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OpenMP
A gentle introduction to OpenMP

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Why OpenMP?

- Simplicity and Portability
- Avoid low-level threading (e.g., pthreads)

Simplicity and Portability

- A de-facto standard API to write shared memory parallel applications in C, C++ and Fortran
- Compiler directives
- Runtime routines
- Environment variables
- Very mature (around since 1997)
- Version 6.0 has been released (11/2024)

Simplicity and Portability

- Portable: supported by GNU, Intel, NVIDIA/PGI, SUN Studio, others
- Portable: supported on many (all important ones) Hardware platforms
- Allows incremental parallelisation (see next slide)
- You can revert to your serial application with a flick of a switch (either set OPENMP NUM THREADS to 1 or don’t link with libopenmp)
- Supports tasks
- Supports other architectures (offloading to accelerators)
- Can be used with MPI for hybrid parallelism

Incremental Approach

Parallelism added incrementally until performance goals are met:

- Start with a serial application
- Benchmark
- Identify hotspots
- Parallelise that section
- Test
- Repeat

Introduction

- OpenMP stands for Open Multi-Processing.
- It is an API for shared-memory parallel programming.
- Supports C, C++, and Fortran.

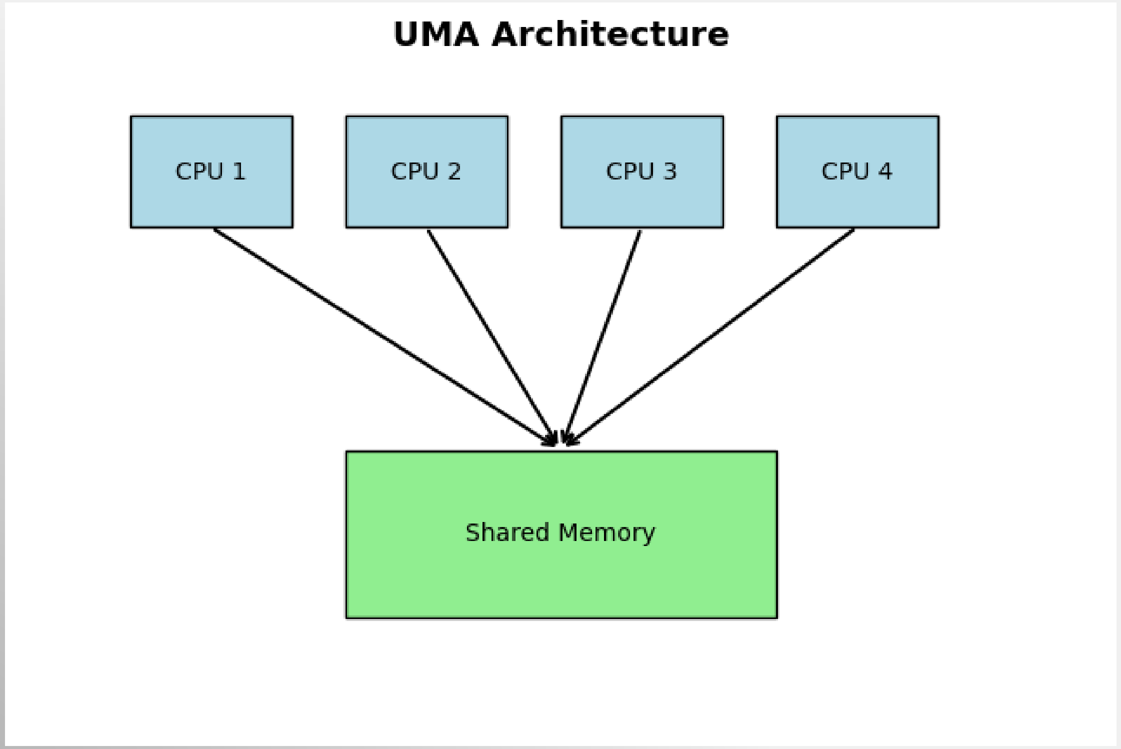
C/C++

```
#pragma omp parallel for
for (int i = 0; i < N; i++)
{
a[i] = b[i] + c[i];
}
```

Fortran

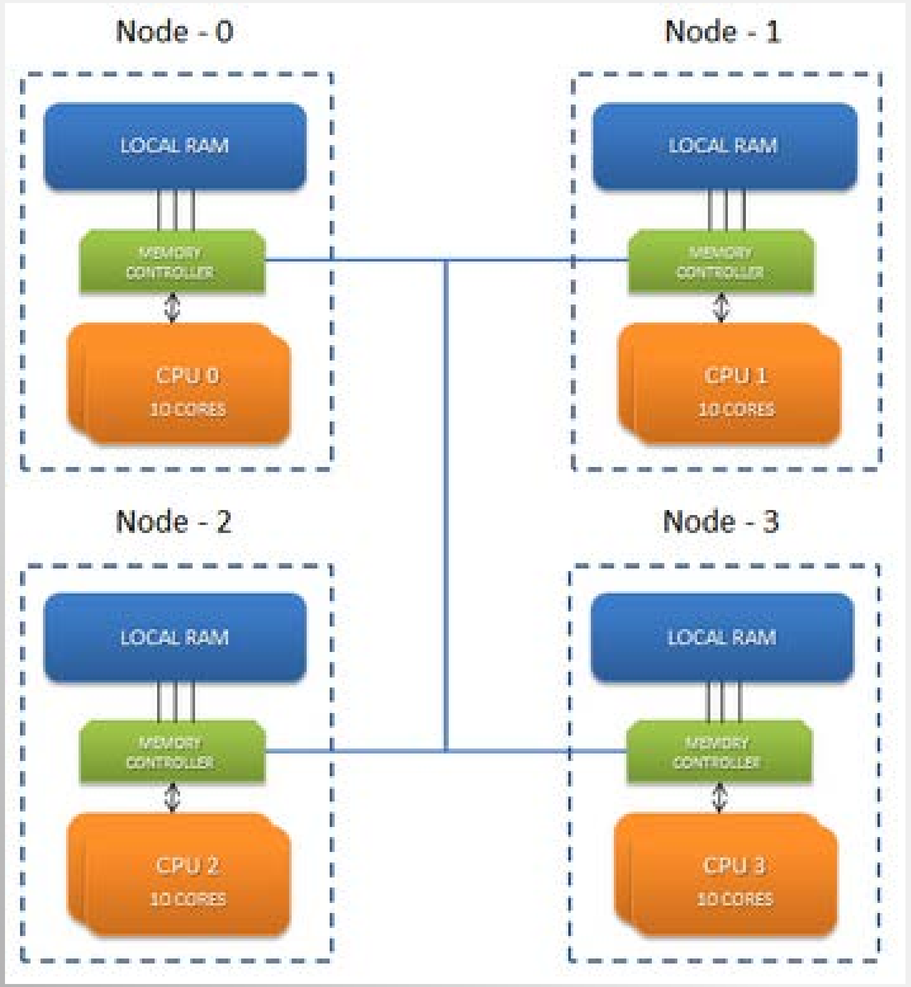
```
!$omp parallel do
do i = 1, N
   a(i) = b(i) + c(i)
end do
!$omp end
parallel do
```

Uniform Memory Access



- All CPUs share the same memory.
- Equal access time for all processors.
- Simpler programming model.
- Common in small-scale systems like desktops or basic servers.

