Subroutines & Operating Systems

Part 8

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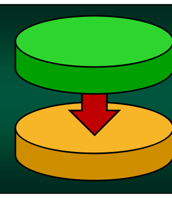

The System Stack

Pile of… Data

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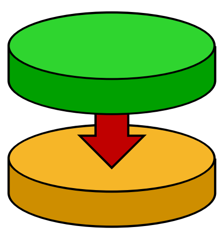
The System Stack

- The processor maintains a stack in memory
- It allows *subroutines*
  - analogous to the "functions" you use in Java and other third-generation languages
  - but, much more simple



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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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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
- Stacks is stored in memory
  - 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) is the *lowest* address in the stack buffer
  - stack grows towards *higher* addresses
- Grow downwards
  - Bottom Pointer (S0) is 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 be stored
- However…
  - stacks are implemented using memory buffers
  - which are finite in size
- If the data exceeds the allocated space, a *stack overflow* error occurs

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Subroutine Call Basics

Organizing Your Program

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Subroutine Call

- The stack is essential for subroutines to work
- How?
  - used to save the return addresses for call instructions
  - backup and restore registers
  - pass data between subroutines

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When you call a subroutine…

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

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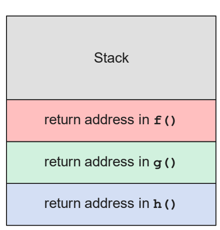
Nesting is Possible

- Subroutines can call other subroutines
- `f()` calls `g()` which then calls `h()`, etc…
- The stack stores the return addresses of the callers
- Just like the "history button" in your web browser, you can store many return addresses



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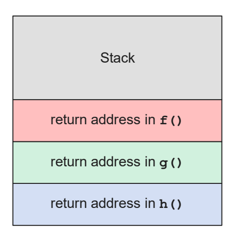
Nesting is Possible

- Each time a subroutine completes, the processor pops the top of the stack
- …then returns to the *caller*
- This allows normal function calls and recursion (a powerful tool)



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x64 Subroutines

Organizing Your Programs … with Intel

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Instruction: Call

- The *Call Instruction* transfers control to a subroutine
- Other processors call it different names such as JSR (<u>J</u>ump <u>S</u>ub<u>r</u>outine)
- The stack is used to save the current IP

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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 instruction pointer is read from the system stack
  - the current instruction pointer 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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Subroutine Example

```
_start:
    mov  rcx, 4
    mov  rbx, 12
    call AddIt
    add  rbx, 1
    ...
AddIt:
    add  rbx, rcx
    ret
```


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Operating Systems

The master software

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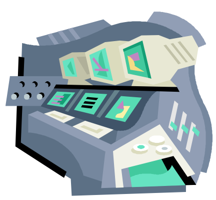
What is an operating system?

- The operating system is simply a series of programs
- These programs, however, run with special privileges which are needed by the OS
- Processors support two modes for executing programs



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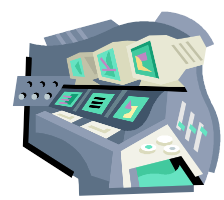
Execution Modes

- *Privileged (supervisor) mode*
  - can run special instructions
  - can talk to all the hardware
  - etc…
- *User mode*
  - can only execute certain instructions
  - can't talk to all the hardware



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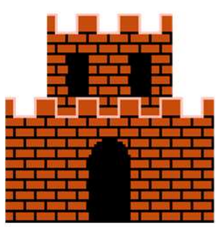
Vector Tables

- Programs (and hardware) often need to talk to the operating system
- Examples:
  - software needs talk to the OS
  - USB port notifies the OS that a device was plugged in



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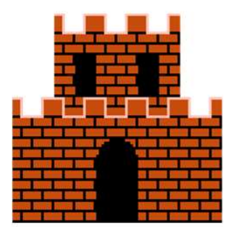
Vector Tables

- But how does this happen?
- The processor can be *interrupted* – alerted – that something must be handled
- It then runs a special program that handles the event



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Vector Table

- During an interrupt, the device sends the processor an *interrupt number*
- The processor looks up the number in the *vector table*
- Table contains the address of *Interrupt Service Routine (ISR)* to execute

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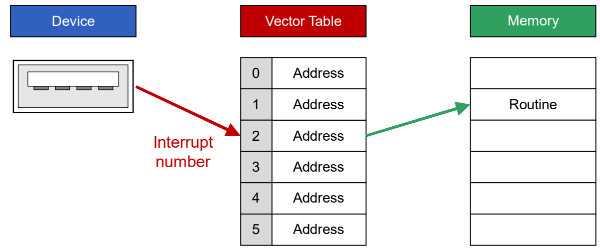
How It Works



