Concurrent Programming with Pthreads

Clay Breshears
Rice University / ERDC MSRC
Henry A. Gabb
Nichols Research Corporation / ERDC MSRC

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Outline

- What are Threads?
- Pthreads (Core functions)
  - Threading Serial Codes
- Concurrent Programming
- Numerical Computation
- Pthreads (Advanced functions)

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Multitasking in Unix

- Heavy-weight processes spawned with fork
  - Preemptive and priority-based scheduling
- Usually do not share common address space
  - Sharing data can be cumbersome
  - Synchronization is complicated by preemption
  - Resources can be exhausted quickly
  - Application doesn't scale well with load

Processes

- Unix process requires:
  - program code, program counter, heap memory, stack memory, stack pointer, file descriptors, virtual memory table, signal table, etc.
- Process embodies two characteristics
  - Unit of Resource Ownership
  - Unit of Dispatching

Processes & Threads

- Can these characteristics be dealt with separately?
  - Recent thought says 'YES'
- Unit of Resource Ownership is PROCESS
- Unit of Dispatching is THREAD

Threads

- Each thread is a separate execution stream
  - private program counter, stack memory, stack pointer, signal table
- Multiple threads may exist within a single process
- Sometimes called “lightweight processes”
- Other thread libraries:
  - Solaris threads, Linux threads, DCE threads, Win32 and OS/2 threads, GNU Portable threads

What is Pthreads?

- POSIX.1c standard
- C language interface
- All threads exist within same Unix process
- All threads are peers
  - No explicit parent-child model
  - Exception: “main thread” holds process information

Advantages of Multithreading

As opposed to multiple processes

- Resource use
- Shared memory
- Low overhead; context switch

Resource Use

- Threads share all resources of process
  - (virtual) memory,
  - files,
  - I/O channels, etc.
- Smaller memory usage for thread control structures
  - Fields default to process control structure

Shared Memory

- Not swapped out for thread context switch
- Threads read/write to shared variables for communication
  - cost of two memory accesses
- Process to process must go through external sharing mechanisms
  - system calls, sockets, network wires

Low Overhead

- Solaris process vs. Solaris thread:
  - 30 times longer to create a process
  - 10 time slower for synchronizing variables
  - 5 times slower for context switch

Pthreads vs. OpenMP

- Pthreads
  - any thread may create new threads
  - computations can be dynamically parallel
  - thus, nested parallelism is possible
- OpenMP
  - nested parallelism not yet supported
  - often implemented as high-level interface to Pthreads

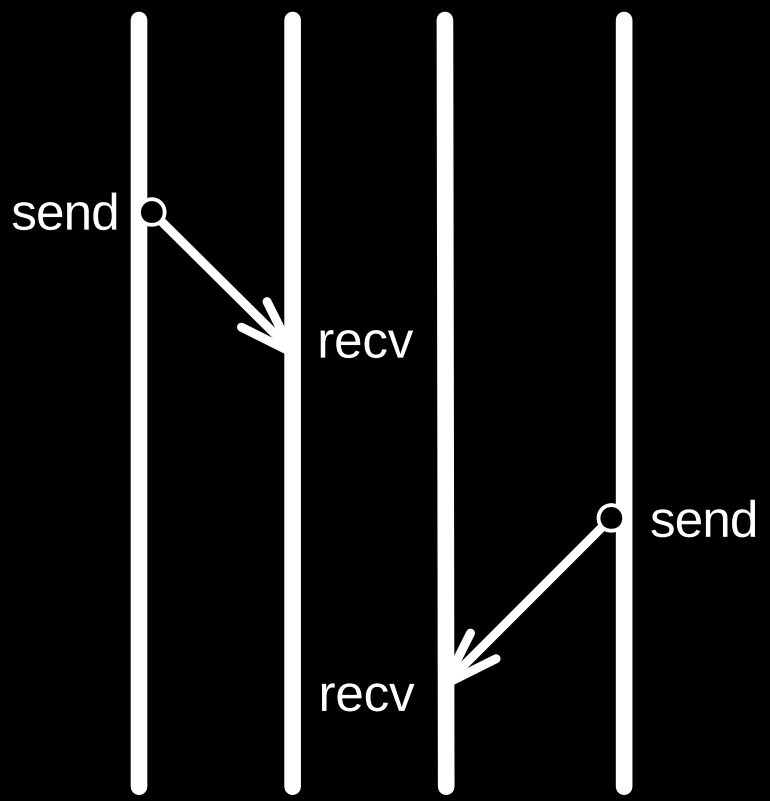
Parallelism or Concurrency?

