Parallel and Concurrent Programming Classical Problems, Data structures and Algorithms

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Outline

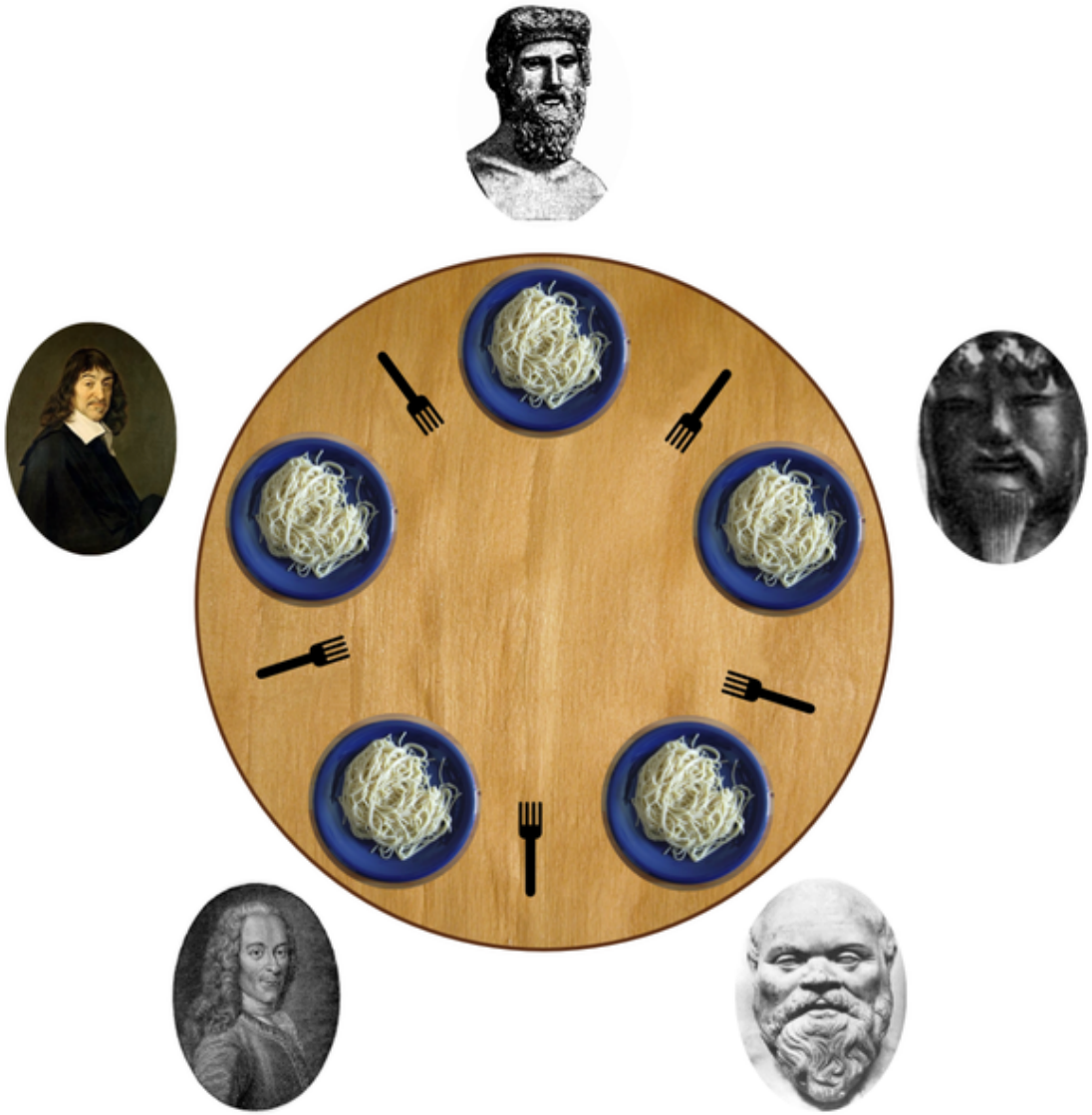
Introduction

Parallel Issues

- When building parallel algorithms, we face two main issues:
  - Find a parallel solution to our problem
  - Minimizing the impact of synchronisation
- A lot of issues are involved here, we will focus on *general* ones: *thread-friendly* data structures, regain control over scheduling, making parallel problems that are not inherently parallel . . .
- In short, this lecture focus on minimizing the use of locks and make an *intelligent* use of threads.
- We began this presentation with a classical problem: *The Dining Philosophers*.

