CSCI 4061: Threads in a Nutshell

Chris Kauffman

Last Updated:
Mon Apr 15 21:20:02 CDT 2019

Logistics

Reading

- Stevens/Rago
  Ch 11-12
- Robbins and Robbins
  Ch 12-13

Goals

- Thread Basics
- Concurrency Issues
- Mutex Lock
- Condition Variable

Lab11: Worms

- How did it go?

Project 2

- Post today/tomorrow
- Due last day of classes

Threads of Control within the Same Process

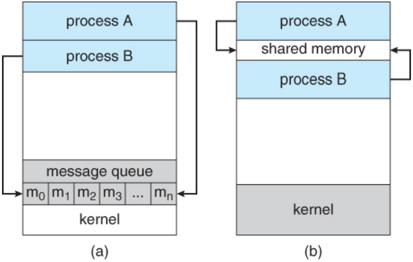
- Parallel execution path within the same process
- Multiple threads execute different parts of the same code for the program concurrently
  - Concurrent: simultaneous or in an unspecified order
- Threads each have their own "private" function call stack
- CAN share stack values by passing pointers to them around
- Share the heap and global area of memory
- In Unix, **Posix Threads (pthreads)** is the most widely available thread library

Threads vs IPC

Process in IPC	Threads in pthreads
(Marginally) Longer startup	(Marginally) Faster startup
Must share memory explicitly	Memory shared by default
Good protection between processes	Little protection between threads
`fork() / waitpid()`	`pthread_create() / _join()`

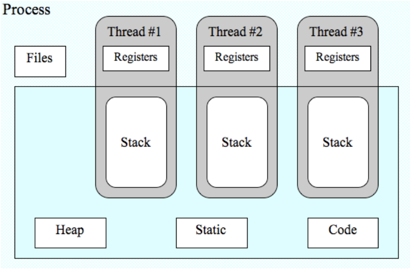
Modern systems (Linux) can use semaphores / mutexes / shared memory / message queues / condition variables to coordinate Processes or Threads

IPC Memory Model



Source

Thread Memory Model



Source

Process and Thread Functions

- Threads and process both represent "flows of control"
- Most ideas have analogs for both

Processes	Threads	Description
`fork()`	`pthread_create()`	create a new flow of control
`waitpid()`	`pthread_join()`	get exit status from flow of control
`getpid()`	`pthread_self()`	get "ID" for flow of control
`exit()`	`pthread_exit()`	exit (normally) from an existing flow of control
`abort()`	`pthread_cancel()`	request abnormal termination of flow of control
`atexit()`	`pthread_cleanup_push()`	register function to be called at exit from flow of control

Stevens/Rago Figure 11.6: Comparison of process and thread primitives

Thread Creation

```
#include <pthread.h>
int pthread_create(pthread_t *thread,
                   const pthread_attr_t *attr,
                   void *(*start_routine) (void *),
                   void *arg);

int pthread_join(pthread_t thread, void **retval);
```

- Start a thread running function `start_routine`
- `attr` may be `NULL` for default attributes
- Pass arguments `arg` to the function
- Wait for thread to finish, put return in `retval`

Minimal Example

Code

```
// Minimal example of starting a
// pthread, passing a parameter to the
// thread function, then waiting for it
// to finish
#include <pthread.h>
#include <stdio.h>

void *doit(void *param){
  int p=(int) param;
  p = p*2;
  return (void *) p;
}

int main(){
  pthread_t thread_1;
  pthread_create(&thread_1, NULL,
                 doit, (void *) 42);
  int xres;
  pthread_join(thread_1, (void **) &xres);
  printf("result is: %d\n",xres);
  return 0;
}
```

Compilation

- Link thread library
  `-lpthreads`
- Lots of warnings

```
> gcc pthreads_minimal_example.c -lpthread
pthreads_minimal_example.c: In function 'doit':
pthreads_minimal_example.c:7:9: warning:
 cast from pointer to integer of different
 size [-Wpointer-to-int-cast]
   int p=(int) param;
         ^
pthreads_minimal_example.c:9:10: warning:
 cast to pointer from integer of different
 size [-Wint-to-pointer-cast]
   return (void *) p;
          ^
> a.out
result is: 84
```

Exercise: Observe this about pthreads

1. Where does a thread start execution?
2. What does the parent thread do on creating a child thread?
3. How much compiler support do you get with pthreads?
4. How does one pass multiple arguments to a thread function?
5. If multiple children are spawned, which execute?

