A bird's-eye view of template<C++>

C++ Italy – June 19, 2021

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What's ahead?

- Introduction
- Templates in practice
- Taming templates
- Template metaprogramming
- Questions 🗨 ❓

A little bit about me

🤓👨‍👩‍👧‍👦🎸🏃🧗

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The premise and goals

🏊‍♀️🆘🥴

Introduction

C++ and libraries today

- Dataflow
- Imperative
- Logic
- Object oriented
- Declarative
- Procedural
- Functional
- Concurrent
- Polymorphic
- Generic
- Constraints
- Macro
- Reflection
- Domain-specific
- Metaprogramming

C++ and libraries today

Imperative

Logic

Object oriented

Dataflow

Declarative

Procedural

Functional

Concurrent

Polymorphic

Generic

Constraints

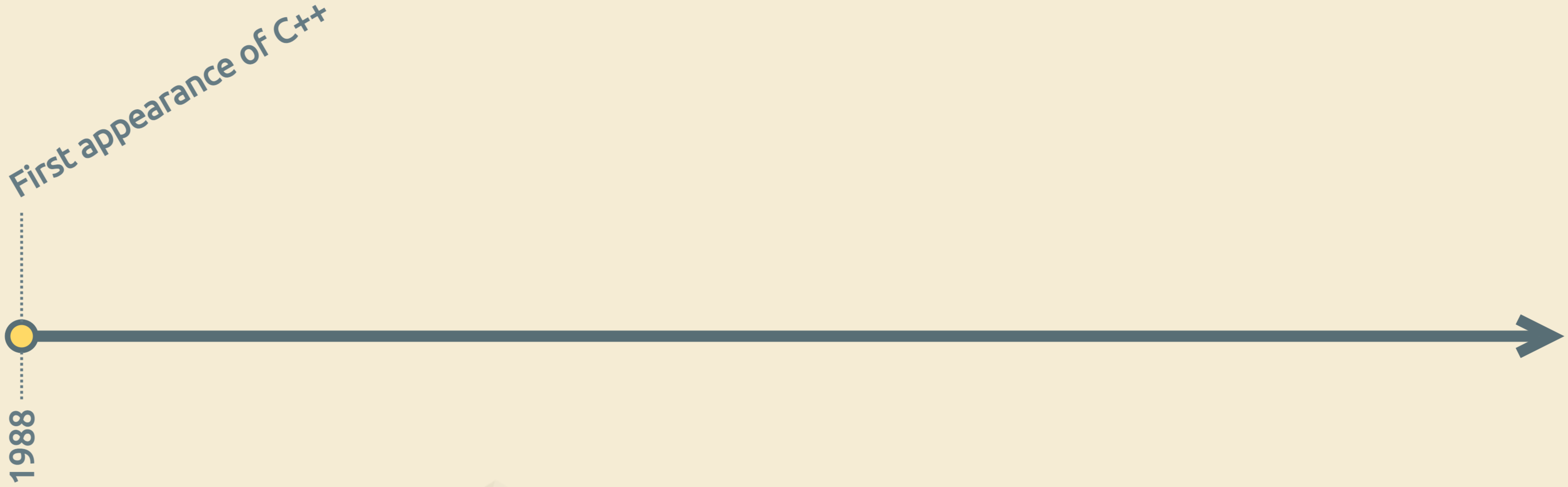
Macro

Reflection

Domain-specific

Metaprogramming

A bit of history..



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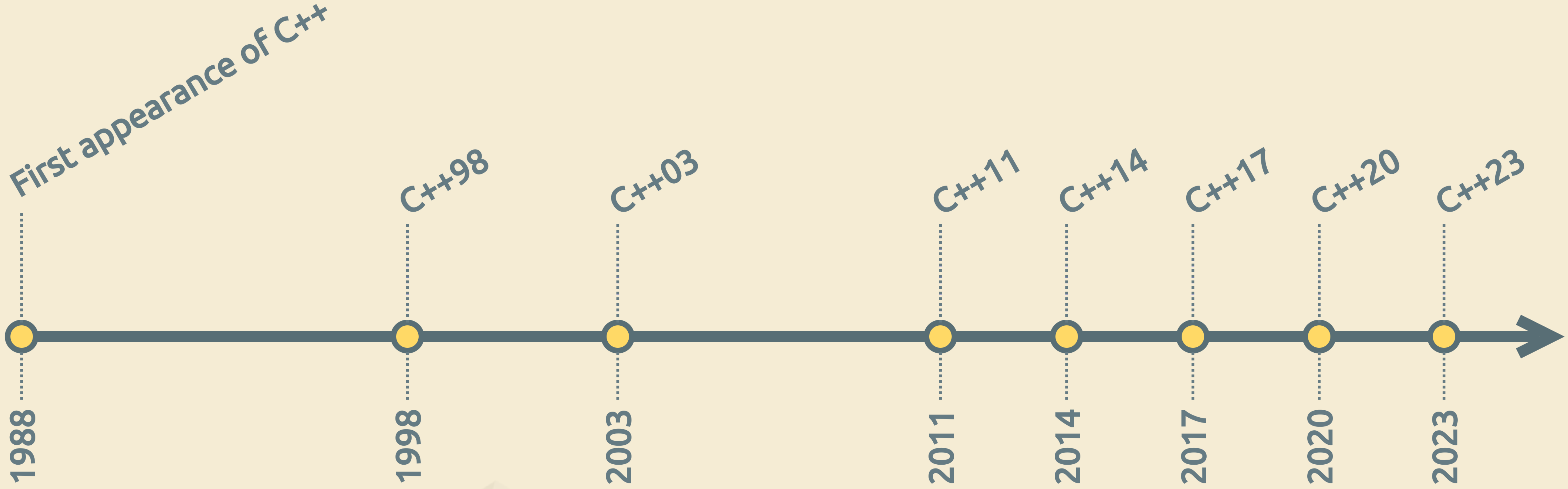

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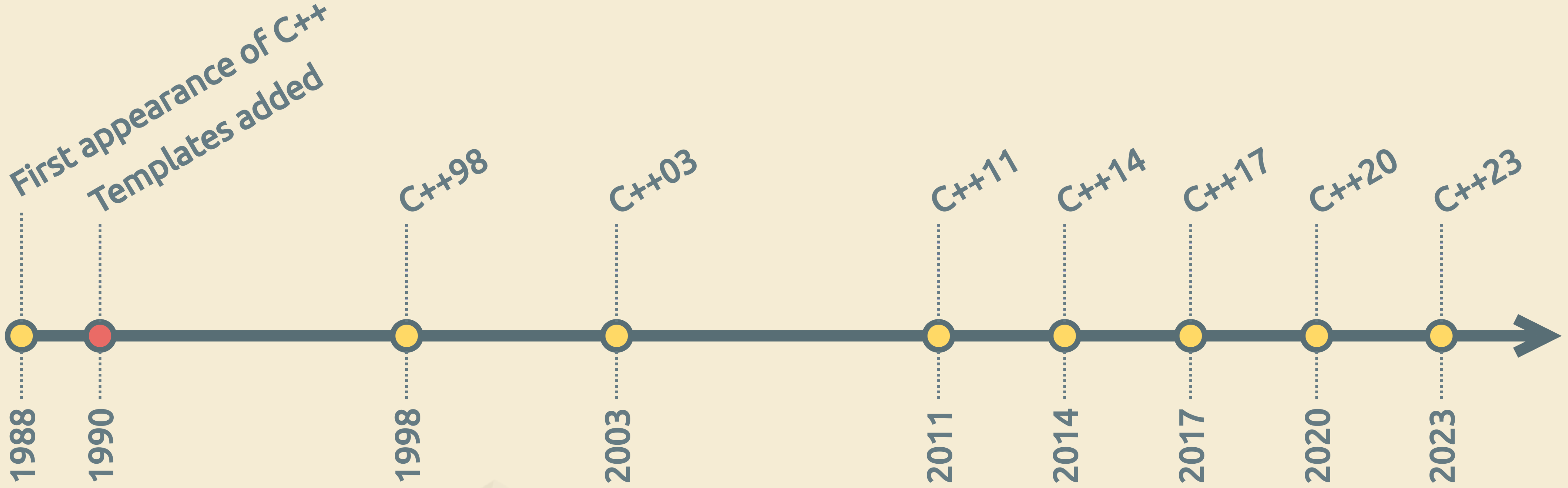

