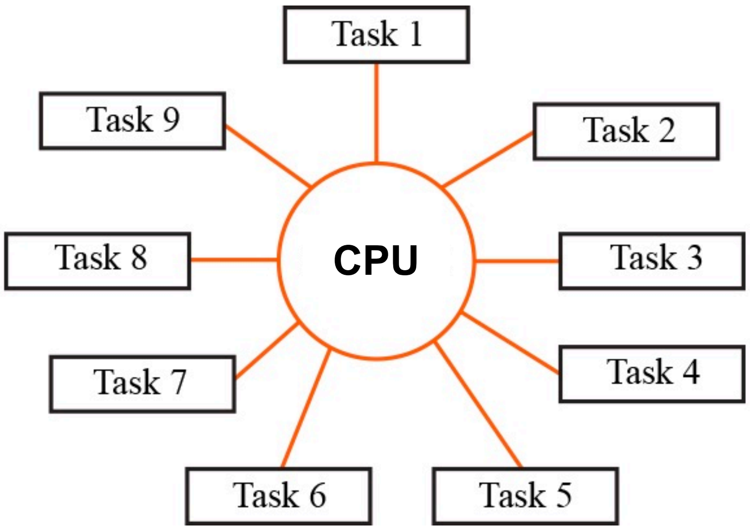
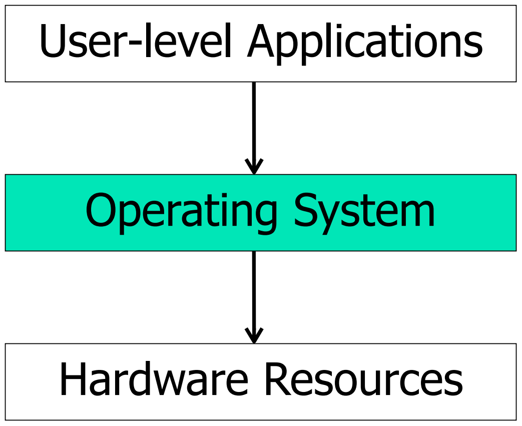
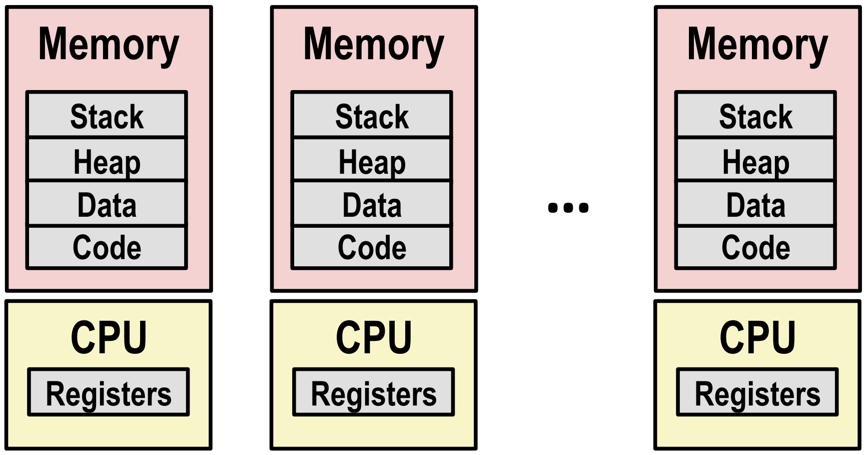
Global Control Flow



