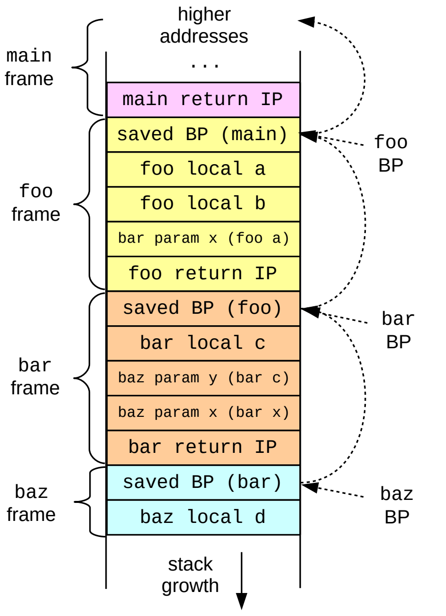
CS 261
Fall 2019

Mike Lam, Professor

```
void foo()        void bar(x)        void baz(x,y)
{                 {                  {
     int a,b;          int c;             int d;
     bar(a)            baz(x,c);          return;
     return;           return;       }
}                 }
```



x86-64 Procedures

Topics

- Procedure calls
  - Runtime stack
  - Control transfer
  - Data transfer
  - Local storage
  - Recursive procedures
  - Security issues

Procedure calls

- A procedure is a portion of code packaged for re-use
  - Key abstraction in software development
  - Provide modularity and encapsulation
  - Many alternative names: functions, methods, subroutines

- Well-designed procedures have:
  - Well-documented, typed arguments and return value(s)
  - Clear impact on program state (or no impact)
    - Also known as “side effects”