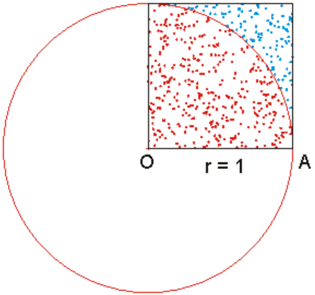
Answers: Observe this about pthreads

1. Where does a thread start execution?
   - Child thread starts running code in the function passed to `pthread_create()`, function `doit()` in example
2. What does the parent thread do on creating a child thread?
   - Continues immediately, much like `fork()` but child runs the given function while parent continues as is
3. How much compiler support do you get with pthreads?
   - Little: must do a lot of casting of arguments/returns
4. How does one pass multiple arguments to a thread function?
   - Create a struct or array and pass in a pointer
5. If multiple children are spawned, which execute?
   - Can't say which order they will execute in, similar to `fork()` and children

Model Problem: A Slice of Pi

- Calculate the value of $\pi \approx 3.14159$
- Simple *Monte Carlo* algorithm to do this
- Randomly generate positive `(x,y)` coords
- Compute distance between `(x,y)` and `(0,0)`
- If distance ≤ 1 increment "hits"
- Counting number of points in the positive quarter circle
- After large number of hits, have approximation

$$\pi \approx 4 \times \frac{\text{total hits}}{\text{total points}}$$



Algorithm generates dots, computes fraction of red which indicates area of quarter circle compared to square

Serial Code `picalc.c` and `picalc_rand.c`

- Examine source code for `picalc_rand.c`
- Note basic algorithm is simple and easily parallelizable
- Discuss trouble with the `rand()` function: non-reentrant
- Examine source code for `picalc.c`
- Contrast the `rand_r()` function: reentrant version

Exercise: `pthreads_picalc.c`

http://cs.umn.edu/~kauffman/4061/pthreads_picalc.c

- Examine source code for `pthreads_picalc.c`
- How many threads are created? Fixed or variable?
- How do the threads cooperate? Is there shared information?
- Do the threads use the same or different random number sequences?
- Will this code actually produce good estimates of π?

Answers: `pthreads_picalc.c`

http://cs.umn.edu/~kauffman/4061/pthreads_picalc.c

- Identical to `pthreads_picalc_broken.c`
- How many threads are created? Fixed or variable?
  - Threads specified on command line
- How do the threads cooperate? Is there shared information?
  - Shared global variable `total_hits`
- Do the threads use the same or different random number sequences?
  - Different, seed is based on thread number
- Will this code actually produce good estimates of π?
  - Nope: not coordinating updates to `total_hits` so will likely be wrong

```
> gcc -Wall pthreads_picalc_broken.c -lpthread
> a.out 10000000 4
npoints: 10000000
hits:     3134064
pi_est:  1.253626   # not a good estimate for 3.14159
```

Why is `pthreads_picalc_broken.c` so wrong?

- The instructions `total_hits++;` is **not atomic**
- Translates to assembly

```
// total_hits stored at address #1024
30: load  REG1 from #1024
31: increment REG1
32: store REG1 into #1024
```

- Interleaving of these instructions by several threads leads to undercounting `total_hits`

Mem #1024 `total_hits`	Thread 1 Instruction	REG1 Value	Thread 2 Instruction	REG1 Value
100				
	30: load REG1	100		
	31: incr REG1	101		
101	32: store REG1			
			30: load REG1	101
			31: incr REG1	102
102			32: store REG1	
	30: load REG1	102		
	31: incr REG1	103		
			30: load REG1	**102**
			31: incr REG1	103
103			32: store REG1	
103	32: store REG1			

Critical Regions and Mutex Locks

- Access to shared variables must be coordinated among threads
- A **mutex** allows *mutual exclusion*
- Locking a mutex is an atomic operation like incrementing/decrementing a semaphore

```
pthread_mutex_t lock;

int main(){
  // initialize a lock
  pthread_mutex_init(&lock, NULL);
  ...;
  // release lock resources
  pthread_mutex_destroy(&lock);
}

void *thread_work(void *arg){
  ...
  // block until lock acquired
  pthread_mutex_lock(&lock);

  do critical;
  stuff in here;

  // unlock for others
  pthread_mutex_unlock(&lock);
  ...
}
```

Exercise: Mutex Busy wait or not?

