Languages for Informatics

8 – Signals and Error Handling

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Topics

- Linux programming environment (2h)
- Introduction to C programming (12h)
- Basic system programming in Linux (10h)
  1. Signals and Error Handling
  2. Low-Level System Calls in C
  3. Multi-Tasking in C
  4. Multi-Threading in C
  5. Machine-To-Machine Communication in C

Overview

Introduction

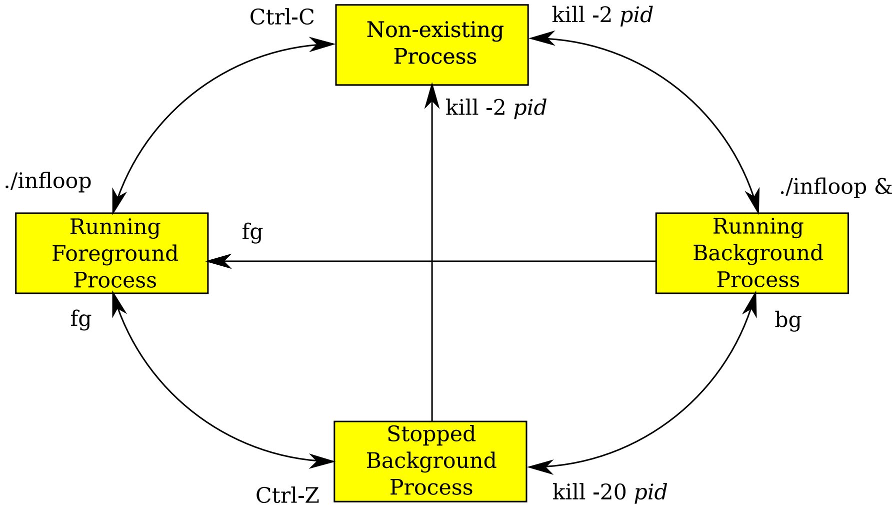
Two fundamental questions:

Q1 How does the **OS** communicate to an **application process**?

Q2 How does an **application process** communicate to the **OS**?

- This lecture: Q1
- Next lecture: Q2

UNIX Process Control (Demo)



What happens exactly?

- 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?
  - `kill` command executes **trap**
  - OS handles trap by sending 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 by sending a `18/SIGCONT` **signal**.

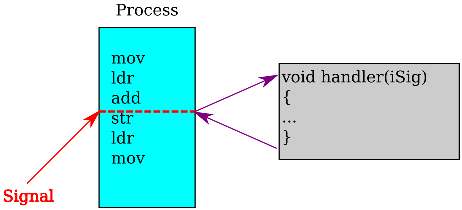
Signals

Q1 How does the **OS** communicate to an **application process**?

A1 through Signals.

Definition

- A **signal** is an **asynchronous** notification of an event that is sent to a process.
  - may occur any time by the kernel (e.g. segment violation, floating point error, illegal instruction) or by the terminal driver (due to user interaction)
  - Event gains attention of the OS
  - OS stops the app. process immediately, sending it a signal
  - **Signal handler** executes to completion
  - Application process resumes where it left off



Examples of Signals

- User types **`Ctrl-c`**
  - Interrupt occurs
  - OS stops the application process immediately, sending it a `2/SIGINT` signal
  - Process receives `2/SIGINT` signal to process
  - Default action for `2/SIGINT` signal is to terminate the process.
- Process makes illegal memory reference
  - Segmentation fault occurs
  - OS stops application process immediately, sending it a comandoblue11/SIGSEGV signal
  - Process receives `11/SIGSEGV` signal to process
  - Default action for `11/SIGSEGV` signal is to terminate the process.

Keystroke based Signals

Three signals can be sent from the keyboard.

