Pattern Matching

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Contents

1 Revision History

- R3
  - Updated Design Overview and other sections: `inspect` is always an expression.
  - Clarified that extractor pattern samples are not proposed for standardisation.
  - Forbid `break` inside `inspect` expression.
  - Removed [Binding Pattern] and simplified Case Pattern.
- R2
  - Modified Dereference Pattern to `(*!) pattern` and `(*?) pattern`
  - Modified Extractor Pattern to `(extractor!) pattern` and `(extractor?) pattern`.
  - Added reasons for the choice of [`let` rather than `auto`].
  - Allowed using [Statements in `inspect` expression].
- R1
  - Modified Wildcard Pattern to use `__` (double underscore).
  - Added new patterns Case Pattern and [Binding Pattern].
  - Removed `^` from Expression Pattern.
  - Modified Dereference Pattern to `*!` and `*?`.
  - Added Structured Binding Pattern usage in variable declaration.
- R0
  - Merged [P1260R0] and [P1308R0]

2 Introduction

As algebraic data types gain better support in C++ with facilities such as `tuple` and `variant`, the importance of mechanisms to interact with them have increased. While mechanisms such as `apply` and `visit` have been added, their usage is quite complex and limited even for simple cases. Pattern matching is a widely adopted mechanism across many programming languages to interact with algebraic data types that can help greatly simplify C++. Examples of programming languages include text-based languages such as SNOBOL back in the 1960s, functional languages such as Haskell and OCaml, and "mainstream" languages such as Scala, Swift, and Rust.

This paper is a result of collaboration between the authors of [P1260R0] and [P1308R0]. A joint presentation by the authors of the two proposals was given in EWGI at the San Diego 2018 meeting, with the closing poll: "Should we commit additional committee time to pattern matching?" — SF: 14, WF: 0, N: 1, WA: 0, SA: 0

3 Motivation and Scope

Virtually every program involves branching on some predicates applied to a value and conditionally binding names to some of its components for use in subsequent logic. Today, C++ provides two types of selection statements: the `if` statement and the `switch` statement.

Since `switch` statements can only operate on a *single* integral value and `if` statements operate on an *arbitrarily* complex boolean expression, there is a significant gap between the two constructs even in inspection of the "vocabulary types" provided by the standard library.

In C++17, structured binding declarations [P0144R2] introduced the ability to concisely bind names to components of `tuple`-like values. The proposed direction of this paper aims to naturally extend this notion by performing **structured inspection** with `inspect` expressions. The goal of `inspect` is to bridge the gap between `switch` and `if` statements with a **declarative**, **structured**, **cohesive**, and **composable** mechanism.

4 Before/After Comparisons

4.1 Matching Integrals

<table>
<tr><th>Before</th><th>After</th></tr>
<tr><td>

```
switch (x) {
  case 0: std::cout << "got zero"; break;
  case 1: std::cout << "got one"; break;
  default: std::cout << "don't care";
}
```

</td><td>

```
inspect (x) {
  0 => { std::cout << "got zero"; }
  1 => { std::cout << "got one"; }
  __ => { std::cout << "don't care"; }
};
```

</td></tr>
</table>

4.2 Matching Strings

<table>
<tr><th>Before</th><th>After</th></tr>
<tr><td>

```
if (s == "foo") {
  std::cout << "got foo";
} else if (s == "bar") {
  std::cout << "got bar";
} else {
  std::cout << "don't care";
}
```

</td><td>

```
inspect (s) {
  "foo" => { std::cout << "got foo"; }
  "bar" => { std::cout << "got bar"; }
  __ => { std::cout << "don't care"; }
};
```

</td></tr>
</table>

4.3 Matching Tuples

<table>
<tr><th>Before</th><th>After</th></tr>
<tr><td>

```
auto&& [x, y] = p;
if (x == 0 && y == 0) {
  std::cout << "on origin";
} else if (x == 0) {
  std::cout << "on y-axis";
} else if (y == 0) {
  std::cout << "on x-axis";
} else {
  std::cout << x << ',' << y;
}
```

</td><td>

```
inspect (p) {
  [0, 0] => { std::cout << "on origin"; }
  [0, y] => { std::cout << "on y-axis"; }
  [x, 0] => { std::cout << "on x-axis"; }
  [x, y] => { std::cout << x << ',' << y; }
};
```

</td></tr>
</table>

4.4 Matching Variants

Before	After

Before

```
struct visitor {
  void operator()(int i) const {
    os << "got int: " << i;
  }
  void operator()(float f) const {
    os << "got float: " << f;
  }
  std::ostream& os;
};
std::visit(visitor{strm}, v);
```

After

```
inspect (v) {
  <int> i => {
    strm << "got int: " << i;
  }
  <float> f => {
    strm << "got float: " << f;
  }
};
```

4.5 Matching Polymorphic Types

```
struct Shape { virtual ~Shape() = default; };
struct Circle : Shape { int radius; };
struct Rectangle : Shape { int width, height; };
```

Before	After

Before

```
virtual int Shape::get_area() const = 0;

int Circle::get_area() const override {
  return 3.14 * radius * radius;
}
int Rectangle::get_area() const override {
  return width * height;
}
```

After

```
int get_area(const Shape& shape) {
  return inspect (shape) {
    <Circle>    [r]    => 3.14 * r * r;
    <Rectangle> [w, h] => w * h;
  };
}
```

4.6 Evaluating Expression Trees

```cpp
struct Expr;

struct Neg {
  std::shared_ptr<Expr> expr;
};

struct Add {
  std::shared_ptr<Expr> lhs, rhs;
};

struct Mul {
  std::shared_ptr<Expr> lhs, rhs;
};

struct Expr : std::variant<int, Neg, Add, Mul> {
  using variant::variant;
};

namespace std {
  template <>
  struct variant_size<Expr> : variant_size<Expr::variant> {};

  template <std::size_t I>
  struct variant_alternative<I, Expr> : variant_alternative<I, Expr::variant> {};
}
```