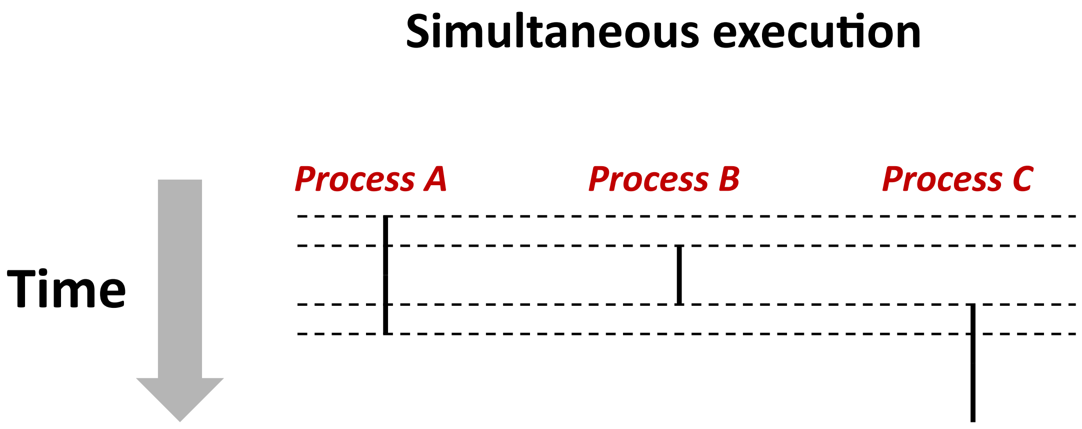
Operating System



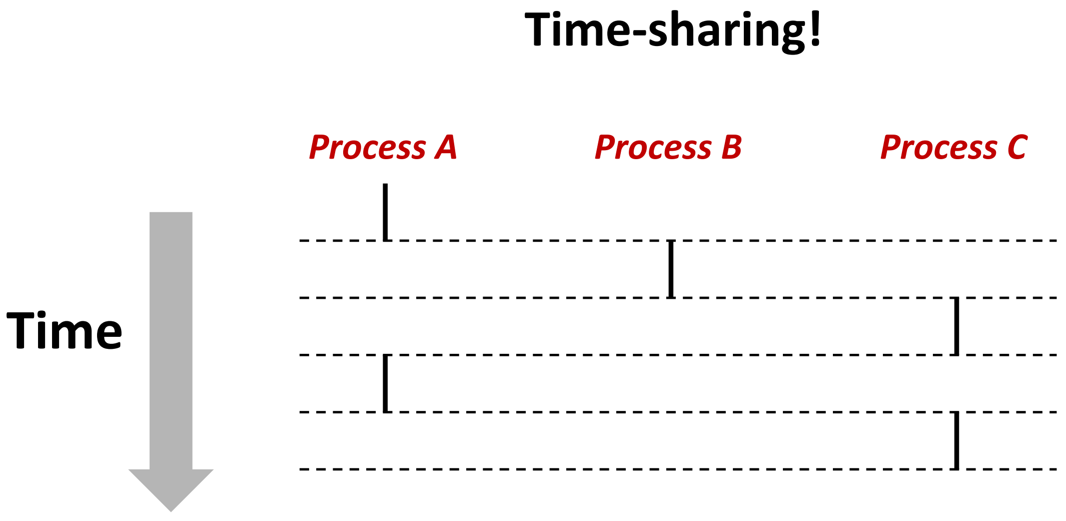
Processes



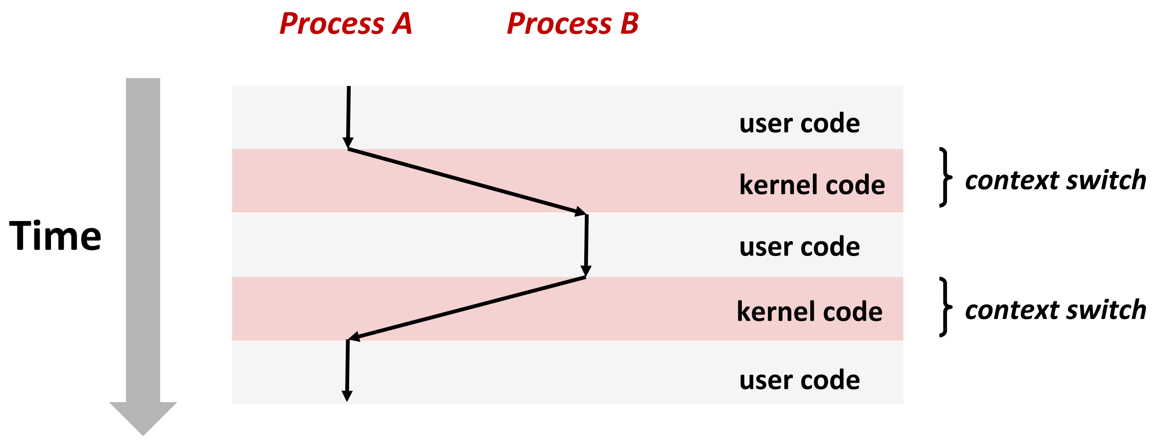
Control Flow Abstraction



