

C++ ABI: the only thing that is more important than performance

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Reading x86-64 Assembly

...for fun and profit

Function Prologue & Epilogue

- Few lines of code at the beginning (*prologue*) and end (*epilogue*) of a function, which **prepares** (and eventually restores)
 - the **stack** and
 - **registers**
- Not part of assembly: **convention** (defined & interpreted differently by different OS and compilers)

Prologue

```
1 push rbp      ; rbp: frame pointer
2 mov rbp, rsp ; rsp: stack pointer
3 sub rsp, N
```

alternatively

```
1 enter N, 0
```

(reserve N bytes on stack for local use)

Epilogue

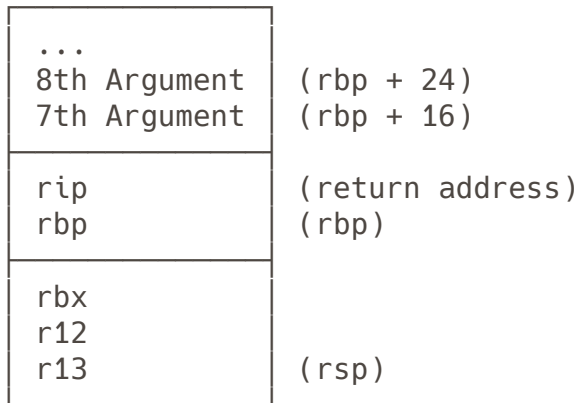
```
1 mov rsp, rbp
2 pop rbp
3 ret
```

alternatively

```
1 leave
2 ret
```

Stack frame for function call

- `CALL` = `PUSH` *address of next instruction* + `JMP` *target*
- `RET` pops return address and transfers control there
- pass arguments 1 ...6 in registers (`rsi`, `rdx`, ...)



(stack frame for function call with 8 arguments and local registers `rbx`, `r12` and `r13`)

Reading assembly for fun and profit

```
1 int f(int x, int y, int z) {  
2     int sum = x + y + z;  
3     return sum;  
4 }
```

godbolt.org/z/MaWcP9

```
# g92 -O0  
| _Z1fiii:  
1| push rbp  
1| mov rbp, rsp  
1| mov DWORD PTR [rbp-20], edi  
1| mov DWORD PTR [rbp-24], esi  
1| mov DWORD PTR [rbp-28], edx  
2| mov edx, DWORD PTR [rbp-20]  
2| mov eax, DWORD PTR [rbp-24]  
2| add edx, eax  
2| mov eax, DWORD PTR [rbp-28]  
2| add eax, edx  
2| mov DWORD PTR [rbp-4], eax  
3| mov eax, DWORD PTR [rbp-4]  
4| pop rbp  
4| ret
```

godbolt.org/z/MaWcP9

Reading assembly for fun and profit

```
1 int f(int x) {  
2     return x + 1;  
3 }  
4  
5 int g(int x) {  
6     return f(x + 2);  
7 }
```

godbolt.org/z/87GK4q

```
# g92 -00  
| _Z1fi:  
1| push rbp  
1| mov rbp, rsp  
1| mov DWORD PTR [rbp-4], edi  
2| mov eax, DWORD PTR [rbp-4]  
2| add eax, 1  
3| pop rbp  
3| ret  
| _Z1gi:  
5| push rbp  
5| mov rbp, rsp  
5| sub rsp, 8  
5| mov DWORD PTR [rbp-4], edi  
6| mov eax, DWORD PTR [rbp-4]  
6| add eax, 2  
6| mov edi, eax  
6| call _Z1fi  
7| leave  
7| ret
```

godbolt.org/z/87GK4q

Reading assembly for fun and profit

```
1 void side_effect();  
2  
3 int f(int& x) {  
4     auto a = x;  
5     side_effect();  
6     return a - x;  
7 }
```