Ctrl-C `2/SIGINT` signal
- Default handler **interrupts** process

Ctrl-Z `20/SIGSTP` signal
- Default handler **suspends** process

Ctrl-\ `3/SIGQUIT` signal
- Default handler **exits** process

Sending Signals via Commands

- `kill` function
  - **`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)
  - When no signal type name or number specified, default is `15/SIGTERM` (exit)
- Examples
  - **`$ kill -2 1234`**
  - **`$ kill -SIGINT 1234`**
  - Same as pressing **`Ctrl-c`** if process `1234` is running in foreground

Sending Signals via POSIX Function Call

- Syntax
```
#include <signal.h>
int kill(pid_t pid, int iSig);
```
  - **Process Identification Data Type `pid_t`** is `signed int`
  - **`getpid()`** returns the pid of the calling process
  - **`iSig`** is the signal to be sent.
  - **Return**: 0 on SUCCESS : −1 otherwise.
- Example (Demo):

```
int main () {
   pid_t process_id;
   process_id = getpid();

   printf("PID: %d\n",process_id);
   kill(process_id, SIGKILL);  /* suicide */
   ...
```

1. Introduction
2. Signals
   - Signal Handling
   - Race Conditions and Critical Sections
   - Blocking Signals
   - Alarms
   - Interval Timers
3. Error Handling

Signal Handling

- Each signal type has a default handler
  - Most default handlers exit the process
- A program can install **a customized handler** for signals of any type
- Exceptions: A program cannot install its own handler for signals of type:
  - `9/SIGKILL`
    - Default handler exits the process
    - Catchable termination signal is `15/SIGTERM`
  - `19/SIGSTOP`
    - Default handler suspends the process
    - Can resume the process with signal `18/SIGCONT`
    - Catchable suspension signal is `20/SIGTSTP`

Installing a Signal Handler signal()

- Whenever process receives a signal of type `iSig`, a signal handler function is invoked
- Syntax:

```
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

Handler Example 1

```
#include<stdio.h>
#include<signal.h>
#include<unistd.h>  //sleep
#include<stdlib.h>
#include<string.h> //strsignal

volatile int flag = 1; //don't cache variable

void myHandler(int iSig) {
  printf("In myHandler with argument %d/%s \n",iSig,strsignal(
    iSig));
  flag = 0;
  }
```

Note

For a real-world program, **printing from a signal handler is not very safe.** A signal handler should do as little as it can, preferably only setting a flag here or there.

Handler Example 1 (Demo)

```
int main() {
/****************************************/
  void (*ret) (int); //fct-pointer int->void
  int ret = signal(SIGINT, myHandler);  // handle Ctrl-C

  if (ret != 0) {    /* Something went wrong */
        exit(EXIT_FAILURE);
  }
/****************************************/
  int i = 0;
  while (flag) {
      printf("%d \n",i);
      i++;
      sleep(1);
  }
  return 0;
}
```

Signals types (Excerpt)

Signal	Value	Action	Comment
SIGINT	2	Term	Interrupt from keyboard **`Ctrl-C`**
SIGQUIT	3	Core	Quit from keyboard **`Ctrl-\`**
SIGILL	4	Core	Illegal Instruction
SIGFPE	8	Core	Floating point exception
SIGKILL	9	Term	Kill signal **`kill -9`**
SIGSEGV	11	Core	Invalid memory reference
SIGTERM	15	Term	Termination signal
SIGALRM	14	Term	Timer signal from alarm
SIGCONT	18	Cont	Continue if stopped
SIGTSTP	20	Stop	Quit from keyboard **`Ctrl-Z`**
SIGUSR1	30	Term	User-defined signal

For details, type **`kill -l`** and check out `man 7 signal`.

Unexpected Interrupt

- Suppose program generates lots of data
  - Data is buffered
  - Data written to file when buffer full or `fclose()` occurs

```
int main(void) {
   FILE *psFile;
   psFile = fopen("temp.txt", "w");
   ...
   fclose(psFile);  /* only here all data flushed to
    file */
   return 0;
}
```

Unexpected Interrupt (cont'd)

- What if user types **Ctrl-c**?
  - OS sends a `2/SIGINT0` signal to the process
  - Default handler of `2/SIGINT` exits the process
- Problem: Data not flushed to file `temp.txt`.
  - Process dies before **fclose()** 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 set flag and close file
  - Install the function as a signal handler for `2/SIGINT`

Unexpected Interrupt - Solution

Demo