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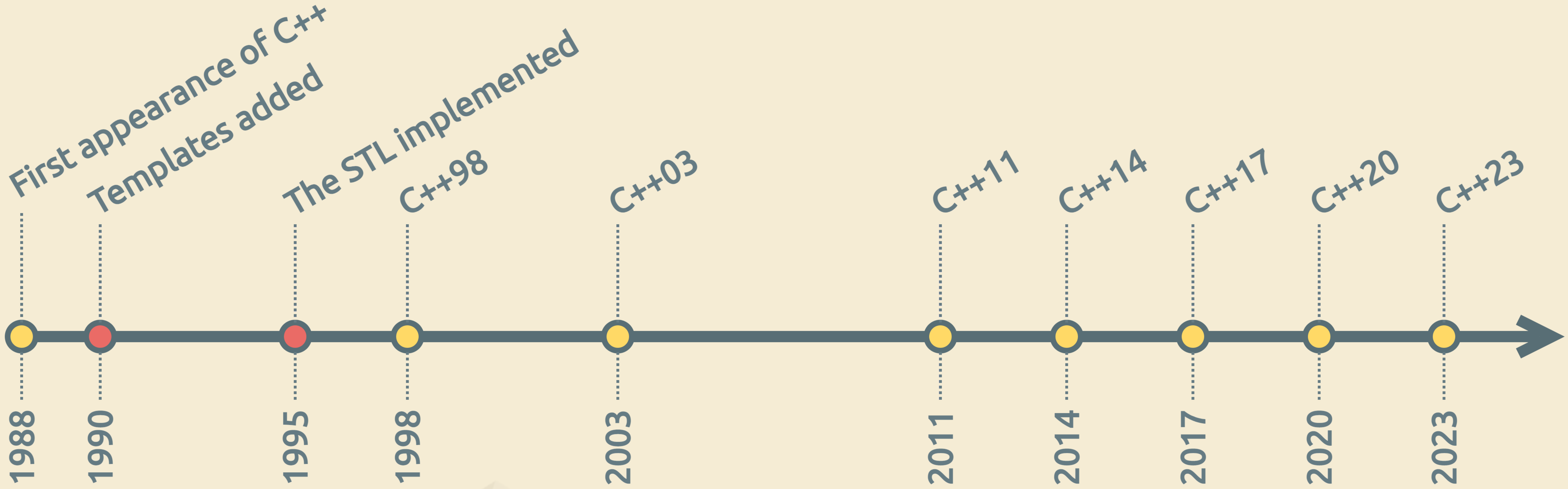

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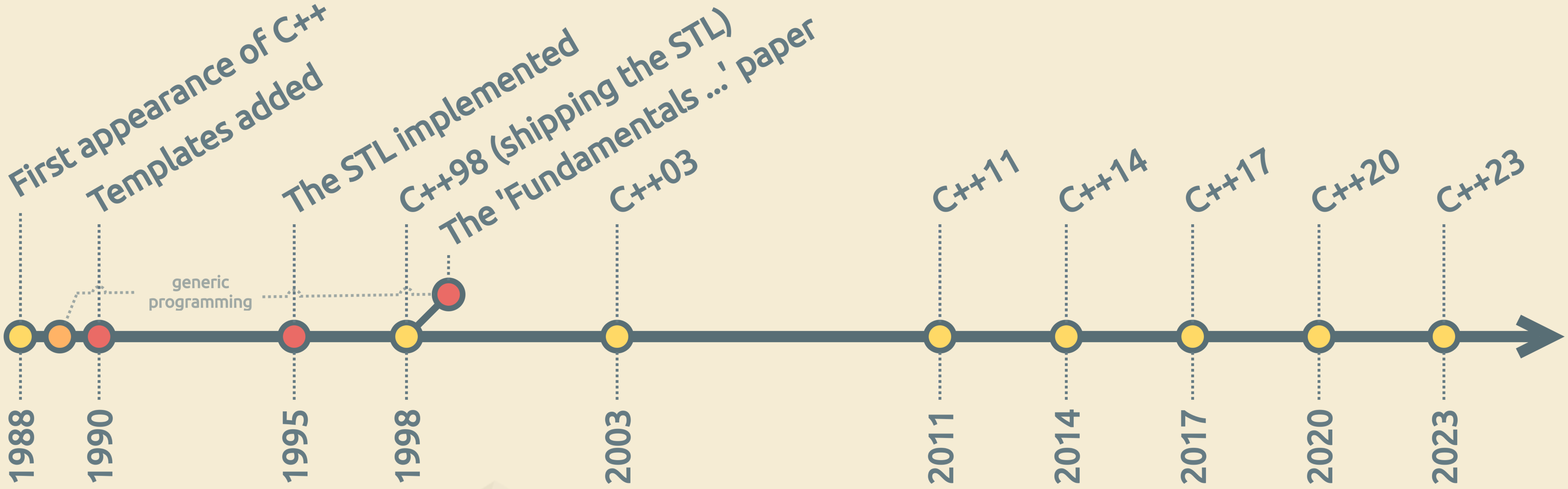

Alexander Stepanov

Fundamentals of Generic Programming

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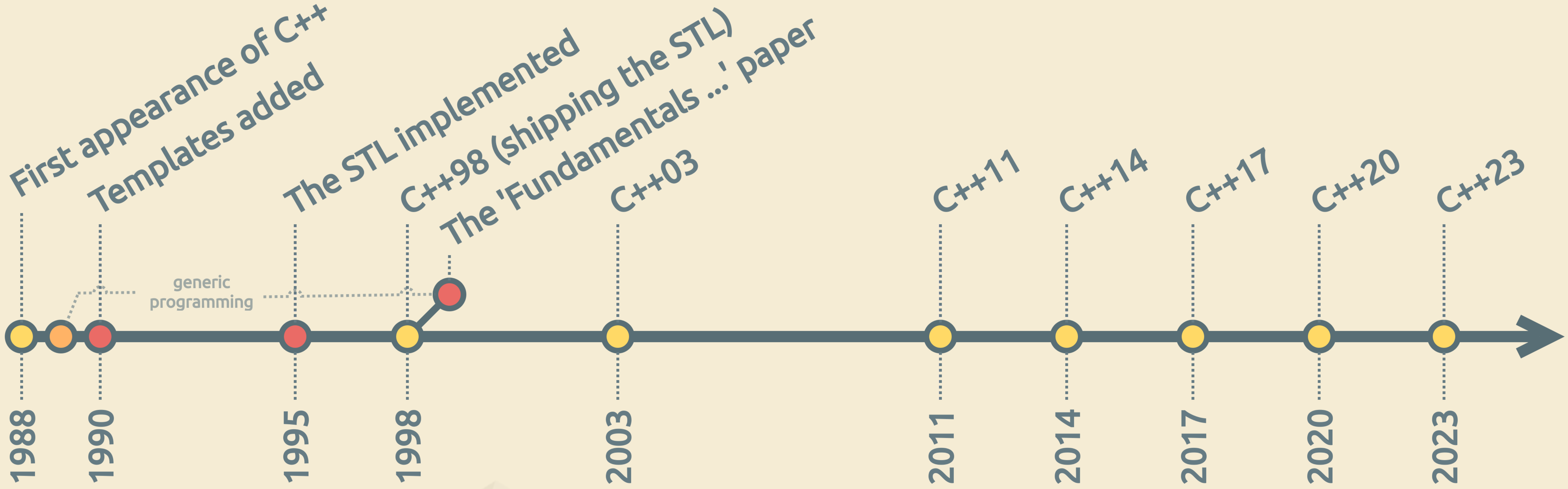
Keywords: Generic programming, operator semantics, concept, regular type.

