The practitioner’s cookbook for good parallel performance on multi- and manycore systems

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SC12 Full-Day Tutorial
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Salt Lake City, Utah

The Plan

- Basic multicore architecture
- Data access on modern processors
- Performance properties of multicore/multisocket systems
  - Micro-bench marks
  - Sync over-head
  - Band-width saturation
- Case study: Sparse matrix-vector multiply (part 1)
- Multicore performance tools Part 1
  - Probing topology
  - Enforcing affinity
- Hands-On session 1

- Basic performance modeling
  - Balance metrics
  - “Motivated” optimizations
- Case study: 3D Jacobi smoother
  - The Roofline Model
- Efficient programming on ccNUMA nodes
- Simultaneous multi-threading (SMT)
  - Theory
  - Impli-cations
  - Facts & fiction
- MPI in multicore environments
  - Intranode vs. internode
  - Rank-subdomain mapping

- Multicore performance tools Part 2
  - Hardware metrics
  - Best practices
- Advanced case studies: Putting cores to better use
  - Wavefront temporal blocking
  - Sparse MVM (part 2)
- Outlook: Advanced performance engineering
  - Sparse MVM (part 3)
  - ECM model
- Conclusions
- Hands-On session 2

Hands-on sessions

- **2x ~45 minutes**
  - Before lunch
  - Before end of tutorial

- **Technical prerequisites for participants**
  - Laptop with stable wireless connection
  - SSH client
  - If you cannot cope with vi: An X server on your laptop
  - Each participant will receive a personal user account on the main compute cluster “LiMa” of RRZE at the University of Erlangen, Germany
  - Linux skills required

- **Details (login procedures, exercises,…) at**

  http://moodle.rrze.uni-erlangen.de/moodle/course/view.php?id=256&username=guest&password=guest

  http://goo.gl/iJ55s

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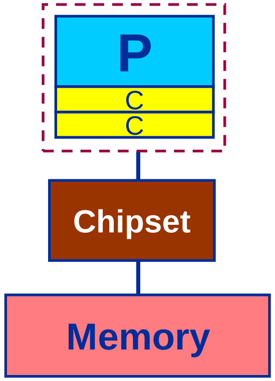
Multicore processor and system architecture

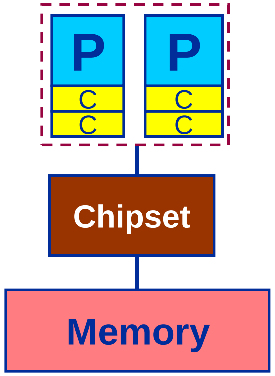
Basics

The x86 multicore evolution so far

Intel Single-Dual-/Quad-/Hexa-/-Cores (one-socket view)

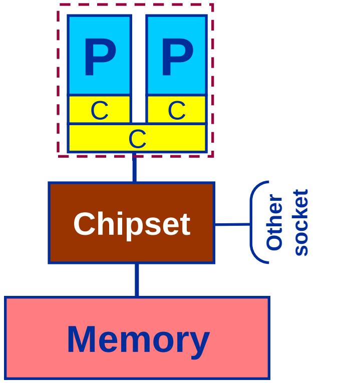
2005: “Fake” dual-core

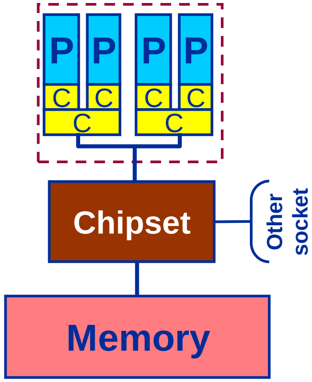




2006: True dual-core

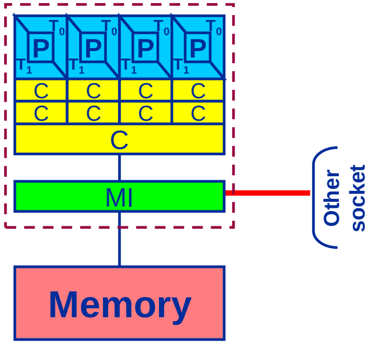
Woodcrest
“Core2 Duo” 65nm





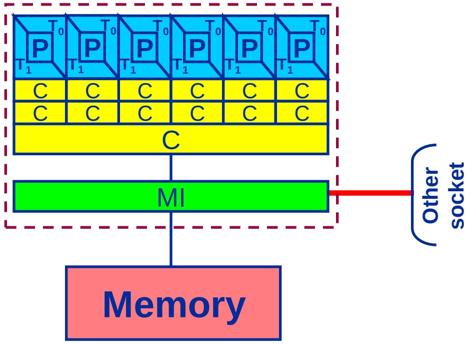
Harpertown
“Core2 Quad” 45nm

2008: Simultaneous Multi Threading (SMT)



Nehalem EP
“Core i7”
45nm

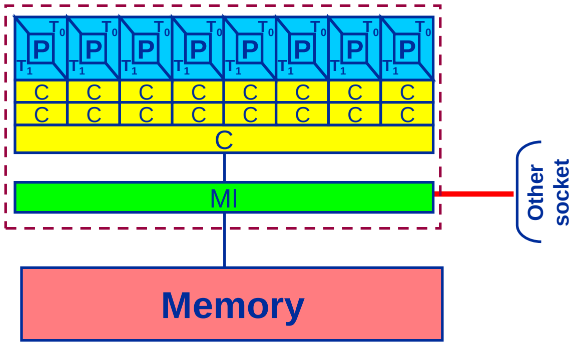
2010: 6-core chip



Westmere EP
“Core i7”
32nm

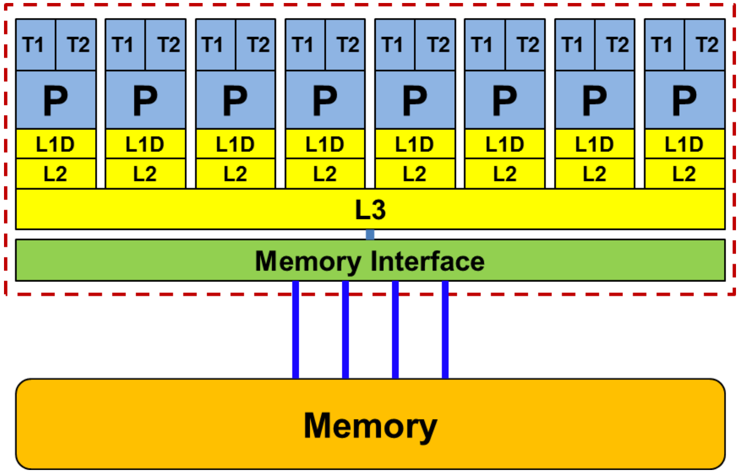
2012: Wider SIMD units

AVX: 256 Bit



Sandy Bridge EP
“Core i7”
32nm

There is no single driving force for chip performance!



Intel Xeon
“Sandy Bridge EP” socket
4,6,8 core variants available

Floating Point (FP) Performance:

$$P = n_{core} * F * S * \nu$$

n_{core}	number of cores:	8
F	FP instructions per cycle: (1 MULT and 1 ADD)	2
S	FP ops / instruction: (256 Bit SIMD registers – “AVX”)	4 (dp) / 8 (sp)
ν	Clock speed :	∽2.7 GHz

TOP500 rank 1 (1995)

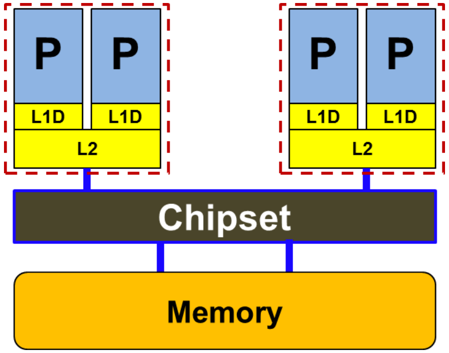
P = 173 GF/s (dp) / 346 GF/s (sp)

But: P=5 GF/s (dp) for serial, non-SIMD code

From UMA to ccNUMA

Basic architecture of commodity compute cluster nodes

Yesterday (2006): Dual-socket Intel “Core2” node:

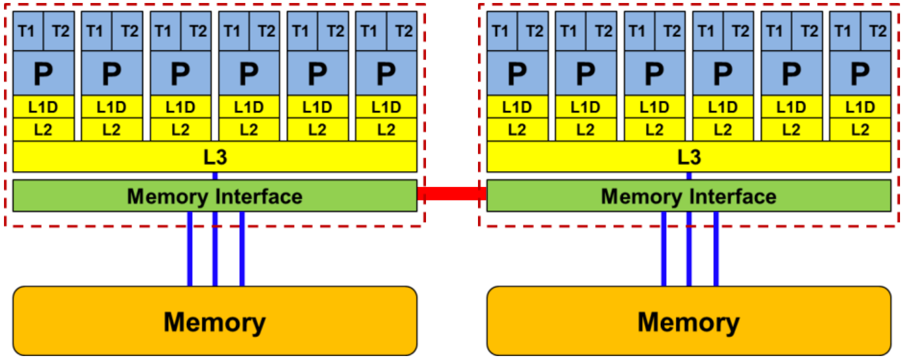


Uniform Memory Architecture (UMA)

Flat memory ; symmetric MPs

But: system “anisotropy”

Today: Dual-socket Intel (Westmere) node:



Cache-coherent Non-Uniform Memory Architecture (ccNUMA)

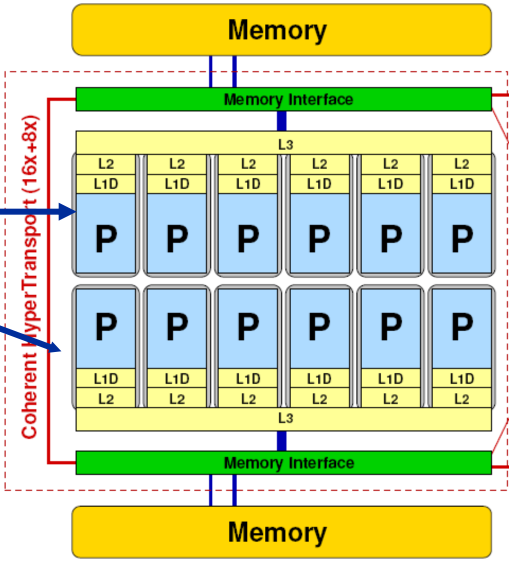
HT / QPI provide scalable bandwidth at the price of ccNUMA architectures: *Where does my data finally end up?*

On AMD it is even more complicated → ccNUMA within a socket!

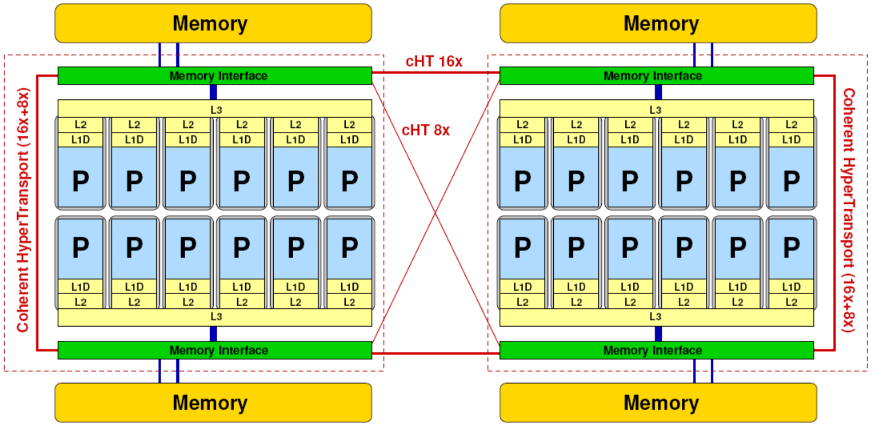
Back to the 2-chip-per-case age

12 core AMD Magny-Cours – a 2x6-core ccNUMA socket

- **AMD: single-socket ccNUMA since Magny Cours**



  - 1 socket: 12-core Magny-Cours built from two 6-core chips → 2 NUMA domains
  - 2 socket server → 4 NUMA domains



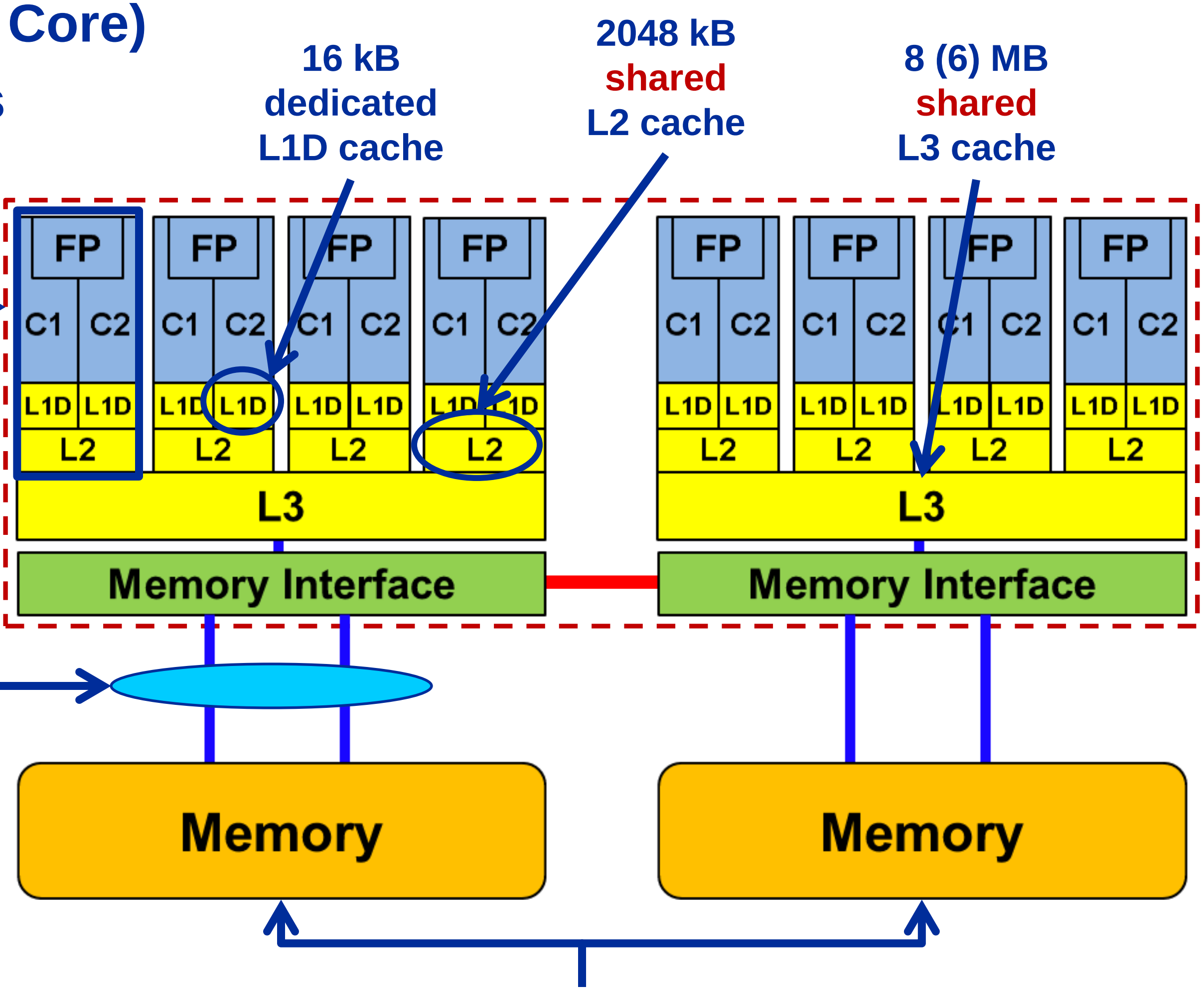
  - 4 socket server: → 8 NUMA domains

- **WHY? → Shared resources are hard two scale: 2 x 2 memory channels vs. 1 x 4 memory channels per socket**

Another flavor of "SMT"

AMD Interlagos / Bulldozer

- Up to 16 cores (8 Bulldozer modules) in a single socket
- Max. 2.6 GHz (+ Turbo Core)
- P_{max} = (2.6 x 8 x 8) GF/s = 166.4 GF/s



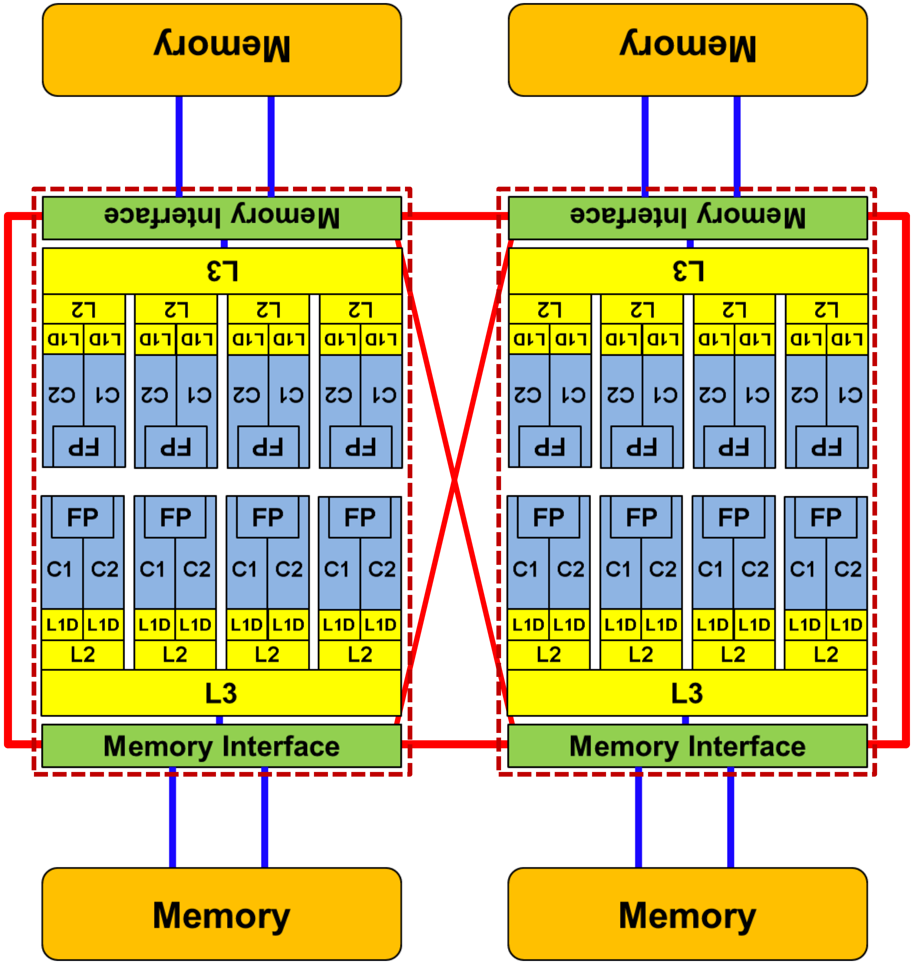
Each Bulldozer module:

- 2 "lightweight" cores
- 1 FPU: 4 MULT & 4 ADD (double precision) / cycle
- Supports AVX
- Supports FMA4

2 DDR3 (shared) memory channel > 15 GB/s

2 NUMA domains per socket

Cray XE6 "Interlagos" 32-core dual socket node

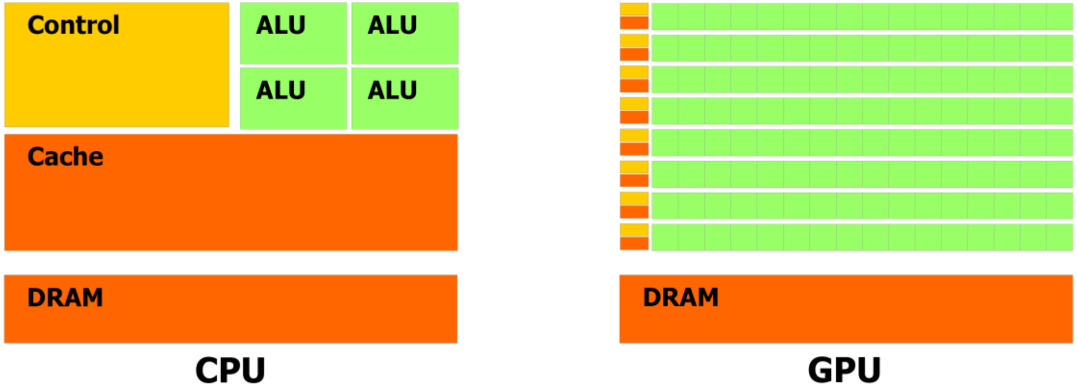


- Two 8- (integer-) core chips per socket @ 2.3 GHz (3.3 @ turbo)
- Separate DDR3 memory interface per chip
  - ccNUMA on the socket!
- Shared FP unit per pair of integer cores ("module")
  - "256-bit" FP unit
  - SSE4.2, AVX, FMA4
- 16 kB L1 data cache per core
- 2 MB L2 cache per module
- 8 MB L3 cache per chip (6 MB usable)

Trading single thread performance for parallelism:
GPGPUs vs. CPUs

GPU vs. CPU
light speed estimate:

1. **Compute bound: 2-5 X**
2. **Memory Bandwidth: 1-5 X**



	Intel Core i5 – 2500 (“Sandy Bridge”)	Intel Xeon E5-2680 DP node (“Sandy Bridge”)	NVIDIA C2070 (“Fermi”)
Cores@Clock	4 @ 3.3 GHz	2 x 8 @ 2.7 GHz	448 @ 1.1 GHz
Performance⁺/core	52.8 GFlop/s	43.2 GFlop/s	2.2 GFlop/s
Threads@stream	<4	<16	>8000
Total performance⁺	210 GFlop/s	691 GFlop/s	1,000 GFlop/s
Stream BW	18 GB/s	2 x 36 GB/s	90 GB/s (ECC=1)
Transistors / TDP	1 Billion* / 95 W	2 x (2.27 Billion / 130W)	3 Billion / 238 W

⁺ *Single Precision*

* *Includes on-chip GPU and PCI-Express*

Complete compute device

Parallel programming models

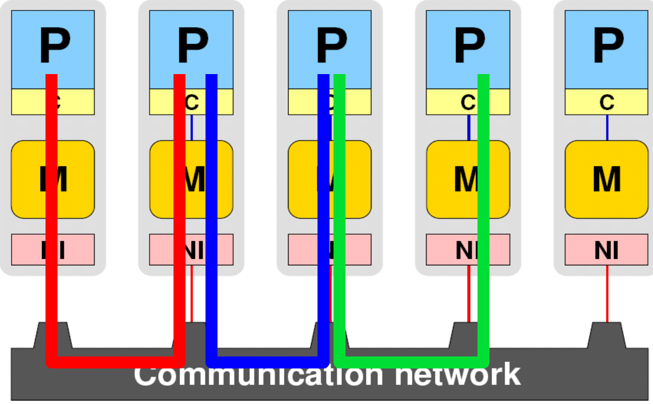
on multicore multisocket nodes

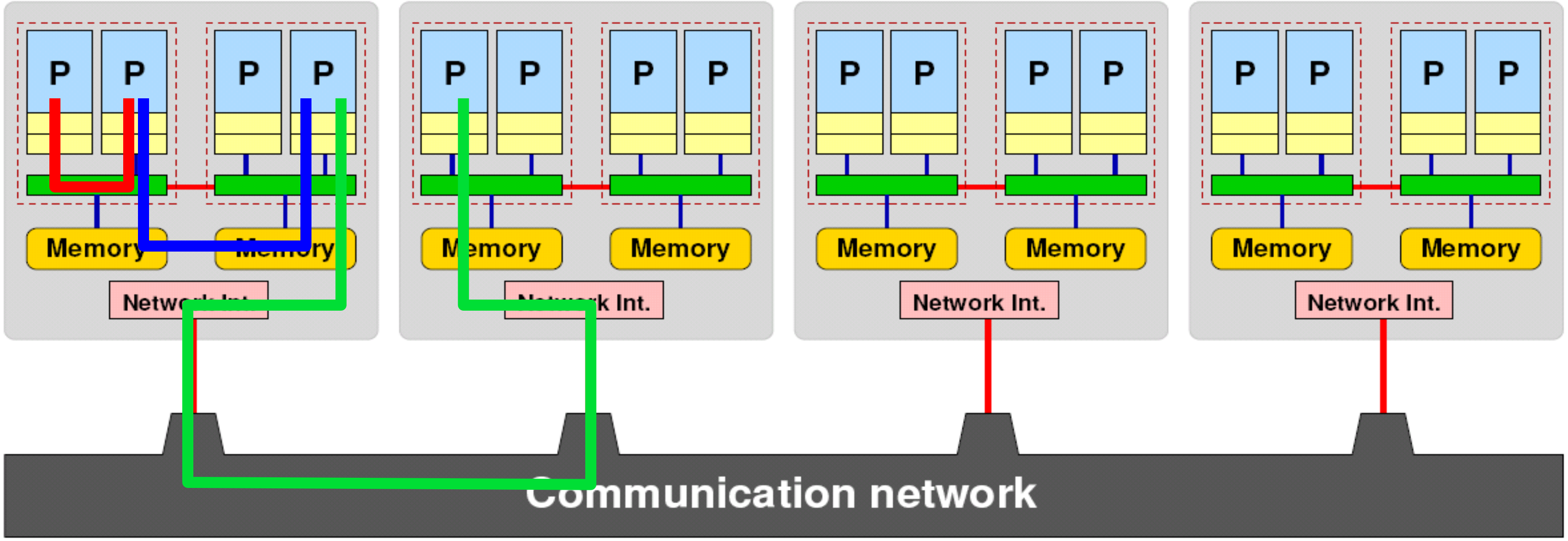
- **Shared-memory (intra-node)**
  - Good old MPI (current standard: 2.2)
  - OpenMP (current standard: 3.0)
  - POSIX threads
  - Intel Threading Building Blocks (TBB)
  - Cilk++, OpenCL, StarSs,… you name it
- **Distributed-memory (inter-node)**
  - MPI (current standard: 2.2)
  - PVM (gone)
- **Hybrid**
  - Pure MPI
  - MPI+OpenMP
  - MPI + any shared-memory model
  - MPI (+OpenMP) + CUDA/OpenCL/…

All models require awareness of *topology* and *affinity* issues for getting best performance out of the machine!

Parallel programming models:
Pure MPI

- **Machine structure is invisible to user:**
  - → Very simple programming model
  - → MPI "knows what to do"!?
- **Performance issues**
  - Intranode vs. internode MPI
  - Node/system topology

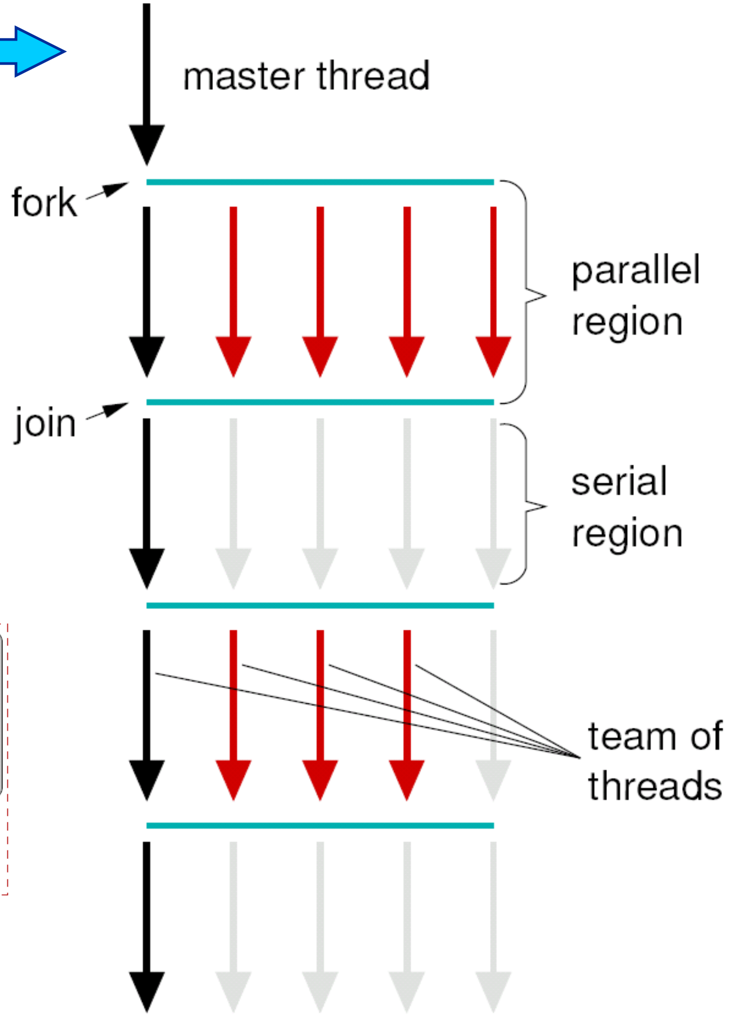


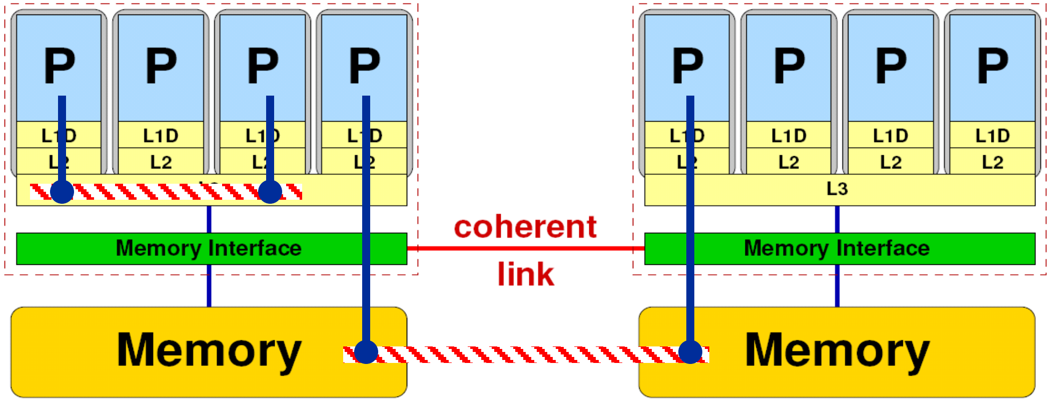


Parallel programming models:

Pure threading on the node

- **Machine structure is invisible to user**
  - → Very simple programming model
  - Threading SW (OpenMP, pthreads, TBB,…) should know about the details
- **Performance issues**
  - Synchronization overhead
  - Memory access
  - Node topology





Parallel programming models:

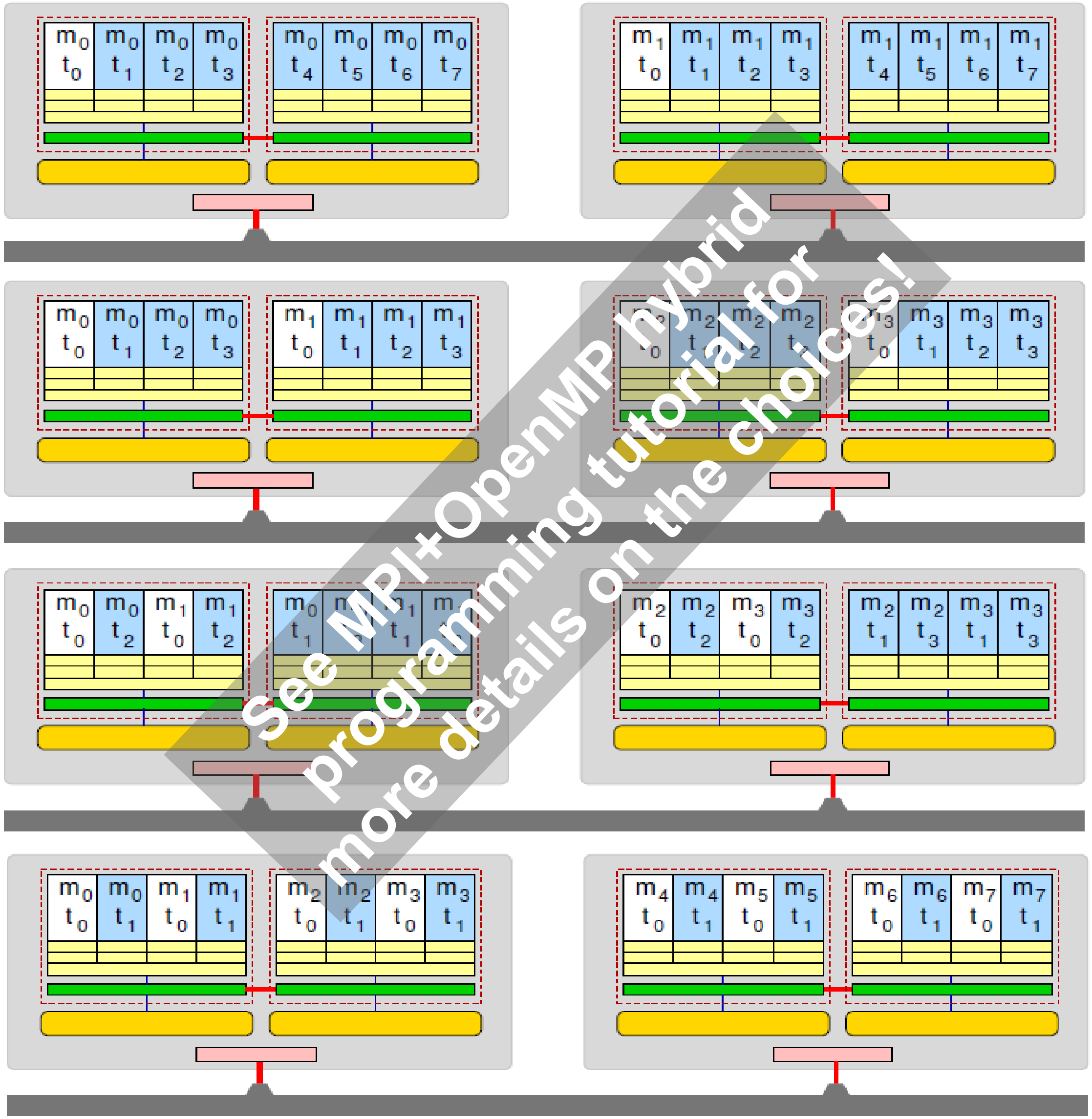
Hybrid MPI+OpenMP on a multicore multisocket cluster

One MPI process / node

One MPI process / socket: OpenMP threads on same socket: **“blockwise”**

OpenMP threads pinned **“round robin”** across cores in node

Two MPI processes / socket OpenMP threads on same socket



See MPI+OpenMP hybrid programming tutorial for more details on the choices!

Warm-up example:
A parallel histogram calculation

Simple issues when dealing with shared-memory parallel code

The problem

- Compute simplified histogram (HIST(0:15)) of a (integer) random number generator: HIST(MODULO(RAND() , 16))

- Check if RAND() generates a homogeneous distribution: HIST(MODULO(RAND() , 16) = N/16 (N: random numbers generated)

- Architecture: Intel Xeon/Sandy Bridge 2.7 GHz (fixed clock speed)
- Compiler: Intel V12.1 (no inlining)
- Simple Random number generator (taken from `man rand` ; there are much better ones…)

```
int myrand(unsigned long* next) {
  *next = *next * 1103515245 + 12345;
  return((unsigned)(*next/65536) % 32768);
}
```

Serial implementation and baseline

Computation

```
lseed = 123;
for(i=0; i<16; ++i)
    hist[i]=0;

timing(&wcstart, &ct);

for(i=0; i<n_loop; ++i)
      hist[ RAND & 0xf]++;

timing(&wcend, &ct);
```

Quality evaluation

```
double av=n_loop/16.0;
double abserr=0.0;

for(i=0; i<16; ++i) {
  err=(((double)hist[i])-av) /av);
  abserr=MAXIMUM(fabs(err,abserr)
}
```

- **Serial baselines ($N=10^9$)**

RAND = myrand(&lseed)
Time =3.6 secs
abserr =$3 * 10^{-6}$

Standard thread-safe random number generator

RAND = rand_r(&lseed)
Time =6.7 secs
abserr =$4 * 10^{-6}$

Straightforward parallelization?!

- Just add a single OpenMP directive…..

```
  lseed = 123;
  for(i=0; i<16; ++i) hist[i]=0;

  timing(&wcstart, &ct);
```

```
#pragma omp parallel for

  for(i=0; i<n_loop; ++i) {
    hist[myrand(&lseed) & 0xf]++;
  }
```

```
  timing(&wcend, &ct);
```

- Result Quality

Threads	abserr
2	~0.38
4	~0.61
8	~0.80
16	~0.89

Baseline: $3*10^{-6}$

- Performance

Threads	Time
2	~20s
4	~23s
8	~28s
16	~105s

Baseline: 3.6s

Problem:
Uncoordinated concurrent updates of **hist[]** and **lseed**
→ Runtime and result changes between runs

Get it correct first!

- Protect update of `lseed` and `hist[]` by `critical` region

- Result Quality

Threads	abserr
2	3 * 10^{-6}
4	3 * 10^{-6}
8	3 * 10^{-6}
16	3 * 10^{-6}

Baseline: 3*10^{-6}

- Performance

Threads	Time
2	201s
4	221s
8	217s
16	427s

Baseline: 3.6s

```
#pragma omp parallel for

  for(i=0; i<n_loop; ++i) {

#omp critical{
    hist[myrand(&lseed) & 0xf]++;}

  }
```

Result Quality: OK
Problem:
Performance: ~50x-100x slower!
Serialization and some (?) more overhead,
e.g. “synchronization”

Avoid complete serialization

- Define a private `lseed`
- Only histogram update needs a `#pragma omp critical`
- Result Quality

Threads	abserr
2	$6 * 10^{-6}$
4	$15 * 10^{-6}$
8	$24 * 10^{-6}$
16	$60 * 10^{-6}$

Baseline: $3*10^{-6}$

```
#pragma omp parallel for &
                  firstprivate(lseed)

  for(i=0; i<n_loop; ++i) {
    value= myrand(&lseed) & 0xf;

#omp critical{ hist[value]++; }


  }
```

- Performance

Threads	Time
2	191s
4	201s
8	194s
16	413s

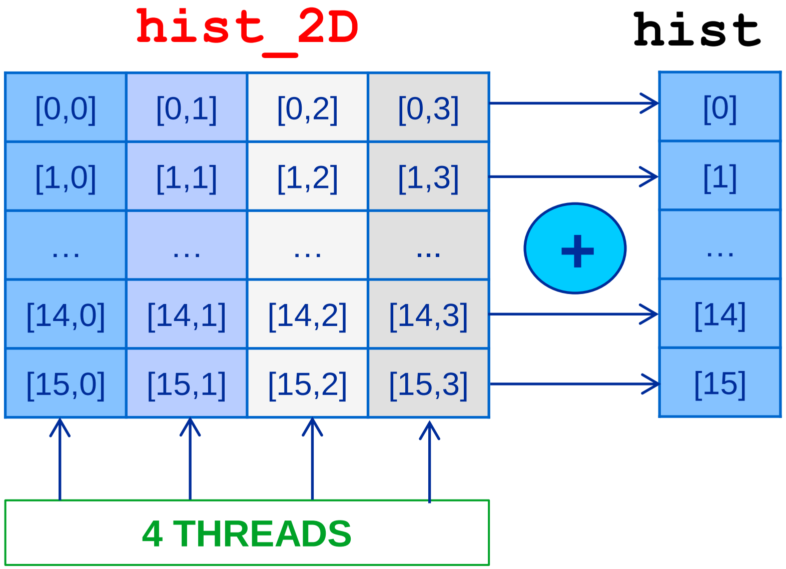
Baseline: 3.6s

Problem: Performance improves only marginally → `critical` is still an issue!

Problem (?): Result Quality is slightly worse than baseline.

Get rid of the `critical` statement (1)

- **Use a shared scoreboard (`hist_2D`):**
  - Each thread writes to a separate column of length 16
  - Sum up the numbers across each row to get the final `hist[]`



hist_2D

[0,0]	[0,1]	[0,2]	[0,3]
[1,0]	[1,1]	[1,2]	[1,3]
…	…	…	…
[14,0]	[14,1]	[14,2]	[14,3]
[15,0]	[15,1]	[15,2]	[15,3]

+

hist

[0]
[1]
…
[14]
[15]

4 THREADS

```
// additional shared array
// assuming 4 threads
  hist_2D[16][4]=0;

#pragma omp parallel {
  threadID=omp_get_num_threads();

#pragma omp for firstprivate(lseed)
  for(i=0; i<n_loop; ++i) {
    value= myrand(&lseed) & 0xf;
    hist_2D[value][threadID]++; }

#pragma omp critical
    hist[]+= hist_2D[][threadID]
}
```

Get rid of the `critical` statement (2)

- **Result Quality**

Threads	abserr
2	$6 * 10^{-6}$
4	$15 * 10^{-6}$
8	$24 * 10^{-6}$
16	$60 * 10^{-6}$

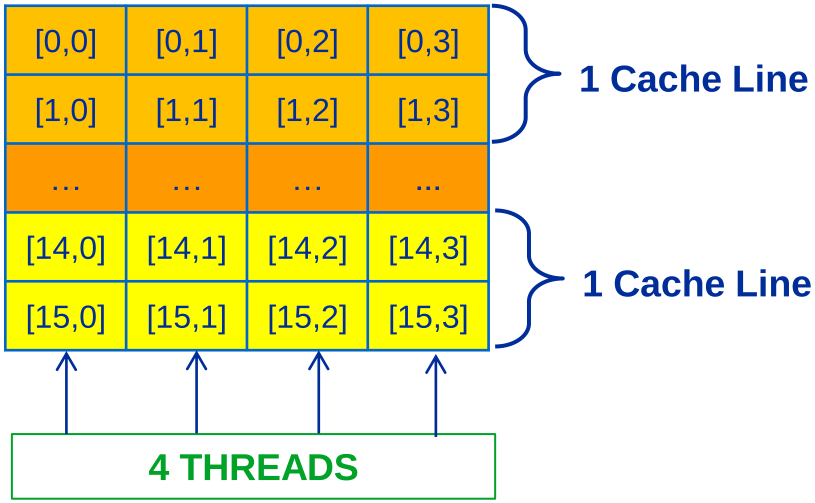
Baseline: $3*10^{-6}$

- **Performance**

Threads	Time
2	11.7s
4	9.3s
8	6.6s
16	19.3s

Baseline: 3.6s

Performance improves 30x but still much slower than serial version ?!

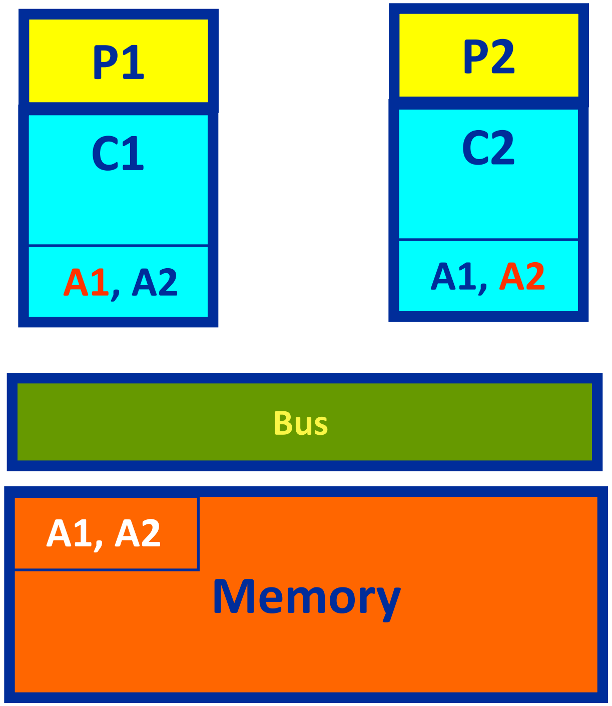


Each thread writes frequently to every cache line of **`hist_2D`**

→ False Sharing

Excursion: Cache coherence protocol → False Sharing

- **Data in cache is only a copy of data in memory**
  - Multiple copies of same data on multiprocessor systems
  - Cache coherence protocol/hardware ensure consistent data view
  - Without cache coherence, shared cache lines can become clobbered: (Cache line size = 2 WORD; A1+A2 are in a single CL)



P1	P2
Load A1	Load A2
Write A1=0	Write A2=0

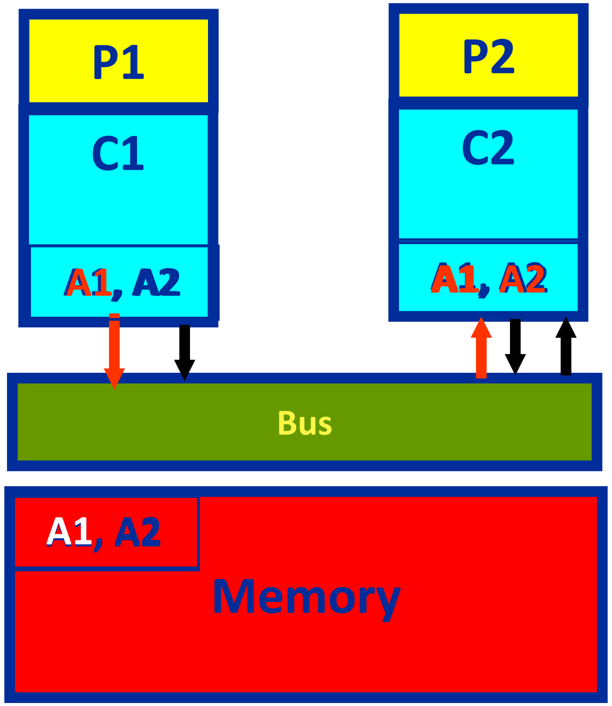
Write-back to memory leads to incoherent data

A1, A2 | A1, A2 | A1, A2

C1 & C2 entry can not be merged to: A1, A2

Excursion:
Cache coherence protocol → False Sharing

- Cache coherence protocol must keep track of cache line status



P1

P2

`Load A1`

`Load A2`

`Write A1=0:`

1. Request exclusive access to CL
2. Invalidate CL in C2
3. Modify A1 in C1

`Write A2=0:`

1. Request exclusive CL access
2. CL write back+ Invalidate
3. Load CL to C2
4. Modify A2 in C2

t

C2 is exclusive owner of CL ←

Avoid False Sharing

- Use thread private histogram (`hist_local[16]`) for thread local computation & sum up all results at the end
- Result Quality

Threads	abserr
2	$6 * 10^{-6}$
4	$15 * 10^{-6}$
8	$24 * 10^{-6}$
16	$60 * 10^{-6}$

Baseline: $3*10^{-6}$

- Performance ☺

Threads	Time
2	1.78s
4	0.89s
8	0.44s
16	0.22s

Baseline: 3.6s

```
#pragma omp parallel {
  int hist_local[16]=0;

#pragma omp for firstprivate(lseed)
  for(i=0; i<n_loop; ++i) {
    value= myrand(&lseed) & 0xf;
    hist_local[value]++; }

#pragma omp critical
    hist[]+= hist_local[]
}
```

Performance: OK now – nice scaling

PROBLEM: Quality still gets worse as number of threads increase?!

Every thread does the same (`lseed` is the same!) → more threads less statistics

Improve Result Quality

- **Use different seeds for each thread!**

- **Result Quality**

Threads	abserr
2	$4 * 10^{-6}$
4	$7 * 10^{-6}$
8	$10 * 10^{-6}$
16	$10 * 10^{-6}$

Baseline: $3*10^{-6}$

- **Performance**

Threads	Time
2	1.78s
4	0.89s
8	0.44s
16	0.22s

Baseline: 3.6s

```
#pragma omp parallel {
  int hist_local[16]=0;

#pragma omp critical {
   int myseed = myrand(&seed); }

#pragma omp for firstprivate(lseed)
  for(i=0; i<n_loop; ++i) {
    value= myrand( &myseed ) & 0xf;
    hist_local[value]++; }

#pragma omp critical
    hist[]+= hist_local[];
}
```

Result quality is slightly worse - we are doing different things than in the serial version……..

Can hyperthreading (SMT) speed up the computation?!

- **PRO SMT**
  - Function evaluation is rather cheap → calling overhead?!
- **CON SMT**
  - Result quality may change
- **Performance benefit of SMT reduces if compiler inlines subroutine call**
- **See later for more info on SMT**

Result Quality

	W/O SMT	SMT
1 core	$3 * 10^{-6}$	$4 * 10^{-6}$
1 socket	$10 * 10^{-6}$	$10 * 10^{-6}$
1 node	$10 * 10^{-6}$	$20 * 10^{-6}$

Baseline: $3*10^{-6}$

Performance

	W/O SMT	SMT
1 core	3.6s	2.2s
1 socket	0.44s	0.29s
1 node	0.22s	0.14s

Baseline: 3.6s

Conclusions from the histogram example

- **Get it correct first!**
  - Race conditions, deadlocks…
- **Avoid complete serialization**
  - Thread-local data
- **Avoid false sharing**
  - Proper shared array layout
  - Padding
- **Parallel random numbers may be non-trivial**

The Plan

Basic multicore architecture

Data access on modern processors

Performance properties of multicore/multisocket systems

Micro-benchmarks

Sync over-head

Band-width saturation

Case study: Sparse matrix-vector multiply (part 1)

Multicore performance tools Part 1

Probing topology

Enforcing affinity

Hands-On session 1

Basic performance modeling

Balance metrics

“Motivated” optimizations

Case study: 3D Jacobi smoother

The Roofline Model

Efficient programming on ccNUMA nodes

Simultaneous multi-threading (SMT)

Theory

Impli-cations

Facts & fiction

MPI in multicore environments

Intranode vs. internode

Rank-subdomain mapping

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Hardware metrics

Best practices

Advanced case studies: Putting cores to better use

Wavefront temporal blocking

Sparse MVM (part 2)

Outlook: Advanced performance engineering

Sparse MVM (part 3)

ECM model

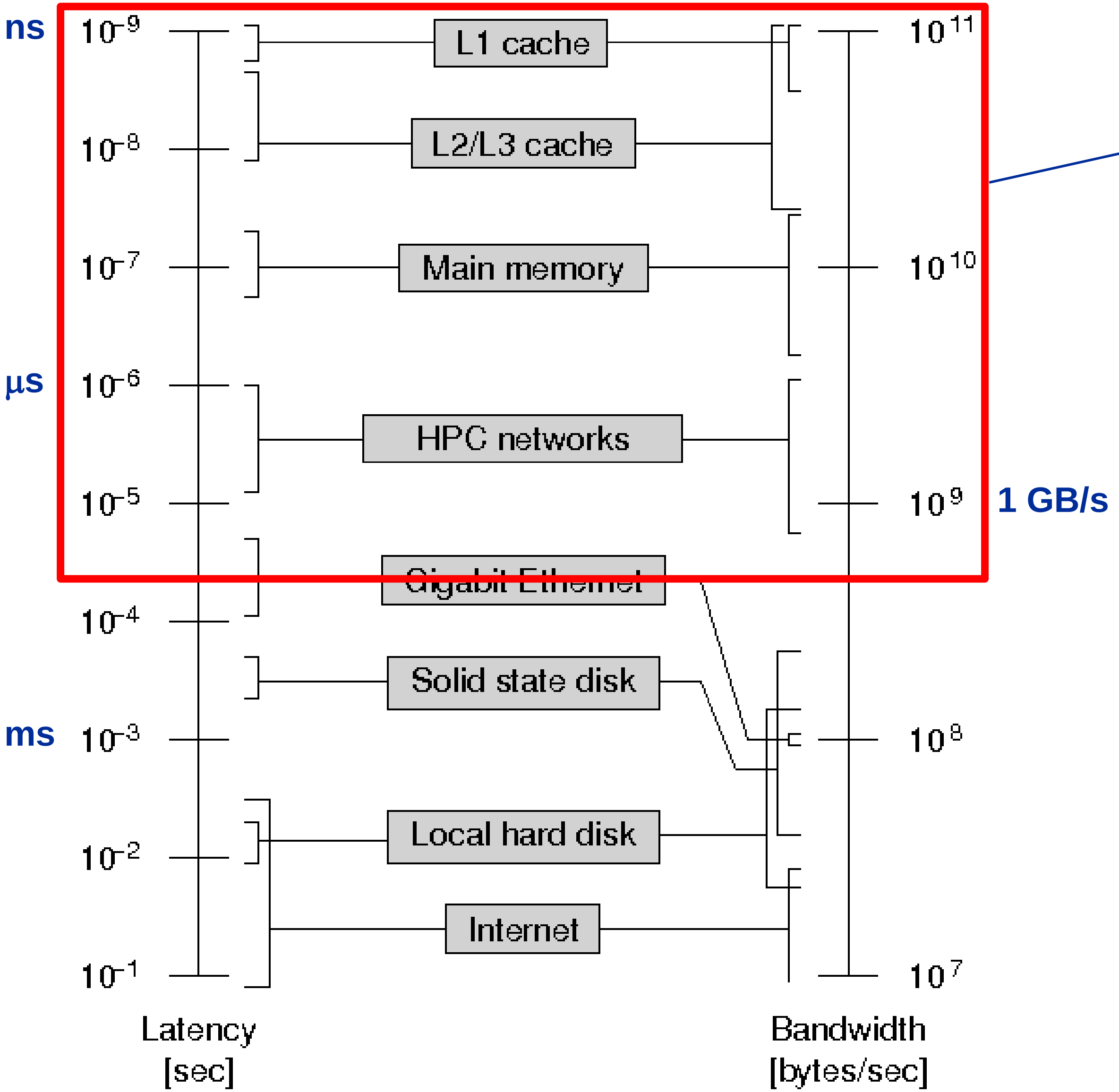
Conclusions

Hands-On session 2

Data access on modern processors

Characterization of memory hierarchies
Balance analysis and light speed estimates
Data access optimization

Latency and bandwidth in modern computer environments

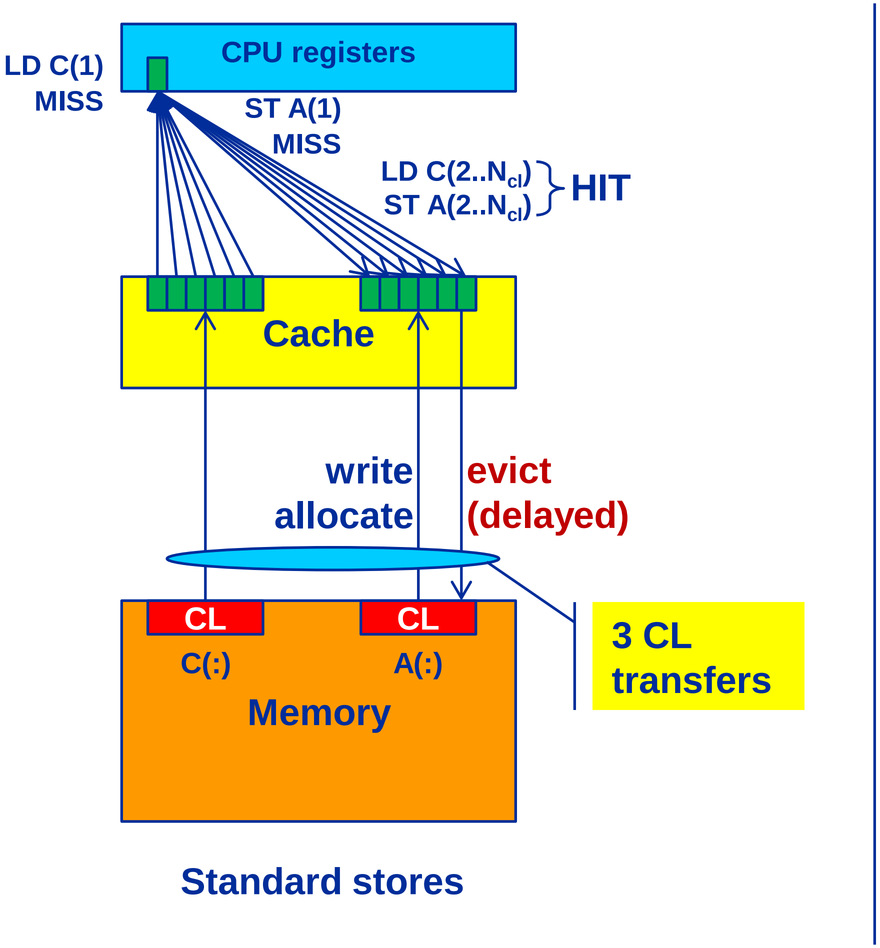


HPC plays here

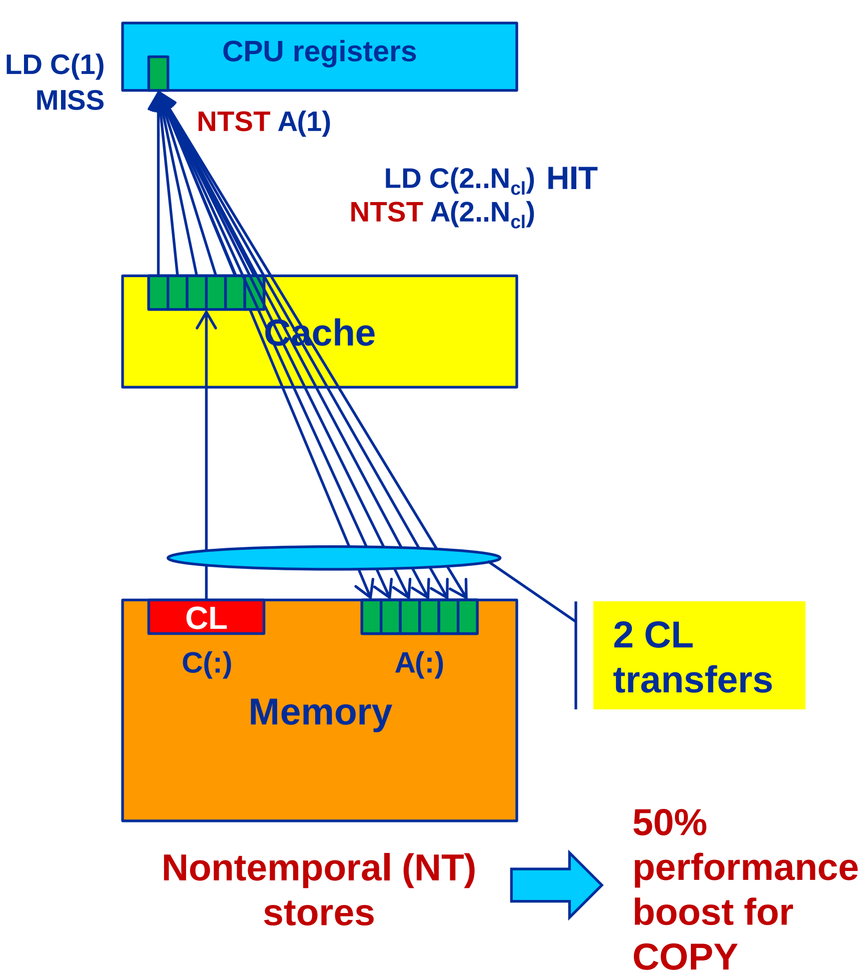
Avoiding slow data paths is the key to most performance optimizations!

