Signals

Goals of this Lecture

Help you learn about:

- UNIX process control
- Sending signals
- Handling signals
- … and thereby …
- How the OS exposes the occurrence of some exceptions to application processes
- How application processes can control their behavior in response to those exceptions

Process Control Examples

Exactly what happens when you:

Type Ctrl-c?

- Keystroke generates **interrupt**
- OS handles interrupt
- OS sends a 2/SIGINT **signal**

Type Ctrl-z?

- Keystroke generates **interrupt**
- OS handles interrupt
- OS sends a 20/SIGTSTP **signal**

Recall ***Exceptions and Processes*** lecture

Sending Signals via Keystrokes

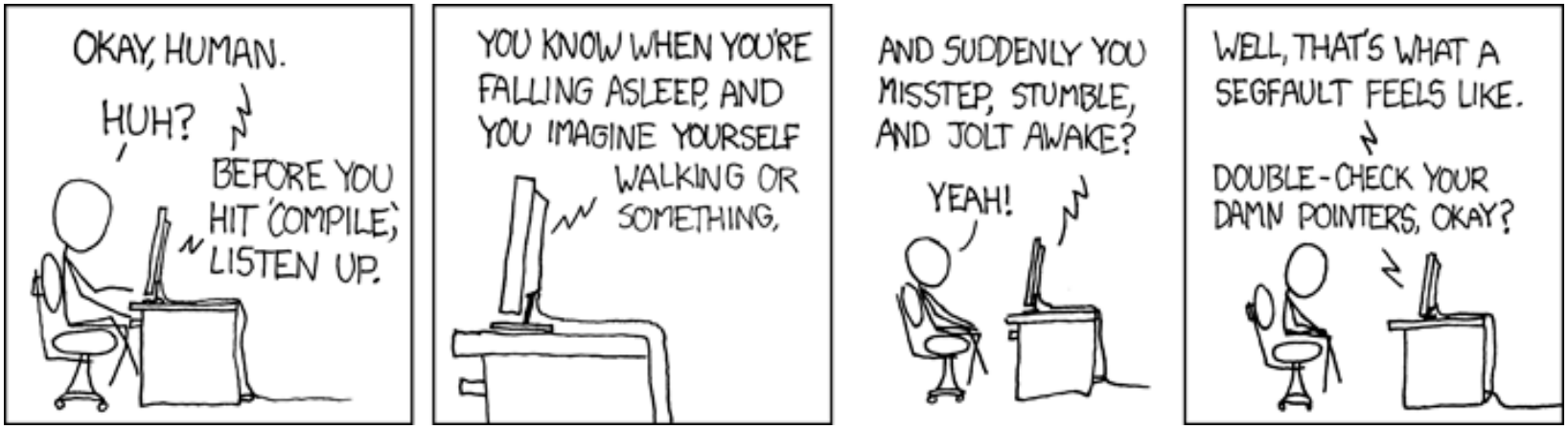
User can send three signals from keyboard:

- **Ctrl-c ⇒ 2/SIGINT** signal
  - Default action is "terminate"
- **Ctrl-z ⇒ 20/SIGTSTP** signal
  - Default action is "stop until next 18/SIGCONT"
- **Ctrl-\ ⇒ 3/SIGQUIT** signal
  - Default action is "terminate"

Examples of Non-keyboard Signals

Process makes illegal memory reference

- Segmentation fault occurs
- OS gains control of CPU
- OS sends 11/SIGSEGV signal to process
- Process receives 11/SIGSEGV signal
- Default action for 11/SIGSEGV signal is "terminate"



https://xkcd.com/371/

Signals Overview

Signal: A notification of an exception

Typical signal sequence:

- Process P is executing
- Exception occurs (interrupt, trap, fault, or abort)
- OS gains control of CPU
- OS wishes to inform process P that something significant happened
- OS **sends** a signal to process P
  - OS sets a bit in **`pending`** **bit vector** of process P
  - Indicates that OS is sending a signal of type X to process P
  - A signal of type X is **pending** for process P

Signals Overview (cont.)

