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 program counter changes	thread program counter changes

program counter = instruction to run next

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 program counter changes	thread program counter changes

program counter = instruction to run next

...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 program counter changes	thread program counter changes

program counter = instruction to run next

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 program counter changes	thread program counter changes

program counter = instruction to run next

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

```
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

```
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)

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**

new program

```
int main() {
    ... // added stuff shown later
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    while (fgets(buf, sizeof buf, stdin)) {
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    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

```
void handle_sigint(int signum) {
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}
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example signal program

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    act.sa_handler = &handle_sigint;
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    act.sa_flags = SA_RESTART;
    sigaction(SIGINT, &act, NULL);

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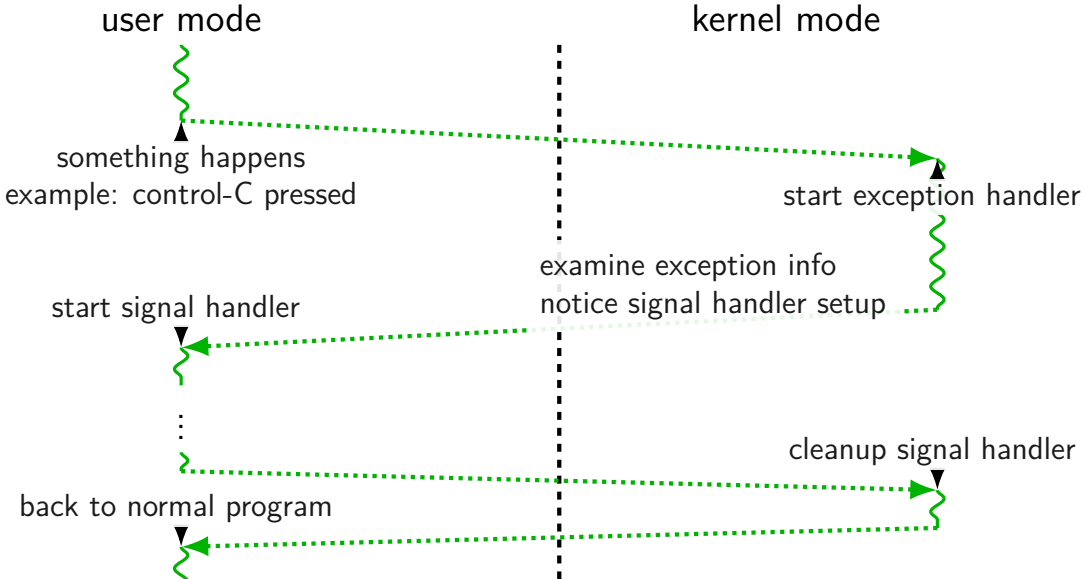

‘forwarding’ exception as signal



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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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
```

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

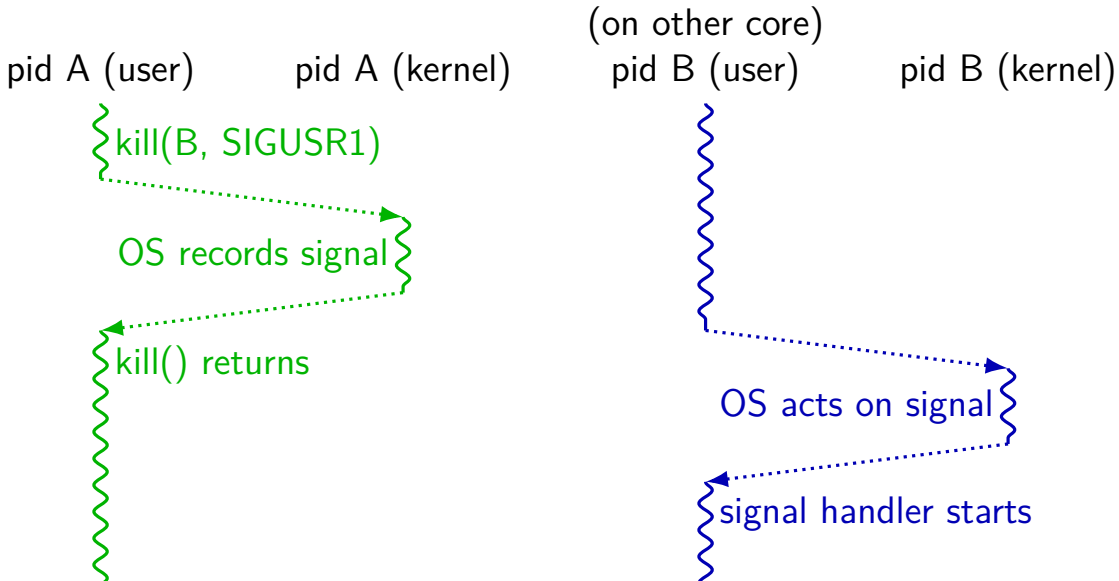
`kill 1234` — sends SIGTERM to pid 1234

in C: `kill(1234, SIGTERM)`

`kill -USR1 1234` — sends SIGUSR1 to pid 1234

in C: `kill(1234, SIGUSR1)`

kill() not always immediate



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 (detect by checking `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

sending signals (1)

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();
}
```

