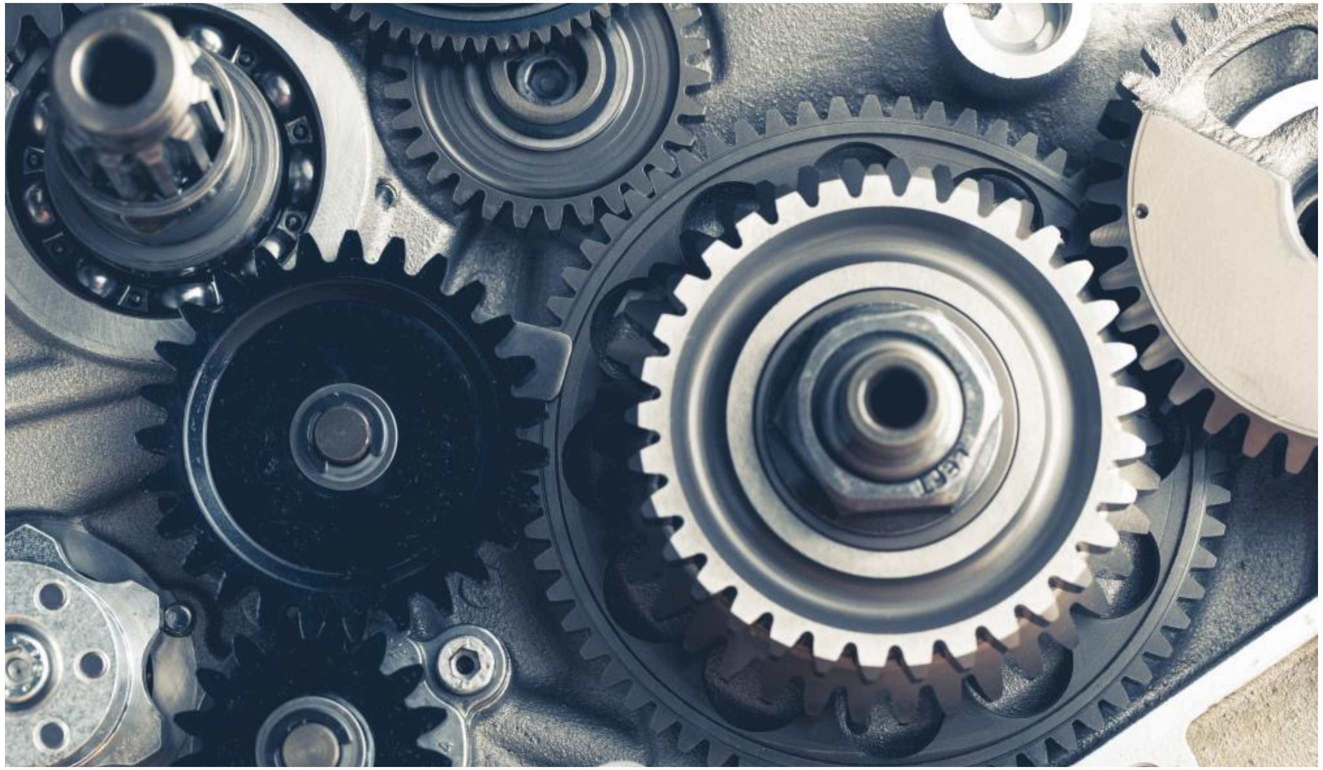
COS 217: Introduction to Programming Systems

Processes



PRINCETON UNIVERSITY

Agenda

Processes

- Illusion: Private address space
- Illusion: Private control flow

Process management in C

- Creating new processes
- Waiting for termination
- Executing new programs

Unix Process Control

- Exceptions
- Signals

Processes

Program

- Executable code
- A static entity

Process

- An instance of a program in execution
- A dynamic entity: has a time dimension
- Each process runs one program
  - E.g. the process with Process ID 12345 might be running `emacs`
- One program can run in multiple processes
  - E.g. PID 12345 might be running `emacs`, and PID 23456 might also be running `emacs` – for the same user or for a different user

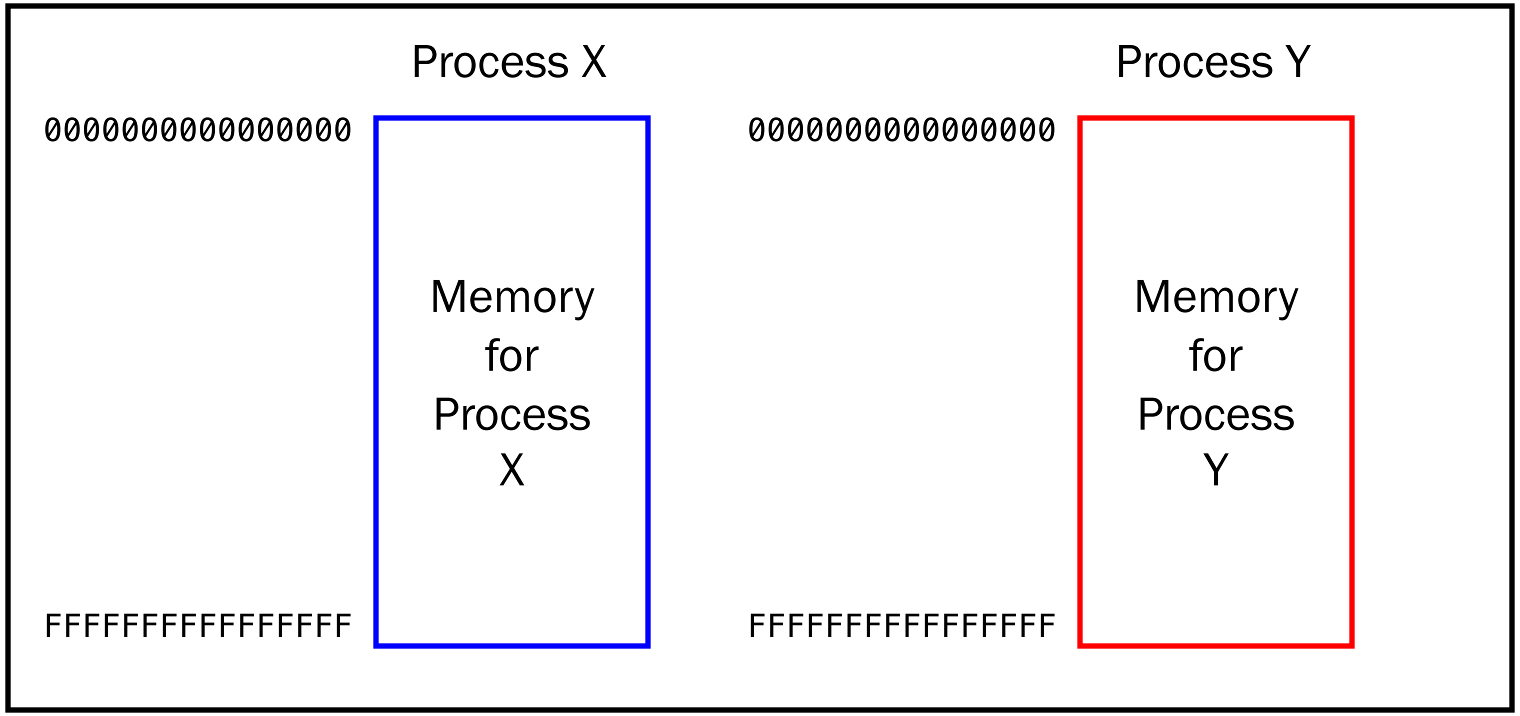
Processes Significance

Process abstraction provides two key illusions:

- Processes believe they have a *private address space*
- Processes believe they have *private control flow*

Process is a profound abstraction in computer science

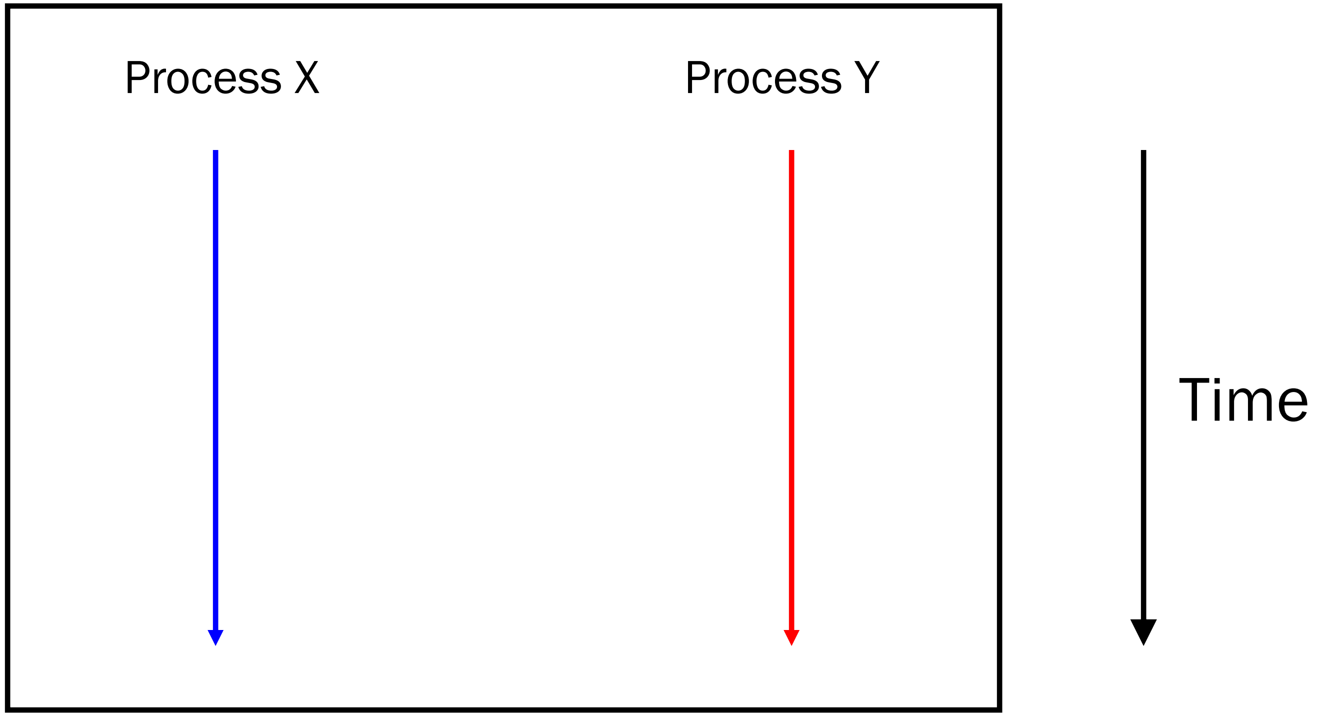
Private Address Space: Illusion



Hardware and OS give each application process the illusion that it is the *only* process using memory

- Enables multiple simultaneous instances of one program!

