# *Exceptions*

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# Control Flow

- Processors do only one thing:
  - From startup to shutdown, a CPU simply reads and executes (interprets) a sequence of instructions, one at a time
  - This sequence is the CPU's *control flow* (or *flow of control*)

*Physical control flow*

Time

<startup>
$inst_1$
$inst_2$
$inst_3$
…
$inst_n$
<shutdown>

# Altering the Control Flow

- Up to now: two mechanisms for changing control flow:
  - Jumps and branches
  - Call and return

  React to changes in ***program state***

- Insufficient for a useful system:
  Difficult to react to changes in *system state*
  - Data arrives from a disk or a network adapter
  - Instruction divides by zero
  - User hits Ctrl-C at the keyboard
  - System timer expires

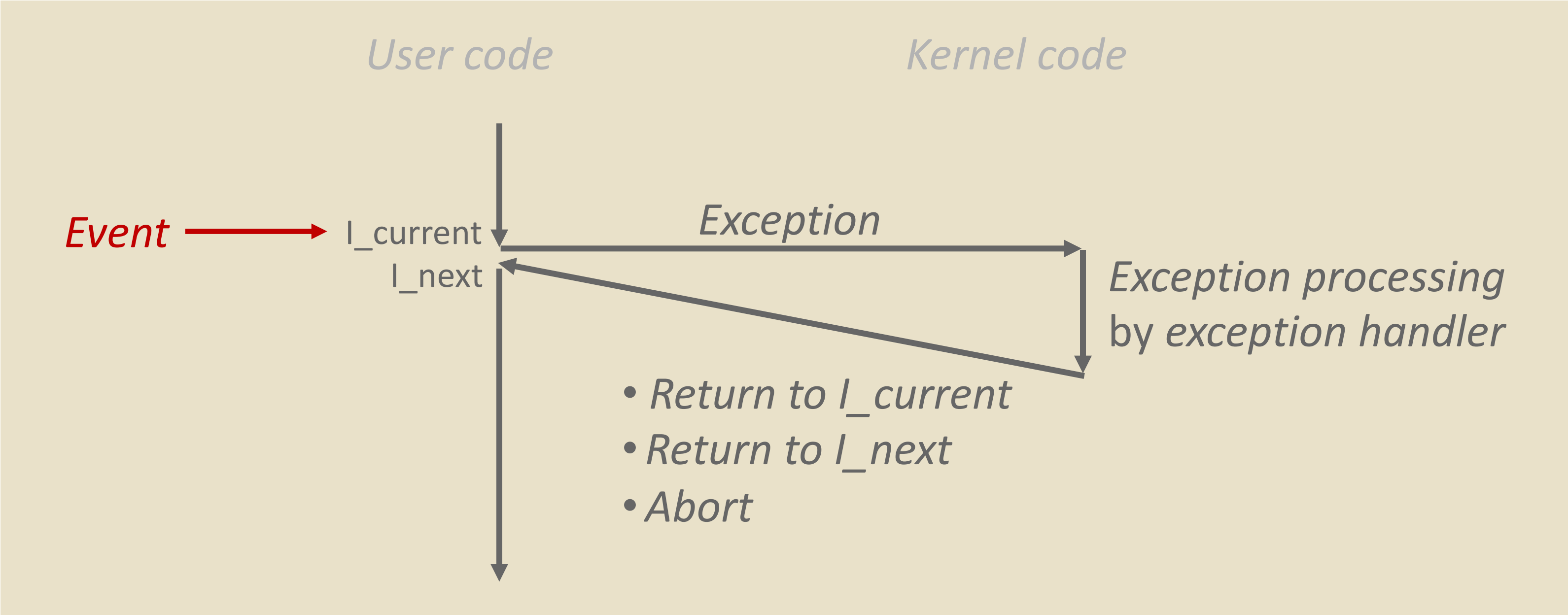
- System needs mechanisms for "exceptional control flow"

# Exceptional Control Flow

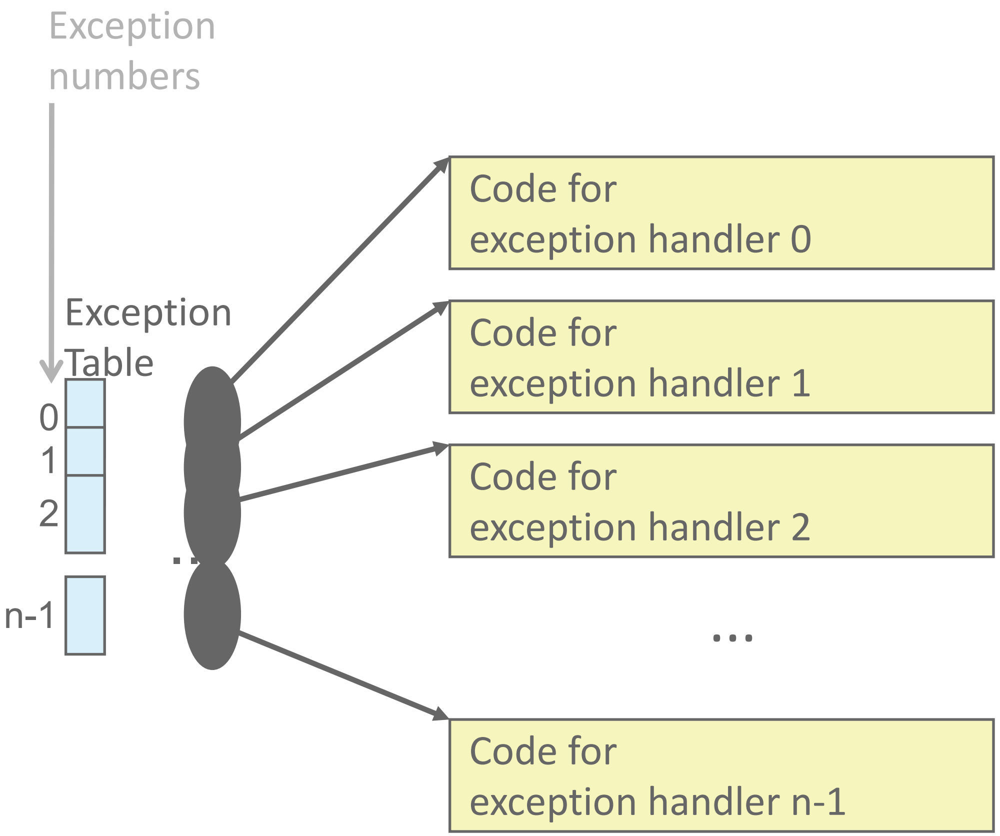
- Exists at all levels of a computer system
- Low level mechanisms
  - 1. **Exceptions**
    - Change in control flow in response to a system event (i.e., change in system state)
    - Implemented using combination of hardware and OS software
- Higher level mechanisms
  - 2. **Process context switch**
    - Implemented by OS software and hardware timer
  - 3. **Signals**
    - Implemented by OS software
  - 4. **Nonlocal jumps**: `setjmp()` and `longjmp()`
    - Implemented by C runtime library

# Exceptions

- An *exception* is a transfer of control to the OS *kernel* in response to some *event* (i.e., change in processor state)
  - Kernel is the memory-resident part of the OS
  - Examples of events: Divide by 0, arithmetic overflow, page fault, I/O request completes, typing Ctrl-C

