Meta-Programming with C++
More Meta-Programming with C++11

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Agenda

- Introduction
- C++ Meta-Programming
  - Binders or Meta-Programming light
  - Expression Templates
  - Templates with Non-Typenames
  - Meta-Programming with Templates
- C++11 Meta-Programming
  - Meta-Programming with constexpr
  - Concepts
  - Meta-Programming with Concepts
  - Variadic Templates

Introduction

- Meta Programming Definitions
  - Programming that manipulates program entities
  - Programs that compute at compile time and generate programs
- Why would we want to do this?
  - Improved type safety
  - Improve runtime performance by computing values at compile-time
  - Improve code readability

Generic Programming vs Meta Programming

- Theoretically,
  - any template instantiation is meta-programming
  - any use of the pre-processor is meta-programming
  - all we do is write generic programs
- Practically, the intent indicates whether it is meta-programming
- When implementing a generic type (min, find_if)
  - I would not feel like writing a meta-program
  - The intent of the exercise is to write one algorithm that is the same for many different types
- When writing a meta-program (difference)
  - I want that the compiler takes a decision at compile time
  - Whether to use the *forward iterator* or *random access iterator* algorithm

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Binders - Motivation

- Want to find an element in a container that fulfills a criterion
- For instance, first element in the container that is less than a given value
- In Java
  - If the container provides this fine (unlikely)
  - If not, we start implementing our own routine

Locating an Element

```
int less_than_17(int x) {
  return x<17;
}

void foo(vector<int> v) {
  vector<int>::iterator b=r.begin(), e=r.end(), i;
  i=find_if(b, e, less_than_17);
  …
}
```

- Having to write that helper function is bothersome
- How can we improve this (without using C++11 lambdas)

Function Objects

Predicates `<functional>`

- `equal_to`, `not_equal_to`
- `greater`, `greater_equal`, `less`, `less_equal`
- `logical_and`, `logical_or`
- `logical_not` (unary)

Arithmetic Operations `<functional>`

- `plus`, `minus`, `multiplies`, `divides`, `modulus`
- `negate` (unary)

Locating an Element

```
void foo(vector<int> v) {
  vector<int>::iterator b=r.begin(), e=r.end(), i;
  i=find_if(b, e, bind2nd(less<int>(),17));
  …
}
```

- We say we want that the greater than function is executed
- Problem greater than takes two arguments
- Solution, the bind2nd function binds one argument to a given value

bind2nd(binop,arg2)

- Binds the second argument of a function
- If I have already a function less/2 one would not like to write another one less/1 for all possible arguments

- Implementation
  - Need to store a binary operation binop and the second argument arg2

  => We need a function object to implement this

our_binder2nd

```
template <typename BinOp>
class our_binder2nd {
protected:
  BinOp op;
  Arg2 arg2;
public:
  our_binder2nd(BinOp o, Arg2 a2) : op(o), arg2(a2) {}
  Res operator() (Arg1 arg1) { return op(arg1,arg2); }
};
```

How can we identify these types?

- Solution
  - Function Object Bases
  - They provide standardized names for arguments, and return types

Function Object Bases

- Provide standardized names for arguments, and return types for function objects
- Use them religiously!

```
template <class Arg, class Res> struct unary_function {
  typedef Arg argument_type;
  typedef Res result_type;
};
template <class Arg, class Res> struct binary_function {
  typedef Arg first_argument_type;
  typedef Arg second_argument_type;
  typedef Res result_type;
};
```

bind2nd

```
template <class BinOp>
class binder2nd : public
  unary_function<BinOp::first_argument_type, BinOp::result_type>
{
protected:
  BinOp op;
  typename BinOp::second_argument_type arg2;
public:
  binder2nd(const BinOp &o,
            const typename BinOp::second_argument_type &a2)
    : op(o),arg2(a2) {}
  result_type operator() (const argument_type &arg1) {
    return op(arg1,arg2); }
};
template<class BinOp, class T> binder2nd<BinOp>
bind2nd(const BinOp &o, const T &v) {
  return binder2nd<BinOp>(o,v); }
```

find_if(…,bind_2nd(less,17))

```
find_if(I f, I l, Op op)
{ while(f!=l) op(*f++); }
```

op=binder_2nd{op=less,a=17}

```
op.operator() (T x)
{ return op(x, a); }
```

```
less(x,17)
```

