Signals

Goals of this Lecture

Help you learn about:

- 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

Agenda

Unix Process Control

Signals

Sending Signals

Handling Signals

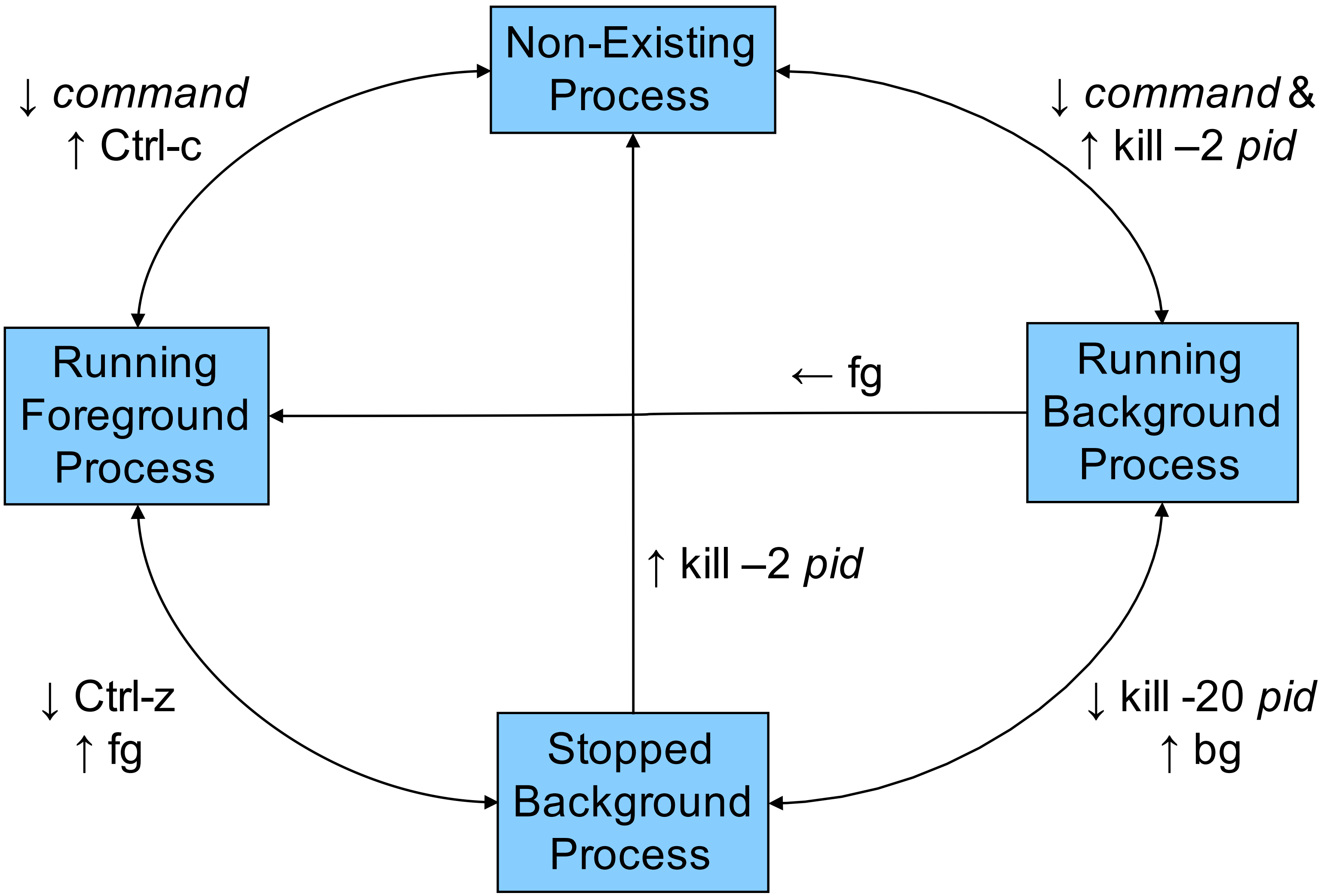
Alarms

(If time) Race Conditions and Critical Sections

(If time) Blocking Signals

(If time) Interval Timers

Unix Process Control



Process Control Implementation

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**

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!)

