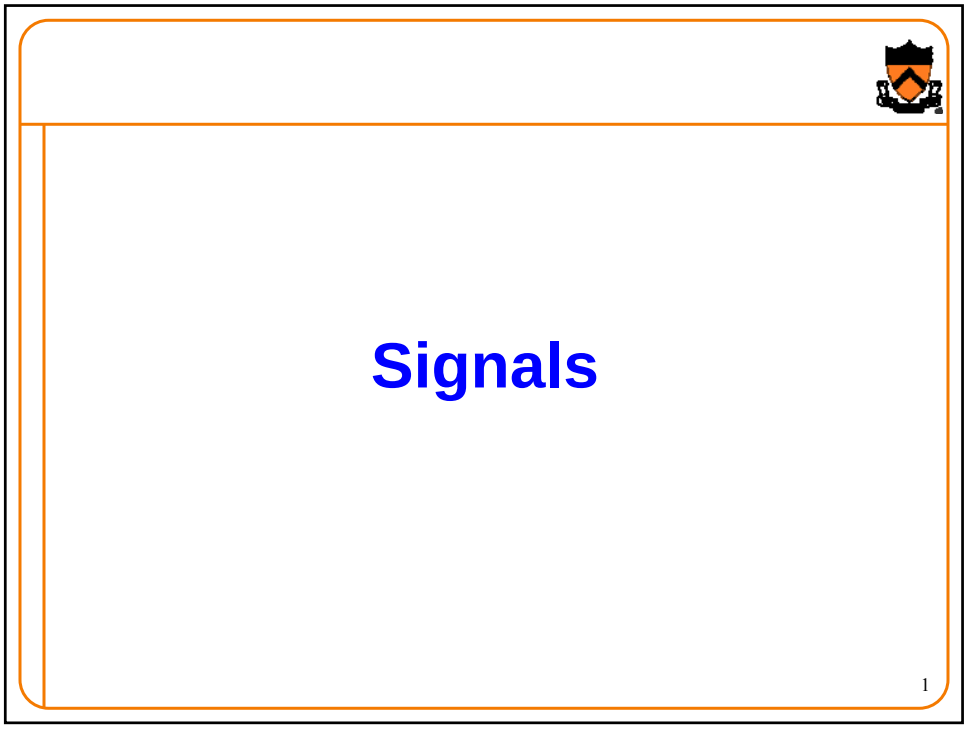
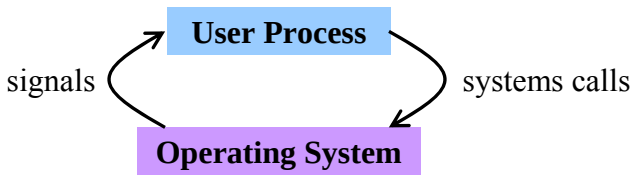


Signals

1

Communicating with the OS



- System call (last lecture)
  - Request to the operating system to perform a task
  - … that the process does not have permission to perform
- Signal (this lecture)
  - Asynchronous notification sent to a process
  - … to notify the process of an event that has occurred

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Outline

1. **UNIX Process Control**
2. Signals
3. Sending Signals
4. Handling Signals
5. Race Conditions
6. Blocking Signals
7. Conclusion
8. (optional) Alarms and Interval Timers

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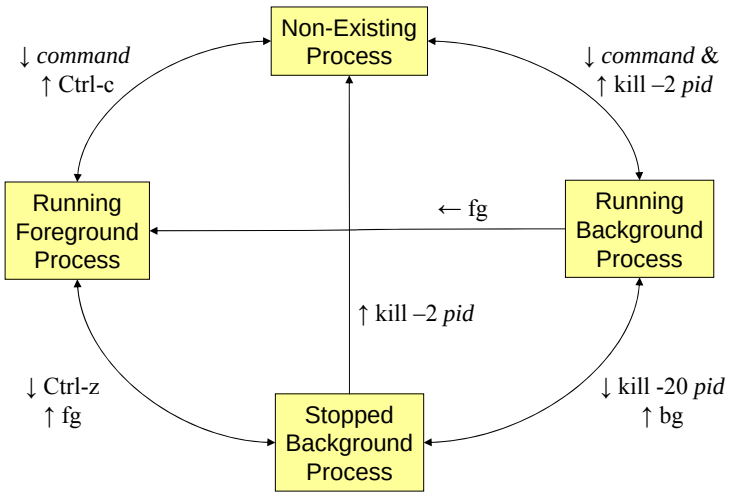
UNIX Process Control



4

UNIX Process Control

[Demo of UNIX process control using infloop.c]

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Process Control Implementation

Exactly what happens when you:

- Type Ctrl-c?
  - Keyboard sends hardware interrupt
  - Hardware interrupt is handled by OS
  - OS sends a 2/SIGINT **signal**
- Type Ctrl-z?
  - Keyboard sends hardware interrupt
  - Hardware interrupt is handled by OS
  - OS sends a 20/SIGTSTP **signal**
- Issue a "kill –*sig pid*" command?
  - OS sends a *sig* **signal** to the process whose id is *pid*
- Issue a "fg" or "bg" command?
  - OS sends a 18/SIGCONT **signal** (and does some other things too!)

