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# Programming Techniques for Supercomputers: Shared-memory parallel processing with OpenMP (II)

OpenMP reductions

OpenMP synchronization

OpenMP basic overheads

OpenMP affinity

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Friedrich-Alexander-Universität Erlangen-Nürnberg, Sommersemester 2026

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# Operations on data across threads

- Recurring problem: Operations across thread-local instances of a variable

```
int i,N;
double a[N], b[N];
...
s=0.;
#pragma omp parallel firstprivate(s)
{
#pragma omp for
  for(i=0; i<N; ++i)
     s = s + a[i] * b[i];
  // How to sum up the different s?
}
```

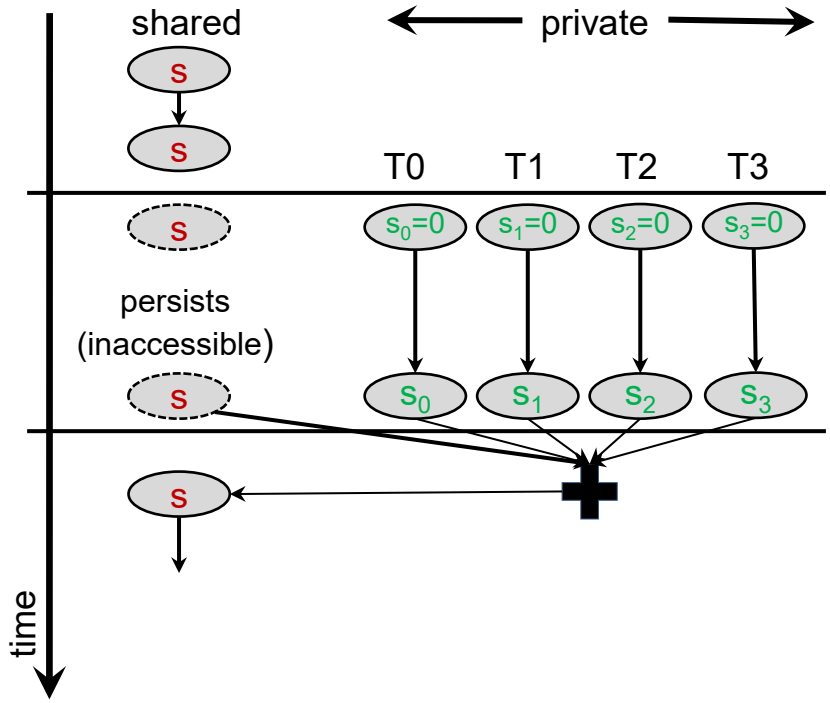
- Solution: `reduction` clause

# Reduction clause on parallel region or workshared loop

```
int i,N;
double a[N], b[N];
...
s=0.;
#pragma omp parallel
{
// s is still shared here
#pragma omp for reduction(+:s)
  for(i=0; i<N; ++i)
     s = s + a[i] * b[i];
// s is shared again here
}
```

At synchronization point:

- reduction operation is performed
- result is transferred to master copy
- restrictions similar to **`firstprivate`**




Reduction variable must be shared in enclosing context!

# Reduction operations: general considerations

Fortran has an analogous set

| Oper-ation | Initial value |
|---|---|
| + | 0 |
| - | 0 |
| * | 1 |
| & | ~0 |
| \| | 0 |
| ^ | 0 |
| && | 1 |
| \|\| | 0 |
| max | MINVAL(type) |
| min | MAXVAL(type) |

Multiple reductions:

```
float x, y, z;
#pragma omp for reduction(+:x, y, z)
```

```
#pragma omp for reduction(+:x, y) \
                reduction(*:z)
```

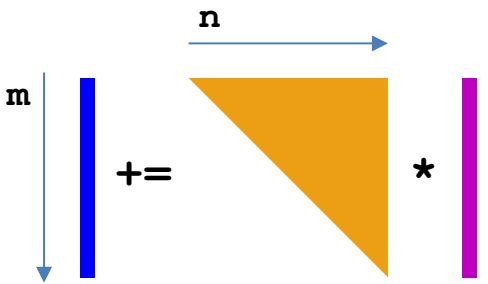
Consistency required!

`x = expr - x` is not allowed

Don't lie.

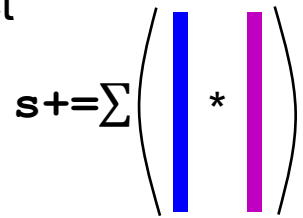
# Reduction operations: Example

```
double s, a[size*size], x[size], y[size];
...
s=0.;
#pragma omp parallel
{
#pragma omp for schedule(???)
    for(int m=0; m<size; m++){
      for(int n=m; n<size; n++){
        y[m] += a[m*size+n] * x[n];
      }
    }
...
#pragma omp for reduction(+:s)
    for(int m=0; m<size;m++) {
      s += x[m] * y[m];
    }
...
}
```




dense triangular MVM

scalar product



# Reductions on arrays

- Elementwise reductions on arrays (or slices thereof)

```
#pragma omp parallel for reduction(+:y[0:rows])
for(int c=0; c<cols; ++c)
  for(int r=0; r<rows; ++r)
     y[r] += a[r+c*rows] * x[c];
```

