Exercises, mostly on pthread

1 Semaphores

A semaphore is an old fashioned synchronisation primitives that generalises the mutex: the semaphore is given a *capacity* and at most capacity threads can be in critical section simultaneously. Hence, a mutex is a semaphore with capacity 1.

For historical reasons semaphore lock is called “wait” and semaphore unlock is called “post”.

Important: Code template for this exercice is available in directory `semaphore` from the companion archive.

1.1 Coding a semaphore

Given a semaphore s initialised to capacity c, critical sections are defined from a call to `wait_semaphore` (s) (analog of `lock_mutex`) to `post_semaphore` (s) (analog of `unlock_mutex`). The semaphore uses an internal counter `nfree` to count the number of threads allowed to enter critical section. The counter is initialised to c at semaphore creation time, then:

- `wait_semaphore` (s) checks that `nfree` is non-null and decrements it. If `nfree` is null, the thread suspends.
- `post_semaphore` (s) increments `nfree` and release waiting threads.

One may write a semaphore with a mutex (to protect the modifications of `nfree`) and a condition variable (to wait on). Complete the following code:

```
/* Signature of mutex and condition variable primitives */

pthread_mutex_t *alloc_mutex(void) ;
void free_mutex(pthread_mutex_t *p) ;
void lock_mutex(pthread_mutex_t *p) ;
void unlock_mutex(pthread_mutex_t *p) ;

pthread_cond_t *alloc_cond(void) ;
void free_cond(pthread_cond_t *p) ;
void wait_cond(pthread_cond_t *c, pthread_mutex_t *m) ;
void signal_cond(pthread_cond_t *c) ;
void broadcast_cond(pthread_cond_t *c) ;


/* Semaphore structure */
typedef struct {
  volatile int nfree ;
  pthread_mutex_t *mutex ;
  pthread_cond_t *cond ;
} semaphore_t ;


semaphore_t *alloc_semaphore(int capacity) { ... }
```

```
void free_semaphore(semaphore_t *p) { ... }

void wait_semaphore(semaphore_t *p) { ... }

void post_semaphore(semaphore_t *p) { ... }
```

1.2 Semaphore usage

We consider `nprocs` threads running function `T1` below, with argument described by ctx_t below:

```
typedef struct {
  int size ;
  pthread_barrier_t *b ;
  semaphore_t *sem ;
} common_t ;

typedef struct {
  int id ;
  common_t *common ;
} ctx_t ;


void *T1(void *_p) {
  ctx_t *p = _p ;
  common_t *q = p->common ;
  for (int k = q->size-1 ; k >= 0 ; k--) {
    wait_semaphore(q->sem) ;
    printf("+") ;
    printf("-") ;
    post_semaphore(q->sem) ;
    wait_barrier(q->b) ;
    if (p->id == 0) printf("\n") ;
    wait_barrier(q->b) ;
  }
  return NULL ;
}
```

With a semaphore of capacity 2, `q->size = 1` and `nprocs == 4`. Classify the following outputs as legal or illegal, giving a short explanation in each case:

1. `++--+-+-`
2. `+++-+---`
3. `-+-+-+-+`
4. `+-+-+-+-`
5. `++++++++`

1.3 C11 coding

Write the same program using C11 standard primitives. To that aim, you may need:

- Documentation, see for instance `https://en.cppreference.com/w/c/atomic` and `https://en.cppreference.com/w/c/thread`.

- A C11 compiler and standard library. On Linux, if your distribution defaults are not sufficient (as it is the case on Ubuntu 18.04 LTS for instance), you can install the `musl-tools` package and use the `musl-gcc` compiler.

The companion archive contains a template `sem11.c`, with missing parts shighlighted by `TODO` comments.

2 Sequentially consistent or not?

The following small programs are written in pseudo-C. Following our usual conventions `x` and `y` are shared memory locations, while `r0` and `r1` are registers. Moreover, `*x = 1` is a store; while `r0 = *x` is a load. Shared locations and registers hold zero as initial value. By definition, a *behaviour* is a choice of final values

Figure 1: Four small programs

```
      Test 1                 Test 2
---------+---------    ---------+---------
  T0    |    T1          T0    |    T1
---------+---------    ---------+---------
 *x = 2  | r0 = *y      *x = 2 | *x = 1
 *y = 1  | *x = 1       *y = 1 | r0 = *y
---------+---------    ---------+---------
  Observe x,r0          Observe: x,r0

      Test 3                 Test 4
---------+---------    ---------+---------
  T0    |    T1          T0    |    T1
---------+---------    ---------+---------
 *x = 1  | *y = 1      *x = 1  | *y = 1
 r0 = *y | r1 = *x     r0 = *x | r1 = *y
---------+---------    ---------+---------
 Observe r0,r1          Observe r0,r1
```

for some observed locations. That is, shared locations `x` and `r0` for `Test 1` and `Test 2`; registers `r0` and `r1` for `Test 3` and `Test 4`.

We consider *valid* behaviours, *i.e.* behaviours that result from executions such that each load of a memory cell reads a value written by a store to the same memory cell or the initial value zero. List all valid behavours of the four tests, identifying sequentially consistent (SC) behaviours.

3 A concurrent component

We aim at building a concurrent component on top of POSIX threads. The component `and_t` operates for `nprocs` participant threads, the number of participant threads being fixed at component allocation time:

```
and_t *alloc_and(int nprocs) ;
```

Each thread will call the following function:

```
int wait_and(and_t *p,int b) ;
```

where `b` is some integer encoding a boolean (*i.e.* `0` is false, while `1` is true). The call `wait_and` returns only when all participants have submitted their boolean and returns the conjunction (and) of all submitted booleans. Hence the `and_t` component looks very much like a synchronisation barrier that additionally returns a boolean.