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The Processor Actions

1. Backup the register file
2. Execute *Interrupt Service Routine (ISR)*
3. Once completed: restore the original executing program & register file

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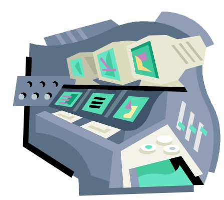
The Kernal

- All these Interrupt Service Routines belong to the *kernal* – the core of the operating system
- Vast majority of the operating system is hidden from the end user



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Interact with Applications

How do WE talk to the OS

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Interact with Applications

- Software also needs to talk to the operating system
- For example:
  - draw a button
  - print a document
  - close this program
  - etc…

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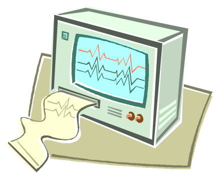
Interact with Applications

- Software can interrupt itself with a specific number
- This interrupt is *designated specifically for software*
- The operating system then handles the software's request



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Application Program Interface

- Programs "talk" to the OS using *Application Program Interface (API)*
- Application → Operating System → IO
- Benefits:
  - makes applications faster and smaller
  - also makes the system more secure since apps do not directly talk to IO

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Instruction: syscall (64-bit)

```
SYSCALL
```

Calls interrupt number reserved for programs needing attention

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Subroutine vs. Interrupt

Subroutine	Interrupt
Executes code	Executes code
Returns when complete	Returns when complete
Called by the application	Executed by the processor
Part of the application	Handles events for the OS

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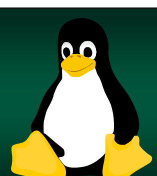

Linux System Calls

How software and hardware "talk"

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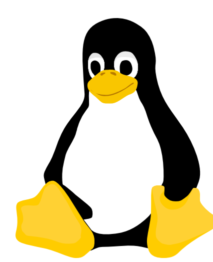
Interrupts on the Linux

- Linux, like other operating systems communicate with applications using *interrupts*
- Applications do not know where (in memory) to contact the kernal – so they ask the processor to do it



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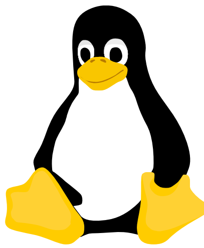
How It Works

1. Fill the registers
2. Interrupt using syscall
   (or INT 0x80 if on 32-bit)
3. Any results will be stored in the registers



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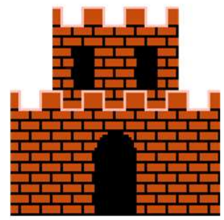
How to Call Linux – 64 bit



- The **rax** register must contain the *system call number*
- This number indicates what you asking the OS to do
- There are only 329 total calls in the entire 64-bit UNIX operating system!

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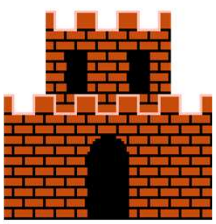
How to Call Linux – 64 bit



- Different registers are used to hold data
- The order is also quite odd: *rdi, rsi, rdx, r10, r8*

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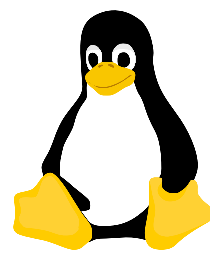
Kernals are Simple!

- Linux only has **1** write and **1** read system call
- The location, number of bytes, and device only change *"write x many bytes from address y to device z"*
- So, writing to the screen, a file, a port, etc…use the same call!



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Some Linux 64 Calls

System Call	rax	rdi	rsi	rdx
read	0	file descriptor	address	max bytes
write	1	file descriptor	address	count
open	2	address	flags	mode
close	3	file descriptor		
get pid	39			
exit	60	error code		

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Linux 64: Sys Write

```
mov  rax, 1
mov  rdi, 1
lea  rsi, address
mov  rdx, length
syscall
```

Linux command for WRITE

1 = Screen

Call Linux

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Linux 64: Sys Read

```
mov  rax, 0
mov  rdi, 0
lea  rsi, address
mov  rdx, maxBytes
syscall
```

- `mov rax, 0`: Linux command for READ
- `mov rdi, 0`: 0 = Keyboard
- `mov rdx, maxBytes`: Maximum number of bytes to read
- `syscall`: Call Linux

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Saving Registers & Lost Data

Avoiding horrible side-effects

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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 <u>very</u> 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 <u>all</u> 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
```

- `push rax` / `push rbx` / `push rcx`: Save registers
- `...`: Your code
- `pop rcx` / `pop rbx` / `pop rax`: Restore them. Note the reverse order

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