Binders, Adapters, Negaters

Binders `<functional>`

- `bind1st`, `bind2nd`

Adapters `<functional>`

- `mem_fun`, `mem_fun_ref`, `ptr_fun`

Negaters `<functional>`

- `not1`, `not2`

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Motivation

- Callback functions can be expensive and difficult to read
  - a=integrate(evaluatef, 0.0, 10.0);
- Multiplication of vectors and arrays is either very expensive or very unreadable
  - Fusion of loops
  - Vector a(…), b(…), c(…); c=a*b+c;
  - Matrix a(…), b(…), c(…); c=a*(b+c);
- Use templates as a mechanism to change how the program is being compiled
  - Also known as meta-programming
  - Yes, templates are not necessarilly the most readable mechanism for this

Function Objects

- Inline expansion possible
- Not always possible
- Sometimes *unreadable*

```
template <class Op>
double integrate(Op op, double x0, double x1) { … }

double evaluatef(double x) { return 2.0*x/(1.0+x); }

void foo() {
  ...
  cout << integrate(evaluatef(), 0.0, 10.0) << endl;
}
```

Expression Templates

- Allow expressions to be passed as function argument
  - `a=integrate(2.0*x/(1.0+x), 0.0, 10.0)`
- This idea is nothing new, binders work similar
  - `i=find_if(…,bind_2nd(less(),17))`
- Taking the expression apart
  - `2.0*x` would be similar to `bind_1st(mul,2.0)`
  - `1.0+x` would be similar to `bind_1st(add,1.0)`
- How do we model the division?

combineops

```
template <class Op, class O1, class O2>
struct combineops_t :
public unary_function<O1::arg_t, Op::res_t> {
  Op op; O1 o1; O2 o2;
  combineops_t(combineops_t(Op binop, O1 op1, O2 op2)
    : op(binop), o1(op1), o2(op2) {}
  res_t operator() (arg_t x) {
    return op(o1(x),o2(x));
  }
};

template <class Op, class O1, class O2>
struct combineops_t
combineops(Op op, O1 o1, Op2 o2) {
  return combineops_t<Op,O1,O2>(op,o1,o2);
}
```

combineops: Usage

```
a=integrate(combineops(div,
                       bind_1st(mul,2.0),
                       bind_1st(add,1.0)),
            0.0, 10.0);
```