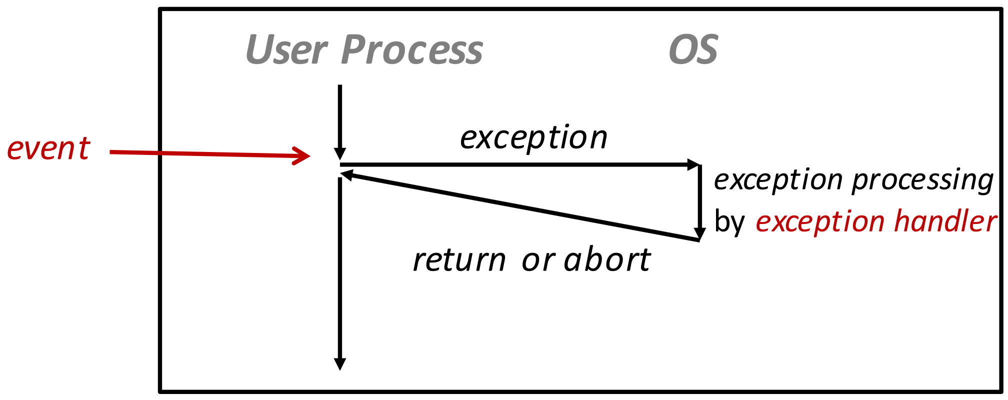
Control Flow Reality



Context Switching



Exceptional Control Flow

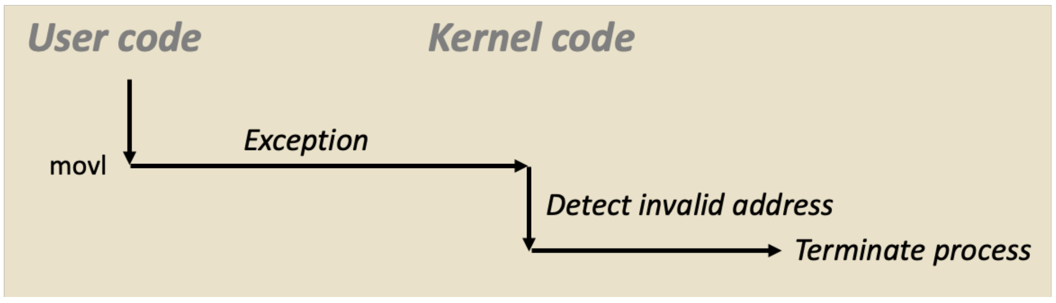


Example: Segmentation Fault

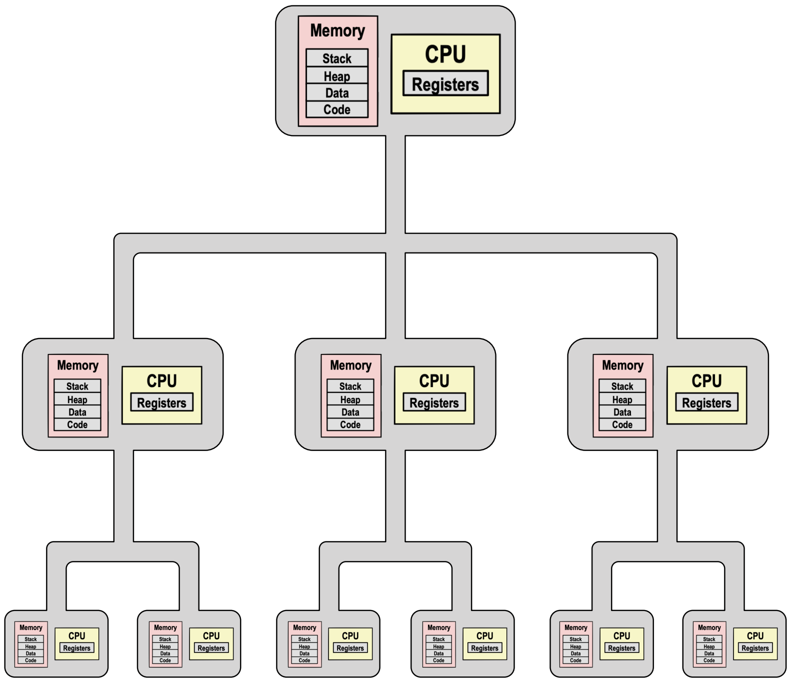
