Constrain yourself

Andrzej Krzemieński

Andrzej's C++ blog
akrzemi1.wordpress.com

Agenda

- Overview
- Case study 1 – Short codes
- Case study 2 – Magic values
- Case study 3 – Hidden semantics
- Conclusion

Compilers detecting bugs

Compilers help already:

```
return i.substr(str, 2);
// intent: str.substr(i, 2);
```

Grey area

No compiler can help:

```
return v < max;
// intent: max < v
```

Compilers detecting bugs

Compilers help already:

```
return i.substr(str, 2);
// intent: str.substr(i, 2);
```

Compiler may be able to help

```
// but we may need
// to help the compiler
```

No compiler can help:

```
return v < max;
// intent: max < v
```

Constraints

- A number of (too) versatile types:
  - `int`
  - `double`
  - `string`
  - `T*`
- What you can use `int` for:
  - mathematical integer
  - index
  - UID
  - enumeration
  - bitmask
  - …
- Do you need all of this at once?

Constraints

```
std::bitset<8> flags;
float f = flags;  // err
flags * 3;        // err
if (flags.any())  // ok
```

```
unsigned flags;
float f = flags;  // ok
flags * 3;        // ok
if (flags)        // ok
```

Constraints

- Focus on what you *cannot* do with the object
  - You will understand your program better
- Clearly encode it in the type system
  - Your intentions are communicated clearly
  - Machines can make use of the information
- Proceed to coding
  - Compiler will protest when you *accidentally* do what you should not

Example: unique_ptr

Single object

```
unique_ptr<int> p = /**/;

p - p; // err
*p;    // ok
p[0];  // err
```

Array of objects

```
unique_ptr<int[]> p = /**/;

p - p; // err
*p;    // err
p[0];  // ok
```

- Change in type → change in allowed operations
- Single object? – no need for `operator[]`
- Array of objects? – no need for `operator*`
- Bad usages detected at compile-time

Example: unique_ptr

```
unique_ptr<int> p = /**/;

p.get() - p.get();
p.get()++;
p.get()[0];
```

- Still possible to do unsafe things
- Safety by default, but disabled on demand

Case study 1 » Short codes

Short codes

- Human-friendly IDs.
- Type `string` can represent any short code (and more).
- Most of `string`'s interface is useless for short codes.
- A short code *is not* a `string` with fixed size.

We need:

- (Fast) comparisons
- Input/Output ops
- Regular ops

We don't need:

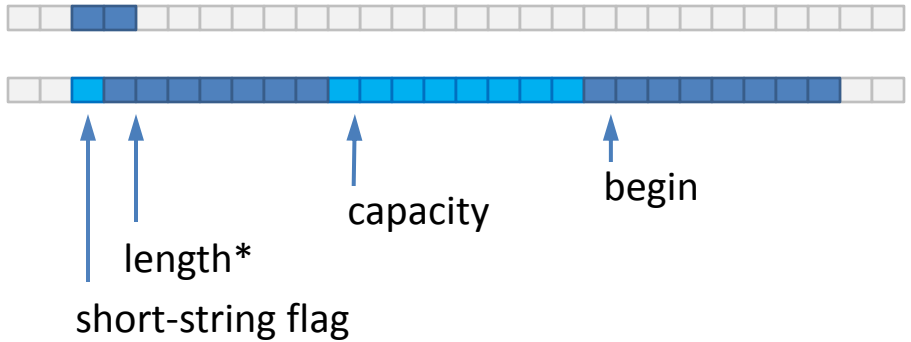
- `find_first_of()`
- `append()`
- `at()`, `front()`
- `substr()`

Optimization opportunities

- How many codes fit into a CPU cache line?
- How fast is the comparison?

`char[2]`

`string` (with SSO)



String with SSO:

- An `if` check
- `sizeof(s) == 3 * 8`

Correctness opportunities

```
map.associate_code("PL", "Poland");
// ...
assert (map.match_code("PL", "Poland")); // fails
```

Why does it fail?