It is important to notice that participants can call `wait_and` several times, just as they can call a POSIX synchronisation barrier several times.

3.1 Barrier encoding

We first write the component by the means of a POSIX synchronisation barrier (described in slides 8–9 of lesson 2). Here is the type of component and the `alloc_and` function:

```
typedef struct {
  pthread_barrier_t *b ; // Posix synchronisation barrier
  int v ;                // You'll need that field to compute result
} and_t ;


and_t *alloc_and(int nprocs) {
  and_t *p = malloc_check(sizeof(*p)) ;
  p->v = 1 ;   // This is the conjunction of zero boolean.
  p->b = alloc_barrier(nprocs) ;
  return p ;
}
```

Write the `wait_and` function. You'll probably have to call `wait_barrier (p->b)` several times.

3.2 Direct coding

We now write the component by the means of the basic POSIX synchronisation primitives: locks and condition variables.

Here is an incomplete definition of type and_t and an incomplete `alloc_and` function:

```
typedef struct {
  pthread_cond_t *cond ;
  pthread_mutex_t *mutex ;
  /* Hum the following should remind you of something... */
  int nprocs,count ;
  int turn ;
  ...
} and_t ;

and_t *alloc_and(int nprocs) {
  and_t *p = malloc_check(sizeof(*p)) ;
  p->cond = alloc_cond();
  p->mutex = alloc_mutex() ;
  p->nprocs = p->count = nprocs ;
  p->turn = 0 ;
  ...
  return p ;
}
```

Complete the above definitions and write the `wait_and` function. You can start from the code of `wait_barrier` on slide 18 of lesson 2.

4 A process farm

We aim at building a simple "process farm" framework:

- A *worker* will perform a computation. More precisely given a task x, a worker computes $y = F(x)$ and accumulate in a "running" result r by calling a function C ($r = C(y, r)$).

- A *master* will allocate some tasks to *workers* and control their execution.

Additionally there cannot be more than `nprocs` workers running concurrently.

We have already seen such a framework in class 01 based upon a FIFO. Here we aim at another solution based upon two components: a *pool* that will manage worker allocation, checking that no more than `nprocs` are running concurrently, and a monitor that will manage computation of partial results and termination. Notice that our process farm will create one (POSIX) thread per task[1].

In practice, you have to write C code for those two components from the templates in directory `pool`. The `pool` directory also contains two examples the simple `tst.c` example and the more sophisticated `run.c` example: The associated `Makefile` builds the executables `tst.out` and `run.out`.

- The `tst` example computes the sum of the first n integers (*i.e.* $F(x) = x$ and $C(y, r) = y + r$).
- The `run` example computes the number of polyominoes of size n, using the code presented in class 01. That is, given x the description of a partial polyomino of size $n-d$, F returns the number of polyominoes of size n that contain x; and $C(y, r) = y + r$ again.

Important: You have to complete the source files `pool.c` and `monitor.c`. Once you are done, you can test your components as follows:

```
% make
% ./tst.out
5050
% ./run.out
27394666
```

You can also try `./tst.out` *nprocs* n, to sum the n first integers using *nprocs* cores; or `./run.out -j` *nprocs* n to compute the number of polyominoes of size n using *nprocs* cores. Both examples will output some information on what happens if you give them the command-line option `-v`, which can be repeated for more diagnostics.

We now describe the simple example `tst.out`, so as to demonstrate the pool and monitor components usage.

Pool

The master simply executes a loop from 1 to n, spawning a worker for each loop indice value:

```
typedef struct {
  pool_t *pool ;
  monitor_t *monitor ;
} common_t ;

void master(int nprocs, int n) {
  common_t c ;
  ...
  c.pool = alloc_pool(nprocs) ;
  for (int k = 1 ; k <= n ; k++) {
    look_pool(c.pool) ;
    spawn_worker(k,&c) ;
  }
  ...
```

More precisely `look_pool` will suspend if `nprocs` or more workers are already running. Otherwise, `look_pool` returns immediately having altered the pool structure that will remember that a worker is running.

It will be the worker responsibility to inform the pool when it becomes available again. In the simple example, it works as follows:

[1] Threads can be cached by another component so as to amortised thread creation costs. We neglect this issue.

```
typedef struct {
  int arg ;
  common_t *common ;
} worker_t ;

void *worker(void *p) {
  worker_t *w = (worker_t *)p ;
  common_t *c = w->common ;
  ...
  leave_pool(c->pool) ;
  return NULL ;
}


void spawn_worker(int arg, common_t *c) {
  worker_t *w = alloc_worker_t(arg,c) ;
  create_thread_detached(worker,w) ;
}
```

That is, the worker thread is created detached (*i.e.* we shall not join on it) to execute `worker` with the appropriate argument that includes the task (here `arg`) and a pointer to `common` that in turn records pointers to the `pool` and `monitor` components. The `worker` code performs the allocated work (not shown yet…), and finally informs the pool that a new worker gets available by calling `leave_pool` just before exiting. In case the master is suspended, `leave_pool` should awake it.

Here are the signatures of the two functions you have to write:

```
typedef struct {
  int maxrun,nrun ; /* Max number of running workers, running workers */
  int waiting ;     /* flag, true when master is waiting */
  pthread_mutex_t *lock ;
  pthread_cond_t *cond ;
} pool_t ;

...

/* To be called by worker: tell pool a worker is free, should awake master if suspended */
void leave_pool(pool_t *p) ;

/* To be called by master: allocate a worker, suspend when none is available */
void look_pool(pool_t *p) ;
```

Monitor

The monitor component manages result computation and program termination. Result computation is performed incrementally by accumulating partial results by the mean of the C function that will be hidden in the monitor.

