2.2.4 Thread Safety

Thread Safety

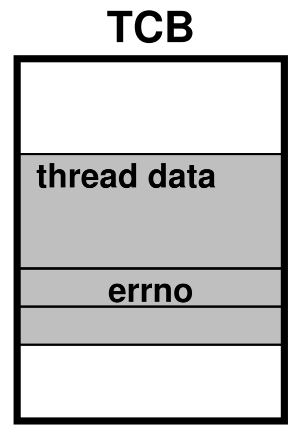
- Unix was developed way before threads were commonly used
  - Unix libraries were built without threads in mind
  - running code using these libraries with threads became unsafe
  - to make these libraries safe to run under *multithreading* is known as *Thread Safety*
    - strictly speaking, making code *thread-safe* is not the same as making code *reentrant*
      - "reentrant" code applies to single thread case as well
      - all "reentrant" code are "thread-safe", but not the other way around
- General problems with the old Unix API
  - global variables
    - e.g., `errno`
  - shared data
    - e.g., `printf()`

Global Variables

```
int IOfunc(int fd) {
  extern int errno;
  ...
  if (write(fd, buffer, size) == -1) {
    if (errno == EIO)
      fprintf(stderr, "IO problems ...\n");
    ...
    return(0);
  }
  ...
}
```

- if 2 threads call this function and both failed, how do you guarantee that a thread would get the right `errno`?
  - the code is *not "reentrant"*
- `errno` is a system-call level *global variable*
  - Unix system-call library was implemented before multi-threading was a common practice

Coping



- Fix Unix's C/system-call interface
  - want backwards compatibility
- Make `errno` refer to a different location in each thread
  - e.g.,

```
#define errno __errno(thread_ID)
```

  - `__errno(thread_ID)` will return the ***thread-specific*** `errno`
    - need a place to store this thread-specific `errno`
    - POSIX threads provides a general mechanism to store ***thread-specific data***
      - Win32 has something similar called thread-local storage
    - POSIX does not specify how this private storage is allocated and organized
      - done with an array of `(void*)`
      - then `errno` would be at a fixed index into this array
      - see textbook on exactly how this is done

Add "Reentrant" Version Of System Call

- `gethostbyname()` system call is not reentrant

```
struct hostent *gethostbyname(const char *name)
```

  - it returns a pointer to a global variable
    - (what a terrible idea!)
  - POSIX's fix for this problem is to add a function to the system library

```
int gethostbyname_r(const char *name,
                    struct hostent *ret,
                    char *buf,
                    size_t buflen,
                    struct hostent **result,
                    int *h_errnop)
```

    - caller of this function must provide the buffer to hold the return data
      - (a good idea in general)
    - caller is aware of thread-safety
      - (a more educated programmer is desirable)

Shared Data

- **Thread 1:**

```
printf("goto statement reached");
```

- **Thread 2:**

```
printf("Hello World\n");
```

- **Printed on display:**

```
goto Hello Wostatement reachedrld
```

Coping

- Wrap library calls with synchronization constructs
- Fix the libraries
- Application can use a mutex
- If application is using the `(FILE*)` object in `<stdio.h>`, can wrap functions like `printf()` around these functions

```
void flockfile(FILE *filehandle)
int ftrylockfile(FILE *filehandle)
void funlockfile(FILE *filehandle)
```

  - basically, `flockfile()` would block until lockcount is 0
    - then it increments the lockcount
  - `funlockfile()` decrements the lockcount

Killing Time ...

- To suspend your thread for a certain duration

```
struct timespec timeout, remaining_time;

timeout.tv_sec = 3;      // seconds
timeout.tv_nsec = 1000; // nanoseconds

nanosleep(&timeout, &remaining_time);
```

  - Unix/Linux is "best-effort"

- What if you don't want to wait for an "event" any more, after you have spent a certain amount of time waiting for it?

```
int pthread_cond_timedwait(
            pthread_cond_t *cond,
            pthread_mutex_t *mutex,
            struct timespec *abstime)
```

