Virtflex: Automatic adaptation to NUMA topology change for OpenMP applications

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NUMA virtualization

Rack-scale computers

- Share-memory, each discrete device is a NUMA node (large number, up to ~50)
- Complex underlying NUMA topology
- Requires dynamic elastic guest NUMA topology to achieve high utilization rate

Current NUMA machine

- Small number of NUMA nodes 1~4
- Simple static guest NUMA topology
- VMs are forced to be pinned into a NUMA node or a small set of NUMA nodes

Lack of support for elastic guest NUMA topology

Hypervisor

- Lack of control for the amount of resources on each guest node
- Express dynamic guest NUMA topolgoy

Linux kernel

- Static ACPI table
  - Guest NUMA topolgoy is obtained at boot time and never changes
- AutoNUMA

  Only suitable in cases where most memory is in the right place. Slow to adapt to topology changes

User application

- Libnuma place memory and threads in a static way, e.g. using specific node #
- Need to rewrite source code to fit dynamic topology

Virtualization background

- vCPU and vCPU hotplug
- Two dimentional address translation
- Ballooning

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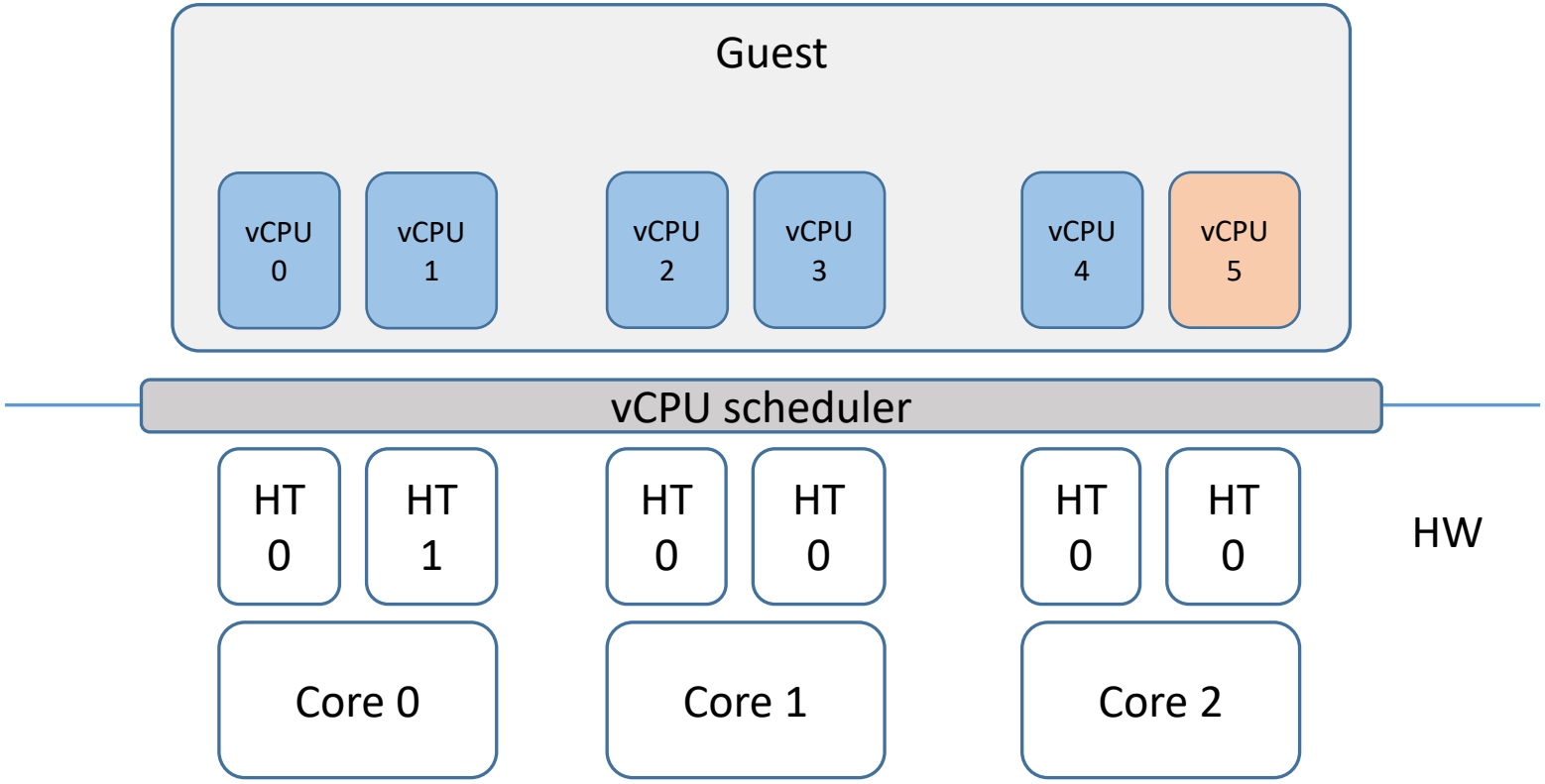

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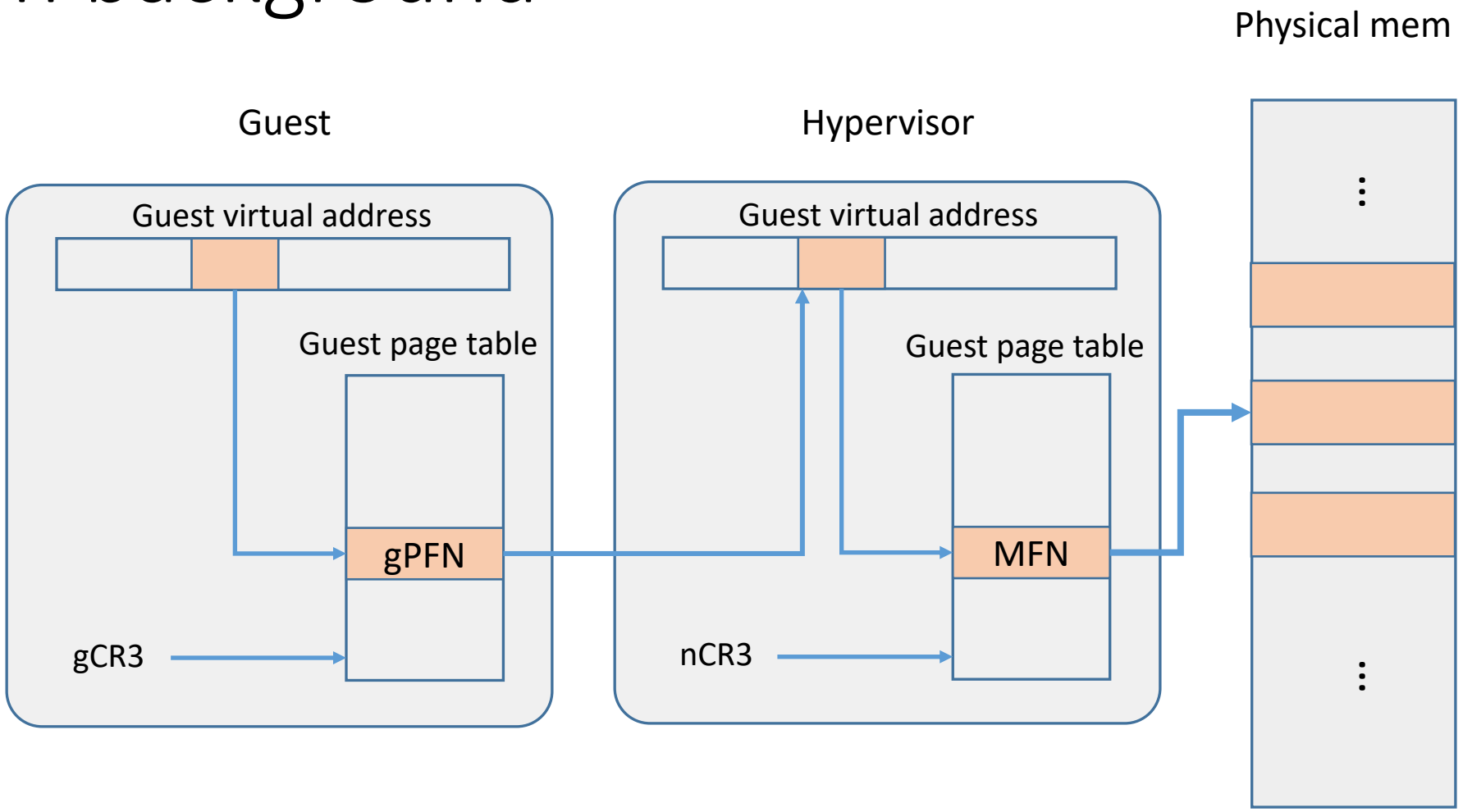