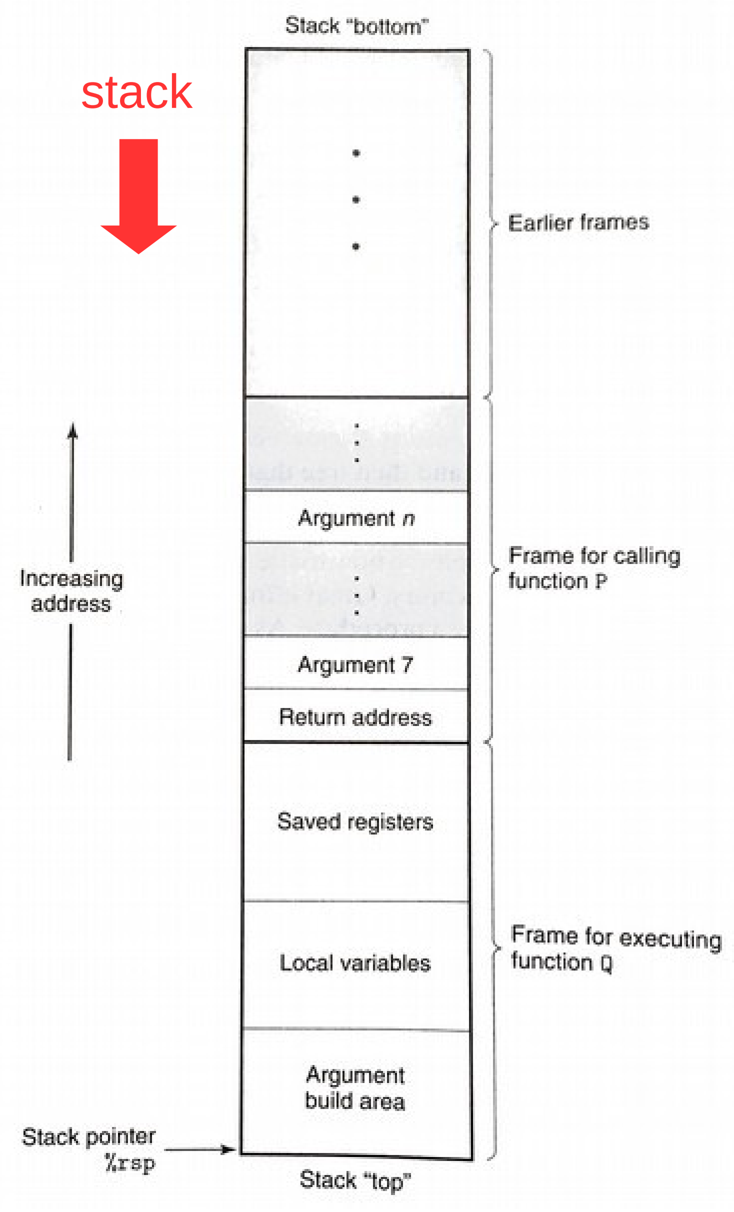
ABI

- Application Binary Interface (ABI)
  - Interface between program & system at the binary level
  - Includes rules about how procedure calls are implemented
  - These rules are referred to as calling conventions
  - We will study the standard x86-64 calling conventions
- Calling conventions specify:
  - Control transfer
  - Data transfer
  - Local storage

Runtime stack

- Basic idea: maintain a system stack frame for each function call
  - All active functions have a frame
  - Each frame stores information about a single active call
    - Arguments, local variables, return address
  - GDB's "backtrace" command follows the chain up
  - Recursion just works!

Here function P has called function Q

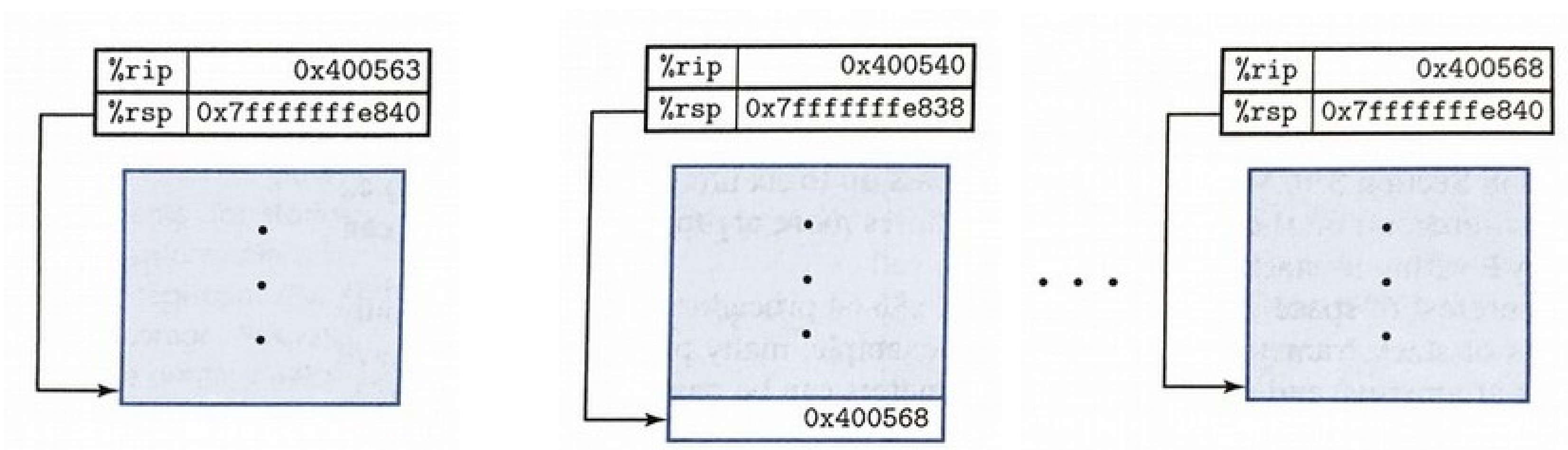


Control transfer

- Use stack to store return addresses
  - Return address: the instruction AFTER the `call`
  - `call` / `callq` pushes 64-bit return address onto stack
  - `ret` / `retq` pops the return address and sets `%rip`

```
400550 <main>:
  ...
  400563   callq 400540 <foo>
  400568   movq 0x8(%rsp), %rdx
  ...
```

```
400550 <foo>:
  400540   xorq %rax, %rax
  ...
  40054d   retq
```



