Peering forward: C++'s next decade

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C++26/29

Major advances are on track

- ☑ `std::execution` (concurrency *and* parallelism)
- ☑ Type and memory safety improvements
- ☐ Reflection + code generation (aka ‘injection’/…)
- ☐ Contracts

☑ means “some initial parts already voted into C++26”

C++26/29

Major advances are on track

`std::execution` (concurrency *and* parallelism)

Type and memory safety improvements

- target: **parity** with other modern languages

Reflection + code generation (aka ‘injection’/…)

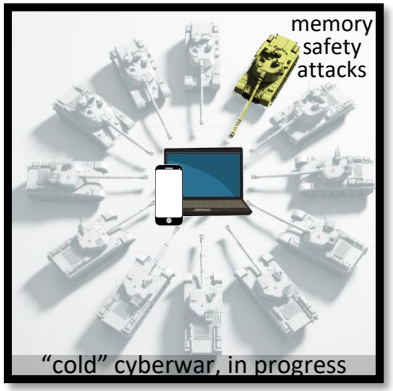
- part of our **tide to compile-time programming**
- arguably **most-impactful** feature ever added
- I expect will **dominate** our next decade

Contracts

1

Reflection

2



Safety

3

Simplicity

1 ∩ 2 includes

- timing: starting in C++26 🤞
- technical: ↓↓UB
- simplicity (3): code & tools

1

Reflection

short definition

the program can **see** itself

and **generate** itself

… hence, **meta**programs

static ⇒ zero runtime overhead

not run-time reflection

(this is not Java or C#)

of course, to use some information at run time, just store it!

part of the 30+-year tide $\rightarrow$ **compile-time meta** programming in C++

“The world’s big things only can be done
*by paying attention to their **humble beginnings**.” — Lao Tzu*

Erwin Unruh: The most famous C++ program that doesn't compile

```
template <int i> struct D { D(void*); operator int(); };

template <int p, int i> struct is_prime {
  enum { prim = (p%i) && is_prime<(i>2 ? p : 0), i-1>::prim };
};

template <int i> struct Prime_print {
  Prime_print<i-1> a;
  enum { prim = is_prime<i, i-1>::prim };
  void f() { D<i> d = prim; }
};

struct is_prime<0,0>  { enum
struct is_prime<0,1>  { enum
struct Prime_print<2> { enum

main () {
    Prime_print<10> a;
}
```

1994: TC!

Original Metaware compiler error messages

```
Type 'enum{}' can't be converted to type 'D<2>' ("primes.cpp",L2/C25).
Type 'enum{}' can't be converted to type 'D<3>' ("primes.cpp",L2/C25).
Type 'enum{}' can't be converted to type 'D<5>' ("primes.cpp",L2/C25).
Type 'enum{}' can't be converted to type 'D<7>' ("primes.cpp",L2/C25).
Type 'enum{}' can't be converted to type 'D<11>' ("primes.cpp",L2/C25).
Type 'enum{}' can't be converted to type 'D<13>' ("primes.cpp",L2/C25).
Type 'enum{}' can't be converted to type 'D<17>' ("primes.cpp",L2/C25).
Type 'enum{}' can't be converted to type 'D<19>' ("primes.cpp",L2/C25).
Type 'enum{}' can't be converted to type 'D<23>' ("primes.cpp",L2/C25).
Type 'enum{}' can't be converted to type 'D<29>' ("primes.cpp",L2/C25).
```

Modern C++ Design

3 languages

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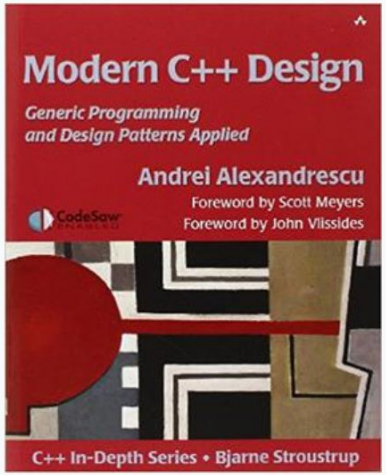
From Wikipedia, the free encyclopedia

Modern C++ Design: Generic Programming and Design Patterns Applied is a book written by Andrei Alexandrescu, published in 2001 by Addison-Wesley. It has been regarded as "one of the most important C++ books" by Scott Meyers.[1]

The book makes use of and explores a C++ programming technique called template metaprogramming. While Alexandrescu didn't invent the technique, he has popularized it among programmers. His book contains solutions to practical problems which C++ programmers

Modern C++ Design



Author	Andrei Alexandrescu
Language	English
Subject	C++
Publisher	Addison-Wesley
Publication date	2001

2001: TMP 💉

ISO C++ & constexpr

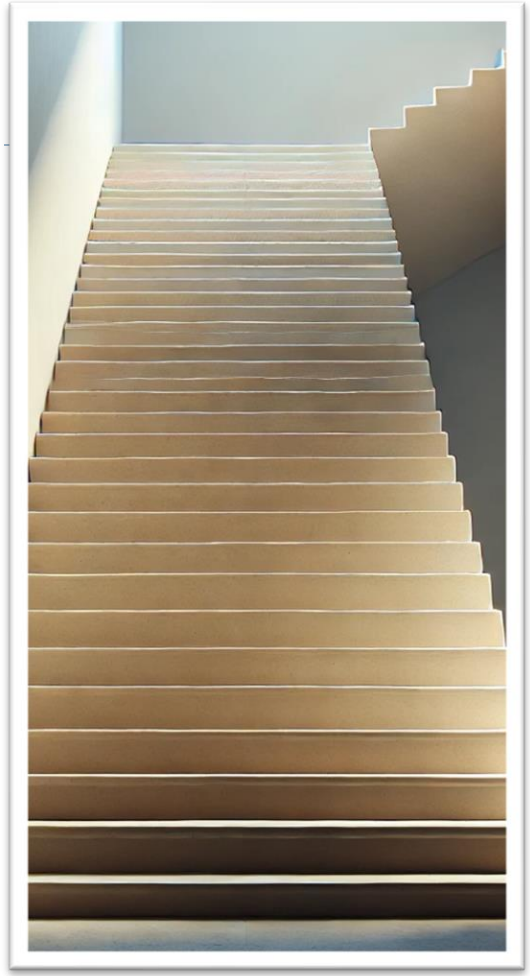
C++ 23 — more math, **allocators**, non-literal params, …

C++ 20 — **new/delete**, virtual, lambdas, **try/catch**, **vector/string**, …

C++ 17 — **lambdas, constexpr destructors**, **if constexpr**, static_assert, …

C++ 14 — more statements, local variables, **if/switch**, **for/while**, member functions, …

C++ 11 — one return statement



ISO C++ & **GPUs**

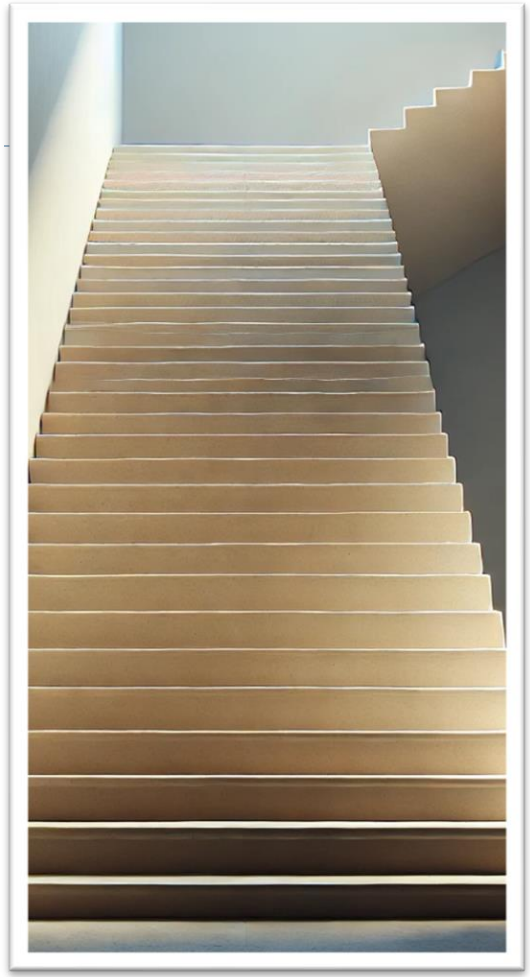
CUDA **12** (2022) — concepts, ranges, '**moar constexpr**,' …

CUDA **11** (2020) — **new/delete**, **constexpr**, CTAD, structured bindings, …

CUDA **7** (2015) — **lambdas**, range-for, variadic templates, static_assert, …

'Moar shaders!' — more statements, local variables, **if/switch**, **for/while**, …

Shaders — throw a few instructions at a pixel as it flies by



ISO C++ & constexpr

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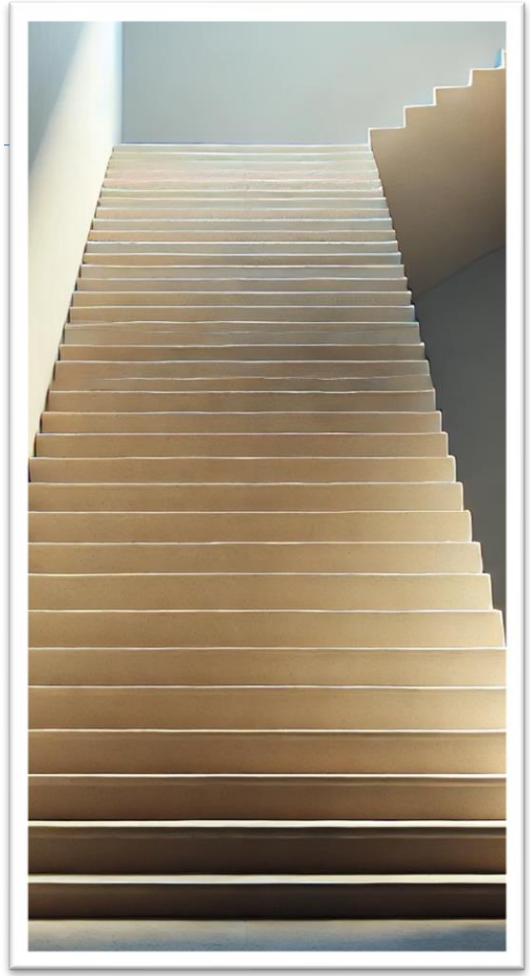


