signals

Unix-like operating system feature

like exceptions for processes:

can be triggered by external process
  kill command/system call

can be triggered by special events
  pressing control-C
  other events that would normal terminate program
    'segmentation fault'
    illegal instruction
    divide by zero

can invoke signal handler (like exception handler)

exceptions v signals

(hardware) exceptions	signals
handler runs in kernel mode	handler runs in user mode
hardware decides when	OS decides when
hardware needs to save PC	OS needs to save PC + registers
processor next instruction changes	thread next instruction changes

exceptions v signals

(hardware) exceptions	signals
handler runs in kernel mode	handler runs in user mode
hardware decides when	OS decides when
hardware needs to save PC	OS needs to save PC + registers
processor next instruction changes	thread next instruction changes

...but OS needs to run to trigger handler
most likely "forwarding" hardware exception

exceptions v signals

(hardware) exceptions	signals
handler runs in kernel mode	handler runs in user mode
hardware decides when	OS decides when
hardware needs to save PC	OS needs to save PC + registers
processor next instruction changes	thread next instruction changes

signal handler follows normal calling convention
not special assembly like typical exception handler

exceptions v signals

(hardware) exceptions	signals
handler runs in kernel mode	handler runs in user mode
hardware decides when	OS decides when
hardware needs to save PC	OS needs to save PC + registers
processor next instruction changes	thread next instruction changes

signal handler runs in same thread ('virtual processor') as process was using before

not running at 'same time' as the code it interrupts

base program

```
int main() {
    char buf[1024];
    while (fgets(buf, sizeof buf, stdin)) {
        printf("read %s", buf);
    }
}
```

base program

```c
int main() {
    char buf[1024];
    while (fgets(buf, sizeof buf, stdin)) {
        printf("read %s", buf);
    }
}
```

---

some input
read some input
more input
read more input
(control-C pressed)
(program terminates immediately)

base program

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int main() {
    char buf[1024];
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read some input
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read more input
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(program terminates immediately)

new program

```c
int main() {
    ... // added stuff shown later
    char buf[1024];
    while (fgets(buf, sizeof buf, stdin)) {
        printf("read %s", buf);
    }
}
```

---

some input
read some input
more input
read more input
(control-C pressed)
Control-C pressed?!
another input **read another input**

new program

```
int main() {
    ... // added stuff shown later
    char buf[1024];
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    }
}
```

---

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read some input
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read more input
(control-C pressed)
Control-C pressed?!
another input **read another input**

new program

```
int main() {
    ... // added stuff shown later
    char buf[1024];
    while (fgets(buf, sizeof buf, stdin)) {
        printf("read %s", buf);
    }
}
```

some input
read some input
more input
read more input
(control-C pressed)
Control-C pressed?!
another input **read another input**

example signal program

```
void handle_sigint(int signum) {
    /* signum == SIGINT */
    write(1, "Control-C pressed?!\n",
        sizeof("Control-C pressed?!\n"));
}

int main(void) {
    struct sigaction act;
    act.sa_handler = &handle_sigint;
    sigemptyset(&act.sa_mask);
    act.sa_flags = SA_RESTART;
    sigaction(SIGINT, &act, NULL);

    char buf[1024];
    while (fgets(buf, sizeof buf, stdin)) {
        printf("read %s", buf);
    }
}
```
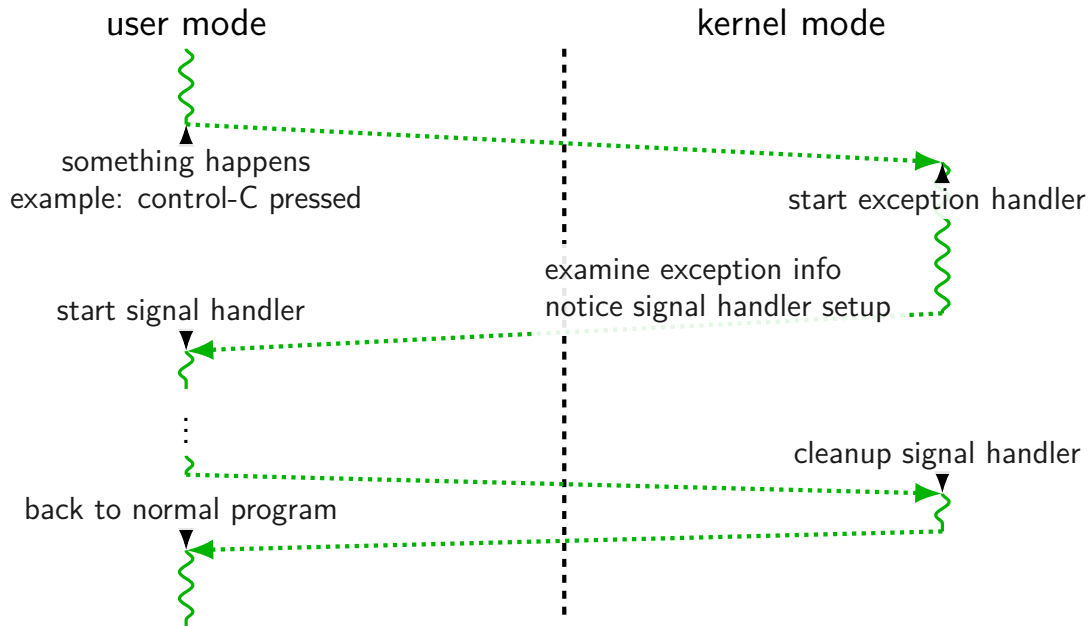
example signal program