  - you need to calculate `abstime` carefully

Timeouts

```
struct timespec relative_timeout, absolute_timeout;
struct timeval now;
relative_timeout.tv_sec = 3;      // seconds
relative_timeout.tv_nsec = 1000; // nanoseconds
gettimeofday(&now, 0);
absolute_timeout.tv_sec = now.tv_sec +
    relative_timeout.tv_sec;
absolute_timeout.tv_nsec = 1000*now.tv_usec +
    relative_timeout.tv_nsec;
if (absolute_timeout.tv_nsec >= 1000000000) {
  // deal with the carry
  absolute_timeout.tv_nsec -= 1000000000;
  absolute_timeout.tv_sec++;
}
pthread_mutex_lock(&m);
while (!may_continue)
  pthread_cond_timedwait(&cv, &m, &absolute_timeout);
pthread_mutex_unlock(&m);
```

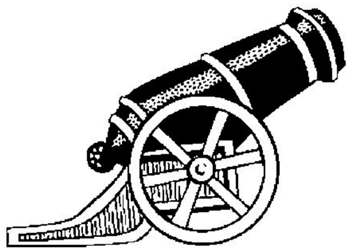
- must check return code of `pthread_cond_timedwait()`

2.2.5 Deviations

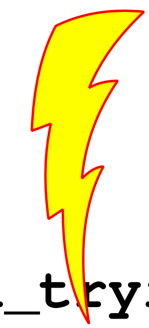
Deviations

- **How do you ask another thread to deviate from its normal execution path?**
  - **Unix's *signal* mechanism**
- **How do you force another thread to terminate cleanly**
  - **POSIX *cancellation* mechanism**

Signals



```
int x, y;

x = 0;
...
y = 16/x;
```



```
for (;;)
  keep_on_trying( );
```

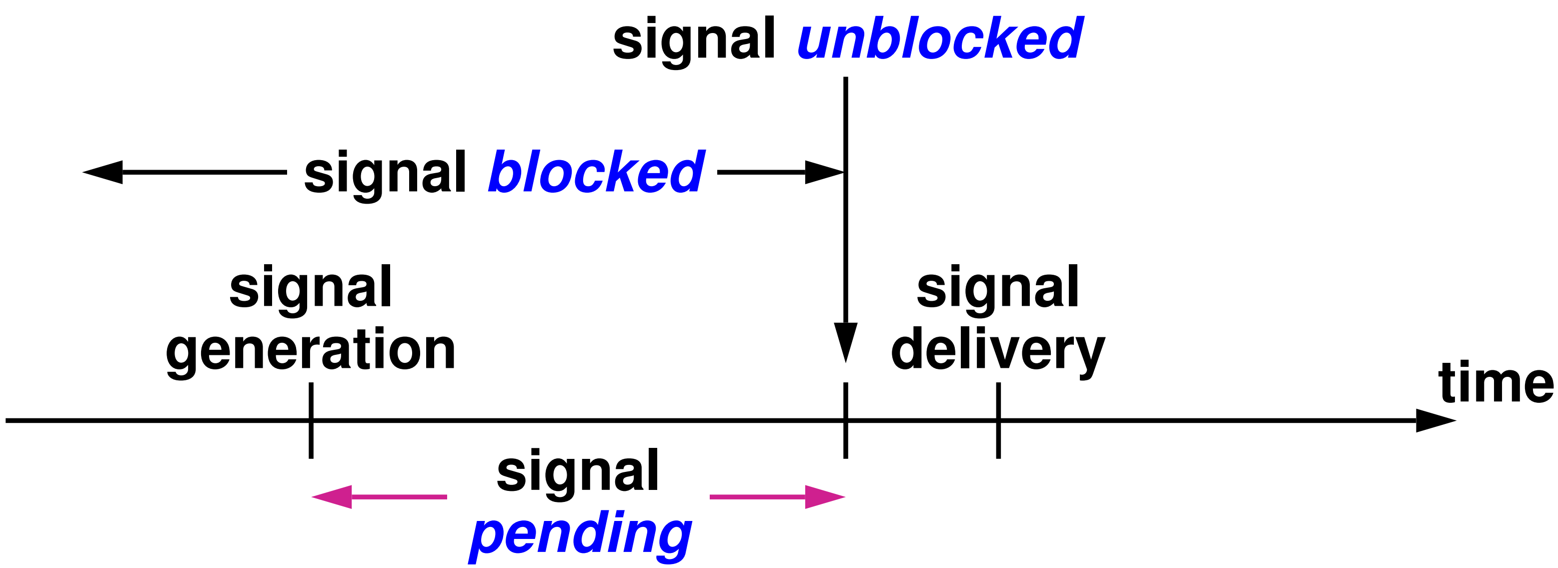
- the original intent of Unix signals was to force the ***graceful termination*** of a process
  - e.g., <Cntrl+C>