- Consider given program
- Threads acquire a mutex, sleep 1s, release
- **Predict** user and real/wall times if
  1. Mutex uses busy waiting (polling)
  2. Mutex uses interrupt driven waiting (sleep/wakup when ready)
- Can verify by compiling and running

  `time a.out`

```c
int glob = 1;
pthread_mutex_t glob_lock;

void *doit(void *param){
  pthread_mutex_lock(&glob_lock);
  glob = glob*2;
  sleep(1);
  pthread_mutex_unlock(&glob_lock);
  return NULL;
}

int main(){
  printf("BEFORE glob: %d\n",glob);

  pthread_mutex_init(&glob_lock, NULL);
  pthread_t thread_1;
  pthread_create(&thread_1, NULL, doit, NULL);
  pthread_t thread_2;
  pthread_create(&thread_2, NULL, doit, NULL);

  pthread_join(thread_1, (void **) NULL);
  pthread_join(thread_2, (void **) NULL);

  printf("AFTER glob: %d\n",glob);
  pthread_mutex_destroy(&glob_lock);

  return 0;
}
```

Answers: Mutex Busy wait or not? NOT

- Locking is **Not** a busy wait
- Either get the lock and proceed OR
- Block and get woken up when the lock is available
- Timing is
  - real: 2.000s
  - user: 0.001s
- If it were busy should be roughly
  - real: 2.000s
  - user: 1.001s
- `pthread_spinlock_*` like mutex locks but more likely to busily wait

```
int glob = 1;
pthread_mutex_t glob_lock;

void *doit(void *param){
  pthread_mutex_lock(&glob_lock);
  glob = glob*2;
  sleep(1);
  pthread_mutex_unlock(&glob_lock);
  return NULL;
}

int main(){
  printf("BEFORE glob: %d\n",glob);

  pthread_mutex_init(&glob_lock, NULL);
  pthread_t thread_1;
  pthread_create(&thread_1, NULL, doit, NULL);
  pthread_t thread_2;
  pthread_create(&thread_2, NULL, doit, NULL);

  pthread_join(thread_1, (void **) NULL);
  pthread_join(thread_2, (void **) NULL);

  printf("AFTER glob: %d\n",glob);
  pthread_mutex_destroy(&glob_lock);

  return 0;
}
```

Exercise: Protect critical region of `picalc`

- Insert calls to `pthread_mutex_lock()` and `pthread_mutex_unlock()`
- Protect the critical region
- Predict effects on code

```
int total_hits=0;
int points_per_thread = ...;
pthread_mutex_t lock;                     // initialized in main()

void *compute_pi(void *arg){
  long thread_id = (long) arg;
  unsigned int rstate = 123456789 * thread_id;
  for (int i = 0; i < points_per_thread; i++) {
    double x = ((double) rand_r(&rstate)) / ((double) RAND_MAX);
    double y = ((double) rand_r(&rstate)) / ((double) RAND_MAX);
    if (x*x + y*y <= 1.0){
      total_hits++;                               // update
    }
  }
  return NULL;
}
```

Answers: Protect critical region of `picalc`

- Naive approach

```
if (x*x + y*y <= 1.0){
  pthread_mutex_lock(&lock);    // lock global variable
  total_hits++;                 // update
  pthread_mutex_unlock(&lock);  // unlock global variable
}
```

- Ensures correct answers but...
- Severe effects on performance

Speedup?

- Dividing work among workers should decrease wall (real) time
- Shooting for **linear speedup**

$$\text{Parallel Time} = \frac{\text{Serial Time}}{\text{Number of Workers}}$$

```
> gcc -Wall picalc.c -lpthread
> time a.out 100000000 > /dev/null          # SERIAL version
real    0m1.553s                            # 1.55 s wall time
user    0m1.550s
sys     0m0.000s
> gcc -Wall pthreads_picalc_mutex.c -lpthread
> time a.out 100000000 1 > /dev/null        # PARALLEL 1 thread
real    0m2.442s                            # 2.44s wall time ?
user    0m2.439s
sys     0m0.000s
> time a.out 100000000 2 > /dev/null        # PARALLEL 2 threads
real    0m7.948s                            # 7.95s wall time??
user    0m12.640s
sys     0m3.184s
> time a.out 100000000 4 > /dev/null       # PARALLEL 4 threads
real    0m9.780s                           # 9.78s wall time???
user    0m18.593s                          # wait, something is
sys     0m18.357s                          # terribly wrong...
```