- This expression is not yet more readable BUT soon it will be

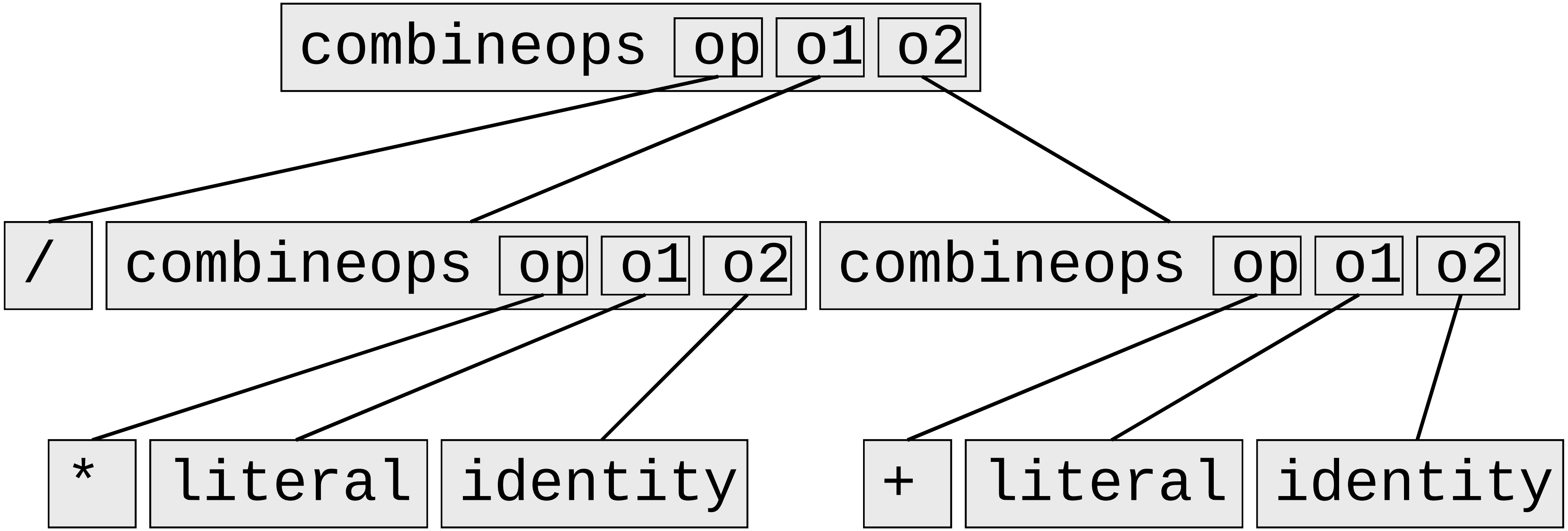
`combineops`: Readability I

New (unary) function objects

- `literal_t/literal` returning a constant
- `identity_t/identity` returning x (the argument itself)

```
void foo() {
  identity_t<double> x();
  a=integrate(combineops(div,
              combineops(mul,literal(2.0),x),
              combineops(add,literal(1.0),x)),
            0.0, 10.0);
  cout << a << endl;
}
```

Expression Tree



combineops: Readability II

- Define operators /, *, … returning the according combineops objects

```
template<class T>
combineops_t<mul, literal_t<T>, identity_t<T> >
operator* (literal_t<T> l, identity_t<T> i) {
  typedef combineops_t<mul,literal_t<T>,identity_t<T> > r;
  return r(mul,l,i);
}

// define *, /, … for
// literal_t and combineops_t
// identity_t and identity_t
// identity_t and combineops_t
// …
```

`combineops`: Usage

```
void foo() {
  identity_t<double> x();
  double a;
  a=integrate(literal(2.0)*x/(literal(1.0)+x)),
              0.0, 10.0);
  cout << a << endl;
}
```

- Looks good?
- `literal(2.0)` could be be written as 2.0 if `operator*(double, …)` were defined as well

