

Exceptional Control Flow: Signals and Nonlocal Jumps

15-213: Introduction to Computer Systems
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ECF Exists at All Levels of a System

■ Exceptions

- Hardware and operating system kernel software

■ Process Context Switch

- Hardware timer and kernel software

■ Signals

- Kernel software and application software

■ Nonlocal jumps

- Application code

Previous Lecture

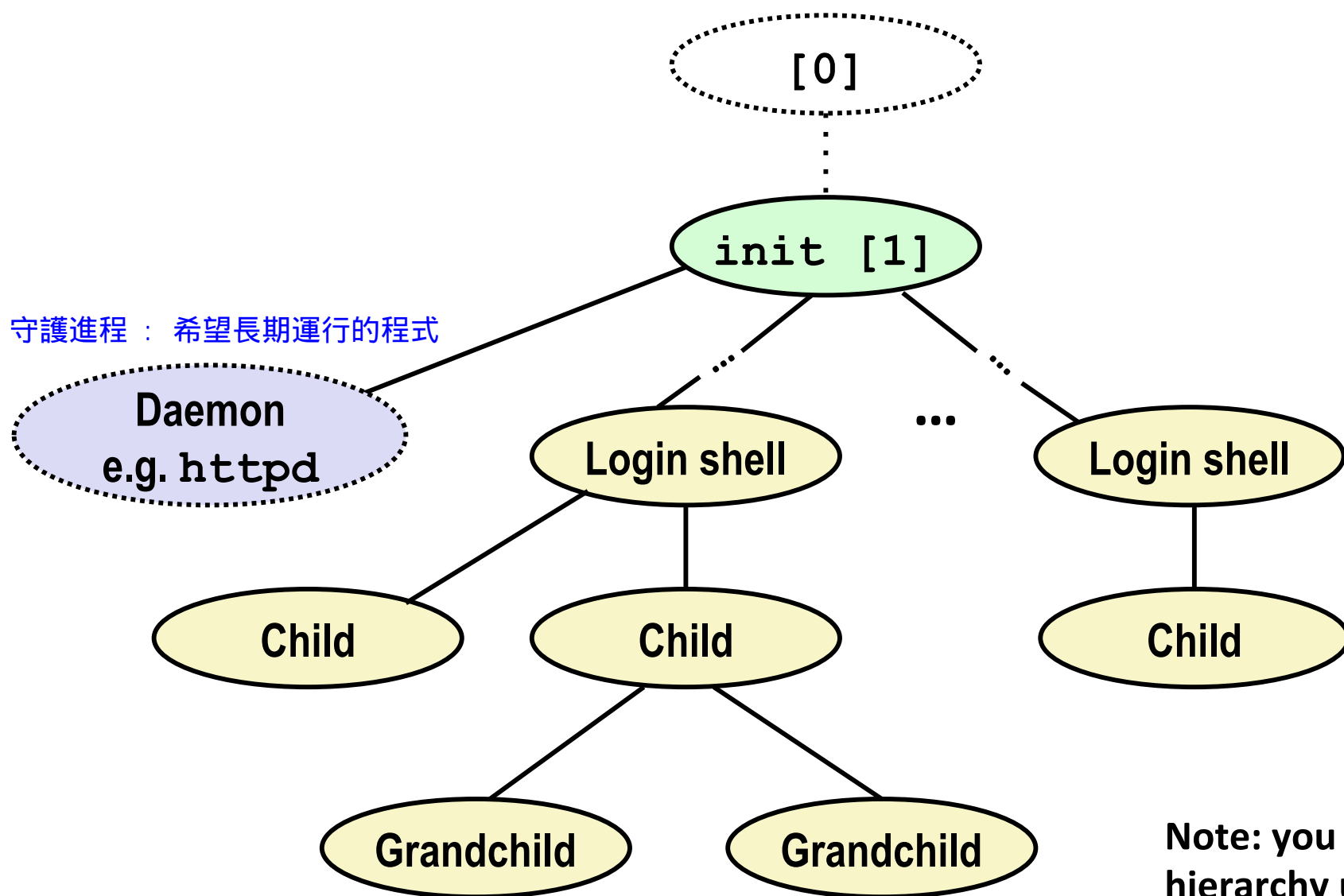
This Lecture

**Textbook and
supplemental slides**

Today

- **Shells**
- Signals
- Nonlocal jumps

Linux Process Hierarchy



Note: you can view the hierarchy using the Linux `ps tree` command

Shell Programs

- A *shell* is an application program that runs programs on behalf of the user.

- `sh` Original Unix shell (Stephen Bourne, AT&T Bell Labs, 1977)
- `csh/tcsh` BSD Unix C shell (
- `bash` "Bourne-Again" Shell (default Linux shell)

```

int main()
{
    char cmdline[MAXLINE]; /* command line */

    while (1) {
        /* read */
        printf("> ");
        Fgets(cmdline, MAXLINE, stdin);
        if (feof(stdin))
            exit(0);

        /* evaluate */
        eval(cmdline);
    }
}

```

取指令
评估指令

shellex.c

*Execution is a
sequence of read/
evaluate steps*

Simple Shell eval Function

```

void eval(char *cmdline)
{
    char *argv[MAXARGS]; /* Argument list execve() */
    char buf[MAXLINE];    /* Holds modified command line */
    int bg;               /* Should the job run in bg or fg? */
    pid_t pid;            /* Process id */

    strcpy(buf, cmdline);
    bg = parseline(buf, argv); ← 解析命令功能
    if (argv[0] == NULL)
        return; /* Ignore empty lines */
    if (!builtin_command(argv)) {
        if ((pid = Fork()) == 0) { /* Child runs user job */
            if (execve(argv[0], argv, environ) < 0) {
                printf("%s: Command not found.\n", argv[0]);
                exit(0);
            }
        }
        /* Parent waits for foreground job to terminate */
        if (!bg) {
            int status;
            if (waitpid(pid, &status, 0) < 0)
                unix_error("waitfg: waitpid error");
        }
        else
            printf("%d %s", pid, cmdline);
    }
    return;
}

```

是否為 shell 內建指令
 若僅 print 一行，並不會等待子進程結束，可能導致內存洩漏或是崩潰錯誤...

若返回只有一行
 bg 運行表示父進程不會等待子進程結束

Problem with Simple Shell Example

- Our example shell correctly waits for and reaps foreground jobs

■ But what about background jobs?

- Will become zombies when they terminate
- Will never be reaped because shell (typically) will not terminate
- Will create a memory leak that could run the kernel out of memory

ECF to the Rescue!