pause to consider what this implies

C++ is the language we want at compile time

C++ is the language we want on GPUs

ISO C++ & **reflection**

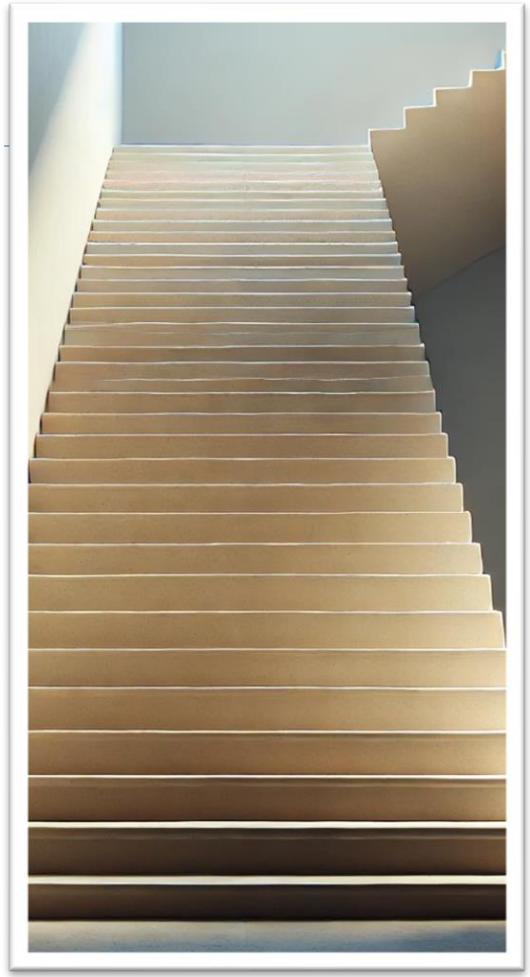
P3294 code generation/injection

P3157 generative extensions

P3273 introspection of closure types

P3096 function parameters

P2996 reflection, splicers, meta::info, metafunctions



P2996 example: Basic command-line option parser

Thanks to Matúš Chochlík!

```
struct MyOpts {
    std::string file_name = "input.txt";    // "--file_name <string>"
    int         count     = 1;              // "--count <int>"
};

int main(int argc, char *argv[]) {
    MyOpts opts = parse_options<MyOpts>(
        std::vector<std::string_view>(argv+1, argv+argc)
    );
    std::cout << "opts.file="  << opts.file_name << '\n';
    std::cout << "opts.count=" << opts.count     << '\n';
}
```

the **type itself** is a function input

```
template<typename Opts>
consteval auto parse_options(std::span<std::string_view const> args) -> Opts
{
    Opts opts;
    template for (constexpr auto dm : nonstatic_data_members_of(^^Opts)) {
        auto it = std::ranges::find_if(args,
            [](std::string_view arg){
                return arg.starts_with("--")
                    && arg.substr(2) == identifier_of(dm);
            });

        if (it == args.end()) {
            continue; // not provided, use default
        } else if (it + 1 == args.end()) {
            std::print(stderr, "Option {} is missing a value\n", *it);
            std::exit(EXIT_FAILURE);
        }
```

expansion statement

^^ reflection expression and std::meta:: **metafunctions**

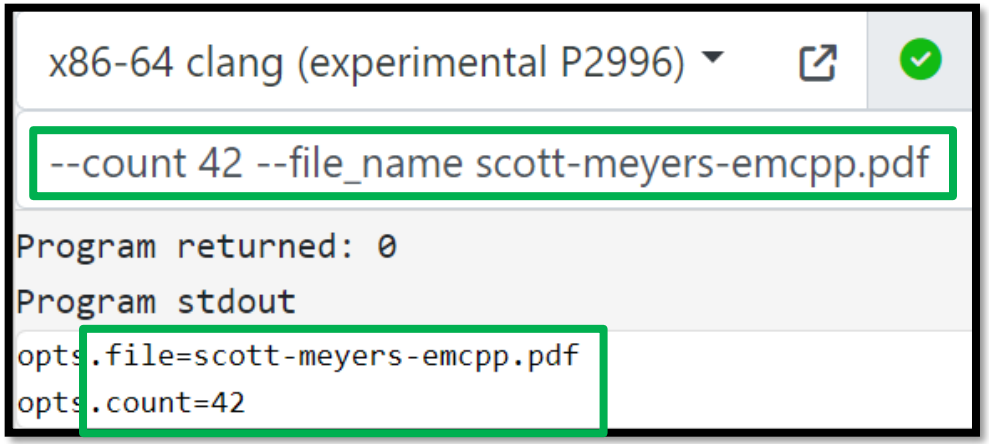
```
                    && arg.substr(2) == identifier_of(dm);
            });

        if (it == args.end()) {
            continue; // not provided, use default
        } else if (it + 1 == args.end()) {
            std::print(stderr, "Option {} is missing a value\n", *it);
            std::exit(EXIT_FAILURE);
        }

        using T = typename[:type_of(dm):];
        auto iss = std::ispanstream(it[1]);
        if (iss >> opts.[:dm:]; !iss) {
            std::print(stderr, "{} is not a valid {}\n",
                       *it, display_string_of(dealias(^^T)));
            std::exit(EXIT_FAILURE);
        }
    }
    return opts;
}
```

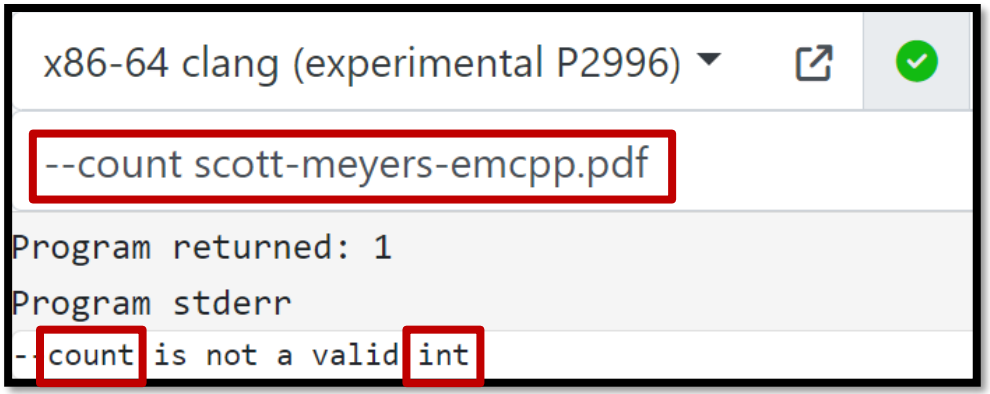
splices

e.g., "**int**" at compile time

better than typeid(T).name()
(e.g., "**i**" at **run time**)

As seen on COMPILER EXPLORER

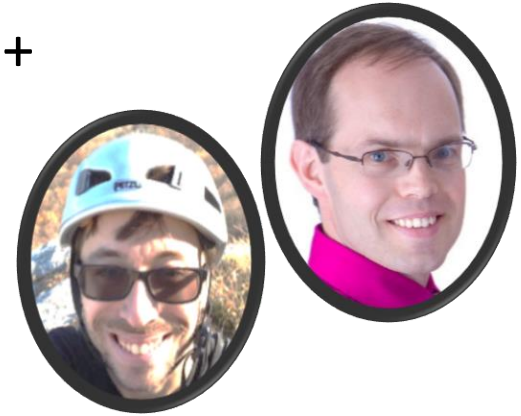




P2996 implementations

Two current implementations tracking P2996 ++

EDG-based	Daveed Vandedoorde (EDG)
Clang-based	Dan Katz (Bloomberg)

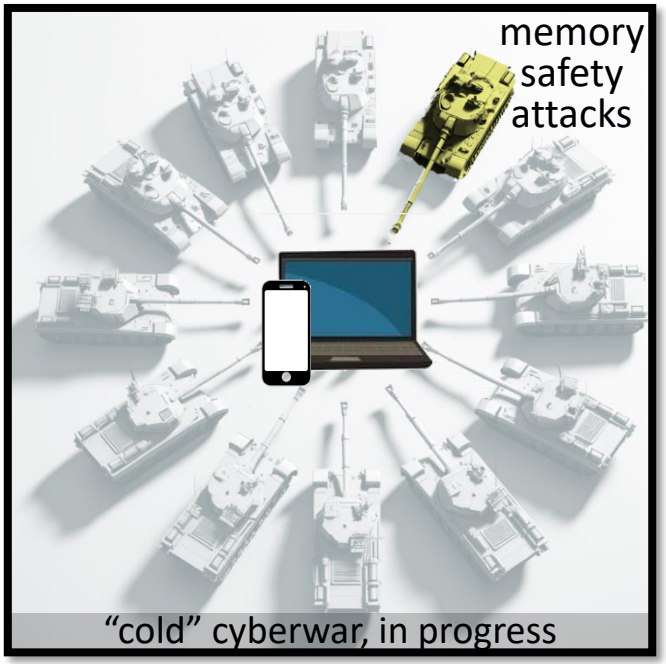


Other related prototype implementations

Clang-based	Andrew Sutton et al. (Lock3)
Cppfront	mine
Circle	Sean Baxter

2

Safety



See essay here: ***tinyurl.com/sutter-safety***
(herbsutter.com/2024/03/11/safety-in-context)

Terms (per ISO/IEC 23643:2020)

Software **security** (or "cybersecurity" or similar)

making software able to **protect its assets** from a malicious attacker

examples: securing power grids, hospitals, banks, personal data, secrets, …

Software **safety** (or "life safety" or similar)

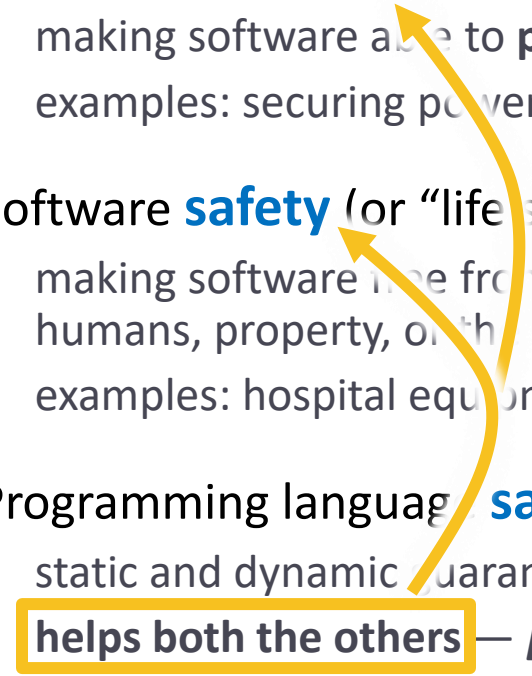
making software free from unacceptable risk of **causing unintended harm** to humans, property, or the environment

examples: hospital equipment, autonomous vehicles/weapons

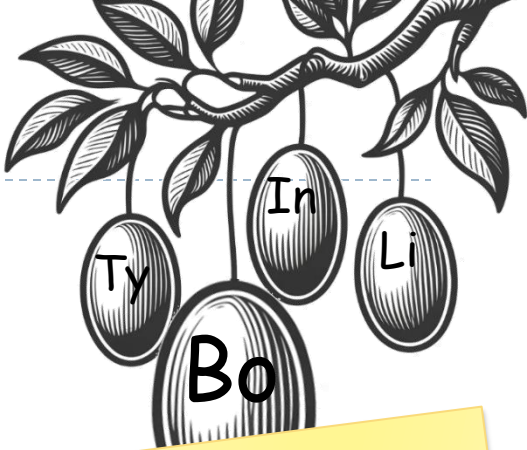
Programming language **safety** (incl. memory safety)

static and dynamic guarantees about **program correctness**

helps both the others — ***[more on this in section 3]***



tl;dr



The actual problem: Safety parity (not perfection)

