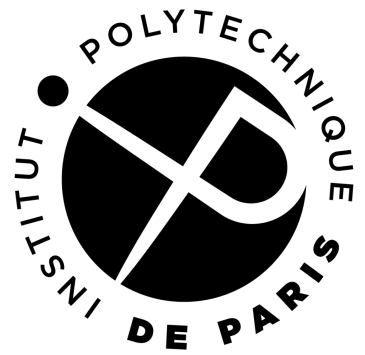


Non uniform memory architectures

Master in computer science of IP Paris

Master CHPS of Paris Saclay

Gaël Thomas

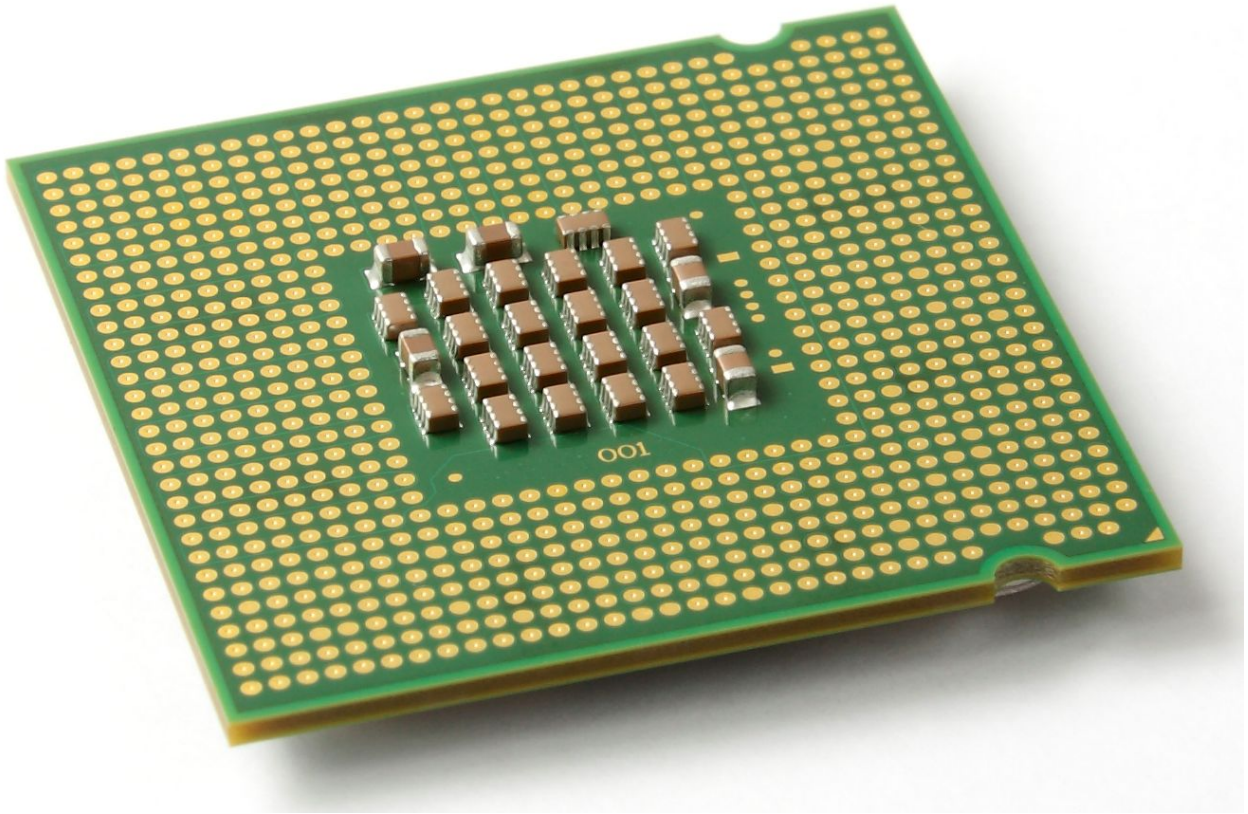
We need computing power

- To analyze large datasets

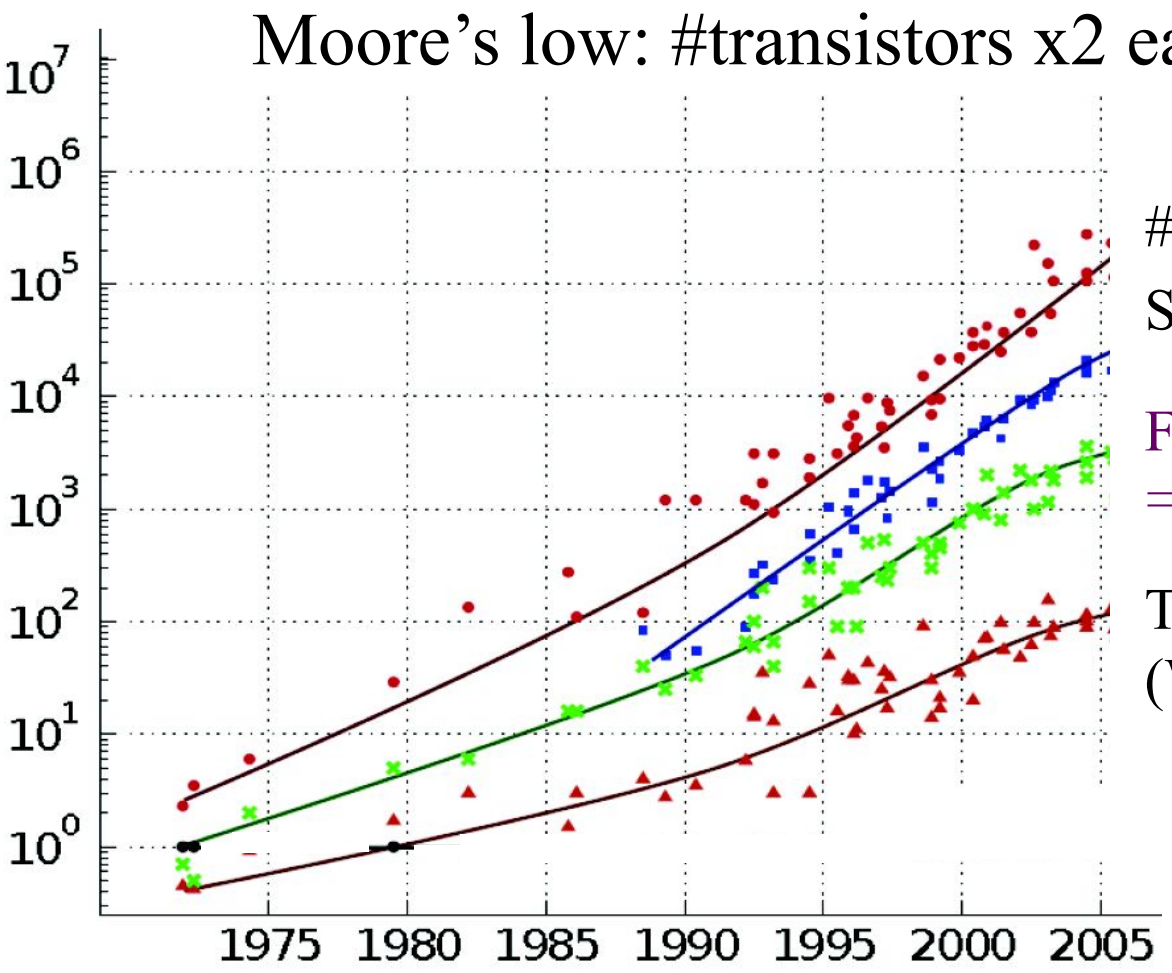
- To perform large computations

- To handle many clients

The computing power is in the CPU



(Old) computing power trends



transistors (thousands)

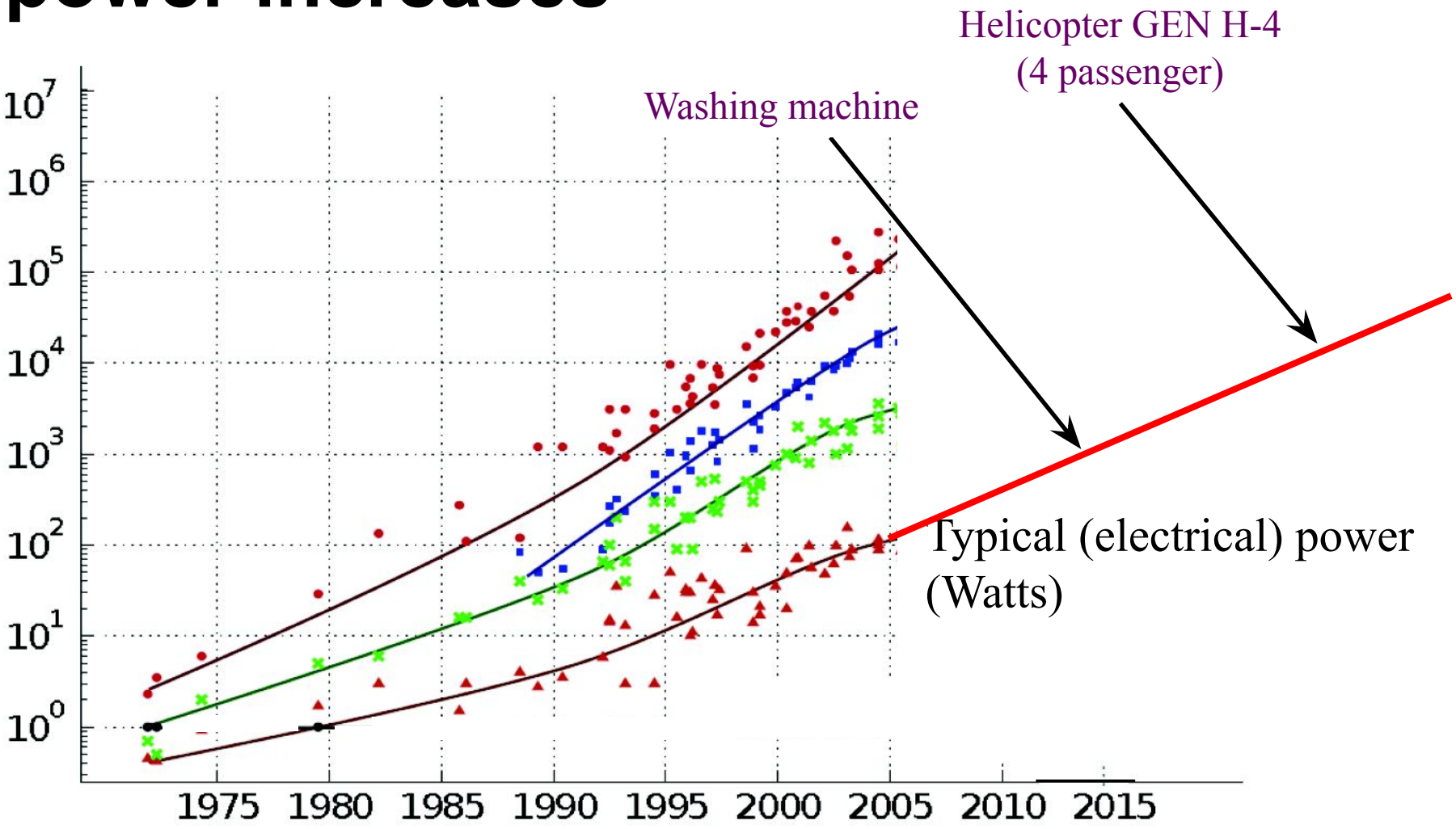
Single step Perf (SpecINT)

Frequency (MHz)
⇒ processing power

Typical (electrical) power (Watts)

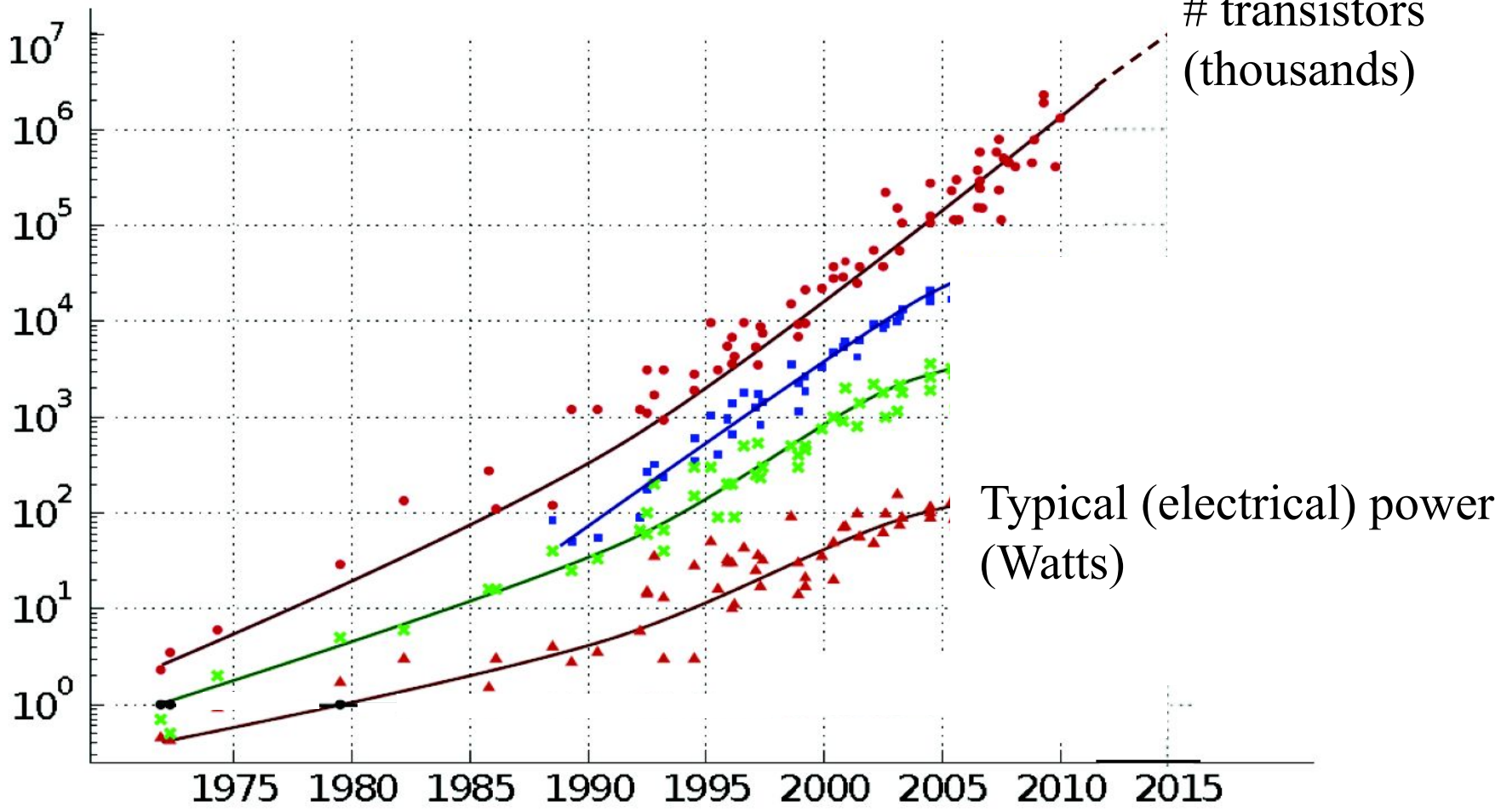
Original data collected and plotted by M. Horowitz, F. Labonte, O. Shacham, K. Olukotun, L. Hammond and C. Batten
Dotted line extrapolations by C. Moore

But frequency increases ⇒ electrical power increases



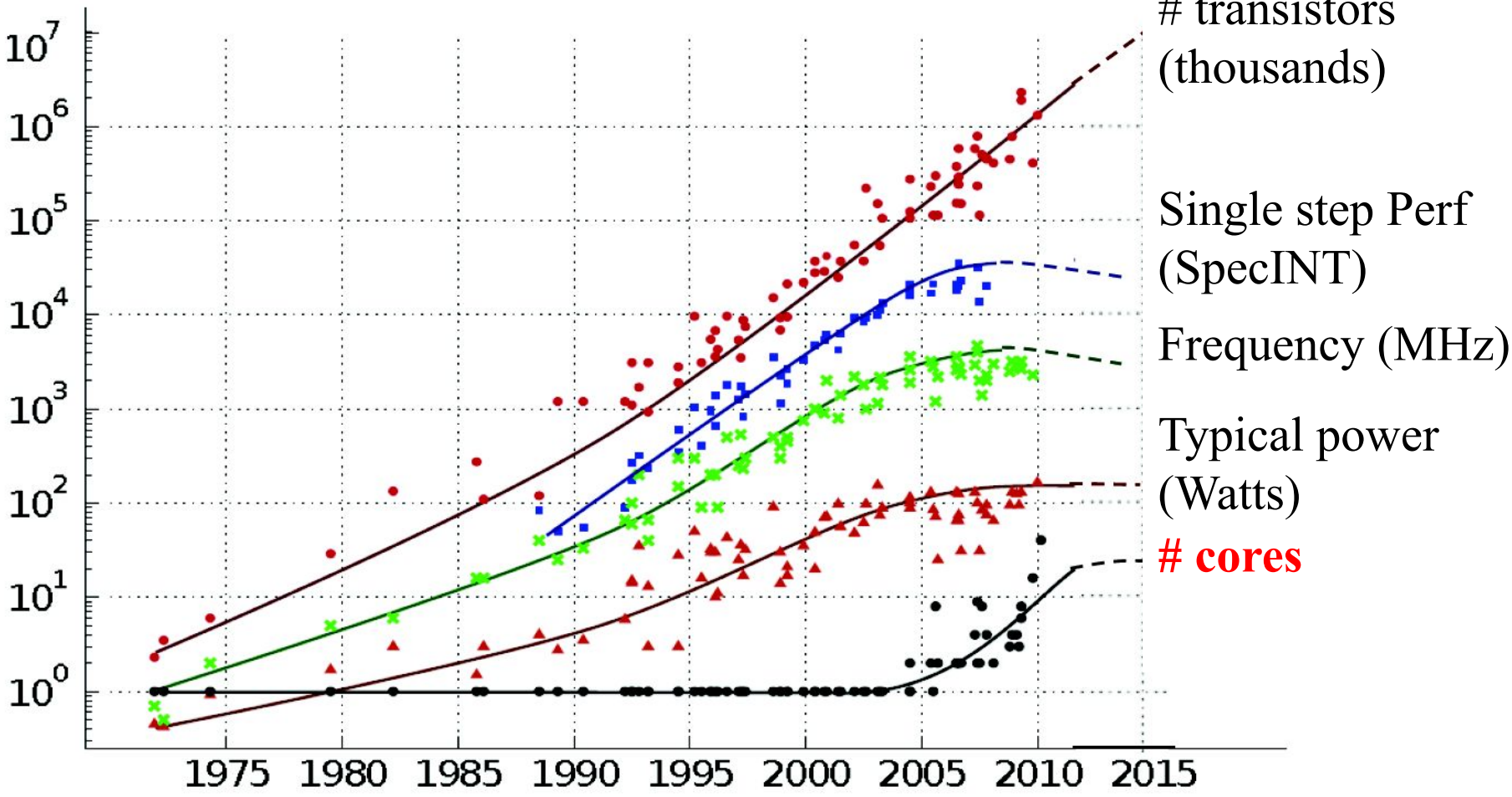
Original data collected and plotted by M. Horowitz, F. Labonte, O. Shacham, K. Olukotun, L. Hammond and C. Batten
Dotted line extrapolations by C. Moore

Fortunately, the Moore's law still hold



Original data collected and plotted by M. Horowitz, F. Labonte, O. Shacham, K. Olukotun, L. Hammond and C. Batten
Dotted line extrapolations by C. Moore

Today: we increase power by increasing the number of cores



Original data collected and plotted by M. Horowitz, F. Labonte, O. Shacham, K. Olukotun, L. Hammond and C. Batten
Dotted line extrapolations by C. Moore

But programming a multicore is hard

```
#include <stdlib.h>

#define N 100000000

int main(int argc, char **argv) {
  int* a = malloc(sizeof(int) * N);

  for(int i=1; i<N; i++) {
    a[i] = a[i] * a[i-1];
  }
}
```

On my laptop at 2k€
(**2 cores** at 2.2GHz)

$ time ./bip
real 0m0.474s

On my server at 15k€
(**48 cores** at 2.2GHz)

$ time ./bip
real 0m1.142s

Not really what we can expect

Multicores radically change the way we design applications

- We have to parallelize our applications

Multicores radically change the way we design applications

- We have to parallelize our applications
- And our parallel algorithms have to scale

Multicores radically change the way we design applications

- We have to parallelize our applications
- And our parallel algorithms have to scale

