

Shared Memory Programming with OpenMP

OpenMP Performance



A common scenario.....



“So I wrote my OpenMP program, and I checked it gave the right answers, so I ran some timing tests, and the speedup was, well, a bit disappointing really. Now what?”.

Most of us have probably been here.

Where did my performance go?

It disappeared into overheads.....

The six (and a half) evils...

- There are six main sources of overhead in OpenMP programs:
 - sequential code
 - idle threads
 - synchronisation
 - scheduling
 - communication
 - hardware resource contention
- and another minor one:
 - compiler (non-)optimisation
- Let's take a look at each of them and discuss ways of avoiding them.



Sequential code

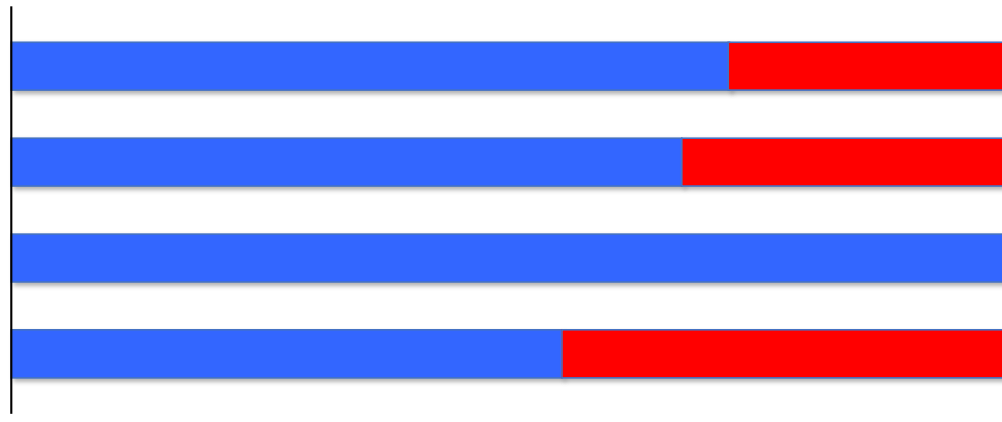


- In OpenMP, all code outside parallel regions, or inside MASTER and SINGLE directives is sequential.
- Time spent in sequential code will limit performance (that's Amdahl's Law).
- If 20% of the original execution time is not parallelised, I can never get more than 5x speedup.
- Need to find ways of parallelising it!

Idle threads



- Some threads finish a piece of computation before others, and have to wait for others to catch up.
- e.g. threads sit idle in a barrier at the end of a parallel loop or parallel region.



Time →

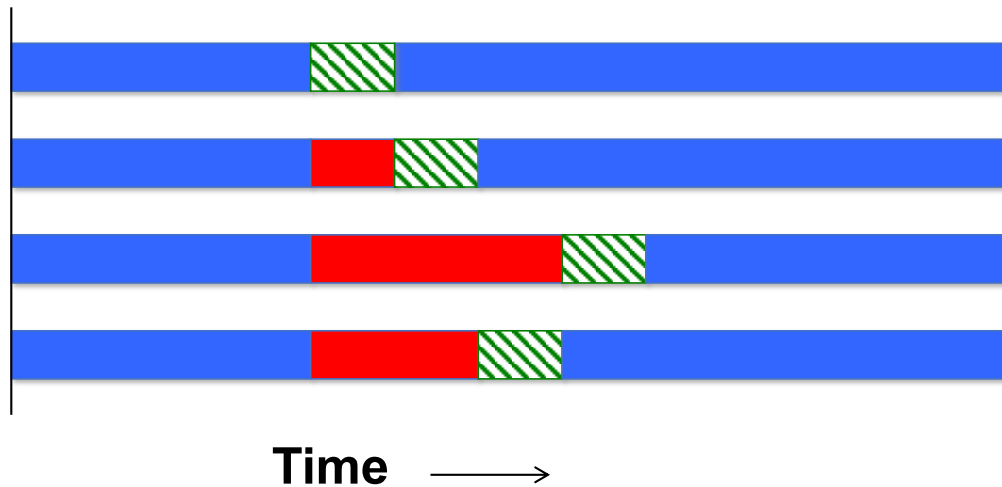
Avoiding load imbalance



- If it's a parallel loop, experiment with different schedule kinds and chunk sizes
 - can use **SCHEDULE (RUNTIME)** to avoid recompilation.
- For more irregular computations, using tasks can be helpful
 - runtime takes care of the load balancing
- Note that it's not always safe to assume that two threads doing the same number of computations will take the same time.
 - the time taken to load/store data may be different, depending on if/where it's cached.

