What does the compiler actually do with my code?

An introduction to the C++ ABI

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1 Introduction
2 What is an ABI?
3 Object layout
4 Function calls
5 Virtual functions
6 Exceptions

The topic for today

How are parts of C++ realized on x86 and AMD64?

- Object layout
- Function calls
- Virtual function calls
- Exceptions

Why?

If you know the implementation...

- ...you can reason about the efficiency of your solution
- ...you can see why some things are undefined behaviour
- (...you can abuse undefined behaviour and do *really* strange things)

Note: Everything discussed here is *highly* system specific, and most likely undefined behavior according to the standard!

How?

- Read the assembler output from the compiler!
  - `g++ -S -masm=intel <file>` or `cl /FAs <file>`
  - `objdump -d -M intel <program>`
  - In a debugger
  - Compiler Explorer
- Figure out why it does certain things:
  - OSDev Wiki (`https://wiki.osdev.org/`)
  - System V ABI (`https://www.uclibc.org/docs/psABI-x86_64.pdf`)
  - x86 instruction reference (`http://ref.x86asm.net/`)
- Lots of tinkering and thinking!

1 Introduction

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3 Object layout

4 Function calls

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What is an ABI (Application Binary Interface)?

Specifies how certain aspects of a language are realized on a particular CPU

Language specification + ABI ⇒ compiler

Specifies:

- Size of built-in types
- **Object layout**
- **Function calls** (calling conventions)
- Exception handling
- Name mangling
- ...

Different systems use different ABIs

There are two major ABIs:

- System V ABI (Linux, MacOS on AMD64)
- Microsoft ABI (Windows)

Variants for many systems:

- **x86**
- **AMD64**
- ARM
- ...

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Integer types and endianness

```
char  a{0x08};
short b{0x1234};       // = 4660
int   c{0x00010203};   // = 66051
long  d{0x1101020304}; // = 73031353092
```

Integer types and endianness

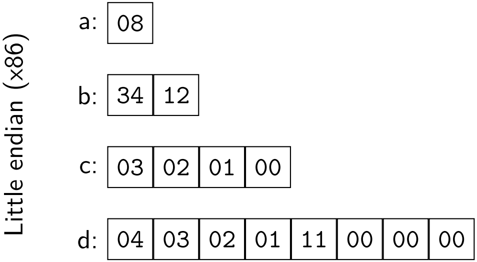
```
char  a{0x08};
short b{0x1234};       // = 4660
int   c{0x00010203};   // = 66051
long  d{0x110102030 4}; // = 73031353092
```

Big endian (ARM)

a:	08							
b:	12	34						
c:	00	01	02	03				
d:	00	00	00	11	01	02	03	04

Integer types and endianness

```
char   a{0x08};
short  b{0x1234};        // = 4660
int    c{0x00010203};    // = 66051
long   d{0x1101020304}; // = 73031353092
```



Little endian (x86)

a: 08

b: 34 12

c: 03 02 01 00

d: 04 03 02 01 11 00 00 00

The type system

The type system is not present in the binary! It just helps us to keep track of how to *interpret* bytes in memory!

```
struct foo {
  int a, b, c;
};

foo x{1, 2, 3};
int y[3] = {1, 2, 3};
short z[6] = {1, 0, 2, 0, 3, 0};
```

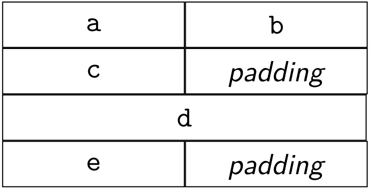
All look the same in memory!

Other types

- Each type has a *size* and an *alignment*
- Members are placed sequentially, respecting the alignment

Example:

```
struct simple {
  int a{1};
  int b{2};
  int c{3};
  long d{100};
  int e{4};
};
```



a	b
c	*padding*
d	
e	*padding*

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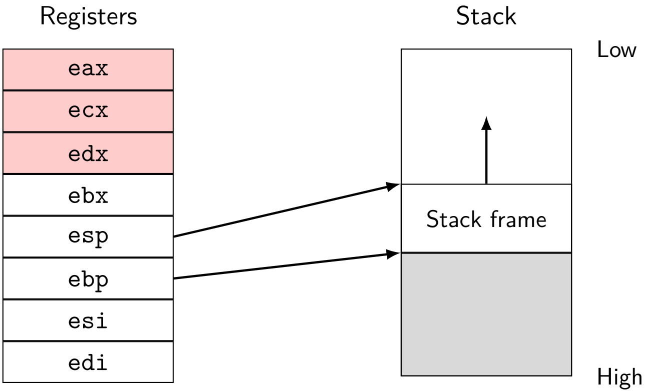
Starting simple – x86

