Signals and Inter-Process Communication

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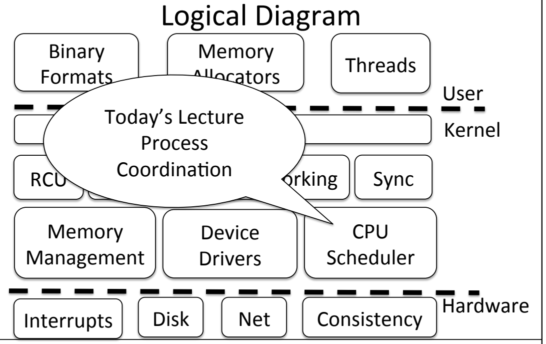
Housekeeping

- Paper reading assigned for next Thurs
  - (Class after midterm)

Logical Diagram



Last time…

- We've discussed how the OS schedules the CPU
  - And how to block a process on a resource (disk, network)
- Today:
  - How do processes block on each other?
  - And more generally communicate?

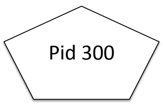
Outline

- Signals
  - Overview and APIs
  - Handlers
  - Kernel-level delivery
  - Interrupted system calls
- Interprocess Communication (IPC)
  - Pipes and FIFOs
  - System V IPC
  - Windows Analogs

What is a signal?

- Like an interrupt, but for applications
  - <64 numbers with specific meanings
  - A process can raise a signal to another process or thread
  - A process or thread registers a handler function
- For both IPC and delivery of hardware exceptions
  - Application-level handlers: divzero, segfaults, etc.
- No "message" beyond the signal was raised
  - And maybe a little metadata
    - PID of sender, faulting address, etc.
    - But platform-specific (non-portable)

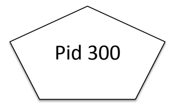
Example

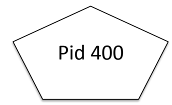



```
int main() {
     ...
     signal(SIGUSR1, &usr_handler);
     ...
}
```

Register usr_handler() to handle SIGUSR1

Example






```
int main() {
     ...    PC
}                          kill(300, SIGUSR1);

int usr_handler() { …
```

Send signal to PID 300

Basic Model

- Application registers handlers with signal or sigaction
- Send signals with kill and friends
  - Or raised by hardware exception handlers in kernel
- Signal delivery jumps to signal handler
  - Irregular control flow, similar to an interrupt

API names are admittedly confusing

Signal Types

- See man 7 signal for the full list: (varies by sys/arch)

SIGTSTP – 1 – Stop typed at terminal (Ctrl+Z)
SIGKILL – 9 – Kill a process, for realzies
SIGSEGV – 11 – Segmentation fault
SIGPIPE – 13 – Broken pipe (write with no readers)
SIGALRM – 14 – Timer
SIGUSR1 – 10 – User-defined signal 1
SIGCHLD – 17 – Child stopped or terminated
SIGSTOP – 19 – Stop a process
SIGCONT – 18 – Continue if stopped

Language Exceptions

- Signals are the underlying mechanism for Exceptions and catch blocks
- JVM or other runtime system sets signal handlers
  - Signal handler causes execution to jump to the catch block

Signal Handler Control Flow

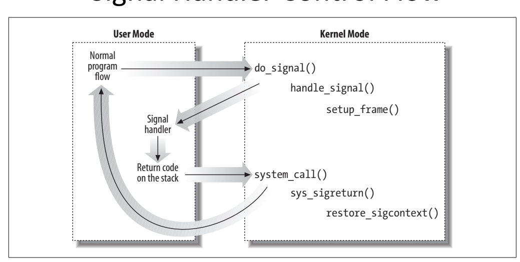


Figure 11-2. Catching a signal

From *Understanding the Linux Kernel*

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Alternate Stacks

- Signal handlers execute on a different stack than program execution.
  - Why?
    - Safety: App can ensure stack is actually mapped
      - And avoid assumptions about application not using space below rsp
  - Set with sigaltstack() system call
- Like an interrupt handler, kernel pushes register state on interrupt stack
  - Return to kernel with sigreturn() system call
  - App can change its own on-stack register state!

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Nested Signals

- What happens when you get a signal in the signal handler?
- And why should you care?

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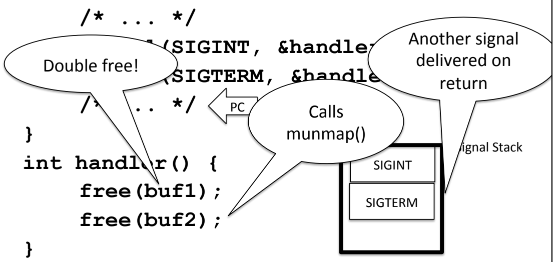
The Problem with Nesting

```
int main() {
    /* ... */
    ...(SIGINT, &handle...
    ...SIGTERM, &handle...
    /* ... */
}
int handler() {
    free(buf1);
    free(buf2);
}
```



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Nested Signals

- The original signal() specification was a total mess!
  - Now deprecated---do not use!
- New sigaction() API lets you specify this in detail
  - What signals are blocked (and delivered on sigreturn)
  - Similar to disabling hardware interrupts
- As you might guess, blocking system calls inside of a signal handler are only safe with careful use of sigaction()

