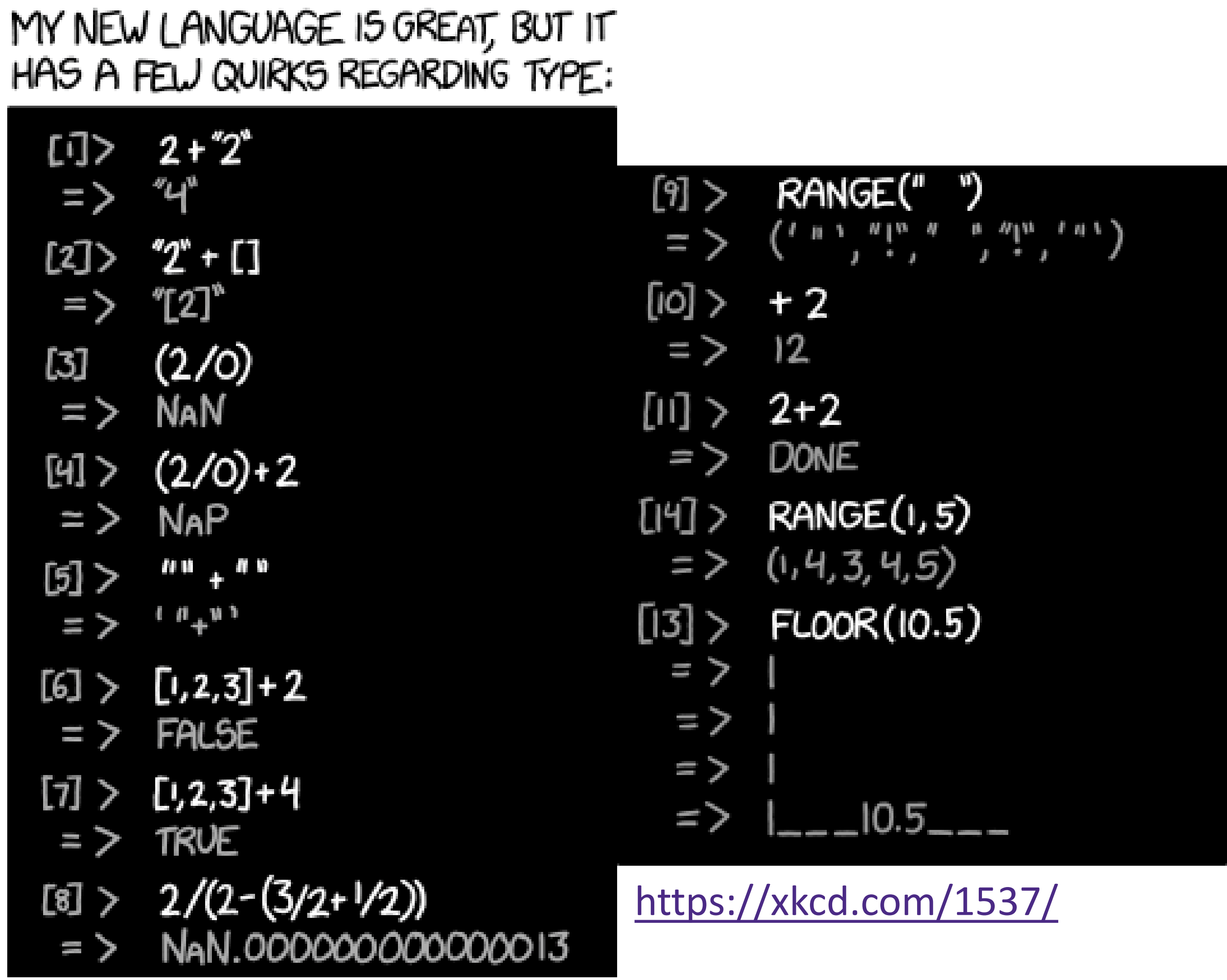
Procedures & Executables

CSE 351 Spring 2018



https://xkcd.com/1537/

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

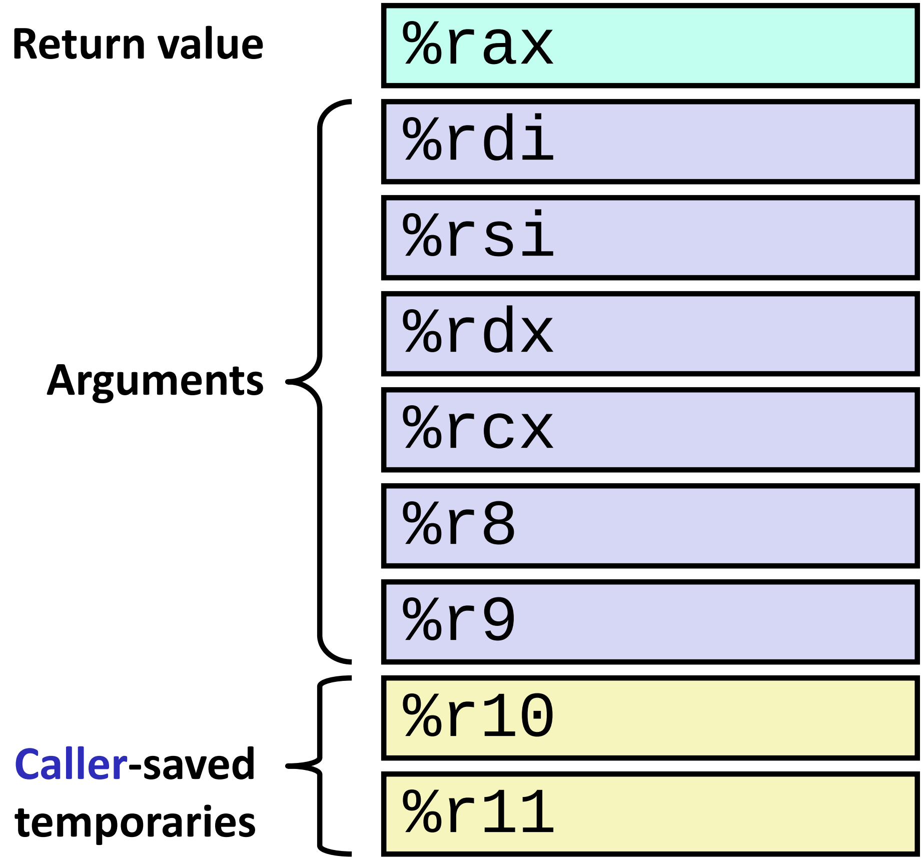
- ***"Caller-saved" registers***
  - It is the **caller**'s responsibility to save any important data in these registers before calling another procedure (*i.e.* the **callee** can freely change data in these registers)
  - **Caller** saves values in its stack frame before calling **Callee**, then restores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