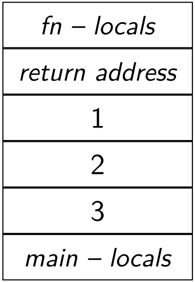


The default on x86 – `cdecl`

```
int fn(int a, int b, int c);

int main() {
  int r = fn(1, 2, 3);
}
```

```
  push 3
  push 2
  push 1
  call fn
  add esp, 12
  mov "r", eax
```



fn – locals

return address

1

2

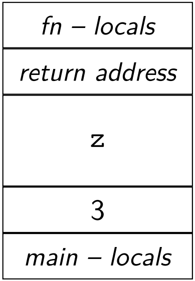
3

main – locals

The default on x86 – `cdecl`

```
struct large { int a, b; };
int fn(large a, int b);
int main() {
  large z{ 1, 2 };
  int r = fn(z, 3);
}
```

```
  push 3
  sub esp, 8
  ;; initialize z at esp
  call fn
  add esp, 12
  mov "r", eax
```



fn – locals

return address

z

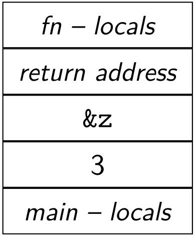
3

main – locals

The default on x86 – cdecl

```
struct large { int a, b; };
int fn(large &a, int b);
int main() {
  large z{ 1, 2 };
  int r = fn(z, 3);
}
```

```
  push 10
  lea eax, "z"
  push eax
  call fn
  add esp, 8
  mov "r", eax
```



fn – locals

return address

&z

3

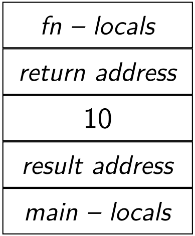
main – locals

The default on x86 – `cdecl`

```
struct large { int a, b; };
large fn(int a);

int main() {
  large z = fn(10);
}
```

```
  push 10
  lea eax, "z"
  push eax
  call fn
  add esp, 8
```



fn – locals

return address

10

result address

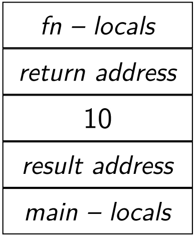
main – locals

The default on x86 – cdecl

```
struct large { int a, b; };
large *fn(large *result, int a);

int main() {
  large z = fn(10);
}
```

```
  push 10
  lea eax, "z"
  push eax
  call fn
  add esp, 8
```



fn – locals

return address

10

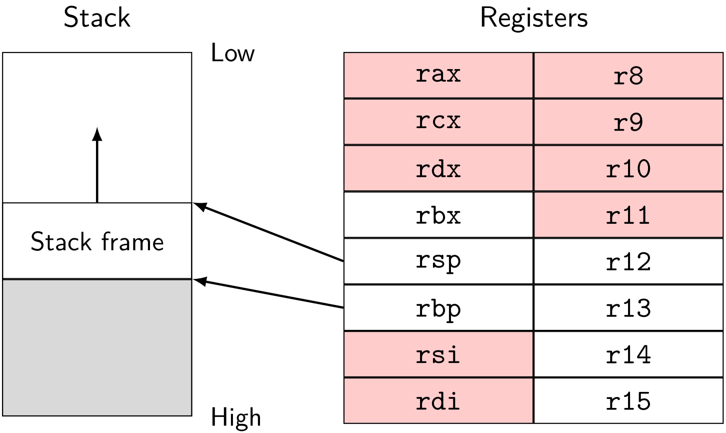
result address

main – locals

More advanced – AMD64 (SystemV)

This is where the fun begins!

More advanced – AMD64 (SystemV)



Stack

Low

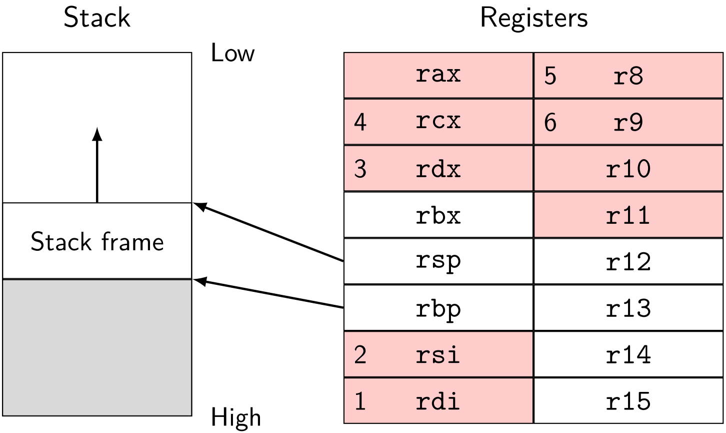
Stack frame

High

Registers

rax	r8
rcx	r9
rdx	r10
rbx	r11
rsp	r12
rbp	r13
rsi	r14
rdi	r15

More advanced – AMD64 (SystemV)



	rax	5	r8
4	rcx	6	r9
3	rdx		r10
	rbx		r11
	rsp		r12
	rbp		r13
2	rsi		r14
1	rdi		r15

Rules (simplified)

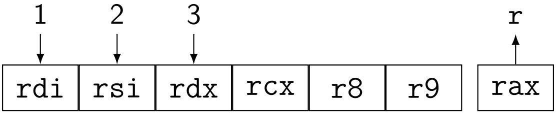
1. If a parameter has a copy constructor or a destructor:
    - Pass by hidden reference
2. If a parameter is larger than 4*8 bytes
    - Pass in memory
3. If a parameter uses more than 2 integer registers
    - Pass in memory
4. Otherwise
    - Pass in appropriate registers (integer/floating-point)