But that's not enough…

We have to handle complex memory architectures

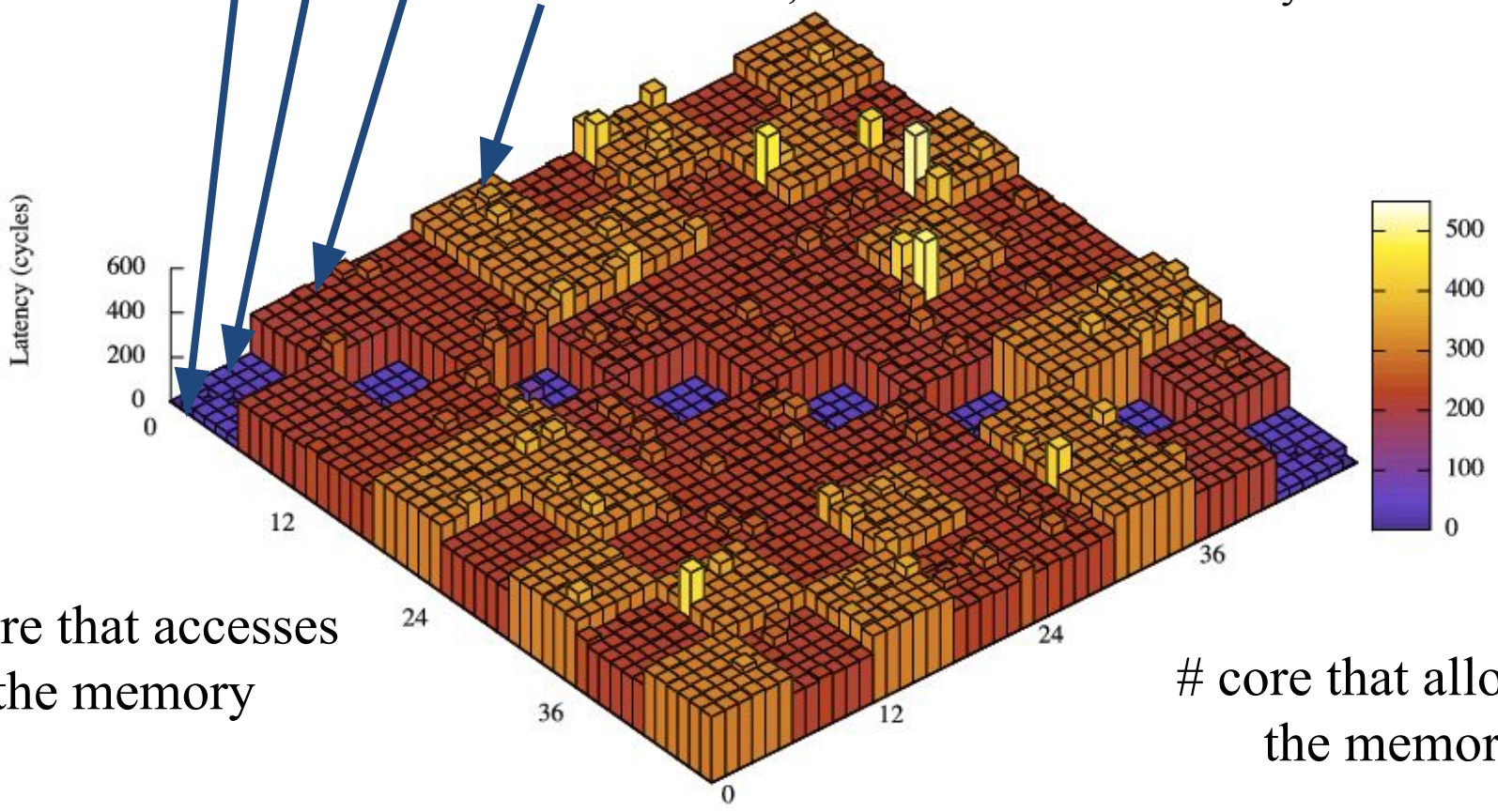
But memory access latency varies a lot

Core 0 allocates, core 0 accesses => ~5 cycles

Core 3 allocates, core 0 accesses => ~50 cycles

Core 15 allocates, core 0 accesses => ~275 cycles

Core 20 allocates, core 0 accesses => ~380 cycles

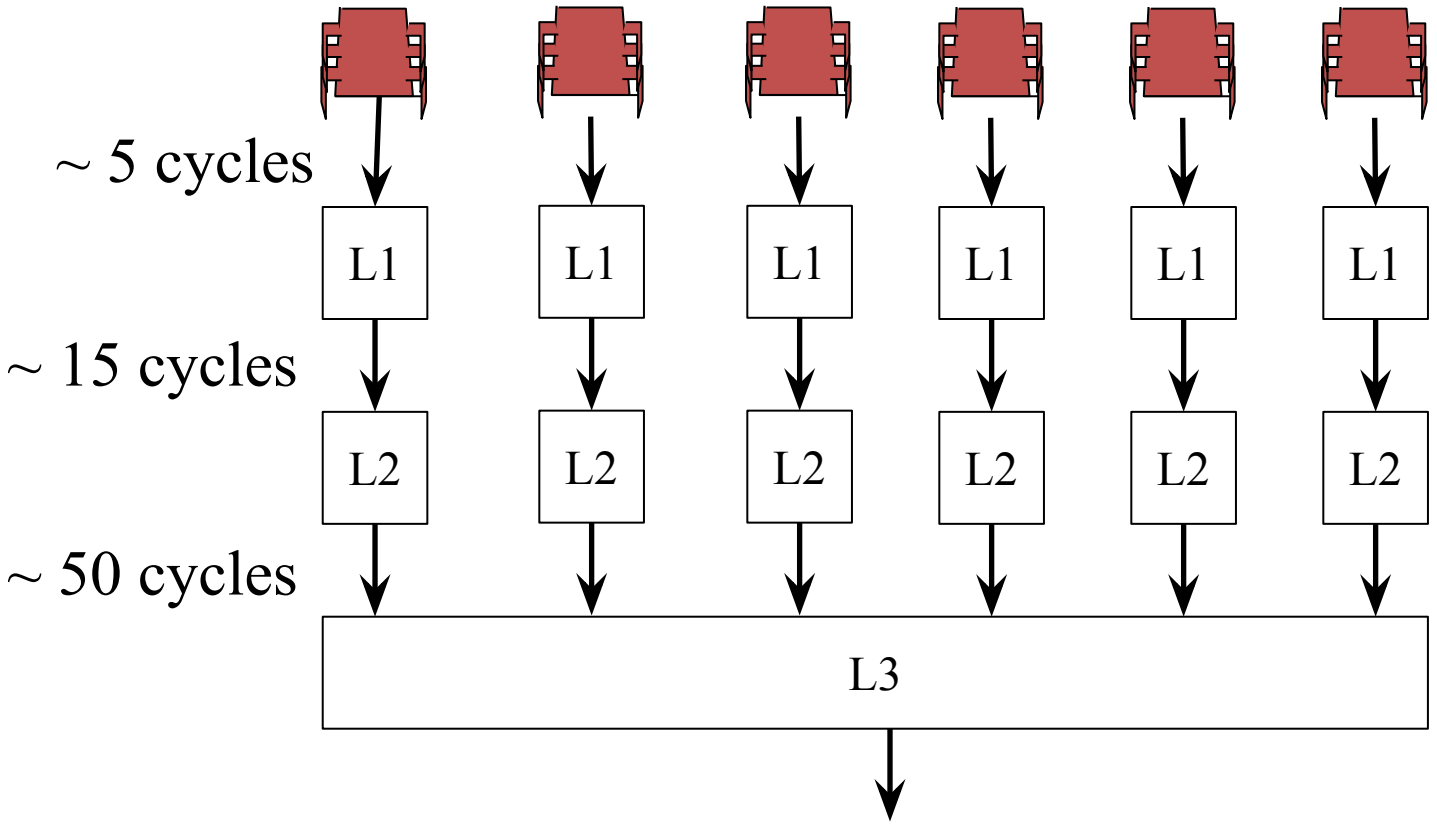


core that accesses the memory

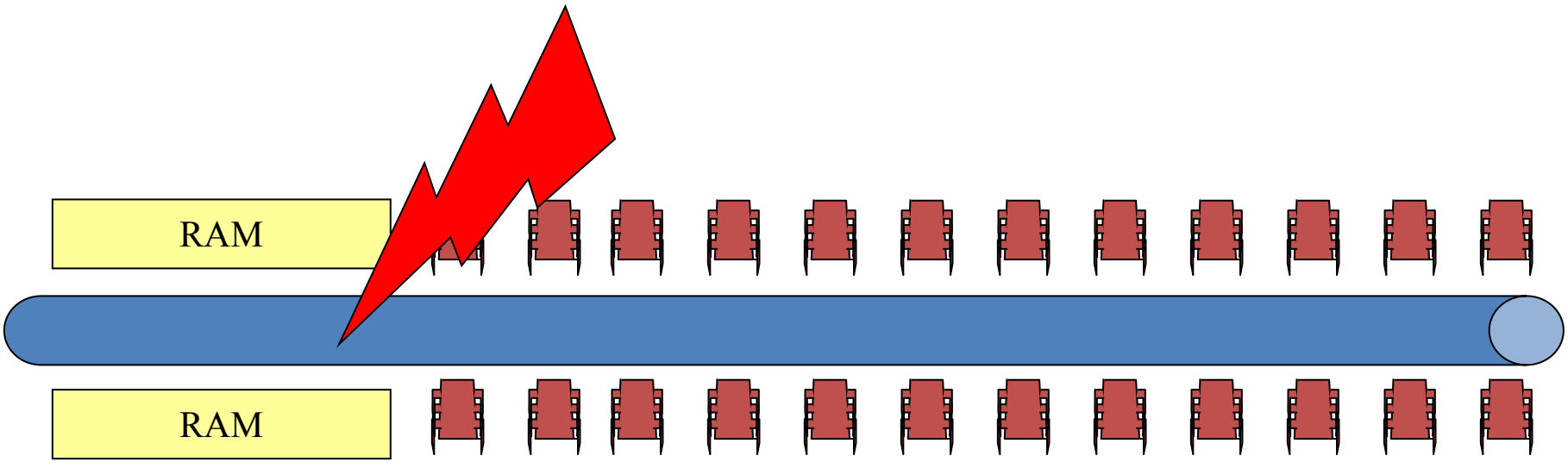
core that allocates the memory

Benchmark : memal on a 48 cores/4 sockets with 128GB (AMD)

We have cache effects

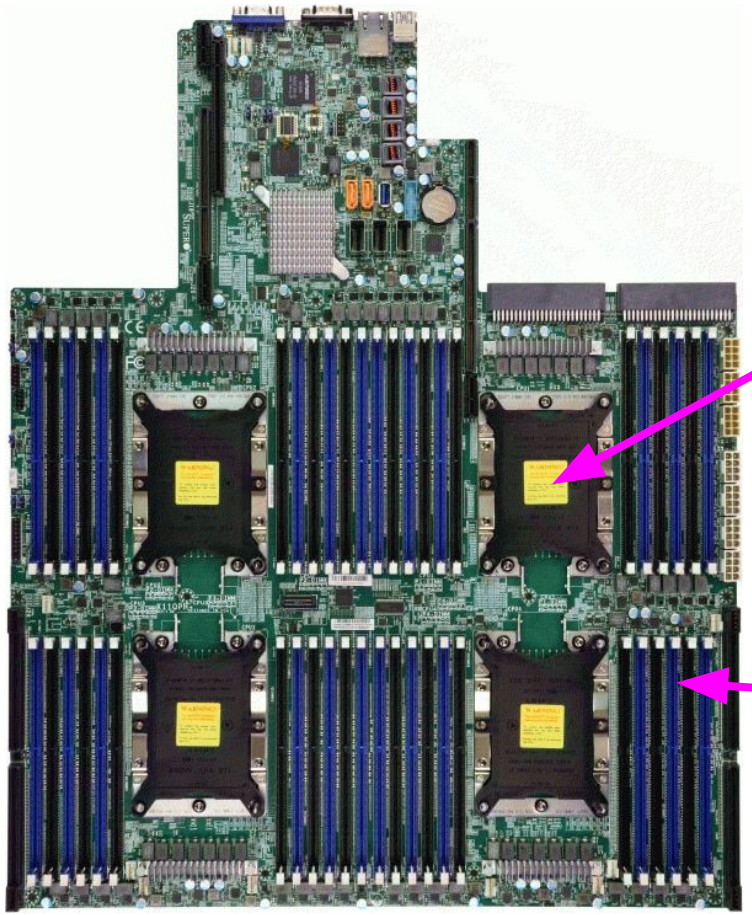


And, since a single bus does not scale...



...we have complex architectures

Total: 64 cores/128 hyperthreads, 256GB
(32x the power of my macbook for 15k€)

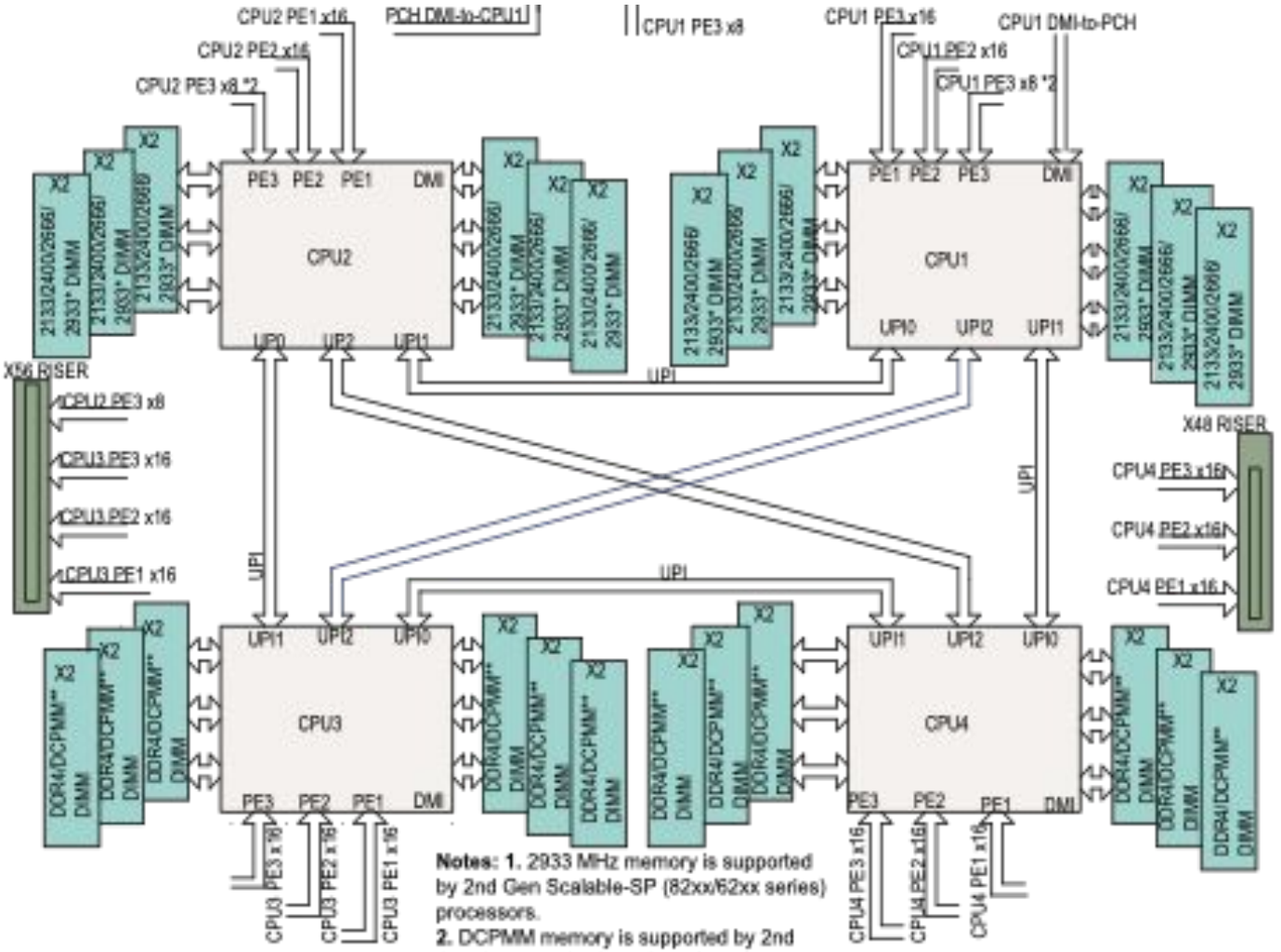


4 x Intel Xeon GOLD 6130
16 cores/32 hyperthreads

16 x 8GB

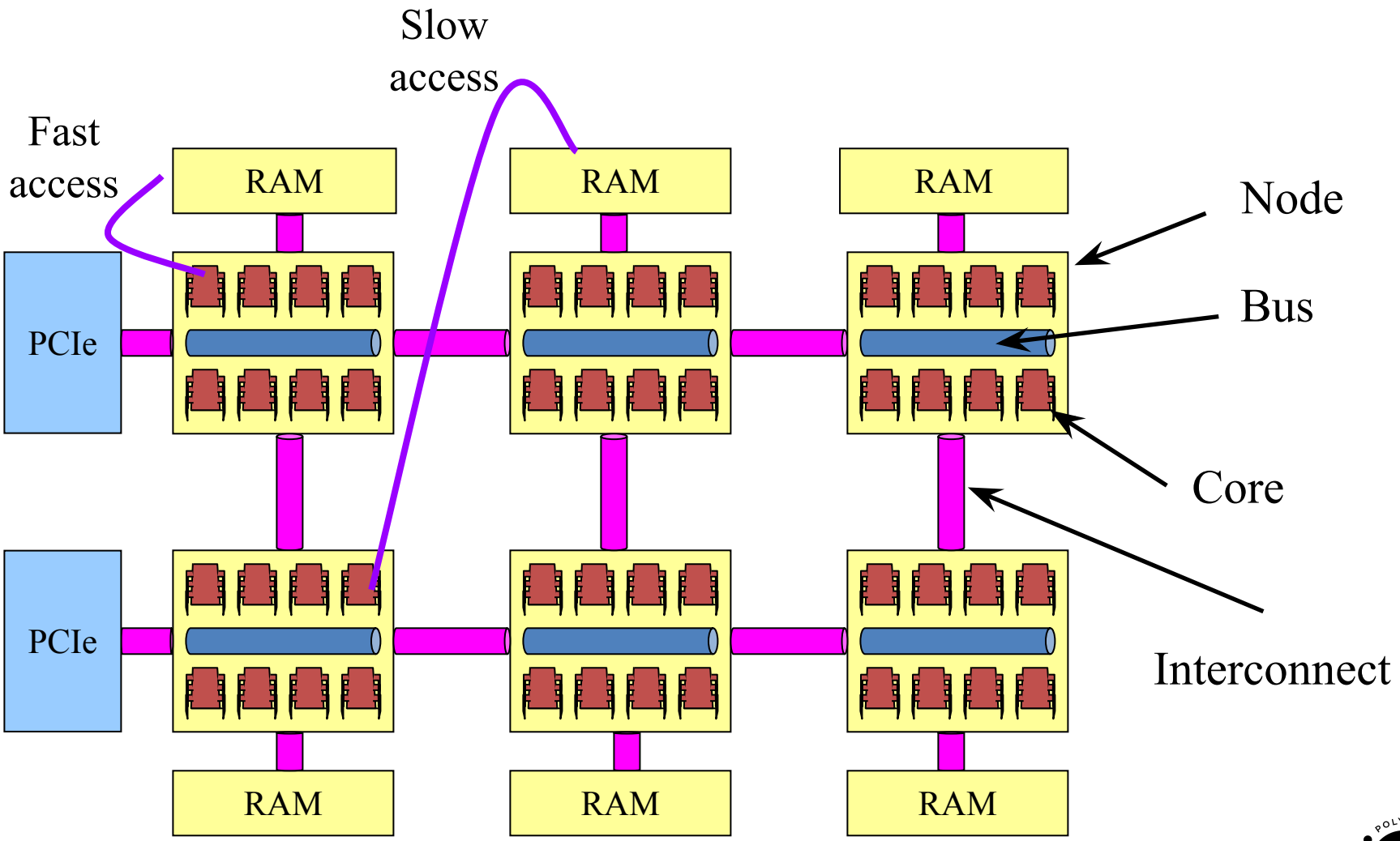
Supermicro X11QPH+

...we have complex architectures



Supermicro X11QPH+

and non uniform memory accesses

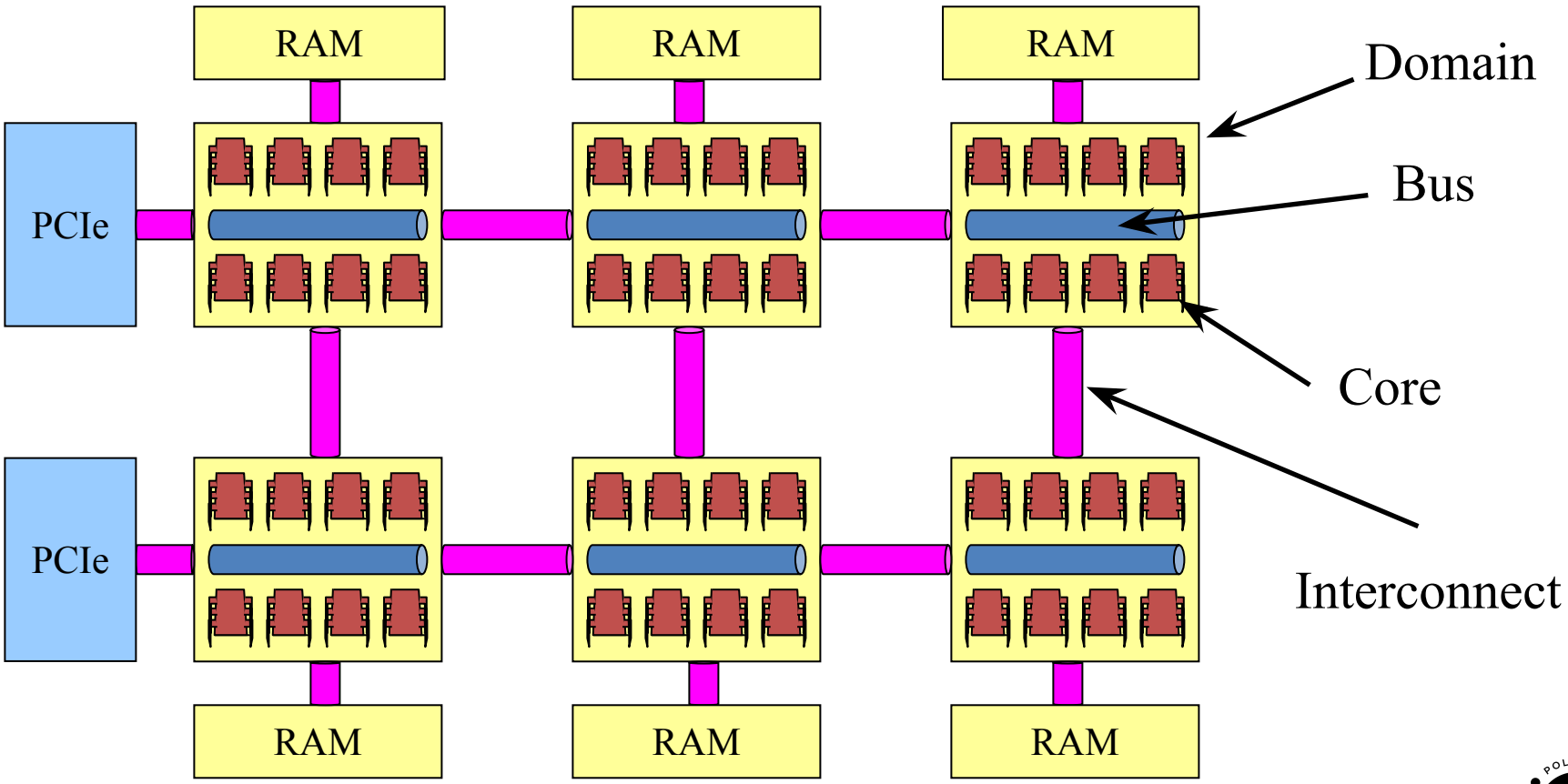


and non uniform memory accesses

On our 48-core AMD with 8 nodes (6 cores per node)

