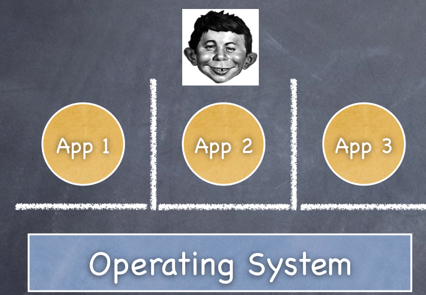
The Kernel

wants to be your friend

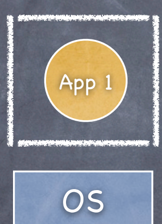
Boxing them in



Reading and writing memory, managing resources, accessing I/O... would you trust it all to him?

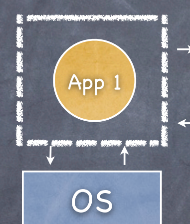
- Buggy apps can crash other apps
- Buggy apps can crash the OS
- Buggy apps can hog all resources
- Malicious apps can violate privacy of other apps
- Malicious apps can change the OS

The Process



- An abstraction for protection
  - the execution of an application program with restricted rights
- Must not hinder functionality
  - still efficient use of hardware
  - enable safe communication

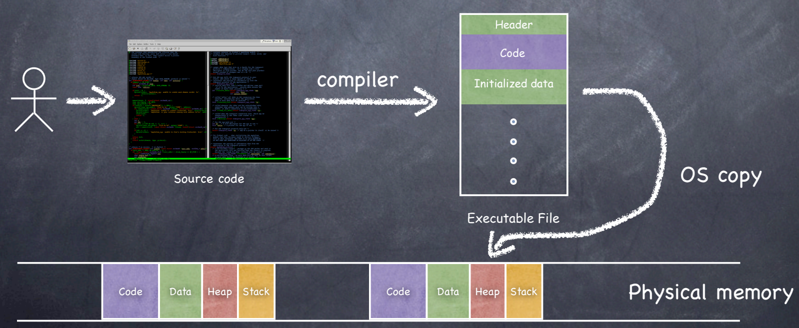
The Process



- An abstraction for protection
  - the execution of an application program with restricted rights
- Restricting rights must not hinder functionality
  - still efficient use of hardware
  - enable safe communication
- So...
  - What is a process? How is it different from a program?
  - How does the OS implement processes?

Getting to know you

- A process is a program during execution
  - program is a static file
  - process = executing program = program + execution state



Keeping track of a process

- A process has code
  - OS must track program counter
- A process has a stack
  - OS must track stack pointer
- OS stores state of process in Process Control Block (PCB)
  - Data (program instructions, stack & heap) resides in memory, metadata is in PCB

How can the OS enforce restricted rights?

- Easy: OS interprets each instruction!
  - slow
  - most instructions are safe: can we just run them in hardware?
- Dual Mode Operation
  - hardware to the rescue: use a mode bit
    - in user mode, processor checks every instruction
    - in kernel mode, unrestricted rights
  - hardware to the rescue (again) to make checks efficient

Efficient protection in dual mode operation

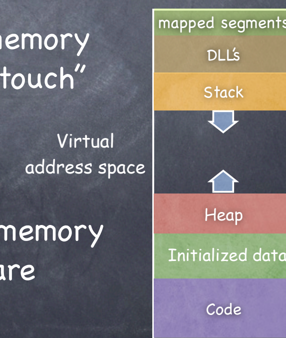
- Hardware must support at least three features:
  - Privileged instructions
    - in user mode, no way to execute potentially unsafe instructions
  - Memory protection
    - in user mode, memory accesses outside a process' memory region are prohibited
  - Timer interrupts
    - kernel must be able to periodically regain control from running process

Privileged instructions

- Set mode bit
  - but how can an app do I/O then?
    - system calls achieve access to kernel mode only at specific locations specified by OS
- Set accessible memory
- Disable interrupts
- Executing a privileged instruction while in user mode causes a processor exception....
  - ...which passes control to the kernel

Memory Protection via Address Translation

- Virtualize memory
  - processes run on physical memory, but perceive the illusion of running on a (almost) infinite virtual memory
- Virtual address space: set of memory addresses that process can "touch"
  - CPU works with virtual addresses
- Physical address space: set of memory addresses supported by hardware



Address Translation

- A function that maps $\langle pid, virtual\ address \rangle$ into $physical\ address$

Advantages:

- protection
- relocation
- data sharing
- multiplexing

Protection

- At all times, the functions used by different processes map to disjoint ranges

Relocation

- The range of the function used by a process can change over time

Relocation

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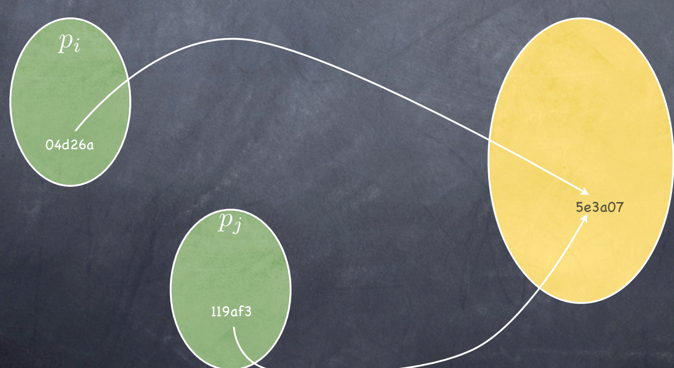
Data Sharing

- Map different virtual addresses of different processes to the same physical address



Multiplexing

- The domain (set of virtual addresses) that map to a given range of physical addresses can change over time

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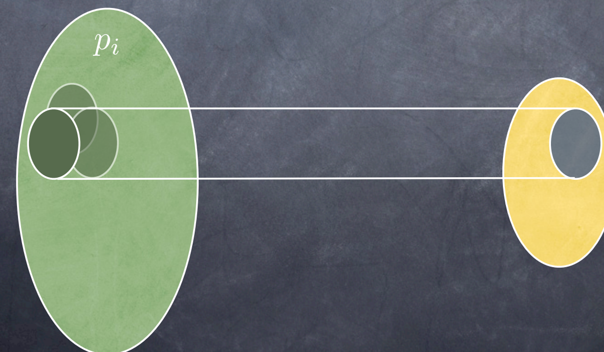

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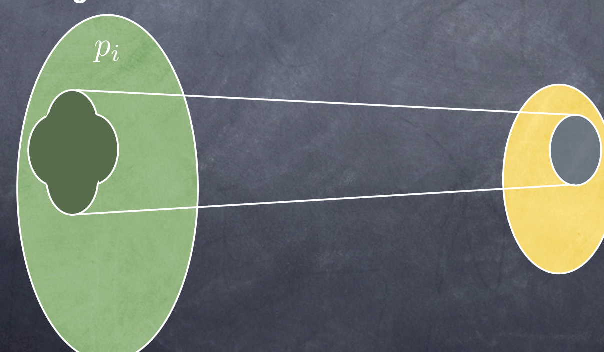
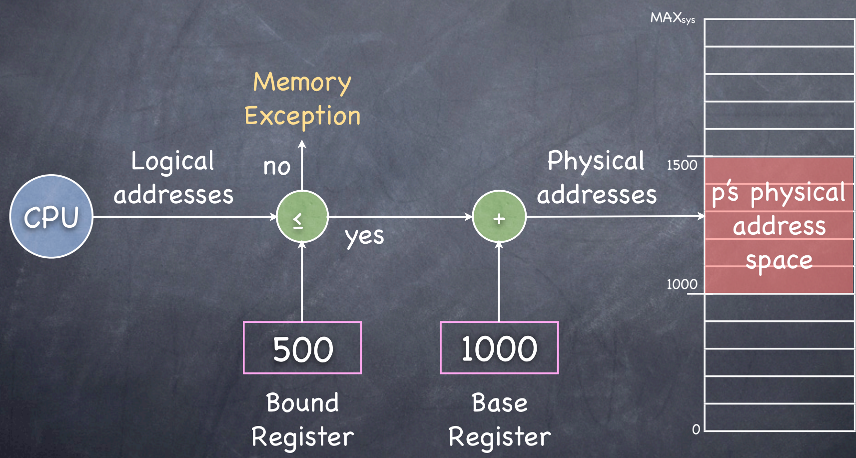