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    /* signum == SIGINT */
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    sigaction(SIGINT, &act, NULL);

    char buf[1024];
    while (fgets(buf, sizeof buf, stdin)) {
        printf("read %s", buf);
    }
}
```

example signal program

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void handle_sigint(int signum) {
    /* signum == SIGINT */
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int main(void) {
    struct sigaction act;
    act.sa_handler = &handle_sigint;
    sigemptyset(&act.sa_mask);
    act.sa_flags = SA_RESTART;
    sigaction(SIGINT, &act, NULL);

    char buf[1024];
    while (fgets(buf, sizeof buf, stdin)) {
        printf("read %s", buf);
    }
}
```

'forwarding' exception as signal

user mode   kernel mode

something happens
example: control-C pressed

start exception handler

examine exception info
notice signal handler setup

start signal handler

cleanup signal handler

back to normal program

SIGxxxx

signals types identified by number…

constants declared in `<signal.h>`

constant	likely use
SIGBUS	"bus error"; certain types of invalid memory accesses
SIGSEGV	"segmentation fault"; other types of invalid memory accesses
SIGINT	what control-C usually does
SIGFPE	"floating point exception"; includes integer divide-by-zero
SIGHUP, SIGPIPE	reading from/writing to disconnected terminal/socket
SIGUSR1, SIGUSR2	use for whatever you (app developer) wants
SIGKILL	terminates process (cannot be handled by process!)
SIGSTOP	suspends process (cannot be handled by process!)
…	…

SIGxxxx

signals types identified by number…

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SIGUSR1, SIGUSR2	use for whatever you (app developer) wants
SIGKILL	terminates process (cannot be handled by process!)
SIGSTOP	suspends process (cannot be handled by process!)
…	…

handling Segmentation Fault

```
...
void handle_sigsegv(int num) {
    puts("got SIGSEGV");
}

int main(void) {
    struct sigaction act;
    act.sa_handler = handle_sigsegv;
    sigemptyset(&act.sa_mask);
    act.sa_flags = SA_RESTART;
    sigaction(SIGSEGV, &act, NULL);

    asm("movq %rax, 0x12345678");
}
```

handling Segmentation Fault

```
...
void handle_sigsegv(int num) {
    puts("got SIGSEGV");
}

int main(void) {
    struct sigaction act;
    act.sa_handler = handle_sigsegv;
    sigemptyset(&act.sa_mask);
    act.sa_flags = SA_RESTART;
    sigaction(SIGSEGV, &act, NULL);

    asm("movq %rax, 0x12345678");
}
```

got SIGSEGV
got SIGSEGV
got SIGSEGV
got SIGSEGV

signal API

`sigaction` — register handler for signal

`kill` — send signal to process
  uses process ID (integer, retrieve from `getpid()`)

`pause` — put process to sleep until signal received

`sigprocmask` — temporarily block/unblock some signals from being received
  signal will still be *pending*, received if unblocked