Before / After

```
int eval(const Expr& expr) {
  struct visitor {
    int operator()(int i) const {
      return i;
    }
    int operator()(const Neg& n) const {
      return -eval(*n.expr);
    }
    int operator()(const Add& a) const {
      return eval(*a.lhs) + eval(*a.rhs);
    }
    int operator()(const Mul& m) const {
      // Optimize multiplication by 0.
      if (int* i = std::get_if<int>(m.lhs.get()); i && *i == 0) {
        return 0;
      }
      if (int* i = std::get_if<int>(m.rhs.get()); i && *i == 0) {
        return 0;
      }
      return eval(*m.lhs) * eval(*m.rhs);
    }
  };
  return std::visit(visitor{}, expr);
}
```

```
int eval(const Expr& expr) {
  return inspect (expr) {
    <int> i => i;
    <Neg> [(*?) e] => -eval(e);
    <Add> [(*?) l, (*?) r] => eval(l) + eval(r);
    // Optimize multiplication by 0.
    <Mul> [(*?) <int> 0, __] => 0;
    <Mul> [__, (*?) <int> 0] => 0;
    <Mul> [(*?) l, (*?) r] => eval(l) * eval(r);
  };
}
```

4.7 Patterns In Declarations

Before / After

```
auto const& [topLeft, unused] = getBoundaryRectangle();
auto const& [topBoundary, leftBoundary] = topLeft;
```

```
auto const& [[topBoundary, leftBoundary], __] = getBoundaryRectangle();
```

4.8 Terminate from Inspect

Before	After

Before:

```
enum class Op { Add, Sub, Mul, Div };
Op parseOp(Parser& parser) {
  const auto& token = parser.consumeToken();
  switch (token) {
    case '+': return Op::Add;
    case '-': return Op::Sub;
    case '*': return Op::Mul;
    case '/': return Op::Div;
    default: {
      std::cerr << "Unexpected " << token;
      std::terminate();
    }
  }
}
```

After:

```
enum class Op { Add, Sub, Mul, Div };
Op parseOp(Parser& parser) {
  return inspect (parser.consumeToken()) {
    '+' => Op::Add;
    '-' => Op::Sub;
    '*' => Op::Mul;
    '/' => Op::Div;
    token => !{
      std::cerr << "Unexpected: " << token;
      std::terminate();
    }
  };
}
```

5 Design Overview

5.1 Basic Syntax

`inspect constexpr`$_{opt}$ `(` *init-statement*$_{opt}$ *condition* `)` *trailing-return-type*$_{opt}$ `{`
  pattern guard$_{opt}$ `=>` *statement*
  pattern guard$_{opt}$ `=>` `!`$_{opt}$ `{` *statement-seq* `}`
  ...
`}`

guard:
  `if (` *expression* `)`

5.2 Basic Model

Within the parentheses, `inspect` is equivalent to `switch` and `if` statements except that no conversion nor promotion takes place in evaluating the value of its condition.

`inspect` is an expression in all contexts. Depending on the enclosed statements it may either yield a `void` result or a value, the type of which will be statically deduced from the statements themselves or specified by a trailing return type. The deduction is analogous to that performed when determining the return type of a lambda expression. A pattern that passes control to a compound statement yields a `void` result. The return types of all patterns must match. If a trailing return type is provided, all patterns must result in an expression returning a type that is implicitly convertible to the trailing return type.

If `!` prefix is used before compound statement - the statement would not contribute to return type deduction for `inspect` expression. Such a statement is not expected to yield a value and should stop the execution either by returning from the enclosing function, throwing an exception or terminating the program. This allows users to express desired no-match behaviour or to act upon broken invariant, without affecting return type of the whole of `inspect` expression. If execution reaches end of the compound statement `std::terminate` is called.

When `inspect` is executed, its condition is evaluated and matched in order (first match semantics) against each pattern. If a pattern successfully matches the value of the condition and the boolean expression in the guard evaluates to `true` (or if there is no guard at all), then the value of the resulting expression is yielded or control is passed to the compound statement, depending on whether the inspect yields a value. If the guard expression evaluates to `false`, control flows to the subsequent pattern.

If no pattern matches, none of the expressions or compound statements specified are executed. In that case if the `inspect` expression yields `void`, control is passed to the next statement. If the `inspect` expression does not yield `void`, `std::terminate` will be called.

5.3 Types of Patterns

5.3.1 Primary Patterns

5.3.1.1 Wildcard Pattern

The wildcard pattern has the form:

`__`

and matches any value `v`.

```
int v = /* ... */;

inspect (v) {
    __ => { std::cout << "ignored"; }
//  ^^ wildcard pattern
};
```

This paper adopts the wildcard identifier `__`, preferred as an example spelling in [P1110R0]. The authors of this paper attempted to reserve `_` for wildcard purposes in [P1469R0] but consensus in EWG was firmly against this option.

5.3.1.2 Identifier Pattern

The identifier pattern has the form:

identifier

and matches any value `v`. The *identifier* behaves as an lvalue referring to `v`, and is in scope from its point of declaration until the end of the statement following the pattern label.

```
int v = /* ... */;

inspect (v) {
    x => { std::cout << x; }
//  ^ identifier pattern
};
```

[*Note:* If the identifier pattern is used at the top-level, it has the same syntax as a `goto` label. — *end note*]

5.3.1.3 Expression Pattern

The expression pattern has the form:

constant-expression

and matches value `v` if a call to member `e.match(v)` or else a non-member ADL-only `match(e, v)` is contextually convertible to `bool` and evaluates to `true` where `e` is *constant-expression*.

The default behavior of `match(x, y)` is `x == y`.

```
int v = /* ... */;

inspect (v) {
    0 => { std::cout << "got zero"; }
    1 => { std::cout << "got one"; }
//  ^ expression pattern
};
```

```
enum class Color { Red, Green, Blue };
Color color = /* ... */;
```

```
inspect (color) {
    Color::Red =>   // ...
    Color::Green => // ...
    Color::Blue =>  // ...
//  ^^^^^^^^^^^ expression pattern
};
```

[*Note:* By default, an *identifier* is an Identifier Pattern. See Case Pattern. — *end note*]

```
static constexpr int zero = 0, one = 1;
int v = 42;

inspect (v) {
    zero => { std::cout << zero; }
//  ^^^^ identifier pattern
};

// prints: 42
```

5.3.2 Compound Patterns

5.3.2.1 Structured Binding Pattern

The structured binding pattern has the following two forms:

[$pattern_0$, $pattern_1$, ... , $pattern_N$]
[$designator_0$: $pattern_0$, $designator_1$: $pattern_1$, ... , $designator_N$: $pattern_N$]