■ Solution: Exceptional control flow

- The kernel will interrupt regular processing to alert us when a background process completes
- In Unix, the alert mechanism is called a **signal**

当背景执行子进程终止时,用
一组信号通知父进程,接着父进
程使用 `waitpid()` 回收终止的子
进程

Today

- Shells
- **Signals**
- Nonlocal jumps

Signals

完全由軟體實現

signal 由 kernel 或其他進程發送
，或是由其他進程要求 kernel 發送

- A **signal** is a small message that notifies a process that an event of some type has occurred in the system

- Akin to exceptions and interrupts
- Sent from the kernel (sometimes at the request of another process) to a process
- Signal type is identified by small integer ID's (1-30)
- Only information in a signal is its ID and the fact that it arrived

有時進程會請求 kernel 發送 signal 給其他進程

ID	Name	Default Action	Corresponding Event
2	SIGINT	Terminate	User typed ctrl-c
9	SIGKILL	Terminate	Kill program (cannot override or ignore)
11	SIGSEGV	Terminate & Dump	Segmentation violation
14	SIGALRM	Terminate	Timer signal
✱ 17	SIGCHLD	Ignore	Child stopped or terminated

每當子進程終止或結束時
kernel 會通知父進程

ex ID 2 : 當你按下 <Ctrl>-C 時 Terminal 會發送了一個 SIGINT (中斷訊號) 給 Shell, Shell 再把 SIGINT 轉發給 ping process, 最後 ping process 收到後就會自己停掉

Signal Concepts: Sending a Signal

- Kernel **sends** (delivers) a signal to a **destination process** by updating some state in the context of the destination process

↳ 透過更改進程特定此特位
而非直接傳遞



- Kernel sends a signal for one of the following reasons:

- Kernel has detected a system event such as divide-by-zero (SIGFPE) or the termination of a child process (SIGCHLD)
- Another process has invoked the **kill** system call to explicitly request the kernel to send a signal to the destination process

Signal Concepts: Receiving a Signal

- A destination process *receives* a signal when it is forced by the kernel to react in some way to the delivery of the signal
- Some possible ways to react:
 - *Ignore* the signal (do nothing)
 - *Terminate* the process (with optional core dump)
 - *Catch* the signal by executing a user-level function called *signal handler*
 - Akin to a hardware exception handler being called in response to an asynchronous interrupt:

(1) **Signal received by process**

(2) **Control passes to signal handler**

(3) **Signal handler runs**

(4) **Signal handler returns to next instruction**

I_{curr}
 I_{next}

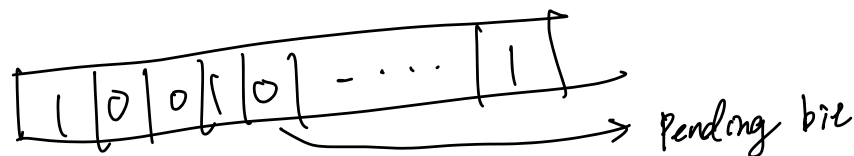
→ signal handler 位於 編寫的代码中
而不像中断處理函数位於 kernel 中

Signal Concepts: Pending and Blocked Signals

- A signal is **pending** if sent but not yet received
 - There can be at most one pending signal of any particular type
 - Important: Signals are not queued
 - If a process has a pending signal of type k, then subsequent signals of type k that are sent to that process are discarded
- A process can **block** the receipt of certain signals
 - Blocked signals can be delivered, but will not be received until the signal is unblocked
- A pending signal is received at most once

→ 後續 signal 將被丟棄

Signal Concepts: Pending/Blocked Bits

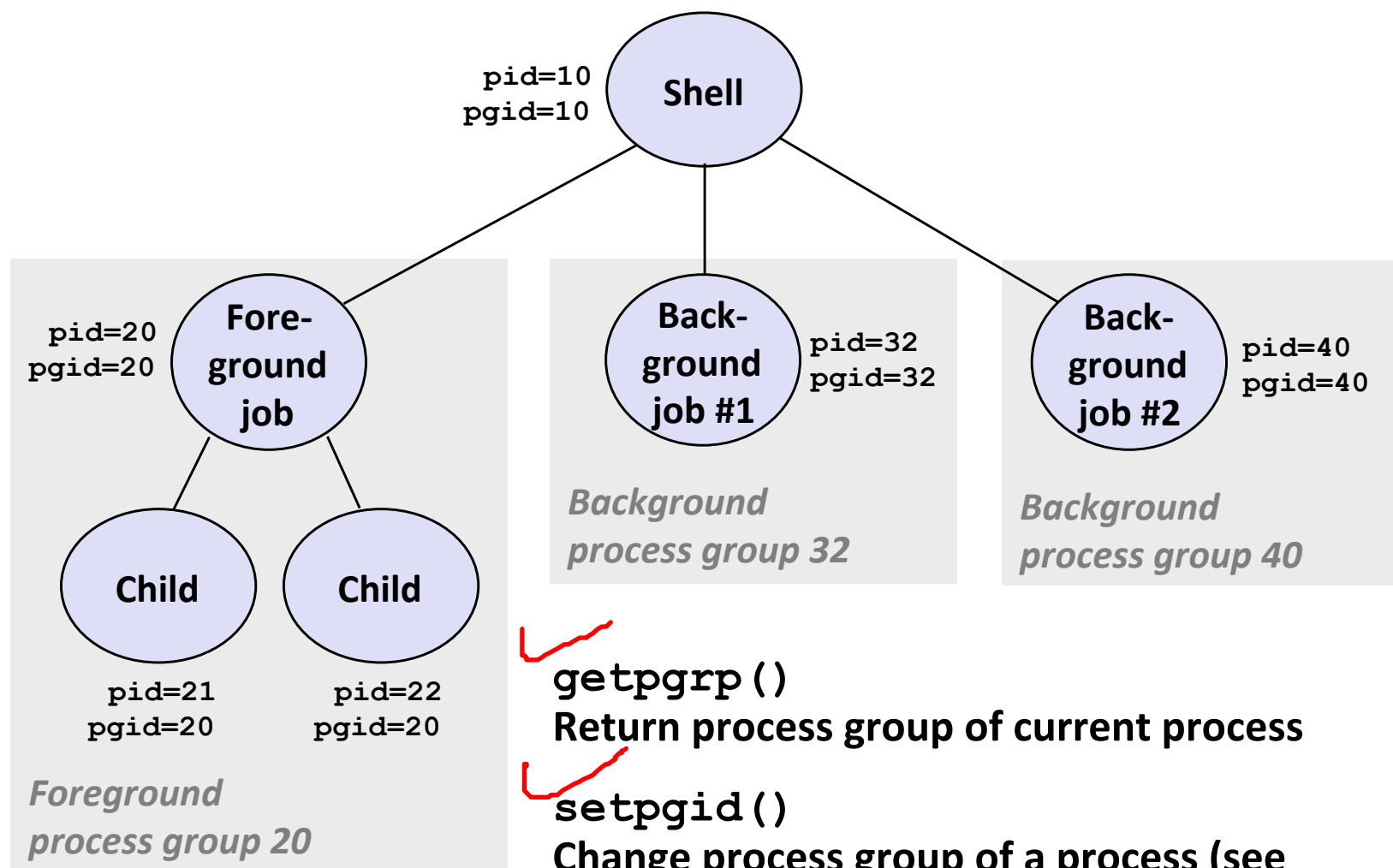


- Kernel maintains **pending** and **blocked** bit vectors in the context of each process
 - **pending**: represents the set of pending signals
 - Kernel sets bit k in **pending** when a signal of type k is delivered
 - Kernel clears bit k in **pending** when a signal of type k is received
 - **blocked**: represents the set of blocked signals
 - Can be set and cleared by using the **sigprocmask** function
 - Also referred to as the *signal mask*.

