Functional Programming in C++

C++ Support for Functional Paradigm

Bartosz Kwaśniewski

Hi did it for all of us ;)

Bjarne Stroustrup

Hi did it for all of us ;)

Bjarne Stroustrup

"I wonder what would happen, if there were a language so complicated, so difficult to learn, that nobody would ever be able to swamp the market with programmers"

Claims and Questions

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Key Messages

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1. Paradigm shift towards functional programming **is necessary** and has already started
2. You could use **many styles** including object oriented and functional to make **better software**
3. There is no other option, **no turning back:** you **must learn** the functional paradigm

But, Why?

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  - Composability (concurrency not scale well)
  - Different approach: functional programming (purity, immutability)

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"When the limestone of imperative programming is worn away, the granite of functional programming will be observed."

Simon Peyton Jones (GHC)

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About Programming Paradigms

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- What does it mean that a language supports a paradigm well?

Paradigm Definition

- What is a paradigm?

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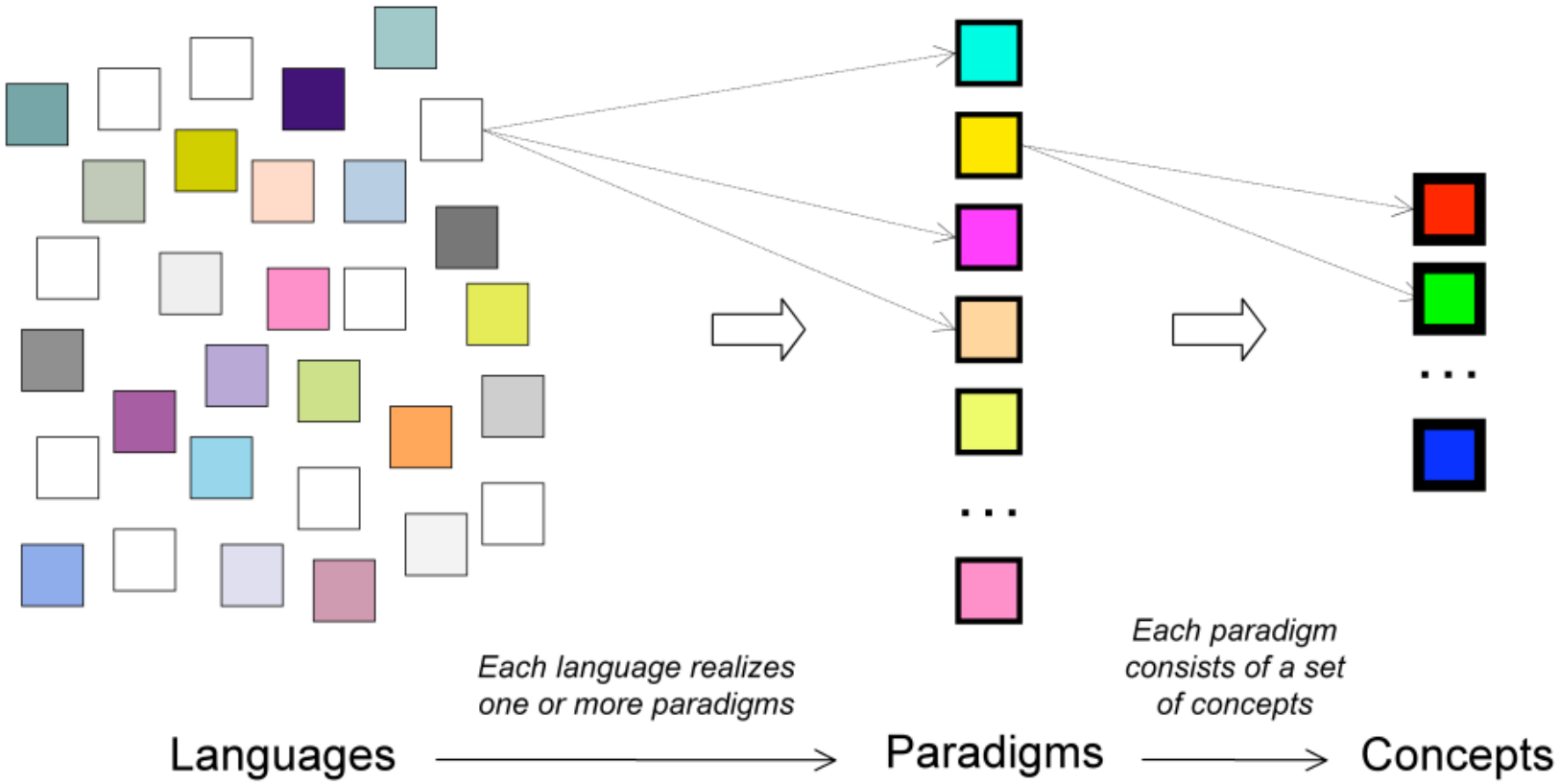
Programming style or approach based on a **coherent set** of programming concepts aimed to solve particular kind of problem.

Programming Languages, Paradigms and Concepts



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  2. However: this requires the **expetise level**

Paradigm Support: Conclusion

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  3. Only self-discipline

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- How does C++ implement functional concepts?

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  The program **is defined** by declarations or expression, not described by the series of steps.