The OS to the Rescue

Signals

- some would call a *signal* a *software interrupt*
  - but it's really not
    - it's a "callback mechanism"
    - implemented in the OS by performing an *upcall*
- generated (by OS) in response to
  - exceptions (e.g., arithmetic errors, addressing problems)
  - external events (e.g., timer expiration, certain keystrokes, actions of other processes such as to terminate or pause the process)
  - user defined events
- effect on process:
  - termination (possibly after producing a core dump)
  - invocation of a procedure that has been set up to be a signal handler
  - suspension of execution
  - resumption of execution

Terminology



- A signal is *pending* if it's generated but *blocked*
  - when the signal becomes unblocked, it can be *delievered*
- Ex: <Cntrl+C>
- If you replaced the word "signal" with "interrupt" and "blocked/unblocked" with "disabled/enabled", everything would be correct for a hardware interrupt

Signal Types

Name	Description	Default Action
SIGABRT	`abort` called	term, core
SIGALRM	alarm clock	term
SIGCHLD	death of a child	ignore
SIGCONT	continue after stop	cont
SIGFPE	erroneous arithmetic operation	term, core
SIGHUP	hangup on controlling terminal	term
SIGILL	illegal instruction	term, core
SIGINT	interrupt from keyboard	term
SIGKILL	kill	forced term
SIGPIPE	write on pipe with no one to read	term
SIGQUIT	quit	term, core
SIGSEGV	invalid memory reference	term, core
SIGSTOP	stop process	forced stop
SIGTERM	software termination signal	term
SIGTSTP	stop signal from keyboard	stop
SIGTTIN	background read attempted	stop
SIGTTOU	background write attempted	stop
SIGUSR1	application-defined signal 1	stop
SIGUSR2	application-defined signal 2	stop

Sending a Signal

- `int kill(pid_t pid, int sig)`
  - send signal `sig` to process `pid`
  - (not always) terminate with extreme prejudice
- Also
  - type Ctrl-c (or <Cntrl+C>)
    - sends signal 2 (SIGINT) to current process
  - `kill` shell command
    - send SIGINT to process with pid=12345: "`kill -2 12345`"
  - do something illegal
    - bad address, bad arithmetic, etc.
- `int pthread_kill(pthread_t thr, int sig)`
  - send signal `sig` to thread `thr`

Handling Signals

- Singnal handler
  - each signal in a *process* can have *at most one handler*
  - to specify a signal handler of a process, use:
    - `sigset/signal()`
      - returns the current handler (which could be the "default handler")
    - `sigaction()`
      - more functionality

```
#include <signal.h>

typedef void (*sighandler_t)(int);

sighandler_t sigset(int signo, sighandler_t handler);
sighandler_t signal(int signo, sighandler_t handler);

sighandler_t OldHandler = sigset(SIGINT, NewHandler);
```

Special Handlers

- SIG_DFL
  - use the default handler
  - usually terminates the process
  - `sigset/signal(SIGINT, SIG_DFL);`
- SIG_IGN
  - ignore the signal
  - `sigset/signal(SIGINT, SIG_IGN);`

Example

```c
#include <signal.h>

int main() {
  void handler(int);

  sigset(SIGINT, handler);
  while(1)
    ;
  return 1;
}

void handler(int signo) {
  printf("I received signal %d. Whoopee!!\n", signo);
}
```

- *SIGINT is blocked* inside `handler()`
- but how do you kill this program from your console?
  - can use the "kill" shell command, e.g., "kill -15 <pid>"
- instead of using `sigset()`, you can also use `sigaction()`

Example

```c
#include <signal.h>

int main() {
  void handler(int);

  sigset(SIGINT, handler);
  while(1)
    ;
  return 1;
}

void handler(int signo) {
  printf("I received signal %d. Whoopee!!\n", signo);
  sigset(SIGINT, handler);
}
```

in some systems, you may have to re-establish the signal handler inside the signal handler if you want to receive the same signal more than once

sigaction

```
int sigaction(int sig,
              const struct sigaction *new,
              struct sigaction *old);

struct sigaction {
  void (*sa_handler)(int);
  void (*sa_sigaction)(int, siginfo_t *, void *);
  sigset_t sa_mask;
  int sa_flags;
};
```

