Practical multicore programming

The DRF fragment

Slides and demos available at
`http://cambium.inria.fr/~maranget/MPRI/`

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Multicore programming, why?

Run faster.

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Run faster.

Some program are much easier to write that way (*e.g.* avoid asynchronous IO).

Run faster, our running example

The n queens puzzle: placing n chess queens on an $n \times n$ chessboard so that no two queens threaten each other.

A classics in backtracking: place one queen per row, from top to bottom:

```
int solve(int n, int row, int *cols) {
  if (row == n) return 1 ;
  int r = 0 ;
  for (int i = 0 ; i < n ; i++) {
    if (ok(i,row,cols)) {
      cols[row] = i ;
      r += solve(n,row+1,cols) ;
    }
  }
  return r;
}
```

Demo (in `queens`):

```
% ./q.out -v -v 8 2>&1 | less
...
```

Run faster, sequentially

Simple implementation (demo in `queens`):

```
% safe ./q.out 15
2279184
status: 0
real: 34.70
user: 34.57
 sys:  0.01
```

Optimised implementation (demo in `queens`):

```
safe ./fast.out 15
2279184
status: 0
real:  0.66
user:  0.66
 sys:  0.00
```

Optimisations: symetries, integers as bitsets, avoiding function calls...
The point is: parallelize the fasted program, not the slowest.

Faster without threads

A process in three steps

1. Place queens in the first d rows.
2. Count how many ways there are for placing the remaining $n - d$ queens.
3. Sum counts.

Step 2 can run concurrently...

Demo (`queens`), two C programs:

- `gen.out -d[d] n` : place the first d queens.
- `run.out` : count solutions with the first d queens placed as read on standard input.

The programs `gen.out` and `run.out` communicate through files.

We shall concurrently run the requested invocations of `run.out`, by using a shell script , a `Makefile`, or the `parallel` utility.

Before we parallelize, a quiz

How do we solve the 8-queens puzzle?

- With `./gen.out` only:

Before we parallelize, a quiz

How do we solve the 8-queens puzzle?

- With `./gen.out` only: set $d = 8$.

  ```
  % ./gen.out -d8 8
  0 8 8 0 4 7 5 2 6 1 3
  1 8 8 0 5 7 2 6 3 1 4
  ...
  45 8 8 5 7 1 3 0 6 4 2
  ```

  With symmetry: $46 \times 2 \rightarrow 92$ solutions.

- With `./run.out` only:

Before we parallelize, a quiz

How do we solve the 8-queens puzzle?

- With `./gen.out` only: set $d = 8$.

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  ...
  45 8 8 5 7 1 3 0 6 4 2
  ```

  With symmetry: $46 \times 2 \rightarrow 92$ solutions.

- With `./run.out` only: set $d = 0$.

  ```
  % ./run.out
  0 8 0
  92
  ```

Aggressive parallelism

```
% sh shell.sh 17 > A/script.sh
```

Here is `script.sh`:

```
# Fork the computing processes, one per line of  "gen.out 17" output
( echo 0 17 2 0 2 | ../run.out > 000.out ) &
( echo 1 17 2 0 3 | ../run.out > 001.out ) &
...
( echo 119 17 2 14 16 | ../run.out > 119.out ) &
# Wait for the computing processes to terminate
wait
# Sum partial results
cat 000.out 001.out ... 119.out > 17.out
( echo 0 && awk '{printf("%s +\n",$1)}' 17.out && echo p ) | dc
```

```
% safe sh script.sh
95815104
real:  4.74
user: 36.66
 sys:  0.07
```

Drawback: Why run more than 8 processes at the same time on a 4 core $\times 2$ hyperthreaded machine?

Controlling parallelism with `make -j N`

`% sh make.sh 17 > B/Makefile`

The `Makefile`:

```
all: 17.out
	@( echo 0 && awk '{printf("%s +\n",$$1)}' 17.out && echo 'p' ) | dc

OUT := 000.out ... 119.out

17.out: $(OUT)
	@cat $(OUT) > 17.out

000.out:
	 echo 1 20 15 1 1 1 1 1 | ../run.out > $@
...
063.out:
	echo 63 20 15 1 2 3 3 3 | ../run.out > $@
```

```
# My machine has 4 X 2 virtual processors
% safe make -C B -j 8
make: Entering directory '/home/maranget/MPRI/01/queens/B'
echo 0 17 2 0 2 | ../run.out > 000.out
...
95815104
make: Leaving directory '/home/maranget/MPRI/01/queens/B'
status: 0
real:  4.79
user: 36.98
 sys:  0.05
#make -j 4 worth trying!
```

With the `parallel` utility

Usage:

`parallel -j` *N command* `--` A_1 `...` A_n

Will run *n* invocations of *command* on arguments $A_1 \ldots A_n$, with at most *N* invocations running concurrently.

This interface is not ideal, as our program `run.out` reads its arguments from standard input.

Easily corrected:

With the `parallel` utility

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Will run *n* invocations of *command* on arguments $A_1 \ldots A_n$, with at most *N* invocations running concurrently.

This interface is not ideal, as our program `run.out` reads its arguments from standard input.

Easily corrected:

```
% cat run.sh
#! /bin/sh
echo $1 | ./run.out
```

Using the `parallel` utility

A `parallel.sh` script that combines `gen.out` and the `parallel` utility:

```
...
./gen.out -g$G $N |\
(
  while read arg; do A="'$arg' $A"; done
  echo 0
  eval "parallel $J sh ./run.sh -- $A" |\
    awk '{printf("%s +\n",$1)}'
  echo p
) | dc
```

Demo (in `queens`):

Using the parallel utility

A parallel.sh script that combines gen.out and the parallel utility:

```
...
./gen.out -g$G $N |\
(
  while read arg; do A="'$arg' $A"; done
  echo 0
  eval "parallel $J sh ./run.sh -- $A" |\
    awk '{printf("%s +\n",$1)}'
  echo p
) | dc
```

Demo (in queens):

```
% J="-j 8" safe sh ./parallel.sh 17
95815104
status: 0
real:  4.80
user: 37.51
 sys:  0.07
```

Processes vs. threads

Up to now we used *processes*.

A process is the running instance of a program:

- A process consists in, register values, memory, file descriptors etc.
- The process own its *memory*.
- Processes communicate (mostly) through the file system.

A *thread* is a lightweight process:

- A process may host several threads.
- A thread consists in register values, file descriptors, etc.
- The threads in a process share the memory (or part of).

Multicore programming, from inside programs

Principle

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This class

- Programming with the C POSIX threads library (pthreads).
- Well synchronised programs only — programming on top of the Data Race Free model (DRF).

Starting a thread, getting its result

A.k.a. "asynchronous function call" — of `f` that accepts an argument of type **void** `*` and returns a result of type **void** `*`

```
void *f (void *arg) { ... }

void run(...) {
```

Starting a thread, getting its result

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```
void *f (void *arg) { ... }

void run(...) {

  // Compute f(arg) asynchronously.
  void *arg = ... ;
  pthread_t th ;
  create_thread(&th,f,arg) ;
```

Starting a thread, getting its result

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```
void *f (void *arg) { ... }

void run(...) {

  // Compute f(arg) asynchronously.
  void *arg = ... ;
  pthread_t th ;
  create_thread(&th,f,arg) ;

  // Some computation performed concurrently with f(arg)
  ...
```

Starting a thread, getting its result

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```
void *f (void *arg) { ... }

void run(...) {

  // Compute f(arg) asynchronously.
  void *arg = ... ;
  pthread_t th ;
  create_thread(&th,f,arg) ;

  // Some computation performed concurrently with f(arg)
  ...

  // Get back f(arg)
  void *r = join_thread(&th) ;
  ...
}
```

Thread create and join, helper functions

Handle error checking — this is C!

```
#include <pthread.h>
#include <stdlib.h>
#include <string.h>
...
static void exit_error (char *msg, int st) {
  fprintf(stderr,"%s: %s\n",msg,strerror(st));
  exit(EXIT_FAILURE);
}

void create_thread
  (pthread_t *th,void *(*f)(void *),void *x) {
  int st = pthread_create(th,NULL,f,x)) ;
  if (st != 0) exit_error("pthread_create",st) ;
}

void *join_thread(pthread_t *th) {
  void *r ;
  int st = pthread_join (*th,&r) ;
  if (st != 0) exit_error("pthread_join",st) ;
  return r ;
}
```

Informal semantics (`man pthread_create`)

```
int pthread_create
  (pthread_t *th,...,void *(*f)(void *),void *z)
```

- Call `f` with argument `z` on a new thread whose identity is stored in `*th`.
- Returns 0 (success), or error status.
- `...` are options, which we ignore for now.

```
int pthread_join(pthread_t th, void **r)
```

- If the thread identified by `th` has returned `v`, store `v` into `*r`.
- If not, suspend and wait for `th` to return.
- Returns 0 (success), or error status.
- It is an error to call `pthread_join` more than once on the same thread.

Notice: Threads can be created "*detached*". Detached threads cannot join (and spare the needed resources).

C11 thread create and join

The "new" C11 standard defines the following functions, with shorter names and (unfortunately) a slightly different interface (in header `threads.h`).

```
typedef int(*thrd_start_t)(void*);
int thrd_create(thrd_t *thr, thrd_start_t func, void *arg);
```

- The spawned function now returns an `int` (was `void *`)
- The 'options' argument is no longer here.

```
int thrd_join(thrd_t thr,int *res);
```

- We still have: if the thread identified by `thr` has returned `v`, store `v` into `*res`.
- But the type of `v` has changed w.r.t. pthreads!

To keep things gcc simple, we stick to pthread.

Asynchronous function call, easy example I

Let us compute:

$$\sum_{k=1}^{n} k^2$$

Sketch

- Fork n threads to compute $1^2, 2^2, \ldots, n^2$.
- Sum square as we get thread results.

Asynchronous function call, easy example I

A bit of boxing.

```
// ''Boxed'' int
typedef struct { int v ; } val_t ;
// Or typedef int val_t ;
val_t *alloc_val(int i) ;
void free_val(val_t *p) ;

// Actual computation
int square(int i) { return i*i ; }

// Stub function
void *f(void *p) {
  val_t *_p = (val_t *)p ;
  int i = _p->v ;
  free_val(_p) ;
  return alloc_val(square(i)) ;
}
```

Safer and cleaner that casting "**int**" (or " **intptr_t** ") into "**void** ***" and back.

Asynchronous function call, easy example II

```
int sum(int n) {
  // Fork
  pthread_t th[n] ;
  for (int k = 0 ; k < n ;  k++)
    create_thread(&th[k],f,alloc_val(k+1)) ;

  // Retrieve and sum results
```

Asynchronous function call, easy example II

```
int sum(int n) {
  // Fork
  pthread_t th[n] ;
  for (int k = 0 ; k < n ;  k++)
    create_thread(&th[k],f,alloc_val(k+1)) ;

  // Retrieve and sum results
  int r = 0 ;
  for (int k = 0 ; k < n ;  k++) {
    val_t *p = (val_t *)join_thread(&th[k]) ;
    r += p->v ;
    free_val(p) ;
  }
  return r ;
}
```

Petty optimisation: spare one thread

```
int sum(int n) {
 // Fork
  pthread_t th[n-1] ;
  for (int k = 0 ; k < n-1 ; k++)
   create_thread(&th[k],f,alloc_val(k+1)) ;

  // Retrieve and sum results
  int r = square(n) ;
  for (int k = 0 ; k < n-1 ; k++) {
   val_t *p = (val_t *)thread_join(&th[k]) ;
   r += p->v ;
   free_val(p) ;
  }
  return r ;
}
```

Exercise I

Count n-queens solutions using aggressive parallelism. That is write:

```
/* count_t is the type of unsigned 64bits integers */
count_t run(int n, int depth)
```

Useful functions:

```
/* Thread create and join*/
void create_thread(pthread_t *th,void *(*f)(void *),void *x) ;
void *join_thread(pthread_t *th) ;

/* Subtask: concretely a placement of the d first queens */
typedef struct { ... } subtask_t ;

/* Run a subtask */
count_t run_subtask(subtask_t *z) ;

typedef void emit_t(subtask_t *z) ;
/* Subtask generator, calls emit on all subtasks,
   returns number of generated subtasks */
int generate_subtasks(int n, int depth, emit_t emit) ;
```

A little help

This is how one uses generator/runner for sequential computation: (`exp1/seq.out`).

```
static count_t sum ;

void emit_run(subtask_t *z) {
  sum += run_subtask(z) ;
}

count_t run(int n, int depth) {
  sum = 0 ;
  (void)generate_subtasks(n,depth,emit_run) ;
  return sum ;
}
```

Hence, write "`emit`" that creates threads and join on them later.
Simplification: you can assume there will be less then `NTASKS` subtasks.