AMD64 (SystemV)

```
int fn(int a, int b, int c);

int main() {
  int r = fn(1, 2, 3);
}
```

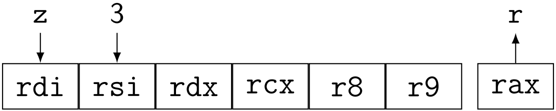
```
mov edi, 1
mov esi, 2
mov edx, 3
call fn
mov "r", rax
```



AMD64 (SystemV)

```
struct large { int a, b; };
int fn(large a, int b);
int main() {
  large z{ 1, 2 };
  int r = fn(z, 3);
}
```

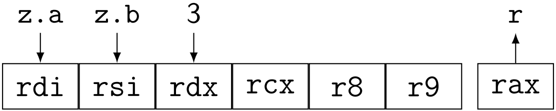
```
mov rdi, "z"
mov rsi, 3
call fn
mov "r", rax
```



AMD64 (SystemV)

```
struct large { long a, b; };
int fn(large a, long b);
int main() {
  large z{ 1, 2 };
  int r = fn(z, 3);
}
```

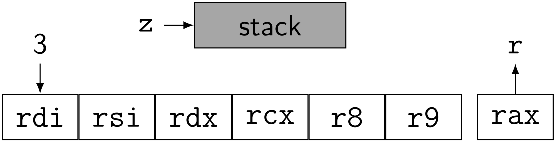
```
mov rdi, "z"
mov rsi, 3
call fn
mov "r", rax
```



AMD64 (SystemV)

```
struct large { long a, b, c; };
int fn(large a, long b);
int main() {
  large z{ 1, 2, 3 };
  int r = fn(z, 4);
}
```

```
push "z.c"
push "z.b"
push "z.a"
mov rdi, 3
call fn
mov "r", rax
```

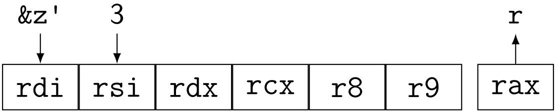


AMD64

```
struct large { /*...*/ };
int fn(large a, long b);
int main() {
  large z{ 1, 2 };
  int r = fn(z, 3);
}
```

```
;; Copy z into z'
lea rdi, "z'"
mov rsi, 3
call fn
mov "r", rax
```

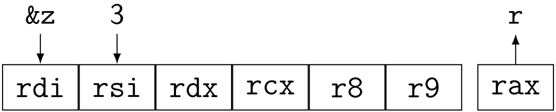
large is not trivially copiable, has a destructor or a vtable



AMD64 (SystemV)

```
struct large { int a, b; };
int fn(large &a, int b);
int main() {
  large z{ 1, 2 };
  int r = fn(z, 3);
}
```

```
lea rdi, "z"
mov rsi, 3
call fn
mov "r", rax
```

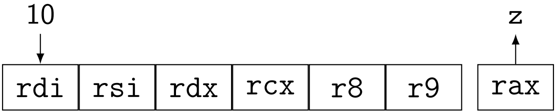


AMD64 (SystemV)

```
struct large { int a, b; };
large fn(int a);

int main() {
  large z = fn(10);
}
```

```
mov rdi, 10
call fn
mov "z", rax
```



10

z

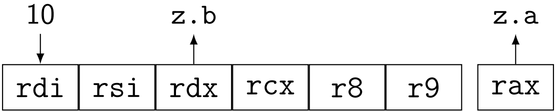
rdi rsi rdx rcx r8 r9 rax

AMD64 (SystemV)

```
struct large { long a, b; };
large fn(int a);

int main() {
  large z = fn(10);
}
```

```
mov rdi, 10
call fn
mov "z", rax
mov "z"+8, rdx
```

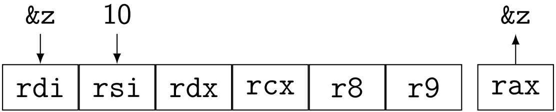


AMD64 (SystemV)

```
struct large { long a, b, c; };
large fn(int a);

int main() {
  large z = fn(10);
}
```

```
mov rdi, 10
call fn
mov "z", rax
mov "z"+8, rdx
```



&z 10 &z

rdi rsi rdx rcx r8 r9 rax

Conclusions

- Passing primitives by value is cheap
- Passing simple types by value is cheap (sometimes cheaper than passing multiple parameters)
  - As long as they are trivially copiable and destructible
  - As long as they are below about 4 machine words or about 64 bytes
- Returning small simple types by value is cheap on AMD64, even without RVO
- Types that are not trivially copiable are more cumbersome: pass them by reference

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Scenario

```
struct base {
  virtual ~base() = default;

  int data{0x1020};

  virtual void fun(int x) = 0;
};

void much_fun(base &x) {
  x.fun(100);
}
```

How do we know what to call here?

Virtual function tables – vtables (SystemV)

Idea: Put some type info in the objects!

This is called a *virtual function table* or *vtable*:

Offset	Symbol
0	`derived::~derived()`
8	`derived::~derived()`
16	`derived::fun(int)`

Note: More complex for multiple and virtual inheritance!

Virtual function tables – vtables (SystemV)

Idea: Put some type info in the objects!