Typical signal sequence (cont.):

- Sometime later…
- OS is ready to give CPU back to process P
- OS checks **`pending`** for process P, sees that signal of type X is pending
- OS forces process P to **receive** signal of type X
  - OS clears bit in process P's **`pending`**
- Process P executes action for signal of type X
  - Normally process P executes **default action** for that signal
  - If **signal handler** was installed for signal of type X, then process P executes signal handler
  - Action might terminate process P; otherwise…
- Process P resumes where it left off

Sending Signals via Commands

User can send any signal by executing command:

`kill` command

- **`kill -sig pid`**
- Send a signal of type ***`sig`*** to process ***`pid`***
- No ***`-sig`*** option specified ⇒ sends 15/SIGTERM signal
  - Default action for 15/SIGTERM is "terminate"
- You must own process ***`pid`*** (or have admin privileges)
- Commentary: Better command name would be **`sendsig`**

Examples

- **`kill -2 1234`**
- **`kill -SIGINT 1234`**
  - Same as pressing Ctrl-c if process 1234 is running in foreground
- **`kill -2 %1`**
  - Same as above, if process 1234 is running as background job 1

Process Control Implementation (cont.)

Exactly what happens when you:

Issue a **`kill -sig pid`** command?

- **`kill`** command executes **trap**
- OS handles trap
- OS sends a ***`sig`*** **signal** to the process whose id is ***`pid`***

Issue a **`fg`** or **`bg`** command?

- **`fg`** or **`bg`** command executes **trap**
- OS handles trap
- OS sends a 18/SIGCONT **signal** (and does some other things too!)

Recall ***Exceptions and Processes*** lecture

Signals signals everywhere

List of the predefined signals, learn many details with these commands:

```
$ kill -l
 1) SIGHUP       2) SIGINT       3) SIGQUIT      4) SIGILL
 5) SIGTRAP      6) SIGABRT      7) SIGBUS       8) SIGFPE
 9) SIGKILL     10) SIGUSR1     11) SIGSEGV     12) SIGUSR2
13) SIGPIPE     14) SIGALRM     15) SIGTERM     17) SIGCHLD
18) SIGCONT     19) SIGSTOP     20) SIGTSTP     21) SIGTTIN
22) SIGTTOU     23) SIGURG      24) SIGXCPU     25) SIGXFSZ
26) SIGVTALRM   27) SIGPROF     28) SIGWINCH    29) SIGIO
30) SIGPWR      31) SIGSYS      34) SIGRTMIN    35) SIGRTMIN+1
36) SIGRTMIN+2  37) SIGRTMIN+3  38) SIGRTMIN+4  39) SIGRTMIN+5
40) SIGRTMIN+6  41) SIGRTMIN+7  42) SIGRTMIN+8  43) SIGRTMIN+9
44) SIGRTMIN+10 45) SIGRTMIN+11 46) SIGRTMIN+12 47) SIGRTMIN+13
48) SIGRTMIN+14 49) SIGRTMIN+15 50) SIGRTMAX-14 51) SIGRTMAX-13
52) SIGRTMAX-12 53) SIGRTMAX-11 54) SIGRTMAX-10 55) SIGRTMAX-9
56) SIGRTMAX-8  57) SIGRTMAX-7  58) SIGRTMAX-6  59) SIGRTMAX-5
60) SIGRTMAX-4  61) SIGRTMAX-3  62) SIGRTMAX-2  63) SIGRTMAX-1
64) SIGRTMAX

$ man 7 signal
```

See Bryant & O'Hallaron book for more actions, triggering exceptions, and how the application program can define signals with unused values

Sending Signals via Function Calls

Program can send any signal by calling function:

`raise()` function

- **`int raise(int iSig);`**
- Commands OS to send a signal of type **`iSig`** to calling process
- Returns 0 to indicate success, non-0 to indicate failure

Example:

- **`iRet = raise(SIGINT);`**
  - Send a 2/SIGINT signal to calling process

One clever use case:

https://www.gnu.org/software/libc/manual/html_node/Signaling-Yourself.html

Sending Signals via Function Calls

`kill()` function

- **`int kill(pid_t iPid, int iSig);`**
- Sends a **`iSig`** signal to the process **`iPid`**
- Equivalent to **`raise(iSig)`** when **`iPid`** is the id of current process
- You must own process ***`pid`*** (or have admin privileges)
- Commentary: Better function name would be **`sendsig()`**

Example

- **`iRet = kill(1234, SIGINT);`**
  - Send a 2/SIGINT signal to process 1234

Handling Signals

Each signal type has a default action

- For most signal types, default action is "terminate"