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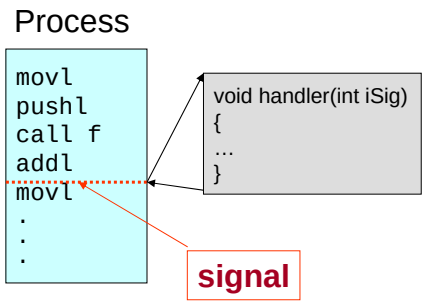
Definition of Signal

Signal: A notification of an event

- Event gains attention of the OS
- OS stops the application process immediately, sending it a signal
- Default action for that signal executes
  - Can install a **signal handler** to change action
- Application process resumes where it left off



8

Examples of Signals

User types Ctrl-c

- Event gains attention of OS
- OS stops the application process immediately, sending it a 2/SIGINT signal
- Default action for 2/SIGINT signal is “terminate”

Process makes illegal memory reference

- Event gains attention of OS
- OS stops application process immediately, sending it a 11/SIGSEGV signal
- Default action for 11/SIGSEGV signal is “terminate”

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Sending Signals via Keystrokes

Three signals can be sent 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"

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Sending Signals via Commands

kill Command

`kill -signal pid`

- Send a signal of type ***`signal`*** to the process with id ***`pid`***
- Can specify either signal type name (-SIGINT) or number (-2)

- No signal type name or number specified => sends 15/SIGTERM signal
  - Default action for 15/SIGTERM is "terminate"
- Editorial: 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

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Sending Signals via Function Calls

raise()

```
int raise(int iSig);
```

- Commands OS to send a signal of type **iSig** to current process
- Returns 0 to indicate success, non-0 to indicate failure

Example

```
int ret = raise(SIGINT); /* Process commits suicide. */
assert(ret != 0);        /* Shouldn't get here. */
```

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Sending Signals via Function Calls

kill()

```
int kill(pid_t iPid, int iSig);
```

- Sends a **iSig** signal to the process whose id is **iPid**
- Equivalent to **raise(iSig)** when **iPid** is the id of current process
- Editorial: Better function name would be **sendsig()**

Example

```
pid_t iPid = getpid(); /* Process gets its id.*/
kill(iPid, SIGINT);  /* Process sends itself a
                        SIGINT signal (commits
                        suicide) */
```

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6. Blocking Signals
7. Conclusion
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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

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Uncatchable Signals

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

- 9/SIGKILL
  - Default action is "terminate"
  - Catchable termination signal is 15/SIGTERM
- 19/SIGSTOP
  - Default action is "stop until next 18/SIGCONT"
  - Catchable suspension signal is 20/SIGTSTP

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Installing a Signal Handler

`signal()`

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

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

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Installing a Handler Example 1

Program testsignal.c:

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

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

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Installing a Handler Example 1 (cont.)

Program testsignal.c (cont.):

```
…
int main(void) {
   void (*pfRet)(int);
   pfRet = signal(SIGINT, myHandler);
   assert(pfRet != SIG_ERR);

   printf("Entering an infinite loop\n");
   for (;;)
      ;
   return 0;
}
```

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Installing a Handler Example 1 (cont.)

[Demo of testsignal.c]

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Installing a Handler Example 2

Program testsignalall.c:

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

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

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Installing a Handler Example 2 (cont.)

Program testsignalall.c (cont.):

```
…
int main(void) {
   void (*pfRet)(int);
   pfRet = signal(SIGHUP,  myHandler);  /* 1 */
   pfRet = signal(SIGINT,  myHandler);  /* 2 */
   pfRet = signal(SIGQUIT, myHandler);  /* 3 */
   pfRet = signal(SIGILL,  myHandler);  /* 4 */
   pfRet = signal(SIGTRAP, myHandler);  /* 5 */
   pfRet = signal(SIGABRT, myHandler);  /* 6 */
   pfRet = signal(SIGBUS,  myHandler);  /* 7 */
   pfRet = signal(SIGFPE,  myHandler);  /* 8 */
   pfRet = signal(SIGKILL, myHandler);  /* 9 */
   …
```

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Installing a Handler Example 2 (cont.)

Program testsignalall.c (cont.):

```
   …
   /* Etc., for every signal. */

   printf("Entering an infinite loop\n");
   for (;;)
      ;
   return 0;
}
```

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Installing a Handler Example 2 (cont.)