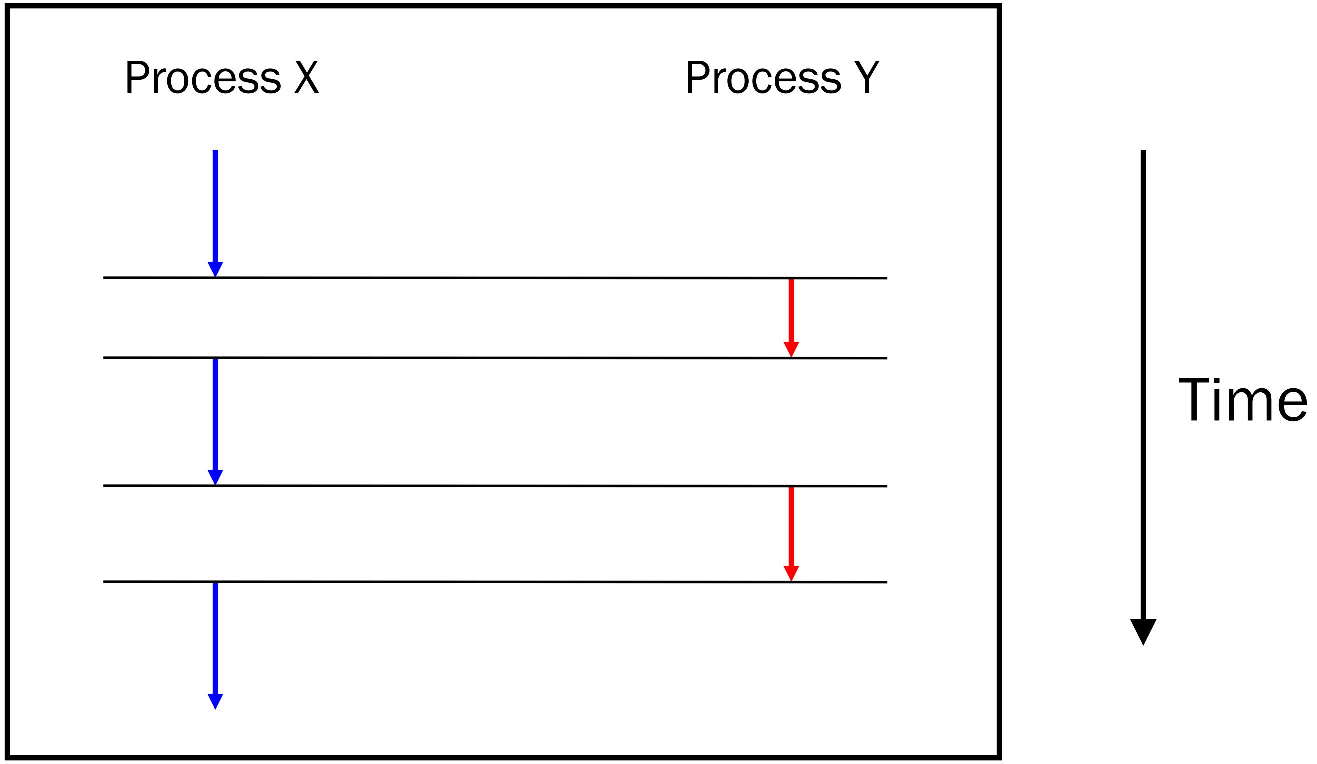
Private Control Flow: Illusion



Simplifying assumption: only one CPU / core

Hardware and OS give each application process the illusion that it is the *only* process running on the CPU

Private Control Flow: Reality



Multiple processes are time-sliced (possibly across multiple CPUs / cores) to run concurrently

OS occasionally preempts running process to give other processes their fair share of CPU time

Process Status

More specifically…

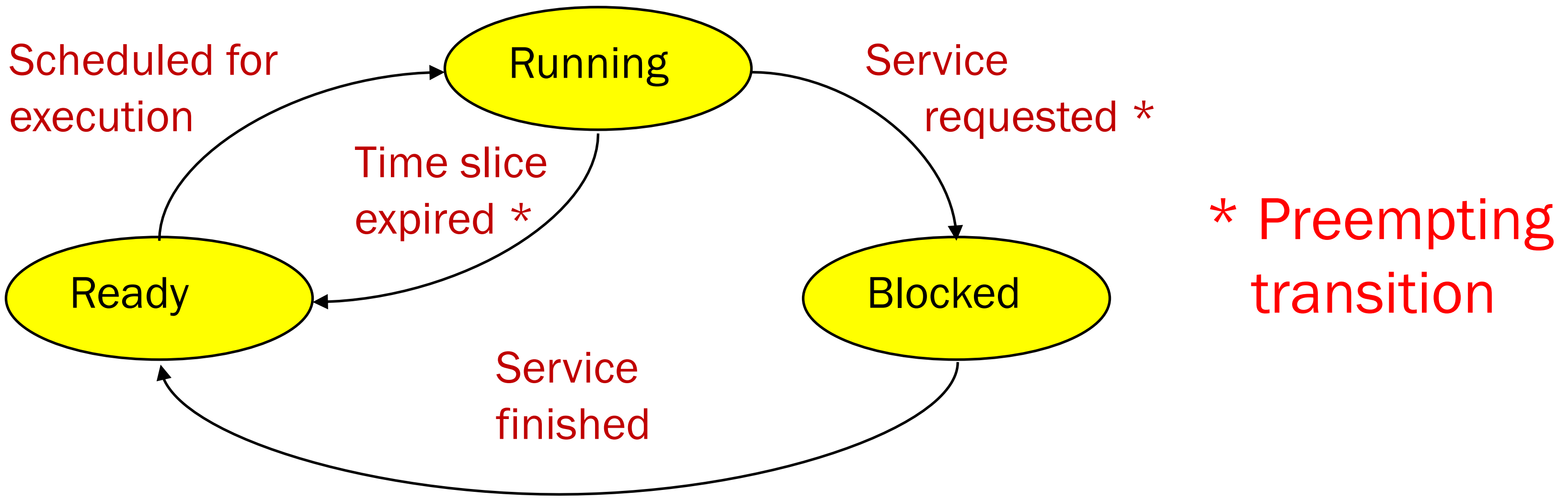
At any time, a process has a **status**:

- **Running**: a CPU is executing instructions for the process
- **Ready**: Process is ready for OS to assign it to a CPU
- **Blocked**: Process is waiting for some requested service (typically I/O) to finish

Modern machines may have multiple CPUs or "cores", but the same principles apply if #processes > #cores

- For simplicity, we will speak of "the" CPU

Process Status Transitions



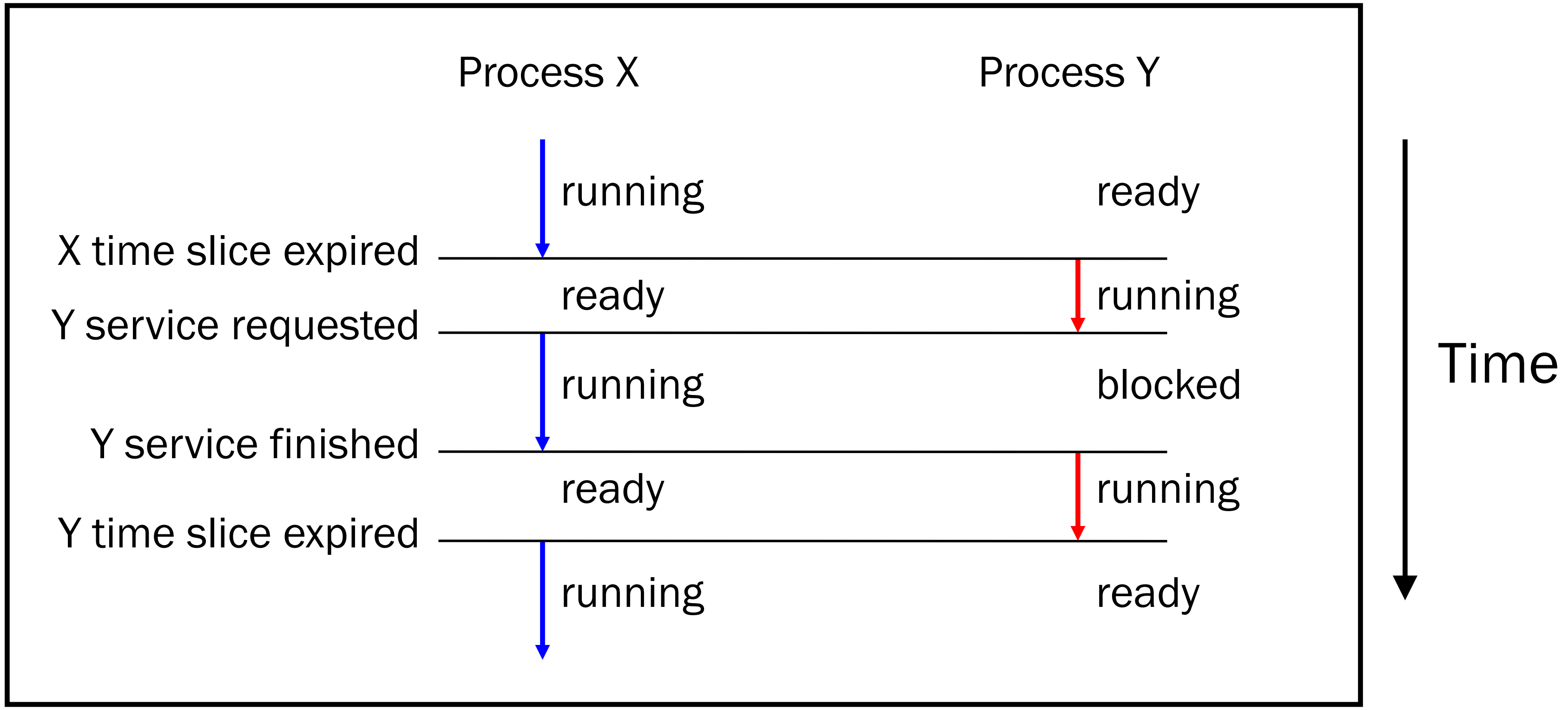
Scheduled for execution: OS selects some process from ready set and assigns CPU to it