… and much more

kill command

kill command-line command : calls the kill() function

`kill 1234` — sends SIGTERM to pid 1234
     in C: `kill(1234, SIGTERM)`

`kill -USR1 1234` — sends SIGUSR1 to pid 1234
     in C: `kill(1234, SIGUSR1)`

SA_RESTART

```
struct sigaction sa; …
sa.sa_flags = SA_RESTART;
    general version:
    sa.sa_flags = SA_NAME | SA_NAME | SA_NAME; (or 0)
```

if SA_RESTART included:

   after signal handler runs, attempt to restart interrupted operations (e.g. reading from keyboard)

if SA_RESTART not included:

   after signal handler runs, interrupted operations return typically an error (errno == EINTR)

output of this?

pid 1000

```
void handle_usr1(int num) {
    write(1, "X", 1);
    kill(2000, SIGUSR1);
    _exit(0);
}

int main() {
    struct sigaction act;
    act.sa_handler = &handle_usr1;
    sigaction(SIGUSR1, &act, NULL);
    kill(1000, SIGUSR1);
}
```

pid 2000

```
void handle_usr1(int num) {
    write(1, "Y", 1);
    _exit(0);
}

int main() {
    struct sigaction act;
    act.sa_handler = &handle_usr1;
    sigaction(SIGUSR1, &act, NULL);
}
```

If these run at same time, expected output?
A. XY   B. X   C. Y
D. YX   E. X or XY, depending on timing   F. crash
G. (nothing)   H. something else

output of this? (v2)

pid 1000

```
void handle_usr1(int num) {
    write(1, "X", 1);
    kill(2000, SIGUSR1);
    _exit(0);
}

int main() {
    struct sigaction act;
    act.sa_handler = &handle_usr1;
    sigaction(SIGUSR1, &act);
    kill(1000, SIGUSR1);
    while (1) pause();
}
```

pid 2000

```
void handle_usr1(int num) {
    write(1, "Y", 1);
    _exit(0);
}

int main() {
    struct sigaction act;
    act.sa_handler = &handle_usr1;
    sigaction(SIGUSR1, &act);
    while (1) pause();
}
```

If these run at same time, expected output?

A. XY   B. X   C. Y
D. YX   E. X or XY, depending on timing   F. crash
G. (nothing)   H. something else

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sending signals (1)

```
void handle_usr1(int num) {
    write(1, "Y", 1);
    kill(2000, SIGUSR2);
}

int main() {
    struct sigaction act;
    ... // initialize act
    act.sa_handler = &handle_usr1;
    sigaction(SIGUSR1, &act, NULL);
    sleep(60); // wait for pid 2000 to start
    kill(2000, SIGUSR1);
    while (1) pause();
}
```

sending signals (2)

pid 1000

```
void handle_usr1(int num) {
    write(1, "Y", 1);
    kill(2000, SIGUSR2);
}

int main() {
    struct sigaction act;
    ... // initialize act
    act.sa_handler = &handle_usr1;
    sigaction(SIGUSR1, &act, NULL);
    sleep(60); // wait for pid 2000 to start
    kill(2000, SIGUSR1);
    while (1) pause();
}
```

pid 2000

```
void handle_usr1(int num) {
    write(1, "X", 1);
    kill(1000, SIGUSR1);
}

void handle_usr2(int num) {
    write(1, "Z", 1);
    kill(1000, SIGTERM);
    _exit(0);
}

int main() {
    struct sigaction act;
    ... // initialize act
    act.sa_handler = &handle_usr1;
    sigaction(SIGUSR1, &act, NULL);
    act.sa_handler = &handle_usr2;
    sigaction(SIGUSR2, &act, NULL);
    while (1) pause();
}
```

sending signals (2)

pid 1000

```c
void handle_usr1(int num) {
    write(1, "Y", 1);
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}

int main() {
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    act.sa_handler = &handle_usr1;
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    kill(2000, SIGUSR1);
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}
```

pid 2000

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void handle_usr1(int num) {
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int main() {
    struct sigaction act;
    ... // initialize act
    act.sa_handler = &handle_usr1;
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sending signals (2)

