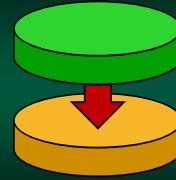




Part 7

The Stack

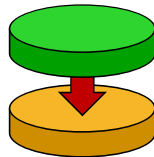


Stacks

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



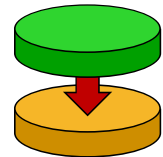
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Stack

- This gives a **First-In-Last-Out** logic (aka FILO)
- Same concept is also called **Last-In-First-Out** (LIFO)



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Examples of Stacks

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



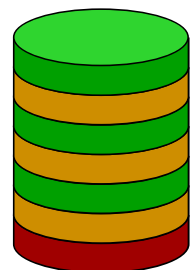
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Stack Operation: Push

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



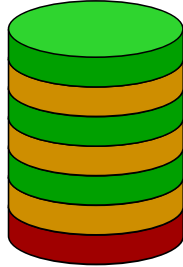
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Stack Operation: Pop

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



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Implementing in Memory

- On a processor, the stack stores integers
 - size of the integer the bit-size of the system
 - 64-bit system → 64-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

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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

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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

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Subroutine Call Basics



Organizing Your Program

Subroutine Call Basics

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



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Why Use Subroutines

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



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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

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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

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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

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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!*



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Passing Through Registers

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



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x64 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

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Instruction: Call

Usually a label
(which is an address)

CALL *address*

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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

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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!

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Instruction: Return

No arguments!

RET

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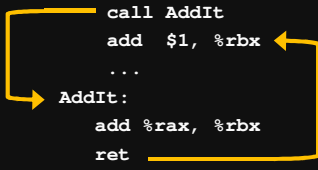
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Subroutine Example

```

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



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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



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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

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Saving Registers... How nice! :-)

```

DoSomething:
    push %rax
    push %rbx
    push %rcx
    ...
    pop %rcx
    pop %rbx
    pop %rax
    ret
    
```



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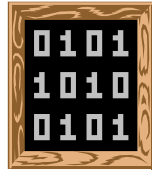


Stack Frames

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



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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

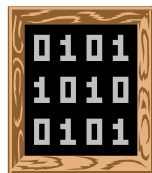
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Stack Frames

- 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



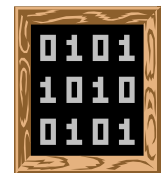
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Stack Frames

- 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*)



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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

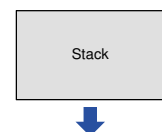
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Nesting is Possible

- 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



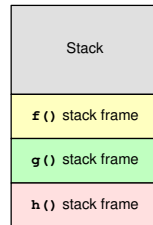
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Nesting is Possible

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



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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

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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

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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

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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

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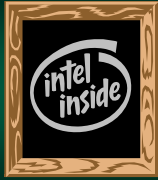
Stack Frame Size Varies

- 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

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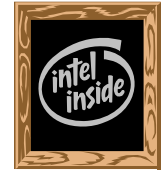


Stack Frames on the x64

Pretty much how its done on all processors

Stack Frames on the x64

- Stack frames on the x64 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



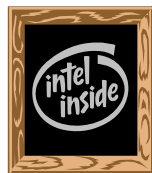
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Stack Frames on the x64

- On the x64, 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



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Stack Frames on the x64

- 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"

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Stack on the x64

- The stack base on the x64 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



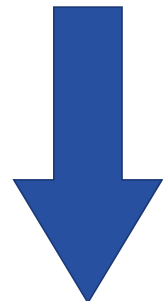
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Stack on the x64

- 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



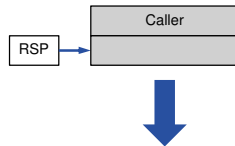
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Structure of a Stack Frame

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



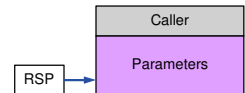
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1. Push Parameters

- 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*



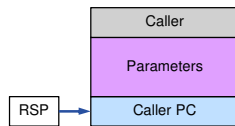
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2. Call the subroutine

- 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



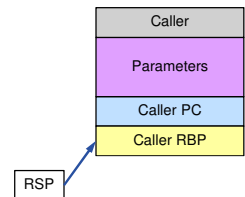
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3. Save the Old Base Pointer

- We need to set the Base Pointer (RBP)
- So, the old version needs to be saved (so it can be restored)
- Old value is pushed



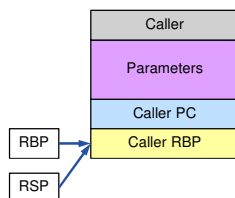
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4. Set the Base Pointer

- Then, it sets the Base Pointer (RBP) to the current stack pointer (RSP) address
- RBP is an "anchor" that we will use



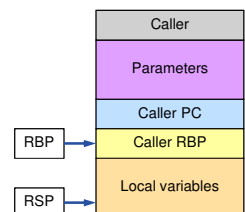
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5. Add Local Variables

- 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



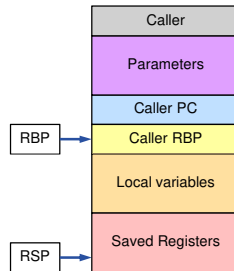
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6. Backup Registers

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



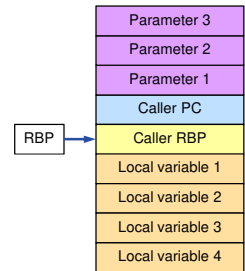
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Parameters & Local Variables

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



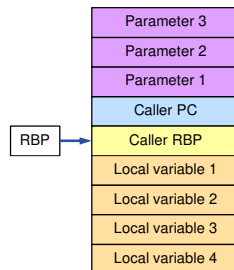
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Size of Stack Values – 64 bit

- x64 stack grows downward, so...
- Variables will have a negative offset
- Parameters will have a positive offset



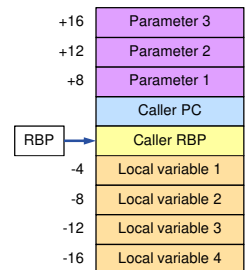
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Size of Stack Values – 32 bit

- 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



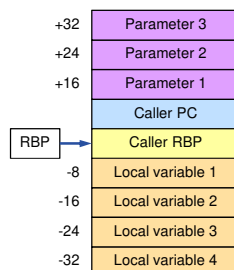
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Size of Stack Values – 64 bit

- 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

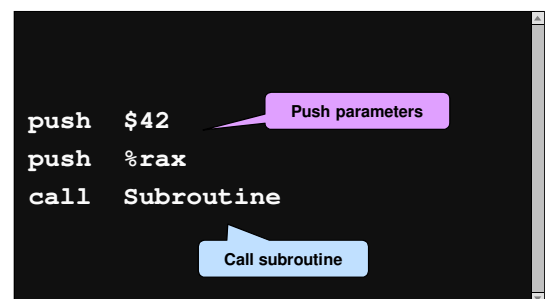


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Caller Example



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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

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Subroutine Data Example

```
mov  16(%rbp), %rax
add  24(%rbp), %rax
mov  %rax, -8(%rbp)
```

Offset from pointer

Parameter 1

Parameter 2

Local variable 1

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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 when the stack is restored

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