Mastering OpenMP Performance

Get OpenMP To Perform Well With Minimal Efforts

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OpenMP®

$ whoishe

My background is in mathematics and physics

Previously, I worked at the University of Utrecht, Convex, SGI, and Sun Microsystems

Currently I am in the Oracle Linux Engineering organization

I have been involved with OpenMP since the introduction

Passionate about performance and OpenMP in particular

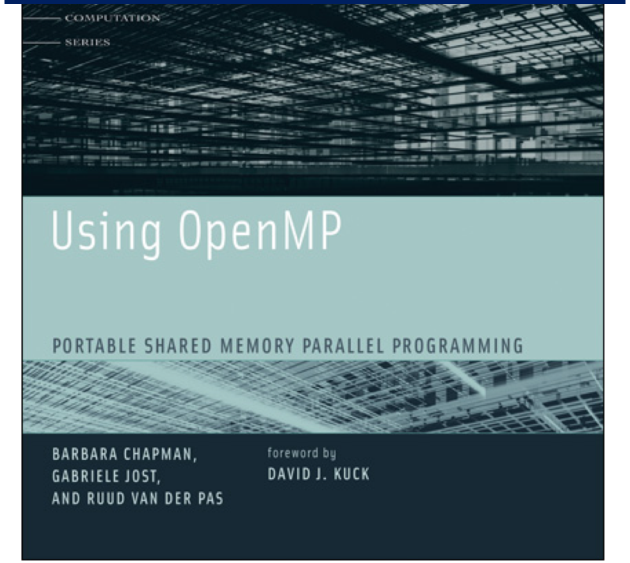
Your Onestop Place for OpenMP

https://www.openmp.org

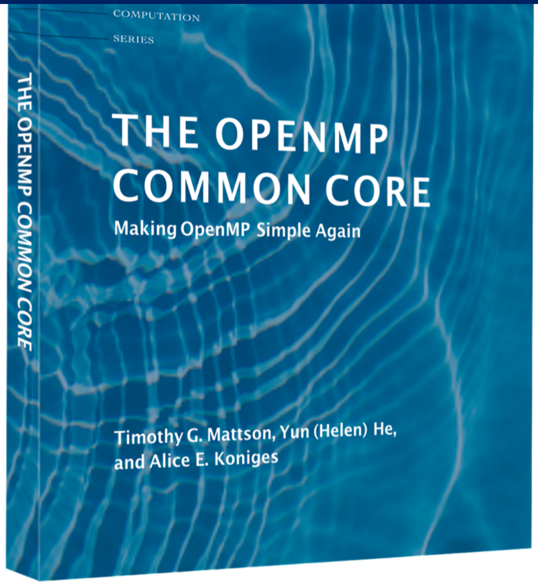
A printed copy of the 5.1 OpenMP specs is also available on Amazon (700+ pages, 1.7 kg)

Food for the Eyes and Brains

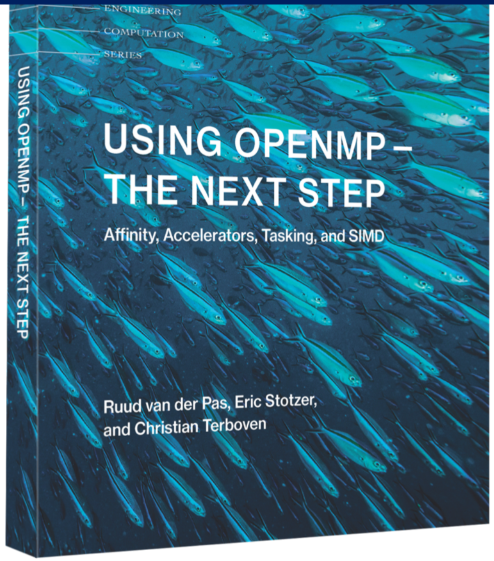
Intro Parallel Computing



Covers the OpenMP Basics



Covers all of the OpenMP 4.5 features



Part I - Tips and Tricks

“OpenMP Does Not Scale”

A common and persistent Myth
A programming model in itself can not “Not Scale”
Some things that may impact scalability:
The tools you use (e.g. the compiler, libraries, etc.), or a mismatch between the system and the resource requirements
Or … You

The OpenMP Performance Court

In this talk we cover the basics how to get good performance

If you follow these guidelines, you should expect decent performance

An OpenMP compiler and runtime should Do The Right Thing

You may not get blazing scalability, but …

The lawyers in the OpenMP Performance Court have no case against you

Ease of Use?

The ease of use of OpenMP is a mixed blessing

Ideas are easy and quick to implement

But some constructs are more expensive than others

*If you write dumb code, you ~~likely~~ **will** get dumb performance*

*Just don’t blame OpenMP, please**

**) It is fine to blame the weather, or politicians, or both though*

How To Not Write Dumb OpenMP Code

About Single Thread Performance

You have to pay attention to single thread performance

Why? If your code performs badly on 1 core, what do you think will happen on 10 cores, or 20 cores, or … ?

Remember, scalability can mask poor performance (a slow code tends to scale better, but is often still slower)

The Basics for All Users

Do NOT parallelize what does NOT matter
Never tune your code without using a profiling tool
Do not share data unless you have to (in other words, use private data as much as possible)
Think BIG and maximize the size of the parallel regions
Minimize the number of times a parallel region is encountered
One "parallel for" is fine. Multiple back to back is EVIL

The Wrong and Right Way of Doing Things

```
#pragma omp parallel for
 { <for loop 1> }

          :

#pragma omp parallel for
 { <for loop n> }
```

```
#pragma omp parallel
{
   #pragma omp for
   { <for loop 1> }
           :
   #pragma omp for nowait
   { <for loop n> }
} // End of parallel region
```

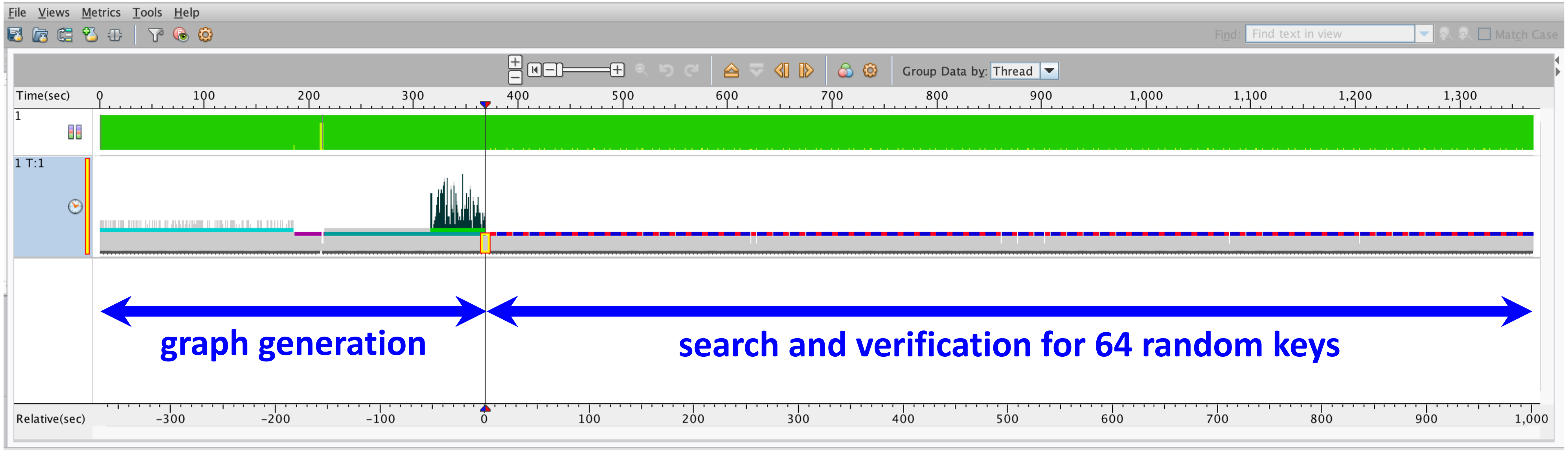
Parallel region cost repeatedly incurred
No potential for the "nowait" clause

Parallel region cost incurred only once
Potential for the "nowait" clause

More Basics

Identify opportunities to use the nowait clause
(a very powerful feature, but be aware of data races)
Use the schedule clause in case of load balancing issues
A good profiling tool is indispensable to find out more!