```
FILE *psFile;
static void cleanup(int iSig) {
    fclose(psFile);
    exit(1);
    }
int main(void) {
    void (*pfRet)(int);
    pfRet = signal(SIGINT, cleanup);

    char *file = "temp.txt";
    psFile = fopen(file, "w");
    /* do something */
    fclose(psFile);    // dump to file, if possible
    return 0;
}
```

Ignoring Signals

- **Ignoring**: The signal is discarded by the kernel without any action being taken.
- Pre-defined signal handler **SIG_IGN**
- tells the kernel to ignore signals
- Note: SIGKILL and SIGSTOP cannot be caught or ignored
- Code snippet

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

- Subsequently, process will ignore 2/SIGINT signals

Restore Default Action

Demo

- Pre-defined signal handler **SIG_DFL**
- tells the kernel that there is no user signal handler i.e., to take default action
- Code snippet (Demo)

```
void myHandler(int iSig) {
    printf("!?*X! -- I got signal %d \n", iSig);
    (void) signal(SIGINT, SIG_DFL); // default next time.
    }
int main()
    {
    void (*ret) (int);
    ret = signal(SIGINT, myHandler); //handle ctrl-c
    ...
    }
```

- Hence, process will handle `2/SIGINT` signals using the default handler.

Race Conditions and Critical Sections

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

Race Condition Example (1)

Consider a handler for hypothetical ”update monthly salary” signal:

```
int iBalance = 200;

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

int main() {
  void (*ret) (int); // fct-pointer int->void
  ret = signal(SIGINT, addBonus);
  ...
  iBalance += 100;
  ...
}
```

Race Condition Example (2)

Race condition example in assembly language

```
int iBalance = 200;

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

int main() {
  void (*ret) (int); //fct-pointer int->void
  ret = signal(SIGINT, addBonus);
  ...
  iBalance += 100;
  ...
}
```

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

```
movl iBalance, %ecx
addl 100, %ecx
movl %ecx, iBalanace
```

Let the compiler generates that assembly language code

Race Condition Example (3)

1. **`main()`** starts to execute

```
int iBalance = 200;

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

int main() {
  void (*ret)(int); //fct-pointer int->void
  ret = signal(SIGINT, addBonus);
  ...
  iBalance += 100;
  ...
}
```

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

```
movl iBalance, %ecx
addl 100, %ecx
movl %ecx, iBalanace
```

200
300

Race Condition Example (4)

2. **SIGINT** interrupt; `addBonus()` executed

```
int iBalance = 200;

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

int main() {
  void (*ret)(int); //fct-pointer int->void
  ret = signal(SIGINT, addBonus);
  ...
  iBalance += 100;
  ...
}
```

```
movl iBalance, %ecx       200
addl 50, %ecx             250
movl %ecx, iBalanace      250
```

```
movl iBalance, %ecx       200
addl 100, %ecx            300
movl %ecx, iBalanace
```

Race Condition Example (5)

3. `addBonus()` terminates; `main()` to be continued

```
int iBalance = 200;

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

int main() {
  void (*ret) (int); //fct-pointer int->void
  ret = signal(SIGINT, addBonus);
  ...
  iBalance += 100;
  ...
}
```

```
movl iBalance , %ecx      200
addl 50, %ecx             250
movl %ecx, iBalanace      250
```

```
movl iBalance , %ecx      200
addl 100, %ecx            300
movl %ecx, iBalanace      300
```

50 € lost !!

Critical Sections

- The **critical sections** are the transactions.
- This piece of the code must not be interrupted.

