

Efficient parallel programming on ccNUMA nodes

Performance characteristics of ccNUMA nodes

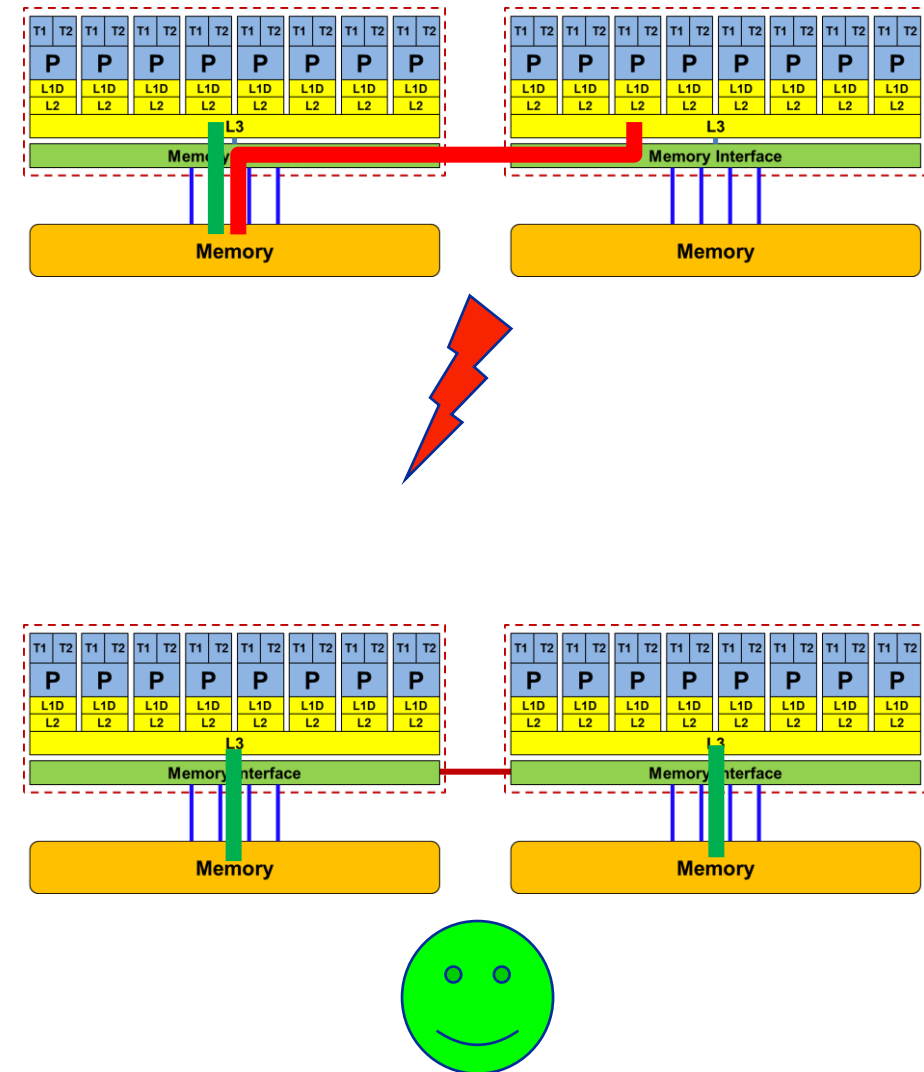
First touch placement policy



ccNUMA – The “other affinity”

- ccNUMA:
 - Whole memory is **transparently accessible** by all processors
 - but **physically distributed** across multiple locality domains (LDs)
 - 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?

Note: Page placement is implemented in units of OS pages (often 4 KiB, possibly more)