Non-Uniform Memory Access

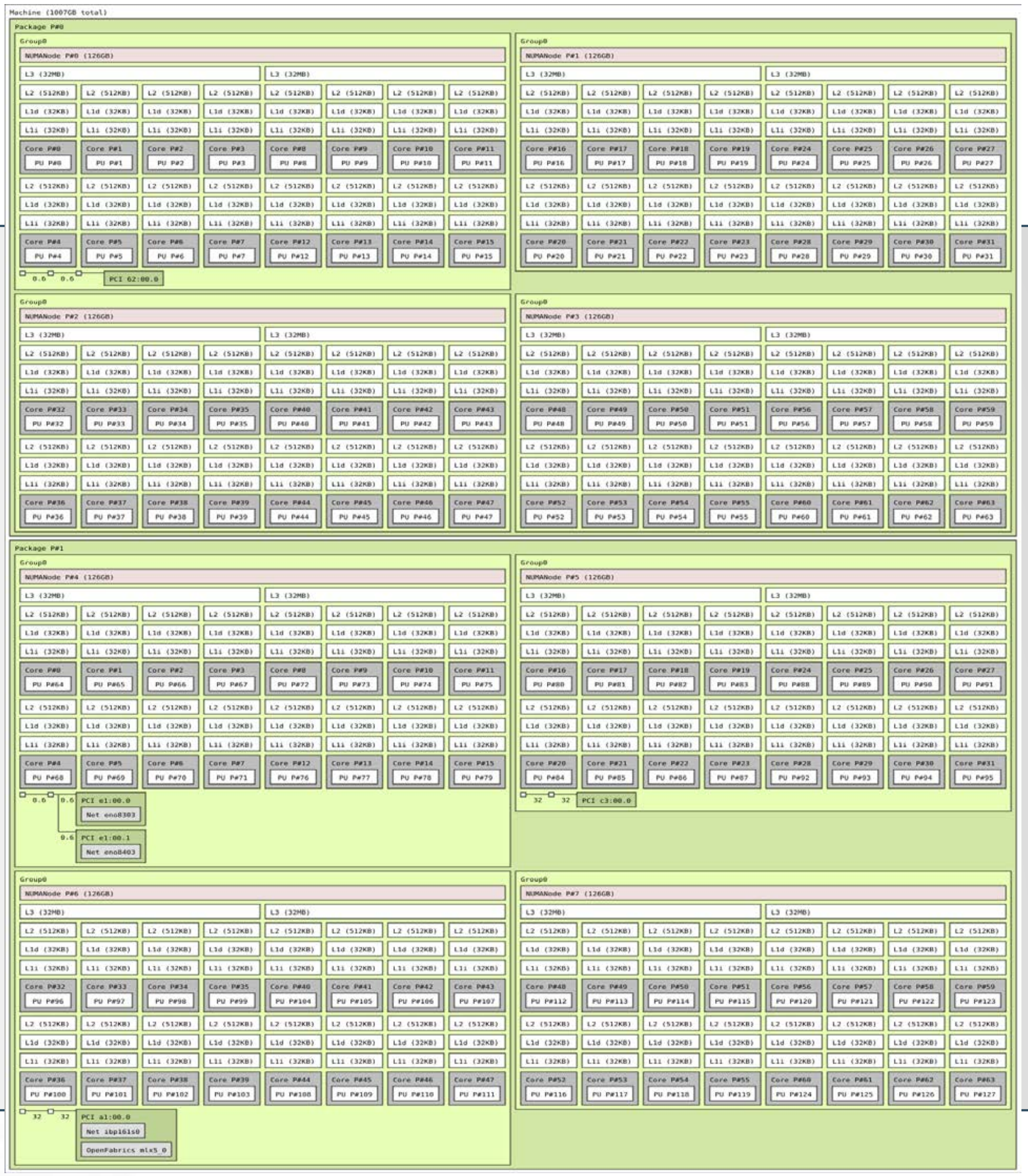


- Each processor has its own local memory, but can also access other CPUs' memory.
- Faster access to local memory, slower to remote memory.
- More complex but scales better for large systems.
- Common in modern HPC nodes and multi-socket servers.

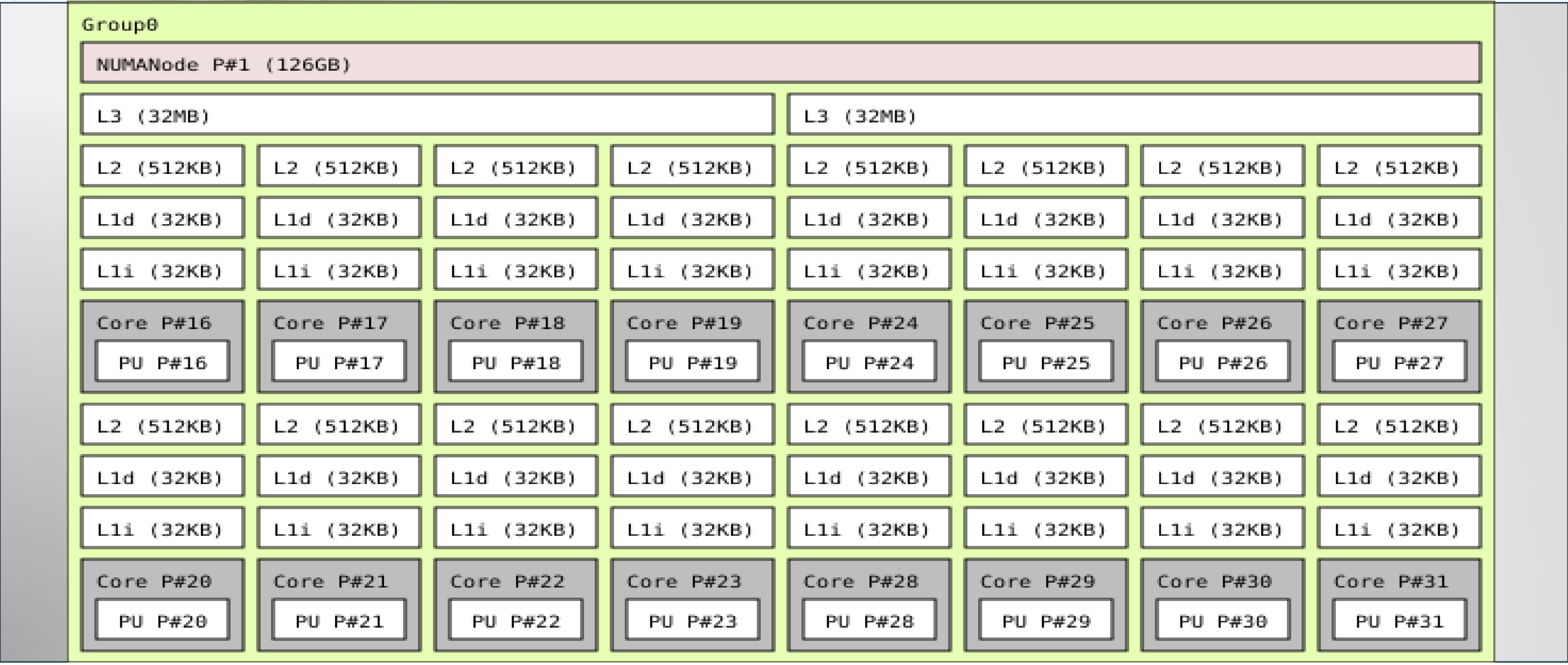
Reality

This is how a Real System looks like. (ARIS expansion)

- Multiple levels of Cache(s)
- Memory could be split/fragmented across CPUs/Sockets
- Sharing of hardware resources across CPUs/Sockets (L3 caches)



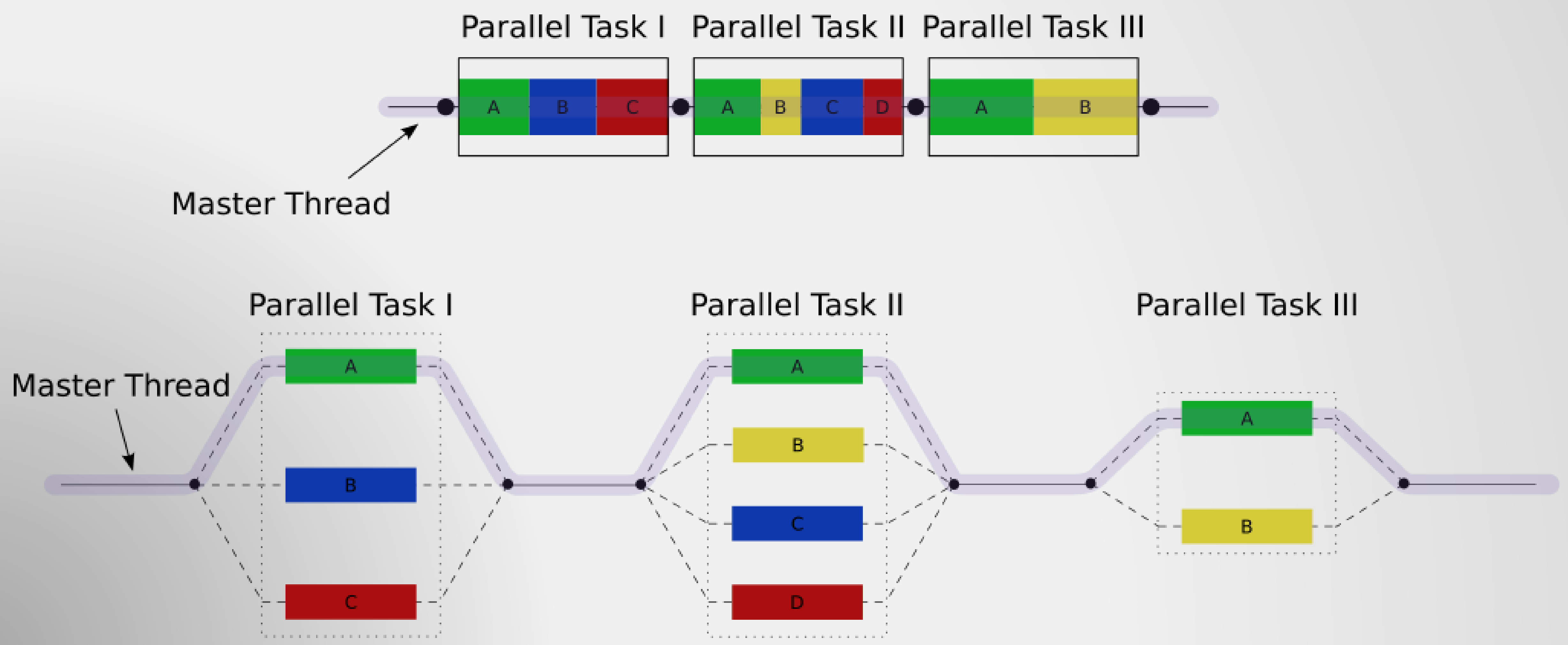
Reality / Closeup



Threaded Programming Model

- OpenMP uses threads.
- A thread is the smallest unit of processing that can be scheduled by an operating system.
- Threads are very light-weight processes; but threads can share memory with other threads.
- However, each Thread has it’s own stack and stack pointers.
- Threads are part of a process. Without a process, threads do not exist.
- Threads can access Shared Data.
- Threads can have Private Data.
- Threads are unique and have their own state (regardless of the other threads).

