Parallel Algorithms

Fork and Join

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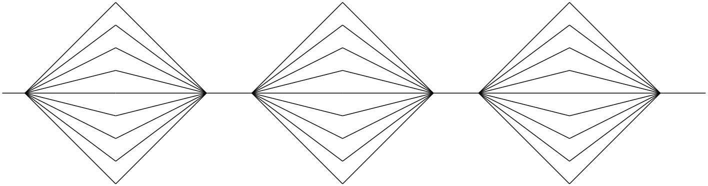

Superstep

Parallel Algorithms

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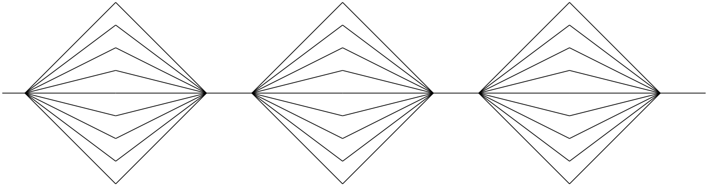

Superstep

Of course, we would like to make the sequential parts between the forks as small as possible

This is quite popular, as many problems decompose this way

Parallel Algorithms

Fork and Join

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For example, multiply two matrices together *then* add in a third matrix

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We could use barriers between the two phases

Parallel Algorithms

Fork and Join

Take care not to confuse the structure of fork and join with the creation and joining of threads

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Parallel Algorithms

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We might want to do the sub-tasks provider/consumer, or manager/worker or thread pool or whatever

It is very unlikely we would want to use `pthread_create` and `pthread_join` every time

Parallel Algorithms

Pipelines/Systolic

Another structuring method we have seen before is the *pipeline*, also called *systolic array*

Pipeline

Parallel Algorithms

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Input data is transformed by several separate stages by several separate processors

Parallel Algorithms

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Pipeline

Input data is transformed by several separate stages by several separate processors

A well-balanced pipeline (eventually) gives perfect speedup and efficiency

Parallel Algorithms

MapReduce

Finally, for now, we look at another concept imported from the functional style: *MapReduce*

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Parallel Algorithms

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This is a combination of a *map* and a *reduce*, and is a kind of divide and conquer

A map takes a function and a structure (a list or vector or tree or whatever) of data, and applies that function to each element in the structure

As long as there is no interference between the items of data, this is trivially parallelisable: stick different items of data on different processors and execute the function on each

Parallel Algorithms

MapReduce

The reduce step then gathers together all the sub-results and merges them together to produce the required answer

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Parallel Algorithms

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Other reductions might be less or more parallelisable

Parallel Algorithms

MapReduce

For example, given a vector of numbers compute the sum of the squares of the values

Parallel Algorithms

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For example, given a vector of numbers compute the sum of the squares of the values

Map: do the squares in parallel

Reduce: add them together in parallel

Parallel Algorithms

MapReduce

Another example: Web search. The data is distributed in chunks across many machines

Parallel Algorithms

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Parallel Algorithms

MapReduce

Another example: Web search. The data is distributed in chunks across many machines

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Reduce: merging and sorting the partial results

MapReduce is much used by Google for their various services, not just searching

Parallel Algorithms

MapReduce

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Parallel Algorithms

MapReduce

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MapReduce also copes well with less than 100% reliability of the hardware

Parallel Algorithms

Aside: Reliability

A quick word on reliability: modern machines are pretty reliable and we are not used to them breaking down too often

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When you have 100s of thousands of machines in your system, you must plan for one to break down in the middle of your computation!

Parallel Algorithms

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Huge clusters are a different proposition entirely

When you have 100s of thousands of machines in your system, you must plan for one to break down in the middle of your computation!