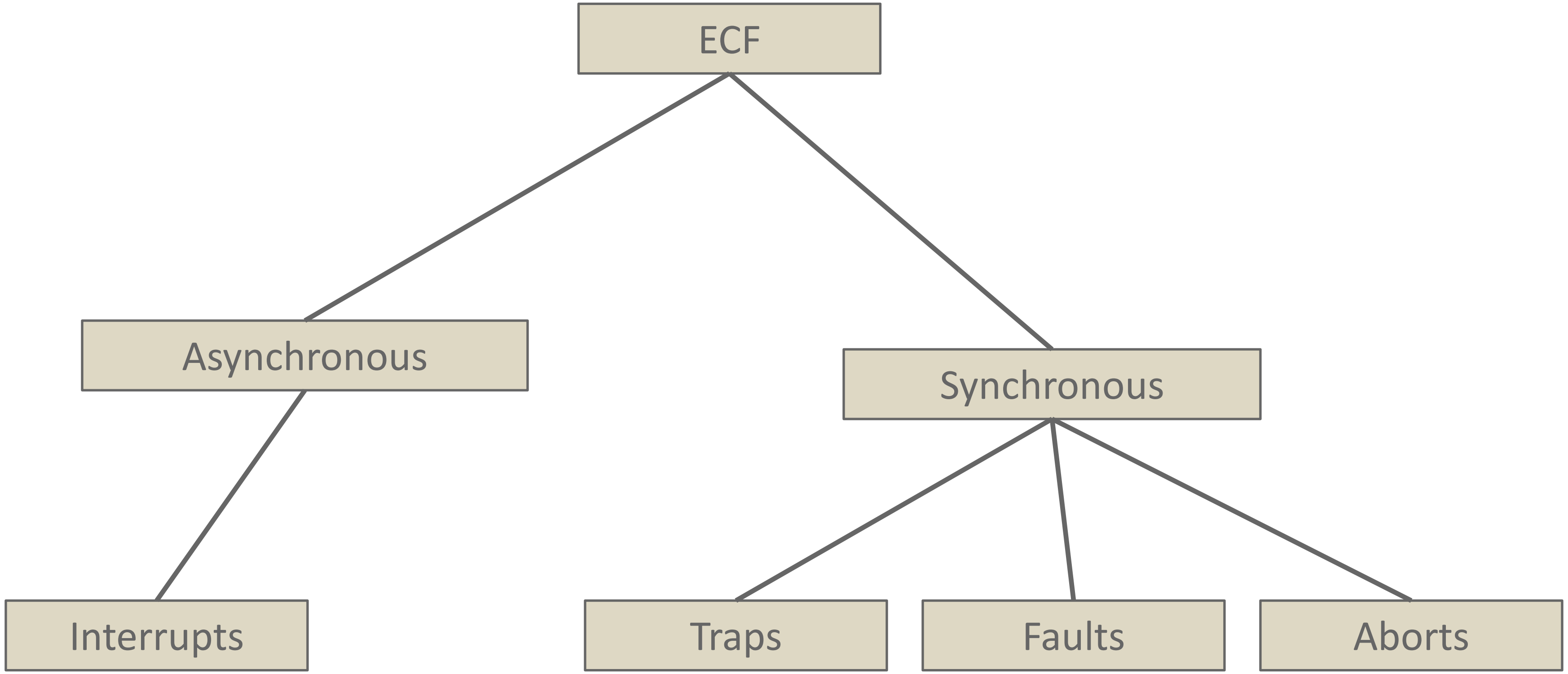


# Exception Tables




- Each type of event has a unique exception number k
- k = index into exception table (a.k.a. interrupt vector)
- Handler k is called each time exception k occurs

# (partial) Taxonomy



# Asynchronous Exceptions (Interrupts)

- Caused by events external to the processor
  - Indicated by setting the processor's *interrupt pin*
  - Handler returns to "next" instruction

- Examples:
  - Timer interrupt
    - Every few ms, an external timer chip triggers an interrupt
    - Used by the kernel to take back control from user programs
  - I/O interrupt from external device
    - Hitting Ctrl-C at the keyboard
    - Arrival of a packet from a network
    - Arrival of data from a disk

# Synchronous Exceptions

- Caused by events that occur as a result of executing an instruction:
  - ***Traps***
    - Intentional, set program up to "trip the trap" and do something
    - Examples: ***system calls***, gdb breakpoints
    - Returns control to "next" instruction
  - ***Faults***
    - Unintentional but possibly recoverable
    - Examples: page faults (recoverable), protection faults (unrecoverable), floating point exceptions
    - Either re-executes faulting ("current") instruction or aborts
  - ***Aborts***
    - Unintentional and unrecoverable
    - Examples: illegal instruction, parity error, machine check
    - Aborts current program

# System Calls

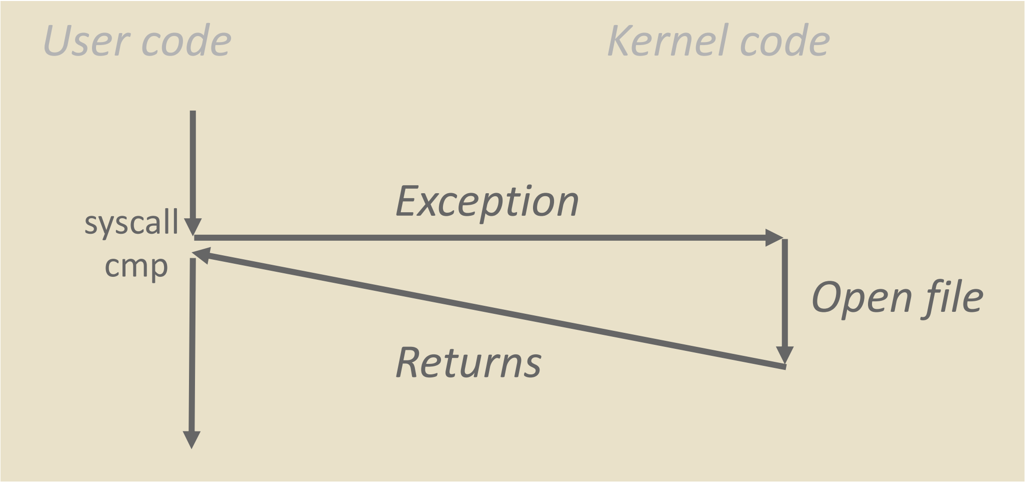
- Each x86-64 system call has a unique ID number
- Examples:

| Number | Name | Description |
|---|---|---|
| 0 | `read` | Read file |
| 1 | `write` | Write file |
| 2 | `open` | Open file |
| 3 | `close` | Close file |
| 4 | `stat` | Get info about file |
| 57 | `fork` | Create process |
| 59 | `execve` | Execute a program |
| 60 | `_exit` | Terminate process |
| 62 | `kill` | Send signal to process |

# System Call Example: Opening File

- User calls: `open(filename, options)`
- Calls `__open` function, which invokes system call instruction `syscall`

```
00000000000e5d70 <__open>:
...
e5d79:   b8 02 00 00 00      mov  $0x2,%eax  # open is syscall #2
e5d7e:   0f 05               syscall         # Return value in %rax
e5d80:   48 3d 01 f0 ff ff   cmp  $0xfffffffffffff001,%rax
...
e5dfa:   c3                  retq
```




- `%rax` contains syscall number
- Other arguments in `%rdi`, `%rsi`, `%rdx`, `%r10`, `%r8`, `%r9`
- Return value in `%rax`
- Negative value is an error corresponding to negative `errno`

# System Call Example: Opening File

- User calls: `open(filename, options)`
- Calls `__open` function, which invokes system call instruction `syscall`

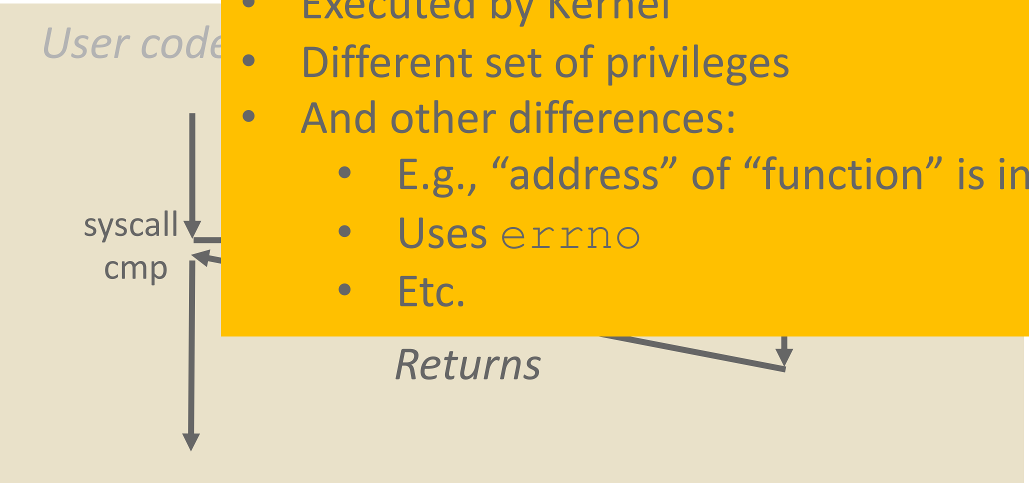
```
0000000000e5d70 <__open>:
...
e5d79:                    all #2
e5d7e:                    in %rax
e5d80:
...
e5dfa:
```

Almost like a function call

- Transfer of control
- On return, executes next instruction
- Passes arguments using calling convention
- Gets result in `%rax`

One Important exception!