A little more help

Define the proper type `val_t` for boxed `count_t`:

```
typedef struct {  count_t c ; } val_t ;

void free_val(val_t *p) ;
val_t *alloc_val(count_t c) ;
```

Define an array to store threads identifiers:

```
static pthread_t th[NTASKS] ;
static int th_next ;
```

Then, it's up to you:

```
void *run_stub(void *z) {
```

A little more help

Define the proper type `val_t` for boxed `count_t`:

```
typedef struct {  count_t c ; } val_t ;

void free_val(val_t *p) ;
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```

Define an array to store threads identifiers:

```
static pthread_t th[NTASKS] ;
static int th_next ;
```

Then, it's up to you:

```
void *run_stub(void *z) {
  count_t r = run_subtask((subtask_t *)z) ; free_arg(z) ;
  return alloc_val(r) ;
}

void emit_thread(subtask_t *z) {
```

A little more help

Define the proper type `val_t` for boxed `count_t`:

```
typedef struct {  count_t c ; } val_t ;

void free_val(val_t *p) ;
val_t *alloc_val(count_t c) ;
```

Define an array to store threads identifiers:

```
static pthread_t th[NTASKS] ;
static int th_next ;
```

Then, it's up to you:

```
void *run_stub(void *z) {
  count_t r = run_subtask((subtask_t *)z) ; free_arg(z) ;
  return alloc_val(r) ;
}

void emit_thread(subtask_t *z) {
  if (th_next >= NTASKS) exit EXIT_FAILURE ; // Enough space?
  create_thread(&th[th_next],run_stub,copy_arg(z)) ; //NB:copy
  th_next++ ;
}
```

Solution I

```
count_t run(int n, int depth) {
  count_t sum = 0 ;

  // Fork
  th_next = 0 ;
  int ntasks = generate_subtasks(n,depth,emit_thread) ;

  // Join
  for (int k = 0 ; k < ntasks ; k++) {
    val_t *r = (val_t *)join_thread(&th[k]) ;
    sum += r->c ;
    free_val(r) ; // optional
  }
  return sum ;
}
```

Demo: Check performance (`queens/tnaive.out`).

```
% safe ./tnaive.out 17
...
real:  4.56
user: 36.17
 sys:  0.06
```

Optimising the sum of squares

Avoid dynamic memory allocation (a frequent C programmer's concern)

```
static volatile int sq ; // Notice `` volatile''

void *f2(void *p) {
  int i = ((val_t *)p)->v ;
  sq += i*i ; // ie int x = sq ; int y = i*i ; sq = x + y ;
  return NULL ;
}
```

Savings achieved:

- Update running sum "sq" instead of returning boxed result.

Also notice:

- Argument space reclaimed by caller.

Optimised sum of squares

```
int sum2(int n) {
  sq = 0 ; // Be cautious
  // Fork
  pthread_t th[n] ; val_t arg[n] ; // Stack allocation
  for (int k = 0 ; k < n ;  k++) {
    val_t *a = &arg[k] ;
    a->v = k+1 ;
    create_thread(&th[k],f2,a) ;
  }

  // Join
  for (int k = 0 ; k < n ;  k++)
    (void)join_thread(&th[k]) ;

  return sq ;
}
```

Do you see a problem?

Optimised sum of squares

```
int sum2(int n) {
  sq = 0 ; // Be cautious
  // Fork
  pthread_t th[n] ; val_t arg[n] ; // Stack allocation
  for (int k = 0 ; k < n ;  k++) {
    val_t *a = &arg[k] ;
    a->v = k+1 ;
    create_thread(&th[k],f2,a) ;
  }

  // Join
  for (int k = 0 ; k < n ;  k++)
    (void)join_thread(&th[k]) ;

  return sq ;
}
```

Do you see a problem? Yes, the program is broken...

A simpler, broken, program

```
static volatile int sum = 0, start = 0 ;

void *f(void *p) {
  while (!start) ; // Wait partner
  sum++ ;
  return NULL ;
}

void run_loose(int n) {
  int broken = 0 ;
  for (int k = 0 ; k < n ; k++) {
    sum = 0 ; start = 0 ;
    pthread_t th1,th2 ;
    create_thread(&th1,f,NULL) ; create_thread(&th2,f,NULL) ;
    start = 1 ;
    (void)join_thread(&th2) ; (void)join_thread(&th1) ;
    if (sum != 2) broken++ ;
  }
  if (broken > 0) printf("Broken: %i/%i\n",broken,n) ;
}
```

Demo (in exp20): `./two.out`

Where broken?

The instructions `sum++` performs two accesses to memory:

```
int x = sum ;    // Access R, read.
int y = x + 1 ; // Compute
sum = y ;        ; // Access W, write.
```

In our programming model (SC) accesses are *atomic* (they don't mix). The effect of a program on memory results of a given interleaving of memory accesses (a.k.a a *schedule*).

Consider the following scheduling for threads 1 and 2:

$$R_1, R_2, W_2, W_1$$

The final value of `sum` is:

Where broken?

The instructions `sum++` performs two accesses to memory:

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Consider the following scheduling for threads 1 and 2:

$$R_1, R_2, W_2, W_1$$

The final value of `sum` is: 1.

Enforcing atomicity with locks

If $[R, W]$ is considered a scheduling unit, the remaining schedules are:

$$[R_1, W_1], [R_2, W_2] \quad [R_2, W_2], [R_1, W_1]$$

And the result is always 2.

In practice, the "scheduling unit" is defined by a *lock* L (or mutual exclusion lock) as:

```
lock(L) ;
sum++ ;
unlock(L) ;
```

The instruction block from `lock` to `unlock` is a *critical section*.
And there can be several locks, only the critical sections of the same lock do not mix.

Mutexes, or locks, creation

We allocate all such primitive data dynamically (calling `malloc`/`free`).

```
pthread_mutex_t *alloc_mutex(void) {
  pthread_mutex_t *r = malloc_check(sizeof(*r)) ;
// Important, initialize mutex
  int st = pthread_mutex_init(r,NULL) ;
  if (st != 0) exit_error("pthread_mutex_init",st) ;
  return r ;
}

void free_mutex(pthread_mutex_t *p) {
  int st = pthread_mutex_destroy(p);
  if (st != 0) error_exit("pthread_mutex_destroy",st) ;
  free(p) ;
}
```

Locking and unlocking (pthreads)

We write some wrappers for error-checking — this is C!

```
void lock_mutex(pthread_mutex_t *p) {
  int st = pthread_mutex_lock(p) ;
  if (st != 0) exit_error("pthread_mutex_lock",st) ;
}

void unlock_mutex(pthread_mutex_t *p) {
  int st = pthread_mutex_unlock(p) ;
  if (st != 0) exit_error("pthread_mutex_unlock",st) ;
}
```

Bonus: C11 locks (not available everywhere)

```
#include <threads.h>

mtx_t *alloc_mutex(void) {
  mtx_t *r = malloc_check(sizeof(*r)) ;
  int st = mtx_init(r,mtx_plain) ;
  if (st != thrd_success) exit_cmd("mtx_init") ;
  return r ;
}
...

void lock_mutex(mtx_t *p) {
  int st = mtx_lock(p) ;
  if (st != thrd_success) exit_cmd("mtx_lock") ;
}
```

Etc. Notice the slightly cleaner interface. . . (*e.g.* **mtx_init** second argument).

The informal semantics of locks

A lock holds a bit of information: taken or free.

- **lock**: Acquire the lock.
  - Read status, if free, then set status to taken – *Atomically*. and return.
  - If taken then wait until free.
    - By polling the status, (*busy wait*),
    - or by going to sleep.
- **unlock**: Release the lock.
  - Set lock status to free,
  - then awake one sleeping thread, if any,
  - then return.

Remark: Same functionality as class 00 (Dekker), *very* different implementation.

Bonus: C11 atomics

C11 atomics feature "atomic" read-modify-write operations.

```
atomic_int sum = ATOMIC_VAR_INIT(0) ;
atomic_int start = ATOMIC_VAR_INIT(0) ;

void *f(void *p) {
  while (!atomic_load_explicit(&start,memory_order_relaxed)) ;
  // Atomic increment of sum
  (void)atomic_fetch_add_explicit(&sum,1,memory_order_relaxed) ;
  return NULL ;
}
```

Besides, conflicting accesses on C11 atomics are not racy.

The simpler program fixed

```
static volatile int sum = 0 ;
static pthread_mutex_t *mutex ;

void *g(void *p) {
  lock_mutex(mutex) ;
  sum++ ;
  unlock_mutex(mutex) ;
  return NULL ;
}

void run_locked(void) {
  sum = 0 ;
  mutex = alloc_mutex() ;

  pthread_t th1,th2 ;
  create_thread(&th1,f,NULL) ; create_thread(&th2,f,NULL) ;
  (void)join_thread(&th2) ; (void)join_thread(&th1) ;
  free_mutex(mutex) ;
  if (sum != 2) printf("Pas possible") ;
}
```

Problems with locks

Performance:

- Critical sections cannot execute simultaneously, and parallelism decreases. Solutions.
  - Write short critical sections, in particular avoid non-termination risks.
  - Use several locks (but see next slide).
- The code for of `lock`/`unlock` takes time. Solution: attempt balance between poll/suspend.
- Contention: when a lot of `lock` are performed simultaneously, performance degrades severely. Solution: hierarchical locks.

Problems with locks

Correction: Locks are error prone. One easily reaches *deadlock*:

Assume that f_1 use lock L_1 and f_2 uses L_2. Then, if f_1 and f_2 are mutually recursive, we may have the following execution trace:

Thread 1	Thread 2
`lock(`L_1`) ;`	`lock(`L_2`) ;`
`...`	`...`
`lock(`L_2`) ;`	`lock(`L_1`) ;`
`...`	`...`
`unlock(`L_2`) ;`	`unlock(`L_1`) ;`
`...`	`...`
`unlock(`L_1`) ;`	`unlock(`L_2`) ;`

As a consequence, programming with lock is not compositional, saved for a crippling discipline: use only one lock (or *master lock*), or take locks following a defined order (hard to check).

Exercise II

Write the *n*-queens solver without `thread_join`.
Thread creation is simplified, since there is no need to save threads somewhere. Termination gets more involved.
To address termination, let us define a new *component* `wait_t` and two primitives:

```
/* Perform a ``tick'' */
void tick(wait_t *p) ;

/* Wait for n ticks ticks */
void wait_done(wait_t *p, int n) ;
```

Synchronisation is as follows, *n* subtasks are generated:

- A tick is performed whenever a subtask is completed,
- Programm terminates having waited for *n* ticks.

Computing a subtask, and ticking

```
static volatile count_t sum ;
static pthread_mutex_t *mutex ;
static wait_t *wait_on ; // New component, to be defined.
```

Computing a subtask, and ticking

```
static volatile count_t sum ;
static pthread_mutex_t *mutex ;
static wait_t *wait_on ; // New component, to be defined.

void *run_stub(void *z) {
  count_t r = run_subtask((subtask_t *)z) ;
  free_arg(z) ;
  lock_mutex(mutex) ;  sum += r ;  unlock_mutex(mutex) ;
  tick(wait_on) ; // Signal I am done
  return NULL ;
}

void emit_thread(subtask_t *z) {
  pthread_t th ; // Hum, looks ok for detached thread!
  // Notice detached, ie no provision for join.
  create_thread_detached(&th,run_stub,copy_arg(z)) ;
}
```

Coding bonus

For the curious, here is the code of `create_thread_detached`:

```
void create_thread_detached
  (pthread_t *th,void *(*f)(void *),void *x) {
  pthread_attr_t tattr;
  int st ;

  st = pthread_attr_init(&tattr) ;
  if (st != 0) exit_error("pthread_attr_init",st) ;

  st = pthread_attr_setdetachstate(&tattr,PTHREAD_CREATE_DETACHED
  if (st != 0) exit_error("pthread_attr_setdetachstate",st) ;

  st = pthread_create(th,&tattr,f,x) ;
  if (st != 0) exit_error("pthread_create",st) ;

  st = pthread_attr_destroy(&tattr) ;
  if (st != 0) exit_error("pthread_attr_destroy",st) ;
}
```

Well... Just remember that one does not join on a detached thread and thus spare the associated resources.

Breaking news: simpler coding...

```
void create_thread_detached
  (pthread_t *th,void *(*f)(void *),void *x) {
  int st ;

  st = pthread_create(th,NULL,f,x) ;
  if (st != 0) exit_error("pthread_create",st) ;
  st = pthread_detach(*th);
  if (st != 0) exit_error("pthread_detach",st) ;
}
```

Exercise II, run function

```
count_t run(int n, int depth) {
  /* Initialise */
  mutex = alloc_mutex() ;
  wait_on = alloc_wait() ;
  sum = 0 ;

  /* Fork all subtasks */
  int ntasks = generate_subtasks(n,depth,emit_thread) ;

  /* Wait result */
  wait_done(wait_on,ntasks) ;
  return sum ;
}
```

Real exercise II

Write the `wait_t` component.

```
/* Component to wait on */
typedef struct {
  pthread_mutex_t *mutex ;
  volatile int nret ;
} wait_t ;

wait_t *alloc_wait(void) {
  wait_t *r = malloc_check(sizeof(*r)) ;
  r->nret = 0 ;
  r->mutex = alloc_mutex() ;
  return r ;
}

void tick(wait_t *p) ;                          // To be written
void wait_done(wait_t *p, int ntasks) ; // To be written
```

Solution II

Function `tick` is easy, we have seen this before:

```
void tick(wait_t *p) {
```

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Function `tick` is easy, we have seen this before:

```
void tick(wait_t *p) {
  lock_mutex(p->mutex) ;
  p->nret++ ;
  unlock_mutex(p->mutex) ;
}
```

Function `wait_on` looks easy:

```
void wait_done(wait_t *p,int ntasks) {
```

Solution II

Function `tick` is easy, we have seen this before:

```
void tick(wait_t *p) {
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}
```

Function `wait_on` looks easy:

```
void wait_done(wait_t *p,int ntasks) {
  while (p->nret < ntasks) ;
}
```

But...

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Function `tick` is easy, we have seen this before:

```
void tick(wait_t *p) {
  lock_mutex(p->mutex) ;
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Function `wait_on` looks easy:

```
void wait_done(wait_t *p,int ntasks) {
  while (p->nret < ntasks) ;
}
```

But...