godbolt.org/z/dG77f4

```
# g92 -O3  
| _Z1fRi:  
3| push rbp  
3| push rbx  
3| mov rbx, rdi  
3| sub rsp, 8  
4| mov ebp, DWORD PTR [rdi]  
5| call _Z11side_effectv  
6| mov eax, ebp  
6| sub eax, DWORD PTR [rbx]  
7| add rsp, 8  
7| pop rbx  
7| pop rbp  
7| ret
```

godbolt.org/z/dG77f4

Name mangling: C++ vs C

```
1 int f(int x) {  
2     return x * x;  
3 }  
4  
5 extern "C" int g(int x) {  
6     return x * x;  
7 }
```

godbolt.org/z/cj7bqx

```
# g92 -O0  
| _Z1fi:  
1| push rbp  
1| mov rbp, rsp  
1| mov DWORD PTR [rbp-4], edi  
2| mov eax, DWORD PTR [rbp-4]  
2| imul eax, eax  
3| pop rbp  
3| ret  
| g:  
5| push rbp  
5| mov rbp, rsp  
5| mov DWORD PTR [rbp-4], edi  
6| mov eax, DWORD PTR [rbp-4]  
6| imul eax, eax  
7| pop rbp  
7| ret
```

godbolt.org/z/cj7bqx

Name mangling: C++ vs C

```
1 int f(int x) {  
2     return x * x;  
3 }  
4  
5 extern "C" int g(int x) {  
6     return x * x;  
7 }
```

godbolt.org/z/cj7bqx

```
# g92 -O1  
| _Z1fi:  
2|     imul edi, edi  
3|     mov eax, edi  
3|     ret  
| g:  
6|     imul edi, edi  
7|     mov eax, edi  
7|     ret
```

godbolt.org/z/87z8vz

Name mangling: C++ vs C

```
1 int f(int x) {  
2     return x * x;  
3 }  
4  
5 extern "C" int g(int x) {  
6     return x * x;  
7 }
```

godbolt.org/z/cj7bqx

Why?

- overloading
- namespaces
- templating

(Name of function doesn't suffice to resolve JMP location)

```
# g92 -01  
| _Z1fi:  
2|     imul edi, edi  
3|     mov eax, edi  
3|     ret  
| g:  
6|     imul edi, edi  
7|     mov eax, edi  
7|     ret
```

godbolt.org/z/87z8vz

Name mangling in C++

```
1 void f(int) {}  
2  
3 void f(double) {}  
4  
5 namespace my_fancy_namespace {  
6 void f(int) {}  
7 } // my_fancy_namespace
```

godbolt.org/z/jWY14x

```
# g92 -O2  
| _Z1fi:  
1| ret  
| _Z1fd:  
3| ret  
| _ZN18my_fancy_namespace1fEi:  
| ret
```

godbolt.org/z/jWY14x

- C++ does not standardize name mangling
- *Annotated C++ Reference Manual* even actively discourages usage of common mangling schemes. (Prevent linking when other aspects of ABI are incompatible.)

cf. name mangling for Itanium ABI:

itanium-cxx-abi.github.io/cxx-abi/abi.html#mangling-structure

What is ABI?

What is ABI (*A*pplication *B*inary *I*nterface)?

Specifies interaction of functions and types across TUs[†] (translation units)

- Platform-specific (e.g., Linux on x86-64 CPU)
- Vendor-specified (e.g., gcc)
- not controlled by WG21

(Titus Winters: *Similar to a binary network protocol*)



Photo by Spencerian at
en.wikipedia.org (2005)

[†] *TU*: ultimate input to the compiler from which an object file is generated (*i.e.*, typically the `.cpp` file)

What is ABI (**A**pplication **B**inary **I**nterface)?

Specifies interaction of functions and types across TUs[†] (translation units) covering:

- Name mangling of functions
- Name mangling of types
- `sizeof` and alignment of objects
- Bytes semantics of the binary representation of objects
- Calling convention

(Titus Winters: *Similar to a binary network protocol*)



Photo by Spencerian at
en.wikipedia.org (2005)

[†] *TU*: ultimate input to the compiler from which an object file is generated (*i.e.*, typically the `.cpp` file)

Why should I care?

