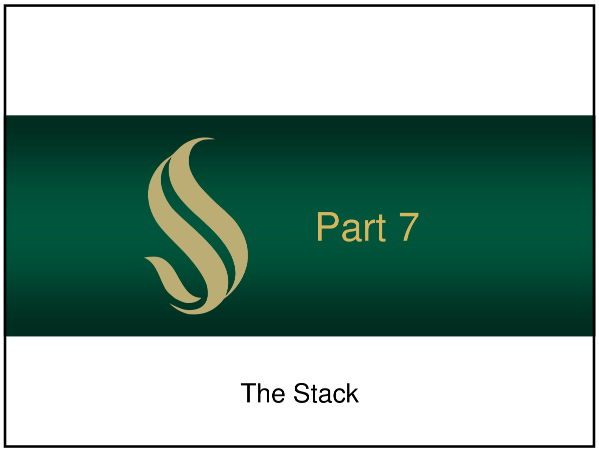
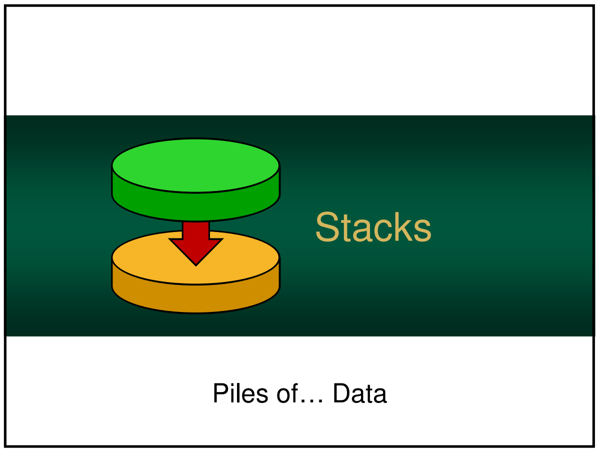


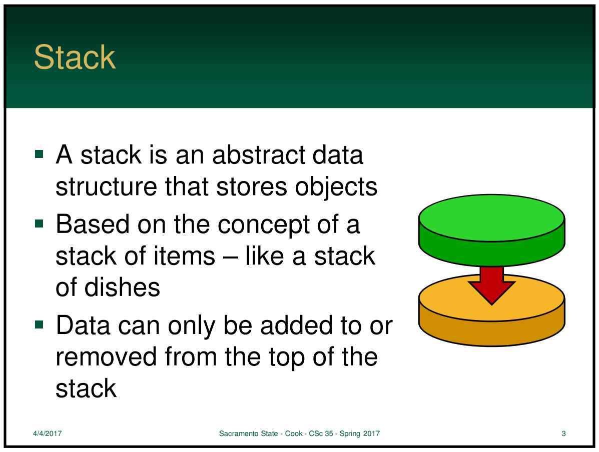
Part 7

The Stack



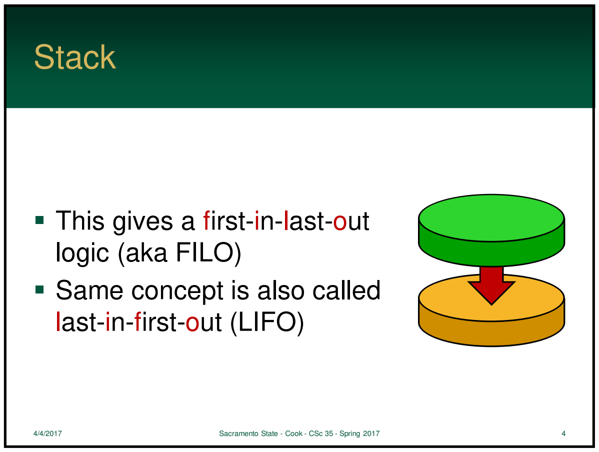
Stacks

Piles of… Data



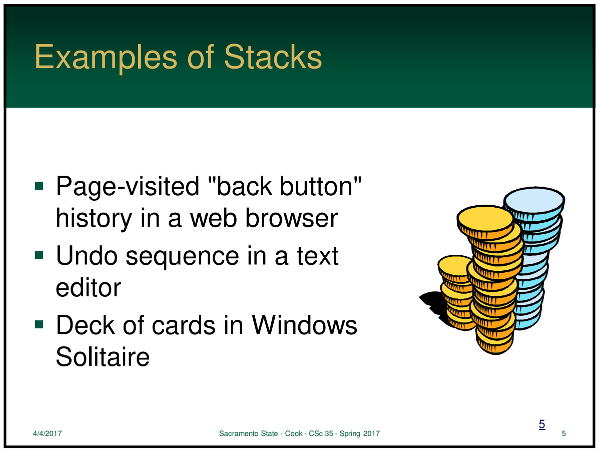
Stack

- A stack is an abstract data structure that stores objects
- Based on the concept of a stack of items – like a stack of dishes
- Data can only be added to or removed from the top of the stack



Stack

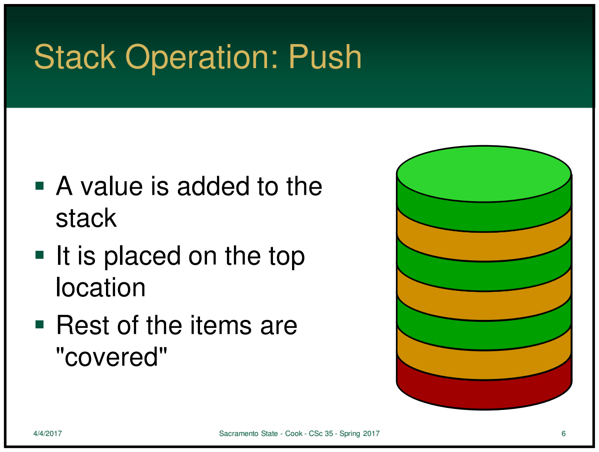
- This gives a first-in-last-out logic (aka FILO)
- Same concept is also called last-in-first-out (LIFO)



Examples of Stacks

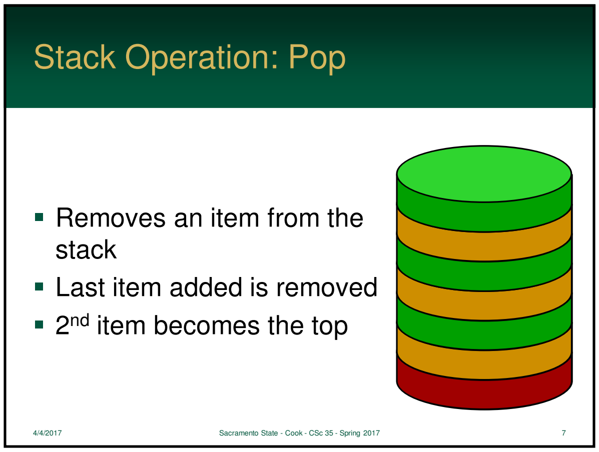
- Page-visited "back button" history in a web browser
- Undo sequence in a text editor
- Deck of cards in Windows Solitaire

5



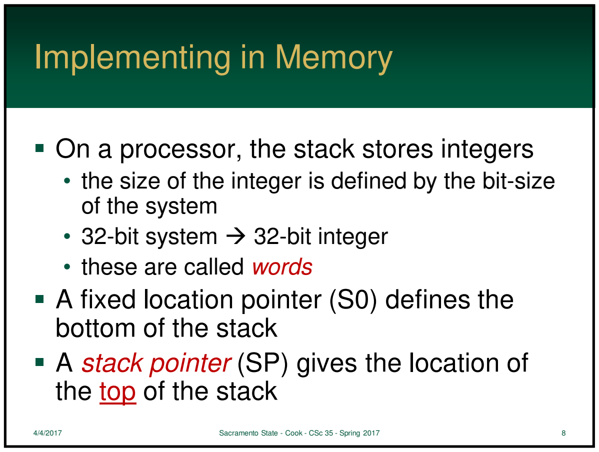
Stack Operation: Push

- A value is added to the stack
- It is placed on the top location
- Rest of the items are "covered"



