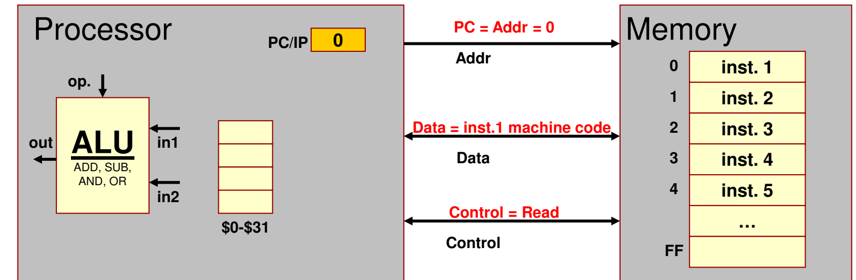
CS356 Unit 6

x86 Procedures

Basic Stack Frames

Review of Program Counter (Instruc. Pointer)

- PC/IP is used to __________ an instruction
  - PC/IP contains the __________ of the next instruction
  - The value in the PC/IP is placed on the address bus and the memory is told to read
  - The PC/IP is incremented, and the process is repeated for the next instruction



Procedures (Subroutines)

CS:APP 3.7.1

- Procedures (aka subroutines or ___________) are ________ sections of code that we can call from some location, execute that procedure, and then ______________________________

C code:

```
int main() {

  ...
  x = 8;
  res = avg(x,4);
  printf("%d\n", res);
}

int avg(int a, int b){
  return (a+b)/2;
}
```

We call the procedure to calculate the average and when it is finished it will return to where we left off

A procedure to calculate the average of 2 numbers

Procedures

- Procedure calls are similar to __________ instructions where we go to a new location in the code

C code:

```
int main() {

  ...
  x = 8;
  res = avg(x,4);
  printf("%d\n", res);
}

int avg(int a, int b){
  return (a+b)/2;
}
```

1 Call "avg" procedure will require us to jump to that code

Normal Jumps vs. Procedures

- Difference between normal jumps and procedure calls is that with procedures we have to __________ to where we left off
- We need to ____________ to the return location ________ we jump to the procedure…if we wait until we get to the function __________________

C code:

```
int main() {

  ...
  x = 8;
  res = avg(x,4);
  printf("%d\n", res);
}

int avg(int a, int b){
  return (a+b)/2;
}
```

1. Call "avg" procedure will require us to jump to that code
2. After procedure completes, return to the statement in the main code where we left off

Implementing Procedures

- To implement procedures in assembly we need to be able to:
  - Jump to the procedure code, leaving a "return link" (i.e. _________________) to know where to return
  - Find the return address and go back to that location

C code:

Call
```
...
res = avg(x,4);
...
```

Definition
```
int avg(int a, int b)
{ return (a+b)/2; }
```

Desired return location

Assembly:

```
         .text
         ...
0x4001b  call  AVG    # save a link
0x40020  next inst.   # to next instruc.

AVG:
0x40180  movl  %edi, %eax
0x40183  addl  %esi, %eax
0x40186  sarl  1, %eax
0x40188  ret
```


Return Addresses

- When calling a procedure, the address to jump to is _______ _______________
- The location where a procedure returns ________________
  - Always the address of the instruction ___________________

Assembly:

PC 0004 0000 → 0x40000 call AVG

PC 0004 0024 → 0x40024 call AVG

```
0x40000  call AVG     _______ is the return address for this call
0x40004  add
         ...
0x40024  call AVG     _______ is the return address for this call
0x40028  sub
         ...

0x40180  AVG:
         ...
         ret
```


Return Addresses

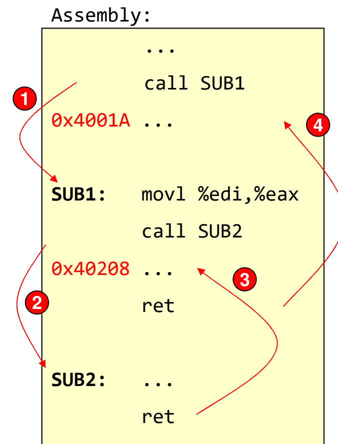
- A further (very common) complication is _________ procedure calls
  - One procedure calls __________
- Example: Main routine calls SUB1 which calls SUB2
- Must store both return addresses but where?
  - Registers? __________________
  - Memory? _________________ memory for deep levels of nesting