Dining Philosophers Problem

The Dining Philosophers



The Dining Philosophers

- A great *classic* in concurrency by Hoare (in fact a *retold version* of an illustrative example by Dijkstra.)
- The first goal is to illustrate **deadlock** and **starvation**.
- The problem is quite simple:
  - N philosophers (originally $N = 5$) are sitting around a round table.
  - There's only N chopstick on the table, each one between two philosophers.
  - When a philosopher want to eat, he must acquire his left and his right chopstick.
- Naive solutions will cause deadlock and/or starvation.

mutex and condition based solution

```c
/* Dining Philosophers */
#define _XOPEN_SOURCE 600

#include <stdlib.h>
#include <unistd.h>
#include <stdio.h>
#include <time.h>
#include <errno.h>
#include <signal.h>
#include <pthread.h>

#define NPHI 5
#define LEFT(k) (((k)+(NPHI-1))%NPHI)
#define RIGHT(k) (((k)+1)%NPHI)

enum e_state {THINKING,EATING,HUNGRY};

typedef struct s_table *table;
struct s_table
{
  enum e_state states[NPHI];
  pthread_cond_t        can_eat[NPHI];
  pthread_mutex_t      *lock;
};

struct s_thparams
{
  table table;
  pthread_barrier_t    *sync;
  int id;
};
```

```c
/* return 1 after receiving SIGINT */
int is_done(int yes)
{
 static pthread_spinlock_t *lock=NULL;
 static int                 done=0;
 if (!lock) {
  lock=malloc(sizeof(pthread_spinlock_t));
  pthread_spin_init(lock,
        PTHREAD_PROCESS_PRIVATE);
 }
 pthread_spin_lock(lock);
 if (yes)
  done = yes;
 pthread_spin_unlock(lock);
 return done;
}

/* where all the magic is !  */
/* test if we are hungry and */
/* our neighbors do no eat   */
void test(table t, int k)
{
 if (t->states[k] == HUNGRY
     && t->states[LEFT(k)] != EATING
     && t->states[RIGHT(k)] != EATING){
  t->states[k] = EATING;
  pthread_cond_signal(&(t->can_eat[k]));
 }
}
```

mutex and condition based solution

```
void pick(table t, int i)
{
 pthread_mutex_lock(t->lock);
 t->states[i] = HUNGRY;
 printf("Philosopher %d: hungry\n",i);
 test(t,i);
 while (t->states[i] != EATING)
  pthread_cond_wait(&t->can_eat[i],
                    t->lock);
 printf("Philosopher %d: eating\n",i);
 pthread_mutex_unlock(t->lock);
}

void put(table t, int i)
{
 pthread_mutex_lock(t->lock);
 t->states[i] = THINKING;
 printf("Philosopher %d: thinking\n",i);
 test(t,LEFT(i));
 test(t,RIGHT(i));
 pthread_mutex_unlock(t->lock);
}

void thinking()
{
 struct timespec        reg;
 reg.tv_sec = random()%6;
 reg.tv_nsec = 1000000*(random()%1000);
 if (nanosleep(&reg,NULL) == -1) {
  if (errno != EINTR || is_done(0))
  pthread_exit(NULL);
 }
}
```

```
void eating()
{
 struct timespec        reg;
 reg.tv_sec = random()%2;
 reg.tv_nsec = 1000000*(random()%1000);
 nanosleep(&reg,NULL);
}

void *philosopher(void *ptr)
{
 struct s_thparams    *p;
 p = ptr;
 pthread_barrier_wait(p->sync);
 printf("Philosopher %d:thinking\n",p->id);
 while (!is_done(0))
 {
  thinking();
  pick(p->table, p->id);
  eating();
  put(p->table, p->id);
 }
 pthread_exit(NULL);
}

void handle_int(int sig)
{
 is_done(1);
 signal(sig,handle_int);
}
```

mutex and condition based solution

```
int main(int argc, char *argv[])
{
 table                 t;
 struct s_thparams    *p;
 pthread_t             th[NPHI];
 pthread_mutex_t       lock;
 pthread_barrier_t     sync;
 size_t                i, seed=42;

 signal(SIGINT, handle_int);

 if (argc>1)
  seed = atoi(argv[1]);
 srandom(seed);

 t = malloc(sizeof (struct s_table));
 pthread_barrier_init(&sync,NULL,NPHI);
 pthread_mutex_init(&lock,NULL);
 t->lock = &lock;

 for (i=0; i<NPHI; ++i)
 {
  t->states[i] = THINKING;
  pthread_cond_init(&t->can_eat[i],NULL);
 }

 for (i=0; i<NPHI; ++i)
 {
  p = malloc(sizeof (struct s_thparams));
  p->table = t;
  p->sync = &sync;
  p->id = i;
  pthread_create(th+i,NULL,philosopher,p);
 }

 for (i=0; i<NPHI; ++i)
  pthread_join(th[i], NULL);

 return 0;
}
```