Abstract. **Generic programming depends on the decomposition of programs into components which may be developed separately and combined arbitrarily, subject only to well-defined interfaces. Among the interfaces of interest, indeed the most pervasively and unconsciously used, are the fundamental operators common to all C++ built-in types, as extended to user-defined types, e.g. copy constructors,**

stepanovpapers.com

A bit of history..



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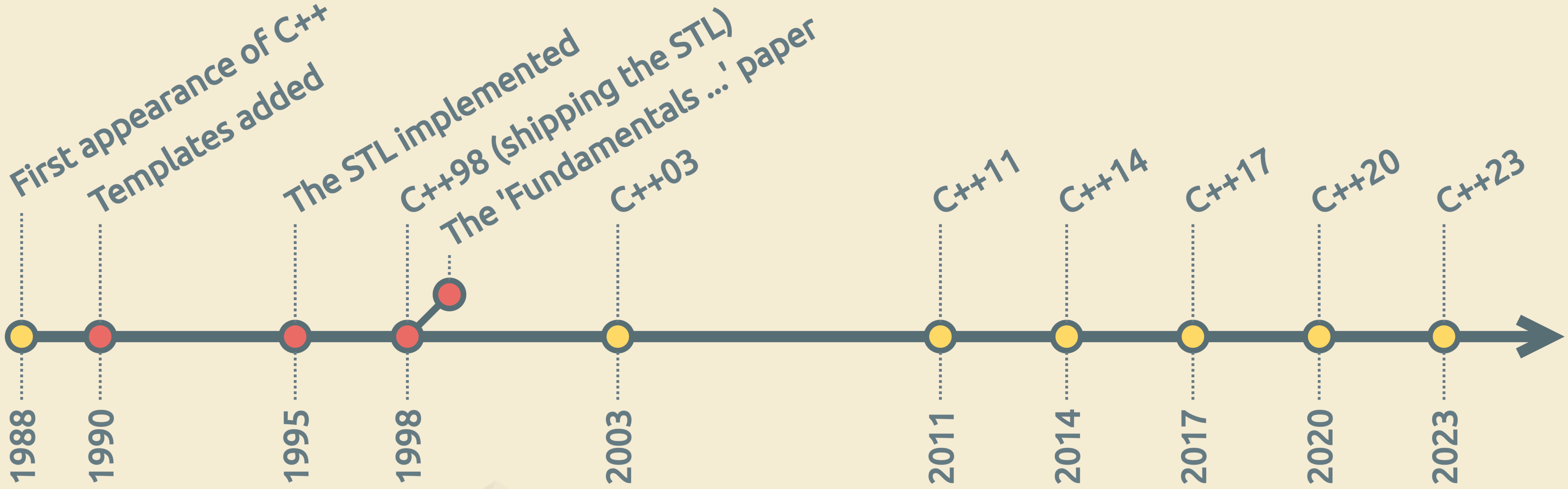
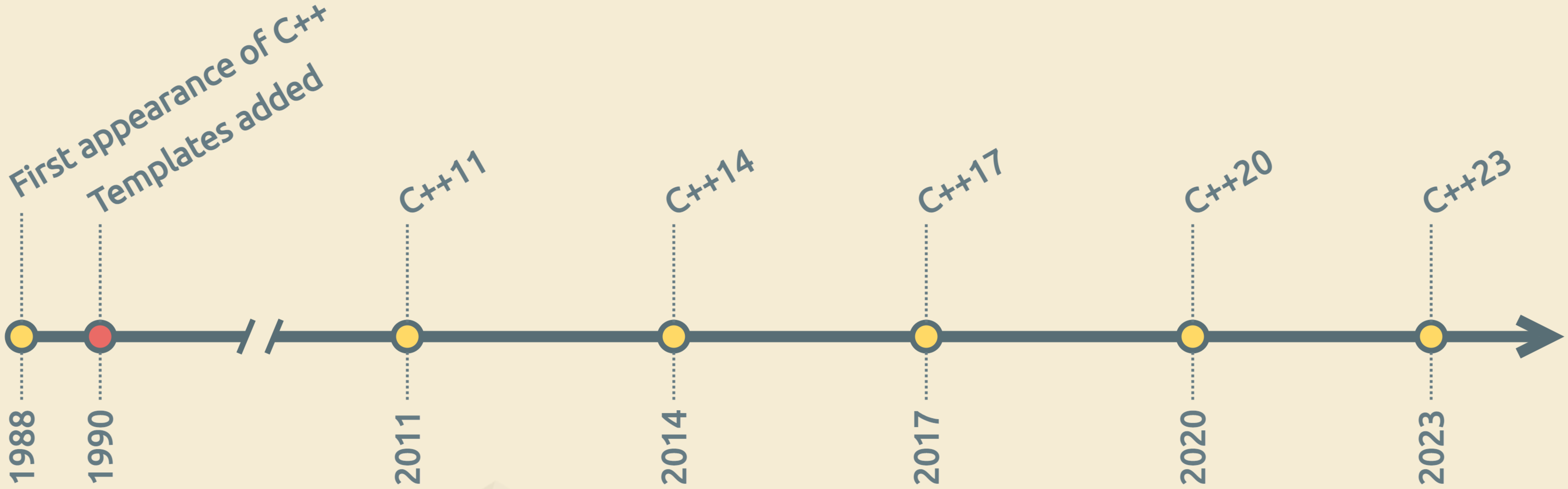
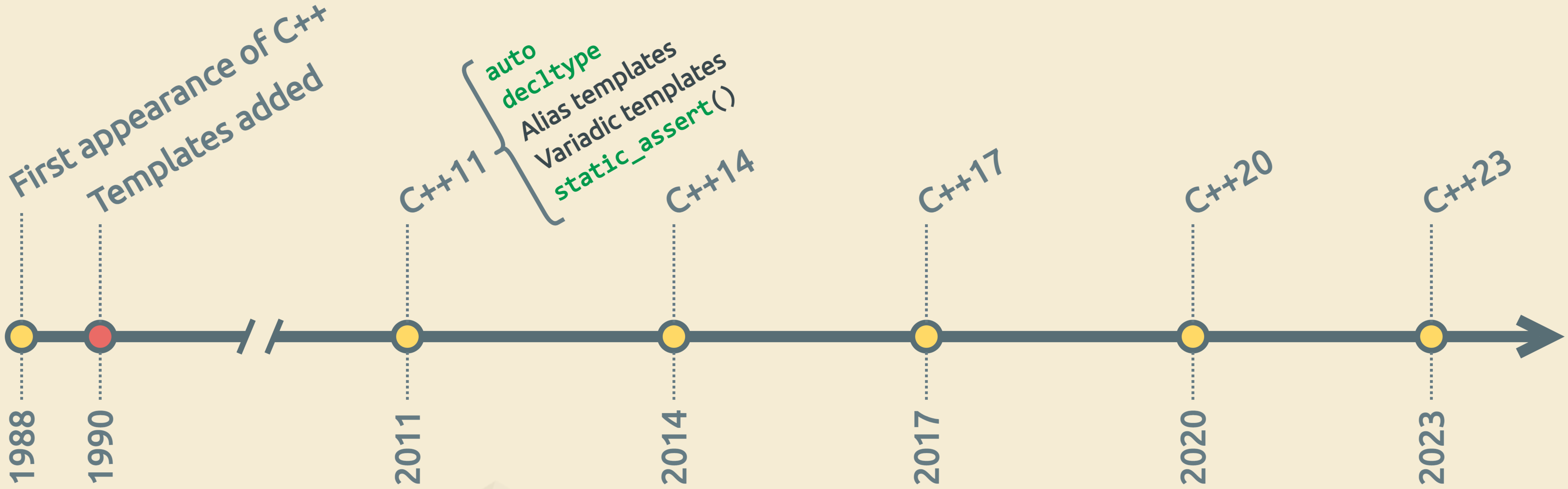


A bit of history..