- Busy waiting degrades performance (demo `queens/busy.out`, can be worse)
- We are no longer in the DRF fragment of pthreads!

Data Race Free guarantee

Race: occurs when two different threads access the same shared location *simultaneously*, and when at least one access is a write.

(Non) simultaneous accesses Accesses "ordered" by pthreads calls:

- Accesses in critical sections that use the same lock.
- Accesses performed before calling `pthread_create`, and accesses by the created thread.
- Accesses by thread `th`, and accesses performed by the caller of `phread_join(th,...)`.

DRF execution: An execution with no data races.

DRF guarantee: All executions of a program whose SC executions are DRF (a DRF program) are SC. The behaviour of non-DRF programs is unspecified.

And indeed we have a race on `wait_on->nret`.

Data-race old-style

Simultaneous accesses to data may, in some circumstance, yield absurd results. On some 32bits mode, we execute simultaneously:

```
void P0(void *p) {                    ||  void P1(void *p) {
  uint64_t *x = (uint64_t)p;          ||    uint64_t *x = (uint64_t *)p;
  *x = 0x0101010101010101 ;           ||    uint64_t r = *x;
}                                     ||  }
```

Demo :

Data-race old-style

Simultaneous accesses to data may, in some circumstance, yield absurd results. On some 32bits mode, we execute simultaneously:

```
void P0(void *p) {
  uint64_t *x = (uint64_t)p;
  *x = 0x0101010101010101 ;
}
```

‖

```
void P1(void *p) {
  uint64_t *x = (uint64_t *)p;
  uint64_t r = *x;
}
```

Demo :

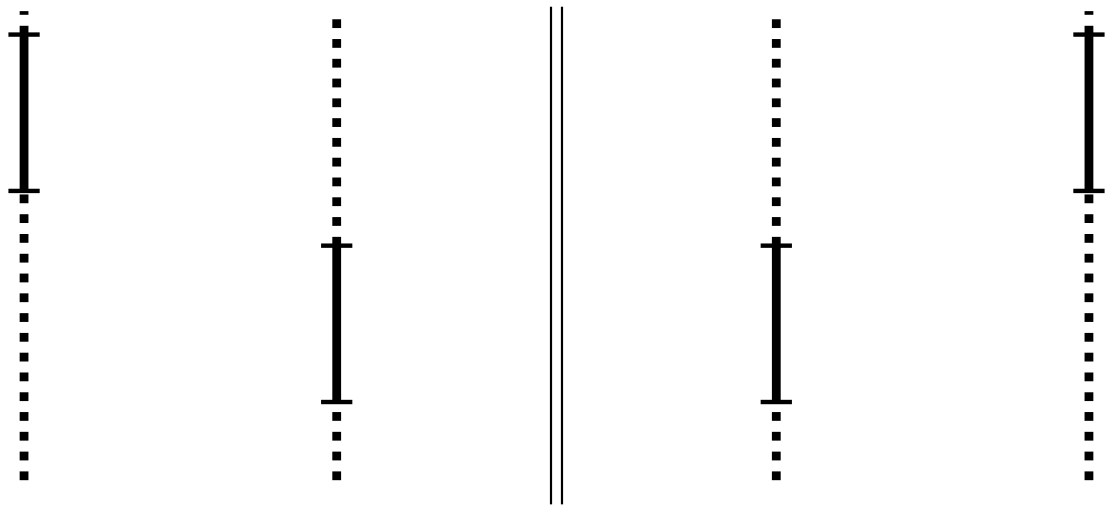
```
# We execute the test (initial value of *x is zero)
10025054:>1:r=0x0;
29906 :>1:r=0x1010101;
9945040:>1:r=0x0101010101010101;
```

Value `0x1010101` results from accesses to quad words not being atomic.

Ordering critical sections

Critical sections restore atomicity by mutual exclusion. That is, the instructions in critical section never execute simultaneously:

As a consequence of critical sections non-overlapping, critical sections are ordered:



Ordering memory accesses

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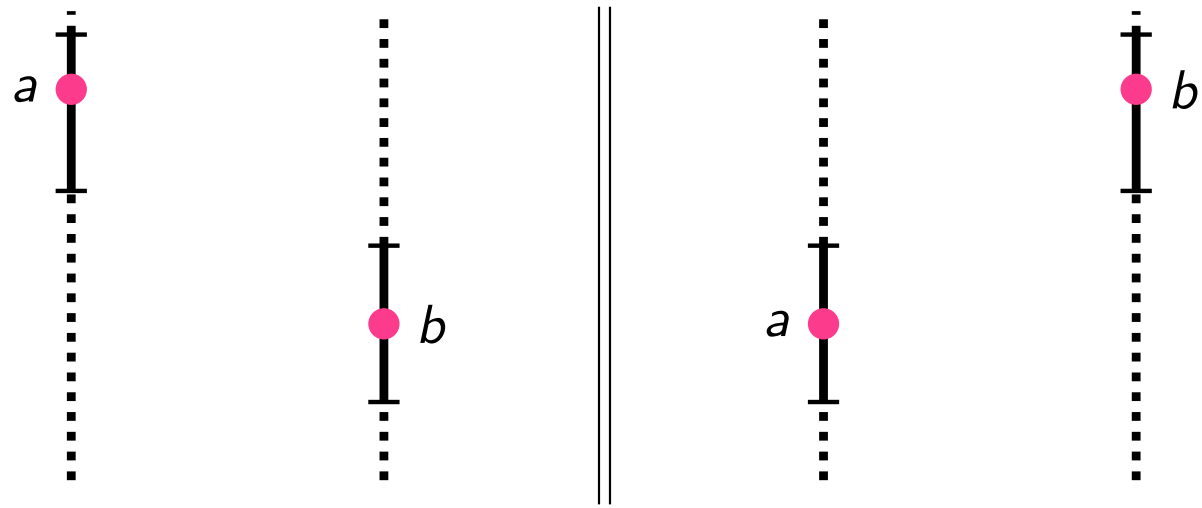

Let a and b be memory accesses.

Ordering memory accesses

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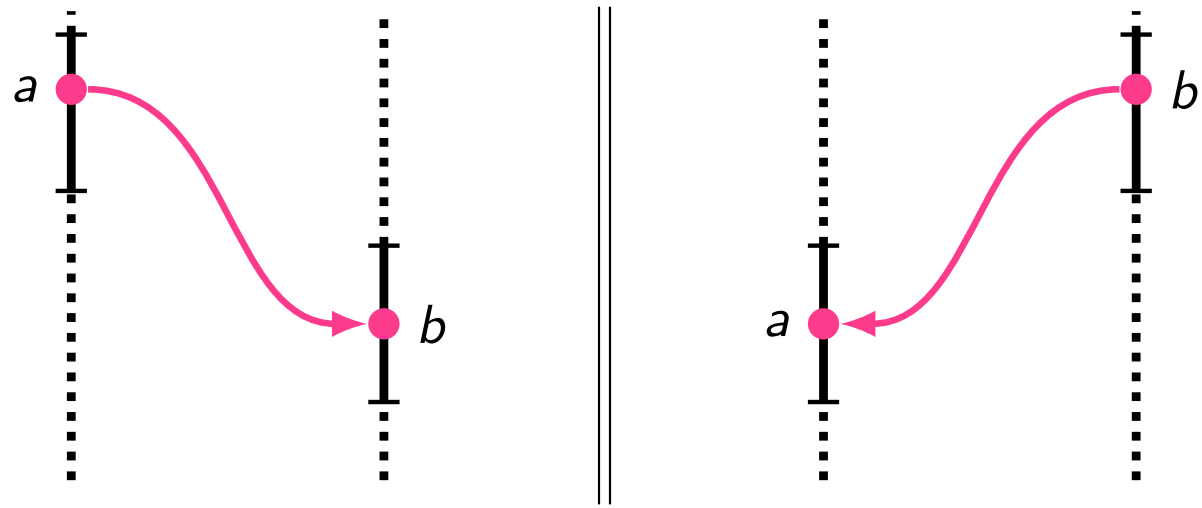
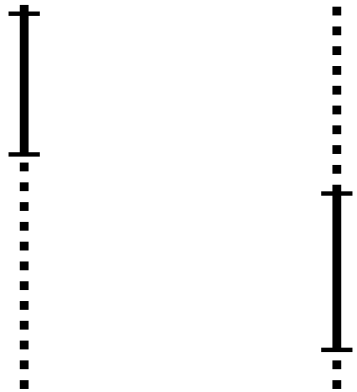


Let a and b be memory accesses.

A usable (*i.e.* with DRF guarantee) memory model will lift critical section ordering to memory accesses.

Ordering accesses, in pthreads

In POSIX threads, two accesses "separated" by synchronisation calls are *not* simultaneous. Hence, they are not *racy*.



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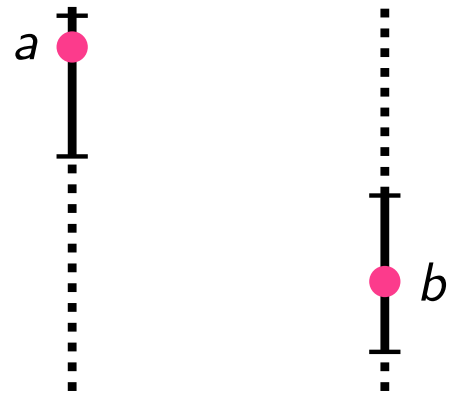

Here, accesses *a* and *b* are separated by the sequence unlock-lock.

- UnLock has *release* semantics (before release $\rightarrow$ order).
- Lock has *acquire* semantics (after acquire $\rightarrow$ order).

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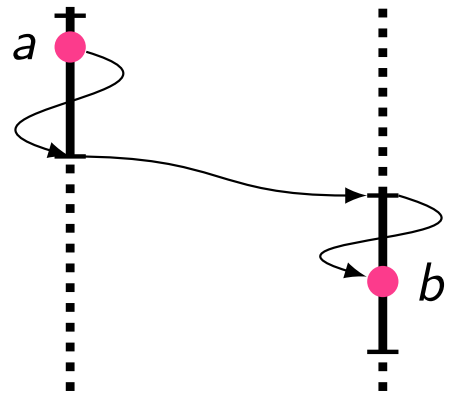

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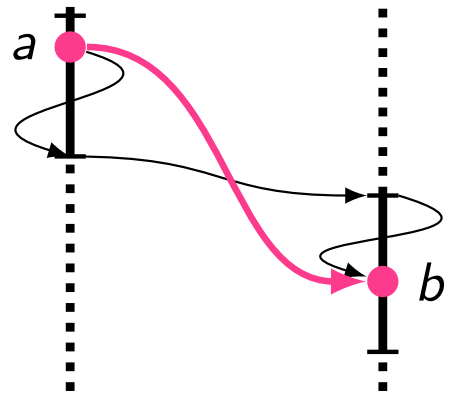

Here, accesses *a* and *b* are separated by the sequence unlock-lock.

- UnLock has *release* semantics (before release $\rightarrow$ order).
- Lock has *acquire* semantics (after acquire $\rightarrow$ order).

Coarse locking

```
void P0
  (int *x,int *y,mtx_t *m) {
    mtx_lock(m);
    *x = 1;
    int r0 = *y;
    mtx_unlock(m);
}
```

‖

```
void P1
  (int *x,int *y,mtx_t *m) {
    mtx_lock(m);
    *y = 1;
    int r1 = *x;
    mtx_unlock(m);
}
```

Demo ?

Coarse locking

```
void P0
  (int *x,int *y,mtx_t *m) {
    mtx_lock(m);
    *x = 1;
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    mtx_unlock(m);
}
```

```
void P1
  (int *x,int *y,mtx_t *m) {
    mtx_lock(m);
    *y = 1;
    int r1 = *x;
    mtx_unlock(m);
}
```

Demo ? All accesses of P_0 (resp. P_1) are performed before those of P_1 (res. P_0). Thus we get:

```
...
Histogram (2 states)
9999825:>0:r0=1; 1:r1=0;
10000175:>0:r0=0; 1:r1=1;
...
```

Notice : The "order" of accesses inside crtitical sections is irrelevant.

Fine-grain locking

To a memory cell, one associate a mutex ($x \rightarrow mx$ and $y \rightarrow my$).

```
void P0 (int *x,int *y,mtx_t *mx,mtx_t *my) {
  mtx_lock(mx);  *x = 1; mtx_unlock(mx);
  mtx_lock(my);  int r0 = *y; mtx_unlock(my);
}

void P1 (int *x,int *y,mtx_t *mx,mtx_t *my) {
  mtx_lock(my); *y = 1; mtx_unlock(my);
  mtx_lock(mx);  int r1 = *x; mtx_unlock(mx);
}
```

Demo ?