Sharing Resources

- The dining philosophers problem emphasizes the need of synchronisation when dealing with shared resources.
- Even with a simple mutex per chopstick, the execution may not (will probably not) be correct, ending with either a global deadlock or some philosophers in starvation.
- It is easy to see that no more than half of the philosophers can eat at the same time: **sharing resources implies less parallelism !**
- This kind of situation is what we want to avoid: *a lot of dependencies between threads*.
- A good parallel program try to avoid shared resources when possible. A good *division* of a problem for parallel computing will divide the global task into *independant tasks*.

Tasks Systems

Direct Manipulation of Physical Threads

- Physical (*system*) threads are not portable
- Most of the time, physical threads are almost independant process
- Creating, joining and cancelling threads is almost as expensive as process manipulations
- Synchronisation often implies kernel/user context switching
- Scheduling is under system control and doesn't take care of synchronisation and memory issues
- Data segmentation for parallel computing is problem **and** hardware driven:
  - Data must be split in order to respect memory and algorithm constraints
  - Number of physical threads needs to be dependant of the number of processors/cores to maximize performances
- ...

Light/Logical Threads

- One can implement threads in full user-space (*light threads*) but we loose physical parallelism.
- A good choice would be to implement *logical threads* with scheduling exploiting physical threads.
- Using logical threads introduces loose coupling between problem segmentation and hardware segmentation.
- *Local* scheduling increase code complexity and may introduce overhead.

Tasks based approach

- A good model for logical threads is a tasks system.
- A task is a sequential unit in a parallel algorithm.
- Tasks perform (*sequential*) computations and may spawn new tasks.
- The tasks system manage scheduling between *open* tasks and available physical threads.
- Tasks systems often use a *threads pool*: the system start a bunch of physical threads and schedule tasks on available threads dynamically.

Simple tasks system: waiting queue.

- *Producer* schedule new *tasks* by pushing it to the queue.
- *Consumer* take new *tasks* from the queue.
- *Producer* and *Consumer* are physical threads, we call them **worker**.
- Each worker may play both role (or not.)
- Tasks can be input values or data ranges for a fixed task's code.
- It is also possible to implement tasks description so producer can push any kinds of task.
- For most cases, we need to handle a kind of *join*: special task pushed when computation's results are ready, in order to closed unfinished tasks (think of a parallel reduce or parallel Fibonacci numbers computation.)

Data Structures

Concurrent Collections

Producers and Consumers Classical Problem

- When using a shared collection, we face two issues:
  - Concurrent accesses;
  - What to do when collection is empty.
- Usual solution for a queue (or any other *push-in/pull-out* collection) is to implement the Producers/Consumers model:
  - The collection is accessed in mutual exclusion;
  - When the collection is empty *pull-out* operations will block until data is available.
- Producers/Consumers is quite easy to implement using semaphores or using mutex and condition variables.
- Producers/Consumers can also be extended to support bounded collections (*push-in* operations may wait until a place is available.)

Producers and Consumers Seminal Solution

Example:

```
void push(void *x, t_queue q)
{
  pthread_mutex_lock(q->m);
  q->q = _push(x,q->q);
  pthread_mutex_unlock(q->m);
  sem_post(q->size);
}

void *take(t_queue q)
{
  void                  *x;
  sem_wait(q->size);
  pthread_mutex_lock(q->m);
  x = _take(&q->q);
  pthread_mutex_unlock(q->m);
  return x;
}
```

Locking Refinement

- Global locking of the collection implies more synchronisation (and thus, less parallelism !)
- Let's consider a *FIFO* queue:
  - Unless there's only one element in the queue, *push-in* and *pull-out* can occur at the same time (careful implementation can also accept concurrent accesses when there's only one element.) [2]
  - The traditionnal circular list implementation of queue can not be used here.
  - The solution is to build the queue using a structures with two pointers (head and tail) on a simple linked list.
- Better locking strategies leads to more parallelism, but as we can see usual implementations may not fit.

Loose Coupling Concurrent Accesses

- When using *map* collections (collections that map keys to values), we can again improve our locking model.
- When accessing such collection we have two kind of operations: read-only and create/update.
- The idea is to see a *map* as a collection of pairs: all operations on the *map* will get a pair (even the create operation) and locking will only impact the pair and not the whole collection.
- In ordrer to support concurrent read we prefer read/write lock.
- Insertion operations can also be seperated in two distinct activities:
  - We create the cell (our pair) give back the pointer to the caller (with appropriate locking on the cell itself.)
  - Independently, we perform the insertion on the structure using a tasks queue and a seperate worker.
- The later strategy minimize even more the need of synchronisation when accessing our collection.

