CS 105

"Tour of the Black Holes of Computing"

Exceptional Control Flow

Topics

- Exceptions
- Signals
- Shells

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Dealing With I/O

Problem: I/O devices are slow

Solution 1: wait for I/O

- CPU stops executing instructions until device gives answer

Solution 2: *polling*

- Keep computing something else while I/O is happening
- Every so often, check to see whether I/O is done

Solution 3: *interrupts*

- Keep computing something else while I/O is happening
- Device eventually *interrupts* CPU to tell it I/O is done

Dealing With Errors

How to handle bad mistakes like divide by 0?

Solution 1: ignore completely

Solution 2: set a flag and let program check

- Used for minor errors like integer overflow
- Nuisance to check after every important operation (e.g., division)

Solution 3: *interrupts*

- Let CPU notify program in a special way when bad things happen
- Mechanism can be (nearly) identical to that used for I/O

Control Flow

Computers do only one thing

- From startup to shutdown, a CPU core simply reads and executes (interprets) a sequence of instructions, one at a time
- This sequence is the system's physical *control flow* (or *flow of control*)

Time

Physical control flow

<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—react to changes in program state
- Call and return using stack discipline—react to program state

Insufficient for a useful system

- Difficult for the CPU to react to other *unexpected* changes in system state
  - Data arrives from a disk or a network adapter
  - Instruction divides by zero
  - User hits control-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 Mechanism

- Exceptions
  - Change in control flow in response to a system event (i.e., change in system state)
- Combination of hardware and OS software

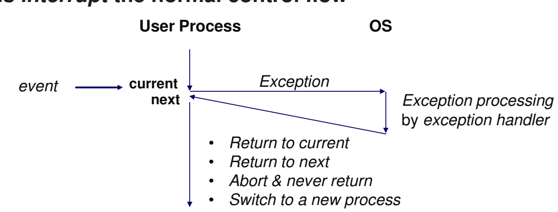
Higher-Level Mechanisms

- Process context switch (done by OS software and hardware timer)
- Signals (done by OS software)
- Nonlocal jumps (throw/catch)—ignored in this course

Exceptions

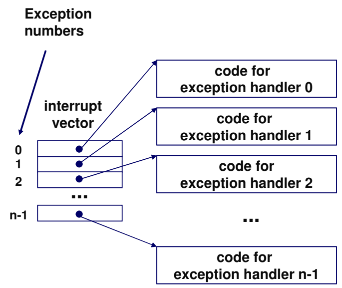
An *exception* is a transfer of control to OS kernel in response to some *event* (i.e., change in processor state)

Exceptions *interrupt* the normal control flow



Think of it as a hardware-initiated function call

Exception Tables (Interrupt Vectors)



- **Each type of event has a unique exception number *k***
- **k = index into exception table (a.k.a., interrupt vector)**
- **Jump table entry *k* points to a function (exception handler).**
- **Handler *k* is called each time exception *k* occurs.**

Asynchronous Exceptions (Interrupts)

Caused by events external to processor

- **Indicated by putting voltage on the processor's interrupt pin(s)**
- **Handler returns to "next" instruction.**

Examples:

- **Timer interrupt**
  - **Every few milliseconds, triggered by external timer chip**
  - **Used by kernel to take control back from user programs**
- **I/O interrupts**
  - **Hitting control-C (or any key) at the keyboard**
  - **Arrival of packet from network**
  - **Finishing writing data to disk**

Synchronous Exceptions

Caused by events that occur as result of executing an instruction:

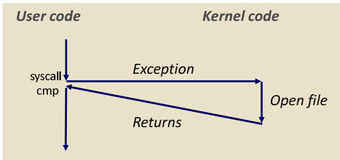
- **Traps**
  - **Intentional**
  - **Examples: system calls, breakpoint traps, special instructions**
  - **Returns control to "next" instruction**
- **Faults**
  - **Unintentional but possibly recoverable**
  - **Examples: page faults (recoverable), protection faults (unrecoverable)**
  - **Either re-executes faulting ("current") instruction or aborts**
- **Aborts**
  - **Unintentional and unrecoverable**
  - **Examples: memory error; machine fails ongoing self-tests**
  - **Aborts current program or entire OS**