Interlude: Data transfers in a memory hierarchy

- How does data travel from memory to the CPU and back?
- Example: Array copy `A(:)=C(:)`



Standard stores



Nontemporal (NT) stores → 50% performance boost for COPY

The parallel vector triad benchmark

A “swiss army knife” for microbenchmarking

Simple streaming benchmark:

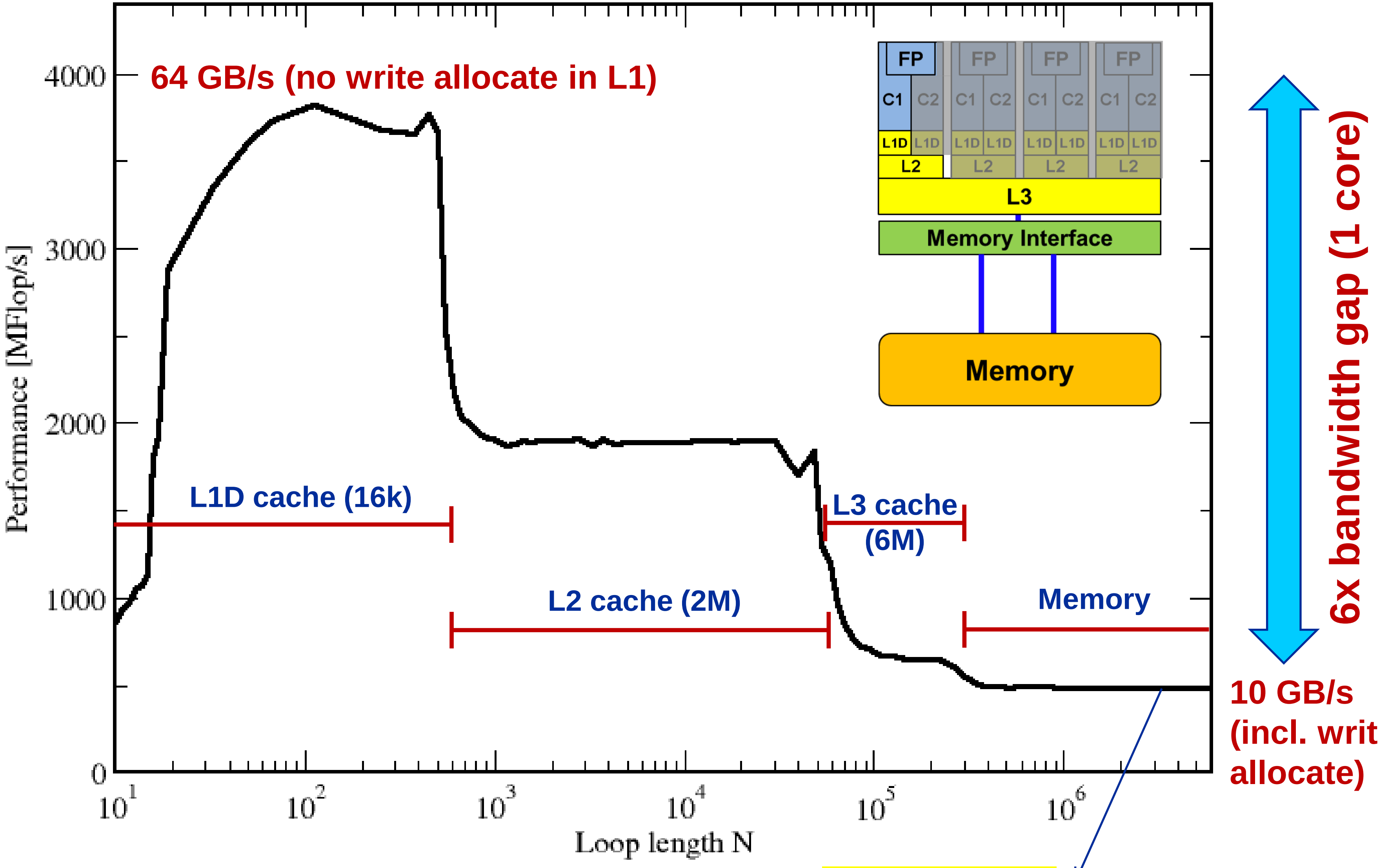
```
double precision, dimension(N) :: A,B,C,D
A=1.d0; B=A; C=A; D=A

do j=1,NITER
  do i=1,N
    A(i) = B(i) + C(i) * D(i)
  enddo
  if(.something.that.is.never.true.) then
    call dummy(A,B,C,D)
  endif
enddo
```

Prevents smarty-pants compilers from doing “clever” stuff

- **Report performance for different N**
- **Choose NITER so that accurate time measurement is possible**
- **This kernel is limited by data transfer performance for all memory levels on all current architectures!**

`A(:)=B(:)+C(:)*D(:)` on one Interlagos core



64 GB/s (no write allocate in L1)

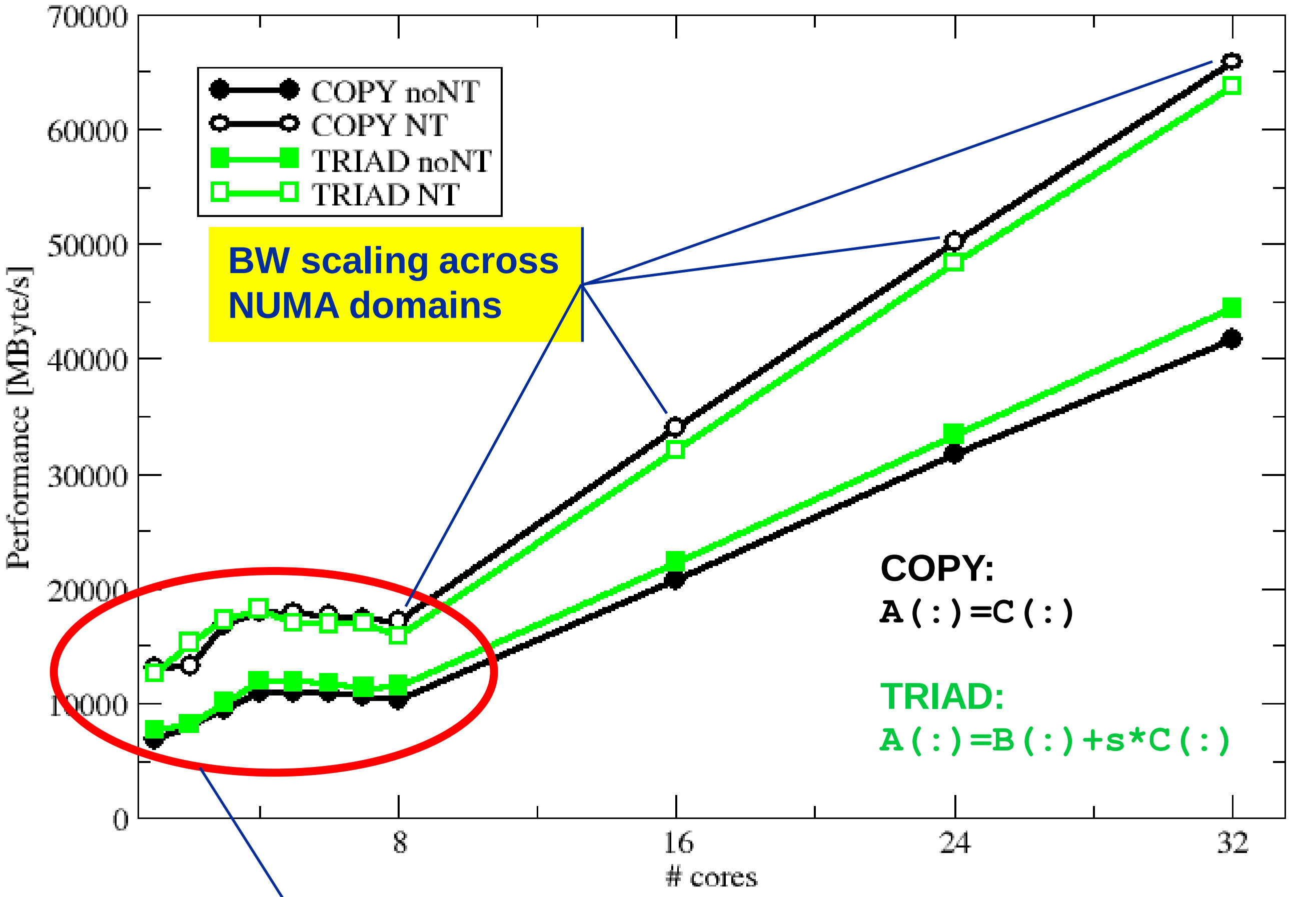
6x bandwidth gap (1 core)

10 GB/s (incl. write allocate)

Is this the limit???

STREAM benchmarks:

Memory bandwidth on Cray XE6 Interlagos node



BW scaling across NUMA domains

COPY:
`A(:)=C(:)`

TRIAD:
`A(:)=B(:)+s*C(:)`

BW saturation within the 8-core chip

- STREAM is the “standard” for memory BW comparisons
- NT store variants save write allocate on stores → 50% boost for copy, 33% for TRIAD
- STREAM BW is practical limit for all codes

The Plan

Basic multicore architecture

Data access on modern processors

Performance properties of multicore/multisocket systems

Micro-bench marks

Sync over-head

Band-width saturation

Case study: Sparse matrix-vector multiply (part 1)

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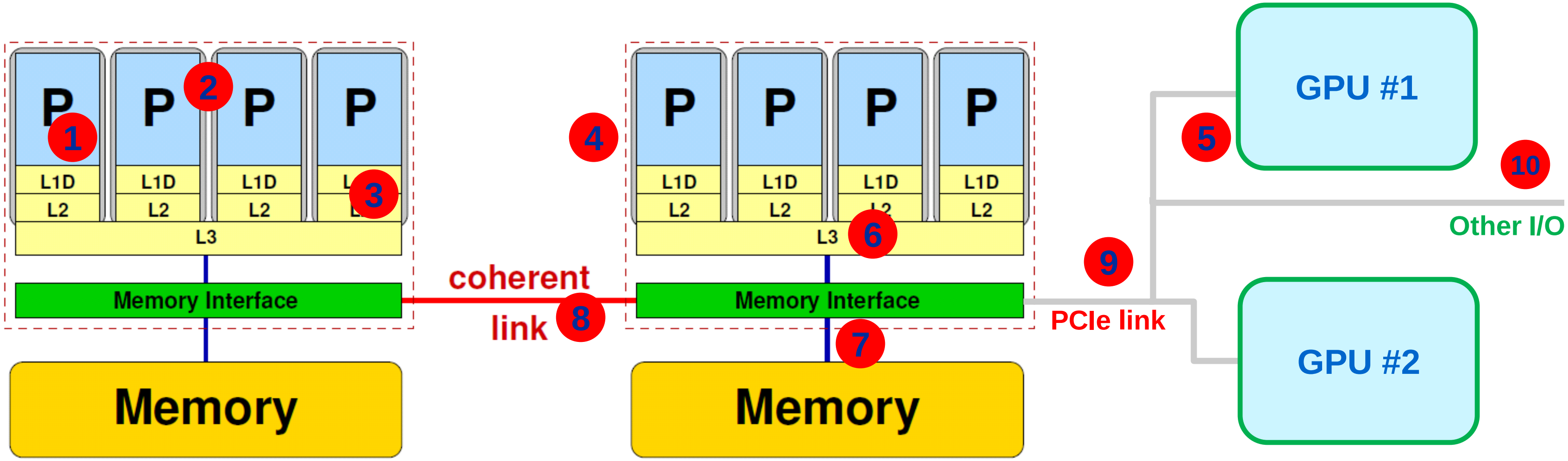
General remarks on the performance properties of multicore multisocket systems

Parallelism in modern computer systems

- Parallel and shared resources within a shared-memory node



Parallel resources:

- Execution/SIMD units 1
- Cores 2
- Inner cache levels 3
- Sockets / memory domains 4
- Multiple accelerators 5

Shared resources:

- Outer cache level per socket 6
- Memory bus per socket 7
- Intersocket link 8
- PCIe bus(es) 9
- Other I/O resources 10

How does your application react to all of those details?

The parallel vector triad benchmark

(Near-)Optimal code on (Cray) x86 machines

```
call get_walltime(S)
!$OMP parallel private(j)
do j=1,R
  if(N.ge.CACHE_LIMIT) then
!DIR$ LOOP_INFO cache_nt(A)
!$OMP ~~parallel~~ do
    do i=1,N
      A(i) = B(i) + C(i) * D(i)
    enddo
!$OMP end ~~parallel~~ do
  else
!DIR$ LOOP_INFO cache(A)
!$OMP ~~parallel~~ do
    do i=1,N
      A(i) = B(i) + C(i) * D(i)
    enddo
!$OMP end ~~parallel~~ do
  endif
  ! prevent loop interchange
  if(A(N2).lt.0) call dummy(A,B,C,D)
enddo
!$OMP end parallel

call get_walltime(E)
```

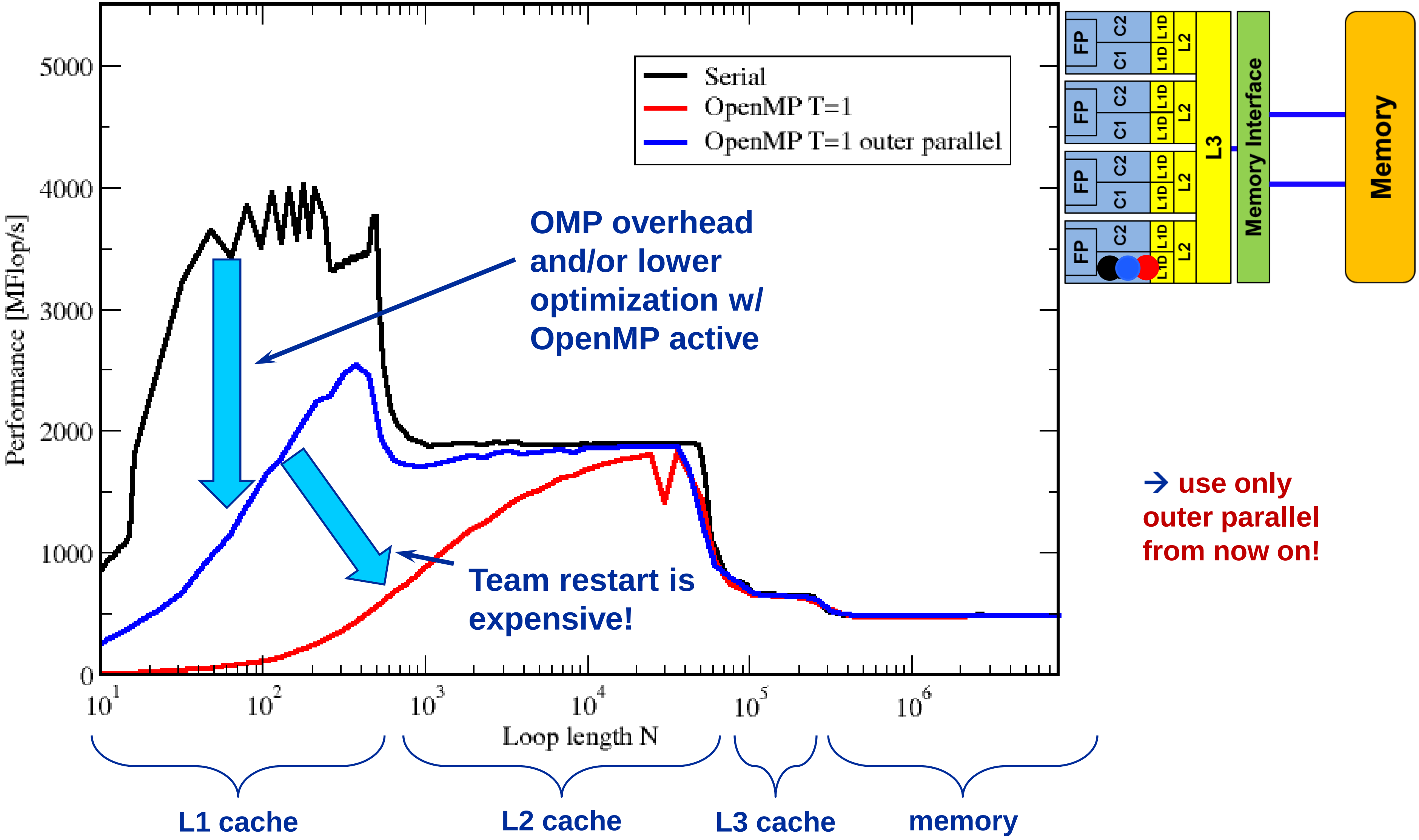
"outer parallel": Avoid thread team restart at every workshared loop

Large-N version (nontemporal stores)

Small-N version (standard stores)

The parallel vector triad benchmark

Single thread on Cray XE6 Interlagos node



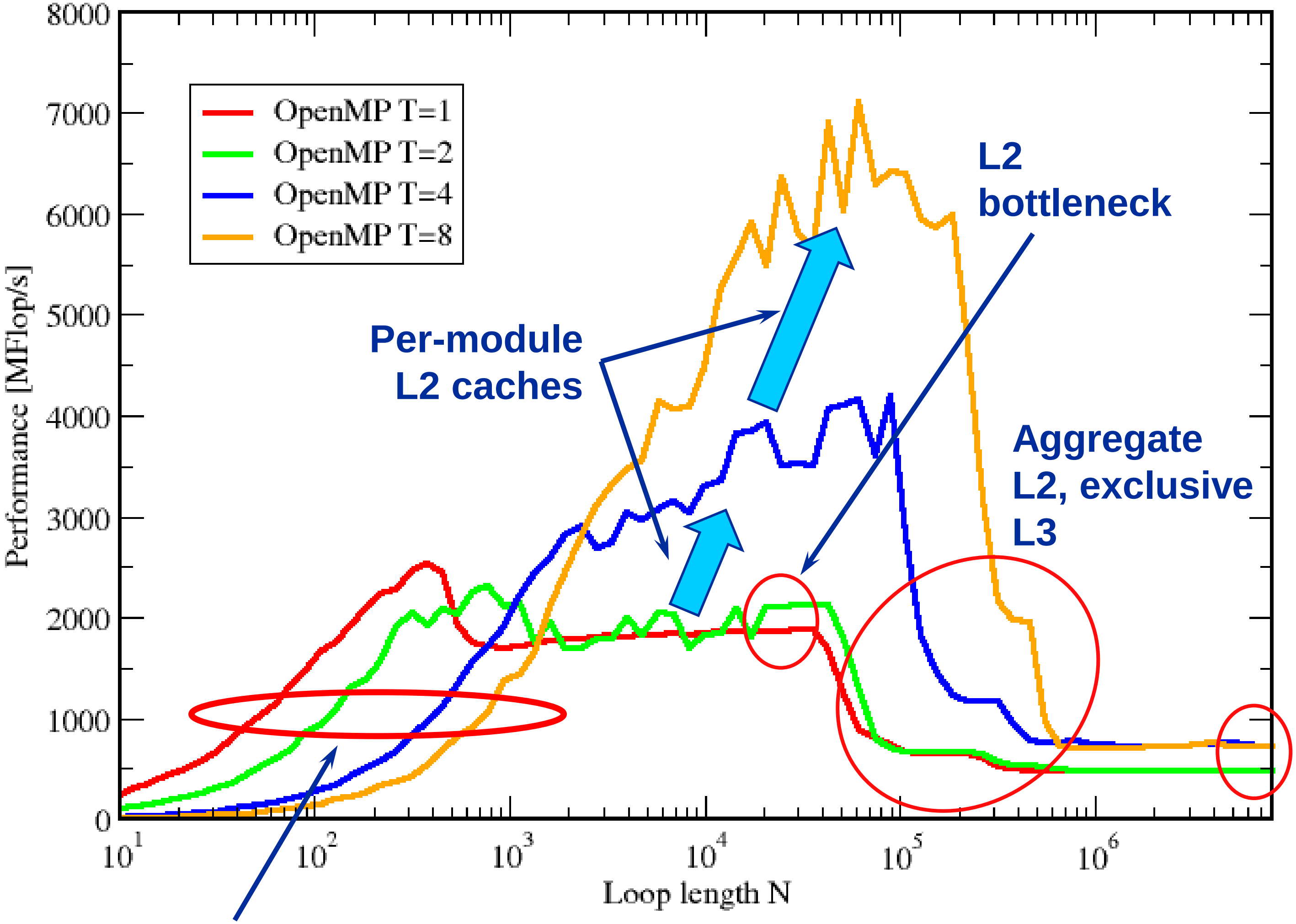
OMP overhead and/or lower optimization w/ OpenMP active

Team restart is expensive!

→ use only outer parallel from now on!

The parallel vector triad benchmark

Intra-chip scaling on Cray XE6 Interlagos node



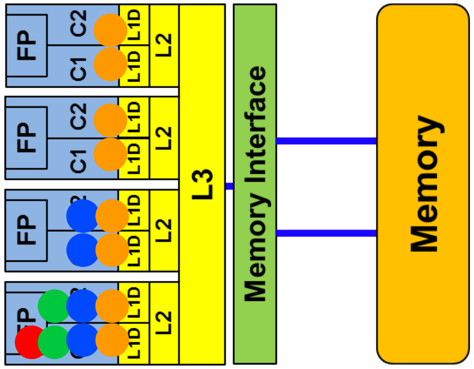
Per-module L2 caches

L2 bottleneck

Aggregate L2, exclusive L3

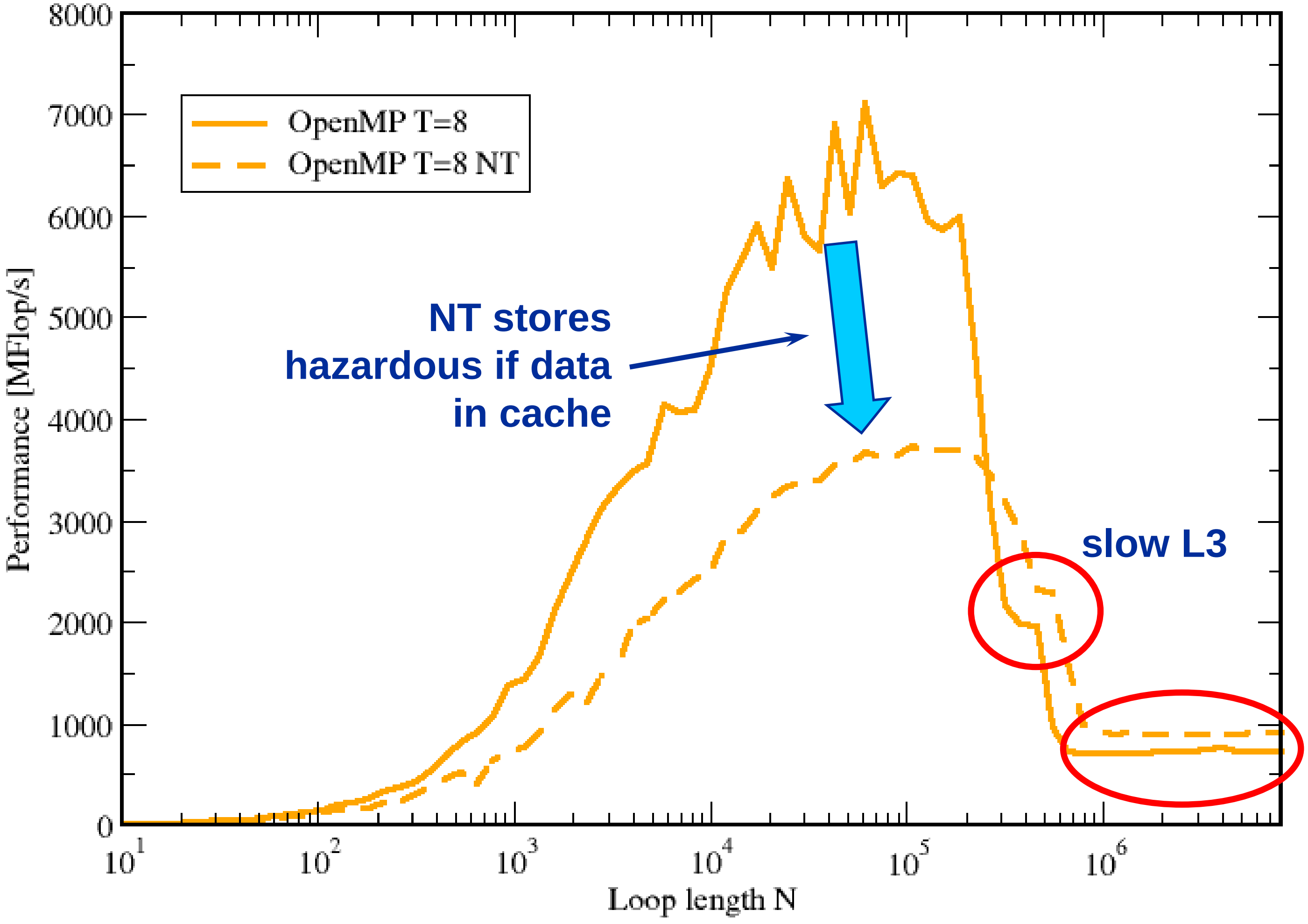
Memory BW saturated @ 4 threads

sync overhead



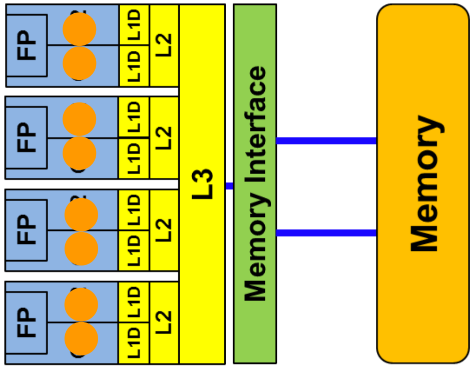
The parallel vector triad benchmark

Nontemporal stores on Cray XE6 Interlagos node



NT stores hazardous if data in cache

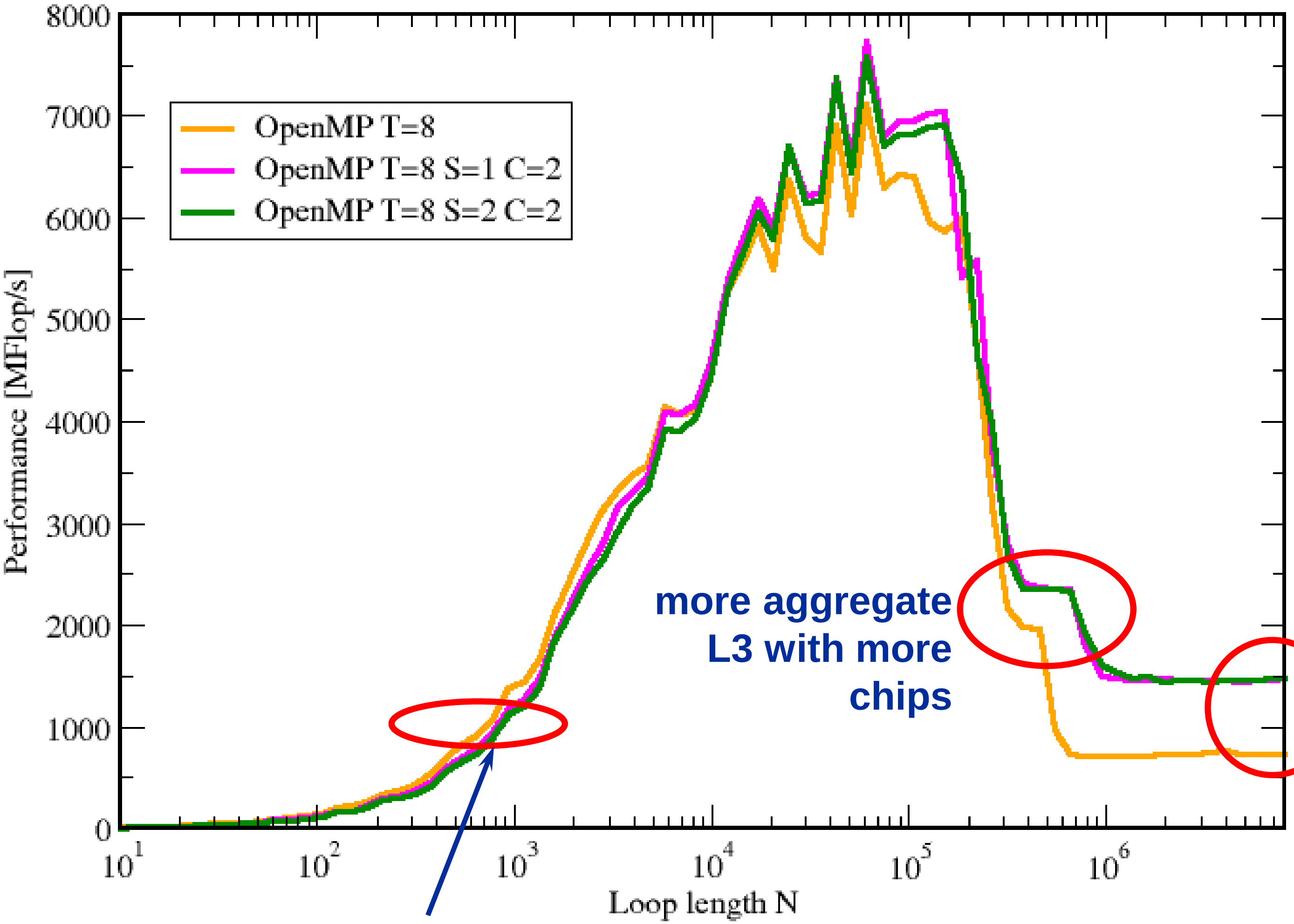
slow L3



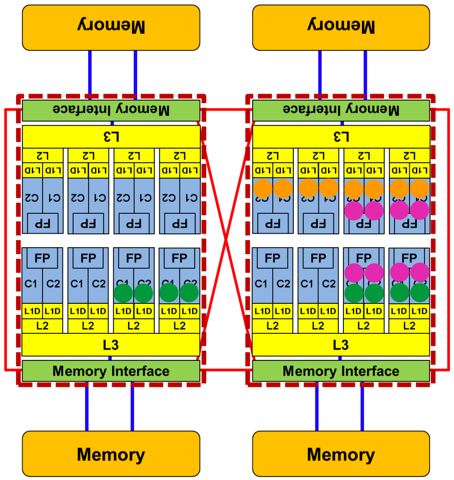
25% speedup for vector triad in memory via NT stores

The parallel vector triad benchmark

Topology dependence on Cray XE6 Interlagos node



more aggregate L3 with more chips

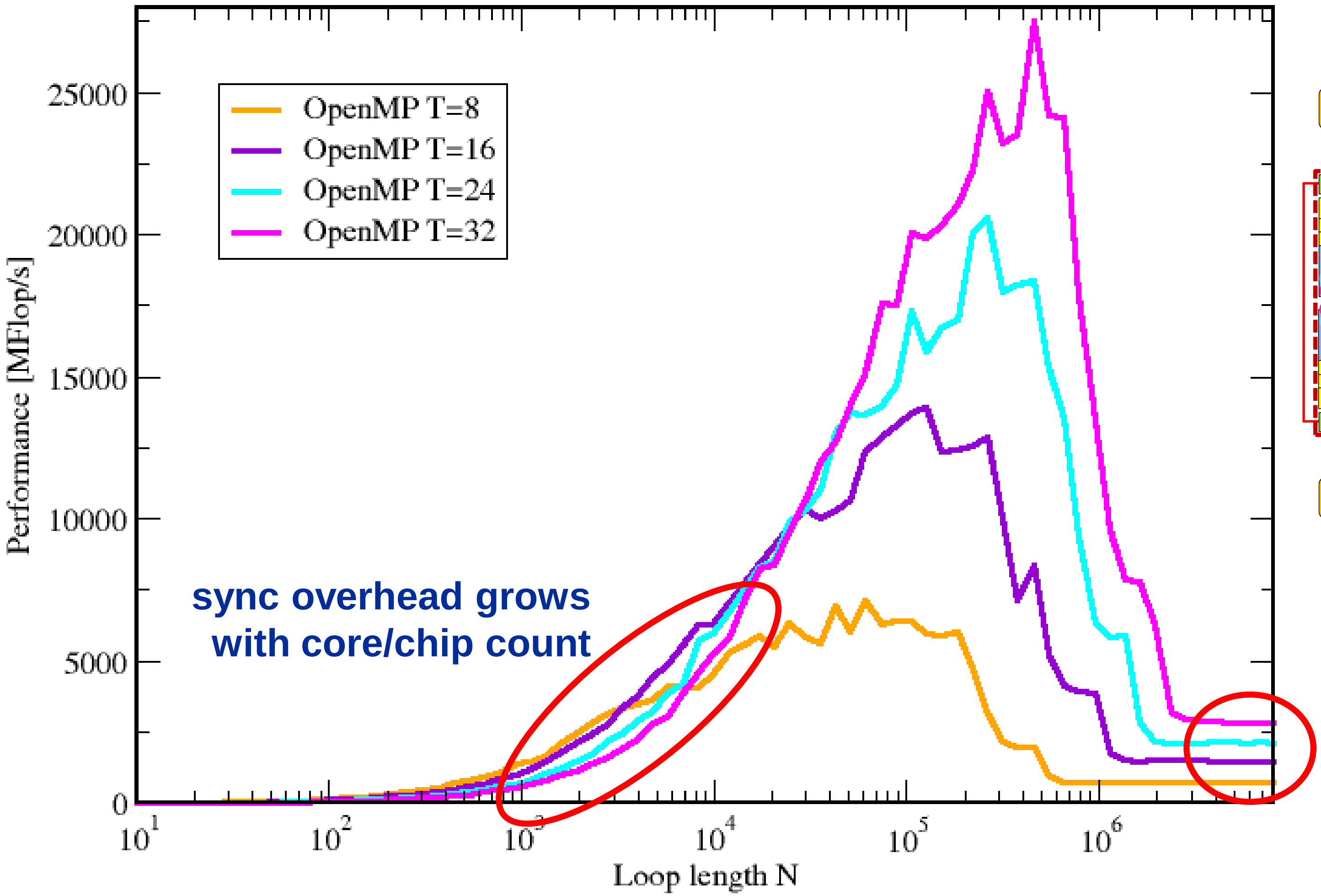


bandwidth scalability across memory interfaces

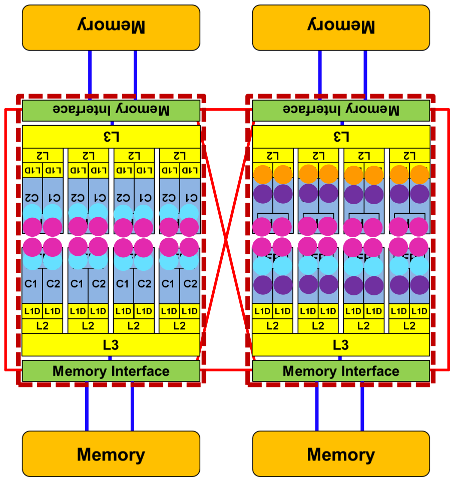
sync overhead nearly topology-independent @ constant thread count

The parallel vector triad benchmark

Inter-chip scaling on Cray XE6 Interlagos node



sync overhead grows with core/chip count



bandwidth scalability across memory interfaces

Some data on synchronization overhead

Welcome to the multi-/many-core era

Synchronization of threads may be expensive!

```
!$OMP PARALLEL …
…
!$OMP BARRIER
!$OMP DO
…
!$OMP ENDDO
!$OMP END PARALLEL
```

Threads are synchronized at **explicit** AND **implicit** barriers. These are a main source of overhead in OpenMP progams.

Determine costs via modified OpenMP Microbenchmarks testcase (epcc)

On x86 systems there is no hardware support for synchronization!

- **Next slide: Test OpenMP Barrier performance…**
- **for different compilers**
- **and different topologies:**
  - **shared cache**
  - **shared socket**
  - **between sockets**
- **and different thread counts**
  - **2 threads**
  - **full domain (chip, socket, node)**

Thread synchronization overhead on AMD Interlagos

OpenMP barrier overhead in CPU cycles

2 Threads	Cray 8.03	GCC 4.6.2	PGI 11.8	Intel 12.1.3
Shared L2	258	3995	1503	128623
Shared L3	698	2853	1076	128611
Same socket	879	2785	1297	128695
Other socket	940	2740 / 4222	1284 / 1325	128718

☹ Intel compiler barrier very expensive on Interlagos

OpenMP & Cray compiler ☺

Full domain	Cray 8.03	GCC 4.6.2	PGI 11.8	Intel 12.1.3
Shared L3	2272	27916	5981	151939
Socket	3783	49947	7479	163561
Node	7663	167646	9526	178892

Thread synchronization overhead on Intel CPUs

pthreads vs. OpenMP vs. Spin loop

2 Threads	Q9550 (shared L2)	i7 920 (shared L3)
pthreads_barrier_wait	**23739**	6511
omp barrier gcc 4.3.3	22603	7333
omp barrier icc 11.0	**399**	**469**
Spin loop	**231**	**270**

Nehalem 2 Threads	Shared SMT threads	shared L3	different socket
pthreads_barrier_wait	**23352**	4796	49237
omp barrier (icc 11.0)	**2761**	**479**	**1206**
Spin loop	17388	**267**	787

pthreads → OS kernel call ☹

Syncing SMT threads is expensive ☹

Spin loop does fine for shared cache sync

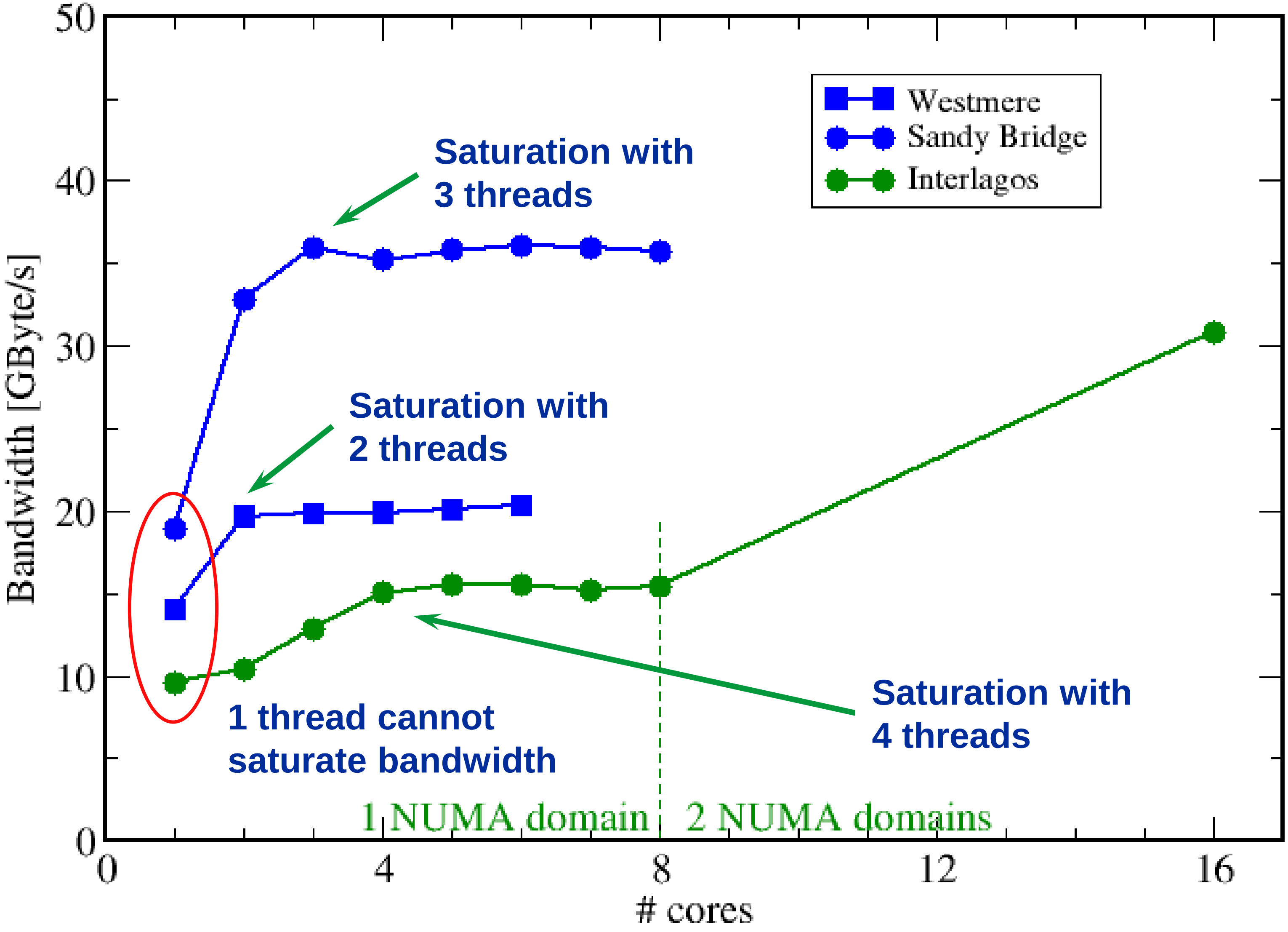
OpenMP & Intel compiler ☺

Bandwidth saturation effects in cache and memory

A look at different processors

Bandwidth limitations: Main Memory

Scalability of shared data paths inside a NUMA domain **(V-Triad)**



Saturation with 3 threads

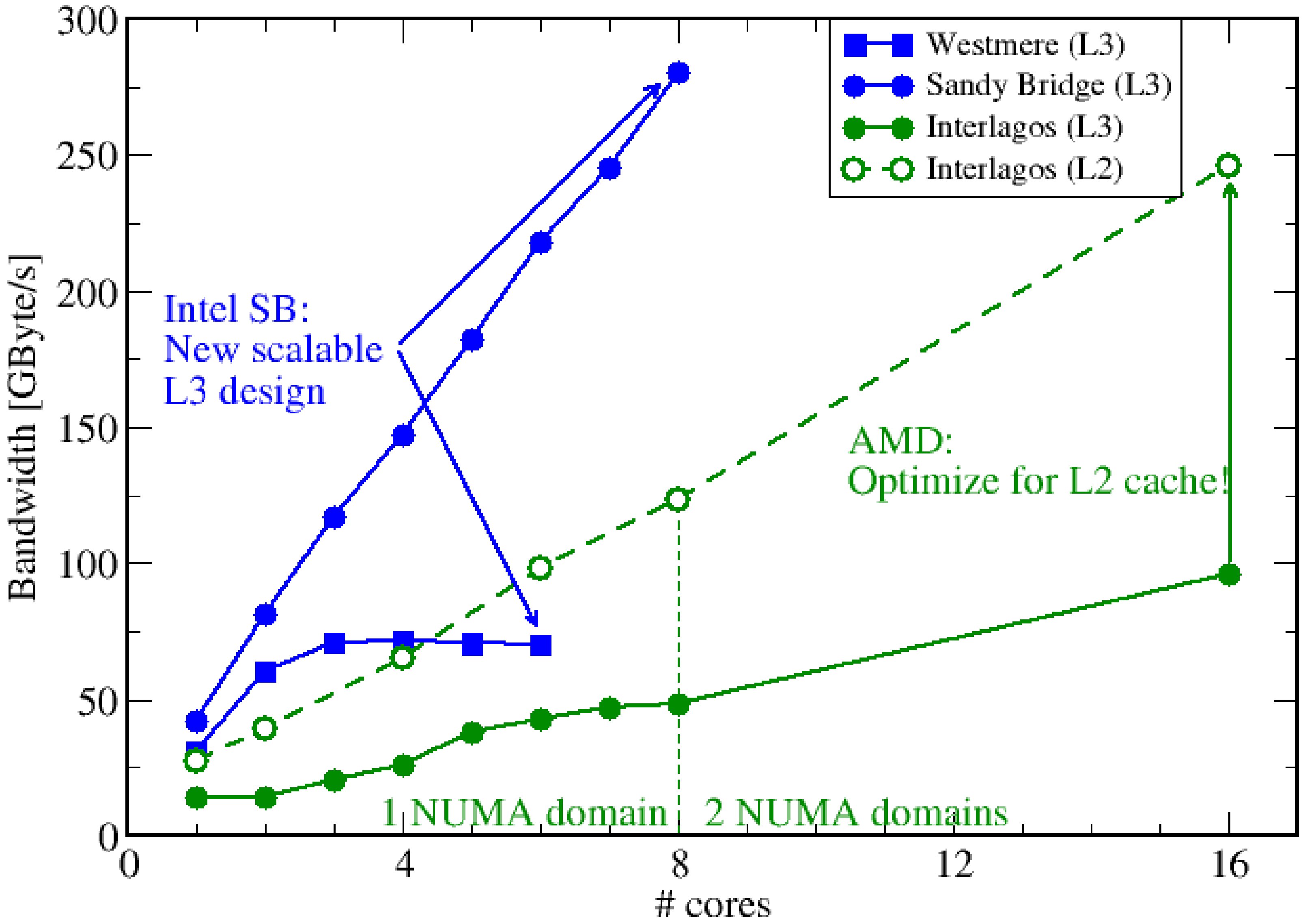
Saturation with 2 threads

1 thread cannot saturate bandwidth

Saturation with 4 threads

Bandwidth limitations: Outer-level cache

Scalability of shared data paths in L3 cache



Conclusions from the data access properties

- **Affinity matters!**
  - Almost all performance properties depend on the position of
    - Data
    - Threads/processes
  - Consequences
    - Know where your threads are running
    - Know where your data is

- **Bandwidth bottlenecks are ubiquitous**

- **Synchronization overhead may be an issue**
  - … and also depends on affinity!