We first examine its interface with the worker:

```
void *worker(void *p) {
  worker_t *w = (worker_t *)p ;
  common_t *c = w->common ;
  int arg = w->arg ;

  int y = compute(arg) ;
  ...
  leave_monitor(c->monitor,y) ;
  return NULL ;
}
```

Hence, the worker computes. It then passes the partial result `y` to the monitor, for it to accumulate partial results into the final result.

The interface with the master is as follows:

```
uintmax_t add(uintmax_t y,uintmax_t r) { return y+r; }

void master(int nprocs, int n) {
  common_t c ;
  c.monitor = alloc_monitor(add,0) ;
  c.pool = alloc_pool(nprocs) ;
  for (int k = 1 ; k <= n ; k++) {
    look_pool(c.pool) ;
    enter_monitor(c.monitor) ;
    spawn_worker(k,&c) ;
  }
  int r = wait_monitor(c.monitor,n) ;
  ...
}
```

The master first creates the monitor with `alloc_monitor(add,0)`, arguments are the C function (here a simple addition function) and the initial value of result (here `0`). Then, the master create all tasks (and spawn all workers) with the for loop.

Observe that the master calls `enter_monitor` before spawning the worker. It does so to inform the monitor that a new task is being computed. In practice, the monitor will record the number of tasks being computed with some internal counter. Of course `leave_monitor` (called by workers) should now also decrease this internal counter.

Finally the master wait on the monitor, passing it the number of generated tasks as an argument. The function `wait_monitor` should behave as follows:

- If `n` tasks are completed then return the accumulated result.
- Otherwise suspend.

Hence, if the master suspends, someone should awake it. This will be the responsibility of the *last* worker that calls `leave_monitor`. The internal counter of tasks being computed may help workers to know when they are this last worker.

Here are the signatures of the three functions you have to write:

```
typedef struct {
  int nrun ;        /* number of tasks being executed */
  int ncompleted ; /* number if tasks being completed */
  int waiting ;    /* flag set if master is waiting  */
  pthread_mutex_t *lock;
  pthread_cond_t *cond ;
  compose_t compose ; /* compose function */
  uintmax_t r ;     /* result of computation */

} monitor_t ;

...

/*
   To be called by worker :
   1. Pass partial result y, so as to update result of computation
      [m->r = m->compose(y,m->r)]
   2. Signals a task is completed
*/
void leave_monitor(monitor_t *m,uintmax_t y) ;
```

```
/* To be called by master to signal a task is being executed */
void enter_monitor(monitor_t *m) ;

/* To be called by master to wait for ntasks being completed.
   returns computation result */
uintmax_t wait_monitor(monitor_t *m,int ntasks) ;
```

5 Controlling workers with a stack

We aim at controlling a set of `nprocs` worker threads by the mean of a stack. The stack will be a concurrent, bounded, blocking stack. This means ("bounded") that the stack is of limited capacity (from now `sz`) and ("blocking") that attempting to push on a full stack or to pop from an empty stack will block the calling thread.

The exercise has two steps: first (5.1) write `push` and `pop` operations that are blocking; and second (5.2) write a `kill` functionality that controls termination.

We provide a starting point for you to write the code, in sub-directory `stack`, with two testing applications `tst.out` and `run.out`. The former application `tst.out` is a simple test than spawn `nprocs` "popper" threads:

```
void *popper(void *p) {
  // Various initialisation from p
  ...
  void *item ;
  while ((item = pop(c->stack)) != NULL) {
    boxed_int_t *q = item ;
    int v = q->v ;
    free_boxed_int(q) ;
    (void)__sync_fetch_and_add(&c->sum,v);
    if (verbose) fprintf(stderr,"POPPER<%i> GOT %i\n",id,v) ;
  }
  if (verbose) fprintf(stderr,"POPPER<%i> OUT\n",id) ;
  return NULL ;
}
```

Hence, a popper pops items from the stack, until `NULL` is returned. The popped item is a boxed integer, whose contents is added atomically to a running `sum`, which is common to all poppers.

Moreover there are `nprocs` "pusher" threads that will push items on the stack:

```
void *pusher(void *p) {
  // Various initialisations from p
  ...
  // push 1 id+1 times, id is pushed id in 0,...,nprocs-1
  for (int k = 0 ; k <= id ; k++) {
    if (verbose) fprintf(stderr,"PUSHER<%i> PUT %i\n",id,1) ;
    push(c->stack,alloc_boxed_int(1)) ;
  }
  return NULL ;
}
```

Hence, the `nprocs` pushers will push the integer "1" $1 + 2 + \cdots +$ `nprocs` times. As a result, reading the accumulating sum once all pushers and poppers have finished, should yield the value $1 + 2 + \cdots +$ `nprocs`. For instance, with default value 2 for `nprocs` and 100 for `sz` the size of the stack, we should get:

```
% ./tst.out -v
nprocs=2, sz=100
PUSHER<1> PUT 1
```

```
PUSHER<0> PUT 1
PUSHER<1> PUT 1
POPPER<0> GOT 1
POPPER<0> GOT 1
POPPER<0> GOT 1
POPPER<0> OUT
SUM=3, OK=3
POPPER<1> OUT
```

The second test computes the number of polyominoes of size p, as we have seen in the first class. With default value of 15 for p, we get:

```
% ./run.out
27394666
```

Running "`./run.out -v`" gives additional information.