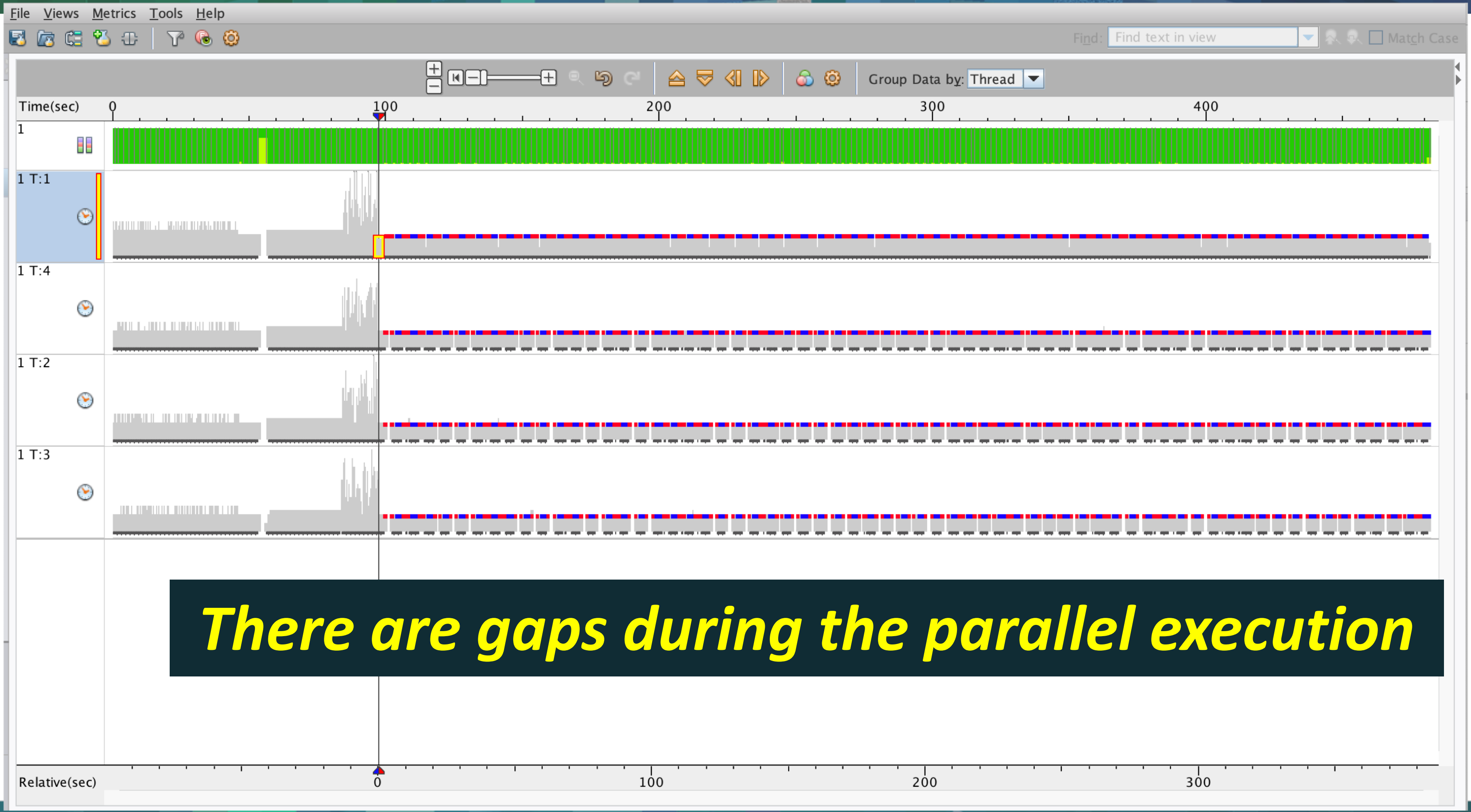
An Example from Graph Analysis



	BFS Search		**Verification**

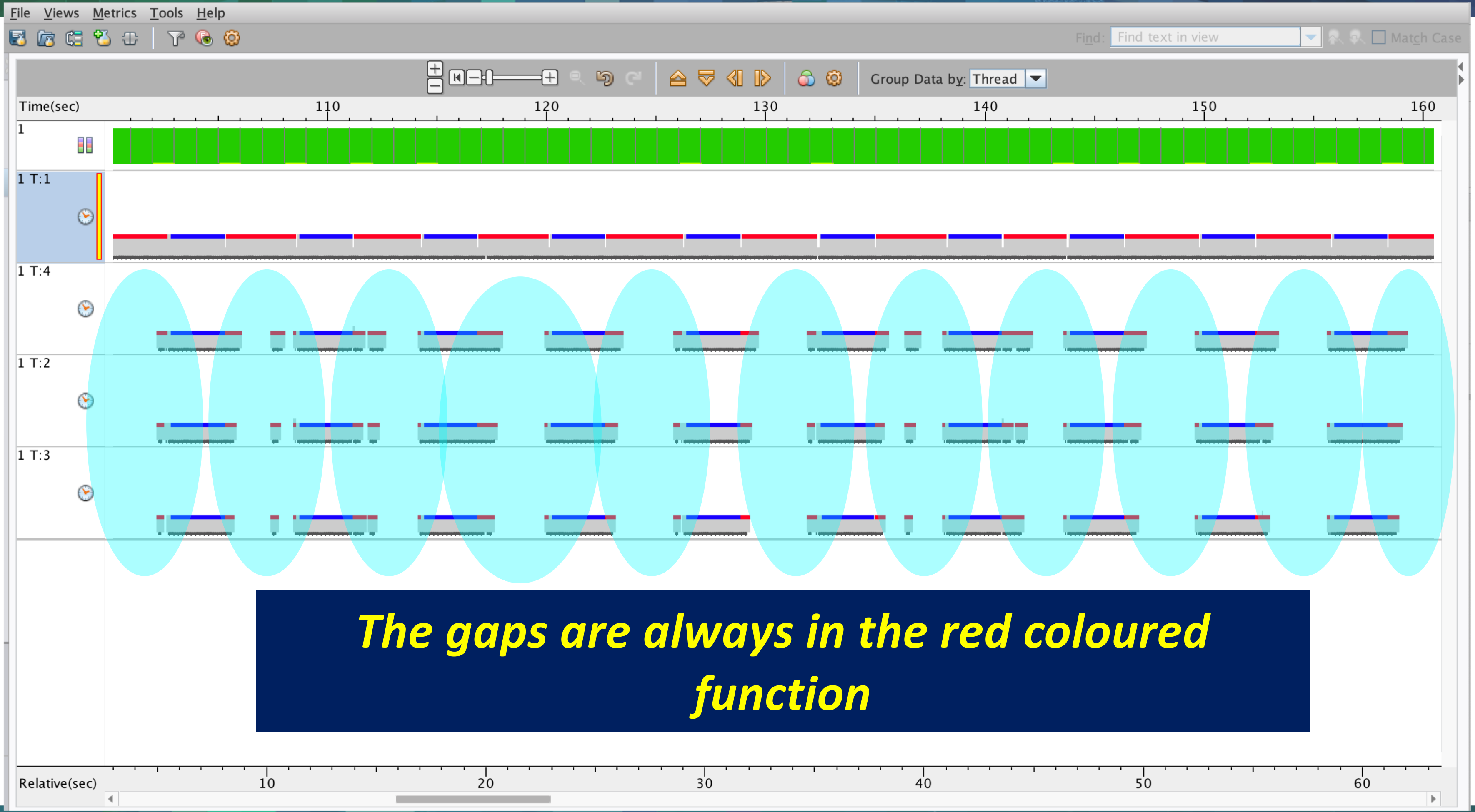
Note: The Oracle Studio Performance Analyzer was used to generate this timeline