Case study:
OpenMP-parallel sparse matrix-vector multiplication (part 1)

A simple (but sometimes not-so-simple) example for bandwidth-bound code and saturation effects in memory

Case study: Sparse matrix-vector multiply

- **Important kernel in many applications (matrix diagonalization, solving linear systems)**
- **Strongly memory-bound for large data sets**
  - Streaming, with partially indirect access:

```
!$OMP parallel do
do i = 1,N_r
 do j = row_ptr(i), row_ptr(i+1) - 1
  c(i) = c(i) + val(j) * b(col_idx(j))
 enddo
enddo
!$OMP end parallel do
```

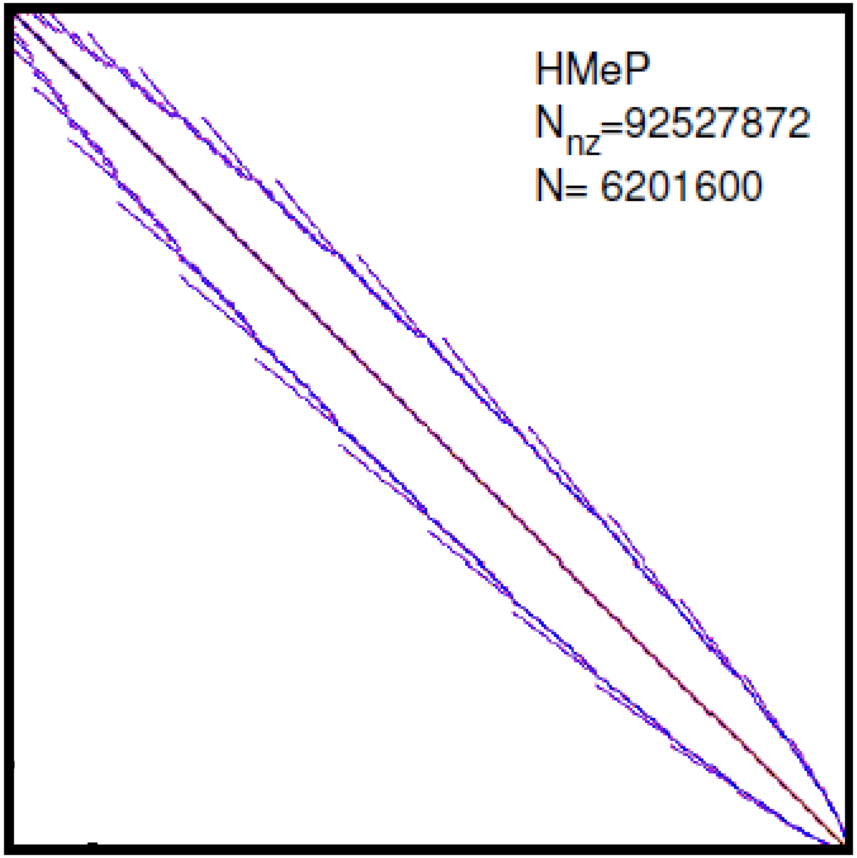
  - Usually many spMVMs required to solve a problem

- **Following slides: Performance data on one 24-core AMD Magny Cours node**

Bandwidth-bound parallel algorithms:
Sparse MVM

- **Data storage format is crucial for performance properties**
  - Most useful general format: Compressed Row Storage (CRS)
  - SpMVM is easily parallelizable in shared and distributed memory

- **For large problems, spMVM is inevitably memory-bound**
  - Intra-LD saturation effect on modern multicores

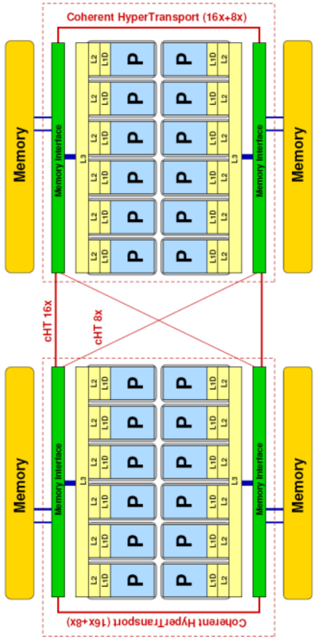


- **MPI-parallel spMVM is often communication-bound**
  - See later part for what we can do about this…

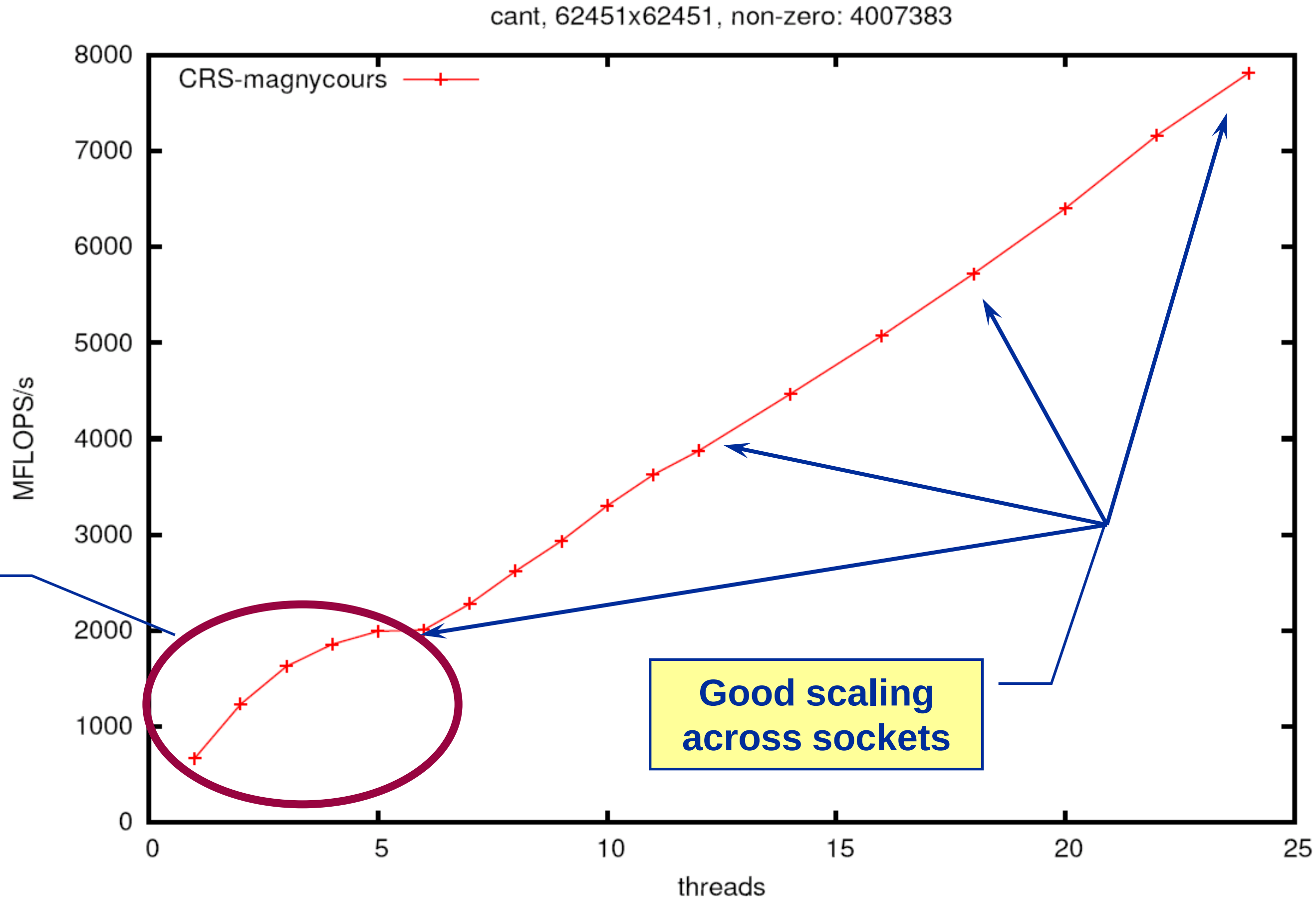
Application: Sparse matrix-vector multiply

Strong scaling on one XE6 Magny-Cours node

- ## Case 1: Large matrix



Intrasocket bandwidth bottleneck

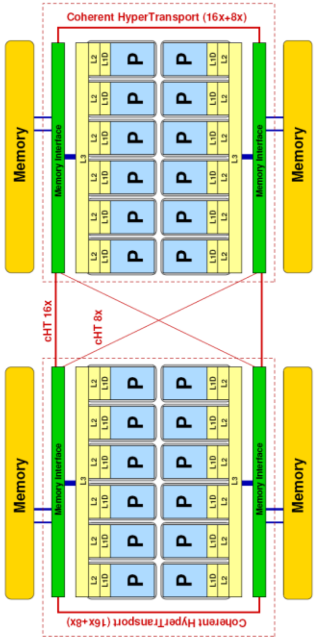


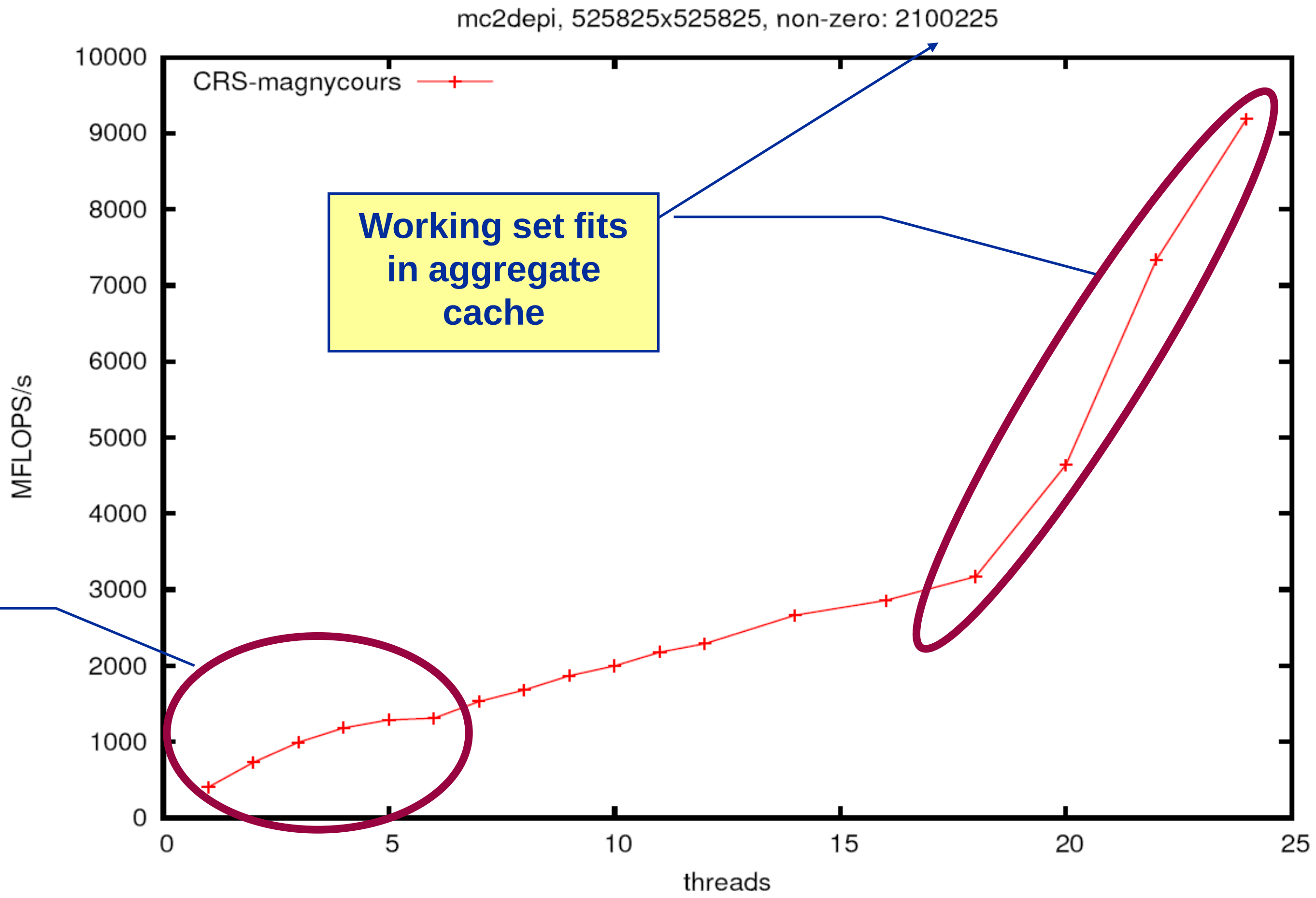
Good scaling across sockets

Application: Sparse matrix-vector multiply

Strong scaling on one XE6 Magny-Cours node

- **Case 2: Medium size**


Coherent HyperTransport (16x+8x)
Memory
Memory Interface
P
L1D
L2
L3
cHT 16x
cHT 8x
Memory
Coherent HyperTransport (16x+8x)



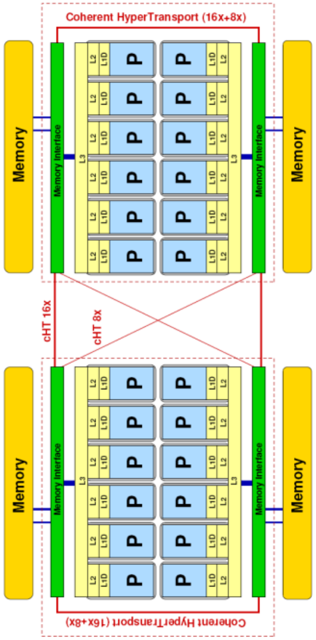
Working set fits in aggregate cache

Intrasocket bandwidth bottleneck

Application: Sparse matrix-vector multiply

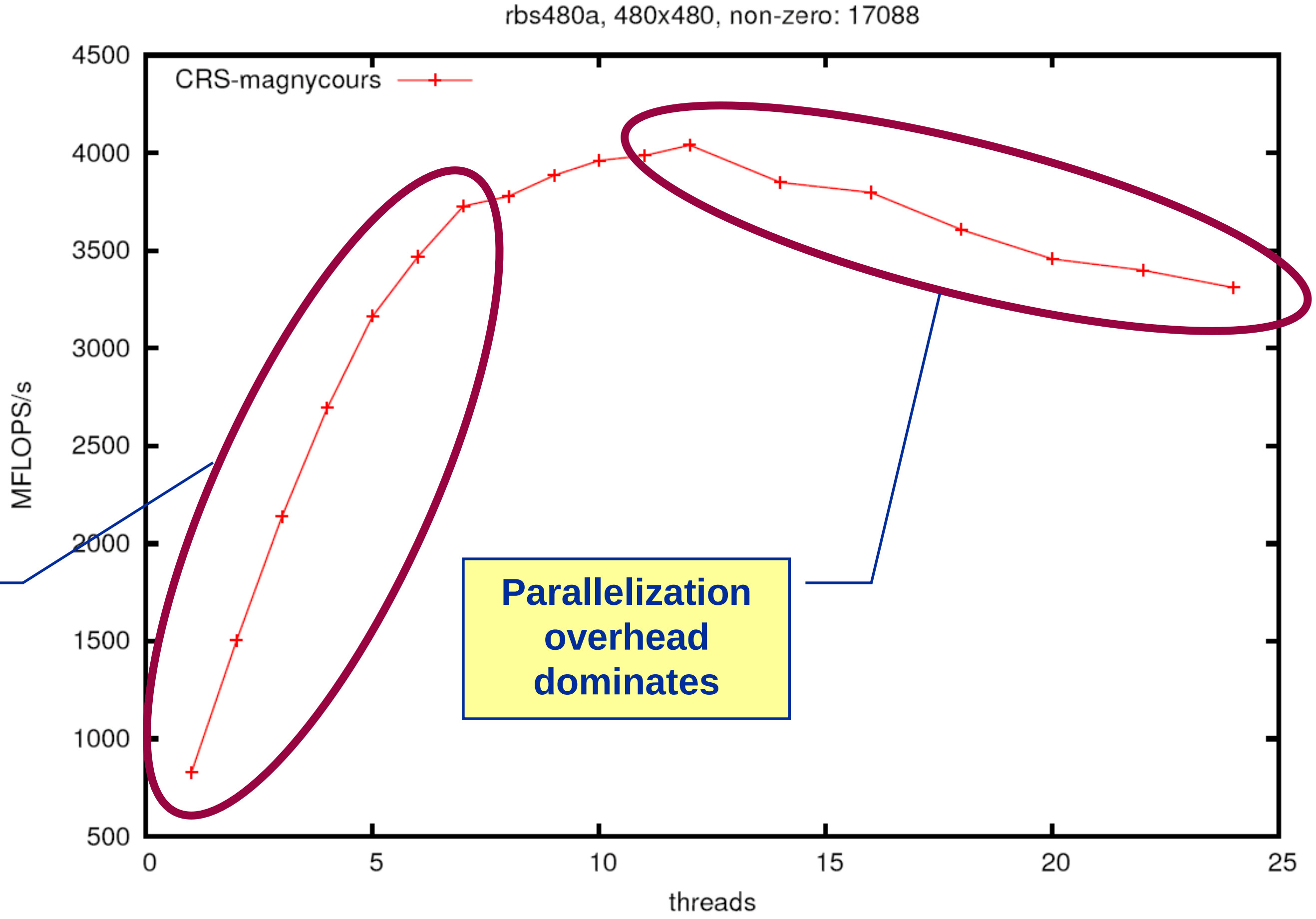
Strong scaling on one Magny-Cours node

- ## Case 3: Small size



Coherent HyperTransport (16x+8x)
Memory
Memory Interface
L3
L2
L1D
P
cHT 16x
cHT 8x
Coherent HyperTransport (16x+8x)

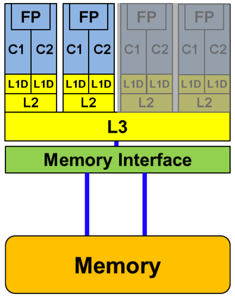
No bandwidth bottleneck

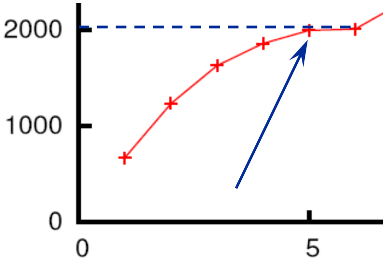


Parallelization overhead dominates

Conclusions from the spMVM benchmarks

- **If the problem is “large”, bandwidth saturation on the socket is a reality**
  - → There are “spare cores”
  - Very common performance pattern
- **What to do with spare cores?**
  - Let them idle → saves energy with minor loss in time to solution
  - Use them for other tasks, such as MPI communication
- **Can we predict the saturated performance?**
  - Bandwidth-based performance modeling!
  - What is the significance of the indirect access? Can it be modeled?
- **Can we predict the saturation point?**
  - … and why is this important?





See later for answers!

The Plan

- Basic multicore architecture
- Data access on modern processors
- Performance properties of multicore/multisocket systems
  - Microbenchmarks
  - Sync overhead
  - Bandwidth saturation
- Case study: Sparse matrix-vector multiply (part 1)
- Multicore performance tools Part 1
  - Probing topology
  - Enforcing affinity
- Hands-On session 1

- Basic performance modeling
  - Balance metrics
  - “Motivated” optimizations
- Case study: 3D Jacobi smoother
- The Roofline Model
- Efficient programming on ccNUMA nodes
- Simultaneous multi-threading (SMT)
  - Theory
  - Implications
  - Facts & fiction
- MPI in multicore environments
  - Intranode vs. internode
  - Rank-subdomain mapping

- Multicore performance tools Part 2
  - Hardware metrics
  - Best practices
- Advanced case studies: Putting cores to better use
  - Wavefront temporal blocking
  - Sparse MVM (part 2)
- Outlook: Advanced performance engineering
  - Sparse MVM (part 3)
  - ECM model
- Conclusions
- Hands-On session 2

Probing node topology

- Standard tools
- likwid-topology

How do we figure out the node topology?

- **Topology =**
  - Where in the machine does core #n reside? And do I have to remember this awkward numbering anyway?
  - Which cores share which cache levels?
  - Which hardware threads (“logical cores”) share a physical core?
- **Linux**
  - `cat /proc/cpuinfo` is of limited use
  - Core numbers may change across kernels and BIOSes even on identical hardware
  - **`numactl --hardware`** prints ccNUMA node information ➔
  - Information on caches is harder to obtain

```
$ numactl --hardware
available: 4 nodes (0-3)
node 0 cpus: 0 1 2 3 4 5
node 0 size: 8189 MB
node 0 free: 3824 MB
node 1 cpus: 6 7 8 9 10 11
node 1 size: 8192 MB
node 1 free: 28 MB
node 2 cpus: 18 19 20 21 22 23
node 2 size: 8192 MB
node 2 free: 8036 MB
node 3 cpus: 12 13 14 15 16 17
node 3 size: 8192 MB
node 3 free: 7840 MB
```

Likwid Lightweight Performance Tools

- Lightweight command line tools for Linux
- Help to face the challenges without getting in the way
- Focus on X86 architecture

- Philosophy:
  - Simple
  - Efficient
  - Portable
  - Extensible

Open source project (GPL v2):

http://code.google.com/p/likwid/

likwid-topology – Topology information

- **Based on `cpuid` information**
- **Functionality:**
  - Measured clock frequency
  - Thread topology
  - Cache topology
  - Cache parameters (-c command line switch)
  - ASCII art output (-g command line switch)
- **Currently supported (more under development):**
  - Intel Core 2 (45nm + 65 nm)
  - Intel Nehalem + Westmere (Sandy Bridge in beta phase)
  - AMD K10 (Quadcore and Hexacore)
  - AMD K8
  - Linux OS

Output of `likwid-topology -g`

on one node of Cray XE6 “Hermit”

```
-------------------------------------------------------------
CPU type:       AMD Interlagos processor
*************************************************************
Hardware Thread Topology
*************************************************************
Sockets:                2
Cores per socket:       16
Threads per core:       1
-------------------------------------------------------------
HWThread        Thread          Core            Socket
0               0               0               0
1               0               1               0
2               0               2               0
3               0               3               0
[...]
16              0               0               1
17              0               1               1
18              0               2               1
19              0               3               1
[...]
-------------------------------------------------------------
Socket 0: ( 0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 )
Socket 1: ( 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 )
-------------------------------------------------------------

*************************************************************
Cache Topology
*************************************************************
Level:  1
Size:   16 kB
Cache groups:   ( 0 ) ( 1 ) ( 2 ) ( 3 ) ( 4 ) ( 5 ) ( 6 ) ( 7 ) ( 8 ) ( 9 ) ( 10 ) ( 11 ) ( 12 ) ( 13
) ( 14 ) ( 15 ) ( 16 ) ( 17 ) ( 18 ) ( 19 ) ( 20 ) ( 21 ) ( 22 ) ( 23 ) ( 24 ) ( 25 ) ( 26 ) ( 27 ) (
28 ) ( 29 ) ( 30 ) ( 31 )
```

Output of likwid-topology continued

```
-------------------------------------------------------------
Level:  2
Size:   2 MB
Cache groups:   ( 0 1 ) ( 2 3 ) ( 4 5 ) ( 6 7 ) ( 8 9 ) ( 10 11 ) ( 12 13 ) ( 14 15 ) ( 16 17 ) ( 18
19 ) ( 20 21 ) ( 22 23 ) ( 24 25 ) ( 26 27 ) ( 28 29 ) ( 30 31 )
-------------------------------------------------------------
Level:  3
Size:   6 MB
Cache groups:   ( 0 1 2 3 4 5 6 7 ) ( 8 9 10 11 12 13 14 15 ) ( 16 17 18 19 20 21 22 23 ) ( 24 25 26
27 28 29 30 31 )
-------------------------------------------------------------

*************************************************************
NUMA Topology
*************************************************************
NUMA domains: 4
-------------------------------------------------------------
Domain 0:
Processors:  0 1 2 3 4 5 6 7
Memory: 7837.25 MB free of total 8191.62 MB
-------------------------------------------------------------
Domain 1:
Processors:  8 9 10 11 12 13 14 15
Memory: 7860.02 MB free of total 8192 MB
-------------------------------------------------------------
Domain 2:
Processors:  16 17 18 19 20 21 22 23
Memory: 7847.39 MB free of total 8192 MB
-------------------------------------------------------------
Domain 3:
Processors:  24 25 26 27 28 29 30 31
Memory: 7785.02 MB free of total 8192 MB
-------------------------------------------------------------
```

Output of likwid-topology continued

```
********************************************************************
Graphical:
********************************************************************
Socket 0:
+-----------------------------------------------------------------------------------------------------------------------------------------------------------------+
| +-------+ +-------+ +-------+ +-------+ +-------+ +-------+ +-------+ +-------+ +-------+ +-------+ +-------+ +-------+ +-------+ +-------+ +-------+ +-------+ |
| |   0   | |   1   | |   2   | |   3   | |   4   | |   5   | |   6   | |   7   | |   8   | |   9   | |  10   | |  11   | |  12   | |  13   | |  14   | |  15   | |
| +-------+ +-------+ +-------+ +-------+ +-------+ +-------+ +-------+ +-------+ +-------+ +-------+ +-------+ +-------+ +-------+ +-------+ +-------+ +-------+ |
| +-------+ +-------+ +-------+ +-------+ +-------+ +-------+ +-------+ +-------+ +-------+ +-------+ +-------+ +-------+ +-------+ +-------+ +-------+ +-------+ |
| | 16kB  | | 16kB  | | 16kB  | | 16kB  | | 16kB  | | 16kB  | | 16kB  | | 16kB  | | 16kB  | | 16kB  | | 16kB  | | 16kB  | | 16kB  | | 16kB  | | 16kB  | | 16kB  | |
| +-------+ +-------+ +-------+ +-------+ +-------+ +-------+ +-------+ +-------+ +-------+ +-------+ +-------+ +-------+ +-------+ +-------+ +-------+ +-------+ |
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| |  16   | |  17   | |  18   | |  19   | |  20   | |  21   | |  22   | |  23   | |  24   | |  25   | |  26   | |  27   | |  28   | |  29   | |  30   | |  31   | |
| +-------+ +-------+ +-------+ +-------+ +-------+ +-------+ +-------+ +-------+ +-------+ +-------+ +-------+ +-------+ +-------+ +-------+ +-------+ +-------+ |
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| |                                     6MB                                     | |                                     6MB                                     | |
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```

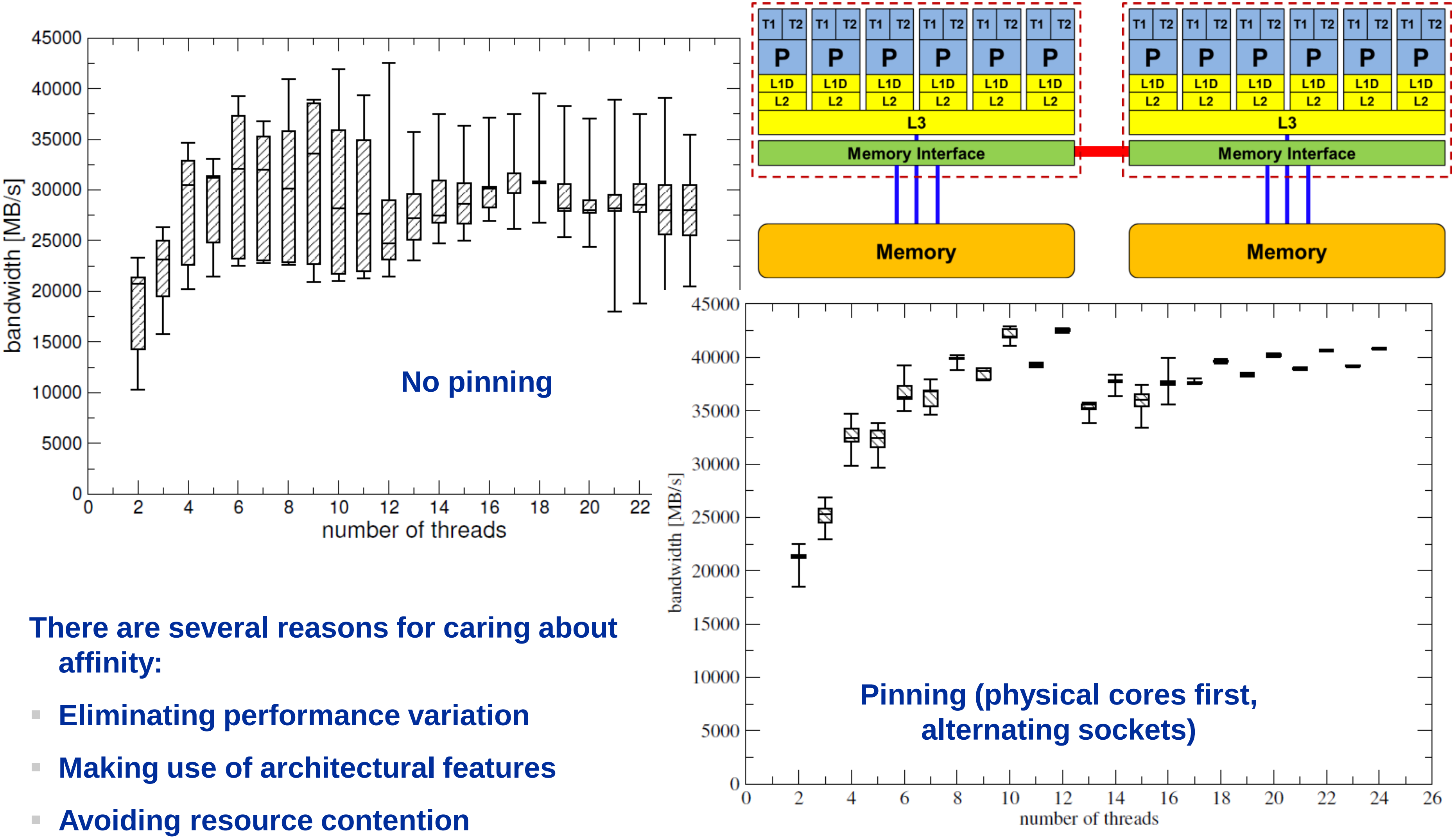
Enforcing thread/process-core affinity under the Linux OS

Standard tools and OS affinity facilities under program control

likwid-pin

Motivation: STREAM benchmark on 12-core Intel Westmere

Anarchy vs. thread pinning



No pinning

Pinning (physical cores first, alternating sockets)

There are several reasons for caring about affinity:

- Eliminating performance variation
- Making use of architectural features
- Avoiding resource contention

Generic thread/process-core affinity under Linux

Overview

- `taskset [OPTIONS] [MASK | -c LIST ] \`
  `[PID | command [args]...]`

- `taskset` binds processes/threads to a *set of CPUs*. Examples:

```
taskset 0x0006 ./a.out
taskset -c 4 33187
mpirun -np 2 taskset -c 0,2 ./a.out # doesn't always work
```

- Processes/threads can still move within the set!
- Alternative: let process/thread bind itself by executing syscall

```
#include <sched.h>
int sched_setaffinity(pid_t pid, unsigned int len,
                      unsigned long *mask);
```

- Disadvantage: which CPUs should you bind to on a non-exclusive machine?

- Still of value on multicore/multisocket cluster nodes, UMA or ccNUMA

Generic thread/process-core affinity under Linux

- **Complementary tool: `numactl`**

  Example: `numactl --physcpubind=0,1,2,3 command [args]`
  Bind process to specified physical core numbers

  Example: `numactl --cpunodebind=1 command [args]`
  Bind process to specified ccNUMA node(s)

- **Many more options (e.g., interleave memory across nodes)**
  - → see section on ccNUMA optimization

- **Diagnostic command (see earlier):**
  `numactl --hardware`

- **Again, this is not suitable for a shared machine**

More thread/Process-core affinity ("pinning") options

- **Highly OS-dependent system calls**
  - But available on all systems

Linux:	**`sched_setaffinity()`**, PLPA (see below) → hwloc
Solaris:	**`processor_bind()`**
Windows:	**`SetThreadAffinityMask()`**
…	

- **Support for "semi-automatic" pinning in some compilers/environments**
  - Intel compilers > V9.1 (**`KMP_AFFINITY`** environment variable)
  - PGI, Pathscale, GNU
  - SGI Altix **`dplace`** (works with logical CPU numbers!)
  - Generic Linux: **`taskset`**, **`numactl`**, **`likwid-pin`** (see below)
- **Affinity awareness in MPI libraries**
  - SGI MPT
  - OpenMPI
  - Intel MPI
  - …

If combined with OpenMP, issues may arise

Likwid-pin

Overview

- **Part of the LIKWID tool suite: `http://code.google.com/p/likwid`**
- **Pins processes and threads to specific cores without touching code**
- **Directly supports pthreads, gcc OpenMP, Intel OpenMP**
  - Detects OpenMP implementation automatically
- **Based on combination of wrapper tool together with overloaded pthread library → binary must be dynamically linked!**
- **Can also be used as a superior replacement for taskset**

- **Usage examples:**
  - **Physical numbering:**

```
likwid-pin -c 0,2,4-6  ./myApp parameters
```

  - **Logical numbering (4 cores on socket 0) with “skip mask” specified:**

```
likwid-pin -s 3 -c S0:0-3 ./myApp parameters
```

Likwid-pin

Example: Intel OpenMP

- **Running the STREAM benchmark with likwid-pin:**

```
$ export OMP_NUM_THREADS=4
$ likwid-pin -s 0x1 -c 0,1,4,5 ./stream
[likwid-pin] Main PID -> core 0 - OK
----------------------------------------------
 Double precision appears to have 16 digits of accuracy
 Assuming 8 bytes per DOUBLE PRECISION word
----------------------------------------------
[... some STREAM output omitted ...]
 The *best* time for each test is used
 *EXCLUDING* the first and last iterations
[pthread wrapper] PIN_MASK: 0->1  1->4  2->5
[pthread wrapper] SKIP MASK: 0x1
[pthread wrapper 0] Notice: Using libpthread.so.0
        threadid 1073809728 -> SKIP
[pthread wrapper 1] Notice: Using libpthread.so.0
        threadid 1078008128 -> core 1 - OK
[pthread wrapper 2] Notice: Using libpthread.so.0
        threadid 1082206528 -> core 4 - OK
[pthread wrapper 3] Notice: Using libpthread.so.0
        threadid 1086404928 -> core 5 - OK
[... rest of STREAM output omitted ...]
```

Main PID always pinned

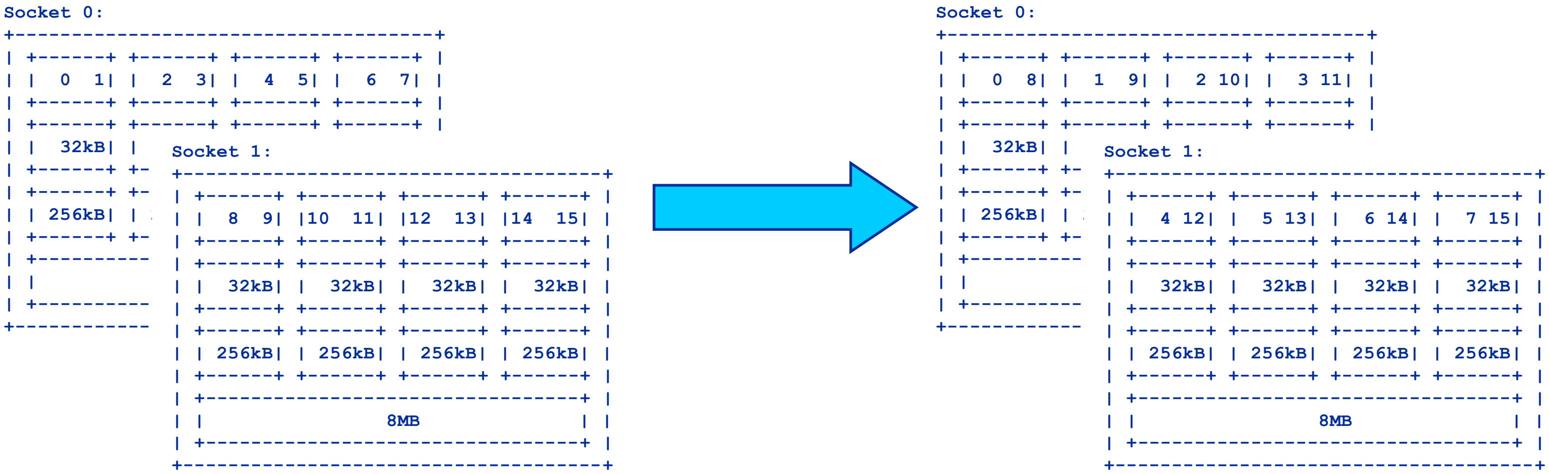
Skip shepherd thread

Pin all spawned threads in turn

Likwid-pin

Using logical core numbering

- **Core numbering may vary from system to system even with identical hardware**
  - Likwid-topology delivers this information, which can then be fed into likwid-pin
- **Alternatively, likwid-pin can abstract this variation and provide a purely logical numbering (physical cores first)**



```
Socket 0:
+-------------------------------------+
| +-------+ +-------+ +-------+ +-------+ |
| |  0  1| |  2  3| |  4  5| |  6  7| |
| +-------+ +-------+ +-------+ +-------+ |
| +-------+ +-------+ +-------+ +-------+ |
| |  32kB| |
| +-------+ +-
| +-------+ +-
| | 256kB| |
| +-------+ +-
| +-----------
| |
| +-----------
+------------
```

```
Socket 1:
+-------------------------------------+
| +-------+ +-------+ +-------+ +-------+ |
| |  8  9| |10  11| |12  13| |14  15| |
| +-------+ +-------+ +-------+ +-------+ |
| +-------+ +-------+ +-------+ +-------+ |
| |  32kB| |  32kB| |  32kB| |  32kB| |
| +-------+ +-------+ +-------+ +-------+ |
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| | 256kB| | 256kB| | 256kB| | 256kB| |
| +-------+ +-------+ +-------+ +-------+ |
| +---------------------------------+ |
| |              8MB                | |
| +---------------------------------+ |
+-------------------------------------+
```

```
Socket 0:
+-------------------------------------+
| +-------+ +-------+ +-------+ +-------+ |
| |  0  8| |  1  9| |  2 10| |  3 11| |
| +-------+ +-------+ +-------+ +-------+ |
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| |  32kB| |
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| | 256kB| |
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```

```
Socket 1:
+-------------------------------------+
| +-------+ +-------+ +-------+ +-------+ |
| |  4 12| |  5 13| |  6 14| |  7 15| |
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| |              8MB                | |
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+-------------------------------------+
```

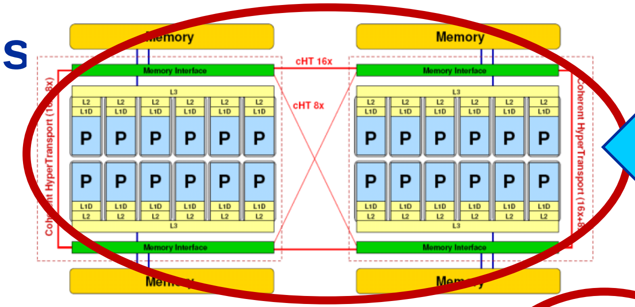
  - Across all cores in the node:
    `OMP_NUM_THREADS=8 likwid-pin -c N:0-7 ./a.out`
  - Across the cores in each socket and across sockets in each node:
    `OMP_NUM_THREADS=8 likwid-pin -c S0:0-3@S1:0-3 ./a.out`

Likwid-pin

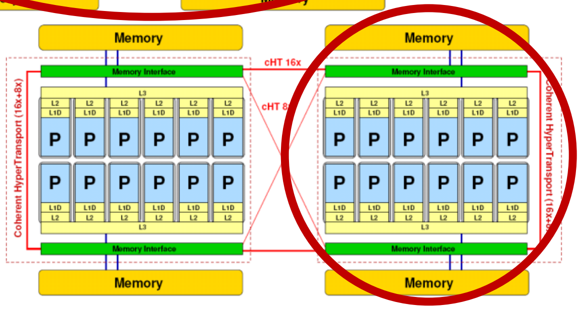
Using logical core numbering

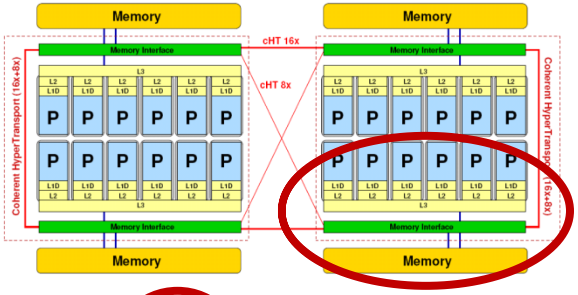
- **Possible unit prefixes**

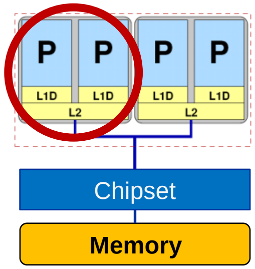
N	**node**
S	**socket**
M	**NUMA domain**
C	**outer level cache group**



Default if –c is not specified!







likwid-mpirun

MPI startup and Hybrid pinning

- How do you manage **affinity with MPI or hybrid MPI/threading?**
- In the long run a unified standard is needed
- Till then, **likwid-mpirun** provides a portable/flexible solution
- The examples here are for Intel MPI/OpenMP programs, but are also applicable to other threading models

Pure MPI:

```
$ likwid-mpirun -np 16 -nperdomain S:2 ./a.out
```

Hybrid:

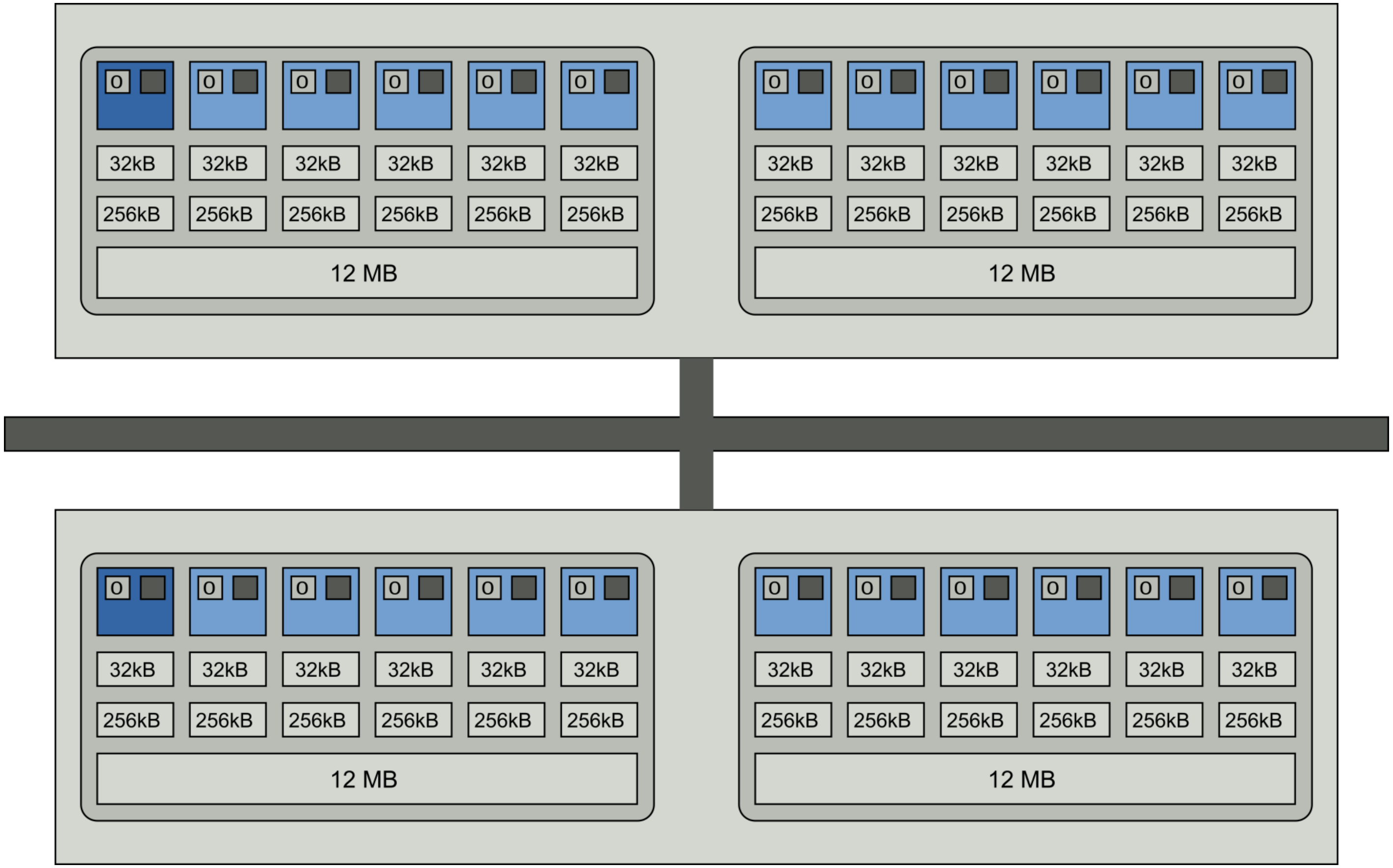
```
$ likwid-mpirun -np 16 -pin S0:0,1_S1:0,1 ./a.out
```

likwid-mpirun

1 MPI process per node

SKIPPED

```
likwid-mpirun -np 2 -pin N:0-11  ./a.out
```



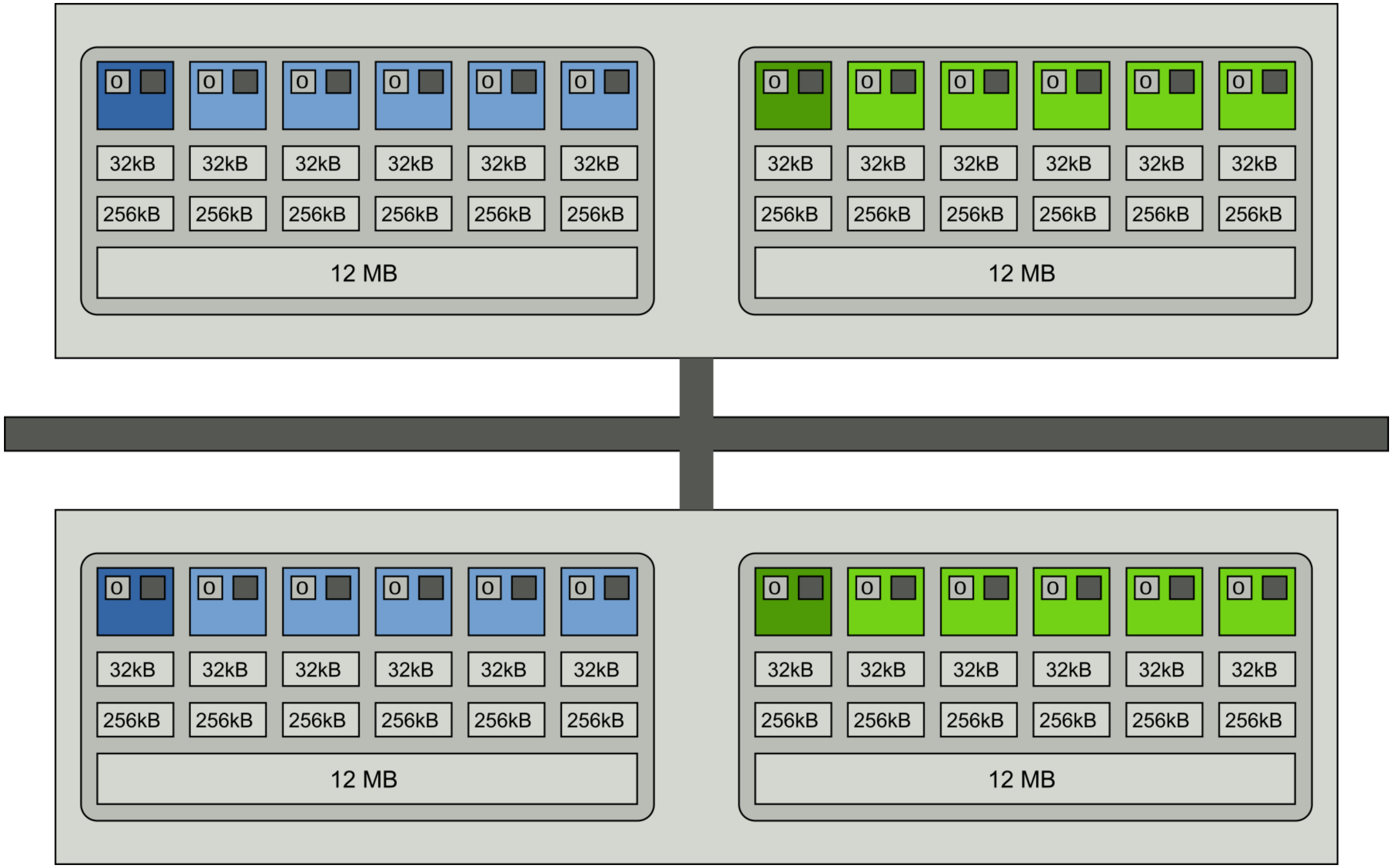
Intel MPI+compiler:

```
OMP_NUM_THREADS=12 mpirun -ppn 1 -np 2 -env KMP_AFFINITY scatter ./a.out
```

likwid-mpirun

1 MPI process per socket

```
likwid-mpirun -np 4 -pin S0:0-5_S1:0-5 ./a.out
```



Intel MPI+compiler:

```
OMP_NUM_THREADS=6 mpirun -ppn 2 -np 4 \
     -env I_MPI_PIN_DOMAIN socket -env KMP_AFFINITY scatter ./a.out
```

likwid-mpirun

Integration of likwid-perfctr

SKIPPED

- likwid-mpirun can optionally set up likwid-perfctr for you

```
$ likwid-mpirun -np 16 -nperdomain S:2 -perf FLOPS_DP \
     -marker -mpi intelmpi  ./a.out
```

- likwid-mpirun generates an intermediate perl script which is called by the native MPI start mechanism
- According the MPI rank the script pins the process and threads

- If you use perfctr after the run for each process a file in the format `Perf-<hostname>-<rank>.txt`

  Its output which contains the perfctr results.

- In the future analysis scripts will be added which generate reports of the raw data (e.g. as html pages)

The Plan

Basic multicore architecture

Data access on modern processors

Performance properties of multicore/multisocket systems

Micro-benchmarks

Sync overhead

Bandwidth saturation

Case study: Sparse matrix-vector multiply (part 1)

Multicore performance tools Part 1

Probing topology

Enforcing affinity

Hands-On session 1

Basic performance modeling

Balance metrics

“Motivated” optimizations

Case study:
3D Jacobi smoother

The Roofline Model

Efficient programming on ccNUMA nodes

Simultaneous multi-threading (SMT)

Theory

Implications

Facts & fiction

MPI in multicore environments

Intranode vs. internode

Rank-subdomain mapping

Multicore performance tools Part 2

Hardware metrics

Best practices

Advanced case studies:
Putting cores to better use

Wavefront temporal blocking

Sparse MVM (part 2)

Outlook: Advanced performance engineering

Sparse MVM (part 3)

ECM model

Conclusions

Hands-On session 2

The Plan

Basic multicore architecture

Data access on modern processors

Performance properties of multicore/multisocket systems

- Micro-benchmarks
- Sync overhead
- Bandwidth saturation

Case study: Sparse matrix-vector multiply (part 1)

Multicore performance tools Part 1

- Probing topology
- Enforcing affinity

Hands-On session 1

Basic performance modeling

- Balance metrics
- "Motivated" optimizations

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Simultaneous multi-threading (SMT)

- Theory
- Implications
- Facts & fiction

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- Intranode vs. internode
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Multicore performance tools Part 2

- Hardware metrics
- Best practices

Advanced case studies: Putting cores to better use

- Wavefront temporal blocking
- Sparse MVM (part 2)

Outlook: Advanced performance engineering

- Sparse MVM (part 3)
- ECM model

Conclusions

Hands-On session 2

Basic performance modeling and “motivated optimizations”

Machine and code balance

Example: The Jacobi smoother

The Roofline Model

Balance metric: Machine balance

- The **machine balance** for data memory access of a specific computer is given by (architectural limitation)

$$\boxed{B_m = \frac{b_S\,[\text{words/s}]}{P_{\max}\,[\text{flops/s}]}}$$

- Bandwidth: 1 W = 8 bytes = 64 bits
  b_S = achievable bandwidth over the slowest data path

  Floating point peak: $P_{\max}$

- **Machine Balance** = How many input operands can be delivered for each FP operation?

- Typical values (main memory):

  AMD Interlagos (2.3 GHz): $B_m = \{(17/8)\ \text{GW/s}\} / \{4 \times 2.3 \times 8\ \text{GFlop/s}\}$ ~**0.029 W/F**

  Intel Sandy Bridge EP (2.7 GHz): ~**0.025 W/F**

  NEC SX9 (vector): ~**0.3 W/F**

  nVIDIA GTX480 ~**0.026 W/F**

Machine Balance: Typical values beyond main memory

Data path	Balance B_M [W/F]
Cache	0.5 – 1.0
Machine (main memory)	0.01 – 0.5
Interconnect (Infiniband)	0.001 – 0.002
Interconnect (GBit ethernet)	0.0001 – 0.0007
Disk (or disk subsystem)	0.0001 – 0.001

Double precision: W ←→ 64-Bit

$1/B_M$ = “Computational Intensity”: How many FP ops can be performed before FP performance becomes a bottleneck?