The first form matches value `v` if each $pattern_i$ matches the i^{th} component of `v`. The components of `v` are given by the structured binding declaration: `auto&& [__e`$_0$`, __e`$_1$`, ..., __e`$_N$`] = v;` where each `__e`$_i$ are unique exposition-only identifiers.

```
std::pair<int, int> p = /* ... */;

inspect (p) {
    [0, 0] => { std::cout << "on origin"; }
    [0, y] => { std::cout << "on y-axis"; }
//      ^ identifier pattern
    [x, 0] => { std::cout << "on x-axis"; }
//      ^ expression pattern
    [x, y] => { std::cout << x << ',' << y; }
//  ^^^^^^ structured binding pattern
};
```

The second form matches value `v` if each *pattern*$_i$ matches the direct non-static data member of `v` named *identifier* from each *designator*$_i$. If an *identifier* from any *designator*$_i$ does not refer to a direct non-static data member of `v`, the program is ill-formed.

```
struct Player { std::string name; int hitpoints; int coins; };

void get_hint(const Player& p) {
    inspect (p) {
        [.hitpoints: 1] => { std::cout << "You're almost destroyed. Give up!\n"; }
        [.hitpoints: 10, .coins: 10] => { std::cout << "I need the hints from you!\n"; }
        [.coins: 10] => { std::cout << "Get more hitpoints!\n"; }
        [.hitpoints: 10] => { std::cout << "Get more ammo!\n"; }
        [.name: n] => {
            if (n != "The Bruce Dickenson") {
                std::cout << "Get more hitpoints and ammo!\n";
            } else {
                std::cout << "More cowbell!\n";
            }
        }
    };
}
```

[*Note:* Unlike designated initializers, the order of the designators need not be the same as the declaration order of the members of the class. — *end note*]

5.3.2.2 Alternative Pattern

The alternative pattern has the following forms:

< `auto` > *pattern*
< *concept* > *pattern*
< *type* > *pattern*
< *constant-expression* > *pattern*

Let `v` be the value being matched and `V` be `std::remove_cvref_t<decltype(v)>`.
Let `Alt` be the entity inside the angle brackets.

Case 1: `std::variant`-like

If `std::variant_size_v<V>` is well-formed and evaluates to an integral, the alternative pattern matches `v` if `Alt` is compatible with the current index of `v` and *pattern* matches the active alternative of `v`.

Let `I` be the current index of `v` given by a member `v.index()` or else a non-member ADL-only `index(v)`. The active alternative of `v` is given by `std::variant_alternative_t<I, V>&` initialized by a member `v.get<I>()` or else a non-member ADL-only `get<I>(v)`.

`Alt` is compatible with `I` if one of the following four cases is true:

— `Alt` is `auto`
— `Alt` is a *concept* and `std::variant_alternative_t<I, V>` satisfies the *concept*.
— `Alt` is a *type* and `std::is_same_v<Alt, std::variant_alternative_t<I, V>>` is `true`
— `Alt` is a *constant-expression* that can be used in a `switch` and is the same value as `I`.

<table>
<tr><th>Before</th><th>After</th></tr>
<tr><td>

```
std::visit(
  [&](auto&& x) {
    strm << "got auto: " << x;
  },
  v);
```

</td><td>

```
inspect (v) {
  <auto> x => {
    strm << "got auto: " << x;
  }
};
```

</td></tr>
<tr><td>

```
std::visit([&](auto&& x) {
  using X = std::remove_cvref_t<decltype(x)>;
  if constexpr (C1<X>()) {
    strm << "got C1: " << x;
  } else if constexpr (C2<X>()) {
    strm << "got C2: " << x;
  }
}, v);
```

</td><td>

```
inspect (v) {
  <C1> c1 => {
    strm << "got C1: " << c1;
  }
  <C2> c2 => {
    strm << "got C2: " << c2;
  }
};
```

</td></tr>
<tr><td>

```
std::visit([&](auto&& x) {
  using X = std::remove_cvref_t<decltype(x)>;
  if constexpr (std::is_same_v<int, X>) {
    strm << "got int: " << x;
  } else if constexpr (
      std::is_same_v<float, X>) {
    strm << "got float: " << x;
  }
}, v);
```

</td><td>

```
inspect (v) {
  <int> i => {
    strm << "got int: " << i;
  }
  <float> f => {
    strm << "got float: " << f;
  }
};
```

</td></tr>
<tr><td>

```
std::variant<int, int> v = /* ... */;

std::visit(
  [&](int x) {
    strm << "got int: " << x;
  },
  v);
```

</td><td>

```
std::variant<int, int> v = /* ... */;

inspect (v) {
  <int> x => {
    strm << "got int: " << x;
  }
};
```

</td></tr>
<tr><td>

```
std::variant<int, int> v = /* ... */;

std::visit([&](auto&& x) {
  switch (v.index()) {
    case 0: {
      strm << "got first: " << x; break;
    }
    case 1: {
      strm << "got second: " << x; break;
    }
  }
}, v);
```

</td><td>

```
std::variant<int, int> v = /* ... */;

inspect (v) {
  <0> x => {
    strm << "got first: " << x;
  }
  <1> x => {
    strm << "got second: " << x;
  }
};
```

</td></tr>
</table>

Case 2: `std::any`-like

< *type* > *pattern*

If `Alt` is a *type* and there exists a valid non-member ADL-only `any_cast<Alt>(&v)`, let `p` be its result. The alternative pattern matches if `p` contextually converted to `bool` evaluates to `true`, and *pattern* matches `*p`.

Before

```
std::any a = 42;

if (int* i = any_cast<int>(&a)) {
  std::cout << "got int: " << *i;
} else if (float* f = any_cast<float>(&a)) {
  std::cout << "got float: " << *f;
}
```

After

```
std::any a = 42;

inspect (a) {
  <int> i => {
    std::cout << "got int: " << i;
  }
  <float> f => {
    std::cout << "got float: " << f;
  }
};
```

Case 3: Polymorphic Types

< *type* > *pattern*

If `Alt` is a *type* and `std::is_polymorphic_v<V>` is `true`, let `p` be `dynamic_cast<Alt'*>(&v)` where `Alt'` has the same *cv*-qualifications as `decltype(&v)`. The alternative pattern matches if `p` contextually converted to `bool` evaluates to `true`, and *pattern* matches `*p`.

While the **semantics** of the pattern is specified in terms of `dynamic_cast`, [N3449] describes techniques involving vtable pointer caching and hash conflict minimization that are implemented in the [Mach7] library, as well as mentions of further opportunities available for a compiler intrinsic.