```
int a[1000];

int main() {
    a[5000] = 7;
    ...
}
```

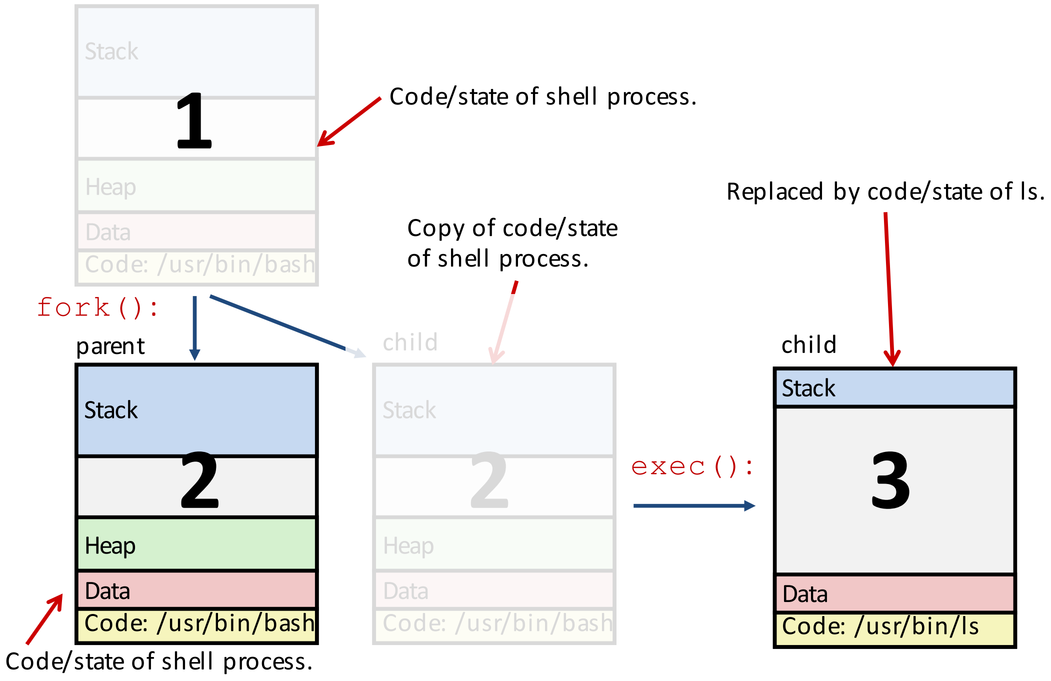
```
 80483b7:    c7 05 60 e3 04 08 07    movl    $0x7,0x804e360
```



