# Procedures & Executables

CSE 351 Autumn 2017

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## Administrivia

- Lab 2 due Friday (10/27)
- Homework 3 released tomorrow (10/24)
- Lab 1 grading
  - Double-check your total
  - See Piazza for common misconceptions

- **Midterm** next Monday (10/30, 5pm, KNE 120)
  - Make a cheat sheet! – two-sided letter page, *handwritten*
  - Check Piazza this week for announcements
  - **Review session** 5:30-7:30pm on Friday (10/27) in EEB 105

## Procedures

- Stack Structure
- Calling Conventions
  - Passing control
  - Passing data
  - Managing local data
- Register Saving Conventions
- Illustration of Recursion

## Register Saving Conventions

- When procedure `yoo` calls `who`:
  - `yoo` is the ***caller***
  - `who` is the ***callee***
- Can registers be used for temporary storage?

```
yoo:
    • • •
    movq $15213, %rdx
    call who
    addq %rdx, %rax
    • • •
    ret
```

?

```
who:
    • • •
    subq $18213, %rdx
    • • •
    ret
```

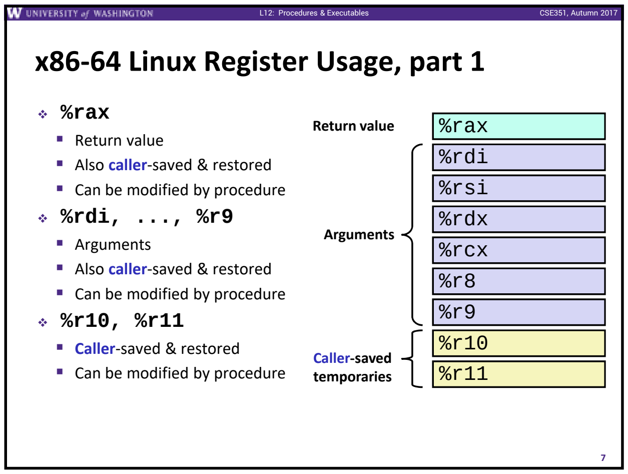
- No! Contents of register `%rdx` overwritten by `who`!
- This could be trouble – something should be done. Either:
  - ***Caller*** should save `%rdx` before the call (and restore it after the call)
  - ***Callee*** should save `%rdx` before using it (and restore it before returning)

## Register Saving Conventions

- ***"Caller-saved" registers***
  - It is the caller's responsibility to save any important data in these registers before calling another procedure (*i.e.* the callee can freely change data in these registers)
  - Caller saves values in its stack frame before calling Callee, then restores values after the call
- ***"Callee-saved" registers***
  - It is the callee's responsibility to save any data in these registers before using the registers (*i.e.* the caller assumes the data will be the same across the callee procedure call)
  - Callee saves values in its stack frame before using, then restores them before returning to caller

## Silly Register Convention Analogy

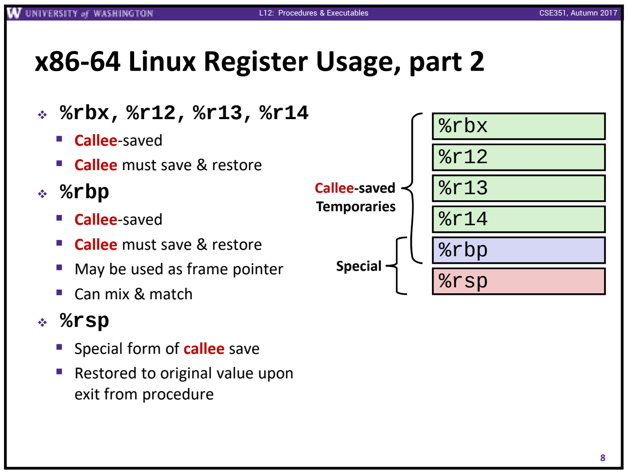
1) Parents (***caller***) leave for the weekend and give the keys to the house to their child (***callee***)
   - Being suspicious, they put away/hid the valuables (***caller**-saved*) before leaving
   - Warn child to leave the bedrooms untouched: "These rooms better look the same when we return!"
2) Child decides to throw a wild party (*computation*), spanning the entire house
   - To avoid being disowned, child moves all of the stuff from the bedrooms to the backyard shed (***callee**-saved*) before the guests trash the house
   - Child cleans up house after the party and moves stuff back to bedrooms
3) Parents return home and are satisfied with the state of the house
   - Move valuables back and continue with their lives