This is called a *virtual function table* or *vtable*:

Offset	Symbol	
0	`derived::~derived()`	doesn't call `delete`
8	`derived::~derived()`	calls `delete`
16	`derived::fun(int)`	

Note: More complex for multiple and virtual inheritance!

Virtual dispatch

```
void much_fun(base &x) {
  x.fun(100);
}
```

```
  mov rdi, "x"        ; Put x in a register
  mov rax, [rdi]      ; Read vtable
  mov rax, [rax+16] ; Read slot #2
  mov rsi, 100        ; Add parameter
  call [rax]          ; Call the function
```

Pointers to members (SystemV)

Function pointers are fairly straight forward... What about pointers to members?

```
plain_ptr  x = &MyClass::static_member;
member_ptr y = &MyClass::normal_member;
member_ptr z = &MyClass::virtual_member;
```

Let's look at their sizes:

```
sizeof(x) == ?;
sizeof(y) == ?;
sizeof(z) == ?;
```

Pointers to members (SystemV)

Function pointers are fairly straight forward... What about pointers to members?

```
plain_ptr  x = &MyClass::static_member;
member_ptr y = &MyClass::normal_member;
member_ptr z = &MyClass::virtual_member;
```

Let's look at their sizes:

```
sizeof(x) == sizeof(void *);
sizeof(y) == sizeof(void *)*2;
sizeof(z) == sizeof(void *)*2;
```

What?

Let’s look at the code!

```
call_member:
  mov rax, "ptr.ptr"
  and rax, 1
  test rax, rax
  jne .L12
  mov rax, "ptr.ptr"
  jmp .L13
```

```
.L12:
  mov rax, "ptr.offset"
  add rax, "&c"
  mov rdx, [rax]
  mov rax, "ptr"
  mov rax, [rax+rdx-1]
.L13:
  mov rdi, "ptr.offset"
  add rdi, "&c"
  call [rax]
```

Let's look at the code!

```
struct member_ptr {
  // Pointer or vtable offset
  size_t ptr;

  // Object offset
  size_t offset;
};
```

Let's look at the code!

```
void member_call(MyClass &c, member_ptr ptr) {
  void *obj = (void *)&c + ptr.offset;
  void *target = ptr.ptr;
  // Is it a vtable offset?
  if (ptr.ptr & 0x1) {
    void *vtable = *(void **)obj;
    target = *(size_t *)(vtable + ptr - 1);
  }
  // Call the function!
  (obj->*target)();
}
```

Pointers to members

- This is realized differently on x86 on Windows
  - There, *thunks* are used instead.
- This is one of the reasons why you can't just cast member function pointers to `void *`!
- Pointers to member variables are simpler, they're just the offset of the variable.

What about `typeid`?

```
const type_info &find_typeinfo(base &var) {
  return typeid(var);
}
```

How does the compiler know the actual type of `var`?

Let’s look at the code!

```
_Z13find_typeinfoR4base:
    push    rbp                ; Function prolog
    mov     rbp, rsp
    mov     rax, rdi           ; First parameter
    mov     rax, QWORD PTR [rax]
    mov     rax, QWORD PTR [rax-8]
    pop     rbp                ; Function epilog
    ret
```

Let's look at the code!

```
_Z13find_typeinfoR4base:
    push    rbp                  ; Function prolog
    mov     rbp, rsp
    mov     rax, rdi             ; First parameter
    mov     rax, QWORD PTR [rax]
    mov     rax, QWORD PTR [rax-8]
    pop     rbp                  ; Function epilog
    ret
```

There is something at offset -8 of the vtable!

A closer look at the vtable

```
_ZTV7derived:
  .quad 0
  .quad _ZTI7derived
  .quad _ZN7derivedD1Ev
  .quad _ZN7derivedD0Ev
  .quad _ZN7derived3funEi
```

A closer look at the vtable

Offset	Symbol	
-16	(offset)	
-8	`typeinfo for derived`	
0	`derived::~derived()`	doesn't call `delete`
8	`derived::~derived()`	calls `delete`
16	`derived::fun(int)`	

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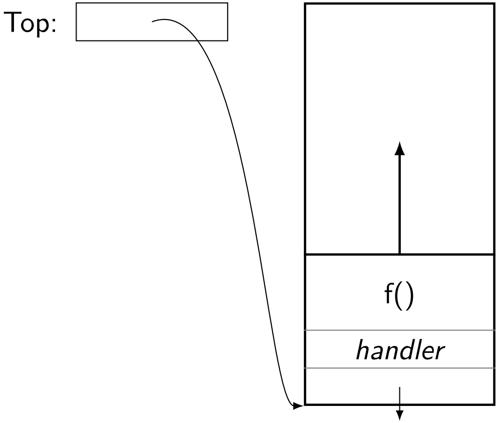
SEH – x86, Win32