Time slice expired: OS moves running process to ready set because process consumed its fair share of CPU time

Service requested: OS moves running process to blocked set because it requested a (time consuming) system service (often I/O)

Service finished: OS moves blocked process to ready set because the requested service finished

Process Status Transitions Over Time



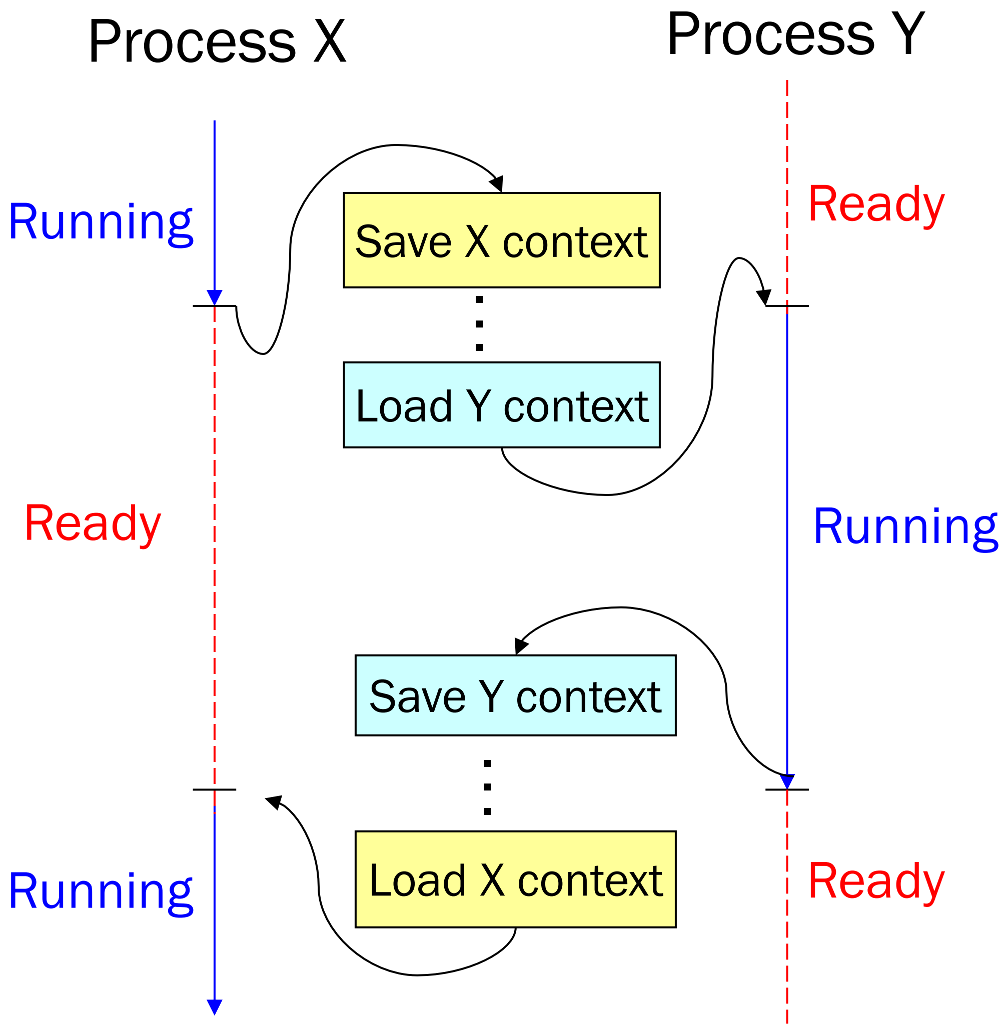
Throughout its lifetime, a process's status switches between running, ready, and blocked

Process Contexts

Each process has a **context**

- The process's state, that is...
- Contents of registers
- Memory contents
  - TEXT, RODATA, DATA, BSS, HEAP, and STACK
  - More specifically, **page tables** mapping this process's VM
  - Even more specifically, ***pointer*** to page tables used for this process

Context Switch



Context switch:

- OS saves context of running process
- OS loads context of some ready process
- OS passes control to newly restored process

- Manageable cost: just registers, plus an indication of which page tables to use

Agenda

	Processes	Illusion: Private address space Illusion: Private control flow
	Process management in C	Creating new processes Waiting for termination Executing new programs
	Unix Process Control	Exceptions Signals

System-Level Process Management Functions

Function	Description
exit()	Terminate the process
fork()	Create a child process
wait()	Wait for child process termination
execvp()	Execute a program in current process

Why Create New Processes?

Why create a new process?

- Scenario 1: Program wants to run an additional instance of itself
  - E.g., **web server** receives request; creates additional instance of itself to handle the request; original instance continues listening for requests
- Scenario 2: Program wants to run a different program
  - E.g., **shell** receives a command; creates an additional instance of itself; additional instance overwrites itself with requested program to handle command; original instance continues listening for commands

How to create a new process?

- A "parent" process **forks** a "child" process
- (Optionally) child process overwrites itself with a new program, after performing appropriate setup

`fork` System-Level Function

```
pid_t fork(void);
```

- Create a new process by duplicating the calling process
- New (child) process is an exact duplicate* of the calling (parent) process

* Almost – the call to `fork` has a different return value (wait 1 slide)

`fork()` is called once in parent process

`fork()` returns twice

- Once in parent process
- Once in child process

`fork` and Return Values

Return value of fork has meaning

- In child, `fork()` returns 0
- In parent, `fork()` returns process id of child


```
pid = fork();

if (pid == 0) {
   /* executed in child */
   ...
} else {
   /* executed in parent */
   ...
}
```

Programs With Processes

Parent process and child process run **concurrently**

- Two CPUs available ⇒
  - Parent process and child process run in **parallel**
- Fewer than two CPUs available ⇒
  - Parent process and child process time-sliced to run **serially**
  - OS provides the **illusion** of parallel execution

Reality: Each ArmLab computer has 96 CPUs

- But each student who is logged in might be concurrently running sshd, bash, emacs, make, gcc217, etc.

Simplifying assumption: there is only one CPU

- We'll speak of "which process gets **the** CPU"
- But which process gets the CPU first? Unknown!

Simple `fork` Example

```
#include <stdio.h>
#include <unistd.h>
int main(void)
{  printf("one\n");
   fork();
   printf("two\n");
   return 0;
}
```

What is the output?

Simple `fork` Example Trace 1 (1)

Parent prints "one"

```c
#include <stdio.h>
#include <unistd.h>
int main(void)
{  printf("one\n");
   fork();
   printf("two\n");
   return 0;
}
```

Simple `fork` Example Trace 1 (2)

Parent forks child

```
#include <stdio.h>
#include <unistd.h>
int main(void)
{  printf("one\n");
   fork();
   printf("two\n");
   return 0;
}
```

Executing concurrently

```
#include <stdio.h>
#include <unistd.h>
int main(void)
{  printf("one\n");
   fork();
   printf("two\n");
   return 0;
}
```

Simple `fork` Example Trace 1 (3)

OS gives CPU to child; child prints "two"

```c
#include <stdio.h>
#include <unistd.h>
int main(void)
{   printf("one\n");
    fork();
    printf("two\n");
    return 0;
}
```

Executing concurrently

```c
#include <stdio.h>
#include <unistd.h>
int main(void)
{   printf("one\n");
    fork();
    printf("two\n");
    return 0;
}
```

Simple `fork` Example Trace 1 (4)

Child exits

```
#include <stdio.h>
#include <unistd.h>
int main(void)
{  printf("one\n");
   fork();
   printf("two\n");
   return 0;
}
```

Executing concurrently

```
#include <stdio.h>
#include <unistd.h>
int main(void)
{  printf("one\n");
   fork();
   printf("two\n");
   return 0;
}
```

Simple `fork` Example Trace 1 (5)

OS gives CPU to parent; parent prints “two”

```
#include <stdio.h>
#include <unistd.h>
int main(void)
{  printf("one\n");
   fork();
   printf("two\n");
   return 0;
}
```

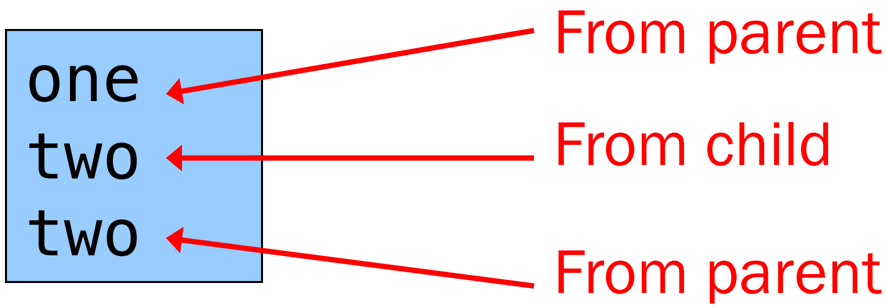
Simple `fork` Example Trace 1 (6)

OS gives CPU to parent; parent prints "two"

```
#include <stdio.h>
#include <unistd.h>
int main(void)
{   printf("one\n");
    fork();
    printf("two\n");
    return 0;
}
```

Simple `fork` Example Trace 1 Output

Output:



Simple `fork` Example Trace 2 (1)

Parent prints "one"

```
#include <stdio.h>
#include <unistd.h>
int main(void)
{  printf("one\n");
   fork();
   printf("two\n");
   return 0;
}
```

Simple `fork` Example Trace 2 (2)

Parent forks child

```
#include <stdio.h>
#include <unistd.h>
int main(void)
{  printf("one\n");
   fork();
   printf("two\n");
   return 0;
}
```

Executing concurrently

```
#include <stdio.h>
#include <unistd.h>
int main(void)
{  printf("one\n");
   fork();
   printf("two\n");
   return 0;
}
```

