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SAN FRANCISCO | APRIL 14-17, 2014

Automatic NUMA Balancing

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Automatic NUMA Balancing Agenda

- What is NUMA, anyway?
- Automatic NUMA balancing internals
- Automatic NUMA balancing performance
  - What workloads benefit from manual NUMA tuning
- Future developments
- Conclusions

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Introduction to NUMA

What is NUMA, anyway?

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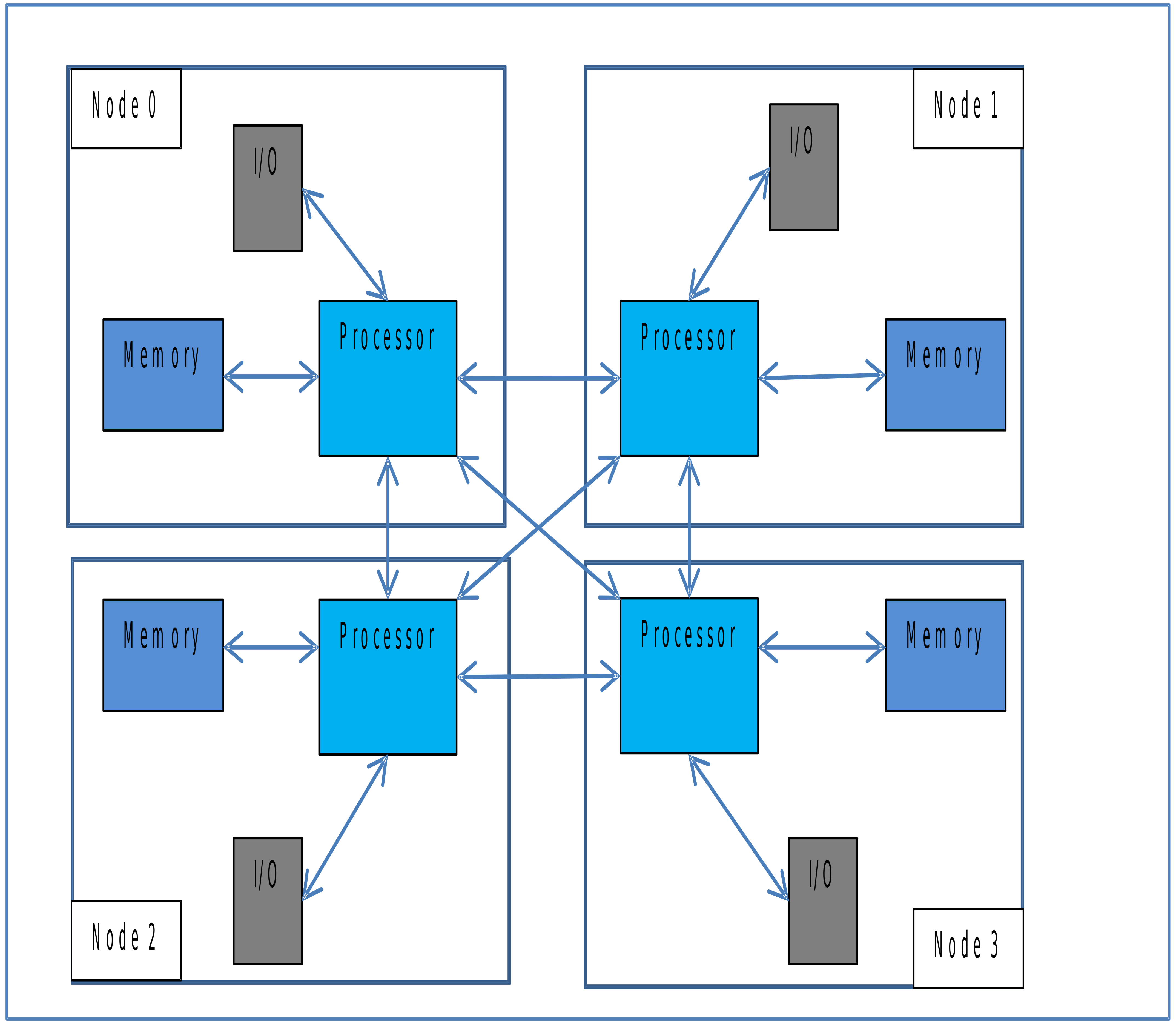
What is NUMA, anyway?

- Non Uniform Memory Access
- Multiple physical CPUs in a system
- Each CPU has memory attached to it
  - Local memory, fast
- Each CPU can access other CPU's memory, too
  - Remote memory, slower

NUMA terminology

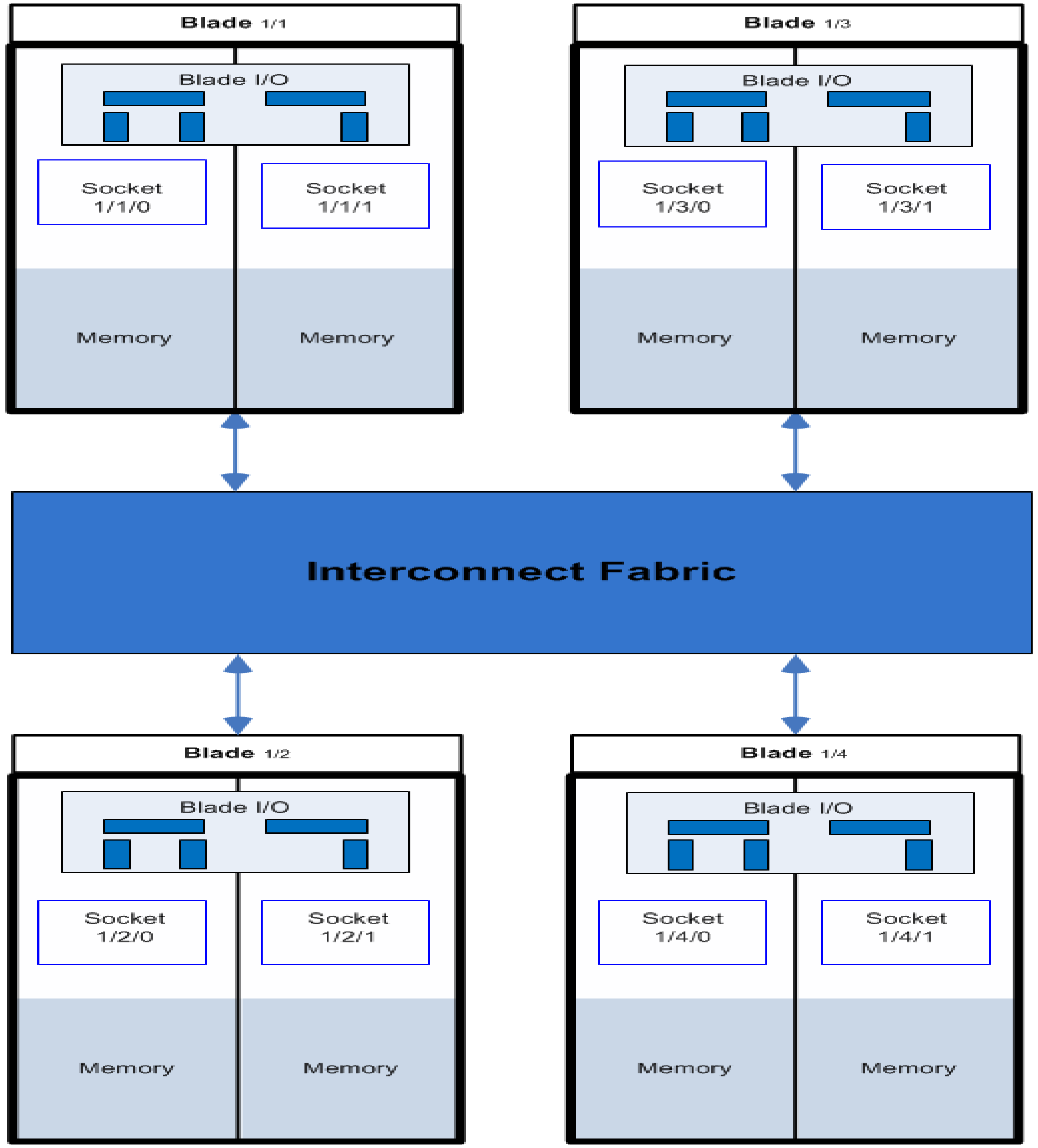
- Node
  - A physical CPU and attached memory
  - Could be multiple CPUs (with off-chip memory controller)
- Interconnect
  - Bus connecting the various nodes together
  - Generally faster than memory bandwidth of a single node
  - Can get overwhelmed by traffic from many nodes

4 socket Ivy Bridge EX server – NUMA topology



```
# numactl -H
available: 4 nodes (0-3)
node 0 cpus: 0 1 2 3 4 5 6 7 8 9 10 11 12 13 14
node 0 size: 262040 MB
node 0 free: 249261 MB
node 1 cpus: 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29
node 1 size: 262144 MB
node 1 free: 252060 MB
node 2 cpus: 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44
node 2 size: 262144 MB
node 2 free: 250441 MB
node 3 cpus: 45 46 47 48 49 50 51 52 53 54 55 56 57 58 59
node 3 size: 262144 MB
node 3 free: 250080 MB
node distances:
node   0   1   2   3
  0:  10  21  21  21
  1:  21  10  21  21
  2:  21  21  10  21
  3:  21  21  21  10
```

8 socket Ivy Bridge EX *prototype* server – NUMA topology



```
# numactl -H
available: 8 nodes (0-7)
node 0 cpus: 0 1 2 3 4 5 6 7 8 9 10 11 12 13 14
node 0 size: 130956 MB
node 0 free: 125414 MB
node 1 cpus: 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29
node 1 size: 131071 MB
node 1 free: 126712 MB
node 2 cpus: 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44
node 2 size: 131072 MB
node 2 free: 126612 MB
node 3 cpus: 45 46 47 48 49 50 51 52 53 54 55 56 57 58 59
node 3 size: 131072 MB
node 3 free: 125383 MB
node 4 cpus: 60 61 62 63 64 65 66 67 68 69 70 71 72 73 74
node 4 size: 131072 MB
node 4 free: 126479 MB
node 5 cpus: 75 76 77 78 79 80 81 82 83 84 85 86 87 88 89
node 5 size: 131072 MB
node 5 free: 125298 MB
node 6 cpus: 90 91 92 93 94 95 96 97 98 99 100 101 102 103 104
node 6 size: 131072 MB
node 6 free: 126913 MB
node 7 cpus: 105 106 107 108 109 110 111 112 113 114 115 116 117 118 119
node 7 size: 131072 MB
node 7 free: 124509 MB
node distances:
node   0   1   2   3   4   5   6   7
  0:  10  16  30  30  30  30  30  30
  1:  16  10  30  30  30  30  30  30
  2:  30  30  10  16  30  30  30  30
  3:  30  30  16  10  30  30  30  30
  4:  30  30  30  30  10  16  30  30
  5:  30  30  30  30  16  10  30  30
  6:  30  30  30  30  30  30  10  16
  7:  30  30  30  30  30  30  16  10
```

NUMA performance considerations

- NUMA performance penalties from two main sources
  - Higher latency of accessing remote memory
  - Interconnect contention
- Processor threads and cores share resources
  - Execution units (between HT threads)
  - Cache (between threads and cores)

Automatic NUMA balancing strategies

- CPU follows memory
  - Try running tasks where their memory is
- Memory follows CPU
  - Move memory to where it is accessed
- Both strategies are used by automatic NUMA balancing
  - Various mechanisms involved
  - Lots of interesting corner cases...