A bit of history..



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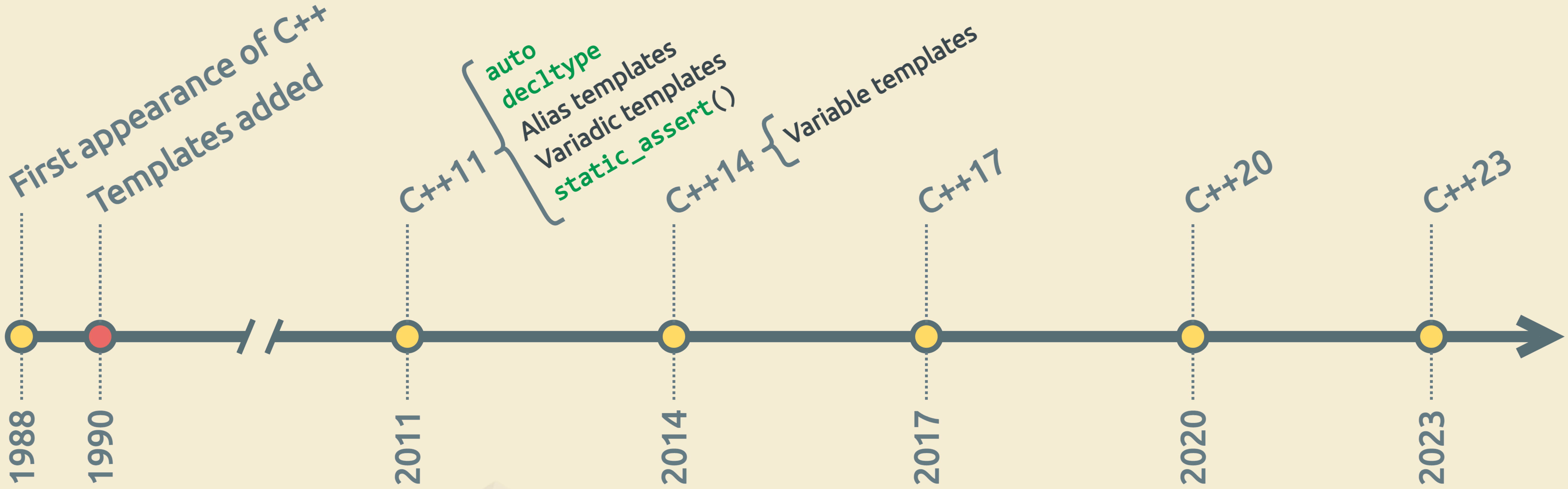

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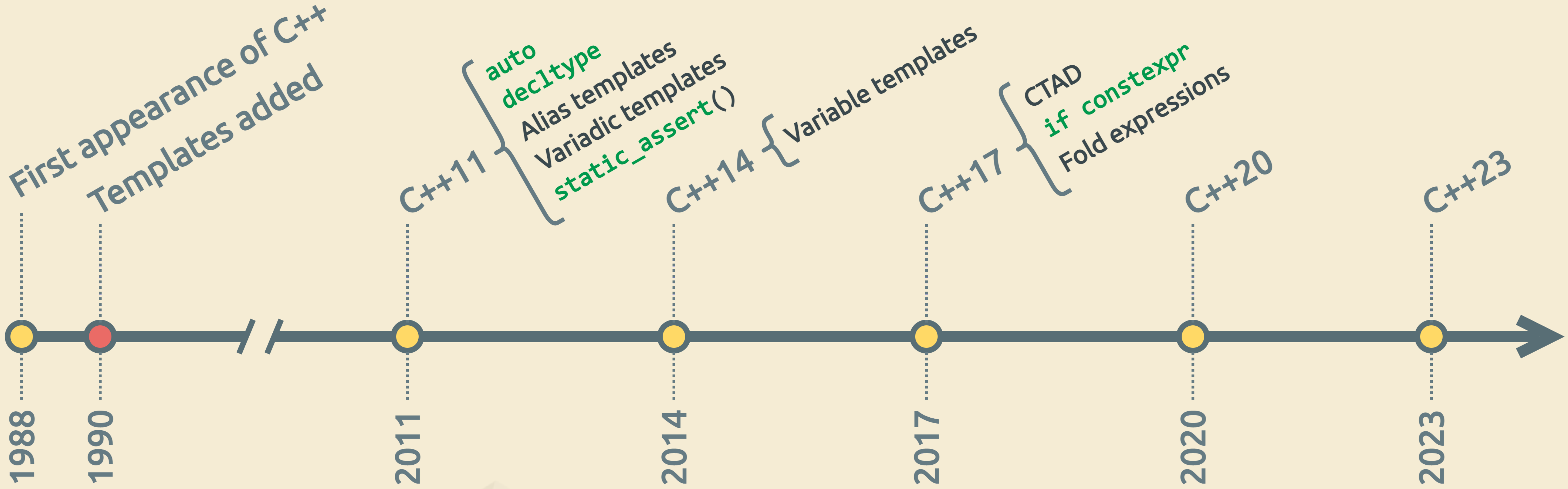

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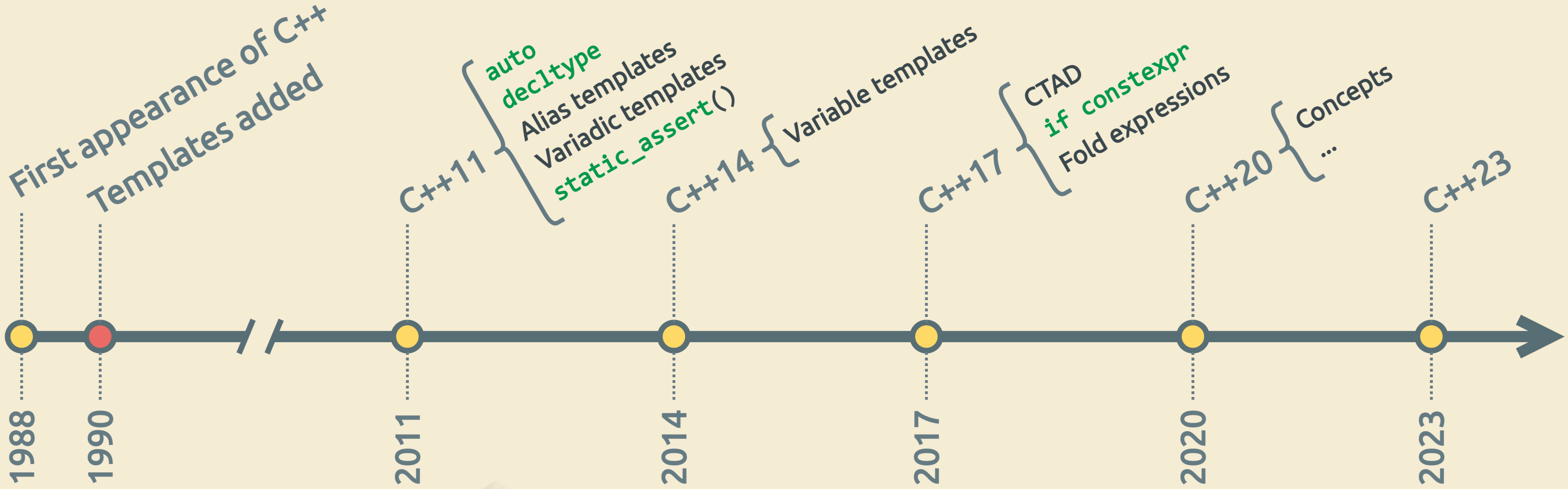


What are templates?