- `sigaction()` allows for more complex behavior
  - e.g., block *additional* signals (specified by `sa_mask`) when handler is called

```
int main() {
  struct sigaction act;
  void sighandler(int);
  sigemptyset(&act.sa_mask);
  act.sa_flags = 0;
  act.sa_handler = sighandler;
  sigaction(SIGINT, &act, NULL);
  ...
}
```

Async-Signal Safety

- ***Async-Signal Safety:*** **Make your code safe when working with asynchronous signals**
- **The general rule to provide async-signal safety:**
  - **any data structure the signal handler accesses must be async-signal safe**
    - **i.e., an async signal cannot corrupt data structures**
- **An alternative is to make async-signal synchronous**
  - **use another thread to receive a particular signal**

Example 1: Waiting for a Signal

```
sigset(SIGALRM, DoSomethingInteresting);
...
struct timeval waitperiod = {0, 1000};
        /* seconds, microseconds */
struct timeval interval = {0, 0};
struct itimerval timerval;

timerval.it_value = waitperiod;
timerval.it_interval = interval;

setitimer(ITIMER_REAL, &timerval, 0);
        /* SIGALRM sent in ~one millisecond */

pause(); /* wait for it */
```

- can SIGALRM occur before `pause()` is called?

Example 2: Status Update

```
#include <signal.h>

computation_state_t state;

int main() {
  void handler(int);
  sigset(SIGINT, handler);
  long_running_proc();
  return 0;
}
```

```
void long_running_proc() {
  while (a_long_time) {
    update_state(&state);
    compute_more();
  }
}

void handler(int signo) {
  display(&state);
}
```

- long-running job that can take days to complete
  - the `handler()` can be used to print a progress report
  - need to make sure that `state` is in a consistent state
  - this is a synchronization issue
  - our `handler()` is not ***async-signal safe***

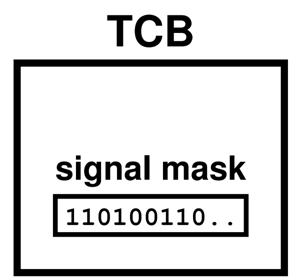
Example 2: Status Update

```
void long_running_proc() {
  while (a_long_time) {
    pthread_mutex_lock(&m);
    update_state(&state);
    pthread_mutex_unlock(&m);
    compute_more();
  }
}

void handler(int signo) {
  pthread_mutex_lock(&m);
  display(&state);
  pthread_mutex_unlock(&m);
}
```

- Does this work?
  - no
  - it may hang in `handler()` and cause *deadlock*
  - signal handler usually gets executed till *completion*
    - in general, keep it simple and brief

Masking (Blocking) Signals

- Solution: ***mask/block the signal***
  - don’t mask/block all signals, just the ones you want
  - a set of signals is represented as a set of bits
    - if a mask bit is 1, the corresponding signal is ***blocked***



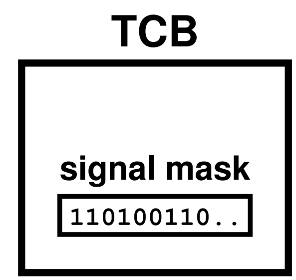
- To examine or change the signal mask of the calling process

```
#include <signal.h>
int sigprocmask(
    int how,
    const sigset_t *set,
    sigset_t *old);
```

- `how` is one of three commands:
  - SIG_BLOCK: the new signal mask is the union of the current signal mask and `set`
  - SIG_UNBLOCK: the new signal mask is the intersection of the current signal mask and the complement of `set`
  - SIG_SETMASK: the new signal mask is `set`

sigset_t

- There are bunch of functions to manipulate `sigset_t`
  - be careful, with *some APIs*, bits that are set correspond to *allowed* signals (with other APIs, they correspond to *blocked* signals)



- To clear a set:

```
int sigemptyset(sigset_t *set);
```

- To add or remove a signal from the set:

```
int sigaddset(sigset_t *set, int signo);
int sigdelset(sigset_t *set, int signo);
```

- Example: to refer to both SIGHUP and SIGINT:

```
sigset_t set;

sigemptyset(&set);
sigaddset(&set, SIGHUP);
sigaddset(&set, SIGINT);
```

```
sigset_t set;

sigfillset(&set);
sigdelset(&set, SIGHUP);
sigdelset(&set, SIGINT);
```