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Automatic NUMA Balancing

Internals

Automatic NUMA balancing internals

- NUMA hinting page faults
- NUMA page migration
- Task grouping
- Fault statistics
- Task placement
- Pseudo-interleaving

NUMA hinting page faults

- Periodically, each task's memory is unmapped
  - Period based on run time, and NUMA locality
  - Unmapped “a little bit” at a time (chunks of 256MB)
  - Page table set to “no access permission” marked as NUMA pte
- Page faults generated as task tries to access memory
  - Used to track the location of memory a task uses
    - Task may also have unused memory “just sitting around”
  - NUMA faults also drive NUMA page migration

NUMA page migration

- NUMA page faults are relatively cheap
- Page migration is much more expensive
  - ... but so is having task memory on the “wrong node”
- Quadratic filter: only migrate if page is accessed twice
  - From same NUMA node, or
  - By the same task
  - CPU number & low bits of pid in page struct
- Page is migrated to where the task is running

Fault statistics

- Fault statistics are used to place tasks (cpu-follows-memory)
- Statistics kept per task, and per numa_group
- “Where is the memory this task (or group) is accessing?”
  - “NUMA page faults” counter per NUMA node
  - After a NUMA fault, account the page location
    - If the page was migrated, account the new location
  - Kept as a floating average

Types of NUMA faults

- Locality
  - “Local fault” - memory on same node as CPU
  - “Remote fault” - memory on different node than CPU
- Private vs shared
  - “Private fault” - memory accessed by same task twice in a row
  - “Shared fault” - memory accessed by different task than last time

Fault statistics example

numa_faults	Task A	Task B
Node 0	0	1027
Node 1	83	29
Node 2	915	17
Node 3	4	31

Task placement

- Best place to run a task
  - Where most of its memory accesses happen

Task placement

- Best place to run a task
  - Where most of its memory accesses happen
- It is not that simple
  - Tasks may share memory
    - Some private accesses, some shared accesses
    - 60% private, 40% shared is possible – group tasks together for best performance
  - Tasks with memory on the node may have more threads than can run in one node's CPU cores
  - Load balancer may have spread threads across more physical CPUs
    - Take advantage of more CPU cache

Task placement constraints

- NUMA task placement may not create a load imbalance
  - The load balancer would move something else
  - Conflict can lead to tasks “bouncing around the system”
    - Bad locality
    - Lots of NUMA page migrations
- NUMA task placement may
  - Swap tasks between nodes
  - Move a task to an idle CPU if no imbalance is created

Task placement algorithm

- For task A, check each NUMA node N
  - Check whether node N is better than task A's current node (C)
    - Task A has a larger fraction of memory accesses on node N, than on current node C
    - Score is the difference of fractions
  - If so, check all CPUs on node N
    - Is the current task (T) on CPU better off on node C?
    - Is the CPU idle, and can we move task A to the CPU?
    - Is the benefit of moving task A to node N larger than the downside of moving task T to node C?
  - For the CPU with the best score, move task A (and task T, to node C).

Task placement examples

NODE	CPU	TASK
0	0	A
0	1	T
1	2	(idle)
1	3	(idle)

Fault statistics	TASK A	TASK T
NODE 0	30% (*)	60% (*)
NODE 1	70%	40%

- Moving task A to node 1: 40% improvement
- Moving a task to node 1 removes a load imbalance
- Moving task A to an idle CPU on node 1 is desirable

Task placement examples

NODE	CPU	TASK
0	0	A
0	1	(idle)
1	2	T
1	3	(idle)

Fault statistics	TASK A	TASK T
NODE 0	30% (*)	60%
NODE 1	70%	40% (*)

- Moving task A to node 1: 40% improvement
- Moving task T to node 0: 20% improvement
- Swapping tasks A & T is desirable

Task placement examples

NODE	CPU	TASK
0	0	A
0	1	(idle)
1	2	T
1	3	(idle)

Fault statistics	TASK A	TASK T
NODE 0	30% (*)	40%
NODE 1	70%	60% (*)

- Moving task A to node 1: 40% improvement
- Moving task T to node 0: 20% worse
- Swapping tasks A & T: overall a 20% improvement, do it

Task placement examples

NODE	CPU	TASK
0	0	A
0	1	(idle)
1	2	T
1	3	(idle)

Fault statistics	TASK A	TASK T
NODE 0	30% (*)	20%
NODE 1	70%	80% (*)

- Moving task A to node 1: 40% improvement
- Moving task T to node 0: 60% worse
- Swapping tasks A & T: overall 20% worse, leave things alone

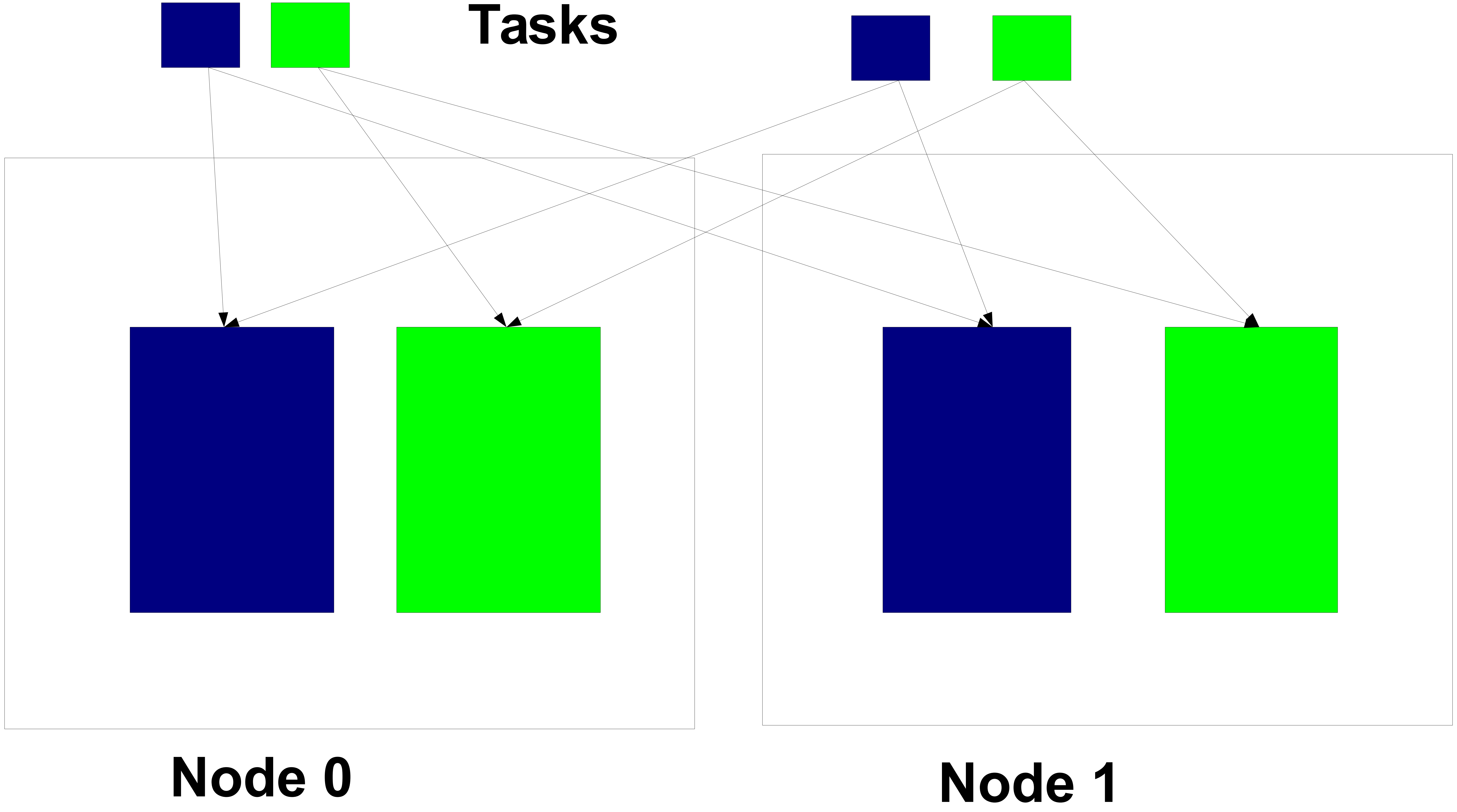
Task grouping

- Multiple tasks can access the same memory
  - Threads in a large multi-threaded process (JVM, virtual machine, ...)
  - Processes using shared memory segment (eg. Database)
- Use CPU num & pid in struct page to detect shared memory
  - At NUMA fault time, check CPU where page was last faulted
  - Group tasks together in numa_group, if PID matches
- Grouping related tasks improves NUMA task placement
  - Only group truly related tasks
  - Only group on write faults, ignore shared libraries like libc.so