Balance metric: Code balance & lightspeed estimates

- B_M tells us what the hardware can deliver at most
- **Code balance (B_C) quantifies the requirements of the code:**

$$B_c = \frac{\text{data transfer (LD/ST) } [\textit{words}]}{\text{arithmetic operations} [\textit{flops}]}$$

- **Expected fraction of peak performance („lightspeed"):**
  l =1 → code is not limited by bandwidth

$$l = \min\left(1, \frac{B_m}{B_c}\right)$$

This is what we get

This is what we need

- **Lightspeed for absolute performance: ($P_{\max}$: "applicable" peak performance)**

$$P = l \cdot P_{\max} = \min\left(P_{\max}, \frac{b_S}{B_C}\right)$$

- **Example: Vector triad `A(:)=B(:)+C(:)*D(:)` on 2.3 GHz Interlagos**
  - B_c = (4+1) Words / 2 Flops = 2.5 W/F (including write allocate)

    B_m/B_c = 0.029/2.5 = 0.012, i.e. **1.2 % of peak performance (~1.7 GF/s)**

Balance metric (a.k.a. the "roofline model")

- **The balance metric formalism is based on some (crucial) assumptions:**
  - The code makes balanced use of MULT and ADD operation. For others (e.g. A=B+C) the peak performance input parameter P_{max} has to be adjusted (e.g. $P_{max} \rightarrow P_{max}/2$)
  - Attainable bandwidth of code = input parameter! Determine effective bandwidth via simple streaming benchmarks to model more complex kernels and applications.
  - Definition is based on 64-bit arithmetic but can easily be adjusted, e.g. for 32-bit
  - Data transfer and arithmetic overlap perfectly!
  - Slowest data path is modeled only; all others are assumed to be infinitely fast
  - Latency effects are ignored, i.e. perfect streaming mode

Balance metric: 2D diffusion equation + Jacobi solver

- **Diffusion equation in 2D** $$\frac{\partial \Phi}{\partial t} = \Delta\Phi$$

- **Stationary solution with Dirichlet boundary conditions using Jacobi iteration scheme can be obtained with:**

```
double precision, dimension(0:imax+1,0:kmax+1,0:1) :: phi
integer :: t0,t1
t0 = 0 ; t1 = 1
do it = 1,itmax    ! choose suitable number of sweeps
  do k = 1,kmax
    do i = 1,imax
      ! four flops, one store, four loads
      phi(i,k,t1) = (  phi(i+1,k,t0) + phi(i-1,k,t0)
                     + phi(i,k+1,t0) + phi(i,k-1,t0) ) * 0.25
    enddo
  enddo
  ! swap arrays
  i = t0 ; t0=t1 ; t1=i
enddo
```

Reuse when computing `phi(i+2,k,t1)`

WRITE ALLOCATE:
LD + ST `phi(i,k,t1)`

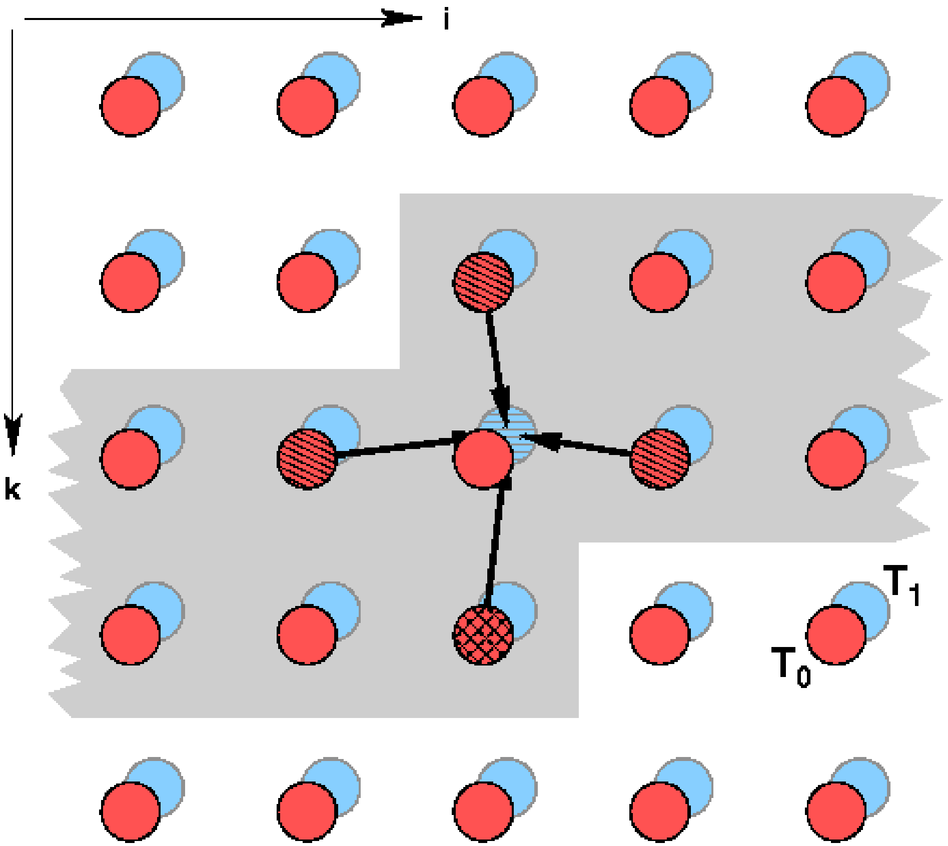
Balance (crude estimate incl. write allocate):

`phi(:,:,t0)`: 3 LD +
`phi(:,:,t1)`: 1 ST+ 1LD

→ B_C = 5 W / 4 FLOPs = 1.25 W / F

Balance metric: 2 D Jacobi

- **Modern cache subsystems may further reduce memory traffic**



If cache is large enough to hold at least 2 rows (shaded region): Each `phi(:,:,t0)` is loaded once from main memory and reused 3 times from cache:

`phi(:,:,t0)`: 1 LD + `phi(:,:,t1)`: 1 ST+ 1LD
→B_C = 3 W / 4 F = 0.75 W / F

If cache is large enough to hold at least one row `phi(:,k-1,t0)` needs to be reloaded:

`phi(:,:,t0)`: 2 LD + `phi(:,:,t1)`: 1 ST+ 1LD
→B_C = 4 W / 4 F = 1.0 W / F

Beyond that:
`phi(:,:,t0)`: 2 LD + `phi(:,:,t1)`: 1 ST+ 1LD
→B_C = 5 W / 4 F = 1.25 W / F

Performance metrics: 2D Jacobi

- **Alternative implementation ("Macho FLOP version")**

```
do k = 1,kmax
  do i = 1,imax
     phi(i,k,t1) =  0.25 * phi(i+1,k,t0) + 0.25 * phi(i-1,k,t0)
                  + 0.25 * phi(i,k+1,t0) + 0.25 * phi(i,k-1,t0)
  enddo
enddo
```

- **MFlops/sec increases by 7/4 but time to solution remains the same**

- **Better metric (for many iterative stencil schemes):**
  Lattice Site Updates per Second (LUPs/sec)

  2D Jacobi example: Compute LUPs/sec metric via

$$P[MLUPs/s] = \frac{it_{\mathrm{max}} \cdot i_{\mathrm{max}} \cdot k_{\mathrm{max}}}{T_{\mathrm{wall}}}$$

Balance metric for 3D Jacobi

- **3D sweep:**

```
do k=1,kmax
 do j=1,jmax
  do i=1,imax
   phi(i,j,k,t1) = oos *(phi(i-1,j,k,t0)+phi(i+1,j,k,t0) &
                       + phi(i,j-1,k,t0)+phi(i,j+1,k,t0) &
                       + phi(i,j,k-1,t0)+phi(i,j,k+1,t0))
  enddo
 enddo
enddo
```

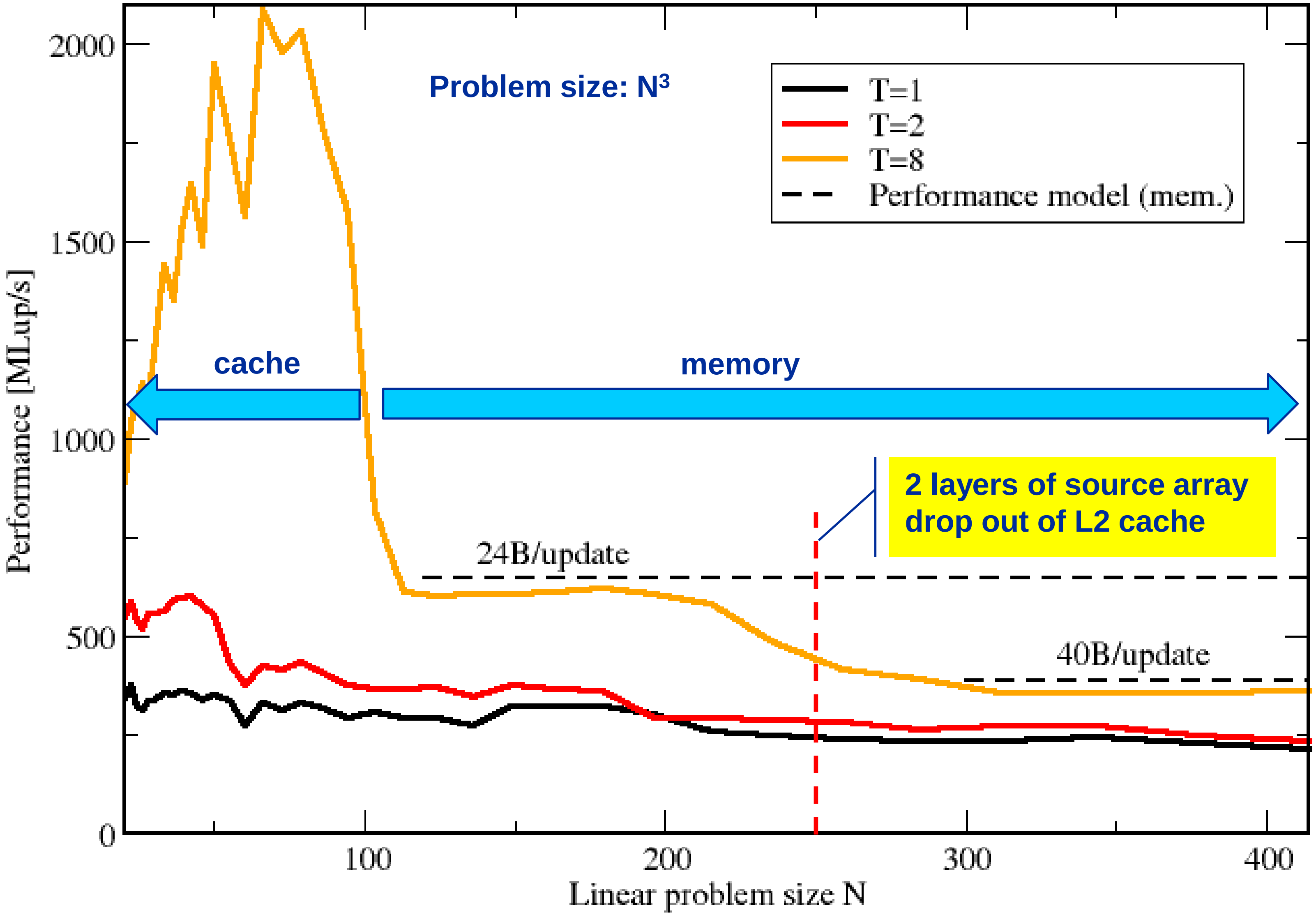
- **Best case balance:** 1 LD `phi(i,j,k+1,t0)`
  1 ST + 1 write allocate `phi(i,j,k,t1)`
  6 flops

→ B_C = 0.5 W/F (24 bytes/update)

- No 2-layer condition but 2 rows fit: B_C = 5/6 W/F (40 bytes/update)
- Worst case (2 rows do not fit): B_C = 7/6 W/F (56 bytes/update)

3D Jacobi solver

Performance of vanilla code on one Interlagos chip (8 cores)



Conclusions from the Jacobi example

- **We have made sense of the memory-bound performance vs. problem size**
  - “Layer conditions” lead to predictions of code balance
  - Achievable memory bandwidth is input parameter

- **The model works only if the bandwidth is “saturated”**
  - In-cache modeling is more involved

- **Optimization == reducing the code balance by code transformations**
  - See below

Data access optimizations

General considerations

Case study: Optimizing a Jacobi solver

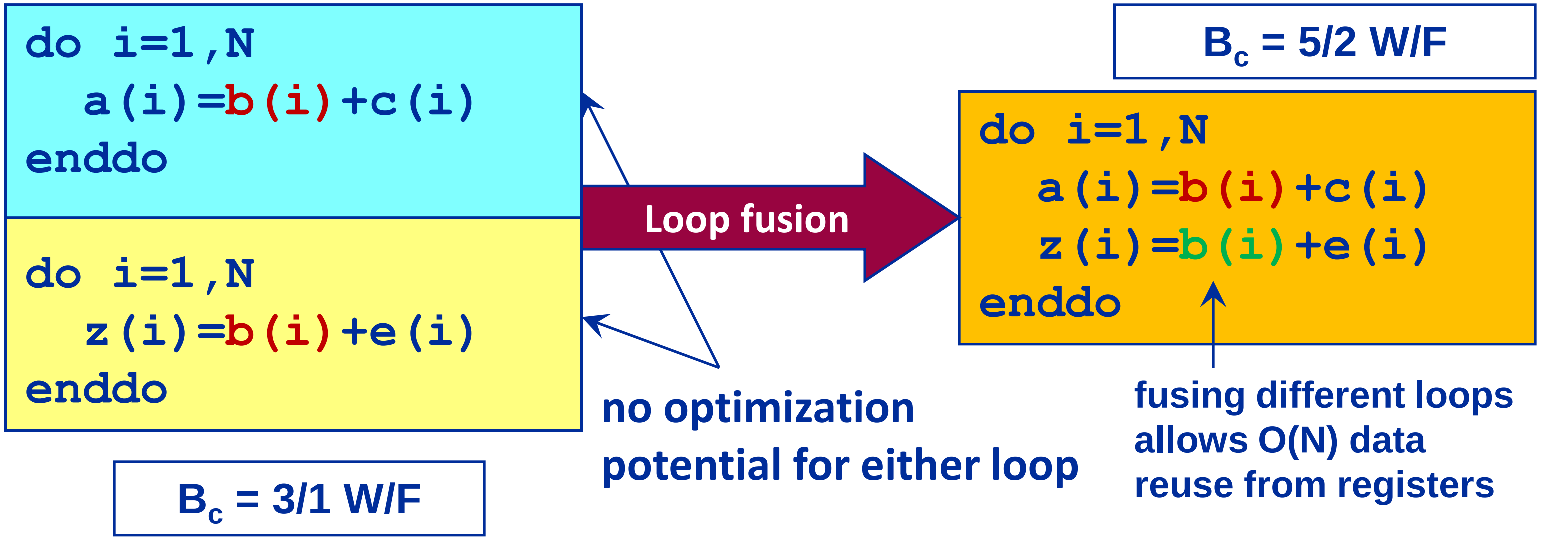
Premise

Data access is the most prevalent performance-limiting factor in computing

Data access – general considerations

optional

- **Case 1: O(N)/O(N) Algorithms**
  - O(N) arithmetic operations vs. O(N) data access operations
  - Examples: Scalar product, vector addition, sparse MVM etc.
  - Performance limited by memory BW for large N (“memory bound”)
  - Limited optimization potential for single loops
    - …at most a constant factor for multi-loop operations
  - Example: successive vector additions



```
do i=1,N
  a(i)=b(i)+c(i)
enddo
```

```
do i=1,N
  z(i)=b(i)+e(i)
enddo
```

B_c = 3/1 W/F

no optimization potential for either loop

B_c = 5/2 W/F

```
do i=1,N
  a(i)=b(i)+c(i)
  z(i)=b(i)+e(i)
enddo
```

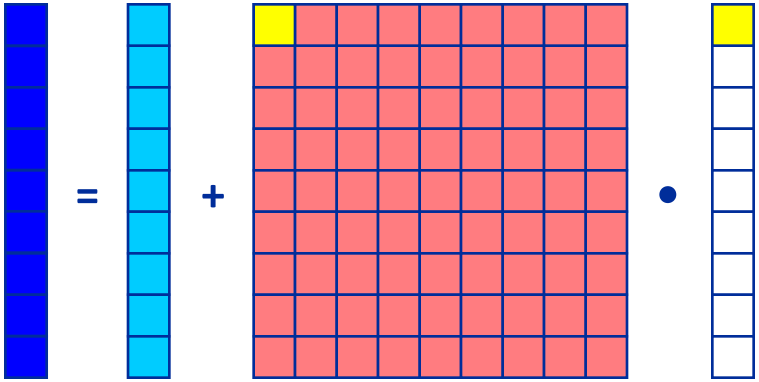
fusing different loops allows O(N) data reuse from registers

Data access – general guidelines

optional

- **Case 2: $O(N^2)/O(N^2)$ algorithms**
  - Examples: dense matrix-vector multiply, matrix addition, dense matrix transposition etc.
    - Nested loops
  - Memory bound for large N
  - Some optimization potential (at most constant factor)
    - Can often enhance code balance by outer loop unrolling or spatial blocking
  - Example: dense matrix-vector multiplication

```
do i=1,N
 do j=1,N
  c(i)=c(i)+a(j,i)*b(j)
 enddo
enddo
```



Naïve version loads b[ ] N times!

optional

Data access – general guidelines

- **O(N^2)/O(N^2) algorithms cont'd**
  - "Unroll & jam" optimization (or "outer loop unrolling")

```
do i=1,N
 do j=1,N
  c(i)=c(i)+a(j,i)*b(j)
 enddo
enddo
```

unroll

```
do i=1,N,2
 do j=1,N
  c(i)  =c(i)  +a(j,i)  *b(j)
 enddo
 do j=1,N
  c(i+1)=c(i+1)+a(j,i+1)*b(j)
 enddo
enddo
```

jam

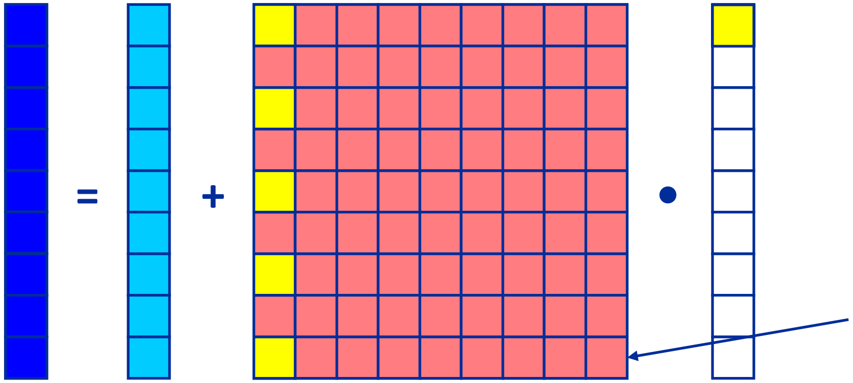
```
do i=1,N,2
 do j=1,N
  c(i)  =c(i)  +a(j,i)  * b(j)
  c(i+1)=c(i+1)+a(j,i+1)* b(j)
 enddo
enddo
```

`b(j)` can be re-used once from register → save 1 LD operation

Lowers B_c from 1 to ¾ W/F

Data access – general guidelines

- **$O(N^2)/O(N^2)$ algorithms cont'd**
  - Data access pattern for 2-way unrolled dense MVM:



Vector `b[]` now only loaded N/2 times!

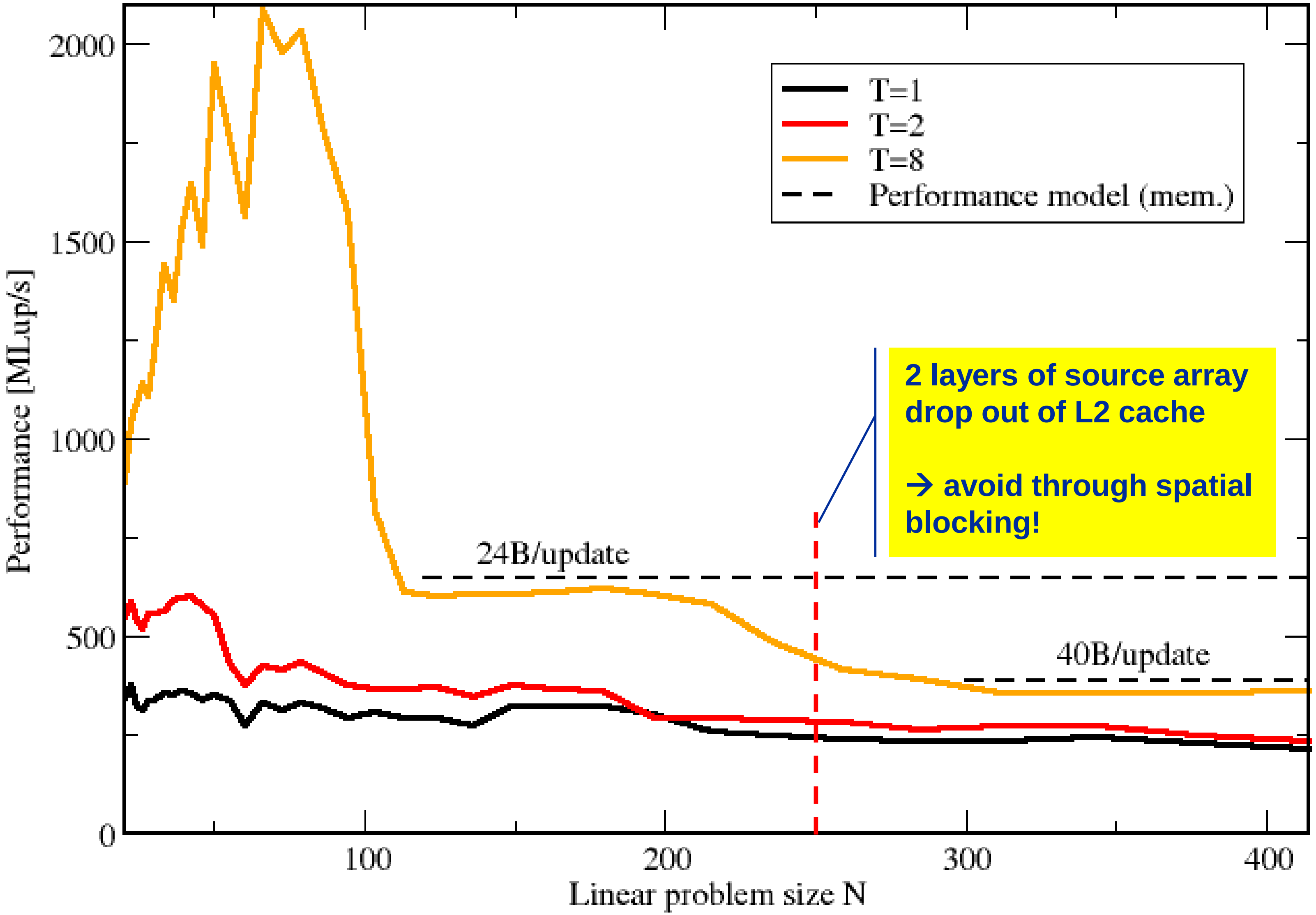
Remainder loop handled separately

  - Data transfers can further be reduced by more aggressive unrolling (i.e., m-way instead of 2-way)
  - Significant code bloat (try to use compiler directives if possible)
    - Main memory limit: **`b[]`** only be loaded once from memory (B_c ≈ ½ W/F) (can be achieved by high unrolling OR large outer level caches)
    - **Outer loop unrolling can also be beneficial to reduce traffic within caches!**
    - Beware: CPU registers are a limited resource
    - Excessive unrolling can cause register spills to memory

Case study:
3D Jacobi solver

Spatial blocking for improved cache utilization

Remember the 3D Jacobi solver on Interlagos?

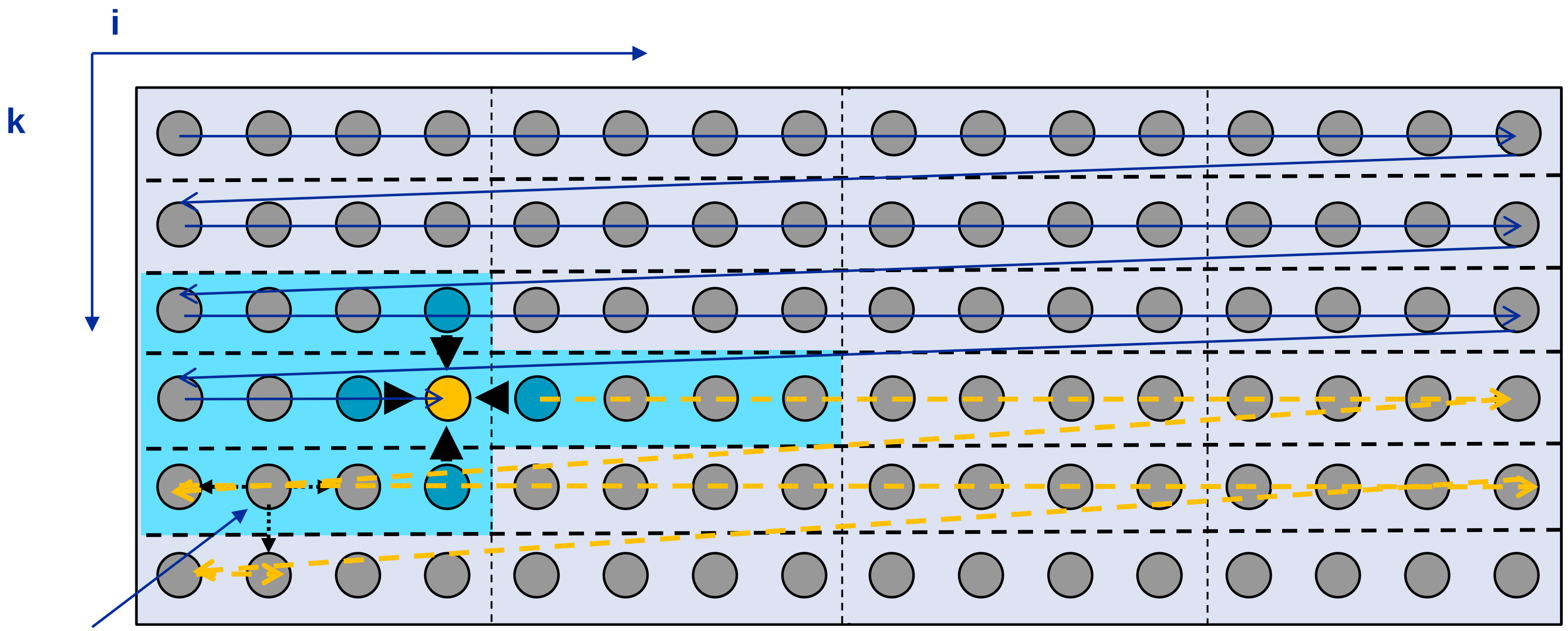


2 layers of source array drop out of L2 cache

→ avoid through spatial blocking!

Jacobi iteration (2D): No spatial Blocking

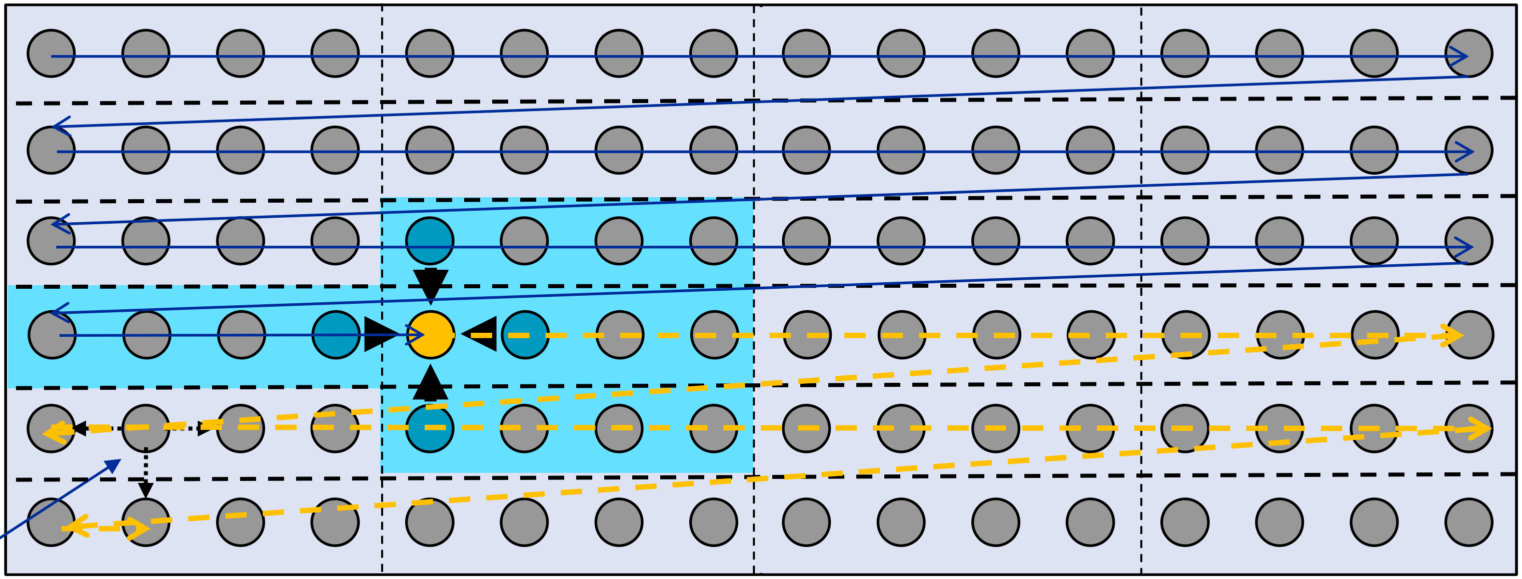
- **Assumptions:**
  - cache can hold 32 elements (16 for each array)
  - Cache line size is 4 elements
  - Perfect eviction strategy for source array



This element is needed for three more updates; but 29 updates happen before this element is used for the last time

Jacobi iteration (2D): No spatial blocking

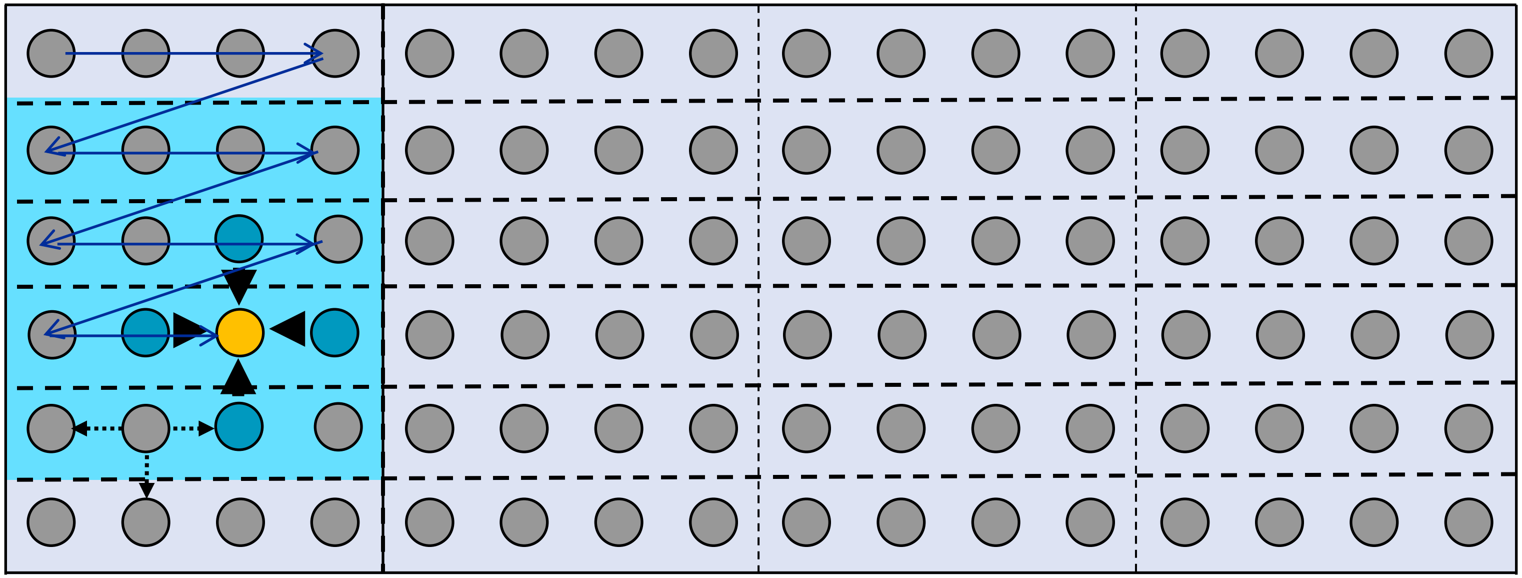
- **Assumptions:**
  - cache can hold 32 elements (16 for each array)
  - Cache line size is 4 elements
  - Perfect eviction strategy for source array



This element is needed for three more updates but has been evicted

Jacobi iteration (2D): Spatial Blocking

- **divide system into blocks**
- **update block after block**
- **same performance as if three complete rows of the systems fit into cache**

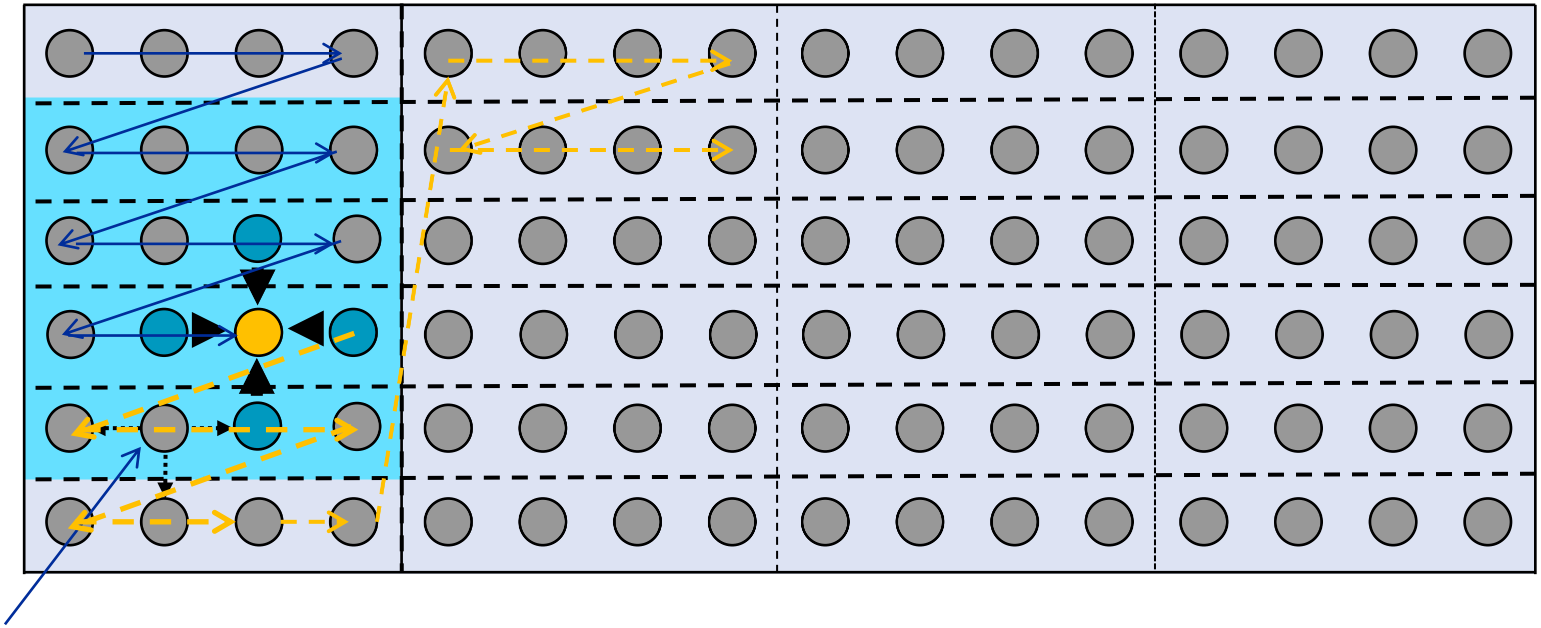


Jacobi iteration (2D): Spatial Blocking

- **Spatial blocking reorders traversal of data to account for the data update rule of the code**

→Elements stay sufficiently long in cache to be fully reused

→Spatial blocking improves temporal locality!
(Continuous access in inner loop ensures spatial locality)



This element remains in cache until it is fully used (only 6 updates happen before last use of this element)

Jacobi iteration (2D): Spatial blocking

- **Implementation:**

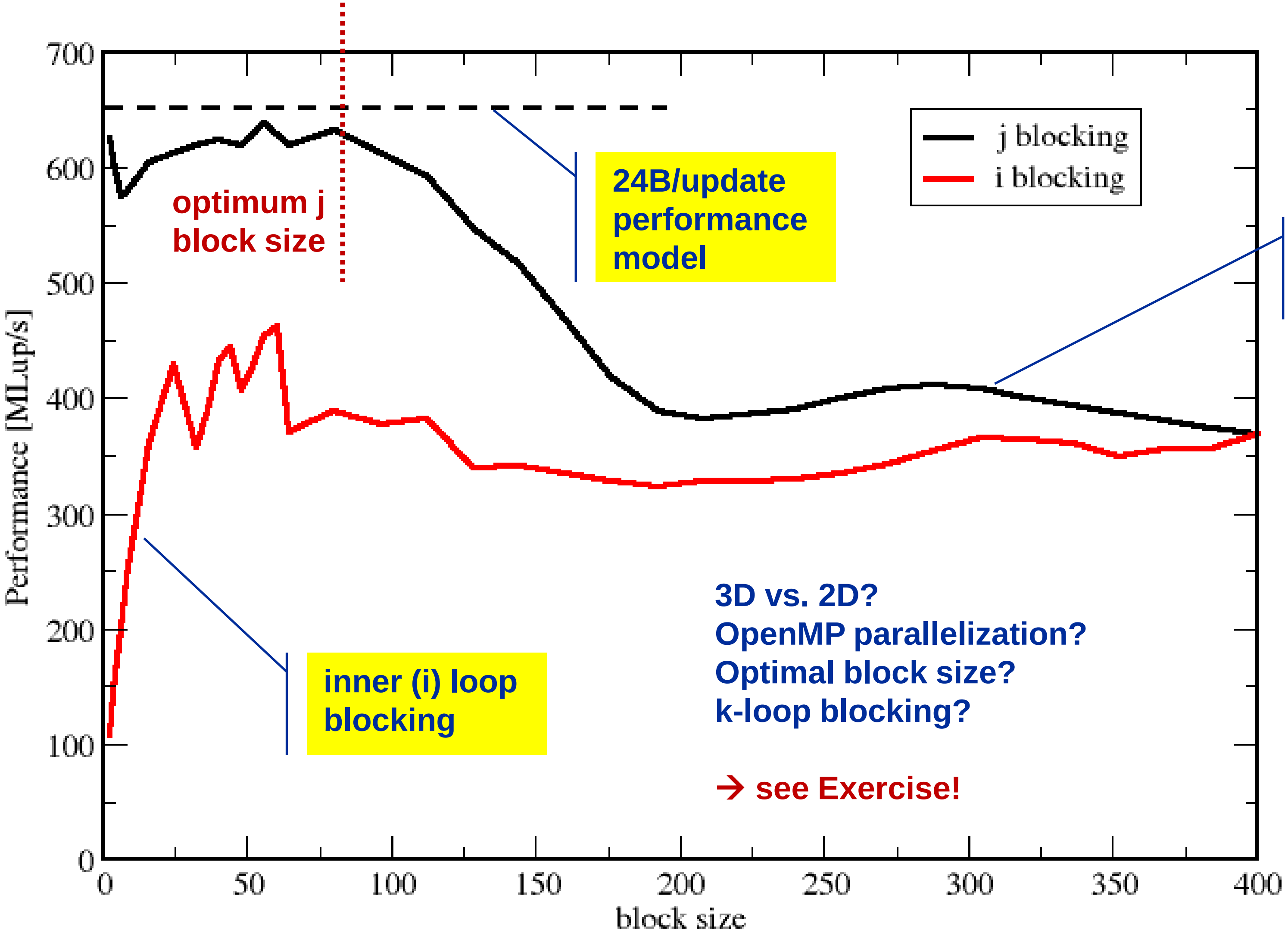
loop over i-blocks

```
do it=1,itmax
  do ioffset=1,imax,iblock
    do k=1,kmax
      do i=ioffset, min(imax,ioffset+iblock-1)
        phi(i, k, t1) = ( phi(i-1, k, t0) + phi(i+1, k, t0)
                        + phi(i, k-1, t0) + phi(i, k+1, t0) )*0.25
      enddo
    enddo
  enddo
enddo
```

- **Guidelines:**
  - Blocking of inner loop levels (traversing continuously through main memory)
  - Blocking size `iblock` large enough to keep elements sufficiently long in cache but cache size is a hard limit!
  - Blocking loops may have some impact on ccNUMA page placement (see later)

3D Jacobi solver (problem size 400^3)

Blocking different loop levels (8 cores Interlagos)



optimum j block size

24B/update performance model

middle (j) loop blocking

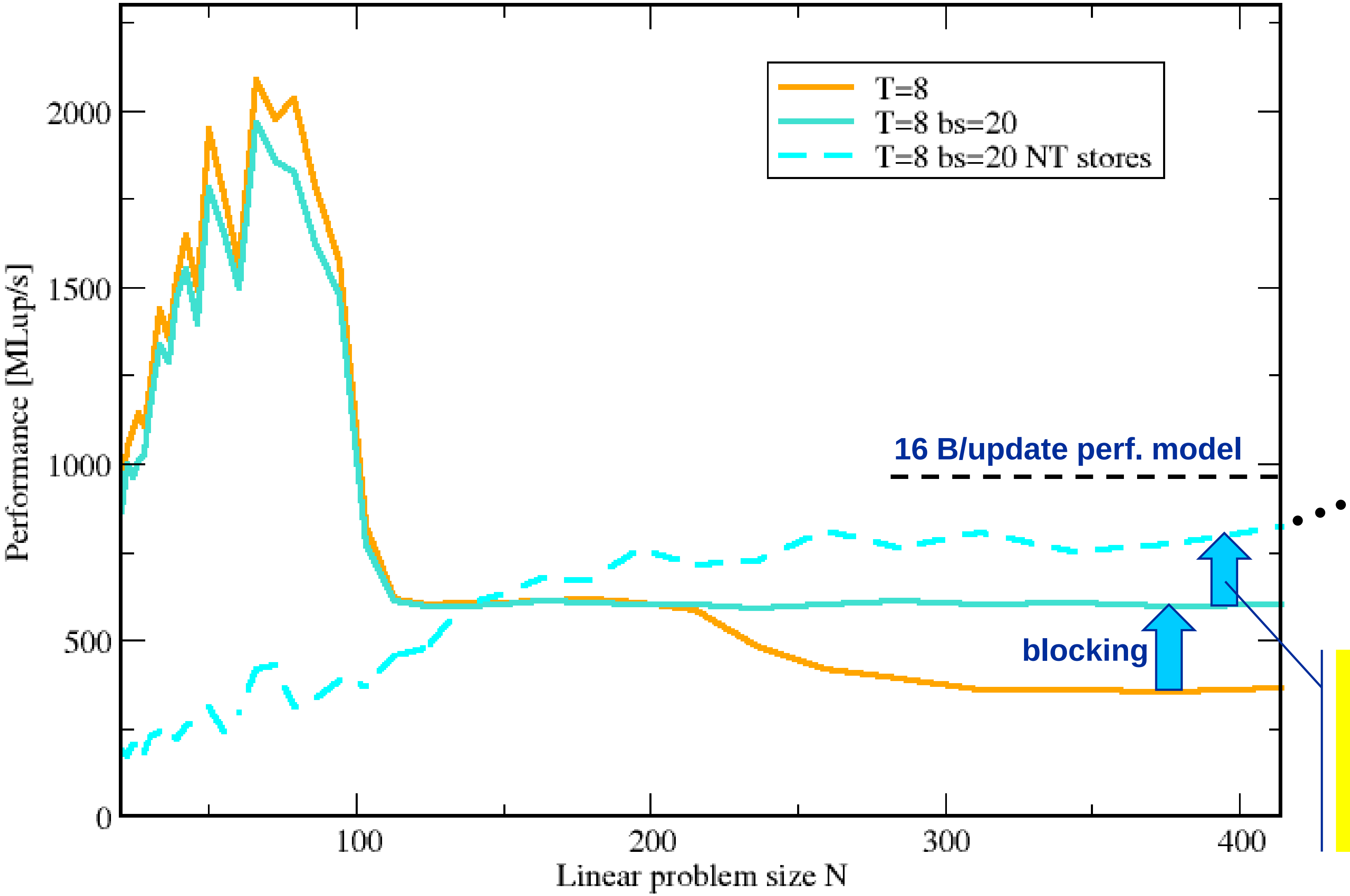
inner (i) loop blocking

3D vs. 2D?
OpenMP parallelization?
Optimal block size?
k-loop blocking?

→ see Exercise!

3D Jacobi solver

Spatial blocking + nontemporal stores



16 B/update perf. model

blocking

NT stores expected boost: 50%

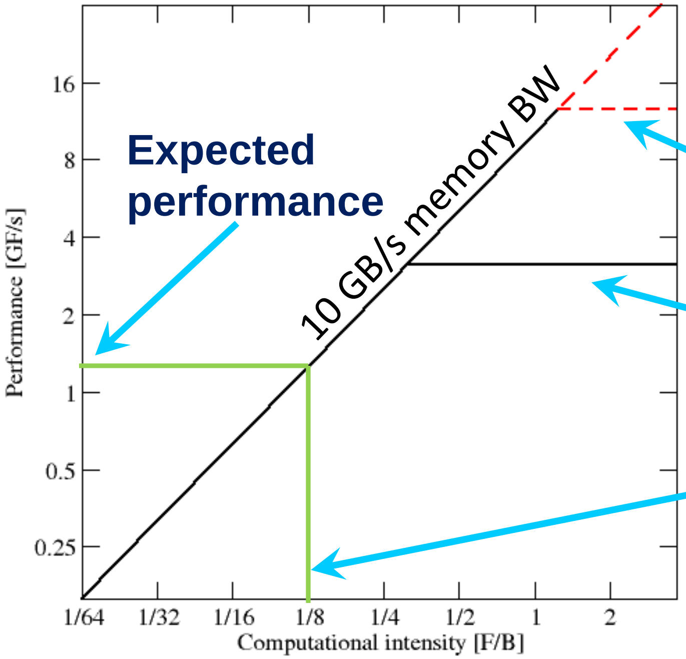
optional

The Roofline Model

The Roofline Model – A tool for more insight

optional

1. Determine the **applicable peak performance** of a loop, assuming that data comes from L1 cache
2. Determine **the computational intensity (flops per byte transferred)** over the slowest data path utilized ($1/B_c$)
3. Determine the **applicable peak bandwidth** of the slowest data path utilized



Example: `do i=1,N; s=s+a(i); enddo`

in DP on hypothetical CPU, N large

ADD peak (half of full peak)

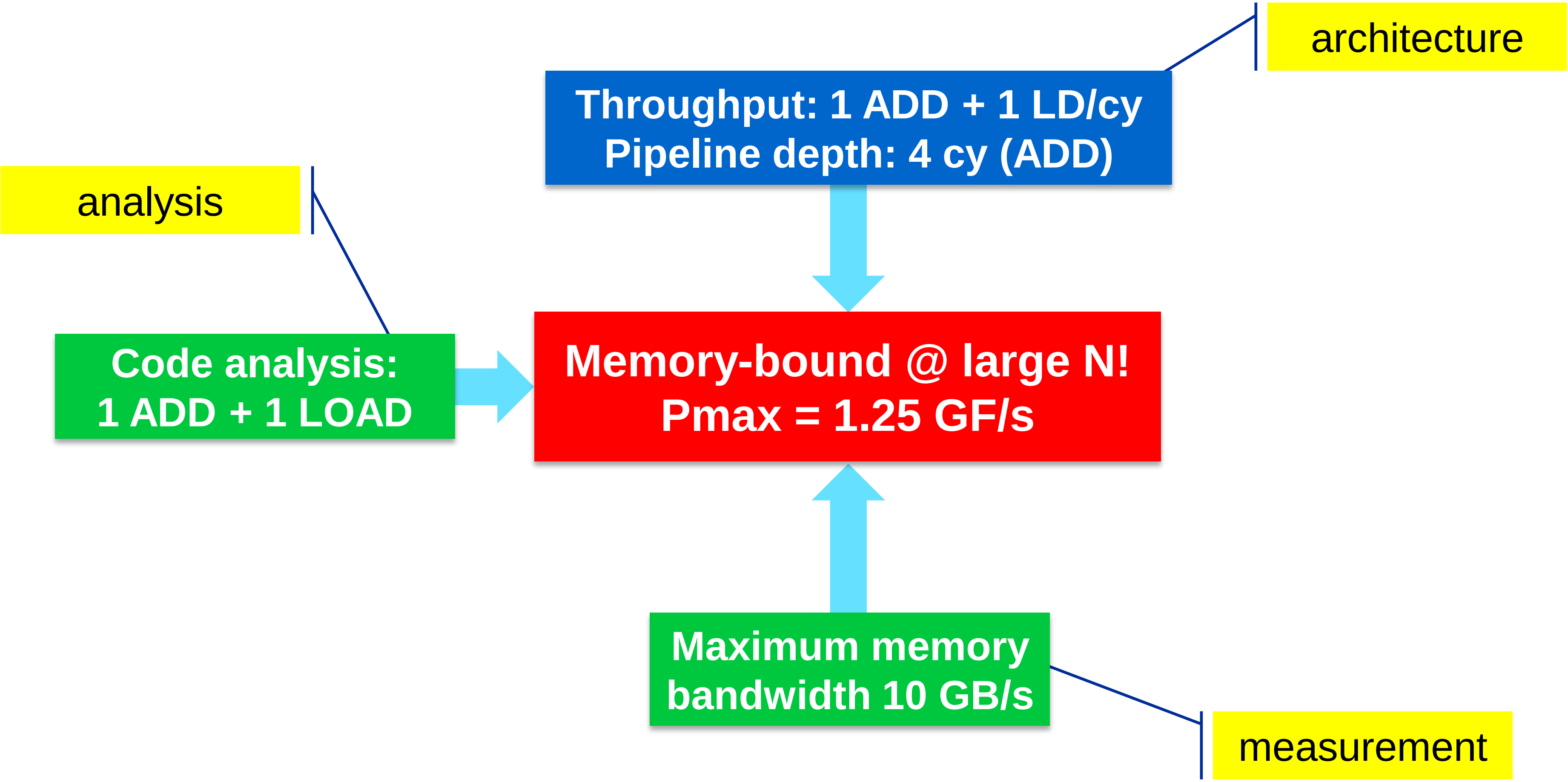
4-cycle latency per ADD if not unrolled

Computational intensity (= $1/B_c$)

optional

Input to the roofline model

… on the example of `do i=1,N; s=s+a(i); enddo`



architecture

Throughput: 1 ADD + 1 LD/cy
Pipeline depth: 4 cy (ADD)

analysis

Code analysis:
1 ADD + 1 LOAD

Memory-bound @ large N!
Pmax = 1.25 GF/s

Maximum memory
bandwidth 10 GB/s

measurement

Factors to consider in the roofline model

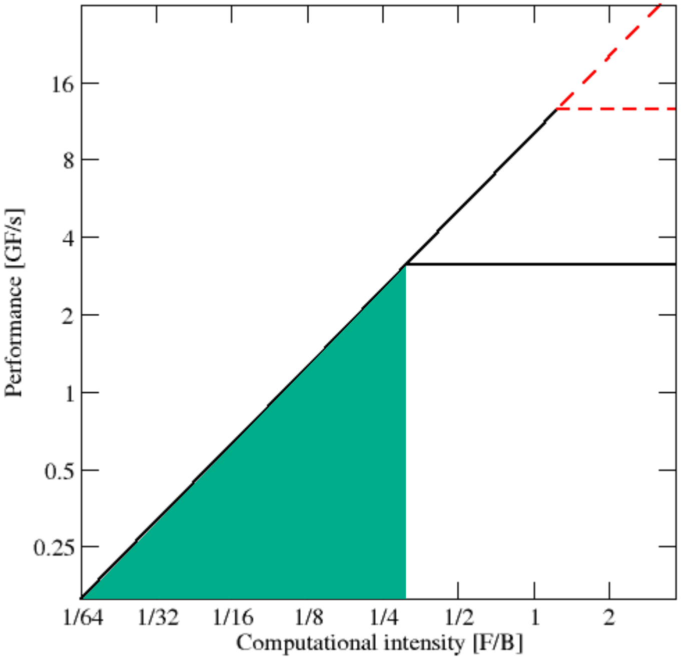
optional

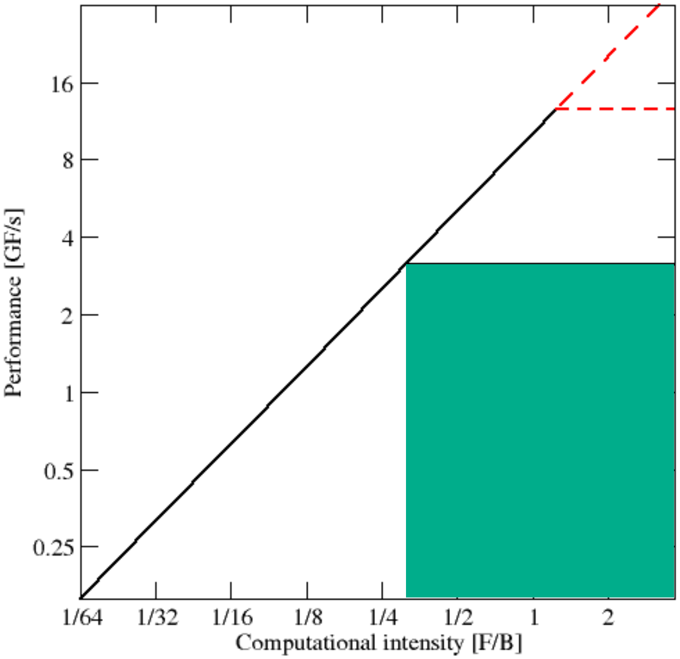
Bandwidth-bound (simple case)

- Accurate traffic calculation (write-allocate, strided access, …)
- Practical ≠ theoretical BW limits
- Erratic access patterns

Core-bound (may be complex)

- Multiple bottlenecks: LD/ST, arithmetic, pipelines, SIMD, execution ports
- Still probably some contributions from data access



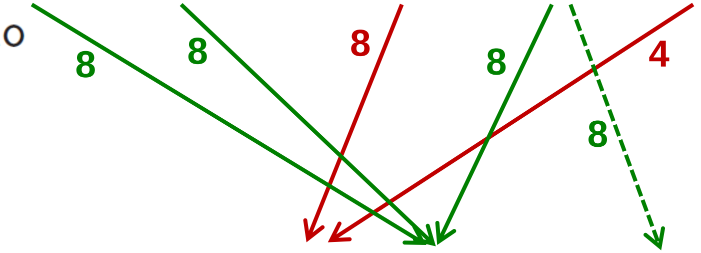


Example: SpMVM node performance model

optional

- **Sparse MVM in**
  double precision w/ CRS:

```
do i = 1,$N_r$
  do j = row_ptr(i), row_ptr(i+1) - 1
    C(i) = C(i) + val(j) * B(col_idx(j))
  enddo
enddo
```



- **DP CRS code balance**
  - κ quantifies extra traffic for loading RHS more than once
  - Predicted Performance = streamBW/B_{CRS}
  - Determine κ by measuring performance and actual memory bandwidth

$$B_{\mathrm{CRS}} = \left(\frac{12+24/N_{\mathrm{nzr}}+\kappa}{2}\right)\frac{\text{bytes}}{\text{flop}} = \left(6+\frac{12}{N_{\mathrm{nzr}}}+\frac{\kappa}{2}\right)\frac{\text{bytes}}{\text{flop}}\,.$$

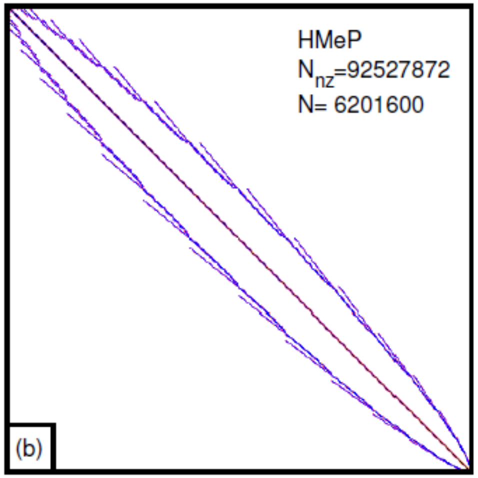
G. Schubert, G. Hager, H. Fehske and G. Wellein: *Parallel sparse matrix-vector multiplication as a test case for hybrid MPI+OpenMP programming*. Workshop on Large-Scale Parallel Processing (LSPP 2011), May 20th, 2011, Anchorage, AK. DOI:10.1109/IPDPS.2011.332, Preprint: arXiv:1101.0091

The sparsity pattern determines κ

optional

- **Analysis for HMeP matrix on Nehalem EP socket**
  - BW used by spMVM kernel = 18.1 GB/s → should get ≈ 2.66 Gflop/s spMVM performance if $\kappa = 0$
  - Measured spMVM performance = 2.25 Gflop/s
  - Solve 2.25 Gflop/s = BW/B_{CRS} for $\kappa \approx 2.5$

    → 37.5 extra bytes per row
    → RHS is loaded 6 times from memory
    → about 33% of BW goes into RHS

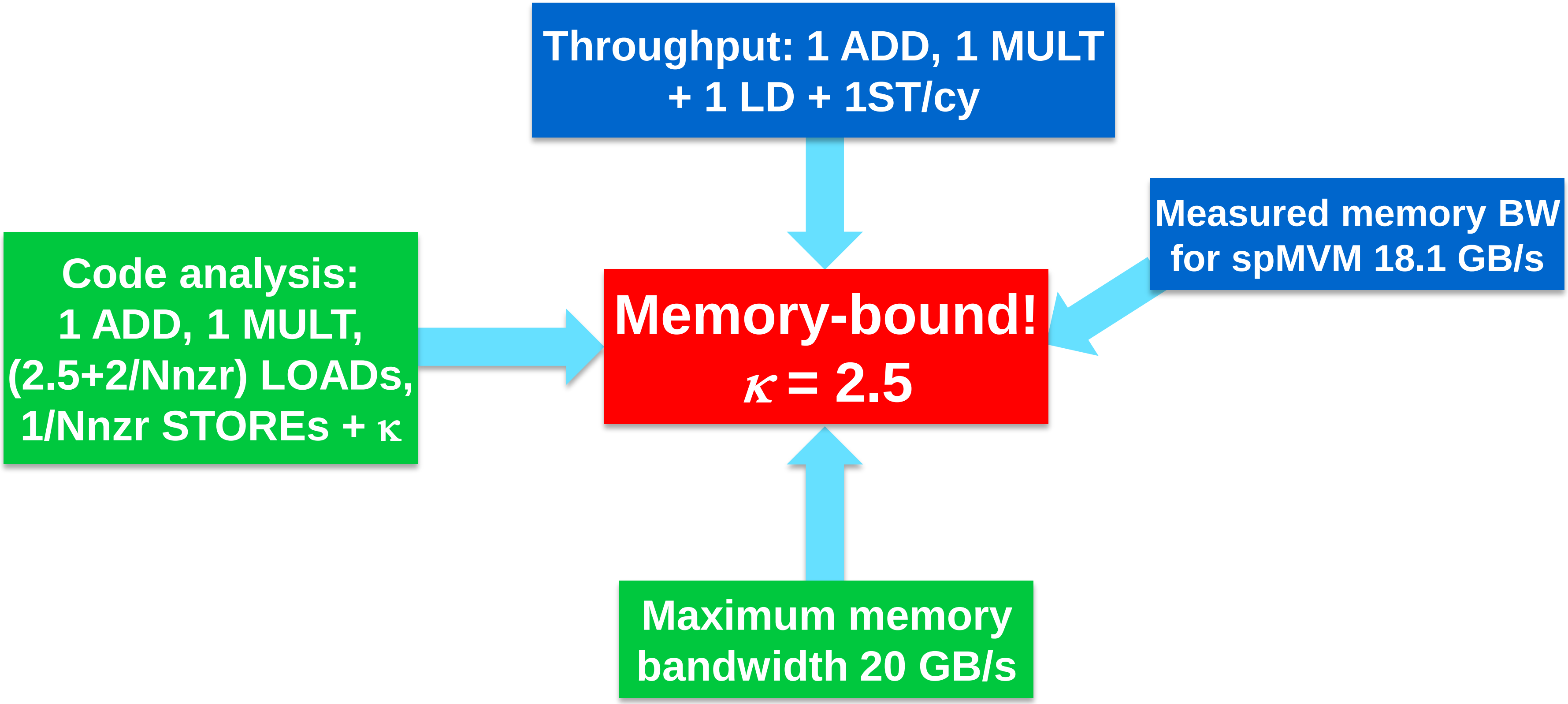


- **Conclusion: Even if the roofline/bandwidth model does not work 100%, we can still learn something from the deviations**