Example 1: Waiting for a Signal

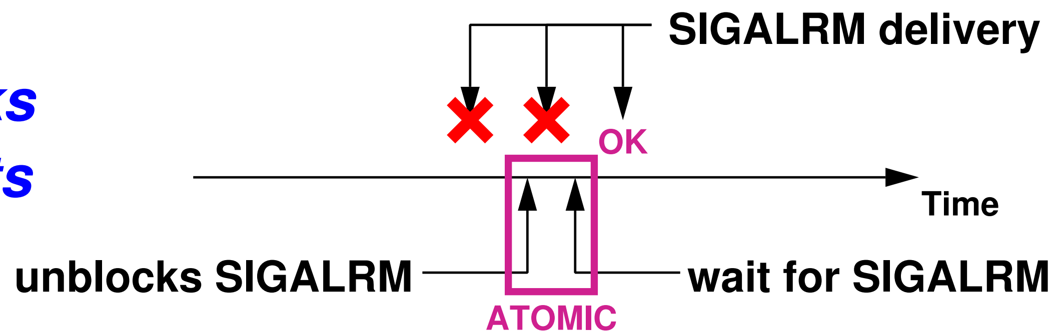
```
sigset_t set, oldset;
sigemptyset(&set);
sigaddset(&set, SIGALRM);
sigprocmask(SIG_BLOCK, &set, &oldset);
    /* SIGALRM now masked */
setitimer(ITIMER_REAL, &timerval, 0);
    /* SIGALRM sent in ~one millisecond */
sigfillset(&set);
sigdelset(&set, SIGALRM);
sigsuspend(&set); /* wait for it safely */
    /* SIGALRM masked again */
...
sigprocmask(SIG_SETMASK, &oldset, (sigset_t *)0);
    /* SIGALRM unmasked */
```

- `sigsuspend()` *replaces* the caller's signal mask with the set of signals pointed to by the argument
  - in the above, all signals are blocked/masked except for SIGALRM
  - *atomically* *unblocks* the signal and *waits* for the signal

Example 1: Waiting for a Signal

```
sigset_t set, oldset;
sigemptyset(&set);
sigaddset(&set, SIGALRM);
sigprocmask(SIG_BLOCK, &set, &oldset);
    /* SIGALRM now masked */
setitimer(ITIMER_REAL, &timerval, 0);
    /* SIGALRM sent in ~one millisecond */
sigfillset(&set);
sigdelset(&set, SIGALRM);
sigsuspend(&set); /* wait for it safely */
    /* SIGALRM masked again */
...
sigprocmask(SIG_SETMASK, &oldset, (sigset_t *)0);
    /* SIGALRM unmasked */
```

- `sigsuspend()`
  - *atomically unblocks* the signal and *waits* for the signal



Example 2: Status Update

```c
#include <signal.h>

computation_state_t state;
sigset_t set;

int main() {
  void handler(int);
  sigemptyset(&set);
  sigaddset(&set, SIGINT);
  sigset(SIGINT, handler);
  long_running_proc();
  return 0;
}
```

```c
void long_running_proc() {
  while (a_long_time) {
    sigset_t old_set;
    sigprocmask(
        SIG_BLOCK,
        &set,
        &old_set);
    update_state(&state);
    sigprocmask(
        SIG_SETMASK,
        &old_set,
        0);
    compute_more();
  }
}

void handler(int signo) {
  display(&state);
}
```

- now SIGINT cannot be delievered in `update_state()`

Signals and Threads

- In Unix, signals are sent to processes, not threads!
  - in a single-threaded process, it's obvious which thread would handle the signal
  - in a multi-threaded process, it's not so clear
    - in POSIX threads, the signal is delivered to a thread chosen *at random*

- What about the signal mask (i.e., blocked/enabled signals)?
  - should one set of sigmask affect all threads in a process?
  - or should each thread gets it own sigmask?
    - this certainly makes more sense

- POSIX rules for a multithreaded process:
  - the thread that is to receive the signal is chosen *randomly* from the set of threads that do not have the signal blocked
    - if all threads have the signal blocked, then the signal remains pending until some thread unblocks it
      - at which point the signal is delivered to that thread

Synchronizing Asynchrony

```
some_state_t state;
sigset_t set;

main() {
  pthread_t thread;
  sigemptyset(&set);
  sigaddset(&set,
            SIGINT);
  sigprocmask(
      SIG_BLOCK,
      &set, 0);
  // main thread
  //     blocks SIGINT
  pthread_create(
      &thread, 0,
      monitor, 0);
  long_running_proc();
}
```