- Parallelism: two or more threads are **executing** at the same time
  - multiple processors
- Concurrency: two or more threads are **in progress** at the same time
  - single or multiple processors
  - preemption of thread due to blocking or timeslice expiration

Thread Considerations

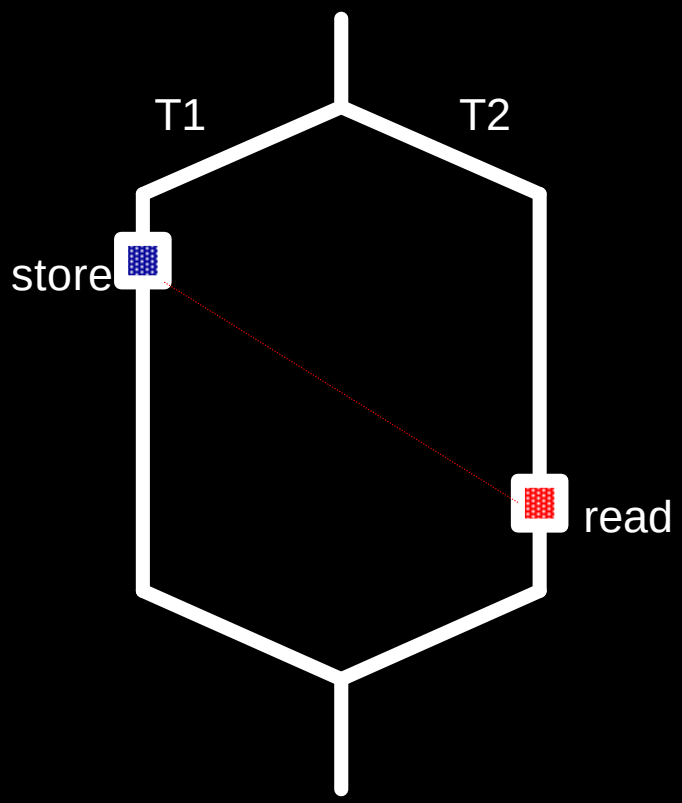
- Shared memory for communication
- Explicit synchronization needed
- Single processor model for development
- Race conditions
  - Read/Write, Write/Write conflicts
  - Models: Monitors, Rendezvous, Producer/Consumer, Readers/Writer

Parallel Communication



- Some parallel tasks wish to share data
- Messages become synchronization points between processes
  - implicitly synchronized

Thread Communication



- T1 stores value in global memory location
- T2 reads value out of global memory location
- Explicit synchronization needed to ensure read occurs after store

Race Condition

- Concurrent access of same variable by multiple threads
  - Read/Write conflict
  - Write/Write conflict
- Cause of other errors:
  - Execution order is assumed but is not guaranteed

Concurrent Execution

- Must consider all possible execution interleavings of thread operations
  - may be running on same processor
  - may be running on different processors
  - processors may have different speeds
- IF different output between separate runs:
  - THEN use some form of synchronization
  - may not show up 99 $^{44}/_{100}$% of the time

Concurrent Programming

- Concurrent programming requires skill
- "Standard" programming models available
  - Monitors
  - Rendezvous
  - Producer/Consumer
  - Readers/Writer

Traditional Thread Applications

- Operating Systems
- ATM (Cash Machine) Network
  - transactions at different locations are independent but act on shared data
- Database Search
  - threads can search different portions of data
  - each thread can satisfy a different query