Correctness opportunities

```
map.associate_code("PL", "Poland");
// ...
assert (map.match_code("PL", "Poland")); // fails
```

Why does it fail?

```
void associate_code(string code, string country);
bool match_code(string country, string code);
```

- Two `string`s are interchangeable.

Correctness opportunities

```
map.associate_code("PL", "Poland");
// ...
assert (map.match_code("PL", "Poland")); // fails
```

Why does it fail?

```
void associate_code(string code, string country);
bool match_code(string country, string code);
```

- Two `string`s are interchangeable.
- A `string` and a `Code` are not.

```
bool match_code(Code code, string country);
bool match_code(string country, Code code);
```

Correctness opportunities

```
bool match(string const& aux_code, record const& rec)
{
  return aux_code == rec.auxiliary_resident_state; // bug
}
```

But the intent was:

```
bool match(string const& aux_code, record const& rec)
{
  return aux_code == rec.auxiliary_code;
}
```

- Type `record` has both (and more) members.

Type design

```
template <int N>
class Code
{
  array<char, N> data_;
  friend bool operator==(Code l, Code r) { return l.data_ == r.data_; }
  friend bool operator< (Code l, Code r) { return l.data_ <  r.data_; }
  // and !=, >, <=, >=
};
```

- Code size is part of type.
- A `Code<2>` and a `Code<3>` are not interchangeable.

Type design » Default construction

- Confusion: what value?
- Danger: someone may use this value.
- Ideally, `Code` should not be default-constructible.

- Needed for default-construct-and-fill idiom:

```
int i [[uninitialized]]; // no such attribute yet
std::cin >> i;
```

- Most XML and DB frameworks require default constructor

Type design » Default construction

Decision: use all zeros to represent the artificial state

- Now we have a *special* state.
- It is *not* singular: all operations can be safely executed.
- Comparisons work: special value ≠ any normal value.
- We now need function `is_initialized()`.
- Objects not always hold a genuine code.

Type design » Default construction

We can emulate the attribute

```
class uninitialized_code_t {};
constexpr uninitialized_code_t uninitialized_code {};
```

- A *tag* class
- Purpose: alter the type system

```
template <int N>
Code<N>::Code(uninitialized_code_t) : data_{}
```

Usage:

```
Code<2> c = uninitialized_code;
Code<2> fun() { return uninitialized_code; }
```

Type design » From string

- The unsafe part: how do you handle bad size?

```
bool Code<N>::from_string(string_view s)
{
  if (BOOST_LIKELY(len == N)) // optimization hint
    return std::memcpy(data_, s.data(), s.size()), true;
  else
    return false;
}
```

- You need an object before conversion
- Bad size is legal: you can use the function for validation
- Alternative: use precondition

Type design » To string

- C-like:

```
const char* Code<N>::data() const { return data_.data(); }
unsigned Code<N>::size() const { return N; }
```

- C++-like:

```
string Code<N>::to_string() const
{
  if (BOOST_LIKELY(is_initialized()))
    return string(data(), size());
  else
    return string(); // so that it is empty
}
```

Type design » Literals

Our goal:

```
Code<2> c1 {"PL"};  // ok
Code<2> c2 {"PLN"}; // compile-time error
```

Implementation:

```
explicit Code<N>::Code( const char (&literal)[N + 1] );
```

- No implicit conversion, even if the size is right
- Error message: "no appropriate constructor found"

Type design » Literals

Alternate implementation:

```
template <int M>
explicit Code<N>::Code( const char (&literal)[M] )
{
  static_assert (M <= N + 1, "too long literal");
  static_assert (M >= N + 1, "too short literal");
  // copy
}
```

- Error message "literal constructor with bad length".
- Error message quality vs allowing other overloads.

