# Signals

Jennifer Rexford

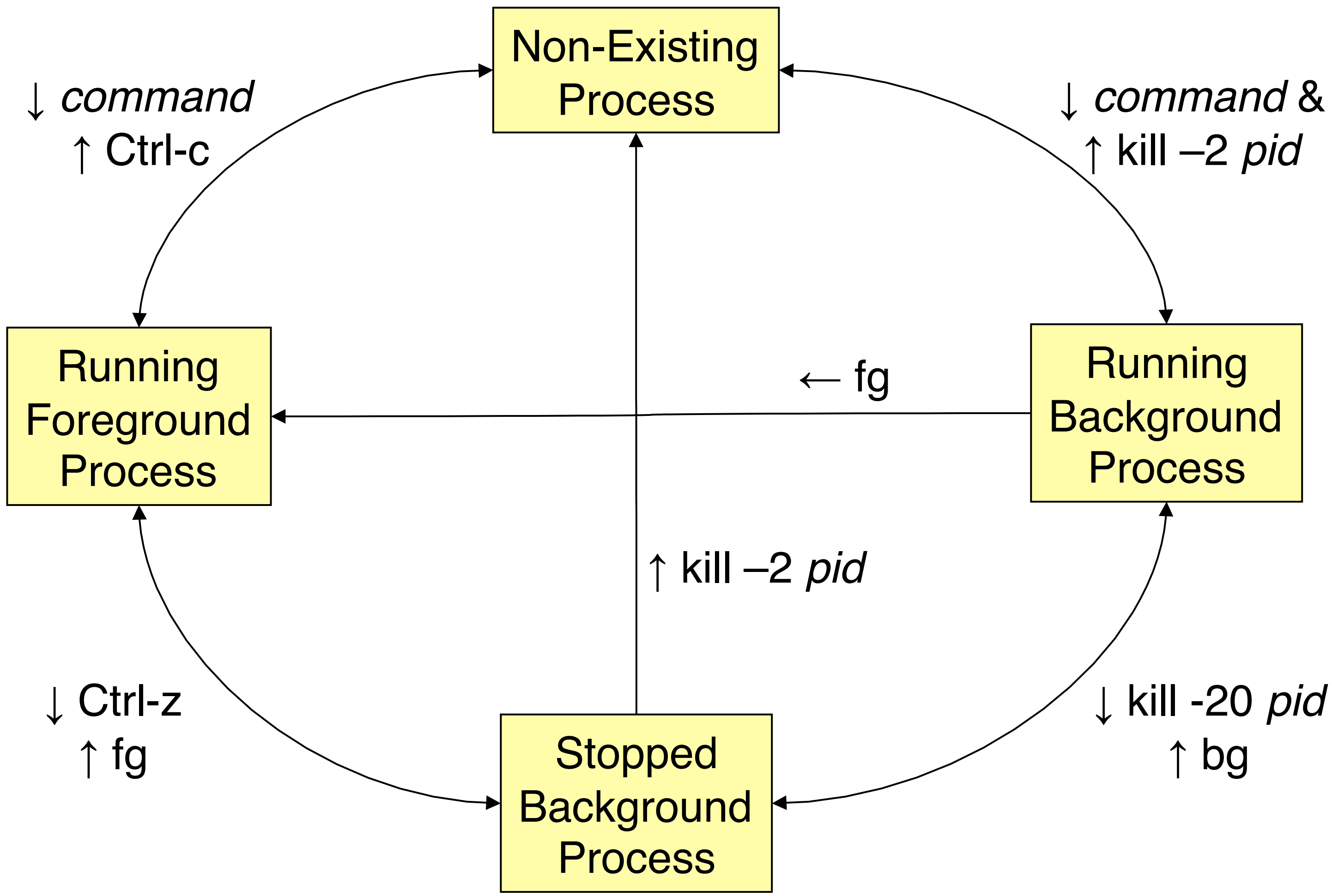
# Goals of this Lecture

- 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

# Outline

1. **Unix Process Control**
2. Signals
3. Sending Signals
4. Handling Signals
5. Race Conditions and Critical Sections
6. Blocking Signals
7. Alarms
8. (If time) Interval Timers
9. Conclusion

# Unix Process Control



# Unix Process Control

[Demo of Unix process control using infloop.c]

# 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**

Recall "Exceptions and Processes" lecture

# 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

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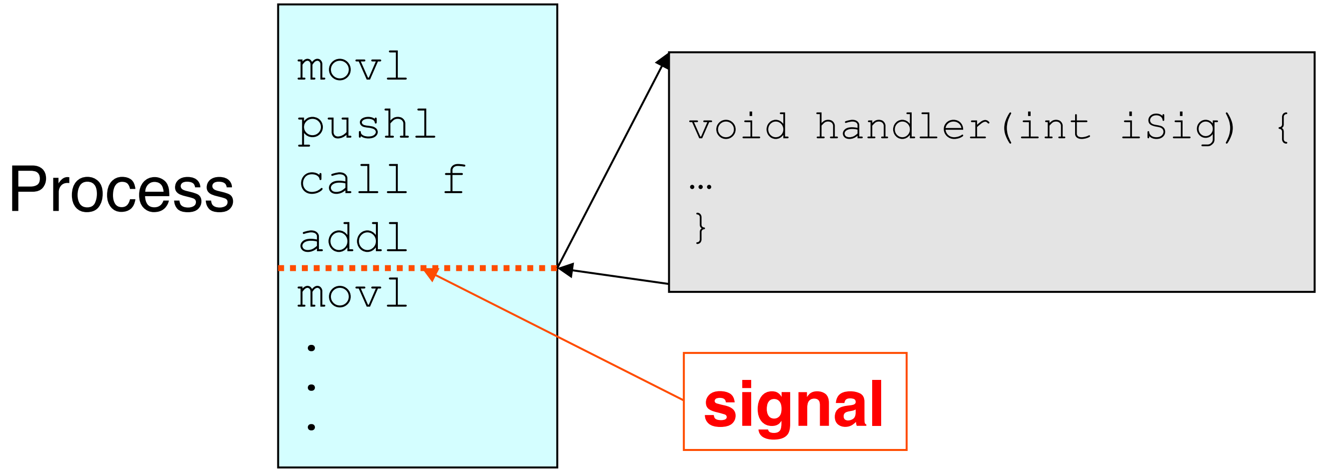
# Signal: Notification of an Event