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- No, we don't need to know that to write functional programs

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C++ Computation Types I

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//1. runtime computations
vector<int> v1{1,2,3};
transform(v1.begin(), v1.end(), v1.begin(), [](int i){return i + 1;});
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- constexpr computations

```
//2. constexpr computations
constexpr int factorial(int n) {
    return n <= 1? 1 : (n * factorial(n - 1));
}
static_assert(factorial(4) == 24);
```

C++ Computation Types II

- types computations

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//3. types computations
using types = mpl::vector<int, char, float, void>;
using pointers = mpl::transform<types, add_const_pointer<mpl::_1>>::type;
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- heterogeneous computations

```
//4. heterogeneous computations
fusion::vector<int, std::string, float> seq{1, "abc", 3.4f};
fusion::vector<std::string, std::string, std::string> strings
    = fusion::transform(seq, [](auto t) {std::stringstream ss;
       ss << t;  return ss.str();});
```

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  - **fold expressions**, constexpr if, constexpr lambda expressions, class template deduction, optional, any, variant, reduce

Functional Concepts

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- How does C++ implement those concepts?

FP Concepts and C++

concept	built-in	substitution
first-class function	-	function pointer, functors, std::function
higher-order function	-	function pointer, functors, std::function
pure function	-	const, move semantics, pass by value
anonymous function	-	lambda expression
nested function	-	nested classes, lambda expressions
type inference	auto, decltype	-
closures	-	lambda expressions
parial application	-	std::bind
currying	-	custom solutions with lambdas and templates
recursion with tco	sometimes	-
algebraic data types	-	compositions
pattern matching	-	mach7
lazy valuation	-	custom solution, suspension idiom
immutable data	-	custom solutions
polymorphic types	-	generics
list comprehension	-	custom solutions, range-v3
type classes and overloading	-	polymorhpism
automatic memory management	semi, smart pointers	-
monads	opional, variant	custom, libraries
combinators	-	custom solutions, libraries

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```
fib :: Int -> Int
fib 0 = 0
fib 1 = 1
fib n = fib (n - 1) + fib (n - 2)
```

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```
twice :: (a -> a) -> a -> a
twice f x = f (f x)
print(twice (+1) 2) -- prints 4
```

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  - lambda expressions

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  - Yes, classes are.
- So there are:
  - callable objects (std::function, custom)
  - lambda expressions

```
auto inc = [](int a){return a + 1;};
auto twice = [](auto f, int a){return f(f(a));};
cout << twice(inc, 2); //prints 4

auto hanatwice = hana::compose(inc,inc);
cout << hanatwice(2);
```

First Class and Higher Order Functions: C++

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- But what about function pointers?
  - It is only the address without bounded variables

Nested function: Haskell

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Nested function: Haskell

- What is a nested function?
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Nested function: Haskell

- What is a nested function?
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```
nested :: Integer -> Integer
nested x = f 1 + f 2 where f y = x + y
print (nested 1)  -- prints 5
```

Nested Function: C++

- Does C++ support nested functions?

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  - No, but we have...

Nested Function: C++

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```
auto nested = [](int x){
  auto f = [x](int y){return x + y;};
  return f(1) + f(2);
};
```

Anonymous Function: Haskell

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```
print ((\x y -> x + y) 1 2)
```

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            return f(a + 1);
        };
    }([](int c){return c + 1;})(2)
```

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```
cout << [](auto f){
        return [f](int a){
            return f(a + 1);
        };
    }([](int c){return c + 1;})(2)
```

- How many lambda expressions do we have here?

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```
cout << [](auto f){
        return [f](int a){
            return f(a + 1);
        };
    }([](int c){return c + 1;})(2)
```

- How many lambda expressions do we have here?
  - Three anonymous lambda expressions

Closure: Haskell

- What is a closure?

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```
sum :: Num a => a -> (a -> a)
sum y = \x -> x + y
```

Closure: C++

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- Closure terms related:
  - Lambda expression: expression, part of a source code
  - Closure class: a functor class generated for each lambda expression
  - Closure: object, instance of closure class

```
function<function<int(int)>(int, int)> closure = [](int a, int b) {
  return [a,b](int c){return a + b + c;};
};
cout << closure(1,2)(3) << endl; //prints 6
```

Partial application: Haskell

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```
partialSum :: Num a => a -> a -> a -> a
partialSum a b c = a + b + c
partialSum1 = partialSum 1
partialSum2 = partialSum1 2
print (partialSum2 3) -- prints 6
```

Partial Application: C++

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```
int addabc(int a, int b, int c) {
    return a + b + c;
}
//cout << addabc(1,2)(3);
//error: no matching function for call to addabc
//note: candidate function not viable: requires 3 args, but 2 were provided

cout << bind(addabc, 1, 2, _1)(3);
cout << hana::partial(addabc, 1, 2)(3);

cout << bind(addabc, 1, _1, _2)(2,3);
cout << hana::partial(addabc, 1)(2,3);

cout << bind(bind(addabc, 1, _1, _2), 2, _1)(3);
cout << hana::partial(hana::partial(addabc, 1),2)(3);
```

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- What is a currying application?

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```
--int to function
--f :: Int -> (Int -> Int)
f :: Int -> Int -> Int
f a b = a + b

--function to int
g :: (Int, Int) -> Int
g (a, b) = a + b

--Bidirectional transformation:
print (f 1 2 + g(1,2) + (curry g) 1 2 + (uncurry f)(1,2))
```

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```
int addabc(int a, int b, int c) {
    return a + b + c;
}

cout << hana::curry<3>(addabc)(1)(2)(3) << endl;
cout << hana::curry<3>(addabc)(1)(2,3) << endl;
cout << hana::curry<3>(addabc)(1,2,3) << endl;
```

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  - TCO reuses the same call stack, and TCO is critical in functional languages
  - No jump-and-add-stack-frame immediately followed by a pop-stack-frame-and-return-to-caller
  - But simply jump to the start of the second routine (goto)

Recursion: Factorial Implementations

```
-- Junior Haskell programmer:
factorial 0 = 1
factorial n = n * factorial (n - 1)