Type design » Adding semantics

```
bool in_country(Airport ac, Country cc);
```

Strings

```
using Country = std::string
using Airport = std::string

Airport port {"LHR"};
Country ctry {"GB"};

in_country(ctry, port);
```

- Compiles
- Does the wrong thing

Codes

```
using Country = Code<2>;
using Airport = Code<3>;

Airport port {"LHR"};
Country ctry {"GB"};

in_country(ctry, port);
```

- Compile-time error

Type design » Adding semantics

```
using Currency = Code<3>;
using Airport  = Code<3>; // same type!
```

Solution: tags

```
template <typename /*tag*/, int N>
class Code { /*...*/ };

using Currency = Code<class Currency_tag, 3>; // different
using Airport  = Code<class Airport_tag,  3>; // types!
```

- A tag, to generate different types
- Opaque typedef emulation

Type design » Adding semantics

```
using Currency = Code<class Currency_tag, 3>;
using Airport  = Code<class Airport_tag,  3>;

bool accepts(Airport ac, Currency cc);
```

If literal constructor was implicit:

```
accepts("EUR", "FRA");      // compiles!
```

If explicit ctors were allowed in type-deduced list-initialization:

```
accepts({"EUR"}, {"FRA"}); // compiles!
```

Current state:

```
accepts(Currency{"EUR"}, Airport{"FRA"}); // fails
```

Testing

Not being able to convert is a feature.

Features need to be tested.

```
using Currency = Code<class Currency_tag, 3>;
using Airport  = Code<class Airport_tag,  3>;

int main()
{
  Currency{"PLN"} == Airport{"WAW"}; // expected failure
}
```

- The compiler should return 1 for this program.
- May not be testable inside the program.
- Not even with SFINAE.

Code bloat prevention

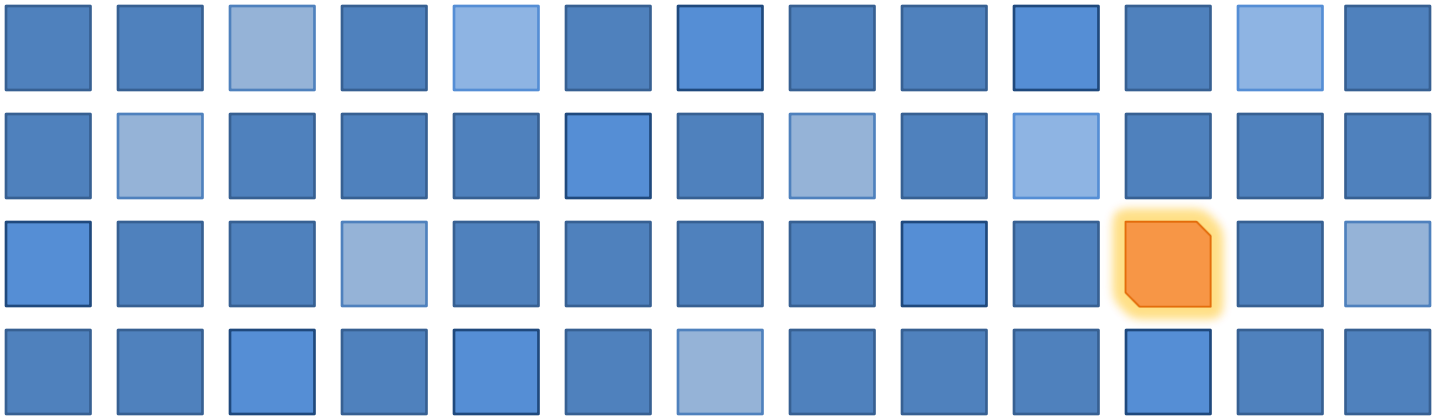
```
template <int N>  class code_base
{
  const char* data() const;
  unsigned size() const;
  // ...
};

template <typename, int N>  class Code :  public code_base<N>
{
  friend bool operator==(code l, code r);
  friend bool operator< (code l, code r);
  // ...
};
```