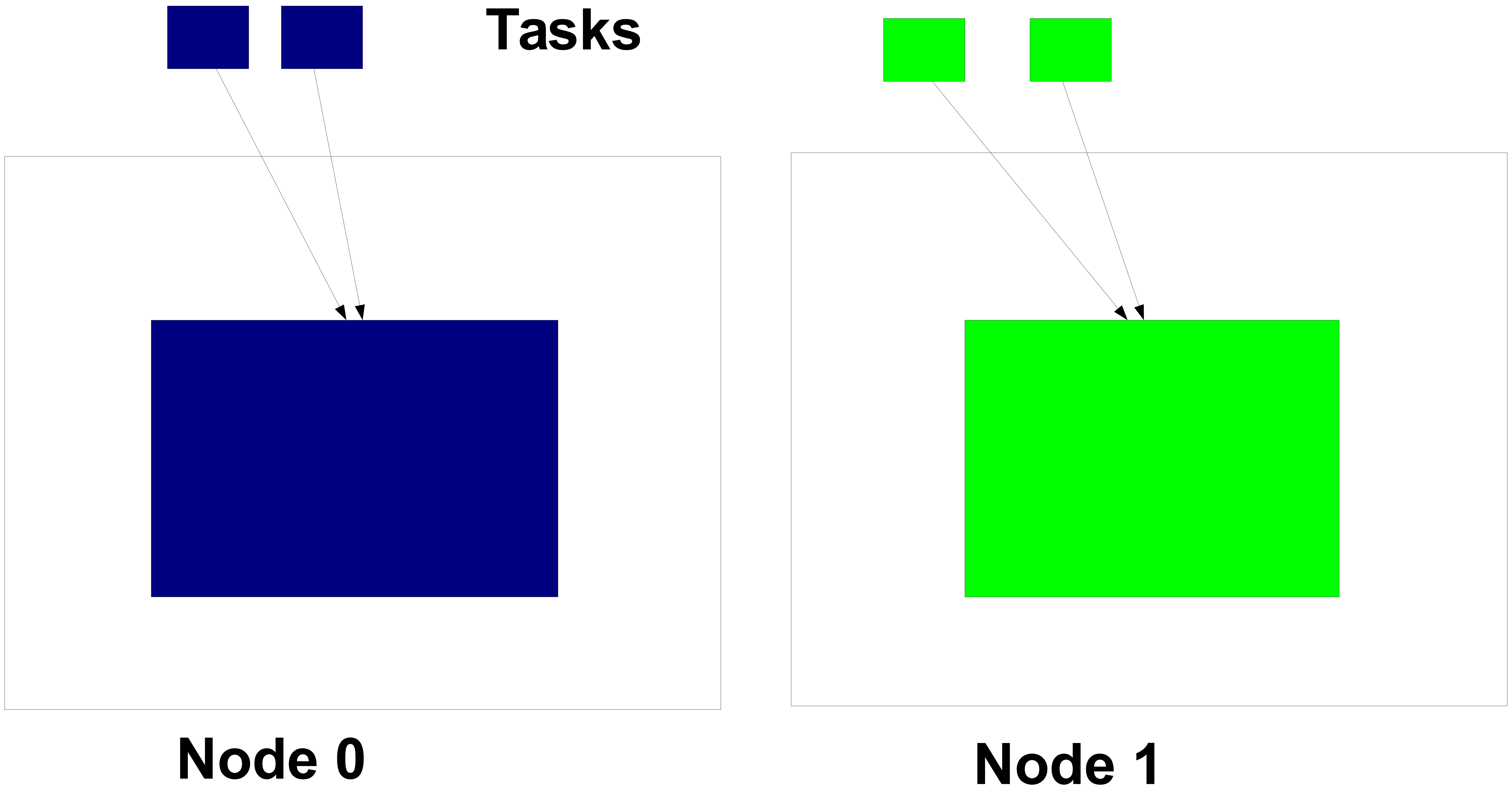
Task grouping & task placement

- Group stats are the sum of the NUMA fault stats for tasks in group
- Task placement code similar to before
- If a task belongs to a numa_group, use the numa_group stats for comparison instead of the task stats
  - Pulls groups together, for more efficient access to shared memory
- When both compared tasks belong to the same numa_group
  - Use task stats, since group numbers are the same
  - Efficient placement of tasks within a group

Task grouping & placement example



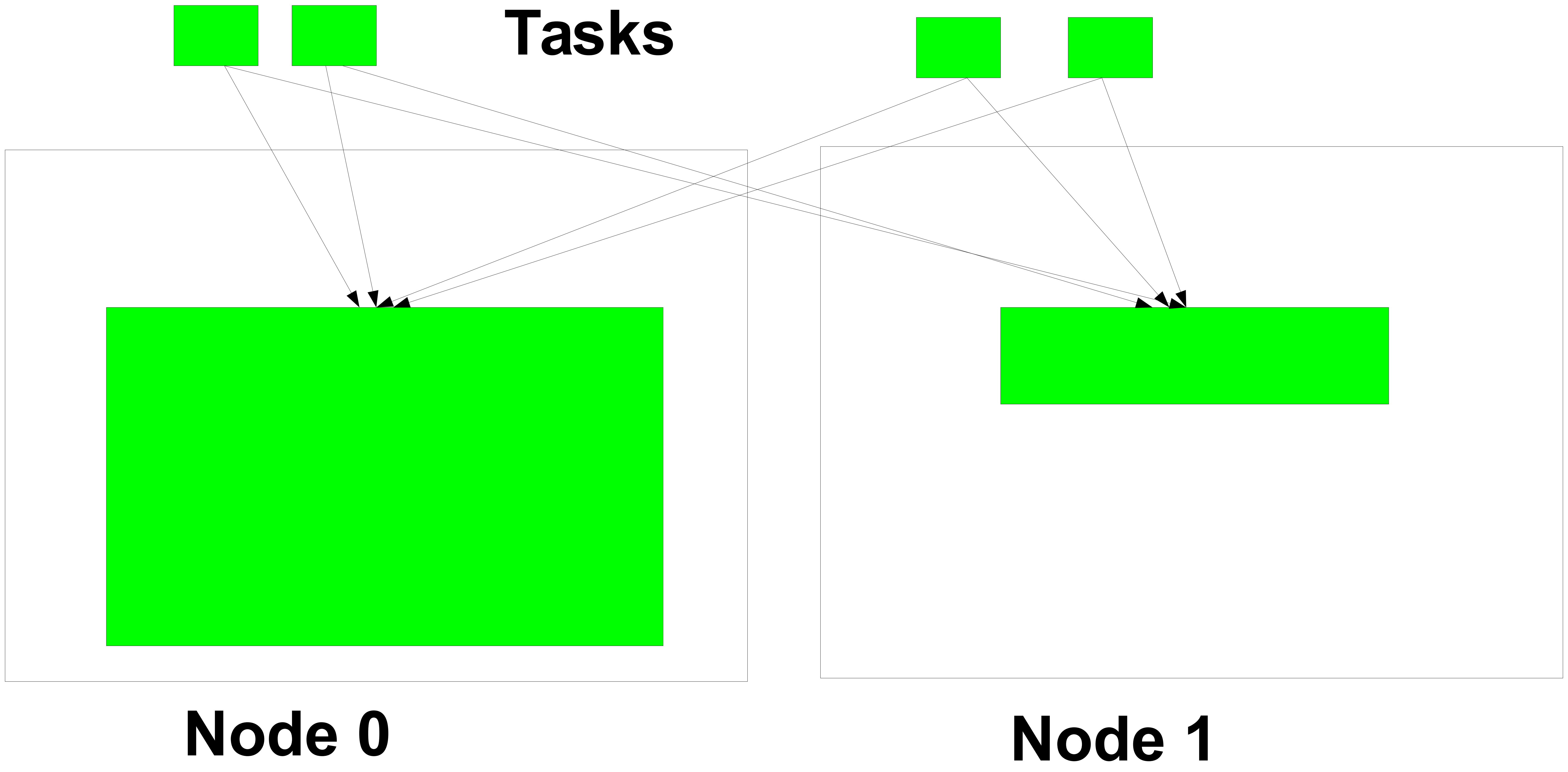
Task grouping & placement example



Pseudo-interleaving

- Sometimes one workload spans multiple nodes
  - More threads running than one node has CPU cores
  - Spread out by the load balancer
- Goals
  - Maximize memory bandwidth available to workload
  - Keep private memory local to tasks using it
  - Minimize number of page migrations

Pseudo-interleaving problem

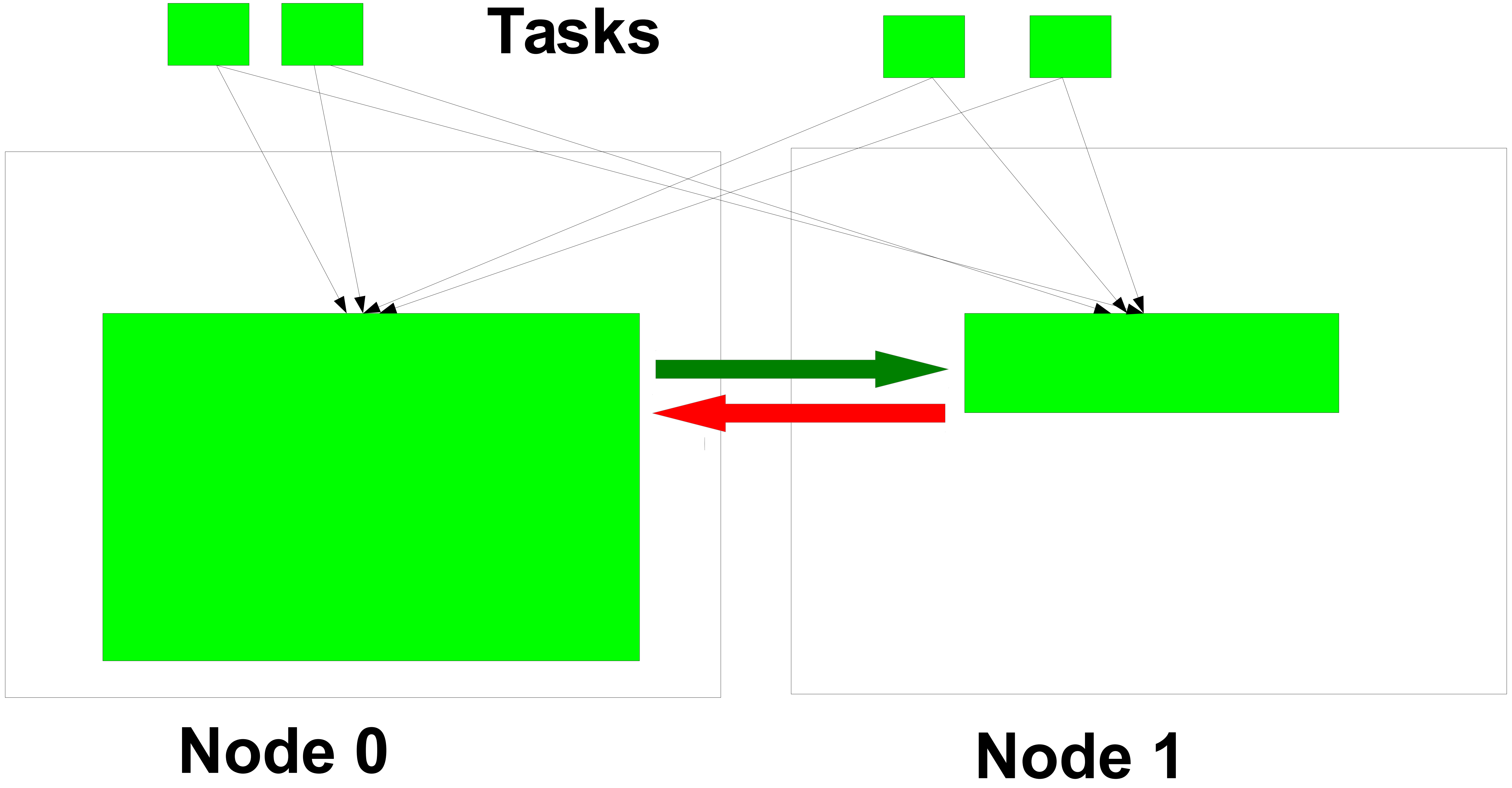


- Most memory on node 0, sub-optimal use of memory bandwidth
- How to fix? Spread out the memory more evenly...