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Signals

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

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

Examples of Signals

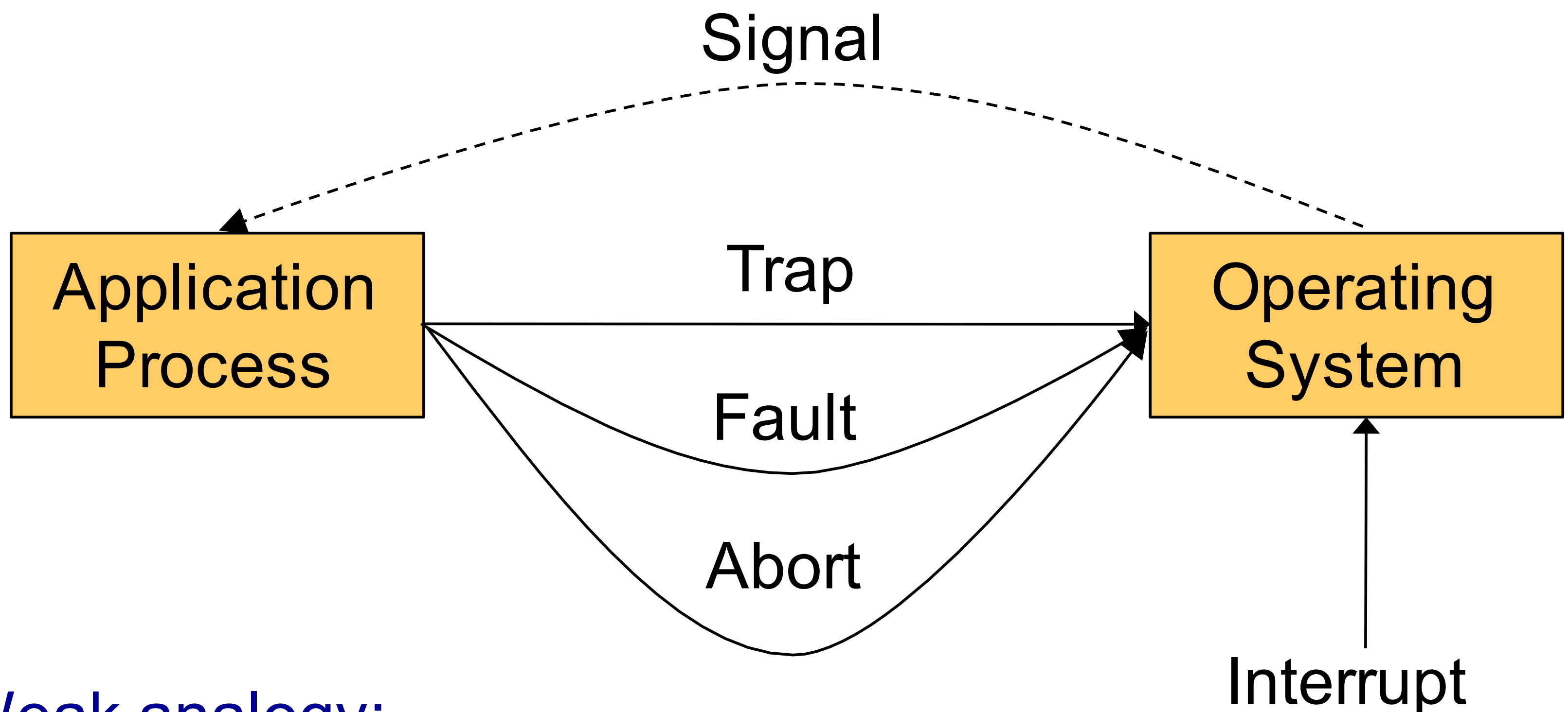
User types Ctrl-c

- Interrupt occurs
- OS gains control of CPU
- OS sends 2/SIGINT signal to process
- Process receives 2/SIGINT signal
- Default action for 2/SIGINT signal is “terminate”

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”

Signals as Callbacks



Weak analogy:

- **Trap** (and fault and abort) is similar to **function call**
    - App process requests service of OS
- **Signal** is similar to **function callback**
    - OS informs app process that something happened