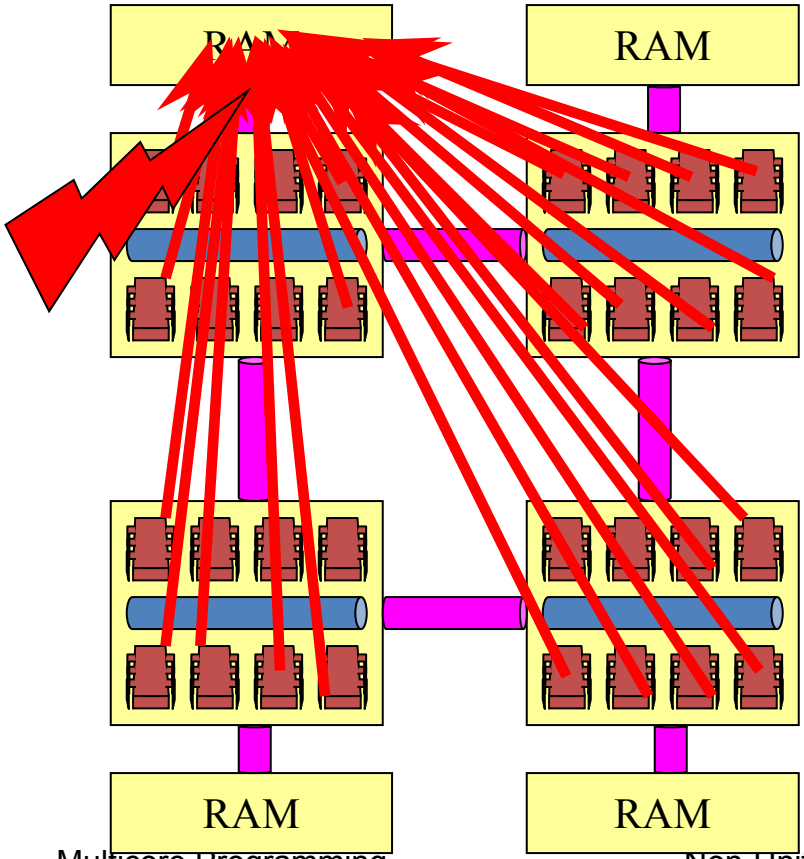
- Local memory access : 155 cycles
- One hop = 275 cycles
- Two hops = 380 cycles

x2,5



Memory access latency can collapse

When all the cores access the same node
(but different cache lines)



870 cycles
(6 times a local access)

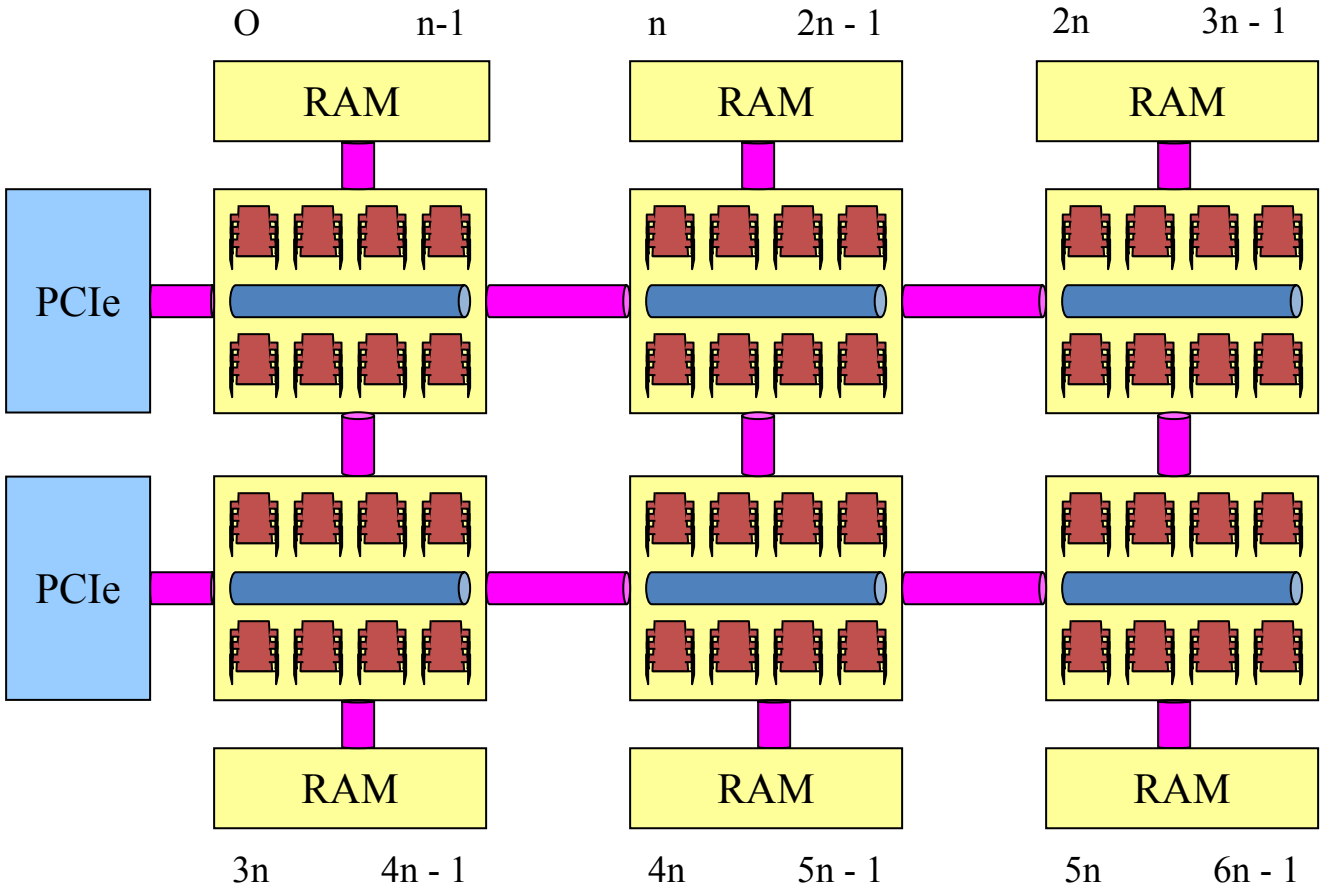
On a NUMA architecture, we need memory placement policies

- To avoid the overload of a single NUMA domain
- To avoid the overload of interconnect links
- To enforce memory access locality

HowTo: NUMA placement policy

Step 1: choose the physical address of a data

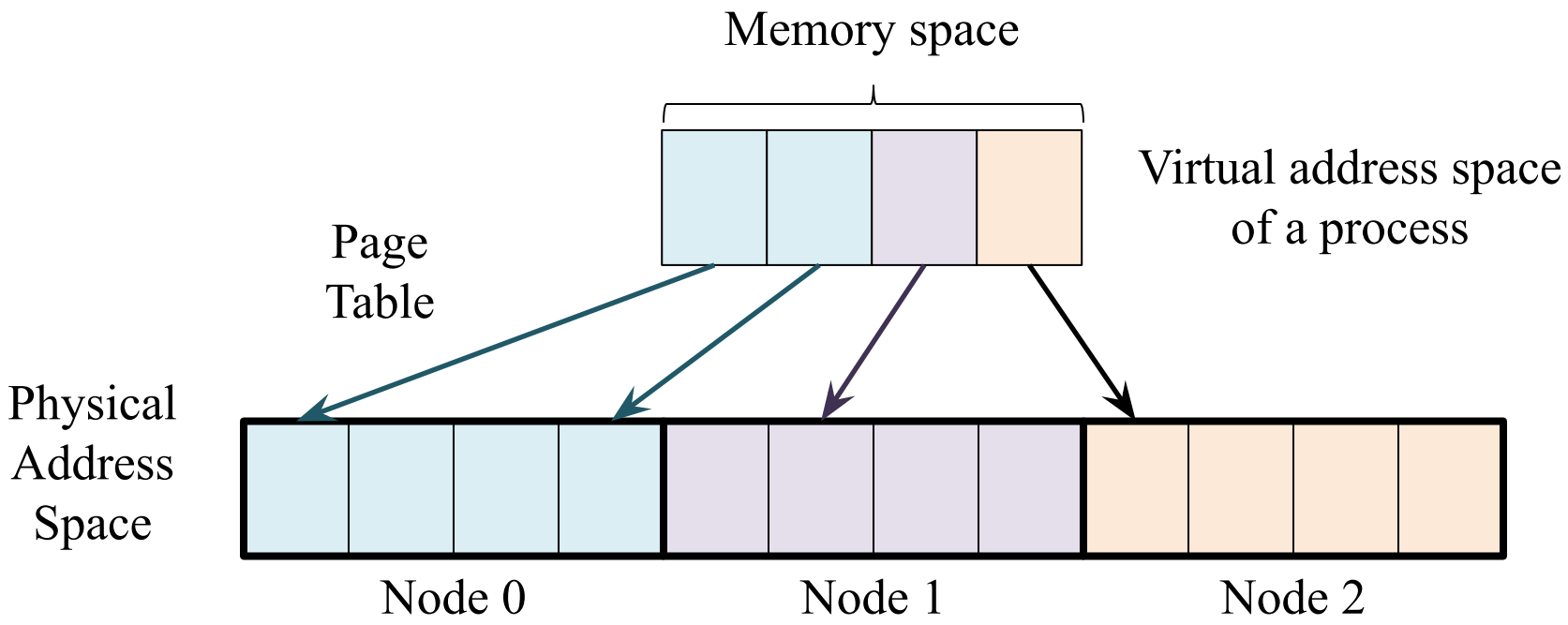
because the physical address space is partitioned among the domains



HowTo: NUMA placement policy

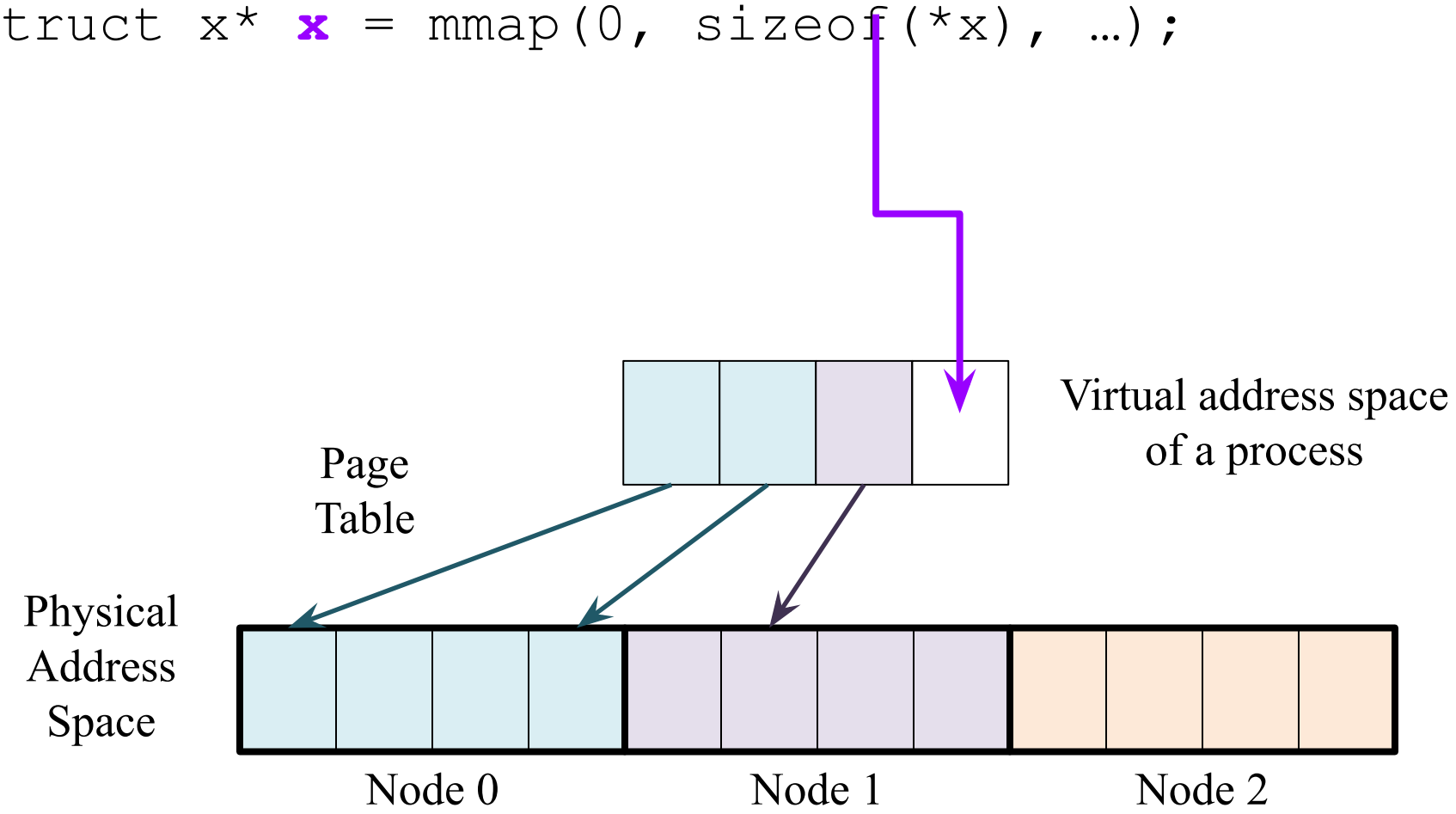
Step 2: leverage the page table

Maps a virtual address to a specific node by
mapping the virtual address to a page that belongs to the node



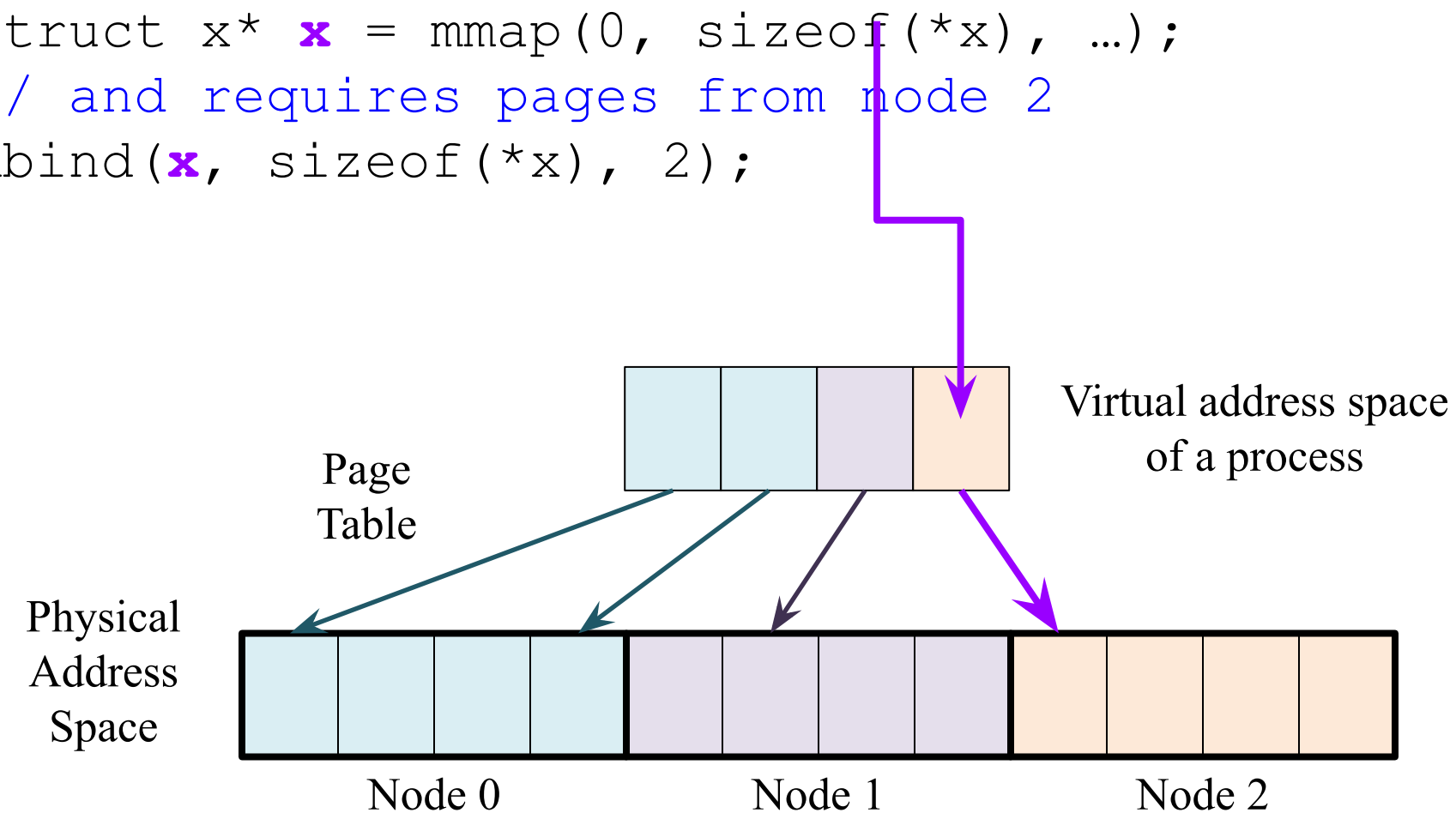
HowTo: NUMA placement policy

```
// reserve a virtual address space
struct x* x = mmap(0, sizeof(*x), …);
```



HowTo: NUMA placement policy

```
// reserve a virtual address space
struct x* x = mmap(0, sizeof(*x), …);
// and requires pages from node 2
mbind(x, sizeof(*x), 2);
```



Main questions

- Does NUMA effect matters in practice?
- If yes, can we mitigate this effect?