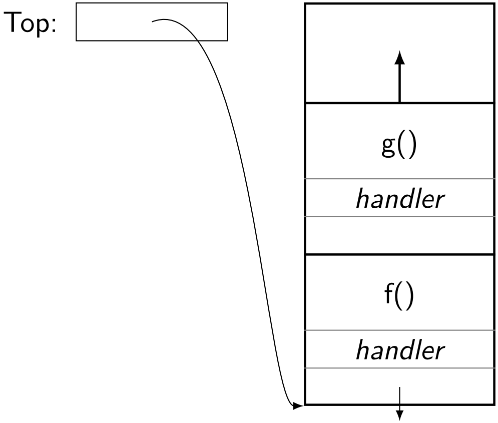
Idea: Functions in need of handling exceptions store an entry in a per-thread list of handlers. Essentially:

```
void function() {
  eh_entry entry;
  entry.next = eh_stack;
  entry.handler = &handle_exception;
  eh_stack = &entry;

  // Code as normal

  eh_stack = entry.next;
}
```

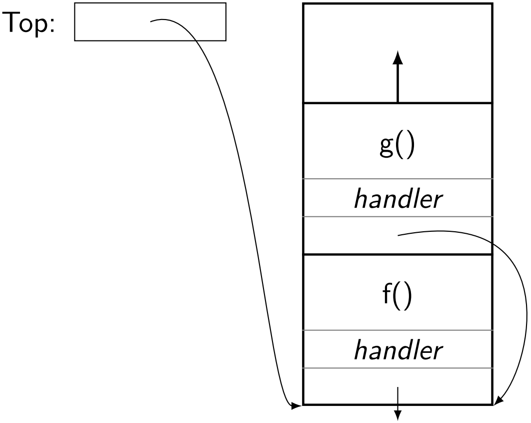
SEH – x86, Win32



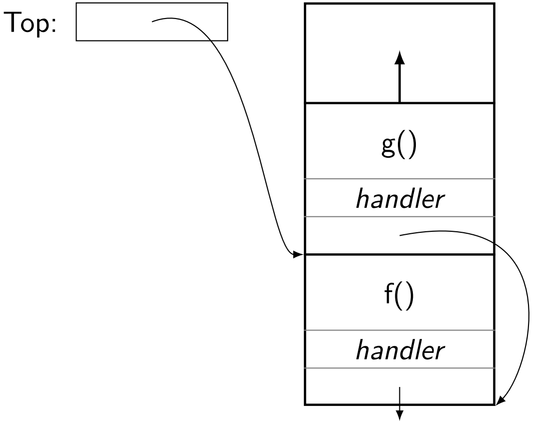
SEH – x86, Win32



SEH – x86, Win32



SEH – x86, Win32



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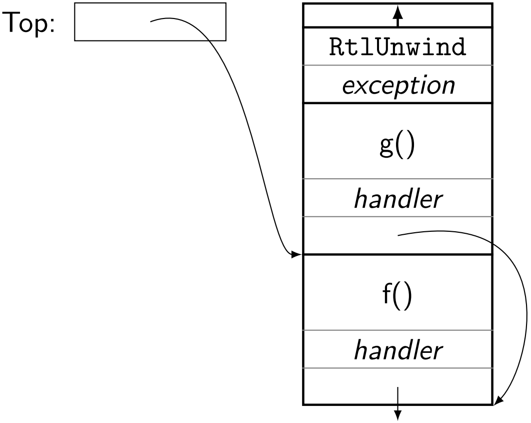
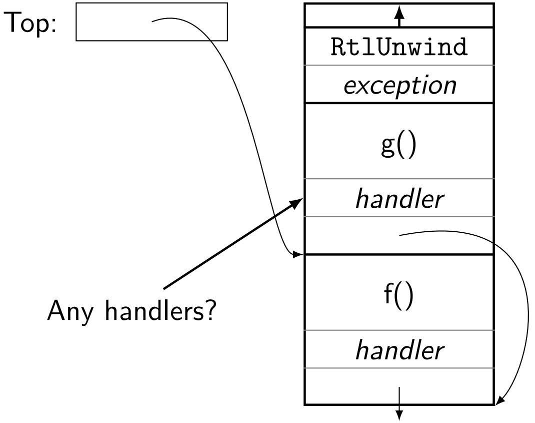