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)

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    write(1, "Y", 1);
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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

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void handle_usr1(int num) {
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    write(1, "Z", 1);
    kill(1000, SIGTERM);
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int main() {
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sending signals (2)

pid 1000

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    act.sa_handler = &handle_usr1;
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    sigaction(SIGUSR2, &act, NULL);
    while (1) pause();
}
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sending signals (2)

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

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");
}
```

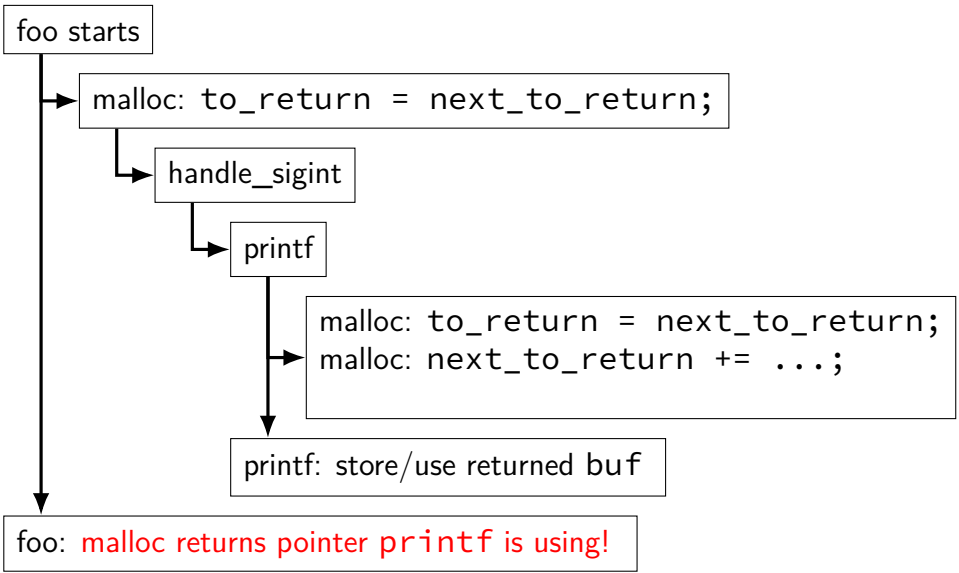
signal handler unsafety (1)

```
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



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*

- delivered if unblocked

blocking signals

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`sigprocmask()`, `pthread_sigmask()`

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signal not *delivered*

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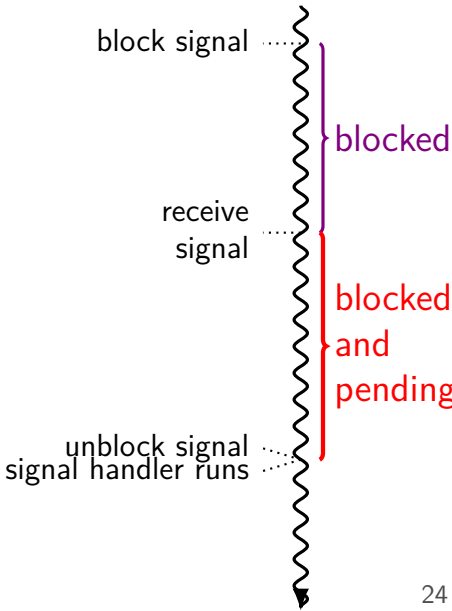