- 4 low-hanging priority targets:
  - **type, bounds, initialization & lifetime safety**
- == 4 most severe CWE categories, 4 that all MSLs do better at

Progress

- Key **safe libraries** moving from 3rd-party to standard
  (e.g., C++20 `std::span<T>` to replace pointer math)
- Safety-related **undefined behavior** being removed
  (e.g., Mar 2024: reading uninit stack vars not UB!)
- Key **static safety rules Profiles:** most known, “shift-left” to compile time
- Add **dynamic safety checks** as needed (e.g., bounds, null)

+ what implementations are doing outside the standard, e.g., `-fhardened`, STL safety

Work in the same kitchen, hold the same knife…

today: “watch out”

performance & control by default,
safety always available

Work in the same kitchen, hold the same knife…

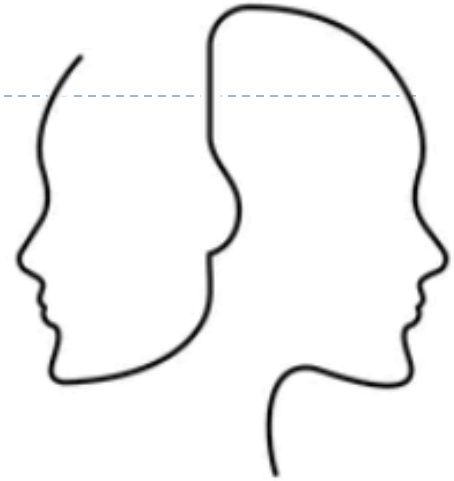
today: “watch out”

performance & control by default,
safety always available

tomorrow: “opt out”

safety by default,
performance & control always available

Safety Profiles



Progressing in WG21: Safety **Profiles** framework

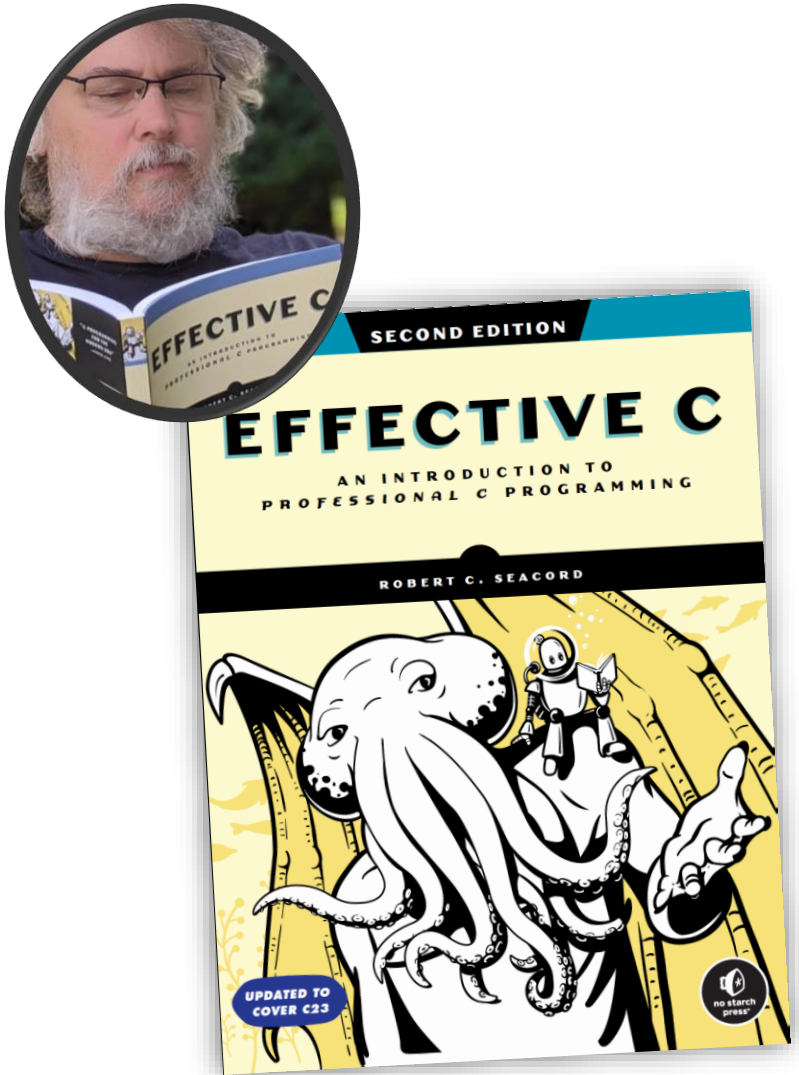
(Stroustrup & Dos Reis)

pro·file /ˈprōˌfīl/ *noun*

*a name for a **set of rules enforced at compile time**,*
*that guarantees the **absence of a class of defects**,*
*and the programmer can **enable for a volume of code***

Profiles can be added over time, and enabled **selectively & incrementally**

Key: take (mostly-already-known) rules, “shift-left” to compile time



from the Praise page

"... This book's emphasis on the security aspects of C programming is unmatched … use all of the available tools it presents to **avoid undefined behavior** in the C programs you write."

— Pascal Cuoq, Chief Scientist, Trustinsoft

"An excellent introduction to modern C."

— Francis Glassborow, ACCU

…

"This is why you should program in C. Because **other languages don't open portals to hell**."

— Michał Zalewski, former CISO, Snap Inc.

C++26: “erroneous behavior”

Undefined behavior means “anything can happen”

- Usual examples — nasal daemons, `format c:`
- Actual bad examples — time travel, leaking secrets

C++26 introduces a new tool: **erroneous** behavior

- **“Well-defined as being Just Wrong”**
- **Not undefined** ⇒ no time travel, or leaked secrets!

A general tool, but first applied to…

Reading uninitialized local variables is not undefined behavior in C++26!

- A C++26 compiler is required to write an “erroneous” value

C++26: “erroneous behavior”

Pause a moment and consider how this is important:

QUANTITATIVELY Automatically eliminates a significant fraction (5%? 10%?) of vulnerabilities and other bugs

Qualitatively Delivered to existing code with **no manual code changes**, just a recompile

⇒ seriousness about **adoptability** & improving safety of **existing** code

Ode to information disclosure

```
auto f1() {
    char a[] = {'s', 'e', 'c', 'r', 'e', 't' };
}

auto f2() {
    char a[6]; // or std::array<char,6>
    print(a);  // today this likely prints "secret"
}

int main() {
    f1();
    f2();
}
```

C++26 “erroneous behavior”

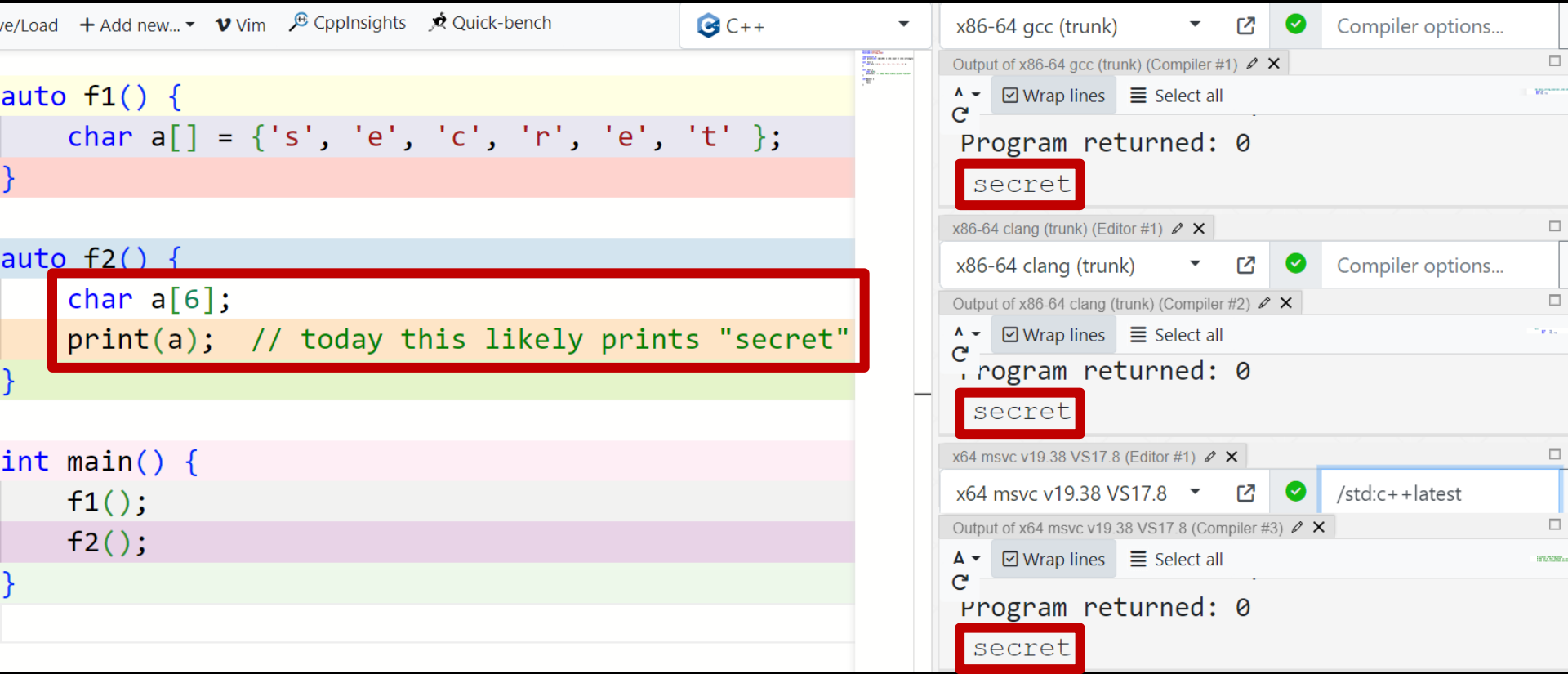
```
auto f1() {
    char a[] = {'s', 'e', 'c', 'r', 'e', 't' };
}

auto f2() {
    char a[6]; // or std::array<char,6>
    print(a);  // C++26: prints "??????" or "" or... but not "secret"
}

int main() {
    f1();
    f2();
}
```