- Executed by Kernel
- Different set of privileges
- And other differences:
  - E.g., "address" of "function" is in `%rax`
  - Uses `errno`
  - Etc.




call number
`%rdi,`
`), %r8, %r9`
`ax`

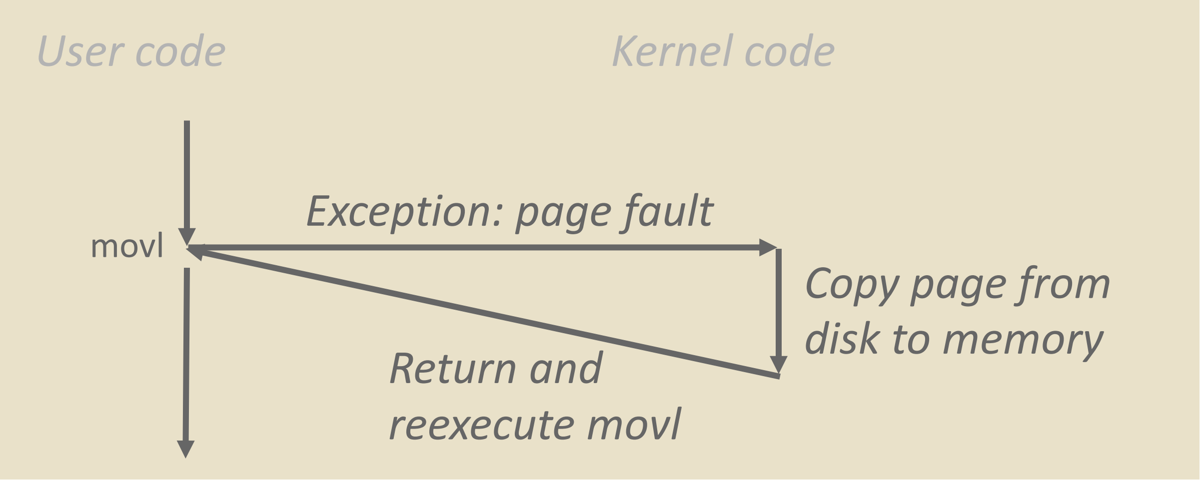
- Negative value is an error corresponding to negative `errno`

# Fault Example: Page Fault

- User writes to memory location
- That portion (page) of user's memory is currently on disk

```
int a[1000];
main ()
{
    a[500] = 13;
}
```

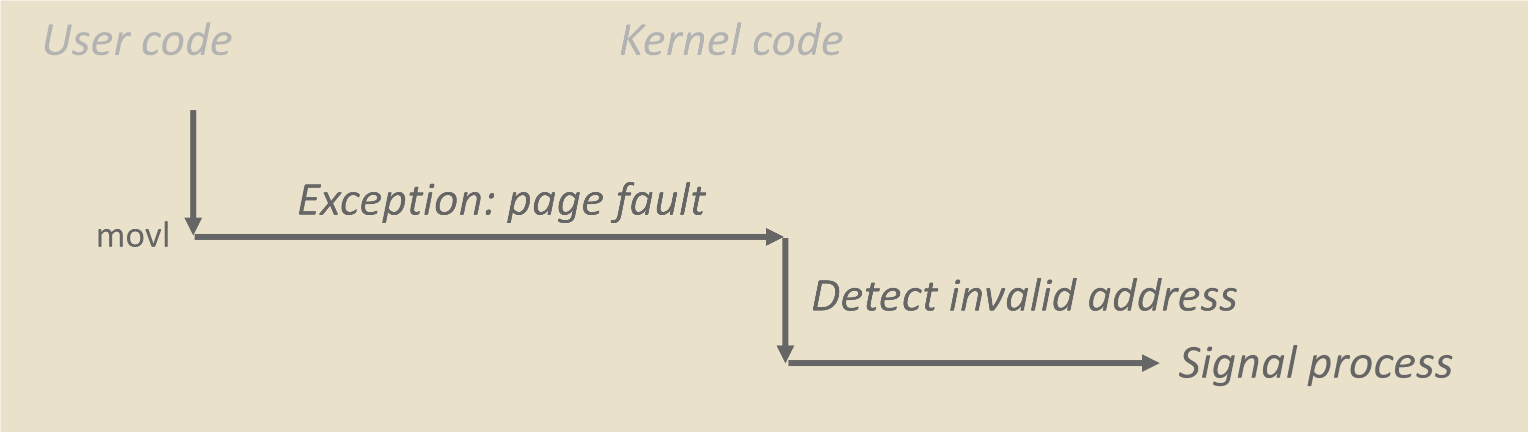
```
80483b7:        c7 05 10 9d 04 08 0d    movl    $0xd,0x8049d10
```



# Fault Example: Invalid Memory Reference

```
int a[1000];
main ()
{
    a[5000] = 13;
}
```

```
80483b7:        c7 05 60 e3 04 08 0d    movl    $0xd,0x804e360
```

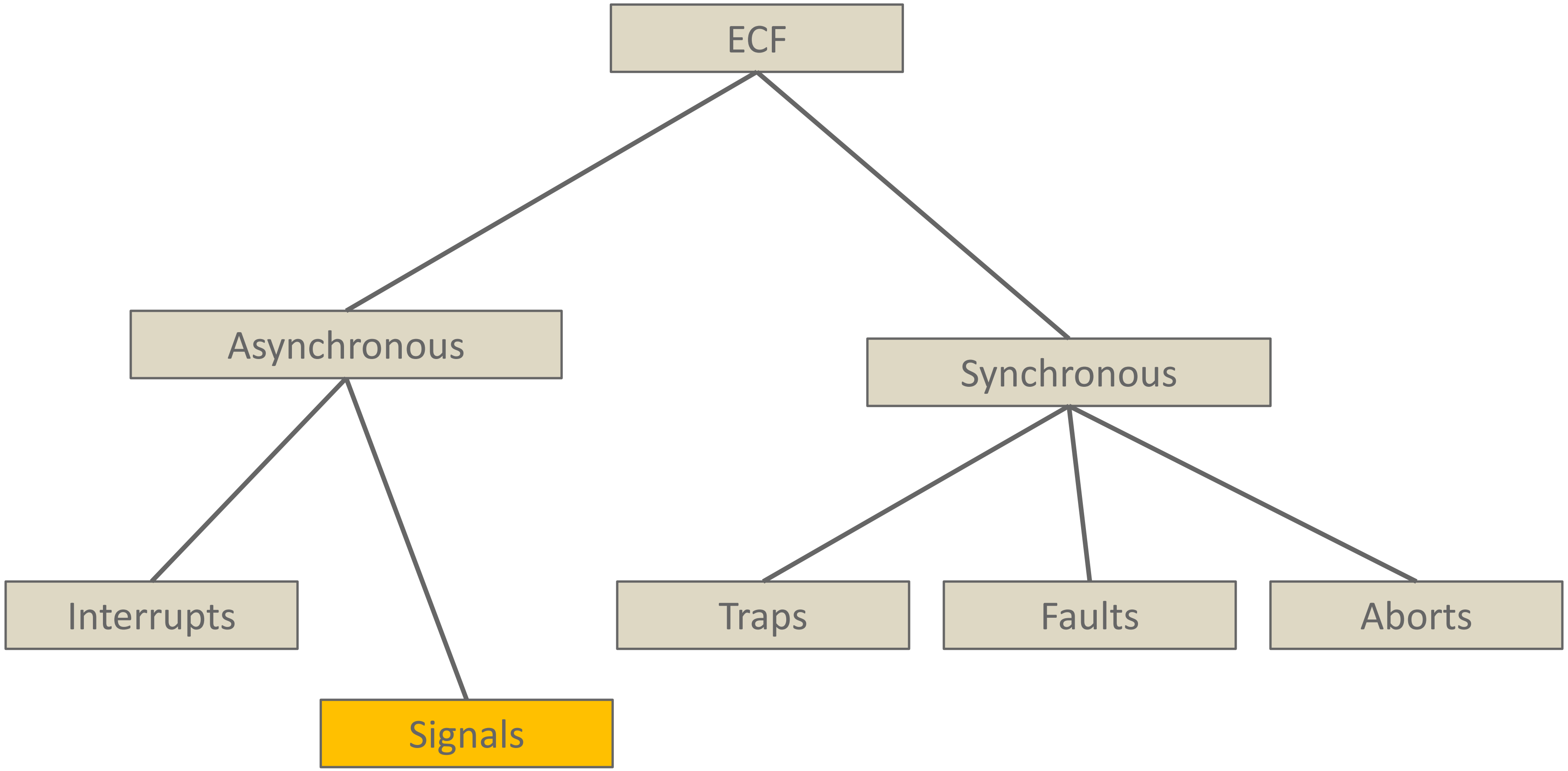



- Sends `SIGSEGV` signal to user process
- User process exits with “segmentation fault”