In theory, NUMA matters

- Abstract cache-unfriendly application
  - 50% of the instructions access memory
  - 30% of the accesses in L1 cache
  - 30% of the accesses in L2 cache
  - 30% of the accesses in L3 cache

- Comparison between best and worst NUMA placements
  - Best: all accesses to local node ⇒ ~ 32 cycles/insn
  - Worst: all accesses to an overloaded node ⇒ ~ 156 cycles/insn

  ⇒ overhead of 385% in the worst case

In theory, NUMA matters

- Abstract cache-friendly application
  - 50% of the instructions access memory
  - 70% of the accesses in L1 cache
  - 70% of the accesses in L2 cache
  - 70% of the accesses in L3 cache

- Comparison between best and worst NUMA placements
  - Best: all accesses to local node ⇒ ~ 7 cycles/insn
  - Worst: all accesses to an overloaded node ⇒ ~ 17 cycles/insn

  ⇒ overhead of 137% in the worst case

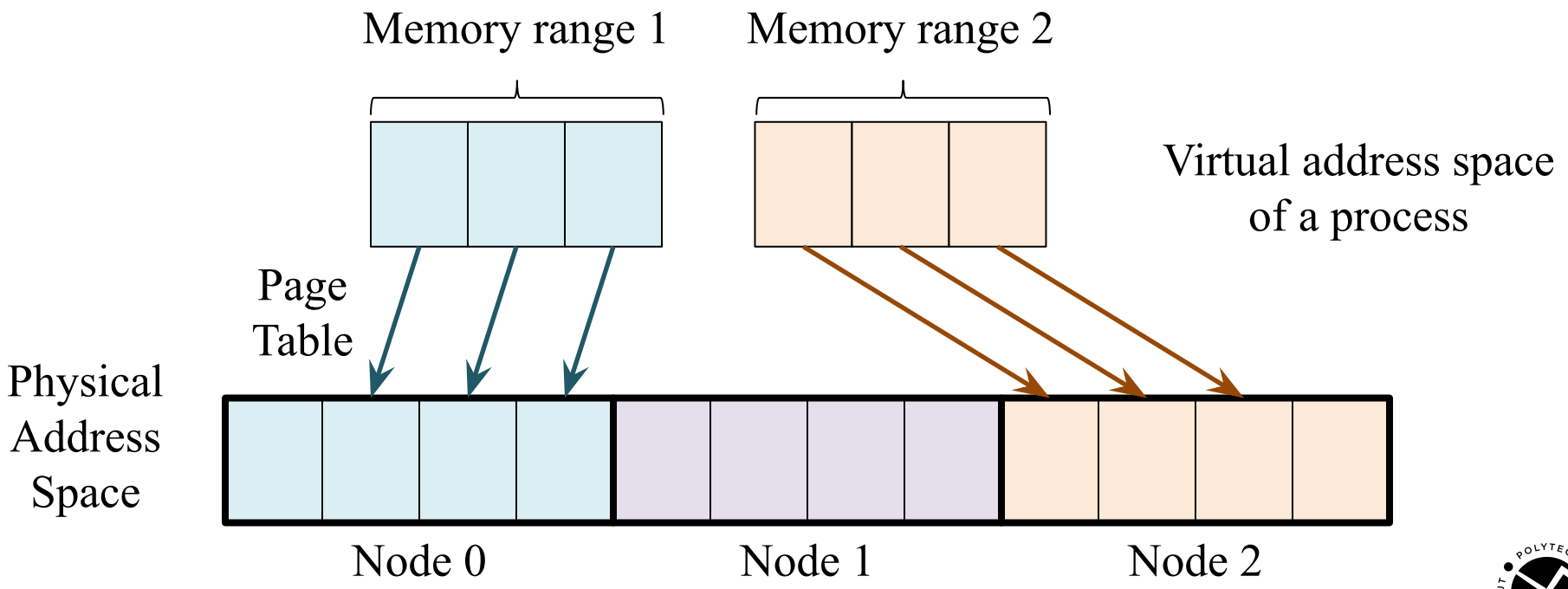
First study

- Goal:
  - Understand how Linux manages NUMA
  - Understand how applications react to NUMA

- How:
  - Study a panel of 29 applications from 5 benchmarks
    (NPB, Parsec, Mosbench, X-stream, YCSB)
  - Evaluate various NUMA management policies

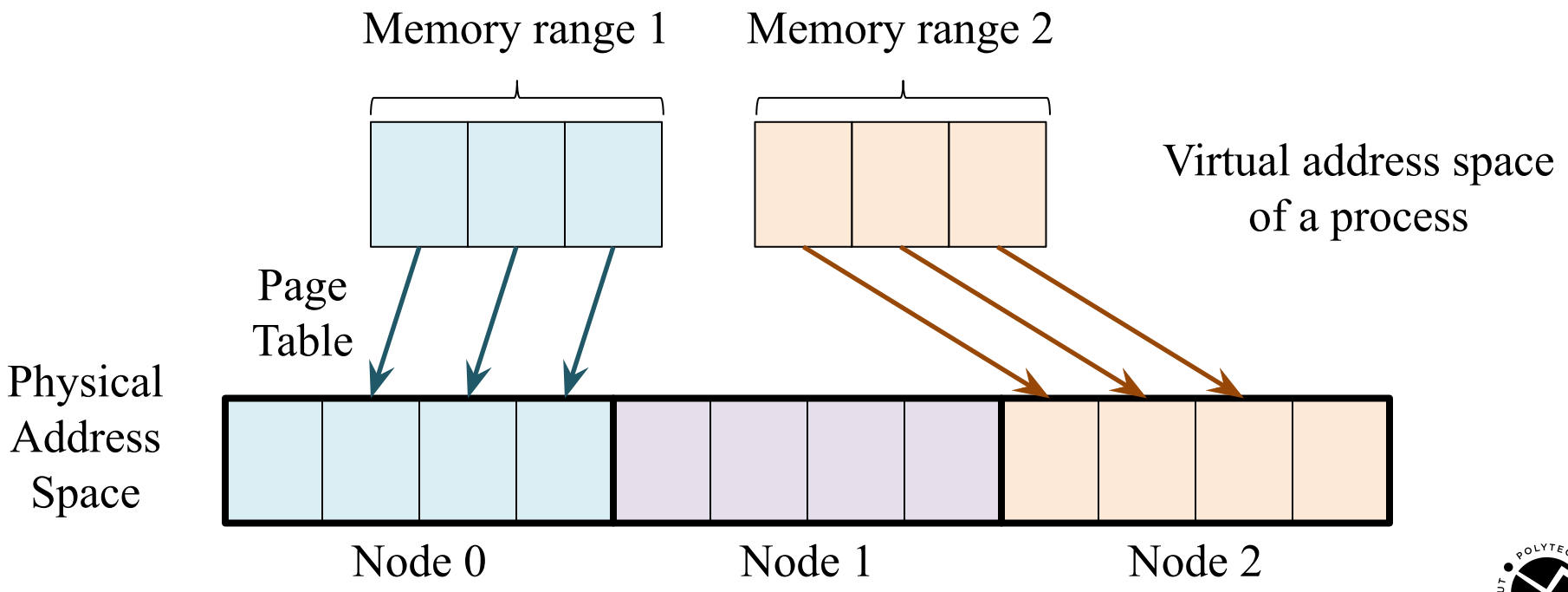
The hand-tuned policy

- Manually place the memory address ranges on the nodes



The hand-tuned policy

- Manually place the memory address ranges on the nodes
  - + Tune the memory placement for an application
  - − A lot of engineering effort for only a single application/hardware



The hand-tuned policy on Linux

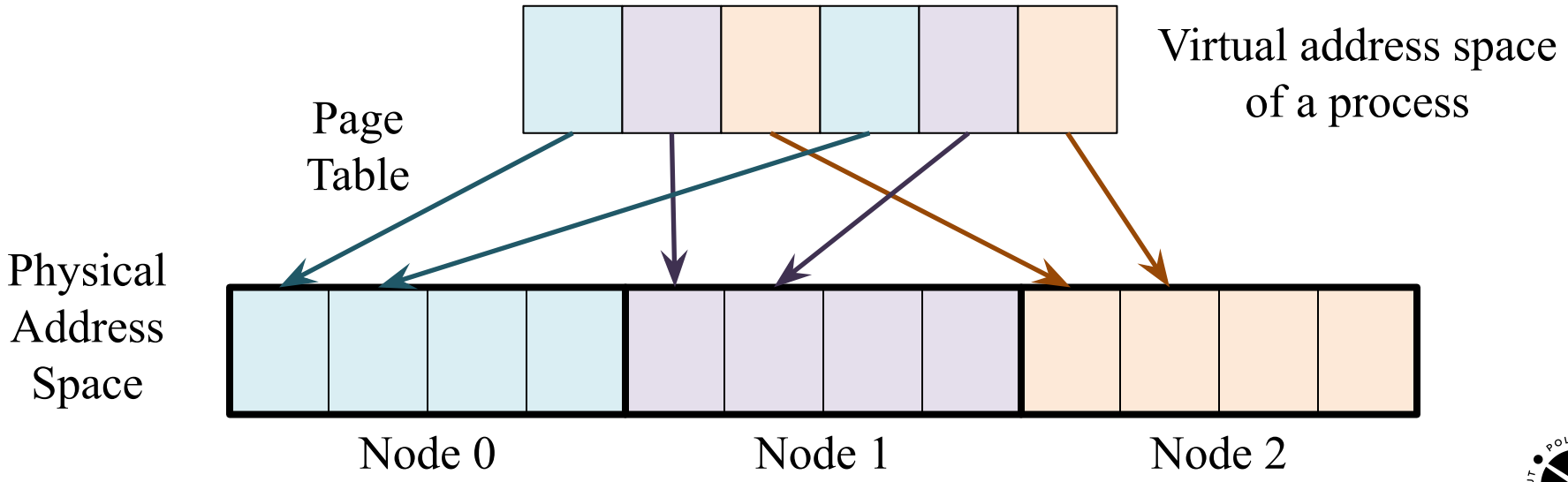
- Hand-tuned thread placement
  - setaffinity(set of cores): for all the threads of a process
  - pthread_setaffinity(set of cores): for a single thread

- Hand-tuned memory placement
  - mbind(virtual address range, set of nodes)

  (granularity of a 4k-page)

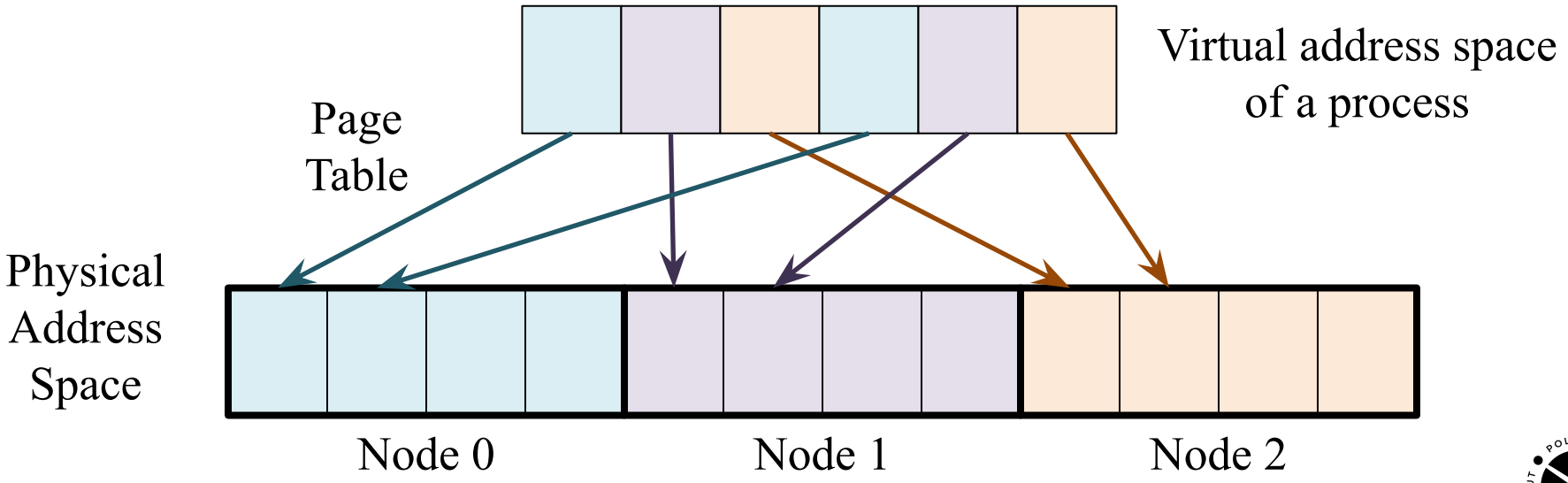
The interleaved policy

- Round-robin from all the nodes



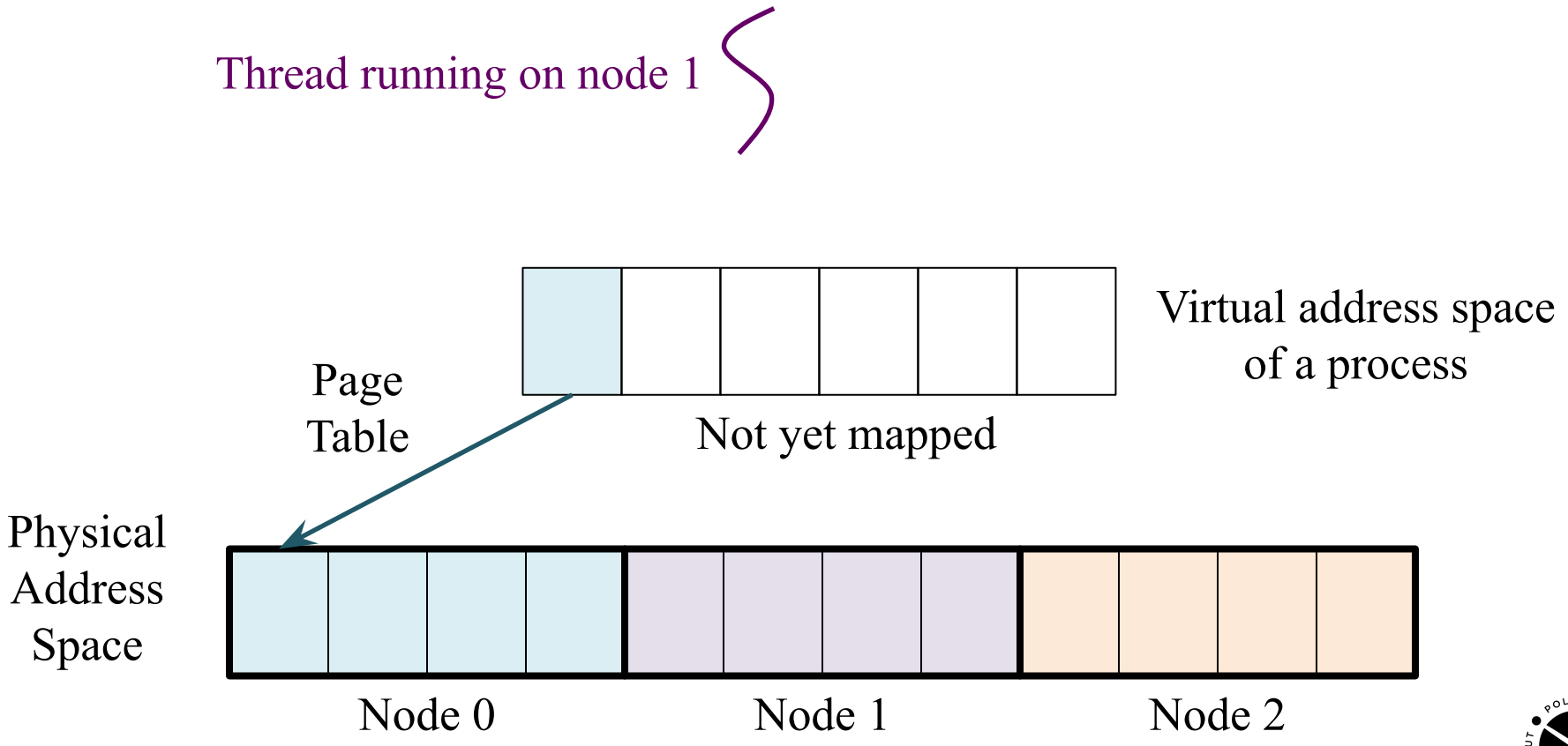
The interleaved policy

- Round-robin from all the nodes
  - \+ Balance the load on all the nodes ⇒ no overloaded node
  - − Many remote accesses ⇒ interconnect can saturate



The first-touch policy

- From the node that triggers the first access
  - Relies on the lazy mapping used in Linux



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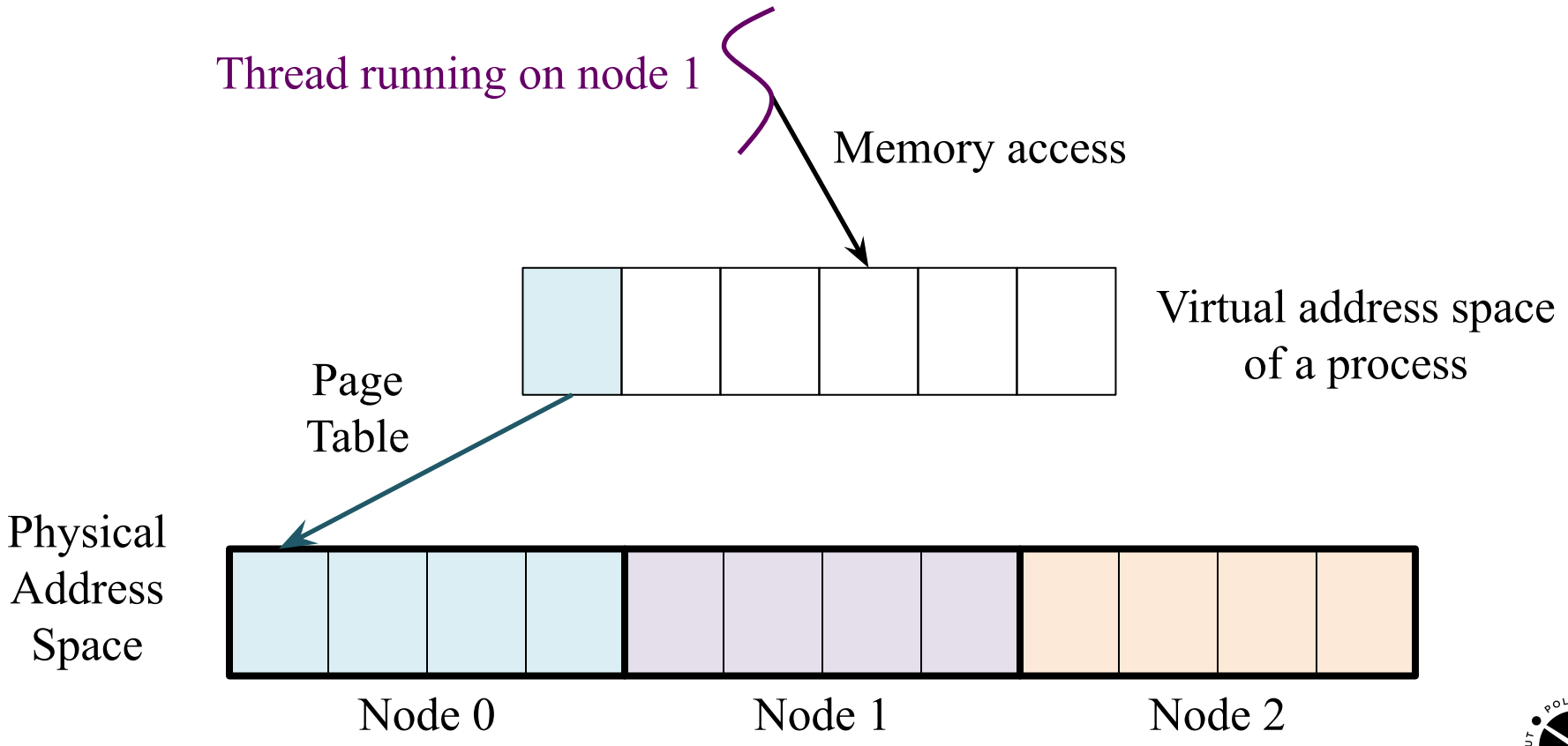