for pre-C++26:

not de jure standard, but de facto available today

GCC, Clang: `-ftrivial-auto-var-init=pattern`

MSVC: `/RTC1`


ve/Load
+ Add new...
Vim
CppInsights
Quick-bench
C++
auto f1() {
char a[] = {'s', 'e', 'c', 'r', 'e', 't' };
}
auto f2() {
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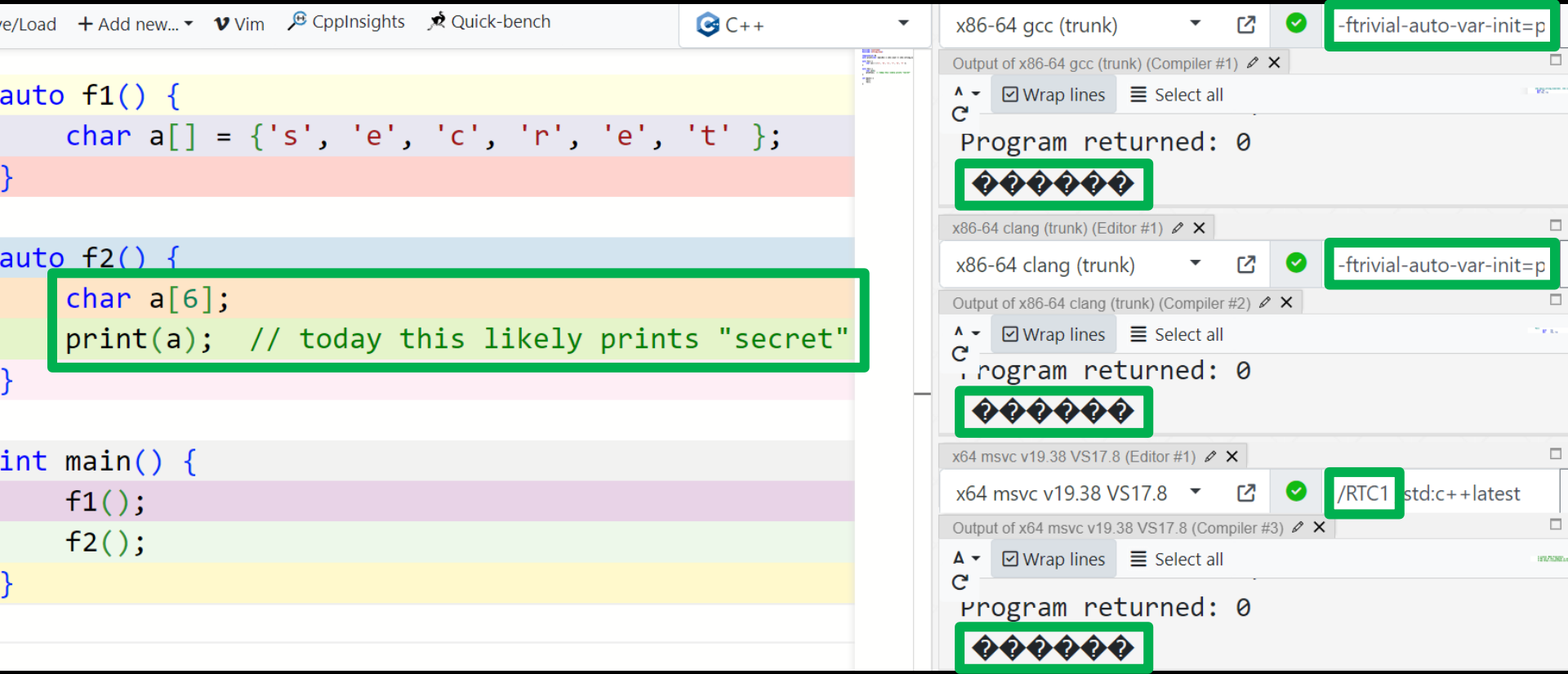
print(a); // today this likely prints "secret"
}
int main() {
f1();
f2();
}
x86-64 gcc (trunk)
Compiler options...
Output of x86-64 gcc (trunk) (Compiler #1)
Wrap lines
Select all
Program returned: 0
secret
x86-64 clang (trunk) (Editor #1)
x86-64 clang (trunk)
Compiler options...
Output of x86-64 clang (trunk) (Compiler #2)
Wrap lines
Select all
Program returned: 0
secret
x64 msvc v19.38 VS17.8 (Editor #1)
x64 msvc v19.38 VS17.8
/std:c++latest
Output of x64 msvc v19.38 VS17.8 (Compiler #3)
Wrap lines
Select all
Program returned: 0
secret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int main() {
f1();
f2();
}
x86-64 gcc (trunk)
-ftrivial-auto-var-init=p
Output of x86-64 gcc (trunk) (Compiler #1)
Wrap lines
Select all
Program returned: 0
x86-64 clang (trunk) (Editor #1)
x86-64 clang (trunk)
-ftrivial-auto-var-init=p
Output of x86-64 clang (trunk) (Compiler #2)
Wrap lines
Select all
Program returned: 0
x64 msvc v19.38 VS17.8 (Editor #1)
x64 msvc v19.38 VS17.8
/RTC1
std:c++latest
Output of x64 msvc v19.38 VS17.8 (Compiler #3)
Wrap lines
Select all
Program returned: 0

Q&A

Why not zero-init?

- If zero isn't a program-meaningful value, just changes one bug into another
  - Not like a world where zero-init was always the language rule!
- Actively hides real problems — makes uninitialization invisible to sanitizers

Can I opt out?

- Yes (this is still C++!)

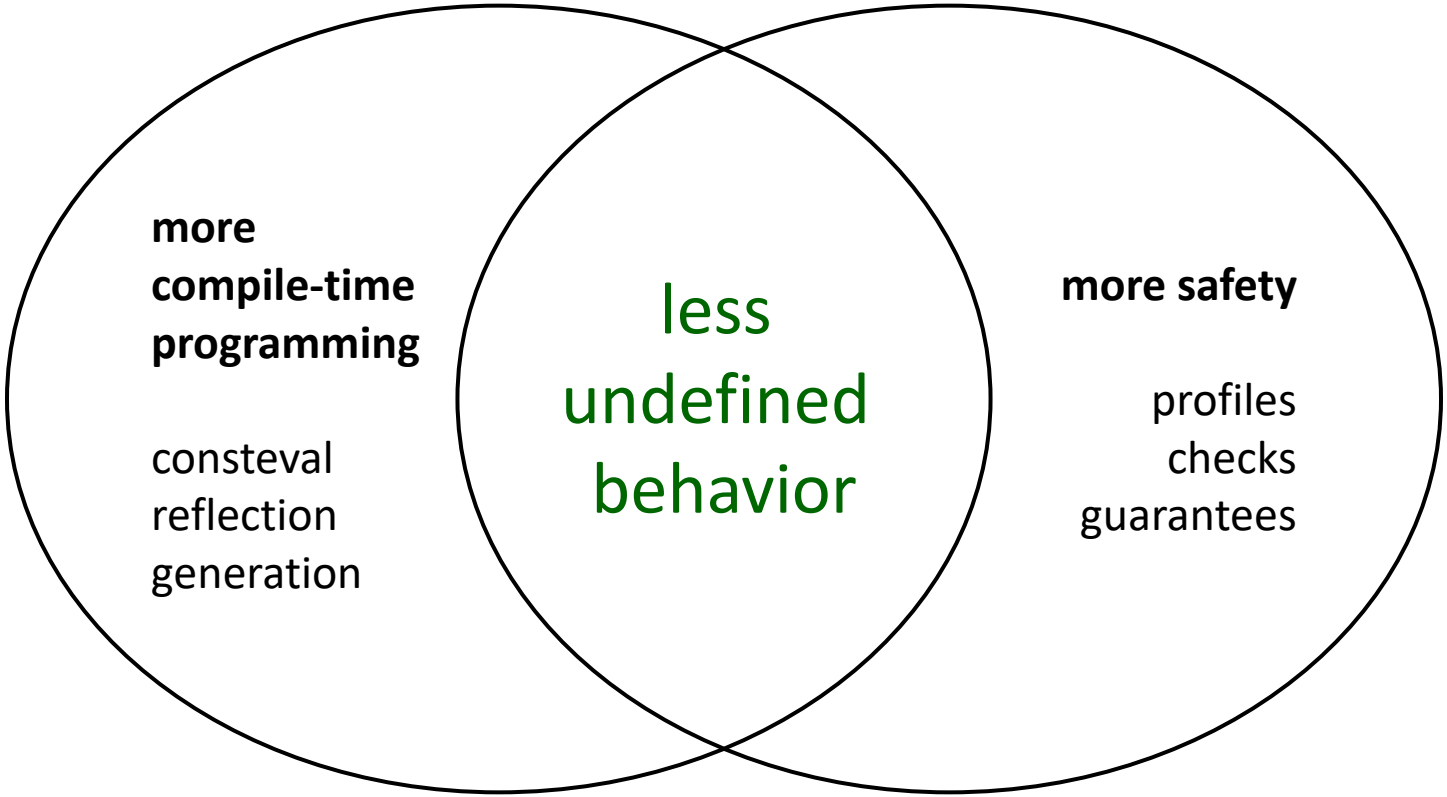
```
int a [[indeterminate]] ;
```

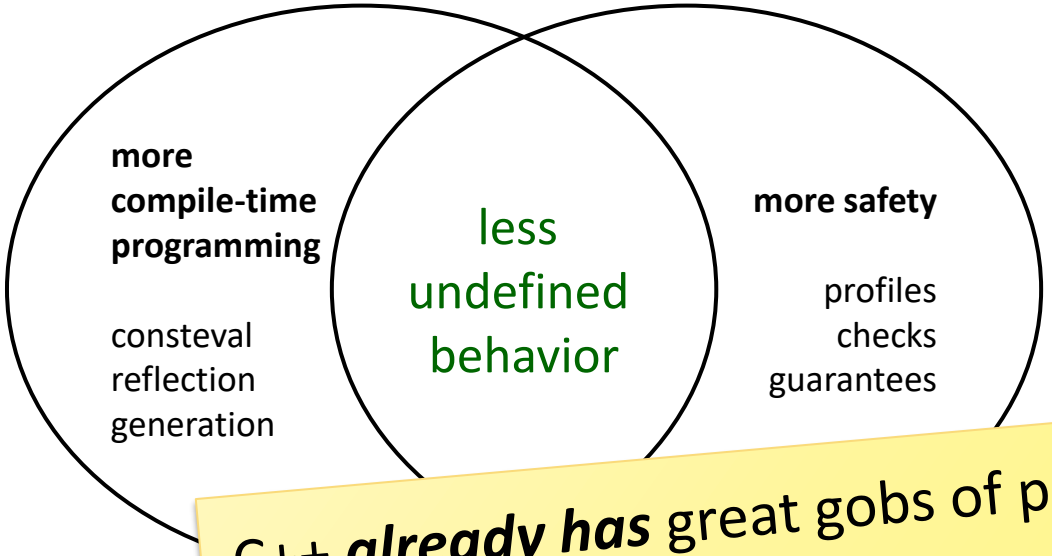
Why didn't C++ always do this?

