Erlangen Regional Computing Center

FRIEDRICH-ALEXANDER UNIVERSITÄT ERLANGEN-NÜRNBERG

Efficient parallel programming on ccNUMA nodes

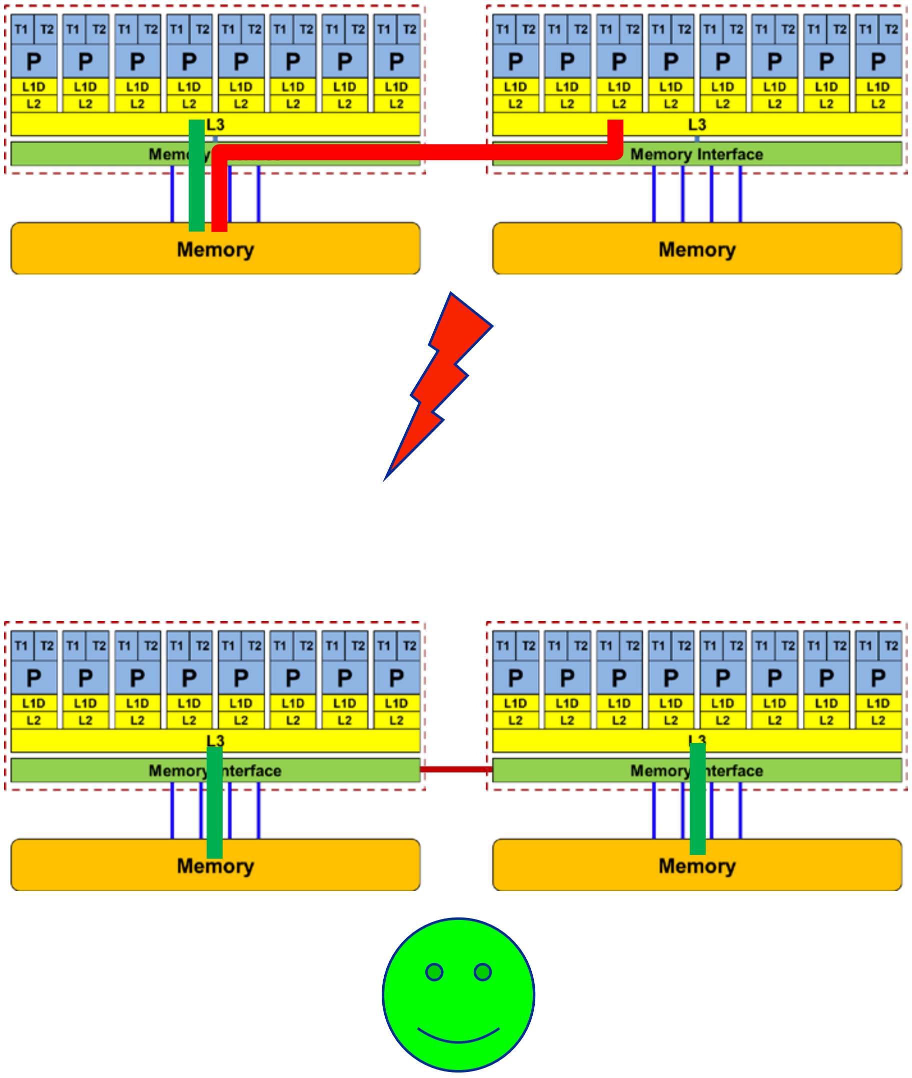
Performance characteristics of ccNUMA nodes

First touch placement policy

High Performance Computing

ccNUMA – The other affinity to care about

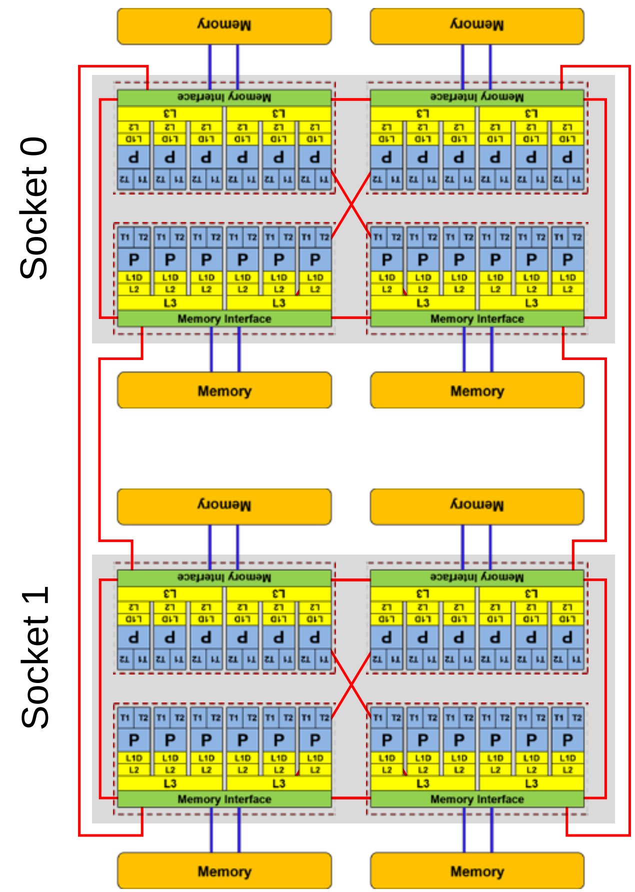
- ccNUMA:
  - Whole memory is transparently accessible by all processors
  - but physically distributed across multiple locality domains (LDs)
  - with varying bandwidth and latency
  - and potential contention (shared memory paths)
- How do we make sure that memory access is always as "local" and "distributed"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