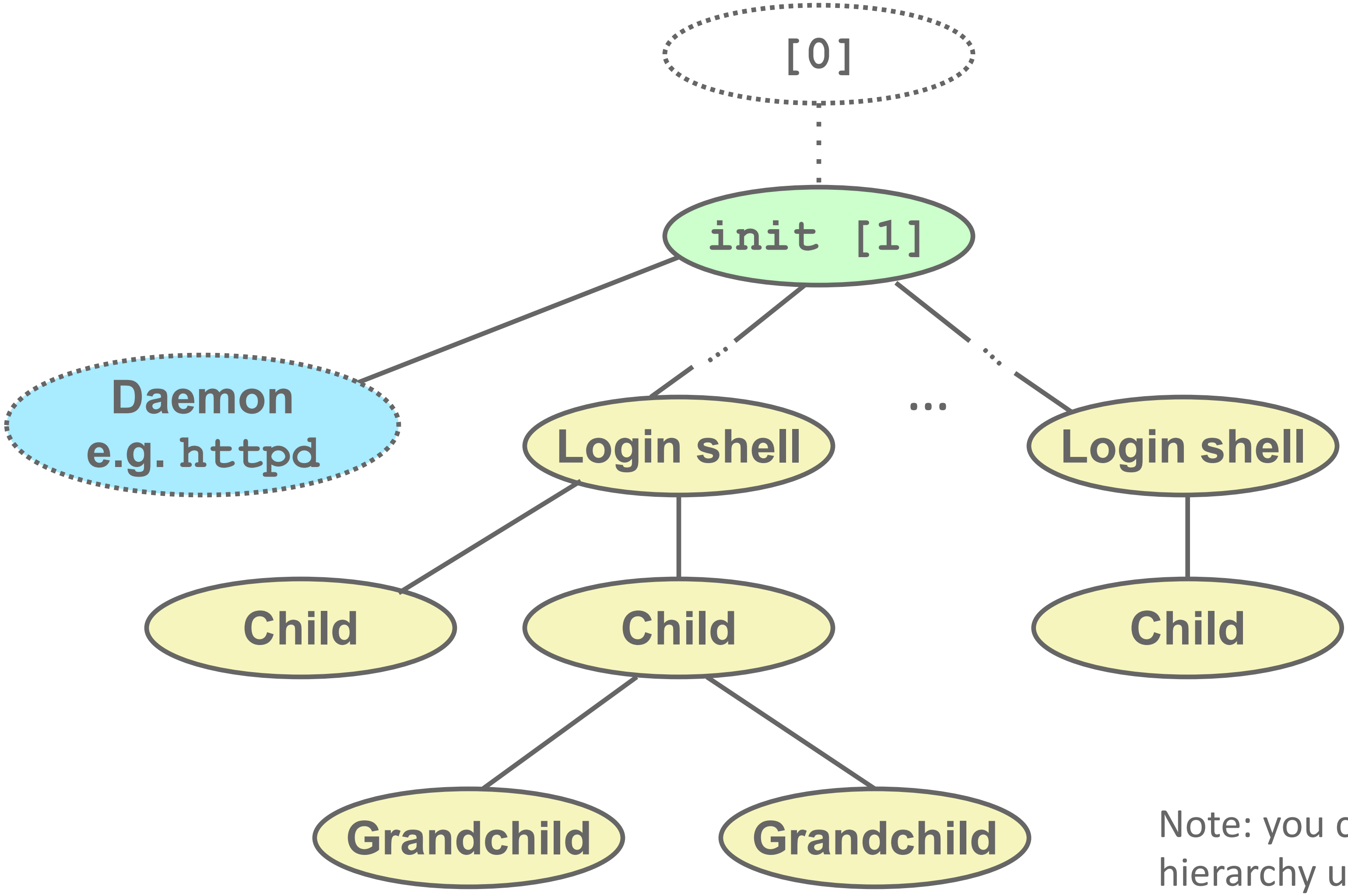
# (partial) Taxonomy

Handled in kernel

Handled in user process



# Linux Process Hierarchy




Note: you can view the hierarchy using the Linux `pstree` command

# Shell Programs

- A *shell* is an application program that runs programs on behalf of the user.
  - **sh** Original Unix shell (Stephen Bourne, AT&T Bell Labs, 1977)
  - **csh/tcsh** BSD Unix C shell
  - **bash** "Bourne-Again" Shell (default Linux shell)
- Simple shell
  - Described in the textbook, starting at p. 753
  - Implementation of a very elementary shell
  - Purpose
    - Understand what happens when you type commands
    - Understand use and operation of process control operations

# Simple Shell Example

```
linux> ./shellex
> /bin/ls -l csapp.c
-rw-r--r-- 1 bryant users 23053 Jun 15  2015 csapp.c
> /bin/ps
  PID TTY          TIME CMD
31542 pts/2    00:00:01 tcsh
32017 pts/2    00:00:00 shellex
32019 pts/2    00:00:00 ps
> /bin/sleep 10 &
32031 /bin/sleep 10 &
> /bin/ps
 PID TTY          TIME CMD
31542 pts/2    00:00:01 tcsh
32024 pts/2    00:00:00 emacs
32030 pts/2    00:00:00 shellex
32031 pts/2    00:00:00 sleep
32033 pts/2    00:00:00 ps
> quit
```

Must give full pathnames for programs

Run program in background

Sleep is running in background

# Problem with Shells

- Shell designed to run indefinitely
  - Should not accumulate unneeded resources
    - Memory
    - Child processes
    - File descriptors
- Our example shell correctly waits for and reaps foreground jobs
- But what about background jobs?
  - Will become zombies when they terminate
  - Will never be reaped because shell (typically) will not terminate
  - Will create a memory leak that could run the kernel out of memory

# ECF to the Rescue!

- Solution: Exceptional control flow
  - The kernel will interrupt regular processing to alert us when a background process completes
  - In Unix, the alert mechanism is called a ***signal***

# Signals

- A *signal* is a small message that notifies a process that an event of some type has occurred in the system
  - Akin to exceptions and interrupts
  - Sent from the kernel (sometimes at the request of another process) to a process
  - Signal type is identified by small integer ID's (1-30)
  - Only information in a signal is its ID and the fact that it arrived

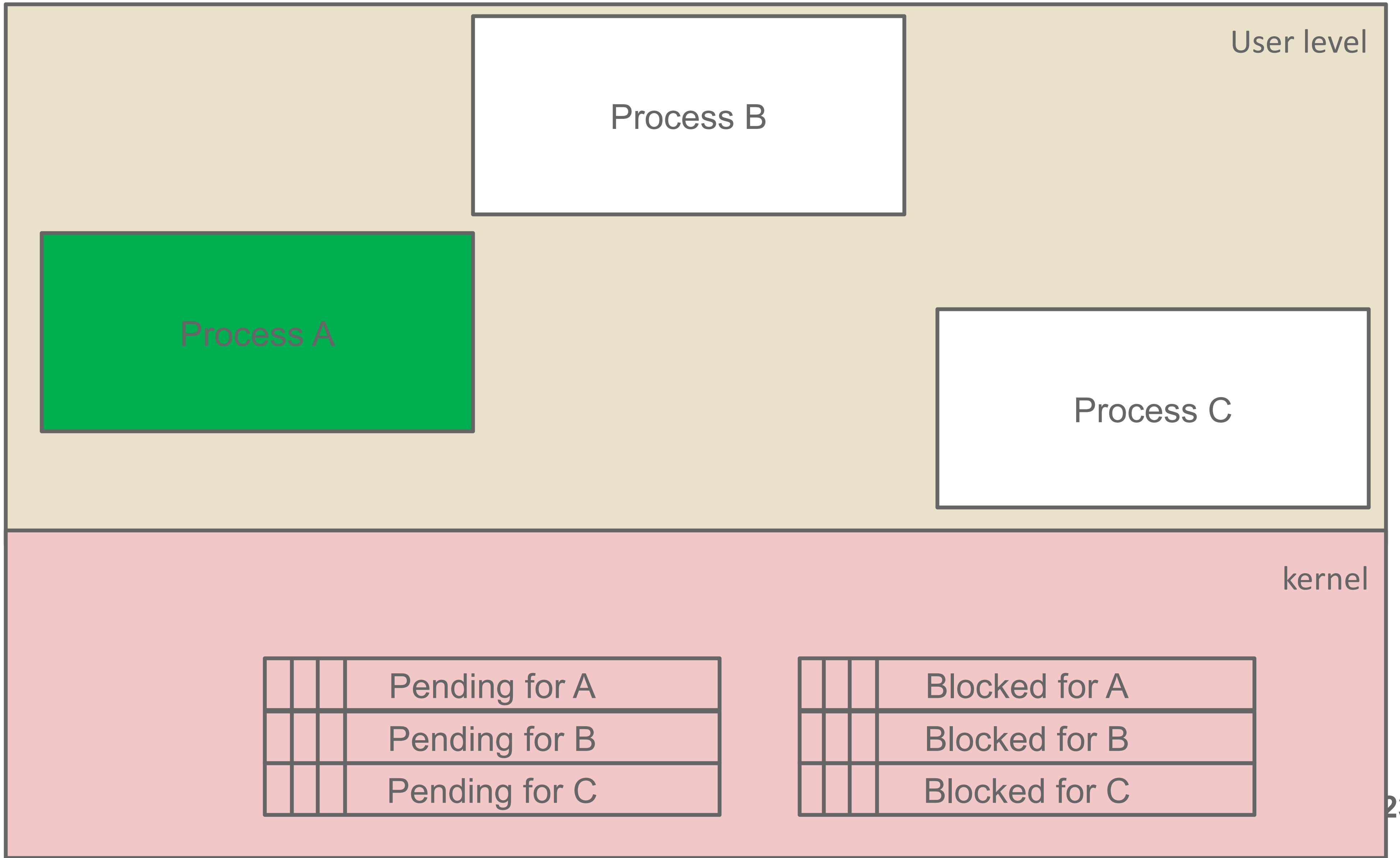
| *ID* | *Name* | *Default Action* | *Corresponding Event* |
|---|---|---|---|
| 2 | SIGINT | Terminate | User typed ctrl-c |
| 9 | SIGKILL | Terminate | Kill program (cannot override or ignore) |
| 11 | SIGSEGV | Terminate | Segmentation violation |
| 14 | SIGALRM | Terminate | Timer signal |
| 17 | SIGCHLD | Ignore | Child stopped or terminated |