Alternative Approach: Local count then merge

- Contention for locks creates tremendous overhead
- Classic divide/conquer or map/reduce or split/join paradigm works here
- Each thread counts its own local hits, combine **only** at the end with single lock/unlock

```
void *compute_pi(void *arg){
  long thread_id = (long) arg;
  int my_hits = 0;                             // private count for this thread
  unsigned int rstate = 123456789 * thread_id;
  for (int i = 0; i < points_per_thread; i++) {
    double x = ((double) rand_r(&rstate)) / ((double) RAND_MAX);
    double y = ((double) rand_r(&rstate)) / ((double) RAND_MAX);
    if (x*x + y*y <= 1.0){
      my_hits++;                               // update local
    }
  }
  pthread_mutex_lock(&lock);                  // lock global variable
  total_hits += my_hits;                      // update global hits
  pthread_mutex_unlock(&lock);                // unlock global variable
  return NULL;
}
```

Speedup!

- This problem is almost **embarassingly parallel**: very little communication/coordination required
- Solid speedup gained but note that the user time increases as # threads increases due to overhead

```
# 8-processor desktop
> gcc -Wall pthreads_picalc_mutex_nocontention.c -lpthread
> time a.out 100000000 1 > /dev/null  # 1 thread
real    0m1.523s                      # 1.52s, similar to serial
user    0m1.520s
sys     0m0.000s
> time a.out 100000000 2 > /dev/null  # 2 threads
real    0m0.797s                      # 0.80s, about 50% time
user    0m1.584s
sys     0m0.000s
> time a.out 100000000 4 > /dev/null  # 4 threads
real    0m0.412s                      # 0.41s, about 25% time
user    0m1.628s
sys     0m0.003s
> time a.out 100000000 8 > /dev/null  # 8 threads
real    0m0.238s                      # 0.24, about 12.5% time
user    0m1.823s
sys     0m0.003s
```

Mutex Gotchas

- Managing multiple mutex locks is fraught with danger
- Must choose protocol carefully: similar to discussion of Dining Philosophers with semaphores
- Same thread locking same mutex twice can cause deadlock depending on options associated with mutex
- Interactions between threads with different scheduling priority are also tough to understand
- Robbins/Robbins 13.8 discusses some problems with the Mars Pathfinder probe resulting from threads/mutex locks
  - Used multiple threads with differing priorities to manage limited hardware
  - Shortly after landing, started rebooting like crazy due to odd thread interactions
  - Short-lived, low-priority thread got a mutex, pre-empted by long-running medium priority thread, system freaked out because others could not use resource associated with mutex

Mutex vs Semaphore

Similarities

- Both used to protect critical regions of code from other processes/threads
- Both use non-busy waiting
  - process/thread blocks if locked by another
  - unlocking wakes up a blocked process/thread
- Both can be process private or shared between processes
  - Shared mutex requires shared memory
  - Private semaphore with option `pshared==0`

Differences

- Semaphores default to Inter-process coordination, Mutexes to Thread coordination
- Semaphores can be arbitrary natural number, usually 0=locked, 1,2,3,..=available
- Mutexes are either locked/unlocked
- Mutexes have a busy locking variant:
  - `pthread_spinlock_t`
  - `pthread_spin_lock()`
  - `pthread_spin_unlock()`

get_thread_id()???