Data Structures Concurrent Friendly

- Some data structures are more *concurrent friendly* than others.
- The idea is again to minimize the impact of locking: we prefer structures where modifications can be kept local rather than global.
- Tree structures based are good candidate: most modification algorithm (insertion/suppression/update) can be kept local to a sub-tree and during the traversal we can release lock on *unimpacted* sub-tree.
  - For example, in *B-tree*, it has been proved that read operations can be perfomed without any locks and Write locks are located to modified block [1].
- Doubly linked lists are probably the worst kind of data structures for concurrent accesses: the nature of linked lists implies global locking to all elements accessible from the cell, so any operations on doubly linked lists will lock the whole list.

Non blocking data structures

- Normally spin waiting is a bad idea, but careful use of spin waiting can increase parallelism in some cases.
- The idea of non-blocking data structures is to interleave the waiting loop with the operation we want to perform.
- Good algorithm for that kind of data structures are harder to implement (and to verify) but offers a more dynamic progression: no thread idle by the system should block another when performing the operation.
- Non blocking operations relies on hardware dependent atomic operations

Concurrent Data Model

Using Data in A Concurrent Context

- Once we have chosen a good data structures, we need to manage concurrent accesses.
- Classical concurrent data structures define locking to enforce global data consistency but problem driven consistency is not considered.
- Most of the time, consistency enforcement provide by data structures are sufficient, but more specific cases requires more attention.
- Even with non-blocking or (almost) lock-free data structures, accessing shared data is a bottleneck (some may call it a *serialization point*.)
- When dealing with shared data, one must consider two major good practices:
  - Enforcing high level of abstraction;
  - Minimize locking by deferring operations to a *data manager* (*asynchronous upates*.)