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

Example: AMD “Epyc” 2-socket system
(8 chips, 2 sockets, 48 cores):
STREAM Triad bandwidth measurements [Gbyte/s]

MEM node \ CPU node	0	1	2	3	4	5	6	7
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** 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 EPYC 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

Most simple case: explicit initialization

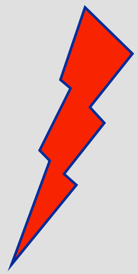
```
integer,parameter :: N=10000000
double precision A(N), B(N)



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 Data Locality

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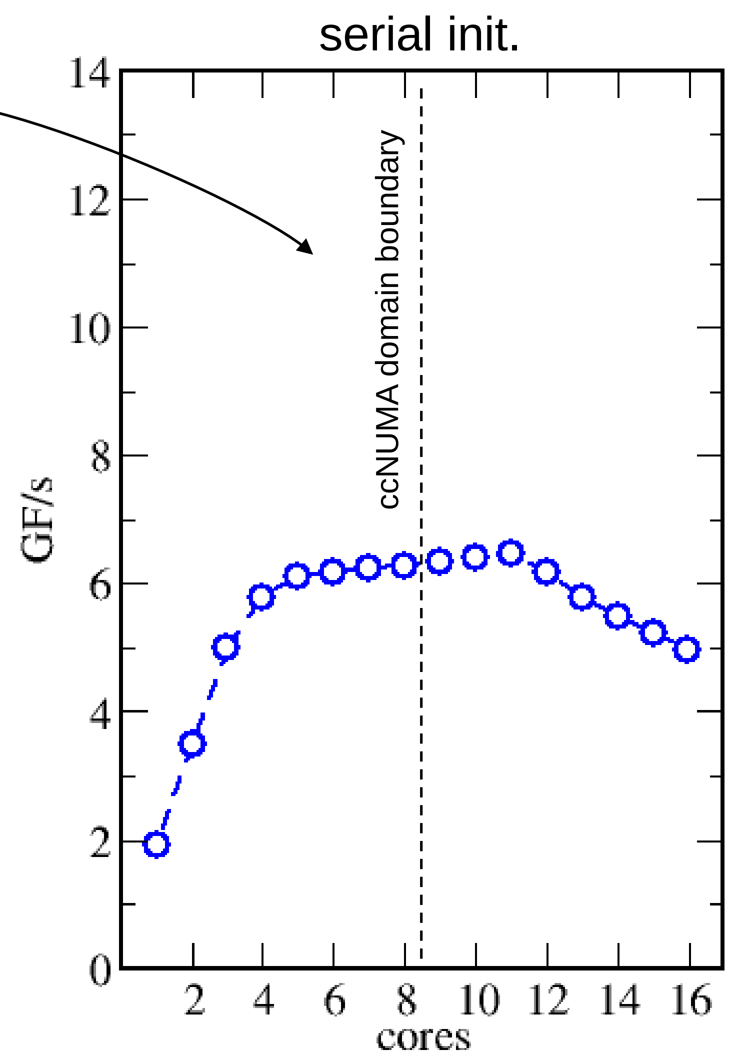
- Required condition: OpenMP loop schedule of initialization must be the same as in all computational loops
  - Only choice: **`static`**! Specify explicitly on all NUMA-sensitive loops, just to be sure…
  - Imposes some constraints on possible optimizations (e.g. load balancing)
  - Presupposes that 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?
  - 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

Diagnosing bad locality

- 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
- Consider using performance counters
  - LIKWID-perfctr can be used to measure nonlocal memory accesses
  - Example for Intel dual-socket system (IvyBridge, 2x10-core):

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



