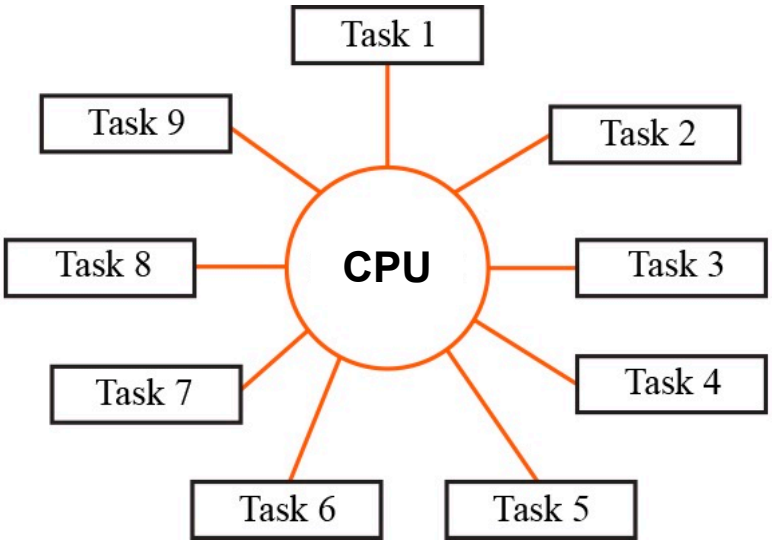
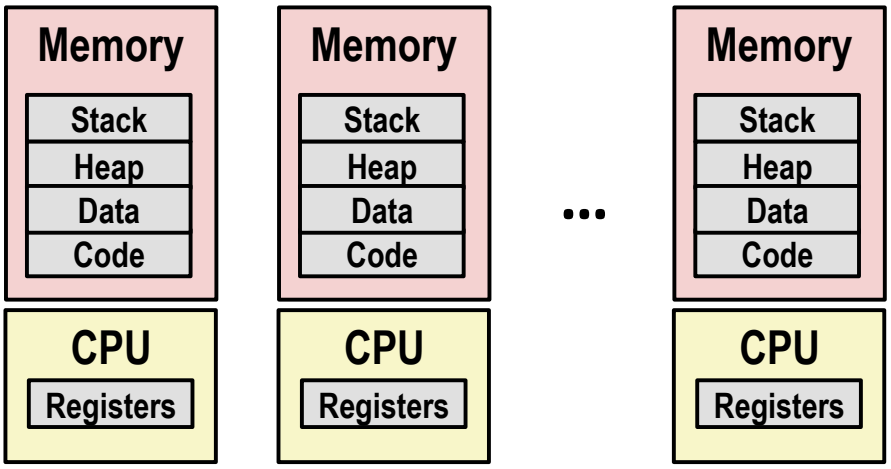
Global Control Flow