Assembly:

```
         ...
         call SUB1
0x4001A  ...

SUB1:    movl %edi,%eax
         call SUB2
0x40208  ...
         ret

SUB2:    ...
         ret
```

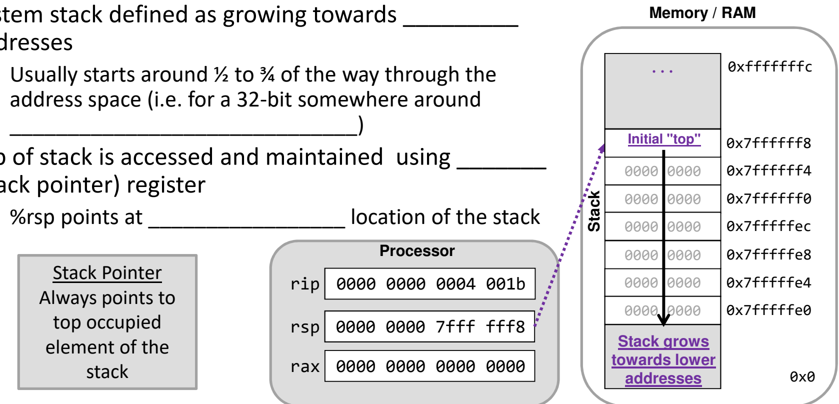
Return Addresses and Stacks

- Note: Return addresses will be accessed in ___________ order as they are stored
  - 0x40208 is the ______ RA to be stored but should be the _____ one used to return
- A ____ structure is appropriate!
- The system stack will be a place where we can store
  - Return addresses and other saved register values
  - _____________ of a function
  - _____________ for procedures



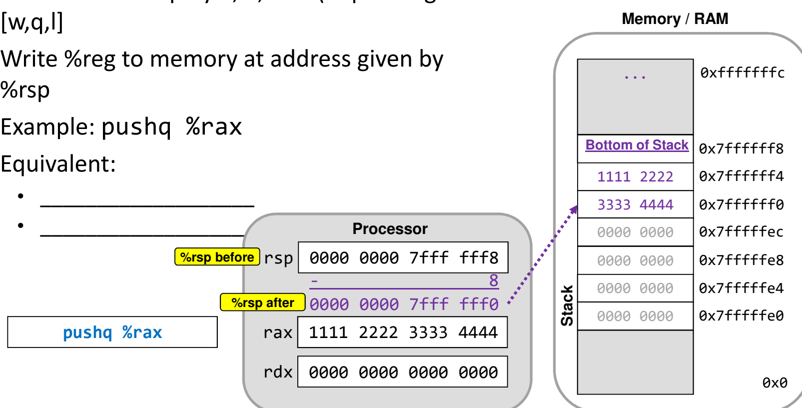
System Stack

- Stack is a data structure where data is accessed in reverse order as it is stored (a.k.a. LIFO = Last-in First-out)
- Use a stack to store the return addresses and other data
- System stack defined as growing towards _________ addresses
  - Usually starts around ½ to ¾ of the way through the address space (i.e. for a 32-bit somewhere around ___________________________)
- Top of stack is accessed and maintained using _______ (stack pointer) register
  - %rsp points at _______________ location of the stack