A program can **install a signal handler**

- To change action of (almost) any signal type

Installing a Signal Handler

`signal()` function

- **`sighandler_t signal(int iSig,`**
  `sighandler_t pfHandler);`

- Install function **`pfHandler`** as the handler for signals of type **`iSig`**
- **`pfHandler`** is a function pointer:
  `typedef void (*sighandler_t)(int);`
- Return the old handler on success, **`SIG_ERR`** on error
- After call, **`(*pfHandler)`** is invoked whenever process receives a signal of type **`iSig`**

SIG_DFL

Predefined value: **SIG_DFL**

Use as argument to **`signal()`** to **restore default action**

```
int main(void)
{   …
    signal(SIGINT, somehandler);
    …
    signal(SIGINT, SIG_DFL);
    …
}
```

Subsequently, process will handle 2/SIGINT signals using default action for 2/SIGINT signals ("terminate")

SIG_IGN

Predefined value: **SIG_IGN**

Use as argument to **`signal()`** to **ignore signals**

```
int main(void)
{   …
    signal(SIGINT, SIG_IGN);
    …
}
```

Subsequently, process will ignore 2/SIGINT signals

Uncatchable Signals

Special cases: A program *cannot* install a signal handler for signals of type:

- **9/SIGKILL**
  - Default action is "terminate"
- **19/SIGSTOP**
  - Default action is "stop until next 18/SIGCONT"

Signal Handling Example 1

Program testsignal.c:

```
#define _GNU_SOURCE /* Use modern handling style */
#include <stdio.h>
#include <signal.h>

static void myHandler(int iSig)
{  printf("In myHandler with argument %d\n", iSig);
}

int main(void)
{  signal(SIGINT, myHandler);
   printf("Entering an infinite loop\n");
   for (;;)
      ;
   return 0; /* Never get here. */
}
```

Error handling code omitted in this and all subsequent programs in this lecture

```
armlab01:~/Test$ ./testsignal
Entering an infinite loop
^CIn myHandler with argument 2
^CIn myHandler with argument 2
^CIn myHandler with argument 2
^CIn myHandler with argument 2
^CIn myHandler with argument 2
^CIn myHandler with argument 2
^CIn myHandler with argument 2
^CIn myHandler with argument 2
^CIn myHandler with argument 2
^Z
[1]+  Stopped                 ./testsignal
armlab01:~/Test$ fg
./signal
^CIn myHandler with argument 2
^CIn myHandler with argument 2
^CIn myHandler with argument 2
^CIn myHandler with argument 2
^CIn myHandler with argument 2
^\Quit
```

Signal Handling Example 2

Program testsignalall.c:

```
#define _GNU_SOURCE
#include <stdio.h>
#include <signal.h>

static void myHandler(int iSig)
{  printf("In myHandler with argument %d\n", iSig);
}

int main(void)
{  int i;
   /* Install myHandler as the handler
      for all kinds of signals. */
   for (i = 1; i < 65; i++)
      signal(i, myHandler);
   printf("Entering an infinite loop\n");
   for (;;)
      ;
   return 0; /* Never get here. */
}
```

```
armlab01:~/Test$ ./a.out
signal 9 not handled
signal 19 not handled
signal 32 not handled
signal 33 not handled
Entering an infinite loop
^CIn myHandler with argument 2
^ZIn myHandler with argument 20
^\In myHandler with argument 3
Killed
```

```
armlab01:~$ ps axu | grep 'a.out'
cmoretti 64220  101  0.0   2432 …
armlab01:~$ kill -9 64220
```

Will fail:

```
signal(9, myHandler)
signal(19, myHandler)
...
```

Signal Handling Example 3

Program generates lots of temporary data

- Stores the data in a temporary file
- Must delete the file before exiting

```
…
int main(void)
{   FILE *psFile;
    psFile = fopen("temp.txt", "w");
    …
    fclose(psFile);
    remove("temp.txt");
    return 0;
}
```

Example 3 Problem

What if user types Ctrl-c?

- OS sends a 2/SIGINT signal to the process
- Default action for 2/SIGINT is "terminate"

Problem: The temporary file is not deleted

- Process terminates before `remove("temp.txt")` is executed

Challenge: Ctrl-c could happen at any time

- Which line of code will be interrupted???