System Call Example

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` (weird!), `%r8`, `%r9`
- Return value in `%rax`
- Negative value is an error corresponding to negative `errno`

Fault Example: Invalid Memory

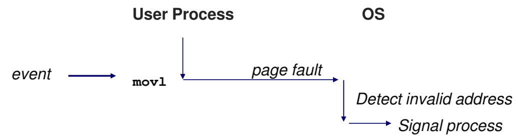
Memory Reference

- User writes to memory location
- Address is not valid

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

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

- Virtual memory system detects invalid address, causes fault
- OS sends `SIGSEGV` signal to user process (discussed in a few minutes)
- User process exits with "segmentation fault"



ECF Exists at All Levels of a System

Exceptions

- Hardware and operating system kernel software

Concurrent processes

- Hardware timer and kernel software

Signals

- Kernel software

Non-local jumps (ignored in this class)

- Application code
- Unsupported in C (except for horrible `setjmp` hack)
- C++/Java `throw`/`catch`
- Python `try`/`except`

Killing a Process

Problem: runaway process (e.g., unintentional infinite loop)

- Solution: kernel has superpowers, can kill it off

Problem: cleaning up after killing process

- Kernel can close open files, release memory, etc.
- Kernel *can't* know whether to delete temporary files or send "bye-bye" message across network

Solution: let processes intercept attempt to kill

- Assumption is that they will clean up and exit gracefully
- No direct enforcement of that assumption!

Signals

A *signal* is a small "message" that notifies a process that an event of some type has occurred in the system

- OS abstraction for exceptions and interrupts
- Sent from OS kernel (sometimes at request of another process) to a process
- Different signals are identified by small integer IDs
- Only information in a signal is its ID and fact of arrival
- Represented internally by *one bit* in kernel

ID	Name	Default Action	Corresponding Event
2	`SIGINT`	Terminate	Interrupt from keyboard (`ctl-c`)
9	`SIGKILL`	Terminate	Kill program (cannot override or ignore)
11	`SIGSEGV`	Terminate & Dump	Segmentation violation
14	`SIGALRM`	Terminate	Timer signal
17	`SIGCHLD`	Ignore	Child stopped or terminated

Signal Concepts: Sending

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 termination of a child process (SIGCHLD)
- Another process has invoked the `kill` system call to explicitly request that the kernel send a signal to the destination process

Signal Concepts: Receiving

A destination process *receives* a signal when it is forced by kernel to react in some way to delivery of the signal

Five possible ways to react:

- *Ignore* the signal (do nothing)
- *Terminate* the process
- Temporarily *stop* the process from running
- *Continue* a stopped process (let it run again)
- *Catch* the signal by executing a user-level function called a signal handler
  - OS-initiated function call
  - Akin to hardware exception handler being called in response to asynchronous interrupt
  - Like interrupts, signal handler might or might not return

Signal Concepts: Pending & Blocked Signals

A signal is *pending* if it has been 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 pending signal of type *k*, then subsequent signals of type *k* for that process are discarded

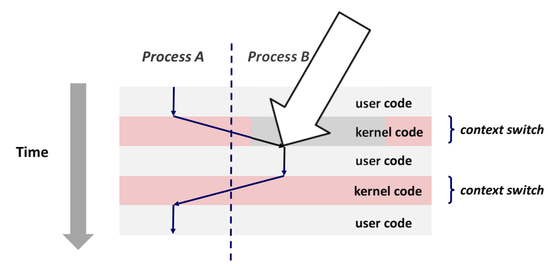
Process can *block* receipt of certain signals

- Blocked signals can be delivered, but won't be received until signal is unblocked

Pending signal is received *at most* once

Receiving Signals

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



Important: All context switches are initiated by calling some exception handler, e.g. timer.