Fork - Join Model



Hello World C/C++

```
#include "omp.h"
#include <stdio.h>
int main ()
{
#pragma omp parallel
    {
    printf("Hello from process: %d \n", omp_get_thread_num ());
    }
}
```

```
gcc -g3 -O2 -Wall -Wextra 01.c -o 01. exe -fopenmp
```

Hello World Fortran

```
PROGRAM Parallel_Hello_World
USE OMP_LIB
!$OMP PARALLEL
PRINT *, "Hello from process: ", OMP_GET_THREAD_NUM ()
!$OMP END PARALLEL
END
```

```
gfortran -g3 -O2 -Wall -Wextra 01. f90 -o 01_f.exe -fopenmp
```

DEMO: Hello OpenMP

```
# compile
gcc -O2 -fopenmp hello_omp.c -o hello_omp


# run
./hello_omp
OMP_NUM_THREADS=8  ./hello_omp
OMP_NUM_THREADS=12 ./hello_omp
```

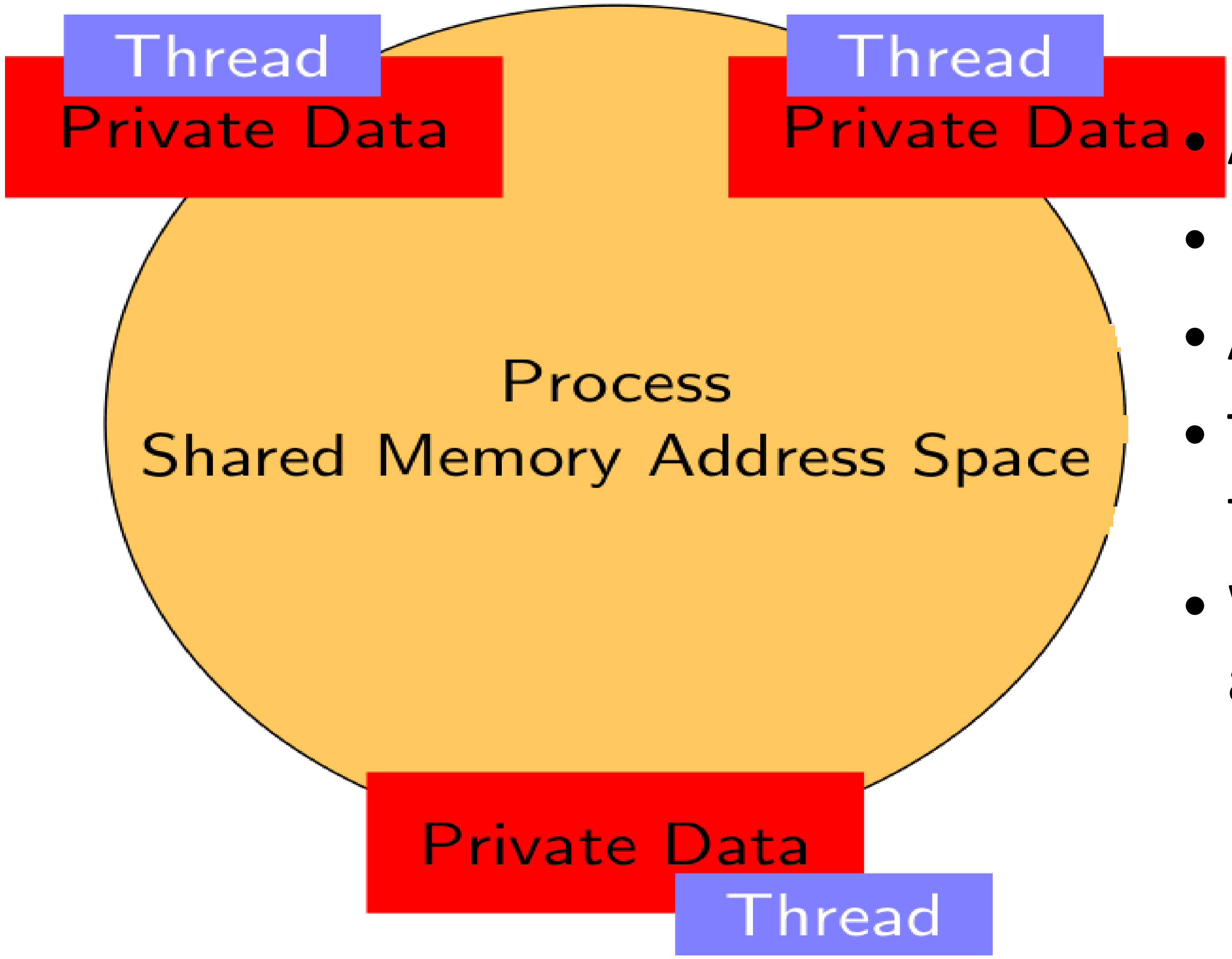
DEMO: Hello OpenMP

```
#include <stdio.h>
#include <omp.h>

int main(void)
{
    #pragma omp parallel
    {
        int tid = omp_get_thread_num();
        int nt  = omp_get_num_threads();

        #pragma omp single
        printf("parallel region: num_threads=%d\n", nt);

        if (tid < 8)
            printf("  hello from thread %d\n", tid);
    }

    return 0;
}
```

Shared Data Model

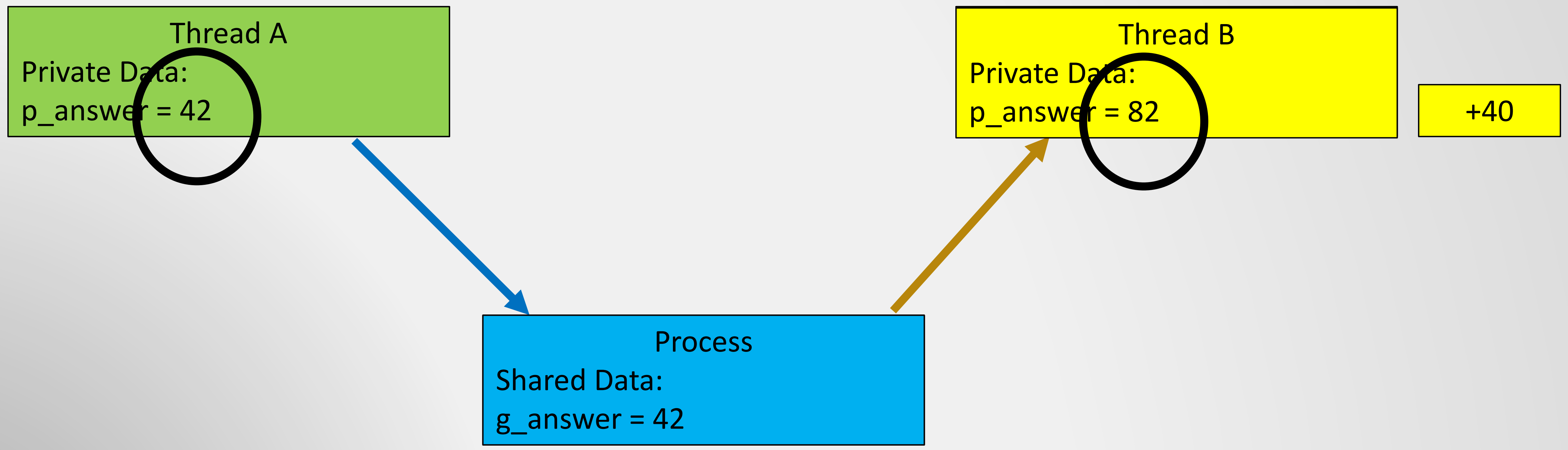
- Threads can (for non-trivial problems they **must**) exchange data.
- Shared Data constructs are used to exchange data.
  - Thread A writes to a shared variable.
  - Thread B reads the shared variable.
- No implicit synchronisation
- No implicit barriers (on entry)
- No implicit checks

Thread Sharing Data



- A single Process; with many Threads
- Each Thread has it's own Private Data
- All Threads share Shared Data
- The OS is responsible for scheduling the Process/Threads
- Without synchronisation, things fall apart

Thread Sharing Data Example



Synchronisation

Simple Example, yet:

- We don’t control the Threads (unless we block them) [**DO NOT**]
- The OS controls thread execution and scheduling
- Threads run at their own pace
- Even in this very simple example, we need to guard that Thread B doesn’t read an uninitialised value from g_answer.
- Even though it takes one line of source code to modify a value; in reality this is a multi-step process (at least three instructions are issued).
- If multiple threads try to modify a shared variable at the same time ...

Synchronisation Example

Simple Example:

- We want to add 8 to 0.
- This is a computationally expensive problem; so we will use OpenMP.
- Since we are adding 8; we will use 8 Threads.
- Each Thread will add 1.
- At the end we will print the result.
- We are expecting to dramatically improve the performance of our application.

Synchronisation Example Single Threaded (C/C++)

```
#include <stdio.h>
#define NUM_TIMES 8
int main ()
{
    int VALUE = 0;
    for (int i = 0; i < NUM_TIMES; ++i)
    {
    VALUE += 1;
    }
    printf("Result :%d \n", VALUE);
}
```

Synchronisation Example Single Threaded (Fortran)

```
PROGRAM Training
Implicit none

integer :: NUM_TIMES = 8, VALUE = 0, n

do n = 1, NUM_TIMES
        VALUE = VALUE + 1
end do
PRINT *, "Result: ", VALUE

END PROGRAM Training
```

Synchronisation Example Single Threaded

```
$ gcc -g3 -O2 -Wall -Wextra -fsanitize=address ,undefined 02.c -o 02. exe
$ ./02. exe
Result :8
```

```
$ gfortran -g3 -O2 -Wall -Wextra -fsanitize=address ,undefined 02. f90 -o
02_f.exe
$ ./02 _f.exe
Result:                    8
```

Parallel Loops

- In most applications; runtime is spent in loops.
- Loops are the first place that we will want to parallelise.
- If a loop is independent then it can be trivially parallelised.
- A loop from 0-99 can be run on one thread running all iterations; or 4 threads can run iterations 0-24/25-49/50-74/75-99 (OpenMP can use other schemes to divide iterations across threads).