## x86-64 Linux Register Usage, part 1

- `%rax`
  - Return value
  - Also **caller**-saved & restored
  - Can be modified by procedure
- `%rdi, ..., %r9`
  - Arguments
  - Also **caller**-saved & restored
  - Can be modified by procedure
- `%r10, %r11`
  - **Caller**-saved & restored
  - Can be modified by procedure

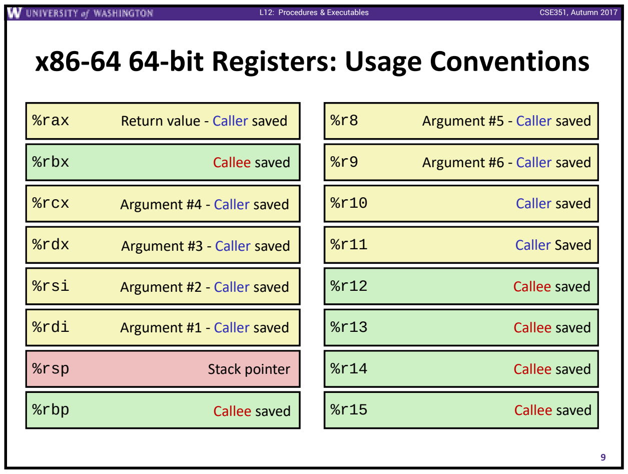
| | |
|---|---|
| **Return value** | `%rax` |
| **Arguments** | `%rdi` |
| | `%rsi` |
| | `%rdx` |
| | `%rcx` |
| | `%r8` |
| | `%r9` |
| **Caller-saved temporaries** | `%r10` |
| | `%r11` |



## x86-64 Linux Register Usage, part 2

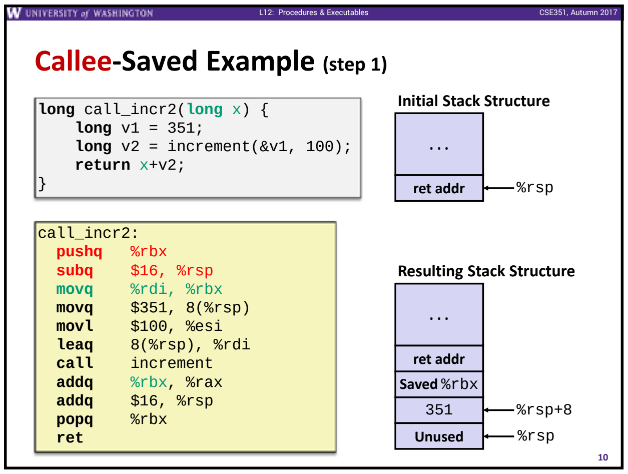
- `%rbx, %r12, %r13, %r14`
  - **Callee**-saved
  - **Callee** must save & restore
- `%rbp`
  - **Callee**-saved
  - **Callee** must save & restore
  - May be used as frame pointer
  - Can mix & match
- `%rsp`
  - Special form of **callee** save
  - Restored to original value upon exit from procedure

| | |
|---|---|
| **Callee-saved Temporaries** | `%rbx` |
| | `%r12` |
| | `%r13` |
| | `%r14` |
| | `%rbp` |
| **Special** | `%rsp` |



## x86-64 64-bit Registers: Usage Conventions

| | | | |
|---|---|---|---|
| `%rax` | Return value - Caller saved | `%r8` | Argument #5 - Caller saved |
| `%rbx` | Callee saved | `%r9` | Argument #6 - Caller saved |
| `%rcx` | Argument #4 - Caller saved | `%r10` | Caller saved |
| `%rdx` | Argument #3 - Caller saved | `%r11` | Caller Saved |
| `%rsi` | Argument #2 - Caller saved | `%r12` | Callee saved |
| `%rdi` | Argument #1 - Caller saved | `%r13` | Callee saved |
| `%rsp` | Stack pointer | `%r14` | Callee saved |
| `%rbp` | Callee saved | `%r15` | Callee saved |