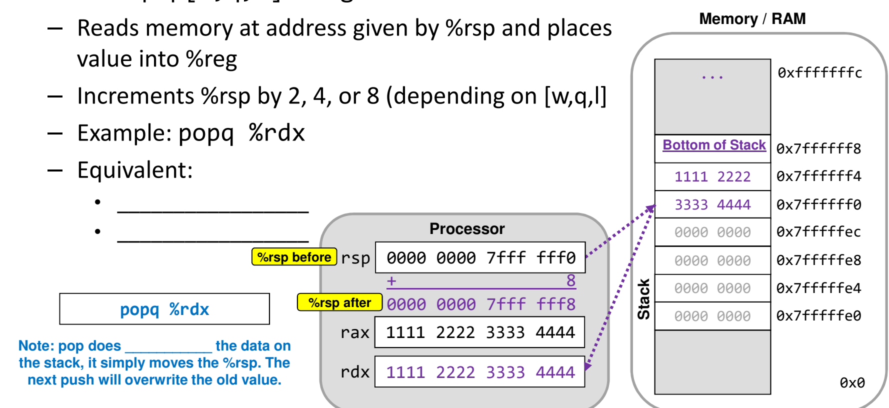
Push Operation and Instruction

- Push operation adds data to system stack
- Format: `push[w,q,l] %reg`
  - Decrements %rsp by 2, 4, or 8 (depending on [w,q,l]
  - Write %reg to memory at address given by %rsp
  - Example: `pushq %rax`
  - Equivalent:
    - _______________
    - _______________



Pop Operation and Instruction

- Pop operation removes data from system stack
- Format: `pop[w,q,l] %reg`
  - Reads memory at address given by %rsp and places value into %reg
  - Increments %rsp by 2, 4, or 8 (depending on [w,q,l]
  - Example: `popq %rdx`
  - Equivalent:
    - _______________
    - _______________



Jumping to a Procedure

CS:APP 3.7.2

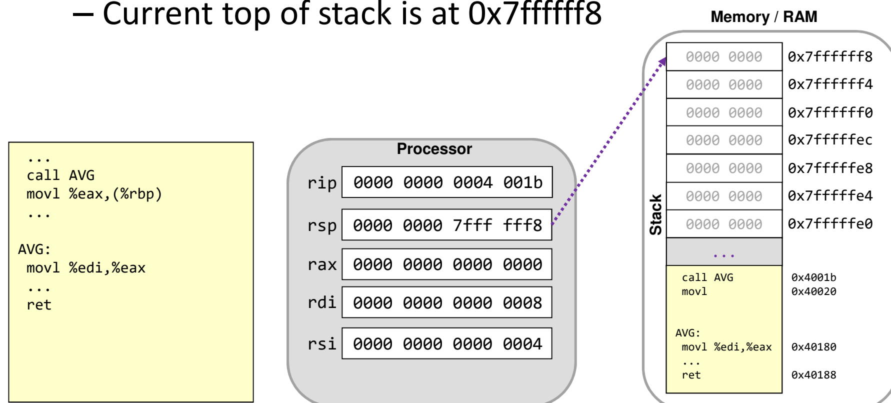
- Format:
  - `call label`
  - `call *operand [e.g. call (%rax)]`
- Operations:
  - Pushes the address of next instruction (i.e. return address (RA)) onto the stack
    - Implicitly performs `subq $8, (%rsp)` and `movq %rip, (%rsp)`
  - Updates the PC to go to the start of the desired procedure [i.e. PC = addr]
    - addr is the address you want to branch to (*Usually specified as a label*)

Returning From a Procedure

- Format:
  - `ret`
- Operations:
  - Pops the return address from the stack into %rip [i.e. PC = return-address]
  - Implicitly performs `movq (%rsp), %rip` and `addq $8, %rsp`

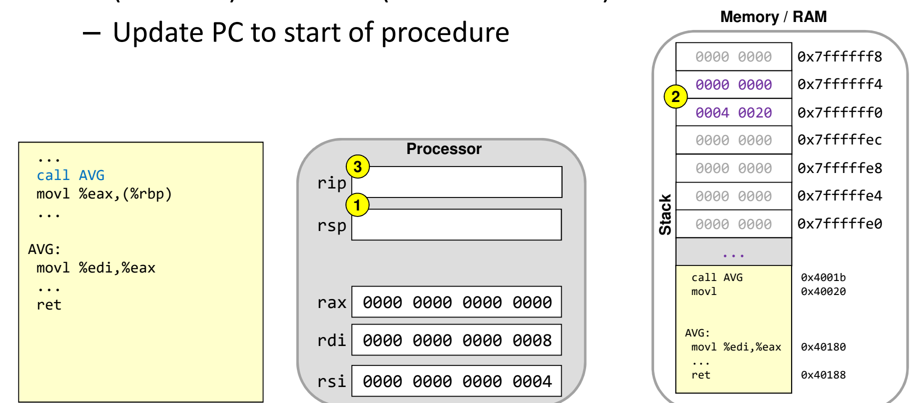
Procedure Call Sequence 1a

- Initial conditions
  - About to execute the 'call' instruction
  - Current top of stack is at 0x7ffffff8