Input to the roofline model

optional

… on the example of spMVM with HMeP matrix



Throughput: 1 ADD, 1 MULT + 1 LD + 1ST/cy

Measured memory BW for spMVM 18.1 GB/s

Code analysis: 1 ADD, 1 MULT, (2.5+2/Nnzr) LOADs, 1/Nnzr STOREs + κ

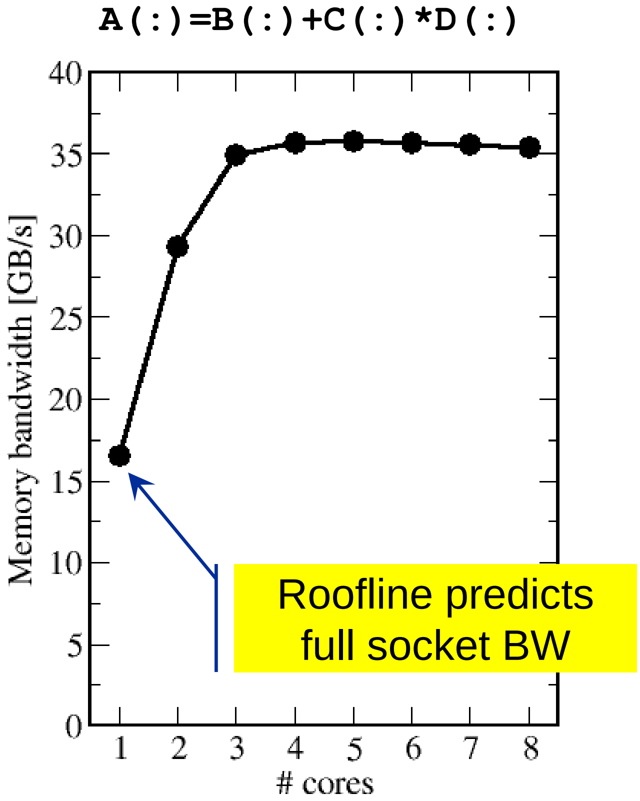
Memory-bound! $\kappa = 2.5$

Maximum memory bandwidth 20 GB/s

Assumptions and shortcomings of the roofline model

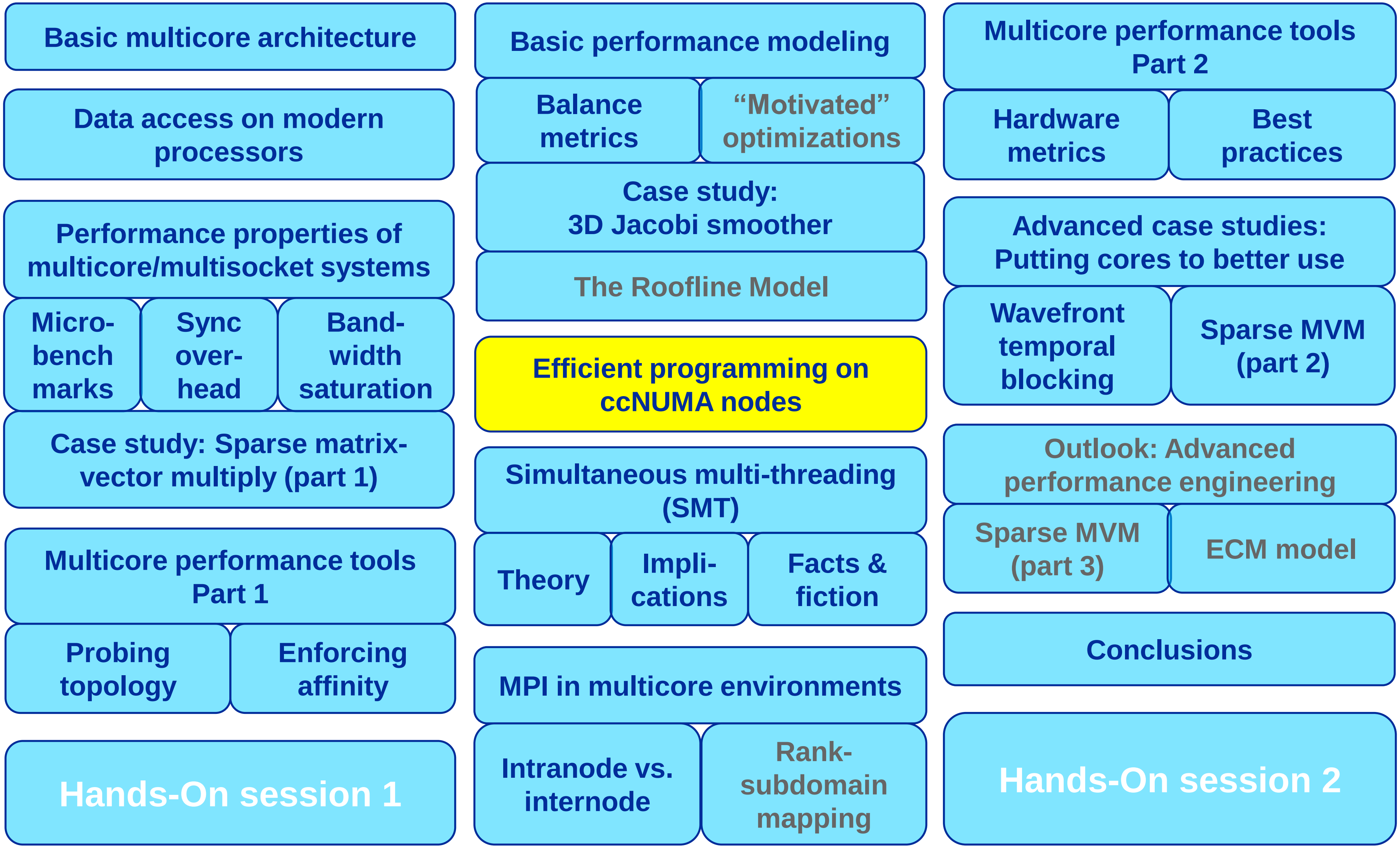
optional

- **Assumes one of two bottlenecks**
  1. In-core execution
  2. Bandwidth of a single hierarchy level
- **Latency effects are not modeled → pure data streaming assumed**
- **In-core execution is sometimes hard to model**
- **Saturation effects in multicore chips are not explained**
  - ECM model gives more insight (see later)



Roofline predicts full socket BW

The Plan



Basic multicore architecture

Data access on modern processors

Performance properties of multicore/multisocket systems

Micro-benchmarks

Sync over-head

Band-width saturation

Case study: Sparse matrix-vector multiply (part 1)

Multicore performance tools Part 1

Probing topology

Enforcing affinity

Hands-On session 1

Basic performance modeling

Balance metrics

“Motivated” optimizations

Case study: 3D Jacobi smoother

The Roofline Model

Efficient programming on ccNUMA nodes

Simultaneous multi-threading (SMT)

Theory

Impli-cations

Facts & fiction

MPI in multicore environments

Intranode vs. internode

Rank-subdomain mapping

Multicore performance tools Part 2

Hardware metrics

Best practices

Advanced case studies: Putting cores to better use

Wavefront temporal blocking

Sparse MVM (part 2)

Outlook: Advanced performance engineering

Sparse MVM (part 3)

ECM model

Conclusions

Hands-On session 2

Efficient parallel programming on ccNUMA nodes

Performance characteristics of ccNUMA nodes

First touch placement policy

C++ issues

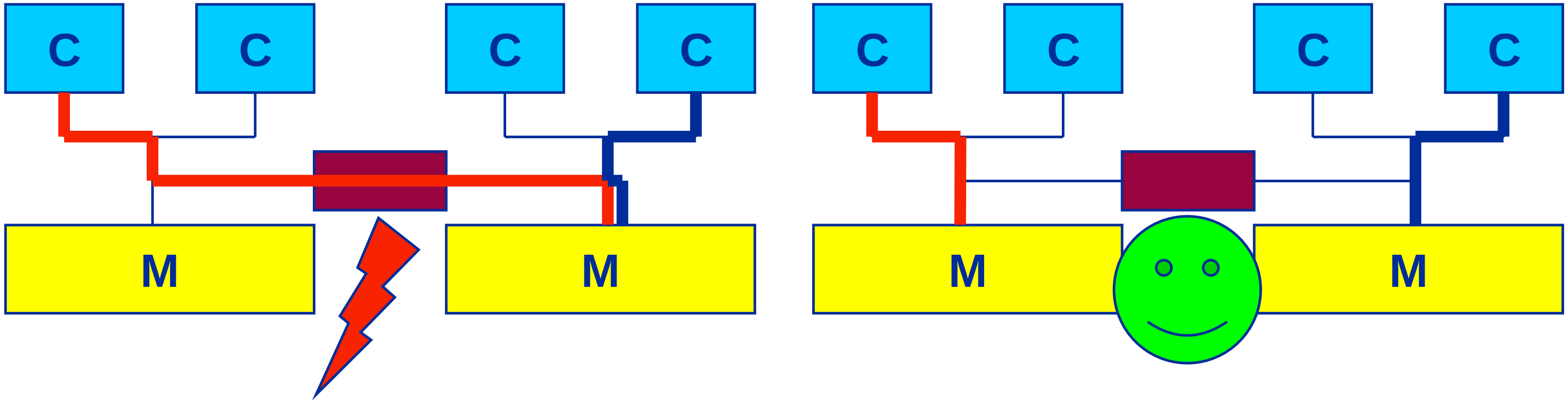
ccNUMA locality and dynamic scheduling

ccNUMA locality beyond first touch

ccNUMA performance problems

"The other affinity" to care about

- **ccNUMA:**
  - Whole memory is transparently accessible by all processors
  - but physically distributed
  - with varying bandwidth and latency
  - and potential contention (shared memory paths)
- **How do we make sure that memory access is always as "local" and "distributed" as possible?**

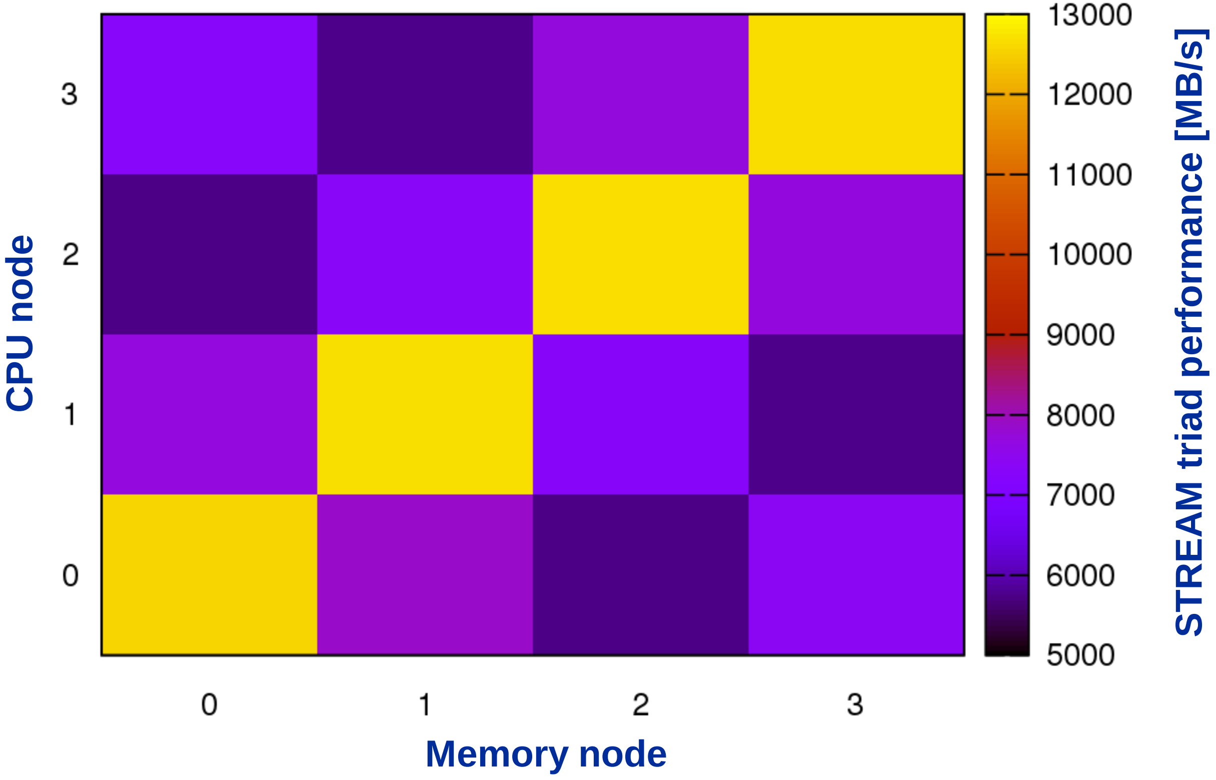


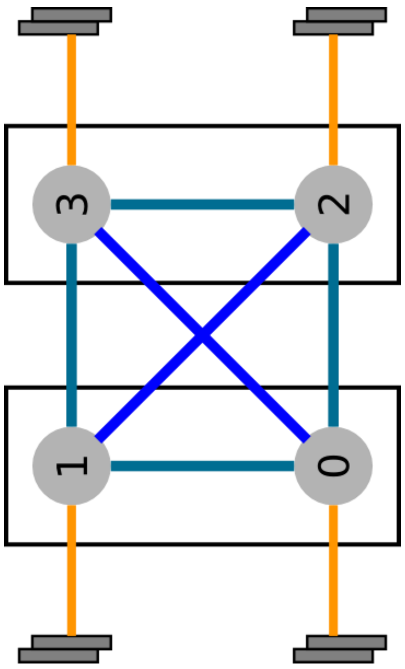
  - Page placement is implemented in units of OS pages (often 4kB, possibly more)

Cray XE6 Interlagos node

4 chips, two sockets, 8 threads per ccNUMA domain

- **ccNUMA map: Bandwidth penalties for remote access**
  - Run 8 threads per ccNUMA domain (1 chip)
  - Place memory in different domain → 4x4 combinations
  - STREAM triad benchmark using nontemporal stores





ccNUMA locality tool numactl:

How do we enforce some locality of access?

- **`numactl` can influence the way a binary maps its memory pages:**

```
numactl --membind=<nodes> a.out     # map pages only on <nodes>
        --preferred=<node>  a.out   # map pages on <node>
                                    # and others if <node> is full
        --interleave=<nodes> a.out # map pages round robin across
                                    # all <nodes>
```

- **Examples:**

```
env OMP_NUM_THREADS=2 numactl --membind=0 --cpunodebind=1 ./stream

env OMP_NUM_THREADS=4 numactl --interleave=0-3 \
                           likwid-pin -c N:0,4,8,12 ./stream
```

- **But what is the default without `numactl`?**

ccNUMA default memory locality

- **"Golden Rule" of ccNUMA:**

  A memory page gets mapped into the local memory of the processor that first touches it!

  - Except if there is not enough local memory available
  - This might be a problem, see later
- **Caveat: "touch" means "write", not "allocate"**
- **Example:**

Memory not mapped here yet

```
double *huge = (double*)malloc(N*sizeof(double));

for(i=0; i<N; i++) // or i+=PAGE_SIZE
   huge[i] = 0.0;
```

Mapping takes place here

- **It is sufficient to touch a single item to map the entire page**

Coding for ccNUMA data locality

- **Most simple case: explicit initialization**

```
integer,parameter :: N=10000000
double precision A(N), B(N)



A=0.d0



!$OMP parallel do
do i = 1, N
  B(i) = function ( A(i) )
end do
!$OMP end parallel do
```

⚡

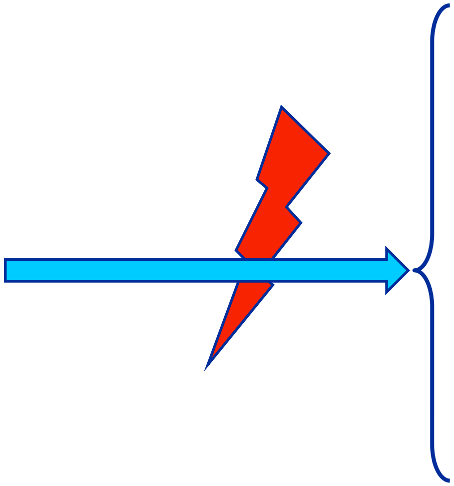
```
integer,parameter :: N=10000000
double precision A(N),B(N)
!$OMP parallel
!$OMP do schedule(static)
do i = 1, N
  A(i)=0.d0
end do
!$OMP end do
...
!$OMP do schedule(static)
do i = 1, N
  B(i) = function ( A(i) )
end do
!$OMP end do
!$OMP end parallel
```

☺

Coding for ccNUMA data locality

- **Sometimes initialization is not so obvious: I/O cannot be easily parallelized, so “localize” arrays before I/O**

```
integer,parameter :: N=10000000
double precision A(N), B(N)




READ(1000) A





!$OMP parallel do
do i = 1, N
  B(i) = function ( A(i) )
end do
!$OMP end parallel do
```



```
integer,parameter :: N=10000000
double precision A(N),B(N)
!$OMP parallel
!$OMP do schedule(static)
do i = 1, N
  A(i)=0.d0
end do
!$OMP end do
!$OMP single
READ(1000) A
!$OMP end single
!$OMP do schedule(static)
do i = 1, N
  B(i) = function ( A(i) )
end do
!$OMP end do
!$OMP end parallel
```

Coding for Data Locality

- **Required condition: OpenMP loop schedule of initialization must be the same as in all computational loops**
  - Only choice: **`static`**! Specify explicitly on all NUMA-sensitive loops, just to be sure…
  - Imposes some constraints on possible optimizations (e.g. load balancing)
  - Presupposes that all worksharing loops with the same loop length have the same thread-chunk mapping
    - Guaranteed by OpenMP 3.0 only for loops in the same enclosing parallel region and static schedule
    - In practice, it works with any compiler even across regions
  - If dynamic scheduling/tasking is unavoidable, more advanced methods may be in order
- **How about global objects?**
  - Better not use them
  - If communication vs. computation is favorable, might consider properly placed copies of global data
  - In C++, STL allocators provide an elegant solution (see hidden slides)

Coding for Data Locality:
Placement of static arrays or arrays of objects

optional

- **Speaking of C++: Don't forget that constructors tend to touch the data members of an object. Example:**

```
class D {
  double d;
public:
  D(double _d=0.0) throw() : d(_d) {}
  inline D operator+(const D& o) throw() {
    return D(d+o.d);
  }
  inline D operator*(const D& o) throw() {
    return D(d*o.d);
  }
...
};
```

→ **placement problem with**

```
D* array = new D[1000000];
```

Coding for Data Locality:
Parallel first touch for arrays of objects

optional

- **Solution: Provide overloaded `D::operator new[]`**

```
void* D::operator new[](size_t n) {
  char *p = new char[n];    // allocate

  size_t i,j;
#pragma omp parallel for private(j) schedule(...)
  for(i=0; i<n; i += sizeof(D))
    for(j=0; j<sizeof(D); ++j)
      p[i+j] = 0;
  return p;
}

void D::operator delete[](void* p) throw() {
  delete [] static_cast<char*>p;
}
```

parallel first touch

- **Placement of objects is then done automatically by the C++ runtime via "placement new"**

Coding for Data Locality:

NUMA allocator for parallel first touch in `std::vector<>`

optional

```
template <class T> class NUMA_Allocator {
public:
  T* allocate(size_type numObjects, const void
              *localityHint=0) {
    size_type ofs,len = numObjects * sizeof(T);
    void *m = malloc(len);
    char *p = static_cast<char*>(m);
    int i,pages = len >> PAGE_BITS;
#pragma omp parallel for schedule(static) private(ofs)
    for(i=0; i<pages; ++i) {
      ofs = static_cast<size_t>(i) << PAGE_BITS;
      p[ofs]=0;
    }
    return static_cast<pointer>(m);
  }
...
};
```

Application:

```
vector<double,NUMA_Allocator<double> > x(10000000)
```

Diagnosing Bad Locality

- **If your code is cache-bound, you might not notice any locality problems**

- **Otherwise, bad locality limits scalability at very low CPU numbers (whenever a node boundary is crossed)**
  - If the code makes good use of the memory interface
  - But there may also be a general problem in your code…

- **Consider using performance counters**
  - LIKWID-perfctr can be used to measure nonlocal memory accesses
  - Example for Intel Nehalem (Core i7):

```
env OMP_NUM_THREADS=8 likwid-perfctr -g MEM -C N:0-7 \
                       -t intel ./a.out
```

Using performance counters for diagnosing bad ccNUMA access locality

- Intel Nehalem EP node:

Uncore events only counted once per socket

```
+-----------------------------------+-------------+-------------+-------------+-------------+-------------+-------------
|               Event               |   core 0    |   core 1    |   core 2    |   core 3    |   core 4    |   core 5
+-----------------------------------+-------------+-------------+-------------+-------------+-------------+-------------
|         INSTR_RETIRED_ANY         | 5.20725e+08 | 5.24793e+08 | 5.21547e+08 | 5.23717e+08 | 5.28269e+08 | 5.29083e+08
|       CPU_CLK_UNHALTED_CORE       | 1.90447e+09 | 1.90599e+09 | 1.90619e+09 | 1.90673e+09 | 1.90583e+09 | 1.90746e+09
|     UNC_QMC_NORMAL_READS_ANY      | 8.17606e+07 |      0      |      0      |      0      | 8.07797e+07 |      0
|      UNC_QMC_WRITES_FULL_ANY      | 5.53837e+07 |      0      |      0      |      0      | 5.51052e+07 |      0
| UNC_QHL_REQUESTS_REMOTE_READS | 6.84504e+07 |      0      |      0      |      0      | 6.8107e+07  |      0
| UNC_QHL_REQUESTS_LOCAL_READS  | 6.82751e+07 |      0      |      0      |      0      | 6.76274e+07 |      0
+-----------------------------------+-------------+-------------+-------------+-------------+-------------+-------------
RDTSC timing: 0.827196 s
+-----------------------------+-----------+-----------+----------+-----------+-----------+-----------+----------+----------+
|           Metric            |  core 0   |  core 1   |  core 2  |  core 3   |  core 4   |  core 5   |  core 6  |  core 7  |
+-----------------------------+-----------+-----------+----------+-----------+-----------+-----------+----------+----------+
|         Runtime [s]         | 0.714167  | 0.714733  | 0.71481  | 0.715013  | 0.714673  | 0.715286  | 0.71486  | 0.71515  |
|             CPI             | 3.65735   | 3.63188   | 3.65488  | 3.64076   | 3.60768   | 3.60521   | 3.59613  | 3.60184  |
| Memory bandwidth [MBytes/s] | 10610.8   |     0     |    0     |     0     | 10513.4   |     0     |    0     |    0     |
|  Remote Read BW [MBytes/s]  |   5296    |     0     |    0     |     0     | 5269.43   |     0     |    0     |    0     |
+-----------------------------+-----------+-----------+----------+-----------+-----------+-----------+----------+----------+
```

Half of read BW comes from other socket!

If all fails…

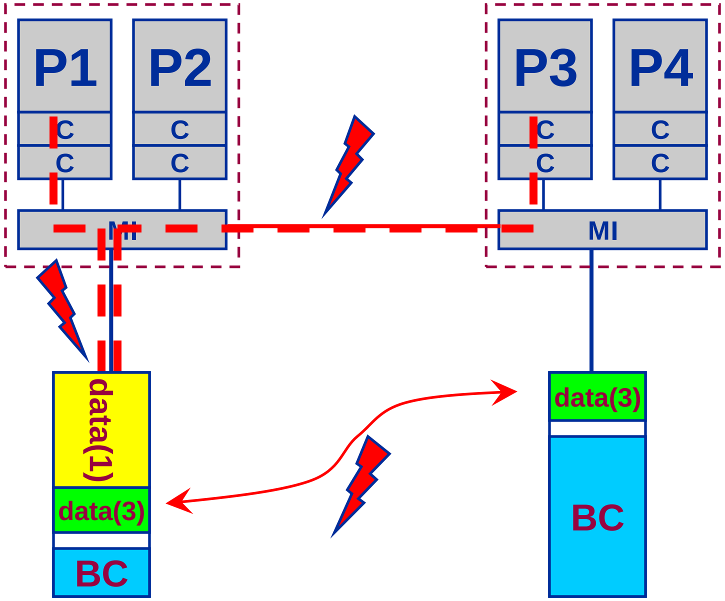
- **Even if all placement rules have been carefully observed, you may still see nonlocal memory traffic. Reasons?**
  - Program has erratic access patters → may still achieve some access parallelism (see later)
  - OS has filled memory with buffer cache data:

```
# numactl --hardware    # idle node!
available: 2 nodes (0-1)
node 0 size: 2047 MB
node 0 free: 906 MB
node 1 size: 1935 MB
node 1 free: 1798 MB
```

```
top - 14:18:25 up 92 days,  6:07,  2 users,  load average: 0.00, 0.02, 0.00
Mem:   4065564k total,  1149400k used,  2716164k free,    43388k buffers
Swap:  2104504k total,     2656k used,  2101848k free,  1038412k cached
```

ccNUMA problems beyond first touch: *Buffer cache*

- **OS uses part of main memory for disk buffer (FS) cache**
  - If FS cache fills part of memory, apps will probably allocate from foreign domains
  - → non-local access!
  - “sync” is not sufficient to drop buffer cache blocks



- **Remedies**
  - Drop FS cache pages after user job has run (admin’s job)
    - seems to be automatic after aprun has finished on Crays
  - User can run “sweeper” code that allocates and touches all physical memory before starting the real application
  - `numactl` tool or `aprun` can force local allocation (where applicable)
  - Linux: There is no way to limit the buffer cache size in standard kernels

ccNUMA problems beyond first touch:
Buffer cache

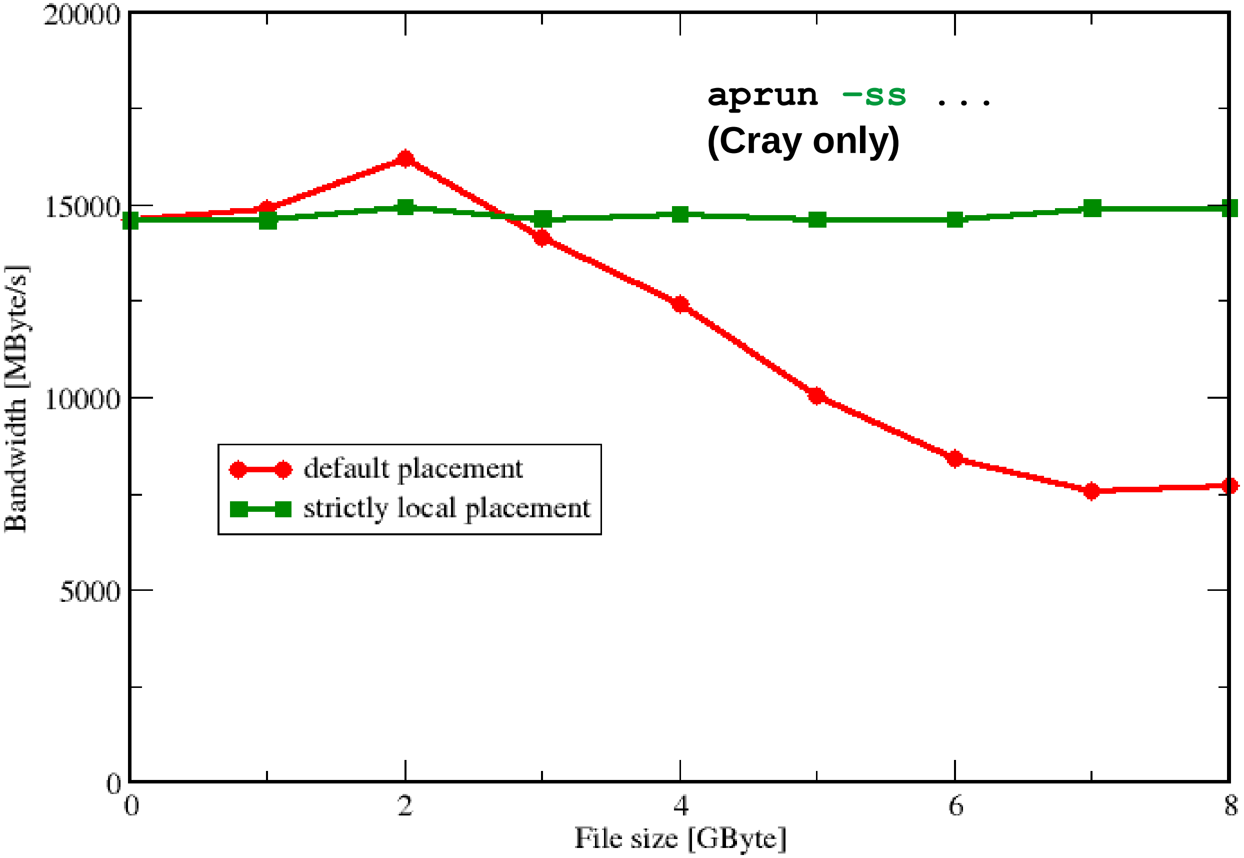
Real-world example: ccNUMA and the Linux buffer cache

Benchmark:

1. Write a file of some size from LD0 to disk
2. Perform bandwidth benchmark using all cores in LD0 and maximum memory installed in LD0

Result: By default, Buffer cache is given priority over local page placement

→ restrict to local domain if possible!



```
aprun -ss ...
```
(Cray only)

ccNUMA placement and erratic access patterns

- Sometimes access patterns are just not nicely grouped into contiguous chunks:

```
double precision :: r, a(M)
!$OMP parallel do private(r)
do i=1,N
  call RANDOM_NUMBER(r)
  ind = int(r * M) + 1
  res(i) = res(i) + a(ind)
enddo
!OMP end parallel do
```

- Or you have to use tasking/dynamic scheduling:

```
!$OMP parallel
!$OMP single
do i=1,N
  call RANDOM_NUMBER(r)
  if(r.le.0.5d0) then
!$OMP task
    call do_work_with(p(i))
!$OMP end task
  endif
enddo
!$OMP end single
!$OMP end parallel
```

- In both cases page placement cannot easily be fixed for perfect parallel access

ccNUMA placement and erratic access patterns

- **Worth a try: Interleave memory across ccNUMA domains to get at least some parallel access**
  1. Explicit placement:

```
!$OMP parallel do schedule(static,512)
do i=1,M
  a(i) = …
enddo
!$OMP end parallel do
```

Observe page alignment of array to get proper placement!

  2. Using global control via `numactl`:

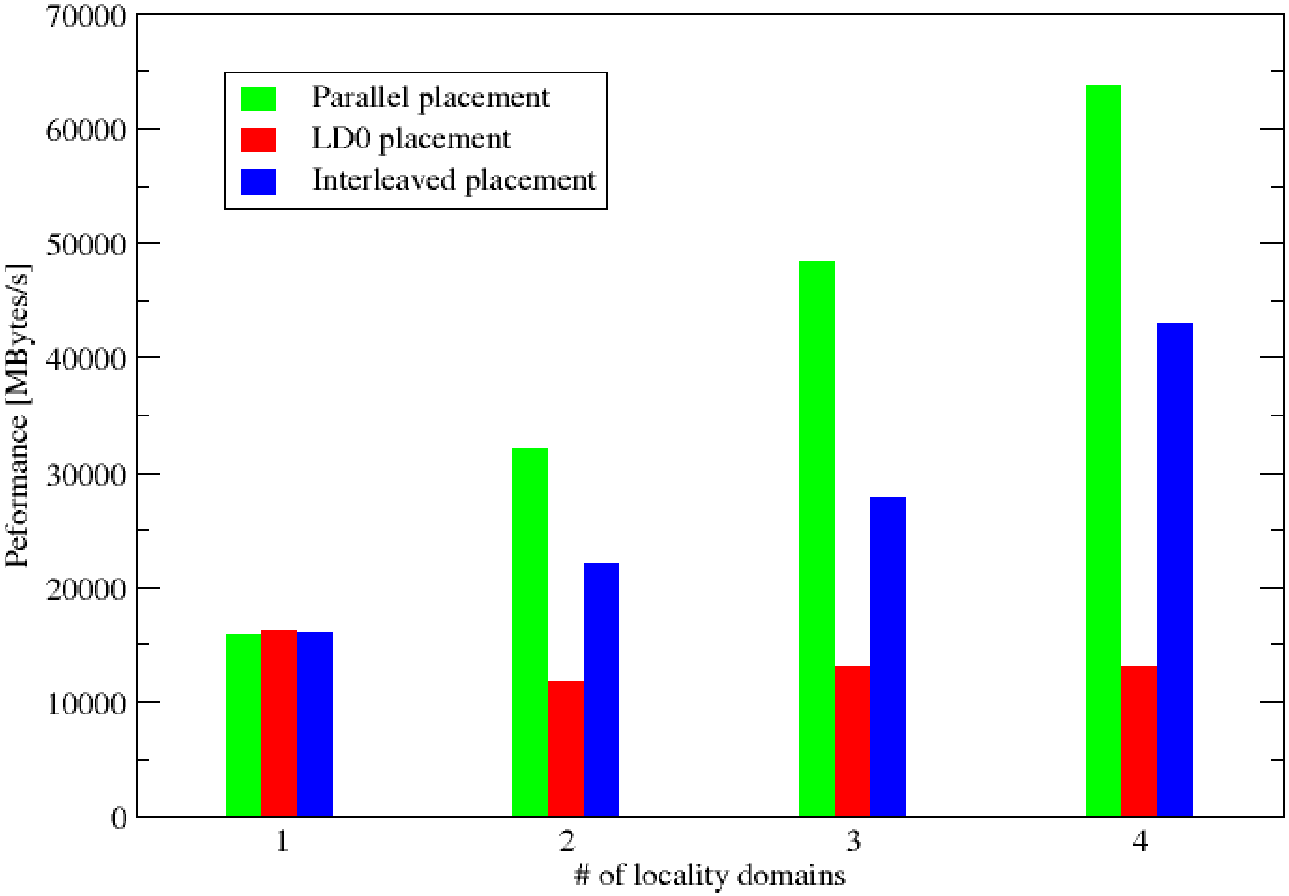
```
numactl --interleave=0-3 ./a.out
```

This is for all memory, not just the problematic arrays!

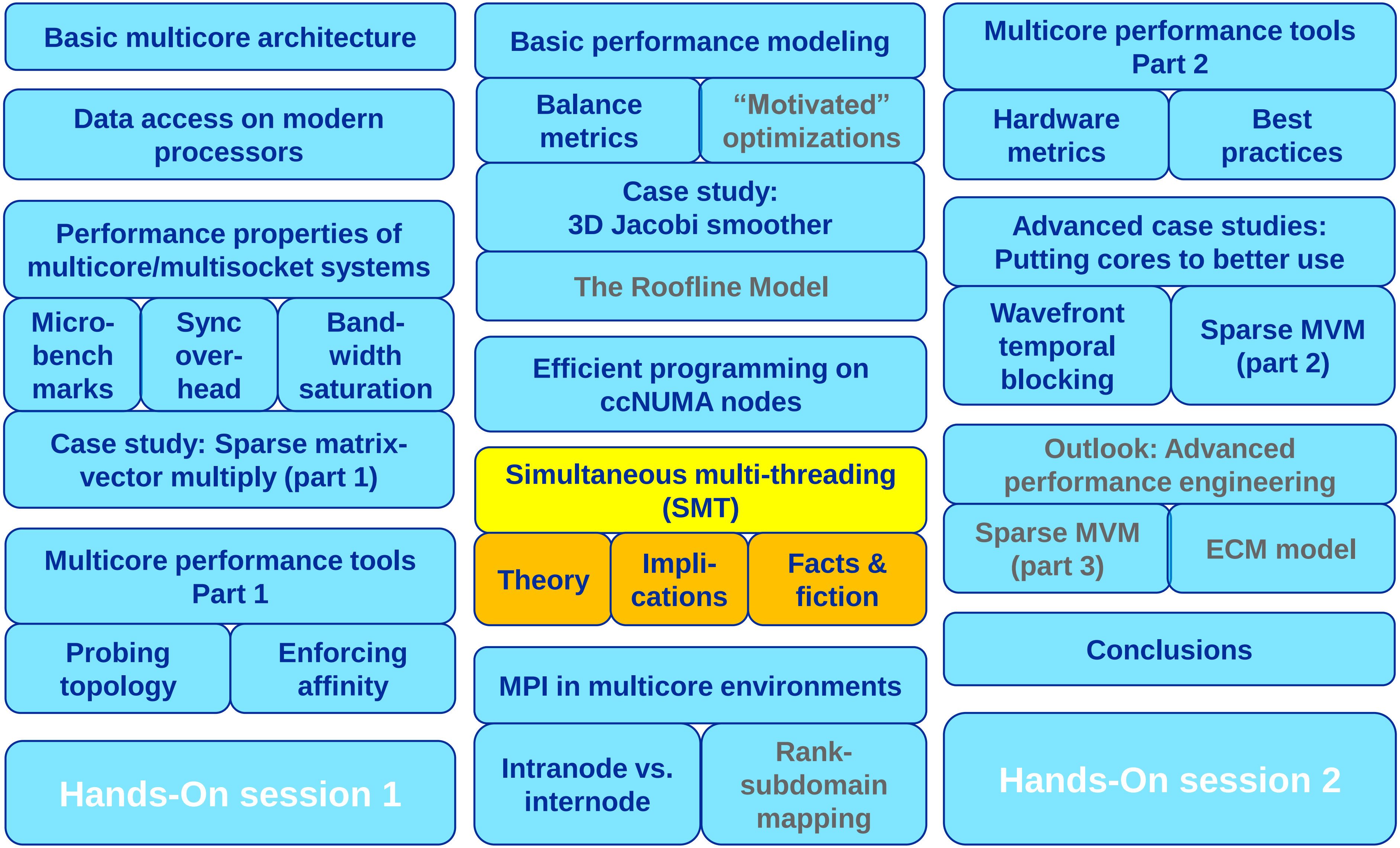
- **Fine-grained program-controlled placement via `libnuma` (Linux) using, e.g., `numa_alloc_interleaved_subset()`, `numa_alloc_interleaved()` and others**

The curse and blessing of interleaved placement:
OpenMP STREAM on a Cray XE6 Interlagos node

- **Parallel init: Correct parallel initialization**
- **LD0: Force data into LD0 via `numactl –m 0`**
- **Interleaved: `numactl --interleave <LD range>`**



The Plan



Basic multicore architecture

Data access on modern processors

Performance properties of multicore/multisocket systems

- Micro-benchmarks
- Sync over-head
- Band-width saturation

Case study: Sparse matrix-vector multiply (part 1)

Multicore performance tools Part 1

- Probing topology
- Enforcing affinity

Hands-On session 1

Basic performance modeling

- Balance metrics
- “Motivated” optimizations

Case study: 3D Jacobi smoother

The Roofline Model

Efficient programming on ccNUMA nodes

Simultaneous multi-threading (SMT)

- Theory
- Impli-cations
- Facts & fiction

MPI in multicore environments

- Intranode vs. internode
- Rank-subdomain mapping

Multicore performance tools Part 2

- Hardware metrics
- Best practices

Advanced case studies: Putting cores to better use

- Wavefront temporal blocking
- Sparse MVM (part 2)

Outlook: Advanced performance engineering

- Sparse MVM (part 3)
- ECM model

Conclusions

Hands-On session 2

Simultaneous multithreading (SMT)

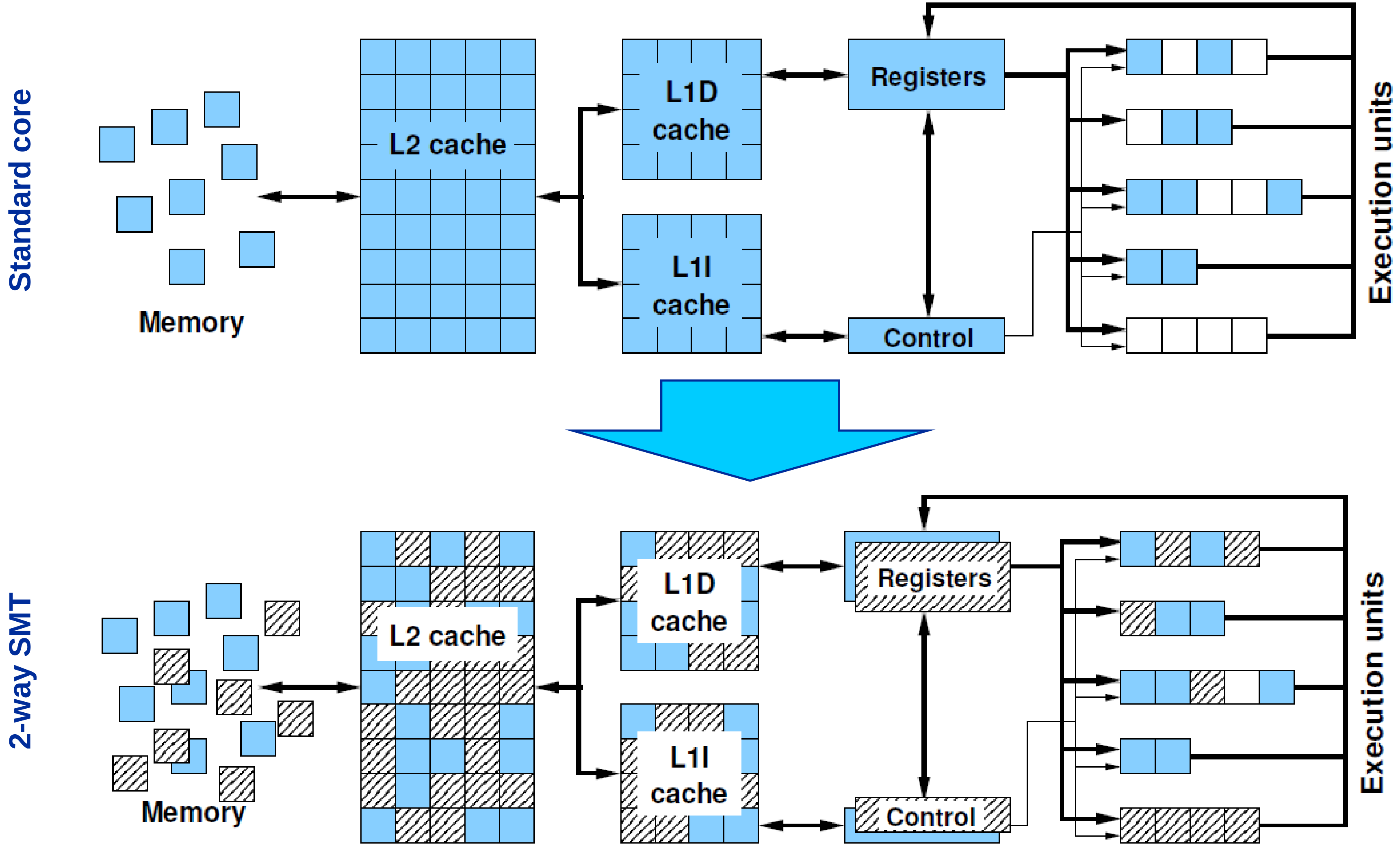
Principles and performance impact

SMT vs. independent instruction streams

Facts and fiction

SMT Makes a single physical core appear as two or more "logical" cores → multiple threads/processes run concurrently

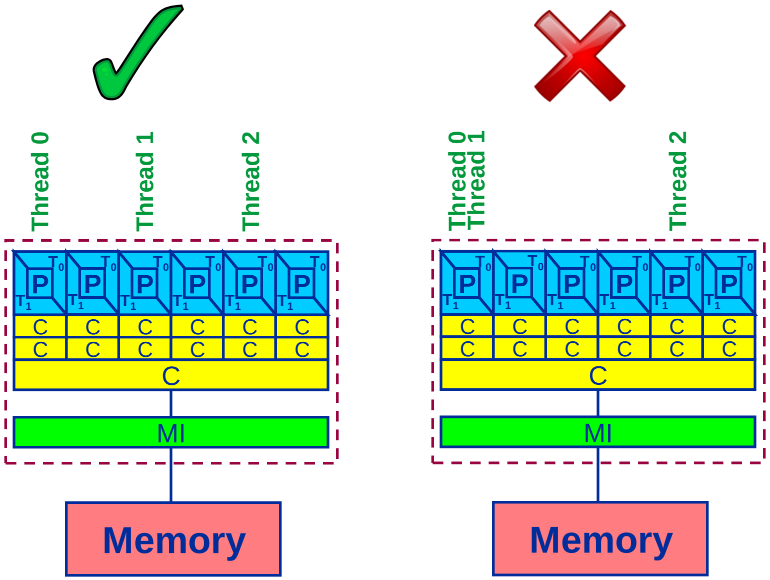
- **SMT principle (2-way example):**



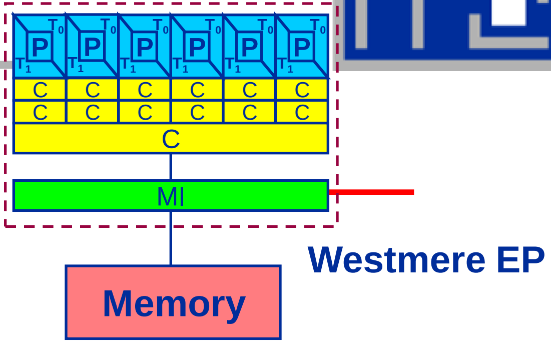
SMT impact

- **SMT is primarily suited for increasing processor throughput**
  - With multiple threads/processes running concurrently
- **Scientific codes tend to utilize chip resources quite well**
  - Standard optimizations (loop fusion, blocking, …)
  - High data and instruction-level parallelism
  - Exceptions do exist

- **SMT is an important topology issue**
  - SMT threads share almost all core resources
    - Pipelines, caches, data paths
  - Affinity matters!
  - If SMT is not needed
    - pin threads to physical cores
    - or switch it off via BIOS etc.



SMT impact



- **SMT adds another layer of topology (inside the physical core)**
- **Caveat: SMT threads share all caches!**
- **Possible benefit: Better pipeline throughput**
  - Filling otherwise unused pipelines
  - Filling pipeline bubbles with other thread's executing instructions:

Thread 0:

```
do i=1,N
  a(i) = a(i-1)*c
enddo
```

Thread 1:

```
do i=1,N
  b(i) = func(i)*d
enddo
```

Dependency → pipeline stalls until previous MULT is over

Unrelated work in other thread can fill the pipeline bubbles

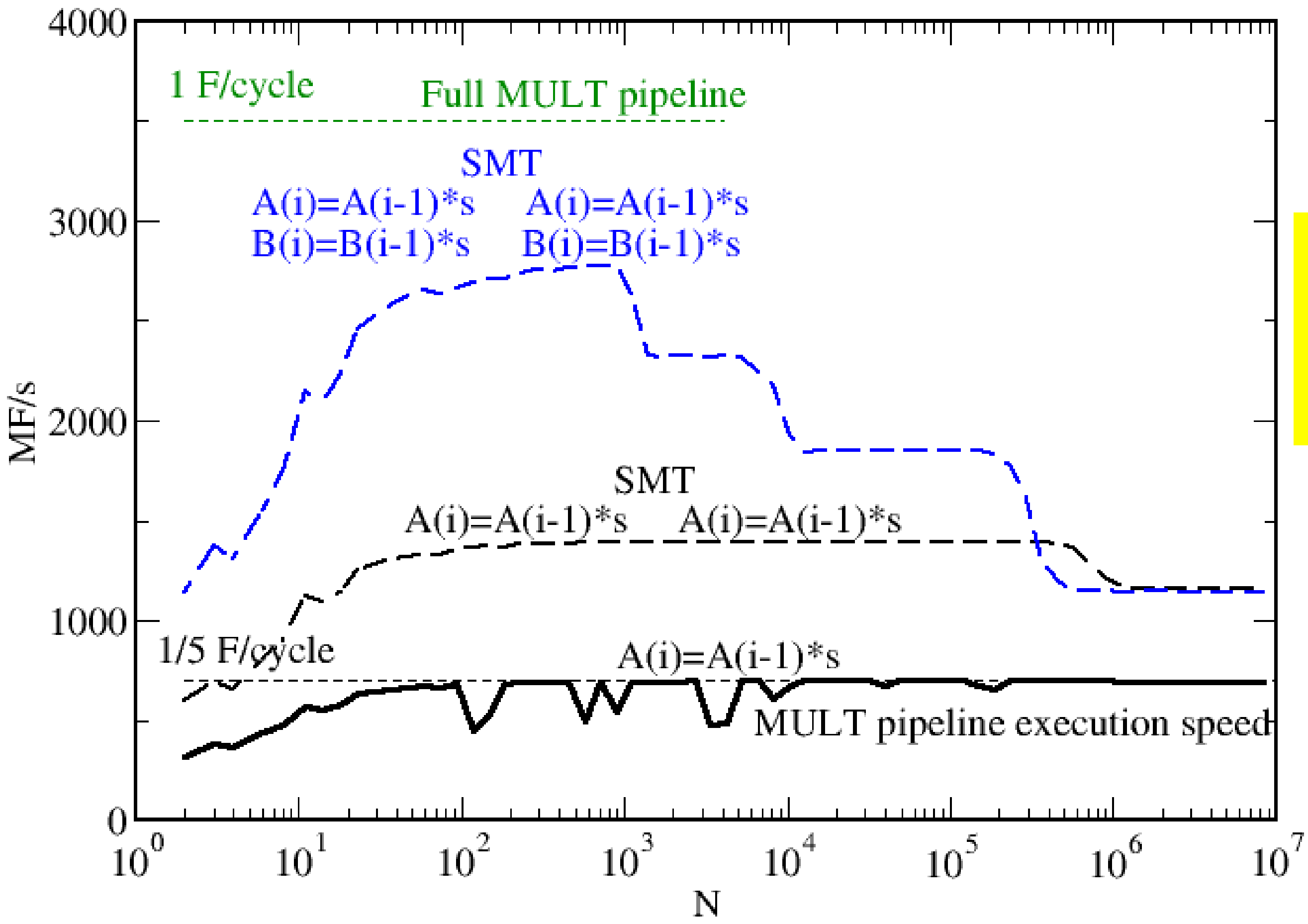
- Beware: Executing it all in a single thread (if possible) may reach the same goal without SMT:

```
do i=1,N
  a(i) = a(i-1)*c
  b(i) = func(i)*d
enddo
```

Simultaneous recursive updates with SMT

Intel Sandy Bridge (desktop) 4-core; 3.5 GHz; SMT

MULT Pipeline depth: 5 stages → 1 F / 5 cycles for recursive update



Fill bubbles via:

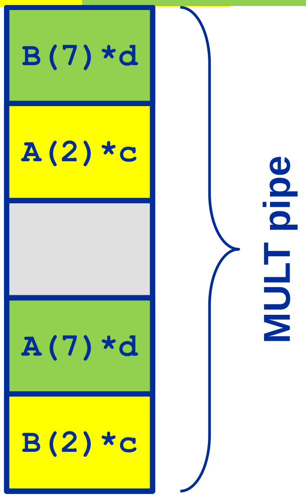
- SMT
- Multiple streams

Thread 0:

```
do i=1,N
A(i)=A(i-1)*c
B(i)=B(i-1)*d
enddo
```

Thread 1:

```
do i=1,N
A(i)=A(i-1)*c
B(i)=B(i-1)*d
enddo
```



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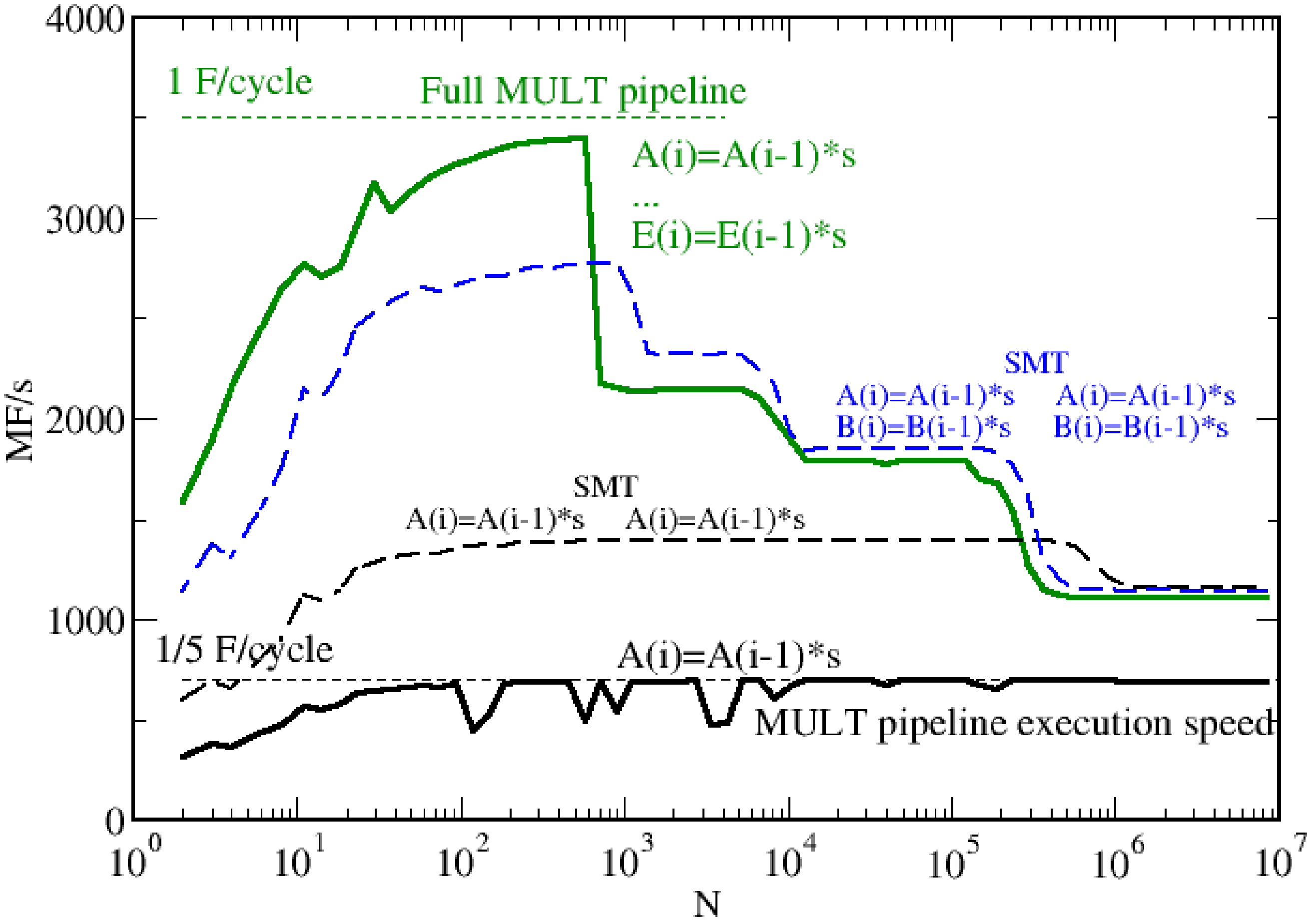
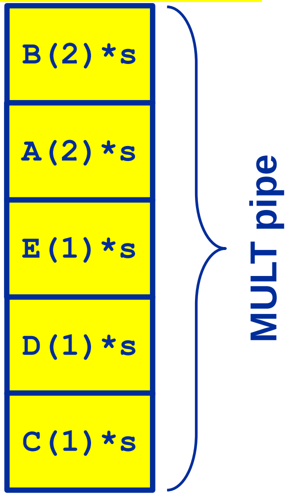


Thread 0:

```
do i=1,N
 A(i)=A(i-1)*s
 B(i)=B(i-1)*s
 C(i)=C(i-1)*s
 D(i)=D(i-1)*s
 E(i)=E(i-1)*s
enddo
```

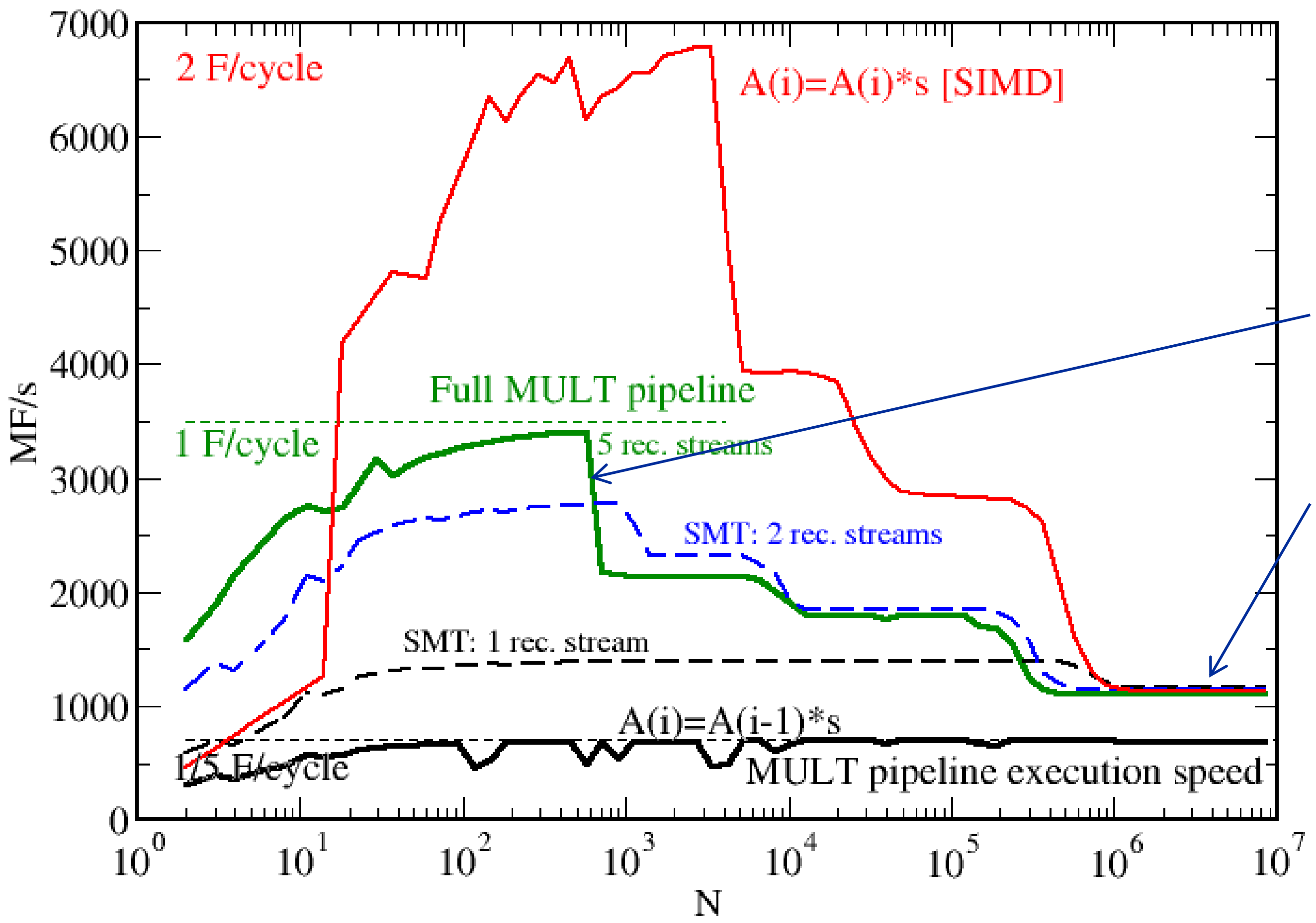


5 independent updates on a single thread do the same job!