-- Another junior haskell developer (tail call optimization)
factorial x = fac' x 1 where
    factorial' 1 y = y
    factorial' x y = factorial' (x-1) (x*y)

-- Senior haskell developer (TCO with strictness)
factorial x = fac' x 1 where
    factorial' 1 y = y
    factorial' x y = factorial' (x-1) $!  (x*y)

-- Tenured professor (teaching Haskell to freshmen)
factorial n = product [1..n]
```

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```
int factco_times (int n, int acc) {
    if (n == 0) return acc;
    else return factco_times(n - 1, acc * n);
}

int factco (int n) {
    return factco_times (n, 1);
}

cout << factco(5) << endl; //prints 120
```

Types System: Haskell and C++

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  - This is what Haskell and C++ have
  - Strong and static type system with type inference

Type Inference: Haskell

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```
Prelude> let sum a b = a + b
Prelude> :t sum
sum :: Num a => a -> a -> a
```

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Type Inference: C++

```
//decltype(auto) and return type deduction for normal functions
auto f() { return 42; } // return type is int
template<typename T, typename U>
auto add(T t, U u) -> decltype(t + u); //return type is operator+(T,U)

//Alternate type deduction when declaring a variable
int i;
auto x4a = (i);                // decltype(x4a) is int
decltype(auto) x4d = (i);      // decltype(x4d) is int&

//Type deduction for lambda arguments
[](auto x, auto y) {return x + y;};
```

Lazy Evaluation: Haskell

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```
lazy n = take n (filter odd [1..])
print (lazy 5) -- prints 1,3,5,7,9
```

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  - Makes the code more reusable
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  - Harder to reason about
  - Performance bottleneck of exhaustive memory deallocations

Lazy Evaluation: Haskell and C++

- Haskell (All)

```
triples = [(x, y, z) | z<-[1..], x<-[1..z], y<-[x..z], x^2 + y^2 == z^2]
main = print (take 10 triples)
```

- C++ (printing part)

```
auto strm = triples().take(10);
forEach(move(strm), [](tuple<int, int, int> const & t) {
    cout << get<0>(t) << ", " << get<1>(t) << ", "<< get<2>(t) << endl;
});
```

Lazy Evaluation: More C++ (Triple)

```
Stream<std::tuple<int, int, int>> triples()
{
    return mbind(intsFrom(1), [](int z)
    {
        return mbind(ints(1, z), [z](int x)
        {
            return mbind(ints(x, z), [x, z](int y)
            {
                return mthen(guard(x*x + y*y == z*z), [x, y, z]()
                {
                    return mreturn(std::make_tuple(x, y, z));
                });
            });
        });
    });
}
```

Lazy Evaluation: More C++ (Functions)

```
Stream<void*> guard(bool b)
{
    if (b) return Stream<void*>(nullptr);
    else return Stream<void*>();
}

template<class T>
Stream<T> mreturn(T v)
{
    return Stream<T>([v]() {
        return Cell<T>(v);
    });
}

template<class T, class F>
auto mthen(Stream<T> stm, F f) -> decltype(f())
{
    return mjoin(fmapv(stm, f));
}
```

Lazy Evaluation: More C++ (Functions)

```
template<class T, class F>
auto fmapv(Stream<T> stm, F f)->Stream<decltype(f())>
{
    using U = decltype(f());
    static_assert(std::is_convertible<F, std::function<U()>>::value,
        "fmapv requires a function type U()");

    if (stm.isEmpty()) return Stream<U>();
    return Stream<U>([stm, f]()
    {
        return Cell<U>(f(), fmapv(stm.pop_front(), f));
    });
}
```

Lazy Evaluation: More C++ (Functions)

```
template<class T, class F>
auto mbind(Stream<T> stm, F f) -> decltype(f(stm.get()))
{
    return mjoin(fmap(stm, f));
}
```

Lazy Evaluation: More C++ (Functions)

```
template<class T>
Stream<T> mjoin(Stream<Stream<T>> stm)
{
    while (!stm.isEmpty() && stm.get().isEmpty())
    {
        stm = stm.pop_front();
    }
    if (stm.isEmpty()) return Stream<T>();
    return Stream<T>([stm]()
    {
        Stream<T> hd = stm.get();
        return Cell<T>( hd.get()
                      , concat(hd.pop_front(), mjoin(stm.pop_front())));
    });
}
```

Lazy Evaluation: More C++ (Functions)

```
template<class T, class F>
void forEach(Stream<T> strm, F f)
{
    while (!strm.isEmpty())
    {
        f(strm.get());
        strm = strm.pop_front();
    }
}
```

Lazy Evaluation: More C++ (Functions)

```
Stream take(int n) const {
    if (n == 0 || isEmpty())
        return Stream();
    auto cell = _lazyCell;
    return Stream([cell, n]()
    {
        auto v = cell->get().val();
        auto t = cell->get().pop_front();
        return Cell<T>(v, t.take(n - 1));
    });
}
```

Lazy Evaluation: More C++ (Functions)

```
Stream<int> ints(int n, int m)
{
    if (n > m)
        return Stream<int>();
    return Stream<int>([n, m]()
    {
        return Cell<int>(n, ints(n + 1, m));
    });
}

Stream<int> intsFrom(int n)
{
    return Stream<int>([n]()
    {
        return Cell<int>(n, intsFrom(n + 1));
    });
}
```