Simple `fork` Example Trace 2 (3)

OS gives CPU to parent; parent prints "two"

```c
#include <stdio.h>
#include <unistd.h>
int main(void)
{  printf("one\n");
   fork();
   printf("two\n");
   return 0;
}
```

Executing concurrently

```c
#include <stdio.h>
#include <unistd.h>
int main(void)
{  printf("one\n");
   fork();
   printf("two\n");
   return 0;
}
```

Simple `fork` Example Trace 2 (4)

Parent exits

```
#include <stdio.h>
#include <unistd.h>
int main(void)
{  printf("one\n");
   fork();
   printf("two\n");
   return 0;
}
```

Executing concurrently

```
#include <stdio.h>
#include <unistd.h>
int main(void)
{  printf("one\n");
   fork();
   printf("two\n");
   return 0;
}
```

Simple `fork` Example Trace 2 (5)

OS gives CPU to child; child prints "two"

```
#include <stdio.h>
#include <unistd.h>
int main(void)
{  printf("one\n");
   fork();
   printf("two\n");
   return 0;
}
```

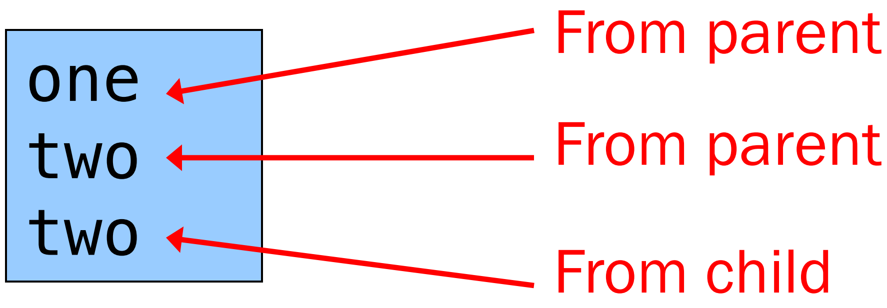
Simple `fork` Example Trace 2 (6)

Child exits

```
#include <stdio.h>
#include <unistd.h>
int main(void)
{  printf("one\n");
   fork();
   printf("two\n");
   return 0;
}
```

Simple `fork` Example Trace 2 Output

Output:



iClicker Question

Q: What is the output of this program?

A. child: 0
   parent: 2

B. parent: 2
   child: 0

C. child: 0
   parent: 1

D. parent: 2
   child: 1

E. A or B

```
#include <stdio.h>
#include <stdlib.h>
#include <unistd.h>
#include <sys/types.h>
int main(void)
{  pid_t pid;
   int x = 1;

   pid = fork();
   if (pid == 0)
   {  x--;
      printf("child: %d\n", x);
      exit(0);
   }
   else
   {  x++;
      printf("parent: %d\n", x);
      exit(0);
   }
}
```

The answer is E.

See following slides.

fork Example Trace 1 (1)

```
#include <stdio.h>
#include <stdlib.h>
#include <unistd.h>
#include <sys/types.h>
int main(void)
{  pid_t pid;
   int x = 1;

   pid = fork();
   if (pid == 0)
   {  x--;
      printf("child: %d\n", x);
      exit(0);
   }
   else
   {  x++;
      printf("parent: %d\n", x);
      exit(0);
   }
}
```

x = 1

fork Example Trace 1 (2)

Parent forks child

```
#include <stdio.h>
#include <stdlib.h>
#include <unistd.h>
#include <sys/types.h>
int main(void)
{  pid_t pid;
   int x = 1;

   pid = fork();
   if (pid == 0)
   {  x--;
      printf("child: %d\n", x);
      exit(0);
   }
   else
   {  x++;
      printf("parent: %d\n", x);
      exit(0);
   }
}
```

x = 1

Executing concurrently

```
#include <stdio.h>
#include <stdlib.h>
#include <unistd.h>
#include <sys/types.h>
int main(void)
{  pid_t pid;
   int x = 1;

   pid = fork();
   if (pid == 0)
   {  x--;
      printf("child: %d\n", x);
      exit(0);
   }
   else
   {  x++;
      printf("parent: %d\n", x);
      exit(0);
   }
}
```

x = 1

fork Example Trace 1 (3)

Assume OS gives CPU to child

```
#include <stdio.h>
#include <stdlib.h>
#include <unistd.h>
#include <sys/types.h>
int main(void)
{  pid_t pid;
   int x = 1;

   pid = fork();
   if (pid == 0)
   {  x--;
      printf(”child: %d\n", x);
      exit(0);
   }
   else
   {  x++;
      printf(”parent: %d\n", x);
      exit(0);
   }
}
```

x = 1

0

Executing concurrently

```
#include <stdio.h>
#include <stdlib.h>
#include <unistd.h>
#include <sys/types.h>
int main(void)
{  pid_t pid;
   int x = 1;

   pid = fork();
   if (pid == 0)
   {  x--;
      printf(”child: %d\n", x);
      exit(0);
   }
   else
   {  x++;
      printf(”parent: %d\n", x);
      exit(0);
   }
}
```

x = 1

fork Example Trace 1 (4)

Child decrements its x, and prints "child: 0"

```
#include <stdio.h>
#include <stdlib.h>
#include <unistd.h>
#include <sys/types.h>
int main(void)
{  pid_t pid;
   int x = 1;

   pid = fork();
   if (pid == 0)
   {  x--;
      printf("child: %d\n", x);
      exit(0);
   }
   else
   {  x++;
      printf("parent: %d\n", x);
      exit(0);
   }
}
```

x = 1

Executing concurrently

```
#include <stdio.h>
#include <stdlib.h>
#include <unistd.h>
#include <sys/types.h>
int main(void)
{  pid_t pid;
   int x = 1;

   pid = fork();
   if (pid == 0)
   {  x--;
      printf("child: %d\n", x);
      exit(0);
   }
   else
   {  x++;
      printf("parent: %d\n", x);
      exit(0);
   }
}
```

x = 0

`fork` Example Trace 1 (5)

Child exits; OS gives CPU to parent

```c
#include <stdio.h>
#include <stdlib.h>
#include <unistd.h>
#include <sys/types.h>
int main(void)
{  pid_t pid;
   int x = 1;

   pid = fork();
   if (pid == 0)
   {  x--;
      printf("child: %d\n", x);
      exit(0);
   }
   else
   {  x++;
      printf("parent: %d\n", x);
      exit(0);
   }
}
```

x = 1

Executing concurrently

```c
#include <stdio.h>
#include <stdlib.h>
#include <unistd.h>
#include <sys/types.h>
int main(void)
{  pid_t pid;
   int x = 1;

   pid = fork();
   if (pid == 0)
   {  x--;
      printf("child: %d\n", x);
      exit(0);
   }
   else
   {  x++;
      printf("parent: %d\n", x);
      exit(0);
   }
}
```

x = 0

fork Example Trace 1 (6)

In parent, fork() returns process id of child

```
#include <stdio.h>
#include <stdlib.h>
#include <unistd.h>
#include <sys/types.h>
int main(void)
{  pid_t pid;
   int x = 1;

   pid = fork();
   if (pid == 0)
   {  x--;
      printf("child: %d\n", x);
      exit(0);
   }
   else
   {  x++;
      printf("parent: %d\n", x);
      exit(0);
   }
}
```

x = 1

Process id of child

`fork` Example Trace 1 (7)

Parent increments its x, and prints "parent: 2"

```
#include <stdio.h>
#include <stdlib.h>
#include <unistd.h>
#include <sys/types.h>
int main(void)
{  pid_t pid;
   int x = 1;

   pid = fork();
   if (pid == 0)
   {  x--;
      printf("child: %d\n", x);
      exit(0);
   }
   else
   {  x++;
      printf("parent: %d\n", x);
      exit(0);
   }
}
```

x = 2

fork Example Trace 1 (8)

Parent exits

```
#include <stdio.h>
#include <stdlib.h>
#include <unistd.h>
#include <sys/types.h>
int main(void)
{  pid_t pid;
   int x = 1;

   pid = fork();
   if (pid == 0)
   {  x--;
      printf("child: %d\n", x);
      exit(0);
   }
   else
   {  x++;
      printf("parent: %d\n", x);
      exit(0);
   }
}
```

x = 2

`fork` Example Trace 1 Output

Example trace 1 output:

```
Child: 0
Parent: 2
```

fork Example Trace 2 (1)

```
#include <stdio.h>
#include <stdlib.h>
#include <unistd.h>
#include <sys/types.h>
int main(void)
{  pid_t pid;
   int x = 1;

   pid = fork();
   if (pid == 0)
   {  x--;
      printf("child: %d\n", x);
      exit(0);
   }
   else
   {  x++;
      printf("parent: %d\n", x);
      exit(0);
   }
}
```

x = 1

fork Example Trace 2 (2)

Parent forks child

```
#include <stdio.h>
#include <stdlib.h>
#include <unistd.h>
#include <sys/types.h>
int main(void)
{  pid_t pid;
   int x = 1;

   pid = fork();
   if (pid == 0)
   {  x--;
      printf("child: %d\n", x);
      exit(0);
   }
   else
   {  x++;
      printf("parent: %d\n", x);
      exit(0);
   }
}
```

x = 1

Executing concurrently

```
#include <stdio.h>
#include <stdlib.h>
#include <unistd.h>
#include <sys/types.h>
int main(void)
{  pid_t pid;
   int x = 1;

   pid = fork();
   if (pid == 0)
   {  x--;
      printf("child: %d\n", x);
      exit(0);
   }
   else
   {  x++;
      printf("parent: %d\n", x);
      exit(0);
   }
}
```

x = 1

`fork` Example Trace 2 (3)

Assume OS gives CPU to parent

```
#include <stdio.h>
#include <stdlib.h>
#include <unistd.h>
#include <sys/types.h>
int main(void)
{  pid_t pid;
   int x = 1;

   pid = fork();
   if (pid == 0)
   {  x--;
      printf("child: %d\n", x);
      exit(0);
   }
   else
   {  x++;
      printf("parent: %d\n", x);
      exit(0);
   }
}
```

x = 1

Process ID of child

Executing concurrently

```
#include <stdio.h>
#include <stdlib.h>
#include <unistd.h>
#include <sys/types.h>
int main(void)
{  pid_t pid;
   int x = 1;

   pid = fork();
   if (pid == 0)
   {  x--;
      printf("child: %d\n", x);
      exit(0);
   }
   else
   {  x++;
      printf("parent: %d\n", x);
      exit(0);
   }
}
```

x = 1

fork Example Trace 2 (4)

