<Iter>
{
  typename value_type;
  typename difference_type;

  const value_type& operator*(const Iter&);
  Iter& operator++(Iter&);
};
```

- Things to note:
  - Has types `value_type` and `difference_type`
  - Has pseudo-signatures for operators ++ and *
  - **Refines** `EqualityComparable`, `Assignable`, and `CopyConstructible`

Opaque template parameters

```
template<typeid Iter> where { InputIterator<Iter> }
InputIterator<Iter>::difference_type
distance(Iter first, Iter last)
{
  InputIterator<T>::difference_type result = 0;
  for (; first != last; ++first)
     ++result;
  return result;
}
```

- `typename` eliminates type checking: you can do anything to `typename` types.
- `typeid` provides type checking: you can do nothing but what you require
- Type checking has two phases already!

`where` clauses

```
template<typeid Iter> where { InputIterator<Iter> }
InputIterator<Iter>::difference_type
distance(Iter first, Iter last)
{
  InputIterator<Iter>::difference_type result = 0;
  for (; first != last; ++first)
     ++result;
  return result;
}
```

- `where` clauses constrain templates
  - Example: `Iter` must **model** the `InputIterator` concept
  - User must pass in types that meet these requirements
  - Implementor must only use types and operations mandated by the requirements

Associated types

```
template<typeid Iter> where { InputIterator<Iter> }
InputIterator<Iter>::difference_type
distance(Iter first, Iter last)
{
  InputIterator<T>::difference_type result = 0;
  for (; first != last; ++first)
     ++result;
  return result;
}
```

- Associated types are additional types used to specify a concept
  - Remember `difference_type` from `InputIterator`?
  - Supersedes traits
  - Note: no `typename`!

How do we call distance?

- Just like we always have:

```
list<int> l; // initialize l
cout << “Length = ”
     << distance(l.begin(), l.end()) << endl;
```

- Most uses of concepts will be invisible
  - They provide better type safety
  - It’s easier to write correct templates
  - Standard library provides its own models
  - Compiler will provide some concepts “for free.”

More same-type constraints

- Consider `std::merge`:

```
template<typeid Iter1, typeid Iter2, typeid OIter,
         typeid T>
  where {
    InputIterator<Iter1>::value_type == T,
    InputIterator<Iter2>::value_type == T,
    Convertible<OutputIterator<OIter>::value_type, T>,
    StrictWeakOrdering<T> }
Oiter merge(Iter1 first1, Iter1 last1,
            Iter2 first2, Iter2 last2, OIter out);
```

Sequence requirements

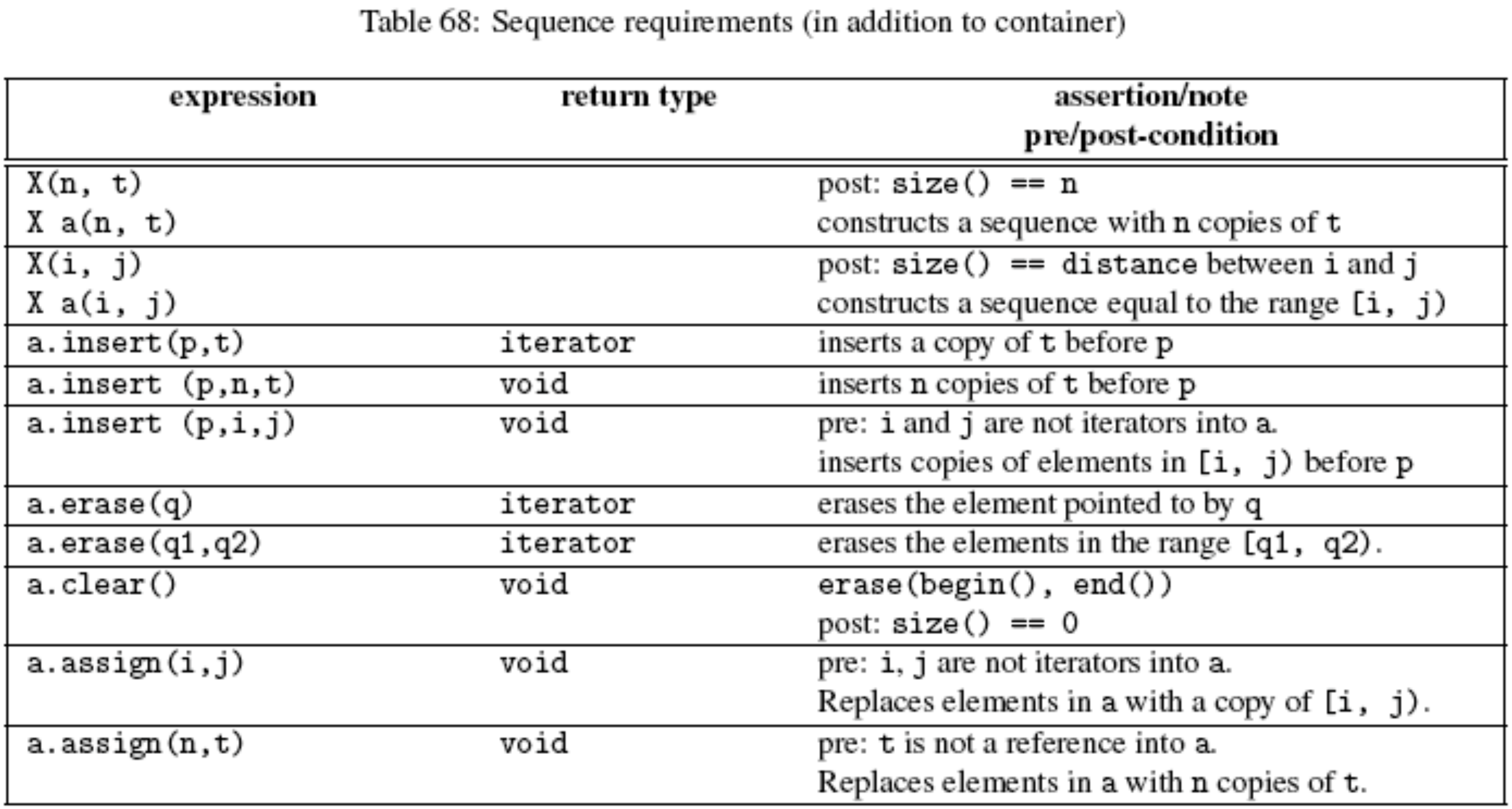

Table 68: Sequence requirements (in addition to container)

expression	return type	assertion/note pre/post-condition
`X(n, t)` `X a(n, t)`		post: `size() == n` constructs a sequence with `n` copies of `t`
`X(i, j)` `X a(i, j)`		post: `size() == distance` between `i` and `j` constructs a sequence equal to the range `[i, j)`
`a.insert(p,t)`	`iterator`	inserts a copy of `t` before `p`
`a.insert (p,n,t)`	`void`	inserts `n` copies of `t` before `p`
`a.insert (p,i,j)`	`void`	pre: `i` and `j` are not iterators into `a`. inserts copies of elements in `[i, j)` before `p`
`a.erase(q)`	`iterator`	erases the element pointed to by `q`
`a.erase(q1,q2)`	`iterator`	erases the elements in the range `[q1, q2)`.
`a.clear()`	`void`	`erase(begin(), end())` post: `size() == 0`
`a.assign(i,j)`	`void`	pre: `i`, `j` are not iterators into `a`. Replaces elements in `a` with a copy of `[i, j)`.
`a.assign(n,t)`	`void`	pre: `t` is not a reference into `a`. Replaces elements in `a` with `n` copies of `t`.

Why propose language support?

- Generic Programming is gaining acceptance
    - C++ Standard Library is prototypical example
    - Still too much work to use GP
    - Java, C# now support templates/generics
- Conventions are okay, but language support is better
    - The ideas of GP can be expressed more clearly
    - Better tool support
- We are at the *tipping point*

Revisiting vector ==

- How does this type-check?:

```
template<typeid T, typeid Alloc>
  where { EqualityComparable<T> }
  bool operator==(const vector<T, Alloc>& x,
                  const vector<T, Alloc>& y)
  {
    return x.size() == y.size()
           && equal(x.begin(), x.end(), y.begin());
  }
```

- The only operations on `T` objects are in `std::equal`
- `std::equal` requires EqualityComparable2
  - Okay, since `EqualityComparable` implies `EqualityComparable2`
- `std::equal` requires InputIterators
  - Okay, since `vector<T>::const_iterator` models `RandomAccessIterator`.

“Small” example

```
template<typeid T, int N>
concept Small
{
  require sizeof(T) <= N;
};

template<typename T, int N>
  where {sizeof(T) <= N }
  model Small<T, N> {};

template<typename T> where {Small<T,200> } void f(T&);
template<typename T> void f(T&);

template<typename T>
  void foo(const T& t)
  {
    f(t);
  }
```