Fine-grain locking

To a memory cell, one associate a mutex (`x` $\rightarrow$ `mx` and `y` $\rightarrow$ `my`).

```
void P0 (int *x,int *y,mtx_t *mx,mtx_t *my) {
  mtx_lock(mx);  *x = 1; mtx_unlock(mx);
  mtx_lock(my);  int r0 = *y; mtx_unlock(my);
}

void P1 (int *x,int *y,mtx_t *mx,mtx_t *my) {
  mtx_lock(my); *y = 1; mtx_unlock(my);
  mtx_lock(mx);  int r1 = *x; mtx_unlock(mx);
}
```

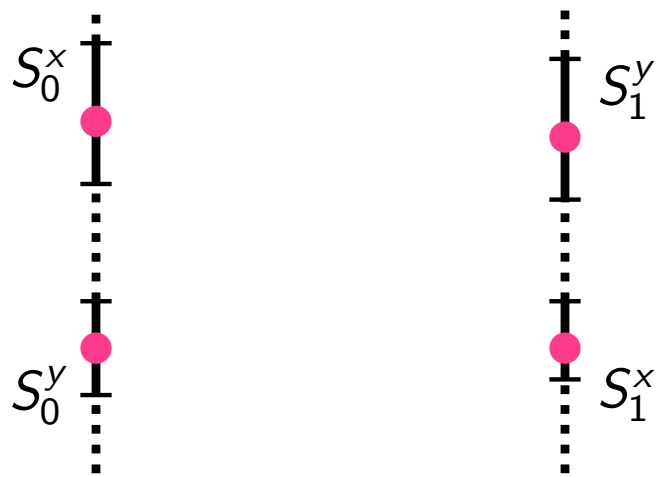
Demo ? (in `litmus/`) All potential *data-races* (*i.e.* all conflicting accesses) are covered One sees that the non-SC outcome (`r0=0` et `r1=0`) is not observed :

```
...
Histogram (3 states)
9455682:>0:r0=1; 1:r1=0;
9280838:>0:r0=0; 1:r1=1;
1263480:>0:r0=1; 1:r1=1;
...
```

Some sufficent condition for fine-grain locking

Let us note S_0^x (write x), S_0^y (read y), S_1^x (read x), S_1^y (write y) les sections critiques.

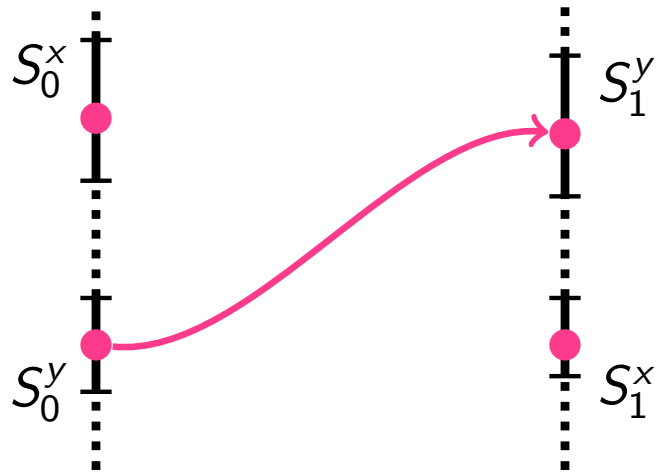
Let us assume



Some sufficent condition for fine-grain locking

Let us note S_0^x (write x), S_0^y (read y), S_1^x (read x), S_1^y (write y) les sections critiques.

Let us assume r0=0 (P_0 reads 0 from y)



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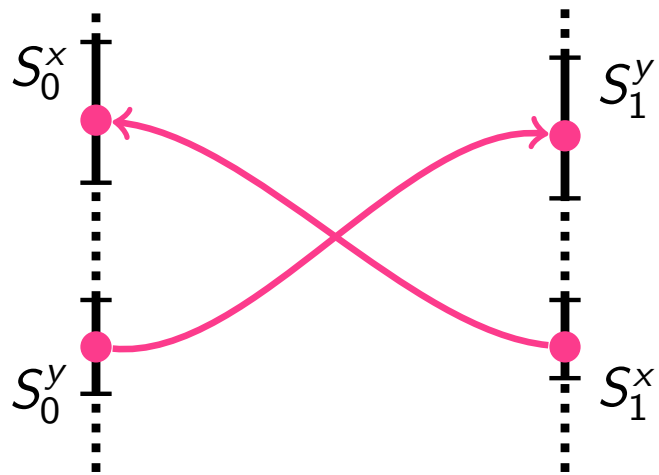

Some sufficent condition for fine-grain locking

Let us note S_0^x (write `x`), S_0^y (read `y`), S_1^x (read `x`), S_1^y (write `y`) les sections critiques.

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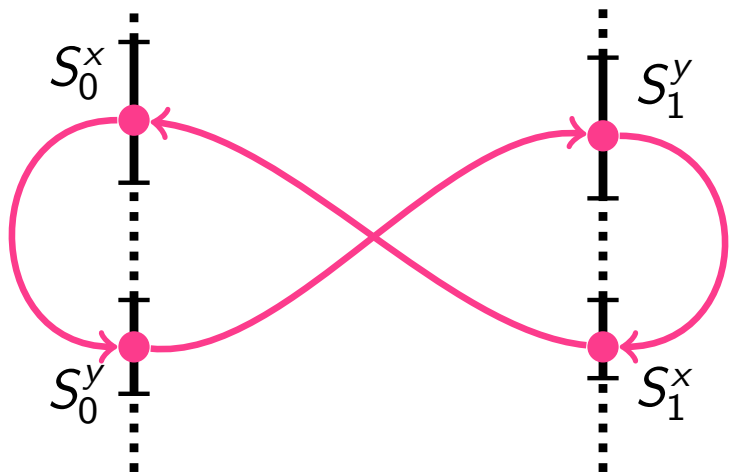

And that critical section of a same thread stay in-order, even when they operate on different mutexes.

Some sufficent condition for fine-grain locking

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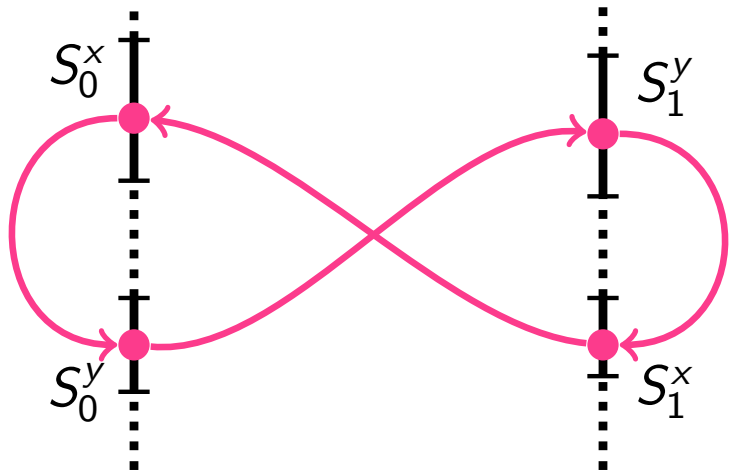
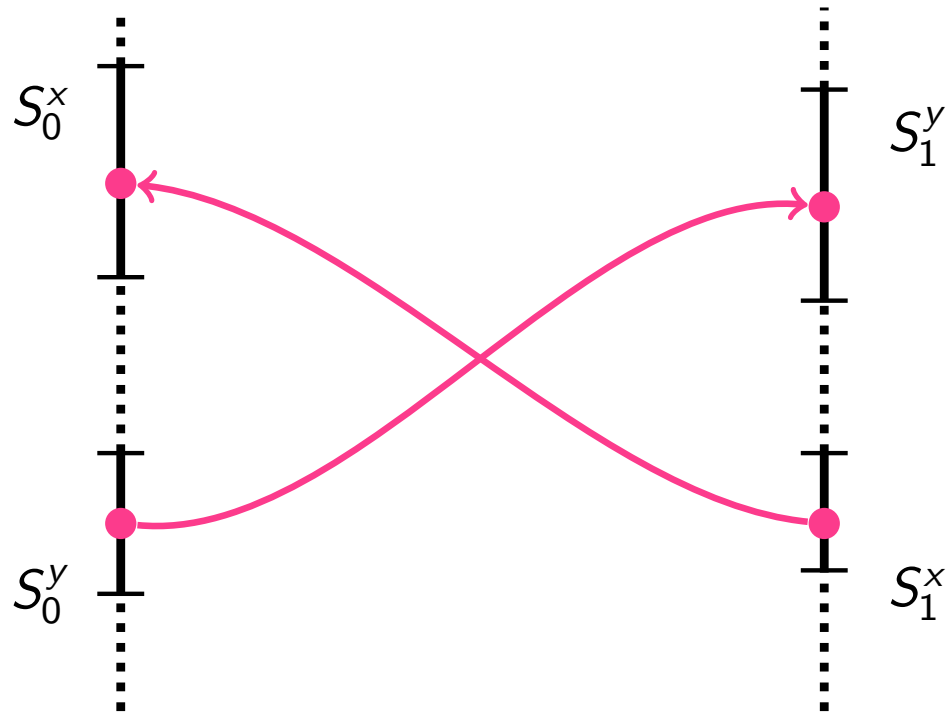


And that critical section of a same thread stay in-order, even when they operate on different mutexes.

Bingo ! (cycle.) That is, the non-SC behaviour is excluded by fine-grain locking.

A more realistic account of fine-grain locking



As `r0=0` and `r1=0`,

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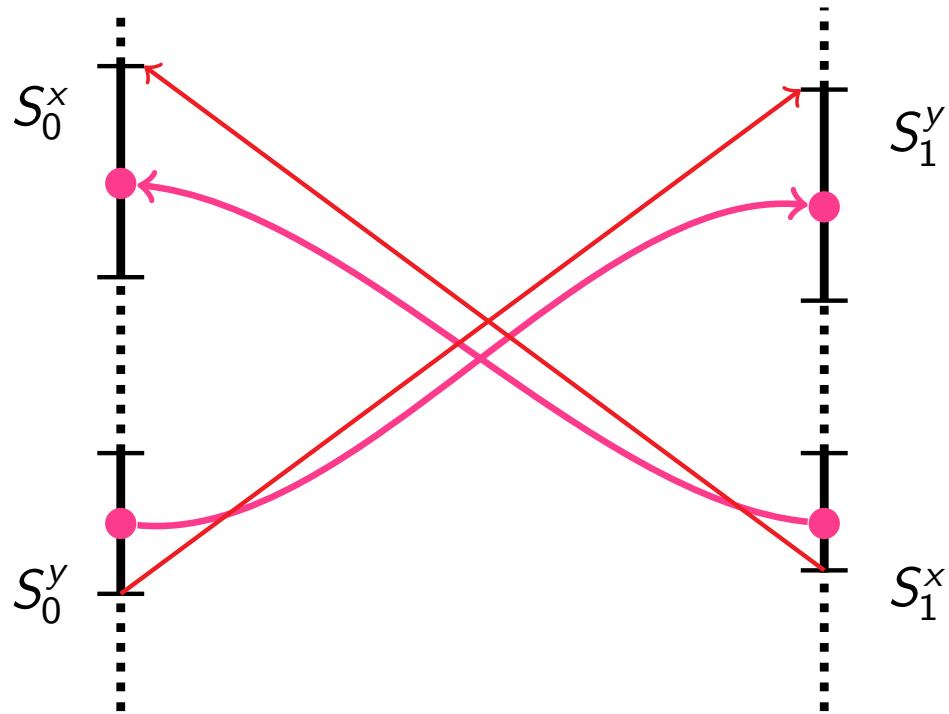

As `r0=0` and `r1=0`, from unlock to lock,

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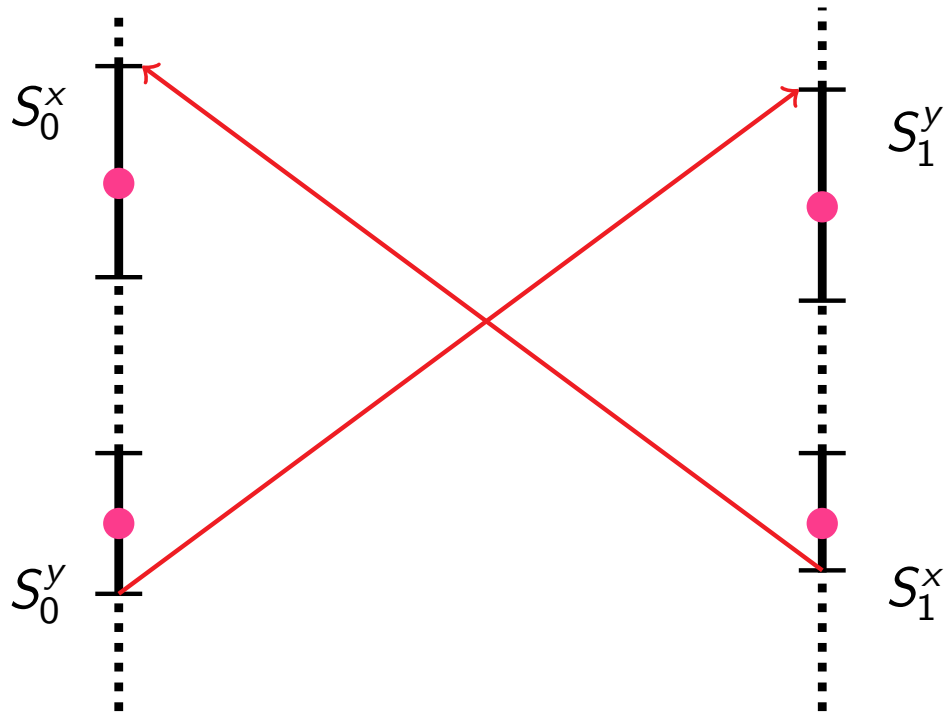