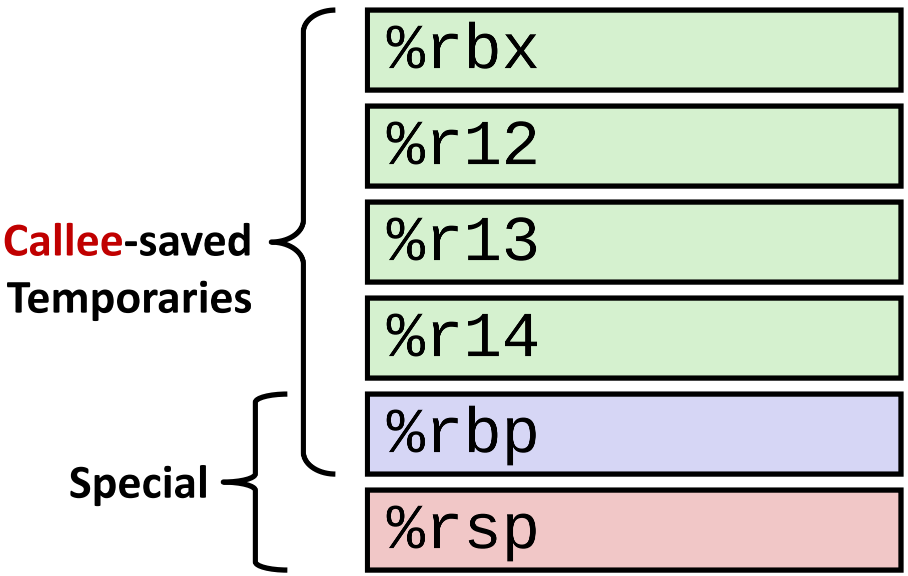
x86-64 Linux Register Usage, part 1

- `%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



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



x86-64 64-bit Registers: Usage Conventions

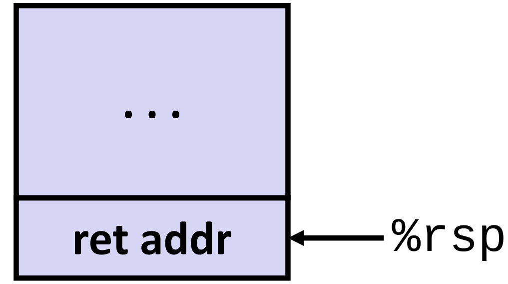
`%rax`	Return value - Caller saved	`%r8`	Argument #5 - Caller saved
`%rbx`	Callee saved	`%r9`	Argument #6 - Caller saved
`%rcx`	Argument #4 - Caller saved	`%r10`	Caller saved
`%rdx`	Argument #3 - Caller saved	`%r11`	Caller Saved
`%rsi`	Argument #2 - Caller saved	`%r12`	Callee saved
`%rdi`	Argument #1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

Callee-Saved Example (step 1)

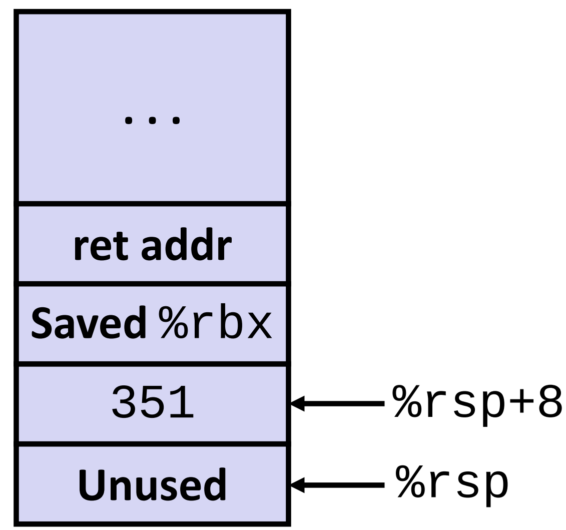
```
long call_incr2(long x) {
    long v1 = 351;
    long v2 = increment(&v1, 100);
    return x+v2;
}
```

```
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



Resulting Stack Structure

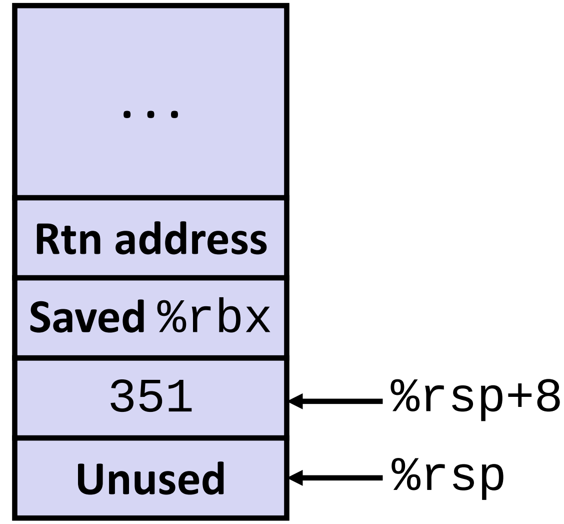


Callee-Saved Example (step 2)

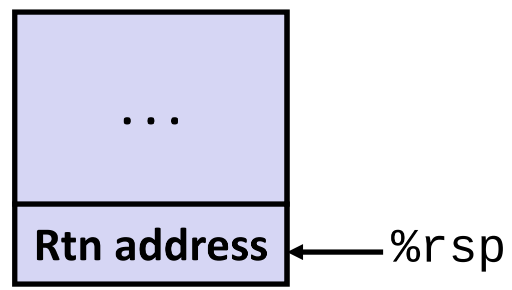
```
long call_incr2(long x) {
    long v1 = 351;
    long v2 = increment(&v1, 100);
    return x+v2;
}
```