Given the following definition of a `Shape` class hierarchy:

```
struct Shape { virtual ~Shape() = default; };

struct Circle : Shape { int radius; };
struct Rectangle : Shape { int width, height; };
```

Before

```
virtual int Shape::get_area() const = 0;

int Circle::get_area() const override {
  return 3.14 * radius * radius;
}

int Rectangle::get_area() const override {
  return width * height;
}
```

After

```
int get_area(const Shape& shape) {
  return inspect (shape) {
    <Circle> [r] => 3.14 * r * r;
    <Rectangle> [w, h] => w * h;
  };
}
```

5.3.2.3 Parenthesized Pattern

The parenthesized pattern has the form:

`(` *pattern* `)`

and matches value `v` if *pattern* matches `v`.

```
std::variant<Point, /* ... */> v = /* ... */;

inspect (v) {
    <Point> ([x, y]) => // ...
//          ^^^^^^^^ parenthesized pattern
};
```

5.3.2.4 Case Pattern

The case pattern has the form:

`case` *expression-pattern*

And matches value `v` if *expression-pattern* matches `v`. This pattern allows using *id-expression* as part of inspect expression. Otherwise any *identifier* would have been interpreted as identifier pattern.

```
enum Color { Red, Green, Blue };
Color color = /* ... */;

inspect (color) {
    case Red =>   // ...
    case Green => // ...
//       ^^^^^ id-expression
    case Blue =>  // ...
//  ^^^^^^^^^ case pattern
};
```

```
static constexpr int zero = 0;
int v = /* ... */;

inspect (v) {
    case zero => { std::cout << "got zero"; }
//       ^^^^ id-expression
    case 1 => { std::cout << "got one"; }
//       ^ expression pattern
    case 2 => { std::cout << "got two"; }
//  ^^^^^^ case pattern
};
```

```
static constexpr int zero = 0, one = 1;
std::pair<int, int> p = /* ... */

inspect (p) {
    [case zero, case one] => {
//        ^^^^       ^^^ id-expression
      std::cout << zero << ' ' << one;
//    Note that    ^^^^ and       ^^^ are id-expressions
//    that refer to the `static constexpr` variables.
    }
};
```

5.3.2.5 Dereference Pattern

The dereference pattern has the following forms:

`(*!)` *pattern*
`(*?)` *pattern*

The first form matches value `v` if *pattern* matches `*v`. The second form matches value `v` if `v` is contextually convertible to `bool` and evaluates to `true`, and *pattern* matches `*v`.

```
struct Node {
    int value;
    std::unique_ptr<Node> lhs, rhs;
};

void print_leftmost(const Node& node) {
    inspect (node) {
        [.value: v, .lhs: nullptr] => { std::cout << v << '\n'; }
        [.lhs: (*!) l] => { print_leftmost(l); }
//              ^^^^ dereference pattern
    };
}
```

[*Note:* Refer to Red-black Tree Rebalancing for a more complex example. — *end note*]

5.3.2.6 Extractor Pattern

The extractor pattern has the following two forms:

`(` *constant-expression* `!` `)` *pattern*
`(` *constant-expression* `?` `)` *pattern*

Let `c` be the *constant-expression*. The first form matches value `v` if *pattern* matches `e` where `e` is the result of a call to member `c.extract(v)` or else a non-member ADL-only `extract(c, v)`.

```
template <typename T>
struct Is {
    template <typename Arg>
    Arg&& extract(Arg&& arg) const {
        static_assert(std::is_same_v<T, std::remove_cvref_t<Arg>>);
        return std::forward<Arg>(arg);
    }
};

template <typename T>
inline constexpr Is<T> is;

// P0480: `auto&& [std::string s, int i] = f();`
inspect (f()) {
    [(is<std::string>!) s, (is<int>!) i] => // ...
//    ^^^^^^^^^^^^^^^^^^^^  ^^^^^^^^^^^^ extractor pattern
};
```

For second form, let `e` be the result of a call to member `c.try_extract(v)` or else a non-member ADL-only `try_extract(c, v)`. It matches value `v` if `e` is contextually convertible to `bool`, evaluates to `true`, and *pattern* matches `*e`.

```
struct Email {
    std::optional<std::array<std::string_view, 2>>
    try_extract(std::string_view sv) const;
};

inline constexpr Email email;

struct PhoneNumber {
    std::optional<std::array<std::string_view, 3>>
    try_extract(std::string_view sv) const;
};

inline constexpr PhoneNumber phone_number;

inspect (s) {
    (email?) [address, domain] => { std::cout << "got an email"; }
    (phone_number?) ["415", __, __] => { std::cout << "got a San Francisco phone number"; }
//  ^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^ extractor pattern
};
```

5.4 Pattern Guard

The pattern guard has the form:

`if` `(` *expression* `)`

Let `e` be the result of *expression* contextually converted to `bool`. If `e` is `true`, control is passed to the corresponding statement. Otherwise, control flows to the subsequent pattern.

The pattern guard allows to perform complex tests that cannot be performed within the *pattern*. For example, performing tests across multiple bindings:

```
inspect (p) {
    [x, y] if (test(x, y)) => { std::cout << x << ',' << y << " passed"; }
//          ^^^^^^^^^^^^^^^ pattern guard
};
```

This also diminishes the desire for fall-through semantics within the statements, an unpopular feature even in `switch` statements.

5.5 inspect constexpr

Every *pattern* is able to determine whether it matches value `v` as a boolean expression in isolation. Let `MATCHES` be the condition for which a *pattern* matches a value `v`. Ignoring any potential optimization opportunities, we're able to perform the following transformation:

inspect	**if**

`inspect (v) {`
`  pattern1 if (cond1) => { stmt1 }`
`  pattern2 => { stmt2 }`
`  // ...`
`};`
	`if (MATCHES(pattern1, v) && cond1) stmt1`
	`else if (MATCHES(pattern2, v)) stmt2`
	`// ...`

`inspect constexpr` is then formulated by applying `constexpr` to every `if` branch.

inspect constexpr	**if constexpr**

`inspect constexpr (v) {`
`  pattern1 if (cond1) => { stmt1 }`
`  pattern2 => { stmt2 }`
`  // ...`
`};`
	`if constexpr (MATCHES(pattern1, v) && cond1) stmt1`
	`else if constexpr (MATCHES(pattern2, v)) stmt2`
	`// ...`

5.6 Exhaustiveness and Usefulness

`inspect` can be declared `[[strict]]` for implementation-defined exhaustiveness and usefulness checking.