Critical sections

- Threads can be idle waiting to access a critical section
 - In OpenMP, critical regions, atomics or lock routines



Avoiding waiting



- Minimise the time spent in the critical section
- OpenMP critical regions are a global lock
 - but can use critical directives with different names
- Use atomics if possible
 - allows more optimisation, e.g. concurrent updates to different array elements
- ... or use multiple locks

Synchronisation



- Every time we synchronise threads, there is some overhead, even if the threads are never idle.
 - threads must communicate somehow.....
- Many OpenMP codes are full of (implicit) barriers
 - end of parallel regions, parallel loops
- Barriers can be very expensive
 - depends on no. of threads, runtime, hardware, but typically 1000s to 10000s of clock cycles.
- Criticals, atomics and locks are not free either.
- ...nor is creating or executing a task

Avoiding synchronisation overheads



- Parallelise at the outermost level possible.
 - Minimise the frequency of barriers
 - May require reordering of loops and/or array indices.
- *Careful* use of NOWAIT clauses.
 - easy to introduce race conditions by removing barriers that are required for correctness
- Atomics *may* have less overhead than critical or locks
 - quality of implementation problem

Scheduling



- If we create computational tasks, and rely on the runtime to assign these to threads, then we incur some overheads
 - some of this is actually internal synchronisation in the runtime
- Examples: non-static loop schedules, task constructs

```
#pragma omp parallel for schedule(dynamic,1)
for (i=0;i<10000000;i++){
    .....
}
```

- Need to get granularity of tasks right
 - too big may result in idle threads
 - too small results in scheduling overheads

Communication



- On shared memory systems, communication is “disguised” as increased memory access costs - it takes longer to access data in main memory or another core’s cache than it does from local cache.
- Memory accesses are expensive! ($O(100)$ cycles for a main memory access compared to 1-3 cycles for a flop).
- Communication between cores takes place via the cache coherency mechanism.
- Unlike in message-passing, communication is fine-grained and spread throughout the program
 - much harder to analyse or monitor.

Cache coherency in a nutshell



- If a thread writes a data item, it gets an exclusive copy of the data in its local cache on the core where it is executing
- Any copies of the data item in other caches get invalidated to avoid reading of out-of-date values.
- Subsequent accesses to the data item by other threads must get the data from the exclusive copy
 - this takes time as it requires moving data from one cache to another

(Caveat : this is a *highly* simplified description!)

Data affinity

- Data will be cached on the cores which are accessing it, so we must reuse cached data as much as possible.
- Need to write code with good *data affinity* - ensure that the same thread accesses the same subset of program data as much as possible.
- Also important to prevent threads migrating between cores while the code is running.
 - use `export OMP_PROC_BIND=true`

Data affinity example 1



```
#pragma omp parallel for schedule(static)
for (i=0;i<n;i++){
    for (j=0; j<n; j++){
        a[i][j] = i+j;
    }
}
```

Balanced loop

An arrow points from the 'Balanced loop' box to the inner loop 'for (j=0; j<n; j++){' of the first code block.

```
#pragma omp parallel for schedule(static,16)
for (i=0;i<n;i++){
    for (j=0; j<i; j++){
        b[j] += a[i][j];
    }
}
```

Unbalanced loop

An arrow points from the 'Unbalanced loop' box to the inner loop 'for (j=0; j<i; j++){' of the second code block.

Different access patterns
for **a** will result in extra
communication

Data affinity example 2

```
#pragma omp parallel for  
for (i=0;i<n;i++){  
    ... = a[i];  
}
```

a will be spread across
multiple caches

```
for (i=0;i<n;i++){  
    a[i] = 23;  
}
```

Sequential code!
a will be gathered into
one cache

```
#pragma omp parallel for  
for (i=0;i<n;i++){  
    ... = a[i];  
}
```

a will be spread across
multiple caches again

Data affinity (cont.)



- Sequential code will take longer with multiple threads than it does on one thread, due to the cache invalidations
- Second parallel region will scale badly due to additional cache misses
- May need to parallelise code which does not appear to take much time in the sequential program!