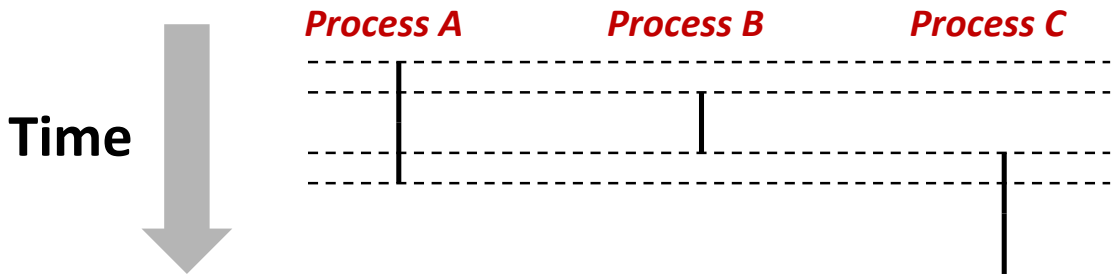


Processes



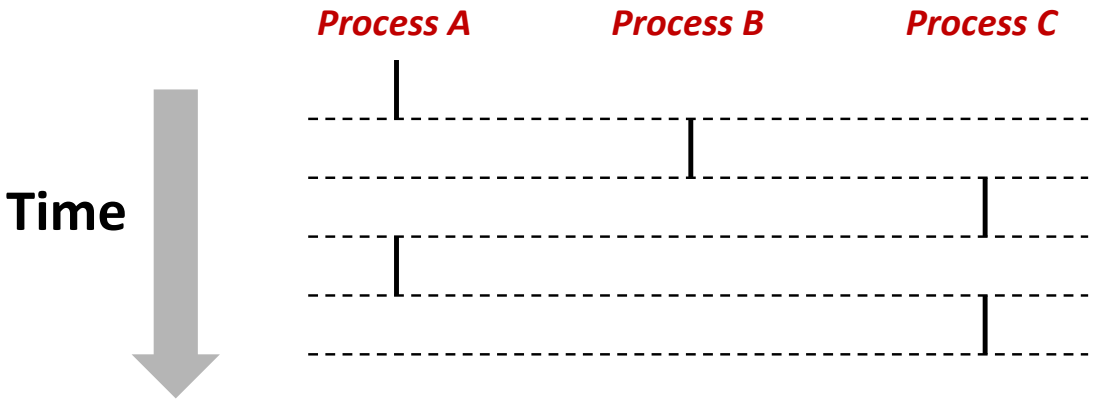
Control Flow Abstraction

Simultaneous execution

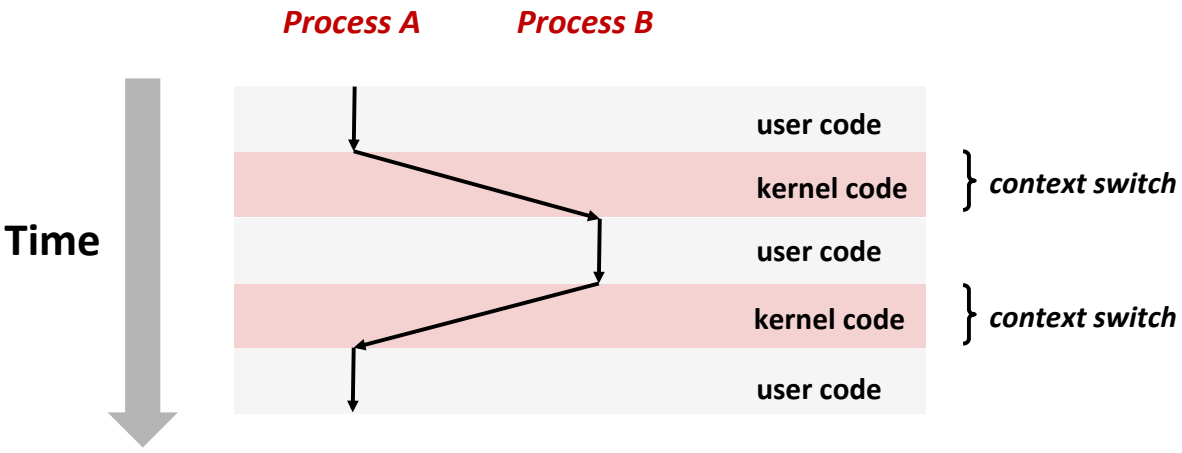


Control Flow Reality

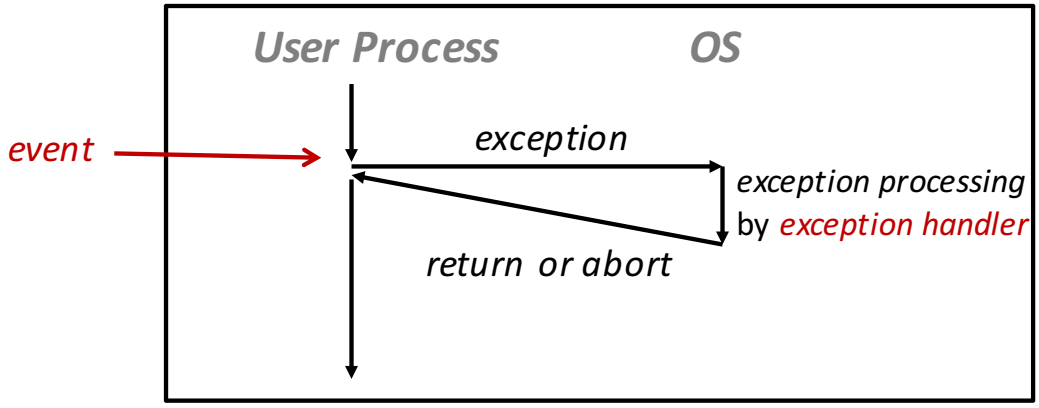
Time-sharing!



