Writing efficient code

Sébastien Ponce
sebastien.ponce@cern.ch

CERN

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Outline

1. Virtues of functional programming
   - Theory using haskell
2. Practical usage and efficiency
   - Functional programming in C^{++}
   - Efficiency
3. It's all about helping the compilers
   - constness, exceptions
   - Avoiding useless copying
4. Do more at compile time
   - Templates
   - `constexpr` and `if constexpr`
   - Virtuality : a counter example
5. Conclusion

Virtues of functional programming

Functional programming

Definition (Wikipedia) and rules

a programming paradigm where programs are constructed by applying and composing functions. Functions have

- no side effects
- no modification of the input
- new return values

Consequences

- no state, no globals, no members
- guaranteed thread-safety !

Usage

- dedicated languages : Haskell, Erlang, Lisp, ...
- modern C++(lambdas, move, copy elision, ...)

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Crash course in functional programing

haskell syntax already tells a lot - godbolt

```haskell
-- declaration
add :: Int -> Int -> Int
-- implementation
add x y = x + y
-- usage
five = add 3 2
add_42 = add 42
```

- everything is a function
- functions always take one single paremeter
- functions with more arguments are functions returning a function

Crash course in functional programing [2]

Functions are regular objects - godbolt

```
apply_operator :: (a -> a -> a) -> a -> a -> a
apply_operator op x y = op x y
inc = apply_operator add 1
double = apply_operator (\ x y -> x * y) 2
```

They can replace loops - godbolt

```
a = [1,2,3,4,5]
b = map double a
-- b is [2,4,6,8,10]
fact5 = fold (*) 1 a -- 120
```

Crash course in functional programing [3]

Actual looping is done via recursion - godbolt

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

-- fold definition
fold :: (a -> b -> b) -> b -> [a] -> b
fold f z []      = z
fold f z (x:xs) = f x (fold f z xs)
```

Crash course in functional programing [4]

Evaluation is lazy - godbolt

```
allEven = filter even [2..]
a = take 5 allEven
-- a is [2 4 6 8 10]
```

Crash course in functional programing [4]

Evaluation is lazy - godbolt

```haskell
allEven = filter even [2..]
a = take 5 allEven
-- a is [2 4 6 8 10]
```

Prime computation - godbolt

```haskell
filterPrime :: [Int] -> [Int]
filterPrime (p:xs) =
  p : filterPrime (filter (\ x -> x `mod` p /= 0) xs)
allPrimes = filterPrime [2..]
a = take 10 allPrimes
-- a is [2 3 5 7 11 13 17 23 29 31]
```

What to conclude ?

- Nice, very elegant, but not so practical...

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- can we use that in python and C^{++}?
- and is all that really efficient ?

What to conclude ?

- Nice, very elegant, but not so practical...
- can we use that in python and C^{++}?
- and is all that really efficient ?

Short answers : Yes, and double Yes

Practical usage and efficiency

Everything is a function, also in C++

Concept

- a class can implement `operator()`
- it's then a "functor" (no relation to functors in math)
- allows to use objects in place of functions
- with constructors and data members

First functor - godbolt

```cpp
struct Adder {
  int m_increment;
  Adder(int increment) : m_increment(increment) {}
  int operator()(int a) { return a + m_increment; }
};
Adder add_42{42};
int i = add_42(3); // 45
```

And we also have lambdas

Definition

a lambda is a function with no name

Syntax

```
[captures] (args) -> type { code; }
```

The type specification is optional

Usage example - godbolt

```
auto add = [](int a, int b) { return a+b; };
auto add_42 = [&add](int b) { return add(42, b); };
```

Lambdas are essentially syntactic sugar

Lambdas

```
[&sum, offset](int x) { sum += x + offset; }
```

Are just functors - cppinsight

```
struct MyFunc {
  int& m_sum;
  int m_offset;
  MyFunc(int& s, int o) : m_sum(s), m_offset(o) {}
  void operator(int x) { m_sum += x + m_offset; }
};
MyFunc(sum, offset)
```

By the way, as lambdas are functors, they can inherit from each other !
And this can be super useful.

Functions are regular objects

They can be passed around - godbolt

```
auto apply = [](auto f, auto a, auto b)
  { return f(a, b); };
auto inc = [&](auto a) { return apply( add, 1, a ); };
auto doubleF = [&](auto a) {
  return apply([](auto x, auto y) {return x*y;}, 2, a);
};
```

They can replace loops - godbolt