The Timeline using 4 Threads



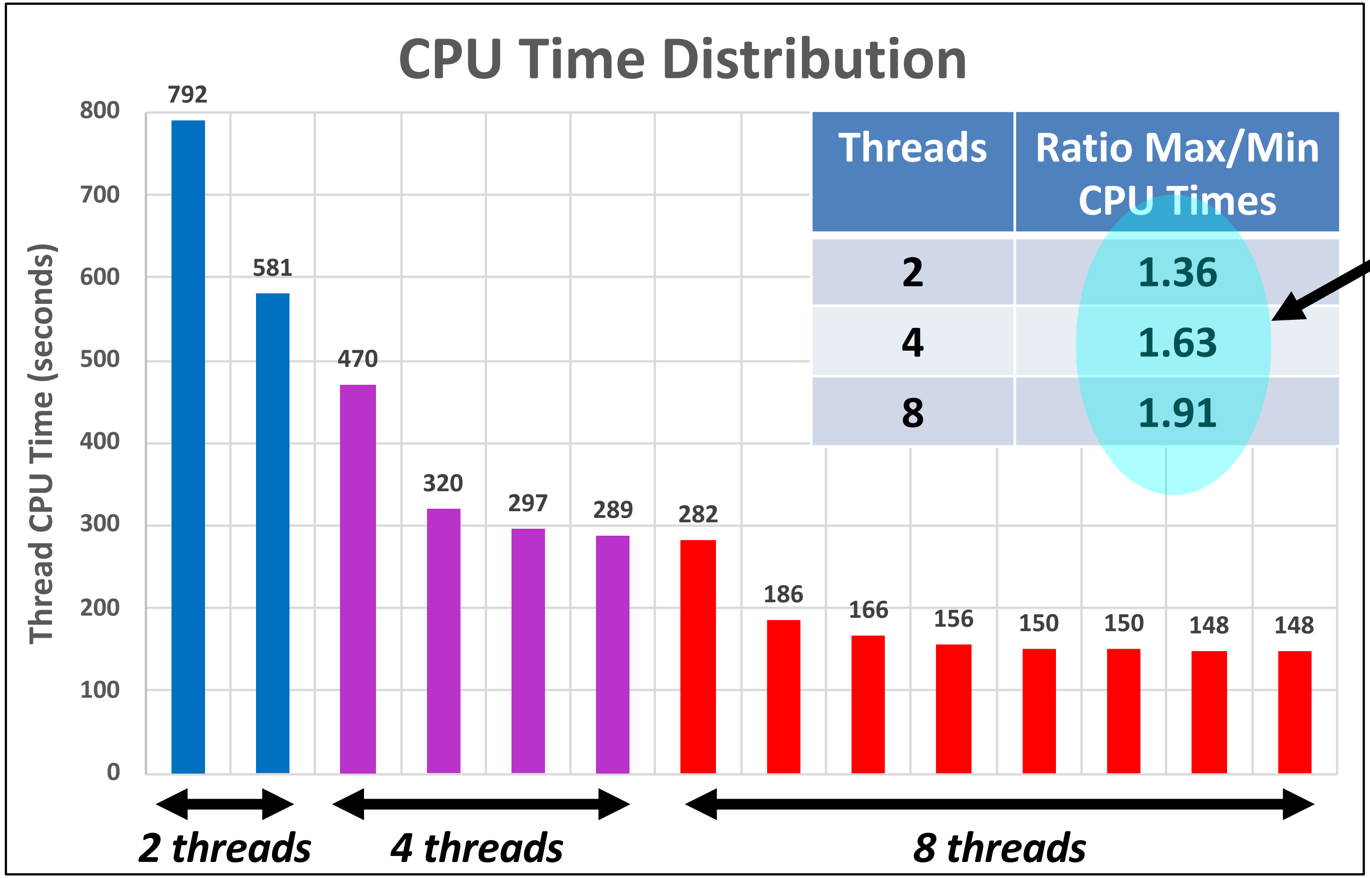
There are gaps during the parallel execution

Zoom In Some More



The gaps are always in the red coloured function

CPU Time Variations



Threads	Ratio Max/Min CPU Times
2	1.36
4	1.63
8	1.91

The load imbalance increases

The Issue

```
#pragma omp for
for (int64_t k = k1; k < oldk2; ++k) {
  const int64_t v = vlist[k];
  const int64_t veo = XENDOFF(v);
  for (int64_t vo = XOFF(v); vo < veo; ++vo) {
    const int64_t j = xadj[vo];
    if (bfs_tree[j] == -1) {
      if (int64_cas (&bfs_tree[j], -1, v)
        if (kbuf < THREAD_BUF_LEN) {
        nbuf[kbuf++] = j;
       } else {
        int64_t voff = int64_fetch
        assert (voff + THREAD_BUF_
        for (int64_t vk =
          vlist[voff + vk]
        nbuf[0] = j;
        kbuf = 1;
       } // End of if-then
     } // End of if
    } // End of if
  } // End of for-loop on vo
} // End of parallel for-loop on k
```

Fixed length loop

Irregular length loop

Irregular control flow

Irregular workload per k-iteration

Observations and the Solution

The #pragma omp for loop uses default scheduling

The default is implementation dependent, but is static scheduling

In this case this leads to load balancing issues

The solution: #pragma omp for schedule(dynamic)

Or an even better solution: #pragma omp for schedule(runtime)

Our setting: $ export OMP_SCHEDULE="dynamic,25"

By the Way

How Do You Know The Chunk Size Should Be 25?