Process Management



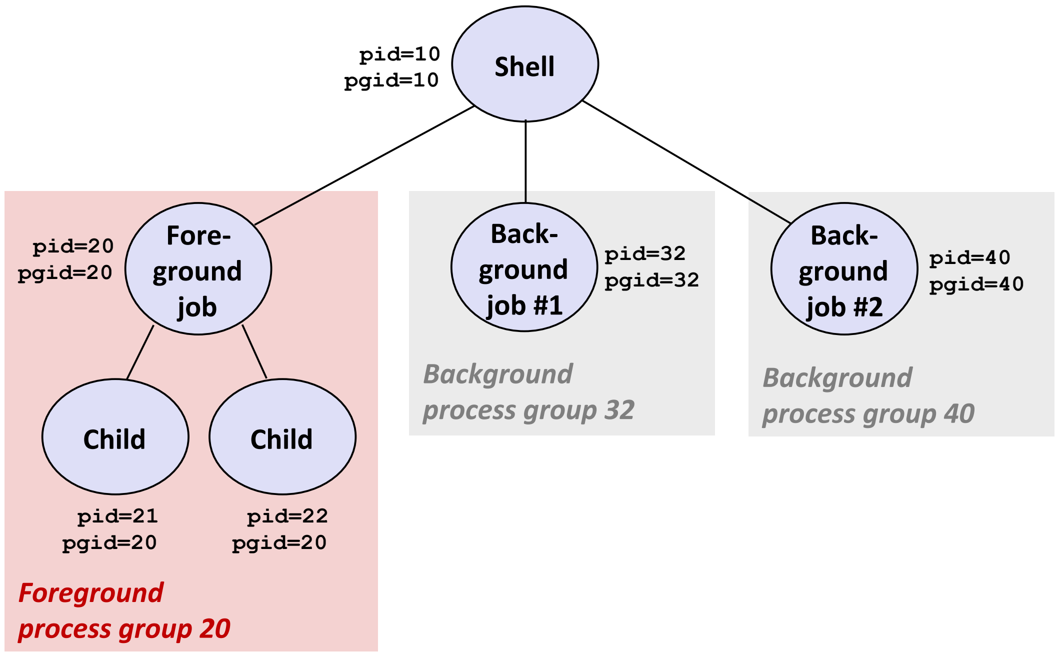
Fork & Exec Example



Basic Shell Design

```
while (true) {
    Print command prompt.
    Read command line from user.
    Parse command line.
    If command is built-in, execute it.
    Else, fork process
        in child:
            Execute requested command with exec
                             (never returns)
        in parent:
            Wait for child to complete with waitpid
}
```

Process Groups



Signals

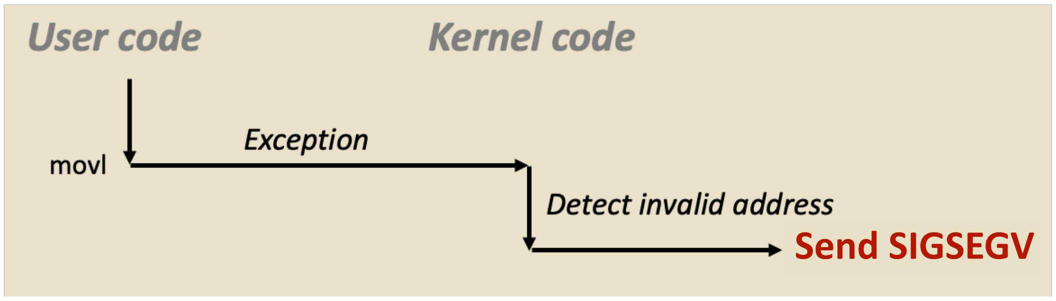
ID	Name	Signal Description	Shell Shortcut	Default Action	Override?
2	SIGINT	Interrupt process	Control-C	Terminate	Yes
9	SIGKILL	Kill process (immediately)		Terminate	**No**
11	SIGSEGV	Segmentation fault		Terminate	Yes
15	SIGTERM	Kill process (politely)		Terminate	Yes
17	SIGCHLD	Child stopped or terminated		Ignore	Yes
18	SIGCONT	Continue stopped process		Continue (Resume)	**No**
19	SIGSTOP	Stop process (immediately)		Stop (Suspend)	**No**
20	SIGTSTP	Stop process (politely)	Control-Z	Stop (Suspend)	Yes