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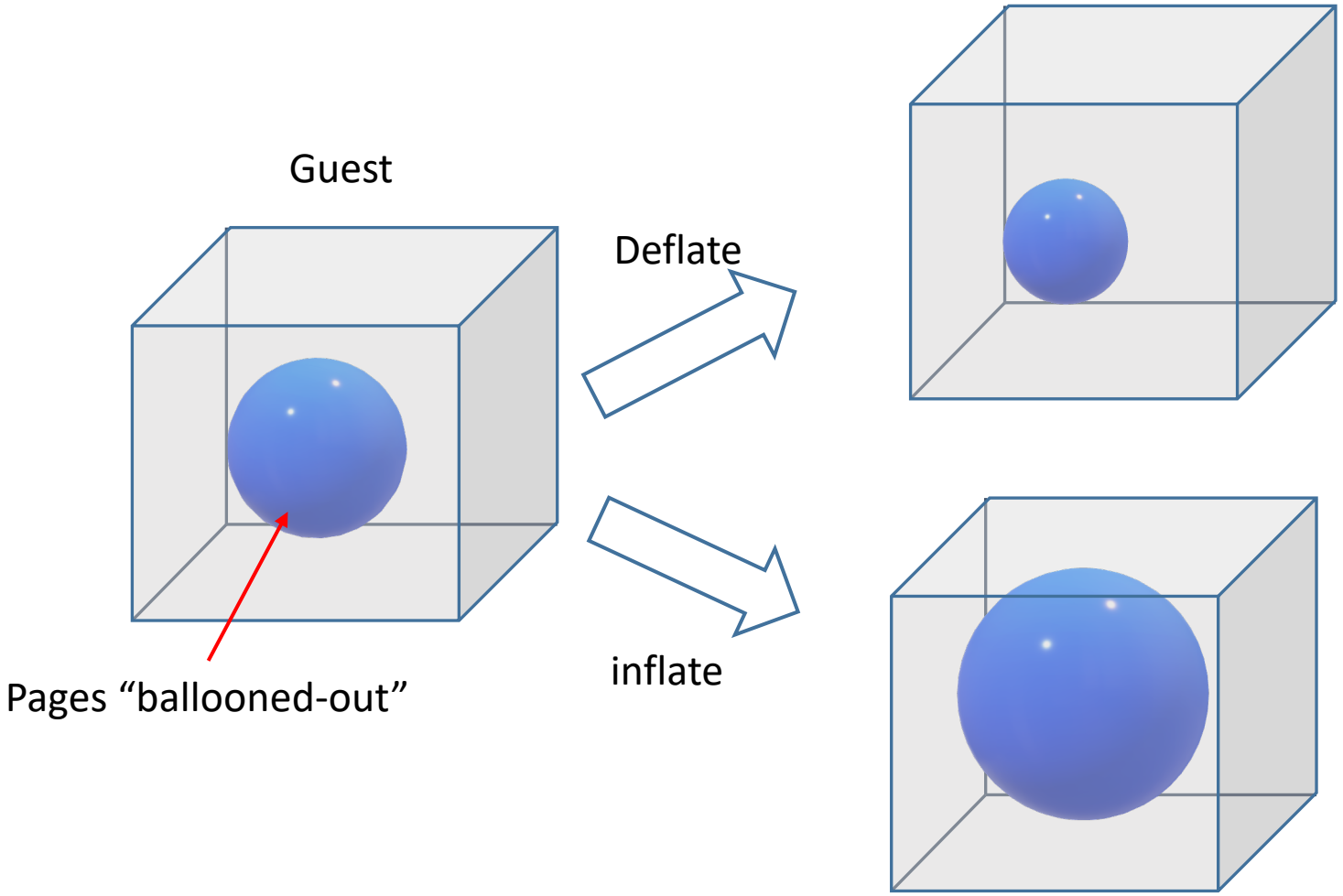
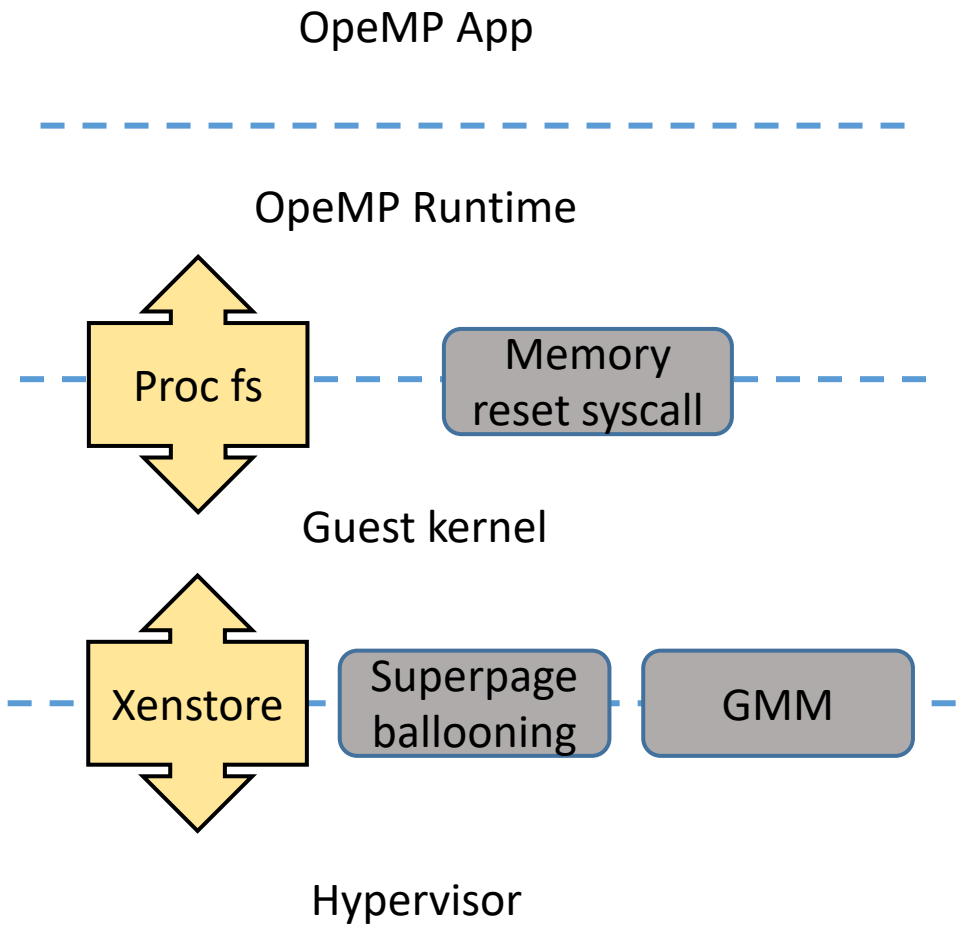