Simultaneous recursive updates with SMT

Intel Sandy Bridge (desktop) 4-core; 3.5 GHz; SMT

Pure update benchmark can be vectorized → 2 F / cycle (store limited)



Recursive update:

- SMT can fill pipeline bubles
- A single thread can do so as well
- Bandwidth does not increase through SMT
- **SMT can not replace SIMD!**

SMT myths: Facts and fiction (1)

- Myth: “If the code is compute-bound, then the functional units should be saturated and SMT should show no improvement.”

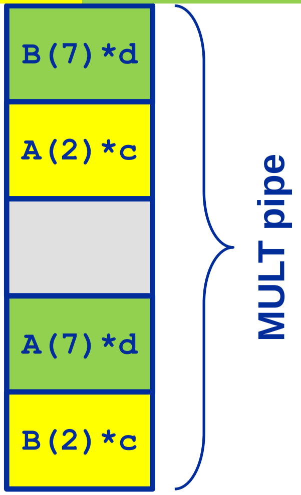
- Truth
  1. A compute-bound loop does not necessarily saturate the pipelines; dependencies can cause a lot of bubbles, which may be filled by SMT threads.
  2. If a pipeline is already full, SMT will not improve its utilization

Thread 0:

```
do i=1,N
A(i)=A(i-1)*c
B(i)=B(i-1)*d
enddo
```

Thread 1:

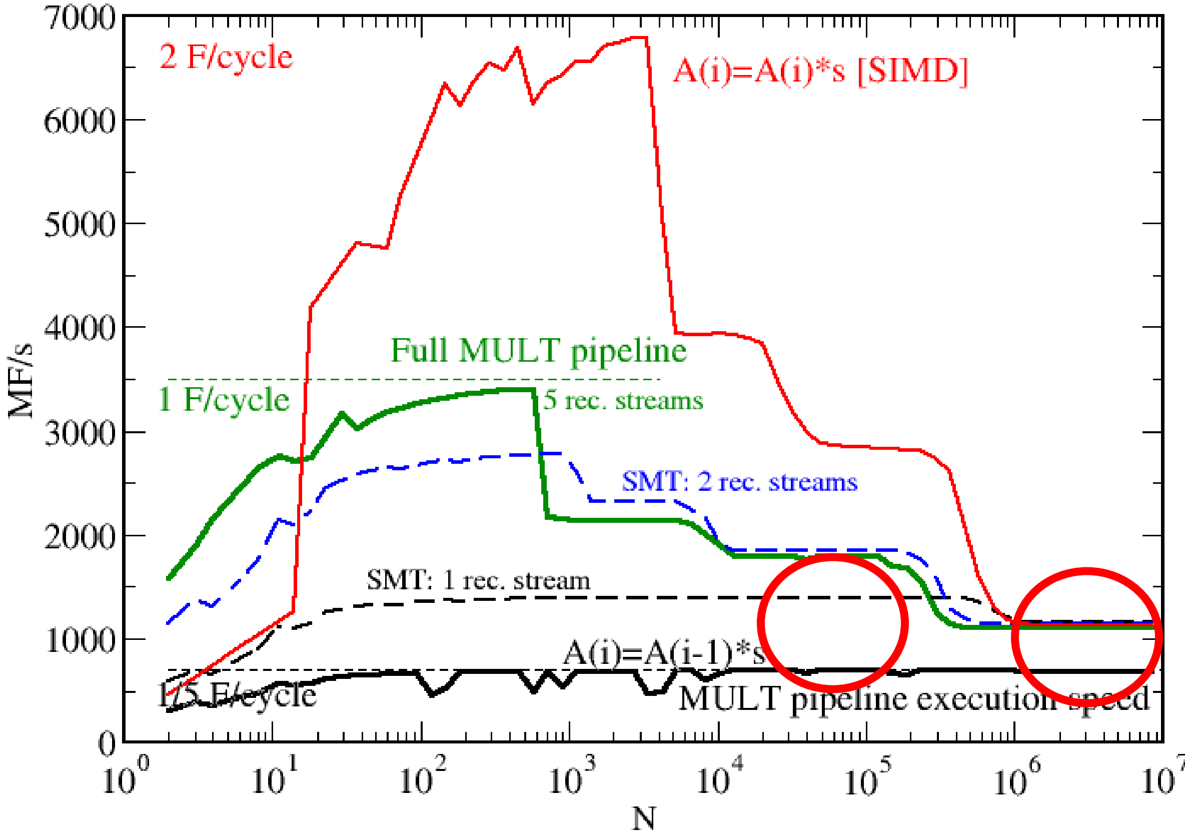
```
do i=1,N
A(i)=A(i-1)*c
B(i)=B(i-1)*d
enddo
```



SMT myths: Facts and fiction (2)

- **Myth: “If the code is memory-bound, SMT should help because it can fill the bubbles left by waiting for data from memory.”**
- **Truth:**
  1. **If the maximum memory bandwidth is already reached, SMT will not help since the relevant resource (bandwidth) is exhausted.**
  2. **If the relevant bottleneck is not exhausted, SMT may help since it can fill bubbles in the LOAD pipeline.**

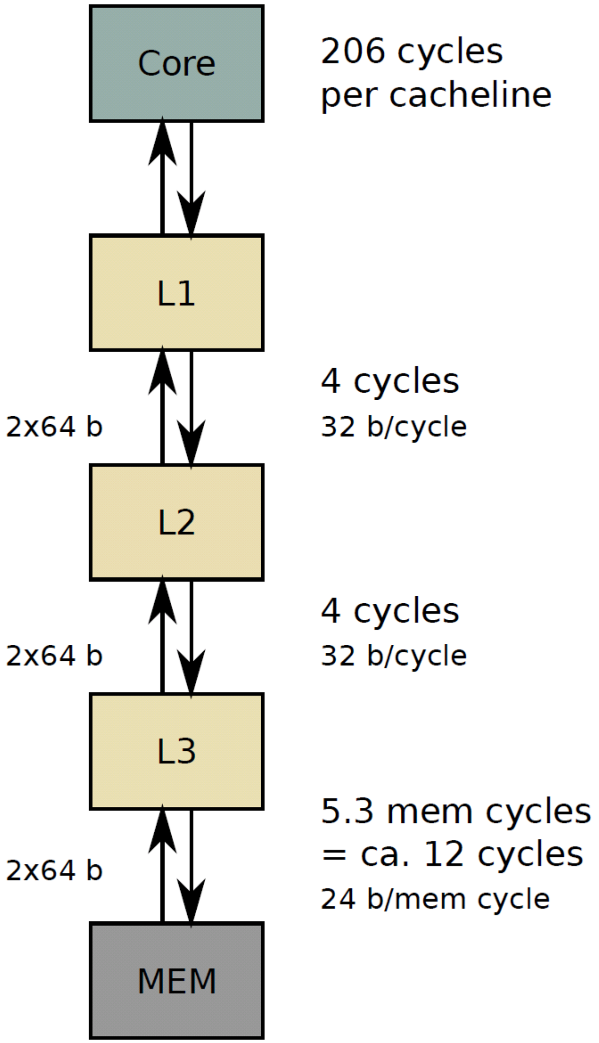
This applies also to other “relevant bottlenecks!”



SMT myths: Facts and fiction (3)

- **Myth: “SMT can help bridge the latency to memory (more outstanding references).”**

- **Truth:**
  Outstanding references may or may not be bound to SMT threads; they may be a resource of the memory interface and shared by all threads. The benefit of SMT with memory-bound code is usually due to better utilization of the pipelines so that less time gets “wasted” in the cache hierarchy.

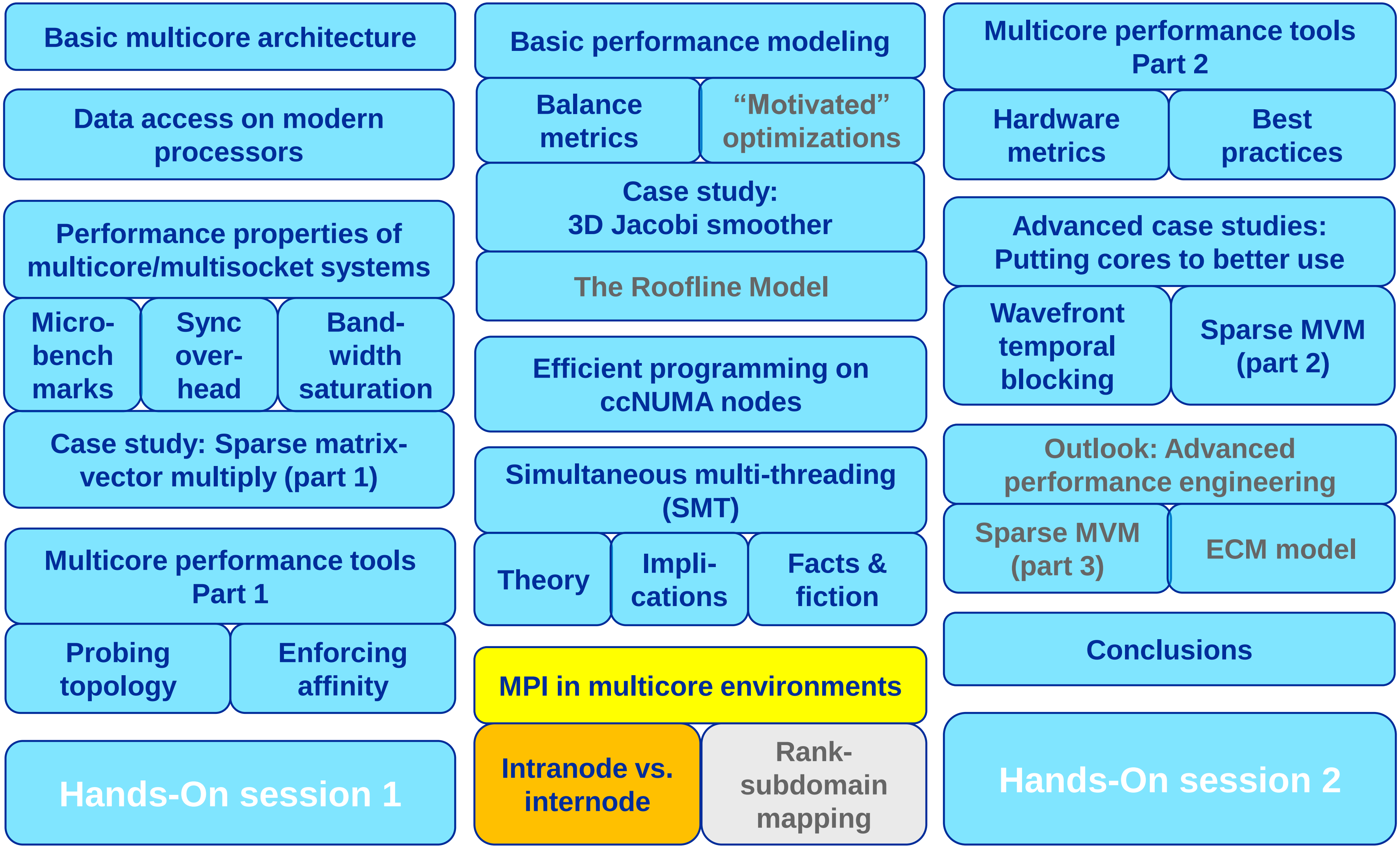


See also the “ECM Performance Model” later on.

SMT: When it may help, and when not

Functional parallelization	✓ ✗
FP-only parallel loop code	✗ ✓
Frequent thread synchronization	✗
Code sensitive to cache size	✗
Strongly memory-bound code	✗
Independent pipeline-unfriendly instruction streams	✓

The Plan



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Micro-benchmarks

Sync overhead

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Implications

Facts & fiction

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Rank-subdomain mapping

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Understanding MPI communication in multicore environments

Intra-node vs. inter-node MPI

MPI Cartesian topologies and rank-subdomain mapping

Intranode MPI

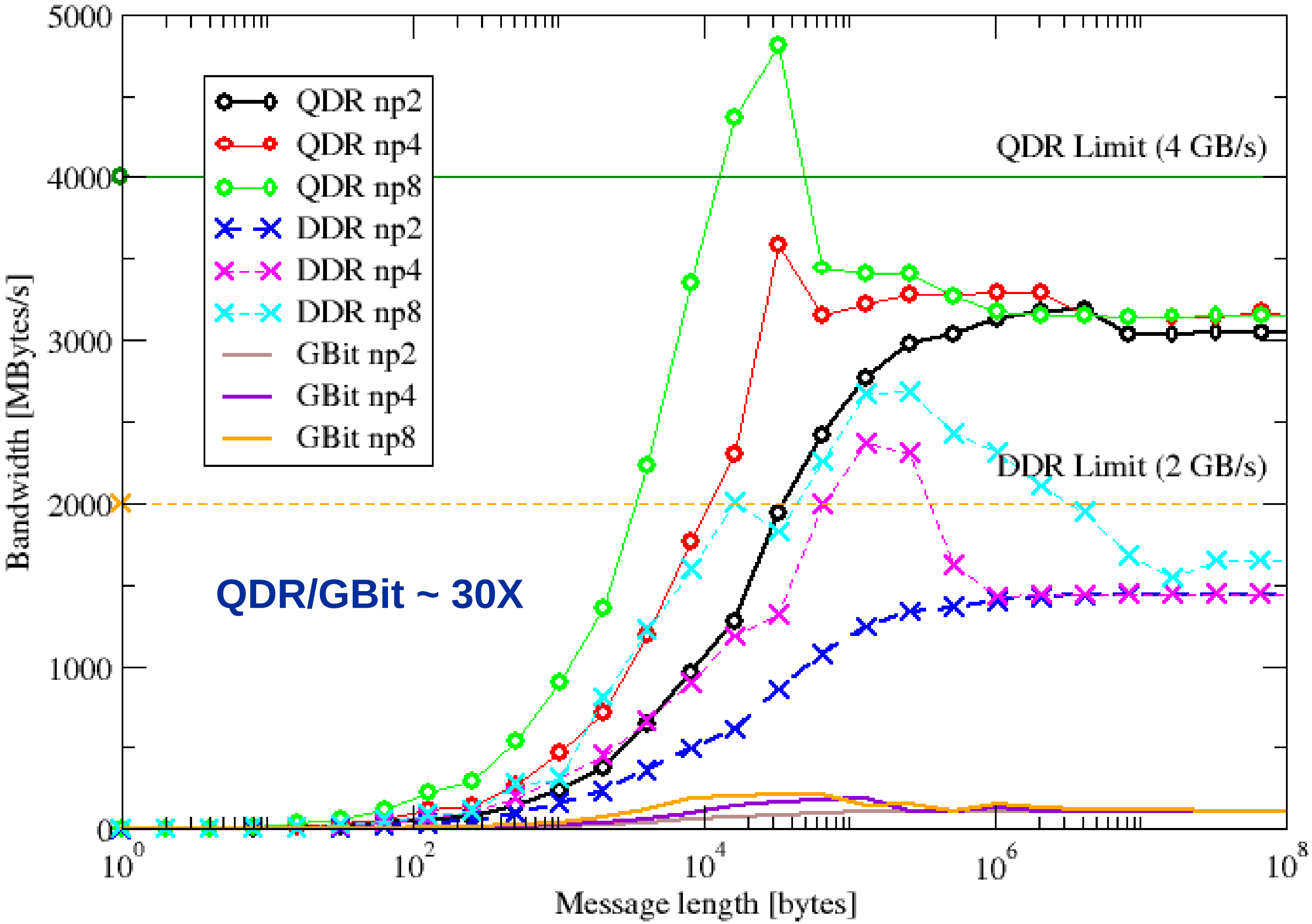
- **Common misconception: Intranode MPI is infinitely fast compared to internode**

- **Reality**
  - Intranode latency is much smaller than internode
  - Intranode asymptotic bandwidth is surprisingly comparable to internode
  - Difference in saturation behavior

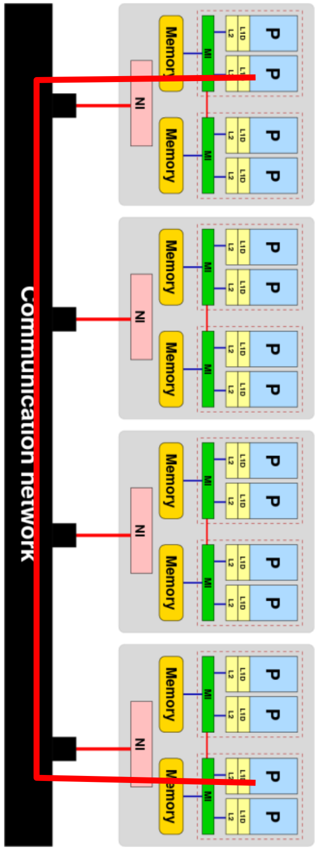
- **Other issues**
  - Mapping between ranks, subdomains and cores with Cartesian MPI topologies
  - Overlapping intranode with internode communication

MPI and Multicores

*Clusters: Unidirectional **internode** Ping-Pong bandwidth*



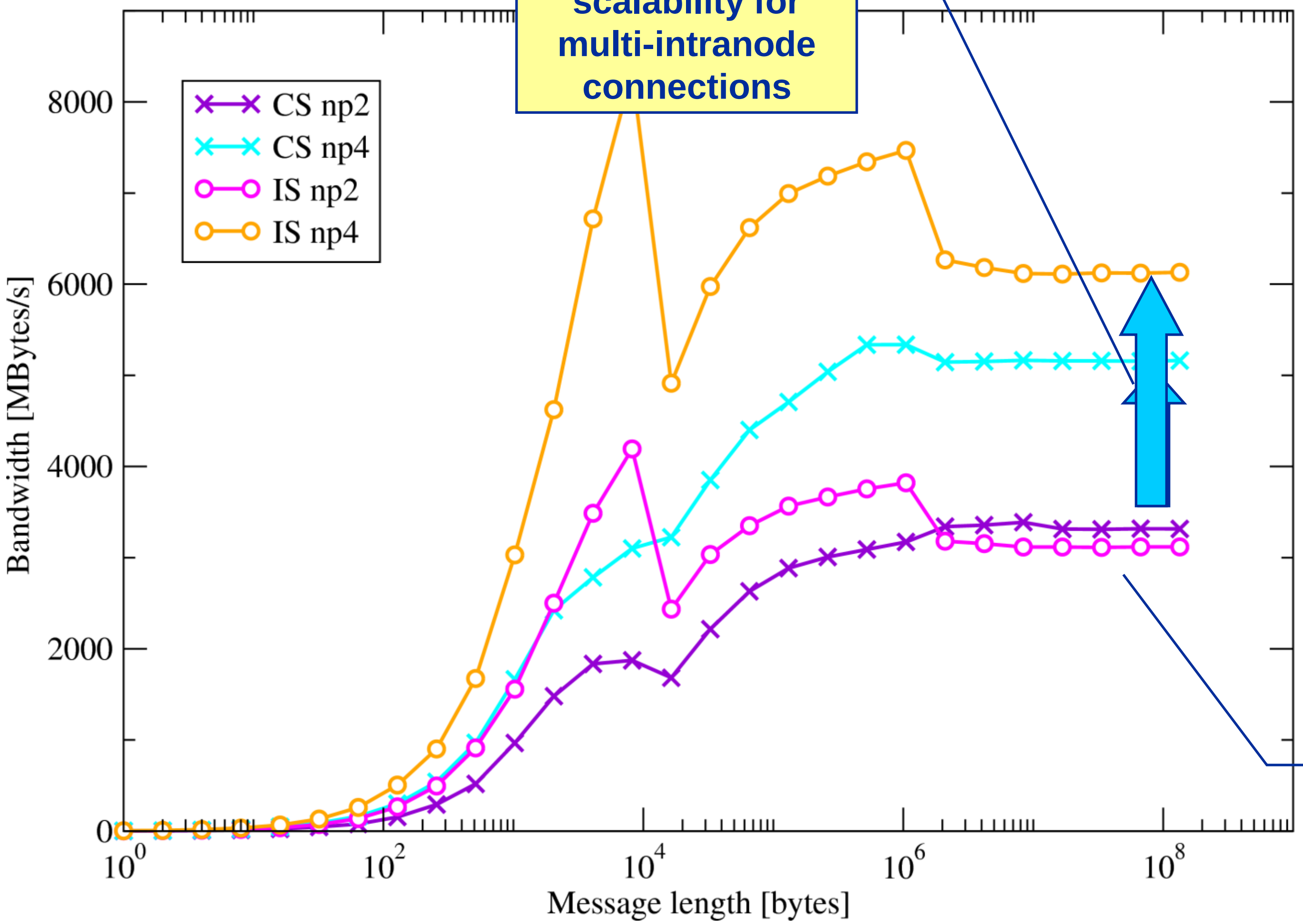
QDR/GBit ~ 30X



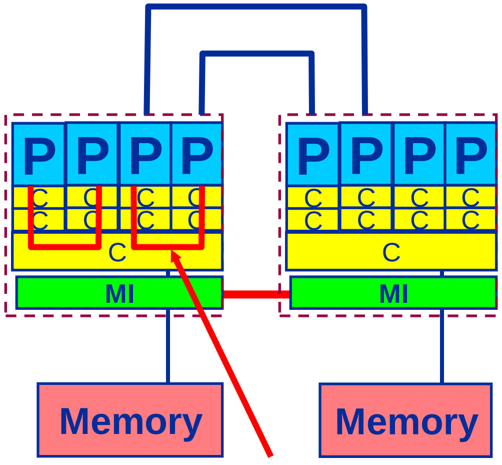
MPI and Multicores

*Clusters: Unidirectional **intranode** Ping-Pong bandwidth*

Some BW scalability for multi-intranode connections



Cross-Socket (CS)



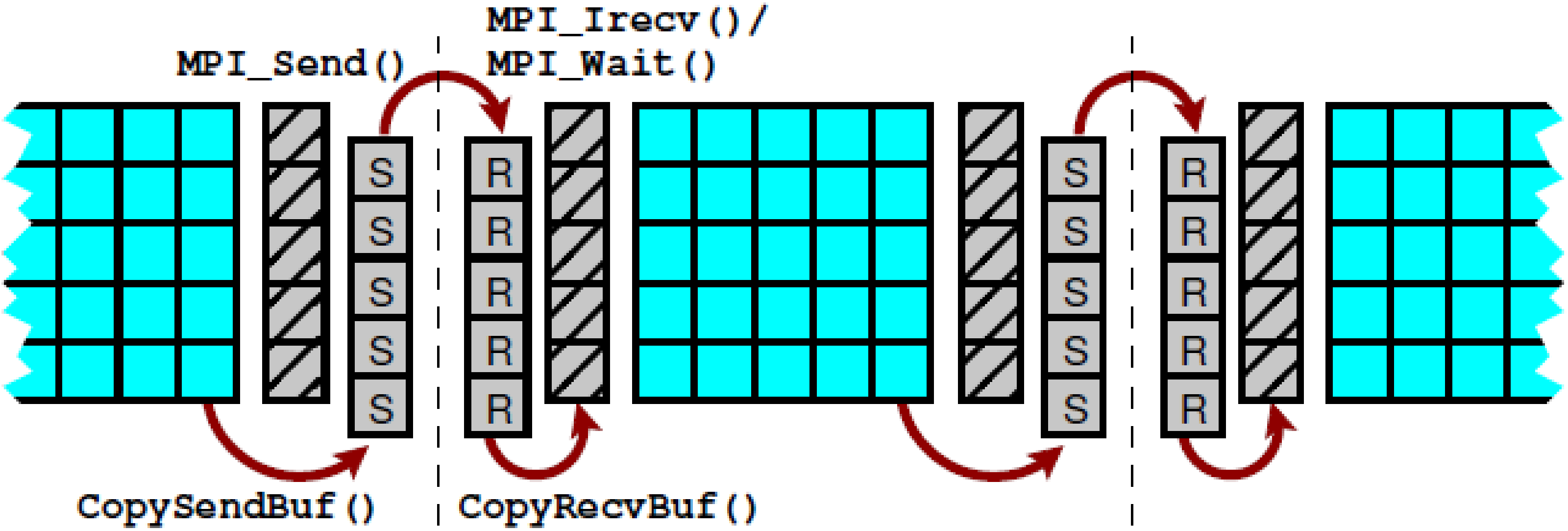
Intra-Socket (IS)

Single point-to-point BW similar to internode

Mapping problem for most efficient communication paths!?

"Best possible" MPI:
Minimizing cross-node communication

- **Example: Stencil solver with halo exchange**

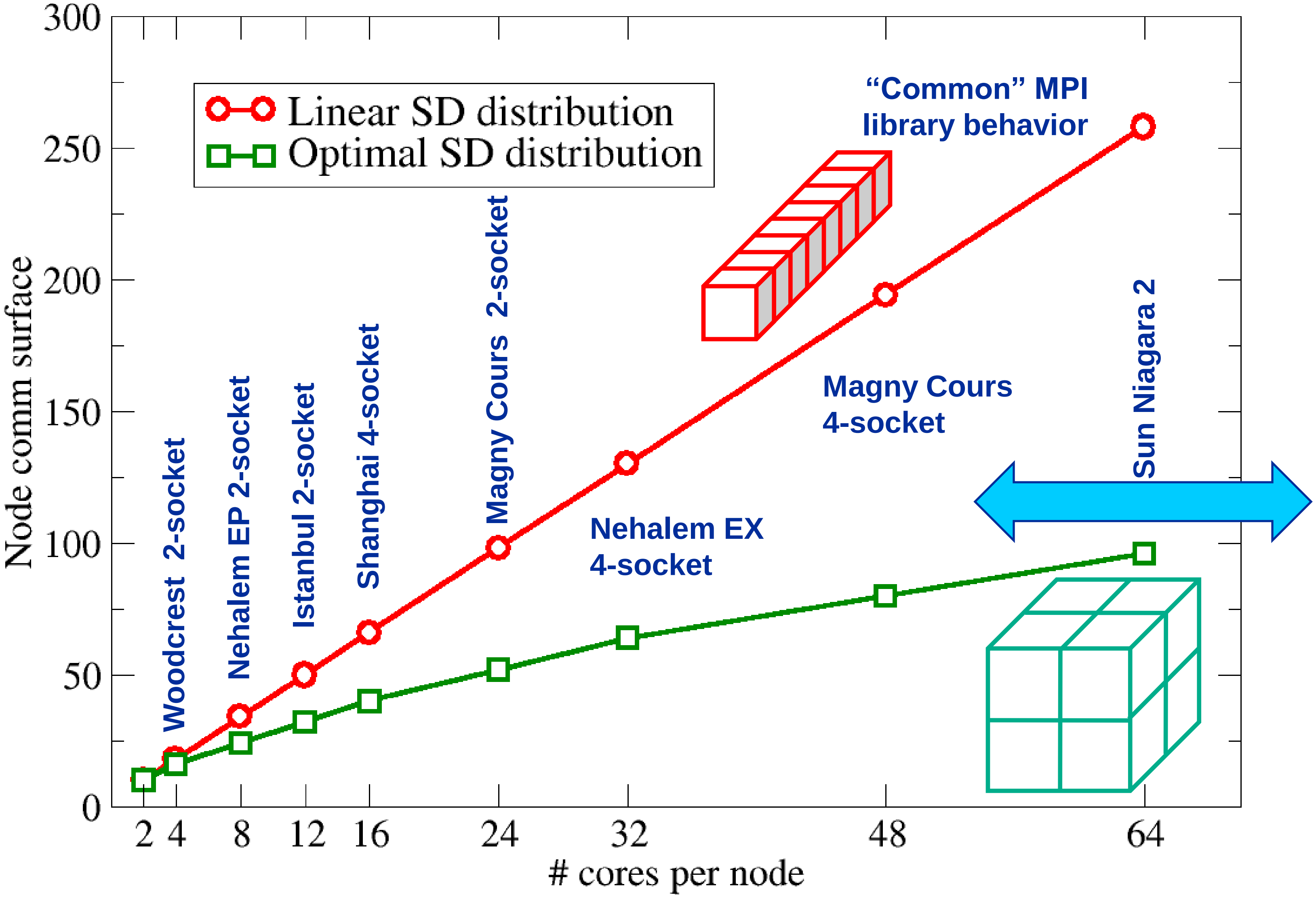


- **Goal: Reduce inter-node halo traffic**
- **Subdomains exchange halo with neighbors**
  - Populate a node's ranks with "maximum neighboring" subdomains
  - This minimizes a node's communication surface

- **Shouldn't `MPI_CART_CREATE` (w/ reorder) take care of this?**

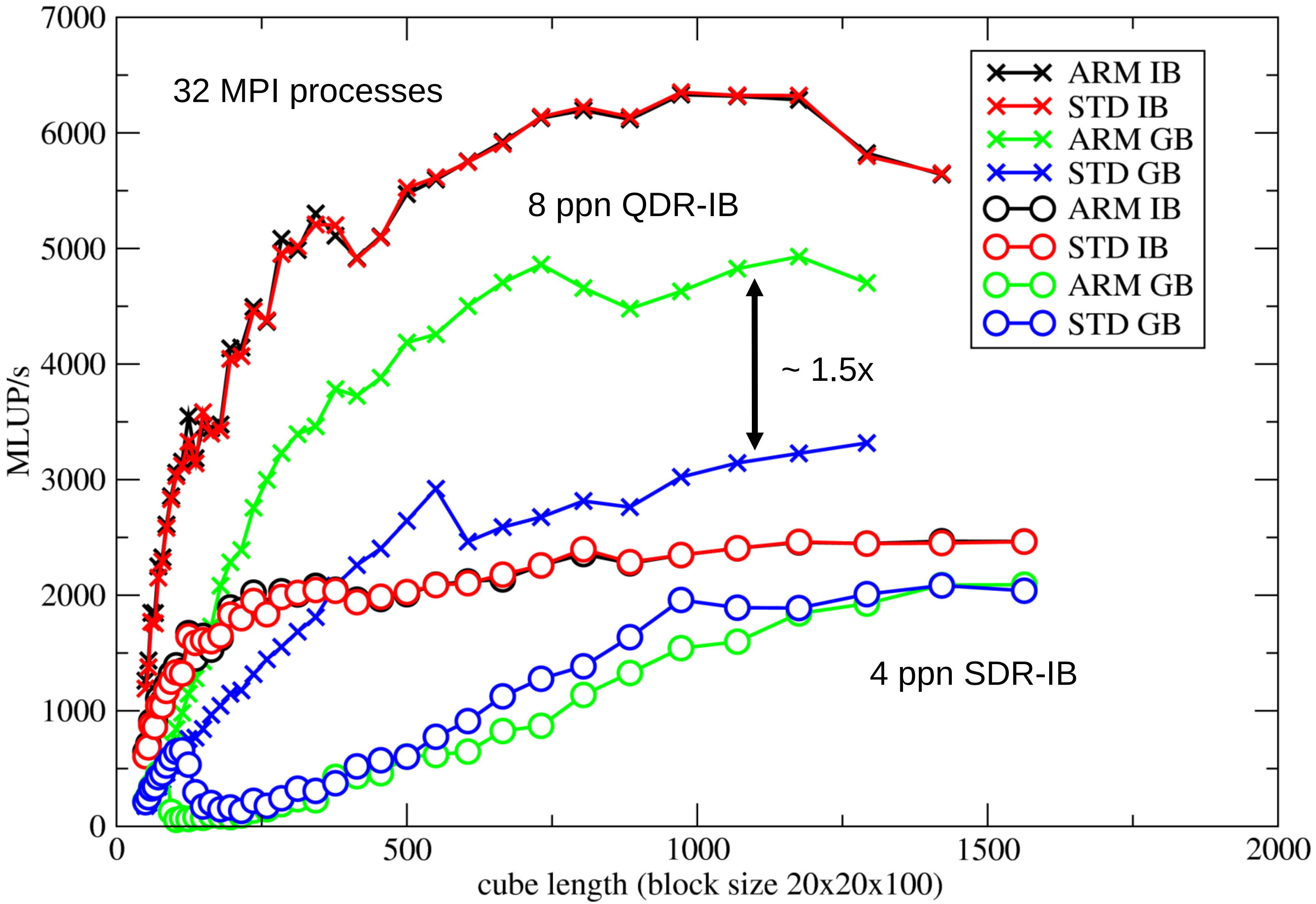
MPI rank-subdomain mapping in Cartesian topologies:

A 3D stencil solver and the growing number of cores per node



MPI rank-subdomain mapping:

3D stencil solver – measurements for 8ppn and 4ppn GBE vs. IB



Summary on MPI multicore issues

- **Intranode MPI**
  - May not be as fast as you think…
  - Becomes more important as core counts increase
  - May not be handled optimally by your MPI library

- **Rank-core mapping may be crucial for best performance**
  - Reduce inter-node traffic
  - Most MPIs do not recognize this
  - Some (e.g., Cray) can give you hints toward optimal placement

The Plan

- Basic multicore architecture
- Data access on modern processors
- Performance properties of multicore/multisocket systems
  - Micro-benchmarks
  - Sync overhead
  - Bandwidth saturation
- Case study: Sparse matrix-vector multiply (part 1)
- Multicore performance tools Part 1
  - Probing topology
  - Enforcing affinity
- Hands-On session 1

- Basic performance modeling
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  - Hardware metrics
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- Outlook: Advanced performance engineering
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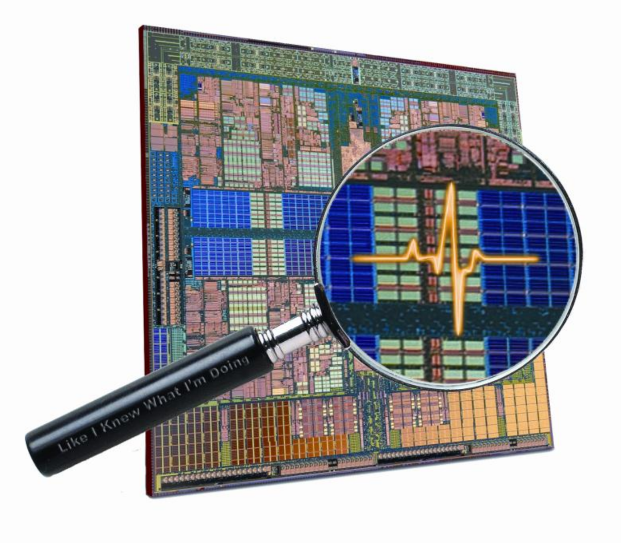


Best practices for using hardware performance metrics

likwid-perfctr

Probing performance behavior

- **How do we find out about the performance properties and requirements of a parallel code?**
  - Profiling via advanced tools is often overkill
- **A coarse overview is often sufficient**
  - likwid-perfctr (similar to “perfex” on IRIX, “hpmcount” on AIX, “lipfpm” on Linux/Altix)
  - Simple end-to-end measurement of hardware performance metrics
  - Operating modes:
    - Wrapper
    - Stethoscope
    - Timeline
    - Marker API
  - Preconfigured and extensible metric groups, list with `likwid-perfctr -a`

```
BRANCH: Branch prediction miss rate/ratio
CACHE: Data cache miss rate/ratio
CLOCK: Clock of cores
DATA: Load to store ratio
FLOPS_DP: Double Precision MFlops/s
FLOPS_SP: Single Precision MFlops/s
FLOPS_X87: X87 MFlops/s
L2: L2 cache bandwidth in MBytes/s
L2CACHE: L2 cache miss rate/ratio
L3: L3 cache bandwidth in MBytes/s
L3CACHE: L3 cache miss rate/ratio
MEM: Main memory bandwidth in MBytes/s
TLB: TLB miss rate/ratio
```

likwid-perfctr

Example usage with preconfigured metric group

```
$ env OMP_NUM_THREADS=4 likwid-perfctr -C N:0-3 -t intel -g FLOPS_DP  ./stream.exe
-------------------------------------------------------------
CPU type:       Intel Core Lynnfield processor
CPU clock:      2.93 GHz
-------------------------------------------------------------
Measuring group FLOPS_DP
-------------------------------------------------------------
YOUR PROGRAM OUTPUT
+--------------------------------------+-------------+-------------+-------------+-------------+
|                Event                 |   core 0    |   core 1    |   core 2    |   core 3    |
+--------------------------------------+-------------+-------------+-------------+-------------+
|          INSTR_RETIRED_ANY           | 1.97463e+08 | 2.31001e+08 | 2.30963e+08 | 2.31885e+08 |
|        CPU_CLK_UNHALTED_CORE         | 9.56999e+08 | 9.58401e+08 | 9.58637e+08 | 9.57338e+08 |
|     FP_COMP_OPS_EXE_SSE_FP_PACKED    | 4.00294e+07 | 3.08927e+07 | 3.08866e+07 | 3.08904e+07 |
|     FP_COMP_OPS_EXE_SSE_FP_SCALAR    |     882     |      0      |      0      |      0      |
| FP_COMP_OPS_EXE_SSE_SINGLE_PRECISION |      0      |      0      |      0      |      0      |
| FP_COMP_OPS_EXE_SSE_DOUBLE_PRECISION | 4.00303e+07 | 3.08927e+07 | 3.08866e+07 | 3.08904e+07 |
+--------------------------------------+-------------+-------------+-------------+-------------+
+---------------------------+------------+----------+----------+----------+
|          Metric           |   core 0   |  core 1  |  core 2  |  core 3  |
+---------------------------+------------+----------+----------+----------+
|        Runtime [s]        |  0.326242  | 0.32672  | 0.326801 | 0.326358 |
|            CPI            |  4.84647   | 4.14891  | 4.15061  | 4.12849  |
| DP MFlops/s (DP assumed)  |  245.399   | 189.108  | 189.024  | 189.304  |
|       Packed MUOPS/s      |  122.698   | 94.554   | 94.5121  | 94.6519  |
|       Scalar MUOPS/s      | 0.00270351 |    0     |    0     |    0     |
|         SP MUOPS/s        |     0      |    0     |    0     |    0     |
|         DP MUOPS/s        |  122.701   | 94.554   | 94.5121  | 94.6519  |
+---------------------------+------------+----------+----------+----------+
```

Always measured

Configured metrics (this group)

Derived metrics

likwid-perfctr

Best practices for runtime counter analysis

Things to look at (in roughly this order)

- Load balance (flops, instructions, BW)
- In-socket memory BW saturation
- Shared cache BW saturation
- Flop/s, loads and stores per flop metrics
- SIMD vectorization
- CPI metric
- # of instructions, branches, mispredicted branches

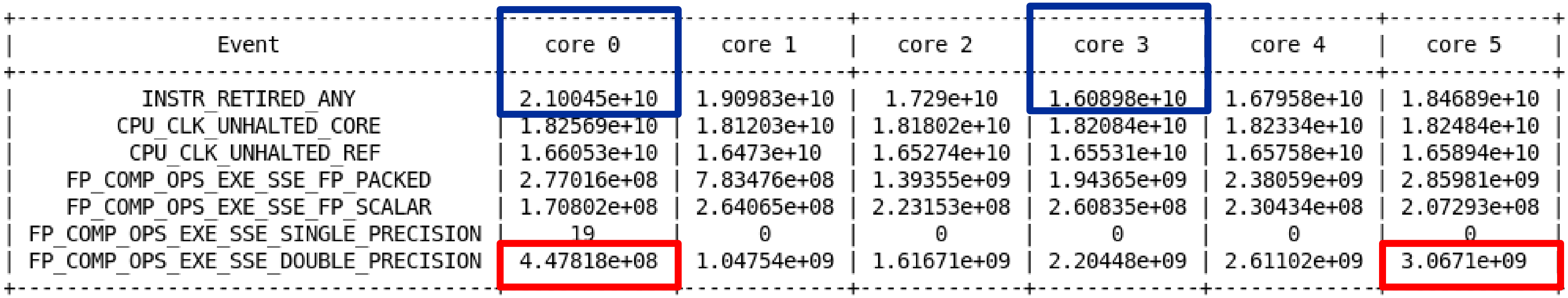
Caveats

- Load imbalance may not show in CPI or # of instructions
  - Spin loops in OpenMP barriers/MPI blocking calls
  - Looking at “top” or the Windows Task Manager does not tell you anything useful
- In-socket performance saturation may have various reasons
- Cache miss metrics are overrated
  - If I really know my code, I can often *calculate* the misses
  - Runtime and resource utilization is much more important

likwid-perfctr

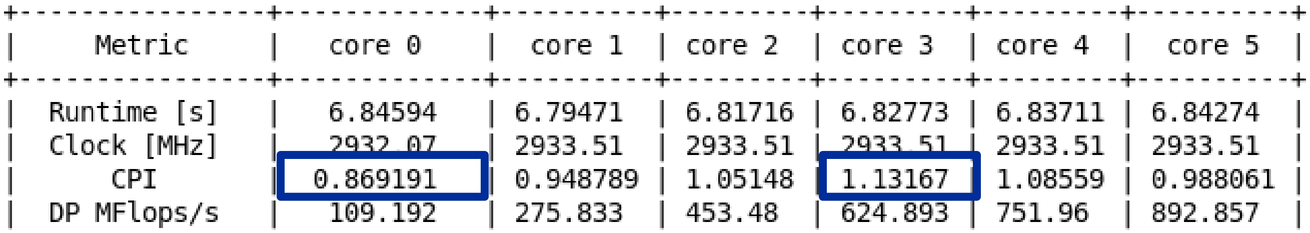
Identify load imbalance…

- **`Instructions retired / CPI` may not be a good indication of useful workload – at least for numerical / FP intensive codes….**
- **Floating Point Operations Executed is often a better indicator**
- **Waiting / “Spinning” in barrier generates a high instruction count**



```
+--------------------------------------+-------------+-------------+-------------+-------------+-------------+-------------+
|                Event                 |   core 0    |   core 1    |   core 2    |   core 3    |   core 4    |   core 5    |
+--------------------------------------+-------------+-------------+-------------+-------------+-------------+-------------+
|          INSTR_RETIRED_ANY           | 2.10045e+10 | 1.90983e+10 |  1.729e+10  | 1.60898e+10 | 1.67958e+10 | 1.84689e+10 |
|         CPU_CLK_UNHALTED_CORE        | 1.82569e+10 | 1.81203e+10 | 1.81802e+10 | 1.82084e+10 | 1.82334e+10 | 1.82484e+10 |
|          CPU_CLK_UNHALTED_REF        | 1.66053e+10 |  1.6473e+10 | 1.65274e+10 | 1.65531e+10 | 1.65758e+10 | 1.65894e+10 |
|       FP_COMP_OPS_EXE_SSE_FP_PACKED  | 2.77016e+08 | 7.83476e+08 | 1.39355e+09 | 1.94365e+09 | 2.38059e+09 | 2.85981e+09 |
|       FP_COMP_OPS_EXE_SSE_FP_SCALAR  | 1.70802e+08 | 2.64065e+08 | 2.23153e+08 | 2.60835e+08 | 2.30434e+08 | 2.07293e+08 |
| FP_COMP_OPS_EXE_SSE_SINGLE_PRECISION |     19      |      0      |      0      |      0      |      0      |      0      |
| FP_COMP_OPS_EXE_SSE_DOUBLE_PRECISION | 4.47818e+08 | 1.04754e+09 | 1.61671e+09 | 2.20448e+09 | 2.61102e+09 |  3.0671e+09 |
+--------------------------------------+-------------+-------------+-------------+-------------+-------------+-------------+
```

```
!$OMP PARALLEL DO
DO I = 1, N
   DO J = 1, I
      x(I) = x(I) + A(J,I) * y(J)
   ENDDO
ENDDO
!$OMP END PARALLEL DO
```

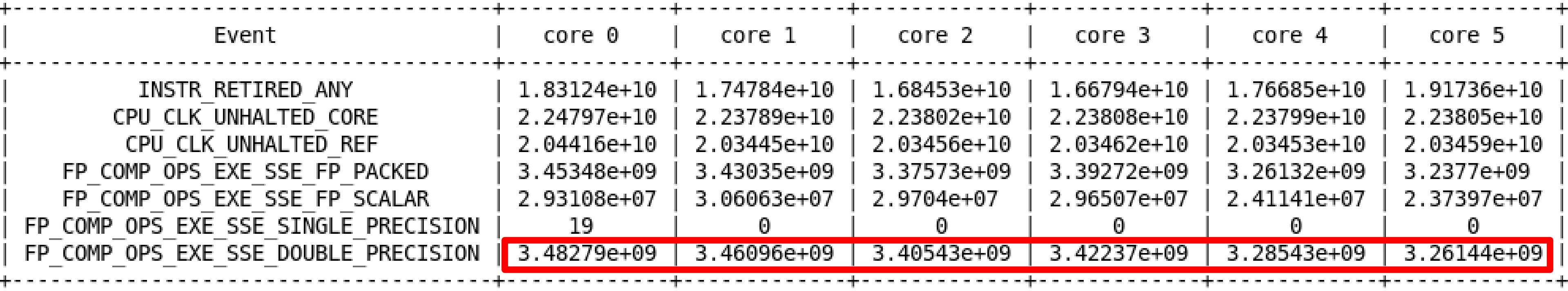


```
+---------------+-------------+-----------+----------+----------+----------+----------+
|    Metric     |   core 0    |  core 1   |  core 2  |  core 3  |  core 4  |  core 5  |
+---------------+-------------+-----------+----------+----------+----------+----------+
|  Runtime [s]  |   6.84594   |  6.79471  | 6.81716  | 6.82773  | 6.83711  | 6.84274  |
|  Clock [MHz]  |   2932.07   |  2933.51  | 2933.51  | 2933.51  | 2933.51  | 2933.51  |
|      CPI      |  0.869191   | 0.948789  | 1.05148  | 1.13167  | 1.08559  | 0.988061 |
|  DP MFlops/s  |   109.192   |  275.833  | 453.48   | 624.893  | 751.96   | 892.857  |
+---------------+-------------+-----------+----------+----------+----------+----------+
```

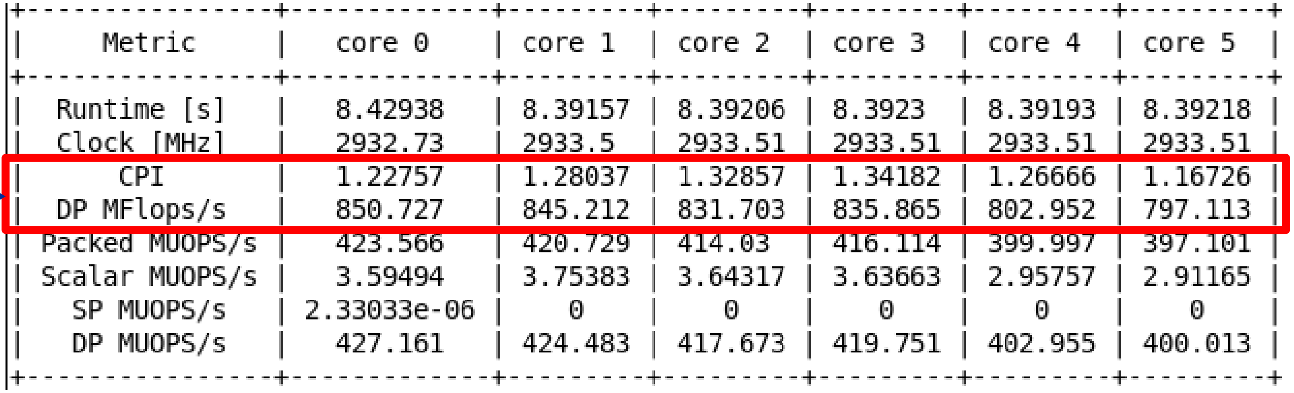
likwid-perfctr

… and load-balanced codes

```
env OMP_NUM_THREADS=6 likwid-perfctr -t intel -C S0:0-5 -g FLOPS_DP ./a.out
```



```
+-----------------------------------+-------------+-------------+-------------+-------------+-------------+-------------+
|               Event               |   core 0    |   core 1    |   core 2    |   core 3    |   core 4    |   core 5    |
+-----------------------------------+-------------+-------------+-------------+-------------+-------------+-------------+
|         INSTR_RETIRED_ANY         | 1.83124e+10 | 1.74784e+10 | 1.68453e+10 | 1.66794e+10 | 1.76685e+10 | 1.91736e+10 |
|       CPU_CLK_UNHALTED_CORE       | 2.24797e+10 | 2.23789e+10 | 2.23802e+10 | 2.23808e+10 | 2.23799e+10 | 2.23805e+10 |
|        CPU_CLK_UNHALTED_REF       | 2.04416e+10 | 2.03445e+10 | 2.03456e+10 | 2.03462e+10 | 2.03453e+10 | 2.03459e+10 |
|    FP_COMP_OPS_EXE_SSE_FP_PACKED  | 3.45348e+09 | 3.43035e+09 | 3.37573e+09 | 3.39272e+09 | 3.26132e+09 | 3.2377e+09  |
|    FP_COMP_OPS_EXE_SSE_FP_SCALAR  | 2.93108e+07 | 3.06063e+07 | 2.9704e+07  | 2.96507e+07 | 2.41141e+07 | 2.37397e+07 |
| FP_COMP_OPS_EXE_SSE_SINGLE_PRECISION |    19    |      0      |      0      |      0      |      0      |      0      |
| FP_COMP_OPS_EXE_SSE_DOUBLE_PRECISION | 3.48279e+09 | 3.46096e+09 | 3.40543e+09 | 3.42237e+09 | 3.28543e+09 | 3.26144e+09 |
+-----------------------------------+-------------+-------------+-------------+-------------+-------------+-------------+
```



```
+-----------------+-------------+---------+---------+---------+---------+---------+
|     Metric      |   core 0    | core 1  | core 2  | core 3  | core 4  | core 5  |
+-----------------+-------------+---------+---------+---------+---------+---------+
|   Runtime [s]   |   8.42938   | 8.39157 | 8.39206 | 8.3923  | 8.39193 | 8.39218 |
|   Clock [MHz]   |   2932.73   | 2933.5  | 2933.51 | 2933.51 | 2933.51 | 2933.51 |
|       CPI       |   1.22757   | 1.28037 | 1.32857 | 1.34182 | 1.26666 | 1.16726 |
|   DP MFlops/s   |   850.727   | 845.212 | 831.703 | 835.865 | 802.952 | 797.113 |
|  Packed MUOPS/s |   423.566   | 420.729 | 414.03  | 416.114 | 399.997 | 397.101 |
|  Scalar MUOPS/s |   3.59494   | 3.75383 | 3.64317 | 3.63663 | 2.95757 | 2.91165 |
|    SP MUOPS/s   | 2.33033e-06 |    0    |    0    |    0    |    0    |    0    |
|    DP MUOPS/s   |   427.161   | 424.483 | 417.673 | 419.751 | 402.955 | 400.013 |
+-----------------+-------------+---------+---------+---------+---------+---------+
```