A simple mapping mechanism: Base & Bound



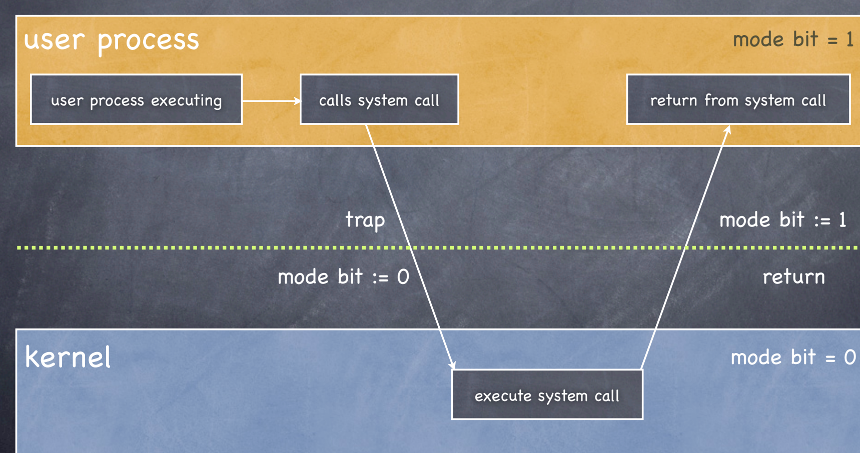
On Base & Limit

- Contiguous Allocation: contiguous virtual addresses are mapped to contiguous physical addresses
- Protection is easy, but sharing is hard
  - Two copies of emacs: want to share code, but have data and stack distinct...
- Managing heap and stack dynamically is hard
  - We want them as far as as possible in virtual address space, but...

Timer Interrupts

- Hardware timer
  - can be set to expire after specified delay (time or instructions)
  - when it does, control is passed back tot he kernel
- Other interrupts (e.g. I/O completion) also give control to kernel

Crossing the line



From user mode to kernel mode...

- Exceptions
  - user program acts silly (e.g. division by zero)
  - attempt to perform a privileged instruction
    - sometime on purpose! (breakpoints)
  - synchronous
- Interrupts
  - HW device requires OS service
    - timer, I/O device, interprocessor
  - aysnchronous
- System calls
  - user program requests OS service
  - synchronous

...and viceversa

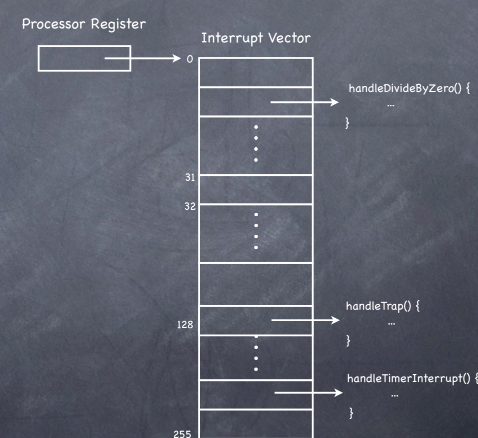
- New process
  - copies program in memory, set PC and SP; toggles mode
- Resume after exception, interrupt or system call
  - restores PC, SP, registers; toggles mode
- Switch to different process
  - loads PC, SP, registers from other process PCB; toggles mode
- User-level upcall
  - a sort of user-level interrupt handling

Safe mode switch

- Common sequences of instructions to cross boundary, which provide:
  - Limited entry
    - entry point in the kernel set up by kernel
  - Atomic changes to process state
    - PC, SP, memory protection, mode
  - Transparent restartable execution
    - user program must be restarted exactly as it was before kernel got control

Interrupt vector

- OS saves state of user program
- Hardware identifies why boundary is crossed
  - if a trap was invoked, which hardware device that caused interrupt, what exception
- Hardware selects entry from interrupt vector
- Appropriate handler is invoked



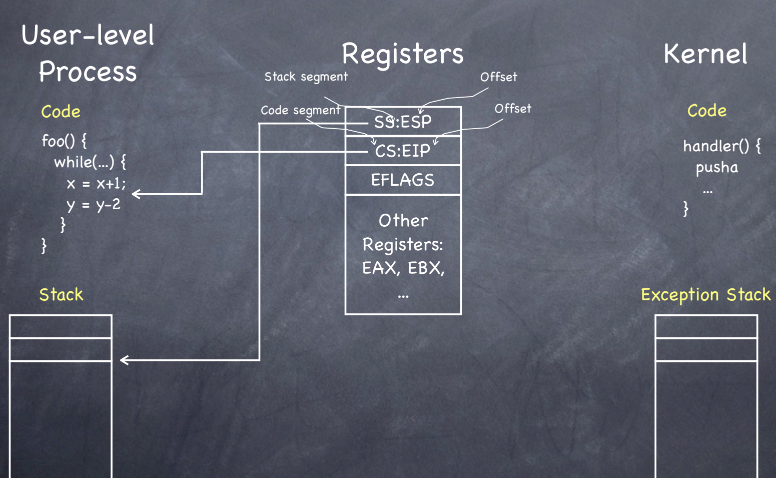
Saving the state of the interrupted process