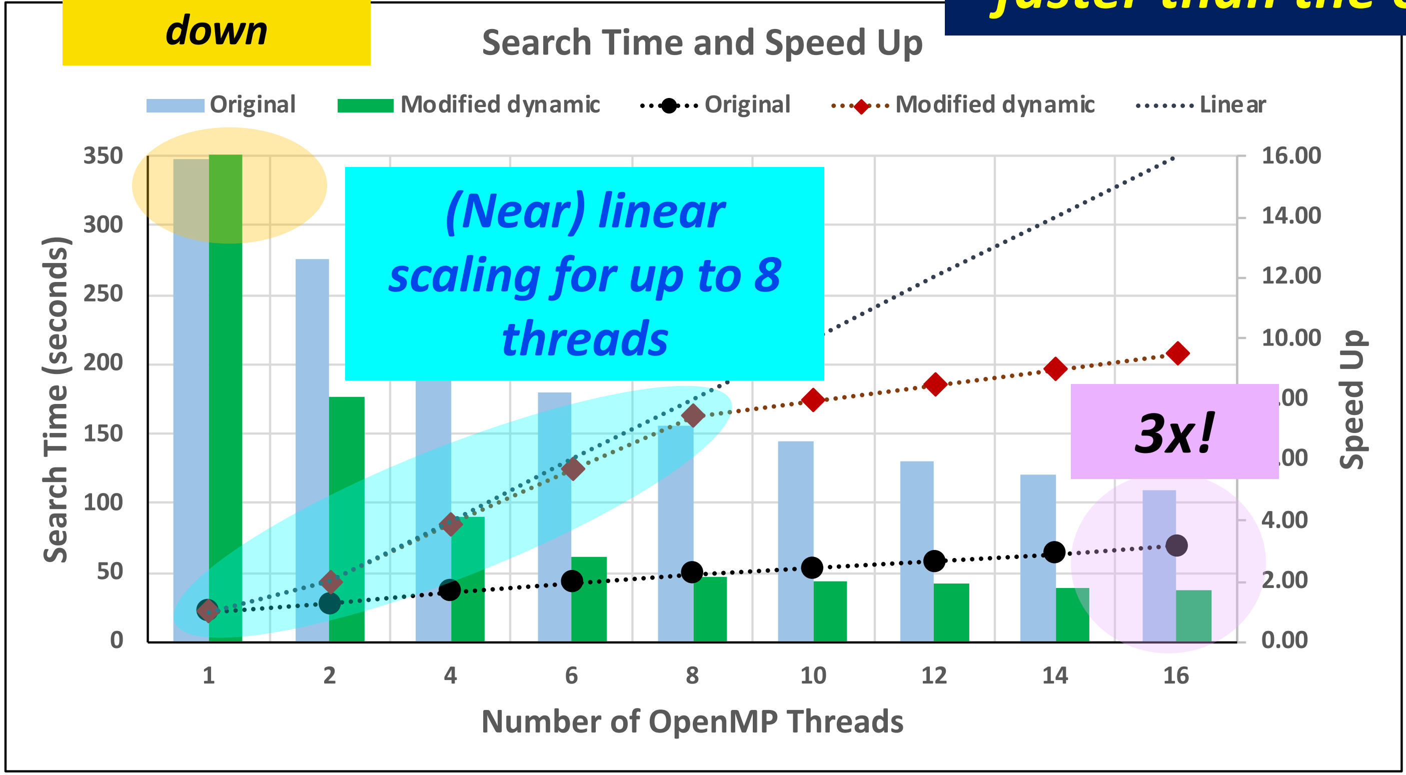
~~***Crystal Ball***~~

Trial And Error

With Dynamic Scheduling Added*

The modified version is 3x faster than the original code

A 1% slow down



****) OMP_SCHEDULE="dynamic,25"***

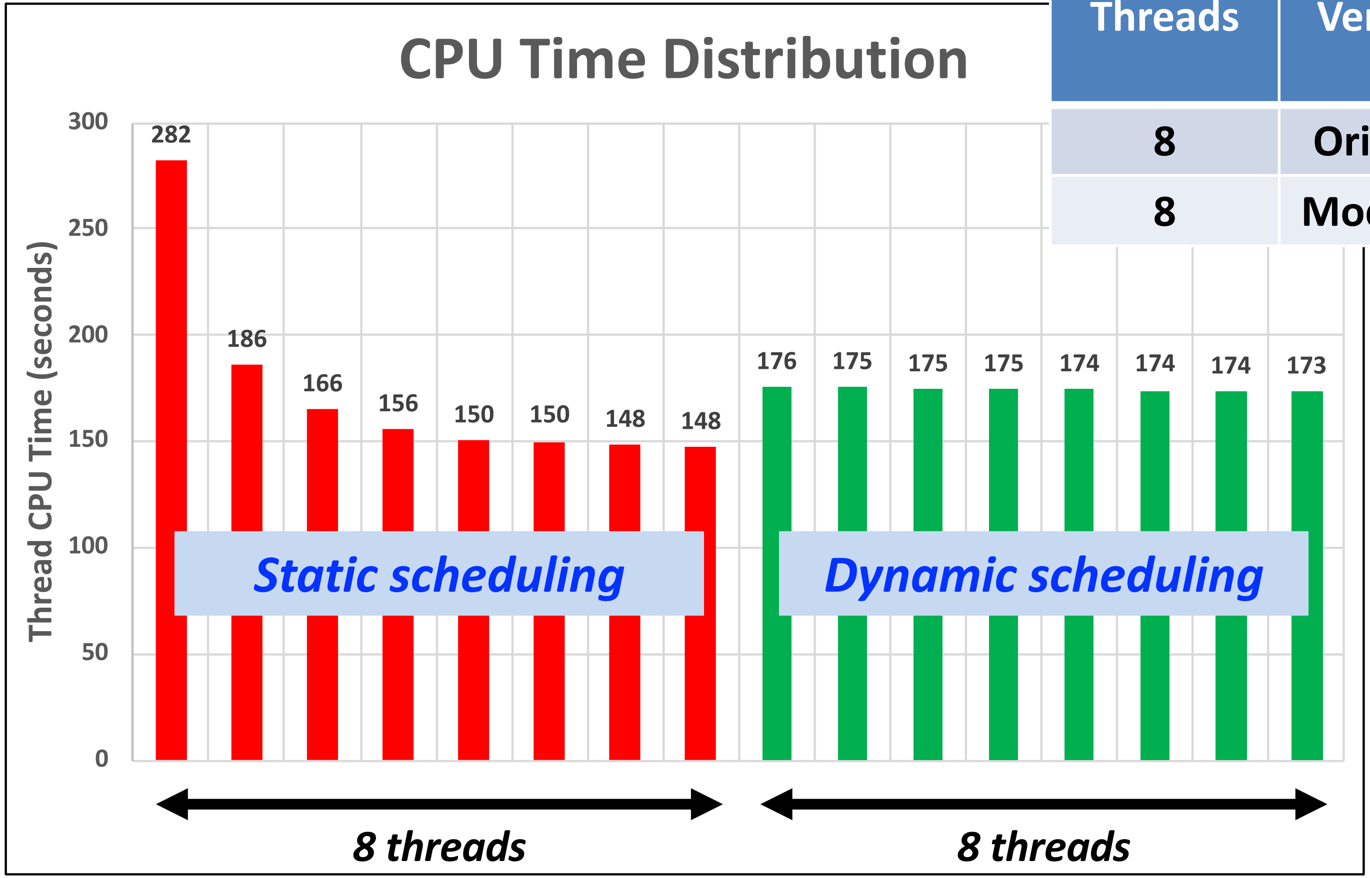
Really Important

Always Verify the Behaviour!

Before and After (8 Threads)

The load imbalance is indeed gone!

The Load Imbalance is Indeed Gone



Threads	Version	Ratio Max/Min CPU Times
8	Original	1.91
8	Modified	1.01

Beyond the Basics, but Don't Forget!

Every barrier matters
(needed, but please use them with care)

The same is true for locks and critical regions
(use atomic operations where possible)

EVERYTHING Matters
(Amdahl's Law: minor overheads get out of hand quickly)

More Things to Remember

Avoid nested parallelism
(the nested barriers really add up)

Consider tasking instead
(provides much more flexibility and finer granularity)

Consider taskloop as an alternative to a non-static loop iteration scheduling algorithm (e.g. dynamic)

When Do Things Get Harder?

Memory access "just happens"

There are however two things to watch out for:

Non-Uniform Memory Access (NUMA)
and False Sharing

They have nothing to do with OpenMP as such and are a characteristic of using a shared memory architecture

They may impact the performance though

What Follows Next

NUMA is covered extensively in the second part

So for now we will stop talking about NUMA and end part I with a topic called "False Sharing"

What is False Sharing?

False Sharing occurs when multiple threads modify the same cache line at the same time

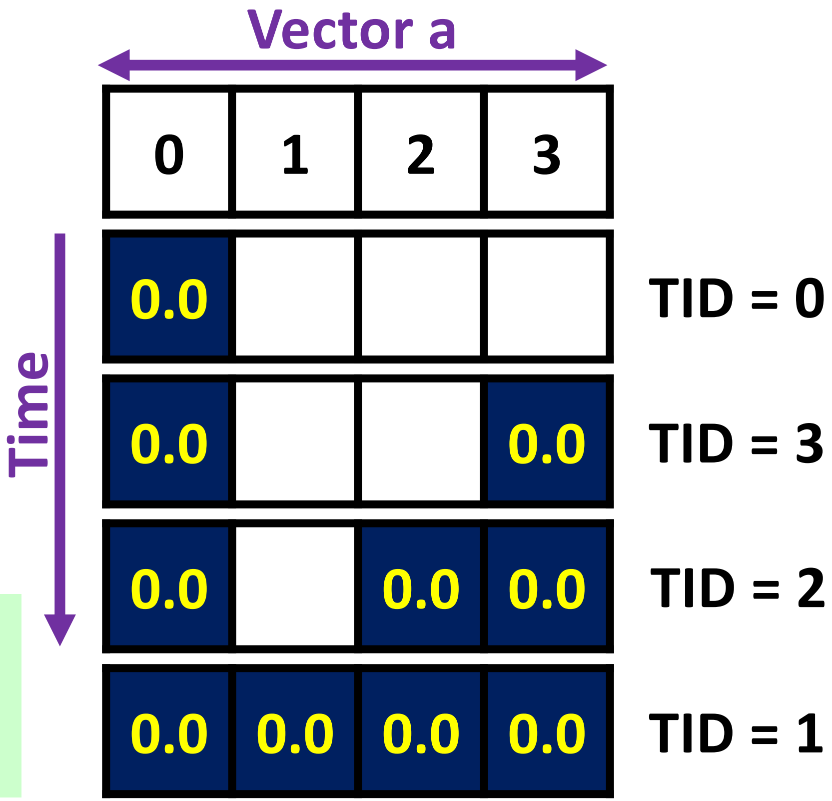
This results in the cache line to move through the system (plus the additional cost of the cache coherence updates)

It is okay if this happens once in a while

It is not okay if this happens very frequently

An Example of False Sharing

```
#pragma omp parallel shared(a)
{
    int TID = omp_get_thread_num();

    a[TID] = 0.0; // False Sharing

} // End of parallel region
```



With each update of "a", the cache line moves to the cache of the thread executing the update

A Tuning Strategy

Follow the guidelines just given and in this order

Where applicable, give it a try

Always make a profile before and after

Details sometimes make all the difference

In many cases, a performance "mystery" is explained by NUMA effects, False Sharing, or both

Part II – OpenMP In The Real World

About this Tutorial

In this second part we want to show several tuning examples

These examples are all based upon real-life experiences

The first challenge is to recognize the underlying issue(s)

We start with some isolated cases

The last example is more elaborate and is all about NUMA (NUMA systems are common and our info may come handy)

More Examples

An Example – What is Wrong Here?

```
#pragma omp single
{
    <some code>
} // End of single region

#pragma omp barrier

<more code>
```

```
#pragma omp single
{
    <some code>
} // End of single region

#pragma omp barrier

<more code>
```

The second barrier is redundant
The single construct has an implied barrier already
(the second barrier will be quick, but still takes time)