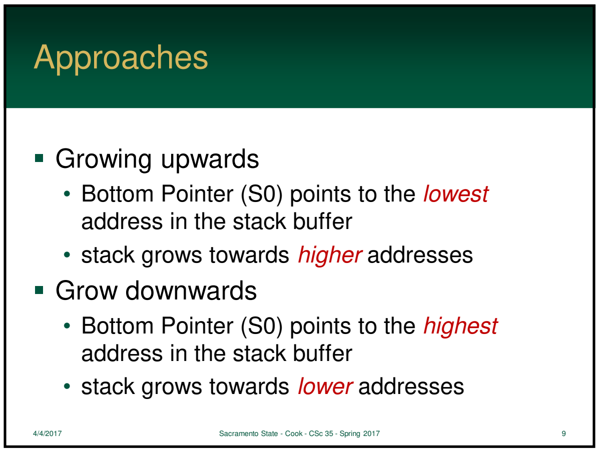
Stack Operation: Pop

- Removes an item from the stack
- Last item added is removed
- 2nd item becomes the top



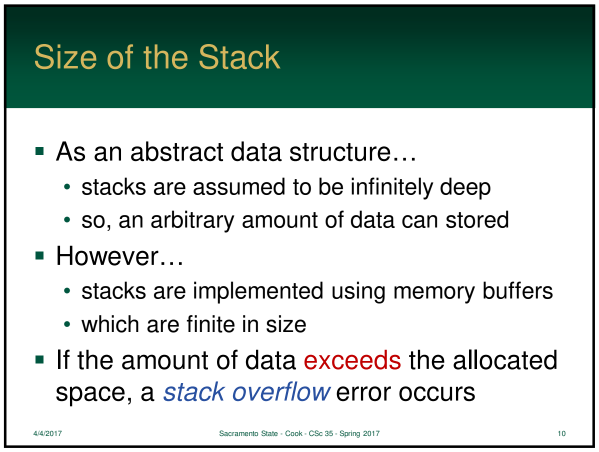
Implementing in Memory

- On a processor, the stack stores integers
  - the size of the integer is defined by the bit-size of the system
  - 32-bit system → 32-bit integer
  - these are called *words*
- A fixed location pointer (S0) defines the bottom of the stack
- A *stack pointer* (SP) gives the location of the top of the stack



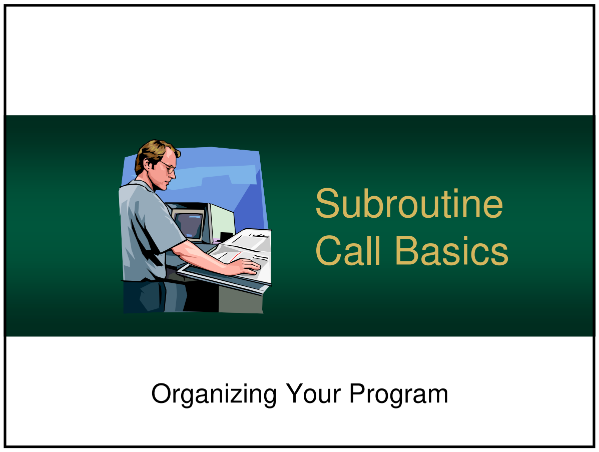
Approaches

- Growing upwards
  - Bottom Pointer (S0) points to the *lowest* address in the stack buffer
  - stack grows towards *higher* addresses
- Grow downwards
  - Bottom Pointer (S0) points to the *highest* address in the stack buffer
  - stack grows towards *lower* addresses



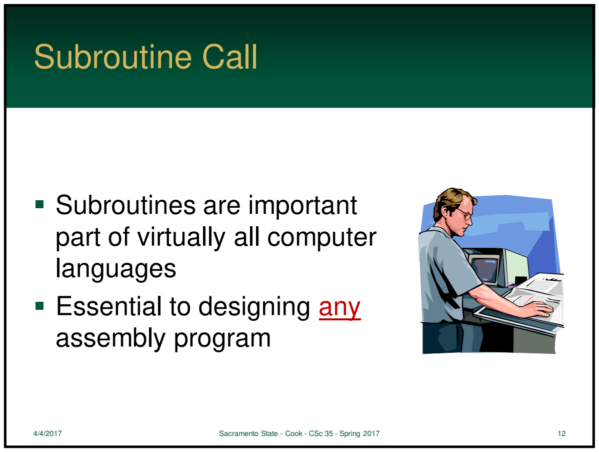
Size of the Stack

- As an abstract data structure…
  - stacks are assumed to be infinitely deep
  - so, an arbitrary amount of data can stored
- However…
  - stacks are implemented using memory buffers
  - which are finite in size
- If the amount of data exceeds the allocated space, a *stack overflow* error occurs



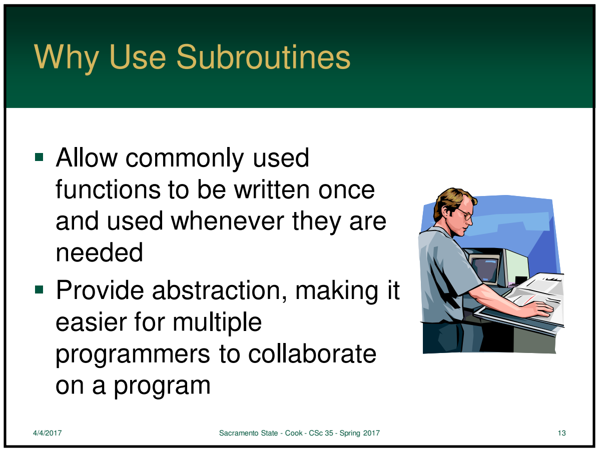
Subroutine Call Basics

Organizing Your Program



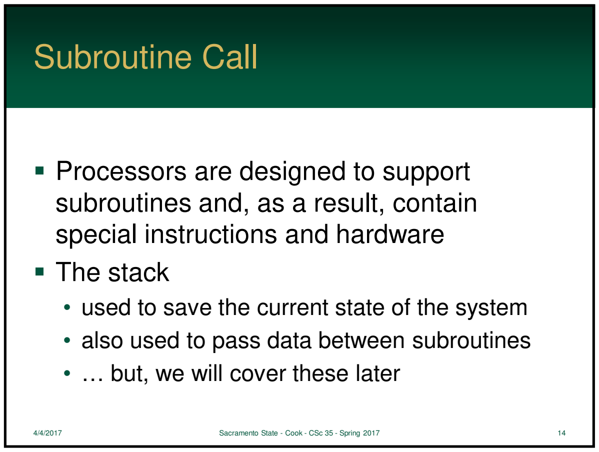
Subroutine Call

- Subroutines are important part of virtually all computer languages
- Essential to designing any assembly program



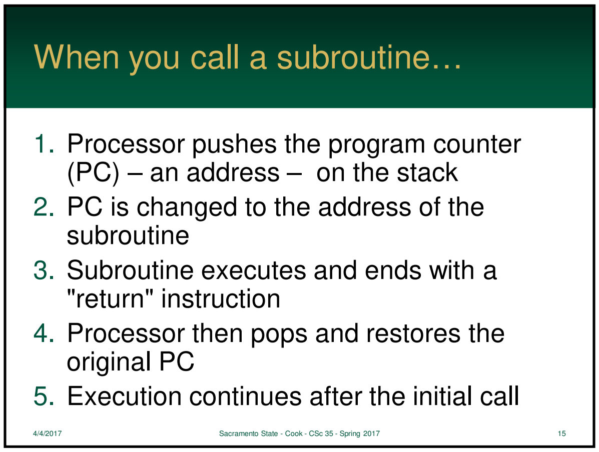
Why Use Subroutines

- Allow commonly used functions to be written once and used whenever they are needed
- Provide abstraction, making it easier for multiple programmers to collaborate on a program