## Callee-Saved Example (step 1)

```
long call_incr2(long x) {
    long v1 = 351;
    long v2 = increment(&v1, 100);
    return x+v2;
}
```

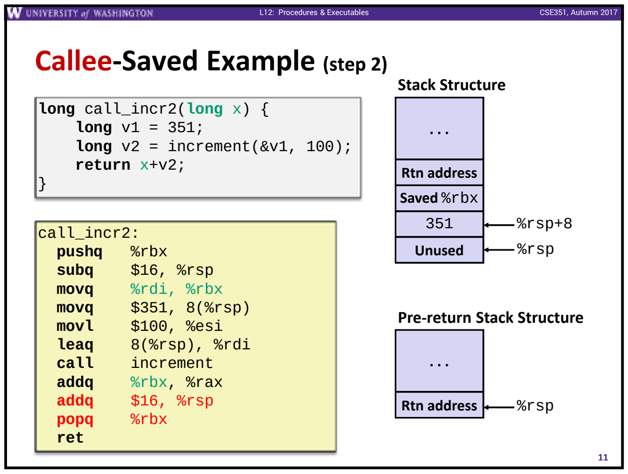
```
call_incr2:
  pushq   %rbx
  subq    $16, %rsp
  movq    %rdi, %rbx
  movq    $351, 8(%rsp)
  movl    $100, %esi
  leaq    8(%rsp), %rdi
  call    increment
  addq    %rbx, %rax
  addq    $16, %rsp
  popq    %rbx
  ret
```

**Initial Stack Structure**

```
| ...        |
| ret addr   | ←%rsp
```

**Resulting Stack Structure**

```
| ...        |
| ret addr   |
| Saved %rbx |
| 351        | ←%rsp+8
| Unused     | ←%rsp
```



## Callee-Saved Example (step 2)

```
long call_incr2(long x) {
    long v1 = 351;
    long v2 = increment(&v1, 100);
    return x+v2;
}
```

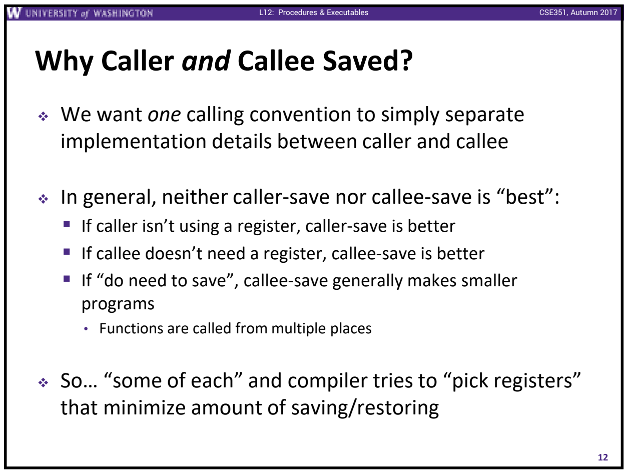
```
call_incr2:
  pushq   %rbx
  subq    $16, %rsp
  movq    %rdi, %rbx
  movq    $351, 8(%rsp)
  movl    $100, %esi
  leaq    8(%rsp), %rdi
  call    increment
  addq    %rbx, %rax
  addq    $16, %rsp
  popq    %rbx
  ret
```

**Stack Structure**

```
| ...         |
| Rtn address |
| Saved %rbx  |
| 351         | ←%rsp+8
| Unused      | ←%rsp
```

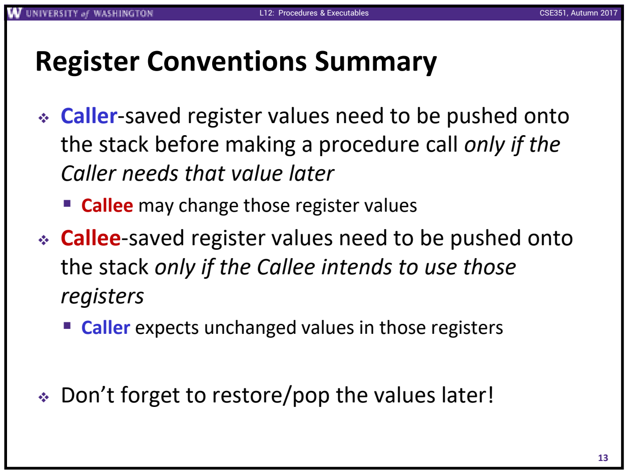
**Pre-return Stack Structure**

```
| ...         |
| Rtn address | ←%rsp
```