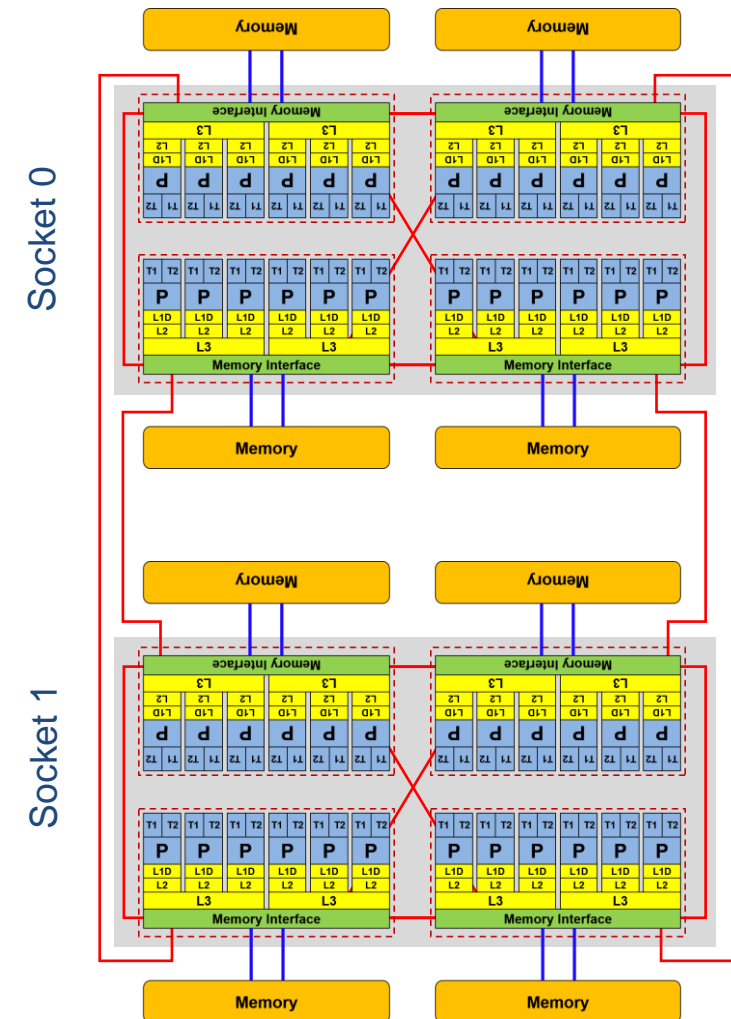
How much does nonlocal access cost?

Example: AMD “Naples” 2-socket system

(8 chips, 2 sockets, 48 cores):

STREAM Triad bandwidth measurements [Gbyte/s]

CPU node		0	1	2	3	4	5	6	7
MEM node									
0		32.4	21.4	21.8	21.9	10.6	10.6	10.7	10.8
1		21.5	32.4	21.9	21.9	10.6	10.5	10.7	10.6
2		21.8	21.9	32.4	21.5	10.6	10.6	10.8	10.7
3		21.9	21.9	21.5	32.4	10.6	10.6	10.6	10.7
4		10.6	10.7	10.6	10.6	32.4	21.4	21.9	21.9
5		10.6	10.6	10.6	10.6	21.4	32.4	21.9	21.9
6		10.6	10.7	10.6	10.6	21.9	21.9	32.3	21.4
7		10.7	10.6	10.6	10.6	21.9	21.9	21.4	32.5



numactl as a simple ccNUMA locality tool :

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:

```
for m in `seq 0 7`; do
  for c in `seq 0 7`; do
    env OMP_NUM_THREADS=6 \
      numactl --membind=$m likwid-pin -c M${c}:0-5 ./stream
  done
done
```

ccNUMA map scan
for Naples system

```
numactl --interleave=0-7 likwid-pin -c E:N:8:1:12 ./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)

- **Caveat:** “to touch” means “to write,” not “to allocate”
- Example:

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

Memory not
mapped here yet

Mapping takes
place here

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

Coding for ccNUMA data locality

Simplest case: explicit initialization

```
integer,parameter :: N=1000000000
double precision, allocatable :: A(:), B(:)
allocate(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=1000000000
double precision, allocatable :: A(:), B(:)
allocate(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
```



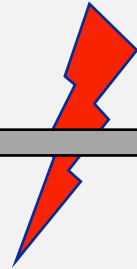
Coding for ccNUMA data locality

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

```
integer,parameter :: N=10000000
double precision, allocatable :: A(:), B(:)
allocate (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, allocatable :: A(:), B(:)
allocate (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**
 - If **dynamic scheduling/tasking** is unavoidable, the problem cannot be solved completely if a team of threads spans more than one LD
 - Static parallel first touch is still a good idea
 - OpenMP 5.0 will have rudimentary memory affinity functionality
- How about **global objects**?
 - Initialized before `main()` is called
 - If communication vs. computation is favorable, might consider **properly placed copies** of global data
- C++: Arrays of objects and `std::vector<>` are by default initialized sequentially
 - **STL allocators** provide an elegant solution