Context Switching



Exceptional Control Flow

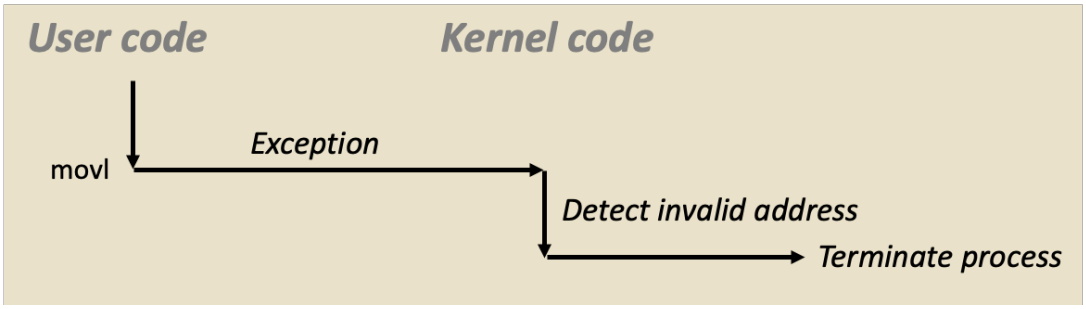


Example: Segmentation Fault

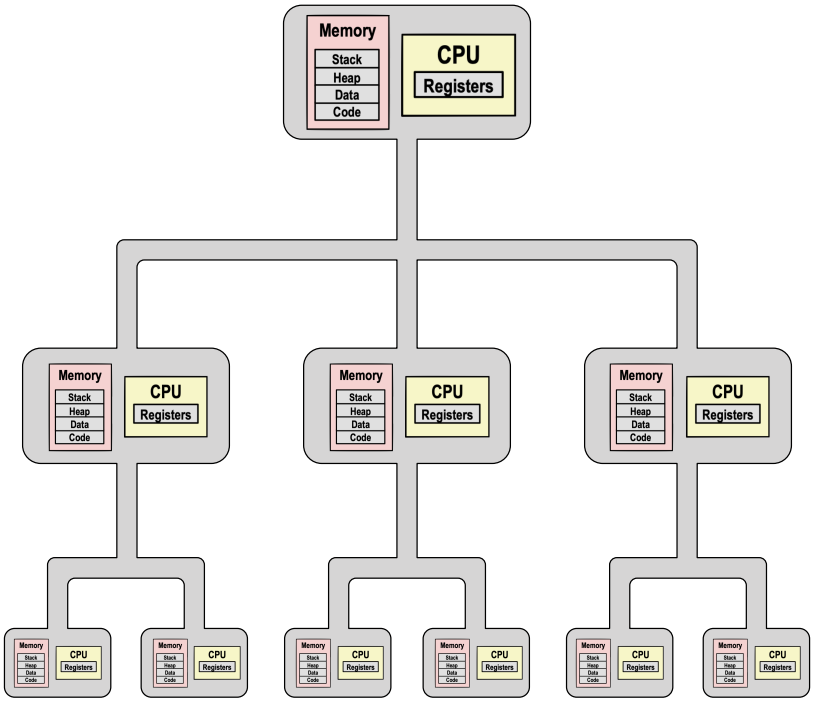
```
int a[1000];

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