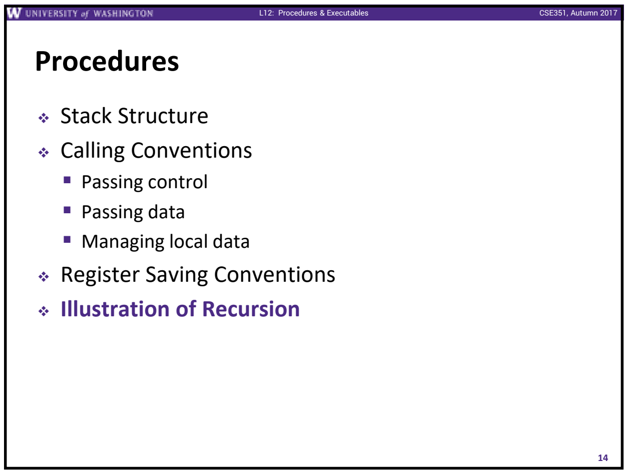
## Why Caller *and* Callee Saved?

- We want *one* calling convention to simply separate implementation details between caller and callee
- In general, neither caller-save nor callee-save is "best":
  - If caller isn't using a register, caller-save is better
  - If callee doesn't need a register, callee-save is better
  - If "do need to save", callee-save generally makes smaller programs
    - Functions are called from multiple places
- So… "some of each" and compiler tries to "pick registers" that minimize amount of saving/restoring



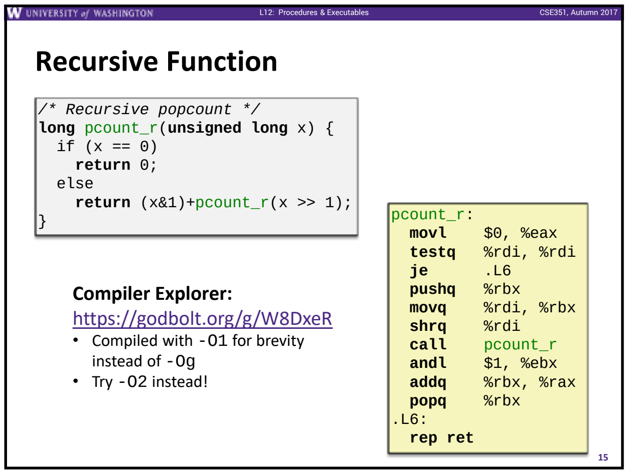
## Register Conventions Summary

- **Caller**-saved register values need to be pushed onto the stack before making a procedure call *only if the Caller needs that value later*
  - **Callee** may change those register values
- **Callee**-saved register values need to be pushed onto the stack *only if the Callee intends to use those registers*
  - **Caller** expects unchanged values in those registers
- Don't forget to restore/pop the values later!



## Procedures

- Stack Structure
- Calling Conventions
  - Passing control
  - Passing data
  - Managing local data
- Register Saving Conventions
- **Illustration of Recursion**

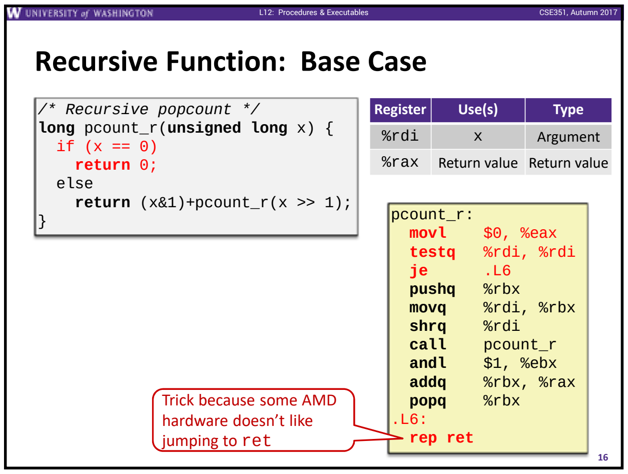


## Recursive Function

```
/* Recursive popcount */
long pcount_r(unsigned long x) {
  if (x == 0)
    return 0;
  else
    return (x&1)+pcount_r(x >> 1);
}
```