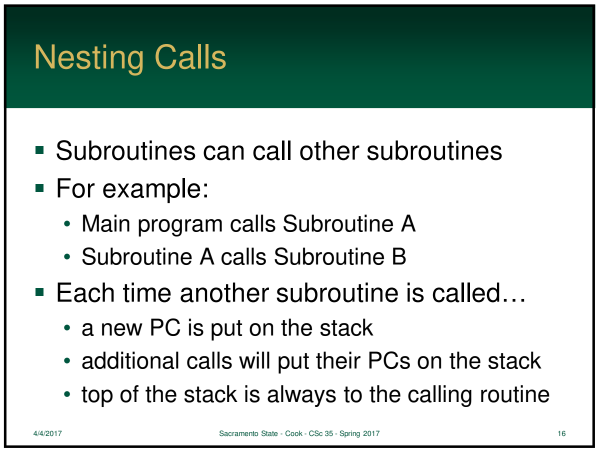
Subroutine Call

- Processors are designed to support subroutines and, as a result, contain special instructions and hardware
- The stack
  - used to save the current state of the system
  - also used to pass data between subroutines
  - … but, we will cover these later



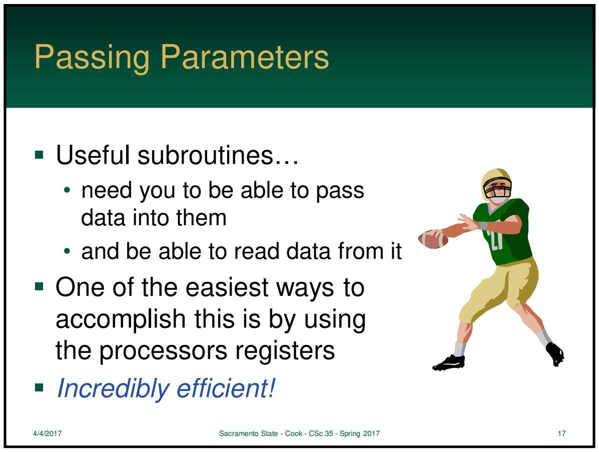
When you call a subroutine…

1. Processor pushes the program counter (PC) – an address – on the stack
2. PC is changed to the address of the subroutine
3. Subroutine executes and ends with a "return" instruction
4. Processor then pops and restores the original PC
5. Execution continues after the initial call



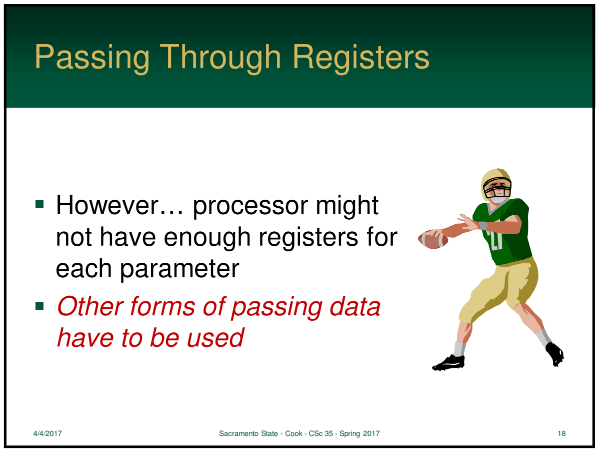
Nesting Calls

- Subroutines can call other subroutines
- For example:
  - Main program calls Subroutine A
  - Subroutine A calls Subroutine B
- Each time another subroutine is called…
  - a new PC is put on the stack
  - additional calls will put their PCs on the stack
  - top of the stack is always to the calling routine



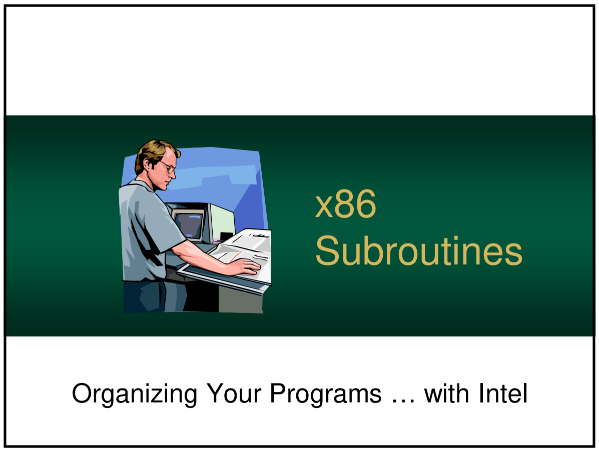
Passing Parameters

- Useful subroutines…
  - need you to be able to pass data into them
  - and be able to read data from it
- One of the easiest ways to accomplish this is by using the processors registers
- *Incredibly efficient!*



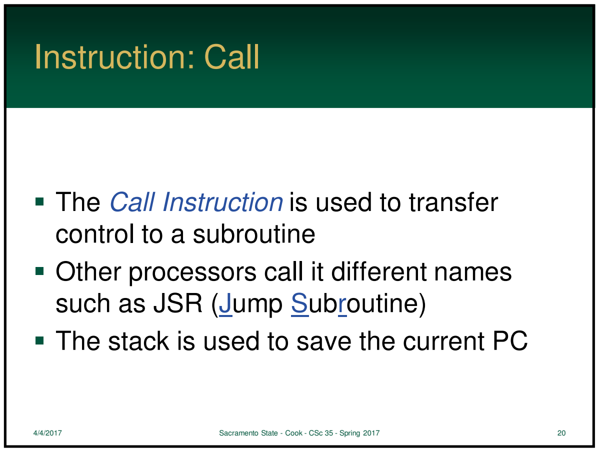
Passing Through Registers

- However… processor might not have enough registers for each parameter
- *Other forms of passing data have to be used*



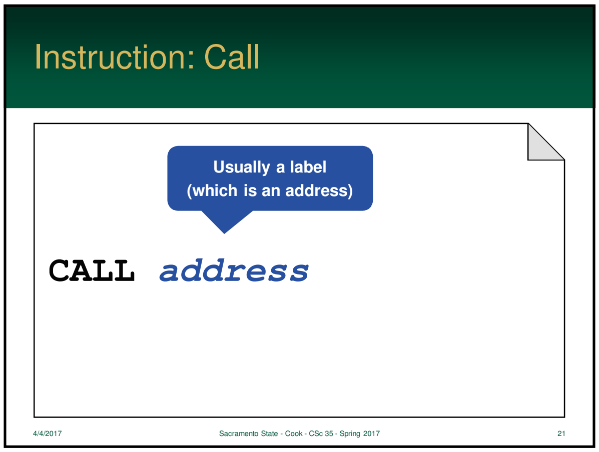
x86 Subroutines

Organizing Your Programs … with Intel



Instruction: Call

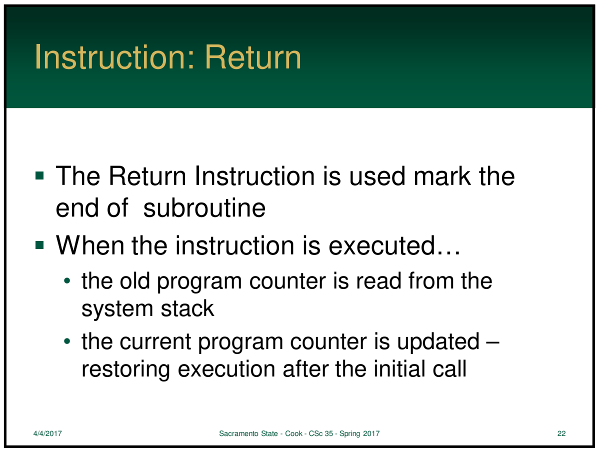
- The *Call Instruction* is used to transfer control to a subroutine
- Other processors call it different names such as JSR (Jump Subroutine)
- The stack is used to save the current PC