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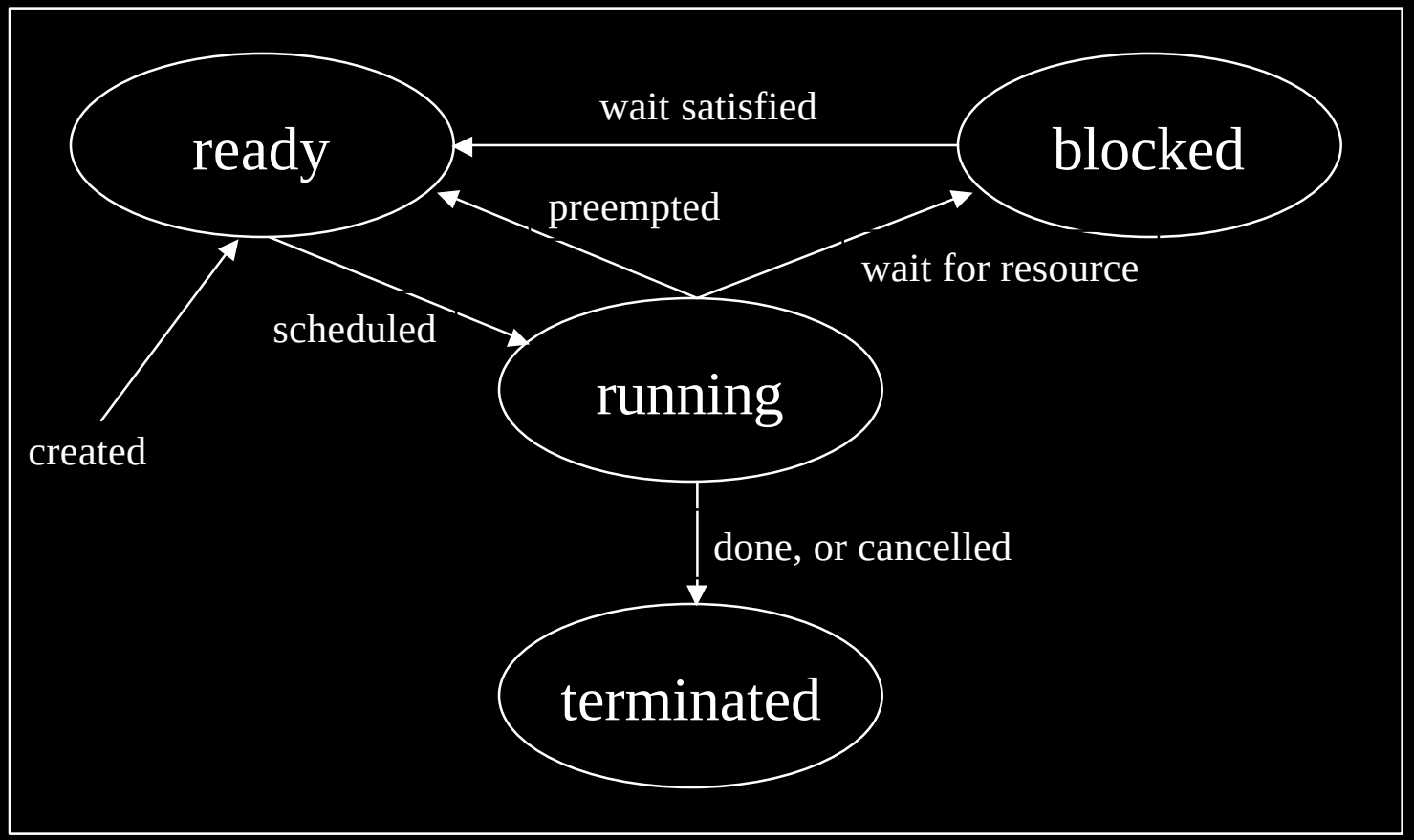
- Concurrent Programming
- Numerical Computation
- Pthreads (Advanced functions)

Overview of Core Functions

- Thread Data Types
- Thread Management
- Mutual Exclusion
- Condition Variables
- Attributes and error codes

"The Life of a Thread"

taken from Programming with POSIX Threads, David R. Butenhof



Thread Management

- pthread_create
  - create a thread
  - start execution of function mapped to thread
- pthread_join
  - wait for thread to finish
  - retrieve exit code from joined thread
- pthread_detach
  - thread can no longer be joined or canceled
  - reclaim thread resources upon termination