Lazy Evaluation: More C++ (Stream)

```
template<class T>
class Stream
{
    std::shared_ptr <Susp<Cell<T>>> _lazyCell;
public:
    Stream() {}
    Stream(std::function<Cell<T>()> f)
        : _lazyCell(std::make_shared<Susp<Cell<T>>>(f))
    {}
    Stream(Stream && stm)
        : _lazyCell(std::move(stm._lazyCell))
    {}
    Stream & operator=(Stream && stm)
    {
        _lazyCell = std::move(stm._lazyCell);
        return *this;
    }
    bool isEmpty() const   { return !_lazyCell;  }
    T get() const  {return _lazyCell->get().val(); }
    Stream<T> pop_front() const  { return _lazyCell->get().pop_front(); }
};
```

Lazy Evaluation: More C++ (Cell)

```
template<class T>
class Cell
{
public:
    Cell() {} // need default constructor for memoization
    Cell(T v, Stream<T> const & tail)
        : _v(v), _tail(tail)
    {}
    explicit Cell(T v) : _v(v) {}
    T val() const {
        return _v;
    }
    Stream<T> pop_front() const {
        return _tail;
    }
private:
    T _v;
    Stream<T> _tail;
};
```

Lazy Evaluation: More C++ (Susp)

```
template<class T> class Susp
{
    static T const & thunkForce(Susp * susp) {
        return susp->setMemo();
    }
    static T const & thunkGet(Susp * susp) {return susp->getMemo();}
    T const & getMemo() {return _memo;}
    T const & setMemo() {
        _memo = _f();
        _thunk = &thunkGet;
        return getMemo();
    }
public:
    explicit Susp(std::function<T()> f)
        : _f(f), _thunk(&thunkForce), _memo(T()) {}
    T const & get() {return _thunk(this); }
private:
    T const & (*_thunk)(Susp *);
    mutable T   _memo;
    std::function<T()> _f;
};
```

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- Fortunately there are Range V3 library, but about it later...

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  - A list of T is either empty or consists of an element of type T followed by a list of T.

Immutable and Persistent Data: C++

```
template<class T> class List {
struct Item {
    Item(T v, std::shared_ptr<const Item> const & tail)
        : _val(v), _next(tail) {}
    T _val;
    std::shared_ptr<const Item> _next;
}
public:
    List() : _head(nullptr) {}
    List(T v, List const & tail)  :
        _head(std::make_shared<Item>(v, tail._head)) {}
    bool isEmpty() const { return !_head; }
    //and many many other functions: pop, push, front map, filter, size,
    //fold, concat, reverse, foreach,
private:
    Item const * _head;
};
```

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```
data Bool = False | True deriving (Ord)
data Day = Monday | ... | Sunday  deriving (Eq, Ord, Show, Bounded, Enum)
data Point = Point Float Float
data Shape = Circle Point Float | Rectangle Point Point
data Maybe a = Nothing | Just a  --Parametric
data List a = Nil | Cons a (List a) --Recursive
data Vector a = Vector a a a deriving (Show)
data Car a b = Car {model::a, year::b} deriving (Show)
```

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```
struct nothing {};
template<class T>
using maybe<T> = boost::variant<T, nothing>;
```

Pattern Matching: Haskell

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```
lucky :: Int -> String
lucky 7 = "LUCKY NUMBER SEVEN!"
lucky x = "Sorry, you're out of luck, pal!"

addVectors :: Double a => (a, a) -> (a, a) -> (a, a)
addVectors (x1, y1) (x2, y2) = (x1 + x2, y1 + y2)
```

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  - Mach7 library (by Yuriy Solodkyy, Gabriel Dos Reis and Bjarne Stroustrup)

Pattern Matching: C++ Mach7 Example

- The use of patterns with built-in types

```
int fib(int n)
{
    var<int> m;

    Match(n)
    {
      Case(1)      return 1;
      Case(2)      return 1;
      Case(2*m)    return sqr(fib(m+1)) - sqr(fib(m-1));
      Case(2*m+1)  return sqr(fib(m+1)) + sqr(fib(m));
    }
    EndMatch
}
```

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```
x = 5
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  - It is impossible to substitute equal-for-equal

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```
id :: a -> a
id a = a

map :: (a->b) -> [a] -> [b]
map f  []  =  []
map f (x:xs)  =  f x : map f xs
```

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class Eq a where
    (==) :: a -> a -> Bool
    (/=) :: a -> a -> Bool
    x == y = not (x /= y)
    x /= y = not (x == y)

data Foo = Foo {x :: Integer, str :: String}

instance Eq Foo where
   (Foo x1 str1) == (Foo x2 str2) = (x1 == x2) && (str1 == str2)
```

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```
print ([x*2 | x <- [1..10], x*2 >= 12])
-- prints [12,14,16,18,20]
```

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```
// Lazy ranges for generating integer sequences
auto const intsFrom = view::iota;
auto const ints = [=](int i, int j) {
    return view::take(intsFrom(i), j-i+1);
};
//Define an infinite range of all the Pythagorean triples:
auto triples =
  view::for_each(intsFrom(1), [](int z) {
    return view::for_each(ints(1, z), [=](int x) {
      return view::for_each(ints(x, z), [=](int y) {
        return yield_if(x*x + y*y == z*z, std::make_tuple(x, y, z));
        });
     });
 });
```

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  - Many C++ constructs turns out those concepts

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```
-- typeclass
class Functor f where
  fmap :: (a -> b) -> f a -> f b  --fmap :: (a -> b) -> (f a -> f b)

-- list functor
instance Functor [] where
  fmap _ []     = []
  fmap g (x:xs) = g x : fmap g xs  -- or we could just say fmap = map

--laws
fmap id = id
fmap (g . h) = (fmap g) . (fmap h)
```

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  - Range v3: views and ranges