Instruction: Call

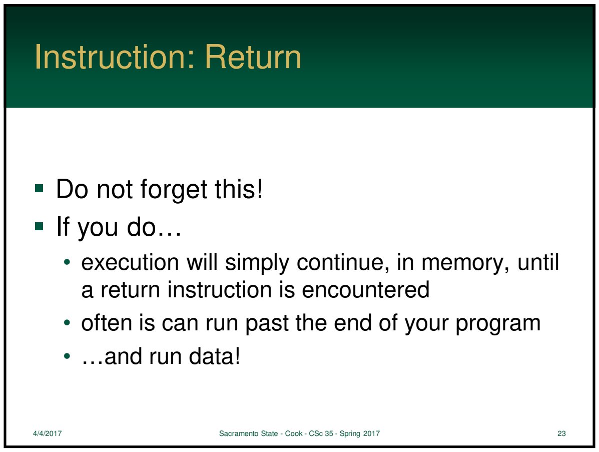
Usually a label (which is an address)

```
CALL address
```



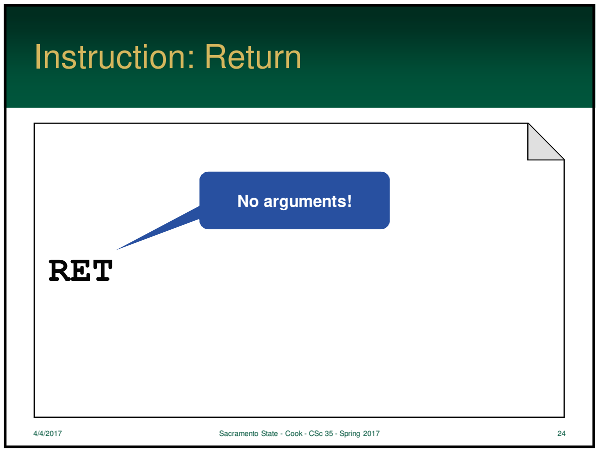
Instruction: Return

- The Return Instruction is used mark the end of subroutine
- When the instruction is executed…
  - the old program counter is read from the system stack
  - the current program counter is updated – restoring execution after the initial call



Instruction: Return

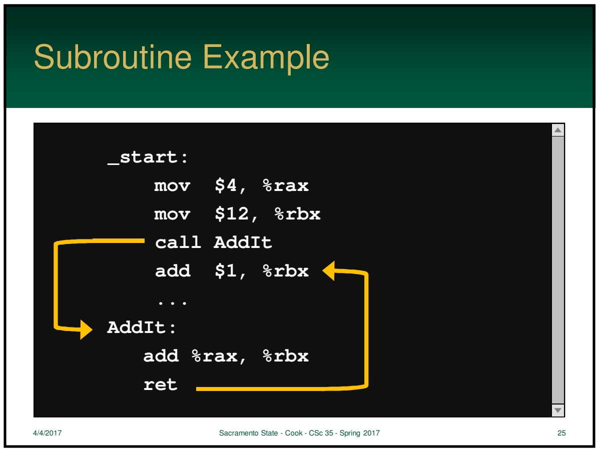
- Do not forget this!
- If you do…
  - execution will simply continue, in memory, until a return instruction is encountered
  - often is can run past the end of your program
  - …and run data!



Instruction: Return

No arguments!

```
RET
```

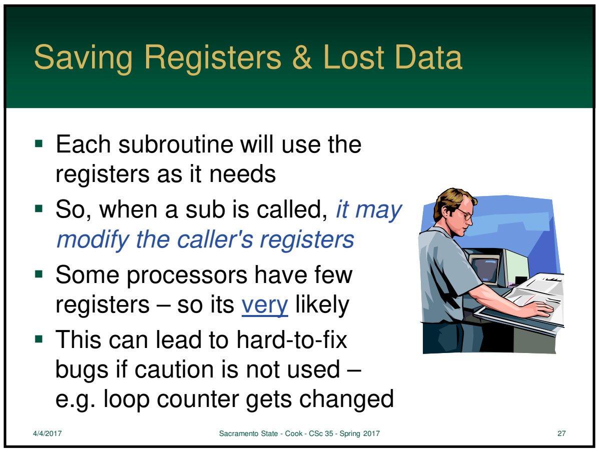


Subroutine Example

```
      _start:
          mov   $4, %rax
          mov   $12, %rbx
          call  AddIt
          add   $1, %rbx
          ...
      AddIt:
         add %rax, %rbx
         ret
```

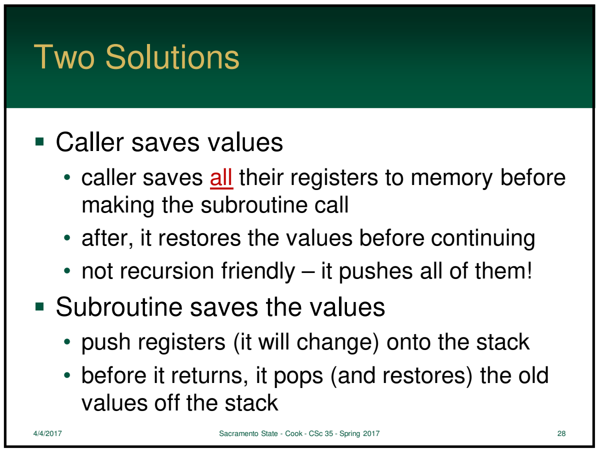
Saving Registers & Lost Data

Avoiding horrible side-effects



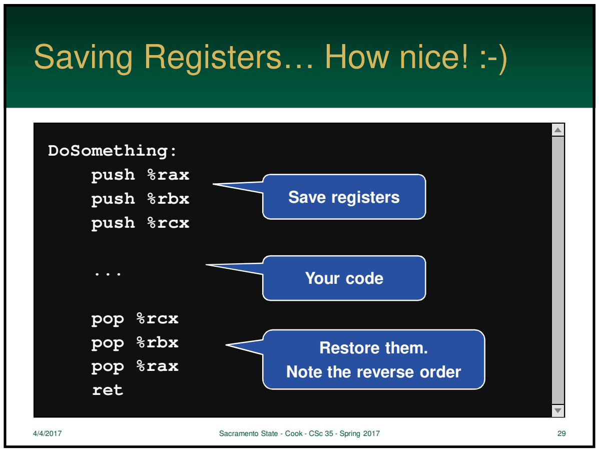
Saving Registers & Lost Data

- Each subroutine will use the registers as it needs
- So, when a sub is called, *it may modify the caller's registers*
- Some processors have few registers – so its very likely
- This can lead to hard-to-fix bugs if caution is not used – e.g. loop counter gets changed



Two Solutions

- Caller saves values
  - caller saves all their registers to memory before making the subroutine call
  - after, it restores the values before continuing
  - not recursion friendly – it pushes all of them!
- Subroutine saves the values
  - push registers (it will change) onto the stack
  - before it returns, it pops (and restores) the old values off the stack



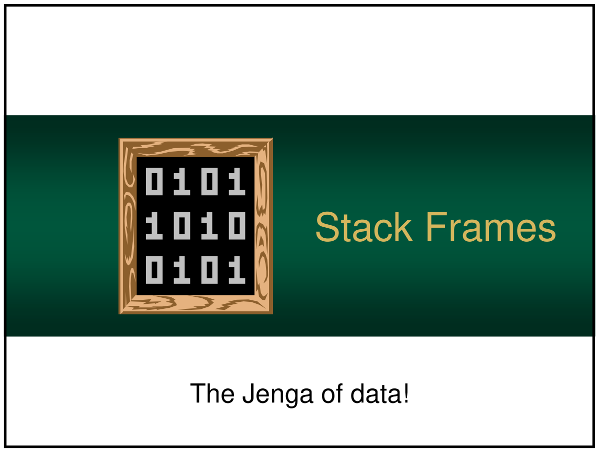
Saving Registers… How nice! :-)

```
DoSomething:
    push %rax
    push %rbx
    push %rcx

    ...

    pop %rcx
    pop %rbx
    pop %rax
    ret
```