Do More Work and Save Time

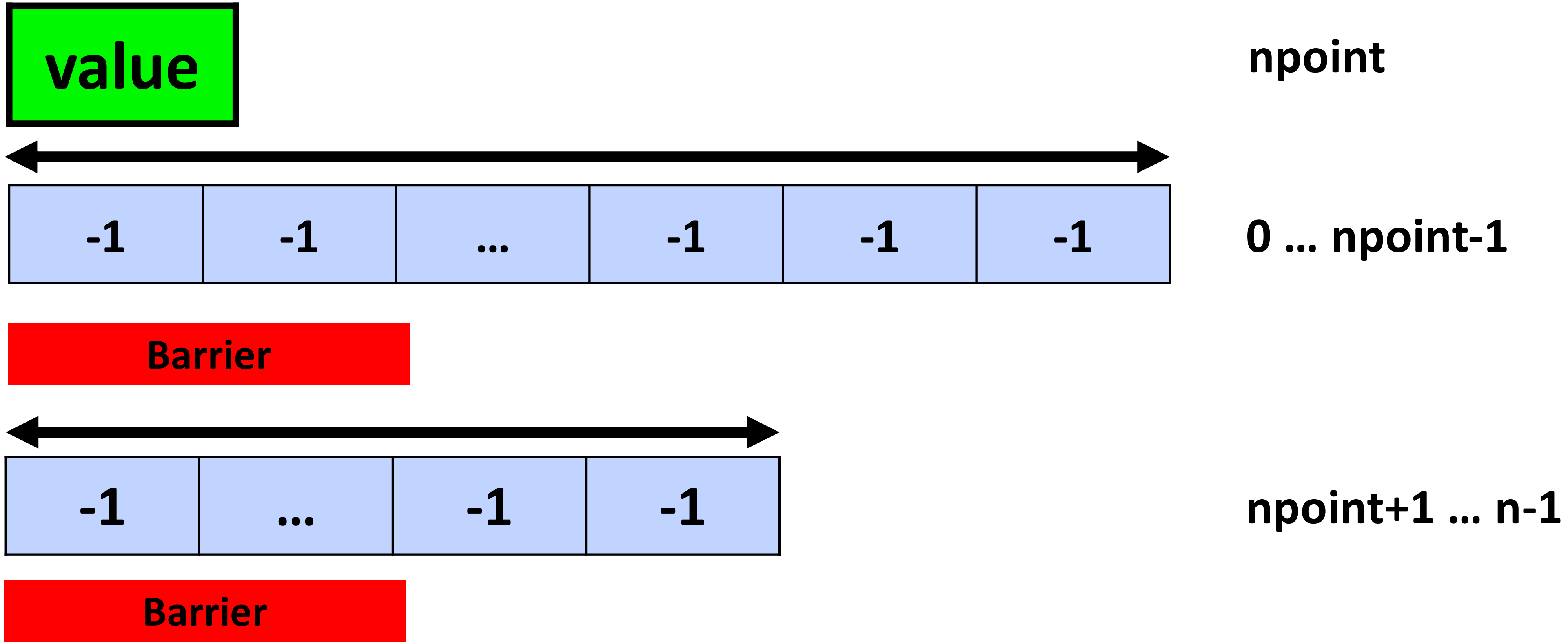
```
a[npoint] = value;
#pragma omp parallel …
{
  #pragma omp for
    for (int64_t k=0; k<npoint; k++)
      a[k] = -1;
  #pragma omp for
    for (int64_t k=npoint+1; k<n; k++)
      a[k] = -1;

  <more code>

} // End of parallel region
```

What is Wrong with this?

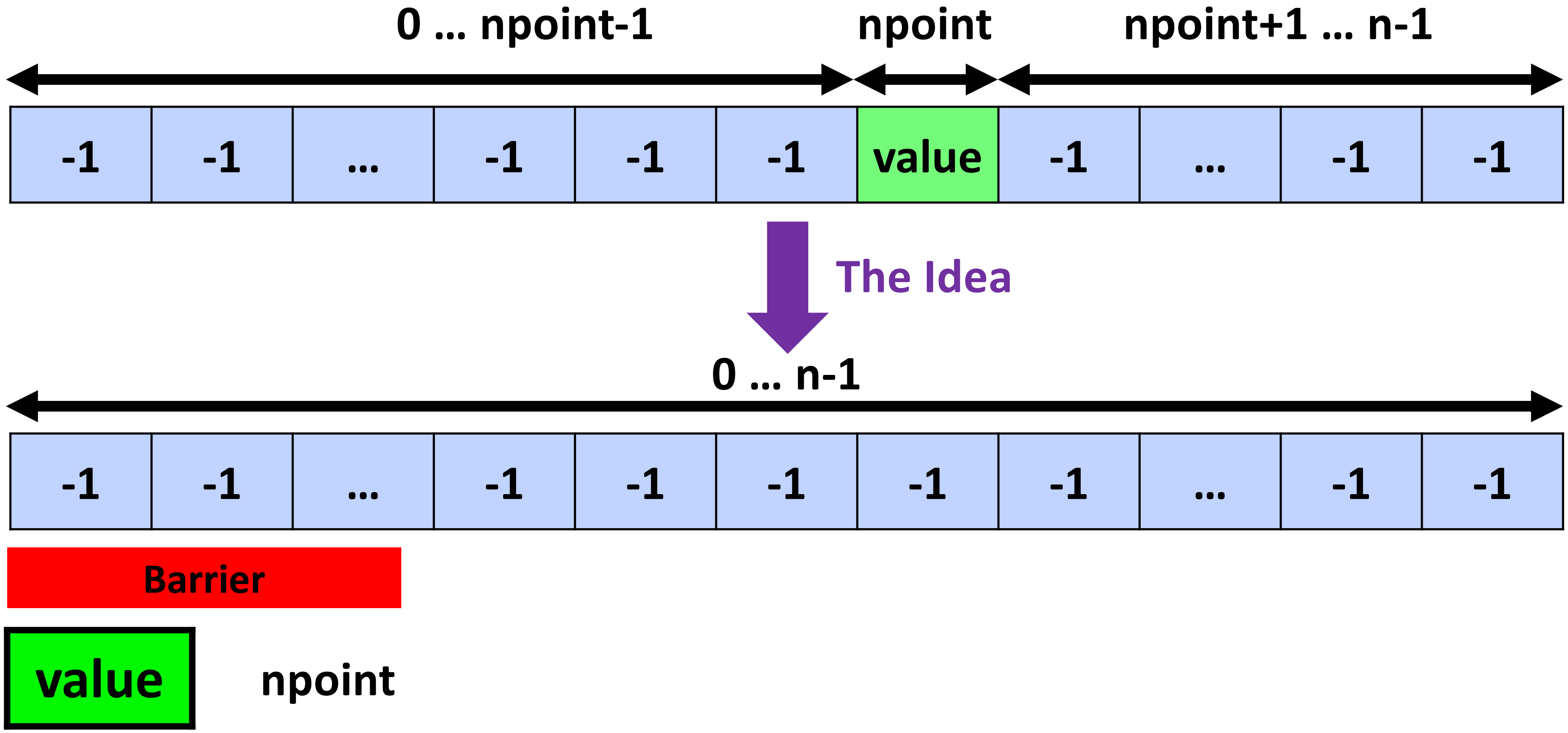
```
a[npoint] = value;
#pragma omp parallel …
{
  #pragma omp for
    for (int64_t k=0; k<npoint; k++)
      a[k] = -1;
  #pragma omp for
    for (int64_t k=npoint+1; k<n; k++)
      a[k] = -1;
  <more code>

} // End of parallel region
```

- *There are 2 barriers*
- *Two times overhead from the “omp for”*
- *Performance benefit depends on the value of variables npoint and n*
- *If npoint is small, the overhead on the first loop is high*
- *If npoint is large, the overhead on the second loop is high*

The Sequence of Operations



The Actual Operation Performed



The Implementation

```
#pragma omp parallel …
{
 #pragma omp for
   for (int64_t k=0; k<n; k++)
     a[k] = -1;

 #pragma omp single nowait
   {a[npoint] = value;}

 <more code>

} // End of parallel region
```

- *Only one barrier*
- *Reduced parallel overhead*
- *Performance depends on the value of n only*

About Real World Performance Tuning

We have just shown the basic hurdles to take
Each one of these speak for themselves
The complicating factor is that they may be mixed
Don’t panic though, be patient, and tackle them one by one
But be prepared for this to be an iterative process
Also, be prepared that sometimes good ideas turn out to be not such good ideas

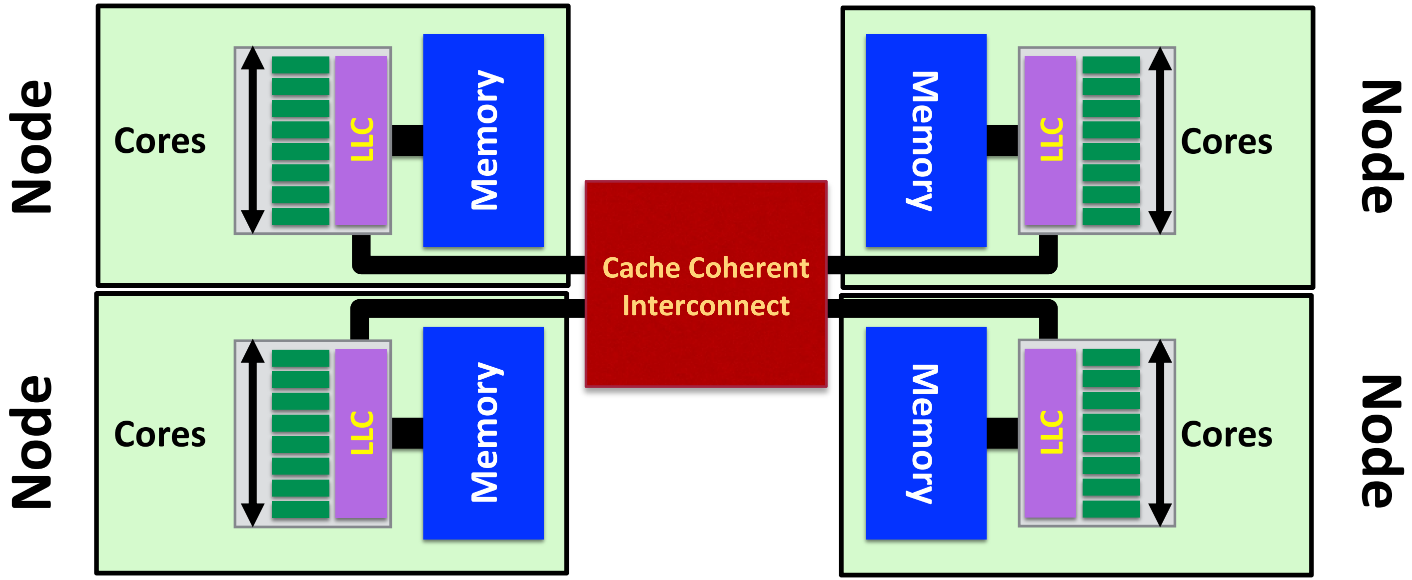
NUMA from Beginning to End

Non-Uniform Memory Access (NUMA)