Parent increments its x and prints "parent: 2"

```
#include <stdio.h>
#include <stdlib.h>
#include <unistd.h>
#include <sys/types.h>
int main(void)
{  pid_t pid;
   int x = 1;

   pid = fork();
   if (pid == 0)
   {  x--;
      printf("child: %d\n", x);
      exit(0);
   }
   else
   {  x++;
      printf("parent: %d\n", x);
      exit(0);
   }
}
```

x = 2

Executing concurrently

```
#include <stdio.h>
#include <stdlib.h>
#include <unistd.h>
#include <sys/types.h>
int main(void)
{  pid_t pid;
   int x = 1;

   pid = fork();
   if (pid == 0)
   {  x--;
      printf("child: %d\n", x);
      exit(0);
   }
   else
   {  x++;
      printf("parent: %d\n", x);
      exit(0);
   }
}
```

x = 1

`fork` Example Trace 2 (5)

Parent exits; OS gives CPU to child

```
#include <stdio.h>
#include <stdlib.h>
#include <unistd.h>
#include <sys/types.h>
int main(void)
{  pid_t pid;
   int x = 1;

   pid = fork();
   if (pid == 0)
   {  x--;
      printf("child: %d\n", x);
      exit(0);
   }
   else
   {  x++;
      printf("parent: %d\n", x);
      exit(0);
   }
}
```

x = 2

Executing concurrently

```
#include <stdio.h>
#include <stdlib.h>
#include <unistd.h>
#include <sys/types.h>
int main(void)
{  pid_t pid;
   int x = 1;

   pid = fork();
   if (pid == 0)
   {  x--;
      printf("child: %d\n", x);
      exit(0);
   }
   else
   {  x++;
      printf("parent: %d\n", x);
      exit(0);
   }
}
```

x = 1

`fork` Example Trace 2 (6)

In child, fork() returns 0

0

```
#include <stdio.h>
#include <stdlib.h>
#include <unistd.h>
#include <sys/types.h>
int main(void)
{  pid_t pid;
   int x = 1;

   pid = fork();
   if (pid == 0)
   {  x--;
      printf("child: %d\n", x);
      exit(0);
   }
   else
   {  x++;
      printf("parent: %d\n", x);
      exit(0);
   }
}
```

x = 1

fork Example Trace 2 (7)

Child decrements its x and prints "child: 0"

```
#include <stdio.h>
#include <stdlib.h>
#include <unistd.h>
#include <sys/types.h>
int main(void)
{  pid_t pid;
   int x = 1;

   pid = fork();
   if (pid == 0)
   {  x--;
      printf("child: %d\n", x);
      exit(0);
   }
   else
   {  x++;
      printf("parent: %d\n", x);
      exit(0);
   }
}
```

x = 0

`fork` Example Trace 2 (8)

Child exits

```
#include <stdio.h>
#include <stdlib.h>
#include <unistd.h>
#include <sys/types.h>
int main(void)
{  pid_t pid;
   int x = 1;

   pid = fork();
   if (pid == 0)
   {  x--;
      printf("child: %d\n", x);
      exit(0);
   }
   else
   {  x++;
      printf("parent: %d\n", x);
      exit(0);
   }
}
```

x = 0

`fork` Example Trace 2 Output

Example trace 2 output:

```
Parent: 2
Child: 0
```

```
armlab01:~$ for i in `seq 1 10000`; do ./fpe | head -n 1; done | sort | uniq -c
     56 child: 0
   9944 parent: 2
```

`wait` System-Level Function

Problem:

- How to control execution order?

Solution:

- Parent calls `wait()`

```
pid_t wait(int *status);
```

- Suspends execution of the calling process until one of its children terminates
- If status is not NULL, stores status information in the int to which it points; this integer can be inspected with macros [see man page for details].
- On success, returns the process ID of the terminated child
- On error, returns -1

Paraphrasing man page

iClicker Question

Q: What is the output of this program?

A. child
   parent

B. parent
   child

C. something other than A or B

D. A or B

E. A or C

```
#include <stdio.h>
#include <stdlib.h>
#include <unistd.h>
#include <sys/types.h>
#include <wait.h>
int main(void)
{  pid_t pid;
   pid = fork();
   if (pid == 0)
   {  printf("child\n");
      exit(0);
   }
   wait(NULL);
   printf("parent\n");
   return 0;
}
```

The answer is A.

See following slides.

`wait` Example Trace 1 (1)

Parent forks child

```
#include <stdio.h>
#include <stdlib.h>
#include <unistd.h>
#include <sys/types.h>
#include <wait.h>
int main(void)
{  pid_t pid;
   pid = fork();
   if (pid == 0)
   {  printf("child\n");
      exit(0);
   }
   wait(NULL);
   printf("parent\n");
   return 0;
}
```

Executing concurrently

```
#include <stdio.h>
#include <stdlib.h>
#include <unistd.h>
#include <sys/types.h>
#include <wait.h>
int main(void)
{  pid_t pid;
   pid = fork();
   if (pid == 0)
   {  printf("child\n");
      exit(0);
   }
   wait(NULL);
   printf("parent\n");
   return 0;
}
```

`wait` Example Trace 1 (2)

OS gives CPU to parent

```c
#include <stdio.h>
#include <stdlib.h>
#include <unistd.h>
#include <sys/types.h>
#include <wait.h>
int main(void)
{  pid_t pid;
   pid = fork();
   if (pid == 0)
   {  printf("child\n");
      exit(0);
   }
   wait(NULL);
   printf("parent\n");
   return 0;
}
```

Executing concurrently

```c
#include <stdio.h>
#include <stdlib.h>
#include <unistd.h>
#include <sys/types.h>
#include <wait.h>
int main(void)
{  pid_t pid;
   pid = fork();
   if (pid == 0)
   {  printf("child\n");
      exit(0);
   }
   wait(NULL);
   printf("parent\n");
   return 0;
}
```

wait Example Trace 1 (3)

Parent calls wait()

```c
#include <stdio.h>
#include <stdlib.h>
#include <unistd.h>
#include <sys/types.h>
#include <wait.h>
int main(void)
{  pid_t pid;
   pid = fork();
   if (pid == 0)
   {  printf("child\n");
      exit(0);
   }
   wait(NULL);
   printf("parent\n");
   return 0;
}
```

Executing concurrently

```c
#include <stdio.h>
#include <stdlib.h>
#include <unistd.h>
#include <sys/types.h>
#include <wait.h>
int main(void)
{  pid_t pid;
   pid = fork();
   if (pid == 0)
   {  printf("child\n");
      exit(0);
   }
   wait(NULL);
   printf("parent\n");
   return 0;
}
```

wait Example Trace 1 (4)

OS gives CPU to child

```
#include <stdio.h>
#include <stdlib.h>
#include <unistd.h>
#include <sys/types.h>
#include <wait.h>
int main(void)
{  pid_t pid;
   pid = fork();
   if (pid == 0)
   {  printf("child\n");
      exit(0);
   }
   wait(NULL);
   printf("parent\n");
   return 0;
}
```

Executing concurrently

```
#include <stdio.h>
#include <stdlib.h>
#include <unistd.h>
#include <sys/types.h>
#include <wait.h>
int main(void)
{  pid_t pid;
   pid = fork();
   if (pid == 0)
   {  printf("child\n");
      exit(0);
   }
   wait(NULL);
   printf("parent\n");
   return 0;
}
```

wait Example Trace 1 (5)

Child prints "child" and exits

```
#include <stdio.h>
#include <stdlib.h>
#include <unistd.h>
#include <sys/types.h>
#include <wait.h>
int main(void)
{   pid_t pid;
    pid = fork();
    if (pid == 0)
    {   printf("child\n");
        exit(0);
    }
    wait(NULL);
    printf("parent\n");
    return 0;
}
```

Executing concurrently

```
#include <stdio.h>
#include <stdlib.h>
#include <unistd.h>
#include <sys/types.h>
#include <wait.h>
int main(void)
{   pid_t pid;
    pid = fork();
    if (pid == 0)
    {   printf("child\n");
        exit(0);
    }
    wait(NULL);
    printf("parent\n");
    return 0;
}
```

`wait` Example Trace 1 (6)

Parent returns from call of wait(), prints "parent", exits

```
#include <stdio.h>
#include <stdlib.h>
#include <unistd.h>
#include <sys/types.h>
#include <wait.h>
int main(void)
{  pid_t pid;
   pid = fork();
   if (pid == 0)
   {  printf("child\n");
      exit(0);
   }
   wait(NULL);
   printf("parent\n");
   return 0;
}
```

`wait` Example Trace 1 Output

Example trace 1 output

```
child
parent
```

wait Example Trace 2 (1)

Parent forks child

```
#include <stdio.h>
#include <stdlib.h>
#include <unistd.h>
#include <sys/types.h>
#include <wait.h>
int main(void)
{  pid_t pid;
   pid = fork();
   if (pid == 0)
   {  printf("child\n");
      exit(0);
   }
   wait(NULL);
   printf("parent\n");
   return 0;
}
```

Executing concurrently

```
#include <stdio.h>
#include <stdlib.h>
#include <unistd.h>
#include <sys/types.h>
#include <wait.h>
int main(void)
{  pid_t pid;
   pid = fork();
   if (pid == 0)
   {  printf("child\n");
      exit(0);
   }
   wait(NULL);
   printf("parent\n");
   return 0;
}
```

`wait` Example Trace 2 (2)

OS gives CPU to child

```
#include <stdio.h>
#include <stdlib.h>
#include <unistd.h>
#include <sys/types.h>
#include <wait.h>
int main(void)
{   pid_t pid;
    pid = fork();
    if (pid == 0)
    {   printf("child\n");
        exit(0);
    }
    wait(NULL);
    printf("parent\n");
    return 0;
}
```