Exhaustiveness means that all values of the type of the value being matched is handled by at least one of the cases. For example, having a `__:` case makes any `inspect` statement exhaustive.

Usefulness means that every case handles at least one value of the type of the value being matched. For example, any case that comes after a `__:` case would be useless.

Warnings for pattern matching [Warnings] discusses and outlines an algorithm for exhaustiveness and usefulness for OCaml, and is the algorithm used by Rust.

5.7 Refutability

Patterns that cannot fail to match are said to be *irrefutable* in contrast to *refutable* patterns which can fail to match. For example, the identifier pattern is *irrefutable* whereas the expression pattern is *refutable*.

The distinction is useful in reasoning about which patterns should be allowed in which contexts. For example, the structured bindings declaration is conceptually a restricted form of pattern matching. With the introduction of expression pattern in this paper, some may question whether structured bindings declaration should be extended for examples such as `auto [0, x] = f();`.

This is ultimately a question of whether structured bindings declaration supports *refutable* patterns or if it is restricted to *irrefutable* patterns.

6 Proposed Wording

The following is the beginning of an attempt at a syntactic structure.

Add to **§8.4** [**stmt.select**] of ...

1 Selection statements choose one of several flows of control.

selection-statement:
`if constexpr`$_{opt}$ `(` *init-statement*$_{opt}$ *condition* `)` *statement*
`if constexpr`$_{opt}$ `(` *init-statement*$_{opt}$ *condition* `)` *statement* `else` *statement*
`switch (` *init-statement*$_{opt}$ *condition* `)` *statement*
`inspect constexpr`$_{opt}$ `(` *init-statement*$_{opt}$ *condition* `)` *trailing-return-type*$_{opt}$ `{` *inspect-case-seq* `}`

inspect-case-seq:
inspect-statement-case-seq
inspect-expression-case-seq

inspect-statement-case-seq:
inspect-statement-case
inspect-statement-case-seq inspect-statement-case

inspect-expression-case-seq:
inspect-expression-case
inspect-expression-case-seq `,` *inspect-expression-case*

inspect-statement-case:
inspect-pattern inspect-guard$_{opt}$ `=>` *statement*

inspect-expression-case:
inspect-pattern inspect-guard$_{opt}$ `=>` *assignment-expression*

inspect-pattern:
alternative-pattern
case-pattern
dereference-pattern
expression-pattern
extractor-pattern
identifier-pattern
structured-binding-pattern
wildcard-pattern

inspect-guard:
`if (` *expression* `)`

Change **§9.1** [**dcl.dcl**]

simple-declaration:
decl-specifier-seq init-declarator-list$_{opt}$ `;`
attribute-specifier-seq decl-specifier-seq init-declarator-list `;`
~~*attribute-specifier-seq*$_{opt}$ *decl-specifier-seq ref-qualifier*$_{opt}$ `[` *identifier-list* `]` *initializer* `;`~~
attribute-specifier-seq$_{opt}$ *decl-specifier-seq ref-qualifier*$_{opt}$ *structured-binding-pattern initializer* `;`

7 Design Decisions

7.1 Extending Structured Bindings Declaration

The design is intended to be consistent and to naturally extend the notions introduced by structured bindings. That is, The subobjects are **referred** to rather than being assigned into new variables.

We propose any **irrefutable** pattern to be **allowed** in structured binding declaration, as it does not introduce any new behaviour. A separate paper will explore possibility of allowing **refutable** patterns to be used in declarations.

7.2 `inspect` rather than `switch`

This proposal introduces a new `inspect` statement rather than trying to extend the `switch` statement. [P0095R0] had proposed extending `switch` and received feedback to "leave `switch` alone" in Kona 2015.

The following are some of the reasons considered:

— `switch` allows the `case` labels to appear **anywhere**, which hinders the goal of pattern matching in providing **structured** inspection.
— The fall-through semantics of `switch` generally results in `break` being attached to every case, and is known to be error-prone.
— `switch` is purposely restricted to integrals for **guaranteed** efficiency. The primary goal of pattern matching in this paper is expressiveness while being at least as efficient as the naively hand-written code.

7.3 First Match rather than Best Match

The proposed matching algorithm has first match semantics. The choice of first match is mainly due to complexity. Our overload resolution rules for function declarations are extremely complex and is often a mystery.

Best match via overload resolution for function declarations are absolutely necessary due to the non-local and unordered nature of declarations. That is, function declarations live in different files and get pulled in via mechanisms such as `#include` and `using` declarations, and there is no defined order of declarations like Haskell does, for example. If function dispatching depended on the order of `#include` and/or `using` declarations being pulled in from hundreds of files, it would be a complete disaster.

Pattern matching on the other hand do not have this problem because the construct is local and ordered in nature. That is, all of the candidate patterns appear locally within `inspect (x) { /* ... */ }` which cannot span across multiple files, and appear in a specified order. This is consistent with `try`/`catch` for the same reasons: locality and order.

Consider also the amount of limitations we face in overload resolution due to the opacity of user-defined types. `T*` is related to `unique_ptr<T>` as it is to `vector<T>` as far as the type system is concerned. This limitation will likely be even bigger in a pattern matching context with the amount of customization points available for user-defined behavior.

7.4 Unrestricted Side Effects

We considered the possibility of restricting side-effects within patterns. Specifically whether modifying the value currently being matched in the middle of evaluation should have defined behavior.

The consideration was due to potential optimization opportunities.

```
bool f(int &);  // defined in a different translation unit.
int x = 1;

inspect (x) {
  0 => { std::cout << 0; }
  1 if (f(x)) => { std::cout << 1; }
```

```
  2 => { std::cout << 2; }
};
```

If modifying the value currently being matched has undefined behavior, a compiler can assume that `f` (defined in a different translation unit) will not change the value of `x`. This means that the compiler can generate code that uses a jump table to determine which of the patterns match.

If on the other hand `f` may change the value of `x`, the compiler would be forced to generated code checks the patterns in sequence, since a subsequent pattern may match the updated value of `x`.