Solution: Install a signal handler

- Define a "clean up" function to delete the file
- Install the function as a signal handler for 2/SIGINT

Example 3 Solution


```
…
static FILE *psFile; /* Must be global. */
static void cleanup(int iSig)
{   fclose(psFile);
    remove("temp.txt");
    exit(0);
}
int main(void)
{   …
    psFile = fopen("temp.txt", "w");
    signal(SIGINT, cleanup);
    …
    cleanup(0);  /* or raise(SIGINT); */
    return 0;  /* Never get here. */
}
```

Alarms

`alarm()` function

- **`unsigned int alarm(unsigned int uiSec);`**
- Send 14/SIGALRM signal after **`uiSec`** seconds
- Cancel pending alarm if **`uiSec`** is 0
- Use **wall-clock time**
  - Time spent executing other processes counts
  - Time spent waiting for user input counts
- Return value is irrelevant for our purposes

Used to implement time-outs

Alarm Example 1

Program testalarm.c:

```
#define _GNU_SOURCE
#include <stdio.h>
#include <signal.h>
#include <unistd.h>

static void myHandler(int iSig)
{  printf("In myHandler with argument %d\n", iSig);
   alarm(2); /* Set another alarm */
}

int main(void)
{  signal(SIGALRM, myHandler);
   alarm(2); /* Set an alarm. */
   printf("Entering an infinite loop\n");
   for (;;)
      ;
   return 0; /* Never get here. */
}
```

Alarm Example 1

Program testalarm.c:

```
#define _GNU_SOURCE
#include <stdio.h>
#include <signal.h>
#include <unistd.h>

static void myHandler(int iSig)
{  printf("In myHandler with argument %d\n", iSig);
   alarm(2); /* Set another alarm */
}

int main(void)
{  signal(SIGALRM, myHandler);
   alarm(2); /* Set an alarm. */
   printf("Entering an infinite loop\n");
   for (;;)
      ;
   return 0; /* Never get here. */
}
```

```
armlab01:~/Test$ ./alarm
Entering an infinite loop
```

```
armlab01:~/Test$ ./alarm
Entering an infinite loop
In myHandler with argument 14
```

```
armlab01:~/Test$ ./alarm
Entering an infinite loop
In myHandler with argument 14
In myHandler with argument 14
```

Alarm Example 2

Program testalarmtimeout.c:

```
#define _GNU_SOURCE
#include <stdio.h>
#include <stdlib.h>
#include <signal.h>
#include <unistd.h>

static void myHandler(int iSig)
{  printf("\nSorry.  You took too long.\n");
   exit(EXIT_FAILURE);
}

int main(void)
{  int i;
   signal(SIGALRM, myHandler);
   printf("Enter a number:  ");
   alarm(5);
   scanf("%d", &i);
   alarm(0);
   printf("You entered the number %d.\n", i);
   return 0;
}
```

Alarm Example 2

Program testalarmtimeout.c:

```
#define _GNU_SOURCE
#include <stdio.h>
#include <stdlib.h>
#include <signal.h>
#include <unistd.h>

static void myHandler(int iSig)
{  printf("\nSorry.  You took too long.\n");
   exit(EXIT_FAILURE);
}

int main(void)
{  int i;
   signal(SIGALRM, myHandler);
   printf("Enter a number:  ");
   alarm(5);
   scanf("%d", &i);
   alarm(0);
   printf("You entered the number %d.\n", i);
   return 0;
}
```

```
armlab01:~/Test$ echo 5 |
> ./a.out
Enter a number:
You entered the number 5.

armlab01:~/Test$ (sleep 10;
> echo 5) |
> ./a.out
Enter a number:
Sorry.  You took too long.
```

Summary

Signals

- Sending signals
  - From the keyboard
  - By calling function: **`raise()`** or **`kill()`**
  - By executing command: **`kill`**
- Catching signals
  - **`signal()`** installs a signal handler
  - Most signals are catchable

Alarms

- Call **`alarm()`** to send 14/SIGALRM signals in wall-clock time
- Alarms can be used to implement time-outs

Wrapping Up the Course

Assignment 7

- Partnered assignment
- Due on Dean's Date at 5 PM (Princeton time)
- No extensions past 11:59 PM without permission of the Dean

Office hours over Reading Period

- Will be announced on Piazza this week!

Final exam

- Watch Piazza for an announcement this week!

Old exams and study info will be posted on the website

Course Summary

We have covered:

Programming in the large

- The C programming language
- Testing
- Building
- Debugging
- Program & programming style
- Data structures
- Modularity
- Performance

Course Summary

We have covered (cont.):

Under the hood

- Number systems
- Language levels tour
  - Assembly language
  - Machine language
  - Assemblers and linkers
- Service levels tour
  - Exceptions and processes
  - Storage management
  - Dynamic memory management
  - Process management
  - I/O management
  - Signals

The end.


```
return EXIT_SUCCESS;
```