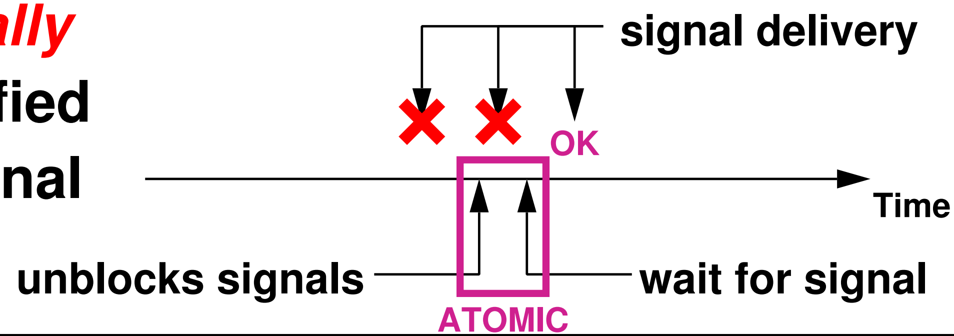
```
void long_running_proc() {
  while (a_long_time) {
    pthread_mutex_lock(&m);
    update_state(&state);
    pthread_mutex_unlock(&m);
    compute_more();
  }
}

void *monitor() {
  int sig;
  while (1) {
    sigwait(&set, &sig);
    pthread_mutex_lock(&m);
    display(&state);
    pthread_mutex_unlock(&m);
  }
  return(0);
}
```

- no need for signal handler!

sigwait

```
int sigwait(sigset_t *set, int *sig)
```

- `sigwait()` blocks until a signal specified in `set` is received
  - return which signal caused it to return in `sig`
  - if you have a signal handler specified for `sig`, it will *not* get invoked when the signal is delivered
    - instead, `sigwait()` will return
- You should make sure that all the threads in your process have these signals blocked!
  - this way, when `sigwait()` is called, the calling thread temporarily becomes the *only* thread in the process who can receive the signal
- `sigwait(set)` *atomically* *unblocks* signals specified in `set` and *waits* for signal delivery



Signals and Blocking System Calls

- What if a signal is generated while a process is blocked in a system call?
  1) deal with it when the system call completes
  2) interrupt the system call, deal with signal, resume system call
  3) interrupt system call, deal with signal, return from system call with indication that something happened

Interrupted System Calls

```
while(read(fd, buffer, buf_size) == -1) {
  if (errno == EINTR) {
    /* interrupted system call; try again */
    continue;
  }
  /* the error is more serious */
  perror("big trouble");
  exit(1);
}
```

- need to check the return value of `read()` because `read()` can return when less than `buf_size` bytes have been read
- can use similar code for writing
  - same consideration as `read()`

Interrupted While Underway

```
remaining = total_count; /* write this many bytes */
bptr = buf;              /* starting from here */
for ( ; ; ) {
  num_xfrd = write(fd, bptr, remaining);
  if (num_xfrd == -1) {
    if (errno == EINTR) {
      /* interrupted early */
      continue;
    }
    perror("big trouble");
    exit(1);
  }
  if (num_xfrd < remaining) {
    /* interrupted in the middle of write() */
    remaining -= num_xfrd;
    bptr += num_xfrd;
    continue;
  }
  /* success! */
  break;
}
```

Inside A Signal Handler

- Which library routines are safe to use *within* signal handlers?

access
aio_error
aio_suspend
alarm
cfgetispeed
cfgetospeed
cfsetispeed
cfsetospeed
chdir
chmod
chown
clock_gettime
close
creat
dup2
dup
execle
execve
_exit
fcntl
fdatasync
fork
fstat
fsync
getegid
geteuid
getgid
getoverrun
getgroups
getpgrp
getpid
getppid
getuid
kill
link
lseek
mkdir
mkfifo
open
pathconf
pause
pipe
rename
rmdir
sem_post
setgid
setpgid
setsid
setuid
sigaction
sigaddset
sigdelset
sigemptyset
sigfillset
sigismember
sigpending
sigprocmask
sigqueue
sigsuspend
sleep
stat
sysconf
tcdrain
tcflow
tcflush
tcgetattr
tcgetpgrp
tcsendbreak
tcsetattr
tcsetpgrp
time
timer_getoverrun
timer_gettime
timer_settime
times
umask
uname
unlink
utime
wait
waitpid
write

