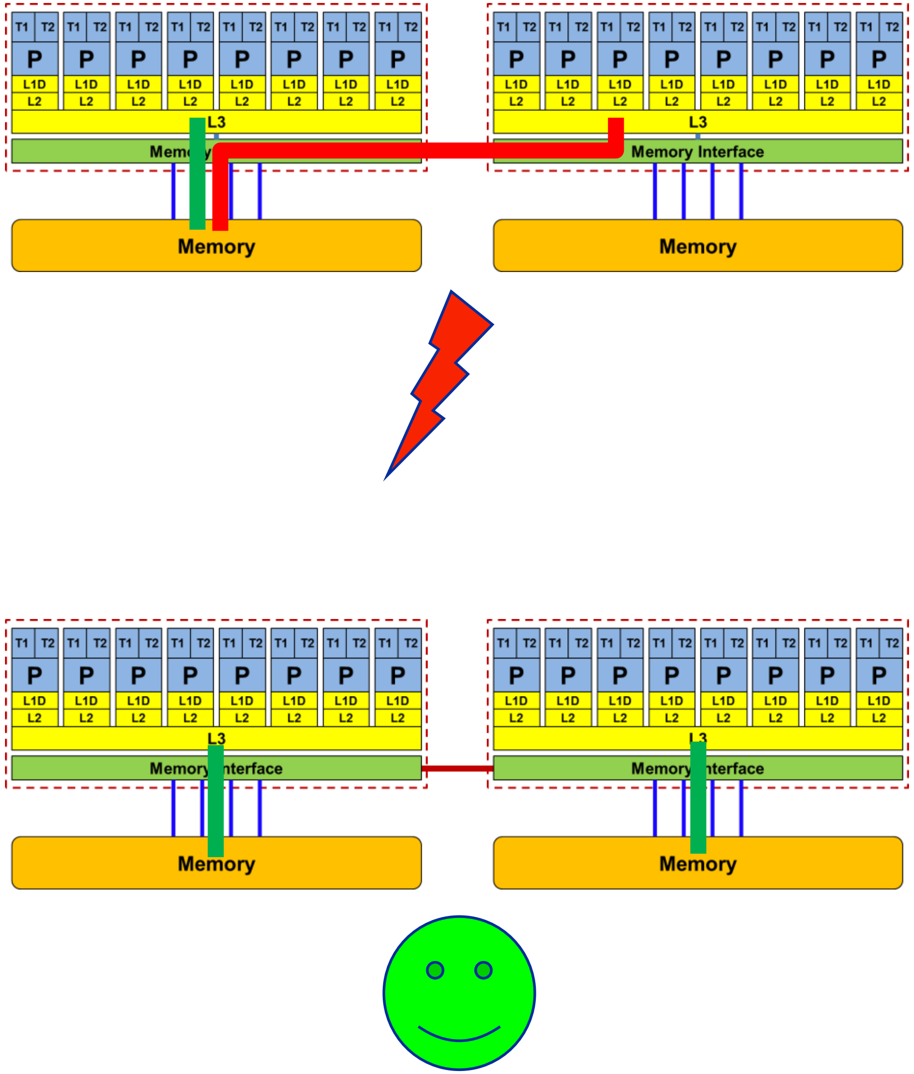
# Efficient parallel programming on ccNUMA nodes

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?