C/C++: Array slice syntax is mandatory

Fortran: No slice necessary on full array reduction

```
!$omp parallel do reduction(+:y)
do c = 1 , C
  do r = 1 , R
     y(r) = y(r) + A(r,c) * x(c)
  enddo
enddo
!$omp end parallel do
```

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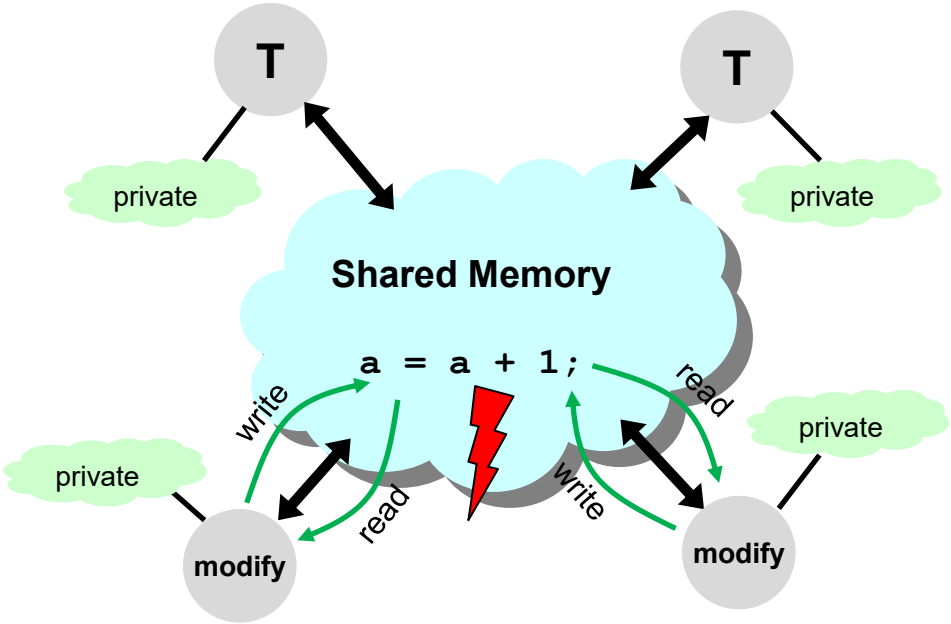
# Shared-memory parallel processing with OpenMP (II)

OpenMP reductions
OpenMP synchronization: Ensuring consistency
OpenMP basic overheads
OpenMP affinity

# Why synchronization?

## Example: variable update (read – modify – write)

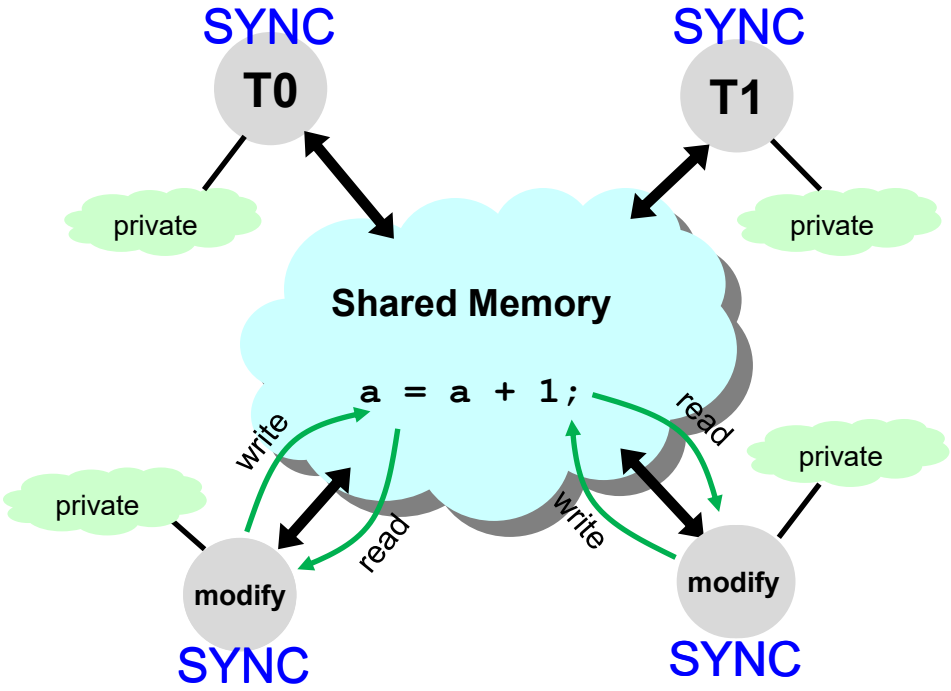



Multiple threads access shared variable, and at least one writes to it
→ “race condition”

Synchronization = means to manage conflicting/uncontrolled accesses

# Why synchronization?

Example: variable update (read – modify – write)