Receiving Signals

Suppose kernel is returning from 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 logical flow for *p*

Else

- Choose lowest-numbered signal *k* in `pnb` and force process *p* to receive signal *k*
- Receipt of signal triggers some *action* by *p*
- Repeat for all nonzero *k* in `pnb`
- Pass control to next instruction in logical flow for *p*

Sending Signals with `kill`

`kill` sends arbitrary signal to a process

Examples

- `kill –KILL 24818`
  - Send SIGKILL to process 24818
  - SIGKILL can't be caught
- `kill –9 24818`
  - Same, for lazy typists

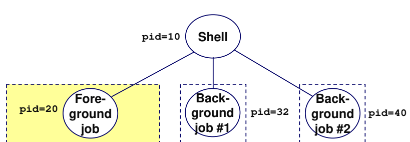
```
linux> ./forks 16
linux> Child1: pid=24818
Child2: pid=24819

linux> ps
  PID TTY          TIME CMD
24788 pts/2    00:00:00 zsh
24818 pts/2    00:00:02 forks
24819 pts/2    00:00:02 forks
24820 pts/2    00:00:00 ps
linux> kill -9 24818
linux> ps
  PID TTY          TIME CMD
24788 pts/2    00:00:00 zsh
24819 pts/2    00:00:03 forks
24823 pts/2    00:00:00 ps
linux>
```


Sending Signals From the Keyboard

Typing ctrl-c (ctrl-z) sends a SIGINT (SIGTSTP) the "foreground" process

- SIGINT – default action is to terminate process
- SIGTSTP – default action is to stop (suspend) process



Sending Signals with `kill`

```
void fork12()
{
    pid_t pid[N];
    int i, child_status;
    for (i = 0; i < N; i++)
        if ((pid[i] = fork()) == 0)
            while(1); /* Child infinite loop (bad style!) */

    /* Parent terminates the child processes */
    for (i = 0; i < N; i++) {
        printf("Killing process %d\n", pid[i]);
        kill(pid[i], SIGINT);
    }

    /* Parent reaps terminated children */
    for (i = 0; i < N; i++) {
        pid_t wpid = wait(&child_status);
        if (WIFEXITED(child_status))
            printf("Child %d terminated with exit status %d\n",
                   wpid, WEXITSTATUS(child_status));
        else
            printf("Child %d terminated abnormally\n", wpid);
    }
}
```

Default Actions

Each signal type has predefined *default action*, which is one of:

- Process terminates
- Process terminates and dumps "core" (memory) to a file
  - Nowadays dump is suppressed in normal operation
  - Was intended for debugging; now usually simpler to rerun under gdb
- Process stops until restarted by a SIGCONT signal
- Process ignores the signal

Installing Signal Handlers

The `sigaction` function modifies the default action associated with receipt of signal `signum`:

- `int *sigaction(int signum, const struct sigaction *act, struct sigaction *oldact)`

`act` is a struct with several useful components:

- `sa_mask` identifies signals you're interested in
- `sa_flags` controls certain options
- `sa_handler` is special value or address of a *signal handler*
  - Referred to as "*installing*" the handler
  - Called when process receives signal of type `signum`
  - Executing handler is called "*catching*" or "*handling*" the signal
  - When handler returns, control passes back to instruction in control flow of process that was interrupted by receipt of the signal
- Special values for `sa_handler`: SIG_IGN (ignore signal) or SIG_DFL (return to default)

Signal-Handling Example

```
#include <signal.h>

/* SIGINT handler */
void sigint_handler(int sig)
{
    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);
}
```

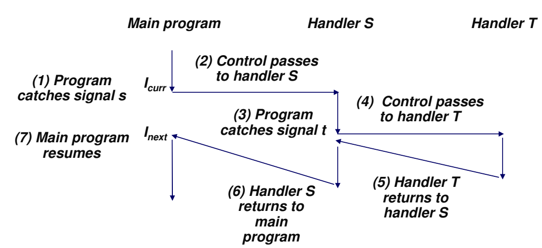
```
int main()
{
    struct sigaction action, oldaction;

    action.sa_flags = 0;
    action.sa_handler = sigint_handler;
    sigemptyset(&action.sa_mask);
    sigaddset(&action.sa_mask, SIGINT);
    /* Install the SIGINT handler */
    sigprocmask(SIG_BLOCK, &action.sa_mask,
      NULL);
    Sigaction(SIGINT, &action, &oldaction);
    if (oldaction.sa_handler == SIG_IGN)
        sigaction(SIGINT, &oldaction, NULL);
    sigprocmask(SIG_UNBLOCK, &action.sa_mask,
      NULL);
    /* Wait for the receipt of a signal */
    pause();
    return 0;
}
```

sigint.c

Nested Signal Handlers

Handlers can be interrupted by other handlers



Guidelines for Writing Safe Handlers

G0: Keep your handlers as simple as possible

- e.g., Set a global flag and return

G1: Call only async-signal-safe functions in your handlers

_exit

- `printf, sprintf, malloc`, and `exit` are not safe!
- (We cheated in the example because we know details of implementation…)