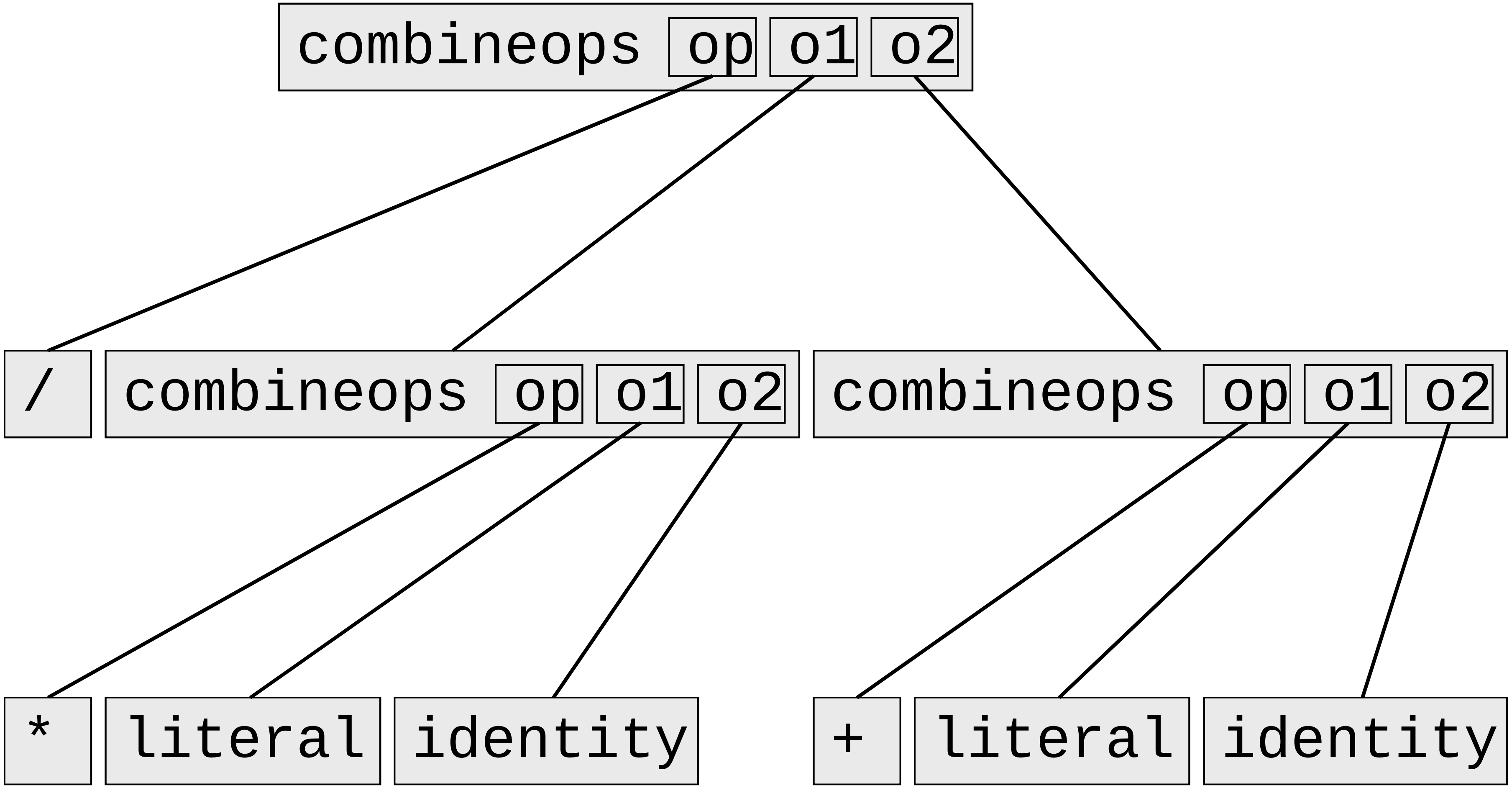
Summary

- + Achieved our goal
- - Somewhat clumsy to define all the different operator combination
- - Error prone