Virtflex

Virtflex

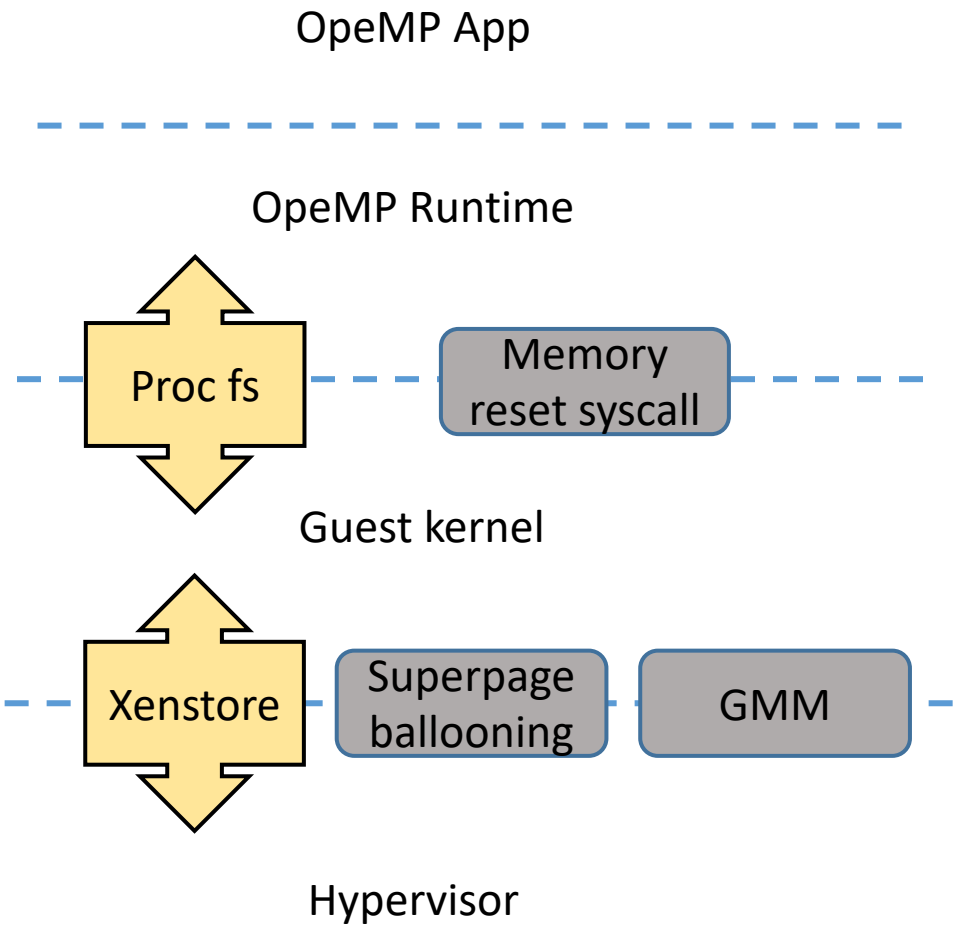


- Virtflex is a multilayered system for enabling unmodified OpenMP applications to adapt automatically to NUMA topology changes.
- Enhancement across the Xen hypervisor, Linux kernel and OpenMP runtime

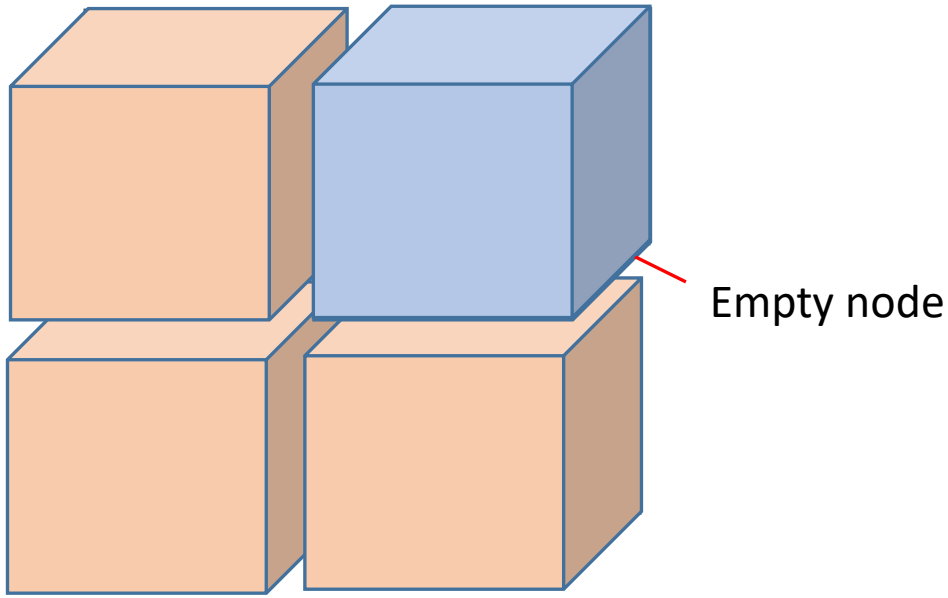
Related works

Virtualization on NUMA machines	Hiding NUMA topology from the guests	Rao [9], Rao [10], Liu [11], Wu [12] improve NUMA vCPU scheduling or memory placement at the hypervisor level.
	Exposing guest NUMA topology	Bui et al [14] abandoned the ACPI interface and propose another interface that allow guest kernel to get notification when topology changes
OpenMP optimization on NUMA machine	Olivier [1], Durand [2], Muddukrishna[3] improved the loop/task scheduler on NUMA machines Broquedis et al. [8] further developed interfaces to maintain thread-memory affinity for OpenMP applications on NUMA machines. Uses next-touch to migrate memory to the correct NUMA node, but it requires guidance from the programmer	