- Privileged hw register points to Exception Stack
  - on switch, hw pushes some of interrupted process registers (SP, PC, etc) on exception stack <u>before</u> handler runs. Why?
  - then handler pushes the rest (`pushad` on x86)
  - On return, do the reverse (`popad` on x86)
- Why not use user-level stack?
  - reliability: even if user's stack points to invalid address, handlers continue to work
  - security: kernel state should not be stored in user space (or could be read/written)
- One interrupt stack per processor/process/thread

Interrupt masking

- What happens if an interrupt occurs while we are running an interrupt handler?
  - can't reset KSP to point to base of kernel's exception stack
- Privileged instruction disables (defers) interrupts
- If no reset, can also simply use the current KSP

Mode switch on x86



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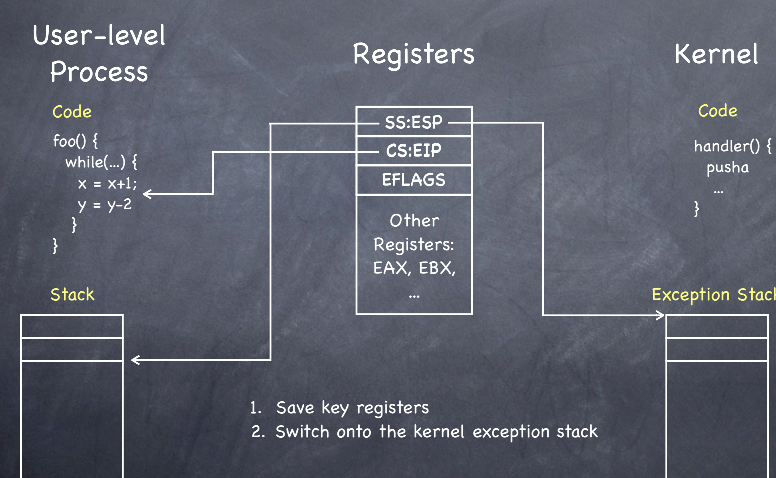