Synchronisation Example Single Threaded (C/C++)

```
#include <stdio.h>
#include "omp.h"    // <=================
#define    NUM_TIMES 8
int main ()
{
     int VALUE = 0;

     #pragma omp  parallel for   // <=================
     for (int i = 0; i < NUM_TIMES; ++i)
     {
          VALUE += 1;
     }
     printf("Result :%d \n", VALUE);
}
```

Synchronisation Example Single Threaded (Fortran)

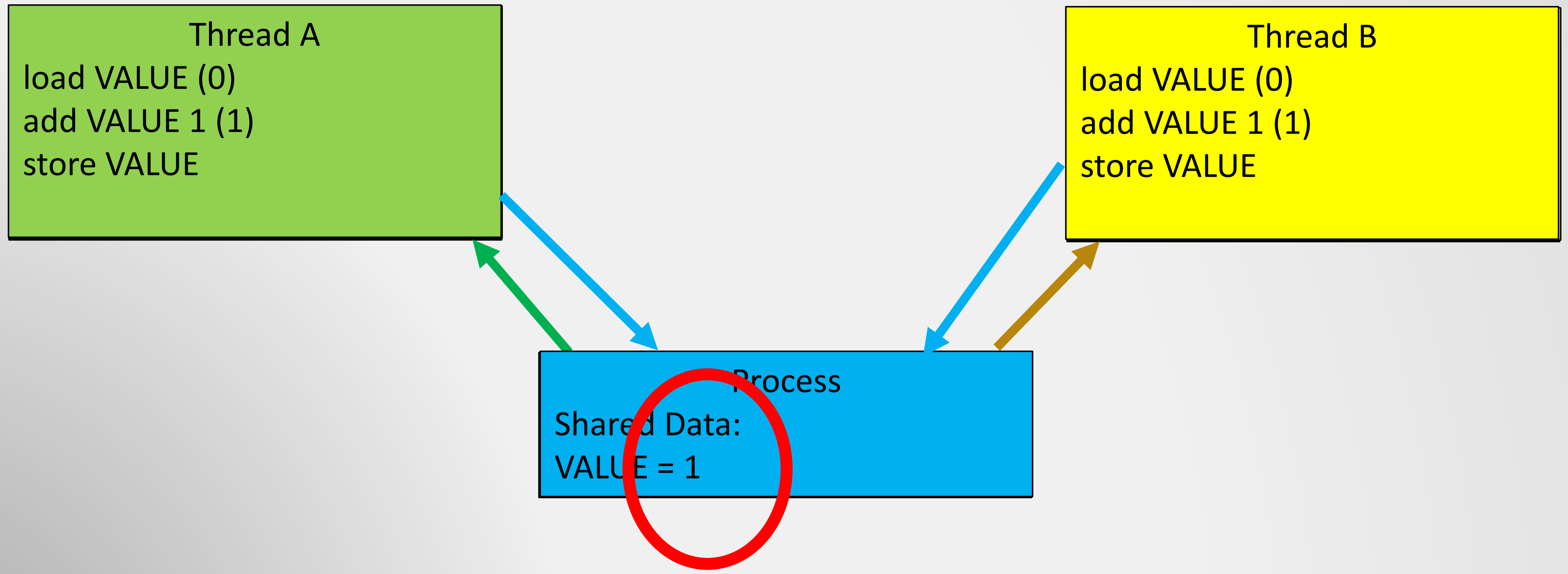
```
PROGRAM Training
USE OMP_LIB  !<=================
Implicit none
integer :: NUM_TIMES = 8, VALUE = 0, n
!$OMP PARALLEL DO !<=================
    do n = 1, NUM_TIMES
        VALUE = VALUE + 1
    end do
    PRINT *, "Result: ", VALUE
END PROGRAM Training
```

Synchronisation Example Single Threaded

```
$ gcc -g3 -O2 -Wall -Wextra -fsanitize=address ,undefined 02.c -o 02. exe -fopenmp
$ ./02. exe
Result: X


$ gfortran -g3 -O2 -Wall -Wextra -fsanitize=address , undefined 02. f90 -o 02_f.exe -fopenmp
$ ./02 _f.exe
Result:                 X
```

Synchronisation Example

Time: 0, 1, 2, 3, 4, 5, 6, 7



Race Condition

- If you run the example code (in Linux or WSL) you will see that the result is not always 8.
- Why?? Sometimes the threads run one after another. Other times they overlap.
- If they overlap and at least one (in our case all of them) writes/updates a shared value; we can have a race condition.
- Race conditions are hard to debug
- Sometimes they can be detected by run-time debuggers

DEMO: Race condition

```
# compile
gcc -O2 -fopenmp race_sum.c -o race_sum


# run
OMP_NUM_THREADS=8 ./race_sum 90000000 0
OMP_NUM_THREADS=8 ./race_sum 90000000 1
OMP_NUM_THREADS=8 ./race_sum 90000000 2


# Expected: mode 0 WRONG; mode 1 OK but slower; mode 2 OK and usually fastest.
```

DEMO: Race condition

```
#include <stdio.h>
#include <stdlib.h>
#include <omp.h>

int main(int argc, char **argv)
{
    long long N = (argc > 1) ? atoll(argv[1]) : 200000000LL; // 2e8
    int mode = (argc > 2) ? atoi(argv[2]) : 0;              // 0=race, 1=atomic, 2=reduction
    long long sum = 0;

    double t0 = omp_get_wtime();

    if (mode == 2) {
        #pragma omp parallel for reduction(+:sum)
        for (long long i = 0; i < N; i++) sum += 1;
    } else if (mode == 1) {
        #pragma omp parallel for
        for (long long i = 0; i < N; i++) {
            #pragma omp atomic
            sum += 1;
        }
    } else {
        #pragma omp parallel for
        for (long long i = 0; i < N; i++) sum += 1; // INTENTIONAL RACE
    }

    double t1 = omp_get_wtime();

    int threads = 1;
    #pragma omp parallel
    #pragma omp single
    threads = omp_get_num_threads();

    printf("threads=%d  N=%lld  mode=%d (0=race,1=atomic,2=reduction)\n", threads, N, mode);
    printf("sum=%lld  expected=%lld  %s\n", sum, N, (sum == N ? "OK" : "WRONG"));
    printf("time=%.3f s\n", t1 - t0);

    return 0;
}
```

OpenMP Basics

- Parallel Regions
- Data sharing & scoping: shared, private, firstprivate, lastprivate, default(shared or none)
- Worksharing: for / do, sections, schedule
- Reductions & loop shaping: reduction, collapse
- Synchronization: barrier, critical, atomic, ordered (loop order), master / masked
- Utilities: omp get num threads(), omp get thread num(), timing via omp get wtime()
- Good practices

Parallel Regions

- This one is simple. Any code inside an OMP pragma is executed by all threads
- Don’t assume that OpenMP will handle special cases for you
- If you have code that writes data to the file system inside an OMP pragma; then you will write the data OMP NUM THREAD times.
- Same for functions. A function called from inside an OMP pragma will be called OMP NUM THREAD times.

Parallel Regions

C/C++
```
#pragma omp parallel
{
   CODE
}
```

Fortran
```
!$omp parallel
  CODE
!$omp end parallel
```

C/C++
```
#pragma omp parallel
{
   FUNCTION <== NUM_THREAD
}
```

Fortran
```
!$omp parallel
  FUNCTION <== NUM_THREAD
!$omp end parallel
```

Parallel Regions

- Parallel Regions can also use clauses
- #pragma omp parallel num threads(4) : Use 4 threads
- #pragma omp parallel for if(condition) : Only start extra threads if condition is TRUE. For example, if the size of an array is less than 10000 run serially. If not, start X number of Threads

Data Sharing

The most important clauses in any Parallel Region are:

- default(shared | none)
- private(list)
- firstprivate(list)
- shared(list)

Data Sharing

Reminder about variables (single variables, arrays, etc):

- SHARED: All threads see the same copy (careful when reading/writing)
- PRIVATE: Every thread sees it’s own copy (careful when you want to exchange data).

Data Sharing

SHARED and PRIVATE variables important caveats:

- When entering any PARALLEL section, PRIVATE variables are uninitialised.
- When exiting any PARALLEL section (even when you have another one starting immediately after) private copies/variables are lost.
- Any variable declared inside a PARALLEL section is PRIVATE.
- Always, always, always use **DEFAULT(none)**. It will save you time and money.