Thread Management

- pthread_self
  - retrieve thread handle
- pthread_exit
  - halt execution of calling thread
  - report exit code

Thread Management Data Types

- pthread_t
  - thread handle
- pthread_attr_t
  - thread attributes:
    - detach state
    - stack size
    - stack address
    - specifying NULL gives default thread attributes

pthread_create

- int pthread_create(tid, attr, function, arg);

pthread_t *tid

handle of created thread

const pthread_attr_t *attr

attributes of thread to be created

void *(*function)(void *)

function to be mapped to thread

void *arg

single argument to function

pthread_create

- Spawn a thread running the function
- Thread handle returned via pthread_t structure
- Specify NULL to use default attributes
- Single argument sent to function
  - If no arguments to function, specify NULL
- Check error codes!

Error codes: pthread_create

- EAGAIN
  - insufficient resources to create thread
- EINVAL
  - invalid attribute

pthread_join

- int pthread_join(tid, val_ptr);

pthread_t tid

handle of thread to be joined

void **val_ptr

exit code reported by joined thread

pthread_join

- Calling thread waits for thread with handle **`tid`** to terminate
- Exit code is returned from joined thread if not NULL
- Threads are joinable by default

Error codes: pthread_join

- ESRCH
  - thread (pthread_t) not found
- EINVAL
  - thread (pthread_t) not joinable

Example: “Hello World”

```
#include <stdio.h>
#include <pthread.h>
#define NUM_THREADS 4
main()
{
   pthread_t tid[NUM_THREADS];

   for (int i = 0; i < NUM_THREADS; i++)
       pthread_create(&tid[i], NULL, hello, NULL);

   for (int i = 0; i < NUM_THREADS; i++)
       pthread_join(&tid[i], NULL);
}
```

Example: “Hello World”

```
hello()
{
   printf(“Hello, World\n”);
}
```

pthread_detach

int pthread_detach(tid);

pthread_t tid

handle of thread to be detached

pthread_detach

- Detach thread **tid**
  - thread **tid** can no longer be joined or canceled
- Upon termination, detached thread resources are reclaimed by the system
- pthread_attr_{get|set}detachstate
  - PTHREAD_CREATE_JOINABLE
  - PTHREAD_CREATE_DETACHED

pthread_self

pthread_t pthread_self();

```
pthread_t tid;
int work, ierr;
if (work) {
   /* perform computation */
}
else {
   tid = pthread_self();
   ierr = pthread_detach( tid );   /* detach thread */
   /* begin independent processing */
}
```

pthread_exit

int pthread_exit(exitcode);

void *exitcode

value to be returned at join

- Terminates the calling thread
- Enables thread to report exit conditions to joining threads
- Allows main thread to exit without terminating process

Example: pthread_exit usage

```
#include <pthread.h>
#include <stdio.h>
#include <errno.h>
main () {
   int ierr;
   pthread_t tid;
   ierr = pthread_create(&tid, NULL, task, NULL);
   if (ierr != 0) {   /* failed to create thread */
      fprintf(stderr, “Error %d: %s\n”, ierr,
                                   strerror(ierr));
      pthread_exit( &ierr );
   }
}
```

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Getting Started

- Identify tasks for threading
- Identify computational model
  - Who does what?
  - Algorithms to use
- Identify how data will be accessed
  - What is global? What is local?
  - How is data to be assigned to threads?