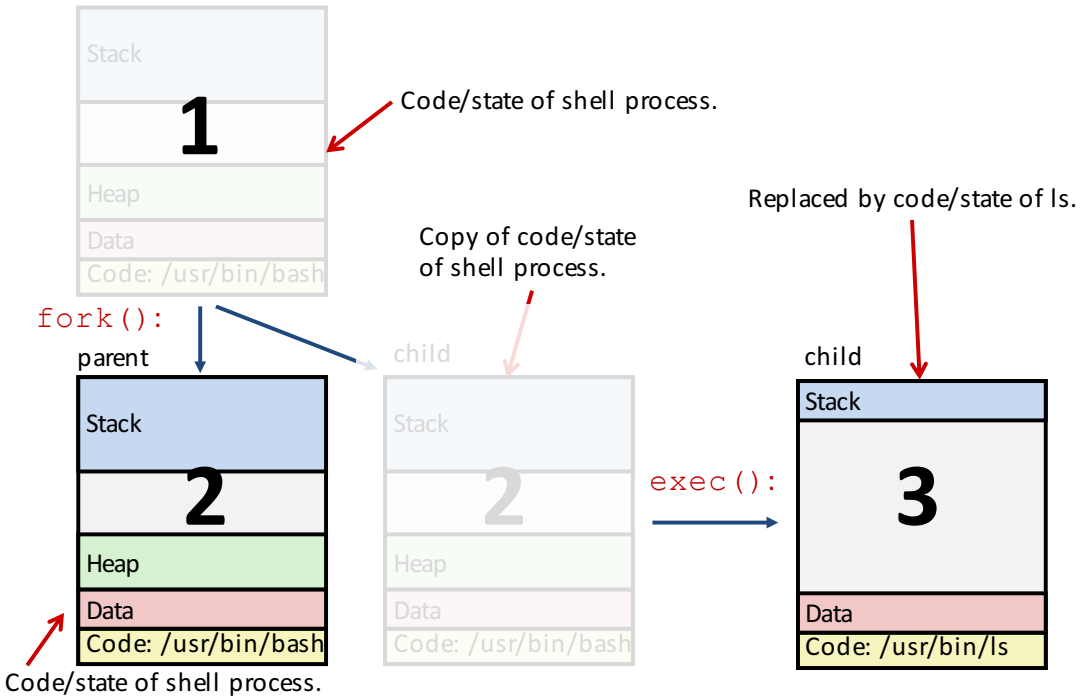
```
80483b7:    c7 05 60 e3 04 08 07    movl   $0x7,0x804e360
```



Process Management



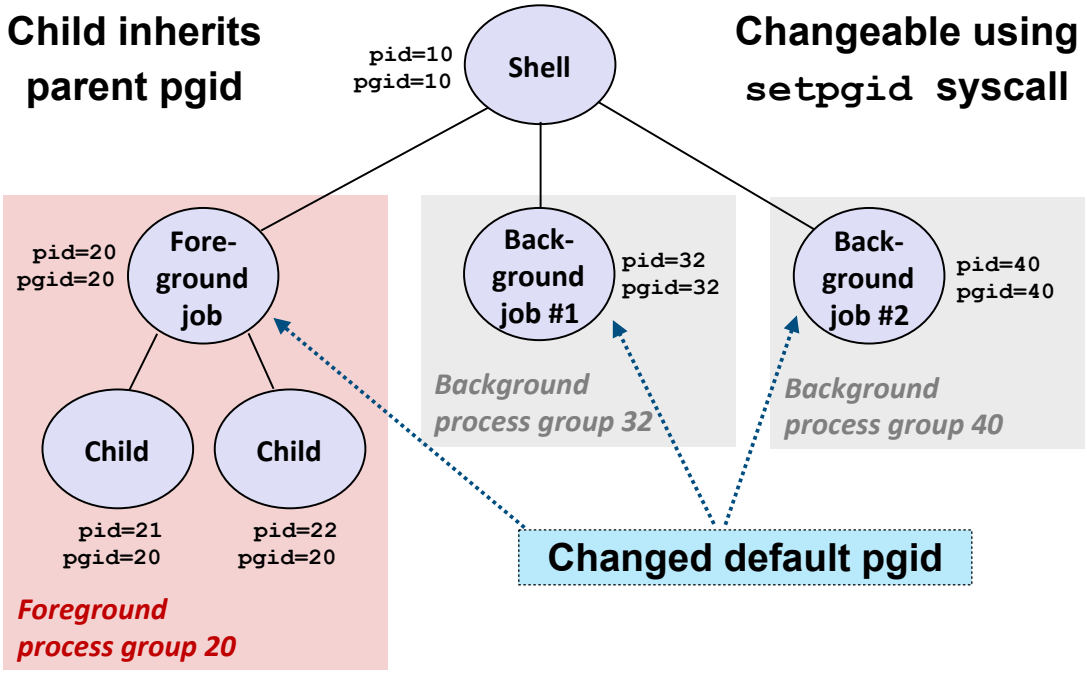
Fork & Exec Example



Basic Shell Design (v1)