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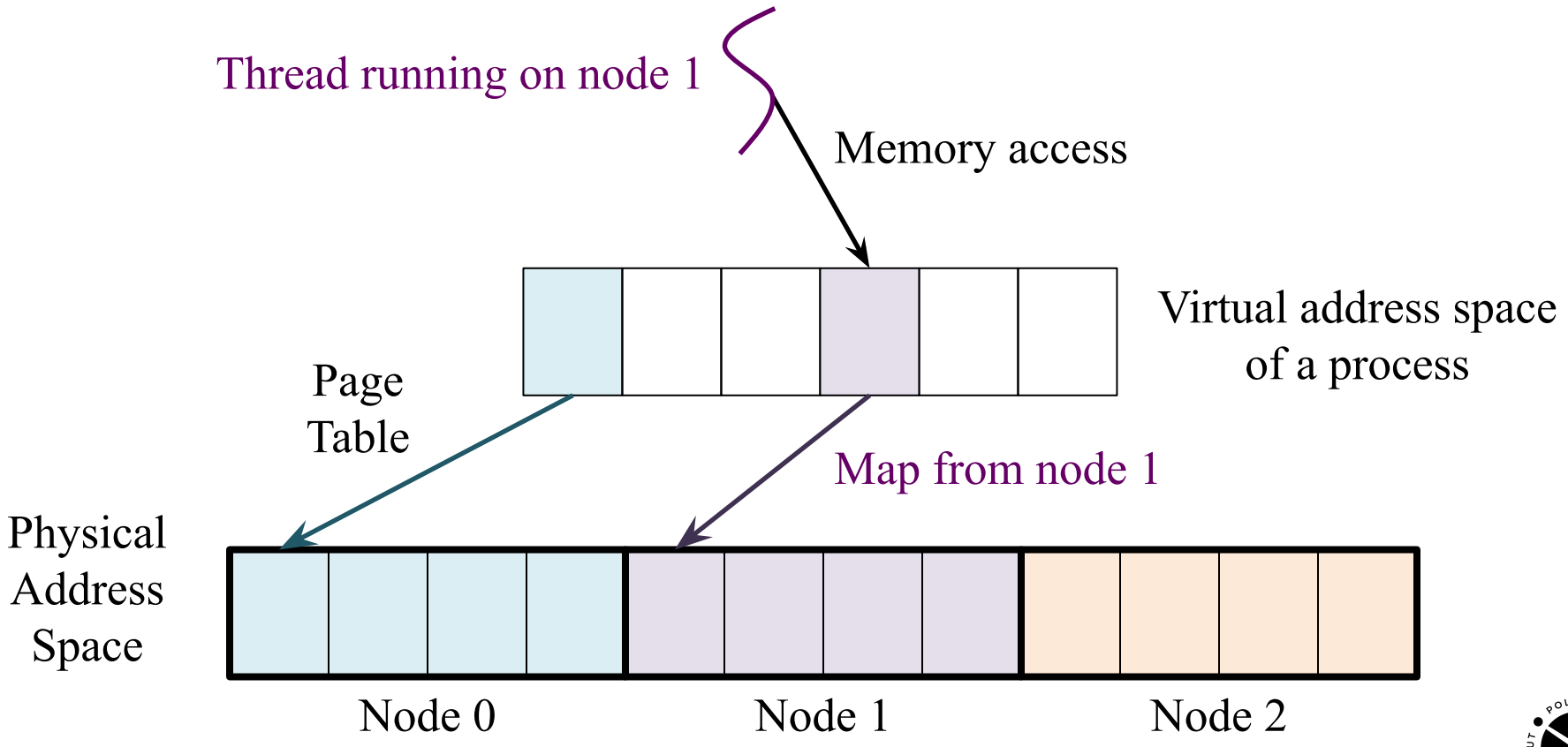
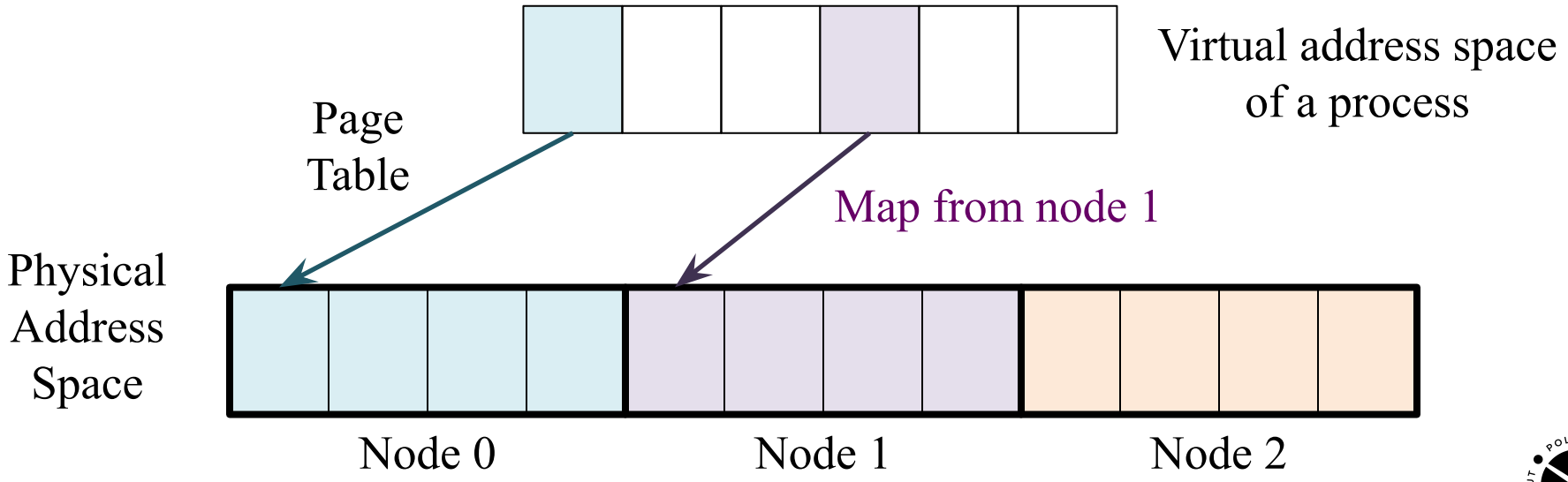


The first-touch policy

- From the node that triggers the first access
  - + Perfect locality and no saturation if a thread accesses its memory
  - − Overloaded nodes if some threads allocate for the others



The Carrefour policy

- Proposed by Dashti et al. (ASPLOS'15)
  - Rebalance the load on all the nodes
  - Prevents the contention of the interconnect

- Dynamically migrate a page
  - From contended to uncontended nodes in case of contented node
  - On the node that uses the page in case of contended interconnect

The Carrefour policy

- Proposed by Dashti et al. (ASPLOS'15)
  - Rebalance the load on all the nodes
  - Prevents the contention of the interconnect

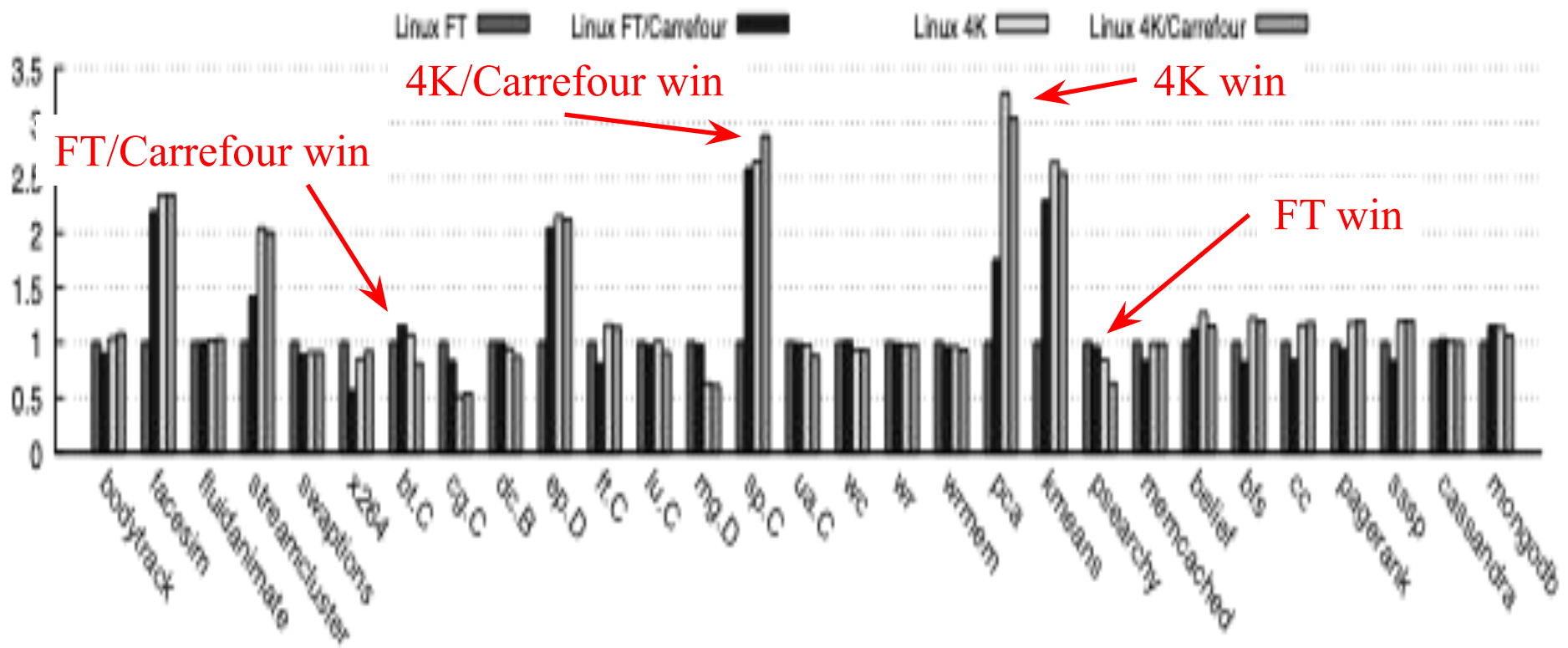
- Dynamically migrate a page
  - From contended to uncontended nodes in case of contented node
  - On the node that uses the page in case of contended interconnect

+ Improves locality and avoid contention in many cases
− Can lead to inefficient placements for applications with different access patterns during the run

Evaluated policies

- Four combinations
  - First-touch (Linux FT)
  - First-touch with Carrefour (Linux FT/Carrefour)
  - Interleaved (Linux 4K)
  - Interleaved with Carrefour (Linux 4K/Carrefour)
- Only considers pages of 4KiB

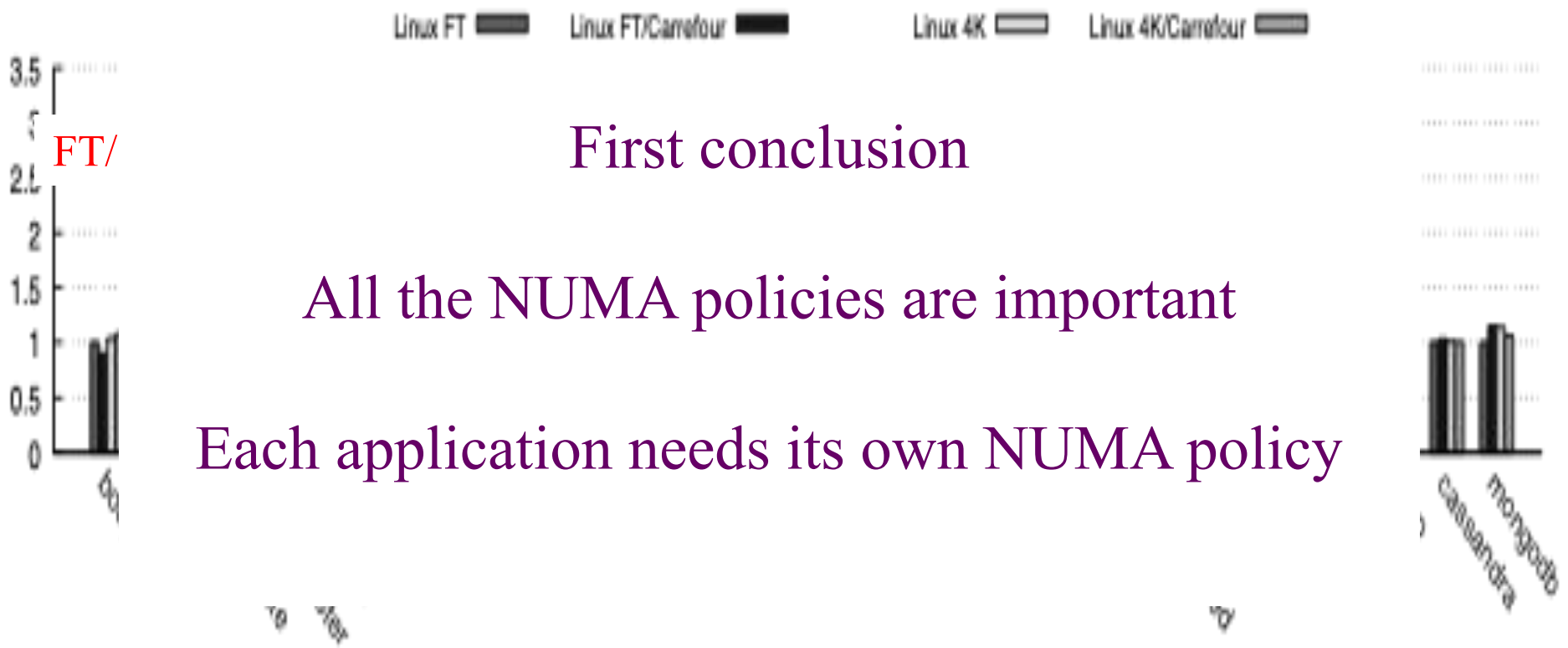
Evaluation of the NUMA policies



Speedup relative to Linux FT

[presented at Eurosys'17]

Evaluation of the NUMA policies



First conclusion

All the NUMA policies are important

Each application needs its own NUMA policy

Speedup relative to Linux FT

Second study

- Predict which NUMA policy is the best for an application

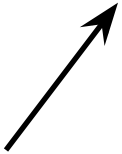
- Goal:
  - Select the most efficient NUMA policy
  - Understand the memory access behavior

Predict the NUMA policy

- Measure the memory access imbalance with first-touch
  Relative standard deviation around the average #accesses per node

Imbalance	0%	40%	62%	83%	107%	138%	185%	283%
# of accessed nodes	8	7	6	5	4	3	2	1

Perfect balance



All the accesses go to a single node

Predict the NUMA policy

- Measure the memory access imbalance with first-touch
  Relative standard deviation around the average #accesses per node

Imbalance	0%	40%	62%	83%	107%	138%	185%	283%
# of accessed nodes	8	7	6	5	4	3	2	1

Low imbalance

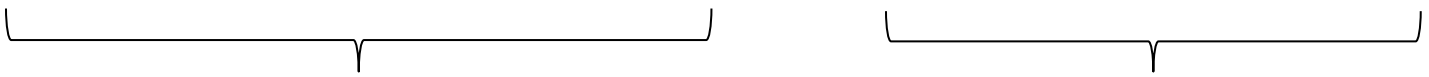
Moderate imbalance

High imbalance

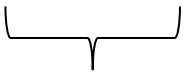
Predict the NUMA policy

Low imbalance with first-touch
Often because we already have a good locality

Imbalance	0%	40%	62%	83%	107%	138%	185%	283%
# of accessed nodes	8	7	6	5	4	3	2	1



Low imbalance



High imbalance

Moderate imbalance

Predict the NUMA policy

Low imbalance with first-touch

Often because we already have a good locality

=> keep first-touch

(1% slower than best in average)

Imbalance	0%	40%	62%	83%	107%	138%	185%	283%
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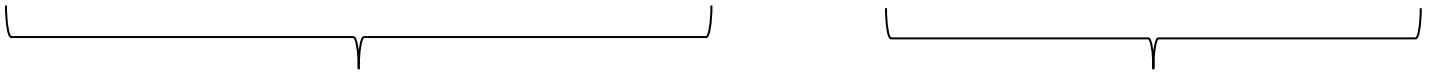
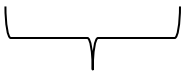


First-touch



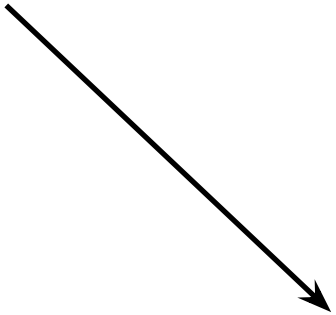
High imbalance

Moderate imbalance

Predict the NUMA policy

Moderate imbalance with first-touch

First-touch roughly balances the load but locality is not perfect



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First-touch

High imbalance

Moderate imbalance

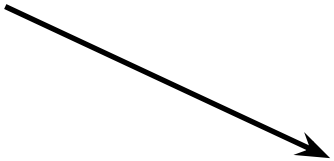
Predict the NUMA policy

Moderate imbalance with first-touch

First-touch roughly balances the load but locality is not perfect

⇒ use First-touch/Carrefour

(2% slower than best in average)



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# of accessed nodes	8	7	6	5	4	3	2	1

First-touch

First-touch/Carrefour

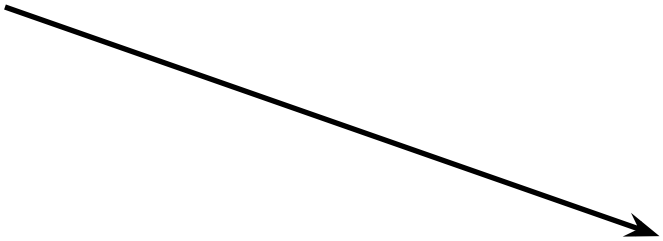
High imbalance

Predict the NUMA policy

High imbalance with first-touch

Interleaved balances the load and Carrefour improves locality

⇒ use Interleaved/Carrefour



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First-touch

First-touch/Carrefour

Interleaved/Carrefour

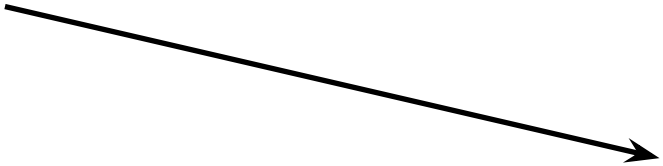
Predict the NUMA policy

High imbalance with first-touch

Interleaved balances the load and Carrefour improves locality

⇒ use Interleaved/Carrefour

(2% slower than best in average)