pending & blocked bit vectors 均為 32 bits int 類型

Sending Signals: Process Groups

- Every process belongs to exactly one process group



Sending Signals with `/bin/kill` Program

- `/bin/kill` program sends arbitrary signal to a process or process group

- Examples

- `/bin/kill -9 24818`
Send SIGKILL to process 24818

-9代表sigkill,
常見於要殺掉某個進程時

- `/bin/kill -9 -24817`
Send SIGKILL to every process in process group 24817

負號代表殺掉所有
pgrp = 24817的進程

```
linux> ./forks 16
Child1: pid=24818 pgrp=24817
Child2: pid=24819 pgrp=24817
```

```
linux> ps
  PID TTY          TIME CMD
 24788 pts/2        00:00:00 tcsh
 24818 pts/2        00:00:02 forks
 24819 pts/2        00:00:02 forks
 24820 pts/2        00:00:00 ps
```

```
linux> /bin/kill -9 -24817
linux> ps
  PID TTY          TIME CMD
 24788 pts/2        00:00:00 tcsh
 24823 pts/2        00:00:00 ps
linux>
```


Sending Signals from the Keyboard

- Typing ctrl-c (ctrl-z) causes the kernel to send a **SIGINT (SIGTSTP)** to every job in the foreground process group.

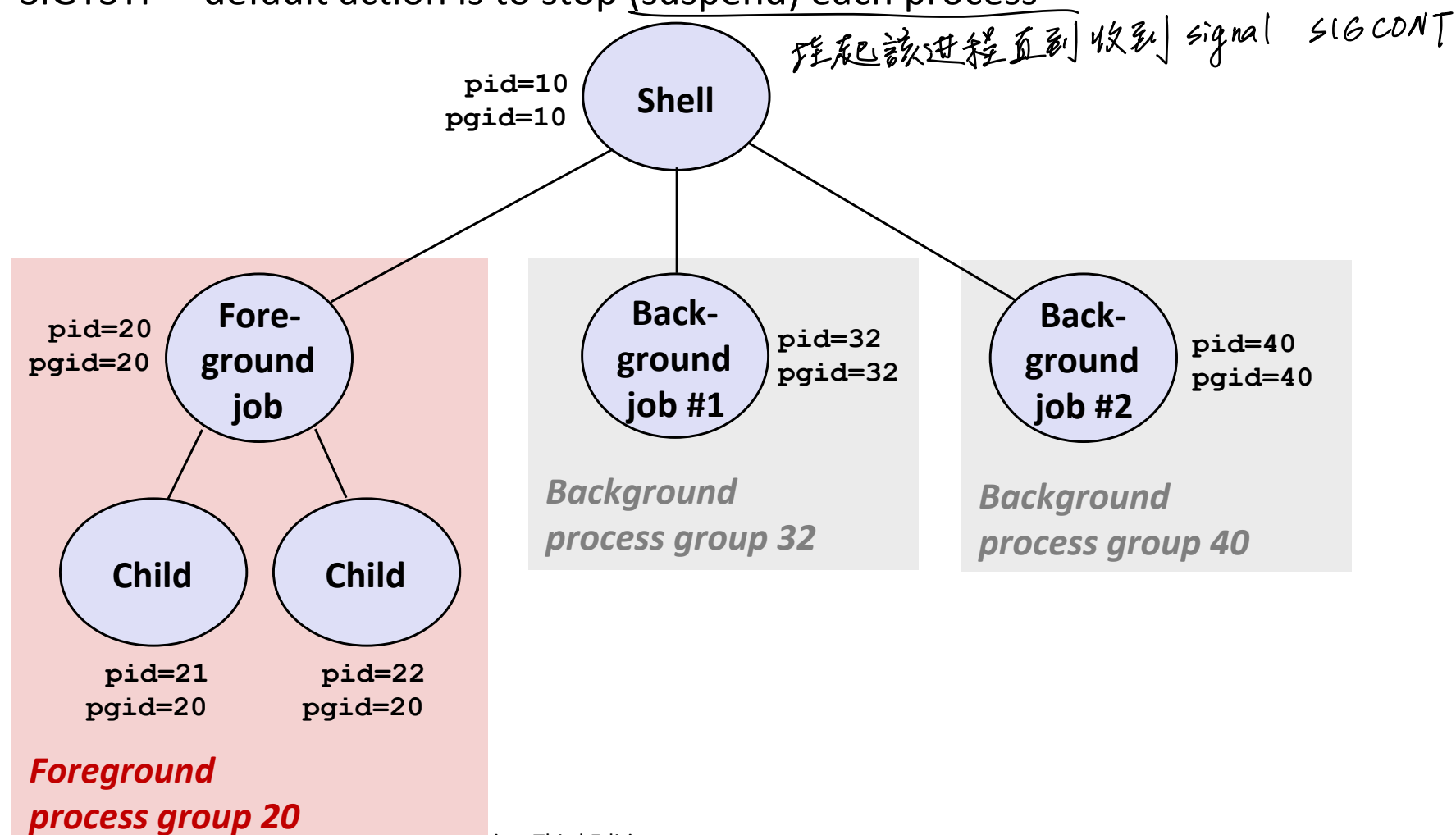
終止

掛起 (suspend)

ctrl+c

ctrl+z

- SIGINT – default action is to terminate each process
- SIGTSTP – default action is to stop (suspend) each process



Example of `ctrl-c` and `ctrl-z`

```
bluefish> ./forks 17
Child: pid=28108 pgrp=28107
Parent: pid=28107 pgrp=28107
<types ctrl-z>
Suspended
bluefish> ps w
```

PID	TTY	STAT	TIME	COMMAND
27699	pts/8	Ss	0:00	-tcsh
28107	pts/8	T	0:01	./forks 17
28108	pts/8	T	0:01	./forks 17
28109	pts/8	R+	0:00	ps w

```
bluefish> fg
./forks 17
<types ctrl-c>
bluefish> ps w
```

PID	TTY	STAT	TIME	COMMAND
27699	pts/8	Ss	0:00	-tcsh
28110	pts/8	R+	0:00	ps w

STAT (process state) Legend:

First letter:

S: sleeping

T: stopped

R: running

Second letter:

s: session leader

+: foreground proc group

See “man ps” for more details


Sending Signals with `kill` Function

```
void fork12()
{
    pid_t pid[N];
    int i;
    int child_status;

    for (i = 0; i < N; i++)
        if ((pid[i] = fork()) == 0) {
            /* Child: Infinite Loop */
            while(1)
                ;
        }

    for (i = 0; i < N; i++) {
        printf("Killing process %d\n", pid[i]);
        kill(pid[i], SIGINT);
    }

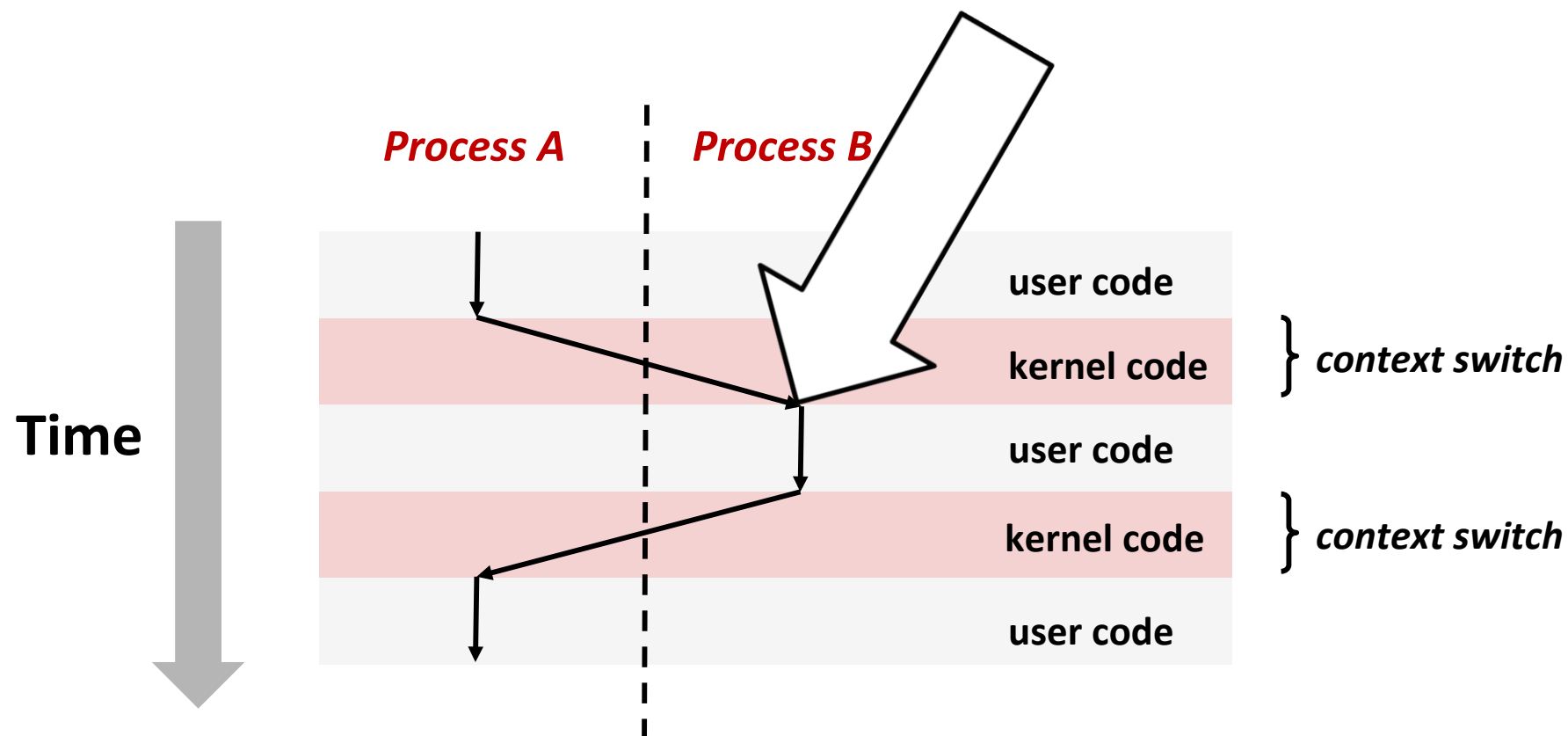
    for (i = 0; i < N; i++) {
        pid_t wpid = wait(&child_status);
        if (WIFEXITED(child_status))
            printf("Child %d terminated with exit status %d\n",
                wpid, WEXITSTATUS(child_status));
        else
            printf("Child %d terminated abnormally\n", wpid);
    }
}
```



forks.c

Receiving Signals

- Suppose kernel is returning from an exception handler and is ready to pass control to process p



Important: All context switches are initiated by calling some exception handler.

Receiving Signals

- Suppose kernel is returning from an exception handler and is ready to pass control to process p
- Kernel computes $\text{pnb} = \text{pending} \& \sim\text{blocked}$
 - The set of pending nonblocked signals for process p
 應該被接收的 non-blocked pending signal
- If ($\text{pnb} == 0$)
 - Pass control to next instruction in the logical flow for p
- Else
 - Choose least nonzero bit k in pnb and force process p to **receive** signal k
 - The receipt of the signal triggers some **action** by p
 - Repeat for all nonzero k in pnb
 - Pass control to next instruction in logical flow for p

Default Actions

- Each signal type has a predefined *default action*, which is one of:
 - The process terminates
 - The process terminates and dumps core
 - The process stops until restarted by a SIGCONT signal
 - The process ignores the signal

Installing Signal Handlers

- The `signal` function modifies the default action associated with the receipt of signal `signum`:
 - `handler_t *signal(int signum, handler_t *handler)`
 ↘ 修改某個 signal 的預設處理機制
- Different values for `handler`:
 - `SIG_IGN`: ignore signals of type `signum`
 - `SIG_DFL`: revert to the default action on receipt of signals of type `signum`
 - Otherwise, `handler` is the address of a user-level *signal handler*
 - Called when process receives signal of type `signum`
 - Referred to as *“installing”* the handler
 - Executing handler is called *“catching”* or *“handling”* the signal
 - ⑨ When the handler executes its return statement, control passes back to instruction in the control flow of the process that was interrupted by receipt of the signal 類似 Interrupt handler