Pseudo-interleaving algorithm

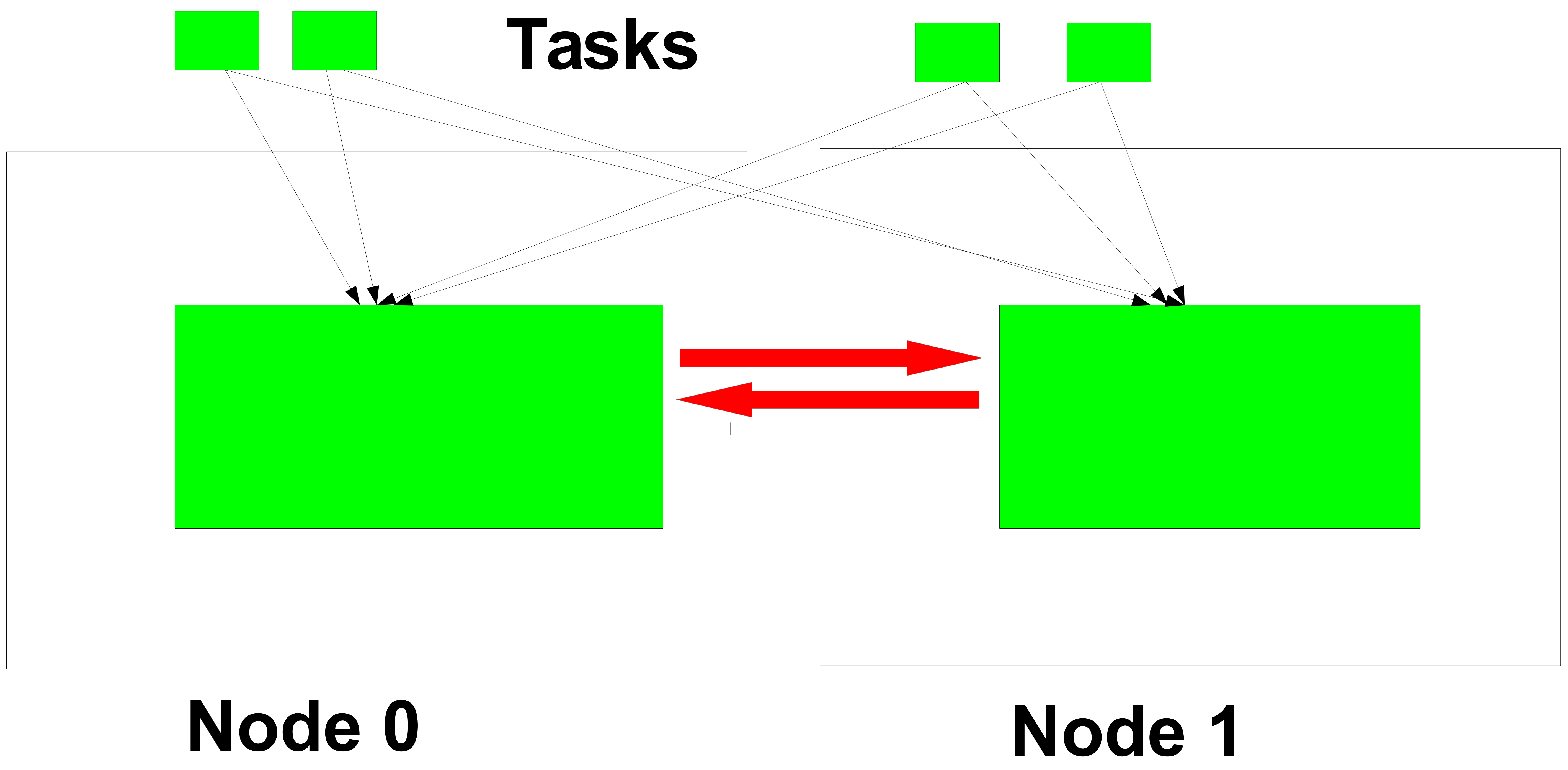
- Determine nodes where workload is actively running
  - CPU time used & NUMA faults
- Always allow private faults (same task) to migrate pages
- Allow shared faults to migrate pages only from a more heavily used node, to a less heavily used node
- Block NUMA page migration on shared faults from one node to another node that is equally or more heavily used

Pseudo-interleaving solution



- Allow NUMA migration on private faults
- Allow NUMA migration from more used, to lesser used node

Pseudo-interleaving converged state



- Nodes are equally used, maximizing memory bandwidth
- NUMA page migration only on private faults
- NUMA page migration on shared faults is avoided

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Automatic NUMA Placement Performance

Show me the numbers!

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Evaluation of Automatic NUMA balancing – *Status update*

- Goal : Study the impact on out-of-box performance with different workloads on bare-metal & KVM guests.

- Workloads being used*:
  - 2 Java workloads
    - SPECjbb2005 used as a workload
    - Multi-JVM server workload
  - Database
    - A *synthetic* DSS workload (using tmpfs)
    - Other DB workloads (with I/O) are in the pipeline...

**** Note: These sample workloads are being used for relative performance comparisons. This is not an official benchmarking exercise!***

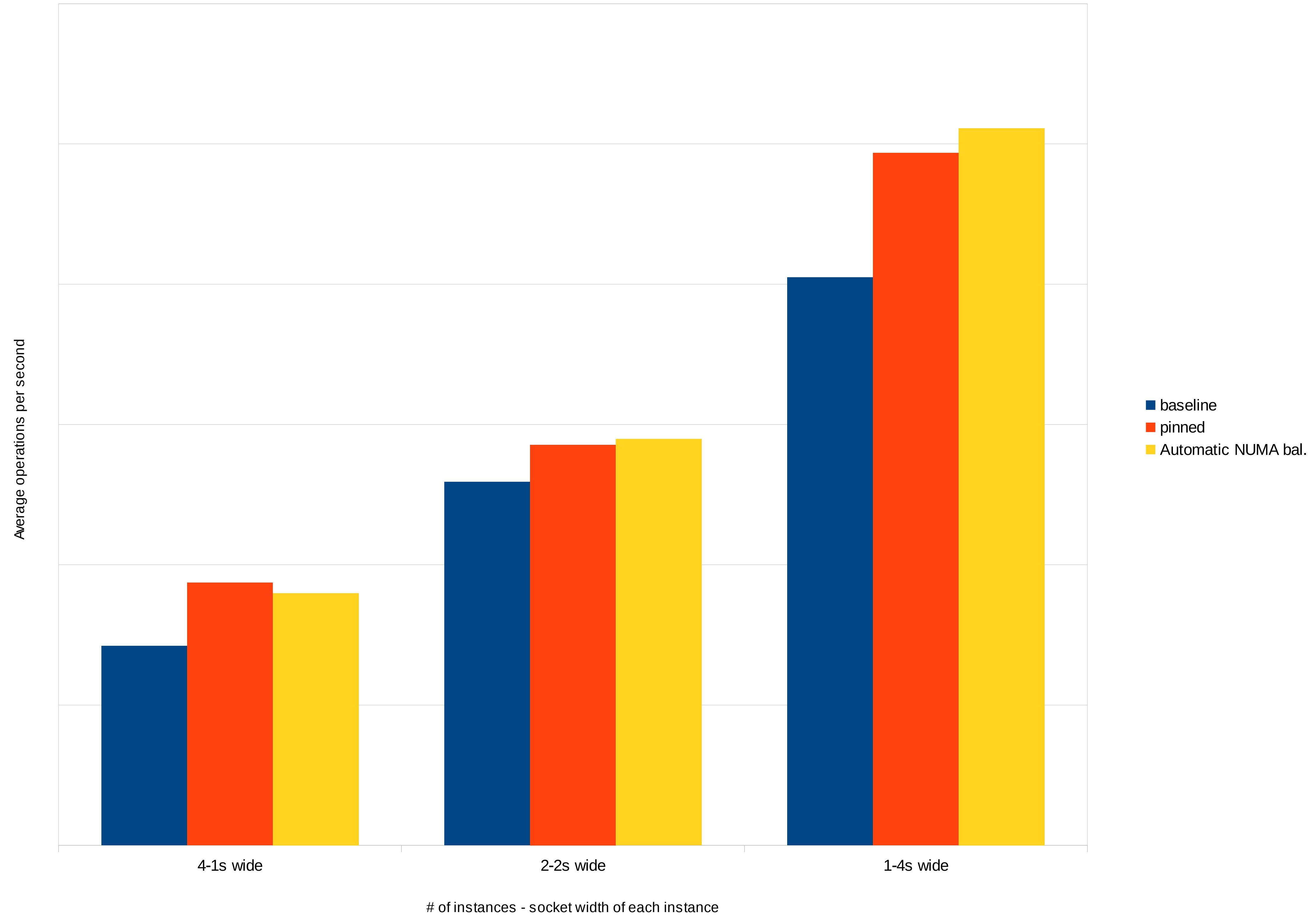
Experiments with bare-metal

- Platforms used :
  - 4-socket Ivy Bridge EX server
  - 8-socket Ivy Bridge EX *prototype* server.
- Misc. settings:
  - Hyper-threading off, THP enabled & cstates set to 1 (i.e. intel_idle.max_cstate=1 processor.max_cstate=1)
- Configurations :
  - Baseline :
    - No manual pinning of the workload
    - No Automatic NUMA balancing
  - Pinned :
    - Manual (numactl) pinning of the workload
  - Automatic NUMA balancing :
    - No manual pinning of the workload.

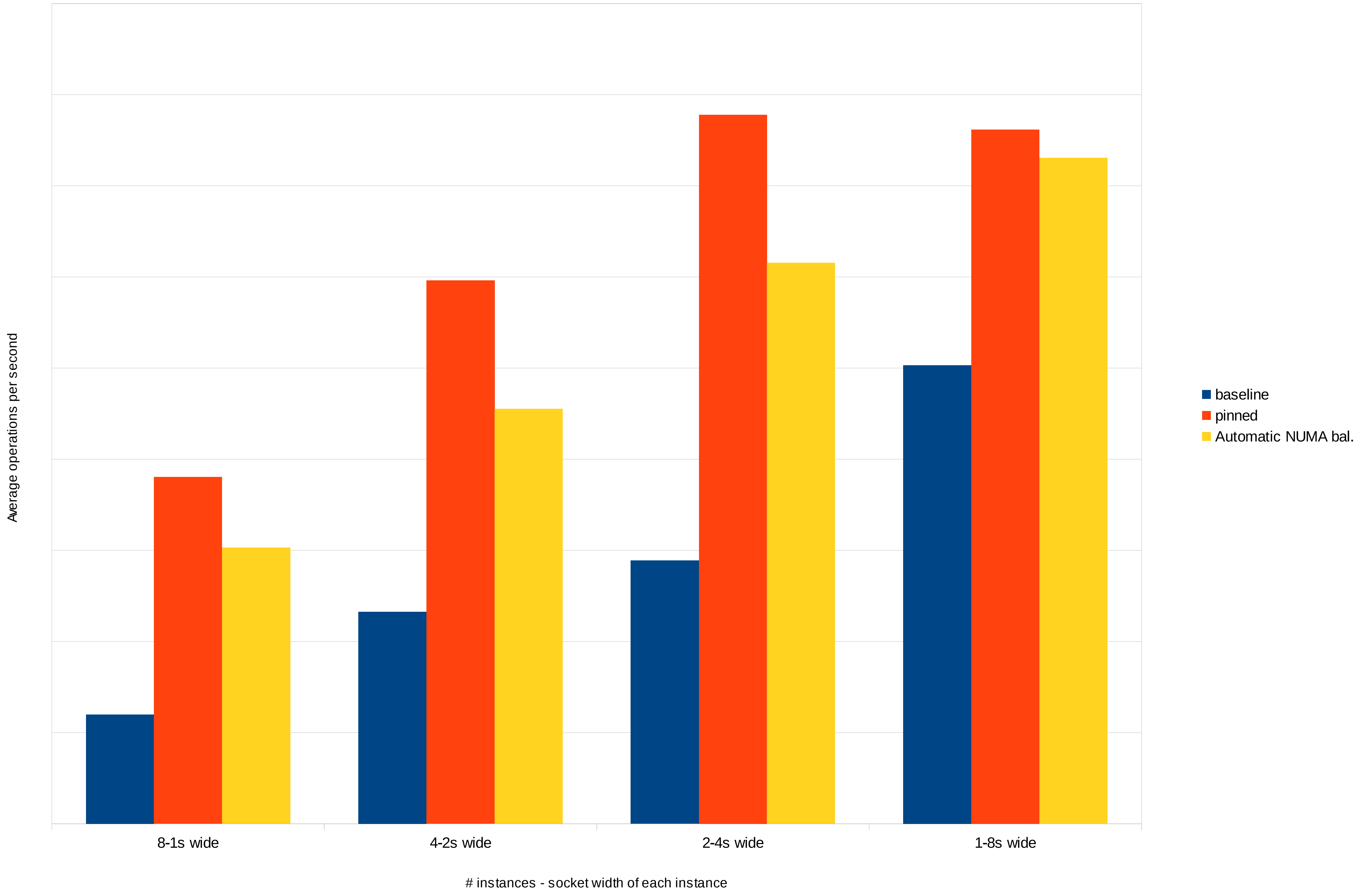
SPECjbb2005 - bare-metal

(4-socket IVY-EX server   vs. 8-socket IVY-EX *prototype* server)

1s wide = 15 warehouse threads, 2s wide = 30 warehouse threads; 4s wide = 60 warehouse threads, 8s wide = 120 warehouse threads



Automatic NUMA balancing case & the Pinned case were pretty close (+/- 4%).