Data Sharing

SHARED and PRIVATE variables important caveats:

- By default, global and static variables are SHARED, and loop indices are private.
- firstprivate: Like PRIVATE, but each thread’s copy is initialized with the value of the original variable at entry
- lastprivate: Like private, but after the parallel region finishes, the variable in the original context is updated with the value from the last iteration (or section) in the region

Data Sharing

```
int a, b=10;
#pragma omp parallel private(a) firstprivate(b)
{
    // 'a' is uninitialized private per thread;
    // 'b' is private per thread each initialized to 10.
}
```

```
integer :: a, b
b = 10
!$omp parallel private(a) firstprivate(b)
    ! 'a' is uninitialized privateper thread
    ! 'b' is private per thread each initialized to 10
!$omp end parallel
```

DEMO: lastprivate

```
# compile
gcc -O2 -fopenmp lastprivate_demo.c -o lastprivate_demo


# run
OMP_NUM_THREADS=8  ./lastprivate_demo 100000 0   # shared "last" (wrong / nondeterministic)
OMP_NUM_THREADS=8  ./lastprivate_demo 100000 1   # lastprivate (correct)

# Expected: mode 0 WRONG; mode 1 OK but slower; mode 2 OK and usually fastest.
```

DEMO: lastprivate

```
#include <stdio.h>
#include <stdlib.h>
#include <omp.h>

int main(int argc, char **argv)
{
    long long N = (argc > 1) ? atoll(argv[1]) : 10000000LL;
    int mode    = (argc > 2) ? atoi(argv[2]) : 0; // 0=shared last (race), 1=lastprivate

    long long last = -1;

    if (mode == 1) {
        #pragma omp parallel for default(none) shared(N) lastprivate(last)
        for (long long i = 0; i < N; i++) {
            last = i; // OpenMP will assign the "logical last iteration" value to last
        }
    } else {
        #pragma omp parallel for
        for (long long i = 0; i < N; i++) {
            last = i; // INTENTIONAL RACE: many threads write "last"
        }
    }

    printf("N=%lld  mode=%d (0=shared race, 1=lastprivate)\n", N, mode);
    printf("last=%lld  expected=%lld  %s\n", last, N-1, (last == N-1 ? "OK" : "WRONG / NONDETERMINISTIC"));

    return 0;
}
```

Worksharing

- Loops (for / do)
- Schedules
- Sections
- Single
- Master

Loops (for / do) [C/C++]

- Loops (for / do): Divides loop iterations among threads in a parallel region

```
int N = 1000
#pragma omp parallel for
for (int i = 0; i < N; i++)
{
            a[i] = b[i] + c[i];
}
```

Schedules

Loops (for / do) support the following schedule types:

- static: assigns fixed chunks in advance
- dynamic: hands out chunks on the fly as threads finish
- guided: starts with large chunks that shrink over time to balance workload.
- auto: the compiler/runtime decides.
- runtime: use OMP_SCHEDULE environment variable or a call to set it.
- chunk: we can define the size of the chunks.

Schedules

- If we know exactly what is going on; static is the fastest.
- If we don’t know; but we know that there is variability, use dynamic. But your data locality (if important) will disappear.
- If we know nothing; then start with guided. More overhead.
- We can also set the chunk size to help the compiler.

Loops (for / do) [C/C++]

Use a dynamic schedule. Each thread will get 4 iterations. The first thread that finishes, will get the next 4; until the end of the loop.

```
int N = 1000
#pragma omp parallel for schedule(dynamic ,4)
for (int i = 0; i < N; i++)
{
		a[i] = b[i] + c[i];
}
```

DEMO: scheduling

```
# compile
gcc -O2 -fopenmp schedule_demo.c -o schedule_demo


# run
OMP_NUM_THREADS=8  ./schedule_demo 40000000 0 0   # static, chunk=1
OMP_NUM_THREADS=8  ./schedule_demo 40000000 1 1   # dynamic, chunk=1
OMP_NUM_THREADS=8  ./schedule_demo 40000000 2 1   # guided,  chunk=1
```

DEMO: scheduling

```
#include <stdio.h>
#include <stdlib.h>
#include <omp.h>

static inline void burn(int iters)
{
    volatile double x = 0.0;
    for (int k = 0; k < iters; k++) x = x * 1.0000001 + 1.0;
}

int main(int argc, char **argv)
{
    long long N = (argc > 1) ? atoll(argv[1]) : 20000000LL; // many iterations
    int mode    = (argc > 2) ? atoi(argv[2]) : 0;           // 0=static,1=dynamic,2=guided
    int chunk   = (argc > 3) ? atoi(argv[3]) : 0;           // 0 means "default" for static

    omp_sched_t kind = omp_sched_static;
    const char *kname = "static";
    if (mode == 1) { kind = omp_sched_dynamic; kname = "dynamic"; }
    if (mode == 2) { kind = omp_sched_guided;  kname = "guided";  }

    // heavy tail: last 10% is heavier
    long long tail = (9LL * N) / 10LL;
    int light_iters = 40;
    int heavy_iters = 400;  // 10x heavier but still "small" so overhead differences show up

    omp_set_schedule(kind, chunk);

    double t0 = omp_get_wtime();

    #pragma omp parallel for schedule(runtime)
    for (long long i = 0; i < N; i++) {
        burn(i < tail ? light_iters : heavy_iters);
    }

    double t1 = omp_get_wtime();

    int threads = 1;
    #pragma omp parallel
    #pragma omp single
    threads = omp_get_num_threads();

    printf("threads=%d  N=%lld  schedule=%s  chunk=%d  tail=last10%%  time=%.3f s\n",
           threads, N, kname, chunk, t1 - t0);

    return 0;
}
```

Sections

- Not all code runs in loops.
- Allows different code blocks to run in parallel.
- Each section block is executed by one thread.
- When all sections complete, threads synchronize (unless nowait is used).

Sections [C/C++]

The two functions will run on two different threads. There is a block at the end of the parallel section; waiting for both threads to finish.

```
#pragma omp parallel sections
{
        #pragma omp section something_interesting_A ();

        #pragma omp section something_interesting_B ();
}
```

Sections

- Pure Sections only allow running 1 Thread per section.
- If somethinginterestingA() needs 10x more CPU; then you are out of luck
- (until the advanced Session which talks about Tasks and Nested Parallelism)

Single

- Single: Ensures a block is executed by only one thread (unspecified which)
- All other threads wait at an implicit barrier at the end of the single region
- Unless nowait is specified.
- You can still use PRIVATE and FIRSTPRIVATE clauses.

Single

```
#pragma omp single
{
        something_only_for_one ();
}
```

```
!$omp single
call something_only_for_one ()
!$omp end single
```

Master

- The Master directive specifies that the enclosed code block is executed only by the master thread (thread 0).
- Unlike single, it has no implicit barrier at entry or exit, so other threads skip it and continue without waiting.
- It’s often used for setup, I/O, or coordination work that must be done once without pausing the other threads.

Reduction operations

- (various) Reduction operations
- Collapse

Reduction operations

- Performs a parallel reduction on a variable across threads.
- Each thread gets a private copy of var
- Updates it with
- At the end all copies are combined (reduced) into a single result.
- Common operators include +, *, max:, min:, etc.
- Why use a reduction?? **Performance!**

Reduction operations [C/C++]

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

Collapse

- When you use an omp parallel do/for you only parallelise the outer loop.
- With COLLAPSE we can tell the OpenMP library to treat the next 2, 3, 4 loops as one big loop and divide it to the available threads.

Collapse [C/C++]

In this example OpenMP will create 3 threads to parallelise the outer loop. This is obviously inefficient (in a machine with 128 cores; 125 will sit IDLE).

```
int i, j;
#pragma omp parallel for
for (i = 1; i <= 3; i++) {
        for (j = 1; j <= 400; j++) {
                printf("Thread %d: i=%d, j=%d\n", omp_get_thread_num (), i, j);
        }
}
```

Collapse [C/C++]

In this example OpenMP will divide the 1200 iterations to all available threads. Better usage of the 128 cores.

```
int i, j;
#pragma omp parallel for collapse (2)
for (i = 1; i <= 3; i++) {
        for (j = 1; j <= 400; j++) {
                printf("Thread %d: i=%d, j=%d\n", omp_get_thread_num (), i, j);
        }
}
```

DEMO: collapse

```
# compile
gcc -O2 -fopenmp collapse_demo.c -o collapse_demo


# run
OMP_NUM_THREADS=8  ./collapse_demo 4 8000000000 0   # no collapse
OMP_NUM_THREADS=8  ./collapse_demo 4 8000000000 1   # collapse(2)

# mode 1 (collapse) uses threads better and is faster when outer loop is small.
```

DEMO: collapse

```c
#include <stdio.h>
#include <stdlib.h>
#include <omp.h>

static inline void burn(long long iters)
{
    volatile double x = 0.0;
    for (long long k = 0; k < iters; k++) x = x * 1.0000001 + 1.0;
}

int main(int argc, char **argv)
{
    int I = (argc > 1) ? atoi(argv[1]) : 4;            // small outer loop
    long long J = (argc > 2) ? atoll(argv[2]) : 200000000LL; // big inner work
    int mode = (argc > 3) ? atoi(argv[3]) : 0;          // 0=no collapse, 1=collapse(2)

    double t0 = omp_get_wtime();

    if (mode == 1) {
        #pragma omp parallel for collapse(2) schedule(static)
        for (int i = 0; i < I; i++) {
            for (long long j = 0; j < J; j++) {
                if ((j & 0x3FFFFF) == 0) burn(2000); // sparse burn to keep runtime reasonable
            }
        }
    } else {
        #pragma omp parallel for schedule(static)
        for (int i = 0; i < I; i++) {
            for (long long j = 0; j < J; j++) {
                if ((j & 0x3FFFFF) == 0) burn(2000);
            }
        }
    }

    double t1 = omp_get_wtime();

    int threads = 1;
    #pragma omp parallel
    #pragma omp single
    threads = omp_get_num_threads();

    printf("threads=%d  I=%d  J=%lld  mode=%d (0=no collapse,1=collapse)  time=%.3f s\n",
           threads, I, J, mode, t1 - t0);

    return 0;
}
```

Synchronisation

- barrier: makes all threads in a team wait until every thread has reached the barrier.
- critical: ensures the enclosed code block is executed by only one thread at a time.
- atomic: makes a simple memory update (e.g. count++) atomic at the hardware level.
- lock: creates user managed lock(s)
- ordered: Enforces the enclosed block to execute in sequential loop order.
- master: Specifies that only the master thread (thread 0) of the team executes the block.
- masked (OpenMP 5.0+): Runs a block on a subset of threads. Without a filter, it behaves like master (only thread 0 executes).