```
std::vector a{1,2,3,4,5};
auto fact =
  std::ranges::fold_right(a, 1, std::multiplies());
std::ranges::transform
  (begin(a), end(a), begin(a), doubleF);
-- a is [2,4,6,8,10]
```

Ranges

Reason of being

- provide easy manipulation of sets of data via views
- simplify the horrible iterator syntax

Syntax

Based on Unix like pipes, and used in range based loops

Example code - godbolt

```
std::vector<int> numbers{1, 2, 3, 4, 5, 6};
auto results =
  numbers | filter([](int n){ return n % 2 == 0; })
          | transform([](int n){ return n * 2; });
for (auto v: results) std::cout << v << " ";
```

Ranges are lazy evaluated

Example code - godbolt

```
using Gen = std::generator<unsigned int>;
Gen source() { for (unsigned x = 2; ; x++) co_yield x; }
Gen filter(Gen& g, int prime) {
  for (unsigned x : g) { if ((x % prime) != 0) co_yield x; }
}
Gen prime(Gen& g) {
  auto p = *g.begin(); co_yield p;
  auto ng = filter(g, p);
  for (auto n : prime(ng)) co_yield n;
}
auto numbers = source();
for (unsigned p : prime(numbers) | std::views::take(10)) {
  std::cout << p << std::endl;
}
```

Practical usage and efficiency

Is this efficient ?

Let's compile this code - godbolt

```cpp
std::array<int, 6> numbers{1, 2, 3, 4, 5, 6};
auto results = numbers |
  std::ranges::views::transform([](int n){ return n * 23; });
for (auto n : results) std::cout << n << " ";
```

Generated code with -O3

```asm
.L2:   imul    esi, DWORD PTR [rbx], 23
       mov     edi, OFFSET FLAT:_ZSt4cout
       add     rbx, 4
       call    std::basic_ostream::operator<<(int)
       cmp     rbp, rbx
       jne     .L2
.LC0:  .long   1
       .long   2
       ...
```

Is this efficient ?

Let's compile this code - godbolt

```cpp
std::array<int, 6> numbers{1, 2, 3, 4, 5, 6};
auto results = numbers |
  std::ranges::views::transform([](int n){ return n * 23; });
for (auto n : results) std::c[illegible] n << " ";
```

Generated code with -O3

```asm
.L2:   imul    esi, [illegible]bx], 23
       mov     edi, [illegible]FLAT:_ZSt4cout
       add     rbx, 4
       call    std::basic_ostream::operator<<(int)
       cmp     rbp, rbx
       jne     .L2
.LC0:  .long   1
       .long   2
       ...
```

~Optimized

Is that efficient ?

Another bit of C^{++}code - godbolt

```
int foo() {
  std::vector<int> a{1,2,3,4,5};
  return std::ranges::fold_right(a, 1, std::multiplies());
}
std::cout << foo() << std::endl;
```

We get (gcc trunk

```
foo():
  ...
  call     operator new(unsigned long)
  movdqa   xmm0, XMMWORD PTR .LC0[rip]
  mov      esi, 20
  mov      DWORD PTR [rax+16], 5
  mov      rdi, rax
  movups   XMMWORD PTR [rax], xmm0
  call     operator delete(void*, unsigned long)
  mov      eax, 120
```

Is that efficient ?

Another bit of C++ code - godbolt

```
int foo() {
  std::vector<int> a{1,2,3,4,5};
  return std::ranges::fold_right(a, 1, std::multiplies());
}
std::cout << foo() << std:
```

We get (gcc trunk

```
foo():
  ...
  call     operator new(unsigned long)
  movdqa   xmm0, XMMWORD PTR .LC0[rip]
  mov      esi, 20
  mov      DWORD PTR [rax+16], 5
  mov      rdi, rax
  movups   XMMWORD PTR [rax], xmm0
  call     operator delete(void*, unsigned long)
  mov      eax, 120
```

Weird

How do we explain that ?

Facts

- what could be precomputed was precomputed
- all functional code is gone
- but vector still created, filled and dropped
  - not even used !

Hypothesis

- creation/deletion of the vector had to be kept in case of side effects
- compiler did not know whether there would be some
- Bottom line :
  - no enough information given to the compiler
  - a.k.a. compiler not clever enough

Switching from vector to array

Another bit of C++ code - godbolt

```
int foo() {
  std::array<int, 5> a{1,2,3,4,5};
  return std::ranges::fold_right(a, 1, std::multiplies());
}
foo();
```

We get (gcc trunk)