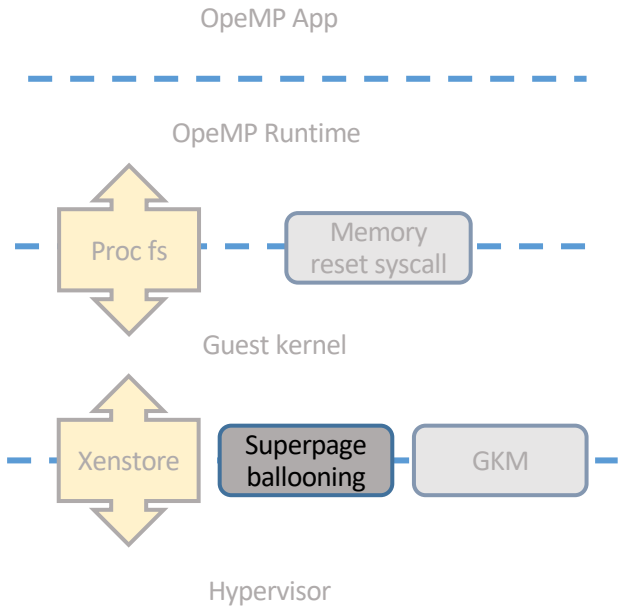
Elasticity of guest NUMA topology

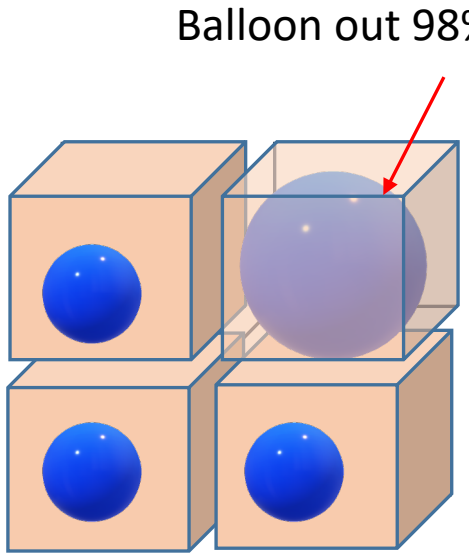


- Efficient adding /removing node



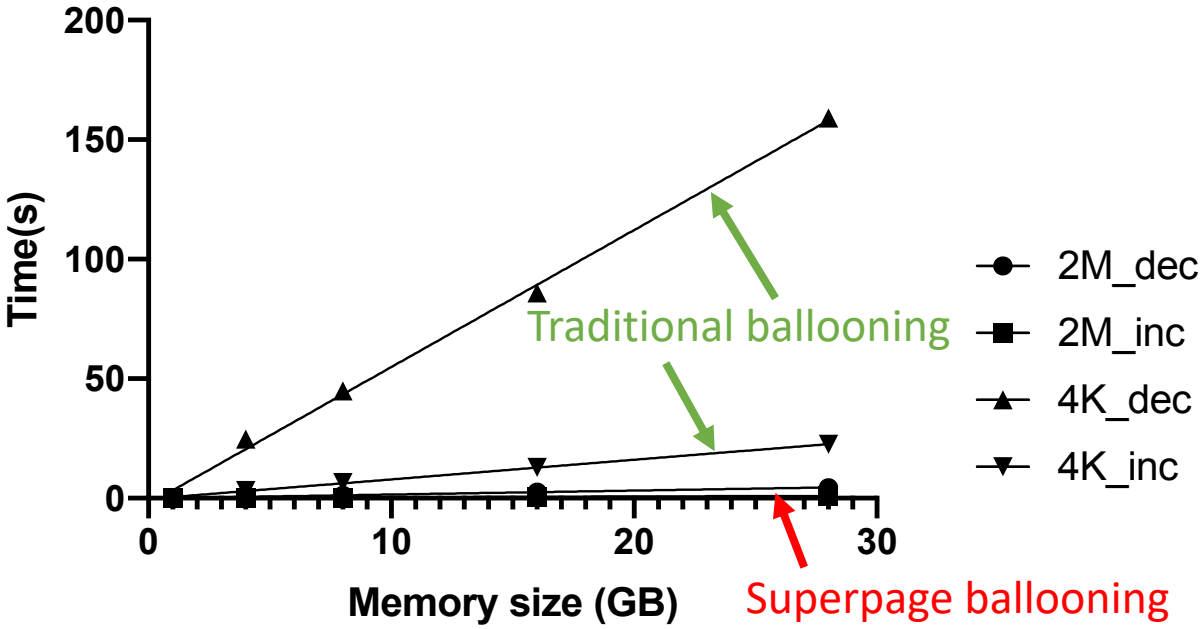
Make topology change fast (NUMA-aware Superpage ballooning)





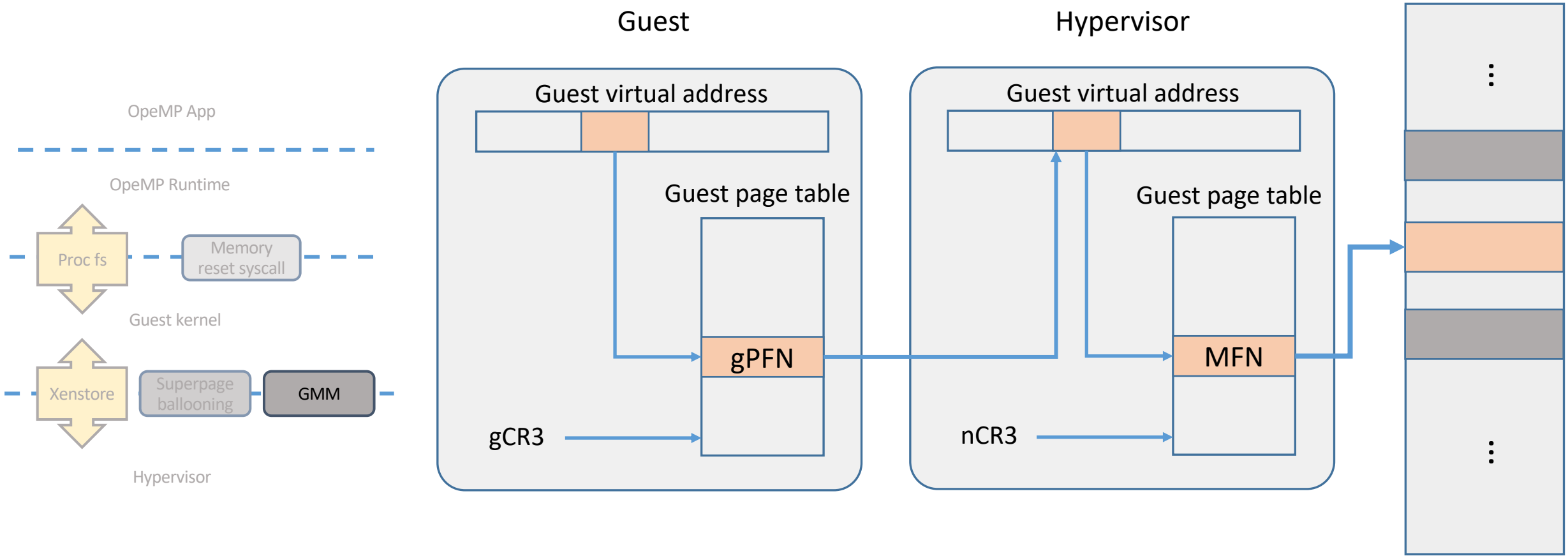
- ~~Not NUMA aware~~
- NUMA awareness of ballooning
  - Each node contains one balloon
- ~~Slow~~
- Superpage ballooning
  - Use superpage for inflation and deflation

Superpage ballooning performance



- Superpage ballooning outperform ballooning by up to 30X
- Decrease reservation more expensive than increase reservation

Make topology change complete (Guest Memory Migraion GMM)



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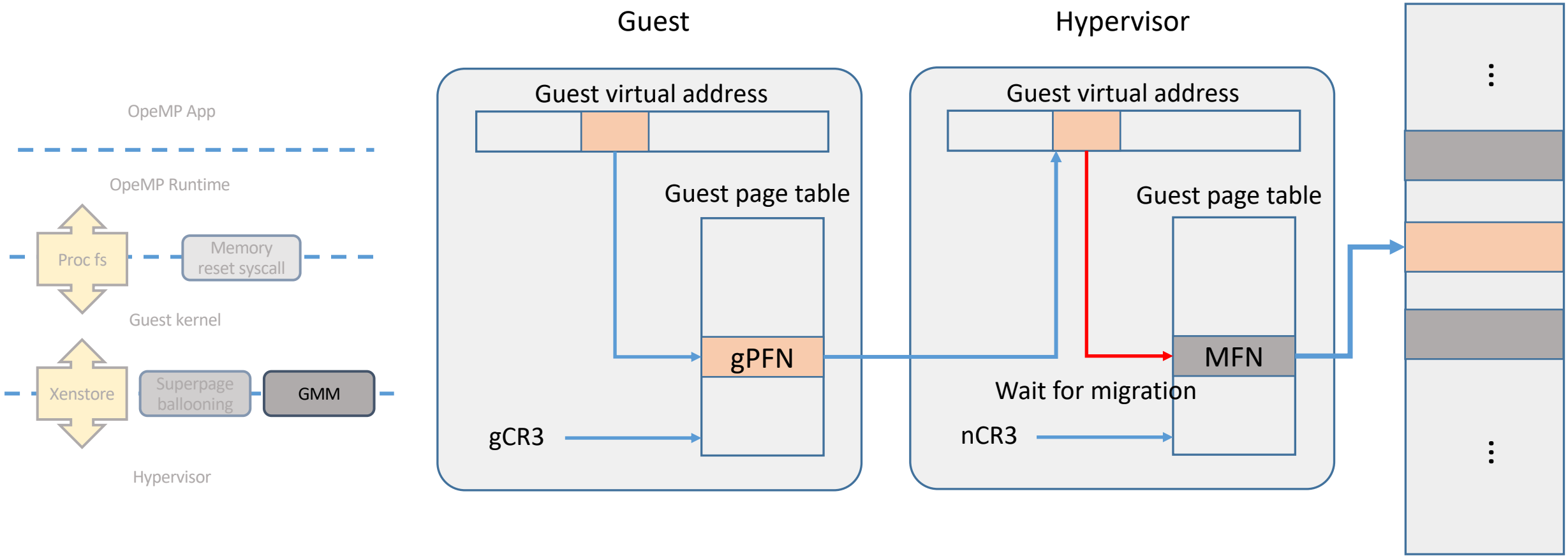