Data affinity: NUMA effects



- Very evil!
- On multi-socket systems, the location of data in main memory is important.
 - Note: all current multi-socket x86 systems are NUMA!
 - Some sockets now contain multiple NUMA domains
- OpenMP has no support for controlling this.
- Common default policy for the OS is to place data on the NUMA domain which first accesses it (first touch policy).
- For OpenMP programs this can be the worst possible option
 - data is initialised in the master thread, so it is all allocated in one NUMA domain
 - having all threads accessing data in the same becomes a bottleneck

Avoiding NUMA effects

- In some OSs, there are options to control data placement
 - e.g. in Linux, can use `numactl` change policy to round-robin
- First touch policy can be used to control data placement indirectly by parallelising data initialisation
 - even though this may not seem worthwhile in view of the insignificant time it takes in the sequential code
- Fairly trivial for arrays, less so for tree/list/graph data structures
- Don't have to get the distribution exactly right
 - some distribution is usually much better than none at all.
- Remember that the allocation is done on an OS page basis
 - typically 4KB to 16KB
 - beware of using large pages!

False sharing

- Very very evil!



(though modern CPUs have some tricks to mitigate the effects)

- The units of data on which the cache coherency operations are done (typically 64 or 128 bytes) are always bigger than a word (typically 4 or 8 bytes).
- Different threads writing to *neighbouring words* in memory may cause cache invalidations!
 - still a problem if one thread is writing and others reading

False sharing patterns

- Worst cases occur where different threads repeatedly write neighbouring array elements.

```
count[omp_get_thread_num()]++;
```

```
#pragma omp parallel for schedule(static,1)
for (i=0;i<n;i++){
    for (j=0; j<i; j++){
        b[i] += a[j][i];
    }
}
```



Hardware resource contention



- There are shared hardware resources which, if all cores try to access them at the same time, do not scale.
 - or, put another way, an application running on a single core can access more than its fair share of the resources
- In particular, cores (and hence OpenMP threads) can contend for:
 - memory bandwidth
 - cache capacity
 - functional units (if using SMT)

Memory bandwidth



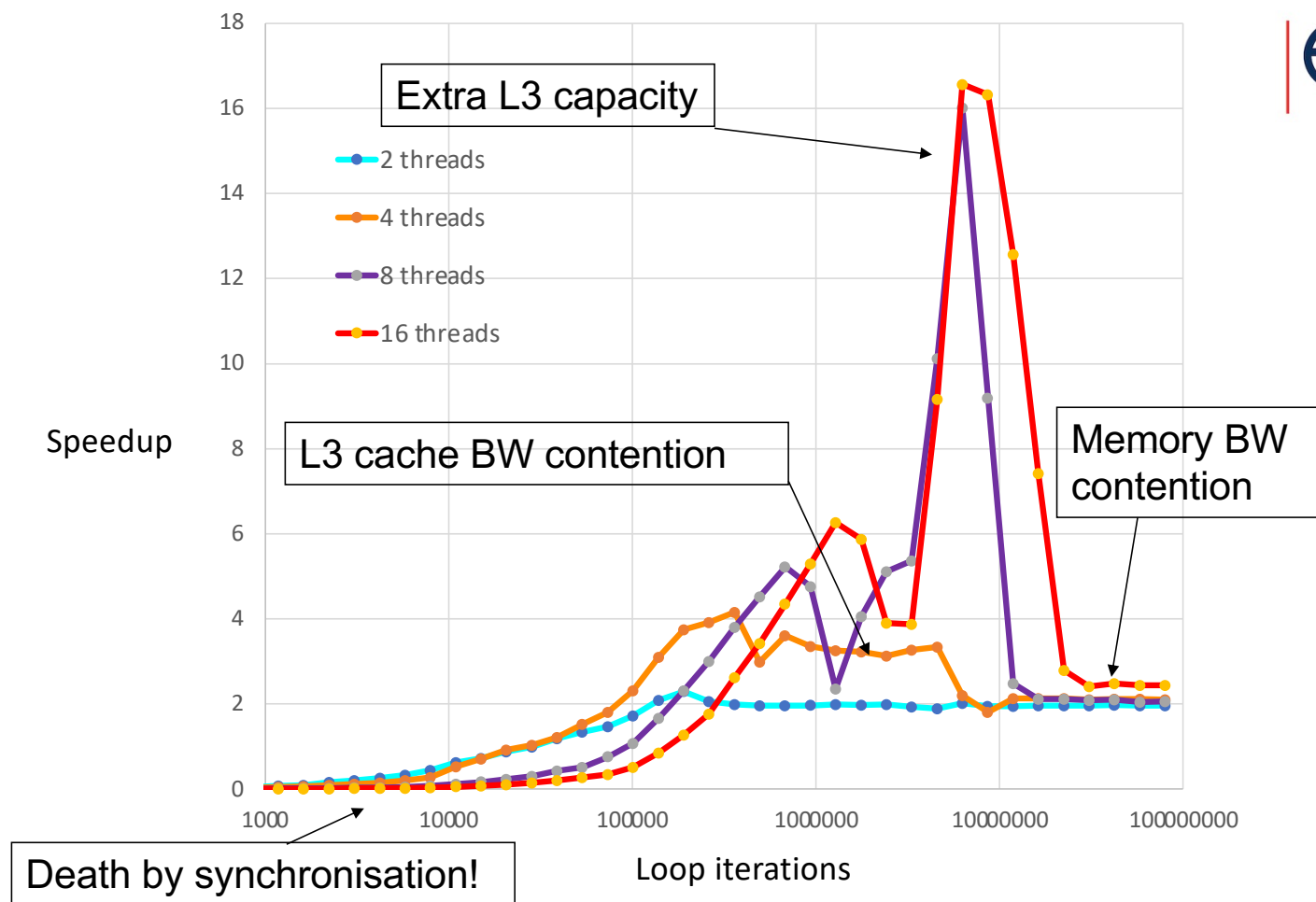
- Codes which are very bandwidth-hungry will not scale linearly on most shared-memory hardware.
- Try to reduce bandwidth demands by improving locality, and hence the re-use of data in caches
 - will benefit the sequential performance as well.
- Can be worth considering recomputing values instead of storing and reloading them from memory
 - do your performance experiments with all cores on the node busy!