SEH – x86, Win32



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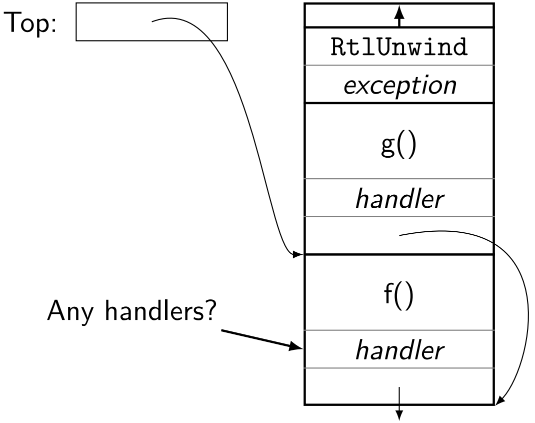
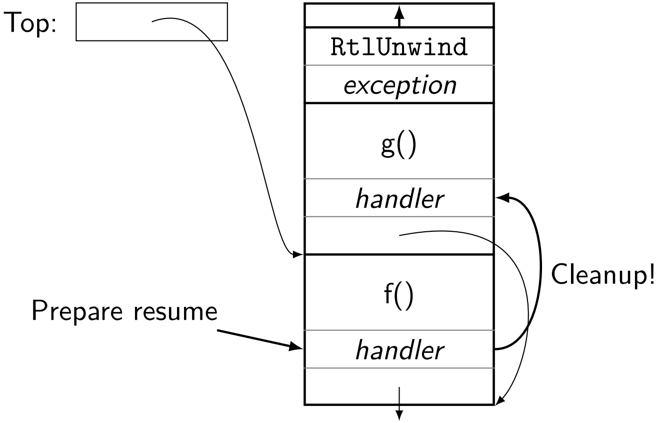
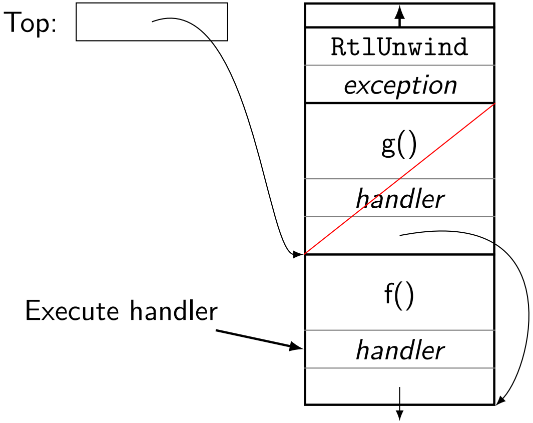


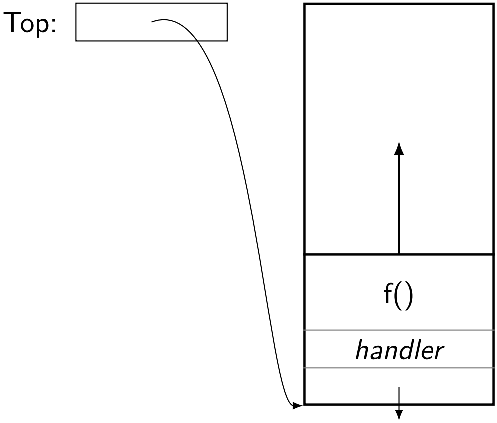
SEH – x86, Win32



SEH – x86, Win32



SEH – x86, Win32



What was thrown?

Table of `typeinfo`-objects in metadata:

```
class A {};

class B :
  public A {};
class C :
  public B {};

void f() {
  try {
    throw C();
  } catch (const A &) {}
}
```

What was thrown?

Table of typeinfo-objects in metadata:

```
class A {};

class B :
  public A {};
class C :
  public B {};

void f() {
  try {
    throw C();
  } catch (const A &) {}
}
```

```
typeinfo *options[] = {
  &typeid(C),
  &typeid(B),
  &typeid(A),
}
```

SEH – x86, Win32

Benefits:

- Language agnostic – almost no pre-defined data structures
- Straightforward unwinding

Drawbacks:

- Overhead in all cases – not only when throwing exceptions
- Storing function pointers on the stack...

For AMD64, a solution similar to DWARF is used

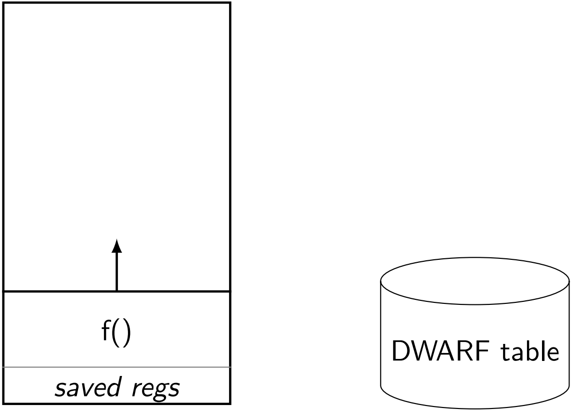
DWARF – System V

Idea: Store unwinding information in big tables somewhere!

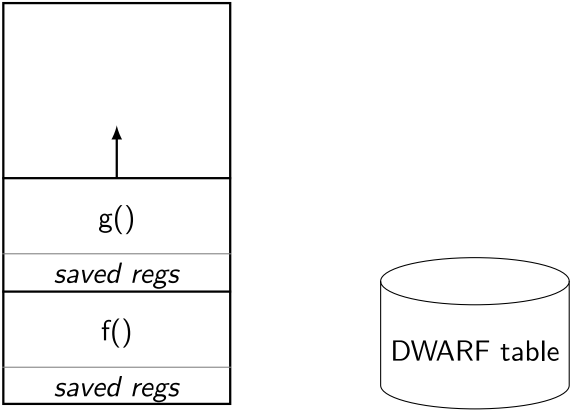
Each function has an entry containing:

- Unwinding information – How to undo any changes to the stack and/or registers done by the function at any point in the function.
- Personality function – Like in SEH, function that determines if a particular exception is handled and hanles cleanup.
- Additonal data – Any additional information required by the personality function.