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First-touch

First-touch/Carrefour

Interleaved/Carrefour

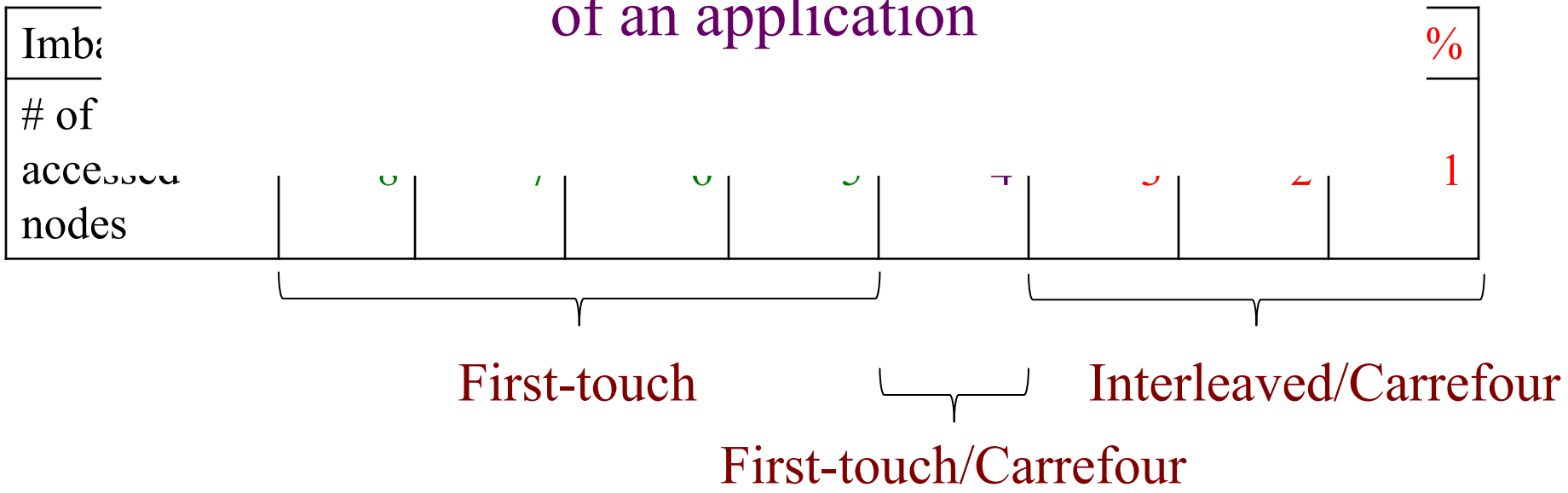
Predict the NUMA policy

High imbalance with first-touch

Interleaved balances the load and Carrefour improves locality

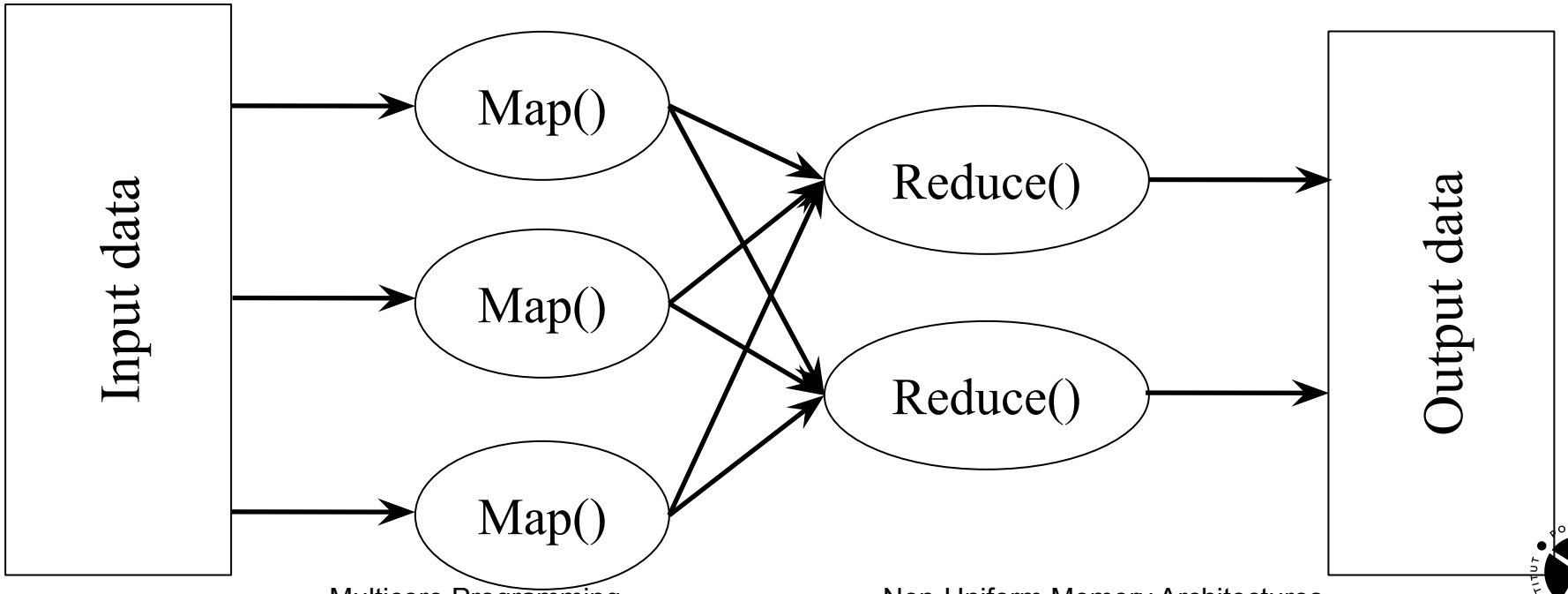
Second conclusion

We can reasonably predict the best NUMA policy of an application

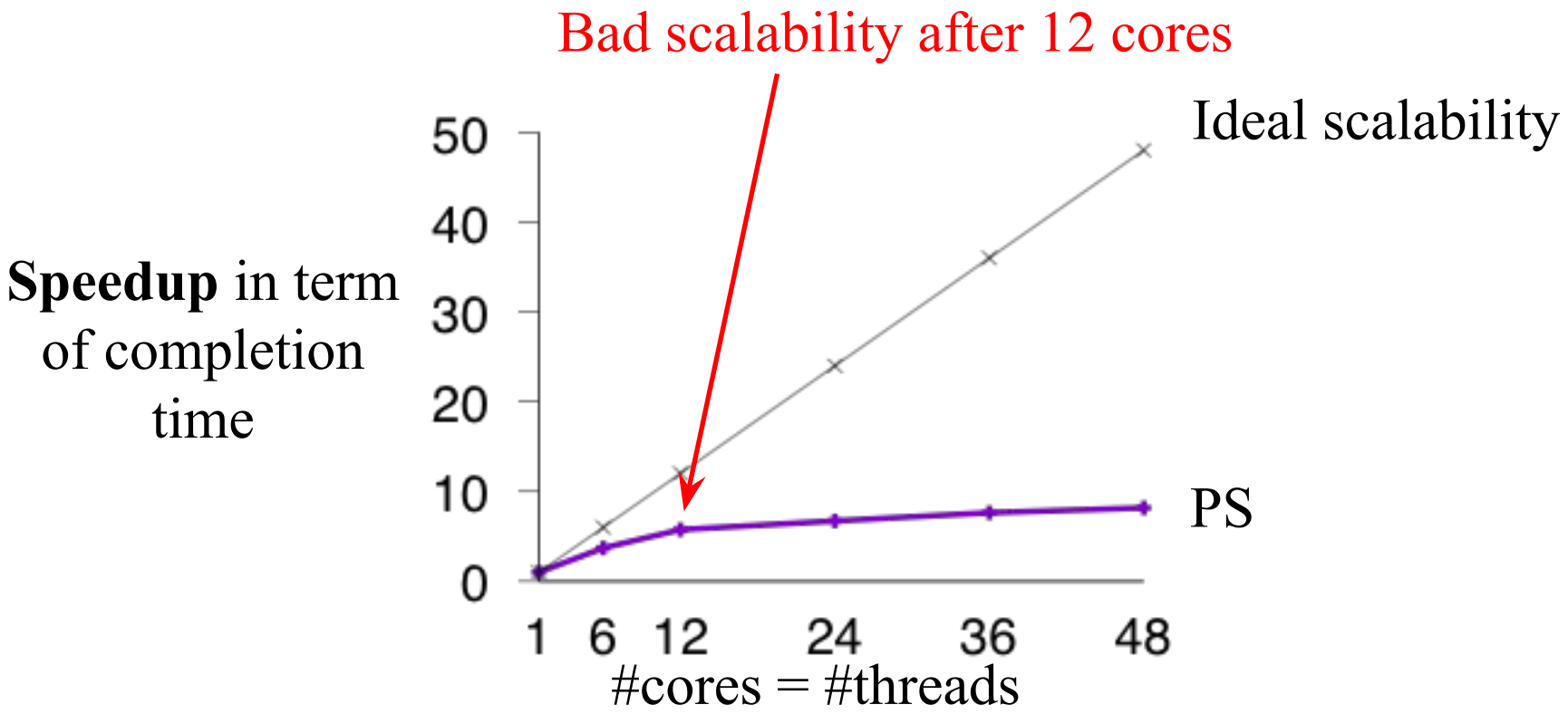


Third study

- How a data analytic application behaves?
  - Page rank query on the friendster dataset with Spark
  - Heap of 40GB, JVM with the Parallel Scavenge (PS) GC

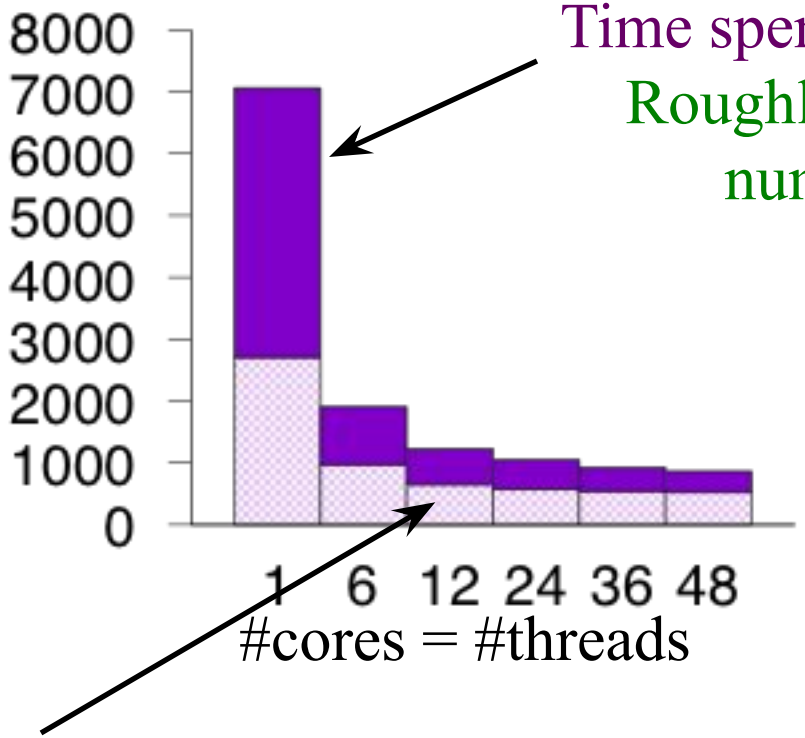


Application scalability of Spark



Performance of Spark (40GB of heap)

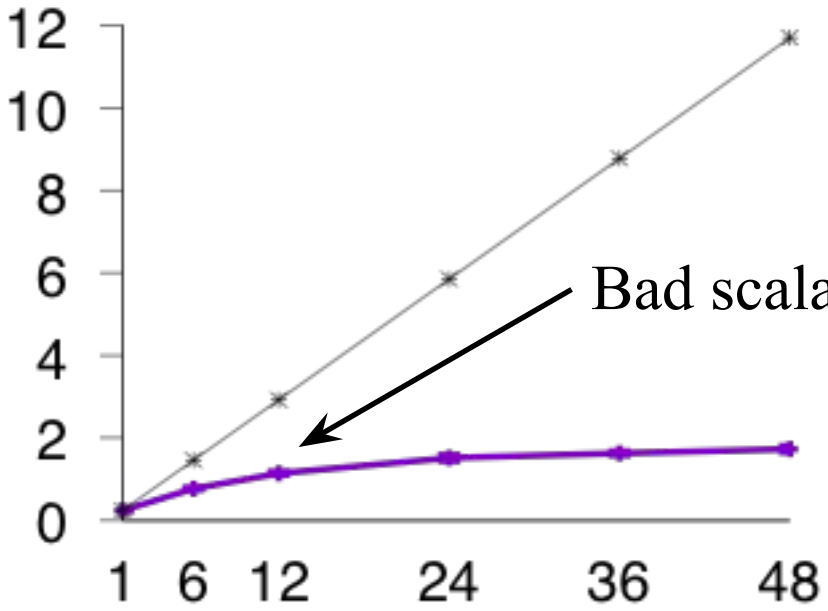
A bottleneck in the garbage collector



A bottleneck in the garbage collector

The garbage collector does not scale

GC throughput (GB collected per second)



#cores = #threads used by the GC

Performance of the GC in Spark (40GB of heap)

First optimizations: synchronizations

- Remove useless synchronizations in the garbage collector
  - Trades the genericity of the code for better performance
- Optimize the locks
  - Futex instead of hand tuned
- Optimized lock-free queue for the work stealing

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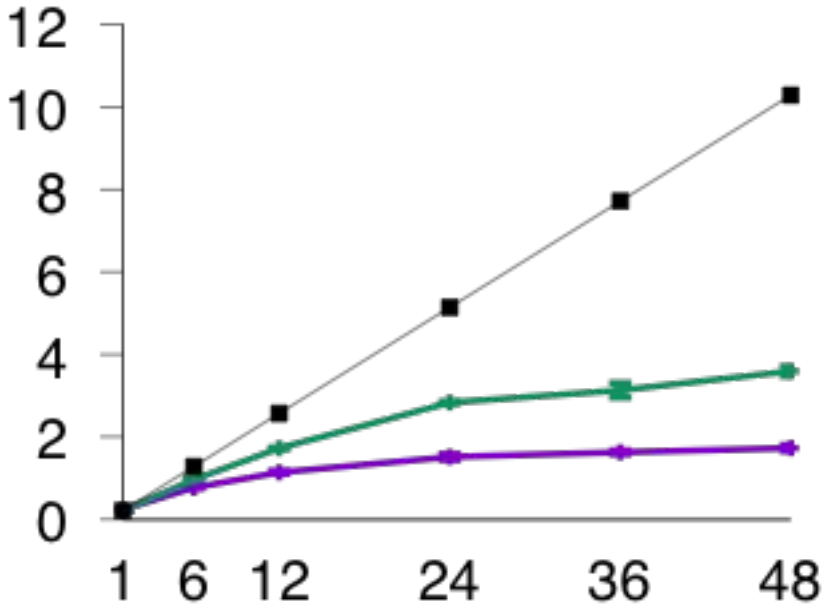
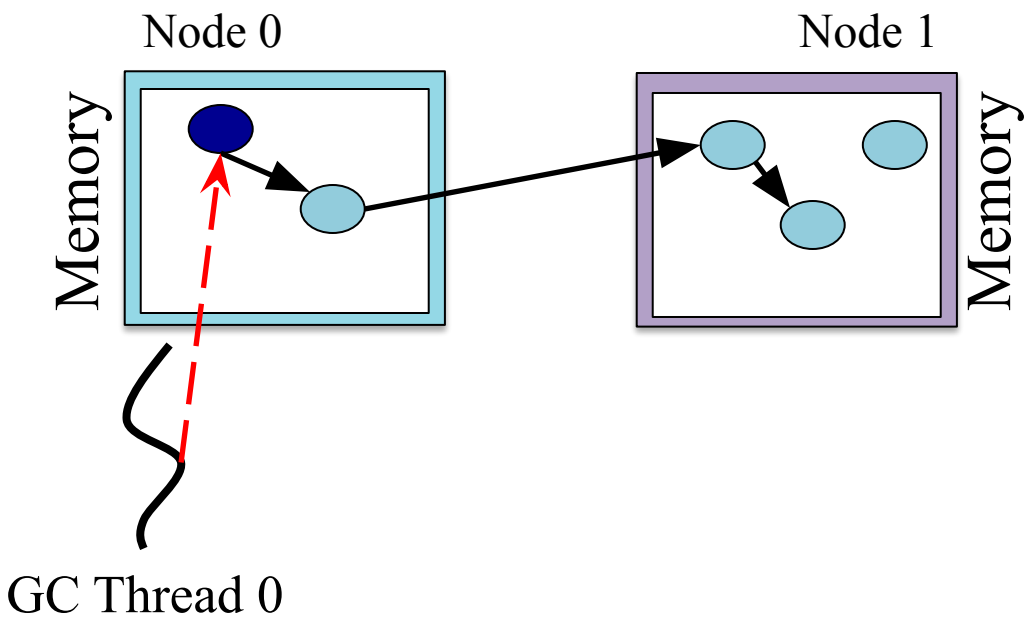


Better performance but does not solve the scalability issue

Second optimizations: NUMAGiC

- The problem: a GC thread accesses any node



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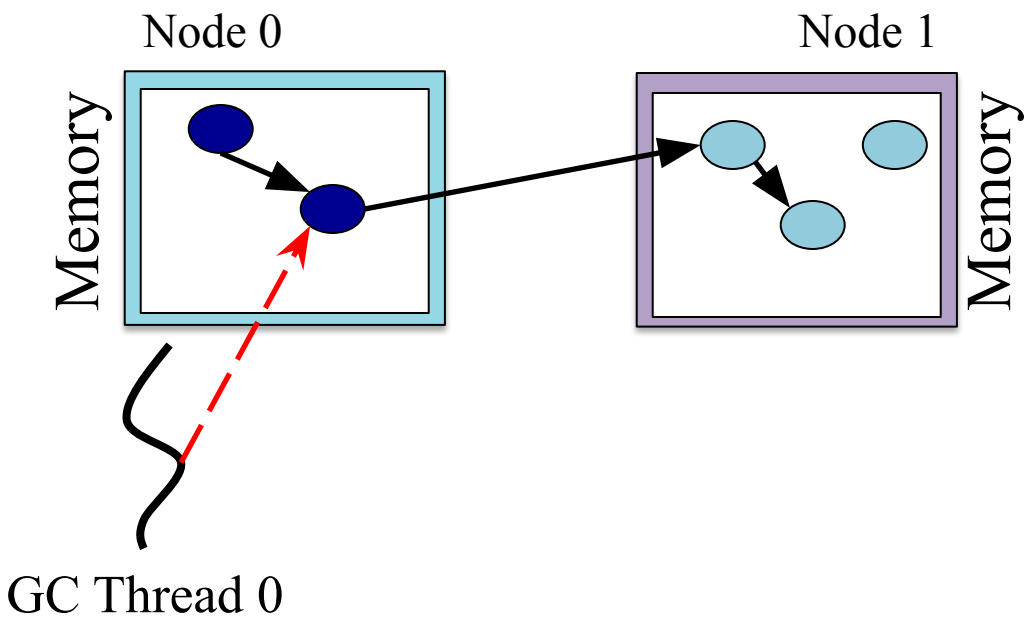

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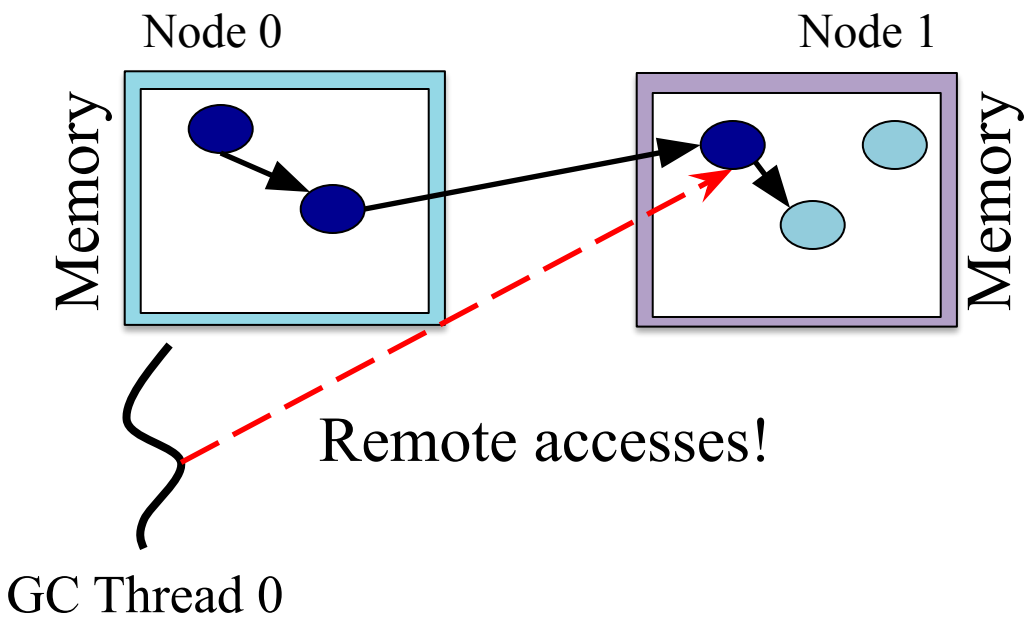

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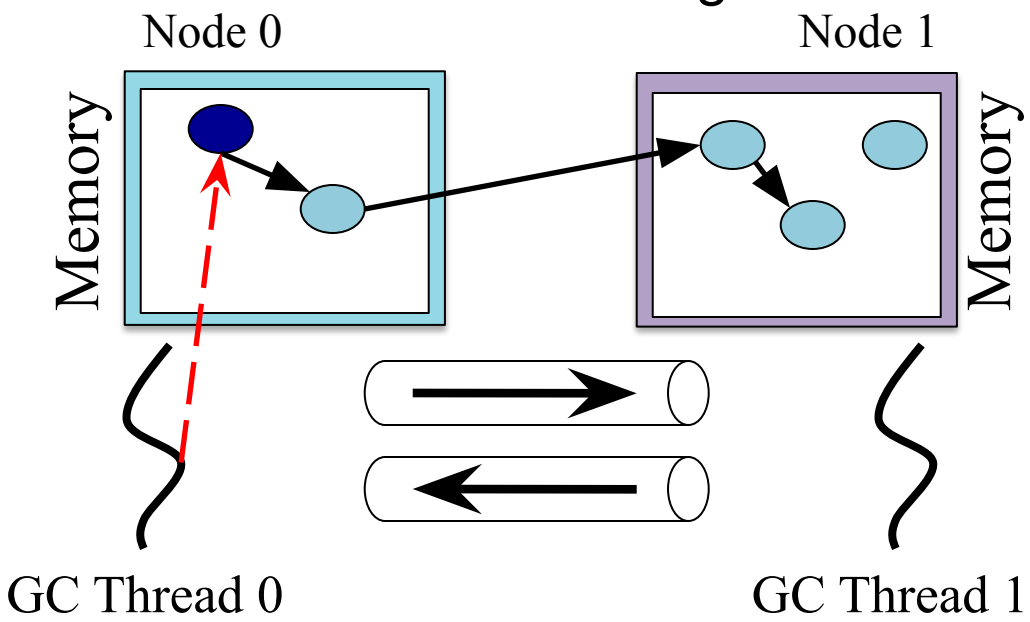

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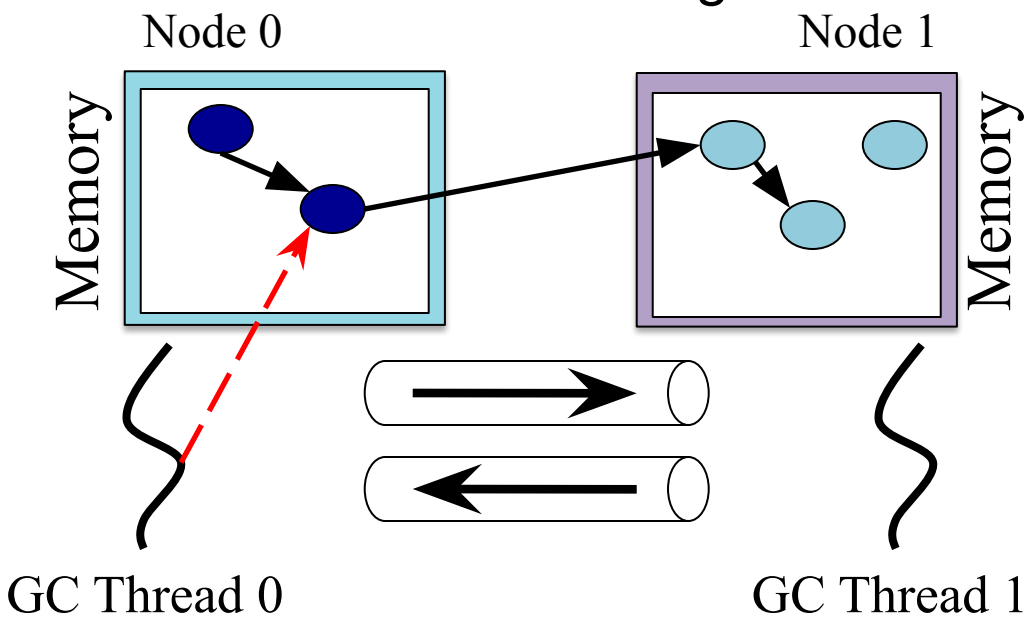