**Compiler Explorer:**
https://godbolt.org/g/W8DxeR
- Compiled with -O1 for brevity instead of -Og
- Try -O2 instead!

```
pcount_r:
  movl    $0, %eax
  testq   %rdi, %rdi
  je      .L6
  pushq   %rbx
  movq    %rdi, %rbx
  shrq    %rdi
  call    pcount_r
  andl    $1, %ebx
  addq    %rbx, %rax
  popq    %rbx
.L6:
  rep ret
```



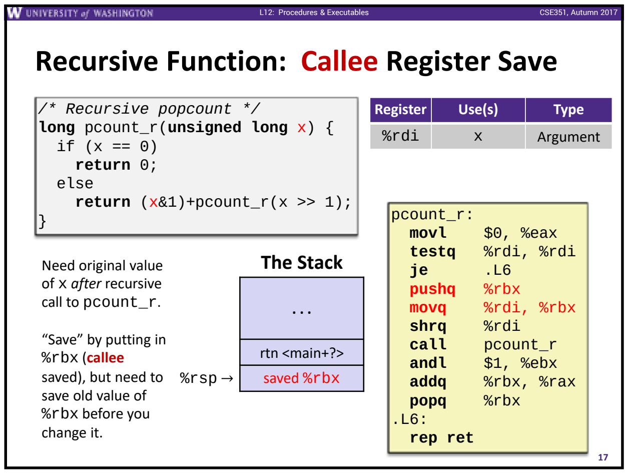
## Recursive Function: Base Case

```
/* Recursive popcount */
long pcount_r(unsigned long x) {
  if (x == 0)
    return 0;
  else
    return (x&1)+pcount_r(x >> 1);
}
```

| Register | Use(s) | Type |
|---|---|---|
| %rdi | x | Argument |
| %rax | Return value | Return value |

```
pcount_r:
  movl    $0, %eax
  testq   %rdi, %rdi
  je      .L6
  pushq   %rbx
  movq    %rdi, %rbx
  shrq    %rdi
  call    pcount_r
  andl    $1, %ebx
  addq    %rbx, %rax
  popq    %rbx
.L6:
  rep ret
```

Trick because some AMD hardware doesn't like jumping to ret



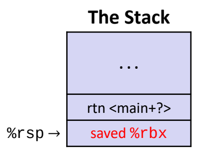
## Recursive Function: Callee Register Save

```
/* Recursive popcount */
long pcount_r(unsigned long x) {
  if (x == 0)
    return 0;
  else
    return (x&1)+pcount_r(x >> 1);
}
```

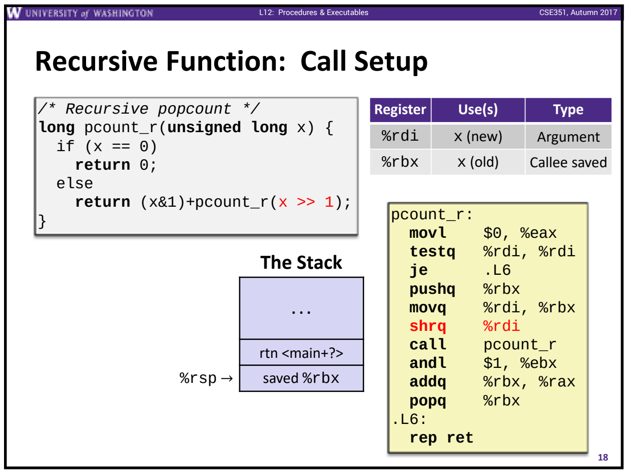
| Register | Use(s) | Type |
|---|---|---|
| %rdi | x | Argument |

Need original value of x *after* recursive call to pcount_r.

"Save" by putting in %rbx (**callee** saved), but need to save old value of %rbx before you change it.