Signal Handling Example

```
void sigint_handler(int sig) /* SIGINT handler */
{
    printf("So you think you can stop the bomb with ctrl-c, do you?\n");
    sleep(2);
    printf("Well...\n");
    fflush(stdout);
    sleep(1);
    printf("OK. :-)\n");
    exit(0);
}

int main()
{
    /* Install the SIGINT handler */
    if (signal(SIGINT, sigint_handler) == SIG_ERR)
        unix_error("signal error");

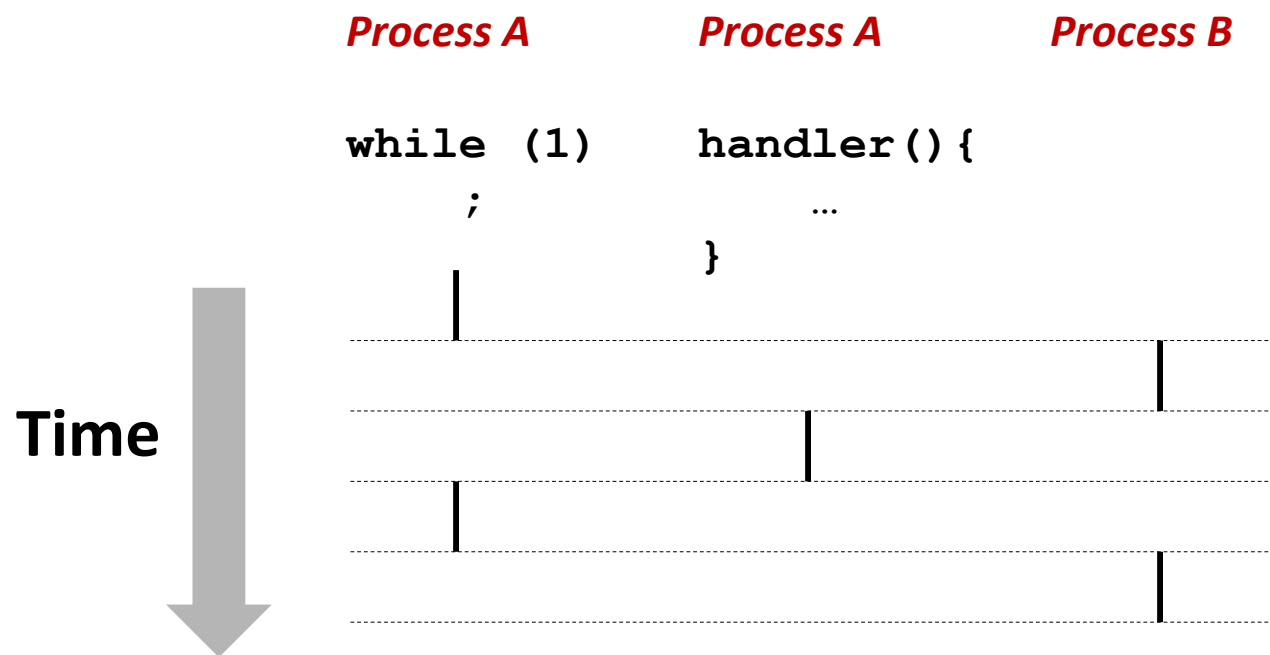
    /* Wait for the receipt of a signal */
    pause();

    return 0;
}
```

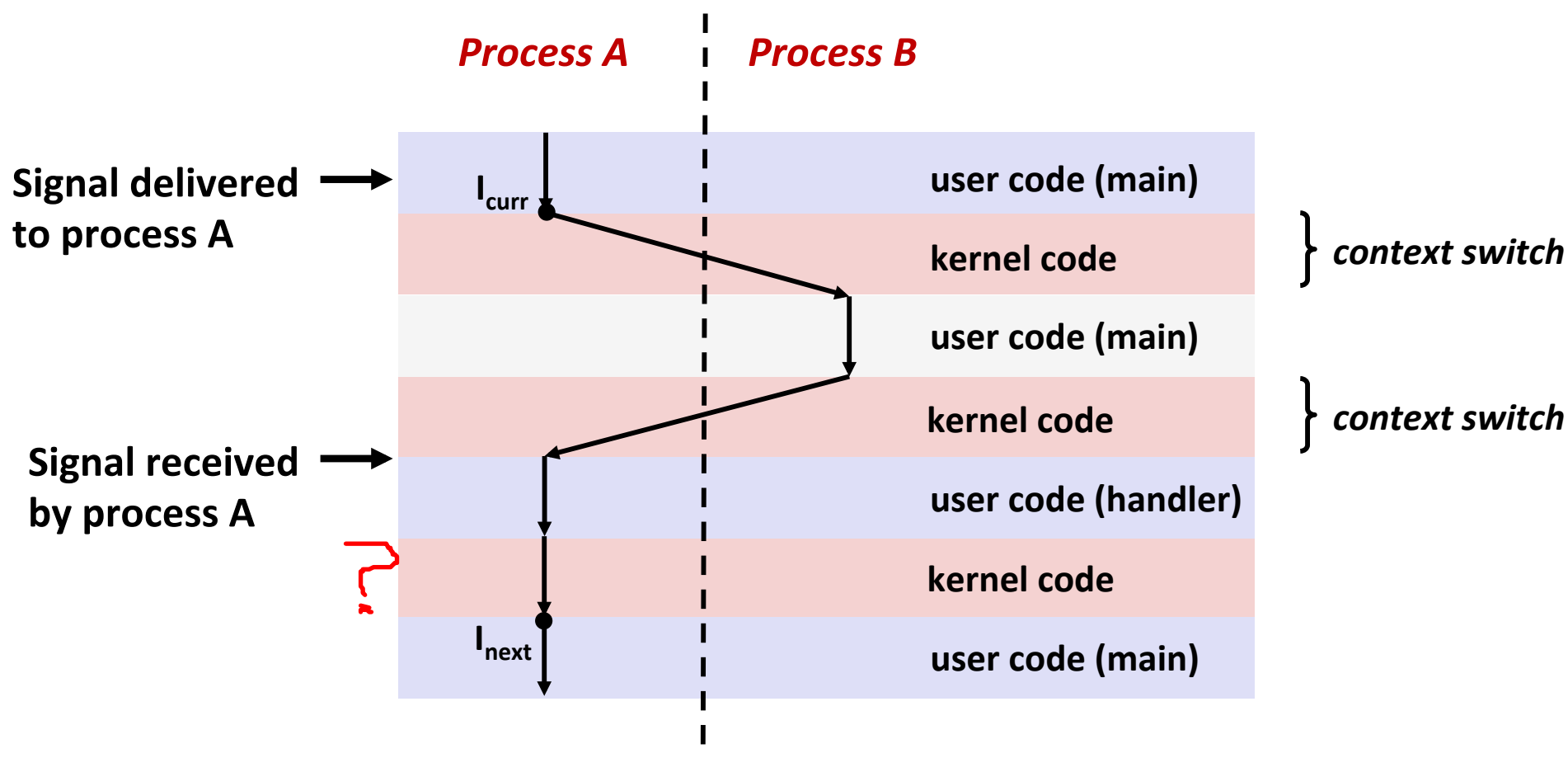
sigint.c

Signals Handlers as Concurrent Flows

- **A signal handler is a separate logical flow (not process) that runs concurrently with the main program**