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Application vs. Kernel

- App: signals appear to be delivered roughly immediately
- Kernel (lazy):
  - Send a signal == mark a pending signal in the task
    - And make runnable if blocked with TASK_INTERRUPTIBLE flag
  - Check pending signals on return from interrupt or syscall
    - Deliver if pending

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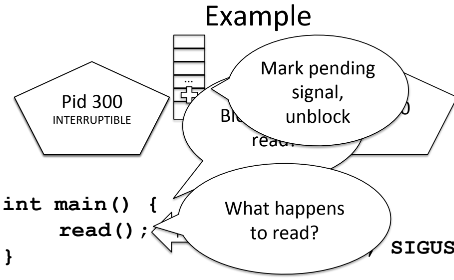
Example




```
int main() {
    read();
}
                          SIGUSR1);

int usr_handler() { …
```

Send signal to PID 300

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Interrupted System Calls

- If a system call blocks in the INTERRUPTIBLE state, a signal wakes it up
- Yet signals are delivered on *return* from a system call
- How is this resolved?
- The system call fails with a special error code
  - EINTR and friends
  - Many system calls transparently retry after sigreturn
  - Some do not – check for EINTR in your applications!

Default handlers

- Signals have default handlers:
  - Ignore, kill, suspend, continue, dump core
  - These execute inside the kernel
- Installing a handler with signal/sigaction overrides the default
- A few (SIGKILL) cannot be overridden

RT Signals

- Default signals are only in 2 states: signaled or not
  - If I send 2 SIGUSR1's to a process, only one may be delivered
  - If system is slow and I furiously hit Ctrl+C over and over, only one SIGINT delivered
- Real time (RT) signals keep a count
  - Deliver one signal for each one sent

Signal Summary

- Abstraction like hardware interrupts
  - Some care must be taken to block other interrupts
  - Easy to write buggy handlers and miss EINTR
- Understand control flow from application and kernel perspective
- Understand basic APIs

Other IPC

- Pipes, Sockets, and FIFOs
- System V IPC
- Windows comparison

Pipes

- Stream of bytes between two processes
- Read and write like a file handle
  - But not anywhere in the hierarchical file system
  - And not persistent
  - And no cursor or seek()-ing
  - Actually, 2 handles: a read handle and a write handle
- Primarily used for parent/child communication
  - Parent creates a pipe, child inherits it

Example

```
int pipe_fd[2];
int rv = pipe(pipe_fd);
int pid = fork();
if (pid == 0) {
       close(pipe_fd[1]); //Close unused write end
       dup2(pipe_fd[0], 0); // Make the read end stdin
       exec("grep", "quack");
} else {
       close (pipe_fd[0]);  // Close unused read end …
```


FIFOs (aka Named Pipes)

- Existing pipes can't be opened---only inherited
  - Or passed over a Unix Domain Socket (beyond today's lec)
- FIFOs, or Named Pipes, add an interface for opening existing pipes

Sockets

- Similar to pipes, except for network connections
- Setup and connection management is a bit trickier
  - A topic for another day (or class)

Select

- What if I want to block until one of several handles has data ready to read?
- Read will block on one handle, but perhaps miss data on a second…
- Select will block a process until a handle has data available
  - Useful for applications that use pipes, sockets, etc.

Synthesis Example: The Shell

- Almost all 'commands' are really binaries
  - /bin/ls
- Key abstraction: Redirection over pipes
  - '>', '<', and '|'implemented by the shell itself

Shell Example

- Ex: **`ls | grep foo`**
- Implementation sketch:
  - Shell parses the entire string
  - Sets up chain of pipes
  - Forks and exec's 'ls' and 'grep' separately
  - Wait on output from 'grep', print to console

Job control in a shell

- Shell keeps its own "scheduler" for background processes
- How to:
  - Put a process in the background?
    - SIGTSTP handler catches Ctrl-Z
    - Send SIGSTOP to current foreground child
  - Resume execution (fg)?
    - Send SIGCONT to paused child, use waitpid() to block until finished
  - Execute in background (bg)?
    - Send SIGCONT to paused child, but block on terminal input

Other hints

- Splice(), tee(), and similar calls are useful for connecting pipes together
  - Avoids copying data into and out-of application

System V IPC

- Semaphores – Lock
- Message Queues – Like a mail box, "small" messages
- Shared Memory – particularly useful
  - A region of non-COW anonymous memory
  - Map at a given address using shmat()
- Can persist longer than an application
  - Must be explicitly deleted
  - Can leak at system level
  - But cleared after a reboot

System V Keys and IDs

- Programmers pick arbitrary 32-bit keys
  - Use these keys to name shared abstractions
- Find a key using shmget(), msgget(), etc.
  - Kernel internally maps key to a 32-bit ID

Windows Comparison

- Hardware exceptions are treated separately from IPC
  - Upcalls to ntdll.dll (libc equivalent), to call handlers
- All IPC types can be represented as handles
  - Process termination/suspend/resume signaled with process handles
  - Signals can be an Event handle
  - Semaphores and Mutexes have handles
  - Shared memory equally complicated (but still handles)
- Single select()-like API to wait on a handle to be signaled

Summary

- Understand signals
- Understand high-level properties of pipes and other Unix IPC abstractions
  - High-level comparison with Windows