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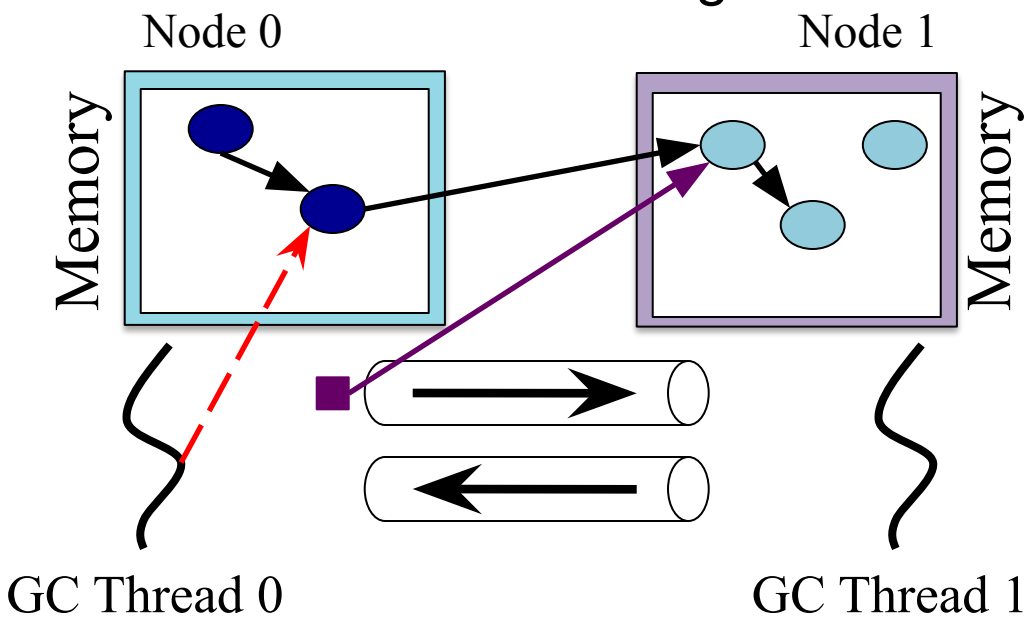

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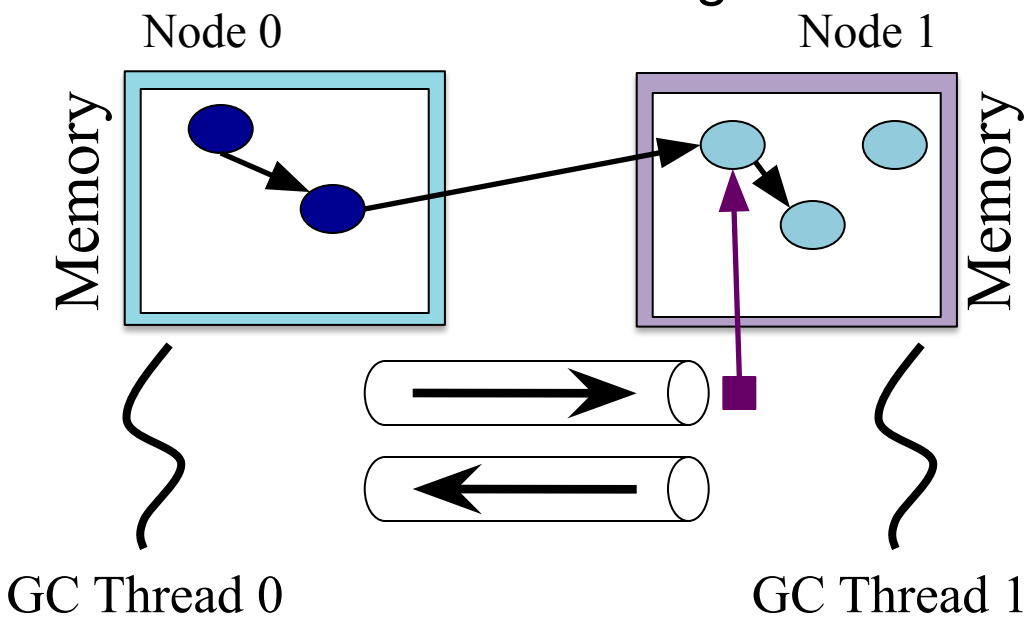

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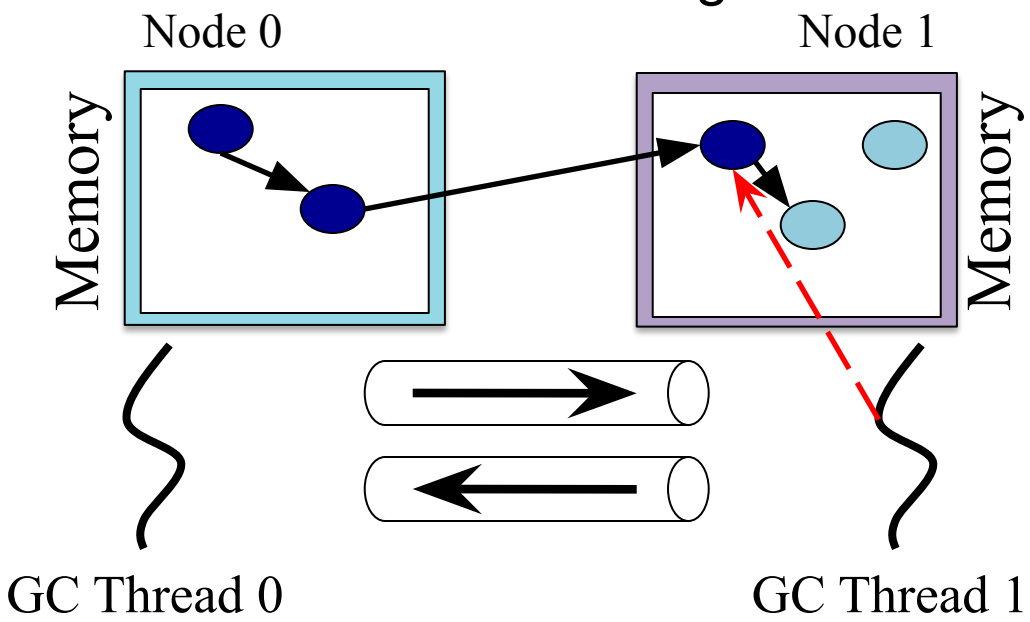

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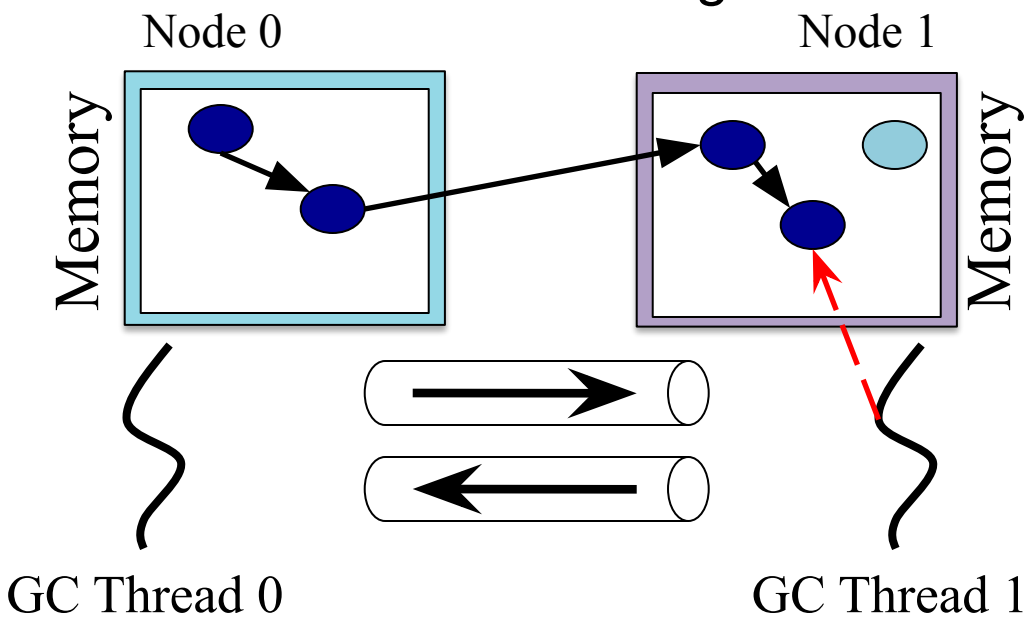
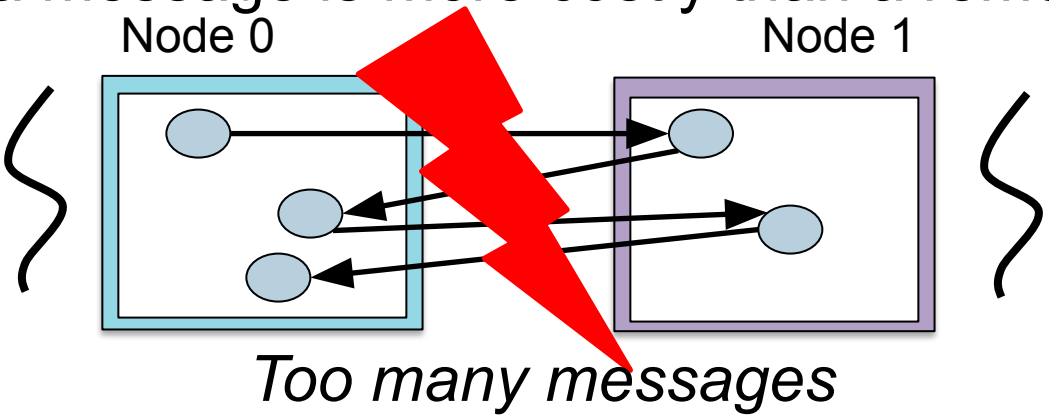


As is, messages degrades performance

- Problem: a message is more costly than a remote access



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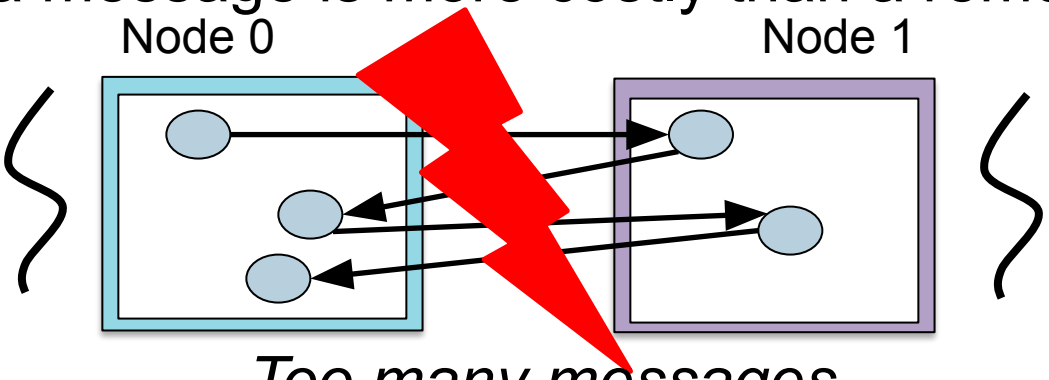

⇒ Inter-node references must be minimized

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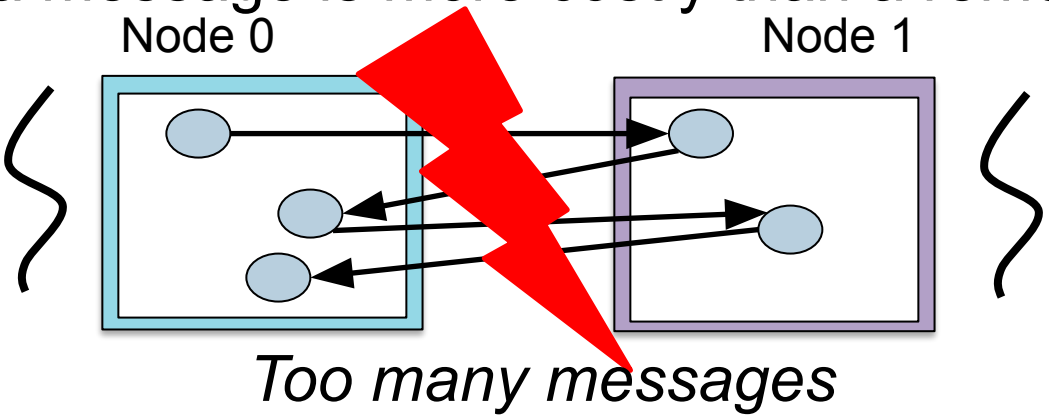
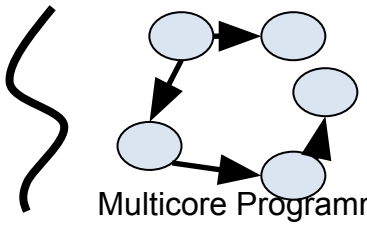


⇒ Inter-node references must be minimized

- Observation: a thread mostly connects objects it has allocated



Only 1% of references
between objects allocated
by different threads in Spark

As is, messages degrades performance

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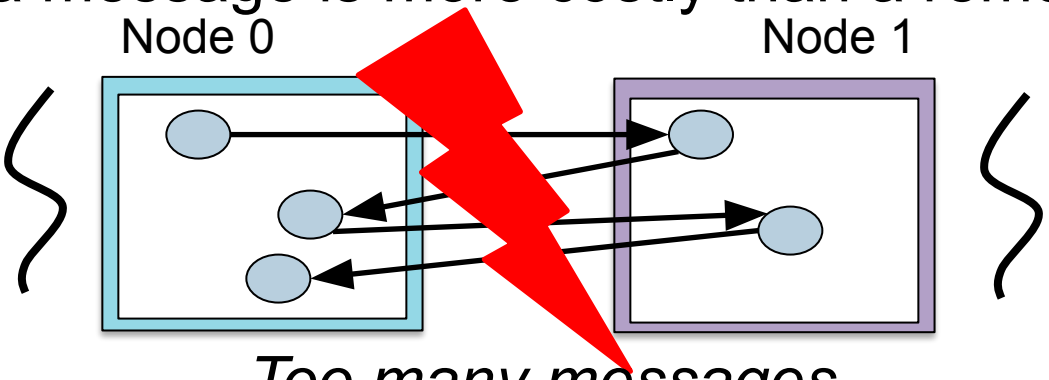
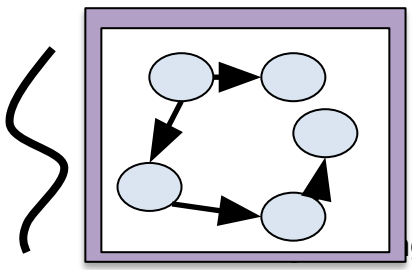
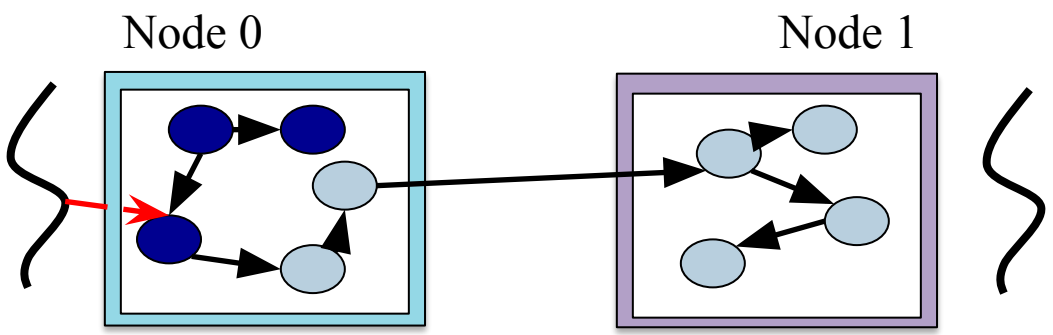


⇒ Inter-node references must be minimized

- Observation: a thread mostly connects objects it has allocated
- Heuristics: allocate and let the objects on their allocation nodes



But few inter-node references degrade the parallelism! ☹



Node 1 idles while node 0 collects its memory

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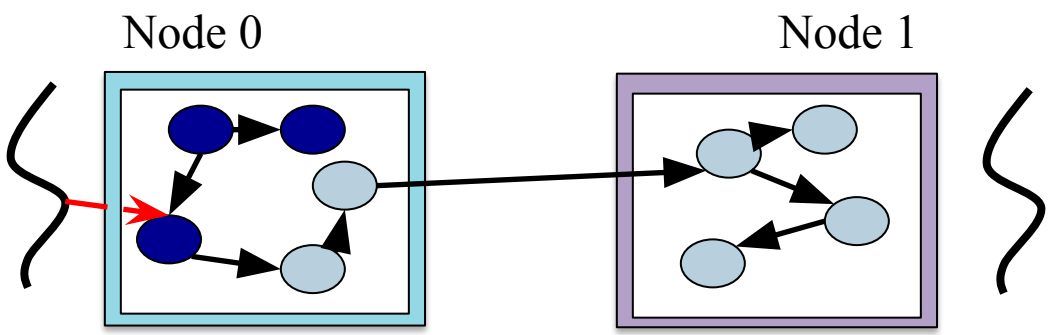
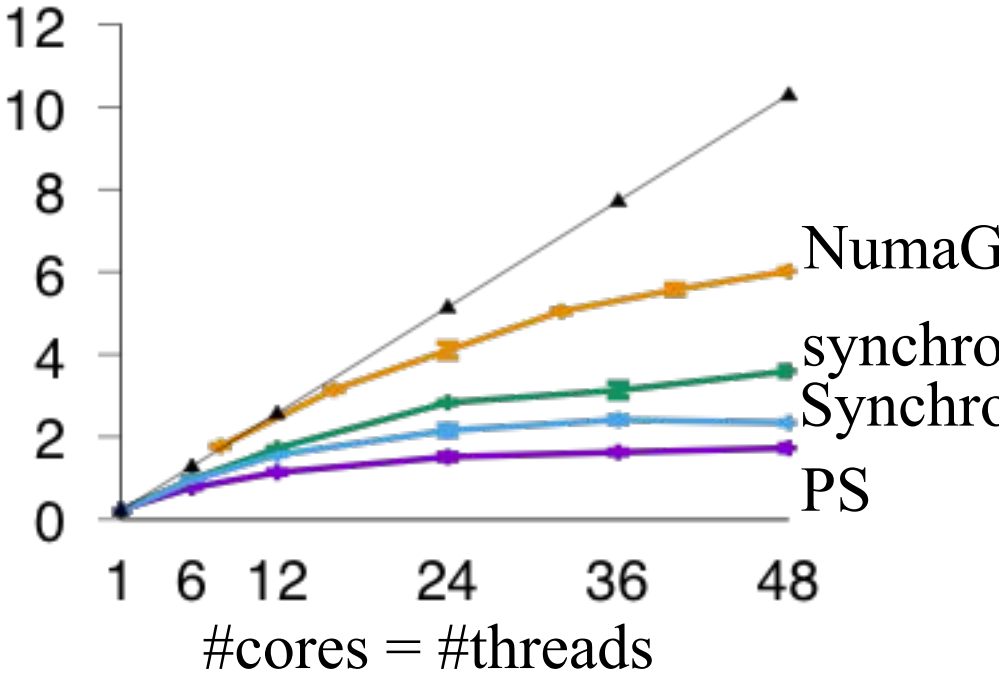


Node 1 idles while node 0 collects its memory

- Solution: adaptive algorithm
  - Local mode: send messages when not idling
  - Thief mode: steal and access remote objects when idling

Performance of NumaGiC

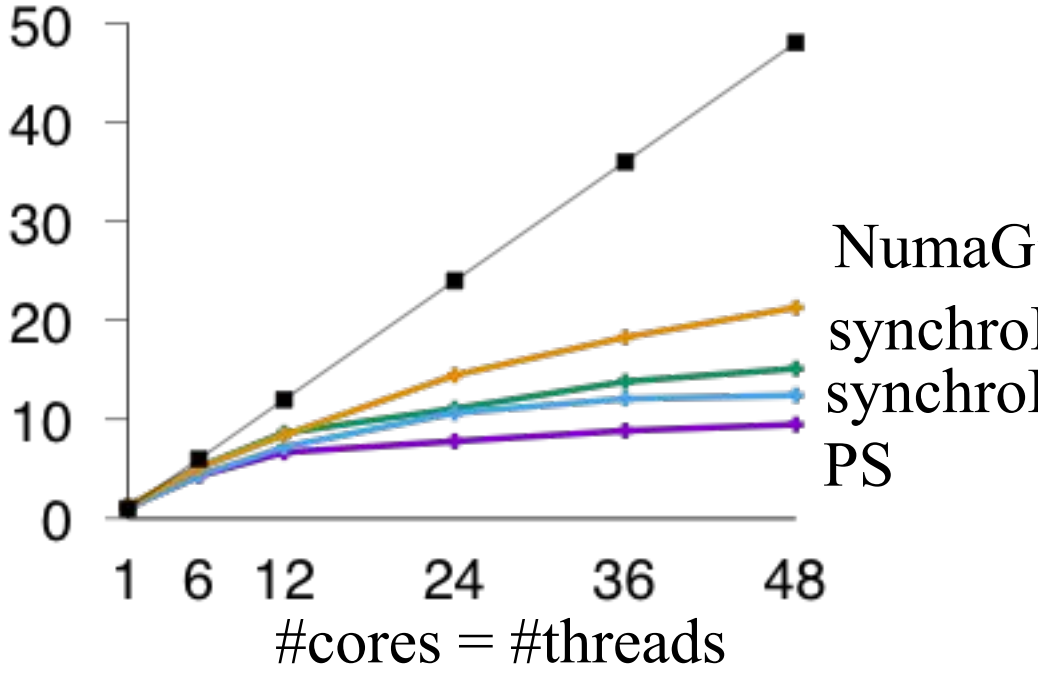
GC throughput
(GB collected per second)



Performance of the GC with Spark (40GB of heap)

Performance of the application

Application speedup in term of completion time



Performance of Spark (40GB of heap)

Completion time divided by two

Third lessons

- NUMA can have a large impact on performance
  - On data analytic applications written in Java
- We can design better NUMA policies than the ones proposed by default in Linux
  - Technically inspired by distributed systems

Fourth study

How a hypervisor behaves on a NUMA machine?