Variable-length codes

```
template <typename, int Lo, int Hi>
class Code
{
  template <int S>
  explicit Code( const char (&literal)[S] )
  {
    static_assert(S >= Lo + 1, "too short literal");
    static_assert(S <= Hi + 1, "too long literal");
    // copy
  }
};
```

- Fill array with zeros
- Need to change `size()` to search for zeros

Case study 2 » Magic values



The problem

```
std::string nested_name(std::string path)
{
  return path.substr(path.find("::") + 2);
}

assert (nested_name("std::data") == "data");
assert (nested_name("::data") == "data");
```

- Can you see the bug?

The problem

```
std::string nested_name(std::string path)
{
  return path.substr(path.find("::") + 2);
}

assert (nested_name("std::data") == "data");
assert (nested_name("::data") == "data");
```

```
return nested_name("") == ""; // crashes!
```

- The `npos` value!

The problem

```
double Flight_plan::weight()
{
  if (Impl* impl = get_impl())
    return impl->compute_weight();
  else
    return BOGUS_WEIGHT; // -1000.0;
}
```

- Can you see the bug?

The problem

```
double Flight_plan::weight()
{
  if (Impl* impl = get_impl())
    return impl->compute_weight();
  else
    return BOGUS_WEIGHT; // -1000.0;
}
```

```
bool too_heavy(Flight_plan const& p)
{
  return p.weight() > p.aircraft().max_weight();
}
```

- if `impl` is null, aircraft is not too heavy!

Hidden semantics

- Two “kinds” of returned value:
  - Either the proper value
  - Or no-value
- Expected usage:

```
auto v = get_val();
if (is_proper(v))
  use (v);
else
  do_something_else();
```

Boost.Optional?

```
auto v = get_val();


if (is_proper(v))
  use (extract(v));
else
  do_something_else();
```

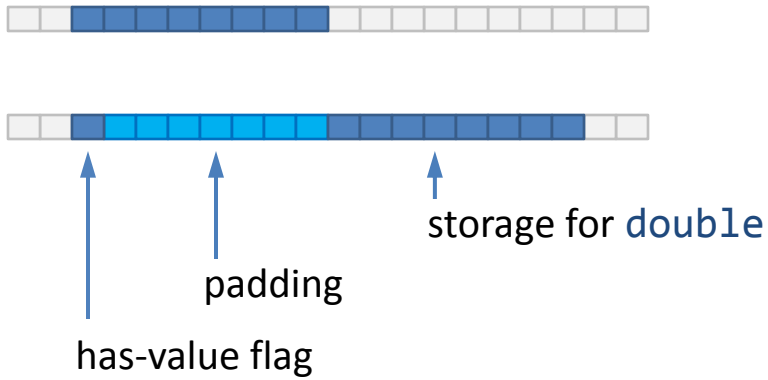
```
optional<T> v = get_val();

use(v); // error

if (v)
  use (*v);
else
  do_something_else();
```

- Exactly this use-pattern
- Value semantics
- `operator*` — no inadvertent use

Boost.Optional – memory layout

`double`

`optional<double>`




```
sizeof(optional<double>) == 2 * sizeof(double)
```

Boost.Optional – type-safety hole

```
optional<double> Flight_plan::weight();
double Aircraft::max_weight();
```

```
bool too_heavy(Flight_plan const& p)
{
  return p.weight() > p.aircraft().max_weight();
}
```

Still compiles!

- `optional<T>` is less-than comparable.
- `T` converts to `optional<T>`!
- This implies 'mixed' less-than comparison.
- Non-`T` < any `T`!

Custom wrapper — design criteria

Boost.Optional doesn't satisfy our criteria?

Create a type that does!