Segmentation Fault (redux)

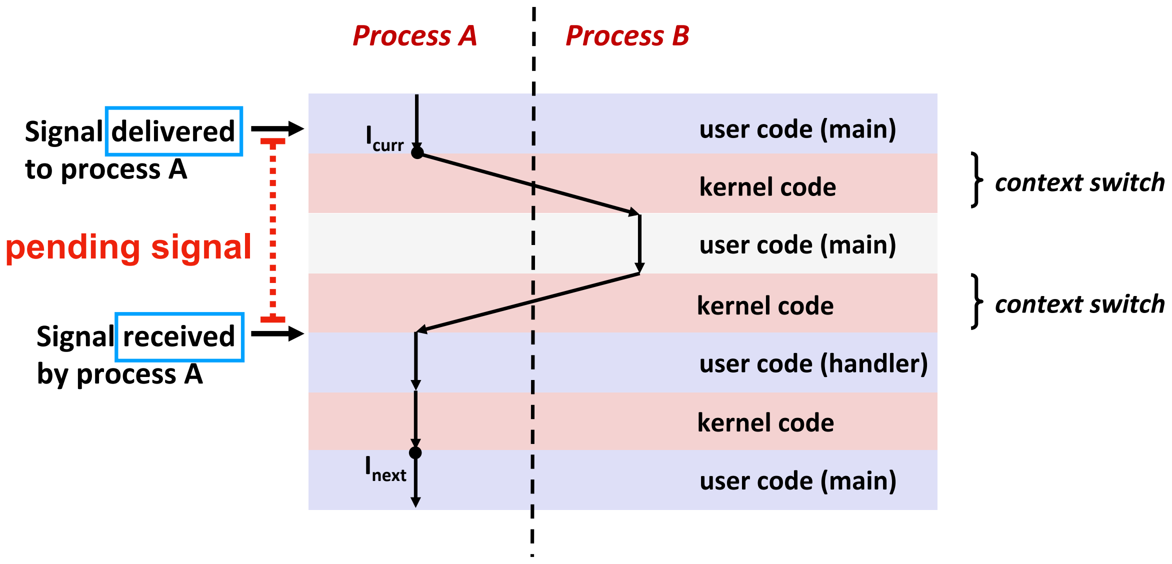
```
int a[1000];

int main() {
    a[5000] = 7;
    ...
}
```

```
 80483b7:    c7 05 60 e3 04 08 07    movl   $0x7,0x804e360
```



Signal Handler Control Flow



Zombies!

Reaping Zombies

```
pid_t waitpid(pid_t pid, int* stat, int ops)
```

Basic Shell Design (redux)

```
while (true) {
    Print command prompt.
    Read command line from user.
    Parse command line.
    If command is built-in, execute it.
    Else, fork process
        in child:
            Execute requested command with exec
                           (never returns)
        in parent:
            Wait for child to complete with waitpid
}
```

How to reap background jobs?