- **Cost, esp for large objects & buffers**…
- In section 3, I'll talk about how we can do even better…

Quick poll

Q: Do you think it's believable that C++ could evolve to **eliminate most safety-related undefined behavior by default?**


more
compile-time
programming
consteval
reflection
generation
less
undefined
behavior
more safety
profiles
checks
guarantees



C++ ***already has*** great gobs of production UB-free code (*)

`constexpr`/`consteval` ***reject:***

signed overflow, some pointer arithmetic, division by zero, …

many are ***directly safety-related***

(e.g., bounds safety includes ‘no pointer arithmetic, use span instead’)

(*) core language UB in a context that requires a constant expression

```
constexpr int f(int n)
{
    int r = n--;
    for (; n > 1; --n) r *= n;
    return r;
}

int main()
{
    constexpr int x = f(13);
    return x;
}
```

x86-64 gcc (trunk) (Editor #1) | Output of x86-64 gcc (trunk) (Compiler #1)

Wrap lines | Select all

```
<source>: In function 'int main()':
<source>:10:24:   in 'constexpr' expansion of 'f(13)'
<source>:4:26: error: overflow in constant expression [-fpermissive]
    4 |     for (; n > 1; --n) r *= n;
```

x86-64 clang (trunk) (Editor #1) | Output of x86-64 clang (trunk) (Compiler #2)

Wrap lines | Select all

```
<source>:10:19: error: constexpr variable 'x' must be initialized by
a constant expression
   10 |     constexpr int x = f(13);
      |                   ^   ~~~~~
```

x64 msvc v19.38 VS17.8 (Editor #1) | Output of x64 msvc v19.38 VS17.8 (Compiler #3)

Wrap lines | Select all

```
example.cpp
<source>(10): error C2131: expression did not evaluate to a constant
<source>(4): note: failure was caused by the '*' operation causing
signed overflow during constant evaluation
```

3

Simplicity

simplification through generalization

key: enable programmer to directly express intent

$\Rightarrow$ elevate coding patterns to declare “what” vs “how”

$\Rightarrow$ use the intent already in the code, instead of “how” annotations

“Inside C++, there is a much smaller and cleaner language struggling to get out.”

— B. Stroustrup (D&E, 1994)

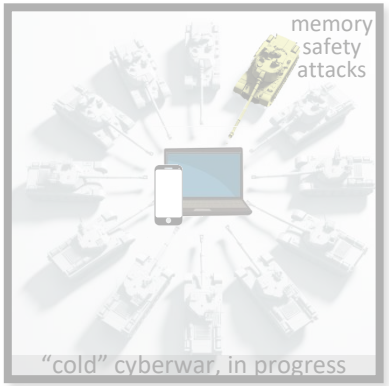
*“Say 10% of the size of C++ … Most of the simplification would come from **generalization**.”*

— Bjarne Stroustrup (ACM HOPL-III, 2007)

1

Reflection

2



Safety

3

Simplicity

Simplification… by addition?

2017: Paper P0707 on metaclass functions

- Main purpose: “yes we need **static reflection + source generation as game-changing,** and here are **North Star examples** of what’s possible”
  - 2017 Toronto meeting: “Hi, I’m their [reflection proposers’] customer”
- First major Cpp2 feature I brought to WG21 & conferences
  - Because it was key to **simplification**: Metaclass functions and parameter passing were the two biggest sources of simplification in Cpp2, because they let programmers **declare their intent**
  - Because it carried the **highest risk**: Would the committee & community accept that huge a leap forward in compile-time programming? Would a full reflection implementation actually work and not hit language/compiler limits?

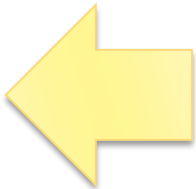
P0707: Small but important sugar

```
// Example 1: Possible with P2996
namespace __prototype { class widget { /*...*/ }; }
consteval{ metafunc( ^^__prototype::widget ); }
    // e.g., generates something like:
    //     class widget {
    //         /* based on the reflection
    //            of __prototype::widget */
    //     };
```

```
// Example 2: P0707 proposes to let class(M) mean
//            "apply M to the class being defined"
class(metafunc) widget{ /*...*/ };
    // identical meaning as above
```

Quick refresher example

```
class IFoo {
public:
  virtual int f() = 0;
  virtual void g(std::string) = 0;
  virtual ~IFoo() = default;
  IFoo() = default;
  IFoo(IFoo const&) = delete;
  void operator=(IFoo const&) = delete;
};
```



```
class(interface) IFoo {
  int f();
  void g(std::string);
};
```

declaring our intent
⇒ the right defaults
⇒ generated functions
⇒ checked constraints

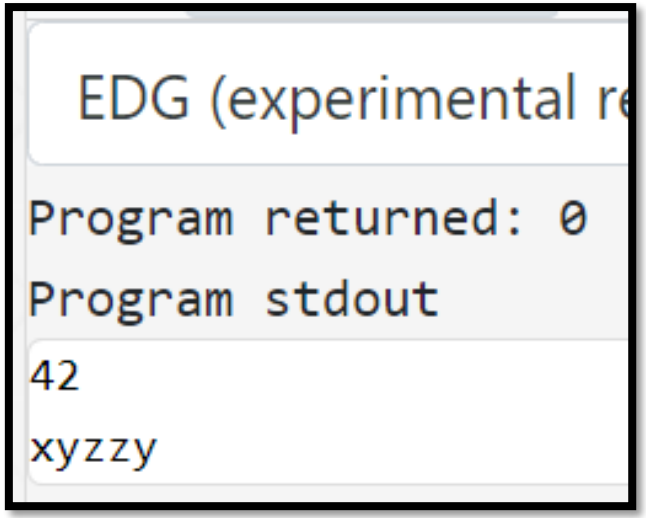
Now in EDG… *godbolt.org/z/rvdabTb5M*

```
namespace __proto {
  class Widget {
    int  f();
    void g(std::string);
  };
}
consteval { interface(^^__proto::Widget); }
```

```
// P0707 proposed sugar
class(interface) Widget {
    int  f();
    void g(std::string);
};
```

```
class MyWidget : public Widget {
public:
  int  f()               override { return 42; }
  void g(std::string s) override { std::cout << s; }
};

int main() {
  unique_ptr<Widget> w = make_unique<MyWidget>();
  cout << w->f() << '\n';
  w->g( "xyzzy" );
}
```



Now in EDG… *godbolt.org/z/rvdabTb5M*

```
consteval void interface(std::meta::info proto) {
    std::string_view name = identifier_of(proto);
    queue_injection(^^{
        class \id(name) {
        public:
            \tokens(make_interface_functions(proto))
            virtual ~\id(name)() = default;
            \id(name)() = default;
            \id(name)(\id(name) const&) = delete;
            void operator=(\id(name) const&) = delete;
        };
    });
}
```

composable ✓

Now in EDG… *godbolt.org/z/rvdabTb5M*

```
consteval auto make_interface_functions(info proto) -> info {
    info ret = ^^{};
    for (info mem : members_of(proto)) {
        if (is_nonspecial_member_function(mem)) {
            ret = ^^{
                \tokens(ret)
                virtual [:\(return_type_of(mem)):]
                    \id(identifier_of(mem)) (\tokens(parameter_list_of(mem))) = 0;
            };
        }
        else if (is_variable(mem)) {
           // --- reporting compile time errors not yet implemented ---
           // print_error( "interfaces may not contain data members" );
        }
        // etc. for other kinds of interface constraint checks
    }
    return ret;
}
```

In the box with cppfront so far… all build to pure ISO C++ & work with GCC/Clang/MSVC

`interface`	An abstract class having only pure virtual functions
`polymorphic_base`	A pure polymorphic base type that is not copyable or movable, and whose destructor is either public+virtual or protected+nonvirtual
`ordered`	A totally ordered type with `operator<=>` that implements `strong_ordering`. Also: `weakly_ordered`, `partially_ordered`
`copyable`	A type that has copy/move construction/assignment
`basic_value`	A `copyable` type that has public default construction and destruction (generated if not user-written) and no protected or virtual functions
`value`	An `ordered basic_value`. Also: `weakly_ordered_value`, `partially_ordered_value`
`struct`	A `basic_value` with all public members, no virtuals, no custom assignment
`enum`	An `ordered basic_value` with all public values
`flag_enum`	An `ordered basic_value` with all public values, and bitwise sets/tests
`union`	A safe (tagged) union with names (unlike `std::variant`)

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`flag_enum`	An `ordered basic_value` with all public values, and bitwise sets/tests
`union`	A safe (tagged) union with names (unlike `std::variant`)
`regex`	A CRTE-style compile time regex, but using reflection+generation (Max Sagebaum)
`print`	Print the reflection as source code at compile time

Optimizing C++ regex

Hana Dusíková: Compile Time Regular Expressions (CTRE)

compile-time-regular-expressions.readthedocs.io/en/latest/

www.compile-time.re

constexpr + templates

For compile-time defined patterns

Compile time parsing

Compile time & run-time matching

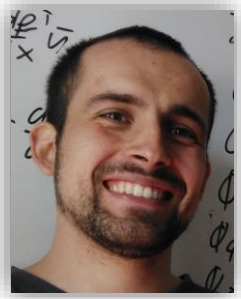
Quick regex matching/searching

Structured bindings

DFA without captures

Very efficient assembly

Compile-time regex…



	CTRE (Hana Dusíková, 2017+)	Cppfront **@regex** (Max Sagebaum, 2024)
Feature set	Nearly full PCRE (Perl)	Most of PCRE
Parsing	Template stack, dedicated engine for each regex	**Reflection + code gen,** dedicated engine for each regex
Engine	Template classes	Template classes