Barrier

#pragma omp barrier

- All threads stop at this point until every thread in the team reaches it.
- It ensures that no thread proceeds past the barrier before the others
- have caught up.
- Useful for synchronizing phases of work across threads.

Barrier [C/C++]

The second function will only be called once all threads have finished executing the first one.

```
#pragma omp parallel
{
        calculate_critical_mass ();

        #pragma omp barrier
        simulate_explosion ();
}
```

Critical

#pragma omp critical [(name)]

- Only one thread at a time can execute the block of code marked critical.
- Threads wait their turn to enter, preventing race conditions on shared data.
- This is straightforward but can become a bottleneck if the protected code is slow.
- Use this to protect updates to shared data when atomic cannot be used.

Critical [C/C++]

Sum will be updated correctly. DO NOT DO THIS. USE A REDUCTION!!

```
#pragma omp parallel for
for ( int i = 0; i < Ni; i++ ) {
        #pragma omp critical
        sum += array[i];
}
```

Atomic

#pragma omp atomic

- Protects a single memory update so it happens without interference from other threads.
- It’s lighter weight than critical because it’s limited to simple operations (e.g., increments, sums).
- Ideal for fine-grained synchronization on shared variables

Atomic [C/C++]

Sum will be updated correctly. DO NOT DO THIS. USE A REDUCTION!!

```
#pragma omp parallel for
for ( int i = 0; i < Ni; i++ ) {
        #pragma omp atomic
        sum += array[i];
}
```

Critical vs Atomic

- Atomic uses hardware instructions
- Atomic does not use lock/unlock on entering/exiting the line of code
- Lower overhead

Lock

- You explicitly create and control a lock object with omp init lock(), omp set lock(), and omp unset lock().
- Locks give you more control over when and where mutual exclusion happens.
- They can protect complex or multiple code regions, but require careful pairing of set/unset to avoid deadlocks.
- Same functionality as a mutex/semaphore.

Lock [C/C++]

```
omp_lock_t myLock;
(void) omp_init_lock (& myLock);
#pragma omp parallel
{
    (void) omp_set_lock (& myLock); // acquire lock
    important_function ();
    (void) omp_unset_lock (& myLock); // release lock
} // End of parallel region
(void) omp_destroy_lock (& myLock);
```

Reality Check: Locks, Critical, Atomic

- Critical sections serialise execution. They **destroy** scalability.
- Locks serialise execution. They **destroy** scalability.
- Atomic uses hardware instructions: CAS instructions.
- CAS instructions still need to fetch data (sometimes from another NUMA node)
- CAS: Compare-and-swap
- Fetching needs time.
- Atomic sooner (or later) **destroy** scalability.
- It’s better to re-think/re-write the algorithm to allow **parallelisation**.

DEMO: critical/atomic/locks

```
# compile
gcc -O2 -fopenmp compound_update.c -o compound_update

# run
OMP_NUM_THREADS=8  ./compound_update 1000 4000000 0 # wrong
OMP_NUM_THREADS=8  ./compound_update 1000 4000000 1 # wrong (atomic can't protect two ops)
OMP_NUM_THREADS=8  ./compound_update 1000 4000000 2 # correct
OMP_NUM_THREADS=8  ./compound_update 1000 4000000 3 # correct

# 0=race, 1=atomics-only (still wrong), 2=critical, 3=lock
```

DEMO: critical/atomic/locks

```c
#include <stdio.h>
#include <stdlib.h>
#include <omp.h>

static inline void tiny_delay(void)
{
    // Encourage interleaving; cheap and portable
    #pragma omp flush
}

int main(int argc, char **argv)
{
    long long tokens0 = (argc > 1) ? atoll(argv[1]) : 1000;     // initial tokens
    long long tries   = (argc > 2) ? atoll(argv[2]) : 200000;   // attempts per thread
    int mode          = (argc > 3) ? atoi(argv[3]) : 0;
    // mode: 0=race, 1=atomics-only (still wrong), 2=critical, 3=lock

    volatile long long tokens = tokens0;
    volatile long long winners = 0;

    omp_lock_t lock;
    if (mode == 3) omp_init_lock(&lock);

    int T = 1;
    #pragma omp parallel
    #pragma omp single
    T = omp_get_num_threads();

    double t0 = omp_get_wtime();

    // Start together to maximize contention
    #pragma omp parallel
    {
        #pragma omp barrier

        for (long long i = 0; i < tries; i++) {

            if (mode == 2) {
                #pragma omp critical
                {
                    if (tokens > 0) { tokens--; winners++; }
                }
            }
            else if (mode == 3) {
                omp_set_lock(&lock);
                if (tokens > 0) { tokens--; winners++; }
                omp_unset_lock(&lock);
            }
            else if (mode == 1) {
                // Atomics on the pieces do NOT make the whole "check-then-act" atomic.
                long long t;
                #pragma omp atomic read
                t = tokens;

                if (t > 0) {
                    tiny_delay(); // widen race window

                    #pragma omp atomic update
                    tokens--;

                    #pragma omp atomic update
                    winners++;
                }
            }
            else {
                // mode 0: pure race
                if (tokens > 0) {
                    tiny_delay();
                    tokens--;
                    winners++;
                }
            }
        }
    }

    double t1 = omp_get_wtime();

    if (mode == 3) omp_destroy_lock(&lock);

    const char *name =
        (mode==0) ? "race" :
        (mode==1) ? "atomics-only (NOT atomic transaction)" :
        (mode==2) ? "critical" : "lock";

    printf("threads=%d  tokens0=%lld  tries/thread=%lld  mode=%d (%s)\n",
           T, tokens0, tries, mode, name);

    printf("tokens=%lld  winners=%lld  (expect: winners <= tokens0 and tokens >= 0)\n",
           (long long)tokens, (long long)winners);

    if (winners > tokens0 || tokens < 0)
        printf("RESULT: WRONG (compound check-then-act broke)\n");
    else
        printf("RESULT: OK\n");
    printf("time=%.3f s\n", t1 - t0);

    return 0;
}
```

Ordered

- For use inside a parallel for, it forces the enclosed code to run in loop-iteration order.
- Only one thread executes the ordered block at a time, and in the correct sequence.
- Handy when most work is parallel but a small part must happen in strict order.

Ordered [C/C++]

```
#pragma omp for ordered
for (i=0; i<n; i++) {
    #pragma omp ordered
    work(i);
}
```

Master

#pragma omp master

- The enclosed code is executed only by the master thread (thread 0).
- Unlike single, it has no implicit barrier before or after, so other threads skip it and keep going.
- Useful for setup, teardown, or I/O handled by a single designated thread.
- Or for MPI operations. Usually, the MPI library requires the Master thread to make MPI calls.

Masked

#pragma omp masked

- Similar to master, but lets you specify which thread(s) should execute the region via a filter expression.
- For example, filter(omp get thread num()==1) would make only thread 1 run the block.
- Other threads skip the block and can continue without waiting.
- Gives more flexibility than master for designating work to a specific thread in the team

Utilities

- omp_get_num_threads() : How many threads we are using
- Careful; will always return 1 if run **outside** a parallel section
- omp_get_thread_num() : Returns our Thread number

Summary

- Tips and Tricks
- Performance
- Resources

Tips and Tricks

- Creating and starting a Parallel section takes time.
- The optimised code must be worth it (it must runs for at least for a couple of seconds).
- If the optimised code doesn’t always run long enough all the time; use the IF clause.
- NOWAIT can help; however, it can cause also cause race conditions.
- CHUNKSIZE is important. It should be tuned. It can be changed at RUNTIME (which is always helpful).

Tips and Tricks

- MASTER, SINGLE and MASKED are useful. However, MASTER is the one with lowest overhead. SINGLE and MASKED require some synchronisation.
- However, if you don’t know beforehand which THREAD will reach the directive first; best to use SINGLE. Most of the time this will be quicker than waiting for the MASTER thread to arrive.

Tips and Tricks

- **Never**, **ever**, **ever** use default(shared).
- **Never, ever, ever** have a parallel section without a default (most implementations default to shared).

Tips and Tricks

- I found the section of my code that takes up most of the runtime ...
- ... but it’s a FOR/DO loop with hundreds lines of code!!!
- How do I set the PRIVATE and SHARED variables??
- You said to never use default(shared)!!

Tips and Tricks

- You need to put that code into a function.
- Use the SCOPE attributes of C/C++ and Fortran and pass everything as an argument to the function.
- Everything else can be a local variable inside the function.
- Test.
- If everything works; start adding PARALLEL sections.

Tips and Tricks

- Sometimes; you will need to refactor your code. Either because it’s on the verge of the standards or because it has already fallen off and it compiles/works with a specific compiler and runs on a specific hardware.

Tips and Tricks

Handy and useful environment variables:

- OMP_WAIT_POLICY=active : Tell the OpenMP runtime to spin IDLE threads; instead of putting them to sleep.
- OMP_DYNAMIC=false : Tell the OpenMP runtime to allocate exactly the number of threads you asked for.
- OMP_PROC_BIND=true : Stop threads from migrating and destroying data locality.

Tips and Tricks

- Modern debuggers support OpenMP (gdb, DDT, TotalView).
- For Race Conditions you need other tools.
- SUN Studio, Intel Inspector (or the Intel Studio), Valgrind DRD, Clang ThreadSanitizer

Tips and Tricks

Timers:

- Don’t use clock() or other system timers. They don’t work well with OpenMP.
- ”srun time myapplication.exe” will give you the correct overall duration of your application.
- Use omp_get_time(). It works perfectly with OpenMP.