5.1 Concurrent push and pop

Write blocking `push` and `pop` function.

The testing source (sub-directory `stack`) includes starting code for the stack (files `stack.h` and incomplete `stack.c`), our wrappers around POSIX thread operations (`basic.h` and `basic.c`), and complete code for the test applications `tst.c` and `run.c`.

The starting code in `stack.c` contains complete `alloc_stack` and `free_stack` functions, and wrong attempts for `push` and `pop`. As a result attempting to run `./tst.out` (or `./run.out`) may fail:

```
% ./tst.out
Segmentation fault (core dumped)
```

Here is for instance the wrong code for `push`:

```c
void *pop(stack_t *p) {
  void *r ;
  while (p->sp <= 0) ;
  p->sp-- ; r = p->t[p->sp] ;
  return r ;
}
```

Notice that the stack includes an array `p->t` of size `p->sz` and that `p->sp` is the stack pointer. As usual, `p->sp` is the indice of the next free position in the stack.

Correct code will probably use the mutex `p->lock` and the two condition variables `is_empty` and `is_full` that are already present in the stack structure definition (defined in `stack.h`) and properly initialised by `allocate_stack` (defined in `stack.c`). You may draw inspiration from the bounded FIFO of class 01.

Once you have written correct `push` and `pop` functions, you still may get wrong sums, as termination is not handled properly yet:

```
% ./tst.out -v
nprocs=2, sz=100
PUSHER<0> PUT 1
PUSHER<1> PUT 1
PUSHER<1> PUT 1
POPPER<0> GOT 1
SUM=1, OK=3
pthread_mutex_destroy: Device or resource busy
```

You may have to run the experiment more than once to get a wrong result (*i.e.* `SUM` different from `OK=3`). Also notice that the de-allocation of resources is not properly performed.

5.2 Controlling termination

She shall now enrich our stack with a "`kill`" functionality that behaves as follows:

- `kill(stack_t *p, int nprocs)` should be called at most once and "kills" the stack. The call to `kill` is blocking and will return once the kill has been acknowledged `nprocs` times (see `pop` below).
- Once `kill` has been called, calling `push` is an error.
- Attempting to pop a stack that is both killed and empty should return `NULL` and acknowledge the kill once.

Hence, you should alter your working `push` and `pop` functions from 5.1 and write the `kill` function. To that aim, you may use new fields for the stack structure: the flag `killed` (to register the kill), the integer `seen` (to count acknowledgements), and the condition variable `wait` (for the killer to suspend on, waiting for acknowledgements).

So as to describe the kill functionality in greater detail, here are the relevant code snippets from `tst.c`. First we recall that poppers exit when `pop` returns `NULL`:

```
void *popper(void *p) {
  // Various initialisation from p
  ...
  void *item ;
  while ((item = pop(c->stack)) != NULL) {
   ...
  }
  if (verbose) fprintf(stderr,"POPPER<%i> OUT\n",id) ;
  return NULL ;
}
```

Then, here is the code that creates poppers and pushers:

```
⋮
/* Create n poppers */
common_popper_t *spawn_poppers(stack_t *stack, int n) {
  common_popper_t *c = alloc_common_popper(stack);
  for (int id = 0 ; id < n ; id++) {
    popper_t *w = alloc_popper_t(id,c) ;
    create_thread_detached(popper,w) ;
  }
  return c ;
}
⋮
/* Create n pushers */
common_pusher_t *spawn_pushers(stack_t *stack, int n) {
  common_pusher_t *c = alloc_common_pusher(stack);
  pthread_t th[n] ;
  for (int id = 0 ; id < n ; id++) {
    pusher_t *w = alloc_pusher_t(id,c) ;
    create_thread(&th[id],pusher,w) ;
  }
  for (int id = 0 ; id < n ; id++) join_thread(&th[id]);
  return c ;
}
```

It can be noticed:

- Both functions allocate specific “common” arguments for poppers and pushers, noticeably to hold a pointer to the common stack. Those arguments are returned so as to be de-allocated once termination is ensured.
- While poppers are created detached (their termination is handled through the kill functionality), the pushers are joined. As a result, when `spawn_pushers` returns, we can be sure that all pushes have been performed.

Finally, here is the overall thread control:

```
void zyva(int nprocs,int sz) {
  if (verbose) fprintf(stderr,"nprocs=%i, sz=%i\n",nprocs,sz);
  // Allocate stack and start all threads
  stack_t *stack = alloc_stack(sz) ;
  common_popper_t *pop = spawn_poppers(stack,nprocs) ;
  common_pusher_t *push = spawn_pushers(stack,nprocs) ;
  // Kill stack
  kill(stack,nprocs) ;
  // Get and check result
  int sum =  __sync_fetch_and_add(&pop->sum,0) ;
  int ok = 0 ;
  for (int k = 1 ; k <= nprocs ; k++) ok += k ;
  printf("SUM=%i, OK=%i\n",sum,ok);
  // Free all data structures
  free_common_popper(pop) ;
  free_common_pusher(push) ;
  free_stack(stack) ;
}
```

Observe:

- The stack is killed only after `spawn_pushers` has returned. As a consequence, and because we know that all pushers have terminated before `spawn_pushers` returns, we know that no further push will ever occur.
- The function `kill` will return only once the `nprocs` poppers have acknowledged the kill. As a result, `pop->sum` is valid. Further notice how `pop->sum` is read, for greater safety — however it can be argued that the `kill`/`pop` synchronisation suffices to allow an ordinary read of `pop->sum`.
- Furthermore, (see `pop` code), no popper will access its “common” argument, nor the stack once it has acknowledged the kill. Hence, freeing the `pop` (poppers common argument) where we do is safe.