...do you depend on any pre-compiled shared library?

Why should I care?

Why should I care?

- **Linking** different TUs requires usage of same ABI
- Typically a problem at API boundaries when combining TUs (e.g., shared libraries) that were compiled at different **times**
- Similar to binary network protocols: ABI tells you how to interpret bytes

Why should I care? \Leftrightarrow Why do network protocols have versions?

(Problem: not all ABIs encode version number)

ABI does not encode version number

- **Q:** How to check if a given TU uses a compatible ABI?
- **A:** You can't!
- What happens if ABI is incompatible?
 - (a) Linking fails during compile time (good)
 - (b) Program spectacularly dies during run time (bad)
- Why isn't this a common problem?
 - Itanium ABI is mostly stable since C++11

History



ABI breakage of `std::string`

- Before C++11: libstdc++ relied on copy-on-write (COW)
- C++11 disallows COW
 - fewer indirections
 - short string optimization (SSO)
- Problem: passing COW string to impl that expects SSO **may link** (same mangled name!)
 - one (quad-)word passed
 - three (quad-)words read
- *Solution*[†]: gcc changed mangled name

```
1 // until C++11
2 struct string {
3     struct control_block {
4         /* ... */
5     };
6     control_block *data;
7 };
8
9 // since C++11
10 struct string {
11     char *data;
12     std::size_t size;
13     std::size_t capacity;
14 }
```

godbolt.org/z/KM5Tvq

↪ Take-away for compiler vendors: ABI break was a huge disaster

[†] RHEL 7 still uses old `std::string` ABI to provide compatibility for older .so

Quiz Time

Quiz: Will it break ABI?

Proposal: make `std::vector<T>::push_back` return a reference to the element in its new location

```
void push_back(const T&);
```



```
T& push_back(const T&);
```

Quiz: Will it break ABI?

```
1  template <typename T>
2  struct vector {
3      void push_back_1(const T&);
4      T& push_back_2(const T&);
5  };
6
7  void f(vector<int> v) {
8      v.push_back_1(42);
9      v.push_back_2(42);
10 }
```

godbolt.org/z/9def7a

```
# g92 -O0
| _Z1f6vectorIiE:
7|  push rbp
7|  mov rbp, rsp
7|  sub rsp, 16
8|  mov DWORD PTR [rbp-8], 42
8|  lea rax, [rbp-8]
8|  mov rsi, rax
8|  lea rdi, [rbp+16]
8|  call _ZN6vectorIiE11push_back_1ERKi
9|  mov DWORD PTR [rbp-4], 42
9|  lea rax, [rbp-4]
9|  mov rsi, rax
9|  lea rdi, [rbp+16]
9|  call _ZN6vectorIiE11push_back_2ERKi
10|  nop
10|  leave
10|  ret
```

godbolt.org/z/9def7a

Quiz: Will it break ABI?

Both, `void push_back` and `T& push_back` have the same mangled name (Itanium ABI)

- **Two** definitions in the old and the new TU
- ODR violation
- Linker will pick only **one** definition (by **overwriting** the other)
- **ABI break**: reading return value from `eax` when there is none

Quiz: Will it break ABI?

Proposal: make `std::vector<T>::emplace_back` return a reference to the element in its new location

```
template<class... Args> void emplace_back(Args&&...);
```



```
template<class... Args> T& emplace_back(Args&&...);
```