```
foo():
        mov     eax, 120
```

Switching from vector to array

Another bit of C++ code - godbolt

```
int foo() {
  std::array<int, 5> a{1,2,
  return std::ranges::f                    1, std::multiplies());
}
foo();
```

Optimized

We get (gcc trunk)

```
foo():
        mov     eax, 120
```

Using a more clever compiler

Another bit of C++ code - godbolt

```cpp
int foo() {
  std::vector<int> a{1,2,3,4,5};
  return std::ranges::fold_right(a, 1, std::multiplies());
}
foo();
```

We get (clang 18)

```asm
foo():
        mov     eax, 120
```

Using a more clever compiler

Another bit of C++ code - godbolt

```
int foo() {
  std::vector<int> a{1,2,3,4
  return std::ranges::f                1, std::multiplies());
}
foo();
```

Optimized

We get (clang 18)

```
foo():
        mov     eax, 120
```

It's all about helping the compilers

Constness

The const keyword

- indicates that the variable is constant
- this is all checked at compile time
- and used by the compiler for optimization

```
int const i = 6;
const int i = 6; // equivalent
// error: i is constant
i = 5;
auto const j = i; // works with auto
```

constness

Non const code - godbolt

```
void foo( int& k );
int bar() {
  int k = 10;
  foo(k);
  return k*k+2*k+1;
}
```

We get

```
bar():
  sub  rsp, 24
  lea  rdi, [rsp+12]
  mov  DW PTR [rsp+12], 10
  call foo(int&)
  mov  eax, DW PTR [rsp+12]
  add  rsp, 24
  mov  edx, eax
  imul edx, eax
  lea  eax, [rdx+1+rax*2]
```

constness

const aware code - godbolt

```cpp
void foo( const int& k );
int bar() {
   const int k = 10;
   foo(k);
   return k*k+2*k+1;
}
```

We get

```asm
bar():
   sub  rsp, 24
   lea  rdi, [rsp+12]
   mov  DW PTR [rsp+12], 10
   call foo(int const&)
   mov  eax, 121
   add  rsp, 24
```

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Data replication can also help

data replication - godbolt

```
void foo( int k );
int bar() {
  int k = 10;
  foo(k);
  return k*k+2*k+1;
}
```

We get

```
bar():
  sub     rsp, 8
  mov     edi, 10
  call    foo(int)
  mov     eax, 121
  add     rsp, 8
```

C^{++}exception support

After a lot of thinking and experiencing, the conclusions of the community on exception handling are :

- Never write an exception specification
- Except possibly an empty one

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one of the reasons : performance

- does not allow compiler optimizations
- on the contrary forces extra checks

C++ exception support

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one of the reasons : performance

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Introducing noexcept

```
int f() noexcept;
```

- somehow equivalent to throw()
- meaning no exception can go out of the function
- but is checked at compile time
- thus allowing compiler optimizations

Impact on generated code - exceptions

C++ code - godbolt

```cpp
struct MyExcept{};
int f(int a); // may throw

int foo() {
  try {
    int a = 23;
    return f(a) + f(-a);
  } catch (MyExcept& e) {
    return 0;
  }
}
```

Generated code

```asm
foo():
  push    rbx
  mov     edi, 23
  call    f(int)
  mov     edi, -23
  mov     ebx, eax
  call    f(int)
  add     eax, ebx
.L1:
  pop     rbx
  ret
  mov     rdi, rax
  mov     rax, rdx
  jmp     .L2
  foo() [clone .cold]:
.L2:
  sub     rax, 1
  jne     .L8
  call    __cxa_begin_catch
  call    __cxa_end_catch
  xor     eax, eax
  jmp     .L1
.L8:
  call    _Unwind_Resume
```

Impact on generated code - noexcept

C++code - godbolt

```cpp
struct MyExcept{};
int f(int a) noexcept;

int foo() {
  try {
    int a = 23;
    return f(a) + f(-a);
  } catch (MyExcept& e) {
    return 0;
  }
}
```

Generated code

```asm
foo():
    push    rbx
    mov     edi, 23
    call    f(int)
    mov     edi, -23
    mov     ebx, eax
    call    f(int)
    add     eax, ebx
    pop     rbx
```

It's all about helping the compilers

Useless copying: the problem

Inefficient code