Save registers

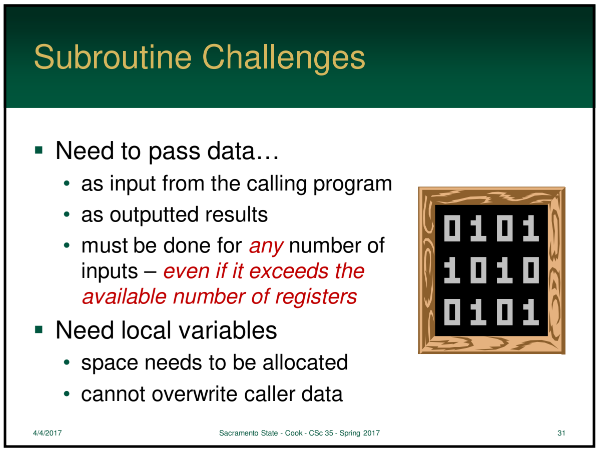
Your code

Restore them.
Note the reverse order



Stack Frames

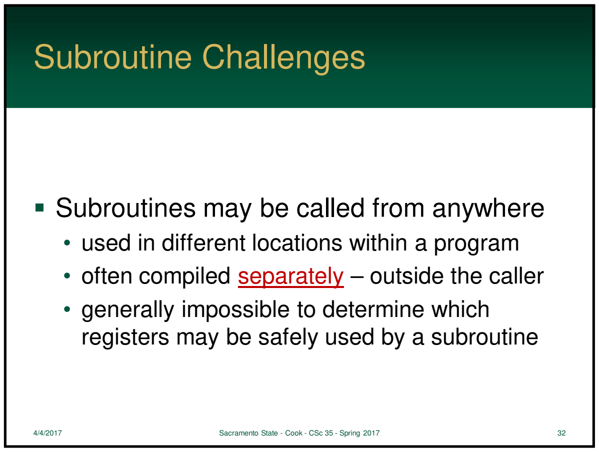
The Jenga of data!



Subroutine Challenges

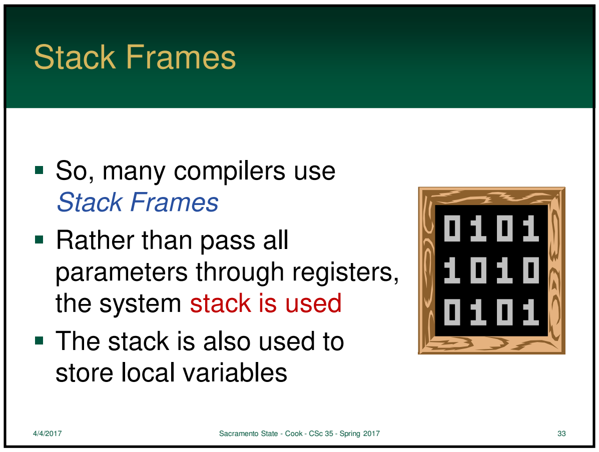
- Need to pass data…
  - as input from the calling program
  - as outputted results
  - must be done for *any* number of inputs – *even if it exceeds the available number of registers*
- Need local variables
  - space needs to be allocated
  - cannot overwrite caller data

0101
1010
0101



Subroutine Challenges

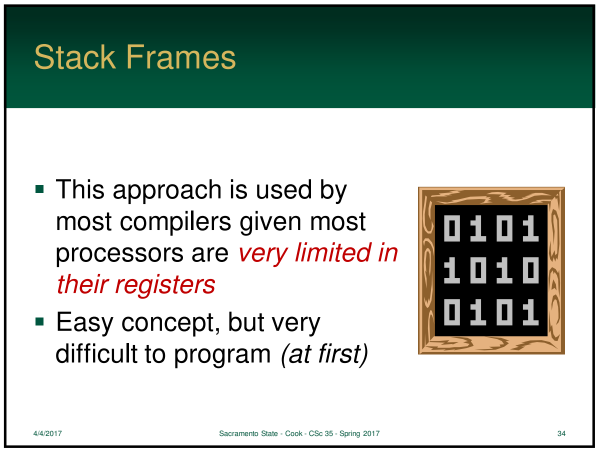
- Subroutines may be called from anywhere
  - used in different locations within a program
  - often compiled separately – outside the caller
  - generally impossible to determine which registers may be safely used by a subroutine



Stack Frames

- So, many compilers use *Stack Frames*
- Rather than pass all parameters through registers, the system stack is used
- The stack is also used to store local variables

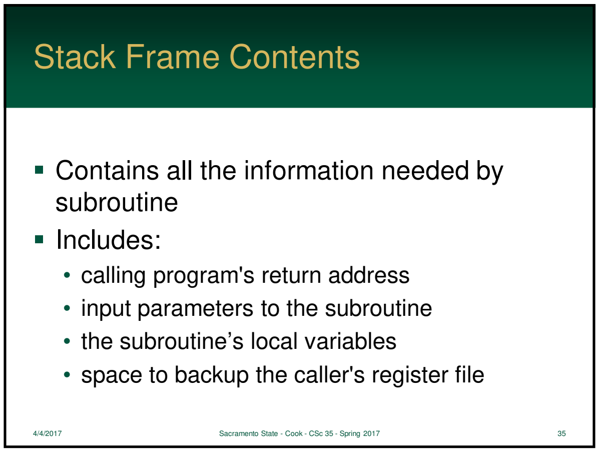
0101
1010
0101



Stack Frames

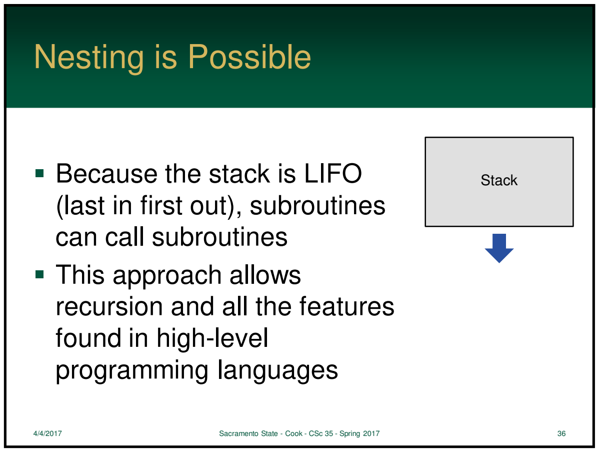
- This approach is used by most compilers given most processors are *very limited in their registers*
- Easy concept, but very difficult to program *(at first)*

0101
1010
0101



Stack Frame Contents

- Contains all the information needed by subroutine
- Includes:
  - calling program's return address
  - input parameters to the subroutine
  - the subroutine's local variables
  - space to backup the caller's register file

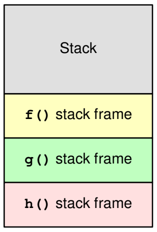


Nesting is Possible

- Because the stack is LIFO (last in first out), subroutines can call subroutines
- This approach allows recursion and all the features found in high-level programming languages

Nesting is Possible

- For example, subroutine **f()** calls **g()** which then calls **h()**
- Since the stack is used, the stack frames follow the LIFO behavior



How it Starts Up

- Caller
  - pushes the subroutine's arguments onto the stack
  - caller calls the subroutine
- Subroutine then…
  - uses the stack to backup registers
  - and *"carve"* out local variables