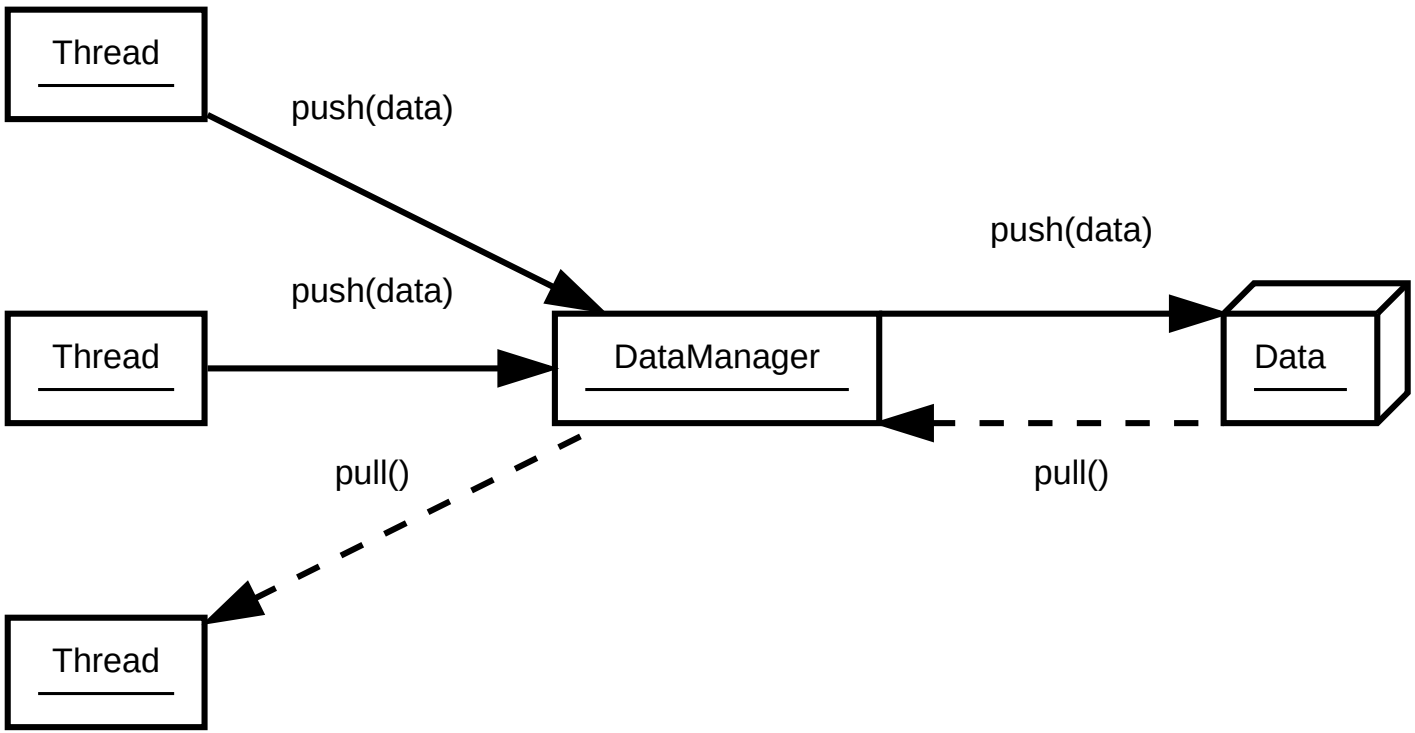
Data Authority and Concurrent Accesses

- **Enforcing high level of abstraction:**
  - Encapsulation of the operations minimize exposition of the locking policy and thus enforce correct use of the data.
  - When possible, using *monitor* (object with native mutual exclusion) can simplify consistency and locking.
  - As usual, abstraction (and thus encapsulation) offers more possibility to use clever operations implementations.

Data Authority and Concurrent Accesses

- **Deferring operations to a kind of *data manager*:**
  - Deferring operations can improve parallelism by letting a different worker performs the real operations: the calling thread (the one that issue the operation) won't be blocked (if possible), the data manager will take care of performing the real operations.
  - Since the data manager is the only entity that can perfom accesses to the data, it can work without any lock, nor any blocking stage.
  - Data manager can *re-order* operations (or simply discard operations) to enforce algorithm specific constraint.

Data Manager



The Future Value Model

- Future are concurrent version of lazy evaluation in functionnal languages.
- Futures (or *promises* or *delays*) can be modeled in many various ways (depending on language model.)
- In short, a future is a variable whose value is computed independently. Here's a simple schematic example (pseudo language with *implicit future*):

```
// Defer computation to another thread
future int                  v = <expr>;
// some computations
// ...
// We now need access to the future value
x <- 42 + v
```

Future for real . . .

- Java has future (see `java.util.concurrent.Future`);
- Futures will normaly be part of C++0x;
- Futures exists in sevral *Actor based* languages, functionnal languages (rather natively like in Haskell or AliceML, or byt the means of external libs like in OCaml) and pure object oriented languages (Smalltalk, AmbientTalk, E ...)
- Implementing simple future using pthread is quite simple: the future initialization create a new thread with a pointer to the operation to perform and when we really need the value we perform a *join* on the thread.
- One can also implements future using a tasks based systems.

Futures' issues

There are several issues when implementing futures. Those issues depend on the usage made of it:

- When we use futures to perform blocking operations or intensive computations, tasks systems may induce important penality.
- Creating a thread for each future induces important overhead.
- In object oriented languages, one have to solve whether message passes should wait on the futures result or not:

```
future int                    v = acker(...);
// ...
v.add(1)
// we can block here waiting for v to complete
// but we can also send the message and let the
// future handle it in time.
```

Algorithms and Concurrency

Easy Parallelism

Problems with simple parallel solutions

- A lot of problems can be solved easily with parallelism: for example when computing a Mandelbrot Set, we can perform the iteration for each pixel independently.
- The remaining issue of *easy parallelism* is scheduling: for our Mandelbrot set we can't start a new thread for each pixel.
- Using tasks systems and range based scheduling offers a good tradeoff between scheduling overhead and efficient usage of physical parallelism.
- Modern tools for parallel computing offers *intelligent* parallel loop constructions (*parallel for*, *parallel reduce* ...) based on range division strategy statisfying hardware constraints (number of processors, cache affinity ...)

Parallel or not, Parallel that is the question !

Parallelism and classical algorithms

- Some classical algorithms won't perform well in parallel context: for example depth first traversal is inherently not parallel.
- Optimizations in classical algorithms can also induce a lot of synchronisation points.
- Backtrack based algorithms can be improved with parallelism, but we must take care of scheduling: if the algorithms have a lot of backtrack point, we have to find a *strategy* to choose which point can be scheduled for parallel execution.

Bibliography

P. L. Lehman and S. B. Yao.
Efficient locking for concurrent operations on B-trees.
ACM Trans. on Database Sys., 6(4):650, December 1981.

Maged Michael and Michael L. Scott.
Simple, fast, and practical non-blocking and blocking concurrent queue algorithms.
In *Proceedings of the Fifteenth Annual ACM Symposium on Principles of Distributed Computing*, pages 267–267, Philadelphia, Pennsylvania, USA, 23–26 May 1996.