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);
    }
    ...
};
```

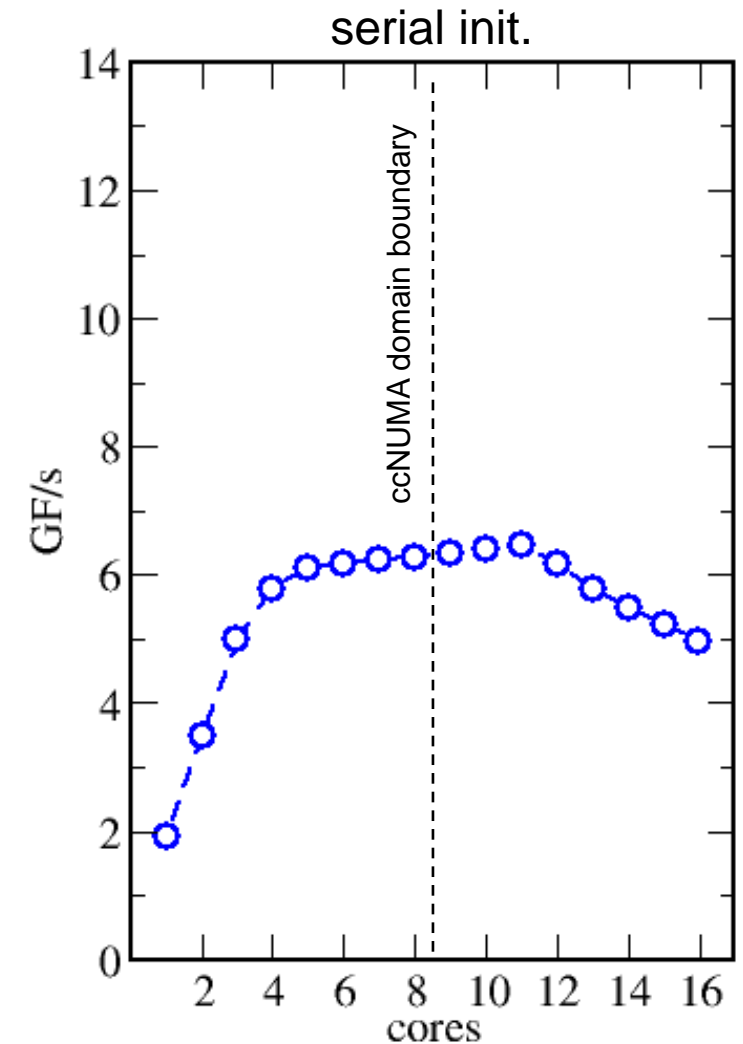
Application:

```
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** (whenever a ccNUMA node boundary is crossed)
 - **Just an indication, not a proof yet**
- Running with **numactl --interleave** might give you a hint
 - See later
- Consider using **performance counters**
 - **likwid-perfctr** can be used to measure non-local memory accesses
 - Example for Intel dual-socket system (Ivy Bridge, 2x10-core):

```
$ likwid-perfctr -g NUMA -C M0:0-4@M1:0-4 ./a.out
```



Using performance counters for diagnosis

- Intel Ice Lake SP node (running 2x32 threads):
measure inter-socket traffic

```
$ likwid-perfctr -g UPI -C S0:0@S1:0 ./a.out
```

- Output:

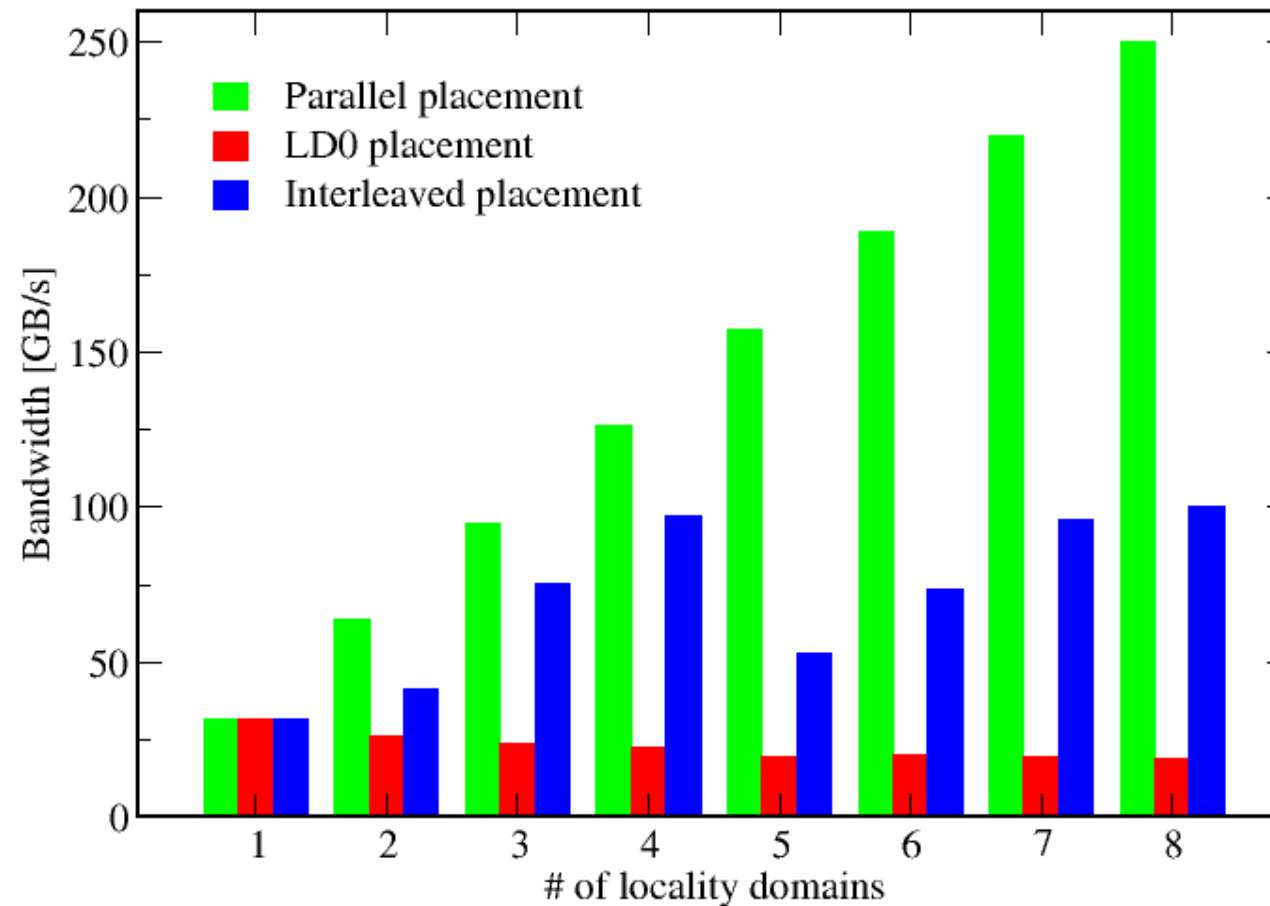
Metric	HWThread 0	HWThread 32
Runtime (RDTSC) [s]	12.3681	12.3681
Runtime unhaltd [s]	12.1108	8.2227
Clock [MHz]	3281.3537	3103.6518
CPI	5.4670	35.5873
Received data bandwidth [MByte/s]	22127.2106	21358.7412
Received data volume [GByte]	273.6708	264.1663
Sent data bandwidth [MByte/s]	21358.7391	22127.2191
Sent data volume [GByte]	264.1663	273.6709
Total data bandwidth [MByte/s]	43485.9496	43485.9603
Total data volume [GByte]	537.8370	537.8372

Caveat: NUMA metrics vary strongly among CPU models

About half of the overall
memory traffic is caused by
the remote domain!