> *A template is a cookie-cutter that specifies how to cut cookies that all look pretty much the same (although the cookies can be made of various kinds of dough, they'll all have the same basic shape).*

From: *The C++ FAQ*

What are templates?

> *A template is a "pattern" that the **compiler** uses to generate a family of classes/functions/variables.*

The trade-off is a longer compilation time ⏱️

What templates can do

- Simplify code and architecture, improve reuse,
- Move code interpretation to compile-time,
- Do certain things otherwise impossible.

<digression> ...

Compile-time programming

Look ma, no templates!

```cpp
constexpr unsigned long factorial(unsigned long value) {
  return (value == 1 ? 1 : value * factorial(value - 1));
}

int main() {
  return factorial(5);
}
```

Output:

```asm
main:
        mov     eax, 120
        ret
```

Away with FUD!

Templates allow compile-time programming.

Not all compile-time programming is templates.

... </digression>

Kinds of templates

- **Function** templates *(since C++98)*
- **Class** template *(since C++98)*
- **Alias** templates *(since C++11)*
- **Variable** templates *(since C++14)*
- **Concepts** *(since C++20)*

Function templates

Regular function:

```cpp
int cube(int value) {
  return value * value * value;
}

```

```cpp
int result = cube(5);
```

Function template:

```cpp
template<typename Type>
Type cube(Type value) {
  return value * value * value;
}
```

```cpp
auto result1 = cube(5);     // int
auto result2 = cube(0.4f); // float
auto result3 = cube(0.73); // double
auto result4 = cube(std::complex{3.2f, 2.73f});
```

Or, using C++20 abbreviated function templates:

```cpp
auto cube(auto value) {
  return value * value * value;
}
```

Class templates

Regular class:

```cpp
class Point {
  int x_ = 0;
  int y_ = 0;

public:
  std::pair<int, int> get() const {
    return {x_, y_};
  }
};
```

```cpp
Point p;

int [x, y] = p.get();
```

Class template:

```cpp
template<typename Type>
class Point {
  Type x_ = {};
  Type y_ = {};

public:
  std::pair<Type, Type> get() const {
    return {x_, y_};
  }
};
```

```cpp
Point<int>   p1;
Point<float> p2;

auto [x1, y1] = p1.get();
auto [x2, y2] = p2.get();
```

Variable templates

Helpers for traits:

```
template<typename Type>
struct trait {
  static constexpr bool value = true;
};

template<typename Type>
static constexpr bool trait_v = trait<Type>::value;
```

```
static_assert(trait<Type>::value, "Trait must hold");
static_assert(trait_v<Type>,      "Trait must hold");
```

Constant variables:

```
template<typename Type>
constexpr Type e = 2.7182818284590452353602874713566L;
```

```
auto threshold1 = 100 * e<float>;
auto threshold2 = 100 * e<double>;
auto threshold3 = 100 * e<long double>;
```

Alias templates

Given this class template:

```
template<typename KeyType, typename ValueType>
struct Map;
```

Regular alias definition:

```
using CharToFloat = Map<char, float>;
using IntToFloat  = Map<int,  float>;
using LongToFloat = Map<long, float>;
```

Alias template:

```
template<typename KeyType>
using FloatMap = Map<KeyType, float>;
```

```
FloatMap<char>        a;
FloatMap<int>         b;
FloatMap<long>        c;
FloatMap<std::string> d;
// ...
```

Concepts

Since C++20, used for modeling syntactic and semantic constraints

Concept:

```cpp
#include <concepts>

template<typename T>
concept EqualityComparable = requires (T a, T b) {
    { a == b } -> std::same_as<bool>;
    { a != b } -> std::same_as<bool>;
};
```

Usage:

```cpp
bool is_equal(const EqualityComparable auto &a,
              const EqualityComparable auto &b) {
  return a == b;
}
```

Ensures `a` and `b` can be compared

Template parameters

Type vs. non-type

Type parameter

```cpp
template<typename Type>
struct List {};

auto l1 = List<int>{};
auto l2 = List<float>{};
```

Non-type parameter

```cpp
template<unsigned int Size>
struct Stack {};

auto s1 = Stack<3>{};
auto s2 = Stack<17>{};
```

Non-type parameters

Examples of non-type parameters:

```
template<auto N> Generic { /* ... */ };
```

Up until C++17 ✅

```
Generic<42>      g1;
Generic<true>    g2;
Generic<'t'>     g3;
Generic<nullptr> g4;
Generic<&obj>    g5;
```

Since C++20 ✅

```
Generic<4.2f>                 g6;
Generic<1.7>                  g7;
Generic<MyCustomType>         g8;
Generic<[]{ return 42; }>     g9;
```

❌

```
Generic<arr[0]> g10;
Generic<"Unix"> g11;
```

Template template parameters

```
template<typename Type>
struct ContainerA { /* ... */ };

template<typename Type>
struct ContainerB { /* ... */ };

template<template<typename> typename Container>
struct IntegerStorage {
  Container<int> container_;
};

IntegerStorage<ContainerA> l1;
IntegerStorage<ContainerB> l2;
```

Template template parameters

```
template<typename Type>
struct ContainerA { /* ... */ };

template<typename Type>
struct ContainerB { /* ... */ };

template<          template<typename> typename Container          >
//                 ^^^^^^^^^^^^^^^^^^
//                   template type with one type argument expected
//
struct IntegerStorage {
  Container<int> container_;
};

IntegerStorage<ContainerA> l1;
IntegerStorage<ContainerB> l2;
```

Variadic templates

```cpp
template<typename... Args>
int naivePrintfWrapper(const std::string& fFormat, Args... fArgs) {
  return printf(fFormat.c_str(), fArgs...); // Just copy all the arguments.
}
```

```cpp
naivePrintfWrapper("How are you today?\n");
naivePrintfWrapper("Message: %s - %d\n", __FUNCTION__, __LINE__);
naivePrintfWrapper("[%.2f, %.2f, %.2f]\n", 3.14f, 2.78f, 10.1f);
```

Related topics: *parameter packs*, *fold expressions*

Templates in practice

A type template

Let's build a simple stack type:

```
class Stack {
  std::deque<...> data_;

public:
  void push(... &&element);
  std::optional<...> pop();
};
```

A type template

```cpp
template<typename Type>
class Stack {
  std::deque<Type> data_;

public:
  void push(Type&& element);
  std::optional<Type> pop();
};
```

```cpp
template<typename Type>
void Stack<Type>::push(Type&& element) {
  data_.push_back(std::move(element));
}

template<typename Type>
std::optional<Type> Stack<Type>::pop() {
  std::optional<Type> result;

  if (data_.empty()) {
    return result;
  }

  result = std::move(data_.back());
  data_.pop_back();

  return result;
}
```

A type template

The stack in action:

```cpp
Stack<int> s1;

s1.push(42);
s1.push(17);

Stack<std::string> s2;

s2.push("World");
s2.push("Peace");
```

```cpp
int v1 = s1.pop().value(); // 17.
int v2 = s1.pop().value(); // 42.

auto v3 = s1.pop(); // std::nullopt;

auto v4 = s2.pop().value(); // "Peace".
auto v5 = s2.pop(); // std::optional of "World".

auto v6 = s2.pop(); // std::nullopt;
auto v7 = s2.pop(); // std::nullopt;
```

Default values for types

Suppose we want the template argument to be optional:

```
template<typename Type> // ???
class Stack {
  std::deque<Type> data_;

public:
  void push(Type&& element);
  std::optional<Type> pop();
};
```

```
Stack s1; // Should instantiate Stack<int>.

s1.push(42);

Stack<std::string> s2;

s2.push("Hey!");

// Etc.
```

Default values for types

Suppose we want the template argument to be optional:

```
template<typename Type = int>
class Stack {
  std::deque<Type> data_;

public:
  void push(Type&& element);
  std::optional<Type> pop();
};
```

```
Stack s1; // Instantiates Stack<int>.

s1.push(42);

Stack<std::string> s2;

s2.push("Hey!");

// Etc.
```

There are limitations as to where default arguments can be used

Non-type template parameter

Let's add a maximum size:

```
template<typename Type, unsigned int MaxSize>
class Stack {
  std::deque<Type> data_;

public:
  void push(Type&& element);
  std::optional<Type> pop();
};
```

```
template<typename Type, unsigned int MaxSize>
void Stack<Type, MaxSize>::push(Type&& element) {
  if (data_.size() < MaxSize) {
    data_.push_back(std::move(element));
  }
}

template<typename Type, unsigned int MaxSize>
std::optional<Type> Stack<Type, MaxSize>::pop() {
  std::optional<Type> result;

  if (data_.empty()) {
    return result;
  }

  result = std::move(data_.back());
  data_.pop_back();

  return result;
}
```

Template specialization

How can we create a specific version for `MaxSize == 1`?