```
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

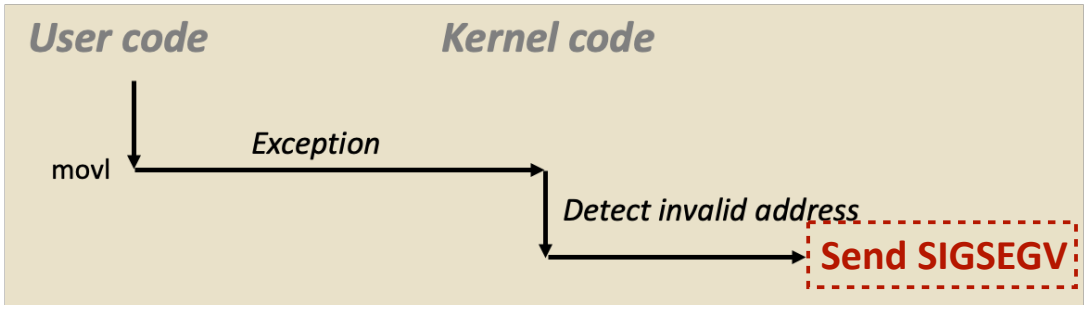
ID	Name	Signal Description	Shell Shortcut	Default Action	Override?
2	SIGINT	Interrupt process	Control-C	Terminate	Yes
9	SIGKILL	Kill process (immediately)		Terminate	**No**
11	SIGSEGV	Segmentation fault		Terminate	Yes
15	SIGTERM	Kill process (politely)		Terminate	Yes
17	SIGCHLD	Child stopped or terminated		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)

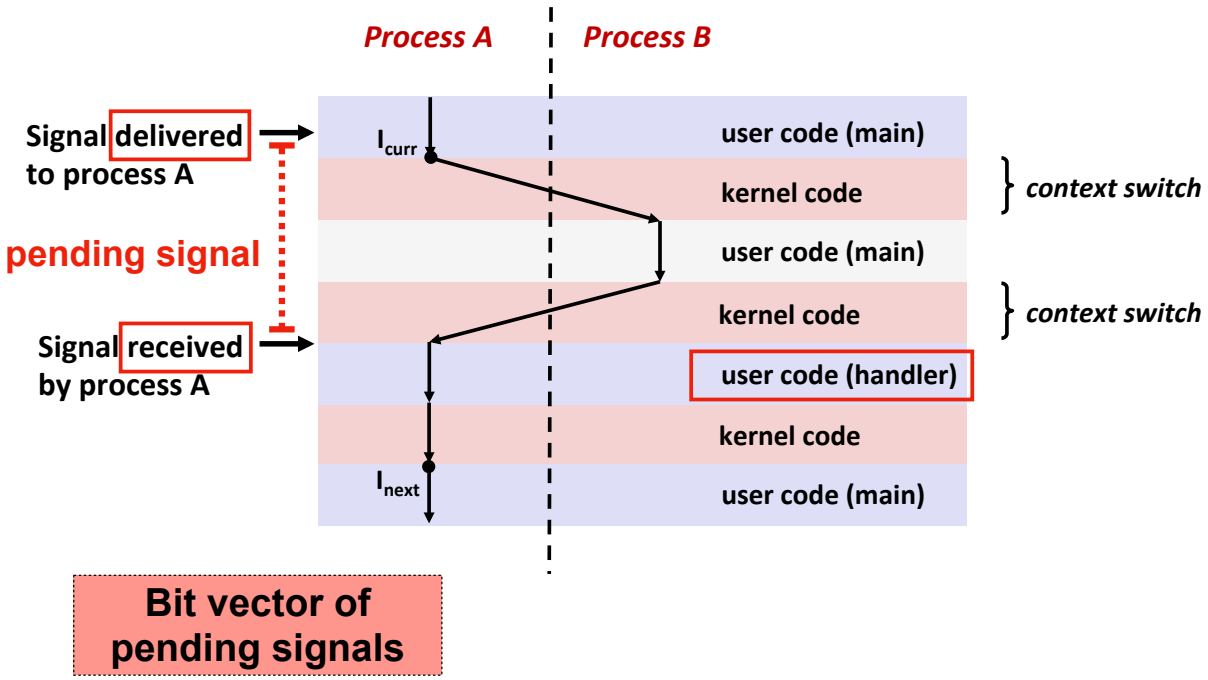
```
int a[1000];

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

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



Signal Handler Control Flow



Reaping Zombies

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


Basic Shell Design (v2)