Quiz: Will it break ABI?

```
1  template <typename T>
2  struct vector {
3      template<class... Args>
4      void emplace_back_1(Args&&...);
5
6      template<class... Args>
7      T& emplace_back_2(Args&&...);
8  };
9
10 void f(vector<int> v) {
11     v.emplace_back_1(42);
12     v.emplace_back_2(42);
13 }
```

godbolt.org/z/dYMsza

Quiz: Will it break ABI?

```
1  template <typename T>
2  struct vector {
3      template<class... Args>
4      void emplace_back_1(Args&&...);
5
6      template<class... Args>
7      T& emplace_back_2(Args&&...);
8  };
9
10 void f(vector<int> v) {
11     v.emplace_back_1(42);
12     v.emplace_back_2(42);
13 }
```

godbolt.org/z/dYMsza

Mangled names: (Itanium ABI)

1. `_ZN6vectorIiE14emplace_back_1IJiEEEvDpOT_`
2. `_ZN6vectorIiE14emplace_back_2IJiEEERiDpOT_`

Quiz: Will it break ABI?

`void emplace_back` and `T& emplace_back` have different mangled names
(cf. Itanium ABI: 5.1.5.3 *Function types*)

- Two definitions in the old and the new TU
- but no ODR violation
- **No ABI break:** old code calls the old one, new code calls the new one
 - proposal was accepted for C++20

Quiz: Will it break ABI?

Proposal: extend `std::lock_guard<T>` to allow for a variadic set of heterogeneous mutexes

```
template<class Mutex> class lock_guard;
```



```
template<class... Mutexes> class lock_guard;
```

Quiz: Will it break ABI?

```
1  template <typename>
2  struct lock_guard_1 {
3      lock_guard_1() {}
4  };
5
6  template <typename...>
7  struct lock_guard_2 {
8      lock_guard_2() {}
9  };
10
11 void f() {
12     lock_guard_1<int> l1{};
13     lock_guard_2<int> l2{};
14 }
```

godbolt.org/z/MKPq35

```
# g92 -O0
| _Z1fv:
11| push rbp
11| mov rbp, rsp
11| sub rsp, 16
12| lea rax, [rbp-1]
12| mov rdi, rax
12| call _ZN12lock_guard_1IiEC1Ev
13| lea rax, [rbp-2]
13| mov rdi, rax
13| call _ZN12lock_guard_2IiEEC1Ev
14| nop
14| leave
14| ret
| _ZN12lock_guard_1IiEC2Ev:
3| push rbp
3| mov rbp, rsp
3| mov QWORD PTR [rbp-8], rdi
3| nop
[...]
```

godbolt.org/z/MKPq35

Quiz: Will it break ABI?

```
1  template <class Mutex>
2  class lock_guard_1 {};
3
4  template <class... Mutexes>
5  class lock_guard_2 {};
6
7  void f(lock_guard_1<int>&) {};
8  void f(lock_guard_2<int>&) {};
```

godbolt.org/z/rvWx8K

ABI break if

- user compiles f using old lock_guard
- user then tries to call it from a TU using new lock_guard

...mangled names don't match: linker error!

```
# g92 -O0
| _Z1fR12lock_guard_1IiE:
7|   push rbp
7|   mov rbp, rsp
7|   mov QWORD PTR [rbp-8], rdi
7|   nop
7|   pop rbp
7|   ret
| _Z1fR12lock_guard_2IjEE:
8|   push rbp
8|   mov rbp, rsp
8|   mov QWORD PTR [rbp-8], rdi
8|   nop
8|   pop rbp
8|   ret
```

godbolt.org/z/rvWx8K

(cf. `std::lock_guard` \mapsto `std::scoped_lock`)

Quiz: Will it break ABI?

Proposal: change hashing by `std::hash` to improve performance of `std::unordered_map` by 3-4x (*cf.* `absl::node_hash_map`)

Quiz: Will it break ABI?

Proposal: change hashing by `std::hash` to improve performance of `std::unordered_map` by 3-4x (cf. `absl::node_hash_map`)

ABI break:

- Hash value for an object is computed in old TU and stored in map
- (Different) hash value is computed in new TU and used to lookup value in map
- **Semantic meaning of binary representation has changed!**

More examples:

- `std::regex` currently is 10-100x slower than equivalents in Rust or Go (*cf.* any talk of Hana Dusíková)
- Make `std::unique_ptr` zero-overhead (*cf.* Chandler Carruth, *There Are No Zero-cost Abstractions*)
- Add `std::int128_t` which already is supported on more and more platforms
- Make `std::bitset` trivially destructible
- Exceptions (would be an entire talk on its own)
- ...