```
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



Pre-return Stack Structure



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);
}
```

```
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
```

Compiler Explorer:

https://godbolt.org/g/W8DxeR

- Compiled with `-O1` for brevity instead of `-Og`
- Try `-O2` instead!

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.

The Stack

...
rtn <main+?>
saved %rbx ← %rsp

```
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

The Stack

. . .
rtn <main+?>
saved %rbx

%rsp → saved %rbx

```
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
```

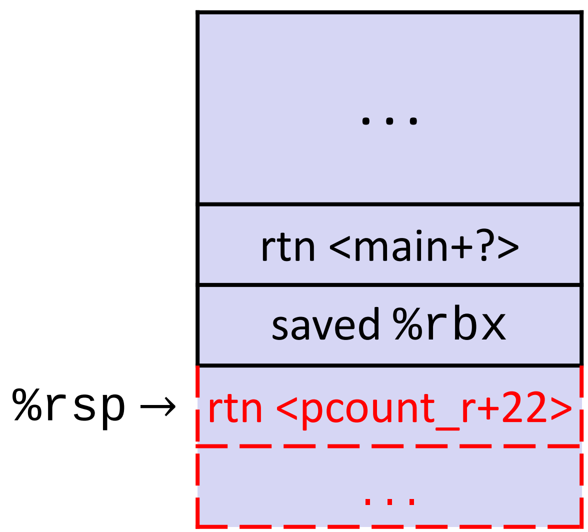
Recursive Function: Call

```
/* 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
```

The Stack



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
```

The Stack

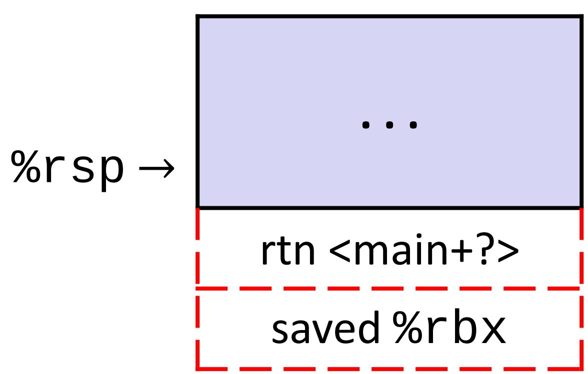
...
rtn <main+?>
%rsp → saved %rbx

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

The Stack




```
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)