The following are **illustrations** of the two approaches written in C++:

Not allowed to modify

```
bool f(int &);
int x = 1;

switch (x) {
  case 0: std::cout << 0; break;
  case 1: if (f(x)) { std::cout << 1; } break;
  case 2: std::cout << 2; break;
}
```

Allowed to modify

```
bool f(int &);
int x = 1;

if (x == 0) std::cout << 0;
else if (x == 1 && f(x)) std::cout << 1;
else if (x == 2) std::cout << 2;
```

However, we consider this opportunity too niche. Suppose we have a slightly more complex case: `struct S { int x; };` and `bool operator==(const S&, const S&);`. Even if modifying the value being matched has undefined behavior, if the `operator==` is defined in a different translation unit, a compiler cannot do much more than generate code that checks the patterns in sequence anyway.

7.5 Language rather than Library

There are three popular pattern matching libraries for C++ today: [Mach7], [Patterns], and [SimpleMatch].

While the libraries have been useful for gaining experience with interfaces and implementation, the issue of introducing identifiers, syntactic overhead of the patterns, and the reduced optimization opportunities justify support as a language feature from a usability standpoint.

7.6 Matchers and Extractors

Many languages provide a wide array of patterns through various syntactic forms. While this is a potential direction for C++, it would mean that every new type of matching requires new syntax to be added to the language. This would result in a narrow set of types being supported through limited customization points.

Matchers and extractors are supported in order to minimize the number of patterns with special syntax. The following are example matchers and extractors that commonly have special syntax in other languages.

Matchers / Extractors	Other Languages
`any_of{1, 2, 3}`	`1 | 2 | 3`
`within{1, 10}`	`1..10`
`(both!) [[x, 0], [0, y]]`	`[x, 0] & [0, y]`
`(at!) [p, [x, y]]`	`p @ [x, y]`

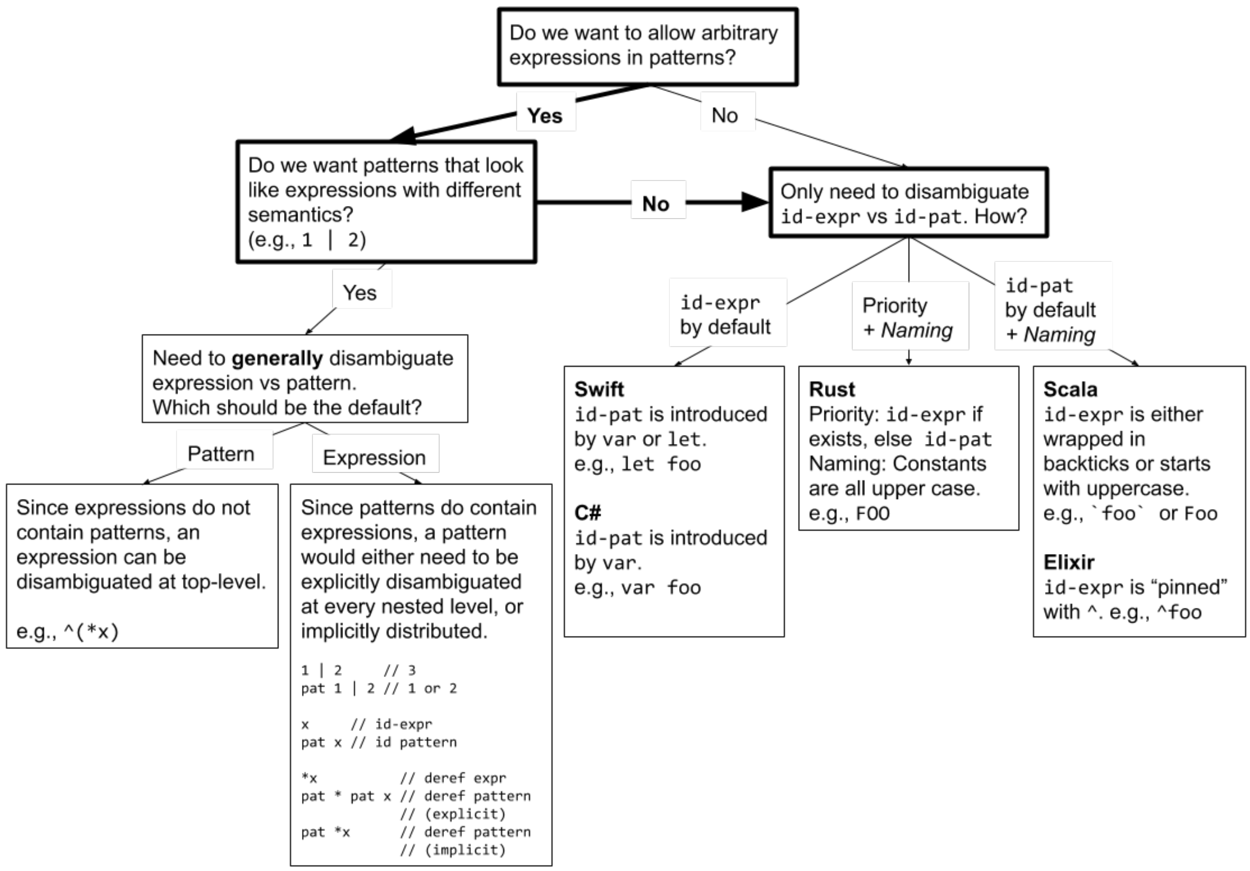
Each of the matchers and extractors can be found in the Examples section. The example extractors and matchers are not proposed for standardisation in this paper, and presented just for demonstration.

7.7 Expression vs Pattern Disambiguation

[P1371R0] had proposed a unary `^` as an "expression introducer". The main motivation was to leave the design space open for patterns that look like expressions. For example, many languages spell the alternation pattern with `|`, resulting in a pattern such as `1 | 2` which means "match `1` or `2`". However, to allow such a pattern a disambiguation mechanism would be required since `1 | 2` is already a valid expression today.

That paper also included what is called a dereference pattern with the syntax of `*` *pattern*. There was clear guidance from EWG to change the syntax of this pattern due to confusion with the existing dereference operator. As such, the design direction proposed in this paper is to allow expressions in patterns without an introducer, and to require that new patterns be syntactically unambiguous with an expression in general.

The following is a flow graph of decisions that need to be made:



7.8 Forbid `break` inside `inspect` expression

Since `inspect` is always an expression we decided to forbid using `break` keyword inside `inspect` expressions.