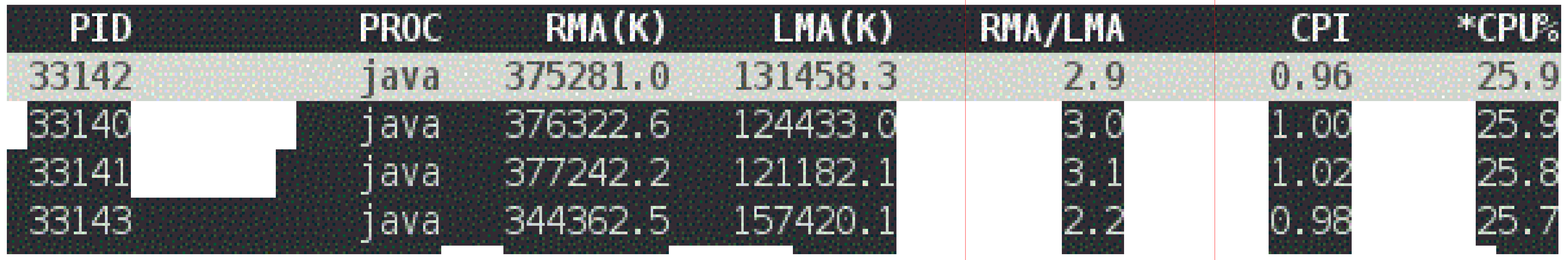
Delta between Automatic NUMA balancing case & the Pinned case was as high as ~20+%

Remote vs. local memory access (RMA/LMA samples)*

(Workload : Multiple 1 socket-wide instances of SPECjbb2005)

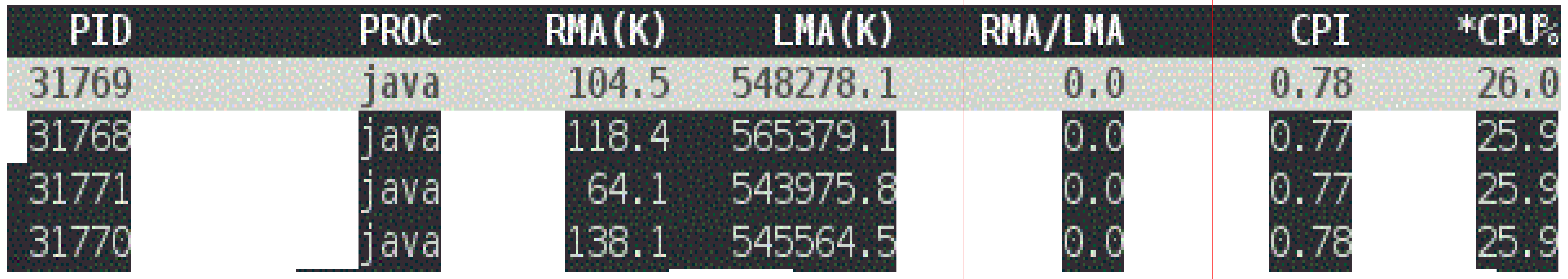
4-socket IVY-EX server

Baseline



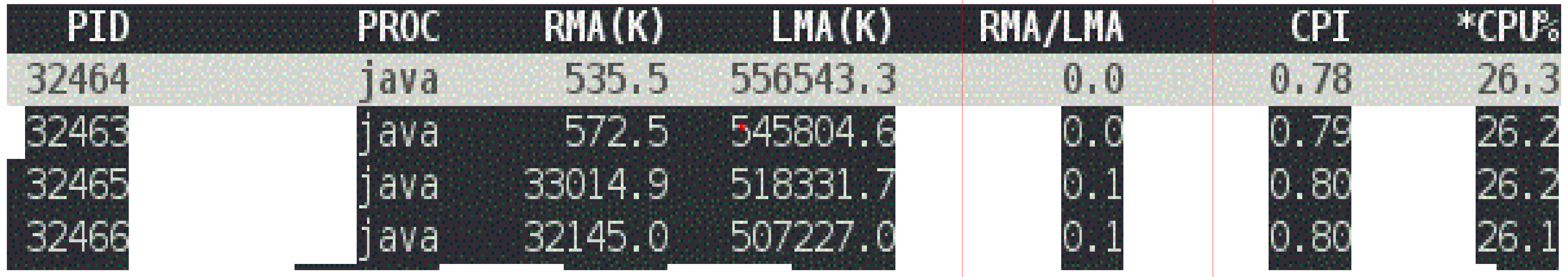
```
  PID          PROC   RMA(K)    LMA(K)    RMA/LMA      CPI    *CPU%
33142          java  375281.0  131458.3       2.9     0.96     25.9
33140          java  376322.6  124433.0       3.0     1.00     25.9
33141          java  377242.2  121182.1       3.1     1.02     25.8
33143          java  344362.5  157420.1       2.2     0.98     25.7
```

Pinned



```
  PID          PROC   RMA(K)    LMA(K)    RMA/LMA      CPI    *CPU%
31769          java     104.5  548278.1       0.0     0.78     26.0
31768          java     118.4  565379.1       0.0     0.77     25.9
31771          java      64.1  543975.8       0.0     0.77     25.9
31770          java     138.1  545564.5       0.0     0.78     25.9
```

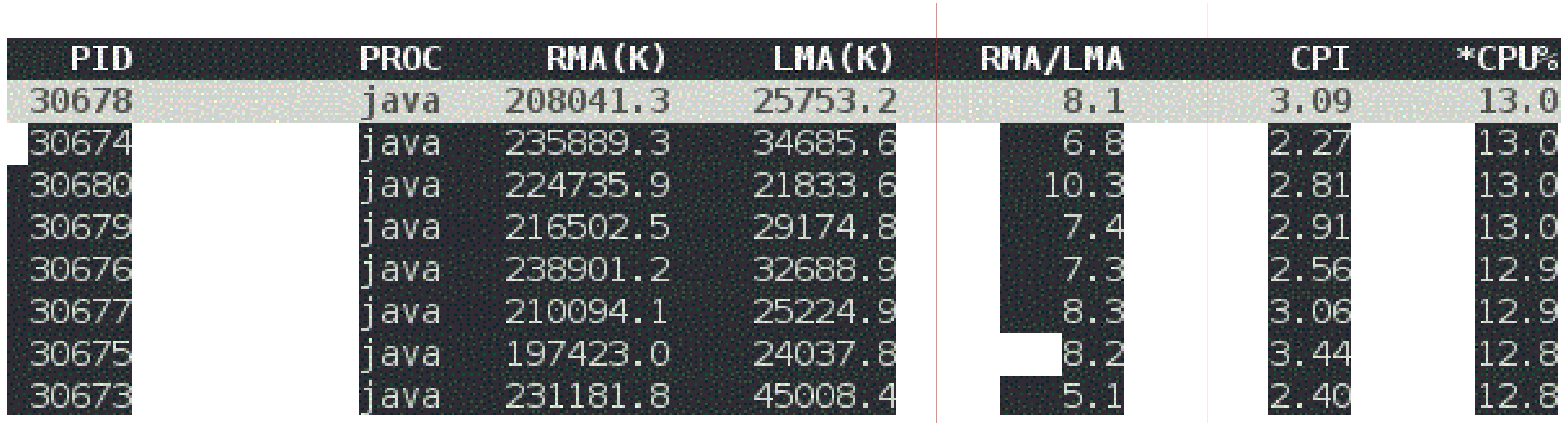
Automatic NUMA balancing



```
  PID          PROC   RMA(K)    LMA(K)    RMA/LMA      CPI    *CPU%
32464          java     535.5  556543.3       0.0     0.78     26.3
32463          java     572.5  545804.6       0.0     0.79     26.2
32465          java   33014.9  518331.7       0.1     0.80     26.2
32466          java   32145.0  507227.0       0.1     0.80     26.1
```