```
void swap(std::vector<int> &a,
          std::vector<int> &b) {
  std::vector<int> c = a;
  a = b;
  b = c;
}
std::vector<int> v(10000), w(10000);
...
swap(v, w);
```

Useless copying: the problem

Inefficient code

```
void swap(std::vector<int> &a,
          std::vector<int> &b) {
  std::vector<int> c = a;
  a = b;
  b = c;
}
std::vector<int> v(10000), w(10000);
...
swap(v, w);
```

What happens during swap

- one allocation and one release for 10k `int`s
- a copy of 30k `int`s

Move semantics

The idea

- a new type of reference : rvalue references
  - used for “moving” objects
  - denoted by &&
- 2 new members in every class, with move semantic :

  a move constructor similar to copy constructor

  a move assignment operator similar to assignment operator (now called copy assignment operator)

  - used when original object can be reused

Move semantics

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  a move constructor similar to copy constructor

  a move assignment operator similar to assignment operator (now called copy assignment operator)

  - used when original object can be reused

Practically

```
T(const T&  other); // copy construction
T(       T&& other); // move construction
T& operator=(const T&  other); // copy assignment
T& operator=(       T&& other); // move assignment
```

Move semantics

A few important points concerning move semantic

- move assignment operator is allowed to destroy source
  - so do not reuse source afterward
- if not implemented, move falls back to copy version
- move is called by the compiler whenever possible
  - and can be forced via `std::move`

Move semantics

A few important points concerning move semantic

- move assignment operator is allowed to destroy source
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- if not implemented, move falls back to copy version
- move is called by the compiler whenever possible
  - and can be forced via `std::move`

Practically

```
void swap(T &a, T &b) {
  T c = std::move(a);  // move construct
  a = std::move(b);    // move assign
  b = std::move(c);    // move assign
}
```

No allocation, no release, 3x3 pointers copied

Guaranteed copy elision

What is copy elision

```
struct Foo { ... };
Foo f() {
  return Foo();
}
int main() {
  // No copy here, compiler must elude the copy
  Foo foo = f();
}
```

From C++17 on

The elision is guaranteed.

- superseeds move semantic in some cases
- so do not hesitate anymore to return plain objects in generators
    - and ban pointers for good

Do more at compile time

Templates

Concept

- The C++ way to write reusable code
  - aka macros on steroids
- Applicable to functions and objects

```cpp
template<typename T>
const T & max(const T &A, const T &B) {
  return A > B ? A : B;
}

template<typename T>
struct Vector {
  int m_len;
  T* m_data;
};
```

Templates

Warning

These are really like macros

- they need to be defined before used
  - so all templated code has to be in headers
- they are compiled n times
- and thus each version is optimized individually !

```cpp
template<typename T>
T func(T a) {
  return a;
}
```

func(3)

```cpp
int func(int a) {
  return a;
}
```

func(5.2)

```cpp
double func(double a) {
  return a;
}
```

A realistic template usage

Generic printing - godbolt

```
template<typename T> struct Print {
  Print(T const& obj) {
    std::cout << "(" << typeid(T).name()
              << ") " << obj << "\n";
  }
};
Print{5};                       // (i) 5
Print("a text string");         // (A14_c) a text string
```

A realistic template usage

Generic printing - godbolt

```
template<typename T>
concept Container = requires( T v1 ) {
  begin(v1);
  end(v1);
};
template<Container T> struct Printer<T> {
  Printer(T const& obj) {
    std::cout << "(" << typeid(T).name() << ") ";
    for( auto& item: obj) { std::cout << item << " "; }
    std::cout << "\n";
  }
};
Print(std::vector<int>{1,2,3});
// (St6vectorIiSaIiEE) 1 2 3
Printer(std::array<double, 3>{2,3,4});
// (St5arrayIdLm3EE) 2 3 4
```

Pros and cons of templates

Gains

- more generic code, thus less code
- better compiler optimization
- allows some compile time processing
  - also known as template metaprograming

The drawbacks

- not so trivial syntax, especially when variadic
- heavy for the compiler if abused
- only usable for what you know at compile time

Do more at compile time

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Generalized Constant Expressions

Reason of being

- use functions to compute constant expressions at compile time

Generalized Constant Expressions

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- use functions to compute constant expressions at compile time

Example