Compile-time regex…

compile-time reflection + source generation

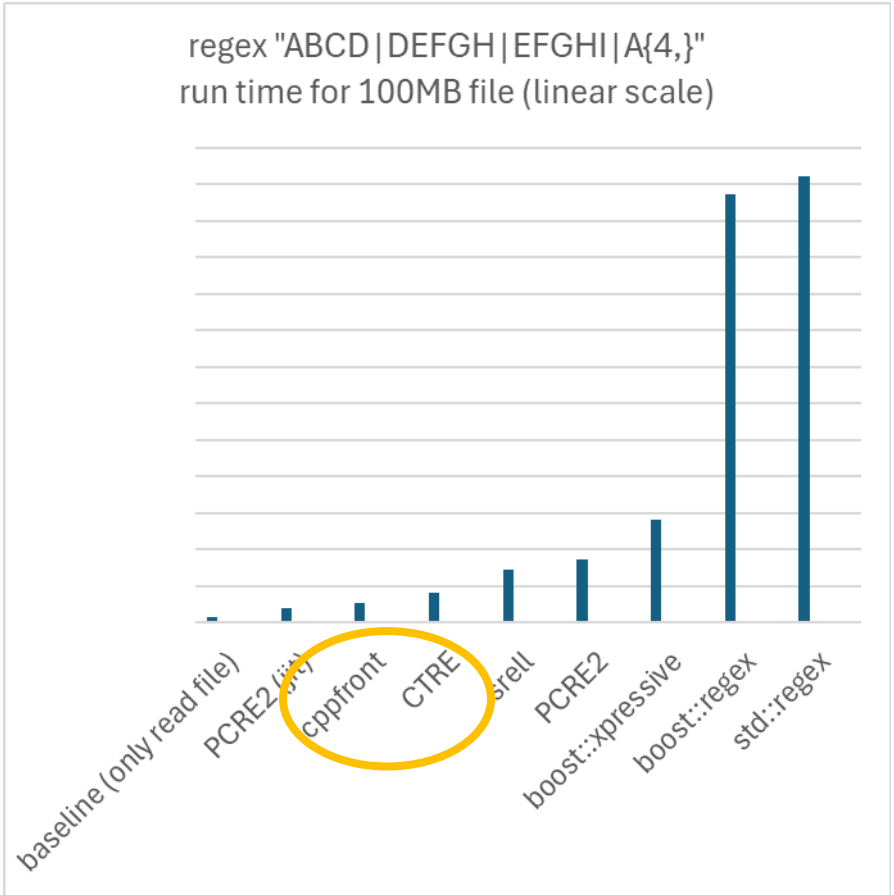
```
//
// CTRE template + constexpr code
//

if (auto m = ctre::match<"ab{0,}bc">(str))
{
    …
}
```

CTRE

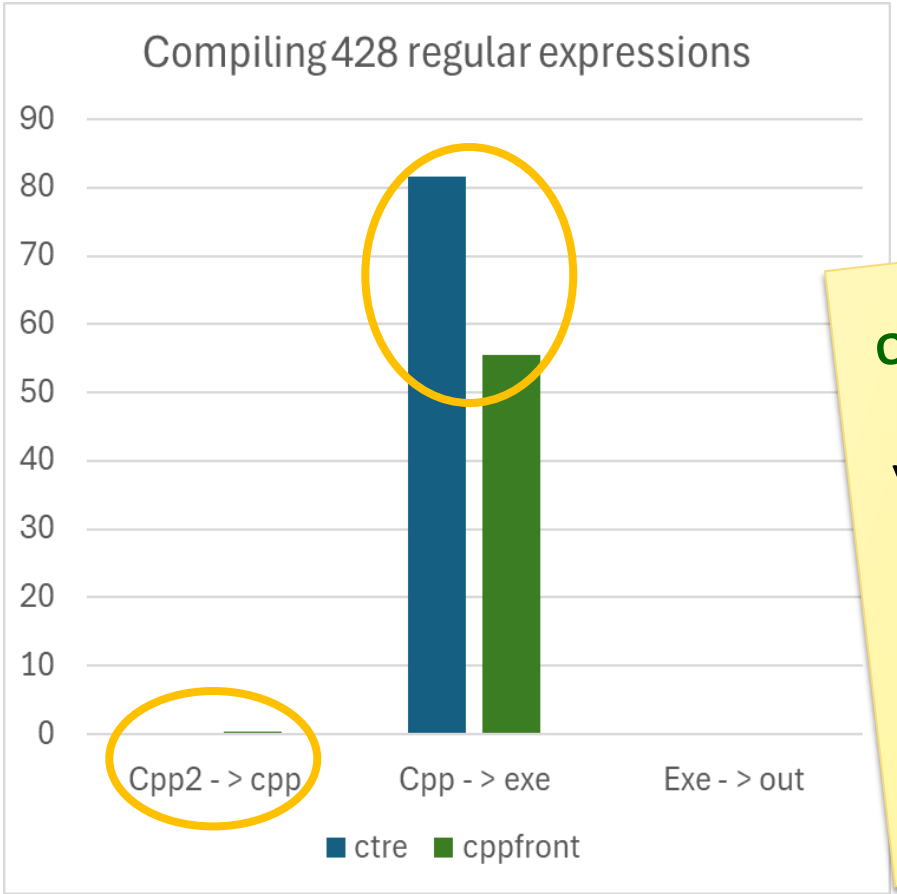
```
my_regexes: @regex type = {
  r := "ab{0,}bc";
}

if (my_regexes::r.search(str).matched)
{
    …
}
```

cppfront

Sample **run-time** results (still incomplete)



Sample **compile-time** results (still incomplete)



Haskell Regex POSIX test suite

hackage.haskell.org/package/regex-posix-unittest

wiki.haskell.org/Regex_Posix

One takeaway already: "Another compile step" does not imply "slower compilation"

When you add new work, also subtract the cost of the work it replaces (**net cost**)

This is why constexpr code (running a 'C++ interpreter' and all!) is often faster than TMP

A pattern: "The compiler helps those who help themselves" by directly expressing intent

QClass (user code)

FROM CPPCON 2017

Qt moc extensions

```
class MyClass : public QObject {
    Q_OBJECT
public:
    MyClass( QObject* parent = 0 );
    Q_PROPERTY(int value READ get_value
WRITE set_value)
    int  get_value() const
        { return value; }
    void set_value(int v)
        { value = v; }
private:
    int value;
signals:
    void mySignal();
public slots:
    void mySlot();
};
```

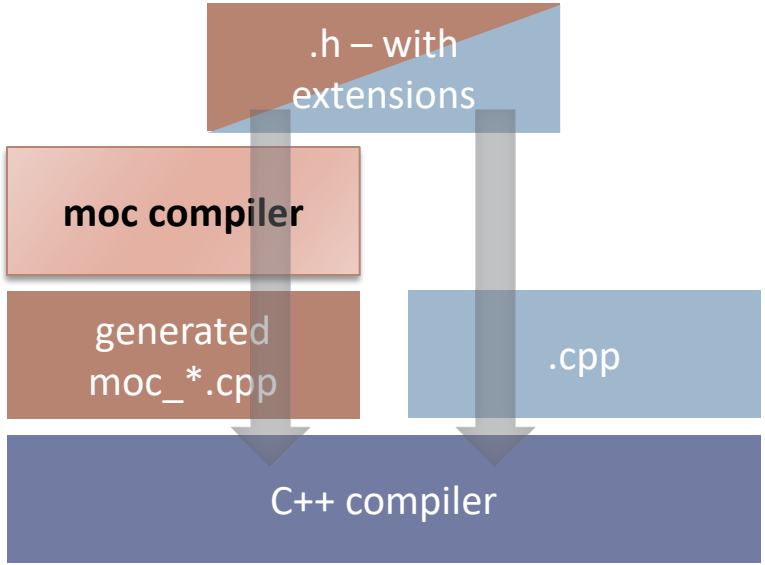
Proposed (strawman)

```
class(Qclass) MyClass {
  property<int> value { };  // default
  signal mySignal();
  slot   mySlot();
};
```

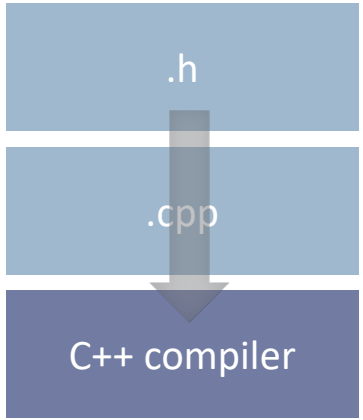
When you can't express it all in C++ code

FROM CPPCON 2017

Qt moc



Proposed



rt_interface (user code)

FROM CPPCON 2017

COM IDL-style extensions

```
[
object,
uuid(a03d1420-b1ec-11d0-8c3a-00c04fc31d2f),
]
interface IFoo : IInspectable {
   [propget]
   HRESULT Get(
      [in] UINT key,
      [out, retval] SomeClass** value
   );
   [propput]
   HRESULT Set(
      [in] UINT key,
      [in] SomeClass* value
   );
};
```

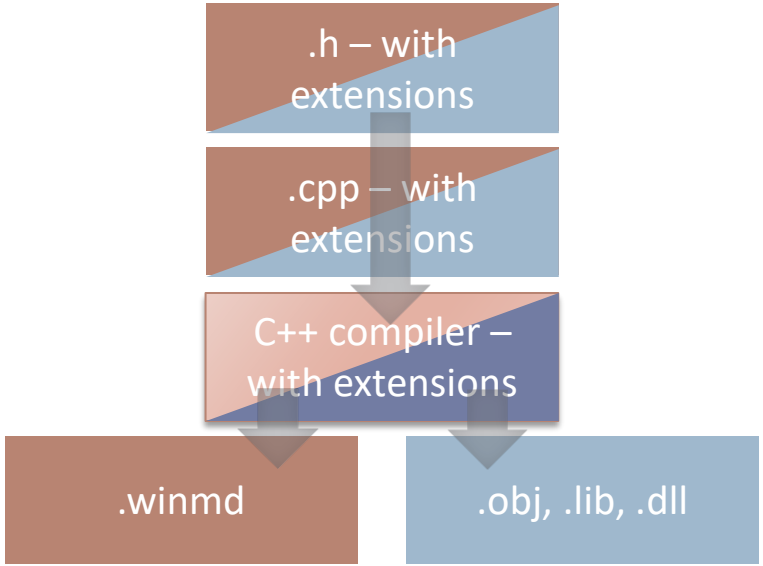
Proposed (strawman)

```
class(rt_interface<
  "a03d1420-b1ec-11d0-8c3a-00c04fc31d2f">)
IFoo {
  property<UINT,SomeClass> value;
};
```