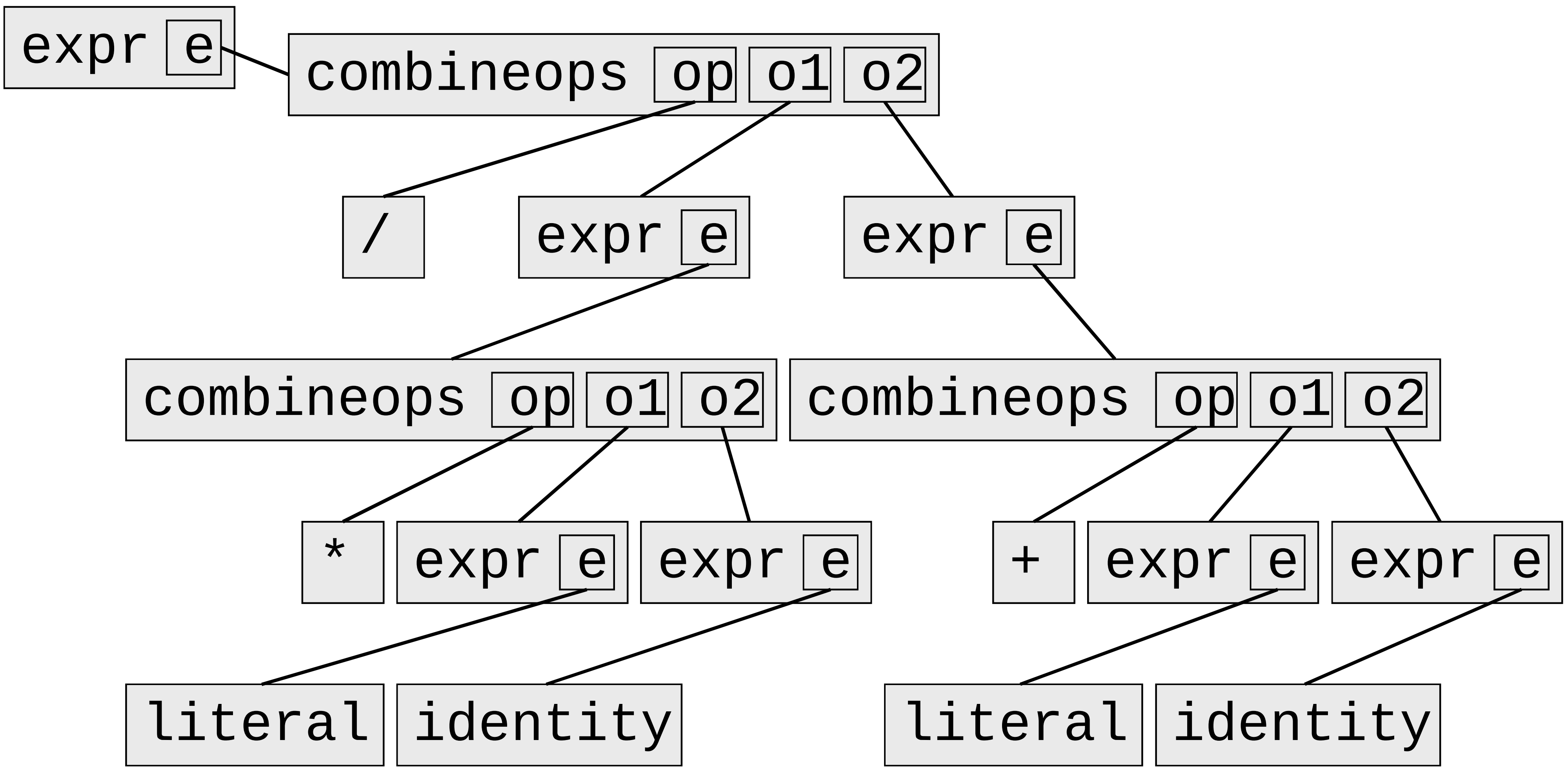
Second Approach

- First approach error prone
  - Too many combinations of argument types for +, /, … operators

Expression Tree (1st)



Expression Tree (2nd)



ET for Vectors

- Vector a(…), b(…), c(…); c=a*b+c;
- Similar to expressions but using iterators
- So where do we place the loop to iterate over all the elements?

```
template<class A>
Dvec& Dvec::operator=(DVExpr<A> expr) {
  for(iterator i=begin(), last=end(),
      i!=last;
      i++, expr++) *i=expr();  // i=*expr in Veldhuizen
  return *this;
}
```

ET for Matrices

- Matrix a(…), b(…), c(…); c=a*b+c;
- See “Generic Programming in POOMA and PETE”…

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Templates with Non-Typenames

- Classes can not only be parameterized over a specific type but also over a specific int (or whatever)

array.cc

```
template<typename T, int SZ>
class array {
  T[SZ] rep;
public:
  T &operator[](int i) {
    if(i>SZ) { /* handle error */ }
    else return rep[i];
  }
  …
```

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Meta-Programming with Templates

- What does this code do? Where would it be useful?