> *As noted in other answers, pthreads does not define a platform-independent way to retrieve an integral thread ID. This answer[1] gives a non-portable way which works on many BSD-based platforms.*
> – *Bleater on Stack Overflow*

```
// Standard opaque object, non-printable
pthread_t opaque = pthread_self();

// Linux only
pid_t tid = gettid(); // system call
printf("Thread %d reporting for duty\n",tid);

// Non-portable, non-linux
pthread_id_np_t tid = pthread_getthreadid_np();
```

[1] http://stackoverflow.com/a/21206357/316487

Thread ID work-arounds

- In many cases `pid_t` is just a `unsigned long`

```
// /usr/include/bits/pthreadtypes.h
typedef unsigned long int pthread_t;
```

- Allows simple printf printing as in

```
  void *doit(void *param){
    pthread_t tid = pthread_self();
    printf("doit: I am thread %ld\n",tid);
    ...;
```

- Thread ids are often LARGE numbers
- See `pthread_ids.c` for full example
- Use this technique for debugging, remove for production and NOT for algorithms
- Establish own logical thread IDs if required by passing parameters to thread worker function

Exercise: Odd-Even workers

```
int count = 0;                 // global variable all threads are modifiying
pthread_mutex_t count_mutex;   // mutex to check/alter count

void *even_work(void *t) {
  // Run by TWO even child threads
  // increment count only if it is EVEN 5 times in a loop
}
void *odd_work(void *t) {
  // Run by TWO odd child threads
  // increment count only if it is ODD 5 times in a loop
}
int main(){
  int tids[] = {0, 1, 2, 3};  pthread_t threads[4];
  pthread_create(&threads[0], NULL, even_work, &(tids[0]));
  pthread_create(&threads[1], NULL, odd_work,  &(tids[1]));
  pthread_create(&threads[2], NULL, even_work, &(tids[2]));
  pthread_create(&threads[3], NULL, odd_work,  &(tids[3]));
  // join threads, WANT: count = 20
}
```

- Propose code which uses a mutex to lock count
- Even/Odd threads update only if it is appropriate
- What kind of control structure must be used?
- What consequences does this have for performance?

Answers: Odd-Even workers `odds_even_busy.c`

Need a loop that

- Acquires a lock
- Checks `count`, proceeds if odd/even
- Otherwise release and try again

Results in busy waiting: can repeatedly get lock despite **condition** of odd/even not changing

```
int count = 0;
pthread_mutex_t count_mutex;
void *even_work(void *t) {
  int tid = *( (int *) t);
  for(int i=0; i<THREAD_ITERS; i++){
    while(1){
      pthread_mutex_lock(&count_mutex);
      if(count % 2 != 0){ // check if even
        break;            // yup: move on
      }                   // nope: try again
      pthread_mutex_unlock(&count_mutex);
    }
    count++;              // locked and even
    pthread_mutex_unlock(&count_mutex);
  }
  return NULL;
}
```

Condition Variables

- Major limitation for locks: can only lock/unlock (duh?)
- Frequently want to check shared resource, take action only under specific **conditions** associated with resource
  - Queue of work is non-empty
  - Two utensils are immediately available
  - It is this threads 'turn' to go
- Mutex on its own is ill-suited for this problem:
  In a loop
  - Lock variables indicating condition
  - Check condition
  - Break from loop if condition is true
  - Unlock and try again if not true
- Semaphores may be of some help but they have to do with counts only
- For this, **condition variables** or monitors are often used

Condition Variable Operations

- Condition variables would be more appropriately named **notification queue**
- Always operate in conjunction with a mutex
- Threads acquire mutex, check condition, block if condition is unfavorable, get notified of changes, automatically relock mutex on wakeup

```
int pthread_cond_init(pthread_cond_t *cond, pthread_condattr_t  attr);
int pthread_cond_destroy(pthread_cond_t *cond);
// Inititalize and destroy

int pthread_cond_wait(pthread_cond_t *cond, pthread_mutex_t *mutex);
// atomically release mutex and block/sleep until notified that
// given condition has changed

int pthread_cond_signal(pthread_cond_t *cond);
// wake up a single thread waiting on the given condition
// woken up thread automatically locks the mutex specified
// in pthread_cond_wait()

int pthread_cond_broadcast(pthread_cond_t *cond);
// wake up all threads waiting on the given condition
// woken up threads automatically lock the mutex specified
// when it is their "turn"
```