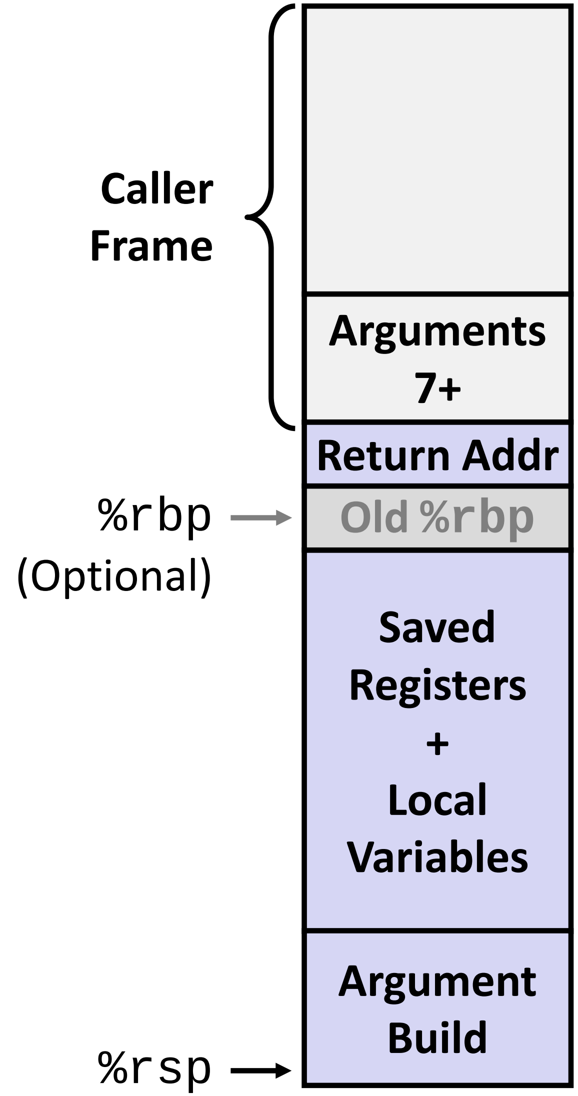
x86-64 Stack Frames

- 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:

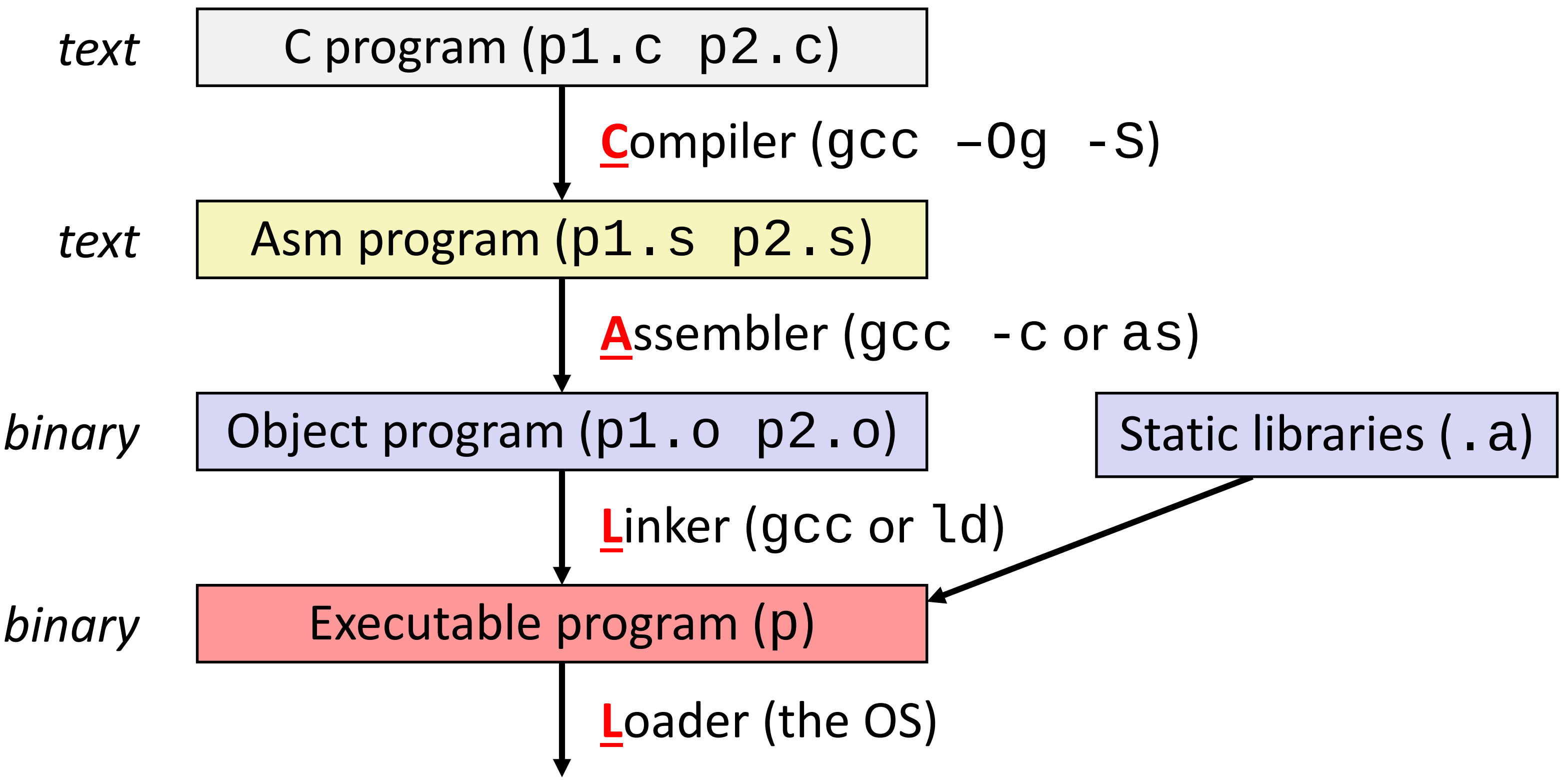
Windows 10 OS X Yosemite

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`

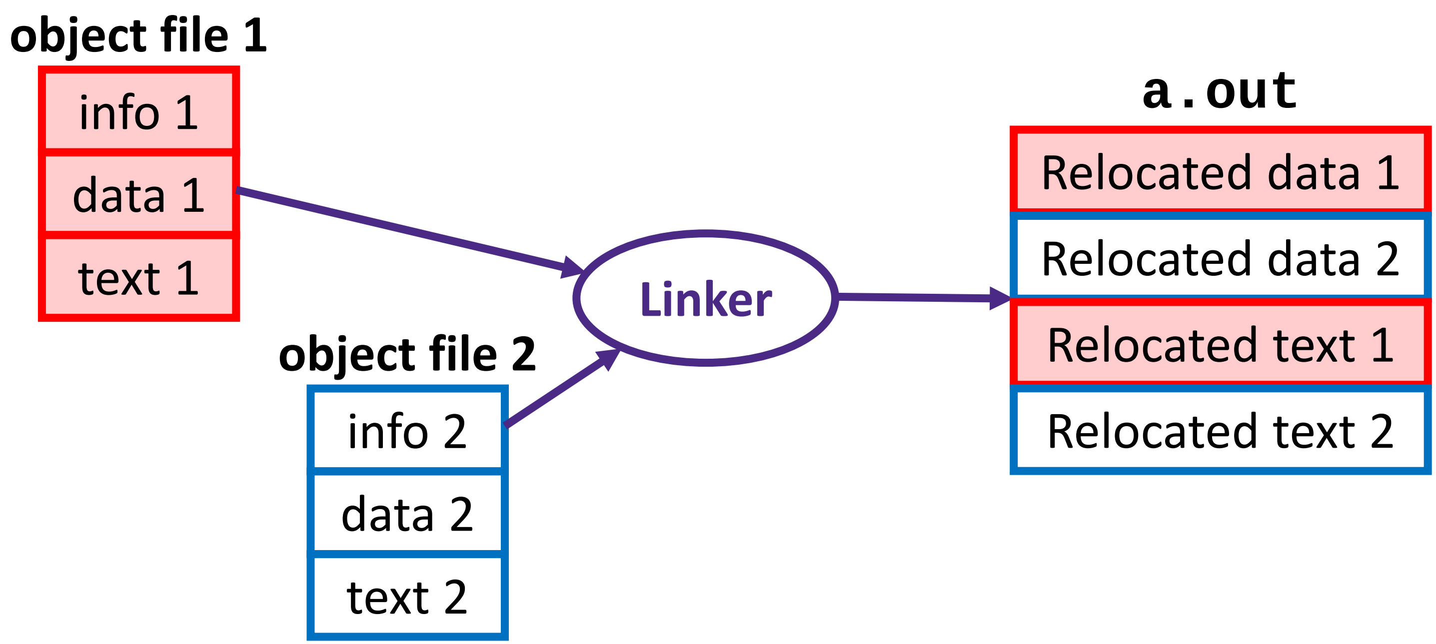
Linker

- **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:
30001005:
3000100a:
```

Reverse engineering forbidden by
Microsoft End User License Agreement

- 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