Once you have completed you kill functionality, try:

```
% ./tst.out -v
nprocs=2, sz=100
PUSHER<1> PUT 1
PUSHER<0> PUT 1
PUSHER<1> PUT 1
POPPER<0> GOT 1
POPPER<0> GOT 1
POPPER<0> GOT 1
POPPER<0> OUT
SUM=3, OK=3
POPPER<1> OUT
```

And:

```
% ./run.out
27394666
% ./run.out 18
1540820542
```

6 Transitive visibility

One of your friends works at Intel and argues that, on processors, "stores obey transitive visibility". As you wonder what "transitive visibility" is, he writes the following three functions, to be executed concurrently:

```c
int x=0, y=0 ;

void writer(void) {
  x = 1 ;
}

void transmitter(void) {
  int r = x ;
  y = r ;
}

void reader(void) {
  int ry = y ;
  int rx = x ;
}
```

He then argues that the reader thread must see `rx == 1` whenever it sees `ry == 1`. Said otherwise, an execution where `ry == 1` and `rx == 0` is not possible.

Is your friend right? To answer, you can draw a diagram for the test, similar to the ones of lesson 03, and consider that Intel processors are TSO.

7 A memory model zoo

Here are the definitions of the SC, TSO and PSO (Partial Store Order) memory models in the axiomatic formalism we used in class (see class 03 slides 20 and 62):

```
(* SC Model *)
acyclic po | rf | fr | co

(* TSO Model *)
acyclic po-loc | rf | fr | co
acyclic (po \ (W*R)) | rfe | fr | co

(* PSO Model *)
acyclic po-loc | rf | fr | co
acyclic (po \ (W*M)) | rfe | fr | co
```

In the above languages expressions are either event sets (such as `M`) or relations (such as `po`, `rf` etc.). Binary operators used are union "`|`", difference "\" and Cartesian product "`*`". Some sets are pre-defined: write events "`W`" read events "`R`" and all memory events "`M`" — Notice that `M` can be defined as `R|W`. Hence, for instance, `po \ (W*R)` is the program-order relation minus write-to-read pairs.

Consider the four tests of Figure 2. Those tests are written in pseudo-code: `x`, `y` are memory locations, `r0`, `r1` are registers, all locations are initialised to zero.

Figure 2: Four litmus tests

```
   Test 2+2W                  Test MP
-----------------          -----------------
  T0    |   T1               T0    |   T1
--------+--------          --------+--------
 x <- 2 | y <- 2            x <- 1 | r0 <- y
 y <- 1 | x <- 1            y <- 1 | r1 <- x
-----------------          -----------------
x = 2 /\ y = 2              r0 = 1 /\ r1 = 0


   Test R                     Test LB
-----------------          -------------------
  T0    |   T1               T0     |   T1
--------+--------          ---------+---------
 x <- 1 |  y <- 2           r0 <- x | r1 <- y
 y <- 1 | r0 <- x            y <- 1 |  x <- 1
-----------------          -----------------
 y = 2 /\ r0 = 0            r0 = 1 /\ r1 = 1
```

A test is valid on a model (written `Ok`), when the final condition of the test can be observed to be true, once a machine that implements the model has run the test. Otherwise the test is invalid, which we write `No`. Fill the cells of following table with `Ok` or `No`, depending upon the result of each test on each model.

	2+2W	MP	R	LB
SC				
TSO				
PSO				

Then argue that any test valid on TSO is also valid on PSO.

Solutions

1 Semaphores

1.1 Coding a semaphore

```
/* Semaphore */

typedef struct {
  volatile int nfree ;
  pthread_mutex_t *mutex ;
  pthread_cond_t *cond ;
} semaphore_t ;

semaphore_t *alloc_semaphore(int capacity) {
  semaphore_t *p = malloc_check(sizeof(*p)) ;
  p->nfree = capacity ;
  p->mutex = alloc_mutex() ;
  p->cond = alloc_cond() ;
  return p ;
}

void free_semaphore(semaphore_t *p) {
  free_mutex(p->mutex) ;
  free_cond(p->cond) ;
  free(p) ;
}

void wait_semaphore(semaphore_t *p) {
  lock_mutex(p->mutex) ;
  while (p->nfree <= 0) wait_cond(p->cond,p->mutex) ;
  p->nfree-- ;
  unlock_mutex(p->mutex) ;
}

void post_semaphore(semaphore_t *p) {
  lock_mutex(p->mutex) ;
  p->nfree++ ;
  broadcast_cond(p->cond) ;
  unlock_mutex(p->mutex) ;
}
```

1.2 Semaphore usage

Without the semaphore, output will consist in `q->size` lines. Each line consists in `nprocs` "`+`" characters and `nprocs` "`-`" characters. In any prefix, there are as many "`-`" as "`+`' characters, or less.

When the semaphore of capacity c is added output follows the additional constraint that no more than c "`+`" will ever follow with no "`-`" in-between.

1. `++--+-+-` is legal, cf. above.
2. `+++-+---` is illegal, as there are 3 "`+`" in a row, hence 3 threads should be in critical section at the same time.
3. `-+-+-+-+` is illegal, no "`-`" can be without a matching "`+`" before.
4. `+-+-+-+-` is legal, and is still legal with $c = 1$.

5. `++++++++` is illegal and is a joke.