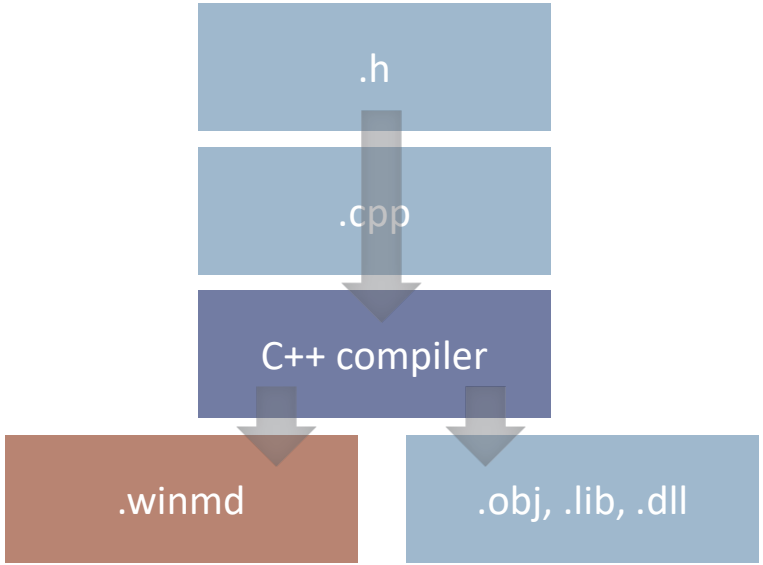
When you can't express it all in C++ code

FROM CPPCON 2017

C++/CX (for WinRT)



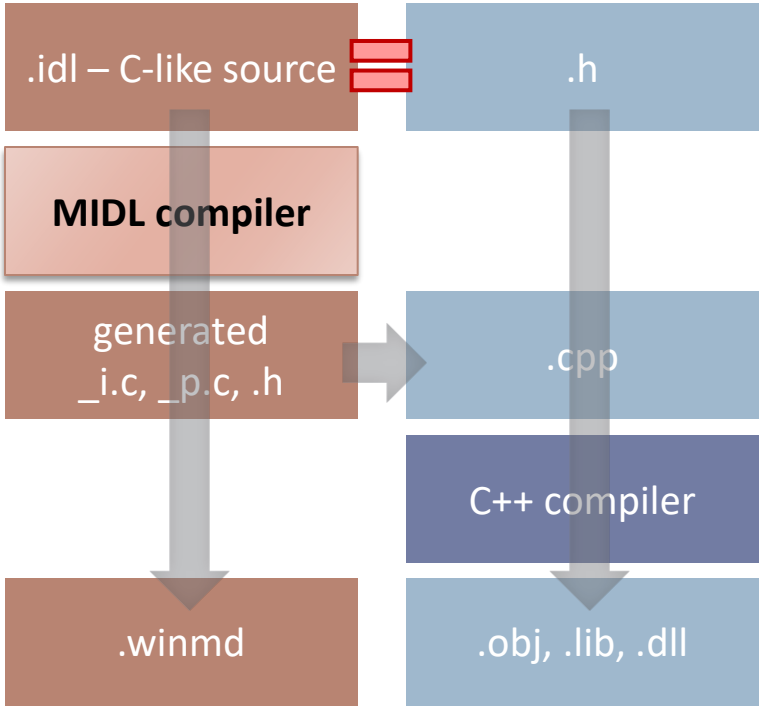
Proposed



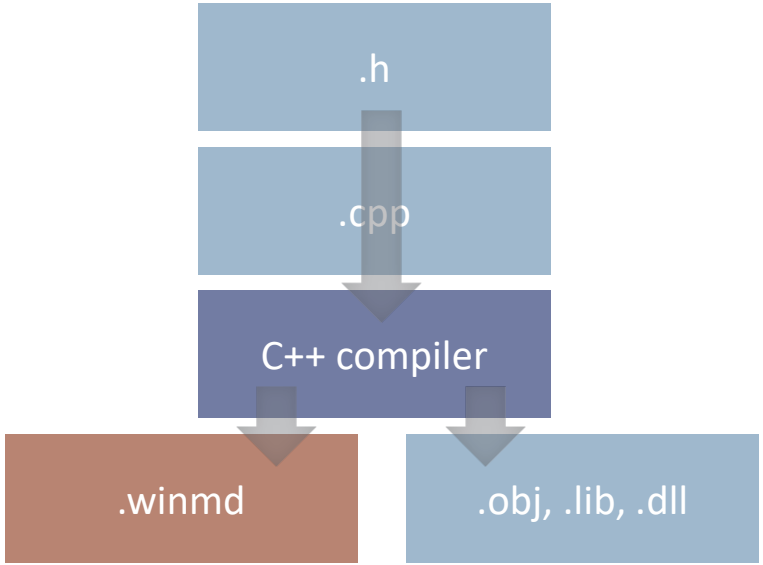
When you can't express it all in C++ code

FROM CPPCON 2017

C++/WinRT IDL (like COM)



Proposed



podio (particle physics data models)

Benedikt Hegner, Axel Naumann

FROM CPPCON 2017

Today (separate YAML script)

```
ExampleHit :
  Description : "Example Hit"
  Author      : "B. Hegner"
  Members:
   - double x      // x-coordinate
   - double y      // y-coordinate
   - double z      // z-coordinate
   - double energy // measured
```

Proposed (strawma

```
class(podio::datatype) ExampleHit {
  string Description = "Example Hit";
  string Author      = "B. Hegner";

  double x;      // x-coordinate
  double y;      // y-coordinate
  double z;      // z-coordinate
  double energy; // measured
};
```

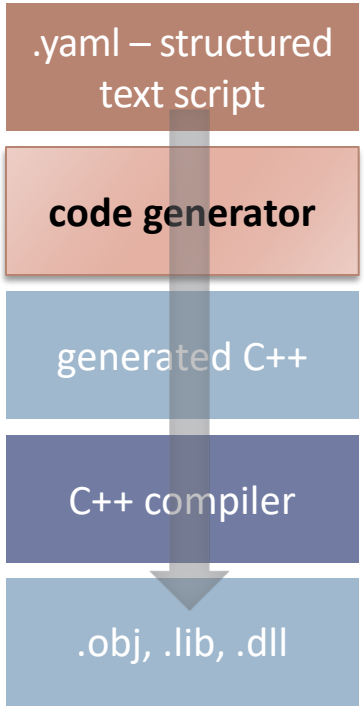
generate: 5 interrelated classes…
X, XCollection, XConst, XData, XObj
how: separate code generator

default + enforce: constexpr static strings
generate: same 5 classes
how: during normal C++ compilation

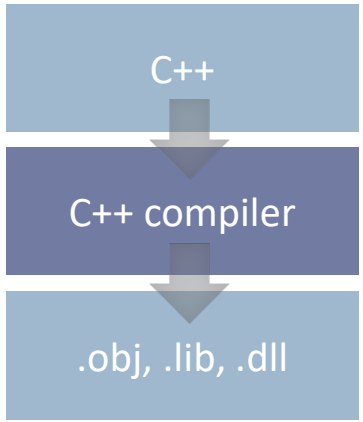
When you can't express it all in C++ code

FROM CPPCON 2017

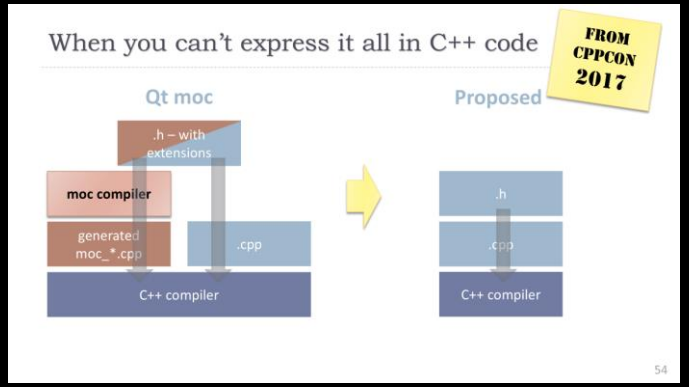
podio YAML

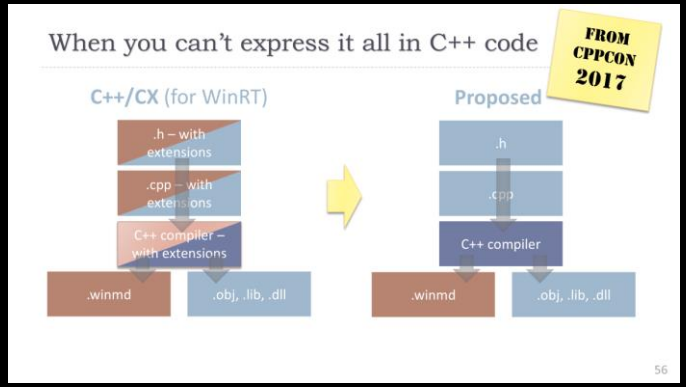


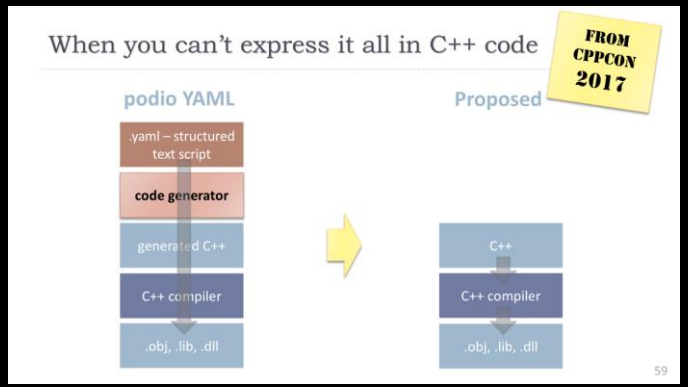
Proposed

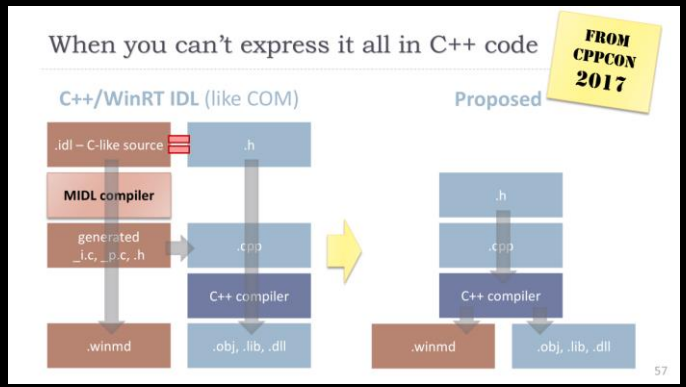


A funny thing happened on the way to the elevator…









Welcome to C++’s next decade!

Conjecture: Reflection+generation will dominate the next decade of C++

Making easier things that are difficult today (e.g., TMP, expression templates)
Making possible things that are infeasible today (e.g., generative programming)

Expect multiple phases… the first phase is “now in sight”

A requirements roadmap: What will we need?