So another issue large systems and the algorithms that run on them have to contend with is machines failing

Parallel Algorithms

Aside: Reliability

For example, you might want to run the same sub-task on more than one processor for reliability: if one breaks you'll still get the result

Parallel Algorithms

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At one point Hector, a UK academic cluster, was having a failure rate of one node per day

Parallel Algorithms

Classical Problems

We now turn to look at a few classical problems that are used to illustrate the issues that arise in designing parallel programs

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Parallel Algorithms

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Some processes may want to simply read data, a *reader*

Others might want to read and then update data, a *writer*

To ensure consistency in the data, a writer must have exclusive access to the database

(A simplification of reality, if you know anything about databases)

Parallel Algorithms

Readers/Writers

When there is no writer using the database, any number of readers can access it simultaneously

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Note, as a consequence of exclusive access, a writer cannot access the database while there is any reader using it

Parallel Algorithms

Readers/Writers

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Note, as a consequence of exclusive access, a writer cannot access the database while there is any reader using it

One solution is to use simple primitives

Parallel Algorithms

Readers/Writers

```
int readers = 0;
rlock = make_lock();      // protect readers
wsem = make_semaphore(1);// sync writers
```

```
void reader()
{
  lock(rlock);
  readers++;
  if (readers == 1) wait(wsem);
  unlock(rlock);
  ... read ...
  lock(rlock);
  readers--;
  if (readers == 0) signal(wsem);
  unlock(rlock);
}
```

```
void writer()
{
  wait(wsem);
  ... write ...
  signal(wsem);
}
```

Parallel Algorithms

Readers/Writers

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This works, but has a problem

Parallel Algorithms

Readers/Writers

The problem is that this code is unfair in the way it treats readers and writers

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- reader 3 arrives; it can continue
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- and so on

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With low probability, but it happens

This is called *readers' preference*

The continuing stream of readers conspire to keep out the writer: the readers never signal the `wsem`

With low probability, but it happens

This is *starvation* of the writer

We might try to fix the writer starvation by having a writer pending count, and have readers wait if there is a writer (or some suitable number of writers) waiting

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Exercise Do this

We might try to fix the writer starvation by having a writer pending count, and have readers wait if there is a writer (or some suitable number of writers) waiting

Exercise Do this

But now we have a writers' preference and readers can be starved

Making this fair for both readers and writers is harder than you think

Parallel Algorithms

Readers/Writers

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Though having a readers' preference is not as bad as you might think, as typical code has more reads than writes

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Exercise Go and read up on the many suggested solutions to readers/writers

Exercise Read about the POSIX `pthread_rwlock`

Exercise Read about *read-copy-update* (RCU) and its choice of compromises

Exercise Think about how you might use GCD queues

Parallel Algorithms

Producers/Consumers

The next classical problem looks at how two or more processes can communicate: passing data between processes

Parallel Algorithms

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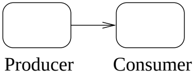

Producer/Consumer

Parallel Algorithms

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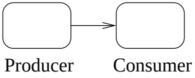

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If the producer sends directly to the consumer, this would require a synchronisation between them for every data item

Parallel Algorithms

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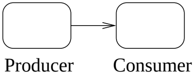

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If the producer sends directly to the consumer, this would require a synchronisation between them for every data item

And it would require the consumer to process data at the same rate as the producer produces it (as in a pipeline)

Parallel Algorithms

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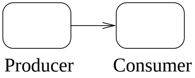

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Exercise Compare with MPI

So, typically, there is a *buffer* between them

Parallel Algorithms

Producers/Consumers

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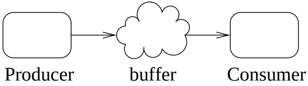

Buffered Producer/Consumer

Parallel Algorithms

Producers/Consumers

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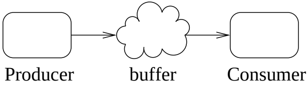

Buffered Producer/Consumer

This is just some area of memory in a shared memory system; or a message queue for a distributed memory system

The advantage is that we can *decouple* the producer and consumer

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- each can work at their own rate, until the buffer fills or empties

Parallel Algorithms

Producers/Consumers

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Parallel Algorithms

Producers/Consumers

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- each can work at their own rate, until the buffer fills or empties
- there is less synchronisation, thus less waiting around
- the producer and consumer are now working *asynchronously*: not synchronising on every message

Parallel Algorithms

Producers/Consumers

When the producer produces data, it writes it into the next free place in the buffer

Parallel Algorithms

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Unless the buffer is full, when the producer must wait until a place becomes free by the consumer reading some data

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Parallel Algorithms

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We need to see how to manage this synchronisation