(a) Executing call (b) After call (c) After ret

Data transfer

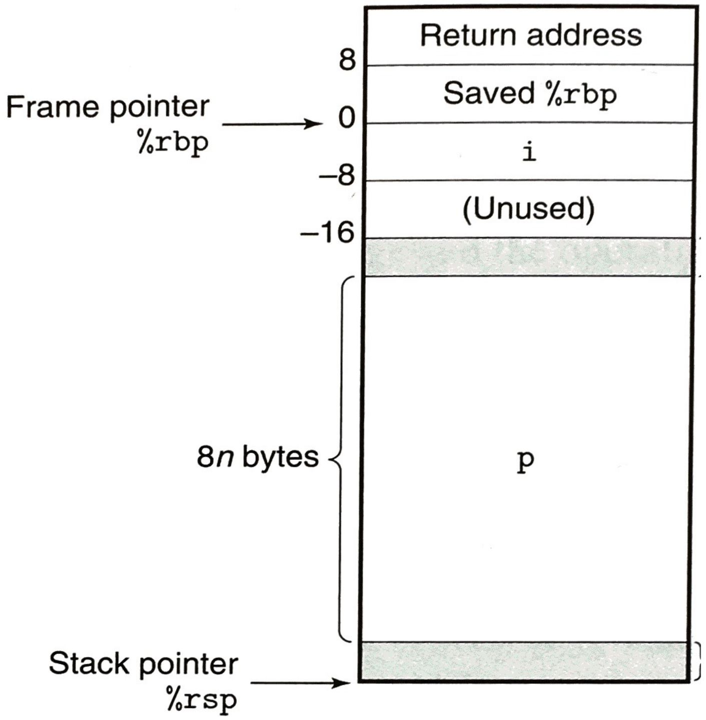
- In x86-64, up to six integral (integer or pointer) arguments are passed to a procedure via registers:
  - `%rdi, %rsi, %rdx, %rcx, %r8, %r9`
  - Other arguments are passed on the stack (and pushed in reverse order)
- A single return value is passed back via `%rax`
  - Large structs often returned via added pointer argument

Local storage (registers)

- Some registers are designated callee-saved
  - In x86-64: `%rbx, %rbp, %r12, %r13, %r14, %r15`
  - A procedure must save/restore these registers (often using push/pop) if they are used during the procedure
  - When possible, avoid using these registers inside procedures (lower overhead)
- Other registers (except `%rsp`) are caller-saved
  - Caller must save them if they need to be preserved
  - The stack pointer is a special case (used for communication)

Local storage (memory)

- Procedures can allocate space on the stack for local variables
  - Subtract # of bytes needed from `%rsp`
  - Deallocate by restoring old `%rsp` value
- Variable-sized allocations require special handling
  - Use base / frame pointer (`%rbp`) to track "anchor" for current frame
  - Save previous base pointer on stack at beginning of function
  - Section 3.10.5 in textbook



Base pointers

CS 430/432 preview

- Use base pointer (`%rbp`) to track the beginning of current frame
  - Parameters at positive offsets
  - Local values at negative offsets
  - Chain of base pointers up the stack
  - Push/pop BP like return address

```
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{                 {                  {
    int a,b;          int c;             int d;
    bar(a)            baz(x,c);          return;
    return;           return;        }
}                 }
```

CALLER

Pre-call:

pushq *<param2>*
pushq *<param1>*
callq *<func>*

Post-return:

subq $16, %rsp
...