```
constexpr int f(int x) {
  if (x > 1) return x * f(x - 1);
  return 1;
}
constexpr int a = f(5); // computed at compile-time
int b = f(5); // maybe computed at compile-time
int n = ...;  // runtime value
int c = f(n); // computed at runtime
```

`if constexpr`

Compile time if statement

- takes a generalized constant expression
- decides which branch to keep at compile time
- drops the other branch

if constexpr

Compile time if statement

- takes a generalized constant expression
- decides which branch to keep at compile time
- drops the other branch

Generic printing - godbolt

```
template<typename T> struct Print {
  Print(T const& obj) {
    std::cout << "(" << typeid(T).name() << ") ";
    if constexpr( Container<T> ) {
      for( auto& item: obj) { std::cout << item << " "; }
    } else {
      std::cout << obj;
    }
    std::cout << "\n";
  }
};
```

Do more at compile time

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Virtuality in a nutshell

Principle

- a base class (aka interface) declares some method virtual
- children can overload these methods (as any other)
- for these method, late binding is applied
- that is most precise type is used

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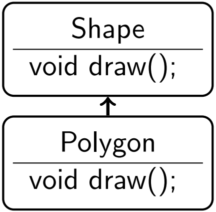
- that is most precise type is used

```
Polygon p;
p.draw(); // Polygon.draw

Shape & s = p;
s.draw(); // Shape.draw
```



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Polygon p;
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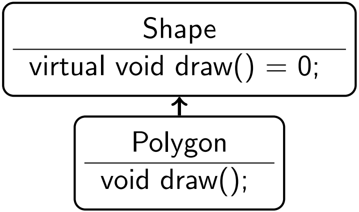
s.draw(); // Polygon.draw
```



The price of virtuality

Actual implementation

- each object has an extra pointer
- to a “virtual table” object in memory
- where each virtual function points to the right overload

Cost

- extra virtual table in memory, per type
- each virtual call does
  - retrieve virtual table pointer
  - load virtual table into memory
  - lookup right call
  - effectively call
- and is thus much more costful than standard function call
- up to 20% difference in terms of nb of instructions

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Actual price of virtuality

Comparison with templates - godbolt / godbolt

```
struct Interface {
  virtual void tick(float n) = 0;
};
struct Counter : Interface {
  float sum{0};
  void tick(float v) override
    { sum += v; }
};
void foo(Interface& c) {
  for (int i = 0; i < 80000; ++i) {
    for (int j = 0; j < i; ++j) {
      c.tick(j);
    }
  }
}
int main() {
  auto obj =
    std::make_unique<Counter>();
  foo(*obj);
}
```

```
struct Counter {
  float sum{0};
  void tick(float v) { sum += v; }
};
template<typename CounterType>
void foo(CounterType& c) {
  for (int i = 0; i < 80000; ++i) {
    for (int j = 0; j < i; ++j) {
      c.tick(j);
    }
  }
}
```

Actual price of virtuality

Comparison with templates - godbolt / godbolt

```
struct Interface {
  virtual void tick(float n) = 0;
};
struct Counter : Interface {
  float sum{0};
  void tick(float v) override
    { sum += v; }
};
void foo(Interface& c) {
  for (int i = 0; i < 80000; ++i) {
    for (int j = 0; j < i; ++j) {
      c.tick(j);
    }
  }
}
int main() {
  auto obj =
    std::make_unique<Counter>();
  foo(*obj);
}
```

```
struct Counter {
  float sum{0};
  void tick(float v) { sum += v; }
};
template<typename CounterType>
void foo(CounterType& c) {
  for (int i = 0; i < 80000; ++i) {
    for (int j = 0; j < i; ++j) {
      c.tick(j);
    }
  }
}
```

Timing	Time(s)	Nb instr(G)
virtual	10.8	35.2
templ	2.97	8.9

- measured on EPYC 7552, with gcc 9.1 and perf

A few explanations

Some consequences of virtuality

- more branching, killing the pipeline
  - here 6.4M vs 0.8M branches !
  - as virtual calls are branches
- lack of inlining possibilities
- lack of optimizations after inlining
  - e.g. auto vectorization

Note that the compiler is trying hard to help

- when it can, when it knows so give it all the knowledge !
- typical on my example

A few explanations

Some consequences of virtuality

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- lack of inlining possibilities
- lack of optimizations after inlining
  - e.g. auto vectorization

Note that the compiler is trying hard to help

- when it can, when it knows so give it all the knowledge !
- typical on my example
  - declare `obj` on the stack and the compiler will "drop" virtuality
    - again : drop pointers !
  - gcc 10/12 does much better : 22/16G instructions and 3s

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Should I use virtuality ?