Signals (redux)

ID	Name	Signal Description	Shell Shortcut	Default Action	Override?
2	SIGINT	Interrupt process	Control-C	Terminate	Yes
9	SIGKILL	Kill process (immediately)		Terminate	**No**
11	SIGSEGV	Segmentation fault		Terminate	Yes
15	SIGTERM	Kill process (politely)		Terminate	Yes
17	SIGCHLD	Child stopped or terminated		Ignore	Yes
18	SIGCONT	Continue stopped process		Continue (Resume)	**No**
19	SIGSTOP	Stop process (immediately)		Stop (Suspend)	**No**
20	SIGTSTP	Stop process (politely)	Control-Z	Stop (Suspend)	Yes

Reaping in Signal Handler

```
int main() {
    pid_t pid;

    signal(SIGCHLD, sigchd_handler); // install signal handler

    while (1) {
        // print prompt, read cmd from user, etc.
        if ((pid = fork()) == 0) {
            exec(...); // child: run target program
        }
        // parent: wait for child to exit if foreground
    }
    return 0;
}
```

```
void sigchld_handler(int sig) {
    while ((pid = waitpid(-1, NULL, WNOHANG)) > 0) {
        // reaped child with process ID pid
    }
}
```

waitpid Wait Sets

```
pid_t waitpid(pid_t pid, int* stat, int ops)
```

wait set

Option Macros

```
pid_t waitpid(pid_t pid, int* stat, int ops)
```

WNOHANG	return immediately if child not already terminated/stopped
WUNTRACED	also wait for stopped (suspended) children

Status Macros

```
pid_t waitpid(pid_t pid, int* stat, int ops)
```

`WEXITSTATUS(*stat)` — numeric **exit code** of child

`WIFEXITED(*stat)` — true if child **terminated normally** (called exit or returned from **`main`**)

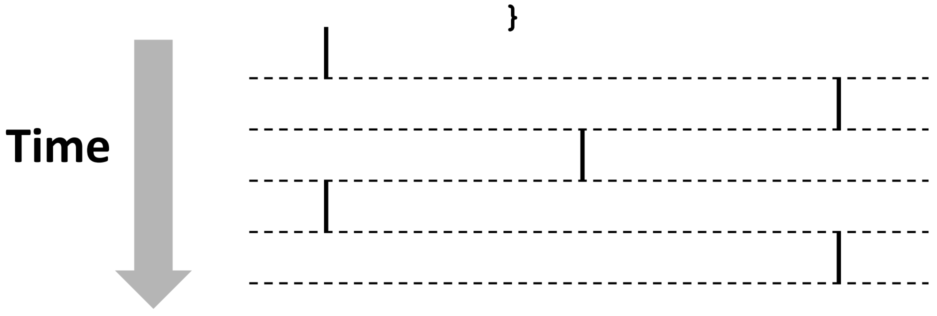
`WIFSIGNALED(*stat)` — true if child **terminated by signal**

`WIFSTOPPED(*stat)` — true if child **stopped** (suspended) by signal

Signal Handler as Concurrent Flow

Process A *Process A* *Process B*

```
while (1)      handler(){
      ;              …
               }
```



Job List Concurrency (1)

```
int main(int argc, char** argv) {
    pid_t pid;

    signal(SIGCHLD, sigchd_handler);
    initjobs(); // initialize job list

    while (1) {
        if ((pid = fork()) == 0) {
            exec(...);
        }
        addjob(pid); // add child to job list
    }
    return 0;
}
```

Concurrent job list modification!

```
void sigchld_handler(int sig) {
    while ((pid = waitpid(-1, NULL, WNOHANG)) > 0) {
        deletejob(pid); // delete child from job list
    }
}
```

Job List Concurrency (2)

```
int main(int argc, char** argv) {
    pid_t pid;
    signal(SIGCHLD, sigchd_handler);
    initjobs(); // initialize job list
    sigset_t mask; // bit vector
    sigemptyset(&mask); // clear all bits
    sigaddset(&mask, SIGCHLD); // set SIGCHILD bit
    while (1) {
        if ((pid = fork()) == 0) {
            exec(...);
        }
        sigprocmask(SIG_BLOCK, &mask, NULL); // block SIGCHLD
        addjob(pid); // add child to job list
        sigprocmask(SIG_UNBLOCK, &mask, NULL); // unblock SIGCHLD
    }
    return 0;
}
```