Performance

I’ve gone through your excellent training and optimised my code using OpenMP. I got a 2% speedup!!

- Sequential Code
- Synchronisation
- Scheduling / Idle Threads
- Communication
- Hardware resources

Performance: Sequential Code

- Anything that is not parallelised (outside PARALLEL section, inside MASTER, SINGLE sections) runs sequentially.
- Amdahl's law states that the maximum speedup is limited by the unparallelised code.
- If exactly 50% of the work can be parallelized, the best possible speedup is 2 times.
- If 95% of the work can be parallelized, the best possible speedup is 20 times.

Performance: Sequential Code

Solutions:

- Try to parallelise everything :-)
- If you can’t, then understand the limitations of your code.

Performance: Synchronisation

- Whenever we synchronise; there is implicit communication between the Threads.
- Communication uses hardware resources (next slides); uses CPU time; sometimes destroys data locality.
- CRITICAL, ATOMIC, LOCKS are points where we lose performance.

Performance: Synchronisation

Solutions:

- Minimise barriers. You may need to refactor your code.
- Use NOWAIT; but be careful.
- Use ATOMIC rather than CRITICAL or LOCKS. But know that every
- time you use it; you lose performance.

Performance: Scheduling / Idle Threads

- More often than not (always); some threads finish first and wait for the others.
- When they wait; they are IDLE. They are not doing anything helpful.
- When multiple Threads reach a CRITICAL section; they start to wait.
- Even worse, they have to talk to each other to pass through the CRITICAL section one at a time.
- Not only they wait and do nothing; they are actually using Hardware Resource to talk to each other!!!

Performance: Scheduling / Idle Threads

The wrong scheduling type or chunksize can have very bad effects.

```
#pragma omp parallel for schedule(dynamic , 1)
for(int i=0; i < 50000000; i++) {
            CODE
}
```

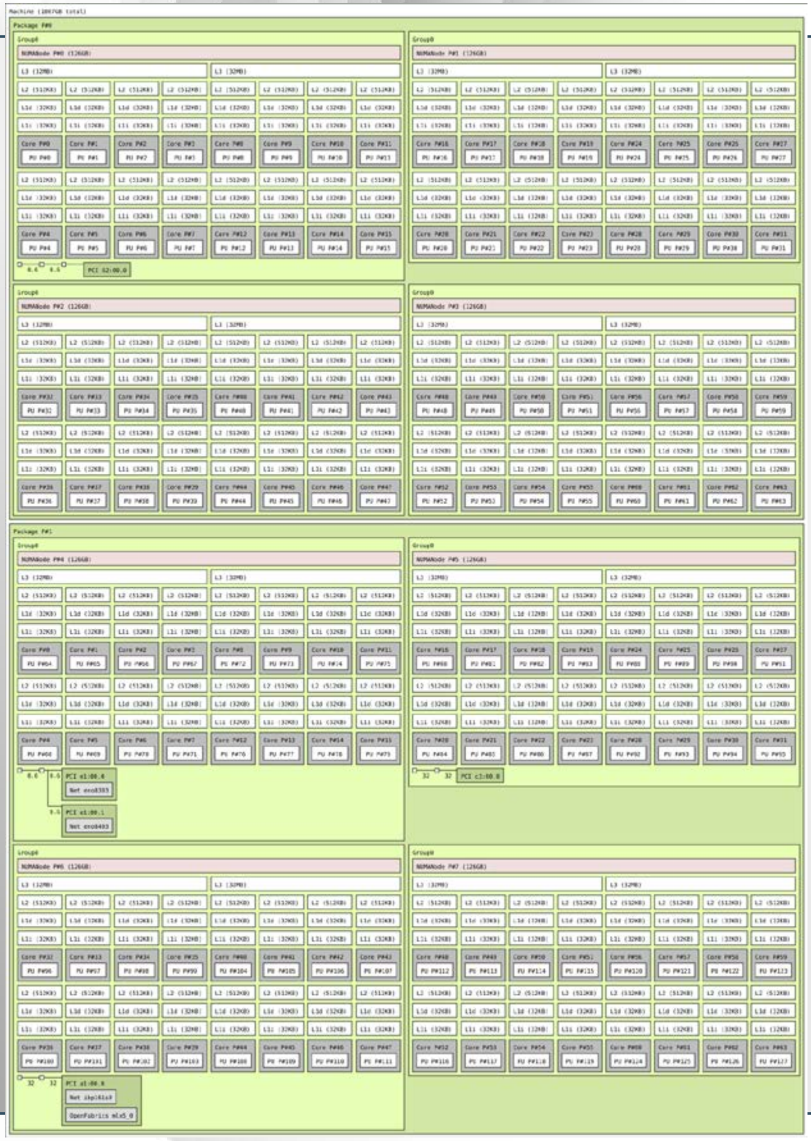
The OpenMP runtime will not be very happy about our choice of scheduler and chunksize.

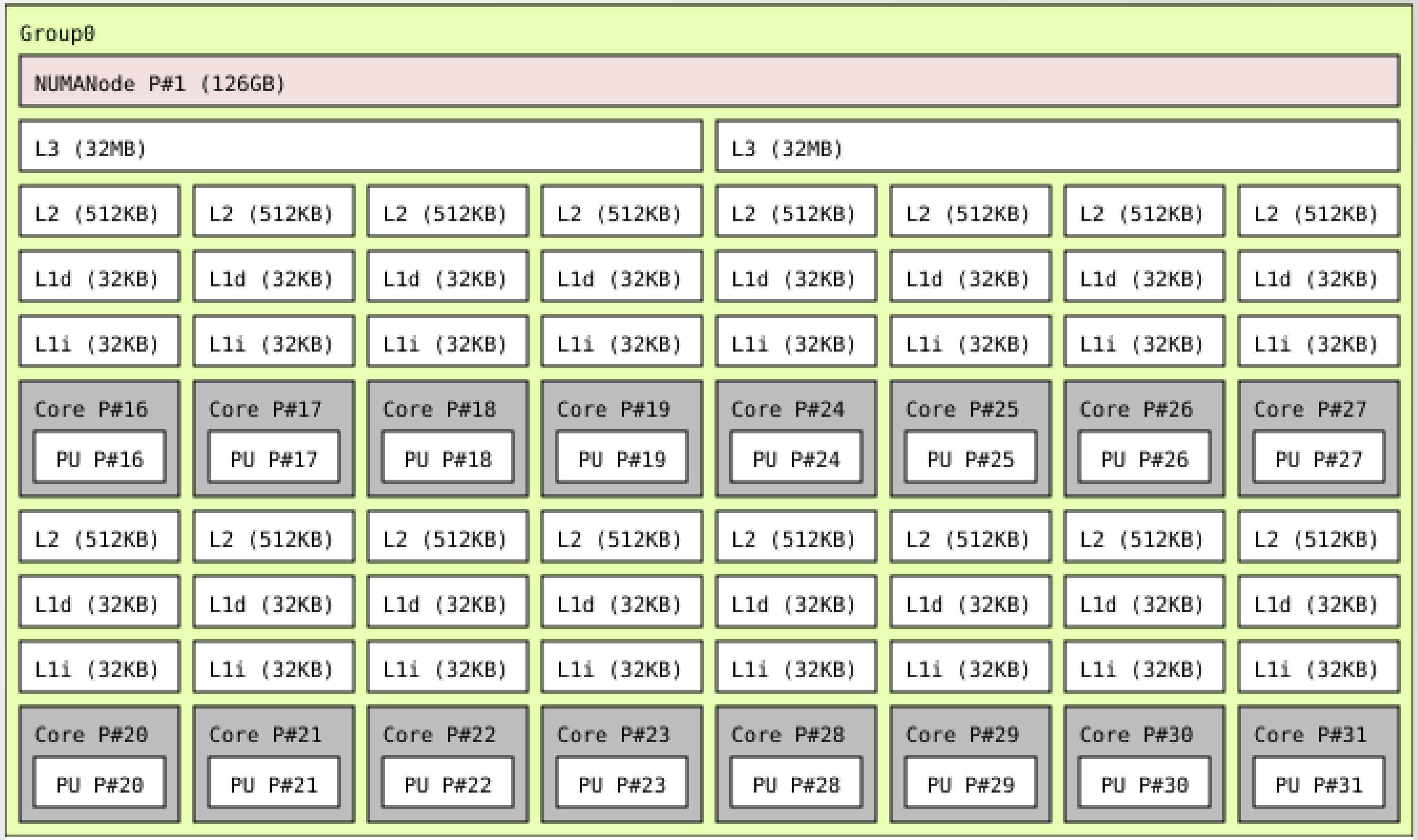
Performance: Scheduling / Idle Threads

Solutions:

- Use sensible SCHEDULE parameters. Experiment with different schedulers.
- Use sensible CHUNKSIZE values. Experiment with different values.
- Too big CHUNKSIZE and you risk some THREADS finishing early and wait.
- Too small CHUNKSIZE and you will cause scheduling overheads and synchronisation bottlenecks in the OpenMP runtime.
- Ideally, we want all threads to finish at the same time.