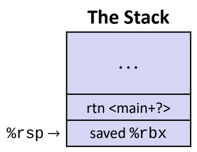
```
pcount_r:
  movl    $0, %eax
  testq   %rdi, %rdi
  je      .L6
  pushq   %rbx
  movq    %rdi, %rbx
  shrq    %rdi
  call    pcount_r
  andl    $1, %ebx
  addq    %rbx, %rax
  popq    %rbx
.L6:
  rep ret
```



## Recursive Function: Call Setup

```
/* Recursive popcount */
long pcount_r(unsigned long x) {
  if (x == 0)
    return 0;
  else
    return (x&1)+pcount_r(x >> 1);
}
```

| Register | Use(s) | Type |
|---|---|---|
| %rdi | x (new) | Argument |
| %rbx | x (old) | Callee saved |



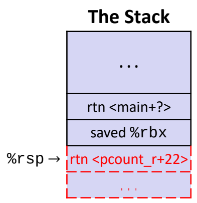
```
pcount_r:
  movl    $0, %eax
  testq   %rdi, %rdi
  je      .L6
  pushq   %rbx
  movq    %rdi, %rbx
  shrq    %rdi
  call    pcount_r
  andl    $1, %ebx
  addq    %rbx, %rax
  popq    %rbx
.L6:
  rep ret
```

## Recursive Function: Call

```
/* Recursive popcount */
long pcount_r(unsigned long x) {
  if (x == 0)
    return 0;
  else
    return (x&1)+pcount_r(x >> 1);
}
```

| Register | Use(s) | Type |
|---|---|---|
| %rax | Recursive call return value | Return value |
| %rbx | x (old) | Callee saved |

```
pcount_r:
  movl    $0, %eax
  testq   %rdi, %rdi
  je      .L6
  pushq   %rbx
  movq    %rdi, %rbx
  shrq    %rdi
  call    pcount_r
  andl    $1, %ebx
  addq    %rbx, %rax
  popq    %rbx
.L6:
  rep ret
```

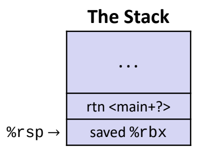


## Recursive Function: Result

```
/* Recursive popcount */
long pcount_r(unsigned long x) {
  if (x == 0)
    return 0;
  else
    return (x&1)+pcount_r(x >> 1);
}
```

| Register | Use(s) | Type |
|---|---|---|
| %rax | Return value | Return value |
| %rbx | x&1 | Callee saved |

```
pcount_r:
  movl    $0, %eax
  testq   %rdi, %rdi
  je      .L6
  pushq   %rbx
  movq    %rdi, %rbx
  shrq    %rdi
  call    pcount_r
  andl    $1, %ebx
  addq    %rbx, %rax
  popq    %rbx
.L6:
  rep ret
```

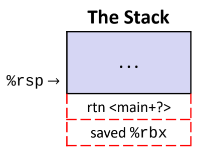


## Recursive Function: Completion

```
/* Recursive popcount */
long pcount_r(unsigned long x) {
  if (x == 0)
    return 0;
  else
    return (x&1)+pcount_r(x >> 1);
}
```

| Register | Use(s) | Type |
|---|---|---|
| %rax | Return value | Return value |
| %rbx | Previous %rbx value | Callee restored |

```
pcount_r:
  movl    $0, %eax
  testq   %rdi, %rdi
  je      .L6
  pushq   %rbx
  movq    %rdi, %rbx
  shrq    %rdi
  call    pcount_r
  andl    $1, %ebx
  addq    %rbx, %rax
  popq    %rbx
.L6:
  rep ret
```



## Observations About Recursion

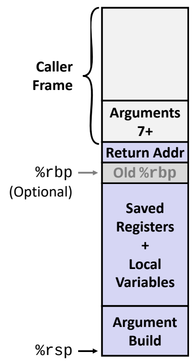
- Works without any special consideration
  - Stack frames mean that each function call has private storage
    - Saved registers & local variables
    - Saved return pointer
  - Register saving conventions prevent one function call from corrupting another's data
    - Unless the code explicitly does so (*e.g.* buffer overflow)
  - Stack discipline follows call / return pattern
    - If P calls Q, then Q returns before P
    - Last-In, First-Out (LIFO)
- Also works for mutual recursion (P calls Q; Q calls P)