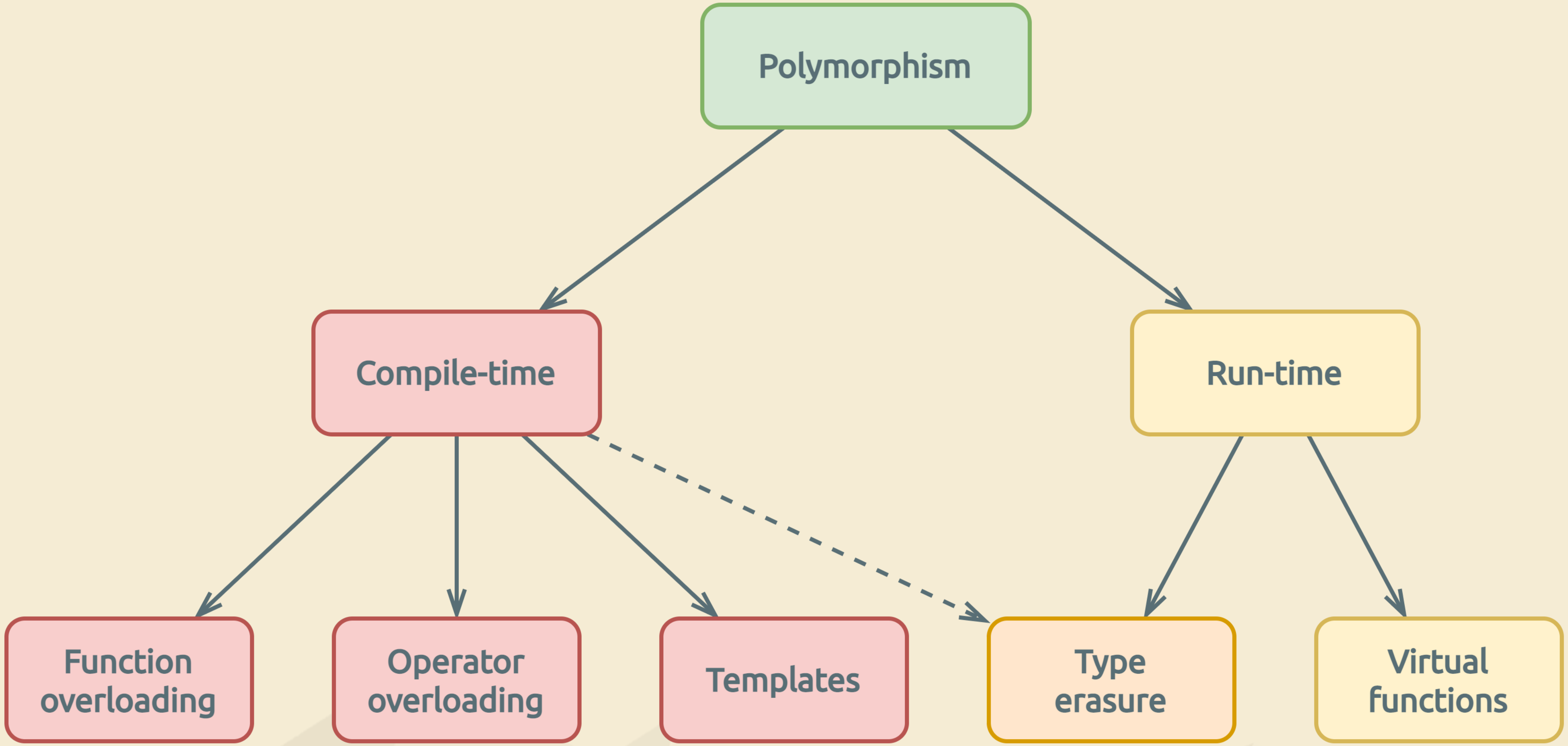
```cpp
template<typename Type, unsigned int MaxSize>
class Stack { /* ... */ }; // 'primary template'.

template<typename Type>
class Stack<Type, 1> {
  Type data_;
  bool empty_ = true;

public:
  void push(Type&& element);
  std::optional<Type> pop();
};
```

This is a *partial specialization*

```cpp
template<typename Type>
void Stack<Type, 1>::push(Type&& element) {
  if (empty_) {
    data_ = std::move(element);
    empty_ = false;
  }
}

template<typename Type>
std::optional<Type> Stack<Type, 1>::pop() {
  std::optional<Type> result;

  if (empty_) {
    return result;
  }

  result = std::move(data_);
  empty_ = true;

  return result;
}
```

Taming templates

Polymorphism in C++



Compile-time polymorphism

Also: **static polymorphism**

```cpp
template<typename Type>
void log(Type& printable) {
  printable.print();
}
```

```cpp
struct A {
  void print() { /* ... */ }
};

struct B {
  void print() { /* ... */ }
};
```

```cpp
A a;
B b;

log(a); // Instantiates 'log<A>()'.
log(b); // Instantiates 'log<B>()'.
```

Implicit interface:

Expects `Type::print()` implicitly

Constraining templated entities

Now let's break it:

```cpp
template<typename Type>
void log(Type& printable) {
  printable.print();
}
```

```cpp
struct A {
  void print() { /* ... */ }
};

struct B {
  // No print()..
};
```

```cpp
A a;
B b;

log(a); // Instantiates 'log<A>()'.
log(b); // Will try to instantiate 'log<B>()'.
```

```
<source>: In instantiation of 'void log(Type&) [with Type = B]':
<source>:   required from here
<source>: error: 'struct B' has no member named 'print'
    |   printable.print();
    |   ~~~~~~~~~~^~~~~
```

That's not so bad really..

Constraining templated entities

```cpp
std::vector<std::vector<int>> v;
auto result = std::find(v.begin(), v.end(), 42); // NOTE: No match for operator==.
```

```
In file included from /opt/include/c++/11.1.0/bits/stl_algobase.h:71,
                 from /opt/include/c++/11.1.0/vector:60,
                 from <source>:1:
/opt/include/c++/11.1.0/bits/predefined_ops.h: In instantiation of 'bool
__gnu_cxx::__ops::_Iter_equals_val<_Value>::operator()(_Iterator) [with _Iterator =
__gnu_cxx::__normal_iterator<std::vector<int>*, std::vector<std::vector<int> > >; _Value = const int]':
/opt/include/c++/11.1.0/bits/stl_algobase.h:2069:14:   required from '_RandomAccessIterator
std::__find_if(_RandomAccessIterator, _RandomAccessIterator, _Predicate, std::random_access_iterator_tag)
[with _RandomAccessIterator = __gnu_cxx::__normal_iterator<std::vector<int>*,
std::vector<std::vector<int> > >; _Predicate = __gnu_cxx::__ops::_Iter_equals_val<const int>]'

                              ...232 more lines...
```

😱

Constraining templated entities

> *Templates create a 'Duck Typing' scenario: anything is allowed. Improve modelling by imposing **constraints**.*

- C++20 *concepts*,
- `static_assert()`,
- Type traits.