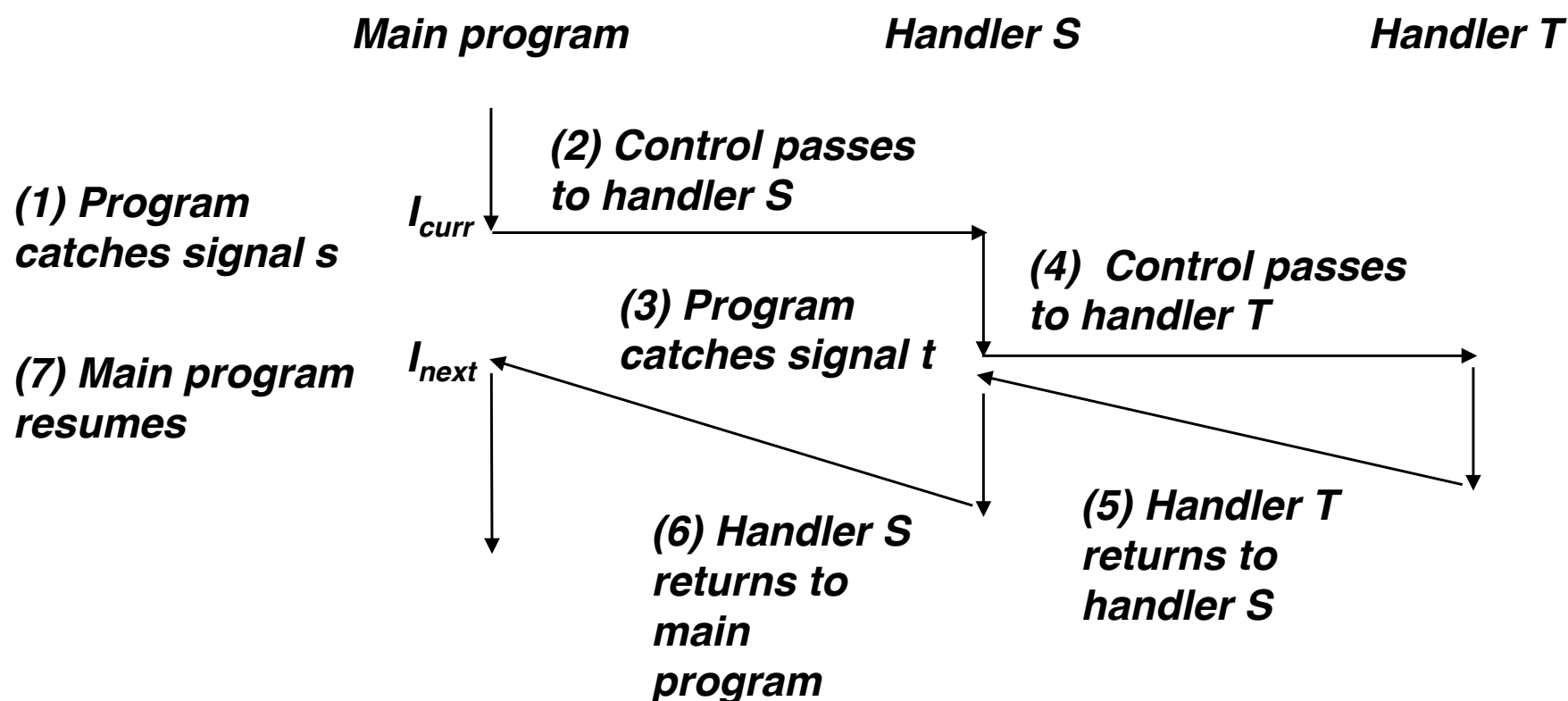


Another View of Signal Handlers as Concurrent Flows



Nested Signal Handlers

- Handlers can be interrupted by other handlers



Blocking and Unblocking Signals

■ Implicit blocking mechanism

- Kernel blocks any pending signals of type currently being handled.
 - E.g., A SIGINT handler can't be interrupted by another SIGINT
-

■ Explicit blocking and unblocking mechanism

- `sigprocmask` function

■ Supporting functions

- `sigemptyset` – Create empty set
- `sigfillset` – Add every signal number to set
- `sigaddset` – Add signal number to set
- `sigdelset` – Delete signal number from set

Temporarily Blocking Signals

```
sigset_t mask, prev_mask;

Sigemptyset(&mask);
Sigaddset(&mask, SIGINT);

/* Block SIGINT and save previous blocked set */
Sigprocmask(SIG_BLOCK, &mask, &prev_mask);

⋮    /* Code region that will not be interrupted by SIGINT */

/* Restore previous blocked set, unblocking SIGINT */
Sigprocmask(SIG_SETMASK, &prev_mask, NULL);
```

Safe Signal Handling

- Handlers are tricky because they are concurrent with main program and share the same global data structures.
 - Shared data structures can become corrupted.
- We'll explore concurrency issues later in the term.
可能会形成死锁
- For now here are some guidelines to help you avoid trouble.

Guidelines for Writing Safe Handlers

- **G0: Keep your handlers as simple as possible**
 - e.g., Set a global flag and return
- **G1: Call only async-signal-safe functions in your handlers**
 - `printf`, `sprintf`, `malloc`, and `exit` are not safe!
- **G2: Save and restore `errno` on entry and exit**
 - So that other handlers don't overwrite your value of `errno`
- **G3: Protect accesses to shared data structures by temporarily blocking all signals.**
 - To prevent possible corruption
- **G4: Declare global variables as `volatile`**
 - To prevent compiler from storing them in a register
- **G5: Declare global flags as `volatile sig_atomic_t`**
 - *flag*: variable that is only read or written (e.g. `flag = 1`, not `flag++`)
 - Flag declared this way does not need to be protected like other globals

Async-Signal-Safety

- Function is *async-signal-safe* if either reentrant (e.g., all variables stored on stack frame, CS:APP3e 12.7.2) or non-interruptible by signals.
- Posix guarantees 117 functions to be async-signal-safe
 - Source: “man 7 signal”
 - Popular functions on the list:
 - `_exit`, `write`, `wait`, `waitpid`, `sleep`, `kill`
 - Popular functions that are **not** on the list:
 - `printf`, `sprintf`, `malloc`, `exit`
 - Unfortunate fact: `write` is the only async-signal-safe output function



可能產生死鎖

Safely Generating Formatted Output

- Use the reentrant SIO (Safe I/O library) from `csapp.c` in your handlers.

- `ssize_t sio_puts(char s[]) /* Put string */`
- `ssize_t sio_putl(long v) /* Put long */`
- `void sio_error(char s[]) /* Put msg & exit */`

```
void sigint_handler(int sig) /* Safe SIGINT handler */
{
    Sio_puts("So you think you can stop the bomb with ctrl-
c, do you?\n");
    sleep(2);
    Sio_puts("Well...\n");
    sleep(1);
    Sio_puts("OK. :-)\n");
    _exit(0);
}
```

sigintsafe.c

Correct Signal Handling

```

int ccount = 0;
void child_handler(int sig) {
    int olderrno = errno;
    pid_t pid;
    if ((pid = wait(NULL)) < 0)
        Sio_error("wait error");
    ccount--;
    Sio_puts("Handler reaped child ");
    Sio_putl((long)pid);
    Sio_puts(" \n");
    sleep(1);
    errno = olderrno;
}

void fork14() {
    pid_t pid[N];
    int i;
    ccount = N;
    Signal(SIGCHLD, child_handler);

    for (i = 0; i < N; i++) {
        if ((pid[i] = Fork()) == 0) {
            Sleep(1);
            exit(0); /* Child exits */
        }
    }
    while (ccount > 0) /* Parent spins */
        ;
}

```

只能代表一个
子进程被终止

■ Pending signals are not queued

- For each signal type, one bit indicates whether or not signal is pending...
- ...thus at most one pending signal of any particular type.