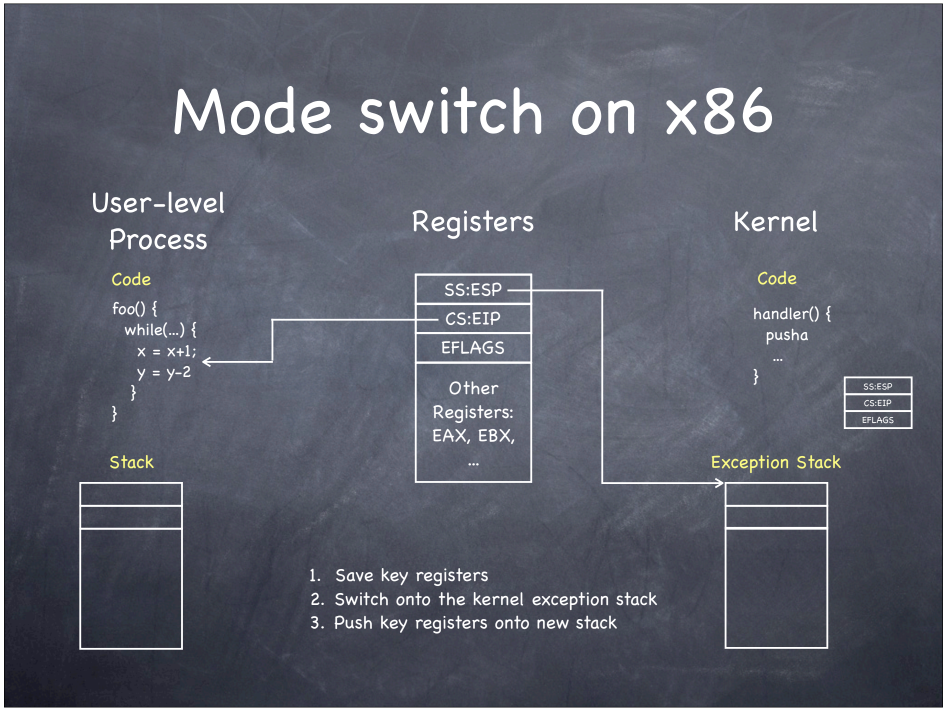
Mode switch on x86
User-level Process
Registers
Kernel
Code
foo() {
while(...) {
x = x+1;
y = y-2
}
}
SS:ESP
CS:EIP
EFLAGS
Other Registers: EAX, EBX, ...
Code
handler() {
pusha
...
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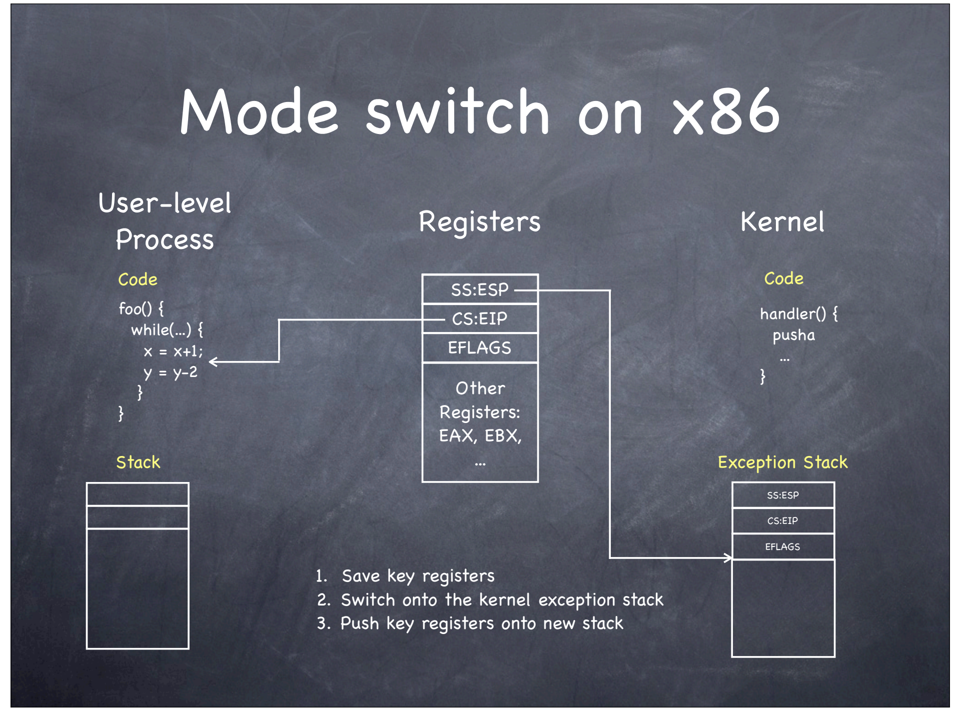
Stack
Exception Stack
1. Save key registers
2. Switch onto the kernel exception stack
3. Push key registers onto new stack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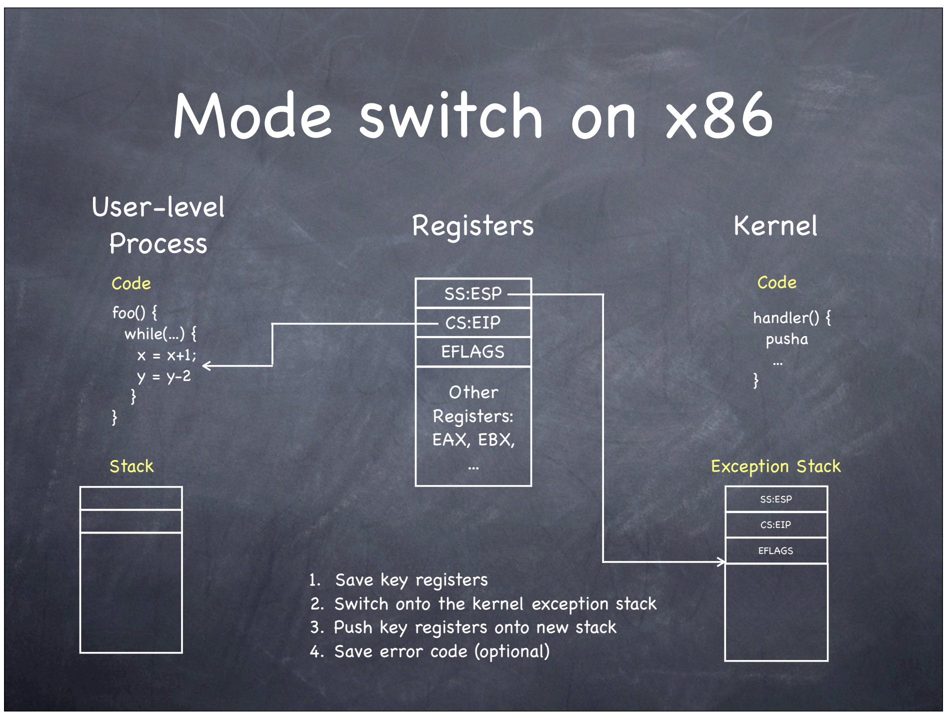
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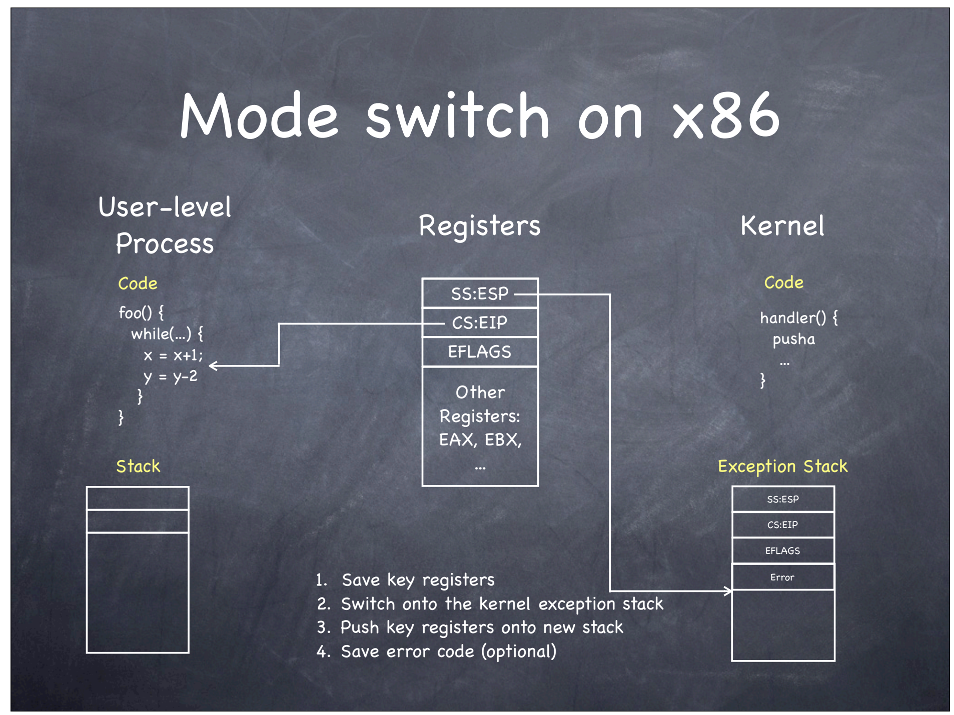
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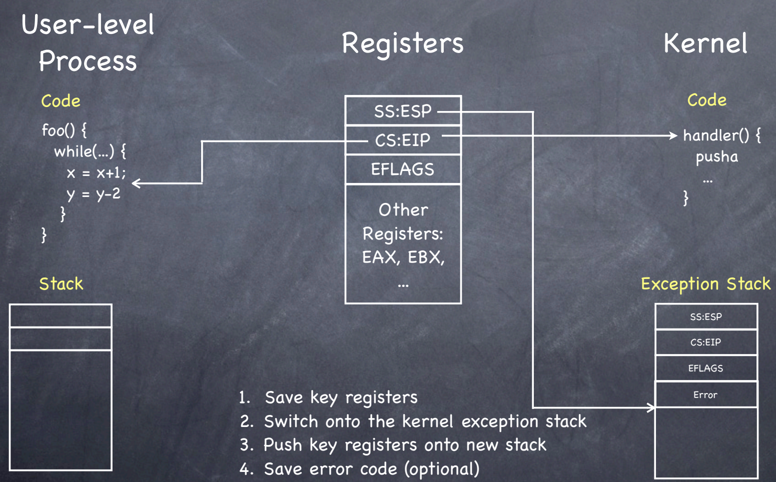