pid 1000

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}
```

pid 2000

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    while (1) pause();
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sending signals (2)

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```

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sending signals (2)

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sending signals (2)

pid 1000

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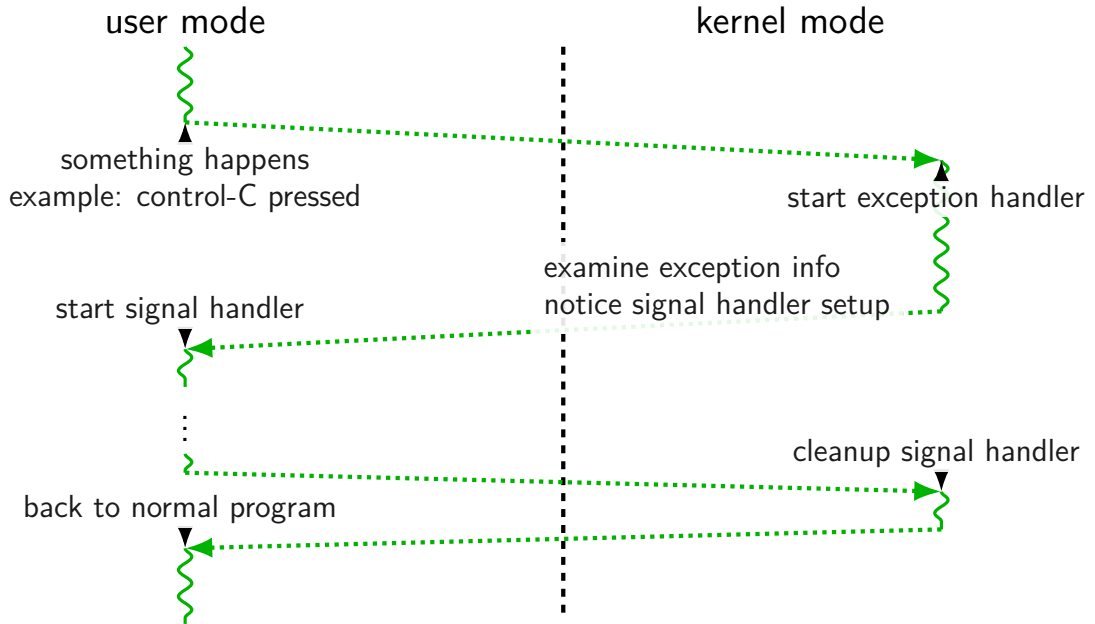
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    while (1) pause();
}
```

'forwarding' exception as signal

user mode   kernel mode

something happens
example: control-C pressed

start exception handler

examine exception info
notice signal handler setup

start signal handler

cleanup signal handler

back to normal program

x86-64 Linux signal delivery (1)

suppose: signal (with handler) happens while `foo()` is running

should stop in the middle of foo()

do signal handler

go back to foo() without…

changing local variables (possibly in registers)

(and foo() doesn't have code to do that)

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should stop in the middle of foo()

do signal handler

go back to foo() without…

changing local variables (possibly in registers)

(and foo() doesn't have code to do that)

x86-64 Linux signal delivery (2)

suppose: signal (with handler) happens while `foo()` is running

OS saves registers to user stack

OS modifies user registers, PC to call signal handler

the stack

address of `__restore_rt`
saved registers
PC when signal happened
local variables for foo
…

stack pointer
when signal handler started

stack pointer
before signal delivered

x86-64 Linux signal delivery (3)

```
handle_sigint:
    ...
    ret
...
__restore_rt:
    // 15 = "sigreturn" system call
    movq $15, %rax
    syscall
```

__restore_rt is return address for signal handler

sigreturn syscall restores pre-signal state
    if SA_RESTART set, restarts interrupted operation
    also handles caller-saved registers
    also might change which signals blocked (depending how sigaction was called)

signal handler unsafety (0)

```
void foo() {
    /* SIGINT might happen while foo() is running */
    char *p = malloc(1024);
    ...
}

/* signal handler for SIGINT
   (registered elsewhere with sigaction() */
void handle_sigint() {
    printf("You pressed control-C.\n");
}
```