Static assertions

Preventing misuse of `Stack<>`:

```cpp
template<typename Type, unsigned int MaxSize>
class Stack {
  static_assert(MaxSize != 0, "MaxSize cannot be zero");

  std::deque<Type> data_;

public:
  void push(Type&& element);
  std::optional<Type> pop();
};
```

```cpp
Stack<int, 16> s1;  // OK.
Stack<int, 0>  s2;  // Compiler error!
```

Static assertions

Preventing misuse of `Stack<>`:

```cpp
template<typename Type, unsigned int MaxSize>
class Stack {
  static_assert(MaxSize != 0, "MaxSize cannot be zero");

  std::deque<Type> data_;

public:
  void push(Type&& element);
  std::optional<Type> pop();
};
```

```cpp
Stack<int, 16> s1;  // OK.
Stack<int, 0>  s2;  // Compiler error!
```

```
error: static_assert failed due to requirement '0U != 0'
         "MaxSize cannot be zero"
  static_assert(MaxSize != 0, "MaxSize cannot be zero");
  ^              ~~~~~~~~~~~~
```

Type traits

> *Type traits enable type* ***evaluation*** *and* ***modification****.*

… at compile-time

A rational number

```
template<typename Type>
class Fraction {
  Type numerator_   = {};
  Type denominator_ = {};

public:
  Fraction(Type numerator, Type denominator)
    : numerator_{numerator},
      denominator_{denominator} {
  }

  Type numerator()   { return numerator_;   }
  Type denominator() { return denominator_; }

  double real() {
    return static_cast<double>(numerator_) / denominator_;
  }
};
```

```
Fraction<int>           a{22, 7};
Fraction<unsigned long> b{355U, 113U};

printf("a = %.8lf\n", a.real());
printf("b = %.8lf\n", b.real());
```

```
a = 3.14285714
b = 3.14159292
```

A rational number

```cpp
template<typename Type>
class Fraction {
  Type numerator_   = {};
  Type denominator_ = {};

public:
  Fraction(Type numerator, Type denominator)
    : numerator_{numerator},
      denominator_{denominator} {
  }

  Type numerator()   { return numerator_;   }
  Type denominator() { return denominator_; }

  double real() {
    return static_cast<double>(numerator_) / denominator_;
  }
};
```

```cpp
Fraction<int>           a{22, 7};
Fraction<unsigned long> b{355U, 113U};
Fraction<double>        c{3.14159265, 1.0};
Fraction<bool>          d{true, true};

printf("a = %.8lf\n", a.real());
printf("b = %.8lf\n", b.real());
printf("c = %.8lf\n", c.real());
printf("d = %.8lf\n", d.real());
```

```
a = 3.14285714
b = 3.14159292
c = 3.14159265
d = 1.00000000
```

Hmmm...

Imposing constraints

```
template<typename Type>
class Fraction {
  static_assert(/* ..insert compile-time check.. */,
                "Not a non-boolean integral type");

public:
  // ...
};
```

```
Fraction<double> c{3.14159265, 1.0};
Fraction<bool>   d{true, true};
```

```
...a compiler error would be nice!...
```

Imposing constraints

```cpp
template<typename Type>
class Fraction {
  static_assert(std::is_integral<Type>::value && !std::is_same<Type, bool>::value,
                "Not a non-boolean integral type");

public:
  // ...
};
```

```cpp
Fraction<double> c{3.14159265, 1.0};
Fraction<bool>   d{true, true};
```

```
<source>: In instantiation of 'class Fraction<double>': required from here:
<source>: error: static assertion failed: Not a non-boolean integral type
    |   static_assert(std::is_integral<Type>::value && !std::is_same<Type, bool>::value,
    |                                         ^~~~~
<source>: In instantiation of 'class Fraction<bool>': required from here:
<source>: error: static assertion failed: Not a non-boolean integral type
    |   static_assert(std::is_integral<Type>::value && !std::is_same<Type, bool>::value,
    |                                                                           ^~~~~
```

Imposing constraints

```
template<typename Type>
class Fraction {
  static_assert(std::is_integral_v<Type> && !std::is_same_v<Type, bool>,
                "Not a non-boolean integral type");

public:
  // ...
};
```

```
Fraction<double> c{3.14159265, 1.0};
Fraction<bool>   d{true, true};
```

```
<source>: In instantiation of 'class Fraction<double>': required from here:
<source>: error: static assertion failed: Not a non-boolean integral type
    |   static_assert(std::is_integral_v<Type> && !std::is_same_v<Type, bool>,
    |                 ~~~~~^~~~~~~~~~~~~
<source>: In instantiation of 'class Fraction<bool>': required from here:
<source>: error: static assertion failed: Not a non-boolean integral type
    |   static_assert(std::is_integral_v<Type> && !std::is_same_v<Type, bool>,
    |                                             ~~~~~^~~~~~~~~
```

C++20 Concepts

A concept is a ***named set of requirements*** *on template parameters. It can be used to select function overloads and template specializations.*

A concept is a ***predicate****, evaluated at compile-time.*

Concept form

template <*template-parameter-list*>
concept *concept-name* = *constraint-expression*;

E.g.:

```
template<typename Type>
concept UnsignedIntegral = std::is_integral_v<Type> && !std::is_signed_v<Type>;
```

```
template<typename Type>
concept Addable = requires (Type x) { x + x; };
```

Back to Fraction

```cpp
#include <type_traits>

template<typename Type>
class Fraction {
  static_assert(std::is_integral_v<Type> && !std::is_same_v<Type, bool>,
                "Not a non-boolean integral type");

public:
  // ...
};
```

```cpp
Fraction<int>   f1; // OK.
Fraction<float> f2; // Error: static assertion fails.
```

Back to Fraction

```cpp
#include <type_traits>

template<typename Type>
concept NonBooleanIntegral = std::is_integral_v<Type> && !std::is_same_v<Type, bool>;

template<NonBooleanIntegral Type>
class Fraction {
public:
  // ...
};
```

```cpp
Fraction<int>   f1; // OK.
Fraction<float> f2; // Error: constraints not satisfied.
```

Back to `Fraction`

```
#include <concepts>

template<typename Type>
concept NonBooleanIntegral = std::integral<Type> && !std::same_as<Type, bool>;

template<NonBooleanIntegral Type>
class Fraction {
public:
  // ...
};
```

```
Fraction<int>   f1; // OK.
Fraction<float> f2; // Error: constraints not satisfied.
```

Concept usage forms

```cpp
template<typename Type>
concept UnsignedIntegral = std::is_integral_v<Type> && !std::is_signed_v<Type>;
```

Form 1:

```cpp
template<UnsignedIntegral Type>
void func(Type value) {
  // ...
}
```

Form 2:

```cpp
template<typename Type> requires UnsignedIntegral<Type>
void func(Type value) {
  // ...
}
```

Form 3:

```cpp
template<typename Type>
void func(Type value) requires UnsignedIntegral<Type> {
  // ...
}
```

The requires keyword

The **requires** keyword introduces a *requires-clause*

Constant expression / **concept**:

```
template<typename Type>
  requires std::is_integral_v<Type>
struct X {
  // ...
};

template<typename Type>
  requires std::integral<Type>
struct X {
  // ...
};
```

Requires-expression:

```
template<typename Type>
concept Addable = requires (Type x) { x + x; };
```

```
template<typename Type>
  requires requires (Type x) { x + x; }
Type add(Type a, Type b) {
  return a + b;
}
```

Template meta-programming

Serendipity

- Template metaprogramming was ‘discovered’
- In 1994 Erwin Unruh demonstrated this at a committee meeting
- In fact, the template system is *Turing-complete*