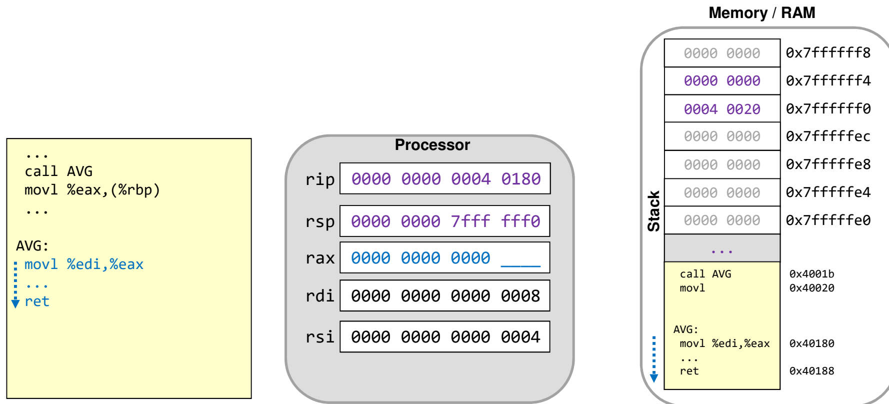
Procedure Call Sequence 1b

- call Operation (i.e. push return address) & jump
  - Decrement stack pointer ($rsp) and ______ RA (0x40020) onto stack (as 64-bit address)
  - Update PC to start of procedure