Category Concepts: Functor in C++

- It is a concept that represents types that can be mapped over (by boost.hana))
- What are the concrete functors in C++?
  - STL Containers with std::transform and iterators
  - Boost.Hana: hana::lazy, hana::optional, hana::tuple
  - Range v3: views and ranges

```
//laws (boost.hana)
transform(xs, id) == xs
transform(xs, compose(g, f)) == transform(transform(xs, f), g)
//examples
auto to_string = [](auto x) { ostringstream ss; ss << x; return ss.str(); };
BOOST_HANA_RUNTIME_CHECK(
hana::transform(hana::make_tuple(1, '2', "345", string{"67"}), to_string)
== hana::make_tuple("1", "2", "345", "67"));

std::vector<int> vi{1,2,3,4,5,6,7,8,9,10};
auto rng = vi | view::transform([](int i){return i * 2;});
```

Category Concepts: Applicative in Haskell

- Apply container of functions to container of values

Category Concepts: Applicative in Haskell

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```
class Functor f => Applicative f where
  pure  :: a -> f a
  (<*>) :: f (a -> b) -> f a -> f b --apply

pure id <*> v = v
pure f <*> pure x = pure (f x)
u <*> pure y = pure ($ y) <*> u
u <*> (v <*> w) = pure (.) <*> u <*> v <*> w

instance Applicative [] where
  pure x = [x]
  fs <*> xs = [f x | f <- fs, x <- xs]

print (pure 123 :: [Int]) --[123]
print([(*0),(+100),(^2)] <*> [1,2,3]) --[0,0,0,101,102,103,1,4,9]
print([(+),(*)] <*> [1,2] <*> [3,4] )
--[(+1),(+2),(*1),(*2)] <*> [3,4], [4,5,5,6,3,4,6,8]
```

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```
//laws
ap(lift<F>(id), xs) == xs
ap(ap(lift<F>(compose), fs, gs), xs) == ap(fs, ap(gs, xs))
ap(lift<F>(f), lift<F>(x)) == lift<F>(f(x))
ap(fs, lift<F>(x)) == ap(lift<F>(apply(-, x)), fs)

//example
hana::ap(hana::just([](auto a, auto b, auto c) {return a * b * c;}),
  hana::just(1), hana::just(2), hana::just(3)
);
```

Category Concepts: Monads in General

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   - are getting more and more important

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```
class Endofunctor c t => Monad c t where
  eta :: c a (t a)
  mu  :: c (t (t a)) (t a)
  (>>=) :: (Monad c t) => c a (t b) -> c (t a) (t b)
  (>>=) f = mu . fmap f
  return :: (Monad c t) => c a (t a)
  return = eta
```

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- What are the Monad from programming pov?

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```
class Applicative m => Monad m where
  return :: a -> m a  --pure
  (>>=)  :: m a -> (a -> m b) -> m b  --bind

data  Maybe a  =  Nothing | Just a
instance  Monad Maybe  where
    (Just x) >>= k      = k x
    Nothing  >>= _      = Nothing

maybeHalf :: Int -> Maybe Int
maybeHalf a
         | even a = Just (div a 2)
         | otherwise = Nothing
```

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```
hana::flatten(hana::make_tuple(hana::make_tuple(1, 2, 3), hana::make_tuple(4, 5
    ==
    hana::make_tuple(1, 2, 3, 4, 5, 6, 7, 8, 9)
```

Combinators: Haskell

- What are the combinators?

Combinators: Haskell

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  - A function which builds program fragments from program fragments: map, filter, fold/reduce

Combinators: Haskell

- What are the combinators?
  - A function which builds program fragments from program fragments: map, filter, fold/reduce
  - Operating on streams

```
foldr f z []     = z
foldr f z (x:xs) = f x (foldr f z xs)

foldl f z []     = z
foldl f z (x:xs) = foldl f (f z x) xs
```

Combinators: C++

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  - transform, reduce, transform_reduce, accumulate, min, max, partition, for_each, for_each_n, all_of, any_of, none_of
- Boost.Hana
  - fold, fold_right, fold_left, min, max, for_each, sum, count, fill, replace, transform, chain, flatten, tap, append, filter, suffix, all, in, find, reverse, scan, zip, zip_with, unfold, partition, insert,

Combinators: C++ Examples

- hana::fold combinator

Combinators: C++ Examples

- hana::fold combinator

```
auto to_string = [](auto x) {
    std::ostringstream ss;
    ss << x;
    return ss.str();
};
int main() {
    auto f = [=](std::string s, auto element) {
        return "f(" + s + ", " + to_string(element) + ")";
    };
    BOOST_HANA_RUNTIME_CHECK(
        hana::fold(hana::make_tuple(2, '3', 4, 5.0), "1", f)
            ==
        "f(f(f(f(1, 2), 3), 4), 5)"
    );
}
```

Concepts Support Summary: Good

- Good support, by built-in features for:

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  - Static typing
  - Polymorphism
  - Algebraic Data Types: std::variant, composition

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  - Combinators: Boost.Hana, Range v3
  - Partial application and currying: Boost.Hana

Concepts Support Summary: None

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- None support:
  - Purity: just self discipline
  - Immutability: custom solutions, self discipline
  - Substitution model: impossible at all

Concepts Support Summary

C++ is in a half way towards full functional paradigm support

C++ Metaprogramming

Metaprogramming as pure functional language

C++ Metaprogramming

Metaprogramming as pure functional language

- Does metaprogramming support functional paradigm?

C++ Metaprogramming

"Within C++, there is a much smaller and cleaner language struggling to get out"

Bjarne Stroustrup

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- C++ metaprogramming is a pure functional compile-time programming

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"Within C++, there is a much smaller and cleaner language struggling to get out"

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- C++ metaprogramming is a pure functional compile-time programming
- Haskell could be used as a pseudocode for it

C++ Metaprogramming: Characteristics

- Why MP is pure functional language

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  - no mutable variables
  - no assignment operator*
  - constant expressions
  - no loops, only recursions*

C++ Metaprogramming: Haskell Factorial

- Factorial in Haskell

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```
fact 0 = 1
fact n = n * fact(n - 1)
main = print(fact 5) --prints 120
```