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2. Switch onto the kernel exception stack
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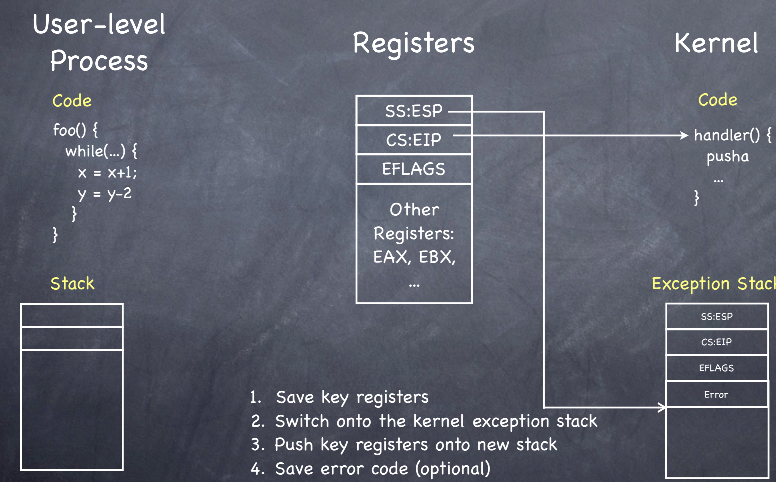
5. Invoke interrupt handler