Our criteria:

- Different type than T
- No spatial overhead
- Safety over convenience

Boost.Optional criteria:

- Different type than T
- Works for any T
- No T created in empty optional
- Convenience over safety

Custom wrapper

```
class opt_int
{
  int _val;
public:
  opt_int() : _val{-1} {}
  explicit opt_int(int i) : _val{i} {}
  bool has_value() const { return _val != -1; }
  int value() const { return _val; } // precondition: has_value()
};
```

- No implicit conversions – no surprises
- `sizeof(opt_int) == sizeof(int)`
- In some places -1 will not do

Custom wrapper

```
template <typename T, T Ev> // requires Regular<T>
class compact_optional
{
public:
  compact_optional() : _val{Ev} {}
  explicit compact_optional(T v) : _val{v} {}
  bool has_value() const { return _val != Ev; }
  T value() const { return _val; } // precondition: has_value()
};
```

- Type-safety: different empty-values render different types
- What about non-int types?
- What about types with no equality?

Empty-value policy

```
template <typename T, typename EVP>
class compact_optional
{
public:
  compact_optional() : _val{EVP::empty()} {}
  bool has_value() const { return !EVP::is_empty(_val); }
  // ...
};
```

```
struct evp_empty_double
{
  static double empty() { return -1000.0; }
  static bool is_empty(double v) { return v == empty(); }
};
```

Empty-value policy

```
struct evp_string
{
  static string empty()                    // may allocte
  {
    return string("\0\0", 2);
  }

  static bool is_empty(string const& s)  // no alloc
  {
    return s.compare(0, s.npos, "\0\0", 2) == 0;
  }
};
```

Empty-value policy

A set of predefined policies:

- `evp_int<Int, v>` – integral type with `v` as empty.
- `evp_fp_nan<FPT>` – floating-point-types with NaN as empty.
- `evp_value_init<T>` – value-initialized `T` as empty.
- `evp_stl_empty<T>` – empty STL container as empty.
- `evp_bool` – empty `bool` encoded in 1 byte.
- empty state as special bit pattern in raw storage
- …

Policy implies the type

```
template <typename EVP> // no type T
class compact_optional
{
  typedef decltype(EVP::empty()) value_type;
  // ...
};
```

- I can deduce `T` from the policy.
- No need to provide it.

Too little semantics

```
using count = compact_optional<evp_int<int, -1>>;
using flat  = compact_optional<evp_int<int, -1000>>;
```

- Different types

```
using count  = compact_optional<evp_int<int, -1>>;
using number = compact_optional<evp_int<int, -1>>;
```

- Same type
- Even though `count` and `number` represent something different

Adding semantics

```
template <typename Ev, typename /*tag*/>
class compact_optional
{
  // ...
};
```

- A tag parameter: only for differentiating types

```
compact_optional<evp_int<int, -1>, class tag_A>;
compact_optional<evp_int<int, -1>, class tag_B>;
```

- Different types
- Remember about the code bloat

Performance over safety

How to 'dump' `compact_optional`:

```
template <typename EVP, typename Tag>
size_t dump(compact_optional<EVP, Tag> const& v)
{
  return dump(v.unsafe_raw_value());
}
```

- Fast, but type-unsafe.
- It must be as fast as dumping raw value.
- Performance first.

Case study 3 » Hidden semantics

Symptoms

Time of day in format HHMM

Actual output	Expected output
045	045
100	140
1010	1650
1225	2025

The root cause

```
struct flight_data
{
  // ...
   date arrival_date;
   int  arrival_time; // minutes since midnight
};
```

- Can you see the bug?

The root cause

```
struct flight_data
{
  // ...
  date arrival_date;
  int  arrival_time; // minutes since midnight
};
```

```
void display(const flight_data& f)
{
  // ...
  cout << f.arrival_date;
  cout << f.arrival_time;
}
```

- 1:40 is 100 minutes

Hotfixes

```
void display(const flight_data& f)
{
  // ...
  cout << f.arrival_date;
  cout << minutes_as_HHMM(f.arrival_time);
}
```

- Did you cover all the places?
- What about the future additions?