controlling when signals are handled

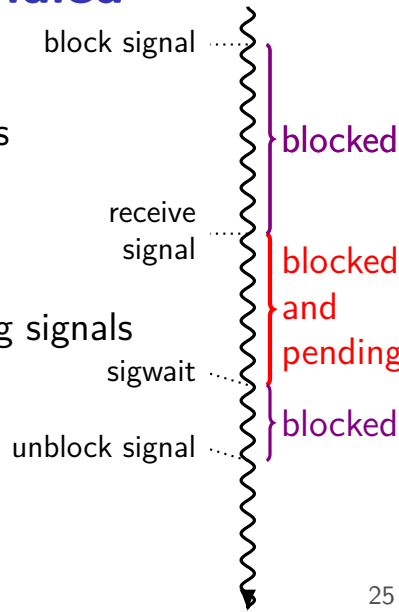
first, block a signal

then either unblock signals only at certain times

- some special functions to help:
  `sigsuspend` (unblock until handler runs),
  `pselect` (unblock while checking for I/O), ...

and/or use API for inspecting/changing pending signals

- example: `sigwait`
- typically instead of having signal handler



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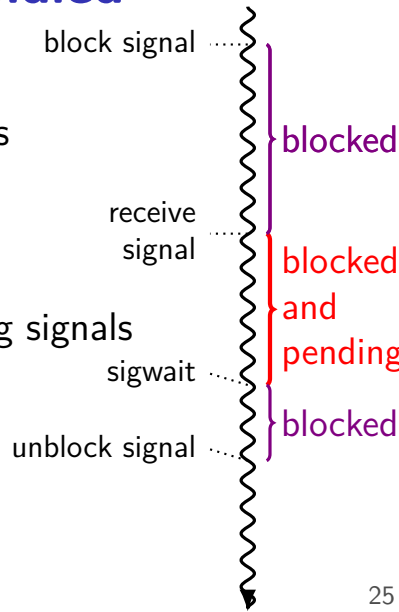


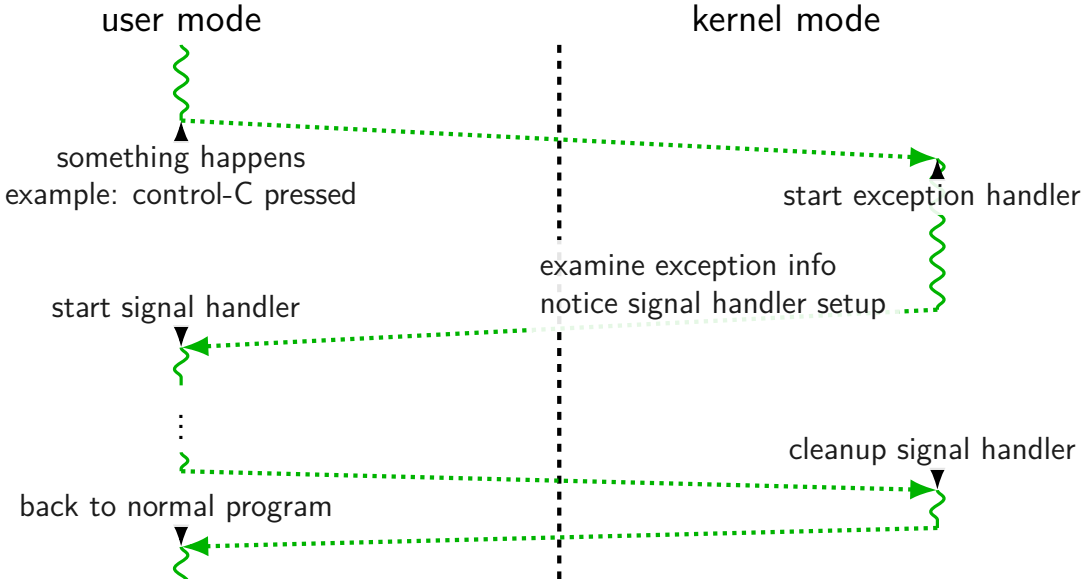
synchronous signal handling

```
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

‘forwarding’ exception as signal



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)

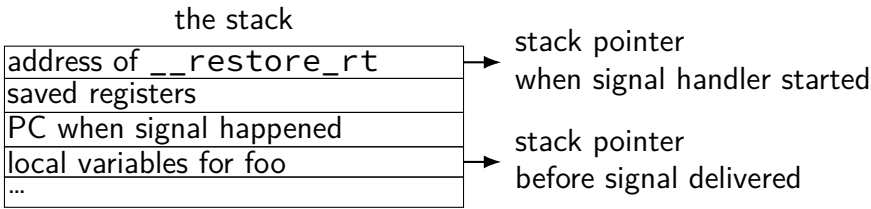
(and foo() doesn't have code to do that)

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



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)