How it Finishes

- Subroutine…
  - restores the original register values
  - removes the local variables from the stack
  - calls the processor "return" instruction
- Caller, then…
  - removes its arguments from the stack
  - handles the result – which can be passed either in a register or on the stack

Calling Convention

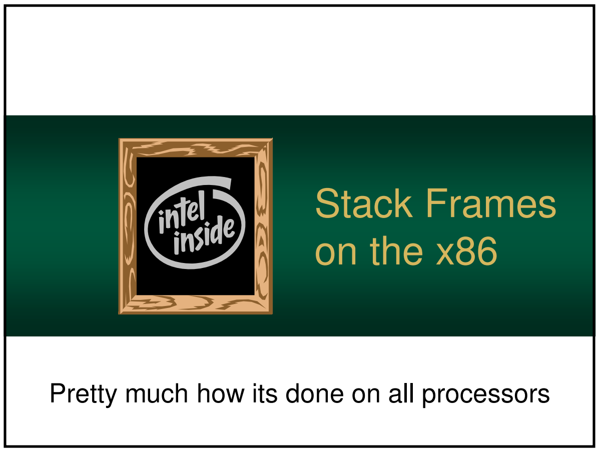
- Different programming systems may arrange the stack frame differently
- A *calling convention* is used by a programming system (e.g. a language) to define *how* data will be passed
- In particular, it defines the structure of the stack frame and how data is returned

Calling convention

- For example:
  - Is the first argument pushed first? Or last?
  - Is the result in a register? Or the stack?
- If all subroutines follow the same format
  - caller can use the same format for each
  - subroutines can also be created separately and linked together

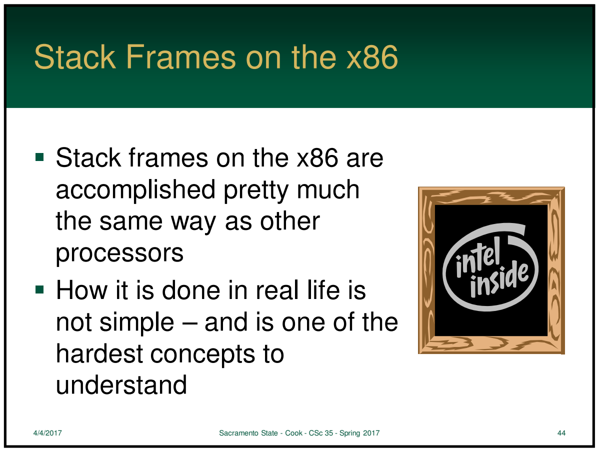
Stack Frame Size Varies

- The number of input arguments and local variables varies from subroutine to subroutine
- The arrangement of data within the stack frame also varies from compiler to compiler
- Stack frames is a *concept* – and it is used with various differences



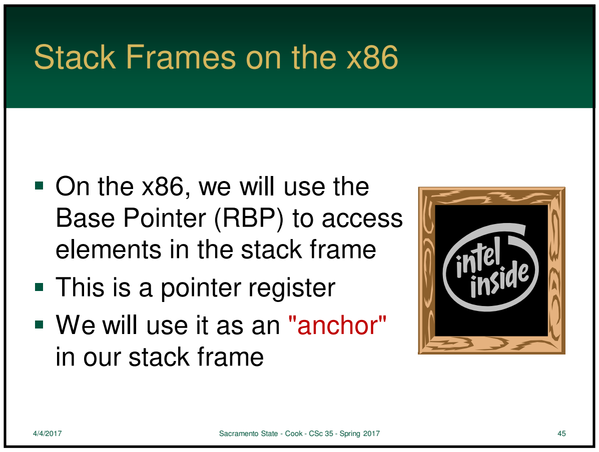
Stack Frames on the x86

Pretty much how its done on all processors



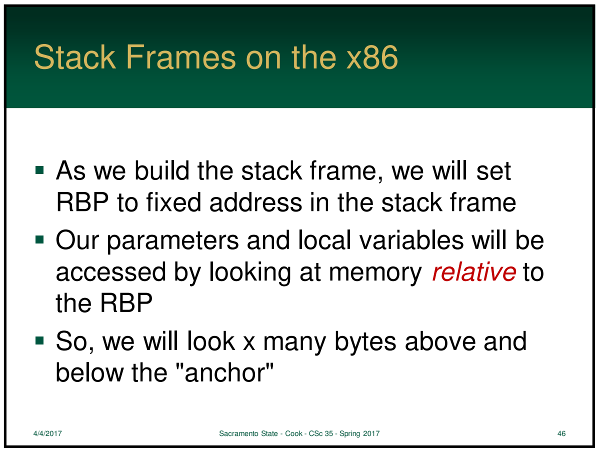
Stack Frames on the x86

- Stack frames on the x86 are accomplished pretty much the same way as other processors
- How it is done in real life is not simple – and is one of the hardest concepts to understand



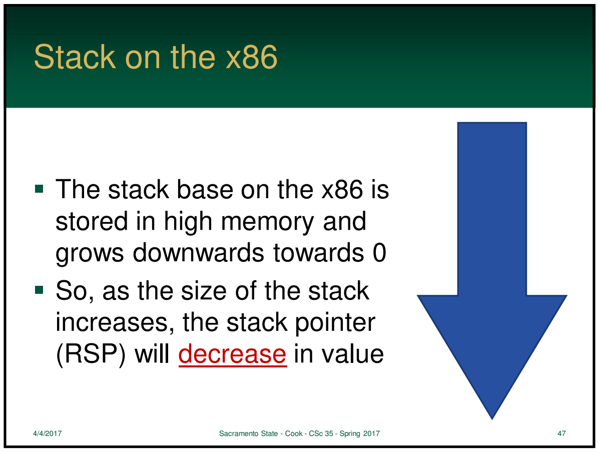
Stack Frames on the x86

- On the x86, we will use the Base Pointer (RBP) to access elements in the stack frame
- This is a pointer register
- We will use it as an "anchor" in our stack frame



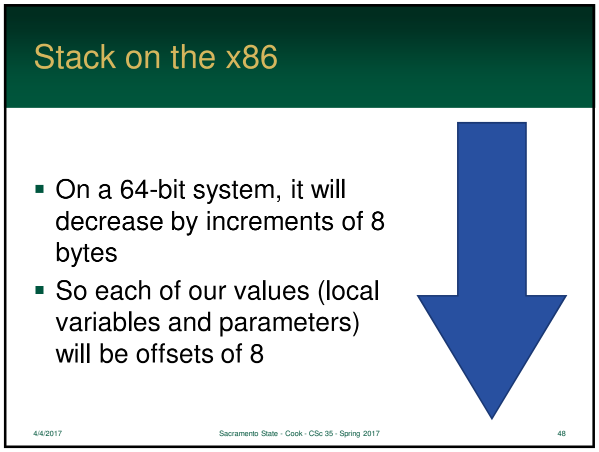
Stack Frames on the x86

- As we build the stack frame, we will set RBP to fixed address in the stack frame
- Our parameters and local variables will be accessed by looking at memory *relative* to the RBP
- So, we will look x many bytes above and below the "anchor"



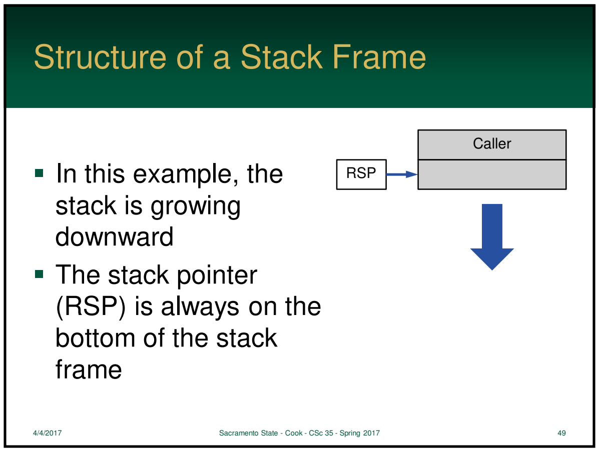
Stack on the x86

- The stack base on the x86 is stored in high memory and grows downwards towards 0
- So, as the size of the stack increases, the stack pointer (RSP) will decrease in value