1.3 C11 Coding

With respect to the POSIX solution, we see a few syntactic changes. The solution applies the change at the mutex and condition variable level (C11 types `mtx_t` and `cnd_t`).

```
#include <stdatomic.h>
  ...

/* Lock  basic wrappers */

mtx_t *alloc_mutex(void) {
  mtx_t *p = malloc_check(sizeof(*p)) ;
  if (mtx_init(p,mtx_plain) != thrd_success) error_exit("mtx_init") ;
  return p ;
}

void free_mutex(mtx_t *p) {
  mtx_destroy(p) ;
  free(p) ;
}

void lock_mutex(mtx_t *p) {
  if (mtx_lock(p) != thrd_success) error_exit("mtx_lock") ;
}

void unlock_mutex(mtx_t *p) {
  if (mtx_unlock(p) != thrd_success) error_exit("mtx_unlock") ;
}

/* Condition variable  basic wrappers */

cnd_t *alloc_cond(void) {
  cnd_t *p = malloc_check(sizeof(*p)) ;
  if (cnd_init(p) != thrd_success) error_exit("cnd_init") ;
  return p ;
}

void free_cond(cnd_t *p) {
  cnd_destroy(p) ;
  free(p) ;
}

void wait_cond(cnd_t *c,mtx_t *m) {
  if (cnd_wait(c,m) != thrd_success) error_exit("cnd_wait") ;
}

void signal_cond(cnd_t *p) {
  if (cnd_signal(p) != thrd_success) error_exit("cnd_signal") ;
}
```

That way, semaphore code is the same as in the POSIX case, up to the types of the fields of the semaphore_t record:

```
/* Semaphore proper */

typedef struct {
  volatile int nfree ;
```

```
  mtx_t *mutex ;
  cnd_t *cond ;
} semaphore_t ;

  ...
```

As regards the spawn/join sequence we directly call the C11 primitives:

```
#include <threads.h>

    ...

void run(int size, int nprocs, int m) {
  ...
  thrd_t th[nprocs] ;
  ctx_t a[nprocs] ;
  for (int k = 0 ; k < nprocs ; k++) {
    ctx_t *p = &a[k] ;
    p->id = k ; p->common = &c ;
    if (thrd_create(&th[k],T1,p) != thrd_success) error_exit("thrd_create") ;
  }
  for (int k = 0 ; k < nprocs ; k++)
    if (thrd_join(th[k],NULL) != thrd_success) error_exit("thrd_join") ;
  ...
}
```

Sequentially consistent or not?

Listing valid bahaviours amounts listing all possible write-to-read matchings and all possible final values of observed shared locations.

- `Test 1` The values written to location `x` are 0, 1 and 2 . The values writtent to `y` are 0 and 1. Hence the following valid behaviours:

  `x=0; r0=0`, `x=0; r0=1`, $\underline{\texttt{x=1; r0=0}}$, $\underline{\texttt{x=1; r0=1}}$, $\underline{\texttt{x=2; r0=0}}$, `x=2; r0=1`

  SC behaviours are underlined. They can be justified by exhibiting scheduling orders or diagrams.

- For `Test 2`, valid behaviours are the sams as for `Test 1`, since stores are the same.

  `x=0; r0=0`, `x=0; r0=1`, $\underline{\texttt{x=1; r0=0}}$, $\underline{\texttt{x=1; r0=1}}$, $\underline{\texttt{x=2; r0=0}}$, $\underline{\texttt{x=2; r0=1}}$

  By contast behaviour `x=2; r0=1` is now SC, as can be seen by considerint the scheduling order:

  $$\texttt{*x = 1} \rightarrow \texttt{*x = 2} \rightarrow \texttt{*y = 1} \rightarrow \texttt{r0 = *y}$$

- Given the possible writes, we have the following valid behaviours t2, valid behaviours are the sams as for `Test 1`, since stores are the same.

  `r0=0; r1=0`, `r0=0; r1=0`, $\underline{\texttt{r0=1; r1=0}}$, $\underline{\texttt{r0=0; r1=1}}$, $\underline{\texttt{r0=1; r1=1}}$

  SC behaviours are underlined.

- `Test 4` is similar as regards valid behaviours and much stronger as regards SC. Namely reading the initial value of a location after a store to the same locaton is an obvious violation of coherence.

  `r0=0; r1=0`, `r0=0; r1=0`, `r0=1; r1=0`, `r0=0; r1=1`, $\underline{\texttt{r0=1; r1=1}}$

2 The and_t component

2.1 Barrier coding

```
int wait_and(and_t *p,int b) {
  if (!b) p->v = 0 ;
  wait_barrier(p->b) ; // Now any false is registered
  int r = p->v ;
  int serial = wait_barrier(p->b) ; // Now, everybody has copied result
  if (serial) p->v = 1 ; // No need for every body to re-initialise
  wait_barrier(p->b) ; // Now component is re-initialised
  return r ;
}
```

One may notice that the code is not race-free, as several threads may write `0` to `p->v` concurrently. In practice, one can probably ignore the issue as all threads write the same value with a single instruction. Thus, it is very unlikely that the races would conduct to `p->v` holding anything else than `0` or that the machine would catch fire.

Nevertheless, if one insists on avoiding races, one easily solves the issue by adding a mutex field to the component and by using it to protect the writes to `p->v`:

```
int wait_and(and_t *p, int b) {
  if (!b) { lock_mutext(p->mutex) ; p->v = 0 ; unlock_mutex(p->mutex) ; }
```

2.2 Direct coding

We add two fields `v` and `saved_v` to the given and_t **struct** definition:

```
typedef struct {
  pthread_cond_t *cond ;
  pthread_mutex_t *mutex ;
  /* Hum the following should remind you of something... */
  int nprocs,count ;
  int turn ;
  int v,saved_v ; // You'll need those fields for return value
} and_t ;

and_t *alloc_and(int nprocs) {
  and_t *p = malloc_check(sizeof(*p)) ;
  p->cond = alloc_cond();
  p->mutex = alloc_mutex() ;
  p->nprocs = p->count = nprocs ;
  p->turn = 0 ;
  p->v = 1 ;
  return p ;
}
```

Notice that `p->v` is initialised to `1`, as in the previous exercise.