[Demo of testsignalall.c]

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Installing a Handler 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;
}
```

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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

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Example 3 Solution

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

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SIG_IGN

Predefined value: **SIG_IGN**

Can use as argument to signal() to **ignore** signals

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

Subsequently, process will ignore 2/SIGINT signals

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SIG_DFL

Predefined value: **SIG_DFL**

Can use as argument to signal() to **restore default action**

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

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

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Race Conditions

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

Race conditions can occur in signal handlers…

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Race Condition Example

```
void addSalaryToSavings(int iSig) {
    int iTemp;
    iTemp = iSavingsBalance;
    iTemp += iMonthlySalary;
    iSavingsBalance = iTemp;
}
```

Handler for hypothetical
"update monthly salary" signal

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Race Condition Example (cont.)

(1) Signal arrives; handler begins executing

```
void addSalaryToSavings(int iSig) {
    int iTemp;
    iTemp = iSavingsBalance;2000
    iTemp += iMonthlySalary;
    iSavingsBalance = iTemp;
}
```

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Race Condition Example (cont.)

(2) Another signal arrives; first instance of handler is interrupted; second instance of handler begins executing

```
void addSalaryToSavings(int iSig) {
   int iTemp;
   iTemp = iSavingsBalance;
   iTemp += iMonthlySalary;
   iSavingsBalance = iTemp;
}
```

2000

```
void addSalaryToSavings(int iSig) {
   int iTemp;
   iTemp = iSavingsBalance;
   iTemp += iMonthlySalary;
   iSavingsBalance = iTemp;
}
```

2000

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Race Condition Example (cont.)

(3) Second instance executes to completion

```
void addSalaryToSavings(int iSig) {
   int iTemp;
   iTemp = iSavingsBalance;
   iTemp += iMonthlySalary;
   iSavingsBalance = iTemp;
}
```

2000

```
void addSalaryToSavings(int iSig) {
   int iTemp;
   iTemp = iSavingsBalance;
   iTemp += iMonthlySalary;
   iSavingsBalance = iTemp;
}
```

2000

2050

2050

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Race Condition Example (cont.)

(4) Control returns to first instance, which executes to completion

```
void addSalaryToSavings(int iSig) {
   int iTemp;
   iTemp = iSavingsBalance;
   iTemp += iMonthlySalary;
   iSavingsBalance = iTemp;
}
```

2000
2050
2050

Lost 50 !!!

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Race Conditions in General

Race conditions can occur elsewhere too

```
int iFlag = 0;

void myHandler(int iSig) {
   iFlag = 1;
}
int main(void) {
   if (iFlag == 0) {
      /* Do something */
   }
}
```

Problem: **`myflag`** might become **`1`** just after the comparison!

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

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Blocking Signals

Blocking signals

- To **block** a signal is to **queue** it for delivery at a later time
- Differs from **ignoring** a signal

Each process has a **signal mask** in the kernel

- OS uses the mask to decide which signals to deliver
- User program can modify mask with **`sigprocmask()`**

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Blocking Signals in General

sigprocmask()

```
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 signal mask
  - **SIG_BLOCK:** Add **psSet** to the current mask
  - **SIG_UNBLOCK:** Remove **psSet** from the current mask
  - **SIG_SETMASK:** Install **psSet** as the signal mask
- Returns 0 iff successful

Functions for constructing signal sets

- **sigemptyset(), sigaddset(), …**

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Blocking Signals Example 1

```
sigset_t sSet;
int main(void) {
   int iRet;
   sigemptyset(&sSet);
   sigaddset(&sSet, SIGINT);
   iRet = sigprocmask(SIG_BLOCK, &sSet, NULL);
   assert(iRet == 0);
   if (iFlag == 0) {
      /* Do something */
   }
   iRet = sigprocmask(SIG_UNBLOCK, &sSet, NULL);
   assert(iRet == 0);
   …
}
```

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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
- Previous "update monthly salary" race condition **cannot happen!!!**
- When/if signal handler returns, block is removed

Additional signal types to be blocked can be defined at time of handler installation…

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Installing a Handler with Blocking

`sigaction()`

```
int sigaction(int iSig,
              const struct sigaction *psAction,
              struct sigaction *psOldAction);
```

- **`iSig`**: The type of signal to be affected
- **`psAction`**: Pointer to a structure containing instructions on how to handle signals of type **`iSig`**, including signal handler name and which signal types should be blocked
- **`psOldAction`**: (Irrelevant for our purposes)
- Installs an appropriate handler
- Automatically blocks signals of type **`iSig`**
- Returns 0 iff successful

Note: More powerful than **`signal()`**

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Blocking Signals Example 2

Program testsigaction.c:

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

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

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Blocking Signals Example 2 (cont.)