Coding Considerations

- Create function to encapsulate computation
  - may be function that already exists
  - use single parameter (C structure for multiple arguments)
  - follow pthread_create template for types

Example: **`void *solve (void *arg)`**

Coding Considerations

- Recast parameter to local variable if needed
  - may be structure of several parameters
- Add code to determine task of thread
  - may need access to global variable
- Add code to access data for task
  - add code to protect global variables
  - shared data access may need to be restricted
- Add code to synchronize thread executions

Static Task Allocation

- Computations/Data are divided equally
  - based on number of threads and thread ID
- Typically access global data
  - must protect potential access overlaps
  - gather results into single location

Example: Numerical Integration

```
#define NUM_THREADS 1024
#define NUM_INTERVALS 65536
float p_sums[NUM_THREADS];
main()
{  pthread_t tid[NUM_THREADS];
   int i, t_num[NUM_THREADS];
   float sum = 0.0;
   for (i = 0; i < NUM_THREADS; i++){
        t_num[i] = i;
        pthread_create(&tid[i], NULL, do_calc, &t_num[i]);
   }
   for (i = 0; i < NUM_THREADS; i++){
        pthread_join(&tid[i], NULL);
        sum += p_sums[i];
   }
   printf("Sum = %f\n", sum);
}
```

Example: Numerical Integration

```
do_calc(void *num)
{  int i, h, myid, start, end;
   float lsum = 0.0, x;

   myid = (int)*num;
   h = 1.0 / NUM_INTERVALS;
   start = (NUM_INTERVALS / NUM_THREADS) * myid;
   end = start + (NUM_INTERVALS / NUM_THREADS);
   for (i = start; i < end; i++){
        x = h * ( (float)i - 0.5 );
        lsum += f(x);
   }
   p_sums[myid] = lsum;
}
float f(a) float a; { return ( 4.0 / (1.0 + a*a ) ); }
```

Dynamic Task Allocation

- Single thread "generates" tasks to be worked on [Boss thread]
- Other threads request new task when done with previous [Worker threads]
- Boss sends kill signal at end
- Workers terminate gracefully
- Good model for unequal amounts of computation between tasks

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Critical Sections

- Critical section
  - portions of program containing shared, modifiable data
  - data or code that must only be used or executed by a single thread at any time
- Example: Airline reservations

```
if (seat[num] == “EMPTY”) then
    seat[num] = customer_name
    print confirmation number
endif
```

Read Set / Write Set

- Read Set
  - those memory locations that a thread will access, but not modify
- Write Set
  - those memory locations that a thread will access and modify
- Applied to statements of code blocks

Access Conflicts

- Read/Write conflicts
  - Thread A reads from seat[57]
  - Thread B writes “Jones” to seat[57]
  - What value does Thread A get?
- Write/Write conflicts
  - Thread A writes “Smith” to seat[57]
  - Thread B writes “Jones” to seat[57]
  - What value is stored in seat[57]?

Race Conditions

- Concurrent access of same variable by multiple threads
  - Read/Write conflict
  - Write/Write conflict
- Execution order is assumed but cannot be guaranteed
- Most common error in concurrent programs
- May not be apparent at all times

Mutual Exclusion

- Enforces single thread access to a critical section
- Enables correct programming structures for avoiding race conditions
- Mechanism is a lock (mutex)
  - Atomic operations
  - Only one thread can "hold" mutex at any time
  - Lock/unlock is a paired operation

Pthread Mutual Exclusion

- pthread_mutex_init
  - initialize mutex variable
- pthread_mutex_lock
  - lock mutex if available, else wait for mutex
- pthread_mutex_unlock
  - return mutex to system or waiting thread
- pthread_mutex_destroy
  - destroy mutex, unavailable w/o initialization

Mutual Exclusion Data Types

- pthread_mutex_t
  - the mutex variable
- pthread_mutexattr_t
  - mutex attributes
    - process sharing
    - scheduling protocol
    - priority ceiling
    - specifying NULL gives default mutex attributes

pthread_mutex_init

int pthread_mutex_init(mutex, attr);

pthread_mutex_t *mutex

mutex to be initialized

const pthread_mutexattr_t *attr

attributes to be given to mutex

- Can also use the static, default initializer
  - PTHREAD_MUTEX_INITIALIZER
- Programmer must pay attention to mutex scope

Error codes: pthread_mutex_init

- ENOMEM
  - insufficient memory for mutex
- EAGAIN
  - insufficient resources (other than memory)
- EPERM
  - no privilege to perform operation

pthread_mutex_lock

- int pthread_mutex_lock(mutex);

  pthread_mutex_t *mutex

  mutex to attempt to lock

pthread_mutex_lock

- Lock mutex
- Mutex is held by calling thread until unlocked
- Mutex lock/unlock must be paired or deadlock occurs
- If mutex is locked by other thread, calling thread is blocked