The problem lies with two possible use cases where `inspect` would be used.

```
for (const auto& el: some_vec) {
  // If-else-if chain
  if (el.type() == "NotInteresting") {
```

```
    break;
  } else if (el.type() == "SomeOther") {
    break;
  }

  // Switch statement
  switch (el.value()) {
    case 1: /* ... */
      break; // no fallthrough
    case 2: /* ... */
      break; // no fallthrough
    default:
      /* ... */
  }
}
```

In the example above, if we're replacing existing `switch` statement, `break` is used to terminate current statement sequence and jump to first statement after the `switch`. In particular it is required to prevent fallthrough.

If the code being replaced is a sequence of if-else branches, `break` there would indicate iteration stop for the enclosing loop.

Both use cases are interesting and valid for `inspect`, but resulting `break` behaviour differs. If we were to adopt one, the other use case would be prone to error. So for now we decided to forbid using `break` statements inside `inspect` expression branches.

Note, it is generally desirable to be able to yield from `inspect` expression branch early, but currently there is no syntax that would allow specifying yield value with `break` statement (i.e. `break 2;`). We think this behaviour is valuable, but not crucial for this proposal.

8 Runtime Performance

The following are few of the optimizations that are worth noting.

8.1 Structured Binding Patterns

Structured binding patterns can be optimized by performing `switch` over the columns with the duplicates removed, rather than the naive approach of performing a comparison per element. This removes unnecessary duplicate comparisons that would be performed otherwise. This would likely require some wording around "comparison elision" in order to enable such optimizations.

8.2 Alternative Patterns

The sequence of alternative patterns can be executed in a `switch`.

8.3 Open Class Hierarchy

[N3449] describes techniques involving vtable pointer caching and hash conflict minimization that are implemented in the [Mach7] library, but also mentions further opportunities available for a compiler solution.

9 Examples

9.1 Predicate-based Discriminator

Short-string optimization using a **predicate** as a discriminator rather than an explicitly stored **value**. Adapted from Bjarne Stroustrup's pattern matching presentation at Urbana-Champaign 2014 [PatMatPres].

```
struct String {
  enum Storage { Local, Remote };

  int size;
  union {
    char local[32];
    struct { char *ptr; int unused_allocated_space; } remote;
  };

  // Predicate-based discriminator derived from `size`.
  Storage index() const { return size > sizeof(local) ? Remote : Local; }

  // Opt into Variant-Like protocol.
  template <Storage S>
  auto &&get() {
    if constexpr (S == Local) return local;
    else if constexpr (S == Remote) return remote;
  }

  char *data();
};

namespace std {
  // Opt into Variant-Like protocol.

  template <>
  struct variant_size<String> : std::integral_constant<std::size_t, 2> {};

  template <>
  struct variant_alternative<String::Local, String> {
    using type = decltype(String::local);
  };

  template <>
  struct variant_alternative<String::Remote, String> {
    using type = decltype(String::remote);
  };
}

char* String::data() {
  return inspect (*this) {
    <Local> l => l;
    <Remote> r => r.ptr;
  };
  // switch (index()) {
  //   case Local: {
  //     std::variant_alternative_t<Local, String>& l = get<Local>();
  //     return l;
```

```
  //   }
  //   case Remote: {
  //     std::variant_alternative_t<Remote, String>& r = get<Remote>();
  //     return r.ptr;
  //   }
  // }
}
```

9.2 “Closed” Class Hierarchy

A class hierarchy can effectively be closed with an `enum` that maintains the list of its members, and provide efficient dispatching by opting into the Variant-Like protocol.

A generalized mechanism of pattern is used extensively in LLVM; `llvm/Support/YAMLParser.h` [YAMLParser] is an example.

```
struct Shape { enum Kind { Circle, Rectangle } kind; };

struct Circle : Shape {
  Circle(int radius) : Shape{Shape::Kind::Circle}, radius(radius) {}

  int radius;
};

struct Rectangle : Shape {
  Rectangle(int width, int height)
    : Shape{Shape::Kind::Rectangle}, width(width), height(height) {}

  int width, height;
};

namespace std {
  template <>
  struct variant_size<Shape> : std::integral_constant<std::size_t, 2> {};

  template <>
  struct variant_alternative<Shape::Circle, Shape> { using type = Circle; };

  template <>
  struct variant_alternative<Shape::Rectangle, Shape> { using type = Rectangle; };
}

Shape::Kind index(const Shape& shape) { return shape.kind; }

template <Kind K>
auto&& get(const Shape& shape) {
  return static_cast<const std::variant_alternative_t<K, Shape>&>(shape);
}

int get_area(const Shape& shape) {
  return inspect (shape) {
    <Circle> c => 3.14 * c.radius * c.radius;
    <Rectangle> r => r.width * r.height;
  };
  // switch (index(shape)) {
```

```
  //   case Shape::Circle: {
  //     const std::variant_alternative_t<Shape::Circle, Shape>& c =
  //         get<Shape::Circle>(shape);
  //     return 3.14 * c.radius * c.radius;
  //   }
  //   case Shape::Rectangle: {
  //     const std::variant_alternative_t<Shape::Rectangle, Shape>& r =
  //         get<Shape::Rectangle>(shape);
  //     return r.width * r.height;
  //   }
  // }
}
```

9.3 Matcher: `any_of`

The logical-or pattern in other languages is typically spelled *pattern*$_0$ `|` *pattern*$_1$ `| ... |` *pattern*$_N$, and matches value `v` if any *pattern*$_i$ matches `v`.

This provides a restricted form (constant-only) of the logical-or pattern.

```
template <typename... Ts>
struct any_of : std::tuple<Ts...> {
  using tuple::tuple;

  template <typename U>
  bool match(const U& u) const {
    return std::apply([&](const auto&... xs) { return (... || xs == u); }, *this);
  }
};
```

```
int fib(int n) {
  return inspect (n) {
    x if (x < 0) => 0;
    any_of{1, 2} => n;  // 1 | 2
    x => fib(x - 1) + fib(x - 2);
  };
}
```

9.4 Matcher: `within`

The range pattern in other languages is typically spelled `first..last`, and matches `v` if `v` $\in$ `[first, last]`.

```
struct within {
  int first, last;

  bool match(int n) const { return first <= n && n <= last; }
};
```

```
inspect (n) {
  within{1, 10} => {  // 1..10
    std::cout << n << " is in [1, 10].";
  }
  __ => {
    std::cout << n << " is not in [1, 10].";
  }
};
```

9.5 Extractor: `both`

The logical-and pattern in other languages is typically spelled *pattern*$_0$ `&` *pattern*$_1$ `& ... &` *pattern*$_\text{N}$, and matches `v` if all of *pattern*$_\text{i}$ matches `v`.