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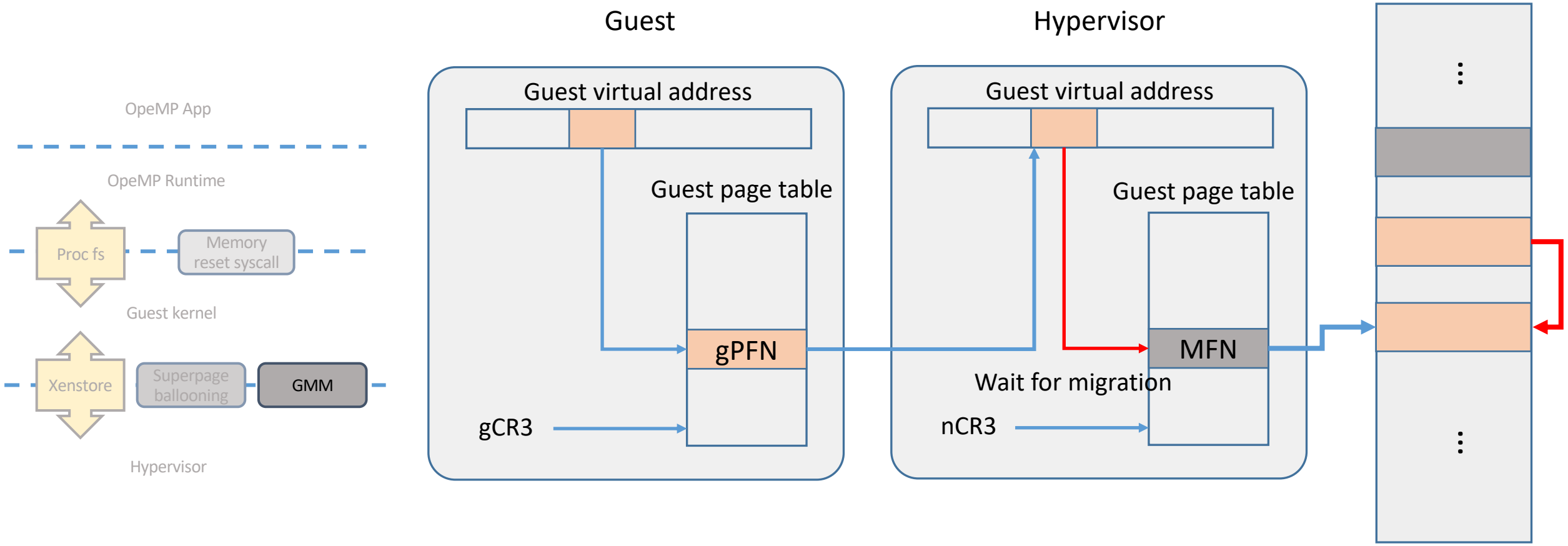

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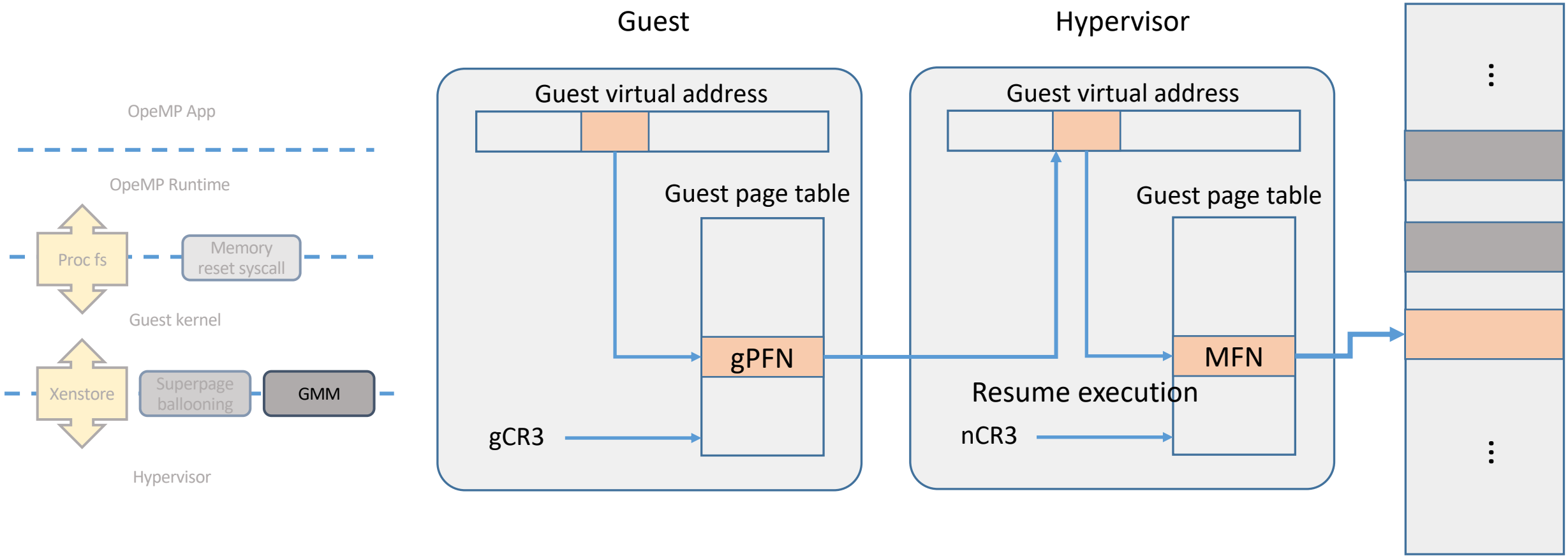
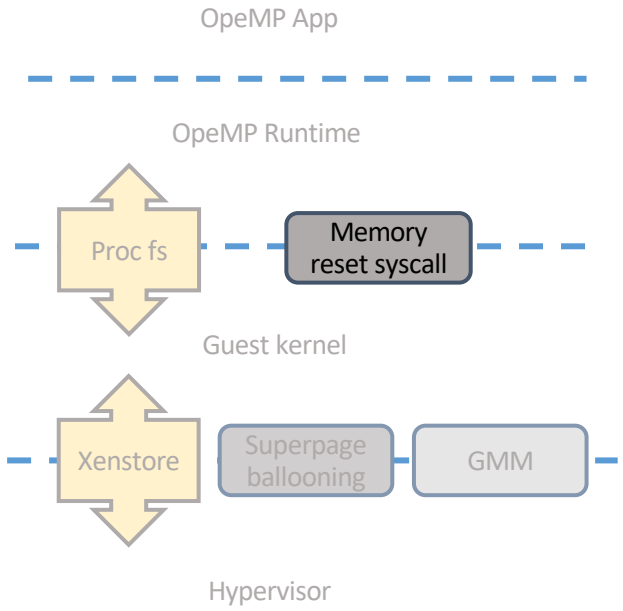
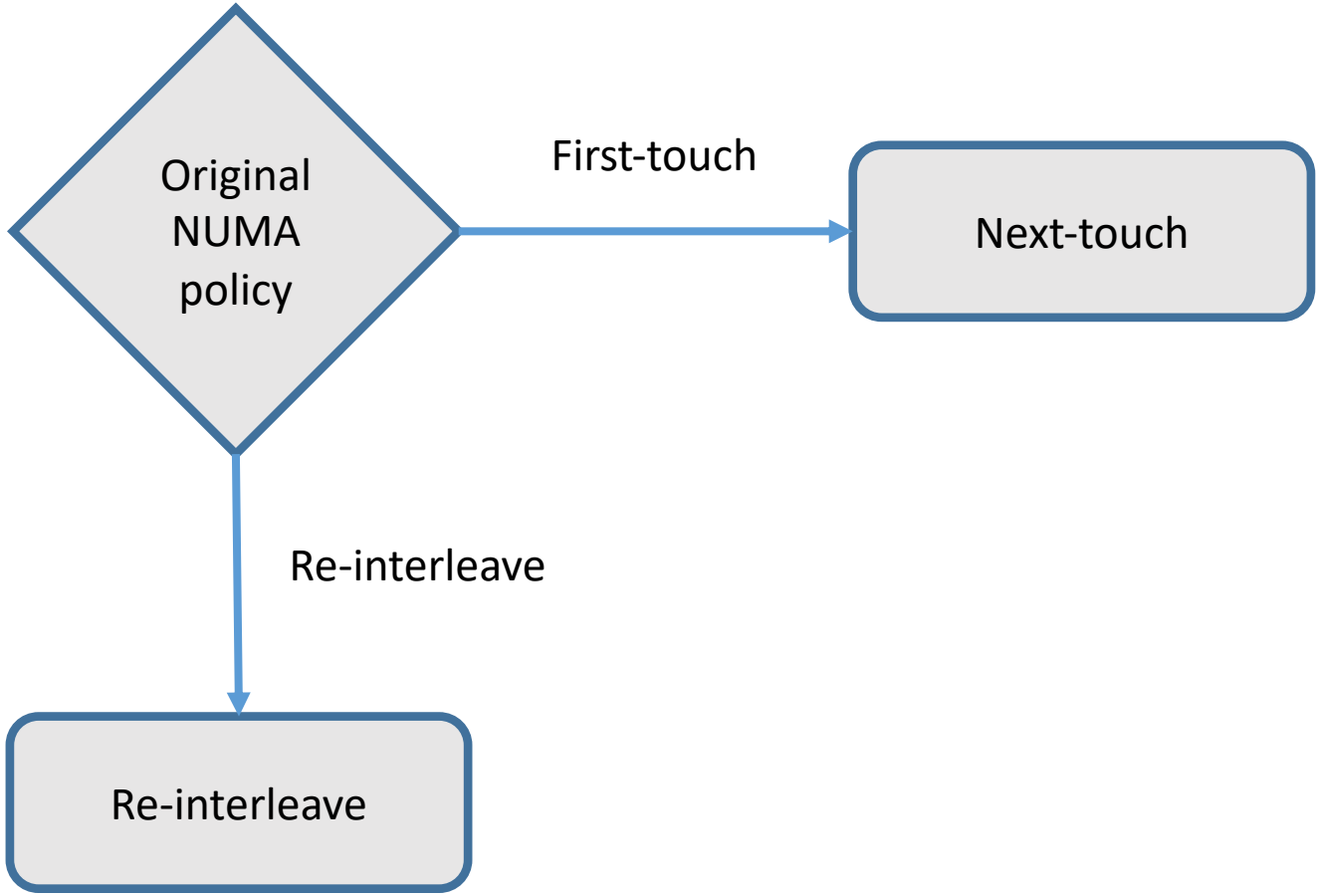