- Note: in general, you should only do what's absolutely necessary inside a signal handler (and figure out where to do the rest)

Cancellation

- The user pressed <Cntrl+C>
  - or a request is generated to terminate the process
  - the chores being performed by the remaining threads are no longer needed
  - in general, we may just want to cancel a bunch of threads and not the entire process

- Concerns
  - getting cancelled at an inopportune moment
    - should not leave a mutex locked
    - or leave a data structure in an inconsistent state
      - e.g., you get a cancellation request when you are in the middle of a `insert()` operation into a doubly-linked list and `insert()` is protected by a mutex
  - cleaning up

Cancellation State & Type

- Send cancellation request to a thread

```
pthread_cancel(thread)
```

- Cancels enabled or disabled

```
int pthread_setcancelstate(
    { PTHREAD_CANCEL_DISABLE,
      PTHREAD_CANCEL_ENABLE},
    &oldstate)
```

- Asynchronous vs. deferred cancels

```
int pthread_setcanceltype(
  { PTHREAD_CANCEL_ASYNCHRONOUS,
    PTHREAD_CANCEL_DEFERRED},
  &oldtype)
```

- By default, a thread has cancellation enabled and deferred
  - it's for a good reason
  - if you are going to change it, you must ask yourself, "Why?" and "Are you sure this is really a good idea?"

POSIX Cancellation Rules

- POSIX threads cancellation rules (part 1):
  - when `pthread_cancel()` gets called, the target thread is marked as having a *pending cancel*
    - the thread that called `pthread_cancel()` does not wait for the cancel to take effect
  - if the target thread has cancellation *disabled*, the target thread stays in the pending cancel state
  - if the target thread has cancellation *enabled* ...
    - if the cancellation type is *asynchronous*, the target thread immediately *acts on the cancel* (i.e., respond to cancellation)
    - if the cancellation type is *deferred*, cancellation is *delayed* until it reaches a *cancellation point* in its execution
      - cancellation points correspond to points in the thread's execution at which it is safe to *act on the cancel*

Cancellation Points

`aio_suspend`	`pthread_join`
`close`	`pthread_testcancel`
`creat`	`read`
`fcntl (when F_SETLCKW is the command)`	`sem_wait`
`fsync`	`sigsuspend`
`mq_receive`	`sigtimedwait`
`mq_send`	`sigwait`
`msync`	`sigwaitinfo`
`nanosleep`	`sleep`
`open`	`system`
`pause`	`tcdrain`
`pthread_cond_wait`	`wait`
`pthread_cond_timedwait`	`waitpid`
	`write`

- `pthread_mutex_lock()` is not on the list!
- `pthread_testcancel()` creates a cancellation point
  - useful if a thread contains no other cancellation point

POSIX Cancellation Rules

- POSIX threads cancellation rules (part 2):
  - when a thread *acts on the cancel*
    - walks through a *stack* of *cleanup handlers*
    - remember that the thread that called `pthread_cancel()` does not wait for the cancel to take effect
      - it may join and wait for the target thread to terminate

```
pthread_cleanup_push(
        (void)(*routine)(void *),
        void *arg)
pthread_cleanup_pop(int execute)
```

Example

```
list_item_t list_head;

void *GatherData(void *arg) {
  list_item_t *item;
  item = (list_item_t*)malloc(sizeof(list_item_t));

  // GetDataItem() contains many cancellation points
  GetDataItem(&item->value);

  insert(item);
  printf("Done.\n");
  return 0;
}
```

- How can this thread control when it acts on cancel?
  - so it doesn't leak memory

Example

```
list_item_t list_head;

void *GatherData(void *arg) {
  list_item_t *item;
  item = (list_item_t*)malloc(sizeof(list_item_t));
  pthread_setcancelstate(PTHREAD_CANCEL_DISABLE, 0);
  // GetDataItem() contains many cancellation points
  GetDataItem(&item->value);
  pthread_setcancelstate(PTHREAD_CANCEL_ENABLE, 0);
  insert(item);
  printf("Done.\n");
  return 0;
}
```

- How can this thread control when it acts on cancel?
  - so it doesn't leak memory
  - may delay cancellation for a long time if `GetDataItem()` takes a long time to run
    - in this example, controlling "when" is not a good idea