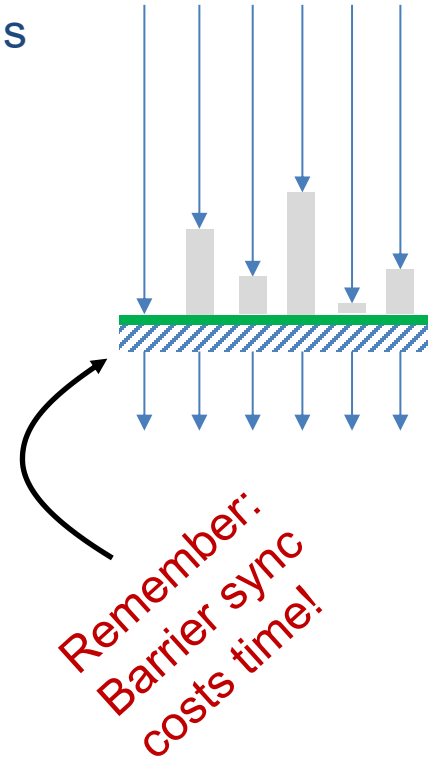



Synchronization: All threads need to wait until last thread enters synchronization

T2: read a
T2: a=a+1
T2: write a
SYNCHRONIZATION
T3: read a
T3: a=a+1
T3: write a
SYNCHRONIZATION

# Barrier synchronization

- `#pragma omp barrier`
  - Each thread blocks upon reaching the barrier until all threads have reached the barrier
  - All accessible shared variables are flushed to the memory hierarchy (similar to `volatile` attribute in C/C++)
  - barrier may not appear within work-sharing construct (e.g., `omp for` block) → potential of deadlock




- Implicit barrier:
  - at the beginning and end of parallel regions
  - at the end of worksharing constructs unless a `nowait` clause is present

# Relaxing synchronization requirements

- The **`nowait`** clause
  - removes the implicit barrier at end of worksharing construct
  - potential performance **improvement** (especially if load imbalance occurs within construct)
  - Programmer is responsible for preventing race conditions!

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

      // ... More parallel work (don't reference a[])

    #pragma omp barrier
      ... = a[i];   // after deferred barrier
}
```

No barrier here

# Case study: reducing barrier cost for dense MVM

- General advice: Parallelize as far out as possible!

```
void dmvm(int n, int m, double *lhs,
          double *rhs, double *mat){
...
#pragma omp parallel for
  for(int c=0; c<n; ++c)
    int offset = m * c;
    for(int r=0; r<m; ++r)
      lhs[r] += mat[r + offset] * rhs[c];
}
```

Only one barrier…

… but race condition on `lhs[]`

# Reducing barrier cost: dense MVM

- Inner loop parallel → correct result

```
void dmvm(int n, int m, double *lhs,
          double *rhs, double *mat){
...
#pragma omp parallel
{
  for(int c=0; c<n; ++c)
    int offset = m * c;
    #pragma omp for
    for(int r=0; r<m; ++r)
      lhs[r] += mat[r + offset] * rhs[c];
}
}
```

Only one parallel region

… but **n** implicit barriers

Result is correct: threads work on separate parts of **lhs[]**

# Reducing barrier cost: dense MVM

- Inner loop parallel → correct result, and use **`nowait`** to avoid barriers