Error codes: pthread_mutex_lock

- EINVAL
  - thread priority exceeds mutex priority ceiling
- EDEADLK
  - calling thread already owns mutex

pthread_mutex_unlock

int pthread_mutex_unlock(mutex);

pthread_mutex_t *mutex

mutex to be unlocked

pthread_mutex_destroy

- int pthread_mutex_destroy(mutex);

  pthread_mutex_t *mutex

  mutex to be uninitialized

- It is not necessary to destroy a statically initialized mutex

Example: Hello World

```
#include<pthread.h>
#define NUM_THREADS 4
pthread_mutex_t printlock = PTHREAD_MUTEX_INITIALIZER;
main()
{
   pthread_t tid[NUM_THREADS];

   for (int i = 0; i < NUM_THREADS; i++)
       pthread_create(&tid[i], NULL, hello, NULL);

   for (int i = 0; i < NUM_THREADS; i++)
       pthread_join(&tid[i], NULL);
}
```

Example: Hello World

```
hello()
{
   pthread_mutex_lock(&printlock);
    /* The printf function is not threadsafe */
   printf("Hello, World\n");
   pthread_mutex_unlock(&printlock);
}
```

Example: Numerical Integration

- Each thread updates a global variable
- The mutex variable has global scope
- The mutex lock/unlock protects critical section from write/write conflicts
- What might happen if **t_num** is replaced by the counter variable **i** in the main thread?

Example: Numerical Integration

```
#define NUM_THREADS 1024
#define NUM_INTERVALS 65536
float global_sum = 0.0;
pthread_mutex_t global_lock;
main()
{  pthread_t tid[NUM_THREADS];
   int i, t_num[NUM_THREADS];
   pthread_mutex_init(&global_lock, NULL);
   for (i = 0; i < NUM_THREADS; i++){
        t_num[i] = i;
        pthread_create(&tid[i], NULL, do_calc, &t_num[i]);
   }
   for (i = 0; i < NUM_THREADS; i++)
        pthread_join(&tid[i], NULL);
   printf("Sum = %f\n", global_sum);
}
```

Example: Numerical Integration

```
do_calc(void *num)
{  int i, myid, start, end;
   float x;

   myid = (int)*num;
   h = 1.0 / NUM_INTERVALS;
   start = (NUM_INTERVALS / NUM_THREADS) * myid;
   end = start + (NUM_INTERVALS / NUM_THREADS);
   for (i = start; i < end; i++){
        x = h * ( (float)i - 0.5 );
        pthread_mutex_lock(&global_lock);
        global_sum += f(x);
        pthread_mutex_unlock(&global_lock);
   }
}
float f(a) float a; { return ( 4.0 / (1.0 + a*a ) ); }
```

Condition Variables

- Semaphores (per Dijkstra)
  - integer variable (non-negative) with queue
  - wait(s): if s = 0 block, else s-- and proceed
  - signal(s): increment s, wake up thread waiting
- Condition variable is associated with an arbitrary conditional
- Provides mutual exclusion

Condition Variable and Mutex

- Mutex is associated with condition variable
  - protects evaluation of the conditional expression
- Prevents "Lost Signal" problem
  - no sleeping thread to catch signal
  - signal is not saved

Condition Variable Algorithm

- Acquire mutex
- While conditional is true, Wait
- Perform critical section computation
  - somehow update conditional
- Signal sleeping thread(s)
- Release mutex

Condition Variables

- pthread_cond_init, pthread_cond_destroy
  - initialize/destroy condition variable
- pthread_cond_wait
  - attempt to hold condition variable
- pthread_cond_signal
  - signal release of condition variable
- pthread_cond_broadcast
  - broadcast release of condition variable

Condition Data Types

- pthread_cond_t
  - the condition variable
- pthread_condattr_t
  - condition attributes
    - process sharing
    - specifying NULL gives default condition attributes

pthread_cond_init

int pthread_cond_init(cond, attr);

pthread_cond_t *cond

condition variable to be initialized

pthread_condattr_t *attr

condition variable attributes to be used

- Can also use the static, default initializer
  - PTHREAD_COND_INITIALIZER
- Programmer must pay attention to condition scope