■ You can't use signals to count events, such as children terminating.

```

whaleshark> ./forks 14
Handler reaped child 23240
Handler reaped child 23241

```

forks.c

Correct Signal Handling

- **Must wait for all terminated child processes**
 - Put `wait` in a loop to reap all terminated children

```
void child_handler2(int sig)
{
    int olderrno = errno;
    pid_t pid;
    while ((pid = wait(NULL)) > 0) {
        ccount--;
        Sio_puts("Handler reaped child ");
        Sio_putl((long)pid);
        Sio_puts(" \n");
    }
    if (errno != ECHILD)
        Sio_error("wait error");
    errno = olderrno;
}
```

```
whaleshark> ./forks 15
Handler reaped child 23246
Handler reaped child 23247
Handler reaped child 23248
Handler reaped child 23249
Handler reaped child 23250
whaleshark>
```

Portable Signal Handling

- Ugh! Different versions of Unix can have different signal handling semantics
 - Some older systems restore action to default after catching signal
 - Some interrupted system calls can return with `errno == EINTR`
 - Some systems don't block signals of the type being handled
- Solution: `sigaction`

```
handler_t *Signal(int signum, handler_t *handler)
{
    struct sigaction action, old_action;

    action.sa_handler = handler;
    sigemptyset(&action.sa_mask); /* Block sigs of type being handled */
    action.sa_flags = SA_RESTART; /* Restart syscalls if possible */

    if (sigaction(signum, &action, &old_action) < 0)
        unix_error("Signal error");
    return (old_action.sa_handler);
}
```

csapp.c

Synchronizing Flows to Avoid Races

- Simple shell with a subtle synchronization error because it assumes parent runs before child.

```
int main(int argc, char **argv)
{
    int pid;
    sigset_t mask_all, prev_all;
```

我們不能擅自推測進程執行的順序
以下例子有可能父進程還來不及 add job
子進程就結束了

```
    Sigfillset(&mask_all);
    Signal(SIGCHLD, handler);
    initjobs(); /* Initialize the job list */
```

```
    while (1) {
        if ((pid = Fork()) == 0) { /* Child */
            Execve("/bin/date", argv, NULL);
        }
        Sigprocmask(SIG_BLOCK, &mask_all, &prev_all); /* Parent */
        addjob(pid); /* Add the child to the job list */
        Sigprocmask(SIG_SETMASK, &prev_all, NULL);
    }
    exit(0);
```

```
}
```

procmask1.c

Synchronizing Flows to Avoid Races

■ SIGCHLD handler for a simple shell

```
void handler(int sig)
{
    int olderrno = errno;
    sigset_t mask_all, prev_all;
    pid_t pid;

    Sigfillset(&mask_all);
    while ((pid = waitpid(-1, NULL, 0)) > 0) { /* Reap child */
        Sigprocmask(SIG_BLOCK, &mask_all, &prev_all);
        deletejob(pid); /* Delete the child from the job list */
        Sigprocmask(SIG_SETMASK, &prev_all, NULL);
    }
    if (errno != ECHILD)
        Sio_error("waitpid error");
    errno = olderrno;
}
```

procmask1.c

Corrected Shell Program without Race

```

int main(int argc, char **argv)
{
    int pid;
    sigset_t mask_all, mask_one, prev_one;

    Sigfillset(&mask_all);
    Sigemptyset(&mask_one);
    Sigaddset(&mask_one, SIGCHLD);
    Signal(SIGCHLD, handler);
    initjobs(); /* Initialize the job list */

    while (1) {
        Sigprocmask(SIG_BLOCK, &mask_one, &prev_one); /* Block SIGCHLD */
        if ((pid = Fork()) == 0) { /* Child process */
            Sigprocmask(SIG_SETMASK, &prev_one, NULL); /* Unblock SIGCHLD */
            Execve("/bin/date", argv, NULL);
        }
        Sigprocmask(SIG_BLOCK, &mask_all, NULL); /* Parent process */
        addjob(pid); /* Add the child to the job list */
        Sigprocmask(SIG_SETMASK, &prev_one, NULL); /* Unblock SIGCHLD */
    }
    exit(0);
}

```

子进程也会复制父进程的 bit vectors, 所以需要先 un-block

procmask2.c

Explicitly Waiting for Signals

- Handlers for program explicitly waiting for SIGCHLD to arrive.

```
volatile sig_atomic_t pid;

void sigchld_handler(int s)
{
    int olderrno = errno;
    pid = Waitpid(-1, NULL, 0); /* Main is waiting for nonzero pid */
    errno = olderrno;
}

void sigint_handler(int s)
{
}
```

waitforsignal.c

Explicitly Waiting for Signals

```
int main(int argc, char **argv) {
    sigset_t mask, prev;
    Signal(SIGCHLD, sigchld_handler);
    Signal(SIGINT, sigint_handler);
    Sigemptyset(&mask);
    Sigaddset(&mask, SIGCHLD);

    while (1) {
        Sigprocmask(SIG_BLOCK, &mask, &prev); /* Block SIGCHLD */
        if (Fork() == 0) /* Child */
            exit(0);
        /* Parent */
        pid = 0;
        Sigprocmask(SIG_SETMASK, &prev, NULL); /* Unblock SIGCHLD */

        /* Wait for SIGCHLD to be received (wasteful!) */
        while (!pid)
            ;
        /* Do some work after receiving SIGCHLD */
        printf(".");
    }
    exit(0);
}
```


Similar to a shell waiting for a foreground job to terminate.

waitforsignal.c

Explicitly Waiting for Signals

- Program is correct, but very wasteful
- Other options:

```
while (!pid) /* Race! */  
    pause();
```



```
while (!pid) /* Too slow! */  
    sleep(1);
```

- Solution: **sigsuspend**

若 signal 發生在 pid 檢查 與 pause() 之間, 那 pause() 永遠都等不到 signal

Waiting for Signals with `sigsuspend`

- `int sigsuspend(const sigset_t *mask)`
- Equivalent to atomic (uninterruptable) version of:

```
sigprocmask(SIG_BLOCK, &mask, &prev);  
pause();  
sigprocmask(SIG_SETMASK, &prev, NULL);
```



Waiting for Signals with `sigsuspend`

```
int main(int argc, char **argv) {
    sigset_t mask, prev;
    Signal(SIGCHLD, sigchld_handler);
    Signal(SIGINT, sigint_handler);
    Sigemptyset(&mask);
    Sigaddset(&mask, SIGCHLD);

    while (1) {
        Sigprocmask(SIG_BLOCK, &mask, &prev); /* Block SIGCHLD */
        if (Fork() == 0) /* Child */
            exit(0);

        /* Wait for SIGCHLD to be received */
        pid = 0;
        while (!pid)
            Sigsuspend(&prev);

        /* Optionally unblock SIGCHLD */
        Sigprocmask(SIG_SETMASK, &prev, NULL);
        /* Do some work after receiving SIGCHLD */
        printf(".");
    }
    exit(0);
}
```

sigsuspend.c

Today

- Shells
- Signals
- **Nonlocal jumps**
 - Consult your textbook and additional slides

Summary

- **Signals provide process-level exception handling**
 - Can generate from user programs
 - Can define effect by declaring signal handler
 - Be very careful when writing signal handlers

- **Nonlocal jumps provide exceptional control flow within process**
 - Within constraints of stack discipline