signal handler unsafety (1)

```
void *malloc(size_t size) {
    ...
    to_return = next_to_return;
    /* SIGNAL HAPPENS HERE */
    next_to_return += size;
    return to_return;
}

void foo() {
    /* This malloc() call interrupted */
    char *p = malloc(1024);
    p[0] = 'x';
}

void handle_sigint() {
    // printf might use malloc()
    printf("You pressed control-C.\n");
}
```
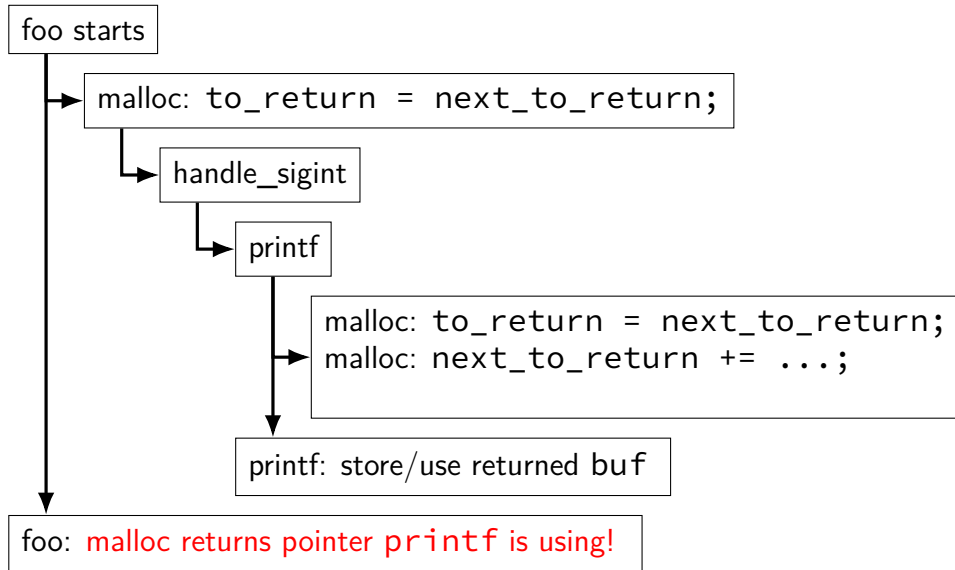
signal handler unsafety (1)

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void *malloc(size_t size) {
    ...
    to_return = next_to_return;
    /* SIGNAL HAPPENS HERE */
    next_to_return += size;
    return to_return;
}

void foo() {
    /* This malloc() call interrupted */
    char *p = malloc(1024);
    p[0] = 'x';
}

void handle_sigint() {
    // printf might use malloc()
    printf("You pressed control-C.\n");
}
```

signal handler unsafety (2)

```
void handle_sigint() {
    printf("You pressed control-C.\n");
}

int printf(...) {
    static char *buf;
    ...
    buf = malloc()
    ...
}
```

signal handler unsafety: timeline

```
foo starts
```

```
malloc: to_return = next_to_return;
```

```
handle_sigint
```

```
printf
```

```
malloc: to_return = next_to_return;
malloc: next_to_return += ...;
```

```
printf: store/use returned buf
```

```
foo: malloc returns pointer printf is using!
```

signal handler unsafety (3)

```
foo() {
  char *p = malloc(1024)... {
    to_return = next_to_return;
    handle_sigint() { /* signal delivered here */
      printf("You pressed control-C.\n") {
        buf = malloc(...) {
          to_return = next_to_return;
          next_to_return += size;
          return to_return;
        }
        ...
      }
    }
  }
  next_to_return += size;
  return to_return;
}
/* now p points to buf used by printf! */
}
```

signal handler unsafety (3)

```
foo() {
  char *p = malloc(1024)... {
    to_return = next_to_return;
    handle_sigint() { /* signal delivered here */
      printf("You pressed control-C.\n") {
        buf = malloc(...) {
          to_return = next_to_return;
          next_to_return += size;
          return to_return;
        }
        ...
      }
    }
    next_to_return += size;
    return to_return;
  }
  /* now p points to buf used by printf! */
}
```

signal handler safety

POSIX (standard that Linux follows) defines "async-signal-safe" functions

these must work correctly no matter what they interrupt

...and no matter how they are interrupted

includes: `write`, `_exit`

does not include: `printf`, `malloc`, `exit`

blocking signals

avoid having signal handlers anywhere:

can instead block signals
    `sigprocmask()`, `pthread_sigmask()`

blocked = signal handled doesn't run
    signal not *delivered*

instead, signal becomes *pending*

controlling when signals are handled

first, block a signal

then use API for inspecting pending signals
  example: `sigwait`
  typically instead of having signal handler

and/or unblock signals only at certain times
  some special functions to help:
  `sigsuspend` (unblock until handler runs),
  `pselect` (unblock while checking for I/O), …

synchronous signal handling

```c
int main(void) {
    sigset_t set;
    sigemptyset(&set);
    sigaddset(&set, SIGINT);
    sigprocmask(SIG_BLOCK, &set, NULL);

    printf("Waiting for SIGINT (control-C)\n");
    int num;
    if (sigwait(&set, &num) != 0) {
        printf("sigwait failed!\n");
    }
    if (num == SIGINT);
        printf("Got SIGINT\n");
    }
}
```

backup slides