Hotfixes

```
struct flight_data
{
  // ...
  date arrival_date;
  int  arrival_time_as_minutes_since_midnight;
};
```

- The name sends a clear message.
- If you rename, compiler will show you all usages.

Hotfixes

```
void display(const flight_data& flt, bool abbreviate, const supplementary_data& suppl)
{
  bool do_vca = supl.do_any_tla;
  bool do_strict = suppl.force_strict || !suppl.aux_vec.empty();

  if (!abbreviate || suppl.traffic && suppl.traffic->do_tse)
    do_strict = true;
    do_vca |= is_interline(flt);

  cout << boost::format("%1%;%2% %3%")
    % boost::str(boost::format("%1%%2%")
      % (do_vca ? flt.status : extend_status(flt.status) % suppl.alteration_str)
    % boost::str(boost::format("from %1% %2% %3%")
      % flt.departure_apt % flt.departure_date
      % (do_strict ? flt.arrival_time_as_minutes_since_midnight : flt.est_arrival_time))
    % boost::str(boost::format("to %1% %2% %3%")
      % flt.arrival_apt % (flt.departure_date + flt.dep_offset)
      % (do_strict ? flt.departure_time : flt.est_departure_time));
}
```

- Will you remember to fix it?

Hotfixes

```
void display(const flight_data& flt, bool abbreviate, const supplementary_data& suppl)
{
  bool do_vca = supl.do_any_tla;
  bool do_strict = suppl.force_strict || !suppl.aux_vec.empty();

  if (!abbreviate || suppl.traffic && suppl.traffic->do_tse)
    do_strict = true;
    do_vca |= is_interline(flt);

  cout << boost::format("%1%;%2% %3%")
    % boost::str(boost::format("%1%%2%")
      % (do_vca ? flt.status : extend_status(flt.status) % suppl.alteration_str)
    % boost::str(boost::format("from %1% %2% %3%")
      % flt.departure_apt % flt.departure_date
      % (do_strict ? flt.arrival_time_as_minutes_since_midnight : flt.est_arrival_time))
    % boost::str(boost::format("to %1% %2% %3%")
      % flt.arrival_apt % (flt.departure_date + flt.dep_offset)
      % (do_strict ? flt.departure_time : flt.est_departure_time));
}
```

- Will you remember to fix it?

Hotfixes

```
void display(const flight_data& flt, bool abbreviate, const supplementary_data& suppl)
{
  bool do_vca = supl.do_any_tla;
  bool do_strict = suppl.force_strict || !suppl.aux_vec.empty();

  if (!abbreviate || suppl.traffic && suppl.traffic->do_tse)
    do_strict = true;
    do_vca |= is_interline(flt);

  cout << boost::format("%1%;%2% %3%")
    % boost::str(boost::format("%1%%2%")
      % (do_vca ? flt.status : extend_status(flt.status) % suppl.alteration_str)
    % boost::str(boost::format("from %1% %2% %3%")
      % flt.departure_apt % flt.departure_date
      % (do_strict ? flt.arrival_time_as_minutes_since_midnight : flt.est_arrival_time))
    % boost::str(boost::format("to %1% %2% %3%")
      % flt.arrival_apt % (flt.departure_date + flt.dep_offset)
      % (do_strict ? flt.departure_time : flt.est_departure_time));
}
```

- Will you remember to fix it?

The solution

```
class Minutes_since_midnight
{
  int minutes_;
  // invariant:  minutes_ >= 0  &&  minutes_ < 24 * 60

public:
  explicit Minutes_since_midnight(int m) : minutes_(m) {}
    // requires:  m >= 0  &&  m < 24 * 60

  int as_int() const { return minutes_; }

  // and relational operators ...
};
```

The solution

No accidental operations on `int` apply:

```
struct flight_data
{
  // ...
  Minutes_since_midnight arrival_time;
};

void display(const flight_data& f)
{
  // ...
  cout << f.arrival_time; // compile-time error!
}
```

- Compiler will tell you where to convert.
- Even in future.