And here is `wait_and`, an enhancement of `wait_barrier`:

```
int wait_and(and_t *p,int b) {
  lock_mutex(p->mutex) ;
  if (!b) p->v = 0 ;
  --p->count ;
  if (p->count > 0) { /* Not last */
    int t = p->turn ;
    do {
      wait_cond(p->cond,p->mutex) ;
    } while (p->turn == t) ;
  } else { /* I'am last */
```

```
    p->saved_v = p->v ;        /* save result */
    p->v = 1 ;                 /* as we erase it here */
    p->count = p->nprocs ;     /* Re-triggers barrier */
    p->turn = 1-p->turn ;       /* Free waiting threads */
    broadcast_cond(p->cond) ;
  }
  int r = p->saved_v ;
  unlock_mutex(p->mutex) ;
  return r ;
}
```

The only difficulty lies in the use of `p->saved_v` to transmit the final value of `p->v` for a given round to the last thread that enters the barrier to the other threads.

Another solution could be for each thread to save its value in some internal array (indexed by `p->count` for instance), and for the last thread to compute the conjunction. This solution has the avantage that the array need not to be be initialised and re-initialised.

3 Processor farm

The solutions are given in files `monitor.sol.c` and `pool.sol.c` in directory `pool`.

We here reproduce our solution:

Pool

```
void leave_pool(pool_t *p) {
  lock_mutex(p->lock) ;
  p->nrun-- ;
  if (p->waiting) signal_cond(p->cond) ;
  unlock_mutex(p->lock) ;
}

void look_pool(pool_t *p) {
  lock_mutex(p->lock) ;
  p->waiting = 1 ;
  while (p->nrun >= p->maxrun) {
    wait_cond(p->cond,p->lock) ;
  }
  p->waiting = 0 ;
  p->nrun++ ;
  unlock_mutex(p->lock) ;
}
```

The solution is quite straightforward: `look_pool` increases the number of running workers, while `leave_pool` decreases it.

The master (cf. `look_pool`) suspends when `maxrun` workers are already running and is awaken by any worker that leaves the pool. Observe that we guard against spurious wakeups in `look_pool` by the means of the classical **while** loop on the sleeping condition.

Monitor

```
/* Called by master */
void enter_monitor(monitor_t *m) {
  lock_mutex(m->lock) ;
  m->nrun++ ;
  unlock_mutex(m->lock) ;
```

```
}

/* Called by worker */
void leave_monitor(monitor_t *m,uintmax_t y) {
  lock_mutex(m->lock) ;
  m->nrun-- ;
  m->ncompleted++ ;
  m->r = m->compose(y,m->r) ;
  if (m->waiting && m->nrun == 0) signal_cond(m->cond) ;
  unlock_mutex(m->lock) ;
}

/* Called by master */
uintmax_t wait_monitor(monitor_t *m,int ntasks) {
  uintmax_t r ;
  lock_mutex(m->lock) ;
  m->waiting = 1 ;
  while (m->ncompleted < ntasks) wait_cond(m->cond,m->lock) ;
  assert(m->nrun == 0) ;
  m->waiting = 0 ;
  r = m->r ;
  unlock_mutex(m->lock) ;
  return r ;
}
```

The only difficult point is the handling of master sleep and wakeup. Quite logically, the master sleeps when strictly less than `ntasks` have been completed. The worker that is last to complete should awake the master in `leave_monitor`. A worker can know it is the last to complete by checking the condition `m->nrun === 0`, because the *master* called `enter_monitor` and thus has incremented `m->nrun`.

If workers were calling `enter_monitor`, then there would be no guarantee that all tasks are completed when `m->nrun == 0`. Consider a scenario where the master leaves the **for** loop while two tasks have been allocated but the workers have not started yet and all other workers have terminated. The value of `m->nrun` is then `0`. The master then suspends. One worker start, increasing `m->nrun` to `1`, performs its work and then decreases `m->nrun` to `0`. As a result the master is awaken, while one task is still pending.

Notice that `enter_monitor` can be called by workers (in fact suppressed) by a different design: the call `wait_monitor(m,ntasks)` would record `ntasks` into the monitor structure, for workers that call `leave_monitor()` to compare `ntasks` with `m->completed`. Then, the last worker to complete would know it is last by the condition `ntasks == m->completed`.

Finally as noticed by a student, the original version of the two examples of had a bug: the master handles program termination as follows:

```
   ...
   uintmax_t r = wait_monitor(...) ;
   free_pool(c.pool) ;
   free_monitor(c.monitor) ;
   ...
}
```

That is, once `wait_monitor` has returned, the master de-allocates the pool and monitor structures. While the buggy worker code was as follows:

```
void *worker(void *p) {
  worker_t *w = (worker_t *)p ;
  common_t *c = w->common ;
...
  leave_monitor(c->monitor,y) ;
  leave_pool(c->pool) ;
  return NULL ;
}
```

Thus, it may be that a worker attempts to access the pool structure after (while!) it has been freed. The bug can be corrected by swapping the calls to `leave_monitor` and `leave_pool` in `worker`, so as to perform the call to `leave_monitor` last:

```
void *worker(void *p) {
  worker_t *w = (worker_t *)p ;
  common_t *c = w->common ;
...
  leave_pool(c->pool) ;
  leave_monitor(c->monitor,y) ;
  return NULL ;
}
```

The issue is solved (up to weak memory effects. . .). Nevertheless, our minimal “process farm” framework appears quite brittle. This can be alleviated by grouping the pool and monitor structures in one single component.