Executing concurrently

```
#include <stdio.h>
#include <stdlib.h>
#include <unistd.h>
#include <sys/types.h>
#include <wait.h>
int main(void)
{   pid_t pid;
    pid = fork();
    if (pid == 0)
    {   printf("child\n");
        exit(0);
    }
    wait(NULL);
    printf("parent\n");
    return 0;
}
```

`wait` Example Trace 2 (3)

Child prints "child" and exits

```
#include <stdio.h>
#include <stdlib.h>
#include <unistd.h>
#include <sys/types.h>
#include <wait.h>
int main(void)
{  pid_t pid;
   pid = fork();
   if (pid == 0)
   {  printf("child\n");
      exit(0);
   }
   wait(NULL);
   printf("parent\n");
   return 0;
}
```

Executing concurrently

```
#include <stdio.h>
#include <stdlib.h>
#include <unistd.h>
#include <sys/types.h>
#include <wait.h>
int main(void)
{  pid_t pid;
   pid = fork();
   if (pid == 0)
   {  printf("child\n");
      exit(0);
   }
   wait(NULL);
   printf("parent\n");
   return 0;
}
```

wait Example Trace 2 (4)

OS gives CPU to parent

```
#include <stdio.h>
#include <stdlib.h>
#include <unistd.h>
#include <sys/types.h>
#include <wait.h>
int main(void)
{  pid_t pid;
   pid = fork();
   if (pid == 0)
   {  printf("child\n");
      exit(0);
   }
   wait(NULL);
   printf("parent\n");
   return 0;
}
```

wait Example Trace 2 (5)

Parent calls wait(); returns immediately

```
#include <stdio.h>
#include <stdlib.h>
#include <unistd.h>
#include <sys/types.h>
#include <wait.h>
int main(void)
{  pid_t pid;
   pid = fork();
   if (pid == 0)
   {  printf("child\n");
      exit(0);
   }
   wait(NULL);
   printf("parent\n");
   return 0;
}
```

`wait` Example Trace 2 (6)

Parent prints "parent" and exits

```
#include <stdio.h>
#include <stdlib.h>
#include <unistd.h>
#include <sys/types.h>
#include <wait.h>
int main(void)
{  pid_t pid;
   pid = fork();
   if (pid == 0)
   {  printf("child\n");
      exit(0);
   }
   wait(NULL);
   printf("parent\n");
   return 0;
}
```

`wait` Example Trace 2 Output

Example trace 2 output

```
child
parent
```

Same as trace 1 output!

`execvp` System-Level Function

Problem: How to execute a new program?

- Usually, in the newly-created child process

Solution: `execvp()`

```
int execvp(const char *file, char *const argv[]);
```

- Replaces the current process image with a new process image
- Provides an array of pointers to null-terminated strings that represent the argument list available to the new program
  - The first argument, by convention, should point to the program's filename
  - The array of pointers must be terminated by a NULL pointer

Paraphrasing man page

execvp System-Level Function

Example: Execute "cat readme"

```
char *newCmd;
char *newArgv[3];
newCmd = "cat";
newArgv[0] = "cat";
newArgv[1] = "readme";
newArgv[2] = NULL;
execvp(newCmd, newArgv);
```

- First argument: name of program to be executed
- Second argument: argv to be passed to main() of new program
  - Must begin with program name, end with NULL

execvp Failure

`fork()`

- If successful, returns **two** times
  - Once in parent, once in child

`execvp()`

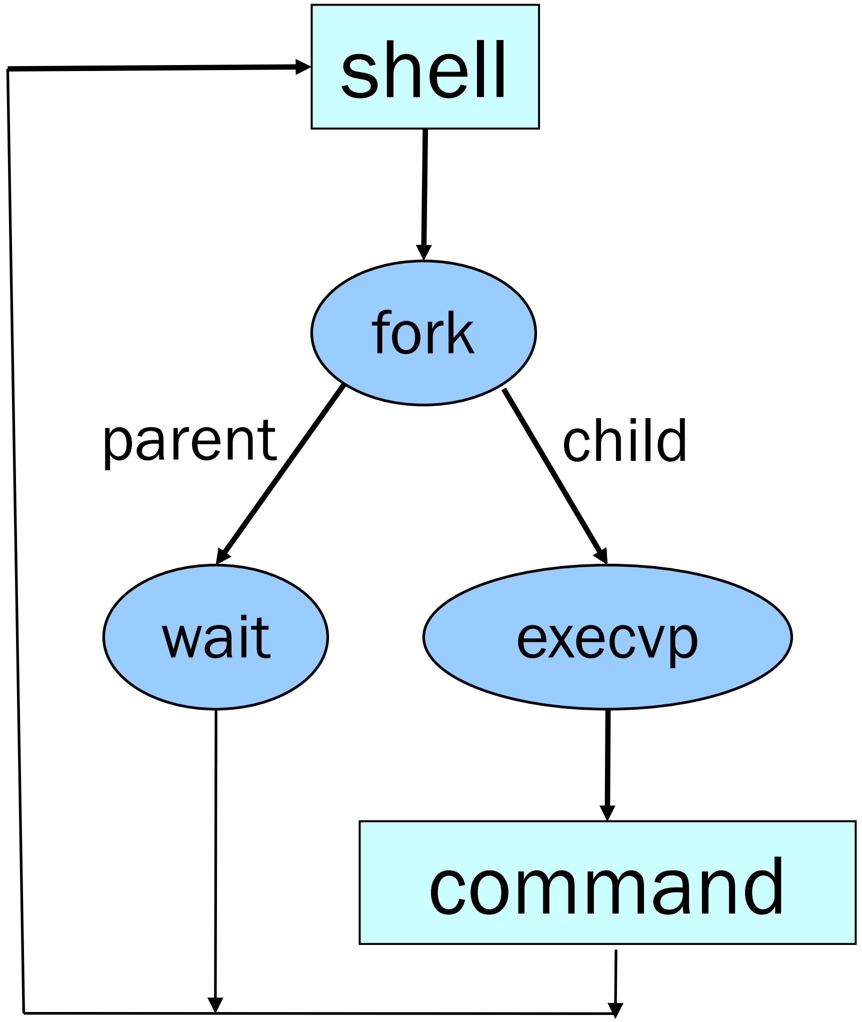
- If successful, returns **zero** times
  - Calling program is overwritten with new program
- Corollary:
  - If `execvp()` returns, then it must have failed

```
char *newCmd;
char *newArgv[3];
newCmd = "cat";
newArgv[0] = "cat";
newArgv[1] = "readme";
newArgv[2] = NULL;
execvp(newCmd, newArgv);
fprintf(stderr, "exec failed\n");
exit(EXIT_FAILURE);
```

Shell Structure

- Parent (shell) reads & parses the command line
- Parent forks child and waits
- Child calls execvp to execute command
- Child exits, parent returns from wait and repeats

```
while (1) {
   Parse command line
   Assign values to somepgm, someargv
   pid = fork();
   if (pid == 0) {
      /* in child */
      execvp(somepgm, someargv);
      fprintf(stderr, "exec failed\n");
      exit(EXIT_FAILURE);
   }
   /* in parent */
   wait(NULL);
}
```



Aside: `system` Function

Common combination of operations

- `fork()` to create a new child process
- `execvp()` to execute new program in child process
- `wait()` in the parent process for the child to complete

Single call that combines all three

- `int system(const char *cmd);`

Example:

```
#include <stdlib.h>
int main(void)
{   system("cat readme");
    return 0;
}
```

Agenda

Processes
- Illusion: Private address space
- Illusion: Private control flow

Process management in C
- Creating new processes
- Waiting for termination
- Executing new programs

Unix Process Control
- Exceptions
- Signals

Exceptions

Exception

- An abrupt change in control flow of a running program corresponding to a change in process state

*Note: Exceptions in OS ≠ exceptions in Java

Implemented using
try/catch and **throw** statements

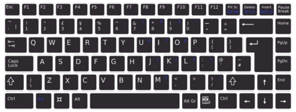
Synchronous Exceptions

Some exceptions are **synchronous**

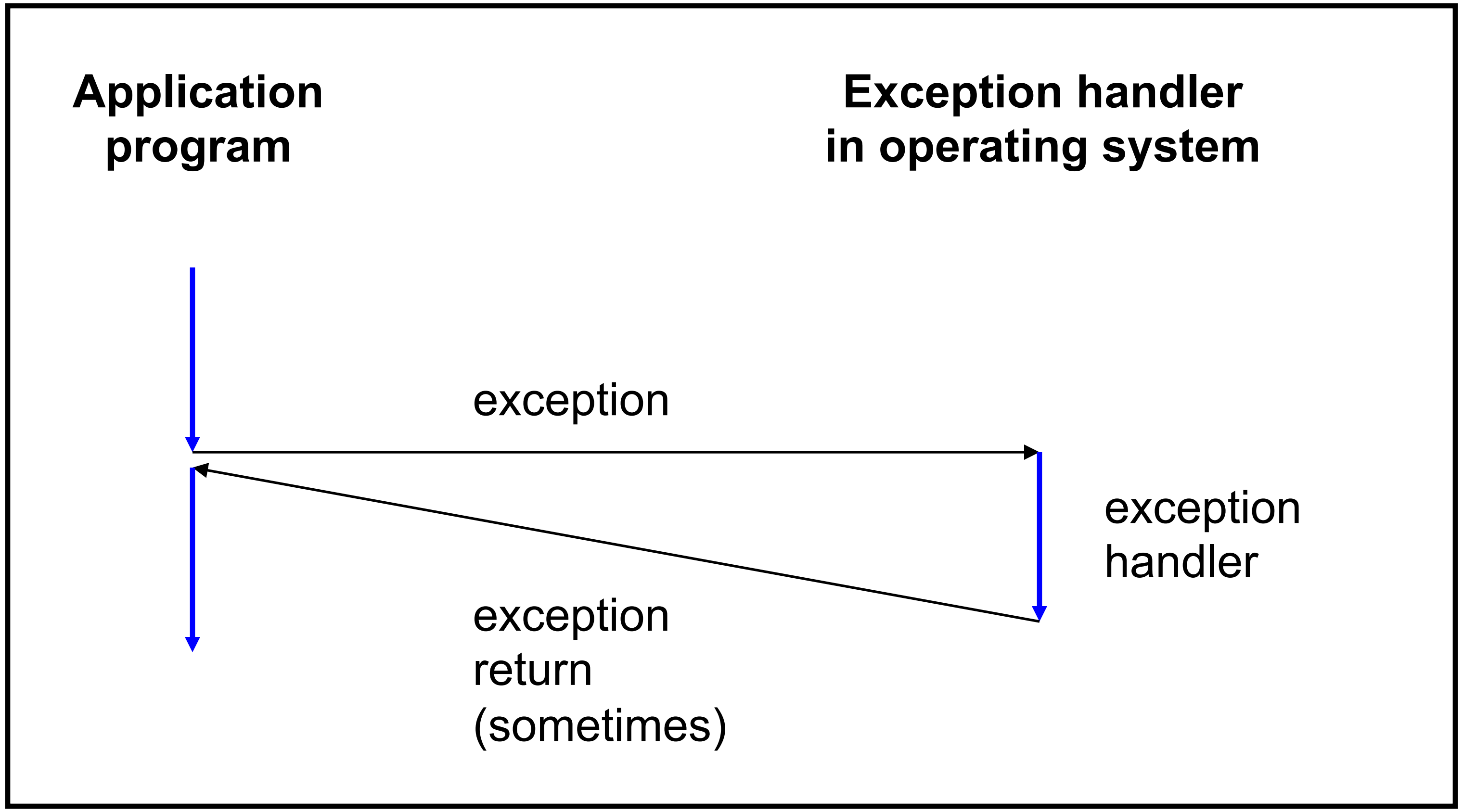
- Occur as result of actions of executing program
- Examples:
  - **System call:** Application requests I/O
  - **System call:** Application requests more heap memory
  - Application pgm attempts integer division by 0
  - Application pgm attempts to access privileged memory
  - Application pgm accesses variable that is not in physical memory