Performance: Communication





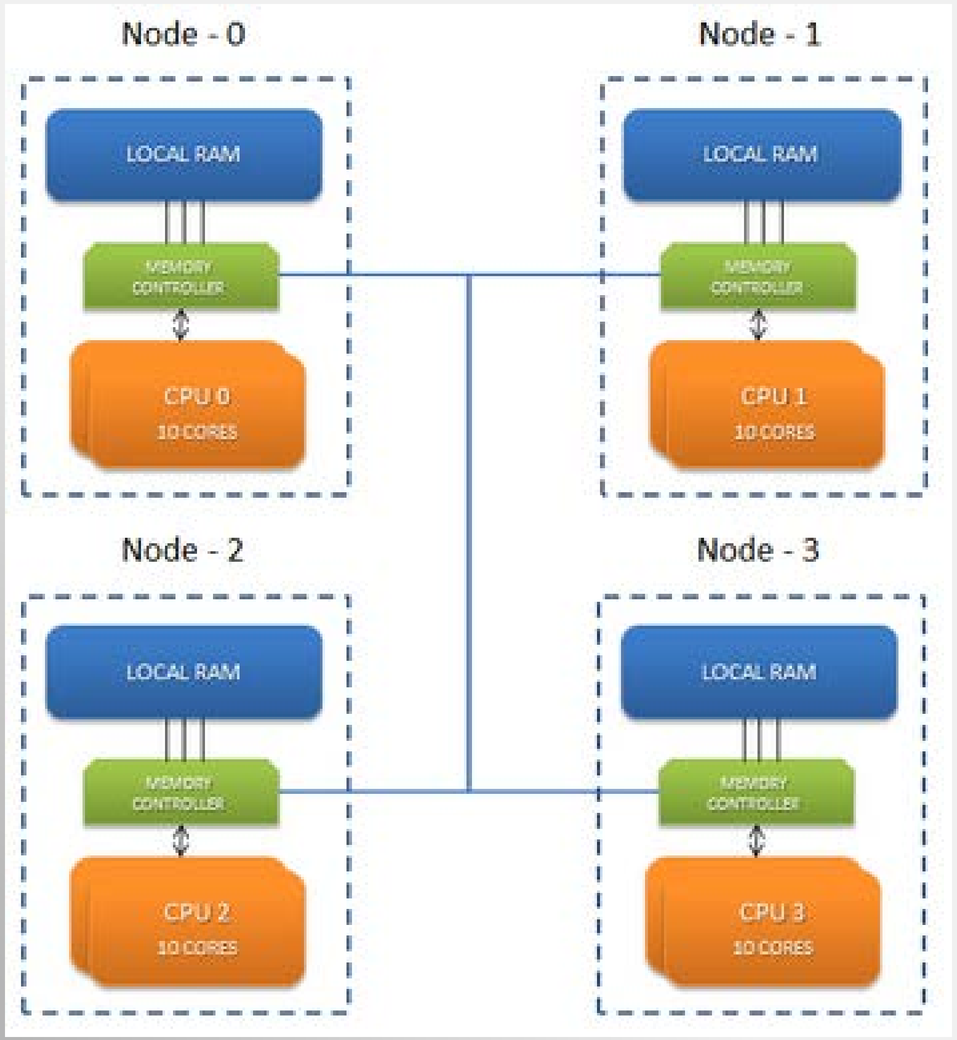
Performance: Communication

- Accessing DATA from Memory is really slow (compared to **CACHE**).
- Really slow means hundreds to thousand times slower.
- If we need to access memory from a remote NUMA node; that’s even worse.
- And that’s only about reading.
- Every READ (and WRITE) operation goes through the Cache Coherency Mechanism.

Performance: Communication

- When we write (modify) data; things become really expensive. When a THREAD (running on CPU#1) writes some data:
- The Cache Coherency fetches the data (from wherever) and brings it to the local CACHE (L3, L2 or L1).
- **All** other copies of that memory are invalidated on all the other CACHEs of all the other CPUs (to avoid reading stale data).
- If another Thread on another CPU wants to read the same data; the Cache Coherency Mechanism needs to fetch and propagate that Memory location to the local CACHE (L3, L2 or L1) of that CPU.
- Imagine if our Threads write to some memory that other Threads need to read. Say goodbye to any performance improvements.

Performance: Cache Coherency Mechanism



Performance: Communication

Solutions (kind of):

- We need to use Data Affinity!
- This means that we should (as much as possible) access (READ/WRITE) the same data with the same THREAD
- Try to use large contiguous memory areas (don’t update single INT8)
- We can then use CACHEd data (ten to hundred times faster than local memory)
- Use OMP_PROC_BIND=true to help pin the threads.

Performance: Communication

More problems with NUMA (most systems):

- Most Operating Systems employ the first touch policy.
- The first touch policy essentially tells the Memory Subsystem to place memory closest to the THREAD (or PROCESS) that asked for the memory.
- That makes sense for sequential applications. The memory is now in the local NUMA node and hopefully in the CACHE as well.
- It doesn’t work for parallel applications.
- Especially if initialisation is done by the MASTER thread. Everything is now in the MASTER thread NUMA node; and everyone else have to wait for the data to trickle across.

Performance: Communication

Solutions (kind of):

- For OpenMP (and parallel applications in general); it’s better to initialise in a parallel section.
- Try to keep the data local. Try not to change the loop iteration forcing data to migrate to other CPUs (or even worse other NUMA nodes).
- Use numactl (on Linux) to change the NUMA policy.

Performance: Communication

More problems:

- Memory is written in 4KB and 16KB pages.
- Some (most) systems use huge pages (2MB, 4MB, 1GB).
- Operating Systems like larger pages because they have to handle less pages overall.
- Less TLB (Translation Lookaside Buffer) misses, mean higher memory access.
- However, if our stride is more than the page size; we will go through the huge pages like a knife through butter.

Performance: Communication

We write an int8 at i*2MB+1byte :

- The TLB updates the mapping of the virtual page to the physical memory frame.
- The CPU fetches the 64 bytes cache line containing the target byte into L1 (read-for-ownership), modifies 1 byte, and later evicts the dirty line.
- For a 1 byte update; we get a 64 bytes read traffic and 64 bytes write traffic (assuming that each CACHE line size is 64 bytes).
- If the same CACHE line was in any other CPU; it needs to get invalidated.
- Since we never use this line again; we don’t get the benefits of the CACHE system.
- Soon we start incurring extra costs; because the TLB misses will start to increase.
- Imagine this scenario with tens or hundreds of THREADs running at the same time.

Performance: Communication

- This problem even has a name: False Sharing.
- We discussed how CACHEs, CACHE line size Memory and the Cache Coherency Mechanism work.
- If we have THREADs updating a single int8, the whole CACHE line get’s invalidated.
- What if we have a SHARED array of int8 counters and each THREAD updates it’s own index.

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

Performance: Communication

- The previous code looks innocent enough.
- However, each update of an index; will invalidate the surrounding 64 bytes.
- The surrounding 64 bytes are 64 entries which will need to start their journey around the NUMA node(s).
- Invalidating all copies. And fetching the new value from the THREAD that did the original update.
- The next THREAD comes along and updates it’s copy (which has been just fetched from who knows where).
- Once the update takes place, all the other copies will get invalidated again.
- Say a big goodbye to your memory bandwidth and to performance.

DEMO: false sharing

```
# compile
gcc -O2 -fopenmp false_sharing.c -o false_sharing

# run
OMP_NUM_THREADS=8  ./false_sharing 800000000 0
OMP_NUM_THREADS=8  ./false_sharing 800000000 1

# 0=false sharing (stride=1), 1=no false sharing (stride=16)
```

DEMO: false sharing

```
#include <stdio.h>
#include <stdlib.h>
#include <omp.h>

int main(int argc, char **argv)
{
    long long iters = (argc > 1) ? atoll(argv[1]) : 400000000LL;
    int mode        = (argc > 2) ? atoi(argv[2]) : 0; // 0=stride1, 1=padded

    int T = omp_get_max_threads();
    int stride = (mode == 1) ? 16 : 1; // 16*8=128B spacing -> usually avoids same cache line

    long long *base = (long long*)calloc((size_t)T * (size_t)stride, sizeof(long long));
    if (!base) { perror("calloc"); return 1; }

    // Treat as volatile to force memory traffic (prevents "register-only" optimization)
    volatile long long *a = (volatile long long*)base;

    double t0 = omp_get_wtime();

    #pragma omp parallel
    {
        int tid = omp_get_thread_num();
        volatile long long *p = &a[tid * stride];

        for (long long i = 0; i < iters; i++) {
            (*p)++;
        }
    }

    double t1 = omp_get_wtime();

    long long total = 0;
    for (int t = 0; t < T; t++) total += base[t * stride];

    printf("threads=%d  iters=%lld  mode=%d (0=stride1,1=padded stride=%d)  total=%lld  time=%.3f s\n",
           T, iters, mode, stride, total, t1 - t0);

    free(base);
    return 0;
}
```

Performance: Hardware resources

Memory bandwidth / Caches:

- As we have seen; memory bandwidth (which is limited) can be exhausted really easily.
- False sharing.
- Not using Data Locality.
- Not using Data Affinity.
- Most systems share a level of CACHE (usually L3)
- Using multithreaded applications, CPUs fight for the same resource. Sometimes, using the whole resource for themselves.

Performance: Hardware resources

- CPU instructions and instructions CACHEs are not infinite.
- For compute intensive codes; they can run out and THREADs have to wait.
- On the other hand, when THREADs wait for memory resources; even compute intensive codes can run happily.
- Don't oversubscribe (unless you are testing).
- Using more THREADs than COREs destroys data locality and is really slow.
- Using more THREADs than COREs is a nice test for your implementation. Sometimes, it makes hard to detect race conditions more prominent.

Resources

- OpenMP: https://openmp.org
- OpenMP: https://www.openmp.org/resources/openmp-presentations/
- Various HPC centers and documentation (EPCC, HLRS, LLNL, others)

EURO Greece

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