"All information in the source code must be reflectable"

If the programmer can know it, they'll want to use it

Examples: Attributes, defaults (meaningful whitespace!)

(note: in the language; likely not preprocessor)

```
class Foo {
    int func1();
public:
    void func2(int);
};

struct Foo {
    int func1();
public:
    void func2(int);
};

class(interface) Foo {
    int func1();
public:
    void func2(int);
};
```

A requirements roadmap: What will we need?

"All information in the source code must be reflectable"

- If the programmer can know it, they'll want to use it
- Examples: Attributes, defaults (meaningful whitespace!)
  - (note: in the language; likely not preprocessor)

"Anything that can be written in source code must be generatable"

- If the programmer can write it by hand, they'll want to write it by generated code
- Examples: Types, free functions, specializations of std:: templates

```
class(class) Foo {
    int func1();
public:
    void func2(int);
};

class(struct) Foo {
    int func1();
public:
    void func2(int);
};

class(interface) Foo {
    int func1();
public:
    void func2(int);
};
```

A requirements roadmap: What will we need? (2)

“All source code must be visible, whether hand-written or generated”

- The final code is the only source of truth.
- Entry level: We need to see what we got ⇒ **pretty-print generated code**
- Then tooling:
  - Debugging (e.g., step into generated code)
  - Visualizing (e.g., expand/collapse generated code)
  - …

Generalizing: **“All output (text + binary) must be possible at compile time”**

- Example: .winmd output files
- Output files for other tools
- …

Risks

Good: Standardizing some now, adding more later

But requires:

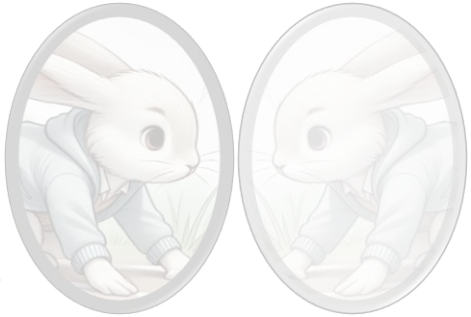
- A “North Star”: We have to know the **end use cases we’re aiming for**
- Design guardrails: We have to know we’re **not going off on a side track**
  - Relatively easy for constexpr and GPUs: “support the language feature, not a divergent special-purpose extension” such as a different kind of loop

Risk of bottom-up design is that we may end up with overlapping pieces that don’t fill in the whole picture

- Suggested aim: P0707 metafunctions, Andrei’s instrumented_vector, reflect+regenerate any type (“identity”)
- Learn from related experience (C#, D, Lock3, cppfront)

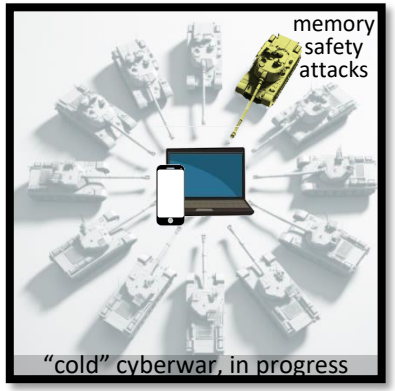
Photo: Die Hard Dice

1



Reflection

2



Safety

3

Simplicity

Terms (per ISO/IEC 23643:2020)

Software **security** (or “cybersecurity” or similar)

making software able to **protect its assets** from a malicious attacker

examples: securing power grids, hospitals, banks, personal data, secrets, …

Software **safety** (or “life safety” or similar)

making software free from unacceptable risk of **causing unintended harm** to humans, property, or the environment

examples: hospital equipment, autonomous vehicles/weapons

Programming language **safety** (incl. memory safety)

static and dynamic guarantees about **program correctness**

helps both the others ← **and increases quality generally**

Consider **initialization** again…

Q: Is this "righteous, most excellent" code?

```
std::array<int,1024> a; // A – uninitialized?
fill(a);                // B – call a function that sets a's values
```

For line A:

- If uninitialized, this program is actually ideal
  - … but analyzers/humans can't prove that `fill(a)` fills a
- If initialized, we know the dummy writes aren't needed…
  - … but optimizers are terrible at removing the "dead writes"
  - **… for the same reason: they can't prove that `fill(a)` fills a**

Usual plea: "But it's obvious! Compiler writers, just try harder!"

Usual answer: "Fine, *you* try to look through an opaque function call!"

Initialization safety: Having our cake *and* eating it

Both “force initialize at declaration” (e.g., C++ Core Guidelines) and “fill with pattern” approaches jam in dummy values

What we really want is “initialize before use”

- C#, Ada, and other language have “definite initialization” rules for local vars
- Experience: easy to specify, **easy to use by mainstream developers**

What I’ve implemented in Cpp2 (github.com/hsutter/cppfront):

- All locals (all types!) **“unconstructed”** if not explicitly initialized ⇒ **fast by default**
- Guaranteed **construction** before first use on any branch path ⇒ **correct always**
- Via either direct construction or passing to a fill function’s “out” parameter
  ⇒ **fully composable init**, generalized delegating constructors

Example (Cpp2 syntax, will propose for ISO C++ syntax too)

Using a fundamental type, for example: **`int`**

```
a: int;                     // allocates space, no initialization
// std::cout << a;          // illegal: can't use-before-init!
a = 5;                      // construction => real initialization!
std::cout << a;             // prints 5
```

Using any type, for example: **`std::vector<std::string>`**

```
b: vector<string>;          // allocates space, no initialization
// std::cout << b.size();   // illegal: can't use-before-init!
b = ("xyzzy", "plugh");     // construction => real initialization!
std::cout << b.size();      // prints "2"
```

```
main: () -> int = {
    words: std::vector<std::string> =
        ( "decorated", "hello", "world" );
    p: *std::string;

    // ... more code ...
    if std::rand()%2 {
        p = words.front()&;
    }

    print_and_decorate( p* );
}
```

FROM CPPCON 2022

```
demo.cpp2(5,5): error: local variable p must be initialized on both branches
or neither branch
demo.cpp2(8,5): error: "if" initializes p on:
  branch starting at line 8
but not on:
  implicit else branch
  ==> program violates initialization safety guarantee - see previous errors
```

```
main: () -> int = {
    x: std::string;                    // note: uninitialized!
    if flip_a_coin() {
        x = "xyzzy";
    } else {
        fill( out x, "plugh", 3 );  // note: constructs x!
    }
    print_decorated(x);
}

fill: (out x: std::string,
       value: std::string,
       count: int)
    [[pre: value.ssize() >= count,
           "value must contain at least count chars"]]
= {
    x = value.substr(0, count);
}
```

FROM CPPCON 2022

```
demo.cpp2... ok (mixed Cpp1/Cpp2, Cpp2 code passes safety checks)
```

Bounds safety: Low-hanging fruit

What I've already implemented in Cpp2 as proof of concept: **For every `a[b]`** where `a` is a contiguous range (incl. `std::size(a)`) and `b` is integral…

- **Inject a call-site bounds check** for `0 <= b && b < std::size(a)`
- Violations reported via normal **contract violation handling ⇒ customizable**

Results so far:

- Seamless: Works perfectly for **all existing std:: contiguous containers/views/ranges**
  - Also works for **C arrays** (before they decay, while their names are in scope)
  - Also works for **most non-std containers/views/ranges** (std::size and operator[] are widely used… "C++ code contains a lot of information!")
- Customization enables easy integration into existing projects' error/logging

Proposal for future ISO C++ code: **"Enable 'bounds' Profile and recompile"**

Example: Looks right, ship it?

```
//   int              a[] = {1, 2, 3};   // uncomment either one: C array
//   std::vector<int> a   = {1, 2, 3};   // or STL container (unmodified)

print(a[1]); print(a[2]); print(a[3]);   // line 7
```

```
C:\demo>cppfr
demo.cpp2...

Microsoft (R)
Copyright (C)

demo.cpp

C:\demo>demo
2
3
```

```
/mnt/c/demo $./cppfront.sh demo.cpp2 gcc
demo.cpp2 ...  ok (mixed Cpp1/Cpp2, Cpp2 code passes safety checks)

g++ (GCC) 14.2.1 20240801 (Red Hat 14.2.1-1)
Copyright (C) 2024 Free Software Foundation, Inc.
This is free software; see the source for copying conditions.  There is NO
warranty; not even for MERCHANTABILITY or FITNESS FOR A PARTICULAR PURPOSE.

/mnt/c/demo $./a.out
2
3
```

```
demo.cpp2(7) int main(): Bounds safety violation: out of bounds access atte
mpt detected - attempted access at index 3, [min,max] range is [0,2]
```

```
demo.cpp2(7) int __cdecl main(void): Bounds safety violation: out of
 bounds access attempt detected - attempted access at index 3, [min,
max] range is [0,2]
```

Risks

Good: Providing safety guarantees

But requires:

- Confidence: We have to know the **rules actually work**
- Adoptability: We have to know **end user code can adopt it**, incl. in existing code
- Impact: We have to know it will help **as much code as possible**, incl. existing code

Risk of ad-hoc safety design is that we may end up with improvements that don't work adoptably at scale and/or for existing code

- Suggested aim: embrace existing **known-good** safety rules + **no heavy/viral annotation** + articulate what % of benefit can be had in existing code **without manual code changes** (just a recompile), not just new/updated code

Photo: Die Hard Dice

simplification through generalization

key: enable programmer to directly express intent

$\Rightarrow$ elevate coding patterns to declare “what” vs “how”

$\Rightarrow$ use the intent already in the code, instead of “how” annotations

“Inside C++, there is a much smaller and cleaner language struggling to get out.”

— B. Stroustrup (D&E, 1994)

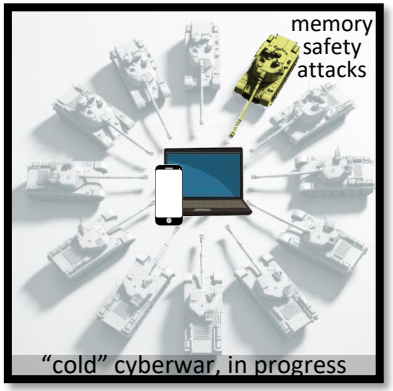
“Say 10% of the size of C++ … Most of the simplification would come from generalization.”

— Bjarne Stroustrup (ACM HOPL-III, 2007)

1

Reflection

2



Safety

3

Simplicity

C++26/29

Major advances are on track

`std::execution` (concurrency *and* parallelism)

Type and memory safety improvements

- target: **parity** with other modern languages

Reflection + code generation (aka ‘injection’/…)

- part of our **tide toward compile-time programming**
- arguably **most-impactful** feature ever added
- I expect will **dominate** our next decade

Contracts

Questions?

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