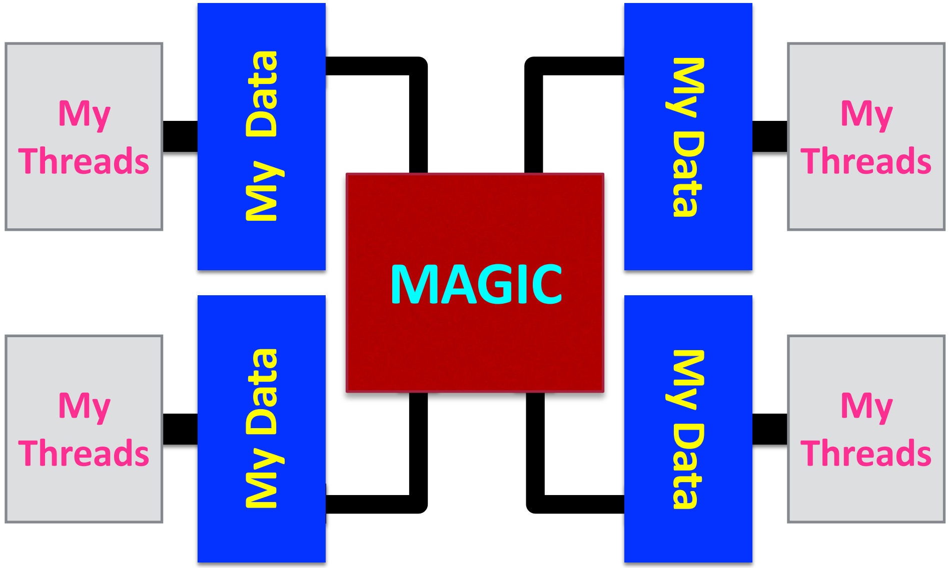
Memory is physically distributed, but logically shared
Shared data is transparently accessible to all threads
You don't know where the data is and it doesn't matter
Unless you care about performance …

NUMA – The System Most of Us Use Today

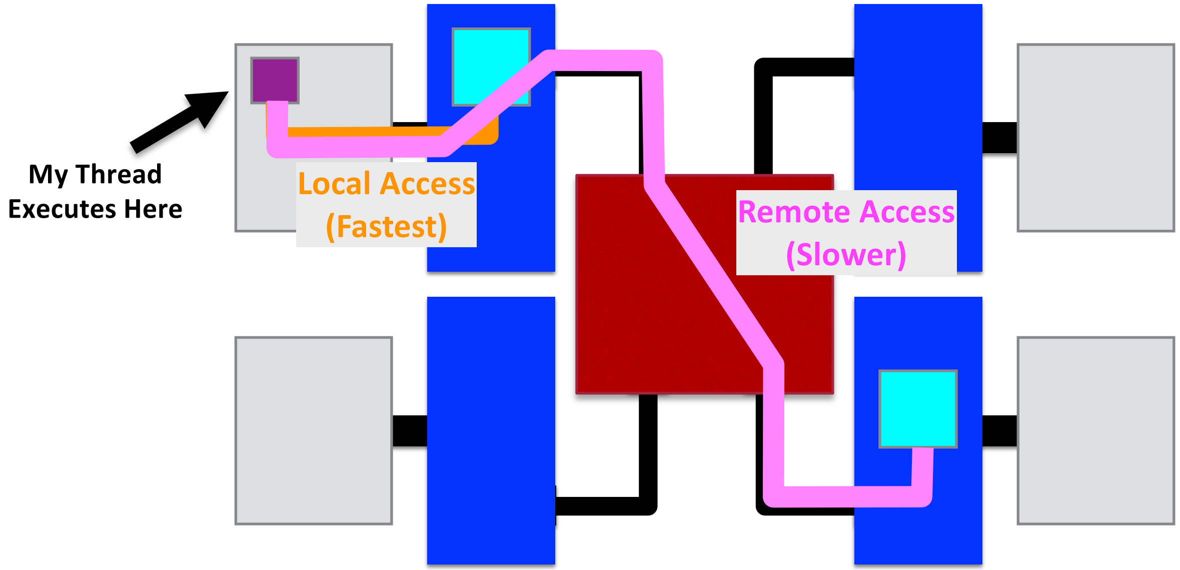
A Generic, but very Common and Contemporary NUMA System



NUMA - The Developer's View



NUMA - Local Versus Remote Access Times



Tuning for NUMA

Tuning for NUMA is about keeping threads and their data close
In OpenMP, a thread may be moved to the data
Not the other way round, because that is more expensive
The affinity constructs in OpenMP control where threads run
This is a powerful feature, but it is up to you to get this right

OpenMP 5.0 NUMA Controls

There are two NUMA related environment variables
OMP_PLACES defines where threads are allowed to execute
Choices are: sockets, cores, threads, or hardware thread IDs
OMP_PROC_BIND controls the mapping of threads onto places
Choices are: master, close, spread

An Example

```
# Use 16 threads:
export OMP_NUM_THREADS=16

# Use 2 sockets to place those threads:
export OMP_PLACES=sockets(2)

# Spread them as far apart as possible:
export OMP_PROC_BIND=spread

# Run the code:
./a.out
```

First Touch Data Placement

So where does data get allocated then?

The First Touch Placement Policy allocates the data page in the memory closest to the thread accessing this page for the first time

This policy is the default on Linux and other OSes

It is the right thing to do for a sequential application

But this may not work so well in a parallel application …

First Touch and Parallel Computing

First Touch works fine, but what if a single thread initializes most, or all of the data ?

Then all the data ends up in the memory of a single node

This increases access times for certain threads and may cause congestion at the memory controller

Luckily, the solution is (often) surprisingly simple

How to Leverage First Touch?

Parallelize the data initialization part!

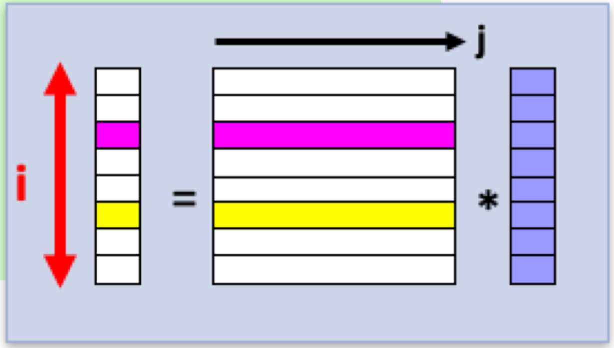
```
#pragma omp parallel for schedule(static)
for (int i=0; i<n; i++)
    a[i] = 0;
```

Each thread has a slice of "a" in its local memory*

****) The allocation is on a virtual memory page basis***

Matrix*Vector Test Code

```
#pragma omp parallel for default(none) \
        shared(m,n,a,b,c) schedule(static)
for (int i=0; i<m; i++)
{
  double sum = 0.0;
  for (int j=0; j<n; j++)
     sum += b[i][j]*c[j];
  a[i] = sum;
}
```




```
for (i=0; i<m; i++)
    for (j=0; j<n; j++)
         b[i][j] = i;

for (j=0; j<n; j++)
      c[j] = 1.0;
```

Data initialization code

Is There Anything Wrong Here?