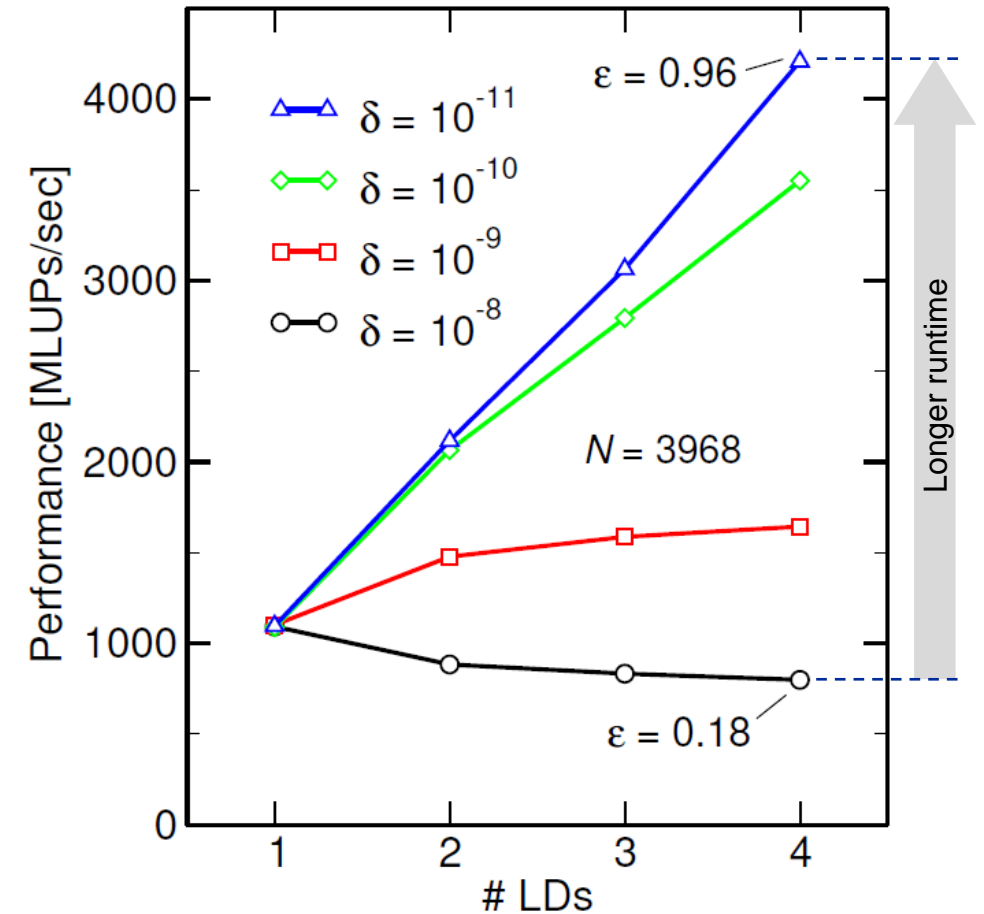
OpenMP STREAM triad on a dual AMD Epyc 7451 (“Naples”) (6 cores per LD)

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



A weird observation

- Experiment: **memory-bound** Jacobi solver with sequential data initialization
 - **No parallel data placement** at all!
 - Expect no scaling across LDs
- Convergence threshold δ determines the runtime
 - The smaller δ , the longer the run
- Observation
 - **No scaling** across LDs for **large δ** (runtime 0.5 s)
 - **Scaling** gets **better** with **smaller δ** up to almost perfect efficiency ε (runtime 91 s)
- **Conclusion**
 - Something seems to “**heal**” the **bad access locality** on a time scale of tens of seconds



Riddle solved: NUMA balancing

- Linux kernel supports automatic page migration

```
$ cat /proc/sys/kernel/numa_balancing
0
$ echo 1 > /proc/sys/kernel/numa_balancing # activate
```

- Active on all current Linux distributions, some performance impact for single core execution
- Parameters control aggressiveness

```
$ ll /proc/sys/kernel/numa*
-rw-r--r-- 1 root root 0 Jun 26 09:16 numa_balancing
-rw-r--r-- 1 root root 0 Jun 26 09:16 numa_balancing_scan_delay_ms
-rw-r--r-- 1 root root 0 Jun 26 09:16 numa_balancing_scan_period_max_ms
-rw-r--r-- 1 root root 0 Jun 26 09:16 numa_balancing_scan_period_min_ms
-rw-r--r-- 1 root root 0 Jun 26 09:16 numa_balancing_scan_size_mb
```

- Default behavior is “take it slow”
- Do not rely on it! Parallel first touch is still a good idea!

Summary on ccNUMA issues

- Identify the problem
 - Is ccNUMA an issue in your code?
 - Simple test: run with `numactl --interleave`
 - Consider performance counters if available
- Apply first-touch placement in initialization loops
 - Consider loop lengths and static scheduling
 - C++ and global/static objects may require special care
- NUMA balancing is active on many Linux systems today
 - Automatic page migration
 - Slow process, may take many seconds (configurable)
 - Not a silver bullet
 - Still a good idea to do parallel first touch
- If dynamic scheduling cannot be avoided
 - Consider round-robin placement as a quick (but non-ideal) fix
 - OpenMP 5.0 has some data affinity support