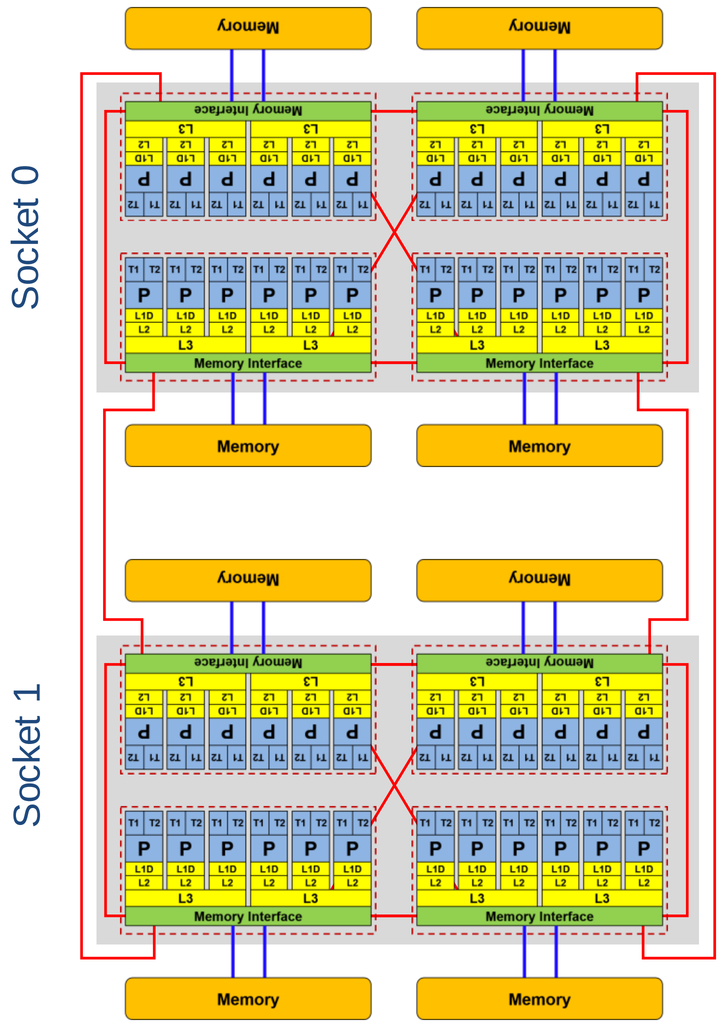



**Note:** Page placement is implemented in units of OS pages (often 4 KiB, possibly more)

# How much does nonlocal access cost?

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

| 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 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

## Simplest case: explicit initialization

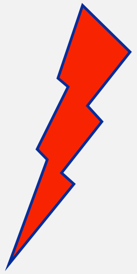
```
integer,parameter :: N=100000000
double precision, allocatable :: A(:), B(:)
allocate(A(N),B(N))



A=0.d0




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



```
integer,parameter :: N=100000000
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
```

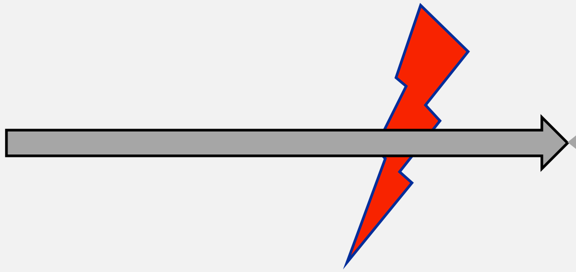
# Coding for ccNUMA data locality

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<>`

```
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);
```

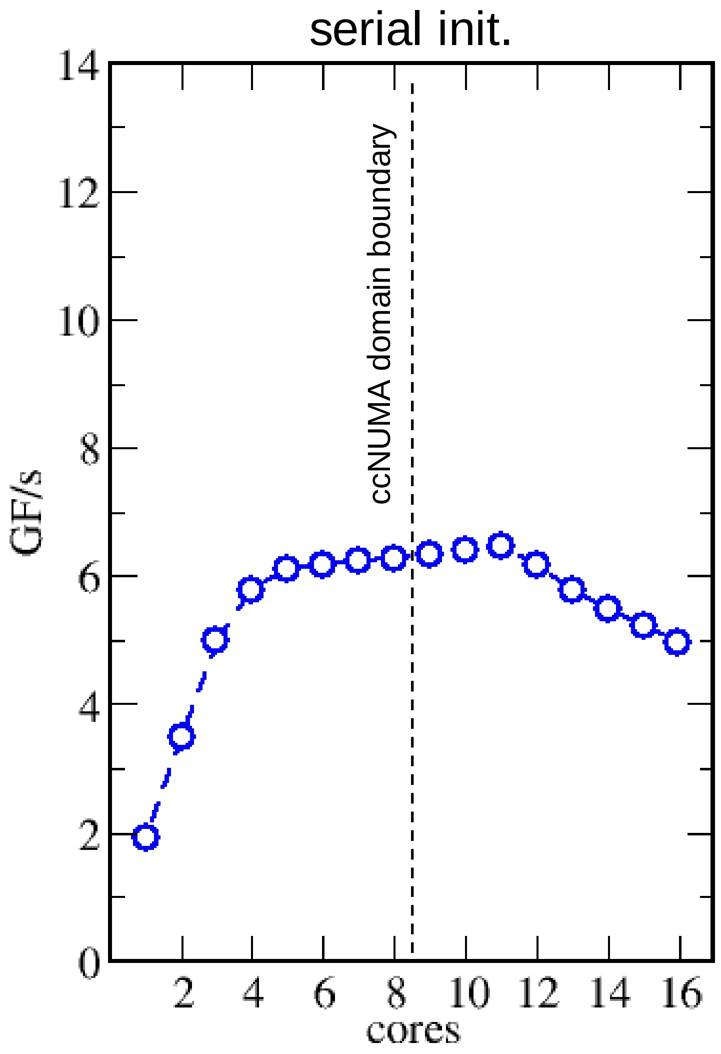
# Diagnosing bad locality

- 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
```