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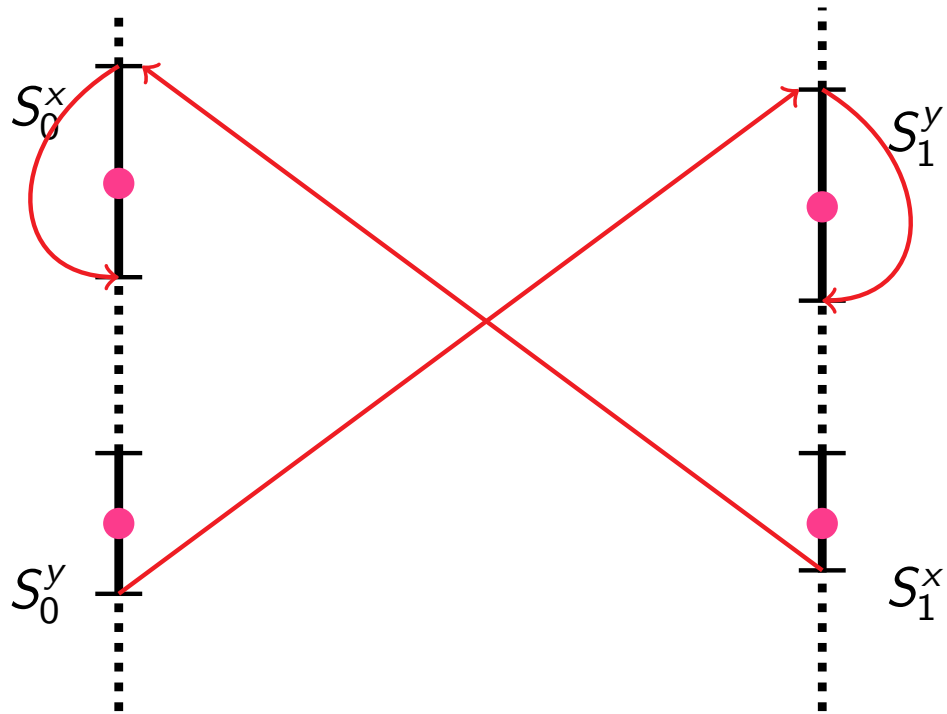

As `r0=0` and `r1=0`, from unlock to lock, acquire,

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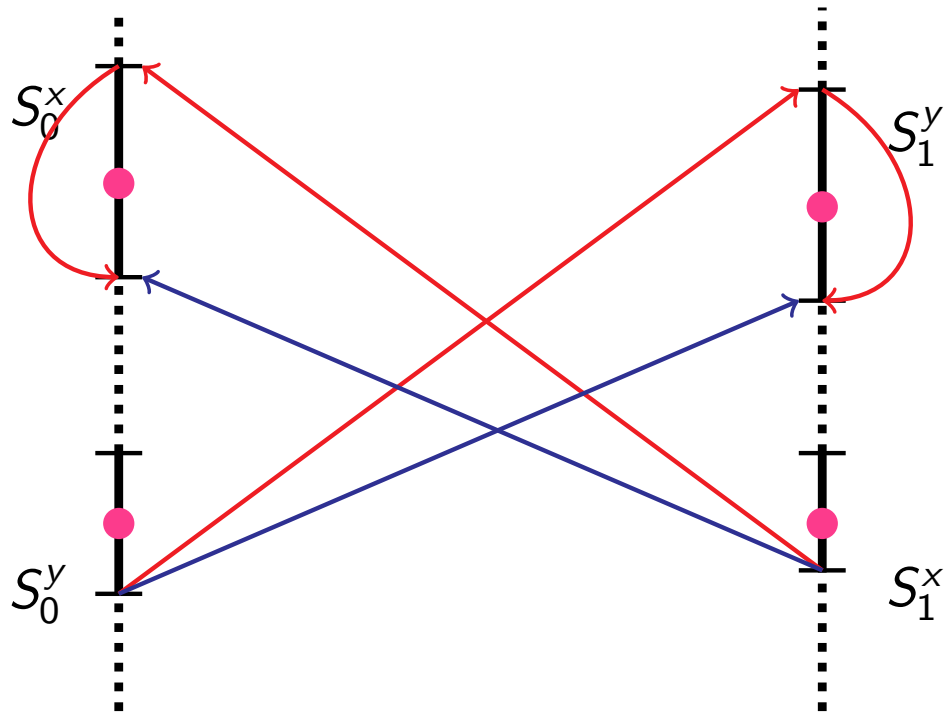
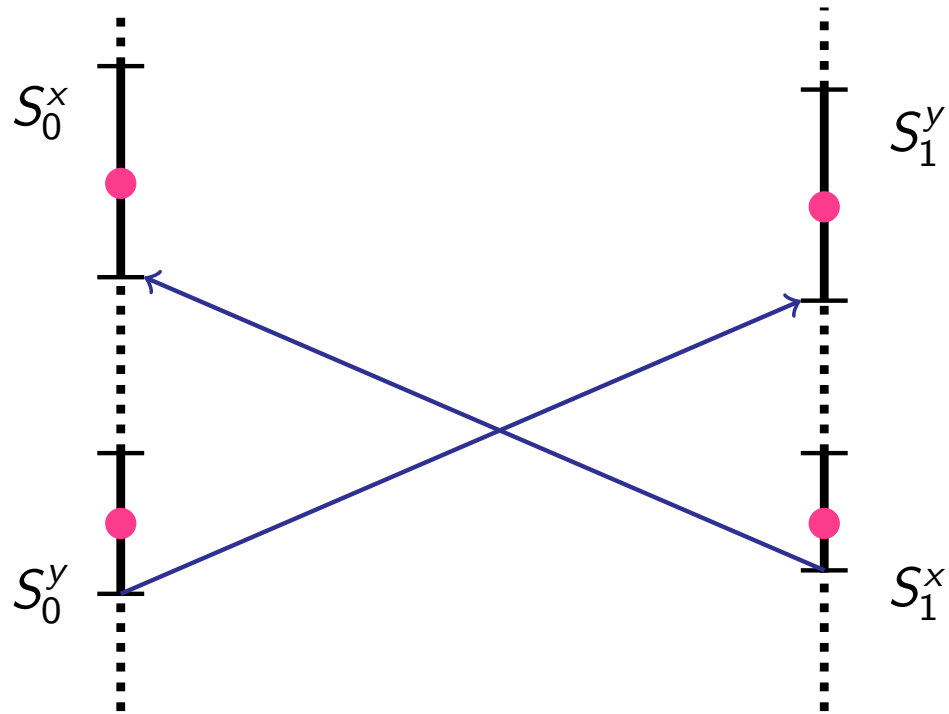


As `r0=0` and `r1=0`, from unlock to lock, acquire, unlocks ordered,

A more realistic account of fine-grain locking



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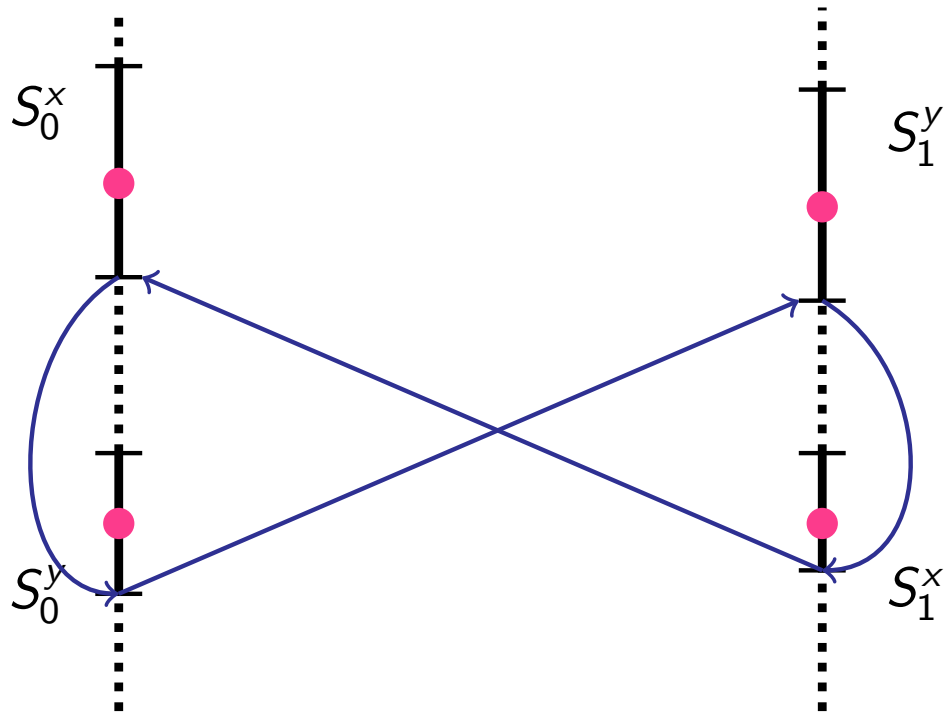
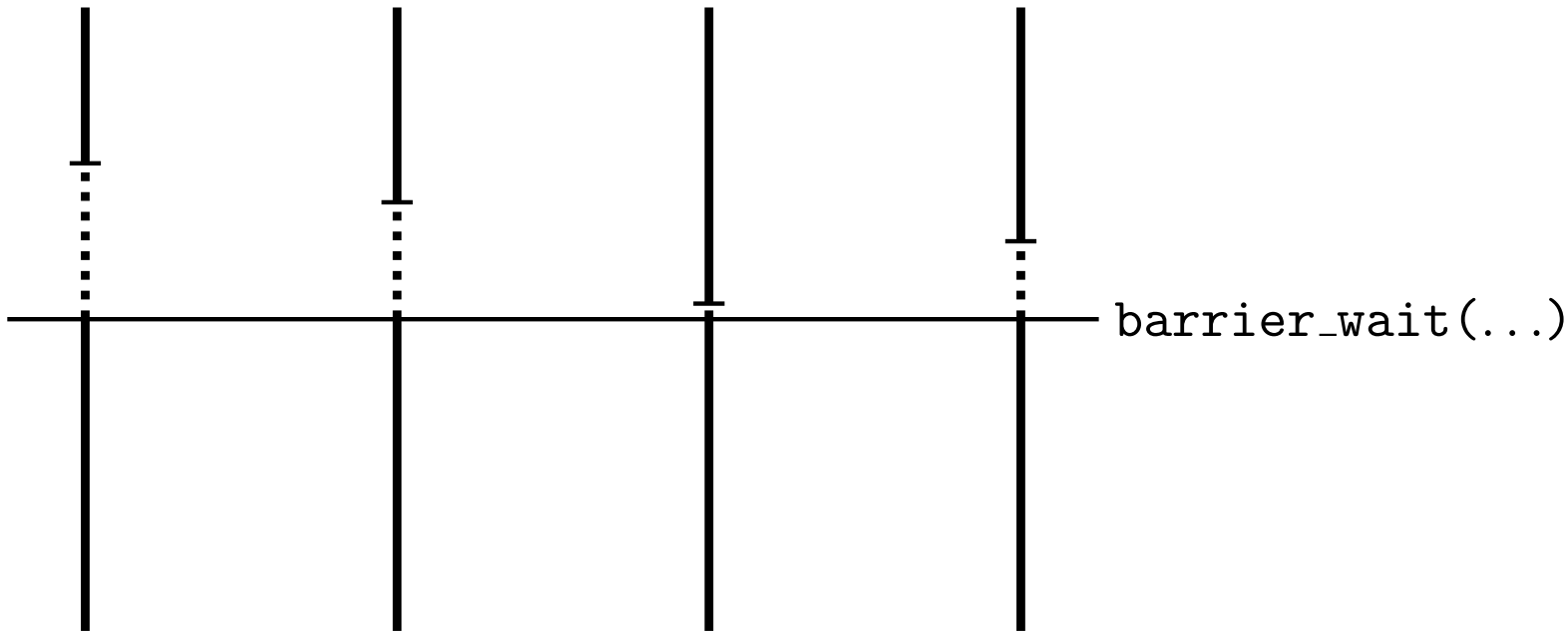


As `r0=0` and `r1=0`, from unlock to lock, acquire, unlocks ordered,release and Bingo!