Changes to OpenMP runtime (~200 loc)

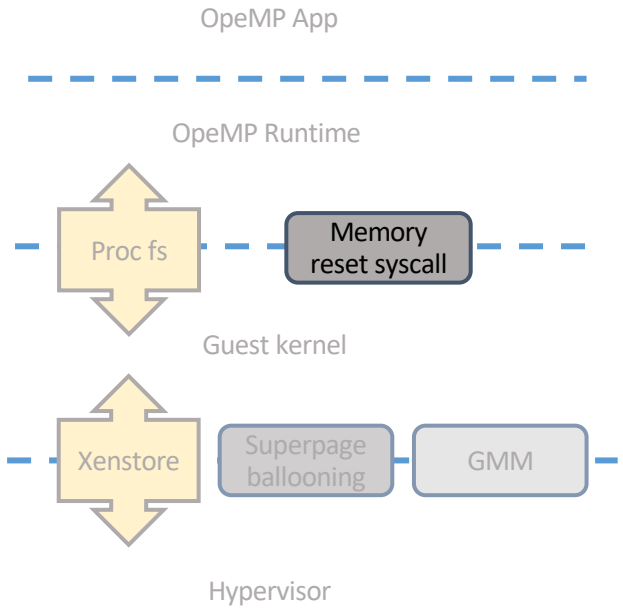
- Topology change notification:
  - Check topology version at the beginning of each parallel session.
- Thread adaptation:
  - Uses OMP_DYNAMIC to dynamically change number of threads
  - Reassign thread affinity on OMP_PLACES if necessary
- Memory adaptation:
  - Issues memory reset system call before launching threads

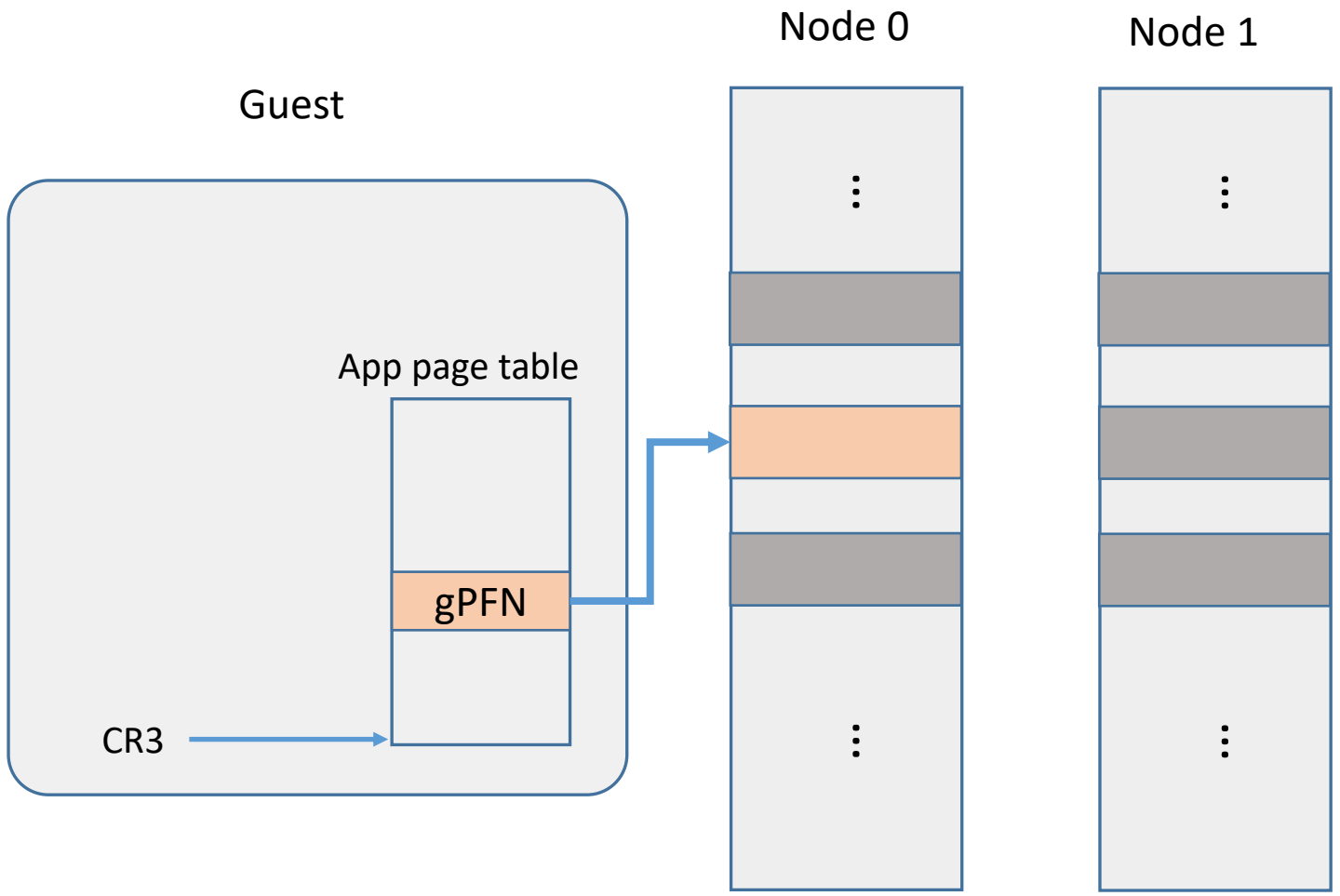
Application adapt to topology change (Memory reset syscall)





Application adapt to topology change (Next-touch)