Memory bandwidth example

- AMD Rome processor
 - 1 NUMA region - 16 cores
 - L1 and L2 caches per core
 - 16 MB shared L3 cache per 4 cores
 - Cray compiler

```
#pragma omp parallel for reduction(+:sum)
for (i=0;i<n;i++){
    sum += a[i];
}
```

- Measure speedup for varying values of n and no. of threads



Cache space contention



- On systems where cores share some level of cache (e.g. L3), codes may not appear to scale well because a single core can access the whole of the shared cache.
- Beware of tuning block sizes for a single thread, and then running multithreaded code
 - each thread will try to utilise the whole cache

Hardware threads



- Most modern CPUs have hardware support for running more than one software thread concurrently
 - Also referred to as SMT, hyperthreads, virtual cores
- When using hardware threads, OpenMP threads running on the same core contend for functional units as well as cache space and memory bandwidth.
- Tends to benefit codes where threads are idle because they are waiting on memory references
 - code with non-contiguous/random memory access patterns
- Codes which are bandwidth-hungry, or which saturate the floating point units (e.g. dense linear algebra) may not benefit from this
 - may actually run slower
 - may not repay the additional parallel overheads resulting from more OpenMP threads

Oversubscription



- Running more threads than hardware execution units (cores or hardware threads) is generally a bad idea.
- OS tries to give each thread a fair share of execution units
- Cost of stopping one thread and starting another is high (1000s of clock cycles)
- Ruins data locality!

Compiler (non-)optimisation



- Very rarely, the addition of OpenMP directives can inhibit compiler from performing sequential optimisations.
- Symptoms: 1-thread parallel code has longer execution time than sequential code.
- Can be hard to find a workaround
- Can sometimes be cured by making shared data private, or making local copies of variables.

Minimising overheads

My code is giving poor speedup. I don't know why.

What do I do now?

1.

- Say “OpenMP is a heap of junk”.
- Give up.

2.

- Try to *classify* and *localise* the sources of overhead.
- What type of problem is it, and where in the code does it occur?
- Use any available tools to help you (e.g. timers, hardware counters, profiling tools).
- Fix problems which are responsible for large overheads first.
- Iterate.



Profilers



- Standard profilers (gprof, IDE profilers) can be confusing
 - they typically accumulate the time spent in functions across all threads.
- You can get a lot out of using timers (`omp_get_wtime()`)
- Add timers round every parallel region, and round the whole code.
 - work out which parallel regions have the worst speedup
 - don't assume the time spent outside parallel regions is independent of the number of threads.

Performance tools



- Intel Vtune
- Linaro MAP
- CrayPAT
- Vampir
 - timeline traces can be very useful for visualising load balance
- Scalasca
 - breaks down overheads into different categories
- TAU
- ParaTools Threadspotter
 - very good for finding cache/memory problems, including false sharing.

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