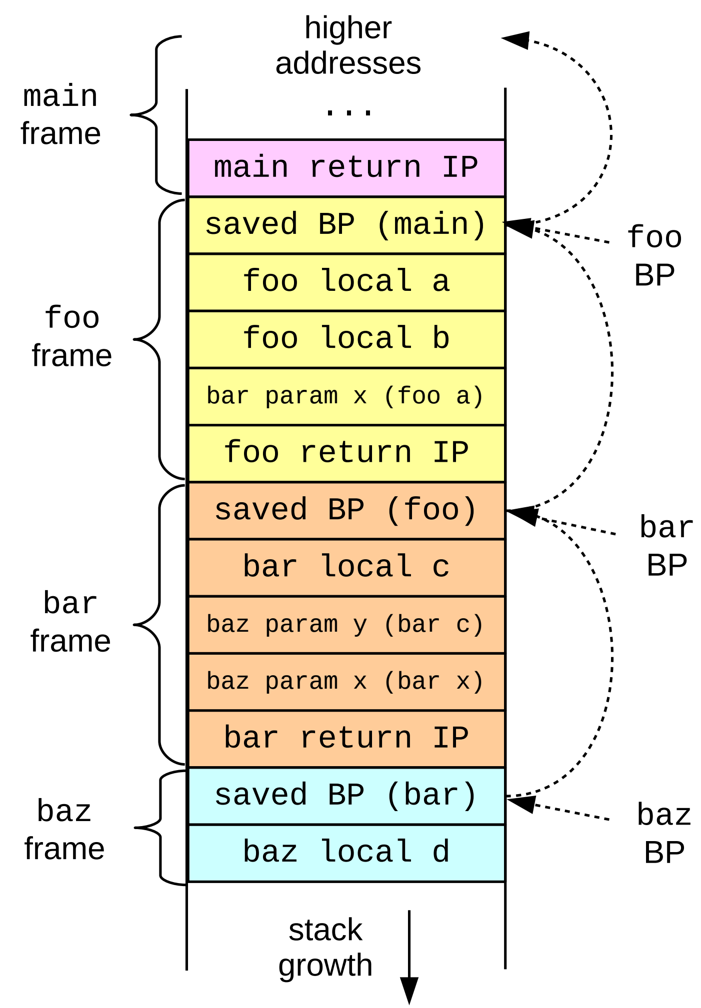
CALLEE

Prologue:

pushq %rbp
movq %rsp, %rbp
subq $*n*, %rsp
...

Epilogue:

movq %rbp, %rsp
popq %rbp
retq



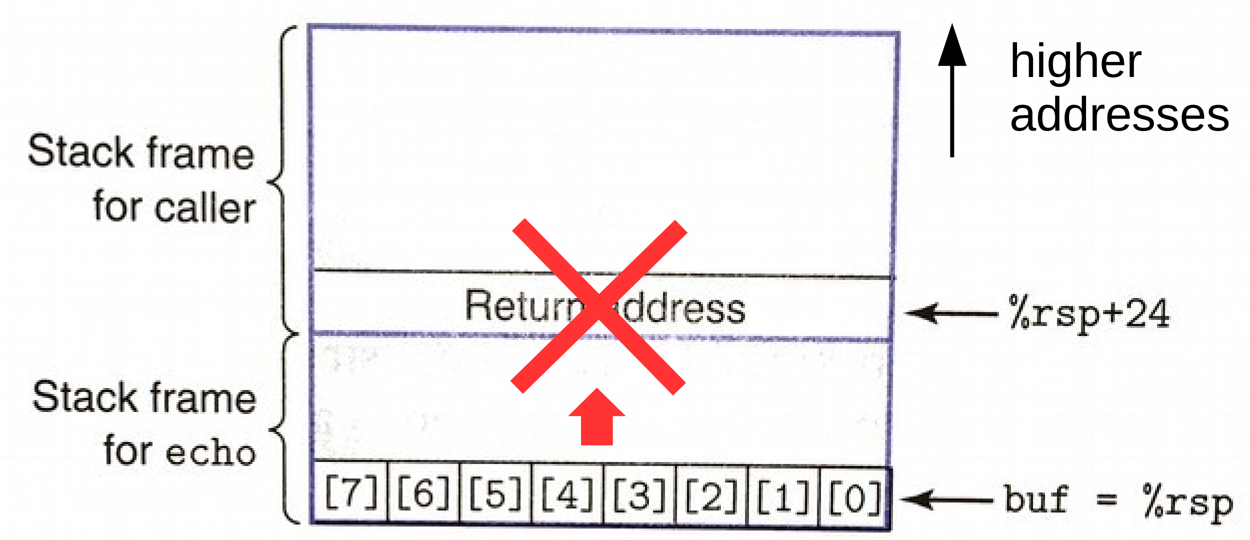
Buffer overflows

- Major x86-64 security issue
  - C and assembly do not check for out-of-bounds array accesses
  - x86-64 stores return addresses and data on the same stack
  - Out-of-bound writes to local variables may overwrite other stack frames
  - Allows attackers to change control flow just by providing the right "data"
  - Many historical exploits (including Morris worm)

```
void echo ()
{
    // other code
    // omitted

    char buf[8];
    gets(buf);
    printf(buf);
}
```

DO NOT WRITE CODE LIKE THIS!