Mode switch on x86



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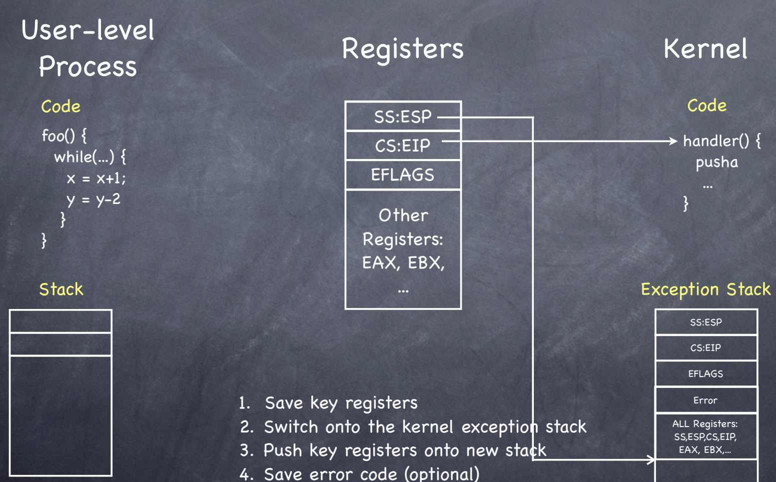

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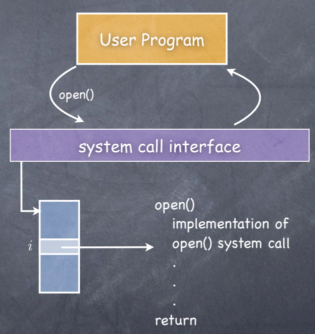
Switching back

- From an interrupt, just reverse all steps!
- From exception and system call, increment PC on return
  - on exception, handler changes PC at the base of the stack
  - on system call, increment is done by hw

System calls

- Programming interface to the services provided by the OS
- Mostly accessed through an API (Application Programming Interface)
  - Win32, POSIX, Java API
- Parameters passed according to calling convention
  - registers, stack, etc.



System call stubs

User

- Set up parameters
- call `int 080` to context switch

```
open:
  movl #SysCall_Open, %eax
  int 080
  ret
```

Kernel

- Locate system call arguments
  - if passed on the stack, they are virtual addresses
- Validate parameters
  - defend against errors in content and format of args
- Copy before check
  - prevent TOCTOU
- Copy back any result