For example, a buffer of size 1, using two semaphores, called `empty` and `full`

```
              empty = make_semaphore(1);
               full = make_semaphore(0);
producer() {                       consumer() {
  produce data                       wait(full);
  wait(empty);                       take from buffer
  insert in buffer                   signal(empty);
  signal(full);                      consume data
}                                  }
```

Parallel Algorithms

Producers/Consumers

A simple extension to a buffer of size *n* is to use counting semaphores `data` and `free` with `free` initialised to *n*

```
    free = make_counting_semaphore(n);
    data = make_counting_semaphore(0);
```

```
producer() {
  produce data
  wait(free);
  append to buffer
  signal(data);
}
```

```
consumer() {
  wait(data);
  remove from buffer
  signal(free);
  consume data
}
```

Parallel Algorithms

Producers/Consumers

But this works only if appending to and reading from the buffer are independent operations

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In this code as written, the producer and consumer might be acting simultaneously on the buffer: we need to make sure the update does not have a data race

Parallel Algorithms

Producers/Consumers

But this works only if appending to and reading from the buffer are independent operations

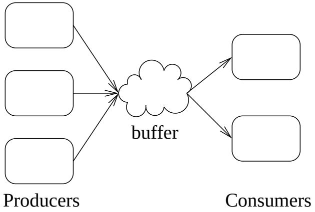
In this code as written, the producer and consumer might be acting simultaneously on the buffer: we need to make sure the update does not have a data race

So, for example, might want a lock on the buffer, or make sure the buffer can otherwise safely support a simultaneous read and write (e.g., for a hash table this might be difficult)

Parallel Algorithms

Producers/Consumers

And things get more interesting when there is more than more producer, or more than one consumer



Multiple Produces/Consumers

Now concurrent access to the buffer is really a problem

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We might use a lock to do this

Parallel Algorithms

Producers/Consumers

Now concurrent access to the buffer is really a problem

We might use a lock to do this

```
               free = make_semaphore(1);
               data = make_semaphore(0);
              buffy =  make_lock();
producer() {                  consumer() {
  produce data                  wait(data);
  wait(free);                   get_lock(buffy);
  get_lock(buffy);              take from buffer
  insert in buffer              free_lock(buffy)
  free_lock(buffy);             signal(free);
  signal(data);                 consume data
}                             }
```

Exercise Prove that this cannot deadlock

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Using one lock means that we cannot insert into the buffer at the same time as reading from it

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This is often an unnecessary restriction, e.g., the buffer is an area of memory where we can read one element at the same time as writing a different one

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Using one lock means that we cannot insert into the buffer at the same time as reading from it

This is often an unnecessary restriction, e.g., the buffer is an area of memory where we can read one element at the same time as writing a different one

Again, this might not be possible if the buffer was some more sophisticated kind of datastructure

So, often we have two locks, one for the insert position and one for the remove position

Parallel Algorithms

Producers/Consumers

So, often we have two locks, one for the insert position and one for the remove position

And we have to be careful when they coincide, e.g., when the buffer is full or empty

Implementations of buffers tend to be either

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- linked lists (unbounded size)

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- linked lists (unbounded size)
- fixed arrays, used circularly

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In any case, the buffers are usually actually *queues*, namely first in first out

Parallel Algorithms

Producers/Consumers

More advanced use of queues is possible

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If you have just **one** producer, you can implement a *lockless* insert into the queue: namely the insert end does not need a lock (or other synchronisation mechanism)

Parallel Algorithms

Producers/Consumers

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If you have just **one** producer, you can implement a *lockless* insert into the queue: namely the insert end does not need a lock (or other synchronisation mechanism)

The “gap” between testing for a space in the buffer and inserting is not a problem as no-one else is inserting data

More advanced use of queues is possible

If you have just **one** producer, you can implement a *lockless* insert into the queue: namely the insert end does not need a lock (or other synchronisation mechanism)

The “gap” between testing for a space in the buffer and inserting is not a problem as no-one else is inserting data

You still have to think carefully about the interaction of this with the removal of data

Symmetrically, if there is just **one** consumer, it is possible to have a lockless read

Parallel Algorithms

Producers/Consumers

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Exercise Find out how to do this (it involves memory barriers!)