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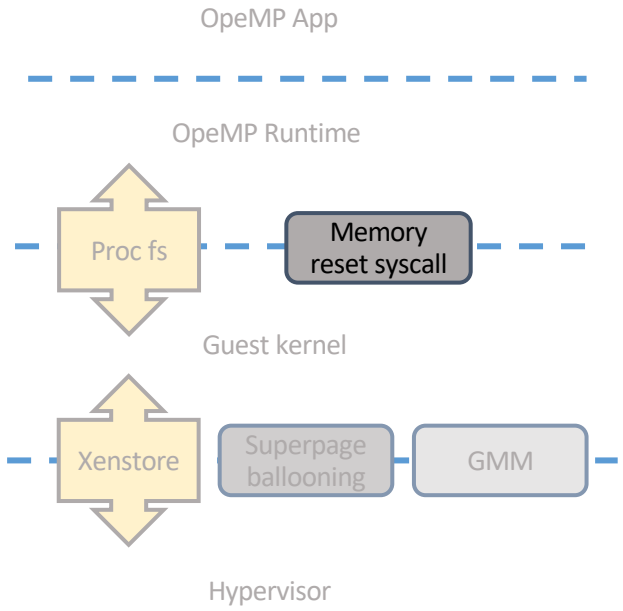

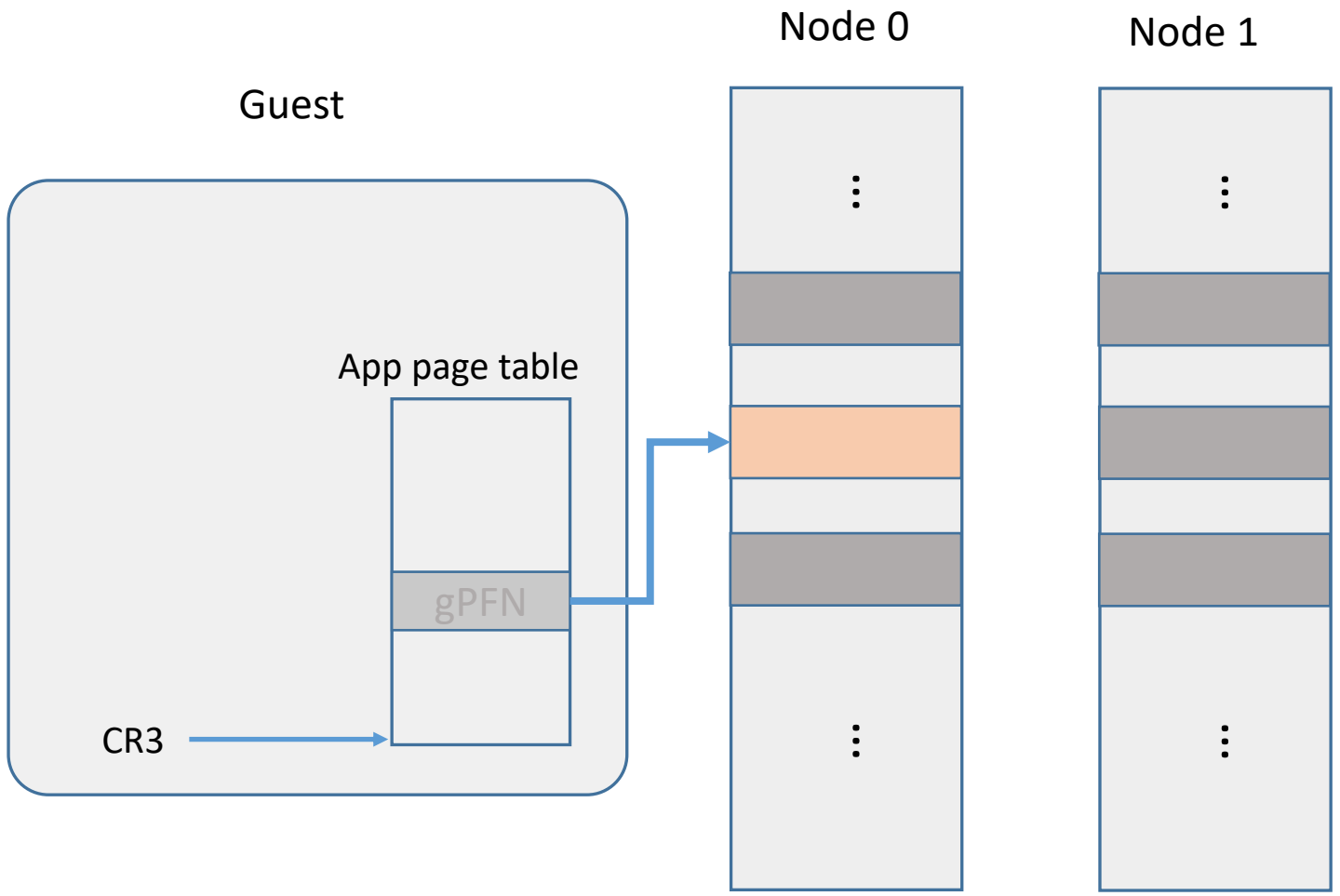

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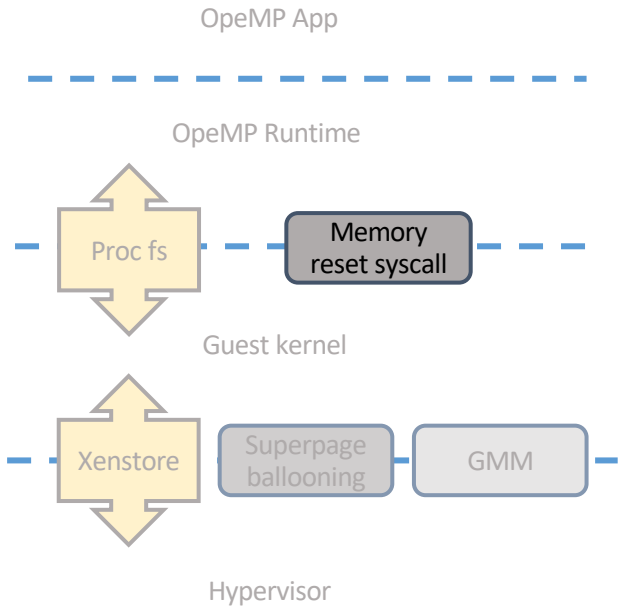