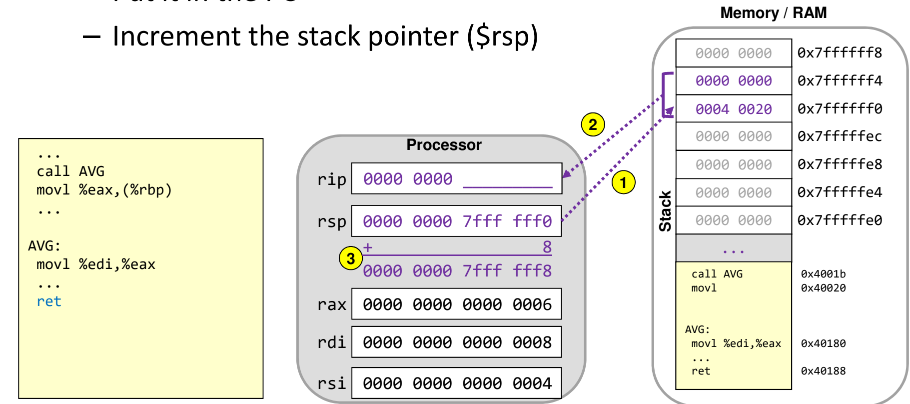
Procedure Call Sequence 1c

- Execute the code for the procedure
- Return value should be in %rax/%eax



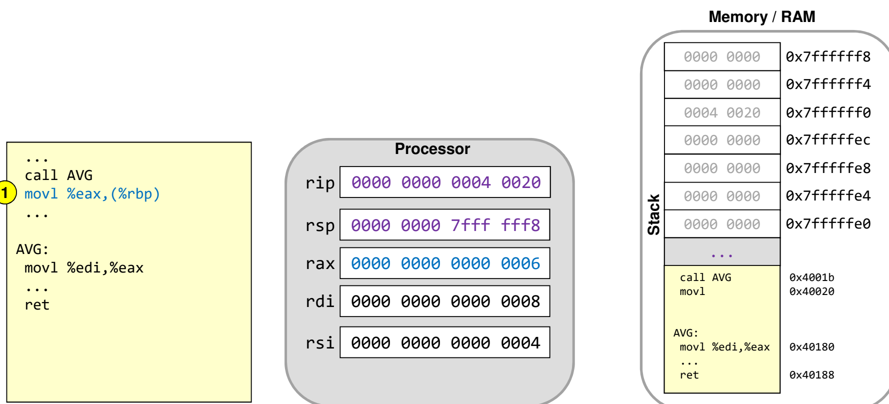
Procedure Call Sequence 1d

- ret Operation (i.e. pop return address)
  - Retrieve RA (0x40020) from stack
  - Put it in the PC
  - Increment the stack pointer ($rsp)



Procedure Call Sequence 1e

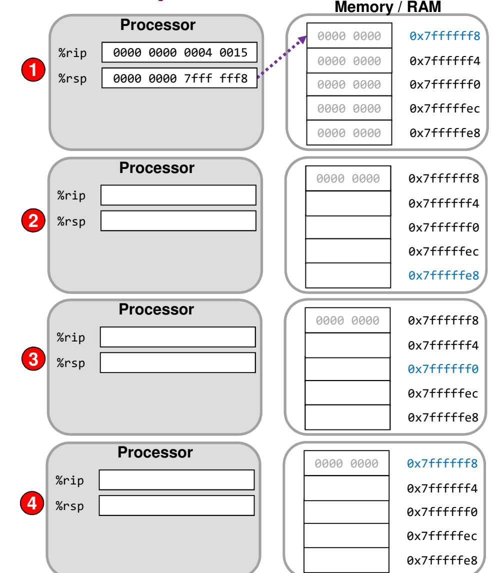
- Execution resumes after the procedure call



Procedure Call Sequence 2

- Show the values of the stack, %rsp, and %rip at the various timestamps for the following code

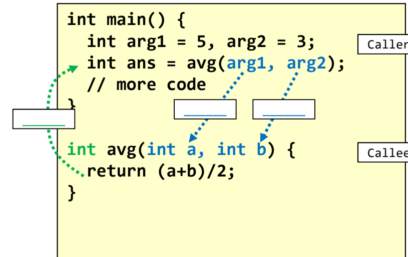
```
            ...
(1) 0x40015 call SUB1
(4) 0x4001A ...

    0x40200
    SUB1:   movl %edi,%eax
            call SUB2
(3) 0x40208 ...
            ret

    0x40380
(2) SUB2:   ...
            ret
```



Arguments and Return Values

CS:APP 3.7.3

- Most procedure calls pass arguments/parameters to the procedure and it often produces return values
- To implement this, there must be locations _____________ by caller and callee for where this information will be found
- x86-64 convention is to use certain registers for this task (**see table**)



1st Argument	________
2nd Argument	________
3rd Argument	%rdx
4th Argument	%rcx
5th Argument	%r8
6th Argument	%r9
Additional arguments	__________
Return value	_________

Passing Arguments and Return Values

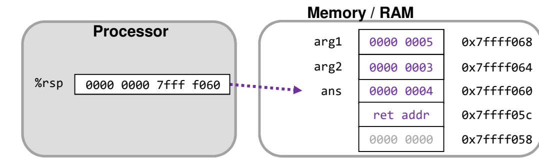
```
void main() {
  int arg1 = 5, arg2 = 3;
  int ans = avg(arg1, arg2);
  // do something
}

int avg(int a, int b) {
  return (a+b)/2;
}
```

%eax %edi %esi

C Code

```
      .text
      movl  $5, 8(%rsp)
      movl  $3, 4(%rbp)
      movl  8(%rsp), %edi
      movl  4(%rsp), %esi
      call  AVG
      movl  %eax, (%rsp)

AVG:
      movl  %edi, %eax
      addl  %esi, %eax
      sarl  1, %eax
      ret
```

Assembly



Compiler Handling of Procedures

- When coding in an high level language & using a compiler, certain conventions are followed that may lead to heavier usage of the stack
  - We have to be careful not to ____________registers that have useful data
- High level languages (HLL) use the stack:
  - to ____________ values including the return address
  - for storage of _______________ declared in the procedure
  - to ______________ to a procedure
- Compilers usually put data on the stack in a certain order, which we call a _________________