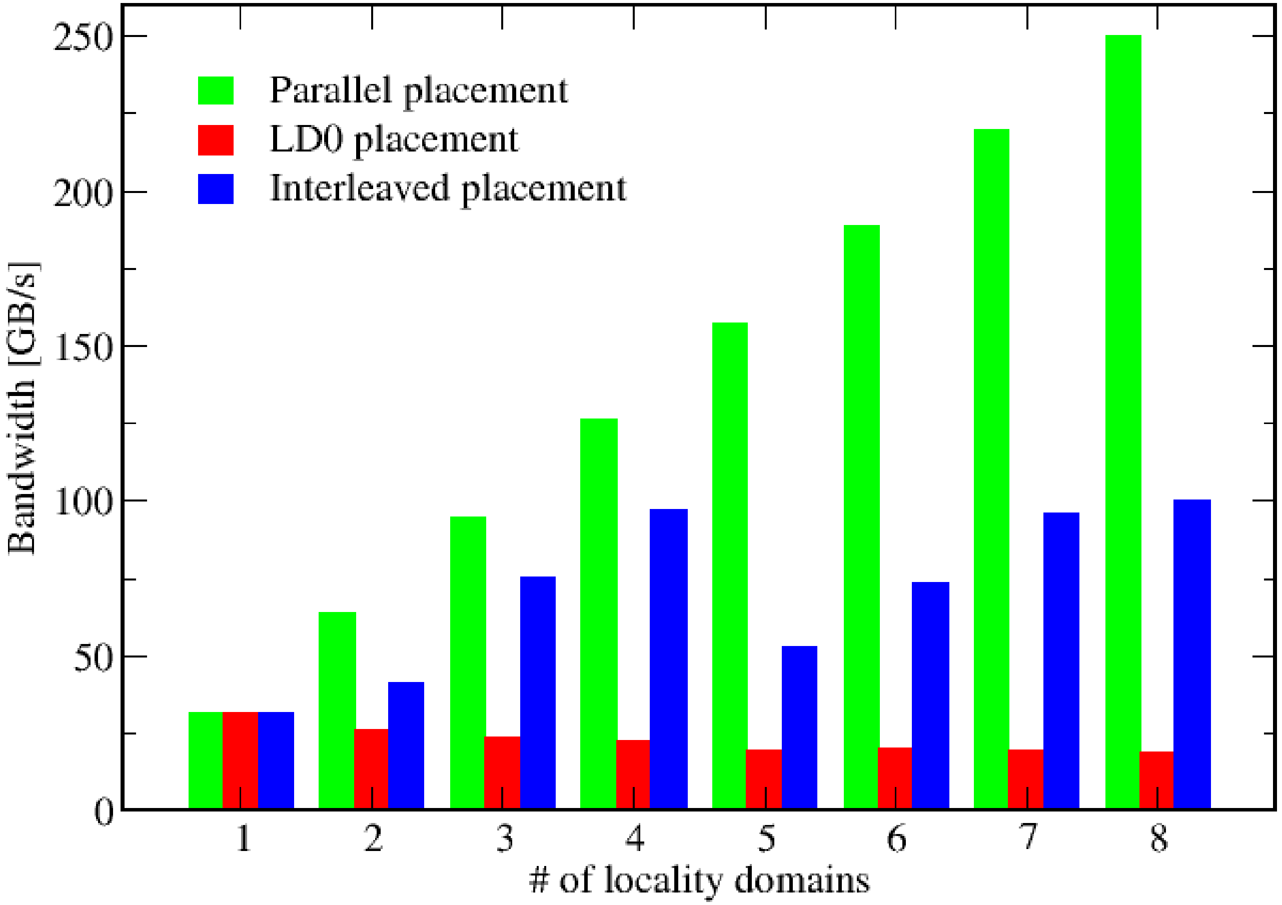
- Output:

```
+-----------------------------------+------------+-------------+
|               Metric              | HWThread 0 | HWThread 32 |
+-----------------------------------+------------+-------------+
|        Runtime (RDTSC) [s]        |    12.3681 |     12.3681 |
|        Runtime unhalted [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 |
+-----------------------------------+------------+-------------+
```