Possible `delete` before `add`!

```
void sigchld_handler(int sig) {
    while ((pid = waitpid(-1, NULL, WNOHANG)) > 0) {
        deletejob(pid); // delete child from job list
    }
}
```

Job List Concurrency (3)

```
int main(int argc, char** argv) {
    pid_t pid;
    signal(SIGCHLD, sigchd_handler);
    initjobs(); // initialize job list
    sigset_t mask; // bit vector
    sigemptyset(&mask); // clear all bits
    sigaddset(&mask, SIGCHLD); // set SIGCHILD bit
    while (1) {
        sigprocmask(SIG_BLOCK, &mask, NULL); // block SIGCHLD
        if ((pid = fork()) == 0) {
            // unblock in child (inherited from parent)
            sigprocmask(SIG_UNBLOCK, &mask, NULL);
            exec(...);
        }
        addjob(pid); // add child to job list
        sigprocmask(SIG_UNBLOCK, &mask, NULL); // unblock SIGCHLD
    }
    return 0;
}
```

Useful System Calls

fork – Create a new process

exec – Run a new program (several variants, e.g. **execve**)

kill – Send a signal

waitpid – Wait for and/or reap child process

setpgid – Change process group ID

sigsuspend – Wait until signal received

sigprocmask – Block or unblock signals

sigemptyset – Create empty signal set

sigfillset – Add every signal number to set

sigaddset – Add signal number to set

sigdelset – Delete signal number from set

System Call Error Handling

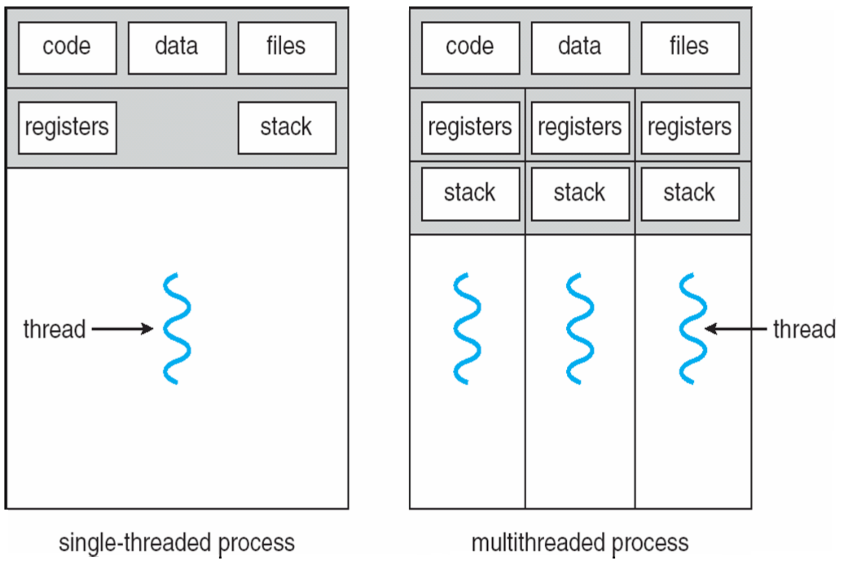
Always check return values!

(<0 means error)

```
pid = fork();
if (pid < 0) {
    printf("fork error: %s\n", strerror(errno));
}
```

global var

Threads



Thread Example

```
/*
 * hello.c - Pthreads "hello, world" program
 */

void* thread(void* vargp);

int main() {

    pthread_t tid;
    pthread_create(&tid, NULL, thread, NULL);
    pthread_join(tid, NULL);
    exit(0);
}
```

hello.c

Thread ID

Thread attributes (usually NULL)

Thread routine

Thread arguments (void *p)

Return value (void **p)

```
void* thread(void* vargp) { /* thread routine */
    printf("Hello, world!\n");
    return NULL;
}
```

hello.c