Stack Frames

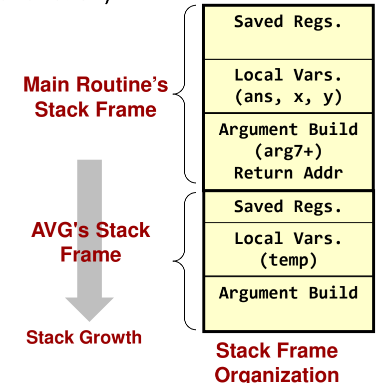
- Frame = ***Def:*** _________ on stack belonging to a procedure / function
  - Space for saved registers
  - Space for local variables (those declared in a function)
  - Space for arguments

```
void main() {
  int ans, x, y;
  ans = avg(x, y);
  ...
}
int avg(int a, int b) {
  int temp=1;  // local vars
  ...
}
```

Main Routine's Stack Frame

AVG's Stack Frame

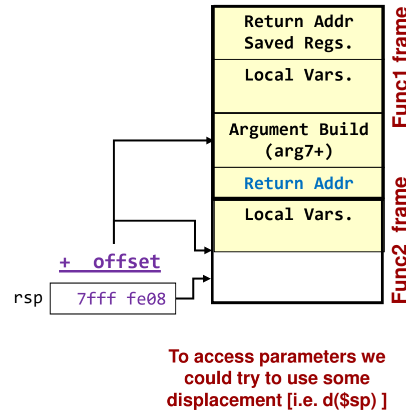
Stack Growth



Stack Frame Organization

Accessing Values on the Stack

- Stack pointer (%rsp) is usually used to access only the top value on the stack
- To access arguments and local variables, we need to access values __________ in the stack
  - We can simply use an offset from %rsp [_____________]



To access parameters we could try to use some displacement [i.e. d($sp)]

Many Arguments Examples

- Examine the following C code and corresponding assembly
- Assume initially %rsp = 0x7ffffff8
- Note how the 7th and 8th arguments are passed via the stack

```
caller:
    pushq   $8
    pushq   $7
    movl    $6, %r9d
    movl    $5, %r8d
    movl    $4, %ecx
    movl    $3, %edx
    movl    $2, %esi
    movl    $1, %edi
    call    f1
    addq    $16, %rsp
    ret
f1:    # 0x40200
    addl    %edi, %esi
    addl    %esi, %edx
    addl    %edx, %ecx
    addl    %ecx, %r8d
    addl    %r8d, %r9d
    movl    %r9d, %eax
    addl    8(%rsp), %eax
    addl    16(%rsp), %eax
    ret
```

```
int caller()
{
  int sum = f1(1, 2, 3, 4, 5, 6, 7, 8);
  return sum;
}

int f1(int a1, int a2, int a3, int a4,
       int a5, int a6, int a7, int a8)
{
  return a1+a2+a3+a4+a5+a6+a7+a8;
}
```

Processor

Register	Value
rip	0000 0000 0004 0020
rsp	0000 0000 7fff fff8
rdi	0000 0000 0000 0001
rsi	0000 0000 0000 0002

Memory / RAM (Stack)

Value	Address
0000 0000	0x7ffffff8
0000 0000	0x7ffffff4
0000 0008	0x7ffffff0
0000 0000	0x7fffffec
0000 0007	0x7fffffe8
0000 0000	0x7fffffe4
0004 0018	0x7fffffe0
...	
... call f1	0x40013
addq	0x40018
f1: movl %edi,%eax	0x40200
... ret	

Local Variables

CS:APP 3.7.4

- For simple integer/pointers the compiler can optimize code by __________________ rather than allocating the variable on the stack
- Local variables need to be allocated on the stack if:
  - No free registers (________________)
  - The _____ operator is used and thus we need to be able to generate an ______________
  - ____________________ are used