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  - two liner
  - pattern matching with two definitions
  - recursion

TMP Factorial

- Factorial in C++98 Template Meta Programming

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```
template <int n> struct fact98 {
  static const int value = n * fact98<n-1>::value;
};

template <> struct fact98<0> {
  static const int value = 1;
};

std::cout << fact98<5>::value << std::endl; //prints 120
```

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  - many liner
  - template instantiation acts as function calls

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```

  - many liner
  - template instantiation acts as function calls
  - pattern matching implemented as specialization

Constexpr C++11 factorial

- Factorial in C++11 Constexpr Meta Programming

Constexpr C++11 factorial

- Factorial in C++11 Constexpr Meta Programming

```
constexpr int fact11(int n) {
    return n <= 1? 1 : (n * fact11(n - 1));
}
std::cout << Int<fact11(5)>::value << std::endl; //prints 120
```

Constexpr C++11 factorial

- Factorial in C++11 Constexpr Meta Programming

```
constexpr int fact11(int n) {
    return n <= 1? 1 : (n * fact11(n - 1));
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std::cout << Int<fact11(5)>::value << std::endl; //prints 120
```

  - looks better

Constexpr C++14 factorial

- Factorial in C++14 Constexpr Meta Programming

Constexpr C++14 factorial

- Factorial in C++14 Constexpr Meta Programming

```
constexpr int fact14(int n) {
    switch(n) {
      case 0: return 1;
      default: return n * fact14(n-1);
    }
}
constexpr int fact14loop(int n) {
    int s = 1;
    for (int i=1; i<=n; i++) {s = s * i;}
    return s;
}
```

Constexpr C++14 factorial

- Factorial in C++14 Constexpr Meta Programming

```
constexpr int fact14(int n) {
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    }
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    return s;
}
```

  - pure functional compile-time meta programming in imperative way

- Within imperative language there is pure functional one with an imperative looking syntax

Predicates: Haskell

- Predicate in Haskell:

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```
isZero 0 = True
isZero n = False
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- Predicate in C+98 TMP:

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template <int> struct isZero {
  static const bool value = false;
};
template <> struct isZero<0> {
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```

- Almost the same

OR combinator and Closure: Haskell

- Or combinator:

OR combinator and Closure: Haskell

- Or combinator:

```
ori :: (Int -> Bool) -> (Int -> Bool) -> Int -> Bool
ori f g = \x -> (f x) || (g x)
main = print(ori isZero isOne 0) --prints True
```

OR combinator and Closure: Haskell

- Or combinator:

```
ori :: (Int -> Bool) -> (Int -> Bool) -> Int -> Bool
ori f g = \x -> (f x) || (g x)
main = print(ori isZero isOne 0) --prints True
```

  - Higher order function, lambda with closure, predicate composition

OR combinator and Closure: TMP C++

- Or with closure in C++98 TMP:

OR combinator and Closure: TMP C++

- Or with closure in C++98 TMP:

```
//int
template <template <int> class f, template <int> class g>
struct or {
  template<int n> struct closure {
    static const bool value = f<n>::value || g<n>::value;
   };
};

//any type
template <template <class> class F, template <class> class G>
struct Or {
  template<class T> struct closure {
    static const bool value = F<T>::value || G<T>::value;
  };
};

cout << or<isZero,isOne>::closure<0>::value; //prints 1
cout << Or<IsIntZero, IsIntOne>::closure<Int<0>>::value; //prints 1
```

all: haskell

- Higher order function operating on list

all: haskell

- Higher order function operating on list
- All algorithm in haskell

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- Higher order function operating on list
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```
all pred [] = True
all pred (head:tail) = (pred head) && (all pred tail)

--all application on int list with two predicate and or combinator
main = print(alli (ori isZero isOne) [1,1,0,1,0]) --true
```

all: haskell

- Higher order function operating on list
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```
all pred [] = True
all pred (head:tail) = (pred head) && (all pred tail)

--all application on int list with two predicate and or combinator
main = print(alli (ori isZero isOne) [1,1,0,1,0]) --true
```

- pattern matching, recursion and composition

all: TMP C++

- The all algorithm equivalence in C++

all: TMP C++

- The all algorithm equivalence in C++

```
template <template <int> class pred, int... list> struct alli;

template <template <int> class pred>
struct alli<pred> { static const bool value = true; };

template <template <int> class pred, int head, int... tail>
struct alli<pred, head, tail...> {
  static const bool value = pred<head>::value && alli<pred, tail...>::value;
};

cout << alli<ori<isZero,isOne>::closure,1,1,0,1,0>::value;
```

all: TMP C++

- The all algorithm equivalence in C++

```
template <template <int> class pred, int... list> struct alli;

template <template <int> class pred>
struct alli<pred> { static const bool value = true; };

template <template <int> class pred, int head, int... tail>
struct alli<pred, head, tail...> {
  static const bool value = pred<head>::value && alli<pred, tail...>::value;
};

cout << alli<ori<isZero,isOne>::closure,1,1,0,1,0>::value;
```

- Forward declaration, template specialization, variadic templates and parameter pack

fold right: haskell

- The foldr algorithm in Haskell

fold right: haskell

- The foldr algorithm in Haskell