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

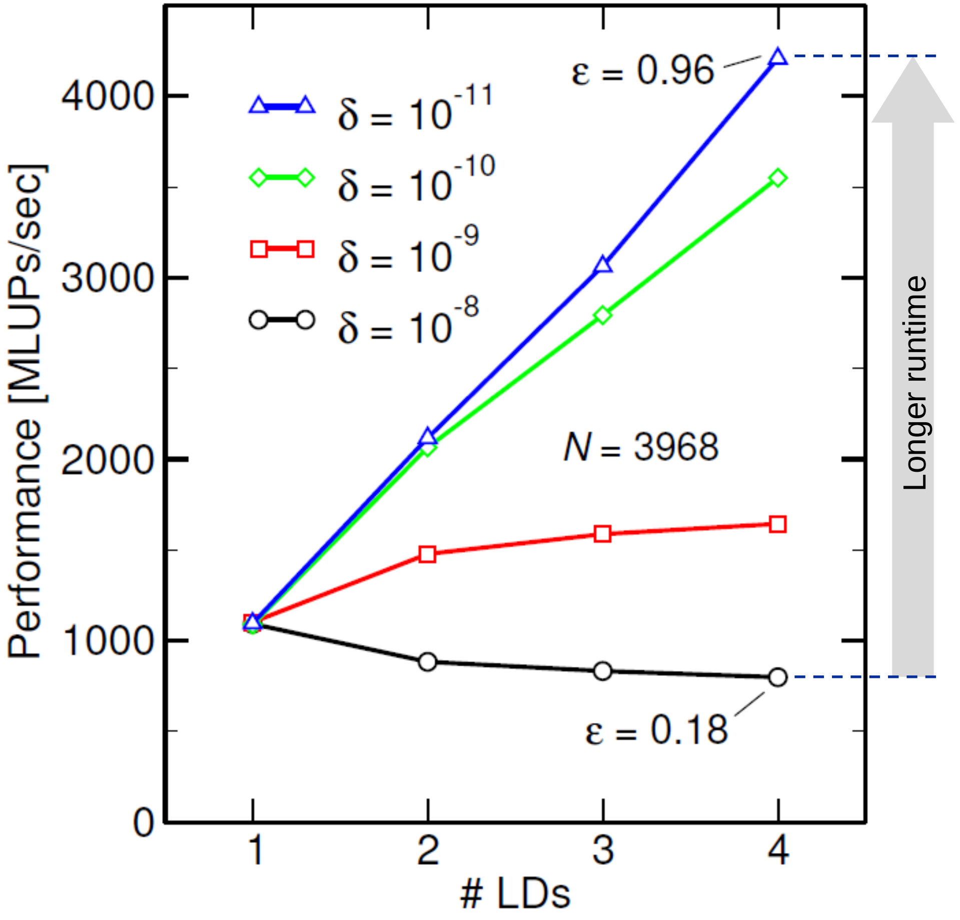
Caveat: NUMA metrics vary strongly among CPU models

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 $\delta$ determines the runtime
  - The smaller $\delta$, the longer the run
- Observation
  - No scaling across LDs for large $\delta$ (runtime 0.5 s)
  - Scaling gets better with smaller $\delta$ up to almost perfect efficiency $\varepsilon$ (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