# Signal Concepts: Sending a Signal

- Kernel *sends* (delivers) a signal to a *destination process* by updating some state in the context of the destination process

- Kernel sends a signal for one of the following reasons:
  - Kernel has detected a system event such as divide-by-zero (SIGFPE) or the termination of a child process (SIGCHLD)
  - Another process has invoked the **`kill`** system call to explicitly request the kernel to send a signal to the destination process

# Signal Concepts: Sending a Signal



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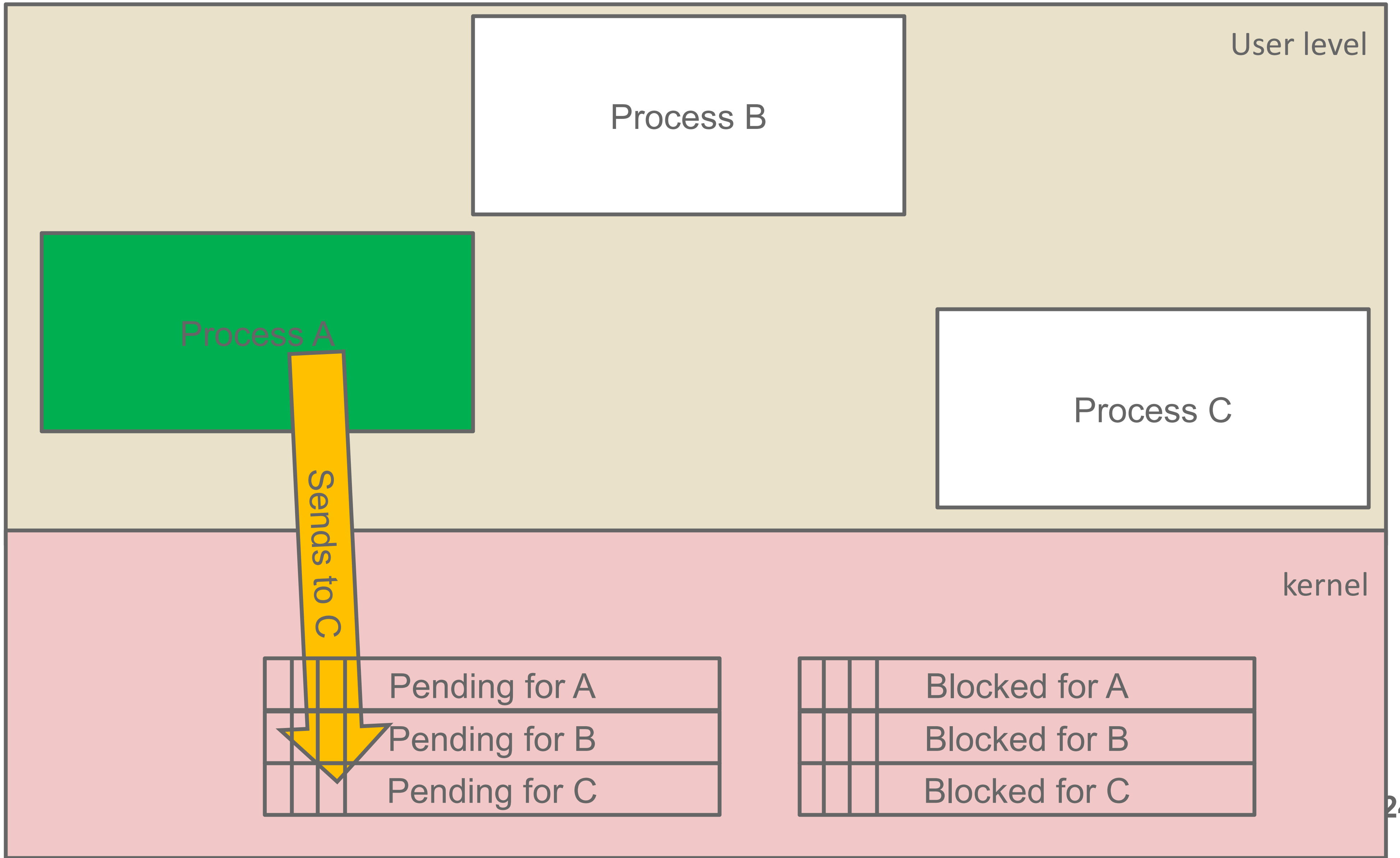
# Signal Concepts: Sending a Signal



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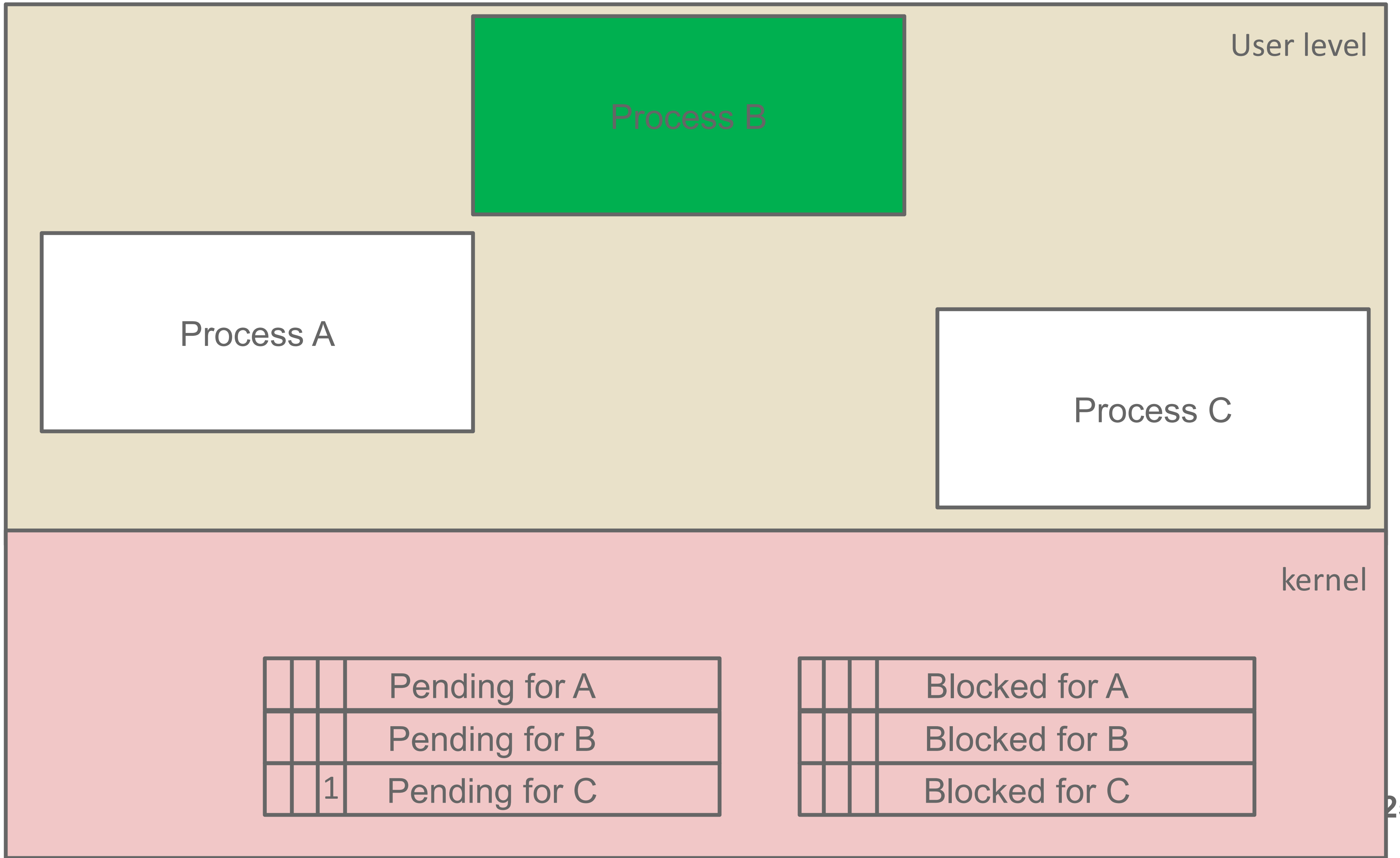