Higher CPI but better performance

```
!$OMP PARALLEL DO
DO I = 1, N
  DO J = 1, N
     x(I) = x(I) + A(J,I) * y(J)
  ENDDO
ENDDO
!$OMP END PARALLEL DO
```

likwid-perfctr

Stethoscope mode

- **likwid-perfctr counts events on cores; it has no notion of what kind of code is running (if any)**

  This enables to listen on what currently happens without any overhead:

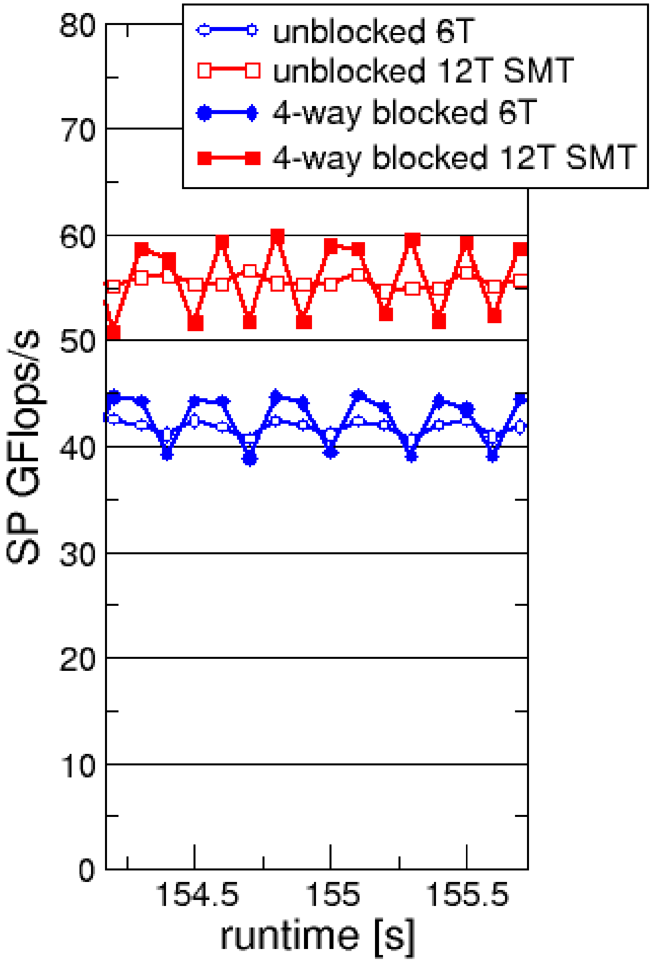
```
likwid-perfctr -c N:0-11 -g FLOPS_DP  -s 10
```

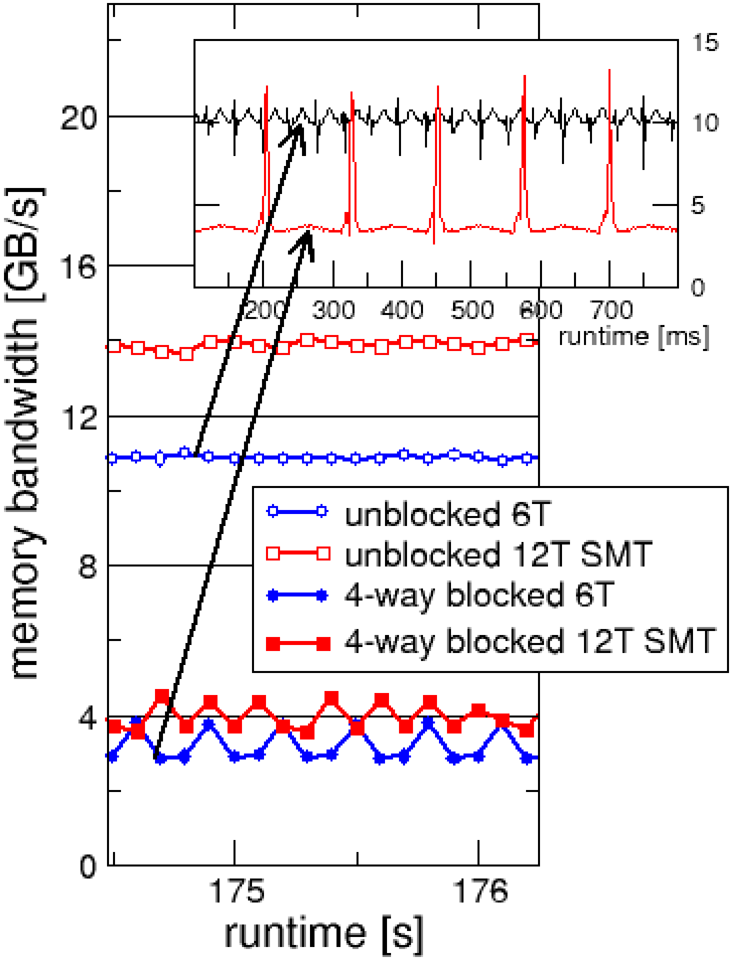
- **It can be used as cluster/server monitoring tool**
- **A frequent use is to measure a certain part of a long running parallel application from outside**

likwid-perfctr
Timeline mode

- **likwid-perfctr supports time resolved measurements of full node:**

```
likwid-perfctr -c N:0-11 -g MEM -d 50ms  > out.txt
```





likwid-perfctr

Marker API

- To measure only parts of an application a marker API is available.
- The API only turns counters on/off. The configuration of the counters is still done by likwid-perfctr application.
- Multiple named regions can be measured
- Results on multiple calls are accumulated
- Inclusive and overlapping Regions are allowed

```
likwid_markerInit();  // must be called from serial region

likwid_markerStartRegion(“Compute”);
. . .
likwid_markerStopRegion(“Compute”);


likwid_markerStartRegion(“postprocess”);
. . .
likwid_markerStopRegion(“postprocess”);


likwid_markerClose();  // must be called from serial region
```

likwid-perfctr

Group files

```
SHORT PSTI
EVENTSET
FIXC0 INSTR_RETIRED_ANY
FIXC1 CPU_CLK_UNHALTED_CORE
FIXC2 CPU_CLK_UNHALTED_REF
PMC0  FP_COMP_OPS_EXE_SSE_FP_PACKED
PMC1  FP_COMP_OPS_EXE_SSE_FP_SCALAR
PMC2  FP_COMP_OPS_EXE_SSE_SINGLE_PRECISION
PMC3  FP_COMP_OPS_EXE_SSE_DOUBLE_PRECISION
UPMC0  UNC_QMC_NORMAL_READS_ANY
UPMC1  UNC_QMC_WRITES_FULL_ANY
UPMC2 UNC_QHL_REQUESTS_REMOTE_READS
UPMC3 UNC_QHL_REQUESTS_LOCAL_READS
METRICS
Runtime [s] FIXC1*inverseClock
CPI  FIXC1/FIXC0
Clock [MHz]  1.E-06*(FIXC1/FIXC2)/inverseClock
DP MFlops/s (DP assumed) 1.0E-06*(PMC0*2.0+PMC1)/time
Packed MUOPS/s   1.0E-06*PMC0/time
Scalar MUOPS/s 1.0E-06*PMC1/time
SP MUOPS/s 1.0E-06*PMC2/time
DP MUOPS/s 1.0E-06*PMC3/time
Memory bandwidth [MBytes/s] 1.0E-06*(UPMC0+UPMC1)*64/time;
Remote Read BW [MBytes/s] 1.0E-06*(UPMC2)*64/time;
LONG
Formula:
DP MFlops/s =  (FP_COMP_OPS_EXE_SSE_FP_PACKED*2 +  FP_COMP_OPS_EXE_SSE_FP_SCALAR)/ runtime.
```

- **Groups are architecture-specific**
- **They are defined in simple text files**
- **Code is generated on recompile of likwid**
- **likwid-perfctr -a outputs list of groups**
- **For every group an extensive documentation is available**

optional

Measuring energy consumption with LIKWID

Measuring energy consumption
likwid-powermeter and likwid-perfctr -g ENERGY

optional

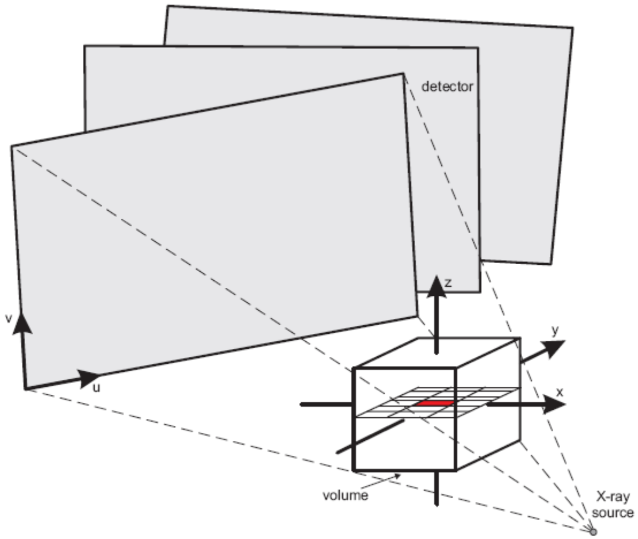
- **Implements Intel RAPL interface (Sandy Bridge)**
- **RAPL = “Running average power limit”**

```
-------------------------------------------------------------
CPU name:       Intel Core SandyBridge processor
CPU clock:      3.49 GHz
-------------------------------------------------------------
Base clock:     3500.00 MHz
Minimal clock:  1600.00 MHz
Turbo Boost Steps:
C1 3900.00 MHz
C2 3800.00 MHz
C3 3700.00 MHz
C4 3600.00 MHz
-------------------------------------------------------------
Thermal Spec Power: 95 Watts
Minimum  Power: 20 Watts
Maximum  Power: 95 Watts
Maximum  Time Window: 0.15625 micro sec
-------------------------------------------------------------
```

Example:

A medical image reconstruction code on Sandy Bridge

optional



Sandy Bridge EP (8 cores, 2.7 GHz base freq.)

Test case	Runtime [s]	Power [W]	Energy [J]
8 cores, plain C	**90.43**	90	8110
8 cores, SSE	29.63	93	2750
8 cores (SMT), SSE	22.61	102	2300
8 cores (SMT), AVX	**18.42**	111	2040

Faster code ➔ less energy

The Plan

Basic multicore architecture

Data access on modern processors

Performance properties of multicore/multisocket systems

Micro-benchmarks

Sync overhead

Bandwidth saturation

Case study: Sparse matrix-vector multiply (part 1)

Multicore performance tools Part 1

Probing topology

Enforcing affinity

Hands-On session 1

Basic performance modeling

Balance metrics

“Motivated” optimizations

Case study: 3D Jacobi smoother

The Roofline Model

Efficient programming on ccNUMA nodes

Simultaneous multi-threading (SMT)

Theory

Implications

Facts & fiction

MPI in multicore environments

Intranode vs. internode

Rank-subdomain mapping

Multicore performance tools Part 2

Hardware metrics

Best practices

Advanced case studies: Putting cores to better use

Wavefront temporal blocking

Sparse MVM (part 2)

Outlook: Advanced performance engineering

Sparse MVM (part 3)

ECM model

Conclusions

Hands-On session 2

Case studies

“Multicore-aware” wavefront temporal blocking:
Making use of shared caches

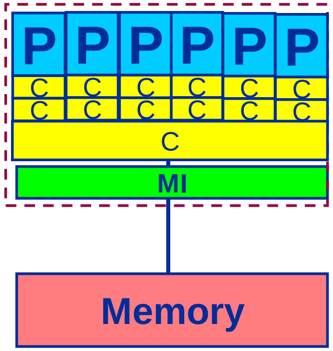
Asynchronous MPI communication in sparse MVM

Multicore-aware wavefront temporal blocking:

Making use of shared caches

Multicore awareness

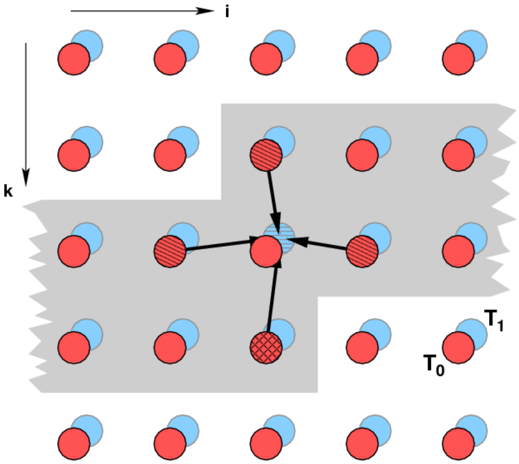
Classical Approaches: Parallelize & Reduce memory pressure



Multicore processors are still mostly programmed the same way as classic n-way SMP single-core compute nodes!

Simple 3D Jacobi stencil update (sweep):

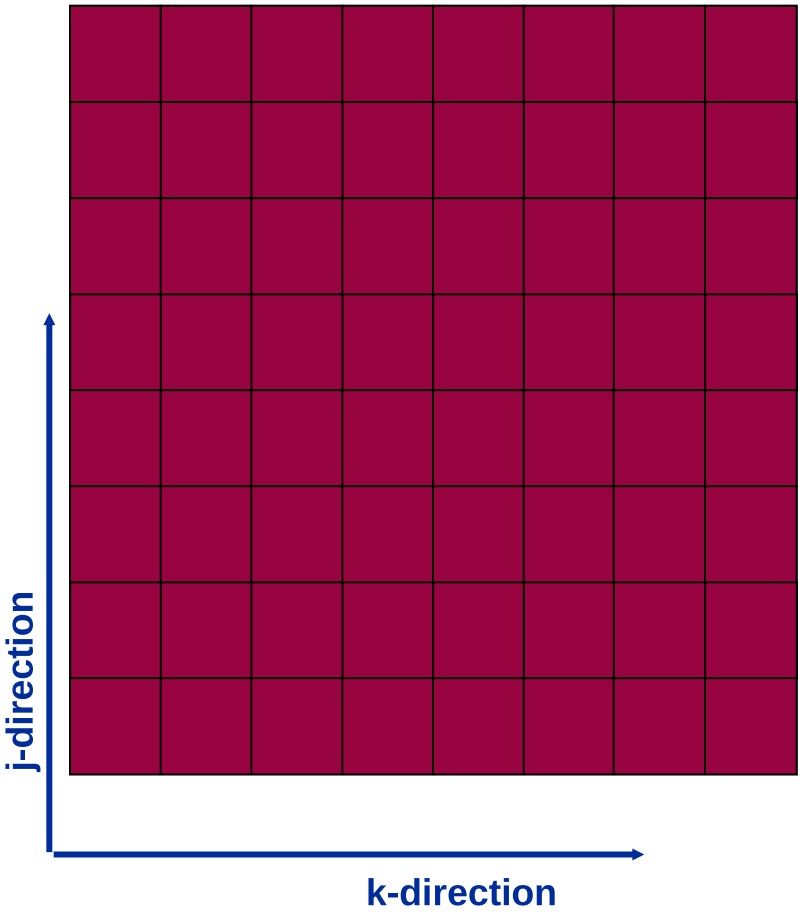
```
do k = 1 , Nk
  do j = 1 , Nj
       do i = 1 , Ni
          y(i,j,k) = a*x(i,j,k) + b*
                     (x(i-1,j,k)+x(i+1,j,k)+
                      x(i,j-1,k)+x(i,j+1,k)+
                      x(i,j,k-1)+x(i,j,k+1))
    enddo
  enddo
enddo
```

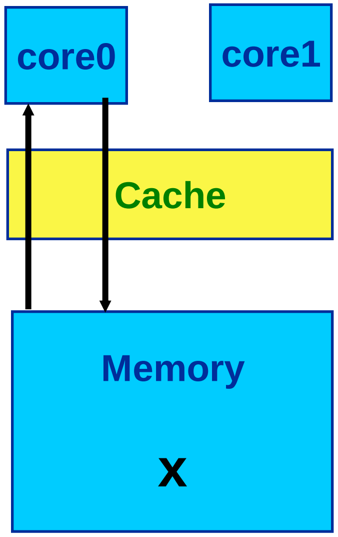


Performance Metric: Million Lattice Site Updates per second (MLUPs)
Equivalent MFLOPs: 8 FLOP/LUP * MLUPs

Multicore awareness

Standard sequential implementation

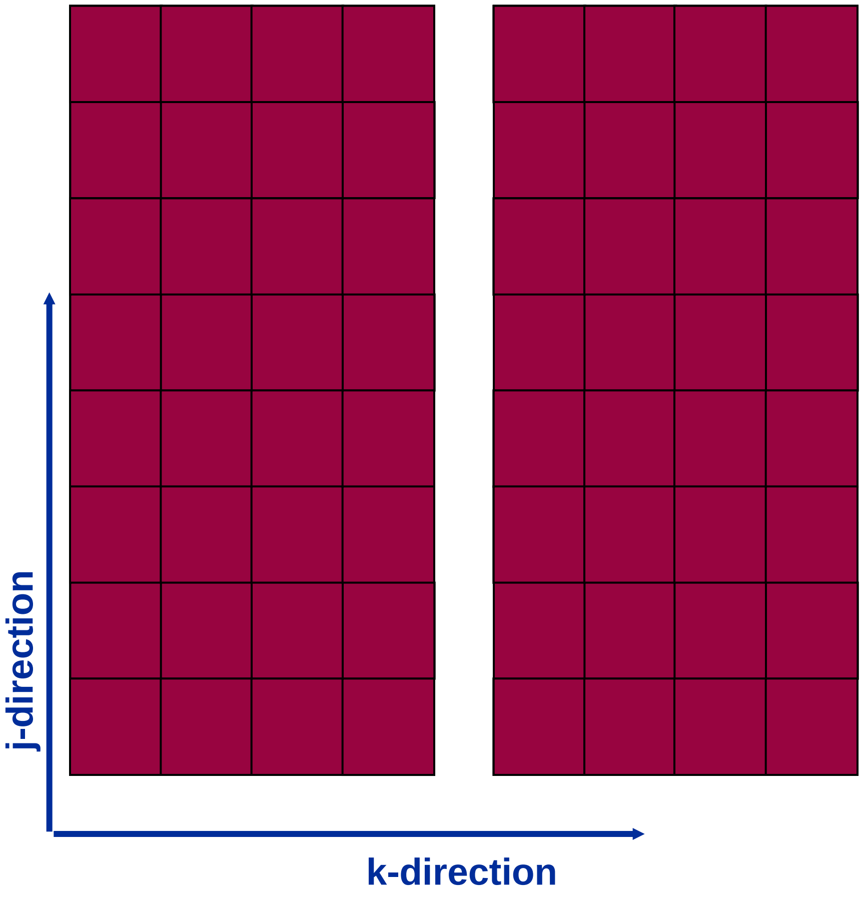


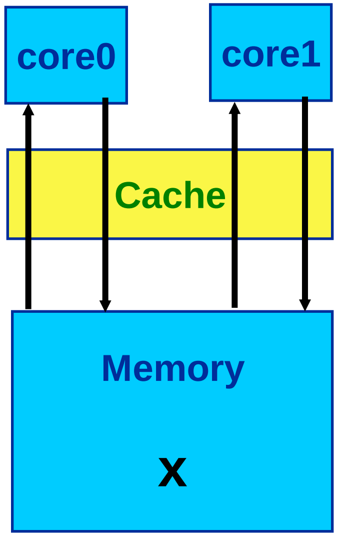


```
do  t=1,t_Max

   do  k=1,N
      do  j=1,N
         do  i=1,N
            y(i,j,k) = …
         enddo
      enddo
   enddo

enddo
```

Multicore awareness

Classical Approaches: Parallelize!

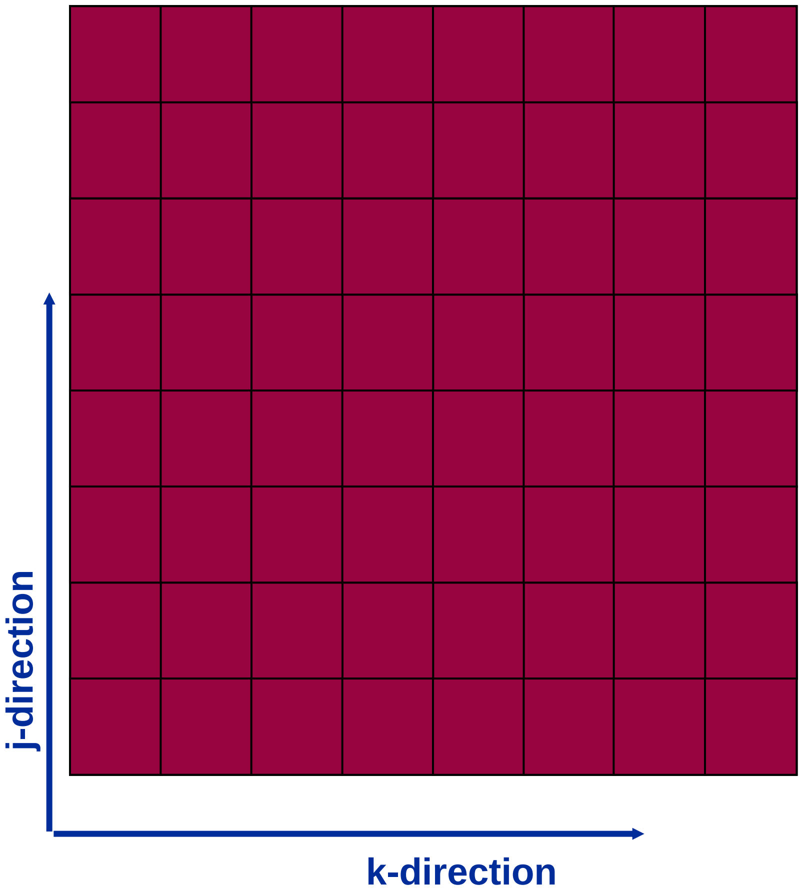


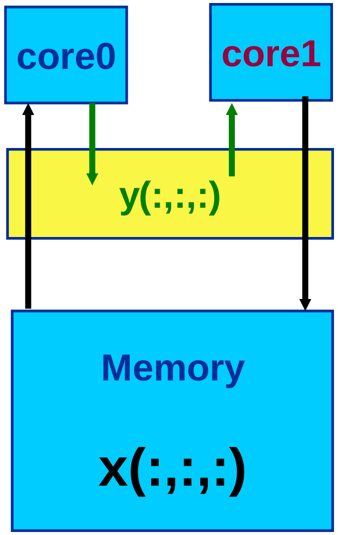


```
do t=1,tMax
!$OMP PARALLEL DO private(…)
  do k=1,N
     do j=1,N
        do i=1,N
           y(i,j,k) = …
        enddo
     enddo
  enddo
!$OMP END PARALLEL DO
enddo
```

Multicore awareness

Parallelization – reuse data in cache between threads





Do not use domain decomposition!

Instead shift 2nd thread by three i-j planes and proceed to the same domain
→ 2nd thread loads input data from shared OL cache!

Sync threads/cores after each k-iteration!

"Wavefront Parallelization (WFP)"

core0: **x(:,:,k-1:k+1)**$_t$ → ***y(:,:,k)***$_{t+1}$

core1: ***y(:,:,(k-3):(k-1))***$_{t+1}$ → **x(:,:,k-2)**$_{t+2}$

Multicore awareness

WF parallelization – reuse data in cache between threads

Use small ring buffer
`tmp(:,:,0:3)`
which fits into the cache

↓

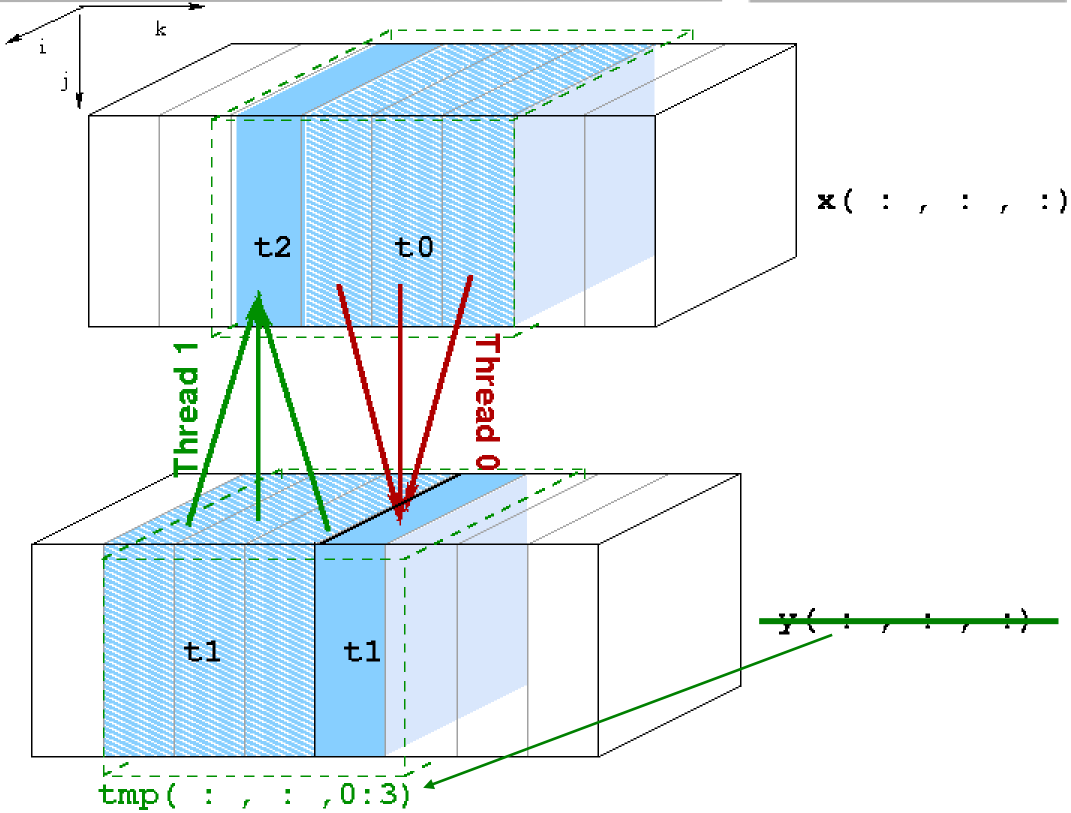
Save main memory data transfers for **`y(:,:,:)`** !

↓

16 Byte / 2 LUP !

↓

8 Byte / LUP !



Compare with optimal baseline (nontemporal stores on y):
Maximum speedup of 2 can be expected
(assuming infinitely fast cache and
no overhead for OMP BARRIER after each k-iteration)

Multicore awareness

WF parallelization – reuse data in cache between threads

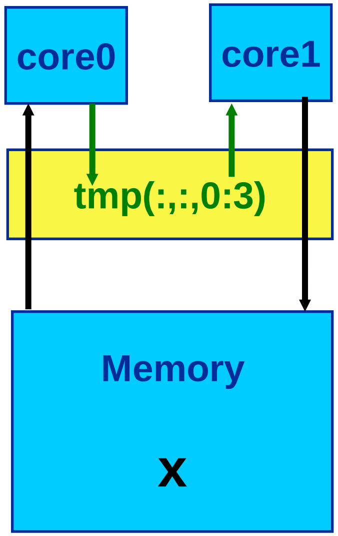
Thread 0: `x(:,:,k-1:k+1)`$_t$ → *`tmp(:,:,mod(k,4))`*

Thread 1: *`tmp(:,:,mod(k-3,4):mod(k-1,4))`* → `x(:,:,k-2)`$_{t+2}$

Performance model including finite cache bandwidth (B_C)

Time for 2 LUP:

$$T_{2LUP} = 16\ \text{Byte}/B_M + x * 8\ \text{Byte} / B_C = T_0\ (1 + x/2 * B_M/B_C)$$



Minimum value: $x = 2$

Speed-Up vs. baseline: $\mathbf{S_W = 2*T_0/T_{2LUP}}$
$\mathbf{= 2 / (1 + B_M/B_C)}$

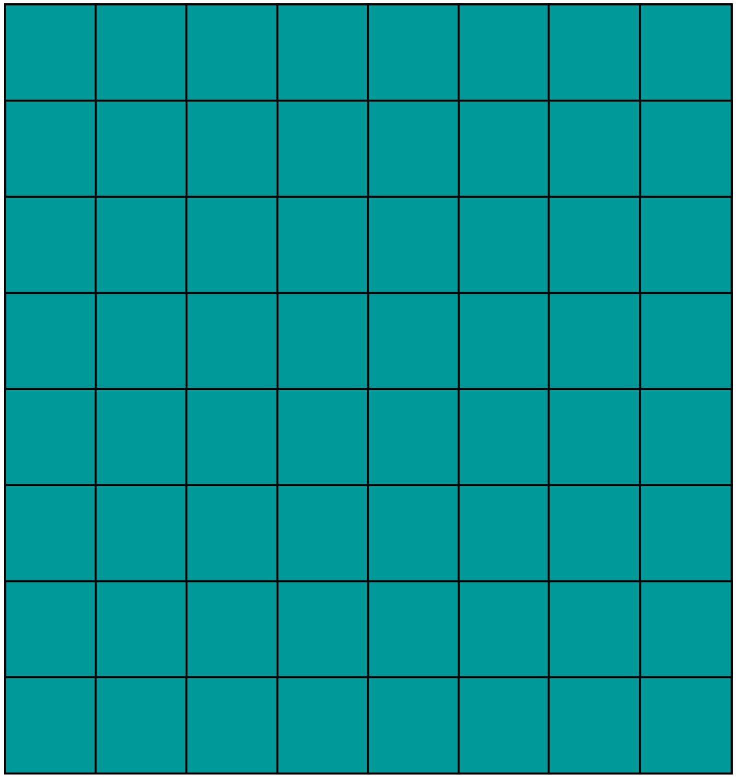
B_C and B_M are measured in saturation runs:

Clovertown: $B_M/B_C = 1/12$ → $S_W = 1.85$

Nehalem : $B_M/B_C = 1/4$ → $S_W = 1.6$

Jacobi solver

WFP: Propagating four wavefronts on native quadcores (1x4)

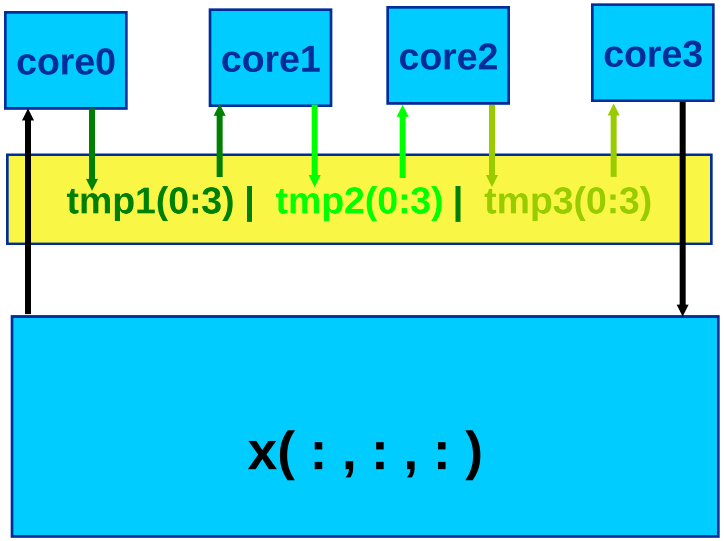


Running **`tb`** wavefronts requires **`tb-1`** temporary arrays **`tmp`** to be held in cache!

Max. performance gain (vs. optimal baseline): **`tb = 4`**

Extensive use of cache bandwidth!

1 x 4 distribution



Jacobi solver

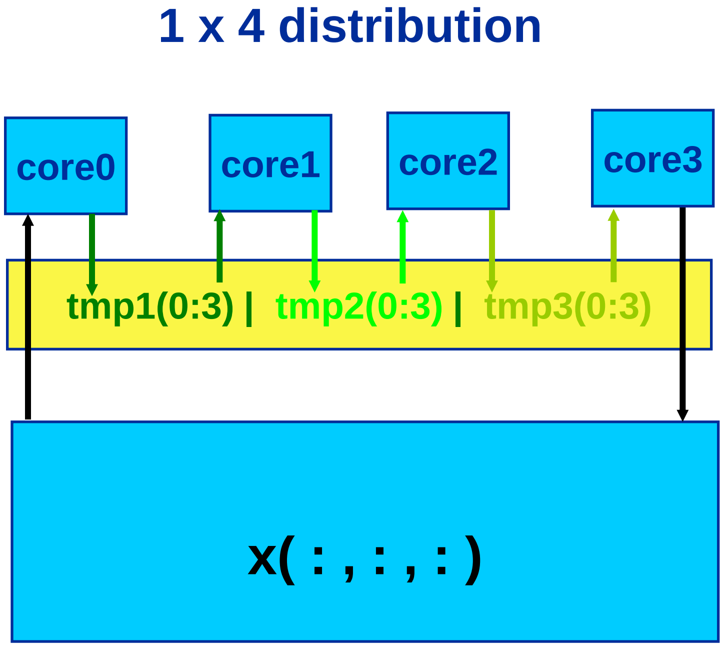
WF parallelization: New choices on native quad-cores

Thread 0: `x(:,:,k-1:k+1)`$_t$ → *`tmp1(mod(k,4))`*

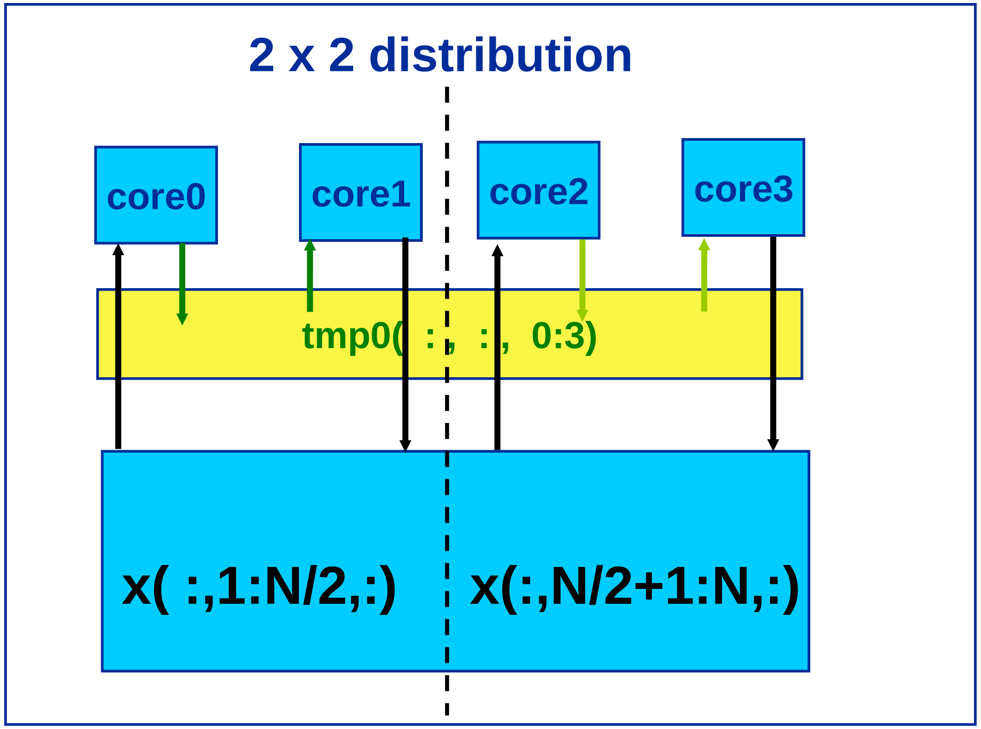
Thread 1: *`tmp1(mod(k-3,4):mod(k-1,4))`* → *`tmp2(mod(k-2,4))`*

Thread 2: *`tmp2(mod(k-5,4:mod(k-3,4))`* → *`tmp3(mod(k-4,4))`*

Thread 3: *`tmp3(mod(k-7,4):mod(k-5,4))`* → `x(:,:,k-6)`$_{t+4}$



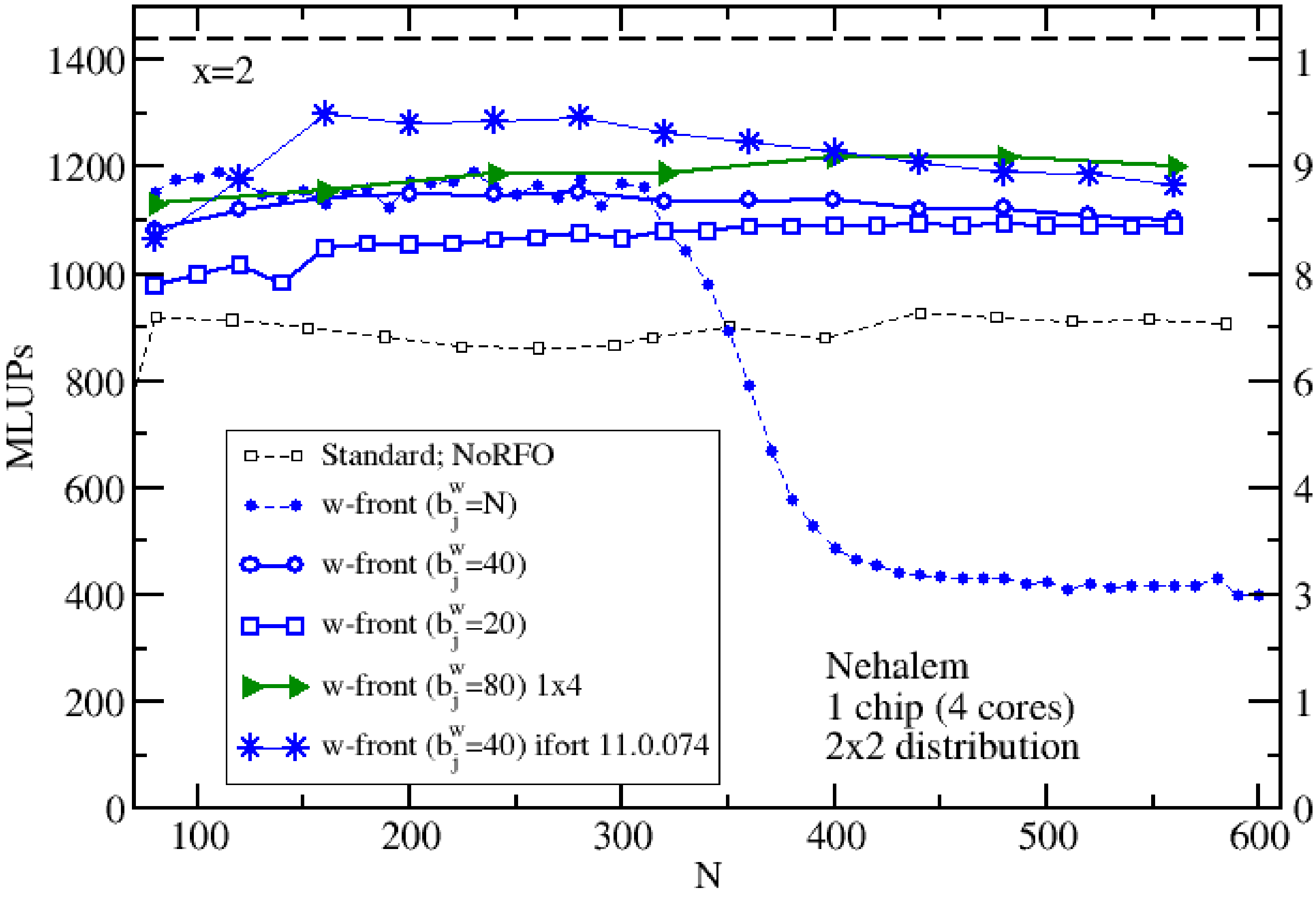
1 x 4 distribution

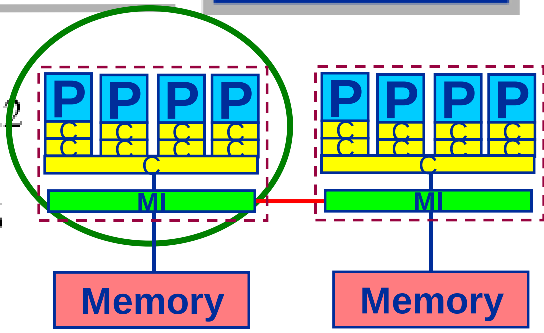


2 x 2 distribution

Jacobi solver

Wavefront parallelization: L3 group Nehalem





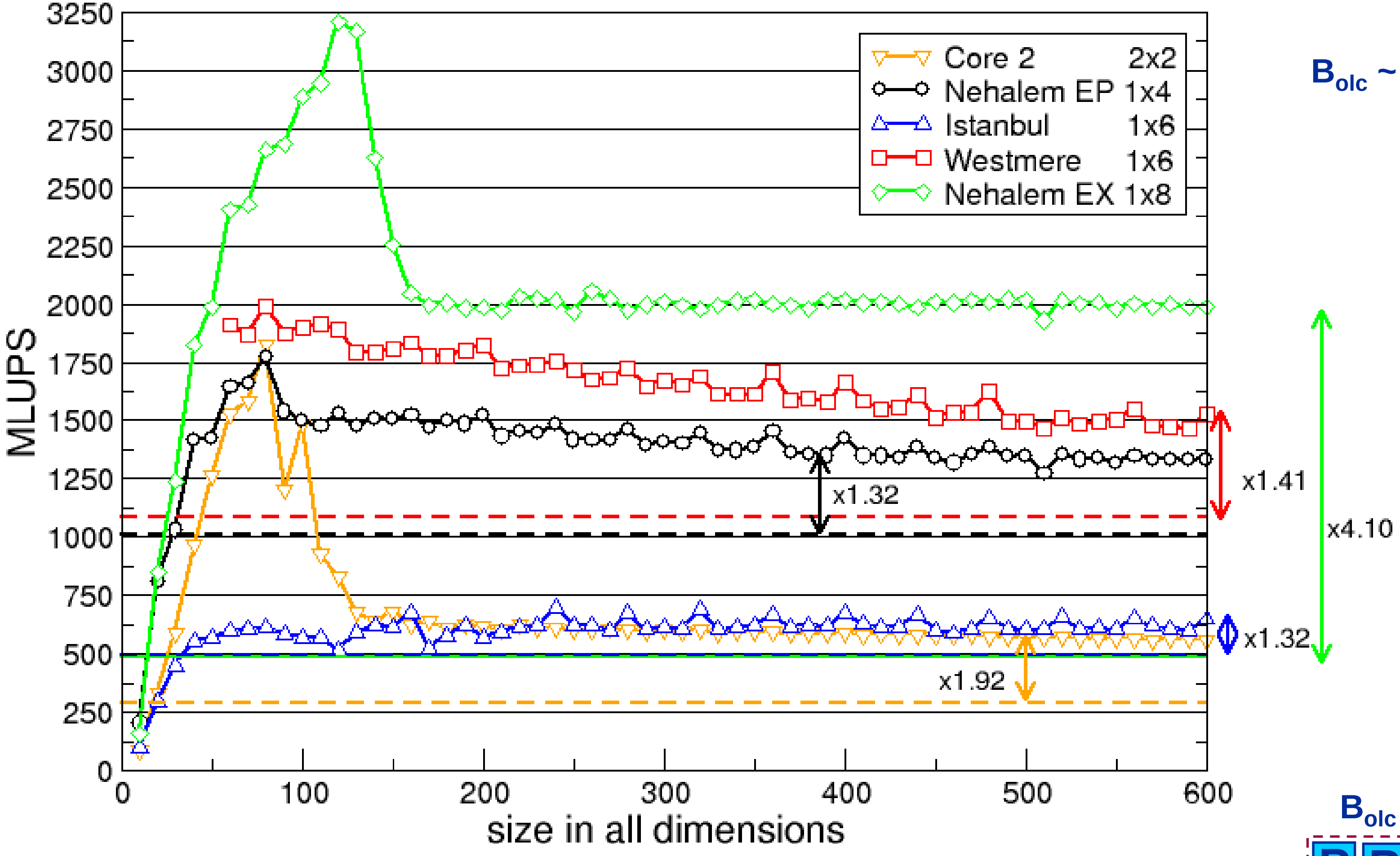
400^3 bj=40	MLUPs
1 x 2	786
2 x 2	1230
1 x 4	1254

Performance model indicates some potential gain → new compiler tested.

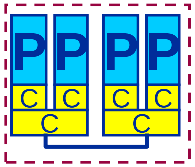
Only marginal benefit when using 4 wavefronts → A single copy stream does not achieve full bandwidth

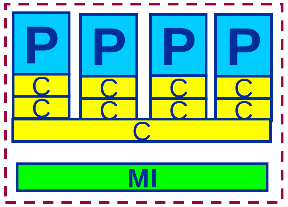
Multicore-aware parallelization

Wavefront – Jacobi on state-of-the art multicores

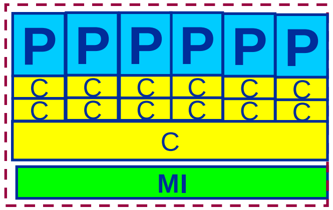


B_{olc} ~ 10

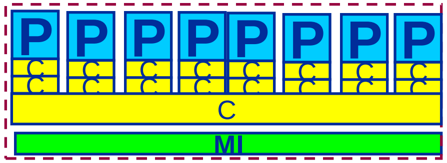




B_{olc} ~ 2-3



B_{olc} ~ 10



Compare against optimal baseline!

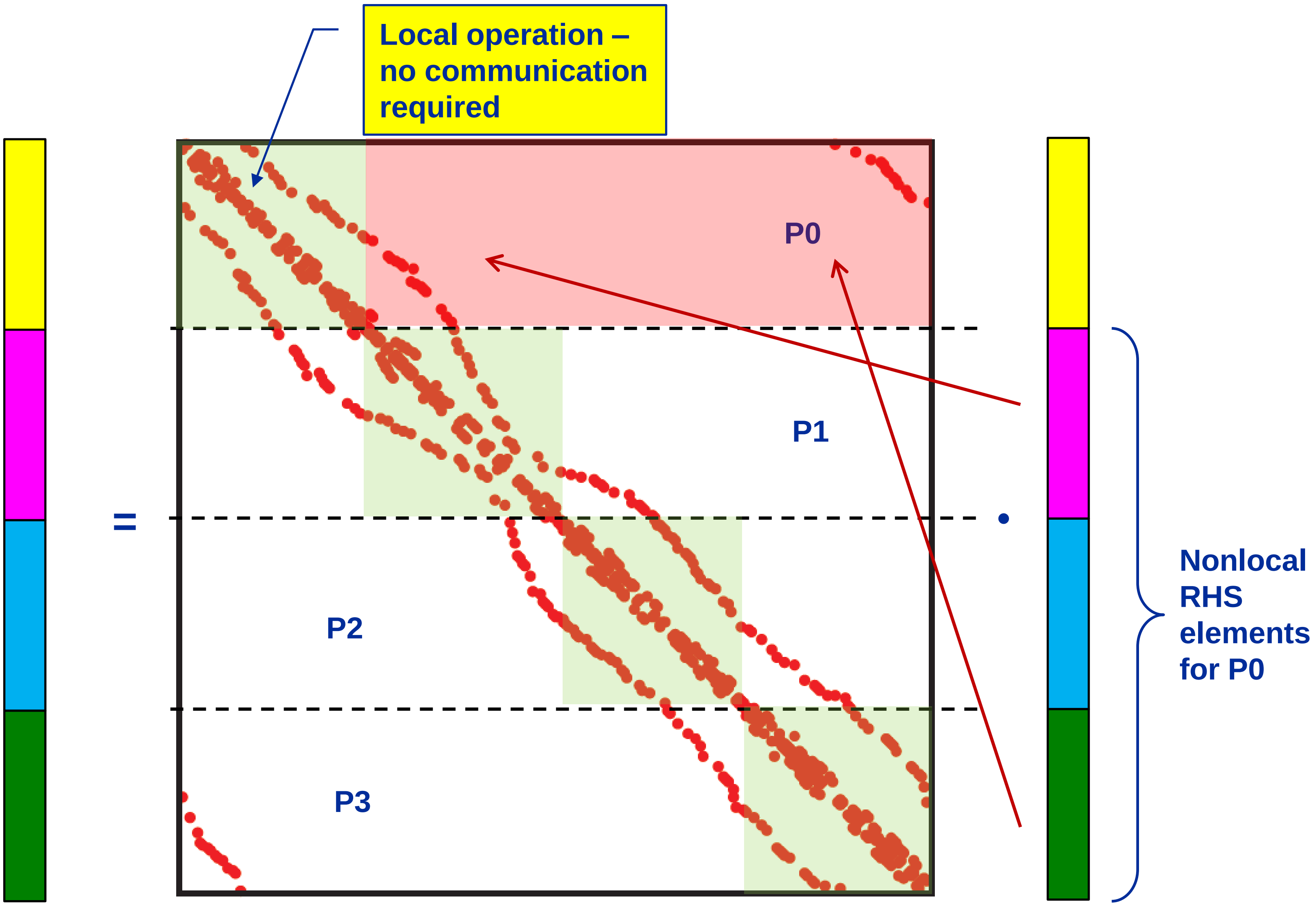
Performance gain ~ B_{olc} = L3 bandwidth / memory bandwidth

Conclusions from wavefront temporal blocking

- **Shared caches are *the* interesting new feature on current multicore chips**
  - Shared caches provide opportunities for fast synchronization (see sections on OpenMP and intra-node MPI performance)
  - Parallel software should leverage shared caches for performance
  - One approach: Shared cache reuse by wavefront temporal blocking
  - In addition fast synchronization (pref. within a socket) allows to exploit parallel structures at finer granularity (shorter loops, frequent synchronisation)
- **Wavefront technique can be extended to many regular stencil based iterative methods, e.g.**
  - Gauß-Seidel (→ done)
  - Lattice-Boltzmann flow solvers (→ done)
  - Multigrid-smoother (→ work in progress)
- **Wavefront technique can be extended to hybrid MPI+OpenMP parallelizaton**
  - See references

Asynchronous MPI communication in sparse MVM

Distributed-memory parallelization of spMVM



Local operation – no communication required

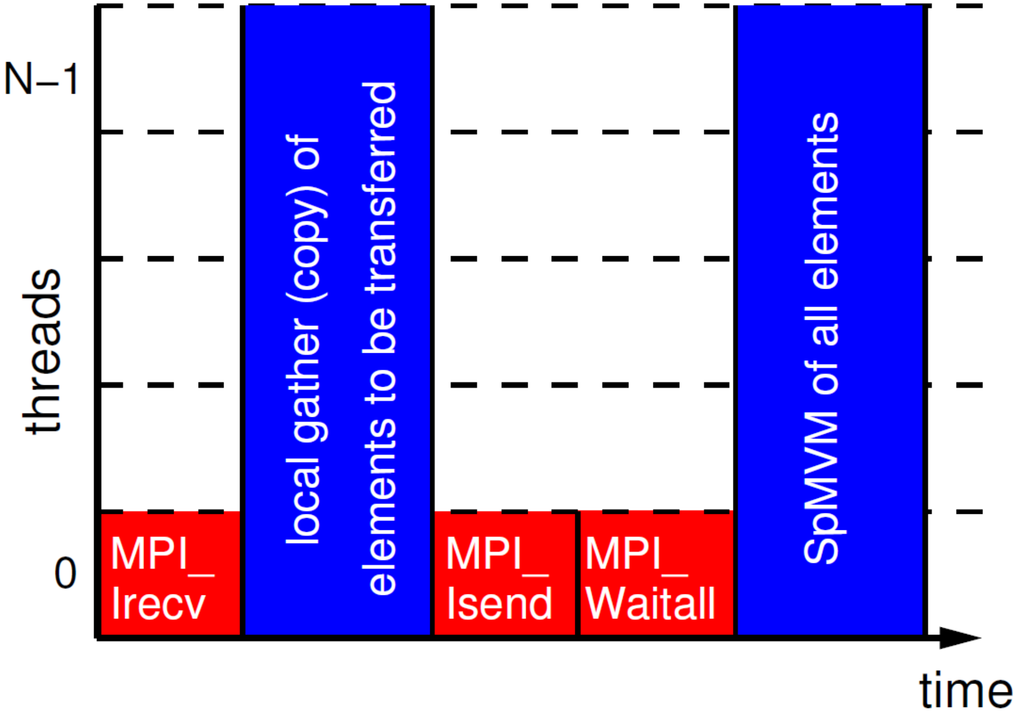
Nonlocal RHS elements for P0

Distributed-memory parallelization of spMVM

- **Variant 1: "Vector mode" without overlap**

- **Standard concept for "hybrid MPI+OpenMP"**
- **Multithreaded computation (all threads)**

- **Communication only outside of computation**



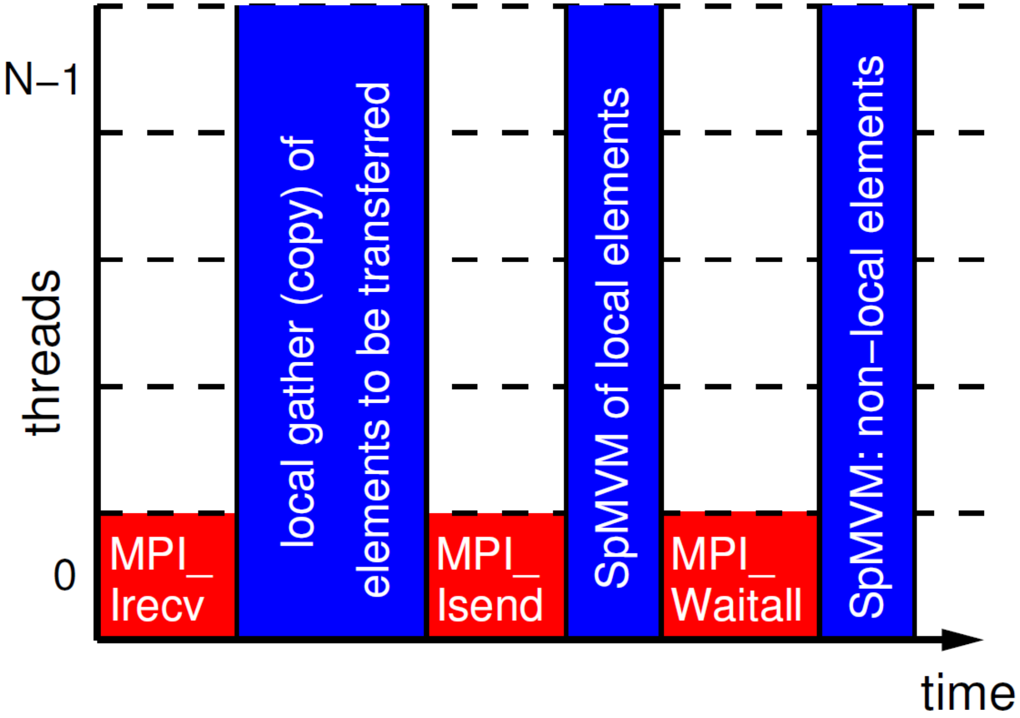
- **Benefit of threaded MPI process only due to message aggregation and (probably) better load balancing**