```
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:
            if foreground:
                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 of reaped process

```
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)
```

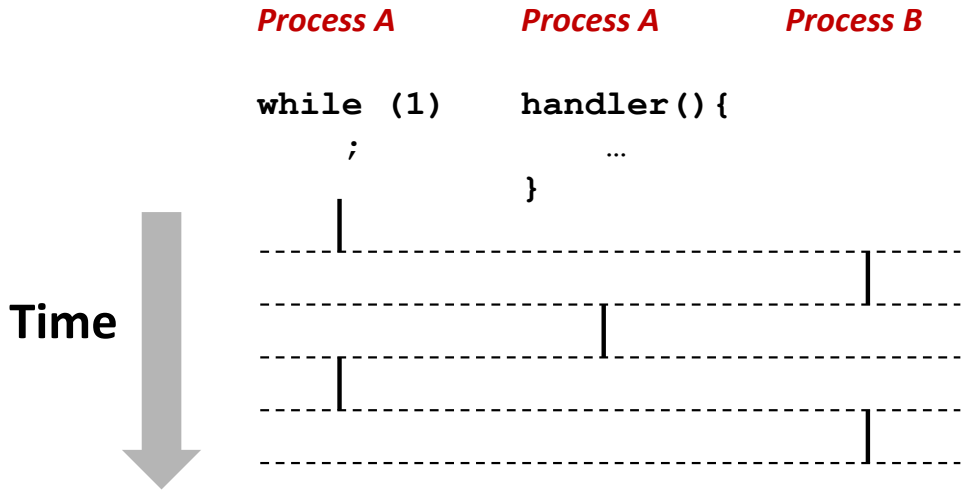
WEXITSTATUS(*stat) — numeric **exit code** of child

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



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

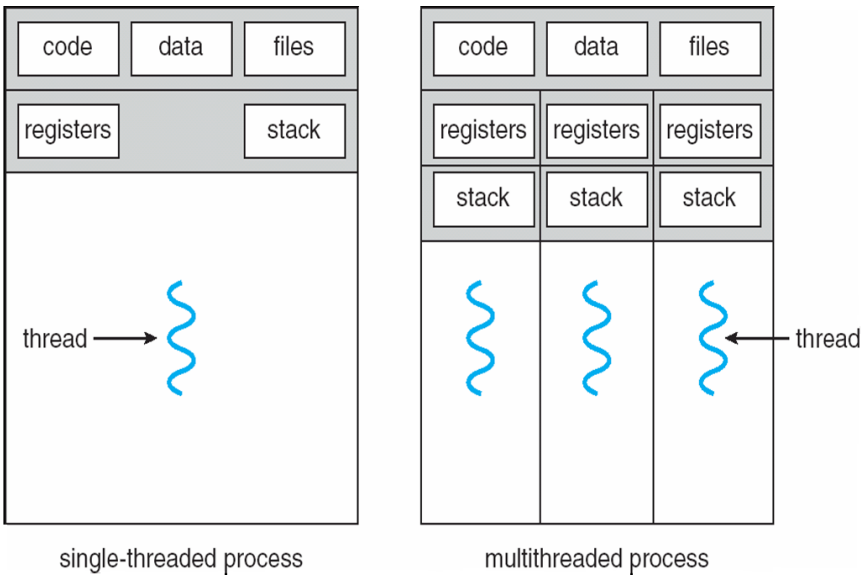
System Call Error Handling

Always check return values!
(<0 means error)

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

global var

Threads



Thread Example