```
--definition
foldr f init [] = init
foldr f init (head:tail) = f head (foldr f init tail)

--with anonymous function
print(foldr (\n acc -> n + acc) 1 [1,2,3]) --prints 7

--with auxilary function
add n acc = n + acc
print(foldr add 1 [1,2,3]) --prints 7
```

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foldr f init (head:tail) = f head (foldr f init tail)

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--with auxilary function
add n acc = n + acc
print(foldr add 1 [1,2,3]) --prints 7
```

- lambda expression, anonymous function, recursion, pattern matching

fold right: TMP C++

- The foldr algorithm equivalence in C++

fold right: TMP C++

- The foldr algorithm equivalence in C++

```
template<template<int, int> class, int, int...> struct foldr;

template<template<int, int> class f, int init> struct
foldr<f, init> {static const int value = init; };

template<template<int, int> class f, int init, int head, int... tail>
struct foldr<f, init, head, tail...> {
    static const int value = f<head, foldr<f, init, tail...>::value>::value;
};

template<int a, int b> struct add {  static const int value = a + b;};
std::cout << foldr<add, 1, 1, 2, 3>::value; //prints 7
```

fold right: TMP C++

- The foldr algorithm equivalence in C++

```
template<template<int, int> class, int, int...> struct foldr;

template<template<int, int> class f, int init> struct
foldr<f, init> {static const int value = init; };

template<template<int, int> class f, int init, int head, int... tail>
struct foldr<f, init, head, tail...> {
    static const int value = f<head, foldr<f, init, tail...>::value>::value;
};

template<int a, int b> struct add {  static const int value = a + b;};
std::cout << foldr<add, 1, 1, 2, 3>::value; //prints 7
```

- Fortunately there is fold C++17 expression

sum: haskell

- Sum algorithm in Haskell

sum: haskell

- Sum algorithm in Haskell
- with pattern matching and recursion:

sum: haskell

- Sum algorithm in Haskell
- with pattern matching and recursion:

```
sum1 [] = 0
sum1 (head:tail) = head + (sum1 tail)
print(sum1 [1,2,3]) --prints 6
```

sum: haskell

- Sum algorithm in Haskell
- with pattern matching and recursion:

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- with function composition and lambda:

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sum1 [] = 0
sum1 (head:tail) = head + (sum1 tail)
print(sum1 [1,2,3]) --prints 6
```

- with function composition and lambda:

```
sum2 lst = foldr2 (\n acc -> n + acc) 0 lst
print(sum2 [1,2,3]) --prints 6
```

sum: TMP C++

- The sum algorithm equivalence in C++

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- The sum algorithm equivalence in C++
- TMP C++ directly:

sum: TMP C++

- The sum algorithm equivalence in C++
- TMP C++ directly:

```
template <int...> struct sum;
template <> struct sum<> {
  static const int value = 0;
};
template <int head, int... tail> struct sum<head, tail...> {
  static const int value = head + sum<tail...>::value;
};
std::cout << sum<1,2,3>::value << std::endl; //prints 6
```

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- TMP C++ with composition:

sum: TMP C++

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template <> struct sum<> {
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template <int head, int... tail> struct sum<head, tail...> {
  static const int value = head + sum<tail...>::value;
};
std::cout << sum<1,2,3>::value << std::endl; //prints 6
```

- TMP C++ with composition:

```
template <int... ints> struct sum2 {
  static const int value = foldr<add,0,ints...>::value;
};
std::cout << sum2<1,2,3>::value << std::endl;//prints 6
```

sum: C++17

- By C++17 fold expression

sum: C++17

- By C++17 fold expression

```
template <int... ints> struct sum3 {
  static const int value = (ints + ...);
};
std::cout << sum3<1,2,3>::value << std::endl;//prints 6
```

count: haskell

- Count algorithm in Haskell

count: haskell

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- with recursion:

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```
count1 [] = 0
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- with recursion:

```
count1 [] = 0
count1 (head:tail) = 1 + count1 tail
```

- with list comprehension:

```
count2 lst = sum2 [1 | x <- lst]
```

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- with list comprehension:

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  - Could we do "list comprehension" in TMP C++?

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- with list comprehension:

```
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```

  - Could we do "list comprehension" in TMP C++?
  - Yes, of course, but ...

count: TMP C++

- Count algorithm in C++

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- Count algorithm in C++
- with recursion:

count: TMP C++

- Count algorithm in C++
- with recursion:

```
template <class... list> struct count;
template <> struct count<> {
  static const int value = 0;
};
template <class head, class... tail> struct count<head, tail...> {
  static const int value = 1 + count<tail...>::value;
};
cout << count1<Int<1>, Int<4>, Char<'a'>>::value; //prints 3
```

count: List Comprehension in TMP C++

- Count algorithm in C++ with list comprehension:

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- Count algorithm in C++ with list comprehension:

```
template <class> struct one { static const int value = 1; };
template<class... lst> struct count {
  static const int value = sum<one<lst>::value...>::value;
};
cout << count<Int<1>, Int<4>, Char<'a'>>::value
```

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```
template <class> struct one { static const int value = 1; };
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cout << count<Int<1>, Int<4>, Char<'a'>>::value
```

- How many expansions are there?

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template <class> struct one { static const int value = 1; };
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```

- How many expansions are there?

```
sum<one<Int<1>>::value, one<Int<4>>::value,  one<Char<'a'>>>.
```

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```
template <class> struct one { static const int value = 1; };
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sum<one<Int<1>>::value, one<Int<4>>::value,  one<Char<'a'>>>.
```

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- There is sizeof... operator, but...

count: List Comprehension in TMP C++

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```
template <class> struct one { static const int value = 1; };
template<class... lst> struct count {
  static const int value = sum<one<lst>::value...>::value;
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cout << count<Int<1>, Int<4>, Char<'a'>>::value
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- There is sizeof... operator, but...
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```
template <class> struct one { static const int value = 1; };
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  static const int value = sum<one<lst>::value...>::value;
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```

- How many expansions are there?