Additional slides

Nonlocal Jumps: `setjmp/longjmp`

- **Powerful (but dangerous) user-level mechanism for transferring control to an arbitrary location**
 - Controlled to way to break the procedure call / return discipline
 - Useful for error recovery and signal handling
- **`int setjmp(jmp_buf j)`**
 - Must be called before `longjmp`
 - Identifies a return site for a subsequent `longjmp`
 - Called **once**, returns **one or more** times
- **Implementation:**
 - Remember where you are by storing the current **register context**, **stack pointer**, and **PC value** in `jmp_buf`
 - Return 0

setjmp/longjmp (cont)

■ `void longjmp(jmp_buf j, int i)`

- Meaning:
 - return from the `setjmp` remembered by jump buffer `j` again ...
 - ... this time returning `i` instead of 0
- Called after `setjmp`
- Called **once**, but **never** returns

■ `longjmp` Implementation:

- Restore register context (stack pointer, base pointer, PC value) from jump buffer `j`
- Set `%eax` (the return value) to `i`
- Jump to the location indicated by the PC stored in jump buf `j`

setjmp/longjmp Example

- Goal: return directly to original caller from a deeply-nested function

```
/* Deeply nested function foo */  
void foo(void)  
{  
    if (error1)  
        longjmp(buf, 1);  
    bar();  
}  
  
void bar(void)  
{  
    if (error2)  
        longjmp(buf, 2);  
}
```

```
jmp_buf buf;

int error1 = 0;
int error2 = 1;

void foo(void), bar(void);

int main()
{
    switch(setjmp(buf)) {
        case 0:
            foo();
            break;
        case 1:
            printf("Detected an error1 condition in foo\n");
            break;
        case 2:
            printf("Detected an error2 condition in foo\n");
            break;
        default:
            printf("Unknown error condition in foo\n");
    }
    exit(0);
}
```

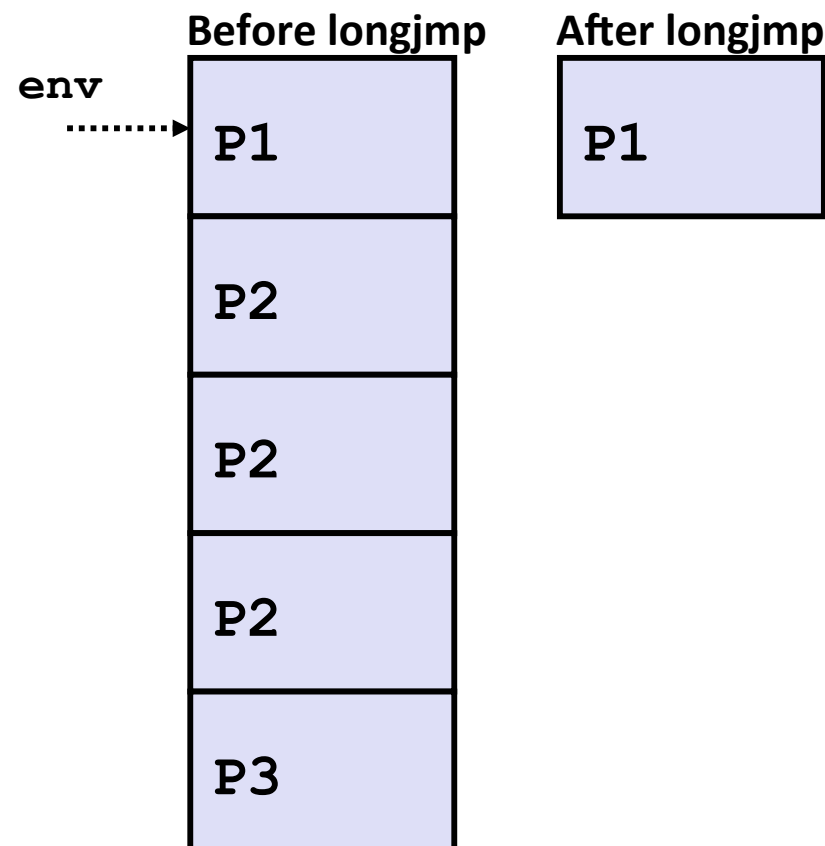
setjmp/longjmp Example (cont)

Limitations of Nonlocal Jumps

■ Works within stack discipline

- Can only long jump to environment of function that has been called but not yet completed

```
jmp_buf env;  
  
P1()  
{  
    if (setjmp(env)) {  
        /* Long Jump to here */  
    } else {  
        P2();  
    }  
}  
  
P2()  
{ . . . P2(); . . . P3(); }  
  
P3()  
{  
    longjmp(env, 1);  
}
```



Limitations of Long Jumps (cont.)

■ Works within stack discipline

- Can only long jump to environment of function that has been called but not yet completed

```

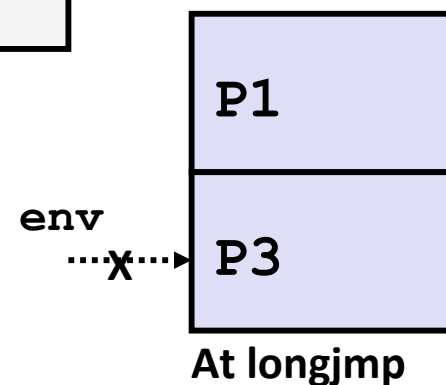
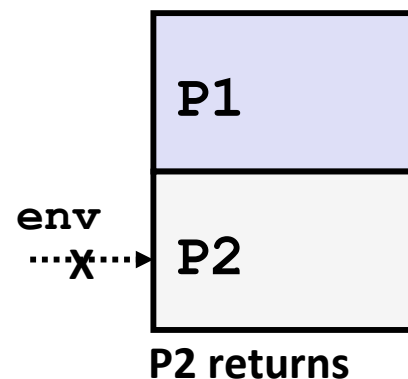
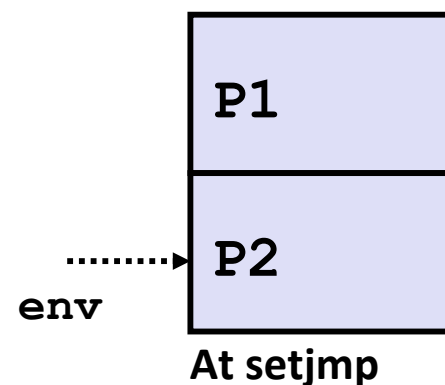
jmp_buf env;

P1 ()
{
    P2 () ; P3 () ;
}

P2 ()
{
    if (setjmp(env)) {
        /* Long Jump to here */
    }
}

P3 ()
{
    longjmp(env, 1) ;
}

```



Putting It All Together: A Program That Restarts Itself When `ctrl-c`'d

```
#include "csapp.h"

sigjmp_buf buf;

void handler(int sig)
{
    siglongjmp(buf, 1);
}

int main()
{
    if (!sigsetjmp(buf, 1)) {
        Signal(SIGINT, handler);
        Sio_puts("starting\n");
    }
    else
        Sio_puts("restarting\n");

    while(1) {
        Sleep(1);
        Sio_puts("processing...\n");
    }
    exit(0); /* Control never reaches here */
}
```

```
greatwhite> ./restart
starting
processing...
processing...
processing...
restarting
processing... ← Ctrl-c
processing...
restarting
processing... ← Ctrl-c
processing...
processing...
```

restart.c