G. Hager, G. Jost, and R. Rabenseifner: *Communication Characteristics and Hybrid MPI/OpenMP Parallel Programming on Clusters of Multi-core SMP Nodes.* In: Proceedings of the Cray Users Group Conference 2009 (CUG 2009), Atlanta, GA, USA, May 4-7, 2009. PDF

- **Variant 2: "Vector mode" with naïve overlap ("good faith hybrid")**

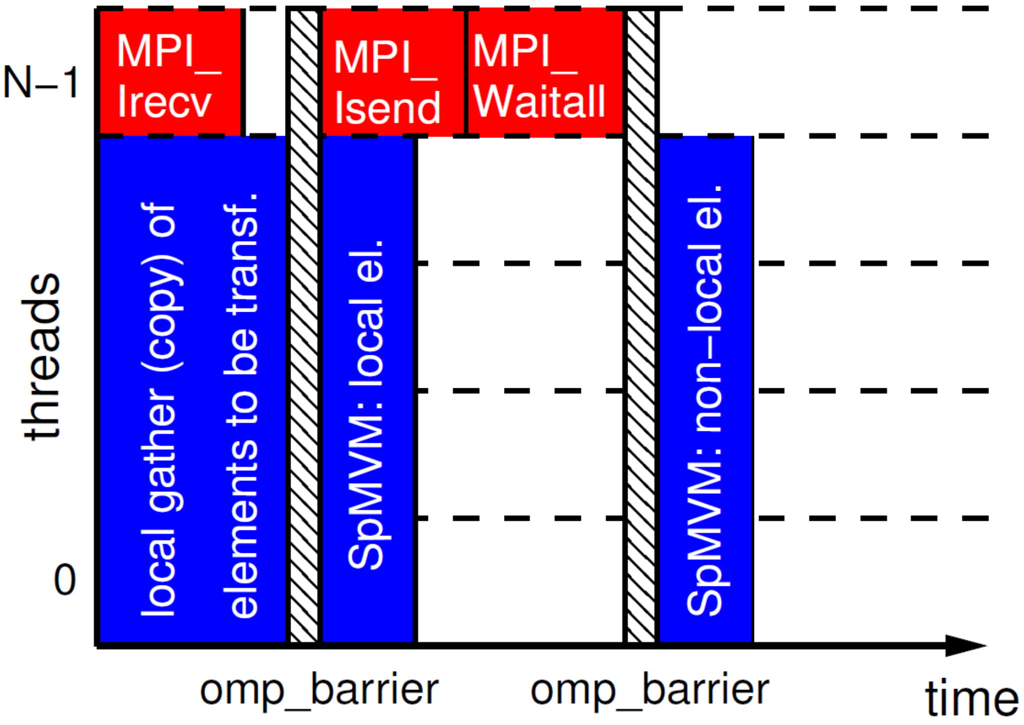
- **Relies on MPI to support async nonblocking PtP**
- **Multithreaded computation (all threads)**

- **Still simple programming**
- **Drawback: Result vector is written twice to memory**
  - modified performance model


N–1
threads
0
MPI_ Irecv
local gather (copy) of elements to be transferred
MPI_ Isend
SpMVM of local elements
MPI_ Waitall
SpMVM: non–local elements
time

Distributed-memory parallelization of spMVM

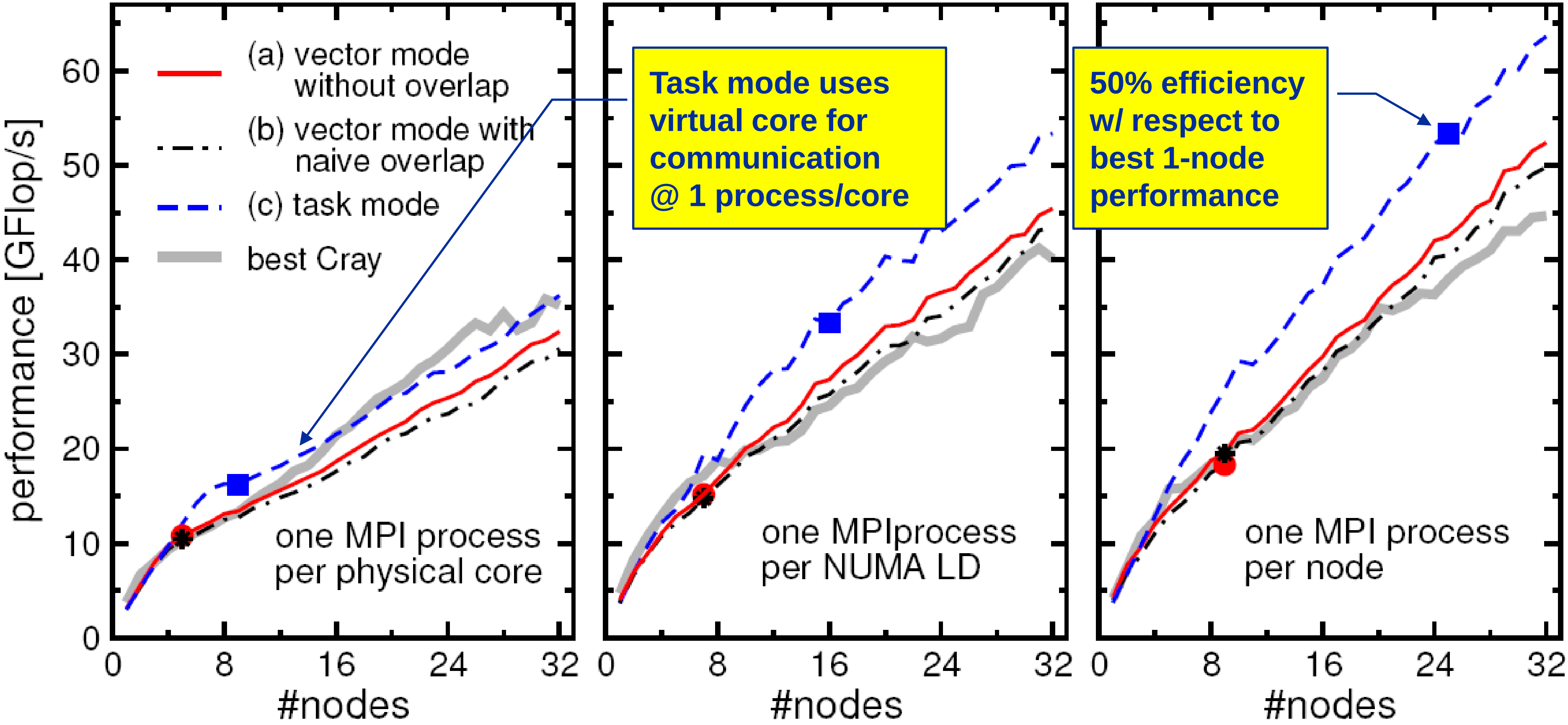
- **Variant 3: “Task mode” with dedicated communication thread**
- **Explicit overlap, more complex to implement**
- **One thread missing in team of compute threads**
  - But that doesn’t hurt here…
  - Using tasking seems simpler but may require some work on NUMA locality
- **Drawbacks**
  - Result vector is written twice to memory
  - No simple OpenMP worksharing (manual, tasking)



R. Rabenseifner and G. Wellein: *Communication and Optimization Aspects of Parallel Programming Models on Hybrid Architectures.* International Journal of High Performance Computing Applications **17**, 49-62, February 2003. DOI:10.1177/1094342003017001005

M. Wittmann and G. Hager: *Optimizing ccNUMA locality for task-parallel execution under OpenMP and TBB on multicore-based systems.* Technical report. Preprint:arXiv:1101.0093

Performance results for the HMeP matrix

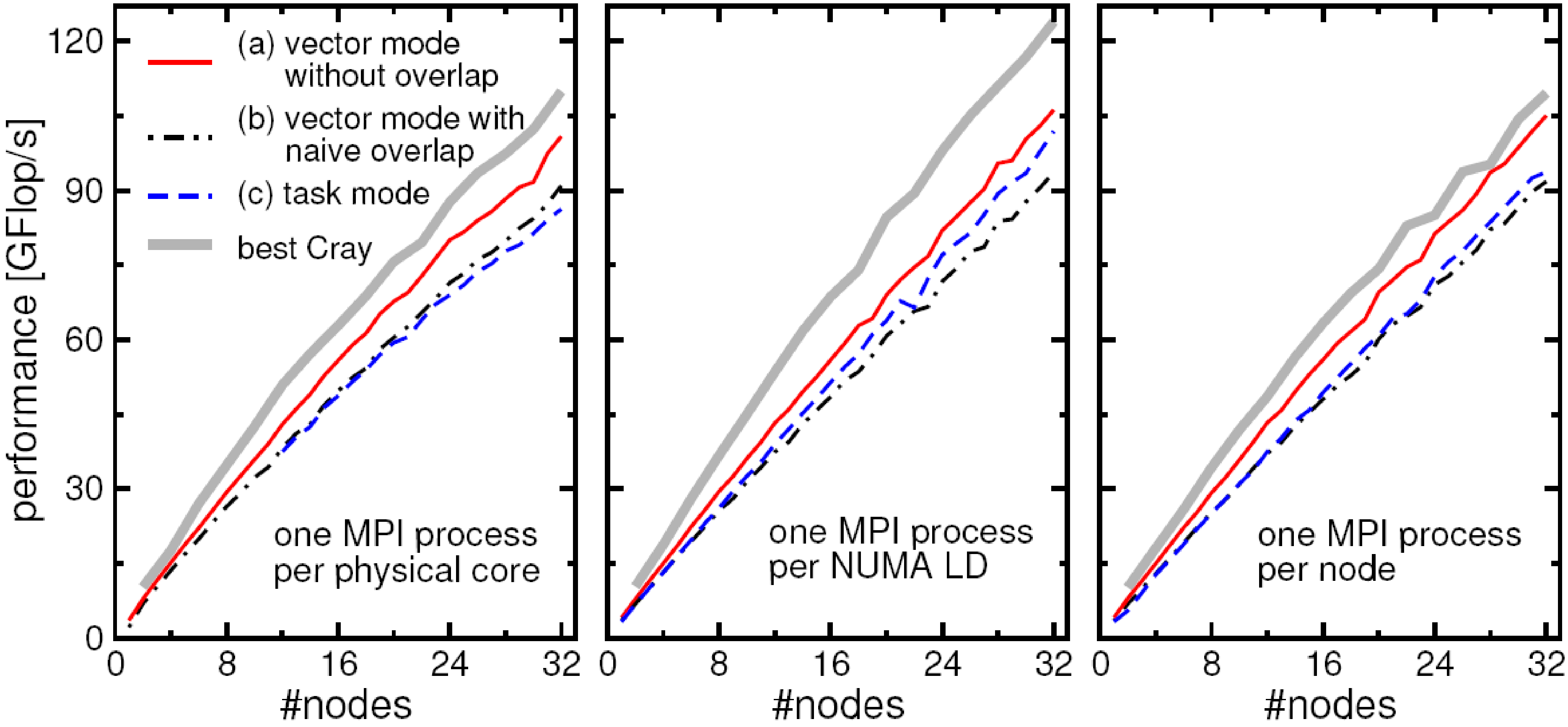


Task mode uses virtual core for communication @ 1 process/core

50% efficiency w/ respect to best 1-node performance

- **Dominated by communication (and some load imbalance for large #procs)**
- **Single-node Cray performance cannot be maintained beyond a few nodes**
- **Task mode pays off esp. with one process (12 threads) per node**
- **Task mode overlap (over-)compensates additional LHS traffic**

Performance results for the sAMG matrix



- **Much less communication-bound**
- **XE6 outperforms Westmere cluster, can maintain good node performance**
- **Hardly any discernible difference as to # of threads per process**
- **If pure MPI is good enough, don’t bother going hybrid!**

Conclusions from hybrid spMVM results

- Do not rely on asynchronous MPI progress
- Sparse MVM leaves resources (cores) free for use by communication threads
- Simple "vector mode" hybrid MPI+OpenMP parallelization is not good enough if communication is a real problem
- "Task mode" hybrid can truly hide communication and overcompensate penalty from additional memory traffic in spMVM
- Comm thread can share a core with comp thread via SMT and still be asynchronous
- If pure MPI scales ok and maintains its node performance according to the node-level performance model, don't bother going hybrid

- Extension to multi-GPGPU is possible
  - See later

The Plan

Basic multicore architecture

Data access on modern processors

Performance properties of multicore/multisocket systems

- Micro-benchmarks
- Sync overhead
- Bandwidth saturation

Case study: Sparse matrix-vector multiply (part 1)

Multicore performance tools Part 1

- Probing topology
- Enforcing affinity

Hands-On session 1

Basic performance modeling

- Balance metrics
- “Motivated” optimizations

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- Best practices

Advanced case studies: Putting cores to better use

- Wavefront temporal blocking
- Sparse MVM (part 2)

Outlook: Advanced performance engineering

- Sparse MVM (part 3)
- ECM model

Conclusions

Hands-On session 2

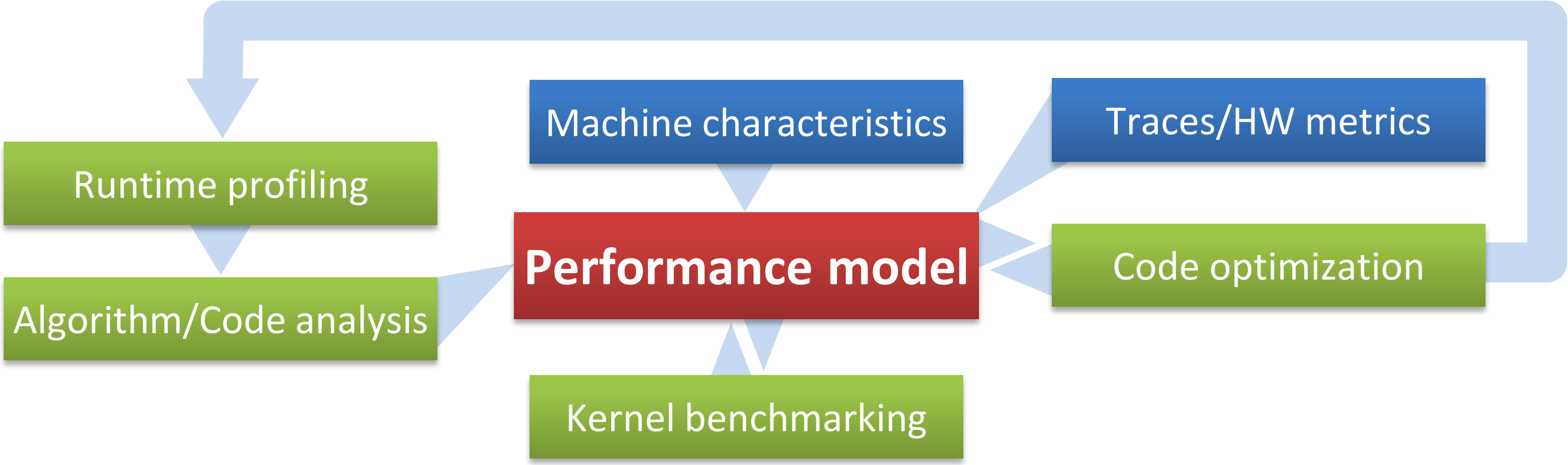
Outlook:
Examples for
Advanced Performance Engineering

Modeling sparse MVM on GPGPU clusters

Beyond the roofline model: ECM

Performance Engineering – What's that?

The Performance Engineering (PE) process:



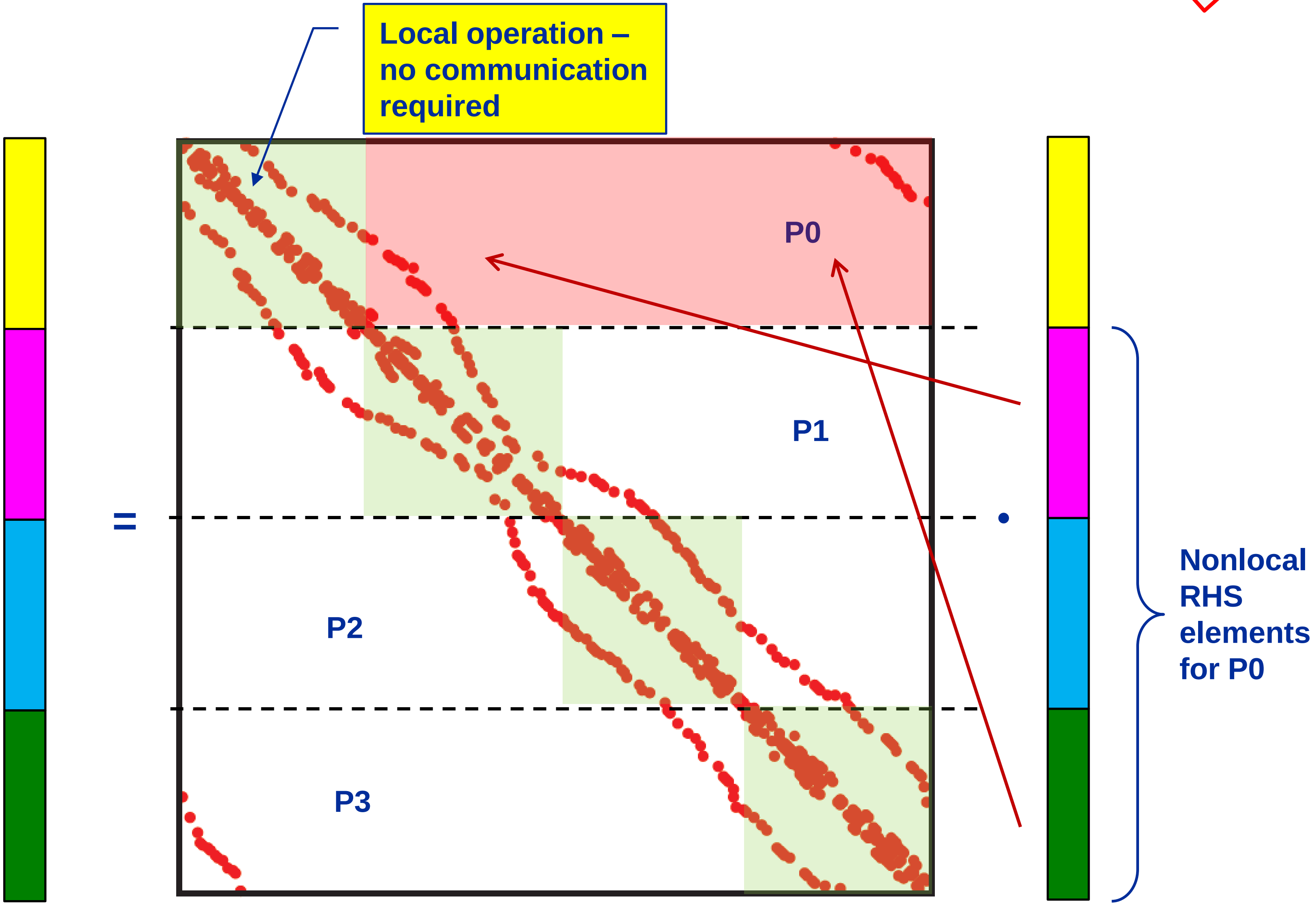
The performance model is the central component – if the model fails to predict the measurement, you learn something!

The analysis has to be done for every loop / basic block!

optional

Sparse MVM on GPGPU clusters

Distributed memory parallelization of SpMVM



Performance model (pJDS matrix format on GPGPU)

optional

- **Code balance:**

$$B_W^{\mathrm{DP}} = \frac{8 + 4 + 8\alpha + 16/N_{nzr}^{max}}{2} \, \frac{\text{bytes}}{\text{flop}}$$

```
c[i] = c[i] + A_val[colStart[j]+i] * x[ A_col[colStart[j]+i]];
```

  - N_{nzr}^{max}**… maximum number of nonzeros per row**
  - $1/N_{nzr}^{max} \leq \alpha \leq 1$ **quantifies possible RHS vector re-usage**
  - **Assumption: `colStart[]` always comes from cache**

M. Kreutzer, G. Hager, G. Wellein, H. Fehske, A. Basermann, and A.R. Bishop: *Sparse matrix-vector multiplication on GPGPU clusters: A new storage format and a scalable implementation*. Workshop on Large-Scale Parallel Processing 2012 (LSPP12) at IPDPS 2012. DOI: 10.1109/IPDPSW.2012.211

Impact of PCIe transfers of LHS/RHS for iterative schemes

optional

- Time for SpMVM:

$$T_{\mathrm{MVM}} = \frac{B^{\mathrm{DP}}}{BW_{\mathrm{GPU}}} * N * N_{nzr} * N_{it} \qquad = \frac{8N}{BW_{\mathrm{GPU}}}\left[N_{nzr}\left(\alpha + \frac{3}{2}\right) + 2\right] * N_{it}$$

N_{it} … number of SpMVMs before PCIe communication has to be done

- Time for PCIe transfers of LHS and RHS: $T_{\mathrm{PCI}} = \frac{16N}{BW_{\mathrm{PCI}}}$

- We want small impact of PCIe transfer, e.g.:

$$T_{\mathrm{MVM}} \geq 10T_{\mathrm{PCI}} \;\Rightarrow\; N_{nzr} \geq \frac{20BW_{GPU}/BW_{PCI}-2}{\alpha+3/2} \overset{\substack{BW_{\mathrm{GPU}} \approx 10BW_{\mathrm{PCI}} \\ \alpha = 1 \\ N_{it} = 1}}{\geq} 80$$

Matrix type →	HMEp	sAMG	DLR1	DLR2	UHBR
N_{nzr}	15	7	144	315	123
Suitable?	×	×	✓	✓	✓

Multi-GPGPU SpMVM: Design patterns

optional

- **Three design patterns for distributed-memory parallel SpMVM:**

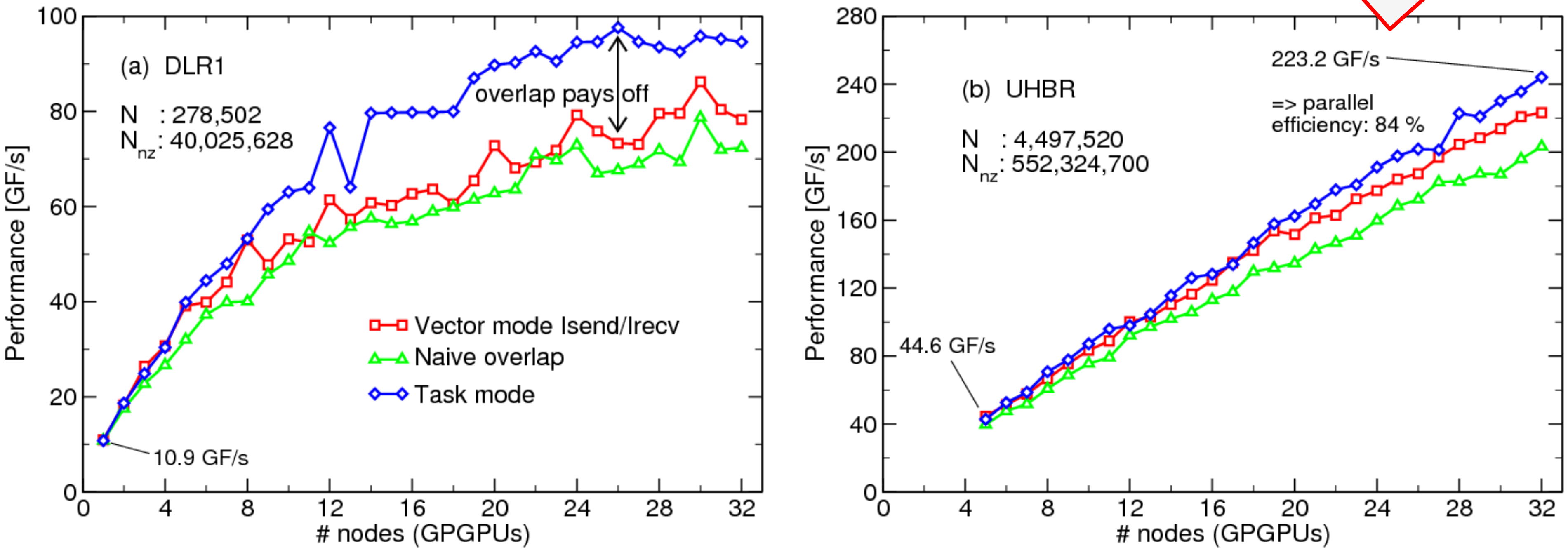
1. **Vector Mode without overlap of communication and computation**
   communication of non-local RHS elements is done before the actual SpMVM

2. **Vector Mode with naive overlap ("good faith hybrid")**
   SpMVM is split into local / non-local part; the local SpMVM may be overlapped with non-local RHS communication using non-blocking MPI (but: not asynchronous in most MPI libraries)

3. **Task Mode with explicit overlap**
   using a dedicated thread for MPI ➔ reliably asynchronous communication

G. Schubert, H. Fehske, G. Hager, and G. Wellein: *Hybrid-parallel sparse matrix-vector multiplication with explicit communication overlap on current multicore-based systems*. Parallel Processing Letters 21(3), 339-358 (2011). DOI: 10.1142/S0129626411000254

Multi-GPGPU SpMVM: Performance results



- ***N*** **is rather small**

  ➔ only few rows left per GPGPU for larger node counts

  ➔ communication becomes dominant

- ***N*** **large**

  ➔ no break-down for larger node counts

- **Low comm. requirements: no big benefit from overlap**

optional

Multi-core saturation: The ECM Model

optional

The multicore saturation mystery

optional

- **Why can a single core often not saturate the memory bus?**
  - Non-overlapping contributions from data transfers and in-cache execution to overall runtime

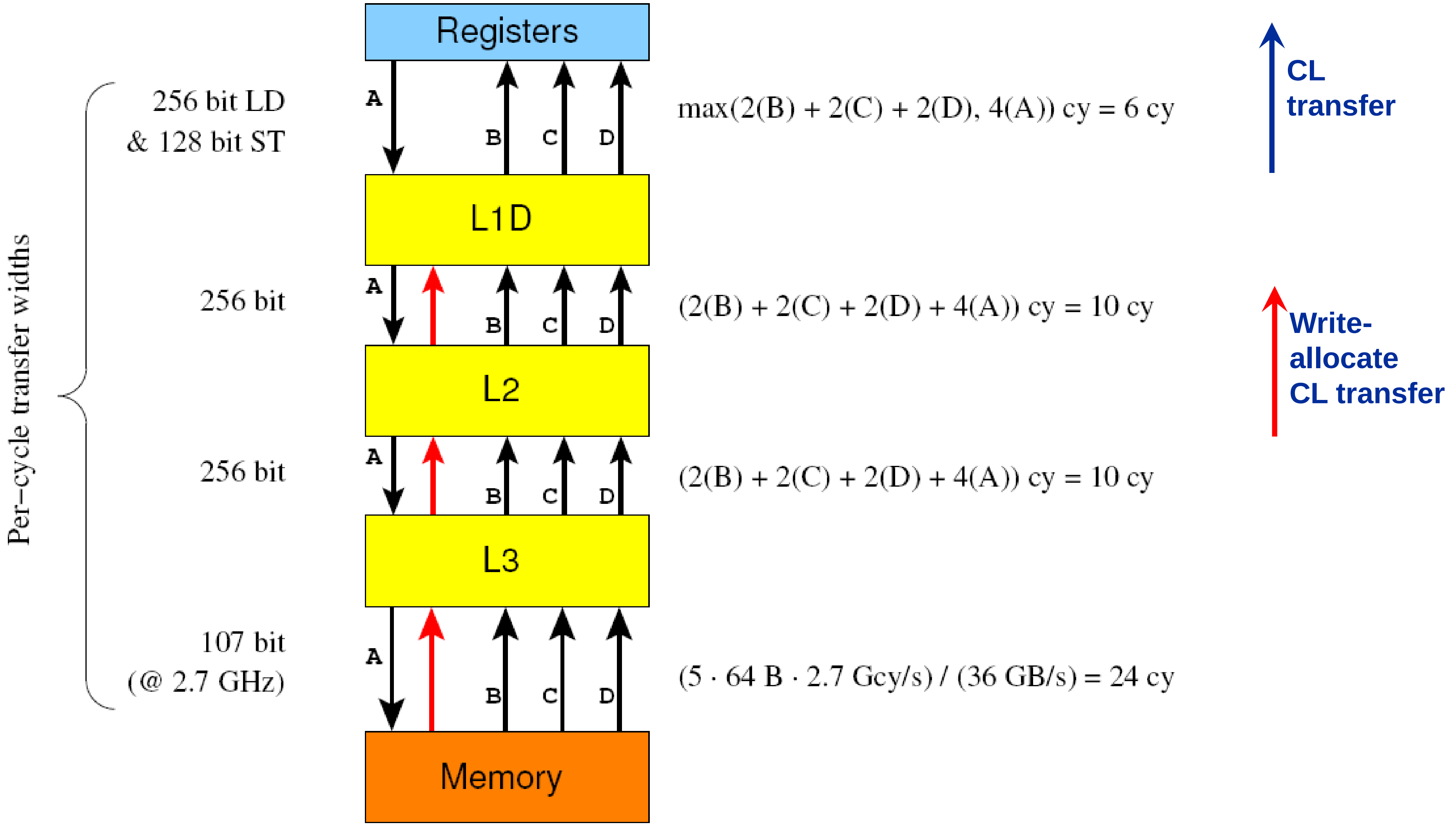
- **What determines the saturation point?**
  - Important question for energy efficiency
  - Saturation == Bandwidth pressure on relevant bottleneck exhausts the maximum BW cacpacity

- **Requirements for an appropriate multicore performance model**
  - Should predict single-core performance
  - Should predict saturation point

→ ECM (Execution – Cache – Memory) model

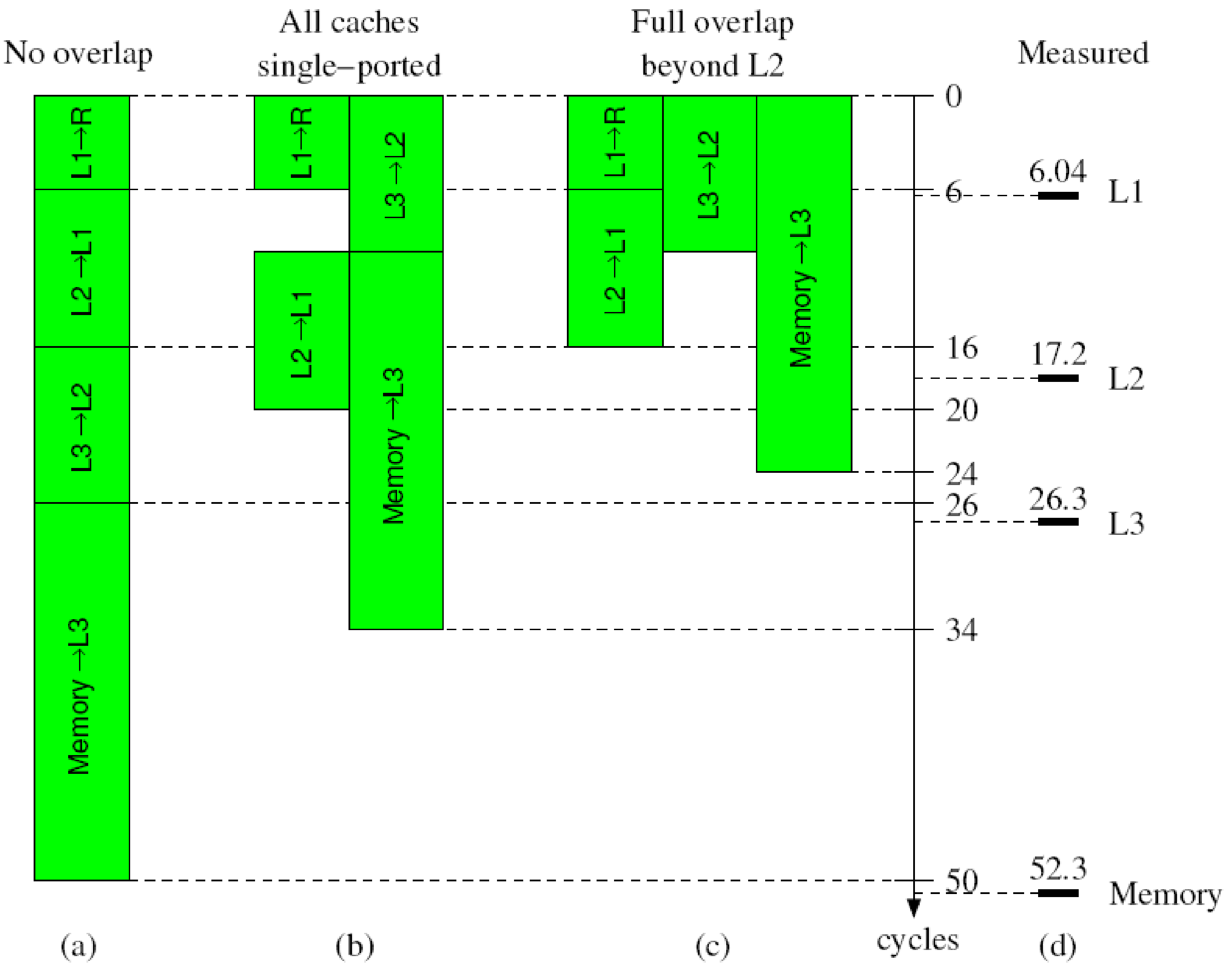
Example: ECM model for Schönauer Vector Triad `A(:)=B(:)+C(:)*D(:)` on a Sandy Bridge Core with AVX

optional



Registers
L1D
L2
L3
Memory
A
B
C
D
Per–cycle transfer widths
256 bit LD
& 128 bit ST
256 bit
256 bit
107 bit
(@ 2.7 GHz)
max(2(B) + 2(C) + 2(D), 4(A)) cy = 6 cy
(2(B) + 2(C) + 2(D) + 4(A)) cy = 10 cy
(2(B) + 2(C) + 2(D) + 4(A)) cy = 10 cy
(5 · 64 B · 2.7 Gcy/s) / (36 GB/s) = 24 cy
CL transfer
Write-allocate CL transfer

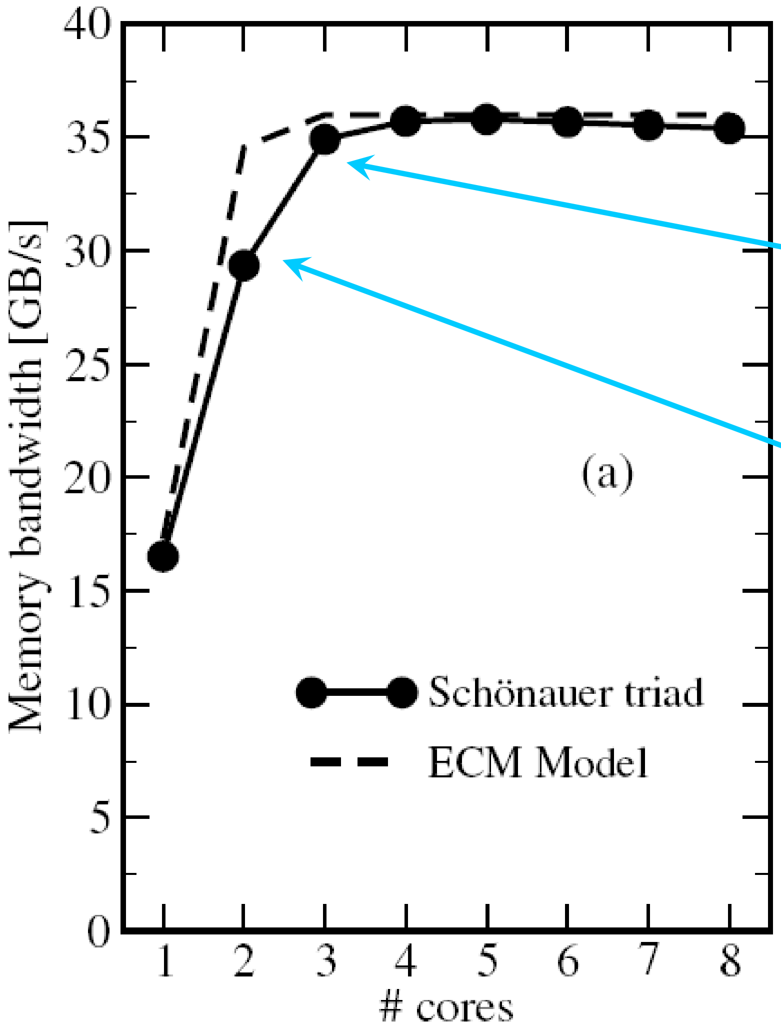
Full vs. partial vs. no overlap



Results suggest no overlap!

ECM prediction vs. measurements for `A(:)=B(:)+C(:)*D(:)` on a Sandy Bridge socket (no-overlap assumption)

optional



Model: Scales until saturation sets in

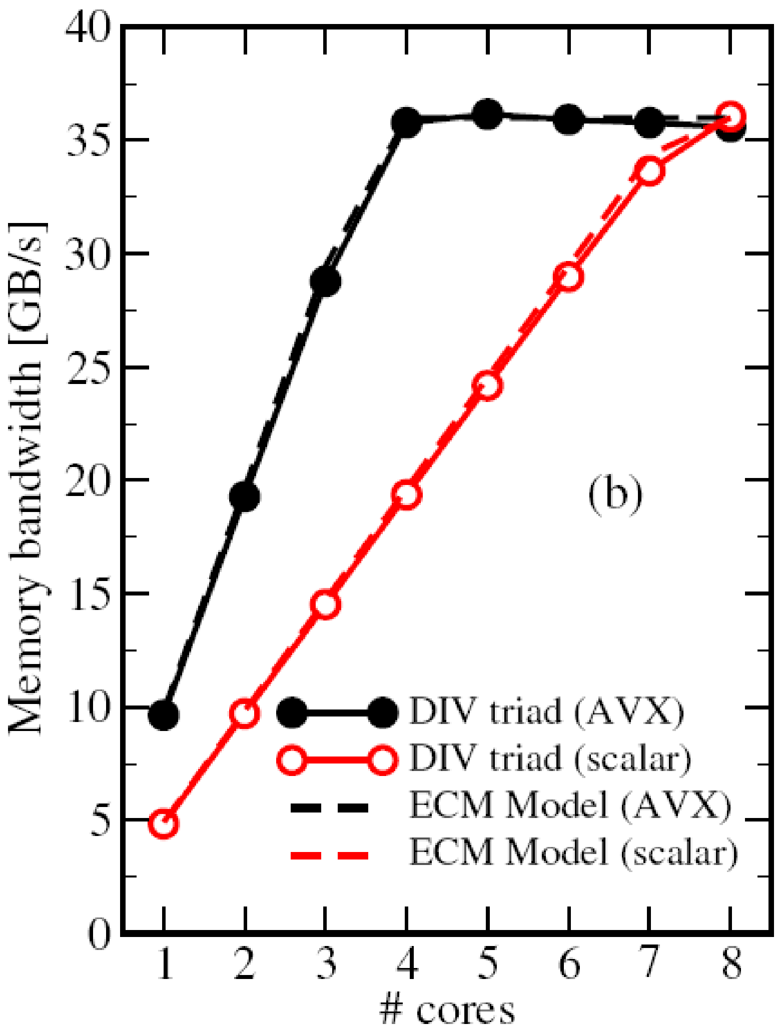
Saturation point (# cores) well predicted

Measurement: scaling not perfect

Caveat: This is specific for this architecture and this benchmark!

Check: Use “overlappable” kernel code

ECM prediction vs. measurements for `A(:)=B(:)+C(:)/D(:)` on a Sandy Bridge socket (full overlap assumption)



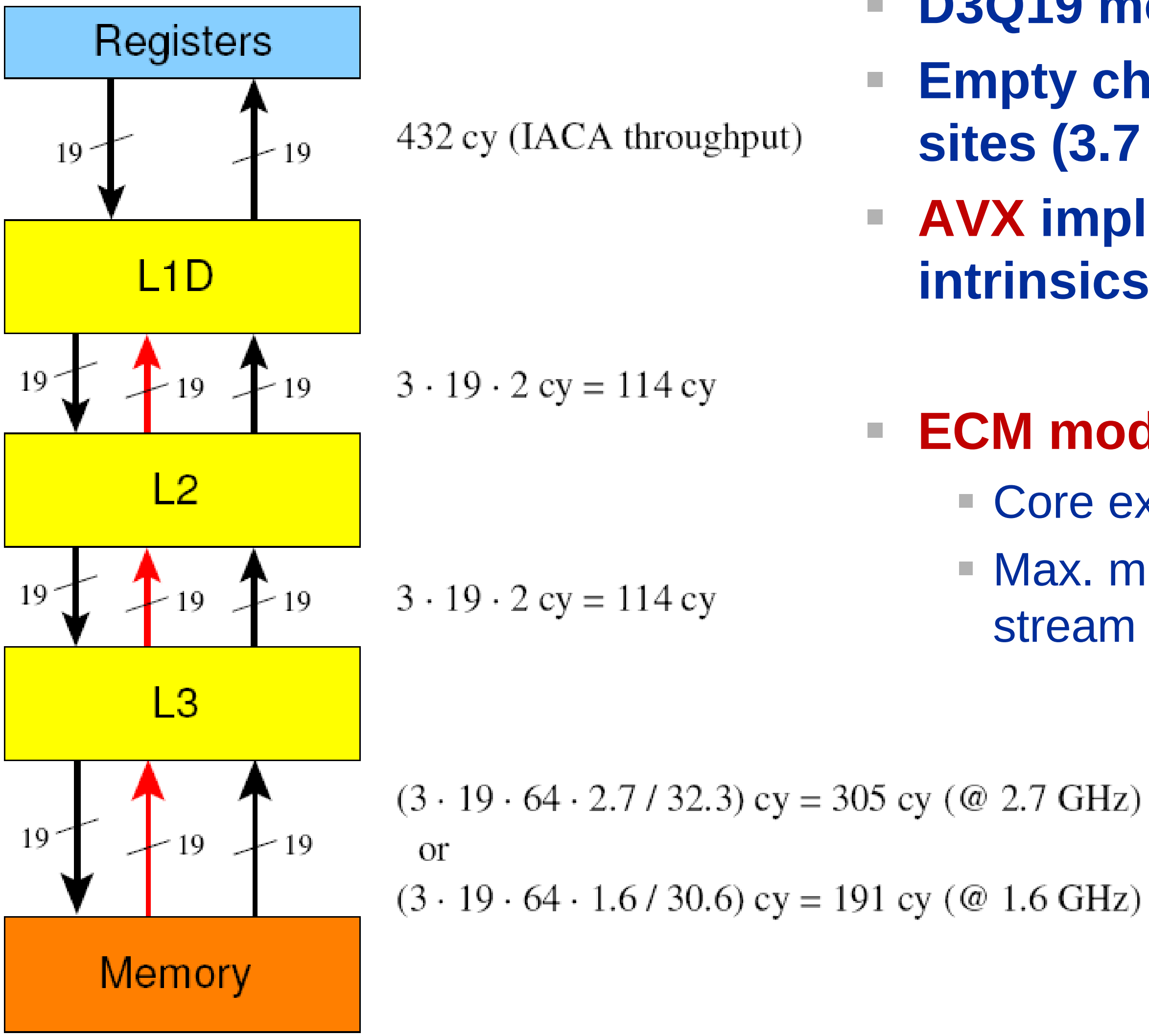
In-core execution is dominated by divide operation

(44 cycles with AVX, 22 scalar)

→ Almost perfect agreement with ECM model

Example: Lattice-Boltzmann flow solver

optional



432 cy (IACA throughput)

$3 \cdot 19 \cdot 2$ cy = 114 cy

$3 \cdot 19 \cdot 2$ cy = 114 cy

$(3 \cdot 19 \cdot 64 \cdot 2.7 / 32.3)$ cy = 305 cy (@ 2.7 GHz)

or

$(3 \cdot 19 \cdot 64 \cdot 1.6 / 30.6)$ cy = 191 cy (@ 1.6 GHz)

- **D3Q19 model**
- **Empty channel, 228^3 fluid lattice sites (3.7 GB of memory)**
- **AVX implementation with compiler intrinsics**

- **ECM model input**
  - Core execution from Intel IACA tool
  - Max. memory bandwidth from multi-stream measurements

Lattice-Boltzmann solver: ECM (no-overlap) vs. measurements

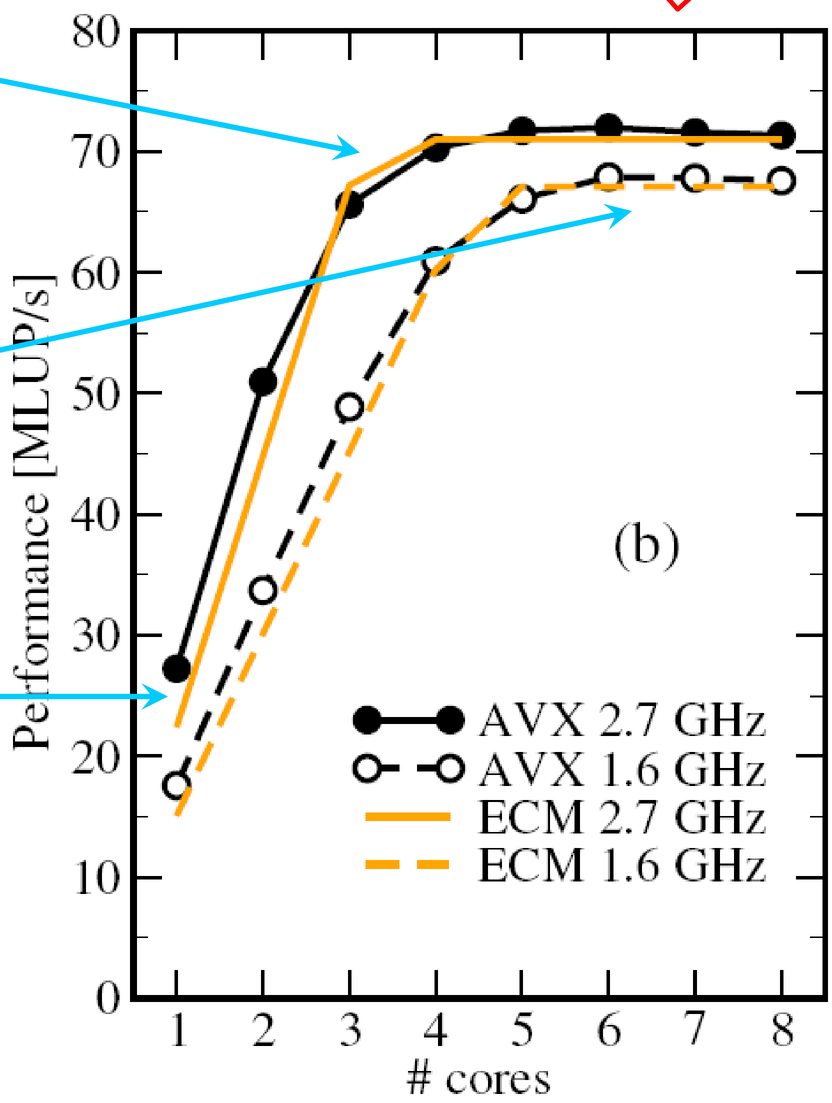
optional

Saturation point again predicted accurately

Saturation performance matches streaming benchmarks

No-overlap assumption seems a little pessimistic

Not all execution is LD and ST



G. Hager, J. Treibig, J. Habich, and G. Wellein: *Exploring performance and power properties of modern multicore chips via simple machine models*. Submitted. Preprint: arXiv:1208.2908

Conclusions from the case studies

optional

- **There is no substitute for knowing what’s going on between your code and the hardware**

- **Make sense of performance behavior through sensible application of performance models**
  - However, there is no “golden formula” to do it all for you automagically

- **Model inputs:**
  - Code analysis/inspection
  - Hardware counter data
  - Microbenachmark analysis
  - Architectural features

- **Simple models work best; do not try to make it more complex than necessary**
  - ECM model refines simple bandwidth/roofline analysis

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Hands-On session 2

Tutorial conclusion

- **Multicore architecture == multiple complexities**
  - Affinity matters → pinning/binding is essential
  - Bandwidth bottlenecks → inefficiency is often made on the chip level
  - Topology dependence of performance features → know your hardware!
- **Put cores to good use**
  - Bandwidth bottlenecks → surplus cores → functional parallelism!?
  - Shared caches → fast communication/synchronization → better implementations/algorithms?

- **Simple modeling techniques help us**
  - … understand the limits of our code on the given hardware
  - … identify optimization opportunities
  - … learn more, especially when they do not work!

- **Simple tools get you 95% of the way**
  - e.g., LIKWID tool suite

Jan Treibig
Johannes Habich
Moritz Kreutzer
Markus Wittmann
Thomas Zeiser
Michael Meier
Faisal Shahzad
Gerald Schubert

KONWIHR II

OMI4papps
HQS@HPC II

THANK YOU.

Bundesministerium
für Bildung
und Forschung

hpcADD
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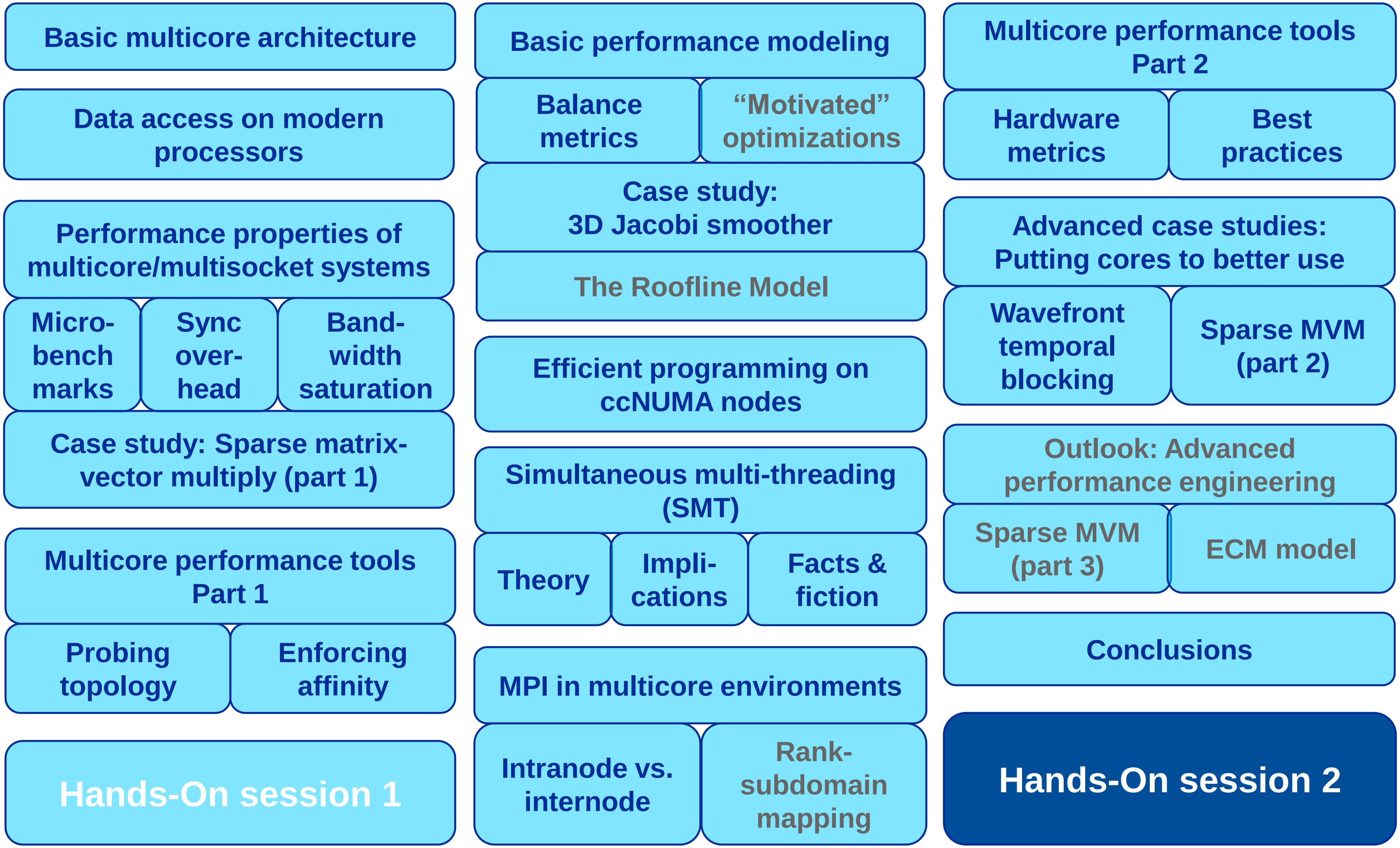
The Plan



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Sparse MVM (part 3)

ECM model

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Presenter Biographies

- **Georg Hager** holds a PhD in computational physics from the University of Greifswald. He has been working with high performance systems since 1995, and is now a senior research scientist in the HPC group at Erlangen Regional Computing Center (RRZE). Recent research includes architecture-specific optimization for current microprocessors, performance modeling on processor and system levels, and the efficient use of hybrid parallel systems. See his blog at http://blogs.fau.de/hager for current activities, publications, and talks.

- **Gerhard Wellein** holds a PhD in solid state physics from the University of Bayreuth and is a professor at the Department for Computer Science at the University of Erlangen. He leads the HPC group at Erlangen Regional Computing Center (RRZE) and has more than ten years of experience in teaching HPC techniques to students and scientists from computational science and engineering programs. His research interests include solving large sparse eigenvalue problems, novel parallelization approaches, performance modeling, and architecture-specific optimization.

Abstract

- **SC12 tutorial tut161: The practitioner's cookbook for good parallel performance on multi- and manycore systems**
- **Presenter(s): Georg Hager, Gerhard Wellein**

- **ABSTRACT:**

The advent of multi- and manycore chips has led to a further opening of the gap between peak and application performance for many scientific codes. This trend is accelerating as we move from petascale to exascale. Paradoxically, bad node-level performance helps to "efficiently" scale to massive parallelism, but at the price of increased overall time to solution. If the user cares about time to solution on any scale, optimal performance on the node level is often the key factor. Also, the potential of node-level improvements is widely underestimated, thus it is vital to understand the performance-limiting factors on modern hardware. We convey the architectural features of current processor chips, multiprocessor nodes, and accelerators, as well as the dominant MPI and OpenMP programming models, as far as they are relevant for the practitioner. Peculiarities like shared vs. separate caches, bandwidth bottlenecks, and ccNUMA characteristics are pointed out, and the influence of system topology and affinity on the performance of typical parallel programming constructs is demonstrated. Performance engineering is introduced as a powerful tool that helps the user assess the impact of possible code optimizations by establishing models for the interaction of the software with the hardware on which it runs.

References

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- G. Hager and G. Wellein: Introduction to High Performance Computing for Scientists and Engineers. CRC Computational Science Series, 2010. ISBN 978-1439811924

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