Examples

Compile-time Fibonacci number calculation:

```
template<int Index, int A = 0, int B = 1>
struct Fibonacci {
  static constexpr int value = Fibonacci<Index - 1, B, A + B>::value;
};

template<int A, int B>
struct Fibonacci<0, A, B> {
  static constexpr int value = A;
};

template<int A, int B>
struct Fibonacci<1, A, B> {
  static constexpr int value = B;
};

int main() {
  return Fibonacci<8>::value;
}
```

Fibonacci sequence:

```
0 1 1 2 3 5 8 13 21 34 ...
                 ^^
```

Build output:

```
main:
        mov     eax, 21
        ret
```

Examples

Compile-time Fibonacci number calculation:

```
template<int Index, int A = 0, int B = 1>
struct Fibonacci {
  static constexpr int value = Fibonacci<Index - 1, B, A + B>::value;
};

template<int A, int B>
struct Fibonacci<0, A, B> {
  static constexpr int value = A;
};

template<int A, int B>
struct Fibonacci<1, A, B> {
  static constexpr int value = B;
};

int main() {
  return Fibonacci<8>::value;
}
```

Instantiations:

```
Fibonacci<8, 0, 1>
```

Examples

Compile-time Fibonacci number calculation:

```cpp
template<int Index, int A = 0, int B = 1>
struct Fibonacci {
  static constexpr int value = Fibonacci<Index - 1, B, A + B>::value;
};

template<int A, int B>
struct Fibonacci<0, A, B> {
  static constexpr int value = A;
};

template<int A, int B>
struct Fibonacci<1, A, B> {
  static constexpr int value = B;
};

int main() {
  return Fibonacci<8>::value;
}
```

Instantiations:

```
Fibonacci<8, 0, 1>
Fibonacci<7, 1, 1>
Fibonacci<6, 1, 2>
Fibonacci<5, 2, 3>
Fibonacci<4, 3, 5>
Fibonacci<3, 5, 8>
Fibonacci<2, 8, 13>
```

Examples

Compile-time Fibonacci number calculation:

```cpp
template<int Index, int A = 0, int B = 1>
struct Fibonacci {
  static constexpr int value = Fibonacci<Index - 1, B, A + B>::value;
};

template<int A, int B>
struct Fibonacci<0, A, B> {
  static constexpr int value = A;
};

template<int A, int B>
struct Fibonacci<1, A, B> {
  static constexpr int value = B;
};

int main() {
  return Fibonacci<8>::value;
}
```

Instantiations:

```
Fibonacci<8, 0, 1>
Fibonacci<7, 1, 1>
Fibonacci<6, 1, 2>
Fibonacci<5, 2, 3>
Fibonacci<4, 3, 5>
Fibonacci<3, 5, 8>
Fibonacci<2, 8, 13>
Fibonacci<1, 13, 21>
```

Done!

Examples

Compile-time Fibonacci number calculation:

```
template<int Index, int A = 0, int B = 1>
struct Fibonacci {
  static constexpr int value = Fibonacci<Index - 1, B, A + B>::value;
};

template<int A, int B>  // Specialization is not used here.
struct Fibonacci<0, A, B> {
  static constexpr int value = A;
};

template<int A, int B>
struct Fibonacci<1, A, B> {
  static constexpr int value = B;
};

int main() {
  return Fibonacci<8>::value;
}
```

Instantiations:

```
Fibonacci<8, 0, 1>
Fibonacci<7, 1, 1>
Fibonacci<6, 1, 2>
Fibonacci<5, 2, 3>
Fibonacci<4, 3, 5>
Fibonacci<3, 5, 8>
Fibonacci<2, 8, 13>
Fibonacci<1, 13, 21>
```

Done!

One slide on SFINAE

Abbreviation for **“Substitution Failure Is Not An Error”**

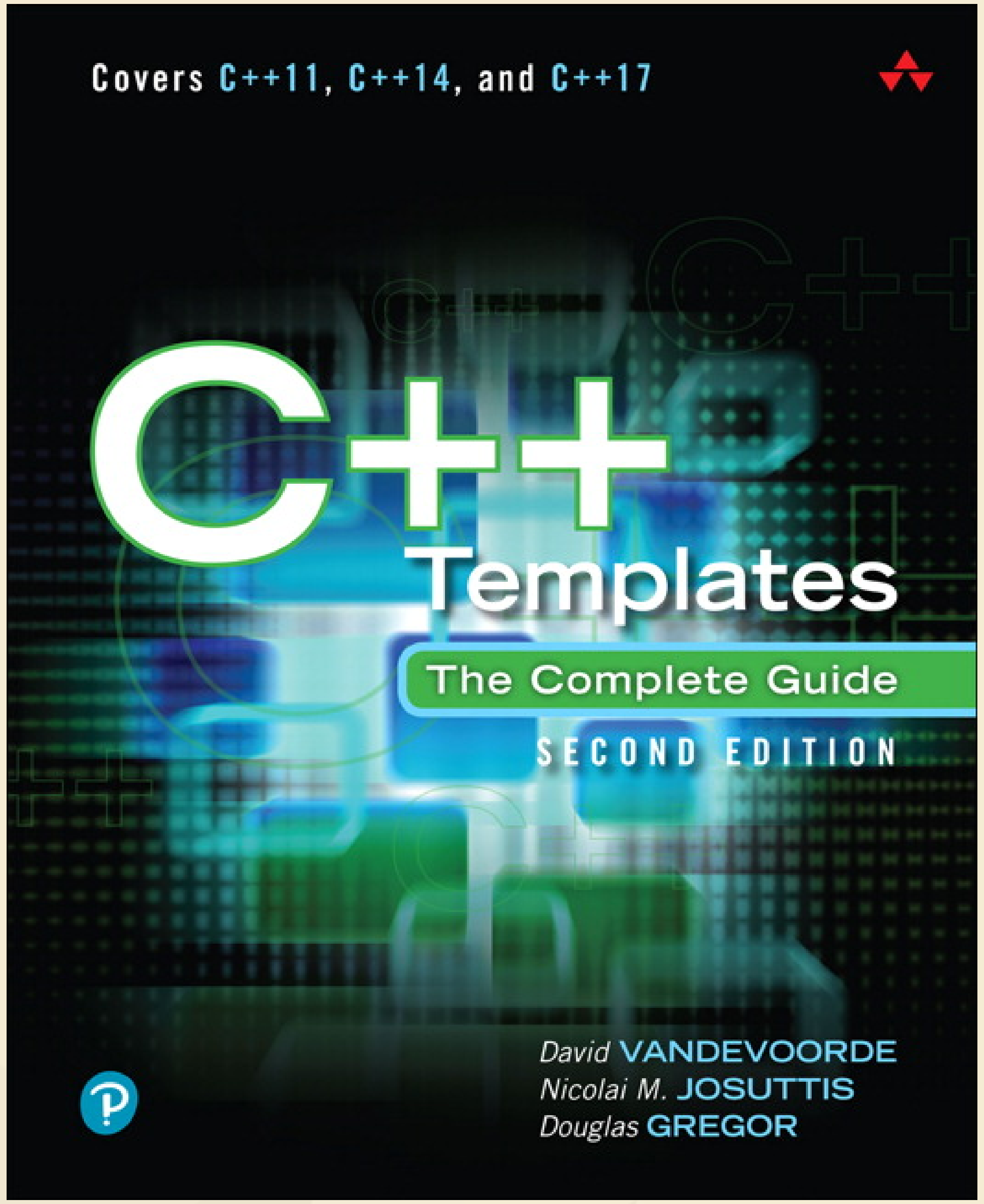
A rule for overload resolution in function templates, used in TMP

☝ *Avoid direct use if possible* ☝

(unless you really know what you’re doing)

End

If you want to know it all



Thank you 😃

If you think this is cooler than ice cream, you've got the makings of a template metaprogrammer. If the templates and specializations, recursive instantiations and `enum` *hacks and [...] make your skin crawl, well, you're a pretty normal C++ programmer.*

— Scott Meyers, Effective C++

🔗 github.com/krisvanrens