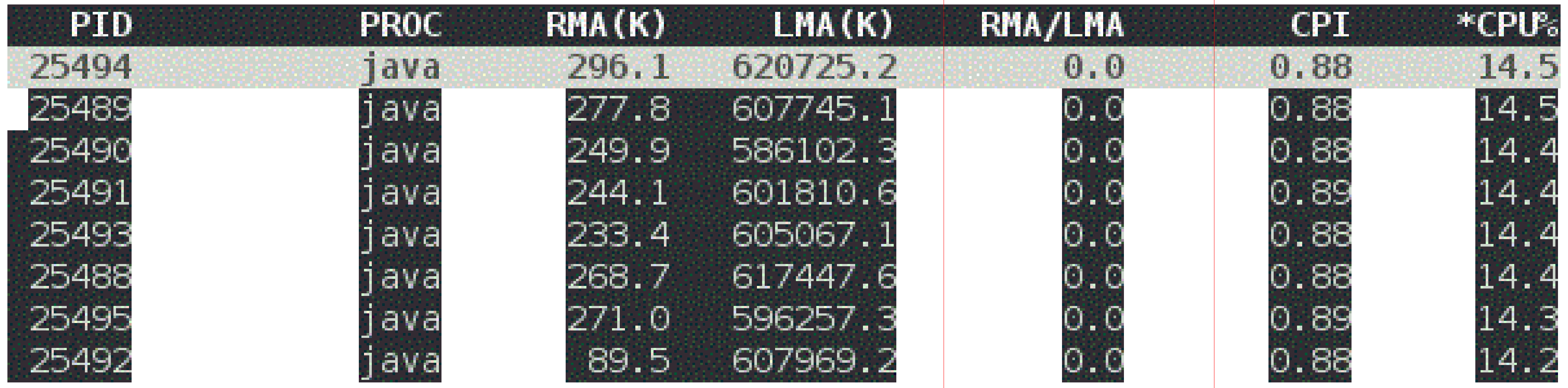
8-socket IVY-EX prototype server

Baseline



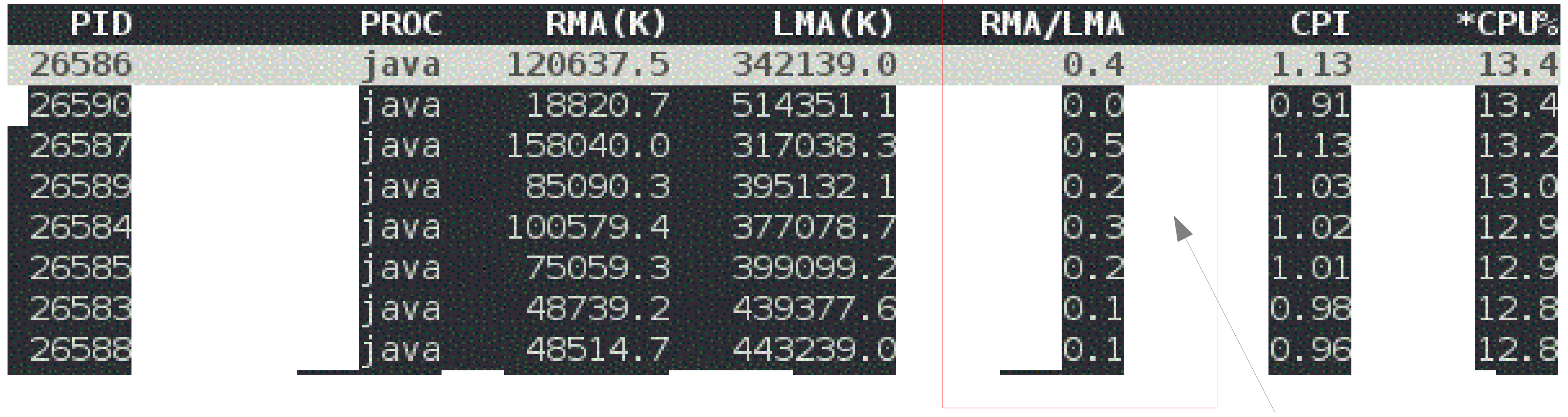
```
  PID          PROC   RMA(K)    LMA(K)    RMA/LMA      CPI    *CPU%
30678          java  208041.3   25753.2       8.1     3.09     13.0
30674          java  235889.3   34685.6       6.8     2.27     13.0
30680          java  224735.9   21833.6      10.3     2.81     13.0
30679          java  216502.5   29174.8       7.4     2.91     13.0
30676          java  238901.2   32688.9       7.3     2.56     12.9
30677          java  210094.1   25224.9       8.3     3.06     12.9
30675          java  197423.0   24037.8       8.2     3.44     12.8
30673          java  231181.8   45008.4       5.1     2.40     12.8
```

Pinned



```
  PID          PROC   RMA(K)    LMA(K)    RMA/LMA      CPI    *CPU%
25494          java     296.1  620725.2       0.0     0.88     14.5
25489          java     277.8  607745.1       0.0     0.88     14.5
25490          java     249.9  586102.3       0.0     0.88     14.4
25491          java     244.1  601810.6       0.0     0.89     14.4
25493          java     233.4  605067.1       0.0     0.88     14.4
25488          java     268.7  617447.6       0.0     0.88     14.4
25495          java     271.0  596257.3       0.0     0.89     14.3
25492          java      89.5  607969.2       0.0     0.88     14.2
```

Automatic NUMA balancing



```
  PID          PROC   RMA(K)    LMA(K)    RMA/LMA      CPI    *CPU%
26586          java  120637.5  342139.0       0.4     1.13     13.4
26590          java   18820.7  514351.1       0.0     0.91     13.4
26587          java  158040.0  317038.3       0.5     1.13     13.2
26589          java   85090.3  395132.1       0.2     1.03     13.0
26584          java  100579.4  377078.7       0.3     1.02     12.9
26585          java   75059.3  399099.2       0.2     1.01     12.9
26583          java   48739.2  439377.6       0.1     0.98     12.8
26588          java   48514.7  443239.0       0.1     0.96     12.8
```

Higher RMA/LMA

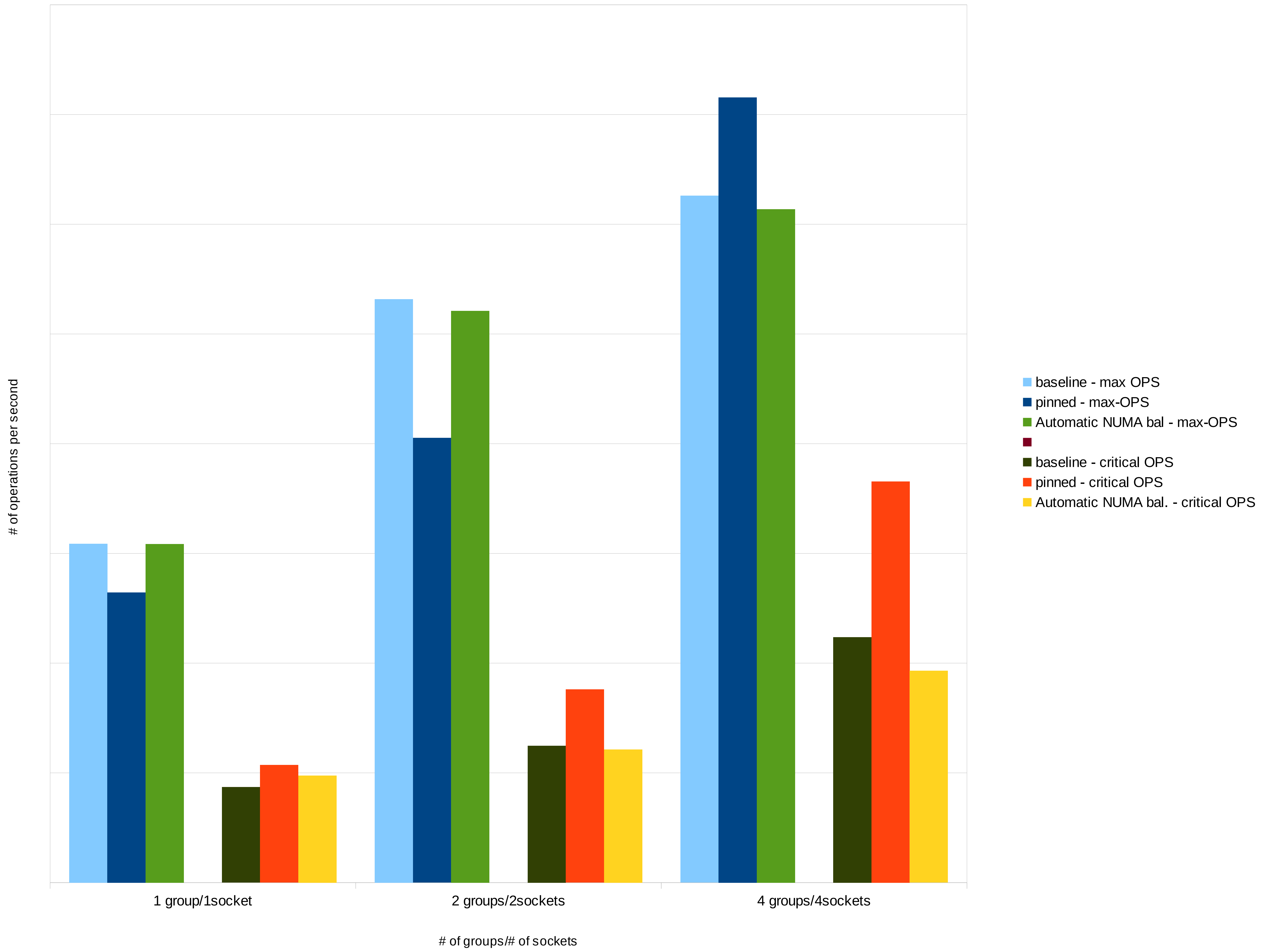
** Courtesy numatop v1.0.2*

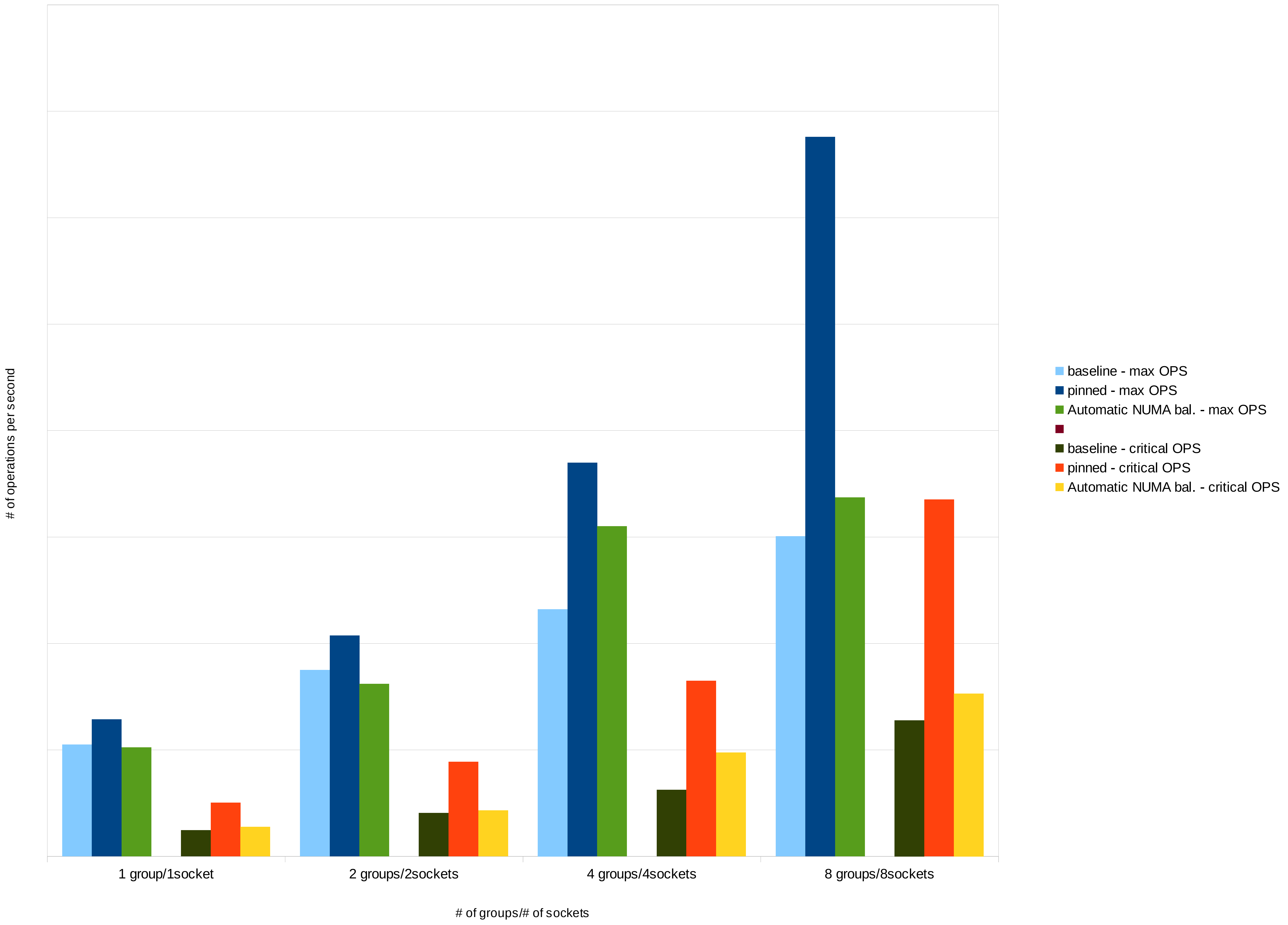
Multi-JVM server workload – bare-metal

(4-socket IVY-EX server vs. 8-socket IVY-EX *prototype* server)