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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"

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

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

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

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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

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"

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`**
  ```

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

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. */
}
```

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. */
}
```

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

SIG_IGN Example

Program testsignalignore.c:

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

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

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(If time) Race Conditions and Critical Sections

(If time) Blocking Signals

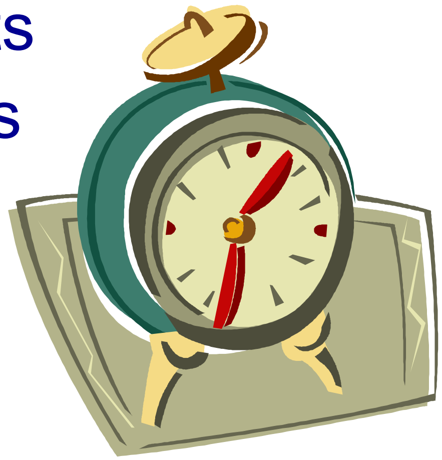
(If time) Interval Timers

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 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;
}
```

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(If time) Race Conditions and Critical Sections

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Race Conditions and Critical Sections

Race condition

- A flaw in a program whereby the correctness of the program is critically dependent on the sequence or timing of events beyond the program's control

Critical section

- A part of a program that must execute atomically (i.e. entirely without interruption, or not at all)

Race Condition Example

```
int iBalance = 2000;
…
static void addBonus(int iSig)
{  iBalance += 50;
}
int main(void)
{  signal(SIGINT, addBonus);
   …
   iBalance += 100;
   …
```

Race Condition Example (cont.)

Race condition example in assembly language

```
int iBalance = 2000;
…
void addBonus(int iSig)
{   iBalance += 50;
}
int main(void)
{   signal(SIGINT, addBonus);
    …
    iBalance += 100;
    …
```

```
movl  iBalance, %ecx
addl  $50, %ecx
movl  %ecx, iBalance
```

```
movl  iBalance, %eax
addl  $100, %eax
movl  %eax, iBalance
```

Let’s say the compiler generates that assembly language code

Race Condition Example (cont.)

(1) main() begins to execute

```
int iBalance = 2000;
…
void addBonus(int iSig)
{   iBalance += 50;
}
int main(void)
{   signal(SIGINT, addBonus);
    …
    iBalance += 100;
    …
```

```
movl iBalance, %ecx
addl $50, %ecx
movl %ecx, iBalance
```

```
movl iBalance, %eax
addl $100, %eax
movl %eax, iBalance
```

2000

2100

Race Condition Example (cont.)

(2) SIGINT signal arrives; control transfers to addBonus()

```
int iBalance = 2000;
…
void addBonus(int iSig)
{   iBalance += 50;
}
int main(void)
{   signal(SIGINT, addBonus);
    …
    iBalance += 100;
    …
```

```
movl iBalance, %ecx
addl $50, %ecx
movl %ecx, iBalance
```

2000
2050
2050

```
movl iBalance, %eax
addl $100, %eax
movl %eax, iBalance
```

2000
2100

Race Condition Example (cont.)

(3) addBonus() terminates; control returns to main()

```
int iBalance = 2000;
…
void addBonus(int iSig)
{   iBalance += 50;
}
int main(void)
{   signal(SIGINT, addBonus);
    …
    iBalance += 100;
    …
```

```
movl iBalance, %ecx     2000
addl $50, %ecx          2050
movl %ecx, iBalance     2050
```

```
movl iBalance, %eax     2000
addl $100, %eax         2100
movl %eax, iBalance     2100
```

Lost $50 !!!