- Study of a set of 29 parallel applications

  Parsec, NPB, MosBench, X-stream, YCSB (Cassandra, MangoDB)
- Hypervisor overhead when we increase the #cores

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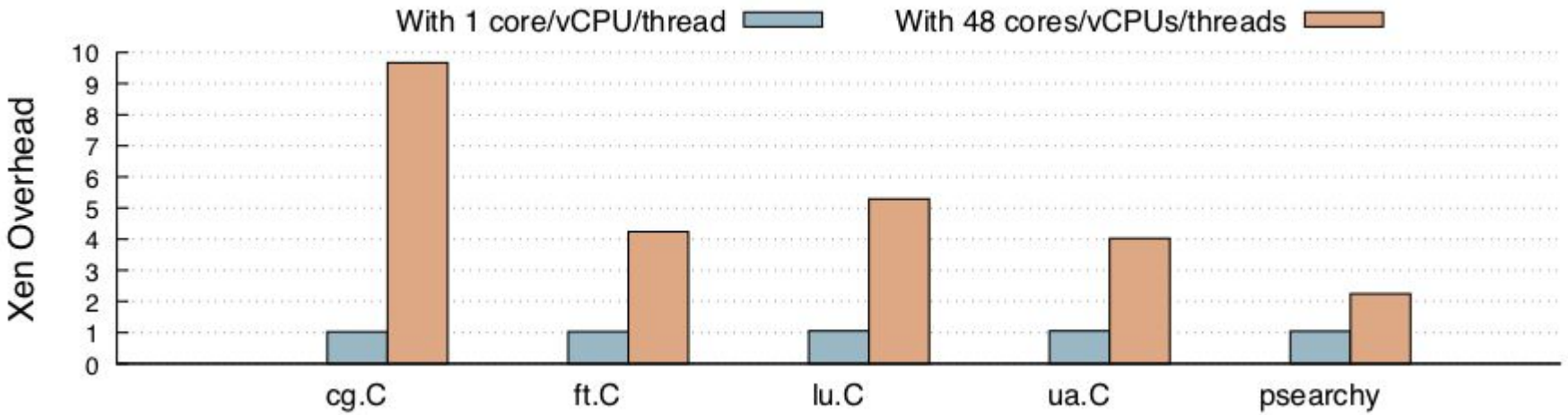
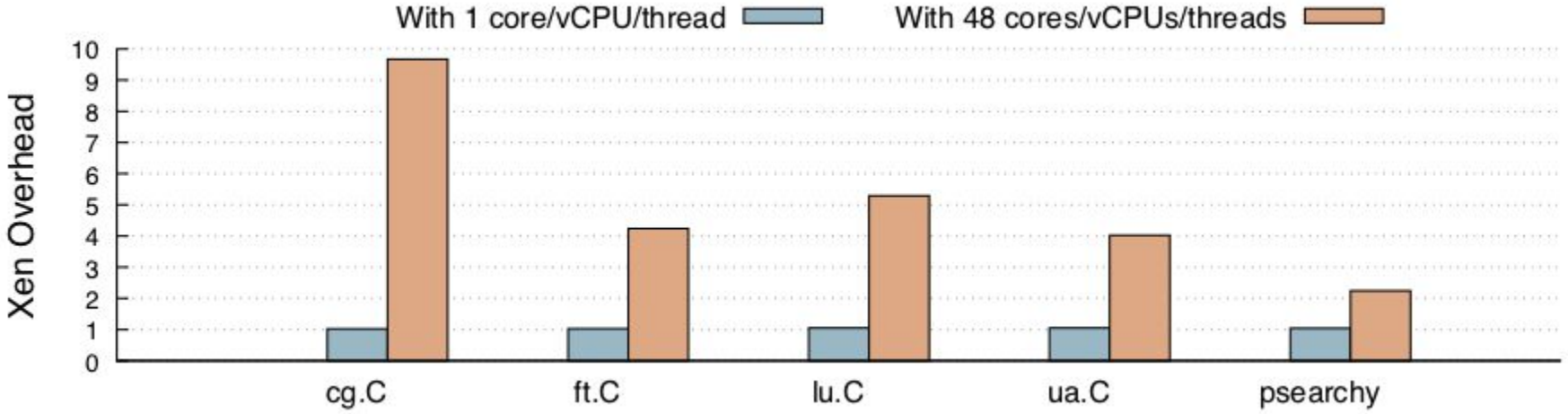
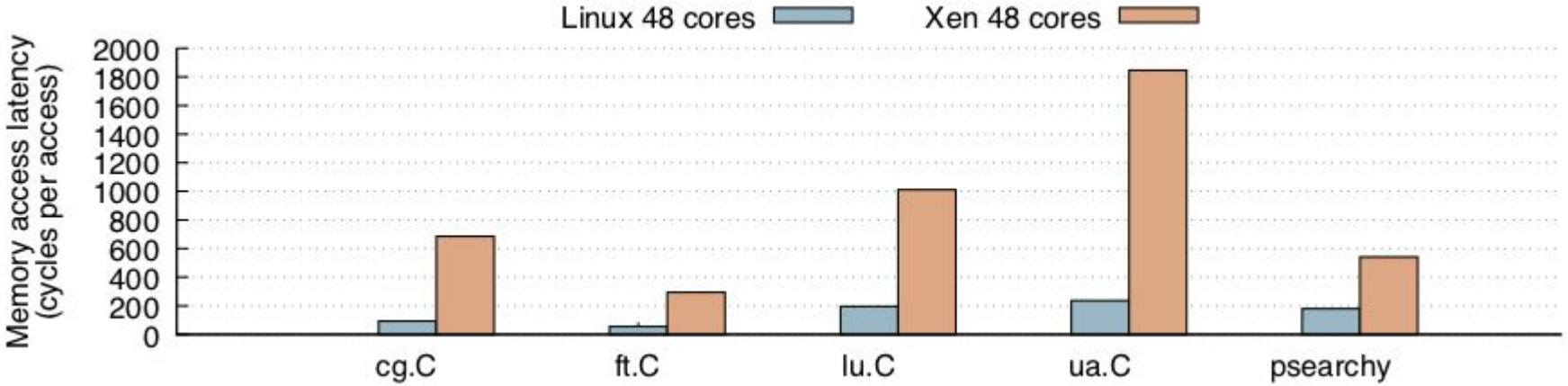


Up to a 9.5 time slowdown in Xen with 48 cores while overhead is negligible with 1 core

Memory access latency causes the overhead





Solution: XenNUMA

- Implement generic NUMA policies in Xen
  - Interleaved: roughly randomize memory access
  - First-touch: allocate from the node that triggers the first access
  - Carrefour: dynamic policies proposed by Dashti et al.

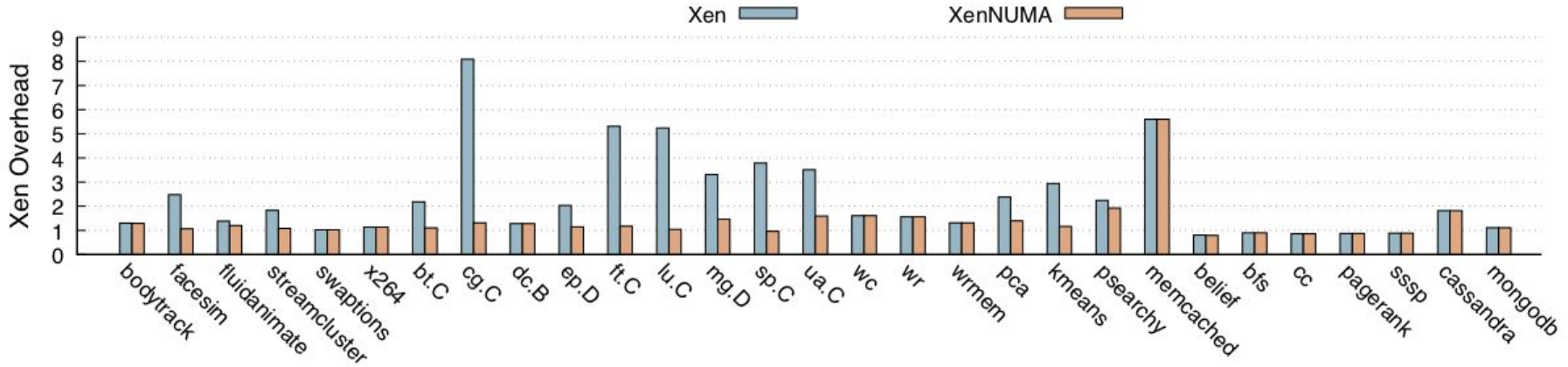
- Add a new interface between Linux and Xen
  - To select a NUMA policy for a process
  - To know which pages are allocated to a process

  In order to allocate a page from the node that triggers the first access

- Rewrite the memory sub-system of Xen

Overhead of Xen with 48 cores/vCPUs

- Settings: 48 vCPUs (pined) on the 48 pCPUs
  - Xen uses the default (nonexistent) NUMA policy
  - XenNUMA uses the best possible NUMA policy



- Results:
  - Performance improvement of up to 700%
  - Virtualization costs less than 50% for
    - 12/29 applications with Xen
    - 23/29 applications with XenNUMA

XenNUMA is not a satisfactory solution because XenNUMA hides the topology

Prevents the use System Runtime Libraries (SLR) optimizations:

- Impossible to use NumaGiC or other application-specific NUMA policies
- Impossible to use NUMA-aware allocators
  - TCMalloc, JEMalloc

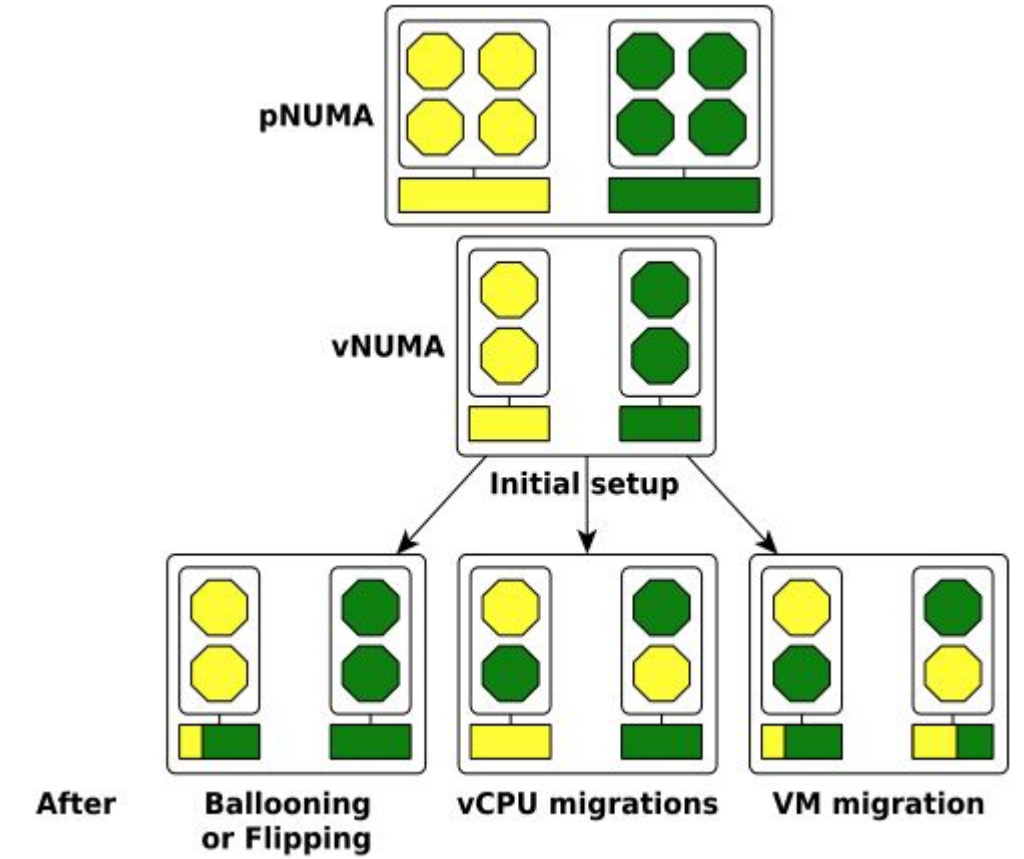
=> Bad performance for many applications

Exposing the topology is not more efficient

vNUMA exposes the initial NUMA topology

- But the hypervisor may change the NUMA topology at runtime

=> makes SLR and OS work with a stale topology



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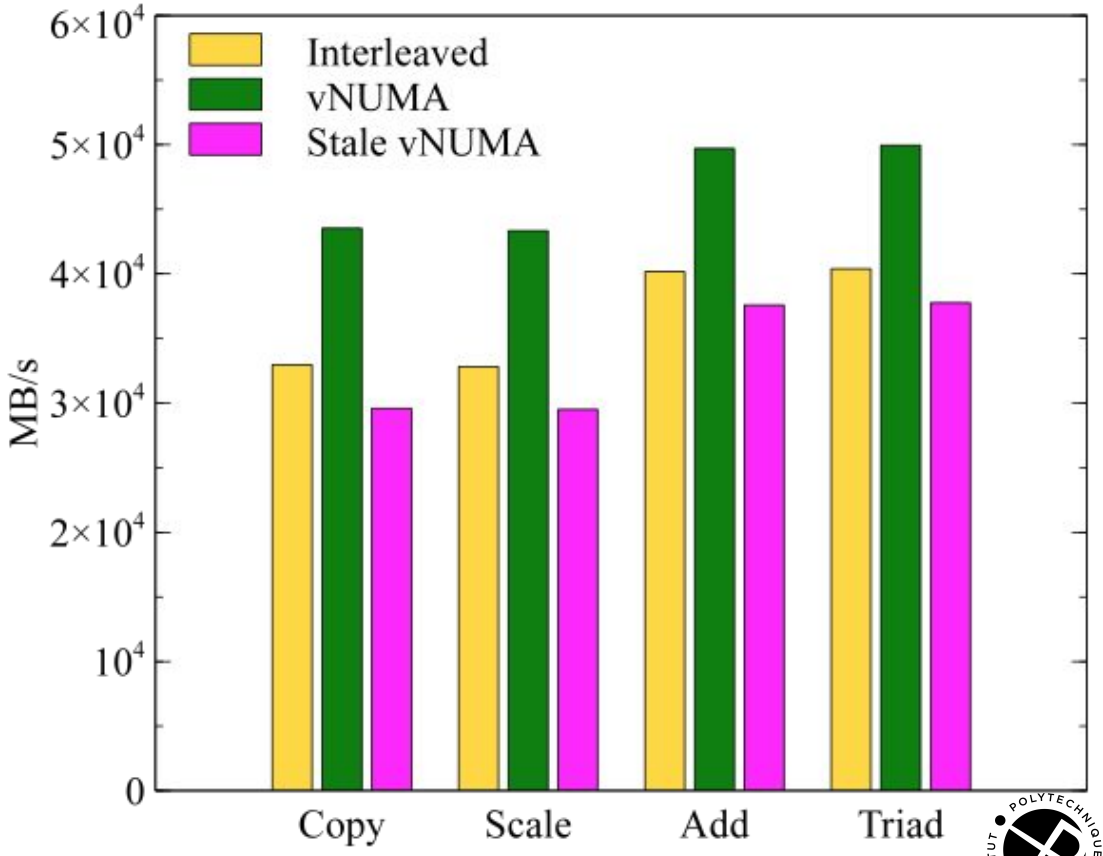


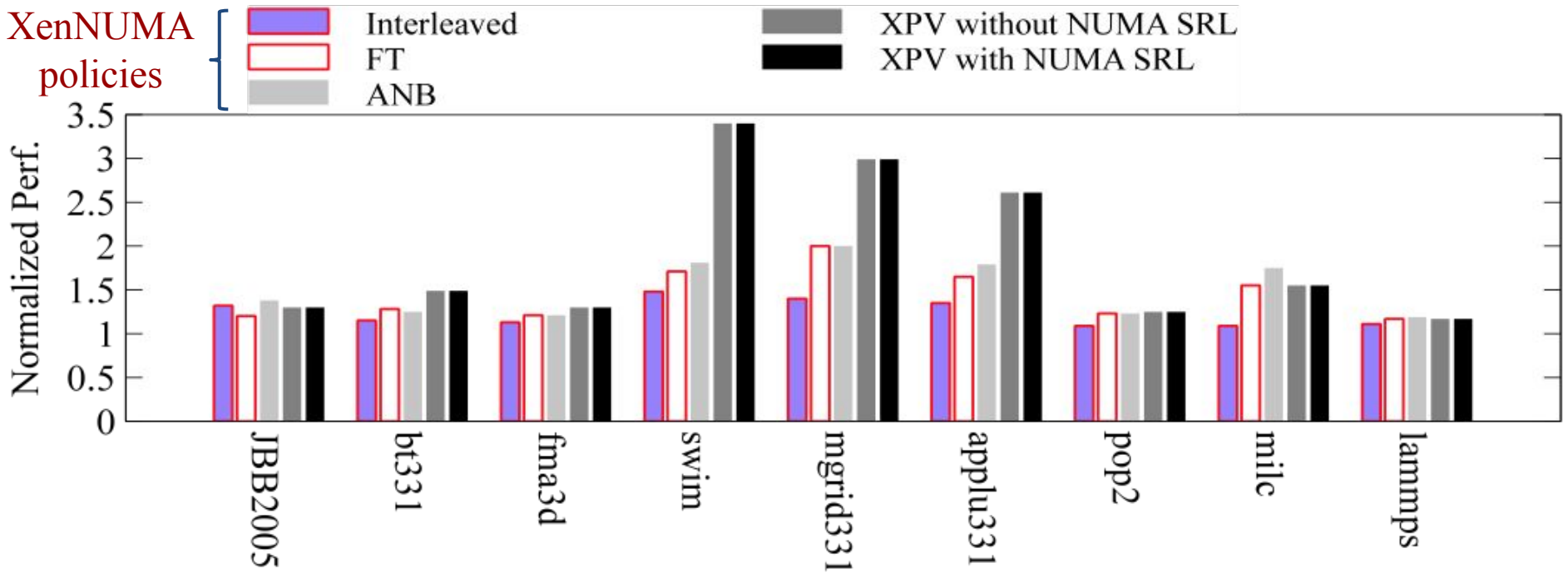
XPV: eXtended ParaVirtualization

- Expose the initial NUMA topology
- Add notifications when the NUMA topology changes
  - Used by the OS and the SLR to update the topology
  - Few lines of code changed

System	# files	# LOC changed
Xen 4.9	8	117
KVM from Linux 4.14	6	218
Linux 4.14	26	670
FreeBSD 11.0	23	708
HotSpot 8	3	53
TCMalloc 2.6.90	3	65
jemalloc 5.0.1	9	86

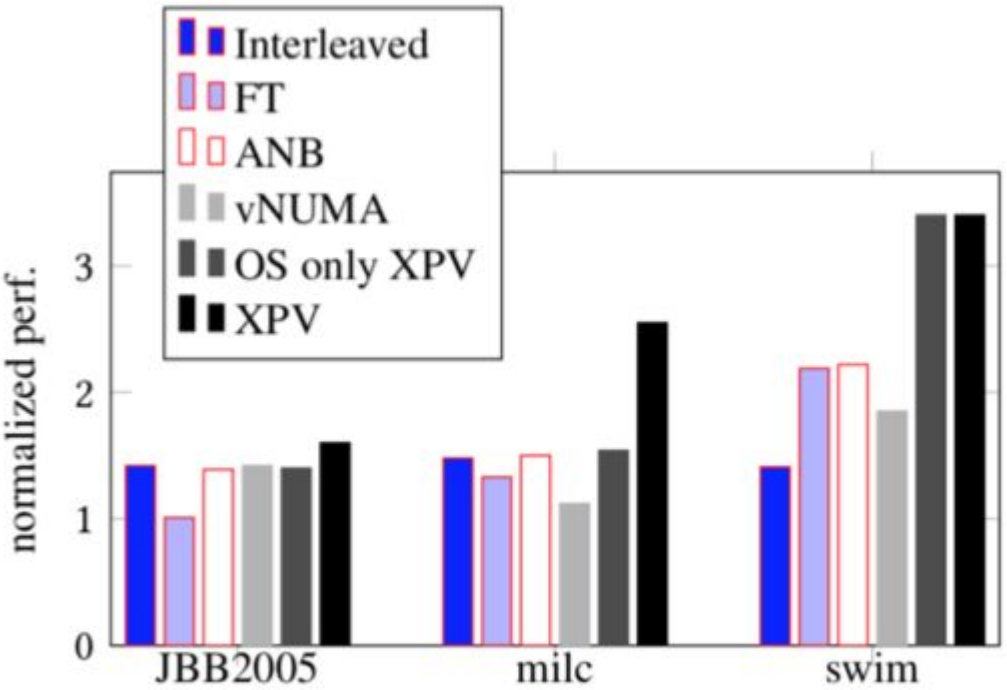
XPV versus XenNUMA (fixed NUMA topology)

By exposing the NUMA topology: up to 130% improvement



XPV facing topology changes

- Xen migrates vCPUs to balance the load
  - Three identical VMs
  - 48 vCPUs/42 pCPUs



Improvement: up to 127%

To take away

- NUMA can have a large impact on performance
  - On many parallel applications (both native and Java)
- We can already significantly improve performances with generic NUMA policies
  - We can predict which generic policy can give the best performance
- For some applications/SLRs, we need specific policies
  - JVM, Databases, locks, NUMA-aware allocators…
- We can mitigate NUMA effects even in hypervisors