Entities within each of the multiple Groups communicate with a Controller (using IPC) within the same host & the frequency of communication increases as the # of Groups increase

Two key metrics : Max throughput (max-OPS) with no constraints & Critical throughput (critical-OPS) under fixed SLA constraints

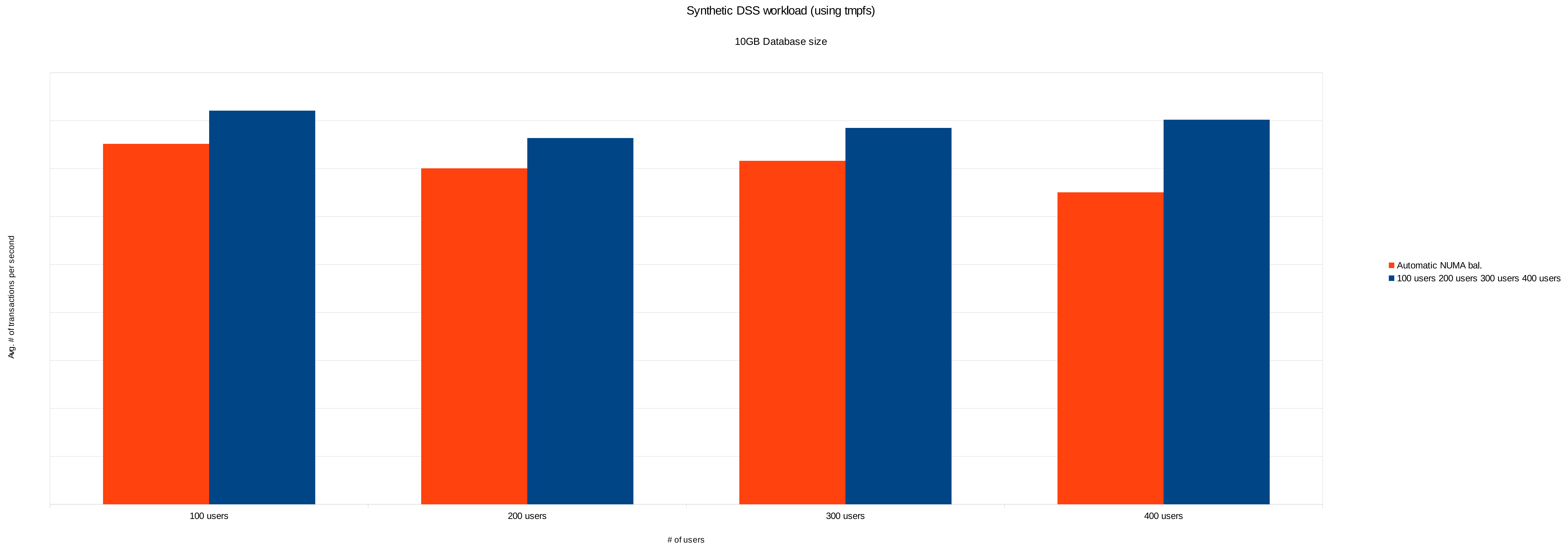




Some workloads will still need manual pinning !

Database workload - bare-metal

(4-socket IVY-EX server)



Static 2M huge pages used for SGA

~9-18% improvement in Average transactions per second with Automatic NUMA balancing

KVM guests

- Size of the guests continue to increase
  - Use cases include classic enterprise scale-up guests & guests in private cloud environments.
- [Ma*nual*] pinning/tuning of individual guests using libvirt/virsh (after taking into account host's NUMA topology) are required to achieve low overhead & predictable performance for workloads running in mid/large sized guests. This is especially true on larger scale-up hosts (e.g. >= 4 socket servers)

```
 <cputune>
   <vcpupin vcpu='0' cpuset='0'/>
   <vcpupin vcpu='1' cpuset='1'/>
   <vcpupin vcpu='2' cpuset='2'/>
   <vcpupin vcpu='3' cpuset='3'/>
…
…
…
   <vcpupin vcpu='29'
cpuset='29'/>

 </cputune>
```

```
<numatune>
    <memory mode='preferred' nodeset='0-1'/>
 </numatune>
```

- … but, its harder to live migrate such pinned guest across hosts – as similar set of backing resources may not be available on the target host (or) the target host may have a different NUMA topology !

KVM guests (contd.)

- Automatic NUMA balancing could help avoid the need for having to manually pin the guest resources
  - Exceptions include cases where a guest's backing memory pages on the host can't be migrated :
    - Guests relying on hugetlbfs (instead of THPs)
    - Guests with direct device assignment (get_user_pages())
    - Guests with real time needs (mlock_all()).
- As the guest size spans more than 1 socket it is highly recommended to enable Virtual NUMA nodes in the guest => helps the guest OS instance to scale/perform.

```
<cpu>
  <topology sockets='2' cores='15' threads='1'/>
  <numa>
    <cell cpus='0-14' memory='134217728'/>
    <cell cpus='15-29' memory='134217728'/>
  </numa>
</cpu>
```

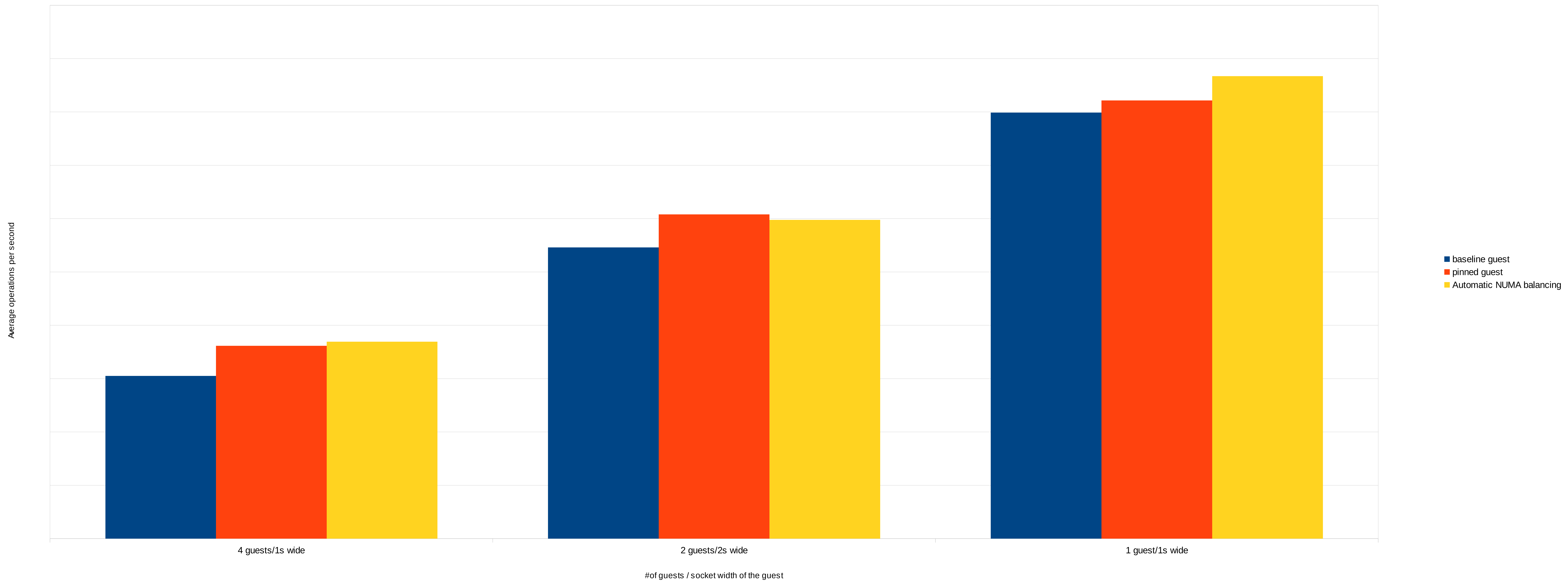
- Virtual NUMA nodes in the guest OS => Automatic NUMA balancing enabled in the guest OS instance.
    - Users can still choose to pin the workload to these Virtual NUMA nodes, if it helps their use case.

Experiments with KVM guests

- Platform used : 4-socket Ivy Bridge EX server
- Guest sizes:
    - 1s-wide guest → 15VCPUs/128GB
    - 2s-wide guest → 30VCPUs/256GB (2 virtual NUMA nodes)
    - 4s-wide guest → 60VCPUs/512GB (4 virtual NUMA nodes)
- Configurations tested: (different possible permutations, but we chose to focus on the following three)
    - Baseline guest *(=> a typical public/private cloud guest today)*
        - No pinning of VCPUs or memory,
        - No Virtual NUMA nodes enabled in the guest (even for >1s wide guest).
        - No Automatic NUMA balancing in Host or Guest OS.
        - Workload not pinned in the guest.
    - Pinned guest *(=> a typical enterprise scale-up guest today)*
        - VCPUs and memory pinned
        - Virtual NUMA nodes enabled in the guest (for >1s wide guest),
        - Workload is pinned in the guest (to the virtual NUMA nodes).
    - Automatic NUMA bal. guest : (=> “out of box” for any type of guest)
        - No manual pinning of VCPUs or memory,
        - Virtual NUMA nodes enabled in the guest (for >1s wide guest),
        - Automatic NUMA balancing in Host and Guest OS.
        - Workload not pinned in the guest. [a user could choose to pin a workload to the virtual NUMA nodes...without tripping over live migration issues.]

SPECjbb2005 in KVM guests

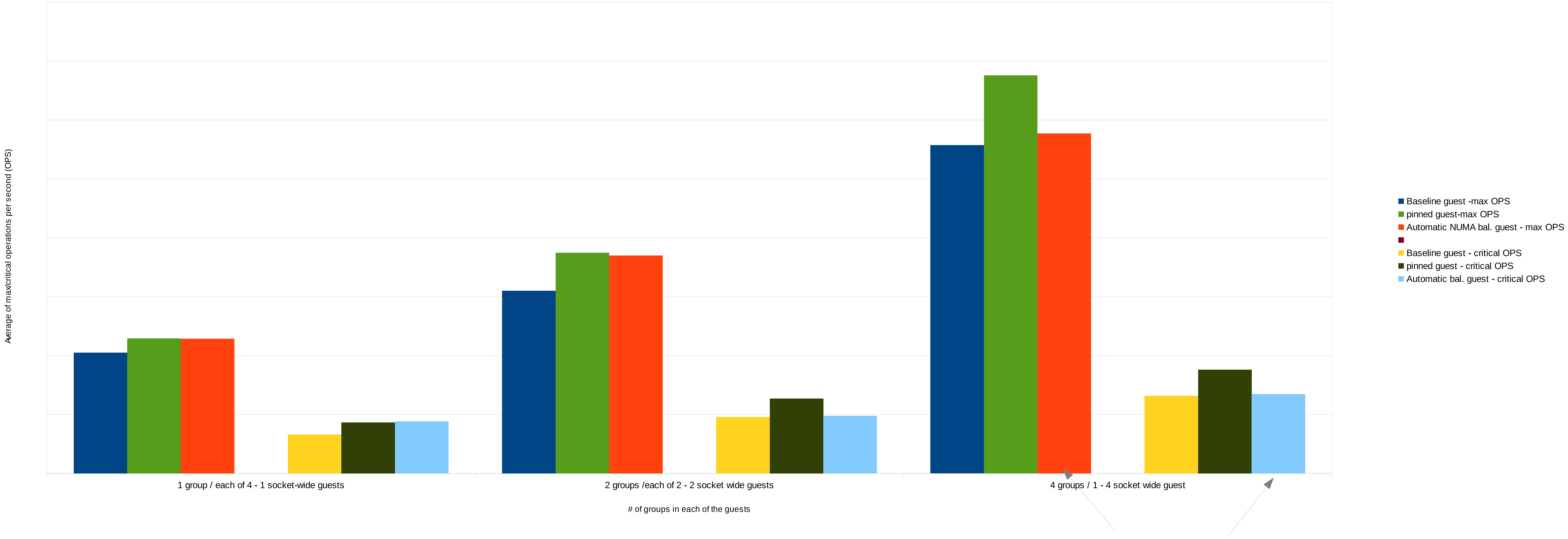
(4 socket IVY-EX server)



Automatic NUMA balancing case &
the Pinned guest case were pretty close (+/- 3%).