Error codes: pthread_cond_init

- ENOMEM
  - insufficient memory for condition variable
- EAGAIN
  - insufficient resources (other than memory)

pthread_cond_destroy

- int pthread_cond_destroy(cond);

  pthread_cond_t *cond

  condition variable to be eliminated

- It is not necessary to destroy a statically initialized condition variable

pthread_cond_wait

- int pthread_cond_wait(cond, mutex);

pthread_cond_t *cond

condition variable attempted to be held

pthread_mutex_t *mutex

mutex associated with condition variable

pthread_cond_wait

- Releases associated mutex
- When signal is received, thread must reacquire mutex before function returns
- Prone to spurious wakeups, thus
  - Acquire mutex
  - Evaluate associated conditional expression
    - if true, block thread (release mutex) to await signal on condition variable
    - if false, release mutex and continue

pthread_cond_signal

int pthread_cond_signal(cond);

pthread_cond_t *cond

condition variable to be released

pthread_cond_signal

- Signal condition variable, wake one waiting thread
- If no threads waiting, no action taken
  - Signal is not saved for future threads
- Before signal, thread must have mutex
  - If not, race condition may result

Example: Denominator

- Two threads oversee a global variable
  - Thread 1 calculates a value
  - Thread 2 waits for this value
- A mutex controls access to this variable
- Thread 1 signals thread 2 (waiting)

Example: Denominator (thread1)

```
#include <pthread.h>

pthread_mutex_t denom_mtx = PTHREAD_MUTEX_INITIALIZER;
pthread_cond_t denom_cond = PTHREAD_COND_INITIALIZER;
float denominator = 0.0;

thread1() {
   pthread_mutex_lock( &denom_mtx );

   denominator = f();              /* calculate denominator */
   pthread_signal( &denom_cond );  /* signal waiting thread */

   pthread_mutex_unlock( &denom_mtx );
}
```

Example: Denominator (thread2)

```
thread2() {
   float local_denom;

   pthread_mutex_lock( &denom_mtx );

   /* wait for non-zero denominator */
   while( denominator == 0.0 )
      pthread_cond_wait( &denom_cond, &denom_mtx );
   local_denom = denominator;

   pthread_mutex_unlock( &denom_mtx );

   /* Use local copy of denominator for division */
}
```

pthread_cond_broadcast

- int pthread_cond_broadcast(cond);

  pthread_cond_t *cond

  condition variable to be released

pthread_cond_broadcast

- Wake all threads waiting on condition variable
- If no threads waiting, no action taken
  - Broadcast is not saved for future threads
- Before broadcast, thread must have mutex
  - If not, race condition may result

Example: Broadcast signal

- Main thread
  - Creates worker threads
  - Reads input data
  - Signals worker threads to begin computation
- Worker threads
  - Wait for signal that data is available
  - Begin work

Example: Main thread

```
#include <pthread.h>
pthread_t tid[N_THREADS];
pthread_mutex_t read_mtx = PTHREAD_MUTEX_INITIALIZER;
pthread_cond_t read_cond = PTHREAD_COND_INITIALIZER;
int ready = 0;

main() {
   for (int i = 0; i < N_THREADS; i++)
      pthread_create(&tid[i], NULL, worker, NULL);
   /* read input data */
   pthread_mutex_lock( &read_mtx );
   ready = 1;                          /* reset condition flag */
   pthread_broadcast( &read_cond );
   pthread_mutex_unlock( &read_mtx );
   pthread_exit();      /* exit without terminating process */
}
```

Example: Worker thread

```
worker() {
   pthread_mutex_lock( &read_mtx );

   /* wait until flag indicates that data is ready */
   while( ready == 0 )
      pthread_cond_wait( &read_cond, &read_mtx );

   pthread_mutex_unlock( &read_mtx );

   /* data is available, begin work */

   pthread_exit();   /* Exit when finished */
}
```