G2: Save and restore `errno` on entry and exit

- So that other handlers don't overwrite your value of `errno`

G3: Protect accesses to shared data structures by temporarily blocking all signals.

- To prevent possible corruption

G4: Declare global variables as `volatile`

- To prevent compiler from storing them in a register

G5: Declare global flags as `volatile sig_atomic_t`

- *flag*: variable that is only read or only written (e.g. flag = 1, not flag++)
- Flag declared this way does not need to be protected like other globals

Shell Programs

A *shell* is an application program that runs programs on behalf of the user

- `sh` – Original Unix Bourne shell
- `csh` – BSD Unix C shell, `tcsh` – Enhanced C shell (both deprecated)
- `bash` – "Bourne-Again" shell
- `zsh` – "Z" shell

```
int main()
{
    char cmdline[MAXLINE];

    while (1) {
        /* read */
        printf("> ");
        Fgets(cmdline, MAXLINE, stdin);
        if (feof(stdin))
            exit(0);

        /* evaluate */
        eval(cmdline);
    }
}
```

Execution is a sequence of read/evaluate steps

Simple Shell `eval` Function

```
void eval(char *cmdline)
{
    char *argv[MAXARGS]; /* argv for execvp() */
    int bg;              /* should the job run in bg or fg? */
    pid_t pid;           /* process id */

    bg = parseline(cmdline, argv);
    if (!builtin_command(argv)) {
        if ((pid = Fork()) == 0) {   /* child runs user job */
            execvp(argv[0], argv);
            fprintf(stderr, "%s: Command not found.\n", argv[0]);
            exit(1);
        }

        if (!bg) {   /* parent waits for fg job to terminate */
            int status;
            if (waitpid(pid, &status, 0) == -1)
                unix_error("waitfg: waitpid error");
        }
        else          /* otherwise, don't wait for bg job */
            printf("%d %s", pid, cmdline);
    }
}
```


Problem with Simple Shell 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
- Eventually you hit process limit and can't do any work

ECF to the rescue:

- SIGCHLD will notify us of child termination
- Ignored by default, so must explicitly catch
- But signal handler must be carefully written (see next two slides)

Signal Handler Funkiness

```
int ccount = 0;
void child_handler(int sig)
{
    int child_status;
    pid_t pid = wait(&child_status);
    ccount--;
    printf("Received signal %d from process %d\n",
           sig, pid);
}

void fork14()
{
    pid_t pid[N];
    int i, child_status;
    ccount = N;
    signal(SIGCHLD, child_handler); /* Old style */
    for (i = 0; i < N; i++)
        if ((pid[i] = fork()) == 0) {
            /* Child: Exit */
            exit(0);
        }
    while (ccount > 0)
        pause();/* Suspend until signal occurs */
}
```

Pending signals are not queued

- For each signal type, just have single bit indicating whether or not signal is pending
- Even if multiple processes have sent this signal!

Living With Nonqueuing Signals

Must check for all terminated jobs

- Typically loop with `waitpid`

```
void child_handler2(int sig)
{
    int child_status;
    pid_t pid;
    while ((pid = waitpid(-1, &child_status, WNOHANG)) != -1) {
        ccount--;
        printf("Received signal %d from process %d\n",
          sig, pid);
    }
}

void fork15()
{
    . . .
    signal(SIGCHLD, child_handler2);
    . . .
}
```


Summary

Signals provide process-level exception handling

- Can generate from user programs
- Can define effect by declaring signal handler

Some caveats

- Very high overhead
  - >10,000 clock cycles
  - Only use for exceptional conditions
- Don't have queues
  - Just one bit for each pending signal type