Signals

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Goals of this Lecture

- Help you learn about:
  - Unix process control
  - Sending signals
  - Handling signals safely

  … 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

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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. (if time) Alarms and Interval Timers

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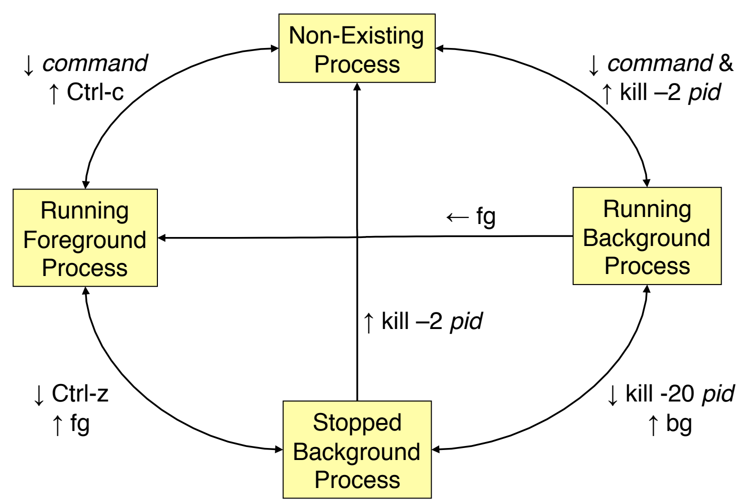
Unix Process Control



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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**
- 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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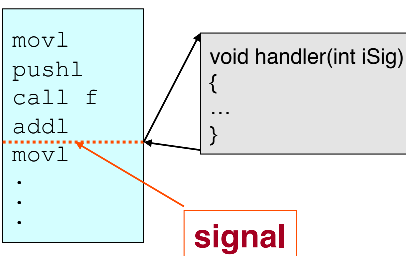
Definition of Signal

Signal: A 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
- When application process regains CPU, default action for that signal executes
  - Can install a **signal handler** to change action
- (Optionally) Application process resumes where it left off

Process



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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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1. Unix Process Control
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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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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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Example

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

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

```
…
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. */
}
```

Ignoring Signals

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

Restoring Default Handling

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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1. Unix Process Control
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5. **Race Conditions**
6. Blocking Signals
7. Conclusion
8. (if time) Alarms and Interval Timers

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…

Race Condition Example

```
void addToSavings(int iSig) {
    int iTemp;
    iTemp = iSavingsBalance;
    iTemp += iDeposit;
    iSavingsBalance = iTemp;
}
```

Handler for hypothetical "handle deposit" and "handle monthly pay check" signals

Race Condition Example (cont.)

(1) "Handle deposit" signal arrives to deposit $50; handler begins executing

```
void addToSavings(int iSig) {
    int iTemp;
    iTemp = iSavingsBalance;   2000
    iTemp += iDeposit;         2050
    iSavingsBalance = iTemp;
}
```

Race Condition Example (cont.)

(2) “Handle monthly pay check” signal arrives to deposit $50;
first instance of handler is interrupted;
second instance begins executing

```
void addToSavings(int iSig) {
   int iTemp;
   iTemp = iSavingsBalance;   2000
   iTemp += iDeposit;         2050
   iSavingsBalance = iTemp;
}
```

```
void addToSavings(int iSig) {
   int iTemp;
   iTemp = iSavingsBalance;   2000
   iTemp += iDeposit;         2050
   iSavingsBalance = iTemp;
}
```

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Race Condition Example (cont.)

(3) Second instance executes to completion

```
void addToSavings(int iSig) {
   int iTemp;
   iTemp = iSavingsBalance;   2000
   iTemp += iDeposit;         2050
   iSavingsBalance = iTemp;
}
```

```
void addToSavings(int iSig) {
   int iTemp;
   iTemp = iSavingsBalance;   2000
   iTemp += iDeposit;         2050
   iSavingsBalance = iTemp;   2050
}
```

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Race Condition Example (cont.)

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

```
void addToSavings(int iSig) {
   int iTemp;
   iTemp = iSavingsBalance;           2000
   iTemp += iDeposit;                 2050
   iSavingsBalance = iTemp;           2050
}
```

Lost $50 !!!

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: **iFlag** 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()`

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
  - E.g.: In previous example, “handle deposit” signals are blocked while handler for “handle deposit” signal is executing
- 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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Outline

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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 pgm can define 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

Summary (cont.)

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);
}
```


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);
   …
```

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;
}
```


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);
}
…
```

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);
   …
```


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;
}
```

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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Course Wrap Up

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The Rest of the Semester

- Final Assignment Due: Sunday Jan 9, 9 p.m.
- Deans Date: Tuesday Jan 11
  - Cannot submit final assignment after 11:59PM
- Final Exam: Saturday, Jan 15
  - 7:30 PM in 20 Washington Road (the old Frick 120)
  - Exams from previous semesters are online at
    - http://www.cs.princeton.edu/courses/archive/fall09/cos217/exam2prep/
  - Covers entire course, with emphasis on second half of the term
  - Closed book, notes, everything
- Office hours during reading/exam period
  - Daily, times TBA on course mailing list
- Review sessions
  - During exam period, time TBA on course mailing list

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Goals of COS 217

- Understand Modularity and Abstraction
  - Separation of interface from implementation
  - Process/Processor, Virtual/Physical memory, etc.
- Understand boundary between code and computer
  - Machine architecture
  - Operating systems
  - Compilers
- Learn C and the Unix development tools
- Improve your programming and debugging skills

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Relationship to Other Courses

- Machine architecture
  - Logic design (306) and computer architecture (471)
  - COS 217: assembly language and basic architecture
- Operating systems
  - Operating systems (318)
  - COS 217: virtual memory, system calls, and signals
- Compilers
  - Compiling techniques (320)
  - COS 217: compilation process, symbol tables, assembly and machine language
- Software systems
  - Numerous courses, independent work, etc.
  - COS 217: programming skills, UNIX tools, and ADTs

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Lessons About Computer Science

- Modularity; Interface versus Implementation
  - Well-defined interfaces between components
  - Allows changing the implementation of one component without changing another
  - The key to managing complexity in large systems
- Resource sharing
  - Time sharing of the CPU by multiple processes
  - Sharing of the physical memory by multiple processes
- Indirection
  - Representing address space with virtual memory
  - Manipulating data via pointers (or addresses)

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Lessons Continued

- Hierarchy
  - Memory: registers, cache, main memory, disk, tape, …
  - Balancing the trade-off between fast/small and slow/big
- Bits can mean anything
  - Code, addresses, characters, pixels, money, grades, …
  - Arithmetic can be done through logic operations
  - The meaning of the bits depends entirely on how they are accessed, used, and manipulated

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Have a Great Holiday

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"I forgot to make a back-up copy of my brain, so everything I learned last semester was lost."