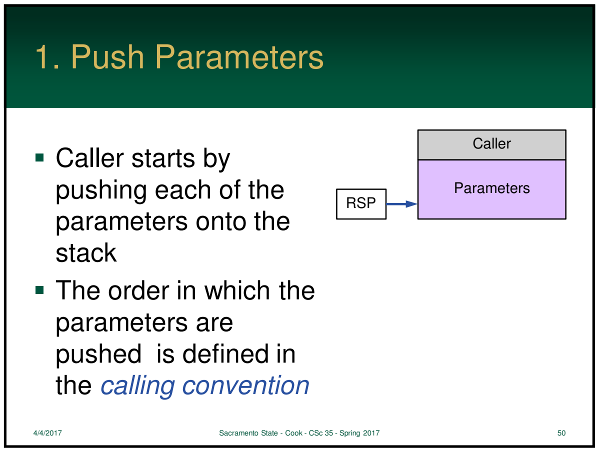
Stack on the x86

- On a 64-bit system, it will decrease by increments of 8 bytes
- So each of our values (local variables and parameters) will be offsets of 8



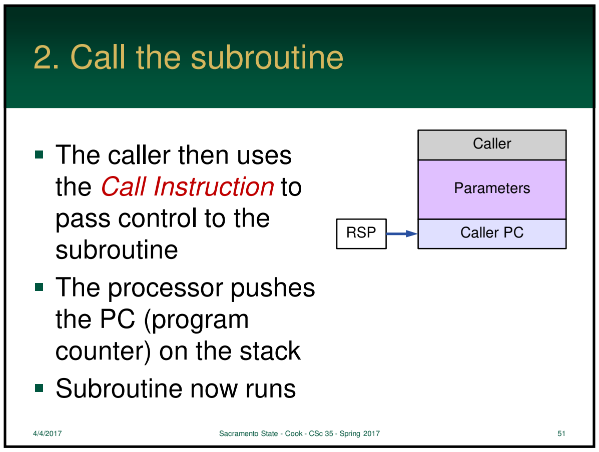
Structure of a Stack Frame

- In this example, the stack is growing downward
- The stack pointer (RSP) is always on the bottom of the stack frame



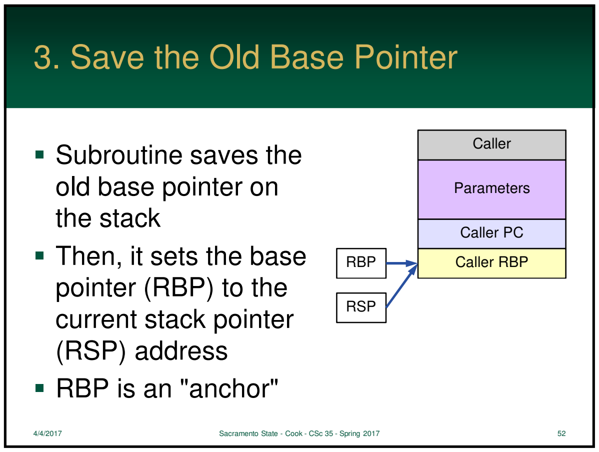
1. Push Parameters

- Caller starts by pushing each of the parameters onto the stack
- The order in which the parameters are pushed is defined in the *calling convention*



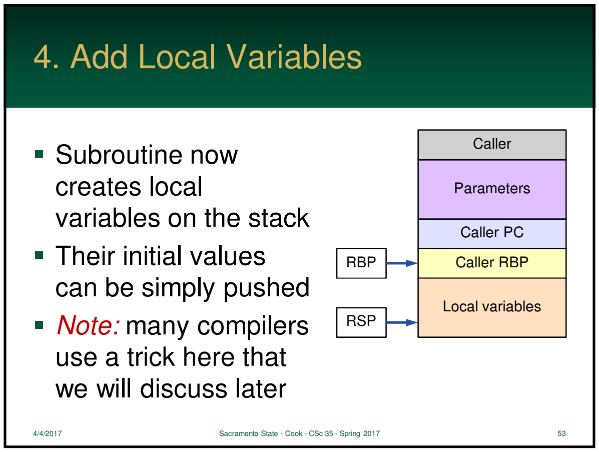
2. Call the subroutine

- The caller then uses the *Call Instruction* to pass control to the subroutine
- The processor pushes the PC (program counter) on the stack
- Subroutine now runs



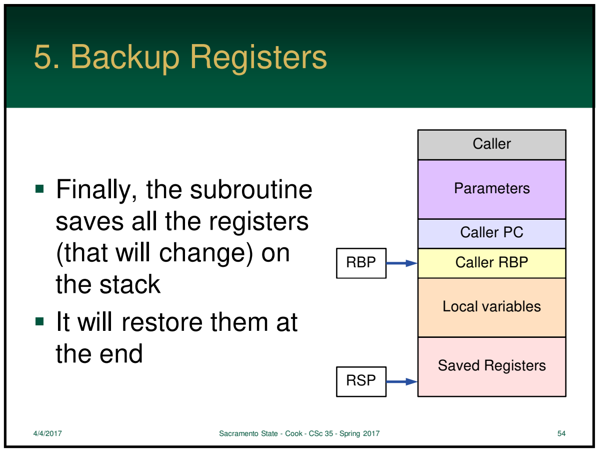
3. Save the Old Base Pointer

- Subroutine saves the old base pointer on the stack
- Then, it sets the base pointer (RBP) to the current stack pointer (RSP) address
- RBP is an "anchor"



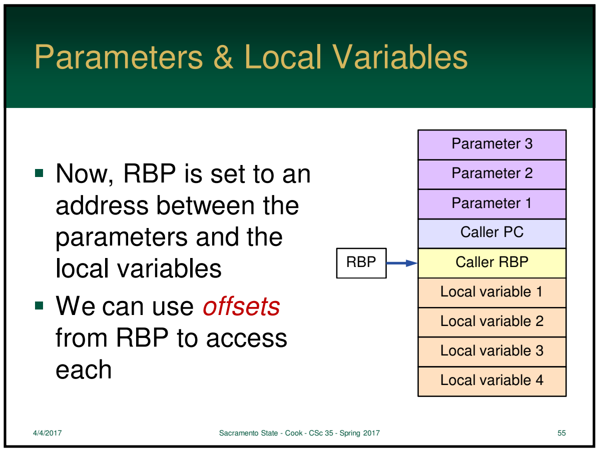
4. Add Local Variables

- Subroutine now creates local variables on the stack
- Their initial values can be simply pushed
- *Note:* many compilers use a trick here that we will discuss later



5. Backup Registers

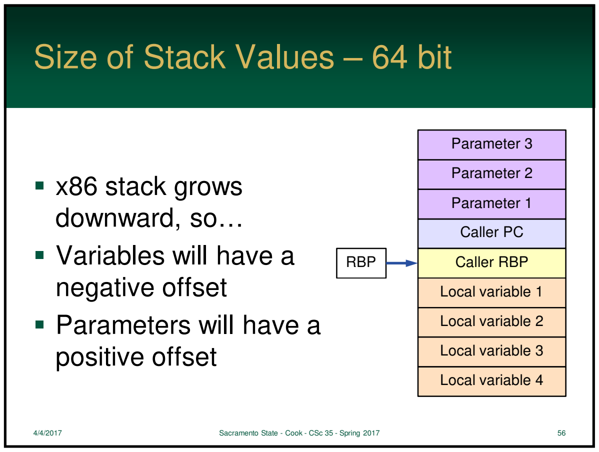
- Finally, the subroutine saves all the registers (that will change) on the stack
- It will restore them at the end