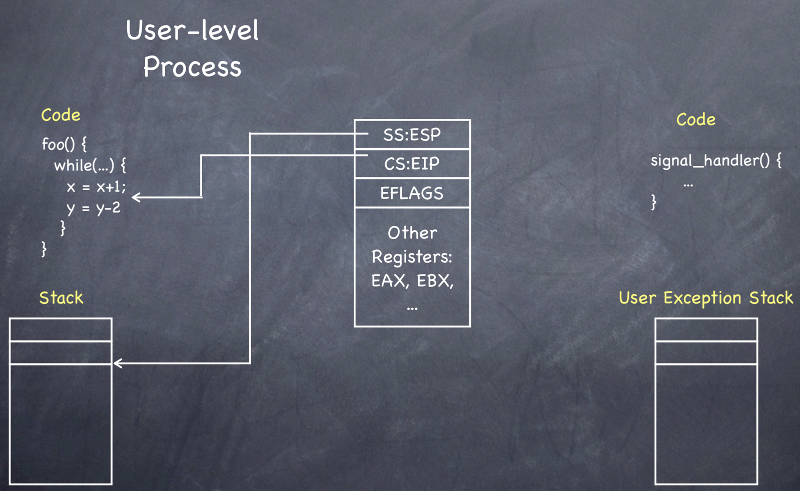
Starting a new process

- A simple recipe:
  - Allocate & initialize PCB
  - Allocate memory
  - Copy program from disk
  - Allocate user-level and kernel-level stacks
  - Copy arguments (if any) to the base of the user-level stack
  - Transfer control to user-mode
    - `popad` + `iret`
    - user stub handles return from `main()`

Upcalls: virtualizing interrupts

Interrupts/Exceptions	Upcalls/Signals
Hardware-defined Interrupts & exceptions	Kernel-defined signals
Interrupt vector for handlers (kernel)	Handlers (user)
Interrupt stack (kernel)	Signal stack (user)
Interrupt masking (kernel)	Signal masking (user)
Processor state (kernel)	Processor State (user)

Unix signals



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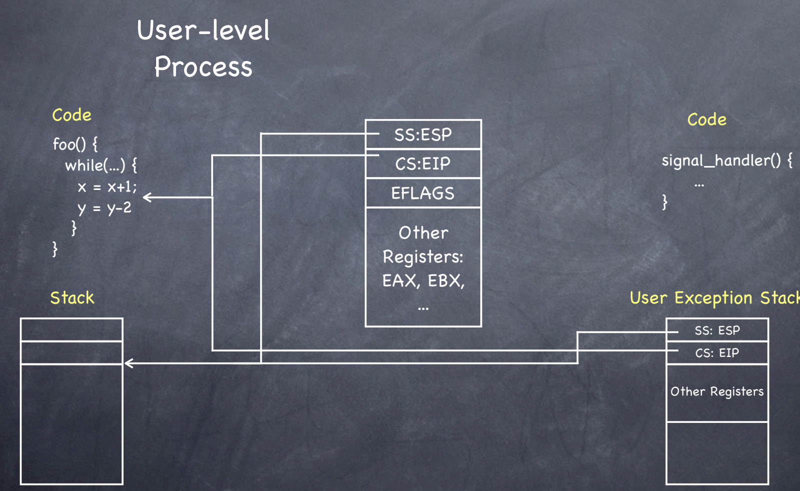

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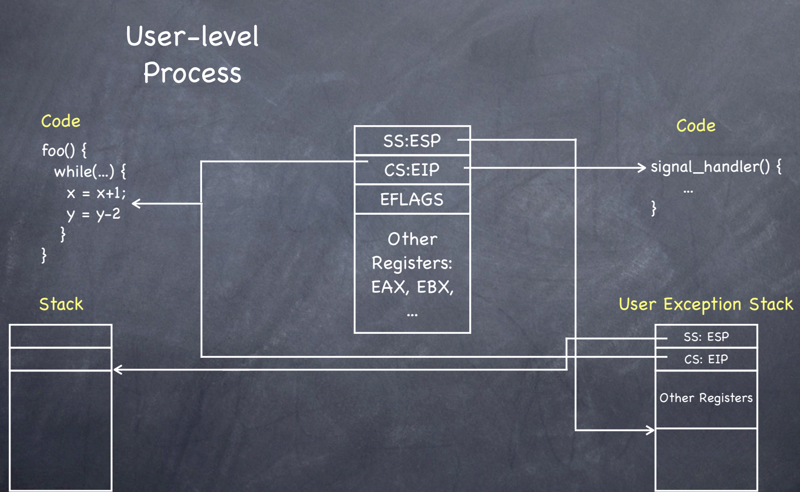

Booting an OS Kernel

- Basic Input/Output System
- In ROM, includes the first instructions fetched and executed
- BIOS copies bootloader, using a cryptographic signature to make sure it has not been tampered with

Booting an OS Kernel

- Bootloader copies OS kernel, checking its cryptographic signature

Booting an OS Kernel

- Kernel initializes its data structures
- Starts first process by copying it from disk
- Let the dance BEGIN!