Using performance counters for diagnosis

- Intel Ivy Bridge EP node (running 2x5 threads): measure NUMA traffic per core

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

- Summary output:

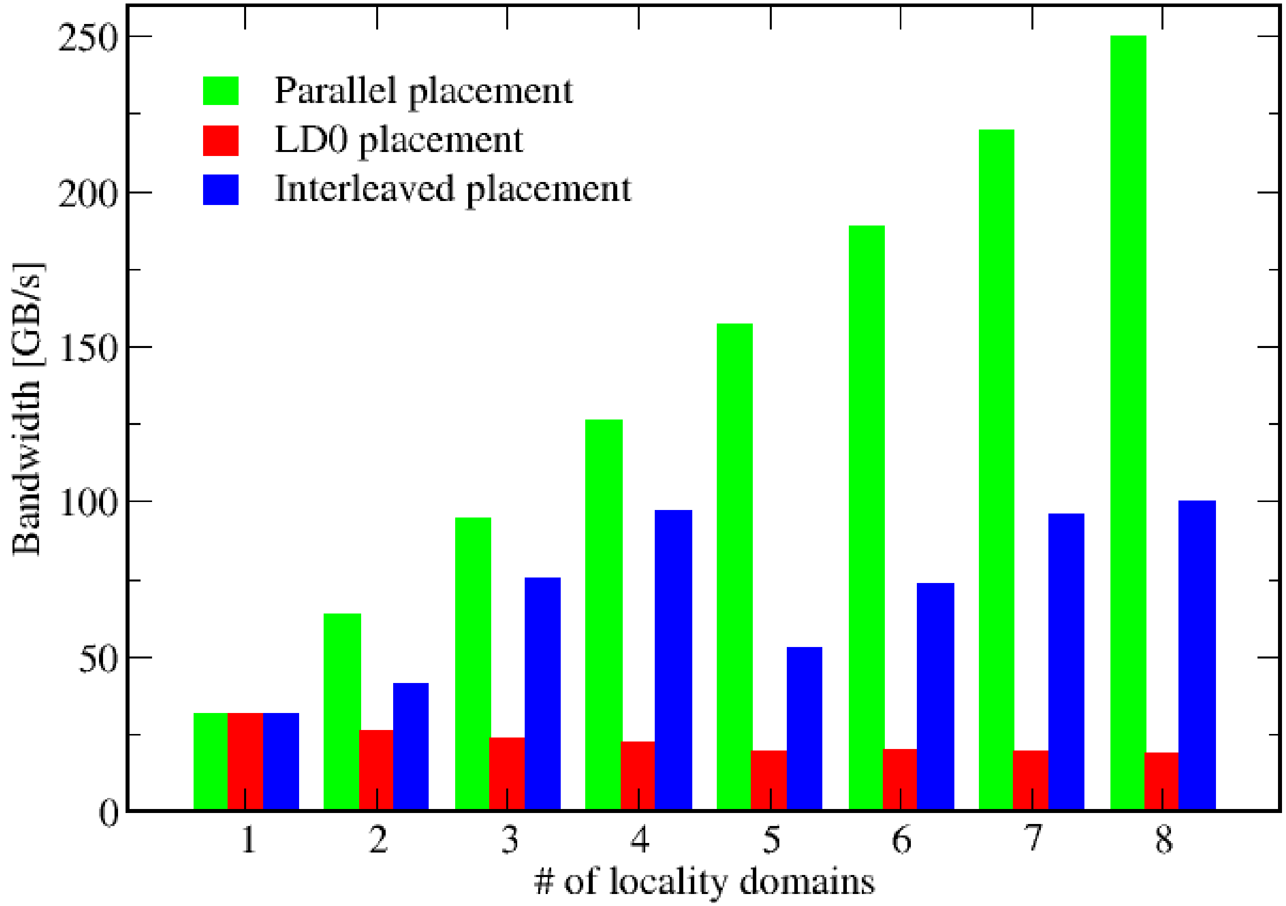
Metric	Sum	Min	Max	Avg
Runtime (RDTSC) [s] STAT	4.050483	0.4050483	0.4050483	0.4050483
Runtime unhalted [s] STAT	3.03537	0.3026072	0.3043367	0.303537
Clock [MHz] STAT	32996.94	3299.692	3299.696	3299.694
CPI STAT	40.3212	3.702072	4.244213	4.03212
Local DRAM data volume [GByte] STAT	7.752933632	0.735579264	0.823551488	0.7752933632
Local DRAM bandwidth [MByte/s] STAT	19140.761	1816.028	2033.218	1914.0761
Remote DRAM data volume [GByte] STAT	9.16628352	0.86682464	0.957811776	0.916628352
Remote DRAM bandwidth [MByte/s] STAT	22630.098	2140.052	2364.685	2263.0098
Memory data volume [GByte] STAT	16.919217152	1.690376128	1.69339104	1.6919217152
Memory bandwidth [MByte/s] STAT	41770.861	4173.27	4180.714	4177.0861

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

- Caveat: NUMA metrics vary strongly between CPU models

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

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



Summary on ccNUMA issues

- **Identify the problem**
  - Is ccNUMA an issue in your code?
  - Simple test: run with **`numactl --interleave`**
- **Apply first-touch placement**
  - Look at 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 will have some data affinity support