Yes, when you cannot know anything at compile time

Typical cases

- you have no knowledge of the implementations of an interface
  - new ones may even be loaded dynamically via shared libraries
- you mix various implementations in a container
  - e.g. `std::vector<MyInterface>`
  - and there is no predefined set of implementations

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- you have no knowledge of the implementations of an interface
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- you mix various implementations in a container
  - e.g. `std::vector<MyInterface>`
  - and there is no predefined set of implementations

Typical alternatives

- templates when everything is compile time
  - allows full optimization of each case
  - and even static polymorphism through CRTP
    - Curiously recurring template pattern
- `std::variant`, `std::any` and visitor
  - when type definitions are known at compile type
  - but not necessary their usage

std::variant, std::any

Purpose

- type safe union and “void*”
- with visitor pattern

std::variant, std::any

Purpose

- type safe union and "void*"
- with visitor pattern

Example code - godbolt

```
using Message = std::variant<int, std::string>;
Message createMessage(bool error) {
  if (error) return "Error"; else return 42;
}
int i = std::get<int>(createMessage(false));
struct Visitor {
  void operator()(int n) const {
    std::cout << "Int " << n << std::endl;
  }
  void operator()(const std::string &s) const {
    std::cout << "String \"" << s << "\"" << std::endl;
  }
};
std::visit(Visitor{}, createMessage(true));
```

std::variant, std::any

Or you use lambdas and their inheritance - godbolt

```
template <class ... P> struct Combine : P... {
  using P::operator()...;
};
template <class ... F> Combine<F...> combine(F... fs) {
  return { fs ... };
}
using Message = std::variant<int, std::string>;
Message createMessage(bool error) {
  if (error) return "Error"; else return 42;
}
auto f = combine(
    [](int n) { std::cout << "Int " << n << std::endl; },
    [](string const &s) {
      std::cout << "String \"" << s << "\"" << std::endl;
    });
std::visit(f, createMessage(true));
```

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A Visitor example

Virtual vs variant - godbolt

```
struct Point { virtual float getR() = 0; };
struct XYZPoint : Point {
  float x, y, z;
  float getR() override { return std::sqrt(x*x+y*y+z*z); }; };
struct RTPPoint : Point {
  float r, theta, phi;
  float getR() override { return r; } };
float sumR(std::vector<std::unique_ptr<Point>>& v) {
  return std::accumulate(begin(v), end(v), 0.0f,
  [&](float s, std::unique_ptr<Point>& p) { return s + p->getR();} );
}

struct XYZPoint { float x,y,z; };  struct RTPPoint { float r, theta, phi; };
using Point=std::variant<XYZPoint, RTPPoint>;
float sumR(std::vector<Point>& v) {
  auto getR = combine(
  [](XYZPoint& p) { return std::sqrt(p.x*p.x+p.y*p.y+p.z*p.z); },
  [](RTPPoint& p) { return p.r; });
  return std::accumulate(begin(v), end(v), 0.0f,
  [&](float s, Point& p) { return s + std::visit(getR, p);} );
}
```

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A Visitor example

Virtual vs variant - godbolt

```
struct Point { virtual float getR() = 0; };
struct XYZPoint : Point {
  float x, y, z;
  float getR() override { ret … *x+y*y+z*z); }; };
struct RTPPoint : Point {
  float r, theta, phi;
  float getR() overrid … };
float sumR(std::vector … e_ptr<Point>>& v) {
  return std::accumulate( … n(v), end(v), 0.0f,
  [&](float s, std::unique_ptr<Point>& p) { return s + p->getR();} );
}

struct XYZPoint { float x,y,z; };  struct RTPPoint { float r, theta, phi; };
using Point=std::variant<XYZPoint, RTPP …
float sumR(std::vector<Point>& v) {
  auto getR = combine(
  [](XYZPoint& p) { return s … y*p.y+p.z*p.z); },
  [](RTPPoint& p) { return …
  return std::accumulate(be … ), 0.0f,
  [&](float s, Point& p) { r … + std::visit(getR, p);} );
}
```

took 3500µs

took 2050µs

Conclusion

Key messages of the day

- functional programming is useful
  - can simplify the code
  - ensures thread safety
  - helps the compiler to optimize better
- the key to performance is the compiler
  - help it by providing information
  - constness, noexcept, fixed lengths, ...
- a lot can be done at compile time
  - find out what you know at compile time
  - make best use of it (templates, variants, ...)

Index of Godbolt code examples