```
int iBalance = 200;

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

int main() {
  void (*ret)(int); //fct-pointer int->void
  ret = signal(SIGINT, addBonus);
  ...
  iBalance += 100;
  ...
}
```

Blocked Signal

- **Blocking** a signal means telling the operating system to **hold it until** it is unblocked at a later time.
- For each process, the kernel also maintains the set of blocked signals in a ”blocked bit” vector (in the kernel memory space). The corresponding bit in the pending signal vector is not cleared until the signal is unblocked and received.
- Blocking certain signals **forces an execution order.**
  - Differs from **ignoring** a signal.
  - **briefly** blocking signals prevent them from interrupting sensitive operations by another signal (race condition).

Blocking/unblocking a signal (1)

Procedure:

- System call **`sigemptyset(const sigset_t *psSet)`** simply initializes the signalmask to empty, i.e. all signals will be received.
- System calls **`sigaddset(sigset_t *psSet, int signum)`** and **`sigdelset`** subroutines respectively add and delete the individual signal specified by the Signal Number `signum` parameter.
- Having added here all the signals you want to have blocked, then block them all with **`sigprocmask`**

Blocking/unblocking a signal (2)

- System call **sigprocmask()** can examine and modify the set of blocked signals. SIGKILL and SIGSTOP cannot be blocked by **sigprocmask()**.
- Prototype

```
int sigprocmask(int how, const sigset_t *psSet,
    sigset_t *oldset);
```

  - The 1. argument can be:
    - SIG_BLOCK: adds the signal types specified by the second argument set to the list of already-blocked signal types.
    - SIG_UNBLOCK: removes the signal types specified by the second argument set to the list of already-blocked signal types.
    - SIG_SETMASK: set to list of blocked signal types to the ones specified by the second argument.
  - **psSet** is a pointer of type `sigset_t *`, which points to a "bit vector"
  - **psOldSet** is irrelevant for our purposes.

Blocking Signals Example

```
int main () {

  sigset_t sSet;              //Declaration of signal set
  ...
  void (*ret) (int);                //fct-pointer int->void
  ret = signal(SIGINT, addBonus);
  ...
  sigemptyset(&sSet);                             //init mask
  sigaddset(&sSet, SIGINT);                       //add Ctrl-C
  sigprocmask(SIG_BLOCK, &sSet, NULL);            //block SIGINT

  iBalance += 100;                  //Critical Section

  sigprocmask(SIG_UNBLOCK, &sSet, NULL);//unblock SIGINT
  ...
```

Drawbacks

- The **`signal()`** function (usually) resets the signal action back to SIG_DFL (default) for almost all signals. This means that the `signal()` handler must reinstall itself as its first action. This opens up a window of vulnerability.
- The effects of **`signal()`** in a multi-threaded process are unspecified.
- The exact behaviour of **`signal()`** varies among systems.

Solution

The system call **`sigaction()`** over comes above drawbacks. Signal that caused the handler to be triggered will by default already be blocked inside the handler.

sigaction(): A more robust approach to **signal()**

The system call **sigaction()** installs an appropriate handler

- Prototype

```
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)
- **Automatically blocks** signals of type `iSig`
- Returns 0 iff successful

The Blocking Signals Example revisited

```
int main () {

  int iRet;     // instead of a pointer

  struct sigaction sAction;
  sAction.sa_flags = 0;    //to deploy the handler
  sAction.sa_handler = &addBonus;
  sigemptyset(&sAction.sa_mask);
  iRet = sigaction(SIGINT, &sAction, NULL);
  if (iRet != 0) {    /* Something went wrong */
     exit(EXIT_FAILURE);
  }

  iBalance += 100;
  ...
```

Alarms

- The **`alarm()`** function sets a real-time timer.
- Prototype:

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

- Sends `14/SIGALRM` signal after `uiSec` seconds
- If there is a previous **`alarm()`** request with time remaining, the return value is this value.
- Cancels pending alarm with **`alarm(0)`**.

Note

If you simply want your process to wait for a given number of seconds, you should use the **`sleep()`** function.