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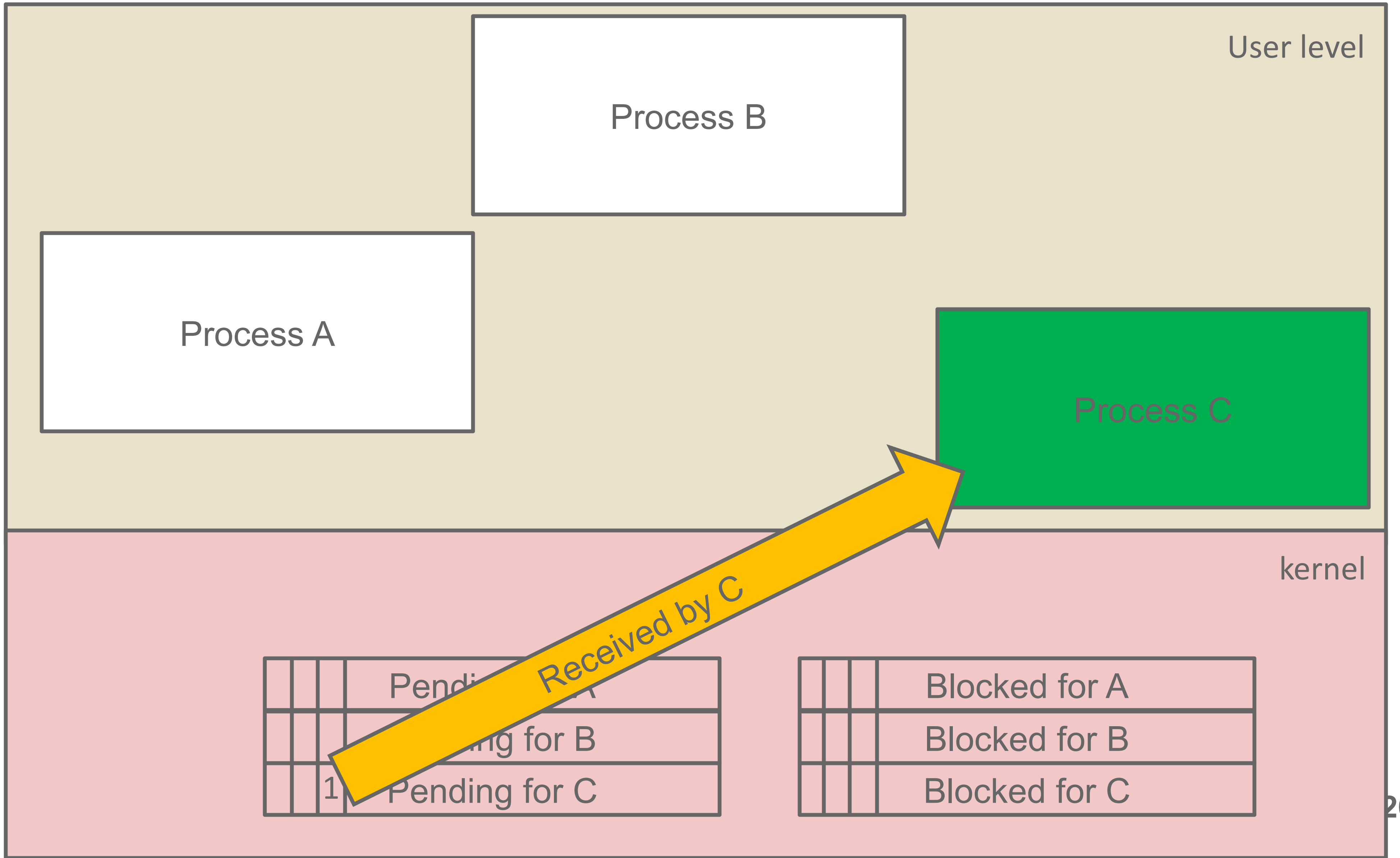
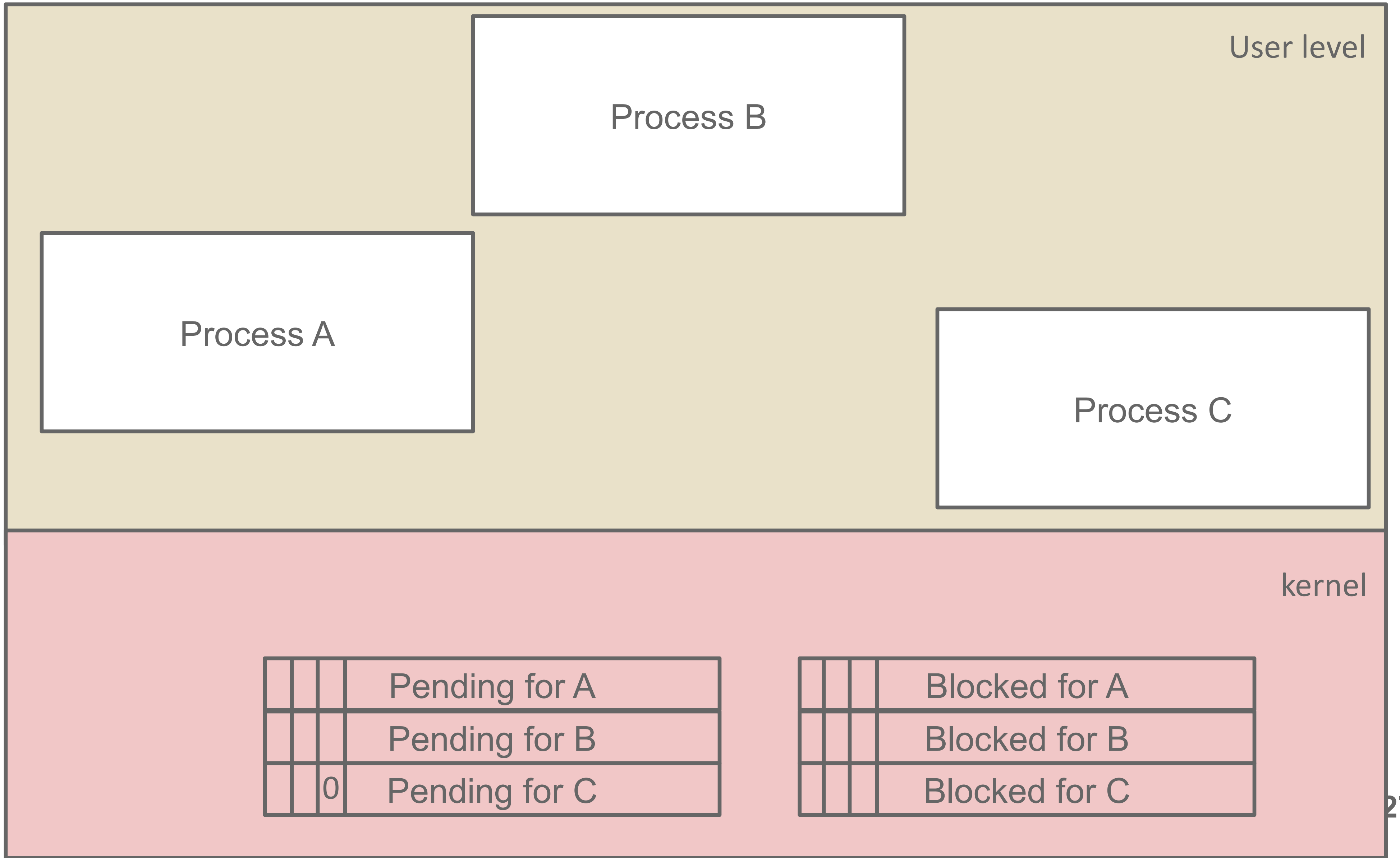
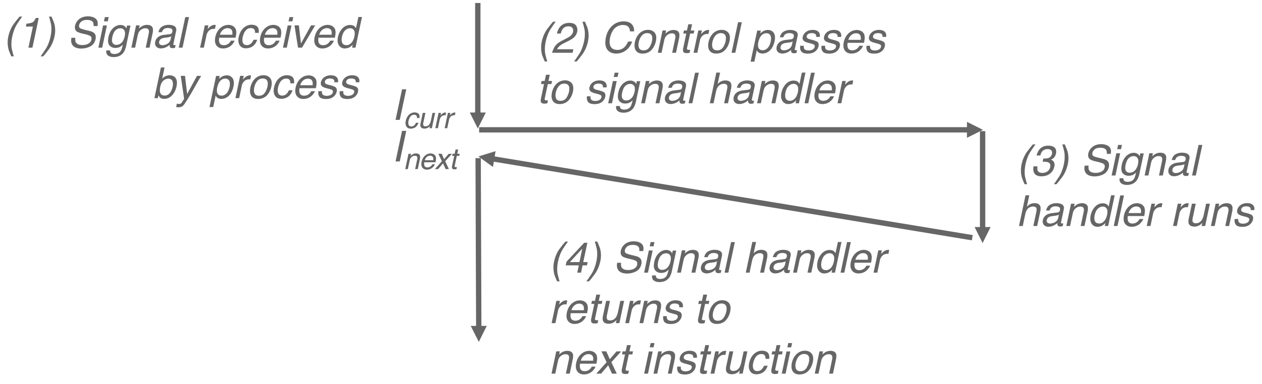