Example

```
list_item_t list_head;

void *GatherData(void *arg) {
  list_item_t *item;
  item = (list_item_t*)malloc(sizeof(list_item_t));
  pthread_cleanup_push(free, item);
  // GetDataItem() contains many cancellation points
  GetDataItem(&item->value);

  insert(item);
  printf("Done.\n");
  return 0;
}
```

- Can act on cancel inside `GetDataItem()`
  - in this case, will invoke `free(item)`
  - in C library, `free()` is defined as: `void free(void *ptr);`
    - perfectly matches the argument types of `pthread_cleanup_push()`

Example

```
list_item_t list_head;

void *GatherData(void *arg) {
  list_item_t *item;
  item = (list_item_t*)malloc(sizeof(list_item_t));
  pthread_cleanup_push(free, item);
  // GetDataItem() contains many cancellation points
  GetDataItem(&item->value);

  insert(item);
  printf("Done.\n");
  return 0;
}
```

- What if it acts on cancel inside `printf()`
  - will end up calling `free(item)` twice
    - can cause segmentation fault later

Example

```
list_item_t list_head;

void *GatherData(void *arg) {
  list_item_t *item;
  item = (list_item_t*)malloc(sizeof(list_item_t));
  pthread_cleanup_push(free, item);
  // GetDataItem() contains many cancellation points
  GetDataItem(&item->value);
  pthread_cleanup_pop(0);
  insert(item);
  printf("Done.\n");
  return 0;
}
```

- What if it acts on cancel inside `printf()`
  - will end up calling `free(item)` twice
    - can cause segmentation fault later
  - pop `free(item)` off the cleanup stack

Example

```
list_item_t list_head;

void *GatherData(void *arg) {
  list_item_t *item;
  item = (list_item_t*)malloc(sizeof(list_item_t));
  pthread_cleanup_push(free, item); // {
  // GetDataItem() contains many cancellation points
  GetDataItem(&item->value);
  pthread_cleanup_pop(0); // }
  insert(item);
  printf("Done.\n");
  return 0;
}
```

must match up *(like a **pair of brackets**)*

- `pthread_cleanup_push()` and the corresponding `pthread_cleanup_pop()` must match up (like a pair of brackets)
  - must not call `pthread_cleanup_push()` in one function and call the corresponding `pthread_cleanup_pop()` in another
    - compile-time error

Cancellation and Cleanup

```
void close_file(int fd) {
  close(fd);
}

fd = open(file, O_RDONLY);
pthread_cleanup_push(close_file, fd);
while(1) {
  read(fd, buffer, buf_size);
  // ...
}
pthread_cleanup_pop(0);
```

- should close any opened files when you clean up
- `int` is compatible with `void*`
  - well, sort of
  - `void*` can be a 64-bit quantity, so may need to be careful (best to be explicit)

Cancellation and Conditions

```
pthread_mutex_lock(&m);
pthread_cleanup_push(CleanupHandler, argument);

while(should_wait)
  pthread_cond_wait(&cv, &m);
// ... (code containing other cancellation points)
pthread_cleanup_pop(0);
pthread_mutex_unlock(&m);
```

- what should `CleanupHandler()` do?
- remember, if the thread is canceled between `push()` and `pop()`, we need to ensure that the mutex is left *unlocked*
- can `CleanupHandler()` just call `pthread_mutex_unlock()`?
  - `pthread_cond_wait()` is a cancellation point
  - must not unlock the mutex twice!
  - should `CleanupHandler()` call `pthread_mutex_lock()` then call `pthread_mutex_unlock()`?
    - what if the mutex is locked?

Cancellation and Conditions

```
pthread_mutex_lock(&m);
pthread_cleanup_push(pthread_mutex_unlock, &m);

while(should_wait)
  pthread_cond_wait(&cv, &m);
// ... (code containing other cancellation points)
pthread_cleanup_pop(1);
```

- pthreads library implementation ensures that a thread, when acting on a cancel inside `pthread_cond_wait()`, would first lock the mutex, before calling the cleanup routines
  - this way, the above code would work correctly

Cancellation & C++

```
void tcode() {
  A a1;
  pthread_cleanup_push(handler, 0);
  foo();
  pthread_cleanup_pop(0);
}

void foo() {
  A a2;
  pthread_testcancel();
}
```

- are the destructors of `a1` and `a2` getting called?
  - not sure
  - they should get called
  - some C++ implementation does not do this correctly!