Alarms

Example – Timeout

```
#include <stdio.h>
#include <stdlib.h>
#include <signal.h>
#include <unistd.h> //alarm

static void myHandler(int iSig)

/* A handler for signals of type
   SIGALRM that prints a timeout message to stdout, and
    exits. */

{
   printf("\nSorry. You took too long.\n");
   exit(EXIT_FAILURE);
}
```

Alarms

Example – Timeout

```
int main(void)

{
    int timeout=5;
    signal(SIGALRM, myHandler);
    printf("Press a key within %d s:  ",timeout);
    alarm(sec);      //set alarm

    getc(stdin);

    printf("Good job! \n");
    return 0;
}
```

Interval Timers

- The function **setittimer()** sets value of an interval timer.
- Syntax

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

  - The system provides each process with three interval timers, each decrementing in a distinct time domain.
  - When any timer expires, a signal is sent to the process, and the timer (potentially) restarts.
  - The time `ITIMER_PROF` in `which` profiles the time spent by the app in user and kernel space, sends `27/SIGPROF`
  - `psValue` specifies timing
  - `psOldValue` is irrelevant for our purposes

Interval Timers (cont'd)

- Uses **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

Example

Execution Profiler

```
#include <signal.h>
#include <stdlib.h>
#include <stdio.h>
#include <sys/time.h>
#include "heavyload.h" // a HUGE for-loop

volatile int count=0;

static void myHandler(int iSig)
{
   count++;
}
```

Example

Execution Profiler (Demo)

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

pfRet = signal(SIGPROF, myHandler);
if (pfRet != 0) {    /* Something went wrong */
        exit(EXIT_FAILURE);
    }
sTimer.it_value.tv_sec = 0;        /* A */
sTimer.it_value.tv_usec = 10;      /* B */
sTimer.it_interval.tv_sec = 0;     /* C */
sTimer.it_interval.tv_usec = 10;   /* D */
iRet = setitimer(ITIMER_PROF, &sTimer, NULL); /* start profiling
      */
... /* check for errors */
heavyload();     // a HUGE for-loop
printf("Time elapsed: %lf sec. \n", (double) count/1000);
return 0;
};
```

Summary

List of 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	16) SIGSTKFLT
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	...

Error Handling

`errno, strerror`

- Basic error codes are defined in the standard library `<errno.h>`.
- The global `errno` variable is used by many functions to **return error values.**
  - When opening a file with `fopen()` fails, the function only returns `NULL` without cause of the failure.
- The value of `errno` is defined only **after a function call** for which it is explicitly stated to be set.
- A string description of the numeric error code can be returned by `char* strerror( int errnum)` from the standard library `<string.h>`.

Example

errno, strerror

```c
#include <stdio.h>
#include <errno.h>
#include <string.h>

int main () {
    FILE *f = fopen("nonexistent.txt", "r");
    if (f == NULL) {
      int r = errno;
      printf("Open file failed errno value %d\n", errno);
      printf("String error '%s' \n",strerror(r));
    }
    return 0;
}
```

Example

errno, strerror

- When the file does not exist,

Output

```
Open file failed errno value 2
String error 'No such file or directory'
```

- When the file does not have sufficient access rights,

Output

```
Open file failed errno value 13
String error 'Permission denied'
```

Error Handling

perror

- While **strerror()** returns a pointer to the error message string, the function

```
void perror(const char *s);
```

can be used to print a customized string along with the human-readable error message.

- The following two implementations are equivalent:

```
printf("fopen(): %s\n", strerror(errno));
perror("fopen()");
```

Other relevant `errno` codes

Common `errno` codes,

Error Code	Macro	Description
12	ENOMEM	Cannot allocate memory
17	EEXIST	File exists
20	ENOTDIR	Not a directory
21	EISDIR	Is a directory
27	EFBIG	File too large
28	ENOSPC	No space left on device
30	EROFS	Read-only file system

errno with signals

How to deal with errno and signal handler in Linux?

- The errno code becomes likely corrupted.
- A properly written signal handler saves and restores the value of **errno**
- Sample code:

```
void signal_handler(int signo){
    int temp_errno = errno;
    /*  code here may change the errno */
    errno = temp_errno;
}
```

Quiz

In UNIX, the ____________ system call is used to send a signal.

1. **`sig`**
2. **`send`**
3. **`kill`**
4. **`sigsend`**