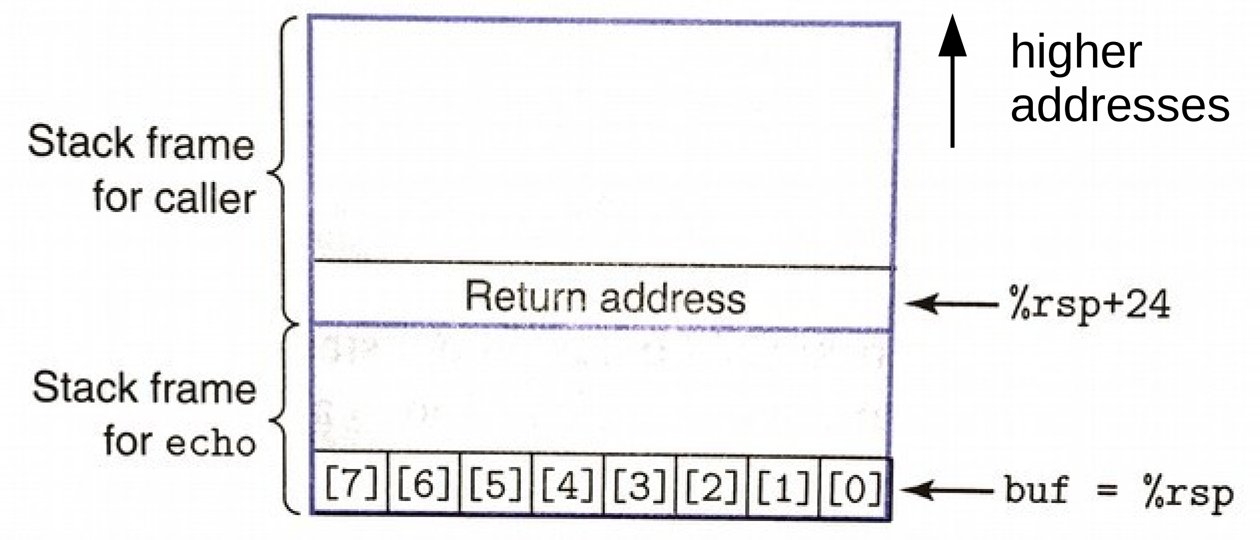


Buffer overflows

- Shellcode (exploit code)
  - Pre-compiled snippets of code that exploit a buffer overflow

```
char shellcode[] =
        "\xeb\x1f\x5e\x89\x76\x08\x31\xc0\x88\x46\x07\x89\x46\x0c\xb0\x0b"
        "\x89\xf3\x8d\x4e\x08\x8d\x56\x0c\xcd\x80\x31\xdb\x89\xd8\x40\xcd"
        "\x80\xe8\xdc\xff\xff\xff/bin/sh";
```

Complication: Must pad the shellcode with address of the buffer (guess and/or use a NOP-sled)



Mitigating buffer overflows

- Stack randomization
  - Randomize starting location of stack
  - Makes it more difficult to guess buffer address
  - In Linux: address-space layout randomization
- Corruption detection
  - Insert a canary (guard value) on stack after each array
  - Check canary before returning from function
- Read-only code regions
  - Mark stack memory as "no-execute"
  - Hinders just-in-time compilation and instrumentation

Exercise

- Trace the following code--what is the value of `%rax` at the end?
  - Initial values: `%rsp = 0x7fffffffe488, %rip = 0x4004e8`

```
4004d6 <leaf>:
  4004d6: 48 8d 7f 0f              leaq   0xf(%rdi),%rdi
  4004da: c3                       retq

4004db <top>:
  4004db: 48 83 ef 05              subq   $0x5,%rdi
  4004df: e8 f2 ff ff ff           callq  4004d6
  4004e4: 48 01 ff                 addq   %rdi,%rdi
  4004e7: c3                       retq

4004e8 <main>:
  4004e8: 48 c7 c7 64 00 00 00     movq   $100,%rdi
  4004ef: e8 e7 ff ff ff           callq  4004db
  4004f4: 48 89 f8                 movq   %rdi,%rax
  4004f7: c3                       retq
```