```
void dmvm(int n, int m, double *lhs,
          double *rhs, double *mat){
...
#pragma omp parallel
{
  for(int c=0; c<n; ++c)
    int offset = m * c;
    #pragma omp for schedule(static) nowait
    for(int r=0; r<m; ++r)
      lhs[r] += mat[r + offset] * rhs[c];
}
}
```

Only one parallel region

No implicit barriers on workshared loop

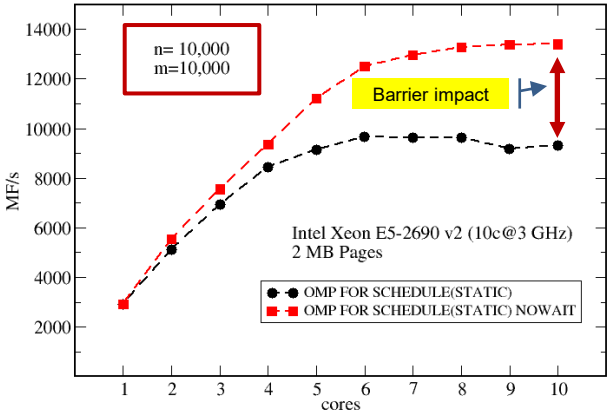
Ensure same iteration-to-thread mapping

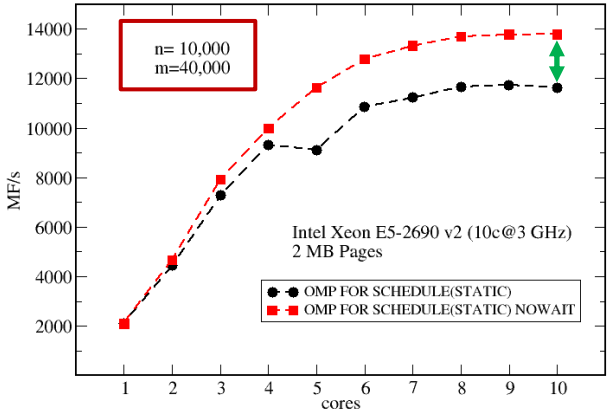
One implicit barrier

Result is correct: threads work on separate parts of **`lhs[]`**

# Reducing barrier cost: dense MVM

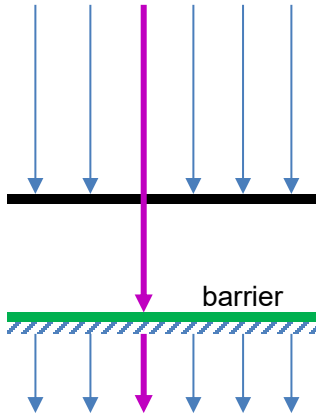
- Barrier overhead may substantially decrease performance
- Performance impact decreases as inner loop length (work per barrier) increases (see m=40,000 vs. m=10,000)
- Use **`nowait`** with due care (correctness)!
- Is the performance as expected? What does the barrier cost?
  - → homework



# The `single` directive

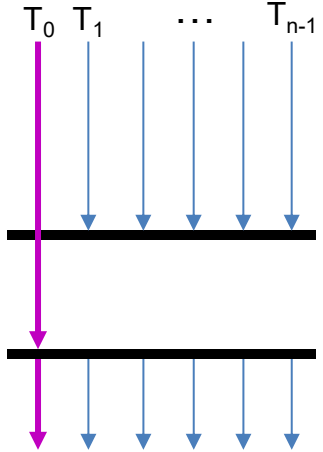
- `#pragma omp single [clause[[,]clause]…]`
  `structured-block`
- Structured block is executed by exactly one thread, which one is unspecified
  - Actually a worksharing directive
- Remaining threads skip the structured block and continue execution.
- Implied barrier at the exit of the single section!




- Do not use within another worksharing construct (deadlock!)
- `nowait` clause suppresses barrier

# The `master` directive

- `#pragma omp master [clause[[,]clause]…]`
  `structured-block`
- Only thread zero executes the structured block
- Other threads continue without synchronization
- Not all threads have to reach the construct

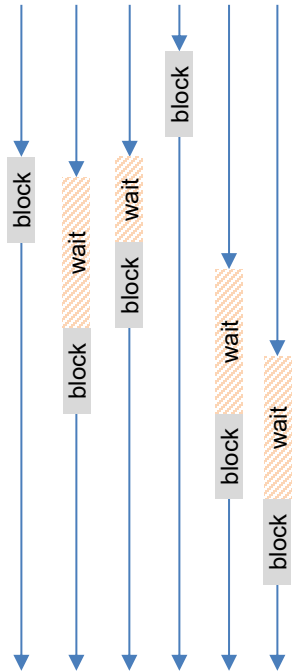



- Essentially equivalent to:

```
#ifdef _OPENMP
if(omp_get_thread_num()==0)
#endif
  structured-block;
```

# Critical region

- `#pragma omp critical`
  `structured-block`
- Only one thread at a time can execute the block
- … but every thread that encounters it will eventually execute it
- Order of execution is undefined!
- All unnamed critical regions are mutually exclusive across the whole program
  - Beware of deadlocks!



# Named critical regions

- What if I want several independent critical regions?
  - Named critical regions to the rescue!
- Regions with different names are mutually independent
- Name can be chosen freely
  - No association with data to be "protected"
- Unnamed critical regions share the same (invisible) name

```
double func(double v) {
  double x;
#pragma omp critical(prand)
    x = v + random_func();
  return x;
}
...
#pragma omp parallel for private(x)
for(int i=0; i<N; ii+) {
  x = sin(2.*M_PI*i/N);
  #pragma omp critical(psum)
    sum += func(x);
}
```

Protect lib-call (random_func)

# Atomic updates

- `#pragma omp atomic [clause[[,] clause] ... ]`
  `expression-stmt`
- Ensures that a storage location is accessed atomically, i.e., the full access cannot be interrupted
- Applies only to the statement immediately following it
- `expression-stmt` can be:

```
x++;
x--;
++x;
--x;
x binop= expr;
x = x binop expr;
x = expr binop x;
```

- Variants of `atomic` for pure read, pure write, and capture are also available

# Why `atomic`?

## Can't I just use a critical region?

1. **`atomic`** *may* be more efficient due to hardware support (no guarantee!)
2. **`atomic`** allows for protecting updates to individual data elements

```
#pragma omp parallel for
for (i=0; i<n; i++) {
  double t = func(table[i]);
  if(t < 0.) {
    #pragma omp atomic
      x[table[i]]++;
  }
  y[i] += other(i);
}
```

Updates of different `x[]` entries do not block each other

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# Basic OpenMP overheads

"Wake up" team of threads