Nothing wrong with this code

But this code is not NUMA aware

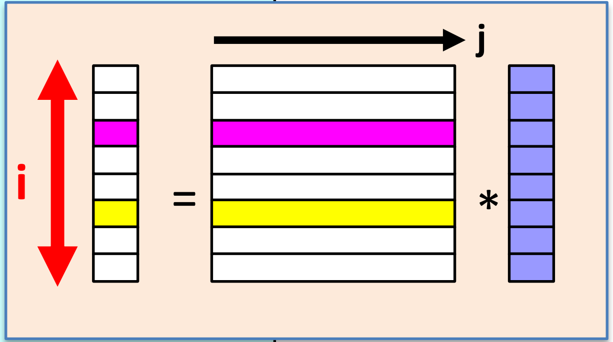
The data initialization is sequential

Therefore, all data ends up in the memory of a single node

This is a more NUMA friendly data initialization:

Data Initialization – NUMA Friendly

```
#pragma omp parallel default(none) \
        shared(m,n,a,b,c) private(i,j)
{
  #pragma omp for schedule(static)
   for (i=0; i<m; i++)
   {
      a[i] = -1957.0;
      for (j=0; j<n; j++)
         b[i][j] = i;
   } // End of omp for

  #pragma omp for schedule(static)
   for (j=0; j<n; j++)
      c[j] = 1.0;

} // End of parallel region
```



NUMA Related Linux Tools*

Two very useful tools to help understand the NUMA topology

lscpu displays many things, including details on the node(s)

numactl –H displays the nodes and the relative latency

(lscpu is part of util-linux and numactl is a standalone package)

****) There are more tools than shown here (e.g. numastat)***

The NUMA Topology of the Target System

AMD EPYC "Naples" based server*

How can you tell what the NUMA topology is?

****) I know, this is an older AMD system ☺***

The NUMA Nodes in the System*

8 NUMA nodes

8 cores/node

```
$ lscpu
        ......
NUMA node0 CPU(s):  0-7   , 64-71
NUMA node1 CPU(s):  8-15  , 72-79
NUMA node2 CPU(s):  16-23 , 80-87
NUMA node3 CPU(s):  24-31 , 88-95
NUMA node4 CPU(s):  32-39 , 96-103
NUMA node5 CPU(s):  40-47 , 104-111
NUMA node6 CPU(s):  48-55 , 112-119
NUMA node7 CPU(s):  56-63 , 120-127
        ......
$
```

Output from "numactl –H"

```
node distances:
node   0   1   2   3   4   5   6   7
  0:  10  16  16  16  32  32  32  32
  1:  16  10  16  16  32  32  32  32
  2:  16  16  10  16  32  32  32  32
  3:  16  16  16  10  32  32  32  32
  4:  32  32  32  32  10  16  16  16
  5:  32  32  32  32  16  10  16  16
  6:  32  32  32  32  16  16  10  16
  7:  32  32  32  32  16  16  16  10
```

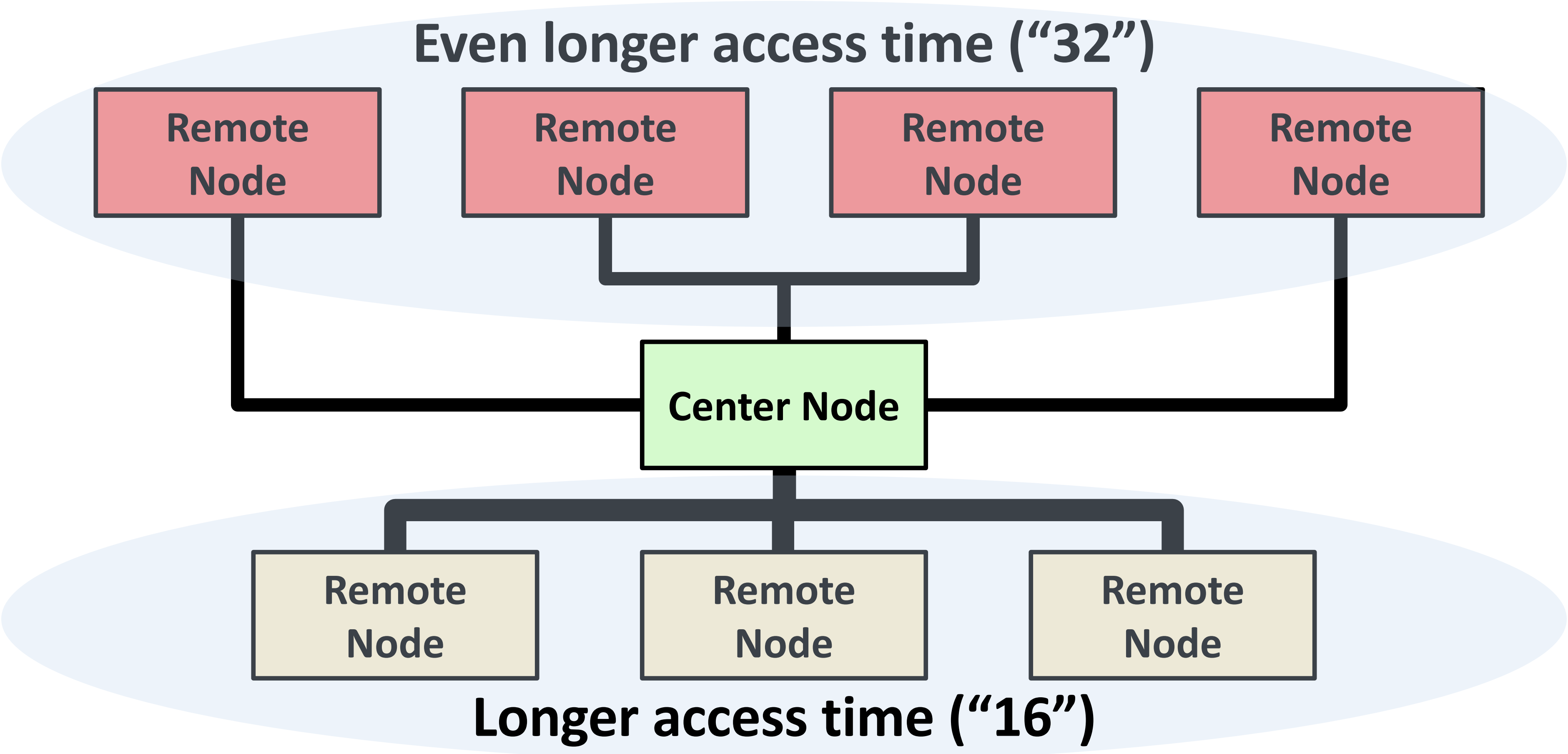
2 hardware threads per core

\) The lay-out information has been slightly reformatted

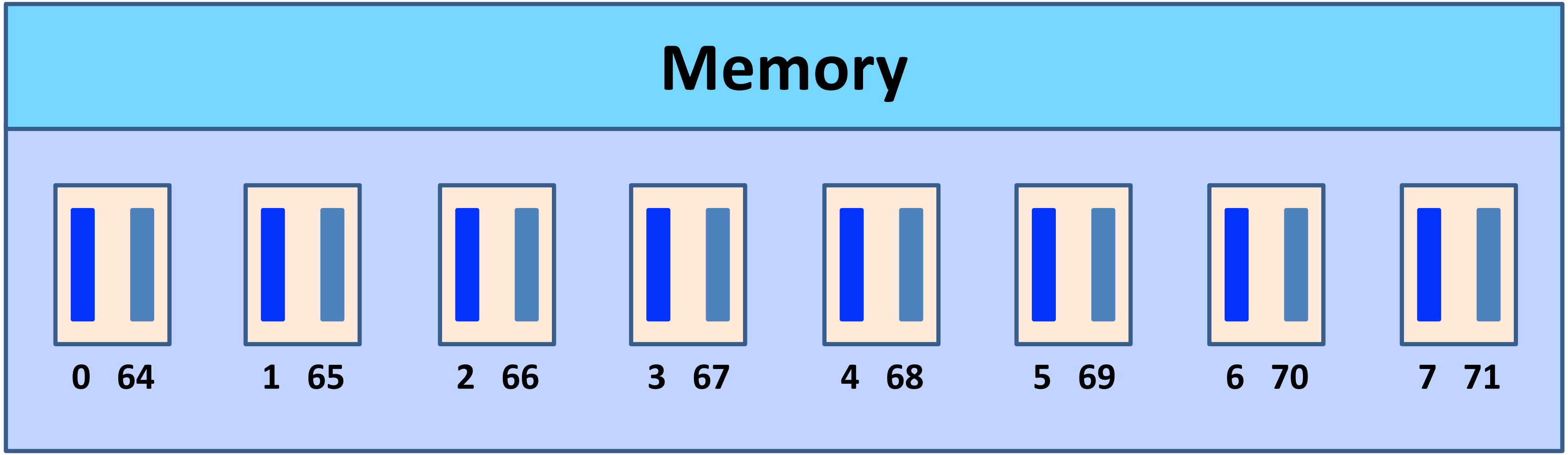
This is the NUMA Structure

There are 8 NUMA nodes
Each NUMA node has 8 cores
Each core has 2 hardware threads
In total there are 64 cores and 128 hardware threads
There are 2 clusters with "remote" nodes ("16" and "32")
Each node has 3 neighbors with a longer access time ("16") and 4 neighbors with an even longer access time ("32")

The Abstract System Topology (numactl –H)



Example – NUMA Node 0 (lscpu output)