## x86-64 Stack Frames

- Many x86-64 procedures have a minimal stack frame
  - Only return address is pushed onto the stack when procedure is called
- A procedure *needs* to grow its stack frame when it:
  - Has too many local variables to hold in caller-saved registers
  - Has local variables that are arrays or structs
  - Uses & to compute the address of a local variable
  - Calls another function that takes more than six arguments
  - Is using caller-saved registers and then calls a procedure
  - Modifies/uses callee-saved registers

## x86-64 Procedure Summary

- Important Points
  - Procedures are a combination of *instructions* and *conventions*
    - Conventions prevent functions from disrupting each other
  - Stack is the right data structure for procedure call/return
    - If P calls Q, then Q returns before P
  - Recursion handled by normal calling conventions
- Heavy use of registers
  - Faster than using memory
  - Use limited by data size and conventions
- Minimize use of the Stack



## Roadmap

C:

```
car *c = malloc(sizeof(car));
c->miles = 100;
c->gals = 17;
float mpg = get_mpg(c);
free(c);
```

Java:

```
Car c = new Car();
c.setMiles(100);
c.setGals(17);
float mpg =
    c.getMPG();
```

Assembly language:

```
get_mpg:
    pushq   %rbp
    movq    %rsp, %rbp
    ...
    popq    %rbp
    ret
```

Machine code:

```
0111010000011000
100011010000010000000010
1000100111000010
110000011111101000011111
```

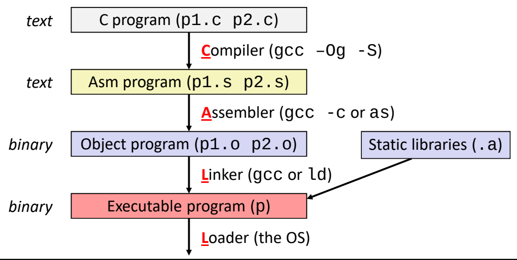
OS:

Computer system:

Memory & data
Integers & floats
x86 assembly
Procedures & stacks
Executables
Arrays & structs
Memory & caches
Processes
Virtual memory
Memory allocation
Java vs. C

## Building an Executable from a C File

- Code in files `p1.c p2.c`
- Compile with command: `gcc -Og p1.c p2.c -o p`
  - Put resulting machine code in file p
- Run with command: `./p`



## Compiler

- **Input:** Higher-level language code (*e.g.* C, Java)
  - `foo.c`
- **Output:** Assembly language code (*e.g.* x86, ARM, MIPS)
  - `foo.s`

- First there's a preprocessor step to handle #directives
  - Macro substitution, plus other specialty directives
  - If curious/interested: http://tigcc.ticalc.org/doc/cpp.html
- Super complex, whole courses devoted to these!
- Compiler optimizations
  - "Level" of optimization specified by capital 'O' flag (*e.g.* `-Og`, `-O3`)
  - Options: https://gcc.gnu.org/onlinedocs/gcc/Optimize-Options.html

## Compiling Into Assembly

- C Code (`sum.c`)

```
void sumstore(long x, long y, long *dest) {
    long t = x + y;
    *dest = t;
}
```

- x86-64 assembly (`gcc –Og –S sum.c`)
  - Generates file `sum.s` (see https://godbolt.org/g/o34FHp)

```
sumstore(long, long, long*):
  addq    %rdi, %rsi
  movq    %rsi, (%rdx)
  ret
```

Warning: You may get different results with other versions of `gcc` and different compiler settings

## Assembler

- **Input:** Assembly language code (*e.g.* x86, ARM, MIPS)
  - `foo.s`
- **Output:** Object files (*e.g.* ELF, COFF)
  - `foo.o`
  - Contains *object code* and *information tables*

- Reads and uses *assembly directives*
  - *e.g.* `.text`, `.data`, `.quad`
  - x86: https://docs.oracle.com/cd/E26502_01/html/E28388/eoiyg.html
- Produces "machine language"
  - Does its best, but object file is *not* a completed binary
- Example: `gcc -c foo.s`

## Producing Machine Language

- **Simple cases:** arithmetic and logical operations, shifts, etc.
  - All necessary information is contained in the instruction itself

- What about the following?
  - Conditional jump
  - Accessing static data (*e.g.* global var or jump table)
  - `call`

- Addresses and labels are problematic because final executable hasn't been constructed yet!
  - So how do we deal with these in the meantime?