```
!$OMP PARALLEL PRIVATE(k)
  do k=1,NITER

!$OMP DO SCHEDULE(…)
    do i=1,N
      A(i)=B(i)+C(i)*D(i)
    enddo
!$OMP END DO

  enddo
!$OMP END PARALLEL
```

Workload distribution

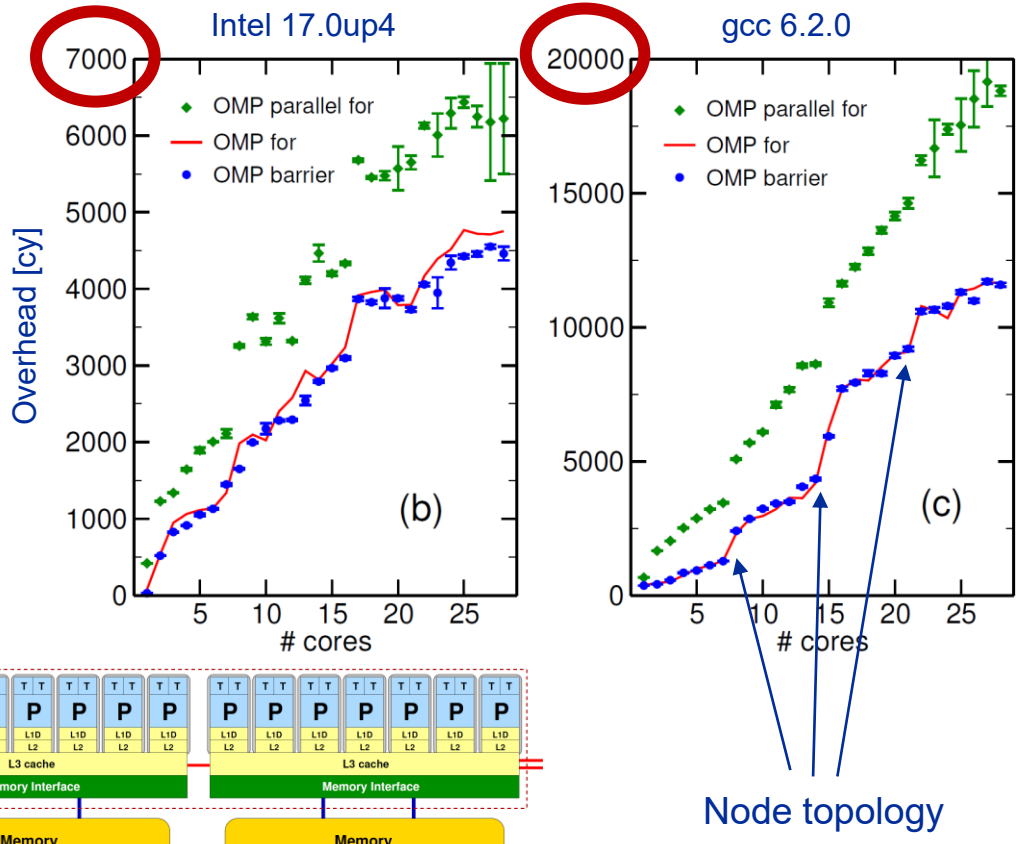
Loop parallelization

Implicit barrier / sychronization

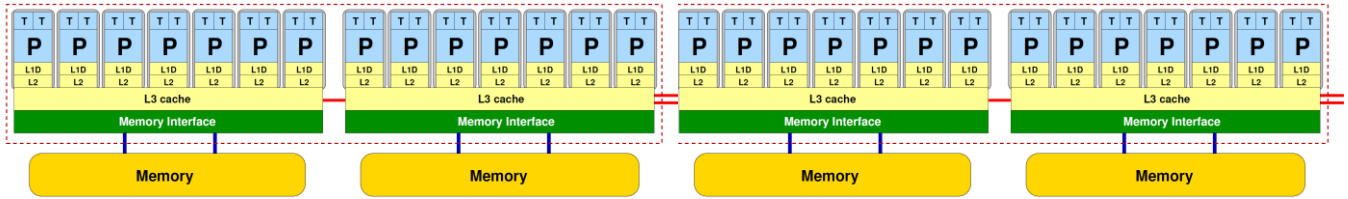
"Retire" team of threads

# OpenMP overheads: loops and barriers

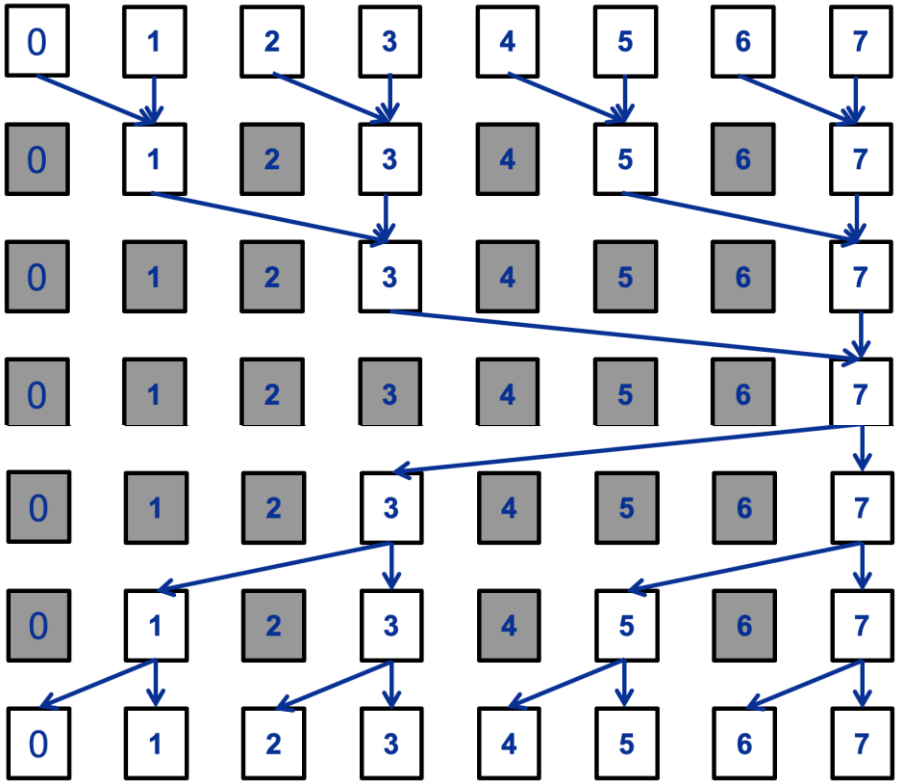
- Benchmarking OpenMP overhead
  - OpenMP parallel for
  - OpenMP for (w/o parallel)
  - OMP barrier
  - Static scheduling
  - Compact pinning (physical cores only)




Intel Xeon “Haswell” E5-2695v3 (2.3GHz) CoD



# OpenMP overheads: Barrier implementation (reminder)

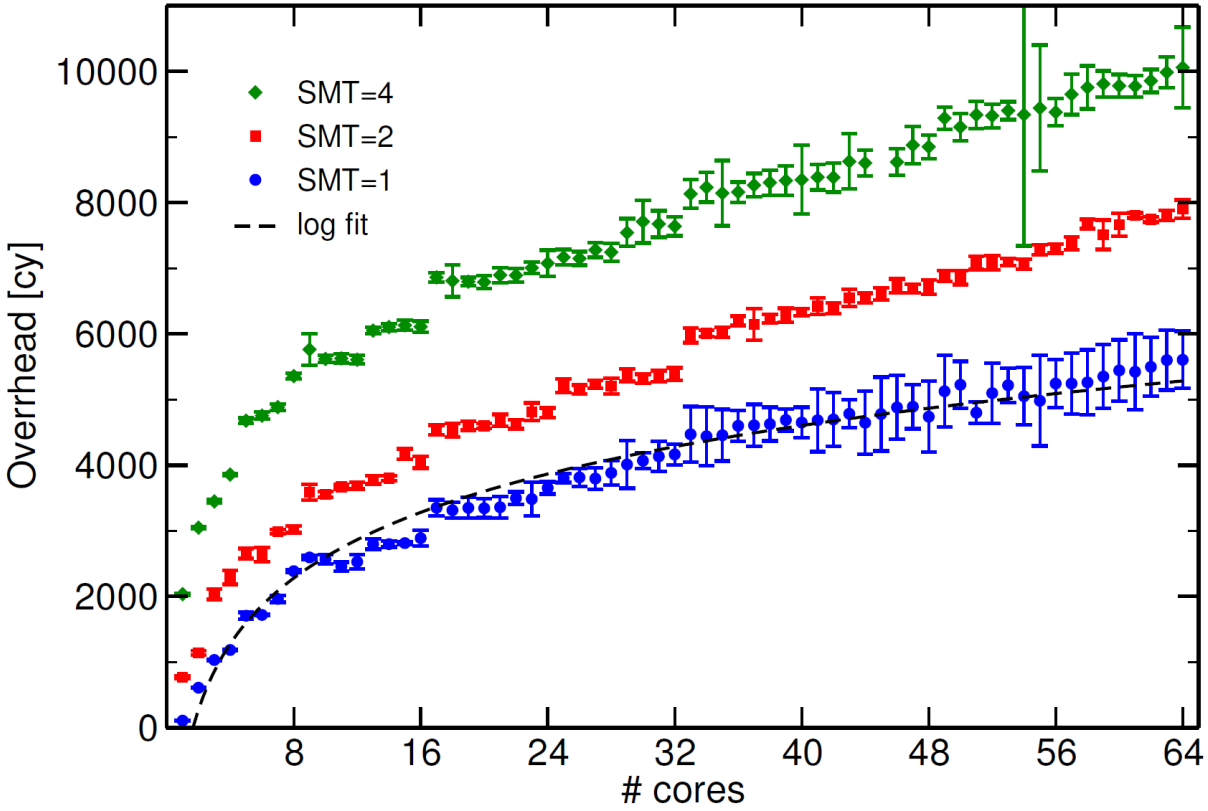



How does a “barrier” scale (best case)?

$$\mathbf{Time}(N) = const \times 2 \times log_2 N$$

Where $N$ is number of threads/processes in the barrier

# OpenMP overheads: Barrier cost on Intel Xeon Phi (KNL)




Intel Xeon Phi
(“Knights Landing”):

64 cores@1.3GHz

1,2,4 SMT per core