Local Variables Example

```
f2: ⓪  pushq   %r12
        pushq   %rbp
        pushq   %rbx
    ①  subq    $0x30, %rsp
        movl    %edi, %r12d
        movq    %fs:0x28, %rax
        movq    %rax, 0x28(%rsp)
        xorl    %eax, %eax
    ②  leaq    0xc(%rsp), %rdi
        call    getInt
    ③  movl    $0, %ebx
        jmp     .L4
.L6:    movslq  %ebx, %rbp
    ⑤  leaq    0x10(%rsp,%rbp,4), %rdi
        call    getInt
    ⑥  movl    0x10(%rsp,%rbp,4), %eax
        cmpl    0xc(%rsp), %eax
        jge     .L5
    ⑦  movl    %eax, 0xc(%rsp)
.L5:    addl    $1, %ebx
.L4: ④ cmpl    $3, %ebx
        jle     .L6
    ⑧  movslq  %r12d, %r12
        movl    0xc(%rsp), %eax
        addl    0x10(%rsp,%r12,4), %eax
    ⑨  movq    0x28(%rsp), %rdx
        xorq    %fs:0x28, %rdx
        je      .L7
        call    __stack_chk_fail
.L7:    addq    $0x30, %rsp
        popq    %rbx
        popq    %rbp
        popq    %r12
        ret
```

```
void getInt(int* ptr);
int f2(int idx)
⓪{
①int dat[4], min;
②getInt(&min); ④
③for(int i=0; i < 4; i++){
⑤  getInt(&dat[i]); ⑦
⑥  if(dat[i] < min) min = dat[i];
   }
⑧return dat[idx] + min;
⑨}
```

- %rdi = %r12 = idx
- %rbp = %ebx = int i
- Notice %rdi must be reused from idx to the arguments for getInt(), thus the use of %r12 to hold idx

Processor

Register	Value
rsp	0000 0000 7fff ffa8
rbp (i)	0000 0000 0000 0001
r12 (idx)	0000 0000 0000 0002

Memory / RAM (Stack Frame)

Value	Address
return	0x7ffffff4
address	0x7ffffff0
saved	0x7fffffec
%r12	0x7fffffe8
saved	0x7fffffe4
%rbp	0x7fffffe0
saved	0x7fffffdc
%rbx	0x7fffffd8
canary	0x7fffffd4
value	0x7fffffd0
0000 0000	0x7fffffcc
0000 0000	0x7fffffc8
dat[3]	0x7fffffc4
dat[2]	0x7fffffc0
dat[1]	0x7fffffbc
dat[0]	0x7fffffb8
min	0x7fffffb4
0000 0000	0x7fffffb0
0000 0000	0x7fffffac
0000 0000	0x7fffffa8

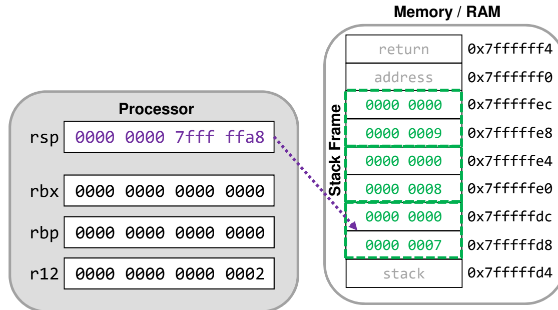
Saved Register Problem

CS:APP 3.7.5

- Procedures are generally compiled ___________________
- The compiler will use registers for some temporaries and ________________
- What could go wrong?

```
f2:     pushq   %r12
        pushq   %rbp
        pushq   %rbx
        subq    $0x30, %rsp
        movl    %edi, %r12d
        ...
        movl    $0, %ebx
        ...
        movslq  %ebx, %rbp
        leaq    0x10(%rsp,%rbp,4), %rdi
        ...
        popq    %rbx
        popq    %rbp
        popq    %r12
        ret

f1:     ...
        movl    $7, %ebx
        movl    $8, %ebp
        movq    $9, %r12
        movl    $2, %rdi
        call    f2
        ...
        add     %ebx, %ebp
        subq    $1, %r12
        ...
```

Why are these needed?