Asynchronous Exceptions

Some exceptions are **asynchronous**

- Do not occur (directly) as result of actions of executing program
- Examples:
  - User presses key on keyboard 
  - Packet received over network 
  - Disk controller finishes reading data 
  - Hardware timer expires 

Exceptional Control Flow



Exceptions vs. Function Calls

Handling an exception is **similar to** calling a function

- Control transfers from original code to other code
- Other code executes
- Control returns to some instruction in original code

Handling an exception is **different from** calling a function

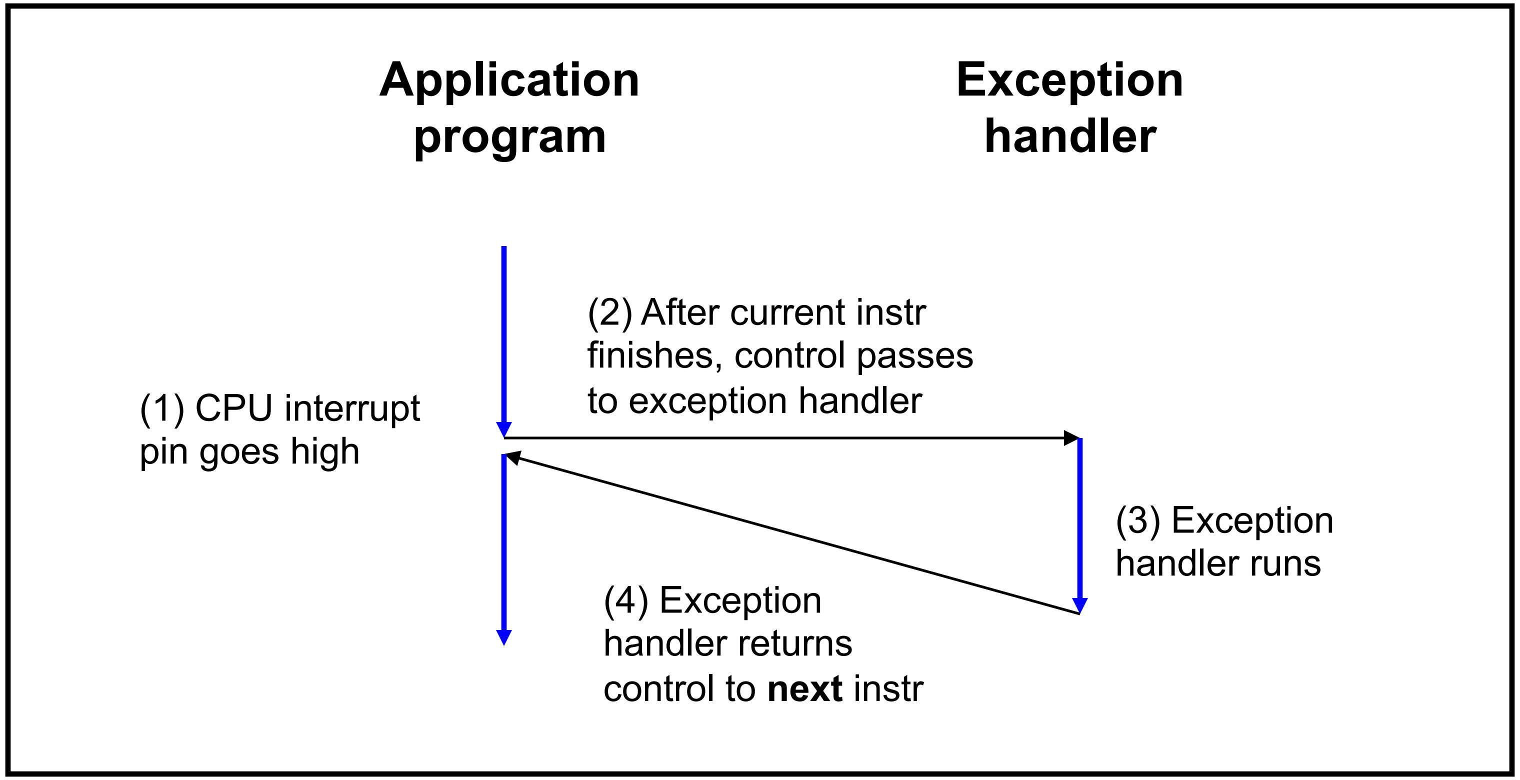
- CPU saves **additional data**
  - E.g. values of all registers
- CPU pushes data onto **OS's stack**, not application pgm's stack
- Handler runs in **kernel/privileged mode**, not in **user mode**
  - Handler can execute all instructions and access all memory
- Control **might return** to some instruction in original code
  - Sometimes control returns to **next** instruction
  - Sometimes control returns to **current** instruction
  - Sometimes control does not return at all!

Classes of Exceptions

There are 4 classes of exceptions...

(1) Interrupts



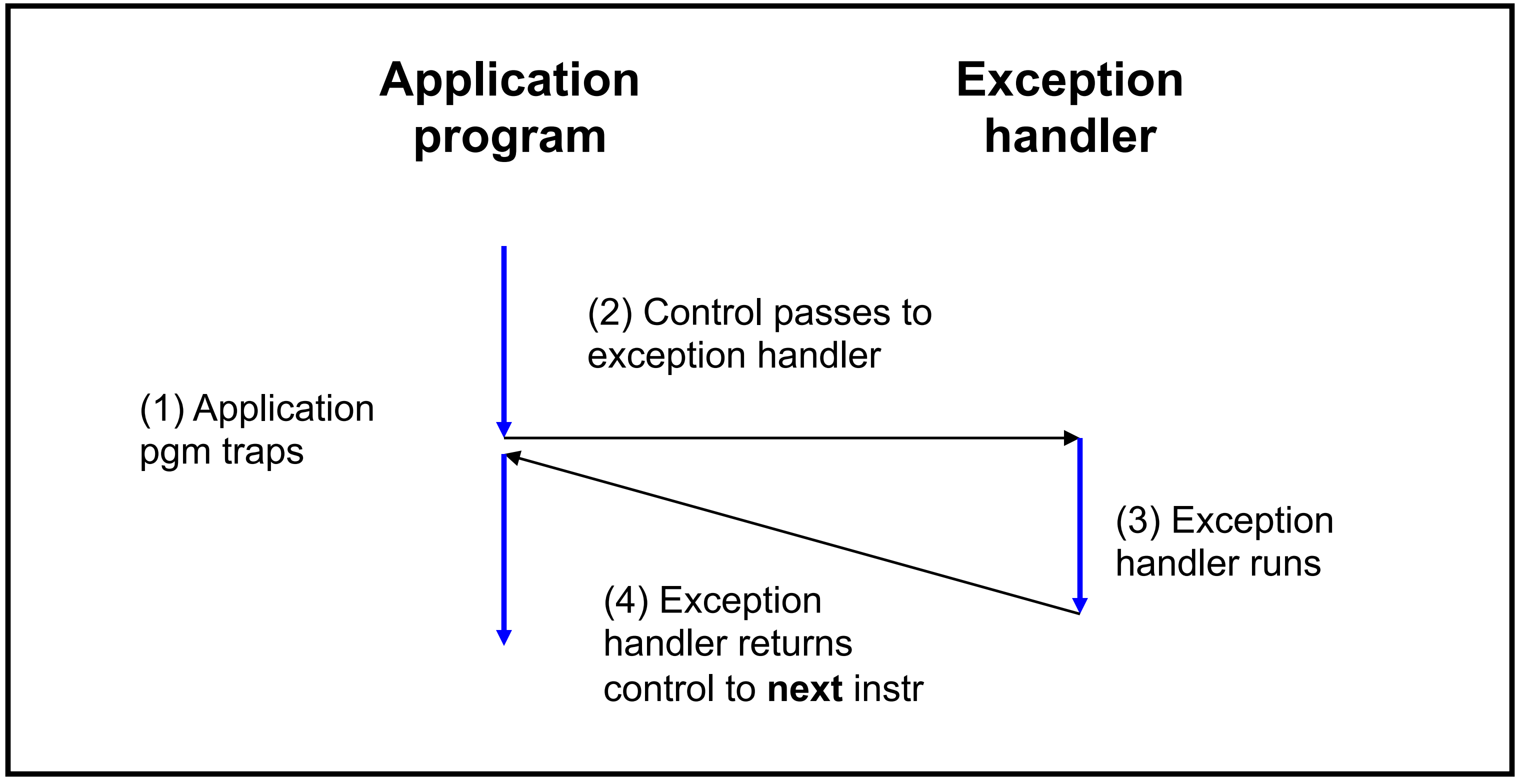



Occurs when: External (off-CPU) device requests attention

Examples:

- User presses key
- Disk controller finishes reading/writing data
- Network packet arrives

(2) Traps



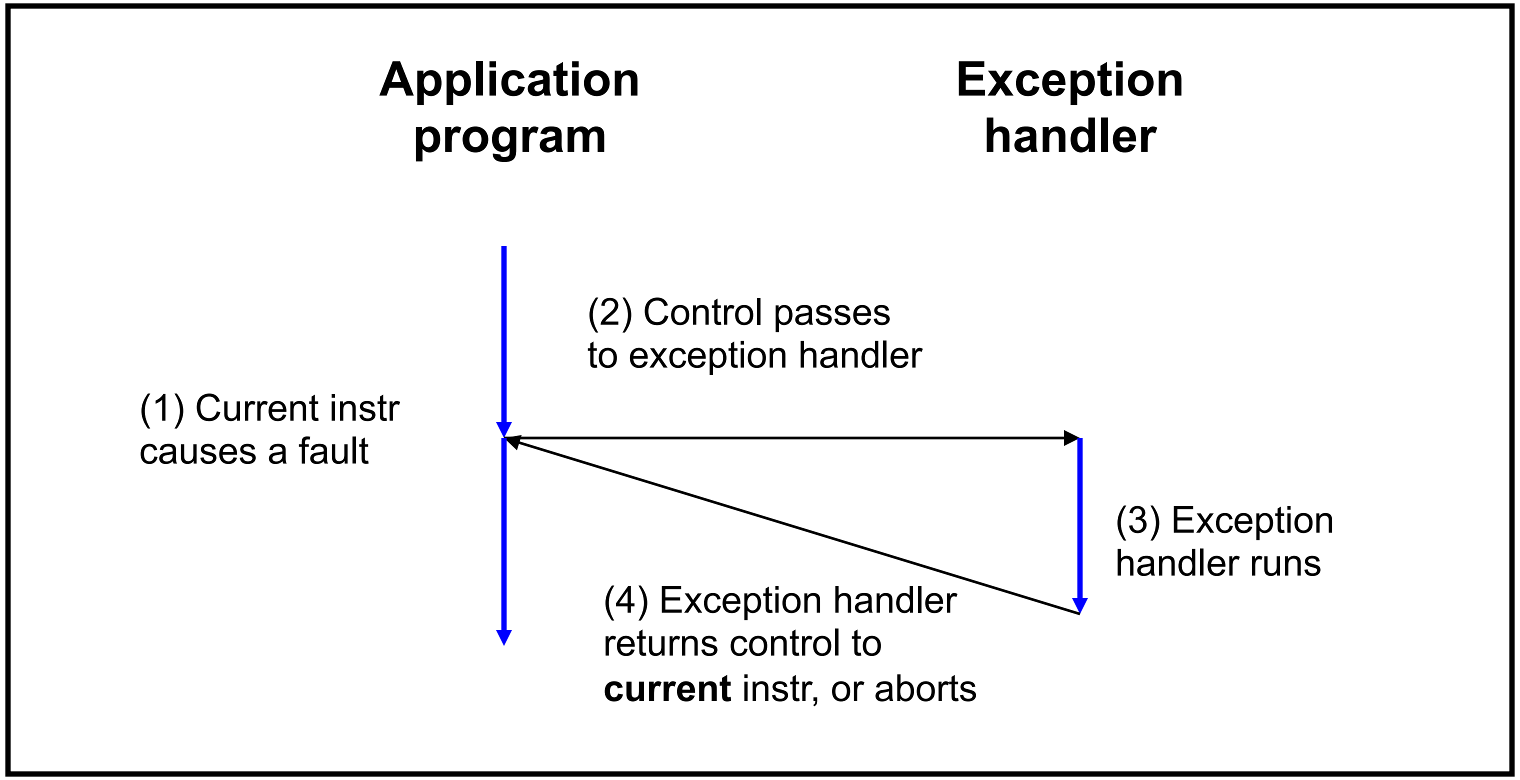
Occurs when: Application pgm requests OS service

Examples:

- Application pgm requests I/O
- Application pgm requests more heap memory

Traps provide a function-call-like interface between application pgm and OS

(3) Faults

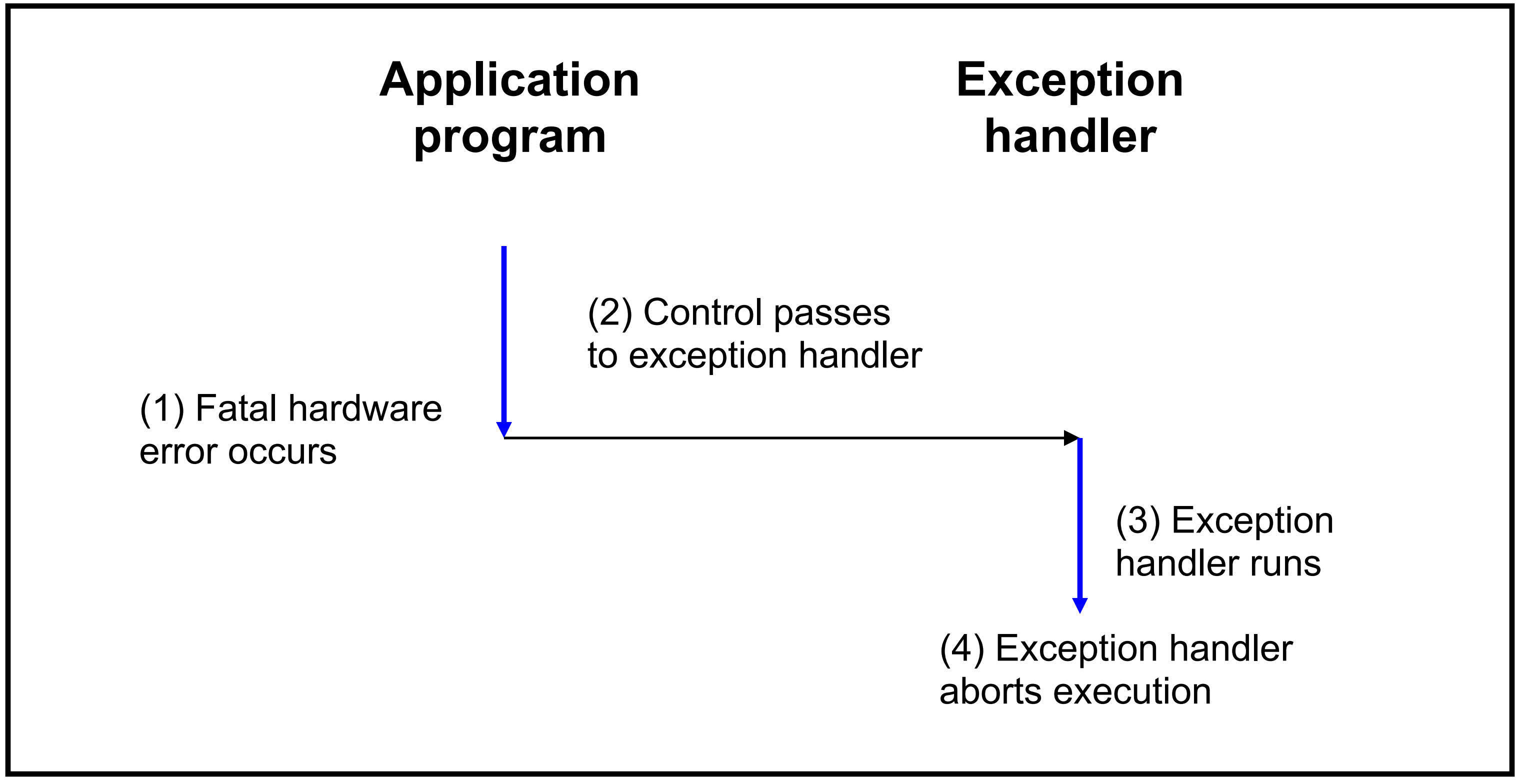


Occurs when: Application pgm causes a (possibly recoverable) error

Examples:

- Application pgm divides by 0
- Application pgm accesses privileged memory (seg fault)
- Application pgm accesses data that is not in physical memory (page fault)

(4) Aborts



Occurs when: HW detects a non-recoverable error

Example:

Parity check indicates corruption of memory bit (overheating, cosmic ray!, etc.)

Summary of Exception Classes

Class	Occurs when	Asynch /Synch	Return Behavior
Interrupt	External device requests attention	Asynch	Return to next instr
Trap	Application pgm requests OS service	Synch	Return to next instr
Fault	Application pgm causes (maybe recoverable) error	Synch	Return to current instr (maybe)
Abort	HW detects non-recoverable error	Synch-ish	Do not return

Process Control Examples

Exactly what happens when you:

Type Ctrl-c?

- Keystroke generates **interrupt**
- OS handles interrupt
- OS sends process a 2/SIGINT **signal**

Type Ctrl-z?

- Keystroke generates **interrupt**
- OS handles interrupt
- OS sends process a 20/SIGTSTP **signal**

Signals Overview

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 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 Overview (cont.)

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

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”

Examples of Non-keyboard Signals

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"

https://xkcd.com/371/

Signals, signals everywhere

List of the predefined signals, learn many details with these commands:

```
$ 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

$ man 7 signal
```

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

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`

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

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. */
}
```

```
armlab01:~/Test$ ./testsignal
Entering an infinite loop
^CIn myHandler with argument 2
^CIn myHandler with argument 2
^CIn myHandler with argument 2
^CIn myHandler with argument 2
^CIn myHandler with argument 2
^CIn myHandler with argument 2
^CIn myHandler with argument 2
^CIn myHandler with argument 2
^CIn myHandler with argument 2
^Z
[1]+  Stopped        ./testsignal
armlab01:~/Test$ fg
./signal
^CIn myHandler with argument 2
^CIn myHandler with argument 2
^CIn myHandler with argument 2
^CIn myHandler with argument 2
^CIn myHandler with argument 2
^\Quit
```

Signal Handling Example 2

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 2 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 2 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);
   return 0;  /* Never get here. */
}
```

Agenda

Processes
- Illusion: Private address space
- Illusion: Private control flow

Process management in C
- Creating new processes
- Waiting for termination
- Executing new programs

Unix Process Control
- Exceptions
- Signals