compute.cc

```
template<int P, int N> struct compute2 {
  static const int res=compute2<P,P%N?N-1:0>::res;
};
template<int P> struct compute2<P,1> {
  static const int res=1; };
template<int P> struct compute2<P,0> {
  static const int res=0; };
template<int N> struct compute {
  static const int res=compute2<N,N-1>::res; };
int main() {
  cout << compute<3>::res << "," << compute<4>::res << ","
       << compute<5>::res << endl; }
```

Meta-Programming with Templates

- Yes, the code checks whether the number is a prime number

primes.cc

```
template<int P, int N> struct isprime2 {
  static const int res=isprime2<P,P%N?N-1:0>::res;
};
template<int P> struct isprime2<P,1> {
  static const int res=1; };
template<int P> struct isprime2<P,0> {
  static const int res=0; };
template<int N> struct isprime {
  static const int res=isprime2<N,N-1>::res; };
int main() {
  cout << isprime<3>::res << "," << isprime<4>::res << ","
       << isprime<5>::res << endl; }
```

Meta-Programming with Templates

- Where is the previous code useful?
- If we need somewhere a prime if we add a template to compute the next prime

```
template<typename T> class my_hash_table {
  T table[compute_next_prime<20000>::res];
  …
};
```

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Meta-Programming in C++11

- Expression Templates as in the integration sample
  - Largely not necessary since we have lambda functions

- If we want to do things like vector multiplications
  - Expression template syntax is still nicer to use
  - Logic hidden in the assignment operator
  - No lambda expression just Vector v=a*b;

- For matrices, we cannot use lmbda expressions
  - Loops need to be enrolled in an interleaved form

Meta-Programming in C++11

- C++11 makes our life easier (and more complicated again)
- Meta-programming with constexpr

```
constexpr bool isprime2(int i, int n) {
  return (n%i==0) ? false
    : (i*i<n) ? isprime2(i+2,n) : true;
}
constexpr bool isprime(int n) {
  return (n%2==0) ? (n==2) : isprime2(3,n);
}
constexpr int nextprime(int i) {
  return isprime(i) ? i : nextprime(i+1);
}
int main(int argc, char *argv[]) {
  constexpr int res=nextprime(1234567890);
  cout << res << endl; }
```

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Concepts

- In C++, we can encode concepts
- These concepts can be used to limit the scope of our templates
  – is_copy_assignable<T>::value: true if type T may be copied (readily supported in C++11)
  – (LessThanComparable<T>) compilation will only succeed if T is LessThanComparable (from boost.org)

```
#include <type_traits>
#include <boost/concept_check.hpp>

template<typename T>
class rpn_calculator {
  static_assert(is_copy_assignable<T>::value,
           "rpn_calculator's number type must be a copy assignable type");
  BOOST_CONCEPT_ASSERT((boost::LessThanComparable<T>));
  …
```

Concepts (cont'd)

- Concepts allow us to catch errors early
- Somewhere we instantiate our rpn_calculator
  - The rpn_calculator is parameterized with complex<float>
  - Somewhere the rpn_calculator uses a min function (again a template)
  - Somewhere the min function uses < (less_than) to identify the minimum
  - Complex numbers do not support < (less_than) which is an error
- Without concepts, the C++ compiler will tell us all this
  - (194 lines of errors in my rpn_calculator implementation)
  - Need to sift through the "entire" implementation to understand the error
  - Now, imagine there may have been more indirections
- Concepts make the compiler fail early
  - At the static_assert
  - The implementor knows what is necessary, typically we do not care why

Concepts (cont'd)

- We can implement more readable/useful concepts as follows
  - CopyAssignable<T>(): true if type T may be copied
  - Ordered<T>(): true if T has an ordering
- There "should" be already libraries available that do this (Bjarne Stroustrup. The C++ Programming Language, 4th Ed.)

```
#include <type_traits>

template<typename T>
class rpn_calculator {
  static_assert(CopyAssignable<T>(),
              "rpn_calculator's number type must be a copy assignable type");
  static_assert(Ordered<T>(),
              "rpn_calculator's number type must be an ordered type");
  …
```