Parameters & Local Variables

- Now, RBP is set to an address between the parameters and the local variables
- We can use *offsets* from RBP to access each

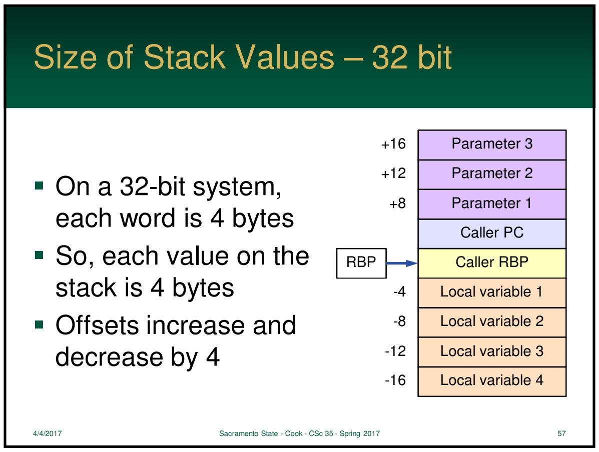
	Parameter 3
	Parameter 2
	Parameter 1
	Caller PC
RBP →	Caller RBP
	Local variable 1
	Local variable 2
	Local variable 3
	Local variable 4



Size of Stack Values – 64 bit

- x86 stack grows downward, so…
- Variables will have a negative offset
- Parameters will have a positive offset

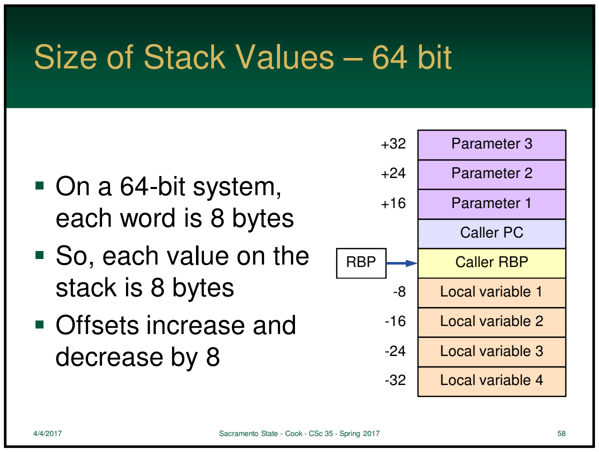
	Parameter 3
	Parameter 2
	Parameter 1
	Caller PC
RBP →	Caller RBP
	Local variable 1
	Local variable 2
	Local variable 3
	Local variable 4



Size of Stack Values – 32 bit

- On a 32-bit system, each word is 4 bytes
- So, each value on the stack is 4 bytes
- Offsets increase and decrease by 4

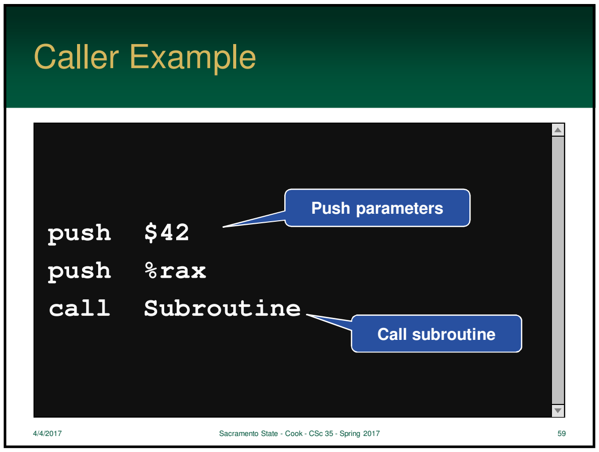
	+16	Parameter 3
	+12	Parameter 2
	+8	Parameter 1
		Caller PC
RBP →		Caller RBP
	-4	Local variable 1
	-8	Local variable 2
	-12	Local variable 3
	-16	Local variable 4



Size of Stack Values – 64 bit

- On a 64-bit system, each word is 8 bytes
- So, each value on the stack is 8 bytes
- Offsets increase and decrease by 8

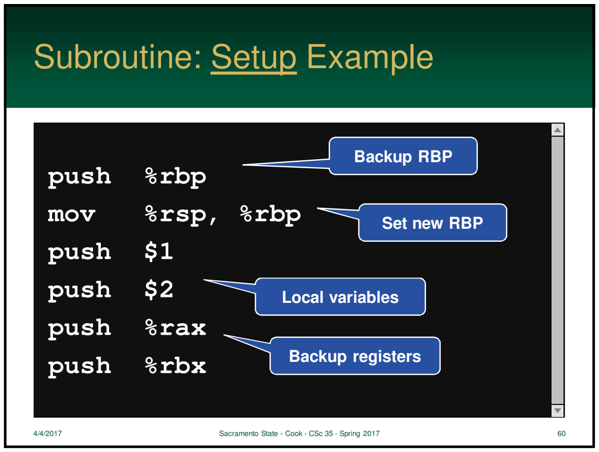
	+32	Parameter 3
	+24	Parameter 2
	+16	Parameter 1
		Caller PC
RBP →		Caller RBP
	-8	Local variable 1
	-16	Local variable 2
	-24	Local variable 3
	-32	Local variable 4



Caller Example

```
push  $42
push  %rax
call  Subroutine
```

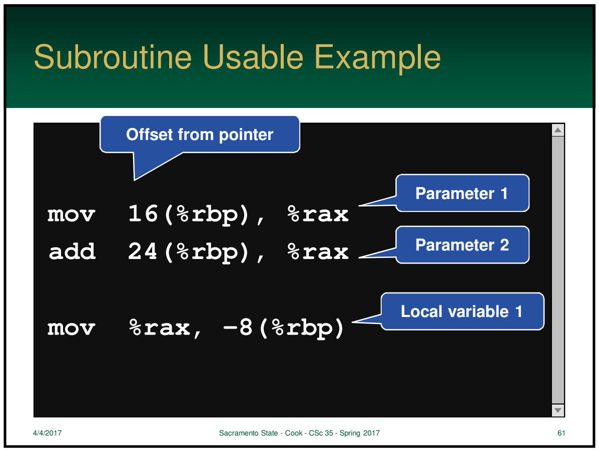
Push parameters
Call subroutine



Subroutine: Setup Example

```
push   %rbp
mov    %rsp, %rbp
push   $1
push   $2
push   %rax
push   %rbx
```

Backup RBP
Set new RBP
Local variables
Backup registers



Subroutine Usable Example

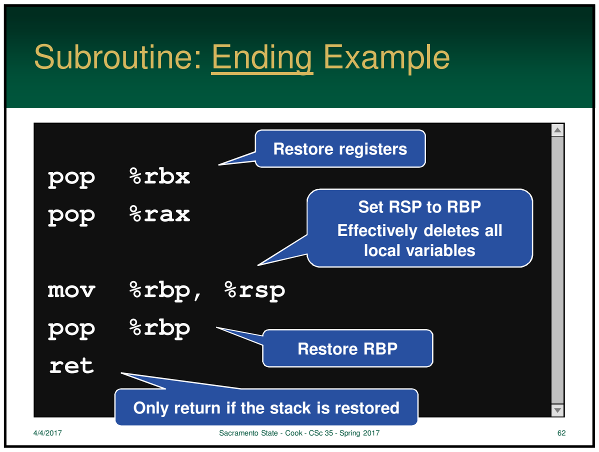
```
mov  16(%rbp), %rax
add  24(%rbp), %rax

mov  %rax, -8(%rbp)
```

Offset from pointer

Parameter 1

Parameter 2

Local variable 1



Subroutine: Ending Example

```
pop  %rbx
pop  %rax

mov  %rbp, %rsp
pop  %rbp
ret
```

Restore registers

Set RSP to RBP
Effectively deletes all local variables

Restore RBP

Only return if the stack is restored