Saved Register Problem

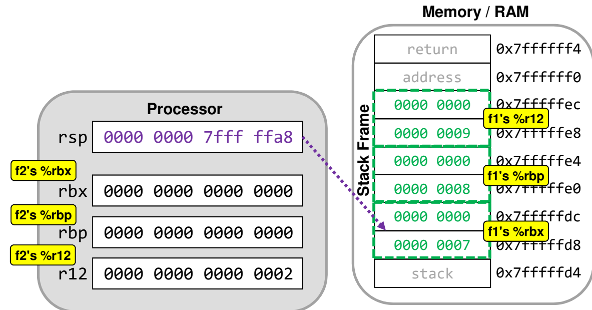
- One procedure might overwrite a register value _______________________
- If f1() had values in %rbx, %rbp, and %r12 before calling f2() and then needed those values upon return, f2() may accidentally overwrite them

```
f2:     pushq   %r12
        pushq   %rbp
        pushq   %rbx
        subq    $0x30, %rsp
        movl    %edi, %r12d
        ...
        movl    $0, %ebx
        ...
        movslq  %ebx, %rbp
        leaq    0x10(%rsp,%rbp,4), %rdi
        ...
        popq    %rbx
        popq    %rbp
        popq    %r12
        ret

f1:     ...
        movl    $7, %ebx
        movl    $8, %ebp
        movq    $9, %r12
        movl    $2, %rdi
        call    f2
        ...
        add     %ebx, %ebp
        subq    $1, %r12
        ...
```

Why are these needed?

Solution: _______________ registers to/from the stack before overwriting it

- Which ones? Any register?



Caller & Callee-Saved Convention

- Having to always play it safe and save a register to the stack before using it can decrease performance
- To increase performance, a standard is set to indicate which registers must be _______________ (callee-saved) and which ones can be ____________________ (caller-saved)
  - Callee Saved: Push values before overwriting them; restore before returning
  - Caller Saved: Push if the register value is needed _______ the function call; callee can freely overwrite; caller will restore upon return

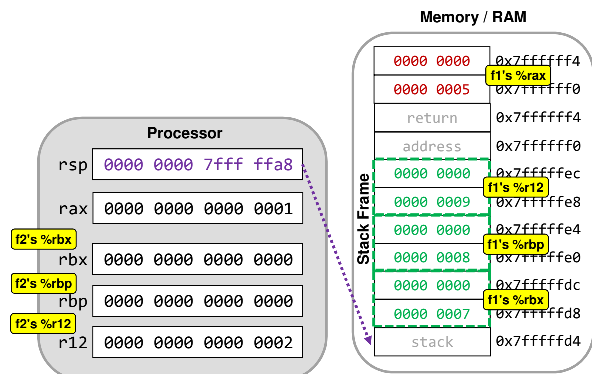
Callee-saved (Callee must ensure the value is not modified)	_______ _______ ___________ %rsp*
Caller-saved (Caller must save the value if it wants to preserve it across a function call)	All other registers

*%rsp need not be saved to the stack but should have the same value upon return as it did when the call was made

Caller vs. Callee Saved

- One procedure might overwrite a register value needed by the caller
- If f1() had values in %rbx, %rbp, and %r12 before calling f2() and then needed those values upon return, f2() may accidentally overwrite them

```
f2:     pushq   %r12
        pushq   %rbp      } Callee Saved
        pushq   %rbx
        subq    $0x30, %rsp
        movl    %edi, %r12d
        movl    $0, %ebx
        movl    $1, %eax
        movslq  %ebx, %rbp
        leaq    0x10(%rsp,%rbp,4), %rdi
        popq    %rbx
        popq    %rbp
        popq    %r12
        ret

f1:     ...
        movl    $7, %ebx
        movl    $8, %ebp
        movq    $9, %r12
        movq    $5, %rax  } Caller Saved
        push    %rax
        movl    $2, %rdi
        call    f2
        pop     %rax
        add     %ebx, %ebp
        subq    $1, %r12
        ...
```



Summary

- To support subroutines we need to save the return address on the stack
  - call and ret perform this implicitly
- There must be agreed upon locations where arguments and return values can be communicated
- The stack is a common memory location to allocate space for saved values and local variables