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# Shared-memory parallel processing with OpenMP (II)

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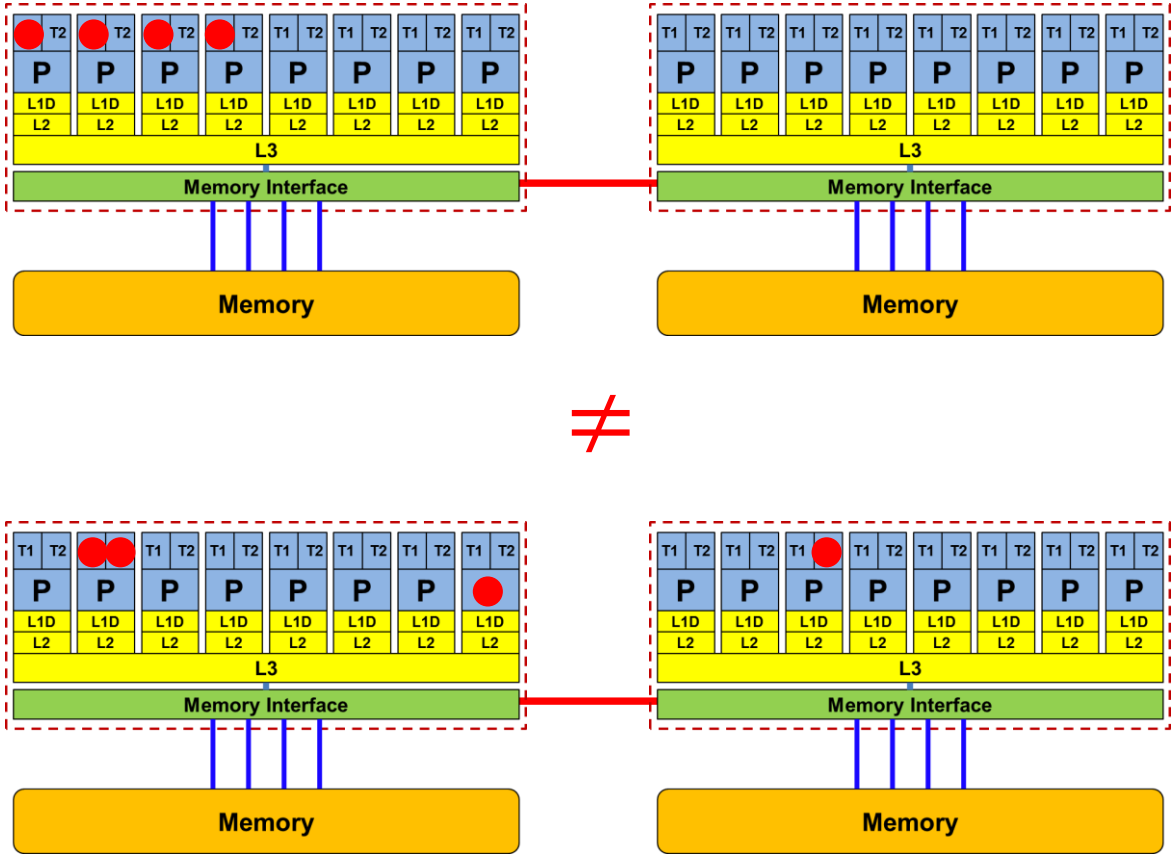
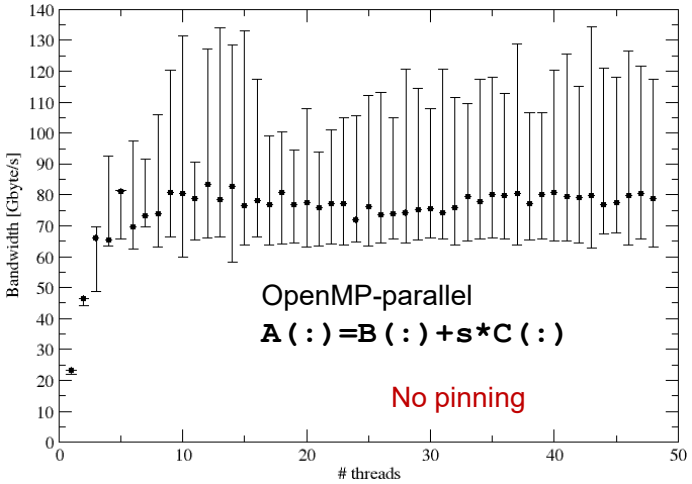
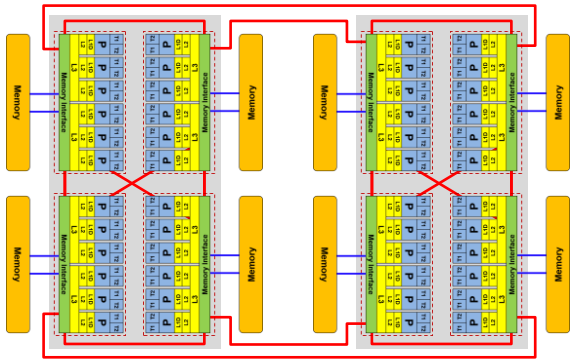
# OpenMP affinity: it matters!

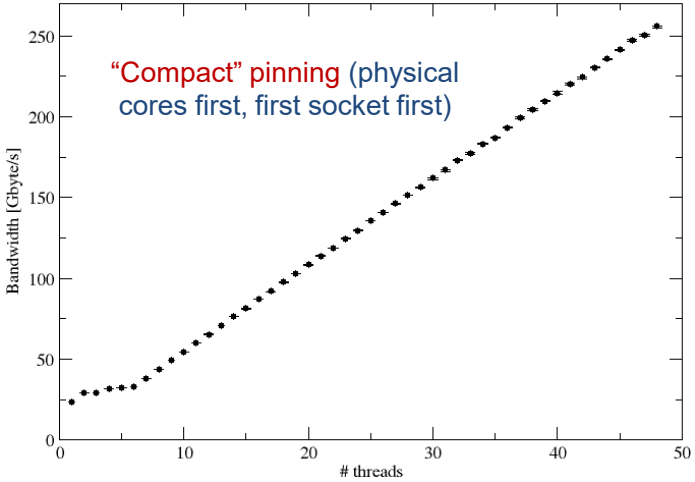
- Remember all the hardware bottlenecks!
- It *does* matter where the threads are running
- Yes, it's up to you
- No, the system will not magically guess what's best



# STREAM benchmark on 2x24-core AMD “Naples”: Anarchy vs. thread pinning




There are several reasons for caring about affinity:

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

# OMP_PLACES and Thread Affinity

- Processor: smallest entity able to run a thread or task (SMT/hyper-thread)
- Place: one or more processors → thread pinning is done place by place
- Free migration of the threads on a place between the processors of that place.

abstract name

| OMP_PLACES | Place == |
|---|---|
| threads | Hardware thread (hyper-thread) |
| cores | All HW threads of a single core |
| sockets | All HW threads of a socket |
| abstract_name(num_places) | Restrict # of places available |

Or use explicit numbering, e.g. 8 places, each consisting of 4 processors:

- `OMP_PLACES="{0,1,2,3},{4,5,6,7},{8,9,10,11}, … {28,29,30,31}"`
- `OMP_PLACES="{0:4},{4:4},{8:4}, … {28:4}"`
- `OMP_PLACES="{0:4}:8:4"`

<lower-bound>:<number of entries>[:<stride>]

Caveat: Actual behavior is implementation defined!

# OMP_PROC_BIND variable / proc_bind() clause

Determines how places are used for pinning:

| OMP_PROC_BIND | Meaning |
|---|---|
| FALSE | Affinity disabled |
| TRUE | Affinity enabled, implementation defined strategy |
| CLOSE | Threads bind to consecutive places |
| SPREAD | Threads are evenly scattered among places |
| MASTER | Threads bind to the same place as the master thread that was running before the parallel region was entered |

If there are more threads than places, consecutive threads are put into individual places (“balanced”)

Example:

```
$ OMP_NUM_THREADS=4 OMP_PROC_BIND=close OMP_PLACES=cores ./a.out
```

# Some simple OMP_PLACES examples

Intel Xeon w/ SMT, 2x10 cores, 1 thread per physical core, fill 1 socket

```
OMP_NUM_THREADS=10
OMP_PLACES=cores
OMP_PROC_BIND=close
```

Intel Xeon Phi with 72 cores, 4-way SMT
32 cores to be used, 2 threads per physical core

```
OMP_NUM_THREADS=64
OMP_PLACES=cores(32)
OMP_PROC_BIND=close    # spread will also do
```

Intel Xeon, 2 sockets, 4 threads per socket (no binding within socket!)

```
OMP_NUM_THREADS=8
OMP_PLACES=sockets
OMP_PROC_BIND=close    # spread will also do
```

Intel Xeon, 2 sockets, 4 threads per socket, binding to cores

```
OMP_NUM_THREADS=8
OMP_PLACES=cores
OMP_PROC_BIND=spread
```

**Always prefer abstract places instead of hardware thread IDs!**

# Wrap-up: beginner's OpenMP toolbox

- Parallel region
- Workshared loop construct
- Data scoping (shared, private, firstprivate)
- Basic reductions with standard operators
- Simple synchronization constructs
  - barrier, nowait
  - (named) critical, atomic
  - single (actually worksharing), master
- OpenMP affinity as defined in the standard

- But wait, there's more…