(read P2028 and P1863 by Titus Winters for more information)

Future Prospects

Break ABI with future releases: move run-time failures to compile-time (when possible) by changing mangled name

- new namespaces: e.g., `std2::` or `std::abi42::`
 - developers now have to choose between `std::optional` and `std2::optional` or duplicate code with overloading
 - when will `std3::` arrive?
- change entire mangling scheme: e.g., $_Z \mapsto _Y$ on Itanium
 - Compiler vendors could ship both forms
- Introduce version number (ABI break)
 - MSVC does already include version numbers in DLLs (MSVCs users are used to recompile with each new version of Visual Studio ...)

- No (major?) ABI breaks since C++11 (**12 years in 2023!**)
- Hyrum's Law (or xkcd.com/1172): passing ABI-unstable types across ABI boundaries happened to work for more than a decade. People rely on ABI stability, even though it was never explicitly promised.
- Expose C-APIs whenever possible
- Rename types and functions, e.g.,
 - `std::lock_guard` \mapsto `std::scoped_lock`
 - `std::mem_fun` \mapsto `std::mem_fn`[†]
 - ...
- (Protect yourself: Build everything from source, all the time!)

[†] cf. Jason Turner on youtu.be/geE-LyR_NrM, C++ Weekly - Ep 239 - *std::mem_fun vs std::mem_fn Fight!*

Standard Meeting, Prague 2020

- WG21 is not in favor of an ABI break in C++23 or C++26
- WG21 is in favor of an ABI break in a future version of C++
- WG21 will take time to consider proposals requiring an ABI break
- WG21 will not promise stability forever
- WG21 wants to keep prioritizing performance over stability



Bryce | BlackLivesMatter @blelba... · 16 Feb

Performance
ABI Stability
Ability to Change

You can pick two, choose wisely.

[#cppprg](#)



Twitter: @blebach (2020)

(Corentin Jabot: There was no applause. But I'm not sure we fully understood what we did and the consequences it could have.)



Jonathan Müller @foonathan · 03 Feb

What's the point of standard library containers if they can't give the best performance?



2



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Titus Winters

@TitusWinters

Replying to @foonathan

They're common and readily available?
(Which does have some value.)

Committing to ABI is like admitting that the standard library is aiming to be McDonald's - It's everywhere, it's consistent, and it technically solves the problem.

18:02 · 03 Feb 20 · [Twitter Web App](#)

2 Retweets 1 Quote Tweet 17 Likes

Twitter: @TitusWinters (2020)

STL alternatives

- `abseil` by Google: `abseil.io`
- `folly` by Facebook:
`github.com/facebook/folly`
- ...

Titus Winters:

*Build everything from source,
with the same flags, at the same time
(if possible)*

Watch:

- Titus Winters, Pacific++ 2018: *C++ Past vs. Future*
- Dave Steffen, CppCon 2020: *Build Everything From Source: A Case Study in Fear*

(More) Literature

- Titus Winters, P2028: *What is ABI, and What Should WG21 Do About It?*
- Titus Winters, P1863: *ABI - Now or Never*
- Roger Orr, P1654: *ABI breakage - summary of initial comments*
- Titus Winters on CppCast #224: *The C++ ABI*
- John Lakos on CppCast #233: *Large Scale C++*
- Corentin Jabot on cor3ntin.github.io/posts/abi/: *The Day The Standard Library Died*
- JeanHeyd Meneide on theiphd.github.io/freestanding-noexcept-allocators-vector-memory-hole
- Danila Kutenin, C++ on Sea 2020: *C++ STL best and worst performance features and how to learn from them*