Implementation of CopyAssignable<T>() and Ordered<T>()

```
#include <type_traits>
template<typename T> constexpr int CopyAssignable() {
  return is_copy_assignable<T>::value; }
template<typename T> struct is_ordered {
  enum { value = 0 }; };
template<> struct is_ordered<int> {
  enum { value = 1 }; };
template<> struct is_ordered<long> {
  enum { value = 1 }; };
template<> struct is_ordered<float> {
  enum { value = 1 }; };
template<> struct is_ordered<double> {
  enum { value = 1 }; };
template <typename T> constexpr int Ordered() {
  return is_ordered<T>::value; }
```

These definitions should be provided as part of a library.

Optimizing rpn_calculator

- Concept checking makes life easy
- In case of the complex numbers not being able to use the rpn_calculator at all may not be very rewarding
- Ideally, we want to disable the minimum function

rpn_calculator with optional min (Naïve approach)

```
template<typename T>
class rpn_calculator {
  …
  void run(void) {
    for(;;) {
      …
      if (…) {
        …
      } else if (cmd=="m" && n>=2 && Ordered<T>()) {
        T b=pop_back(), a=pop_back();
        push_back(min(a,b));
      } else {
        cerr << "Unknown command" << endl;
      }
    }
  }
}
```

Problem: the compiler still compiles the dead code (pruned only afterwards)

Solution: wrap min into mymin

Wrapping min

- We can create mymin as template and use partial specialization
  - Needs to be done for all non-ordered types
- C++11 provides an enable_if function that allows to selectively define functions based on a condition evaluated during compile time

```
template<bool B, typename T=void>
using Enable_if = typename std::enable_if<B,T>::type;

template<typename T>  // standard wrapper for ordered types
Enable_if<Ordered<T>(), T> mymin(T x, T y) {
  return std::min(x, y); }

template<typename T>  // dummy implementation for others
Enable_if<!Ordered<T>(), T> mymin(T x, T y) { return 0; }
```

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Variadic Templates

- Wouldn’t it be nice to have printf that supports user-defined types?
- Let’s implement a simplified printf function
  - Arguments just specified as % (not %d, %g, etc)
  - % represented as %%
  - Our printf identifies the type automatically
  - Supports user-defined types

Variadic Templates (cont'd)

```
void printf(const char *s) {
  if (s==nullptr) return;
  while (*s) {
    if (*s==‘%’ && ++s!=‘%’) throw error(“missing argument”);
    cout << *s++;
  }
}
template<typename T, typename... Args>
void printf(const char *s, T value, Args... Args) {
  if (s==nullptr) throw error(“too many arguments”);
  while (*s) {
    if (*s==‘%’ && ++s!=‘%’) {
      cout << value; return printf(s, args...);
    }
    cout << *s++;
  }
  throw error(“too many arguments”); }
```

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Exercise 1

- Implement a function findIf(Iterator iter, Matcher matcher) in Java that finds the first element in the sequence defined by iter
- Matcher is an interface with a single method match return true if the element matches
- Implement in a separate Java file a benchmark that executes the above on a Vector with several millions of elements
- Implement the same benchmark in C++ with the C++ find_if method and, e.g., lambdas

Exercise 2

- Extend the RPN calculator such that the min function is available for ordered types but unavailable for unordered types (i.e., complex numbers).

Exercise 3

- Implement a function that merges the elements of two containers
  - Think of how to represent the containers
  - How shall the elements be added to the target containers
  - How can fundamentally different containers be merged? map and vector
  - Make use of templates

Exercise 4

- Implement an iterator that encapsulates another iterator (i.e., a sequence) and that performs range checking
- The iterator is initialized with the current element, and the first and last element of the sequence
- If the iterator points to the first element and is decreased OR if the iterator points to the last element and is increased signal an error – choose an appropriate form of signaling the error

Next Lecture

- More C++11 Features, Factories, Multi Methods, Repetitorium

Have fun solving the examples!

See you next week!