Multi-JVM server workload – KVM guests

(4-socket IVY-EX server)

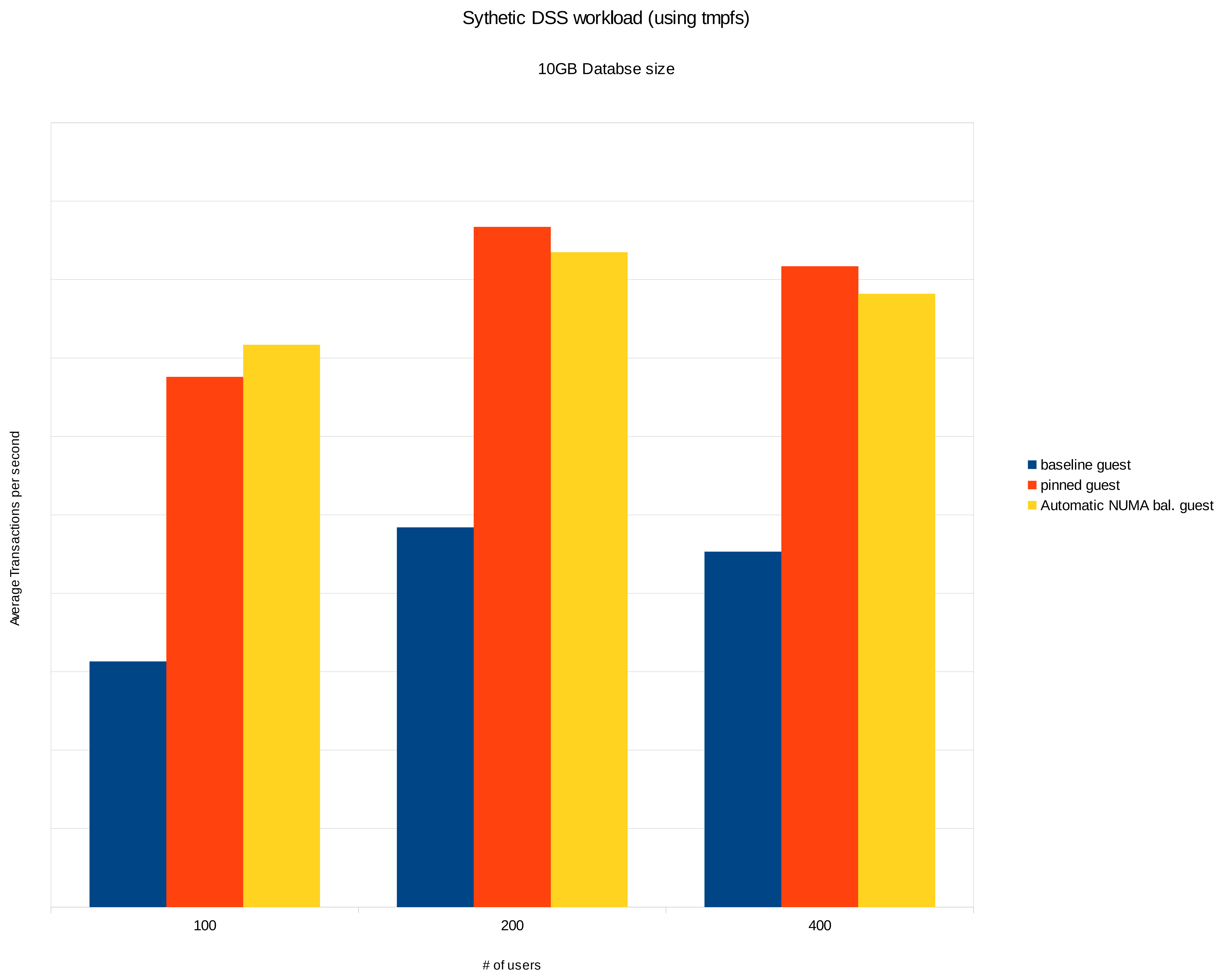


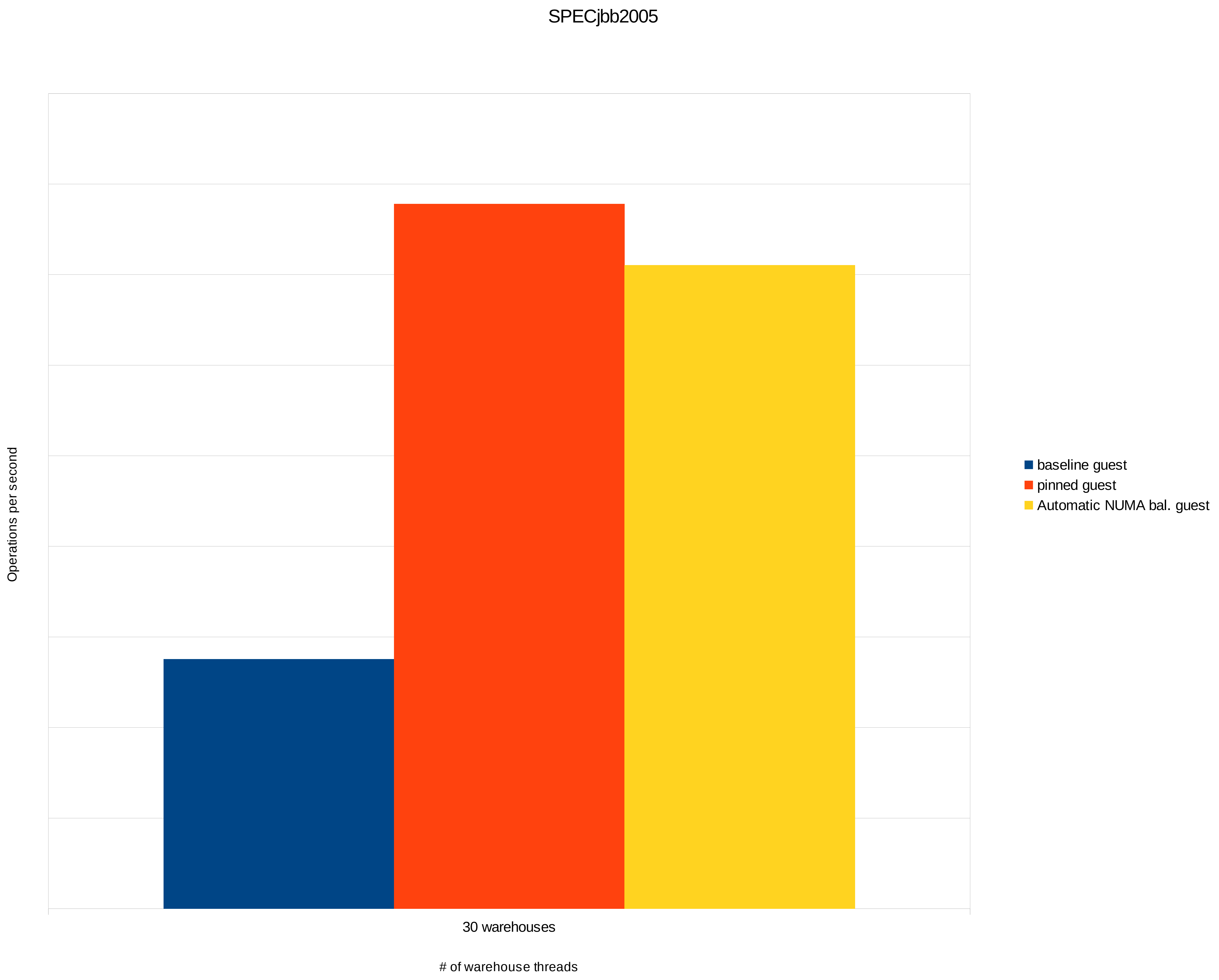
Delta between the Automatic NUMA balancing guest case & the Pinned case was much higher (~14% max-OPS and ~24% of critical-OPS)

Pinning the workload to the virtual NUMA nodes does help

KVM – server consolidation example

(Two 2-socket wide (30VCPU/256GB) guests each running a different workload hosted on 4 Socket IVY-EX server)





Automatic NUMA balancing case & the Pinned case were pretty close (~ 1-2%).

Future Developments

What can't it do (yet)?

NUMA balancing future considerations

- Complex NUMA topologies & pseudo-interleaving
- Unmovable memory
- KSM
- Interrupt locality
- Inter Process Communication

Complex NUMA topologies & pseudo-interleaving

- Differing distances between NUMA nodes
  - Local node, nearby nodes, far away nodes
  - Eg. 20% & 100% performance penalty for nearby vs. far away
- Workloads that are spread across multiple nodes work better when those nodes are near each other
- Unclear how to implement this
  - When is the second-best node no longer the second best?

NUMA balancing & unmovable memory

- Unmovable memory
  - Mlock
  - Hugetlbfs
  - Pinning for KVM device assignment & RDMA
- Memory is not movable ...
  - But the tasks are
  - NUMA faults would help move the task near the memory
  - Unclear if worthwhile, needs experimentation

KSM

- Kernel Samepage Merging
  - De-duplicates identical content between KVM guests
  - Also usable by other programs
- KSM has simple NUMA option
  - “Only merge between tasks on the same NUMA node”
  - Task can be moved after memory is merged
  - May need NUMA faults on KSM pages, and re-locate memory if needed
  - Unclear if worthwhile, needs experimentation

Interrupt locality

- Some tasks do a lot of IO
  - Performance benefit to placing those tasks near the IO device
  - Manual binding demonstrates that benefit
- Currently automatic NUMA balancing only does memory & CPU
- Would need to be enhanced to consider IRQ/device locality
- Unclear how to implement this
  - When should IRQ affinity outweigh CPU/memory affinity?

Inter Process Communication

- Some tasks communicate a LOT with other tasks
  - Benefit from NUMA placement near tasks they communicate with
  - Do not necessarily share any memory
- Loopback TCP/UDP, named socket, pipe, ...
- Unclear how to implement this
  - How to weigh against CPU/memory locality?

Conclusions

- NUMA systems are increasingly common
- Automatic NUMA balancing improves performance for many workloads, on many kinds of systems
  - Can often get within a few % of optimal manual tuning
  - Manual tuning can still help with certain workloads
- Future improvements may expand the range of workloads and systems where automatic NUMA placement works nearly optimal