There is more than locks: synchronisation barrier



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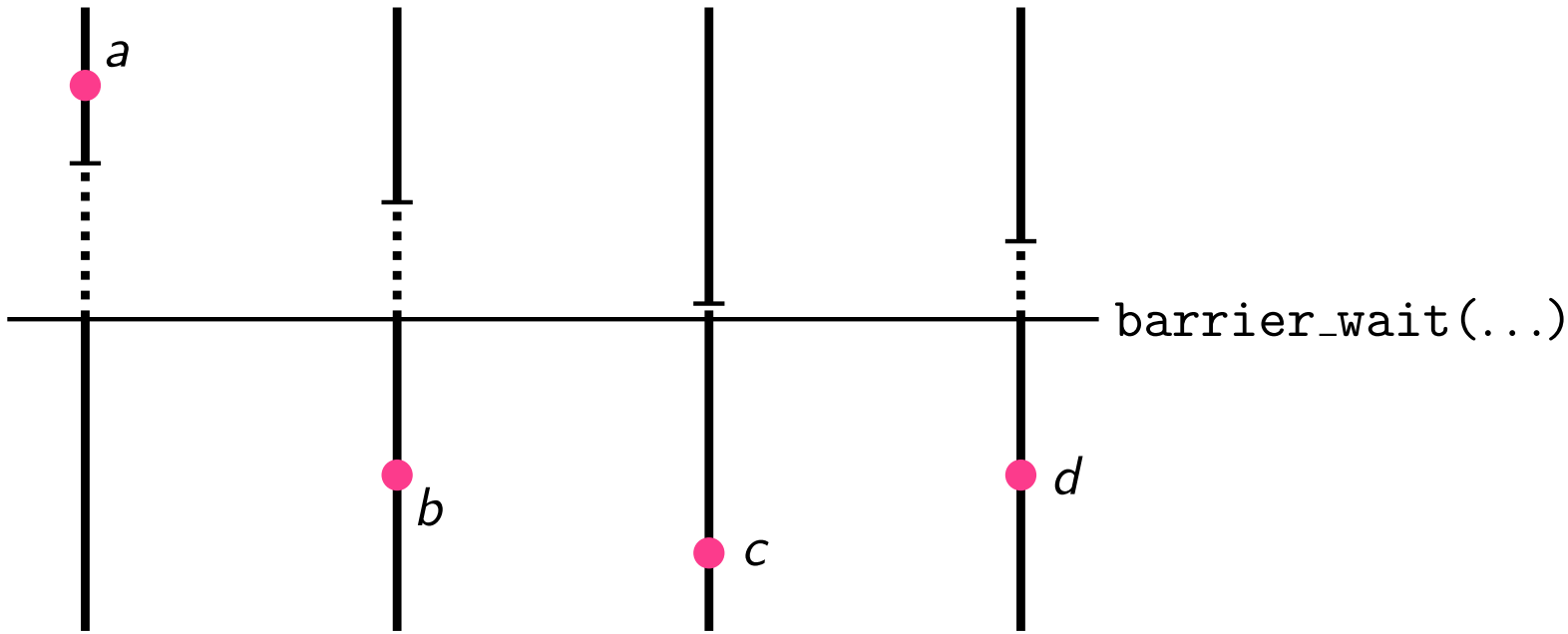
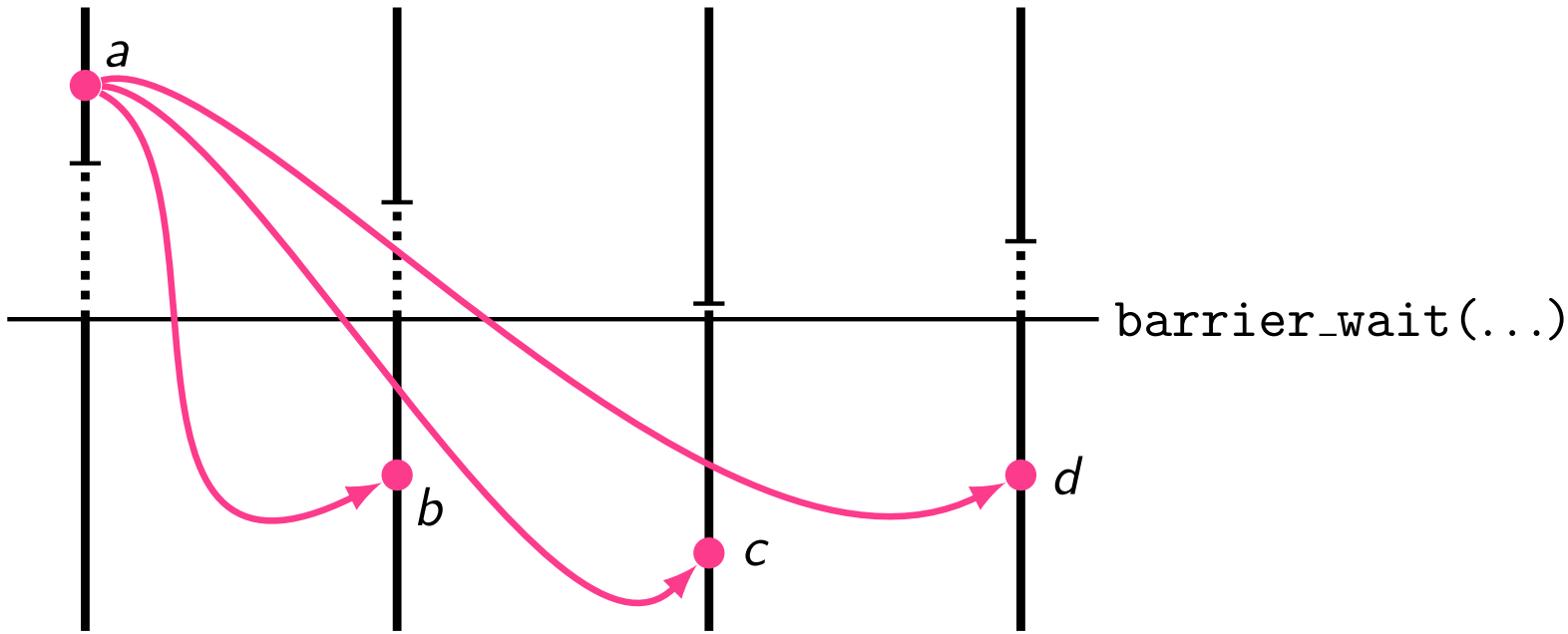


There is more than locks: synchronisation barrier



Accesses before (a) and after (b, c and d) the barrier cannot execute simultaneously. There is no *data-race*.

Back to our race on `p->nret`, bad solutions

We can...

- Ignore the issue (it works on x86).
- Program (correctly) out of the DRF fragment (hard, non-portable, see next classes).

Back to our race on `p->nret`, bad solutions

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Back to our race on p->nret, bad solutions

We can...

- Ignore the issue (it works on x86).
- Program (correctly) out of the DRF fragment (hard, ~~non-portable~~ [no longer true with C11], see next classes).
- Avoid the race, as writes to `p->nret` are protected by `p->mutex`, we additionally protect reads:

```
void wait_done(wait_t *p,int ntasks) {
  for ( ; ; ) {
    int over ;
    lock_mutex(p->mutex) ;
    over = p->nret >= ntasks ;
    unlock_mutex(p->mutex) ;
    if (over) return ;
  }
}
```

Efficiency penalty may be severe (try, demo)... It can be alleviated by introducing a sleep delay in loop (however, introduces latency).

Solving all problems

We aim at:

- The waiting thread sleeps as long as less than `ntasks` computing threads have ticked.
- The last thread to tick awake the main thread.

In fact, we aim at something similar to the "sleep when someone is in critical section" behavior or mutexes.

A condition variable C is a device for doing this.

- `wait(`C`,`L`)`, release the lock L and suspend on condition C *atomically*.
- `signal(`C`)` wake up one thread suspended on C, if any.
- `broadcast(`C`)` wake up all threads suspended on C.

Notice that awaken threads will hold the mutex L they have released when performing `wait(`C`,`L`)`.

A simpler example

A synchronous cell, to be used once (`pthread_join` may use something similar).

```
typedef struct {
  pthread_mutex_t *mutex;
  pthread_cond_t *cond;
  int v,something ;
} cell_t ;

// NB. alloc_cell initialises mutex and condition
cell_t alloc_cell(void) ;
void free_cell(cell_t *p) ;

// Put v in cell
void put(cell_t *p,int v) ;

//Get value from cell, suspending until something is here.
int get(cell_t *p) ;
```

A simpler example, continued

```
void put(cell_t *p,int v) {
  lock_mutex(p->mutex) ;
  if (something) {
    unlock_mutex(p->mutex) ;
    fprintf(stderr,"put more than once!\n") ;
    exit(2)
  }
  p->something = 1 ;
  p->v = v ;
  signal_cond(p->cond) ; // Signal (potential) reader
  unlock_mutex(p->mutex) ;
}
```

A simpler example, continued

```
void put(cell_t *p,int v) {
  lock_mutex(p->mutex) ;
  if (something) {
    unlock_mutex(p->mutex) ;
    fprintf(stderr,"put␣more␣than␣once!\n") ;
    exit(2)
  }
  p->something = 1 ;
  p->v = v ;
  signal_cond(p->cond) ; // Signal (potential) reader
  unlock_mutex(p->mutex) ;
}

int get(cell_t *p) {
  int r ;
  lock_mutex(p->mutex) ;
  // Correct, when wait_cond returns only when signalled
  if (!something) wait_cond(p->cond,mutex) ;
  r = p->v ;
  unlock_mutex(p->mutex) ;
  return r ;
}
```

Spurious wakeups

Notice We wrote **if** `(!something) wait_cond(...)`. While the preferred idiom is **while** `(!something) wait_cond(...)`.

Why so?

- **Spurious wakeups?** `wait_cond` may return for any reason.
- POSIX standard allows spurious wakeups.
  - May facilitate implementation:
    - Interruption/signal handling?
    - Or, `signal_cond` may awake more then one waiter...
  - Program logic (see FIFO later) often commands a loop around `wait_cond` anyway.
- I did not observed them,
- but we have to program according to the standard.

get in presence of spurious wakeups

The function get must be written as follows:

```
int get(cell_t *p) {
  int r ;
  lock_mutex(p->mutex) ;
  // If no spurious wakeup, loop will run at most once
  while (!something) wait_cond(p->cond,mutex) ;
  r = p->v ;
  unlock_mutex(p->mutex) ;
  return r ;
}
```

Exercise II with a condition variable, part A

```
typedef struct {
  pthread_mutex_t *mutex ;
  pthread_cond_t *cond ;
  volatile int nret,ntasks ; // Notice ntasks kept inside
} wait_t ;


wait_t *alloc_wait(void) {
  wait_t *r = malloc_check(sizeof(*r)) ;
  r->nret = 0 ;
  r->ntasks = 0 ;
  r->mutex = alloc_mutex() ;
  r->cond = alloc_cond() ;
  return r ;
}

void tick(wait_t *p) ;                          // To be written
void wait_done(wait_t *p, int ntasks) ; // To be written
```

Solution II with a condition variable

```
void wait_done(wait_t *p,int ntasks) {
```

Solution II with a condition variable

```
void wait_done(wait_t *p,int ntasks) {
  lock_mutex(p->mutex) ;
  p->ntasks = ntasks ;
  while (p->nret < p->ntasks)
    wait_cond(p->cond,p->mutex) ;
  unlock_mutex(p->mutex) ;
}

void tick(wait_t *p) {
```

Solution II with a condition variable

```
void wait_done(wait_t *p,int ntasks) {
  lock_mutex(p->mutex) ;
  p->ntasks = ntasks ;
  while (p->nret < p->ntasks)
    wait_cond(p->cond,p->mutex) ;
  unlock_mutex(p->mutex) ;
}

void tick(wait_t *p) {
  lock_mutex(p->mutex) ;
  p->nret++ ;
  if (p->ntasks > 0 && p->nret >= p->ntasks)
    signal_cond(p->cond) ;
  unlock_mutex(p->mutex) ;
}
```

Controlled parallelism

Remember, using `make -j` N (or `parallel -j` N) we could limit computing processes to N instances.

We want the same for threads.

Idea:

- Have N computing threads,
- which execute available subtasks one after the other, sequentially.

Sometimes called "a processor farm", computing threads are "slaves". A "master" allocates subtasks to slaves.