Critical Sections

Solution: Must make sure that **critical sections** of code are not interrupted

```
int iBalance = 2000;
…
void addBonus(int iSig)
{   iBalance += 50;
}
int main(void)
{  signal(SIGINT, addBonus);
   …
   iBalance += 100;
   …
```

Critical section (→ `iBalance += 50;`)

Critical section (→ `iBalance += 100;`)

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Blocking Signals

Blocking signals

- A process can **block** a signal type to prohibit signals of that type from being received (until unblocked at a later time)
- Differs from **ignoring** a signal

Each process has a **`blocked`** **bit vector** in the kernel

- OS uses **`blocked`** to decide which signals to force the process to receive
- User program can modify **`blocked`** with **`sigprocmask()`**

Function for Blocking Signals

`sigprocmask()` function

-
```
int sigprocmask(int iHow,
                const sigset_t *psSet,
                sigset_t *psOldSet);
```
- **`psSet`**: Pointer to a signal set
- **`psOldSet`**: (Irrelevant for our purposes)
- **`iHow`**: How to modify the **`blocked`** bit vector
  - **`SIG_BLOCK`**: Add signals in **`psSet`** to **`blocked`**
  - **`SIG_UNBLOCK`**: Remove **`psSet`** signals from **`blocked`**
  - **`SIG_SETMASK`**: Install **`psSet`** as **`blocked`**
- Returns 0 iff successful

Functions for constructing signal sets

- **`sigemptyset()`**, **`sigaddset()`**, …

Blocking Signals Example

```
int main(void)
{   sigset_t sSet;
    signal(SIGINT, addBonus);
    …
    sigemptyset(&sSet);
    sigaddset(&sSet, SIGINT);
    sigprocmask(SIG_BLOCK, &sSet, NULL);
    iBalance += 100;
    sigprocmask(SIG_UNBLOCK, &sSet, NULL);
    …
}
```

Block SIGINT signals

Critical section

Unblock SIGINT signals

Blocking Signals in Handlers

How to block signals when handler is executing?

- While executing a handler for a signal of type X, all signals of type X are blocked automatically
- When/if signal handler returns, block is removed

```
void addBonus(int iSig)
{   iBalance += 50;
}
```

SIGINT signals automatically blocked in SIGINT handler

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Interval Timers

`setitimer()` function

```
int setitimer(int iWhich,
              const struct itimerval *psValue,
              struct itimerval *psOldValue);
```

- Send 27/SIGPROF signal continually
- **`psValue`** specifies timing
- **`psOldValue`** is irrelevant for our purposes
- Use **CPU time**
  - Time spent executing other processes does not count
  - Time spent waiting for user input does not count
- Return 0 if successful, -1 otherwise

Used by execution profilers

Interval Timer Example

Program testitimer.c:

```
#define _GNU_SOURCE
#include <stdio.h>
#include <stdlib.h>
#include <signal.h>
#include <sys/time.h>

static void myHandler(int iSig)
{   printf("In myHandler with argument %d\n", iSig);
}
int main(void)
{   struct itimerval sTimer;
    signal(SIGPROF, myHandler);
    sTimer.it_value.tv_sec = 1;      /* Send first signal in 1 second */
    sTimer.it_value.tv_usec = 0;     /* and 0 microseconds. */
    sTimer.it_interval.tv_sec = 1;   /* Send subsequent signals in 1 sec */
    sTimer.it_interval.tv_usec = 0;  /* and 0 microsecond intervals. */
    setitimer(ITIMER_PROF, &sTimer, NULL);
    printf("Entering an infinite loop\n");
    for (;;)
        ;
    return 0; /* Never get here. */
}
```

Summary

List of the predefined signals:

```
$ 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
```

See Bryant & O' Hallaron book for default actions, triggering exceptions

Application program can define signals with unused values

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

Summary (cont.)

Race conditions

- `sigprocmask()` blocks signals in any **critical section** of code
- Signals of type x automatically are blocked while handler for type x signals is running

Interval Timers

- Call `setitimer()` to deliver 27/SIGPROF signals in CPU time
- Interval timers are used by execution profilers

Summary (cont.)

For more information:

Bryant & O'Hallaron, *Computer Systems: A Programmer's Perspective*, Chapter 8

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 Rest of the Course

Lecture on Wednesday

- Program Verification

Assignment 7

- Due on Dean's Date at 5PM
- Cannot submit late (University regulations)
- Cannot use late pass

Office hours and exam prep sessions

- Will be announced on Piazza

Final exam

- When: Friday 5/20, 1:30 PM – 4:30 PM
- Where: Friend Center 101, Friend Center 108
- Closed book, 1-sheet notes, no electronic devices

Thank you!