The solution

Still an `int`, if you need one:

```
int minutes_as_HHMM(Minutes_since_midnight t)
{
  return t.as_int() / 60 * 100 + t.as_int() % 60;
}
```

```
Minutes_since_midnight t;
static_assert(sizeof(t) == sizeof(int), "compactness");
```

- Reality: no abstraction will cover all use cases.
- No loss compared with a raw `int`.

The solution

Ability to define the *invariant:*

```
bool invariant() const
{
  return minutes_ >= 0 && minutes_ < 24 * 60;
}

explicit Minutes_since_midnight(int m) : minutes_(m)
{
  assert (invariant());
}
```

```
Minutes_since_midnight t {1440}; // assertion failure
```

- Not an ideal, but some additional safety measure
- Clear statement of intent

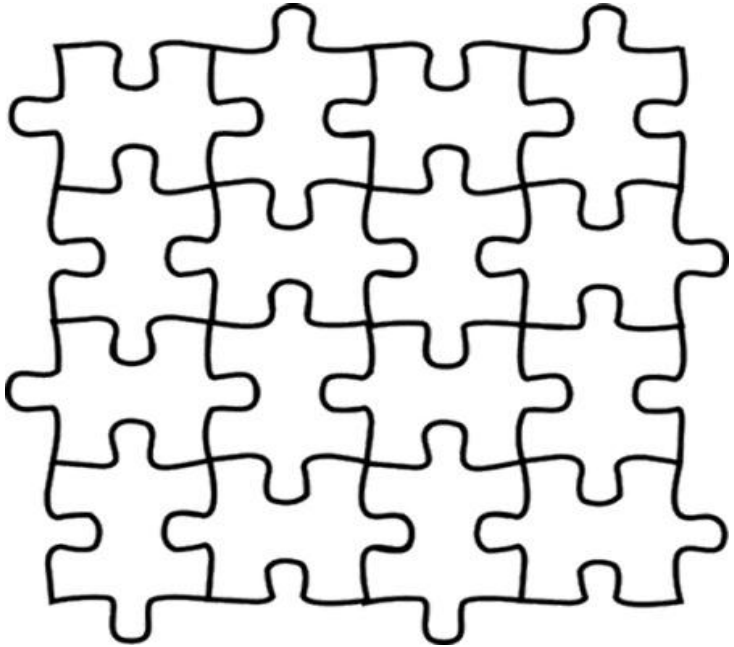
Is solution worth the trouble?

- Good abstraction is likely reused

```
struct flight_data
{
  // ...
  Minutes_since_midnight departure_time;
  Minutes_since_midnight arrival_time;
};
```

- Are bug fixes and patch releases more attractive?

Conclusion



Summary

- Type system performs (limited) static analysis.
- We get the same binary; but more compile-time checks.
- Zero run-time cost.
- Unsafe interface on demand.
- Reveal hidden semantics.
- Sometimes adding constrains comes with optimizations.
- Tag template parameter: opaque typedef for free.

Criteria for adding type wrapper

- Do you suspect how people can accidentally misuse the type?
- Do all operations of a given type make sense for our usage?
- We want some operations never to be called in our program.
- Additional semantics (with identical interface).
- Do we have an invariant?
- Can we get other benefits?

Boost.Units

```
time     t1, t2;
distance d1, d2;
velocity v1, v2; // type different but related

v1 = v1 + v2;    // ok
t1 = v1 + v2;    // error (at compile-time)
t2 = t1 + d2;    // error (at compile-time)
v1 = d1 / t1;    // ok
d1 = d1 / t1;    // error (at compile-time)
```

- Dimensional analysis performed by type system.

More than safety

- Good abstractions.
- Intentions stated clearly.
- Improved communication.
- Even less bugs.