## Object File Information Tables

- **Symbol Table** holds list of "items" that may be used by other files
  - *Non-local labels* – function names for `call`
  - *Static Data* – variables & literals that might be accessed across files
- **Relocation Table** holds list of "items" that this file needs the address of later (currently undetermined)
  - Any *label* or piece of *static data* referenced in an instruction in this file
    - Both internal and external
- Each file has its own symbol and relocation tables

## Object File Format

1) object file header: size and position of the other pieces of the object file
2) text segment: the machine code
3) data segment: data in the source file (binary)
4) relocation table: identifies lines of code that need to be "handled"
5) symbol table: list of this file's labels and data that can be referenced
6) debugging information

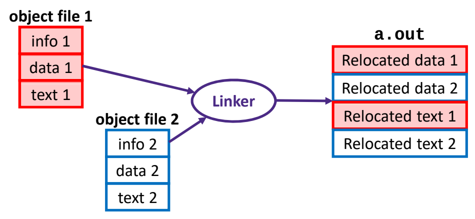
- More info: ELF format
  - `http://www.skyfree.org/linux/references/ELF_Format.pdf`

## Linker

- **Input:** Object files (e.g. ELF, COFF)
  - `foo.o`
- **Output:** executable binary program
  - `a.out`
- Combines several object files into a single executable (*linking*)
- Enables separate compilation/assembling of files
  - Changes to one file do not require recompiling of whole program

## Linking

1) Take text segment from each `.o` file and put them together
2) Take data segment from each `.o` file, put them together, and concatenate this onto end of text segments
3) Resolve References
   - Go through Relocation Table; handle each entry



## Disassembling Object Code

- Disassembled:

```
0000000000400536 <sumstore>:
  400536:  48 01 fe       add    %rdi,%rsi
  400539:  48 89 32       mov    %rsi,(%rdx)
  40053c:  c3             retq
```

- **Disassembler** (`objdump -d sum`)
  - Useful tool for examining object code (`man 1 objdump`)
  - Analyzes bit pattern of series of instructions
  - Produces approximate rendition of assembly code
  - Can run on either `a.out` (complete executable) or `.o` file

## What Can be Disassembled?

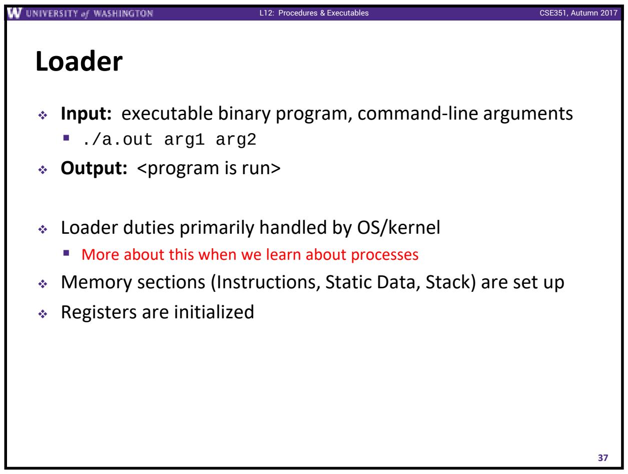
```
% objdump -d WINWORD.EXE

WINWORD.EXE:   file format pei-i386

No symbols in "WINWORD.EXE".
Disassembly of section .text:

30001000 <.text>:
30001000:
30001001:
30001003:         Reverse engineering forbidden by
30001005:         Microsoft End User License Agreement
3000100a:
```

- Anything that can be interpreted as executable code
- Disassembler examines bytes and attempts to reconstruct assembly source



## Loader

- **Input:** executable binary program, command-line arguments
  - `./a.out arg1 arg2`
- **Output:** <program is run>

- Loader duties primarily handled by OS/kernel
  - More about this when we learn about processes
- Memory sections (Instructions, Static Data, Stack) are set up
- Registers are initialized