Program testsigaction.c (cont.):

```
…
int main(void) {
   int iRet;
   struct sigaction sAction;
   sAction.sa_flags = 0;
   sAction.sa_handler = myHandler;
   sigemptyset(&sAction.sa_mask);
   iRet = sigaction(SIGINT, &sAction, NULL);
   assert(iRet == 0);

   printf("Entering an infinite loop\n");
   for (;;)
      ;
   return 0;
}
```

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Blocking Signals Example 2 (cont.)

[Demo of testsigaction.c]

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Predefined Signals

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 events

Applications can define their own signals with unused values

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Summary

Signals

- A **signal** is an asynchronous event
- **`raise()`** or **`kill()`** **sends** a signal
- **`signal()`** **installs a signal handler**
  - Most signals are **catchable**
- Beware of **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
- **`sigaction()`** installs a signal handler, and allows blocking of additional signal types during handler execution

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Summary

Q: How does the OS communicate to application programs?

A: Signals

For more information:

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

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Alarms

`alarm()`

```
unsigned int alarm(unsigned int uiSec);
```

- Sends 14/SIGALRM signal after **`uiSec`** seconds
- Cancels pending alarm if **`uiSec`** is 0
- Uses **real time**, alias **wall-clock time**
  - Time spent executing other processes counts
  - Time spent waiting for user input counts
- Return value is meaningless

Used to implement time-outs

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Alarm Example 1

Program testalarm.c:

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

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

   /* Set another alarm. */
   alarm(2);
}
…
```

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Alarm Example 1 (cont.)

Program testalarm.c (cont.):

```
…
int main(void)
{
   void (*pfRet)(int);
   sigset_t sSet;
   int iRet;

   /* Make sure that SIGALRM is not blocked.
      Compensates for Linux bug. */
   sigemptyset(&sSet);
   sigaddset(&sSet, SIGALRM);
   iRet = sigprocmask(SIG_UNBLOCK, &sSet, NULL);
   assert(iRet == 0);

   pfRet = signal(SIGALRM, myHandler);
   assert(pfRet != SIG_ERR);
   …
```

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Alarm Example 1 (cont.)

Program testalarm.c (cont.):

```
   …

   /* Set an alarm. */
   alarm(2);

   printf("Entering an infinite loop\n");
   for (;;)
      ;

   return 0;
}
```

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Alarm Example 1 (cont.)

[Demo of testalarm.c]

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Alarm Example 2

Program testalarmtimeout.c:

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

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

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Alarm Example 2 (cont.)

Program testalarmtimeout.c (cont.):

```
int main(void) {
   int i;
   void (*pfRet)(int);
   sigset_t sSet;
   int iRet;

   /* Make sure that SIGALRM is not blocked. */
   sigemptyset(&sSet);
   sigaddset(&sSet, SIGALRM);
   iRet = sigprocmask(SIG_UNBLOCK, &sSet, NULL);
   assert(iRet == 0);
   …
```

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Alarm Example 2 (cont.)

Program testalarmtimeout.c (cont.):

```
   …
   pfRet = signal(SIGALRM, myHandler);
   assert(pfRet != SIG_ERR);

   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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Alarm Example 2 (cont.)

[Demo of testalarmtimeout.c]

Interval Timers

`setitimer()`

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

- Sends 27/SIGPROF signal continually
- Timing is specified by **`psValue`**
- **`psOldValue`** is irrelevant for our purposes
- Uses **virtual time**, alias **CPU time**
  - Time spent executing other processes does not count
  - Time spent waiting for user input does not count
- Returns 0 iff successful

Used by execution profilers

Interval Timer Example

Program testitimer.c:

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

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

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Interval Timer Example (cont.)

Program testitimer.c (cont.):

```
…
int main(void)
{
   int iRet;
   void (*pfRet)(int);
   struct itimerval sTimer;

   pfRet = signal(SIGPROF, myHandler);
   assert(pfRet != SIG_ERR);
   …
```

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Interval Timer Example (cont.)

Program testitimer.c (cont.):

```
   …
   /* Send first signal in 1 second, 0 microseconds. */
   sTimer.it_value.tv_sec = 1;
   sTimer.it_value.tv_usec = 0;

   /* Send subsequent signals in 1 second,
      0 microseconds intervals. */
   sTimer.it_interval.tv_sec = 1;
   sTimer.it_interval.tv_usec = 0;

   iRet = setitimer(ITIMER_PROF, &sTimer, NULL);
   assert(iRet != -1);

   printf("Entering an infinite loop\n");
   for (;;)
      ;
   return 0;
}
```

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Interval Timer Example (cont.)

[Demo of testitimer.c]

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Summary

Alarms

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

Interval Timers

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

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