# Signal Concepts: Sending a Signal



# Signal Concepts: Receiving a Signal

- A destination process ***receives*** a signal when it is forced by the kernel to react in some way to the delivery of the signal
- Some possible ways to react:
  - ***Ignore*** the signal (do nothing)
  - ***Terminate*** the process (with optional core dump)
  - ***Catch*** the signal by executing a user-level function called ***signal handler***
    - Akin to a hardware exception handler being called in response to an asynchronous interrupt:



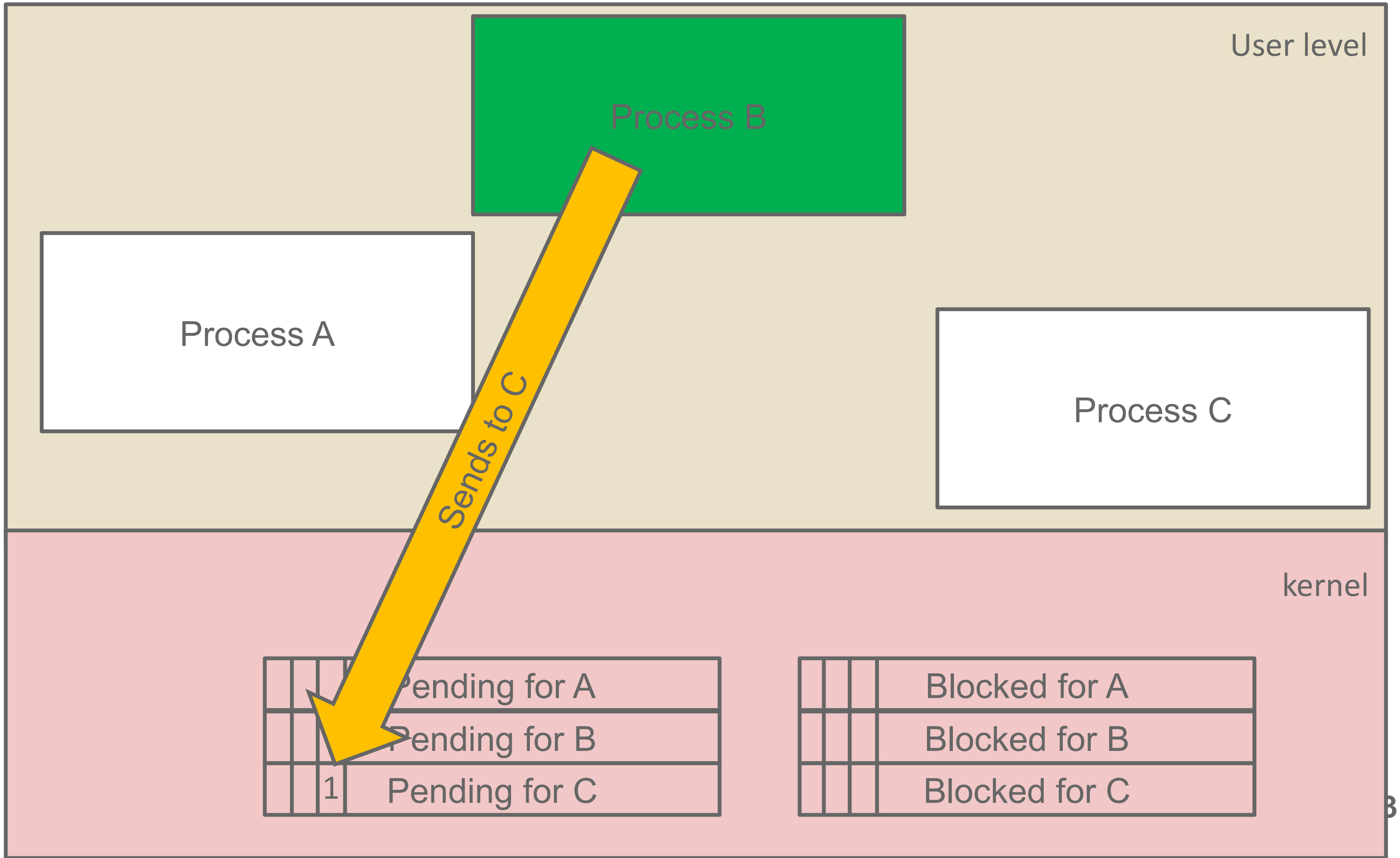
# Signal Concepts: Pending and Blocked Signals

- A signal is *pending* if sent but not yet received
  - There can be at most one pending signal of any particular type
  - Important: Signals are not queued
    - If a process has a pending signal of type k, then subsequent signals of type k that are sent to that process are discarded
- A process can *block* the receipt of certain signals
  - Blocked signals can be delivered, but will not be received until the signal is unblocked
- A pending signal is received at most once

# Signal Concepts: Pending/Blocked Bits

- Kernel maintains `pending` and `blocked` bit vectors in the context of each process
  - **`pending`**: represents the set of pending signals
    - Kernel sets bit k in **`pending`** when a signal of type k is delivered
    - Kernel clears bit k in **`pending`** when a signal of type k is received
  - **`blocked`**: represents the set of blocked signals
    - Can be set and cleared by using the **`sigprocmask`** function
    - Also referred to as the *signal mask*.

# Signal Concepts: Sending a Signal



# Sending Signals with `/bin/kill` Program

- `/bin/kill` program sends arbitrary signal to a process or process group

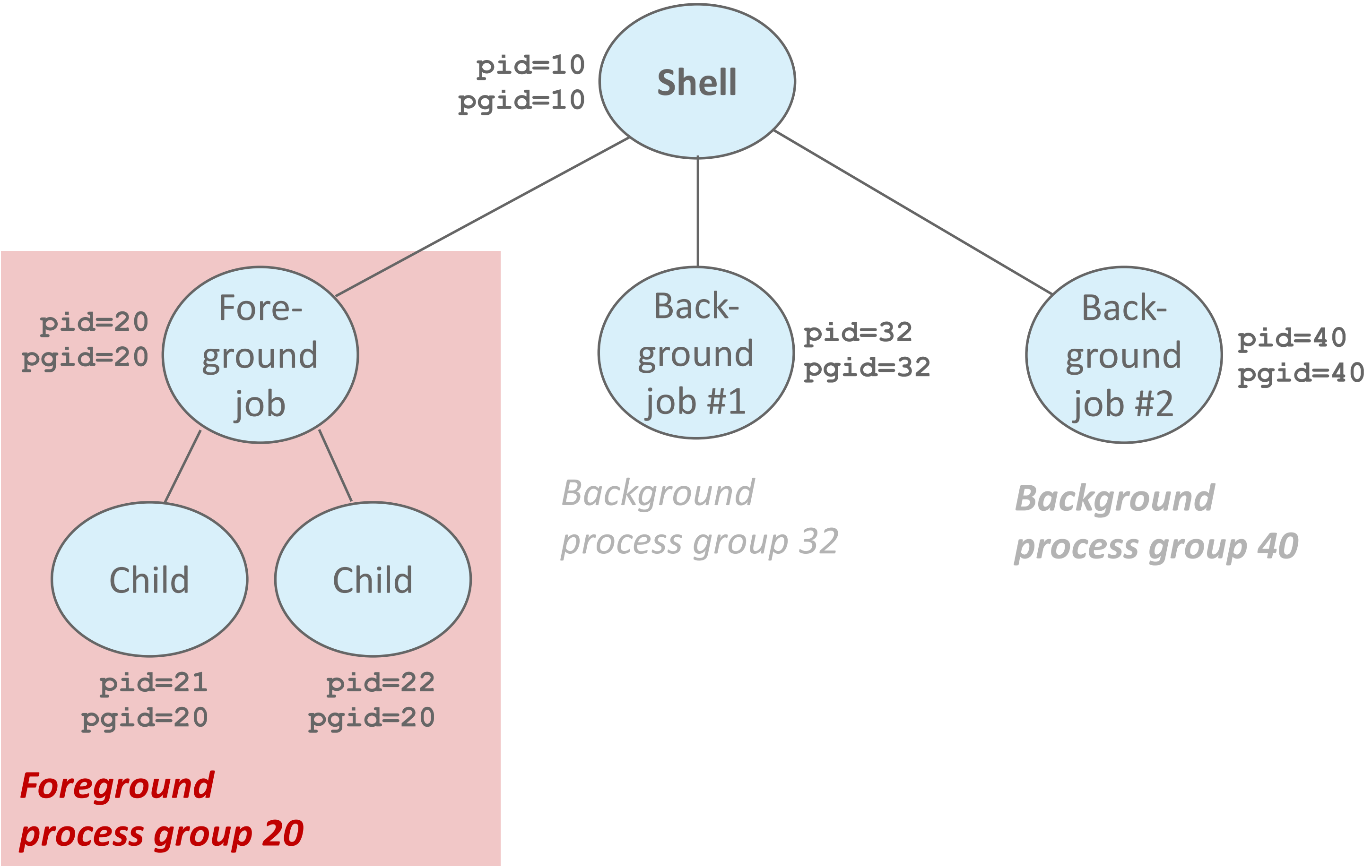
- Examples
  - **`/bin/kill –9 24818`**
    Send SIGKILL to process 24818
  - **`/bin/kill –9 –24817`**
    Send SIGKILL to every process in process group 24817

```
linux> ./forks 16
Child1: pid=24818 pgrp=24817
Child2: pid=24819 pgrp=24817

linux> ps
  PID TTY          TIME CMD
24788 pts/2    00:00:00 tcsh
24818 pts/2    00:00:02 forks
24819 pts/2    00:00:02 forks
24820 pts/2    00:00:00 ps
linux> /bin/kill -9 -24817
linux> ps
  PID TTY          TIME CMD
24788 pts/2    00:00:00 tcsh
24823 pts/2    00:00:00 ps
linux>
```