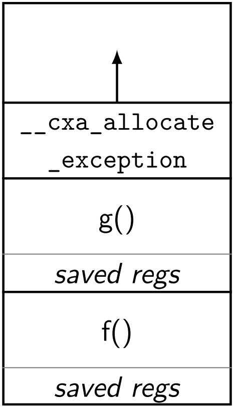
DWARF – SystemV

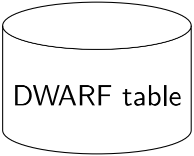


DWARF – SystemV

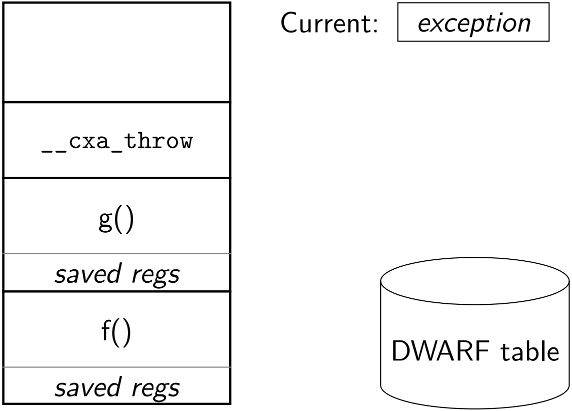


DWARF – SystemV

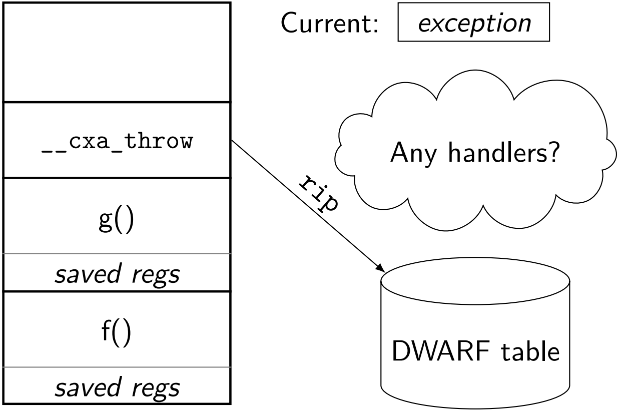




DWARF – SystemV



DWARF – SystemV



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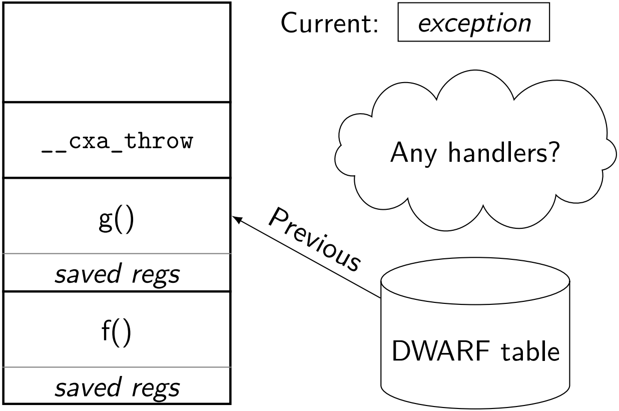
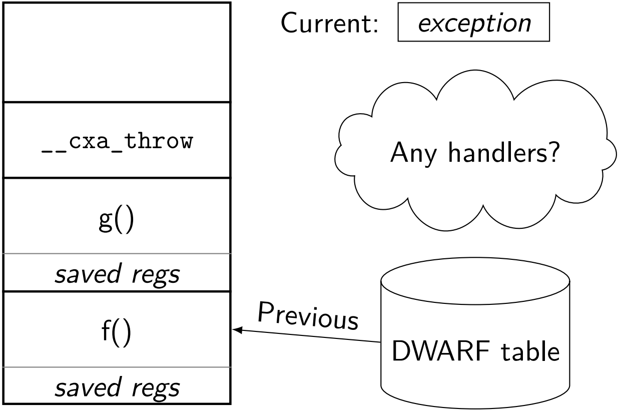


DWARF – SystemV



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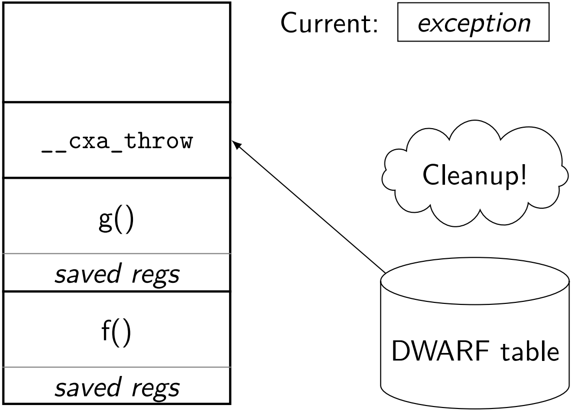

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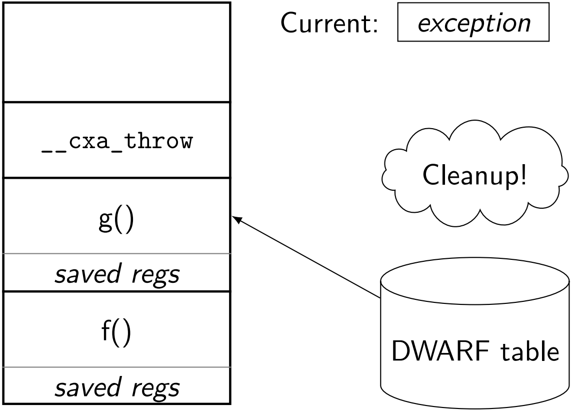