4 Controlling workers with a stack

4.1 Concurrent push and pop

The solution is in file `stack.partial.c`. The code is standard and handles spurious wakeups:

```
void push(stack_t *p, void *q) {
  lock_mutex(p->lock) ;
  while (p->sp >= p->sz) wait_cond(p->is_full,p->lock) ;
  int was_empty = p->sp <= 0 ;
  p->t[p->sp] = q ; p->sp++ ;
  if (was_empty) broadcast_cond(p->is_empty) ;
  unlock_mutex(p->lock) ;
}


void *pop(stack_t *p) {
  void *r ;
  lock_mutex(p->lock) ;
  while (p->sp <= 0) wait_cond(p->is_empty,p->lock) ;
  int was_full = p->sp >= p->sz ;
  p->sp-- ; r = p->t[p->sp] ;
  if (was_full) broadcast_cond(p->is_full) ;
  unlock_mutex(p->lock) ;
  return r ;
}
```

4.2 Controlling termination

The solution is in file `stack.sol.c`.

The easiest alteration is for `push`. We simply crash the program in case of a push attempt on a killed stack:

```
static void stack_error(char *msg) {
  fprintf(stderr,"stack: %s\n",msg) ;
  exit(2);
}

void push(stack_t *p, void *q) {
  lock_mutex(p->lock) ;
  if (p->killed) stack_error("pushing on a killed stack");
```

```
  while (p->sp >= p->sz) wait_cond(p->is_full,p->lock) ;
  int was_empty = p->sp <= 0 ;
  p->t[p->sp] = q ; p->sp++ ;
  if (was_empty) broadcast_cond(p->is_empty) ;
  unlock_mutex(p->lock) ;
}
```

Now, here is the code for `kill`:

```
void kill(stack_t *p,int nprocs) {
  lock_mutex(p->lock) ;
  if (p->killed) stack_error("killing the stack more then once");
  p->killed = 1 ;
  broadcast_cond(p->is_empty) ;
  while (p->seen < nprocs) wait_cond(p->wait,p->lock) ;
  unlock_mutex(p->lock) ;
}
```

After the lock has been acquired:

- Double kill is checked, crashing the program if occurring.
- The `p->killed` flag is set, in effect killing the stack.
- Some poppers may be suspended, waiting for the stack to become non-empty (or to be killed!). We awake them all (with `broadcast_cond`).
- Then we wait for `nprocs` acknowledgements, suspending on the condition variable `p->wait` in a quite standard manner.

The `pop` function is responsible for making acknowledgements:

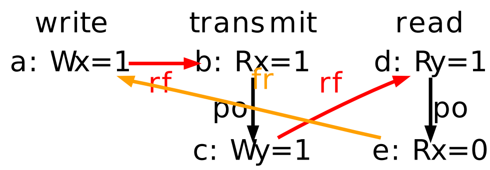
```
void *pop(stack_t *p) {
  void *r ;
  lock_mutex(p->lock) ;
  while (!p->killed && p->sp <= 0) wait_cond(p->is_empty,p->lock) ;
  if (p->sp > 0) {
    int was_full = p->sp >= p->sz ;
    p->sp-- ; r = p->t[p->sp] ;
    if (was_full) broadcast_cond(p->is_full) ;
  } else {
    assert (p->killed) ;
    p->seen++ ;
    signal_cond(p->wait) ;
    r = NULL ;
  }
  unlock_mutex(p->lock) ;
  return r ;
}
```

In effect, `pop` must take some action when the stack is non-empty or killed, or equivalently `pop` must block when the stack is not killed and empty — see the condition `(!p->killed && p->sp <= 0)` above.

If some action have to be taken, observe that retrieving an item from a non-empty stack has priority — see `if (p->sp) {...` above. It the action is a kill acknowledgement, the thread that performed the kill is waiting on the condition variable `p->wait`, we awake it (by instruction `signal_cond(p->cond)`) *after* having acknowledged the kill (by instruction `p->seen++`).

5 Transitive visibility

Here is the diagram:



The diagram follows from:

1. As the `reader` reads value `1` in `y` (written by the `transmitter`), it must be that the `transmitter` has read value `1` in `x` (written by `writer`). Hence the two $\xrightarrow{\text{rf}}$ arrows.

2. As the `reader` reads initial value `0` in `x`, it must be that the read is in $\xrightarrow{\text{fr}}$ with the sole write to `x` by `writer`.

We see first that the execution is not sequentially consistent, as we have a cycle in $\xrightarrow{\text{po}} \cup \xrightarrow{\text{fr}} \cup \xrightarrow{\text{rf}} \cup \xrightarrow{\text{co}}$. The execution is not TSO either, given that no $W \xrightarrow{\text{po}} R$ edge is present in the cycle.

6 A memory model zoo

	2+2W	MP	R	LB
SC	No	No	No	No
TSO	No	No	Ok	No
PSO	Ok	Ok	Ok	No

The TSO and PSO models are similar, up to happens-before relations: PSO happens-before relation is included in the TSO happens-before relation. As a result, a cycle in PSO happens-before is also a cycle in TSO happens-before. The converse implication thus holds for the absence of cycles.