```
sum<one<Int<1>>::value, one<Int<4>>::value,  one<Char<'a'>>>.
```

  - Just one, it is a one-to-one paradigm match
- There is sizeof... operator, but...
  - it is Just sizeof, and...
  - The TMP list comprehension is applicable to any transforming structure

map: haskell

- map and map with continuation

map: haskell

- map and map with continuation

```
--continuation
sum2 [] = 0
sum2 (head:tail) = head + (sum2 tail)

--maps
map f lst = [f x | x <- lst]
mapcont cont f lst = cont [f x | x <- lst]

--transformation
doubleme x = x + x

--application
print(map doubleme [1,2,3]) --prints 2,4,6
print(mapcont sum doubleme [1,2,3]) --prints 12
```

map with continuation: TMP C++

- The map algorithm equivalence in C++

map with continuation: TMP C++

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```
//continuation
template <class... Ts> struct Sum;
template <> struct Sum<> {static const int value = 0;};
template <class head, class... tail> struct Sum<head, tail...> {
  static const int value = head::value + Sum<tail...>::value;
};
//transformation
template <class T> struct Twice {
  static const int value = T::value + T::value;
};
//map with continuation
template <template <class...> class Cont,
template <class> class F, class... Ts> struct Map {
  static const int value = Cont<F<Ts>...>::value;
};
//application
cout <<  Map<Sum, Twice, Int<1>, Int<2>, Int<3>>::value; //prints 12
```

C++ Functional Metaprogramming Libraries

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  - Template metaprogramming framework of compile-time algorithms, sequences and metafunctions.

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- Boost.MPL
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  - Header-only library for C++ metaprogramming suited for computations on both types and values
- Range v3
  - Experimental range library for C++11/14/17 with range comprehension

Hana: Monad:Flatten, MonadPlus:Filter

- Monad::Flatten

Hana: Monad:Flatten, MonadPlus:Filter

- Monad::Flatten

```
//flatten - collapse two levels of monadic structure into a single level
static_assert(
hana::flatten(hana::make_tuple(hana::make_tuple(1, 2, 3),
    hana::make_tuple(4, 5),
    hana::make_tuple(6, 7, 8, 9)))
    ==
    hana::make_tuple(1, 2, 3, 4, 5, 6, 7, 8, 9), "");
```

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    ==
    hana::make_tuple(1, 2, 3, 4, 5, 6, 7, 8, 9), "");
```

- Monad::Filter

```
//filter - filter a monadic structure using a custom predicate
static_assert(
hana::filter(hana::make_tuple(1, 2.0, 3, 4.0), is_integral)
==
hana::make_tuple(1, 3), "");
```

Hana: Sequence: Zip,Partition

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```
//zip_shortest_with - zip one sequence or more with a given function
static_assert(
    hana::zip_shortest_with(hana::mult,
    hana::make_tuple(1, 2, 3, 4), hana::make_tuple(5, 6, 7, 8, "ignored"))
    ==  hana::make_tuple(5, 12, 21, 32), "");
```

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    ==  hana::make_tuple(5, 12, 21, 32), "");
```

- Sequence::Partition

```
//partition - Partition a sequence based on a predicate
BOOST_HANA_CONSTANT_CHECK(
    hana::partition(hana::tuple_c<int, 1, 2, 3, 4, 5, 6, 7>, [](auto x) {
        return x % hana::int_c<2> != hana::int_c<0>;
    })  ==
    hana::make_pair(
        hana::tuple_c<int, 1, 3, 5, 7>,
        hana::tuple_c<int, 2, 4, 6>
    ));
```

Hana: Functional: partial, curry, compose

- Functional::partial

Hana: Functional: partial, curry, compose

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```
//partial - Partially apply a function to some arguments
constexpr auto increment = hana::partial(hana::plus, 1);
static_assert(increment(2) == 3, "");
```

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- Functional::curry

```
//curry - curry a function up to the given number of arguments
hana::curry<3>(add)(1)(2)(3) == 1 + 2 + 3);
hana::curry<3>(add)(1, 2, 3) == hana::curry<3>(add)(1)(2)(3));
```

Hana: Functional: partial, curry, compose

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hana::curry<3>(add)(1, 2, 3) == hana::curry<3>(add)(1)(2)(3));
```

- Functional::compose

```
//compose - return the composition of two functions or more
hana::compose(to_char, increment)(3) == '4');
```

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  - only integers are supported
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  - compile time only
  - lacking of built in combinators
- However:
  - There is **Boost.Hana** that greatly simplify the functional metaprogramming

Future Work, Conclusion, Recommendation

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Future Work: Design Consideration

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  - What about **design patterns**?
    - Maybe some design patterns are **NOT needed** any more or could be **simplified**?
  - Does language **composability capabilities** are increased?

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- Does a paradigm shift in C++ in a FP direction is a good thing?

Conclusion

- Is a C++ a functional language?
  - No. It is an **imperative language** with some functional concepts.
  - Yes. The **metaprogramming** is the compile-time **pure functional** language.
- Does a paradigm shift in C++ in a FP direction is a good thing?
  - Yes, open more opportunities for writing better software, but... its harder from developer pov ;)

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- I'm (We're) **eagerly** awaiting for **"Functional C++"**

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The End

Thank You Very Much

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