# Sending Signals from the Keyboard

- Typing ctrl-c (ctrl-z) causes the kernel to send a SIGINT (SIGTSTP) to every job in the foreground process group.
  - SIGINT – default action is to terminate each process
  - SIGTSTP – default action is to stop (suspend) each process



# Example of `ctrl-c` and `ctrl-z`

```
bluefish> ./forks 17
Child: pid=28108 pgrp=28107
Parent: pid=28107 pgrp=28107
<types ctrl-z>
Suspended
bluefish> ps w
  PID TTY      STAT   TIME COMMAND
27699 pts/8    Ss     0:00 -tcsh
28107 pts/8    T      0:01 ./forks 17
28108 pts/8    T      0:01 ./forks 17
28109 pts/8    R+     0:00 ps w
bluefish> fg
./forks 17
<types ctrl-c>
bluefish> ps w
  PID TTY      STAT   TIME COMMAND
27699 pts/8    Ss     0:00 -tcsh
28110 pts/8    R+     0:00 ps w
```

STAT (process state) Legend:

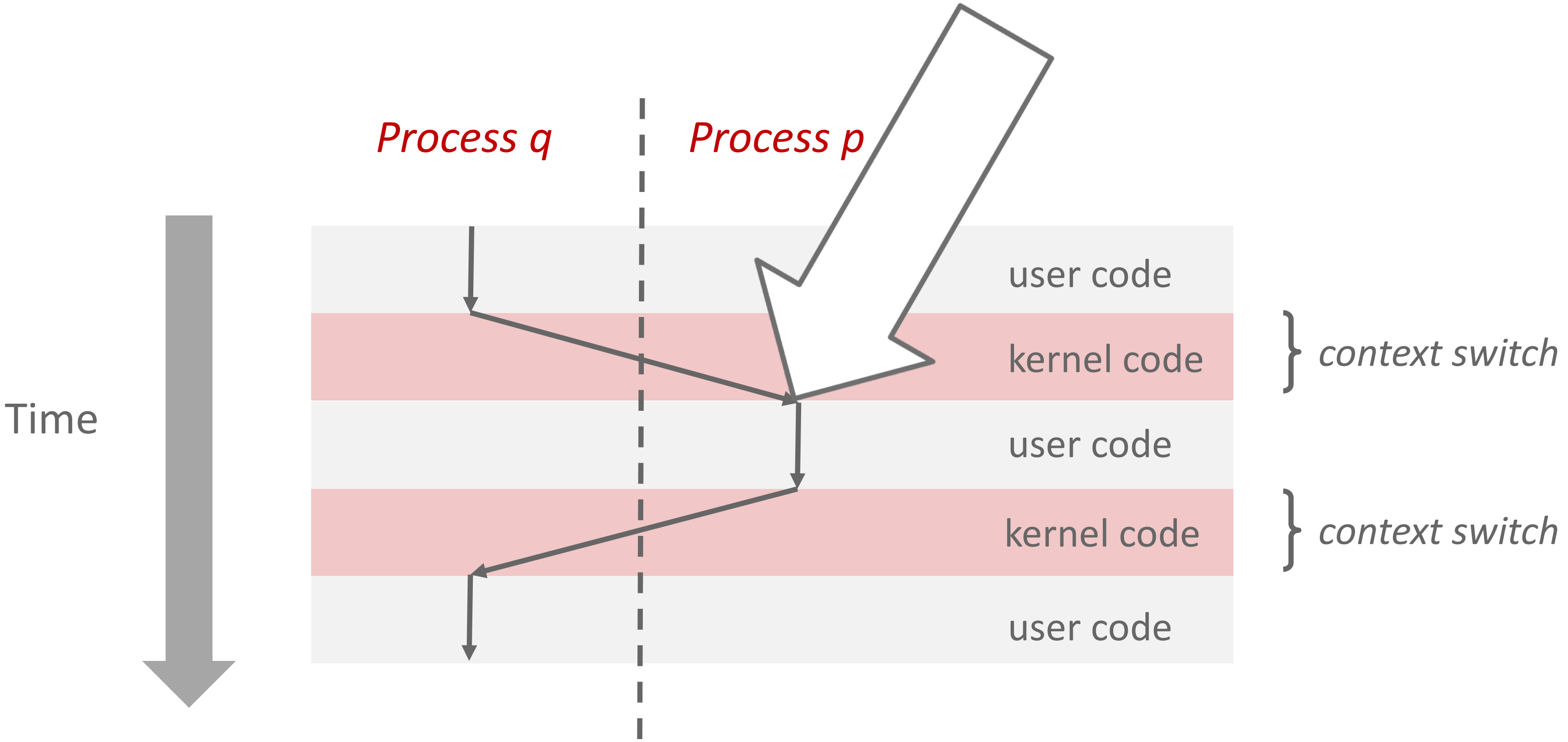
*First letter:*
S: sleeping
T: stopped
R: running

*Second letter:*
s: session leader
+: foreground proc group

See “man ps” for more details

# Receiving Signals

- Suppose kernel is returning from an exception handler and is ready to pass control to process *p*



# Receiving Signals

- Suppose kernel is returning from an exception handler and is ready to pass control to process *p*

- Kernel computes `pnb = pending & ~blocked`
  - The set of pending nonblocked signals for process *p*

- If `(pnb == 0)`
  - Pass control to next instruction in the logical flow for *p*
- Else
  - Choose least nonzero bit *k* in **`pnb`** and force process *p* to ***receive*** signal *k*
  - The receipt of the signal triggers some ***action*** by *p*
  - Repeat for all nonzero *k* in **`pnb`**
  - Pass control to next instruction in logical flow for *p*

# Default Actions

- Each signal type has a predefined *default action*, which is one of:
  - The process terminates
  - The process stops until restarted by a SIGCONT signal
  - The process ignores the signal

# Installing Signal Handlers

- The `signal` function modifies the default action associated with the receipt of signal `signum`:
  - **`handler_t *signal(int signum, handler_t *handler)`**

- Different values for `handler`:
  - SIG_IGN: ignore signals of type **`signum`**
  - SIG_DFL: revert to the default action on receipt of signals of type **`signum`**
  - Otherwise, **`handler`** is the address of a user-level ***signal handler***
    - Called when process receives signal of type **`signum`**
    - Referred to as ***"installing"*** the handler
    - Executing handler is called ***"catching"*** or ***"handling"*** the signal
    - When the handler executes its return statement, control passes back to instruction in the control flow of the process that was interrupted by receipt of the signal

# Signal Handling Example

```
void sigint_handler(int sig) /* SIGINT handler */
{
    printf("So you think you can stop the bomb with ctrl-c, do you?\n");
    sleep(2);
    printf("Well...");
    fflush(stdout);
    sleep(1);
    printf("OK. :-)\n");
    exit(0);
}

int main(int argc, char** argv)
{
    /* Install the SIGINT handler */
    if (signal(SIGINT, sigint_handler) == SIG_ERR)
        unix_error("signal error");

    /* Wait for the receipt of a signal */
    pause();

    return 0;
}
```

sigint.c

# Blocking and Unblocking Signals

- Implicit blocking mechanism
  - Kernel blocks any pending signals of type currently being handled.
  - E.g., A SIGINT handler can't be interrupted by another SIGINT

- Explicit blocking and unblocking mechanism
  - `sigprocmask` function

- Supporting functions
  - `sigemptyset` – Create empty set
  - `sigfillset` – Add every signal number to set
  - `sigaddset` – Add signal number to set
  - `sigdelset` – Delete signal number from set

# Temporarily Blocking Signals

```
sigset_t mask, prev_mask;

Sigemptyset(&mask);
Sigaddset(&mask, SIGINT);

/* Block SIGINT and save previous blocked set */
Sigprocmask(SIG_BLOCK, &mask, &prev_mask);

⋮    /* Code region that will not be interrupted by SIGINT */

/* Restore previous blocked set, unblocking SIGINT */
Sigprocmask(SIG_SETMASK, &prev_mask, NULL);
```

# Summary

- Signals provide process-level exception handling
  - Can generate from user programs
  - Can define effect by declaring signal handler
  - Be very careful when writing signal handlers

- Nonlocal jumps provide exceptional control flow within process
  - Within constraints of stack discipline