- Exception occurs (interrupt, trap, fault, or abort)
  - Context switches to OS
- OS sends signal to application process
  - Sets a bit in a vector indicating that a signal of type X occurred
- Process regains CPU and default action for signal executes
  - Can install a **signal handler** to change action
- (Optionally) Application process resumes where it left off



# Examples of Signals

## User types Ctrl-c

- Interrupt occurs
- Context switches to OS
- OS sends 2/SIGINT signal to application process
- Default action for 2/SIGINT signal is “terminate”

## Process makes illegal memory reference

- Fault occurs
- Context switches to OS
- OS sends 11/SIGSEGV signal to application process
- 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"

# Sending Signals via Commands

## kill Command

```
kill -signal pid
```

- Send a signal of type ***signal*** to the process with id ***pid***
- 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

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

# 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.*/
int iRet = kill(iPid, SIGINT); /* Process sends itself a
assert(iRet != 0);                   SIGINT signal (commits
                                     suicide) */
```

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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()**

```
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**

# 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);
}
…
```

# 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;
}
```

# Installing a Handler Example 1 (cont.)

[Demo of testsignal.c]

# 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);
}
…
```

# 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 */
   …
```

This call fails

# Installing a Handler Example 2 (cont.)

## Program testsignalall.c (cont.):

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

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

# Installing a Handler Example 2 (cont.)

[Demo of testsignalall.c]

# 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;
}
```

# 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) {
   void (*pfRet)(int);
   psFile = fopen("temp.txt", "w");
   pfRet = signal(SIGINT, cleanup);
   …
   cleanup(0);  /* or raise(SIGINT); */
   return 0;  /* Never get here. */
}
```

# 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);
   assert(pfRet != SIG_ERR);
   …
}
```

Subsequently, process will ignore 2/SIGINT signals

# 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);
   assert(pfRet != SIG_ERR);
   …
   pfRet = signal(SIGINT, SIG_DFL);
   assert(pfRet != SIG_ERR);

   …
}
```

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

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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

Race condition example:

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

To save slide space, we ignore error handling here and subsequently

# 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;
    …
```

`iBalance += 50;` →

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

`iBalance += 100;` →

```
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;
    …
```

`iBalance += 50;`

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

`iBalance += 100;`

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

# 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

- **Blocking** a signal **queues** 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()`**

# Function for Blocking Signals

**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()**, …

# 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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# 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 irrelevant for our purposes

Used to implement time-outs

# 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);
}
…
```

# Alarm Example 1 (cont.)

Program testalarm.c (cont.):

```
…
int main(void)
{
   sigset_t sSet;

   /* Make sure SIGALRM signals are not blocked. */
   sigemptyset(&sSet);
   sigaddset(&sSet, SIGALRM);
   sigprocmask(SIG_UNBLOCK, &sSet, NULL);

   signal(SIGALRM, myHandler);
   …
```

Safe, but shouldn't be necessary; compensates for a Linux bug

# Alarm Example 1 (cont.)

Program testalarm.c (cont.):

```
   …

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

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

   return 0;
}
```

# Alarm Example 1 (cont.)

[Demo of testalarm.c]

# 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);
}
```

# Alarm Example 2 (cont.)

Program testalarmtimeout.c (cont.):

Safe, but shouldn't be necessary

```
int main(void) {
   int i;
   sigset_t sSet;

   /* Make sure SIGALRM signals are not blocked. */
   sigemptyset(&sSet);
   sigaddset(&sSet, SIGALRM);
   sigprocmask(SIG_UNBLOCK, &sSet, NULL);

 …
```

# Alarm Example 2 (cont.)

Program testalarmtimeout.c (cont.):

```
   …
   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 (cont.)

[Demo of testalarmtimeout.c]

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# Interval Timers

## `setitimer()`

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

- Sends 27/SIGPROF signal continually
- **`psValue`** specifies timing
- **`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);
}
…
```

# Interval Timer Example (cont.)

Program testitimer.c (cont.):

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

   signal(SIGPROF, myHandler);

   …
```

# 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;

    setitimer(ITIMER_PROF, &sTimer, NULL);

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

# Interval Timer Example (cont.)

[Demo of testitimer.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 exceptions

Application program can define signals with unused values

# Summary

## Signals

- A **signal** is an asynchronous event
- Sending signals
  - `raise()` or `kill()` **sends** a signal
- Catching signals
  - `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

# Summary (cont.)

## 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**

# Summary (cont.)

For more information:

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