This extractor emulates binary logical-and with a `std::pair` where both elements are references to value `v`.

```
struct Both {
  template <typename U>
  std::pair<U&&, U&&> extract(U&& u) const {
    return {std::forward<U>(u), std::forward<U>(u)};
  }
};

inline constexpr Both both;
```

```
inspect (v) {
  (both!) [[x, 0], [0, y]] => // ...
};
```

9.6 Extractor: `at`

The binding pattern in other languages is typically spelled *identifier* `@` *pattern*, binds *identifier* to `v` and matches if *pattern* matches `v`. This is a special case of the logical-and pattern (*pattern*$_0$ `&` *pattern*$_1$) where *pattern*$_0$ is an *identifier*. That is, *identifier* `&` *pattern* has the same semantics as *identifier* `@` *pattern*, which means we get `at` for free from `both` above.

```
inline constexpr at = both;
```

```
inspect (v) {
  <Point> (at!) [p, [x, y]] => // ...
  // ...
};
```

9.7 Red-black Tree Rebalancing

Dereference patterns frequently come into play with complex patterns using recursive variant types. An example of such a problem is the rebalance operation for red-black trees. Using pattern matching this can be expressed succinctly and in a way that is easily verified visually as having the correct algorithm.

Given the following red-black tree definition:

```
enum Color { Red, Black };

template <typename T>
struct Node {
  void balance();

  Color color;
  std::shared_ptr<Node> lhs;
  T value;
  std::shared_ptr<Node> rhs;
};
```

The following is what we can write with pattern matching:

```
template <typename T>
void Node<T>::balance() {
  *this = inspect (*this) {
    // left-left case
    //
    //          (Black) z              (Red) y
    //           /     \               /      \
    //      (Red) y     d        (Black) x  (Black) z
    //      /      \       ->      /   \      /   \
    //   (Red) x    c            a     b    c     d
    //    /    \
    //   a      b
    [case Black, (*?) [case Red, (*?) [case Red, a, x, b], y, c], z, d]
      => Node{Red, std::make_shared<Node>(Black, a, x, b),
                   y,
                   std::make_shared<Node>(Black, c, z, d)};
    [case Black, (*?) [case Red, a, x, (*?) [case Red, b, y, c]], z, d]  // left-right case
      => Node{Red, std::make_shared<Node>(Black, a, x, b),
                   y,
                   std::make_shared<Node>(Black, c, z, d)};
    [case Black, a, x, (*?) [case Red, (*?) [case Red, b, y, c], z, d]]  // right-left case
      => Node{Red, std::make_shared<Node>(Black, a, x, b),
                   y,
                   std::make_shared<Node>(Black, c, z, d)};
    [case Black, a, x, (*?) [case Red, b, y, (*?) [case Red, c, z, d]]]  // right-right case
      => Node{Red, std::make_shared<Node>(Black, a, x, b),
                   y,
                   std::make_shared<Node>(Black, c, z, d)};
    self => self;  // do nothing
  };
}
```

The following is what we currently need to write:

```
template <typename T>
void Node<T>::balance() {
  if (color != Black) return;
  if (lhs && lhs->color == Red) {
    if (const auto& lhs_lhs = lhs->lhs; lhs_lhs && lhs_lhs->color == Red) {
      // left-left case
      //
      //        (Black) z              (Red) y
      //         /     \               /      \
      //     (Red) y    d        (Black) x  (Black) z
      //     /      \       ->     /   \      /   \
      //  (Red) x    c             a     b    c     d
      //   /    \
      //  a      b
      *this = Node{
          Red,
          std::make_shared<Node>(Black, lhs_lhs->lhs, lhs_lhs->value, lhs_lhs->rhs),
          lhs->value,
          std::make_shared<Node>(Black, lhs->rhs, value, rhs)};
      return;
    }
    if (const auto& lhs_rhs = lhs->rhs; lhs_rhs && lhs_rhs->color == Red) {
      *this = Node{  // left-right case
          Red,
          std::make_shared<Node>(Black, lhs->lhs, lhs->value, lhs_rhs->lhs),
          lhs_rhs->value,
          std::make_shared<Node>(Black, lhs_rhs->rhs, value, rhs)};
      return;
    }
  }
  if (rhs && rhs->color == Red) {
    if (const auto& rhs_lhs = rhs->lhs; rhs_lhs && rhs_lhs->color == Red) {
      *this = Node{  // right-left case
          Red,
          std::make_shared<Node>(Black, lhs, value, rhs_lhs->lhs),
          rhs_lhs->value,
          std::make_shared<Node>(Black, rhs_lhs->rhs, rhs->value, rhs->rhs)};
      return;
    }
    if (const auto& rhs_rhs = rhs->rhs; rhs_rhs && rhs_rhs->color == Red) {
      *this = Node{  // right-right case
          Red,
          std::make_shared<Node>(Black, lhs, value, rhs->lhs),
          rhs->value,
          std::make_shared<Node>(Black, rhs_rhs->lhs, rhs_rhs->value, rhs_rhs->rhs)};
      return;
    }
  }
}
```

10 Future Work

10.1 Language Support for Variant

The design of this proposal also accounts for a potential language support for variant. It achieves this by keeping the alternative pattern flexible for new extensions via < *new_entity* > *pattern*.

Consider an extension to `union` that allows it to be tagged by an integral, and has proper lifetime management such that the active alternative need not be destroyed manually.

```
// `: type` specifies the type of the underlying tag value.
union U : int { char small[32]; std::vector<char> big; };
```

We could then allow < *qualified-id* > that refers to a `union` alternative to support pattern matching.

```
U u = /* ... */;

inspect (u) {
  <U::small> s => { std::cout << s; }
  <U::big> b => { std::cout << b; }
};
```

The main point is that whatever entity is introduced as the discriminator, the presented form of alternative pattern should be extendable to support it.

10.2 Note on Ranges

The benefit of pattern matching for ranges is unclear. While it's possible to come up with a ranges pattern, e.g., `{x, y, z}` to match against a fixed-size range, it's not clear whether there is a worthwhile benefit.

The typical pattern found in functional languages of matching a range on head and tail doesn't seem to be all that common or useful in C++ since ranges are generally handled via loops rather than recursion.

Ranges likely will be best served by the range adaptors / algorithms, but further investigation is needed.

11 Acknowledgements

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