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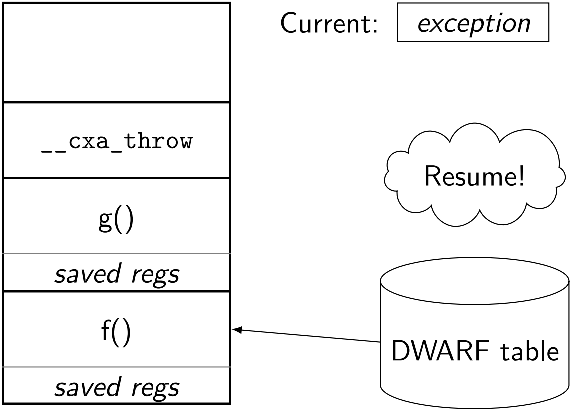

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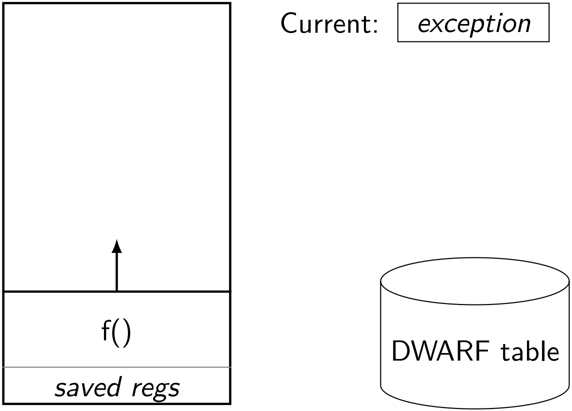

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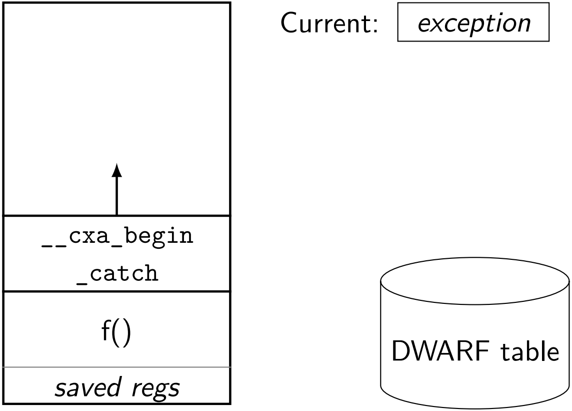

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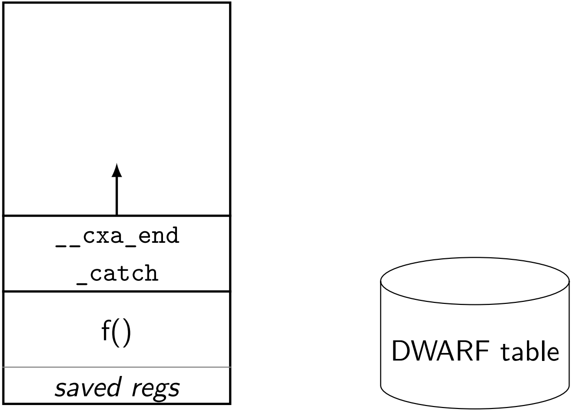
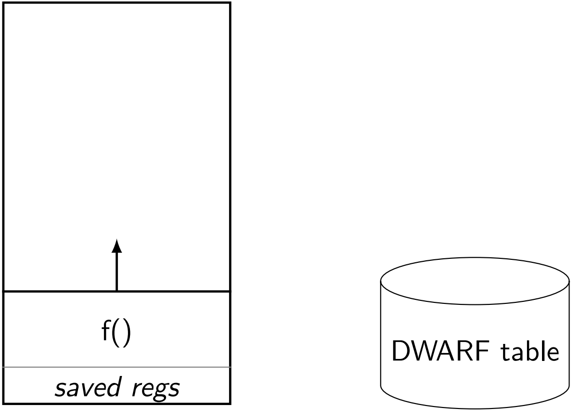


DWARF – SystemV



What was thrown?

Well, `std::typeinfo` is a polymorphic class...

`https://itanium-cxx-abi.github.io/cxx-abi/abi.html`

```
bool matches(_Unwind_Exception *data) {
  std::type_info *type = /* data->type */;
  // perhaps
  return __dynamic_cast(..., type, &typeid(A), -1);

  // not in the ABI:
  return typeid(A).__do_catch(type, ...);
}
```

DWARF - System V

Benefits:

- Low cost (almost zero) unless exceptions are actually thrown
- Difficult to utilize during buffer overflows

Drawbacks:

- Most functions need to provide unwind information (difficult when doing JIT compilation)
- High cost of actually throwing exceptions

Some interesting functions here:
`https://libcxxabi.llvm.org/spec.html`

Conclusions

- There are many ways of implementing exceptions
- Most are expensive, hopefully only when used!
- Don’t use exceptions for normal control-flow!

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