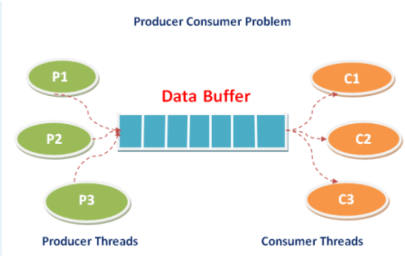
Odds/Evens with Condition Variables

- odds_evens_condvar.c
- Worker loop now uses pthread_cond_wait()
- Blocks and gets notification of changes to count
- Threads call pthread_cond_broadcast() to wake up other threads when count changes: no busy lock/unlock while waiting
- **Question:** Would pthread_cond_signal() which wakes up a single other thread work here?

```
int count = 0;
pthread_mutex_t count_mutex;
pthread_cond_t  count_condv;

void *even_work(void *t) {
  int tid = *( (int *) t);
  for(int i=0; i<THREAD_ITERS; i++){
    pthread_mutex_lock(&count_mutex);
    while(count % 2 != 0){
      pthread_cond_wait(&count_condv,
                        &count_mutex);
    }
    count++;
    pthread_mutex_unlock(&count_mutex);
    pthread_cond_broadcast(&count_condv);
  }
  return NULL;
}
```

Bounded Buffer: Classic Model Problem



Source: Producer Consumer Problem C Program, by Tushar Soni, Coding Alpha

- Shared, fixed sized buffer of items
- Multiple threads/processes acting on buffer

- **Producers** add items to buffer *if space available*
- **Consumers** remove from buffer *if items present*
- Lock buffer to check/alter it
- Lock-only solution involves repeated lock/discard

```
Producer A locks, no space, unlocks
Producer B locks, no space, unlocks
Producer A locks, no space, unlocks
Producer B locks, no space, unlocks
...
```

- CondVars add efficiency through notification changes

```
Producer A locks, no space, sleeps
Producer B locks, no space, sleeps
...
Consumer C locks, removes, signals
Producer A locks, adds, unlocks
...
```

Exercise: Reentrant?

- Recall the meaning of reentrant
- Describe dangerous place to call non-reentrant functions
- What are some notable non-reentrant functions?
- Does this have play in our current discussion of threads?

Reentrant and Thread-Safe

- A variety of VERY useful functions are non-reentrant, notably `malloc() / free()`
- Use some global state manipulate the heap
- Dangerous to call these during a signal handler as they are not **async-signal-safe**
- However, many of these are **thread-safe**: can be called from multiple threads safely (**MT-Safe** for Muti-Thread Safe)
- This is good as it means multiple threads can allocate/free memory safely which would be close to crippling if not allowed
- Check manual pages for library/system calls you plan to use
- **Q:** *Prof Kauffman: how can something be thread-safe but not re-entrant?*
- **A:** I'll give 5 cards to someone who can put up a good Piazza post explaining this by next class. There's a lot of StackOverflow to read and I've got a project to get ready for you.

Mixing Processes and Threads

- You can mix IPC and Threads if you hate yourself enough.

  > *Dealing with signals can be complicated even with a process-based paradigm. Introducing threads into the picture makes things even more complicated.*
  > *– Stevens/Rago Ch 12.8*

- Strongly suggest you examine Stevens and Rago 12.8-12.10 to find out the following **pitfalls**:
- Threads have individual signal masks but share signal disposition (!?)
- Calling `fork()` from a thread creates a new process with all the locks/mutexes of the parent but only one thread (!?)
- Usually implement a `pthread_atfork()` handler for this
- Multiple threads should use `pread() / pwrite()` to read/write from specific offsets; ensure that they do not step on each other's I/O calls

Are they really so different?

- Unix standards strongly distinguish between threads and processes: different system calls, sharing, etc.
- Due to their similarities, you should be skeptical of this distinction as smart+lazy OS implementers can exploit it:

  Linux uses a 1-1 threading model, with (to the kernel) no distinction between processes and threads – everything is simply a runnable task.
  On Linux, the system call `clone()` clones a task, with a configurable level of sharing...

  - *`fork()` calls `clone(least sharing)` and*
  - *`pthread_create()` calls `clone(most sharing)`*

  – *Ryan Emerle, SO:"Threads vs Processes in Linux"*

The "1-1" model is widely used (Linux, BSD, Windows(?)) but conventions vary between OSs: check your implementation for details

End Message: Threads are not a first choice

- Managing concurrency is hard
- Separate processes provide one means to do so, often a good start as defaults to nothing shared
- Performance benefits of threads come with MANY disadvantages and pitfalls
- If forced to use threads, consider design carefully
- If possible, use a higher-level thread manager like OpenMP, well-suited for parallelizing loops for worker threads
- Avoid mixing threads/IPC if possible
- Prepare for a tough slog...