Master and slaves

Assume a (concurrent, blocking, bounded) FIFO component:

Slaves get subtasks from the FIFO:

```
static fifo_t *fifo ;
static count_t sum ;
static pthread_t *mutex ;

void *slave(void *) {
  for ( ; ; ) {
    subtask_t *z = get(fifo) ; // Will block if fifo is empty
    count_t c = run_subtask(z) ;
    free_arg(z) ;
    lock_mutex(mutex) ;
    sum += c ;
    unlock_mutex(mutex) ;
  }
}
```

Master and slaves

While the master (main thread) put subtasks into the fifo.

```
void emit_fifo(subtask_t *z) {
  // Will block if fifo is full
  put(fifo,copy_arg(z)) ;
}
int master(int n, int depth) {
  return generate_subtasks(n, depth, emit_fifo) ;
}
```

Code sketch

```
count_t  run(int n, int depth, int nprocs, int fsz) {
  sum = 0 ;
  //Initialise
  fifo = create_fifo(fsz) ;
  // Fork slaves
  pthread_t th[nprocs] ;
  for (int k = 0 ; k < nprocs ; k++)
    create_thread(&th[k],slave,NULL) ;
  // Act as master
  int ntasks = master(n,depth) ;
  // Shall see master termination later
  ...
}
```

Let us write the fifo

Starting from a non-concurrent, non-blocking, bounded fifo.

```
typedef struct {
  int sz ;
  int fst,lst,nitems ;
  subtask_t **t ; // Array of (subtask_t *)
} fifo_t ;

typedef enum {OK,NO} ret_val ; // Return value for put below

int put(fifo_t *f,subtask_t *z) {
  if (f->nitems == f->sz) return NO ;
  f->t[f->lst] = z ;
  f->lst++ ; f->lst %= f->sz ; f->nitems++ ;
  return OK ;
}

subtask_t *get(fifo_t *f) {
  subtask_t *r ;
  if (f->nitems == 0) return NULL ; // special value
  r = f->t[f->fst] ;
  f->fst++ ; f->fst %= f->sz ; f->nitems-- ;
}
```

Concurrent fifo, definition

```
typedef struct {
  pthread_mutex_t *mutex ;
  pthread_cond_t *is_empty, *is_full ;

  int sz ;
  int fst,lst,nitems ;
  subtask_t **t ;
} fifo_t ;
```

Concurrent fifo, creation

```
fifo_t *alloc_fifo(int sz) {
  fifo_t *r = malloc_check(sizeof(*r)) ;
  r->fst = r->lst = r->nitems = 0 ;
  r->sz = sz ;
  r->t = calloc(sz,sizeof(*r->t)) ;
  if (!r->t) {
    perror("calloc") ;
    exit(2) ;
  }
  r->mutex = alloc_mutex() ;
  r->is_empty = alloc_cond() ;
  r->is_full = alloc_cond() ;
  return r ;
}
```

Concurrent fifo, put

```
void put(fifo_t *f,subtask_t *z) {
```

Concurrent fifo, put

```
void put(fifo_t *f,subtask_t *z) {
  lock_mutex(f->mutex) ;
  // If full ?
```

Concurrent fifo, put

```
void put(fifo_t *f,subtask_t *z) {
  lock_mutex(f->mutex) ;
  // If full ?
  while (f->nitems == f->sz) {
    wait_cond(f->is_full,f->mutex) ;
  }
  // Now store z
```

Concurrent fifo, put

```
void put(fifo_t *f,subtask_t *z) {
  lock_mutex(f->mutex) ;
  // If full ?
  while (f->nitems == f->sz) {
    wait_cond(f->is_full,f->mutex) ;
  }
  // Now store z
  int was_empty = f->nitems == 0 ;
  f->t[f->lst] = z ;
  f->lst++ ; f->lst %= f->sz ; f->nitems++ ;
  // If was empty?
```

Concurrent fifo, put

```
void put(fifo_t *f,subtask_t *z) {
  lock_mutex(f->mutex) ;
  // If full ?
  while (f->nitems == f->sz) {
    wait_cond(f->is_full,f->mutex) ;
  }
  // Now store z
  int was_empty = f->nitems == 0 ;
  f->t[f->lst] = z ;
  f->lst++ ; f->lst %= f->sz ; f->nitems++ ;
  // If was empty?
  if (was_empty) {
    broadcast_cond(f->is_empty) ; // Why not signal?
  }
  unlock_mutex(f->mutex) ;
}
```

Concurrent fifo, get

Exercise III!

```
subtask_t *get(fifo_t *f) {
```

Concurrent fifo, get

Exercise III!

```
subtask_t *get(fifo_t *f) {
  subtask_t *r ;
  lock_mutex(f->mutex) ;
  // If empty?
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Concurrent fifo, get

Exercise III!

```
subtask_t *get(fifo_t *f) {
  subtask_t *r ;
  lock_mutex(f->mutex) ;
  // If empty?
  while (f->nitems == 0) {
    wait_cond(f->is_empty,f->mutex) ;
  }
  // Retrieve value
```

Concurrent fifo, get

Exercise III!

```
subtask_t *get(fifo_t *f) {
  subtask_t *r ;
  lock_mutex(f->mutex) ;
  // If empty?
  while (f->nitems == 0) {
    wait_cond(f->is_empty,f->mutex) ;
  }
  // Retrieve value
  int was_full = f->nitems == f->sz ;
  r = f->t[f->fst] ;
  f->fst++ ; f->fst %= f->sz ; f->nitems-- ;
  // If was full
```

Concurrent fifo, get

Exercise III!

```
subtask_t *get(fifo_t *f) {
  subtask_t *r ;
  lock_mutex(f->mutex) ;
  // If empty?
  while (f->nitems == 0) {
    wait_cond(f->is_empty,f->mutex) ;
  }
  // Retrieve value
  int was_full = f->nitems == f->sz ;
  r = f->t[f->fst] ;
  f->fst++ ; f->fst %= f->sz ; f->nitems-- ;
  // If was full
  if (was_full) {
    broadcast_cond(f->is_full) ;
  }
  unlock_mutex(f->mutex) ;
  return r ;
}
```

Why not signal (instead of broadcast) in `put` and `get`?

If you do not see, try `ex3/bad.out -v 18` (code with signal in place of broadcast).

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We then see no parallelism, why?

Why not signal (instead of broadcast) in `put` and `get`?

If you do not see, try `ex3/bad.out -v 18` (code with signal in place of broadcast).

We then see no parallelism, why?

We witness the following scenario (or a similar one):

- N slaves suspend on the empty fifo,
- The master fills the fifo, awaking one slave while putting the first task.
- As a result, $N - 1$ tasks are suspended and no one awakes them.

How do we detect termination?

Solution (1) the `wait_t` component:

```
void *slave(void *) {
  for ( ; ; ) {
    subtask_t *z = get(fifo) ; // Will block if fifo is empty
    count_t c = run_subtask(z) ;
    ...
    tick(wait_on) ;
  }
}
```

Problem: thread resources are not reclaimed (to that aim `slave` should return...).

```
// Shall see master termination later
  wait_done(wait_on,ntasks) ;
  ...
  return count ;
}
```

(**Going further:** Add a `kill` functionality to the fifo.)

How do we detect termination?

Solution (2): special value **NULL** in fifo means that computation is over.
Master:

```
// Shall see master termination later
  put(fifo,NULL) ;
  for (int k = 0 ; k < nprocs ; k++)
    (void)pthread_join(&th[k]) ;
  ...
```

And slave:

```
void *slave(void *) {
  for ( ; ; ) {
    subtask_t *z = get(fifo) ; // Will block if fifo is empty
    if (z == NULL) {
      put(fifo,NULL) ; // For other slaves..
      return NULL ;
    }
    ...
  }
}
```

Notice: Fifo behaviour is instrumental. **Demo:** Efficiency (`queens/topt.out -j4 -d2 17`).

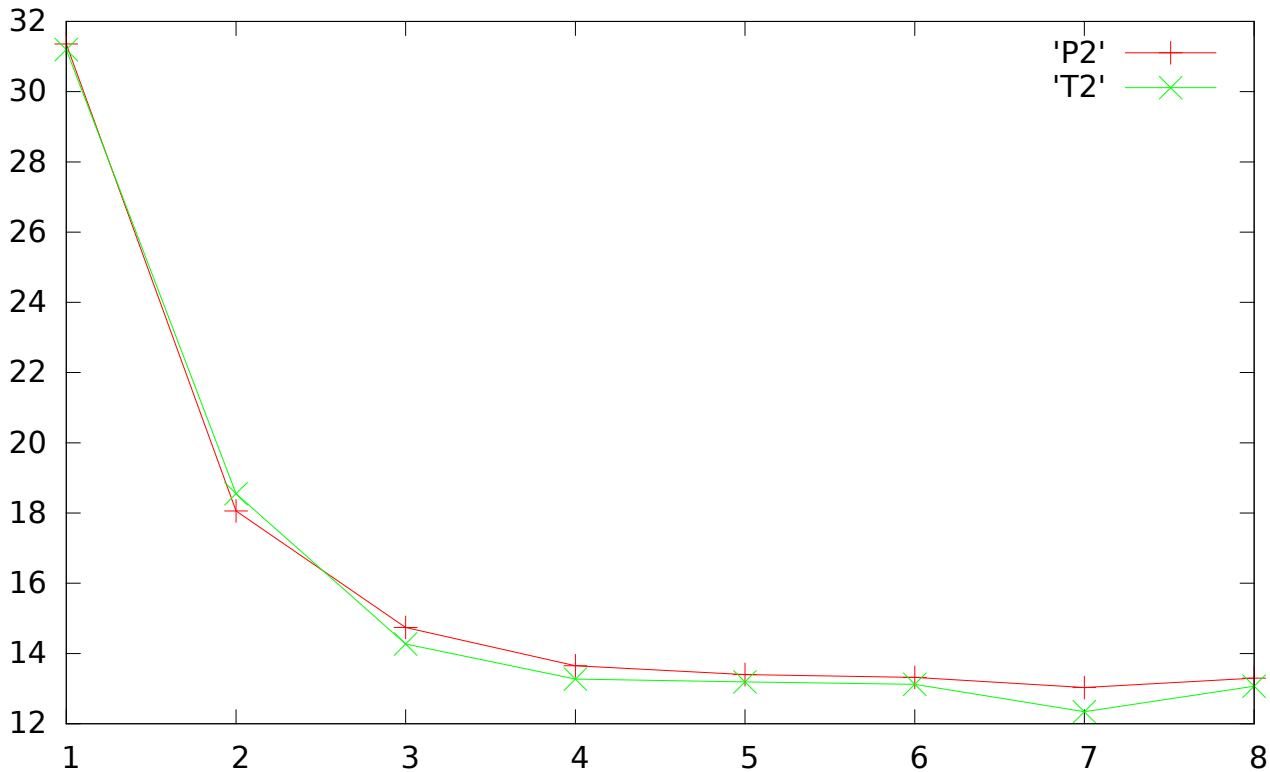
Reclaiming the fifo