8 cores

16 hardware threads

All cores and hardware threads share the memory in the node

About OpenMP and Placement Control

*An OpenMP **place** defines a set where a thread may run*

OpenMP supports abstract names for places:
sockets, cores, and threads

*These abstract names are **preferred** to be used*

But sometimes more explicit control is needed

We will now show an example how to use the explicit controls

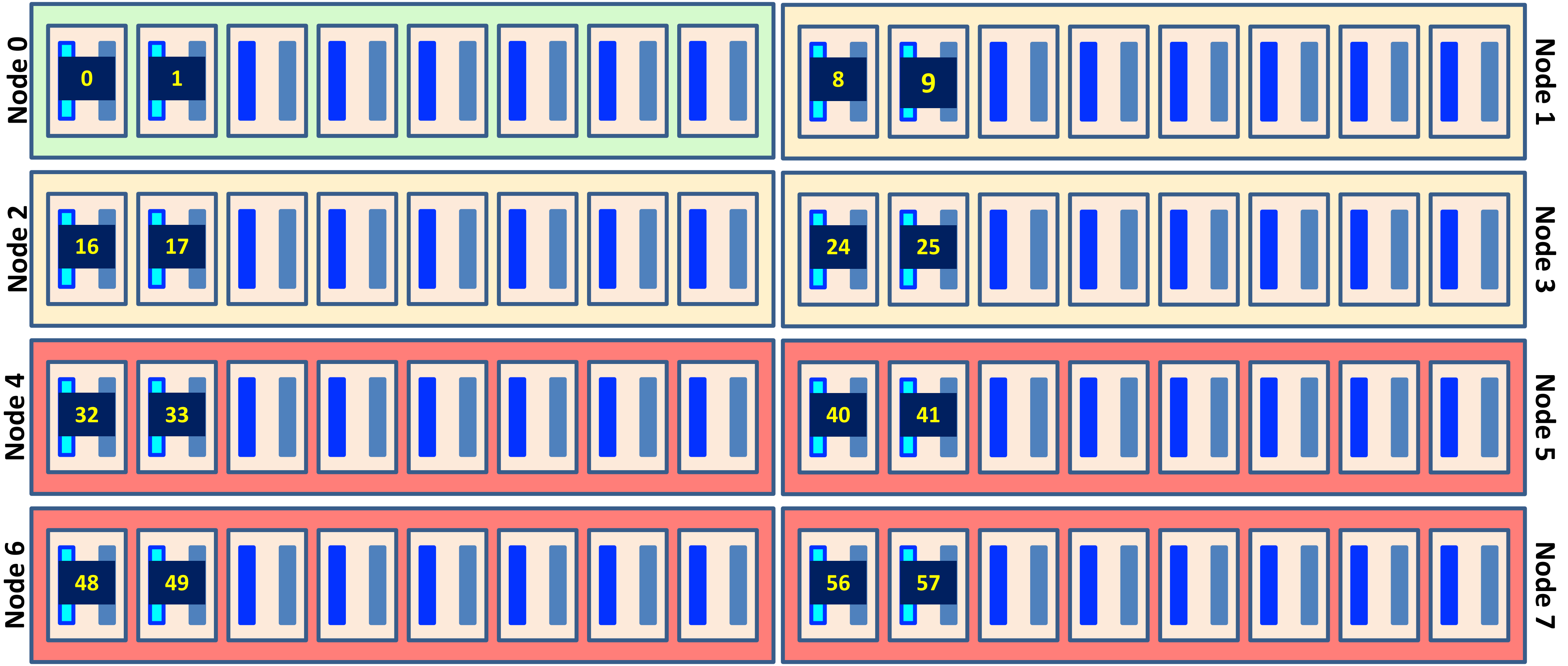
Example - Control the Mapping of Threads

<u>The Goal</u>

Distribute the OpenMP threads evenly across the cores and nodes

As an example, use the first hardware thread of the first two cores of all the nodes

Example - Control the Mapping of Threads



An Example How to Use OpenMP Affinity

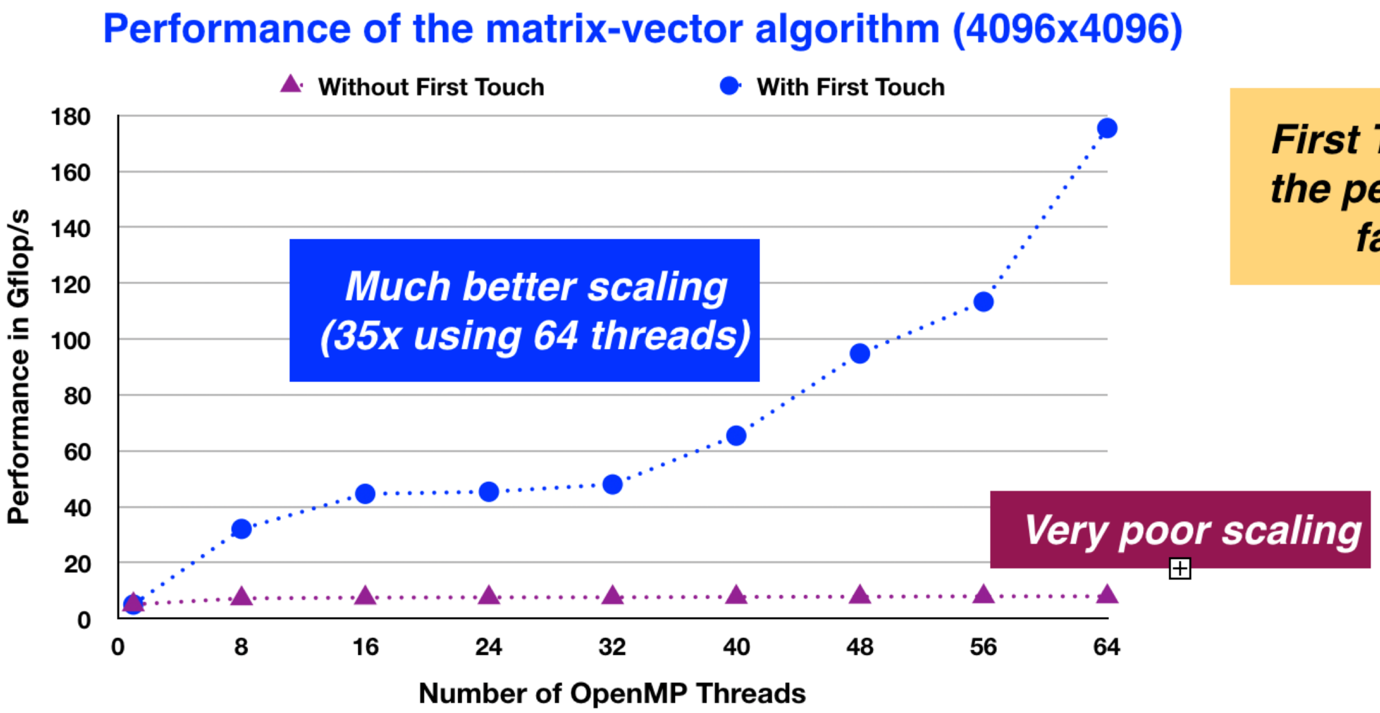
Expands to the first hardware thread on the first 2 cores on each node:
{0}, {8}, {16}, {24}, {32}, {40}, {48}, {56}, {1},{9},{17},{25},{33},{41},{49},{57}

```
$ export OMP_PLACES={0}:8:8,{1}:8:8

$ export OMP_PROC_BIND=close

$ export OMP_NUM_THREADS=16

$ ./a.out
```

```
NUMA node0 CPU(s):  0-7   , 64-71
NUMA node1 CPU(s):  8-15  , 72-79
NUMA node2 CPU(s):  16-23 , 80-87
NUMA node3 CPU(s):  24-31 , 88-95
NUMA node4 CPU(s):  32-39 , 96-103
NUMA node5 CPU(s):  40-47 , 104-111
NUMA node6 CPU(s):  48-55 , 112-119
NUMA node7 CPU(s):  56-63 , 120-127
```

Note: Setting OMP_DISPLAY_ENV=verbose is your friend here!

Performance – 2 Sockets/64 Cores



First Touch improves the performance by a factor of 22x

Oracle Linux with the gcc compiler
NUMA balancing on

NUMA Case Study - Takeaways

Data and thread placement matters (a lot)
Important to leverage First Touch Data Placement
OpenMP has elegant, yet powerful, support for NUMA
More NUMA support has been added in OpenMP 5.0 and 5.1!

Summary - The Tuning Strategy

Think Ahead

Always use a profiling tool to guide you

Never forget to tune for serial performance

Consider your data structures

Find and address the low hanging fruit

Do not forget to consider data placement

Thank You And ... Stay Tuned!

Bad OpenMP
Does Not Scale

Ruud van der Pas

Webinar, March 18, 2021