```
count_t run(int n, int depth, int nprocs, int fsz) {
  sum = 0 ;
  fifo = alloc_fifo(fsz) ;
  mutex = alloc_mutex() ;
  ...
// Complete master cleanup and termination
  put(fifo,NULL) ;
  for (int k = 0 ; k < nprocs ; k++)
    (void)pthread_join(&th[k]) ;
  /*
    At this point, no slave is blocked on fifo,
    since all slaves returned. We can reclaim the fifo
  */
  free_fifo(fifo) ;
  free_mutex(mutex) ; // Reclaim mutex
  return 2*sum ;      // By symetry
}
```

Practical multicore programming

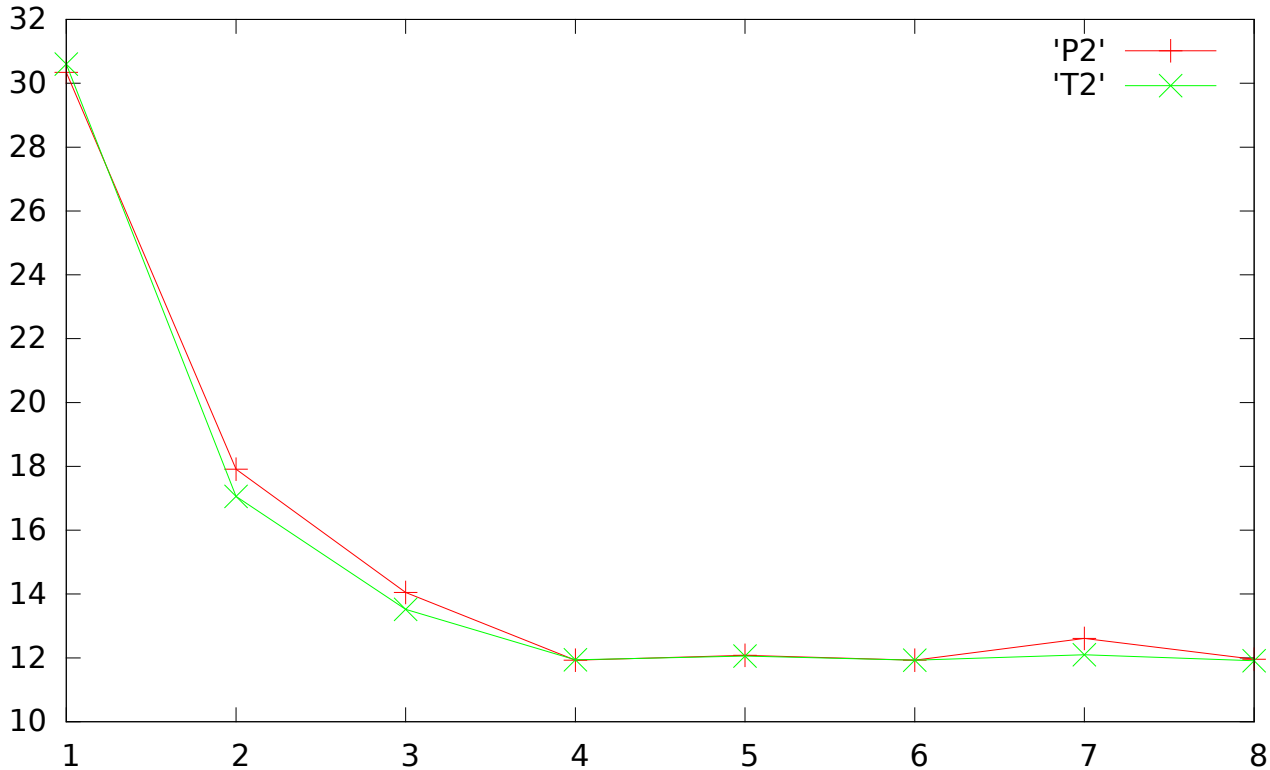
Threads vs. Processes, the *n*-queens experiment

Performance on some 2 cores, $\times 2$ machine



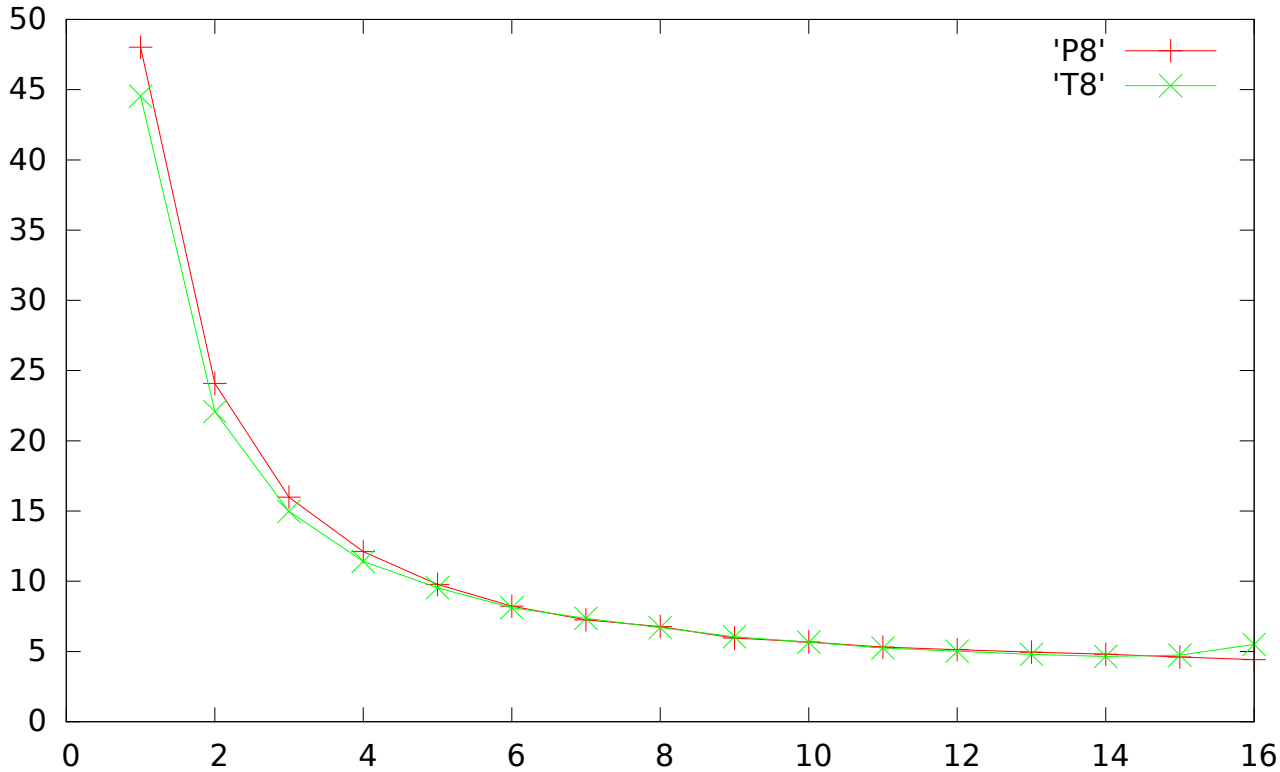
wall clock time in sec. P2 is the "`parallel`" implementation, T2 is the pthreads implementation.

Performance on this 2 cores, ×2 machine



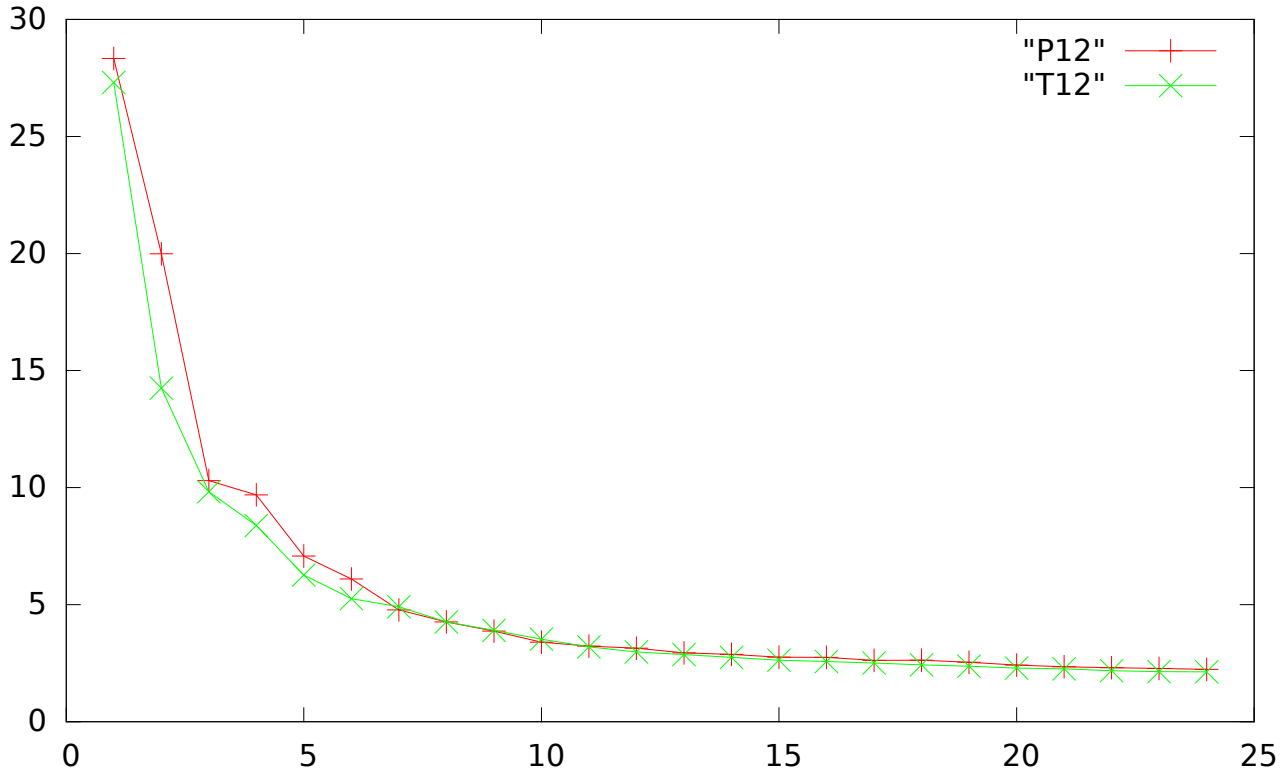
Wall clock time in sec. P2 is the "`parallel`" implementation, T2 is the pthreads implementation.

Performance on a 8 cores, $\times 2$ machine



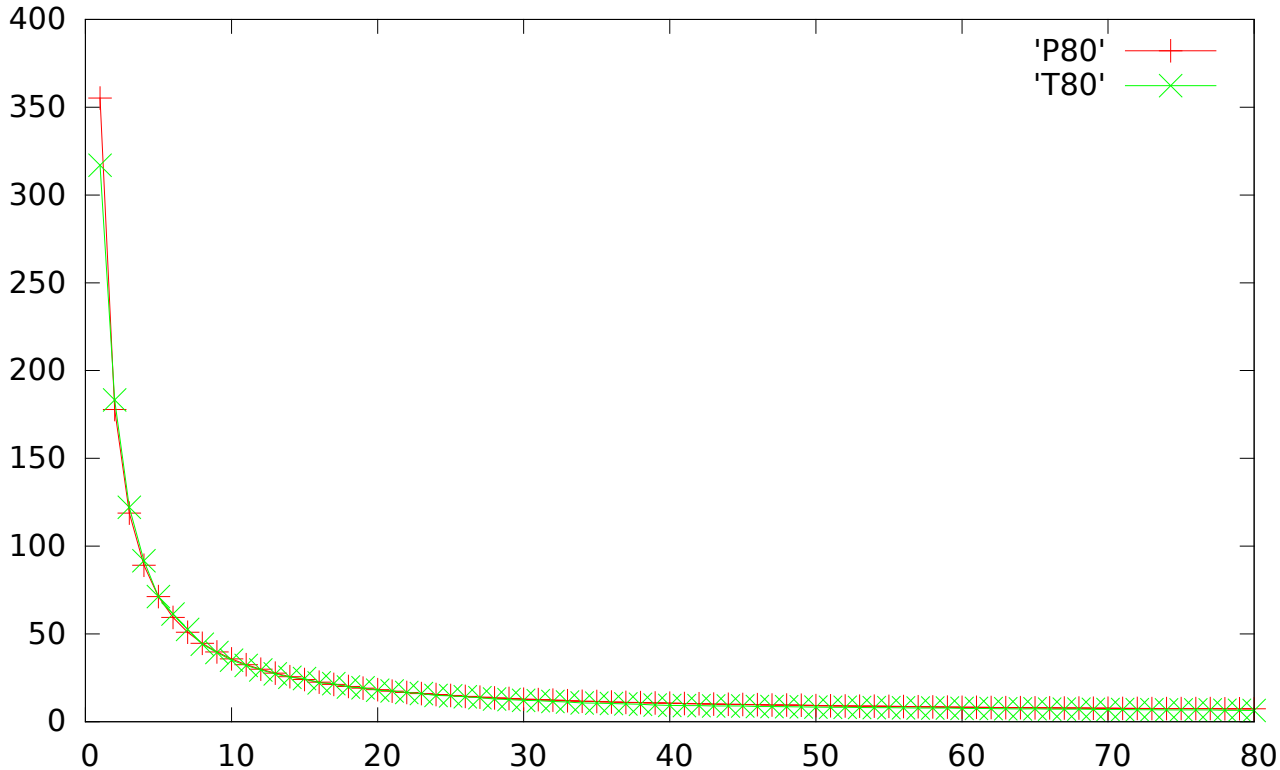
Wall clock time in sec. P8 is the "`parallel`" implementation, T8 is the pthreads implementation.

Performance on a 12 cores, $\times 2$ machine



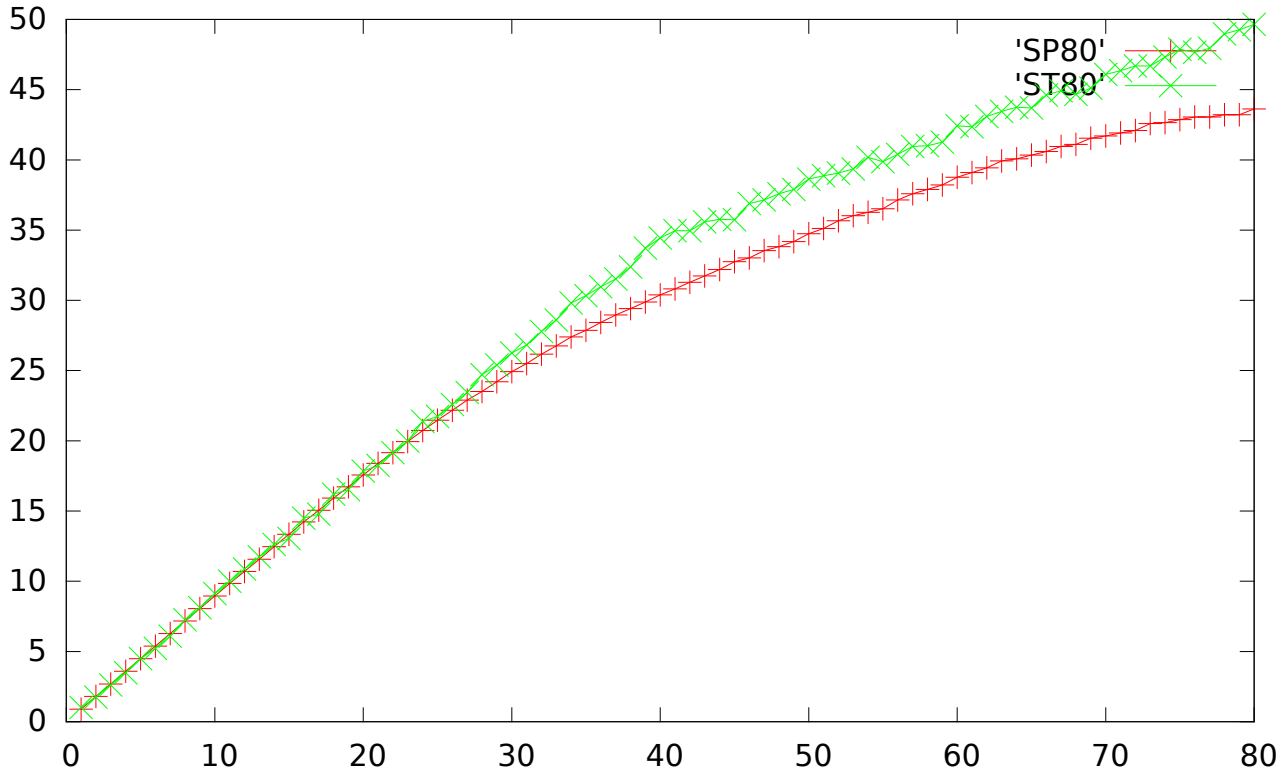
Wall clock time in sec. P12 is the "`parallel`" implementation, T12 is the pthreads implementation.

Performance on a 40 cores, $\times 2$ machine



Wall clock time in sec. P80 is the "`parallel`" implementation, T80 is the pthreads implementation.

Speedup on a 40 cores, $\times 2$ machine



Wallclock times are divided by the running time of our faster sequential implementation: `./fast.out -d3 18`. SP80 is the "`parallel`" implementation, ST80 is the pthreads implementation.