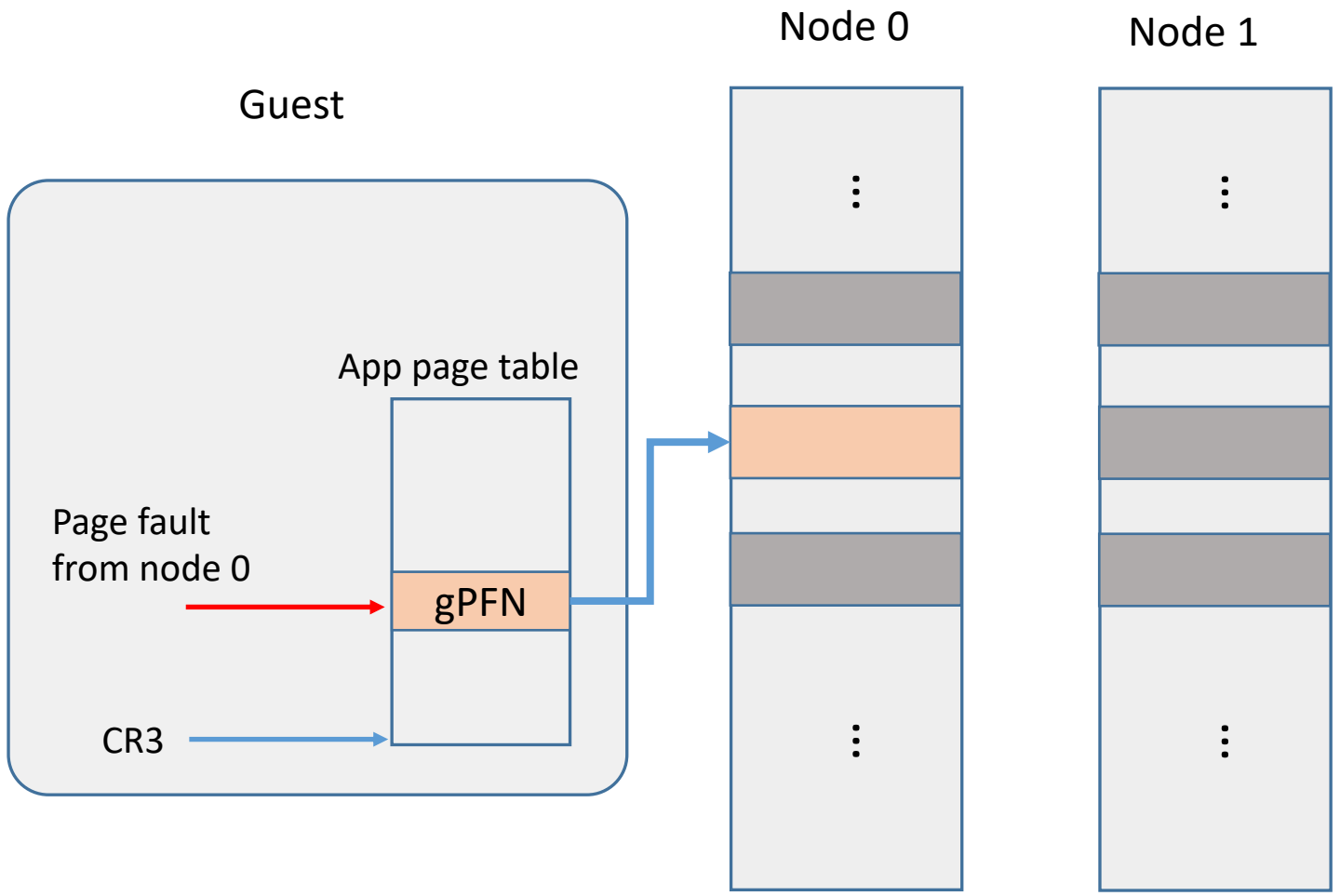

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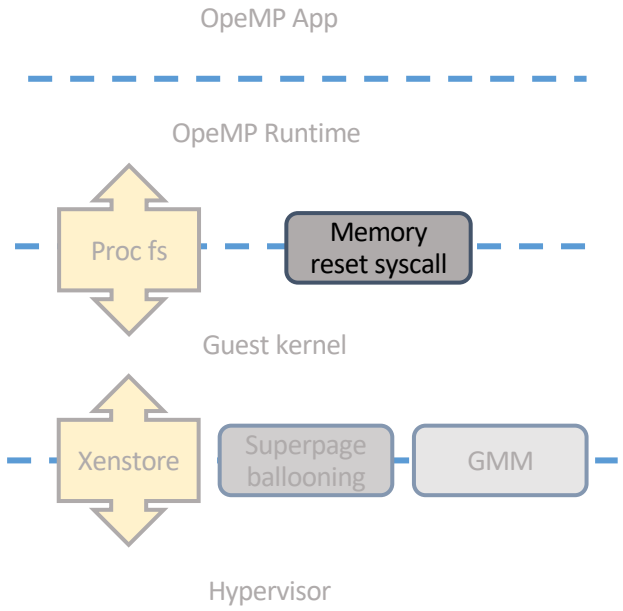

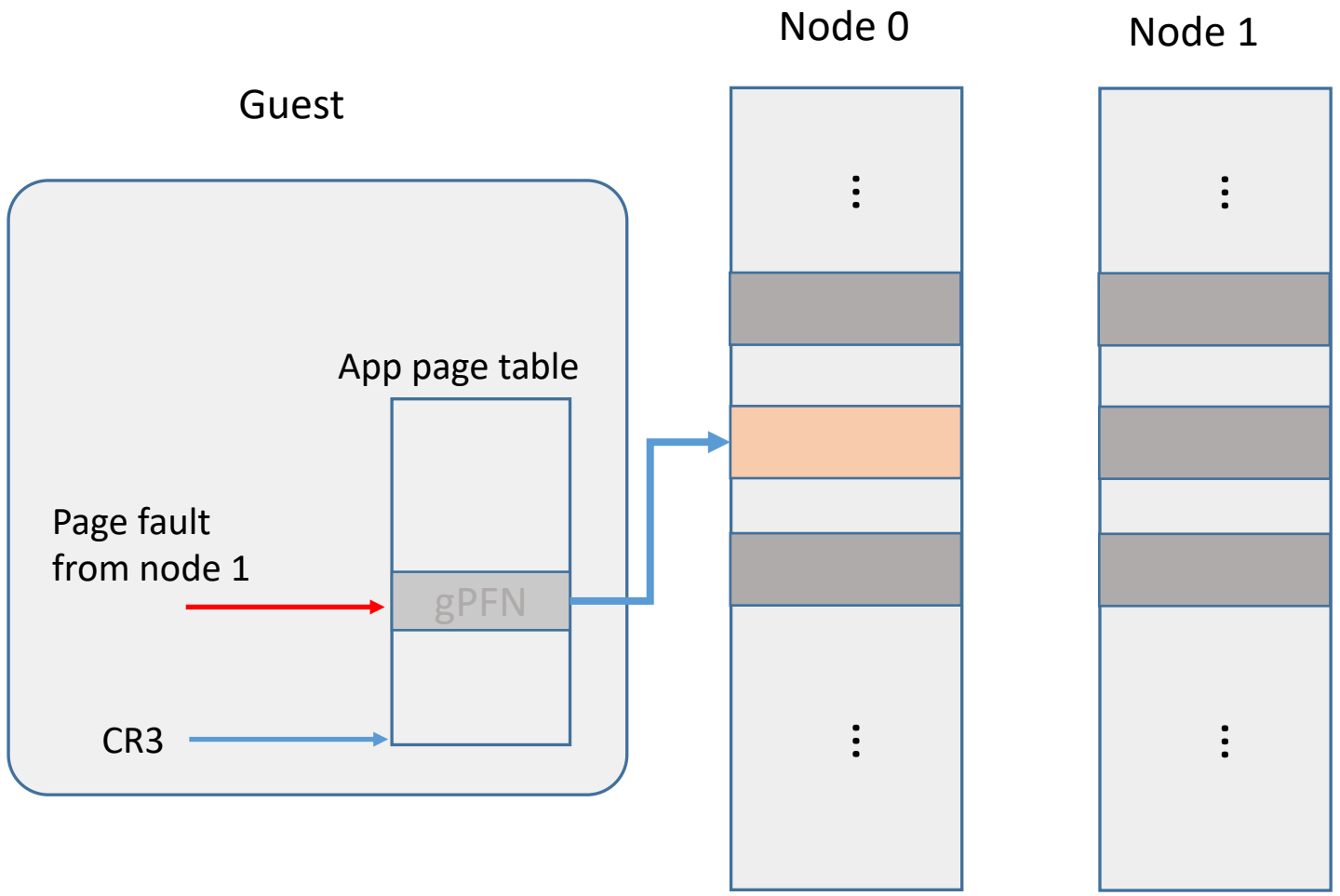

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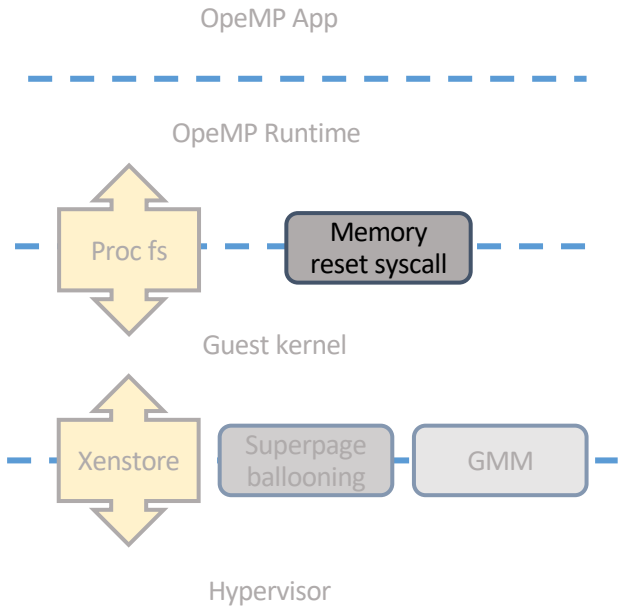

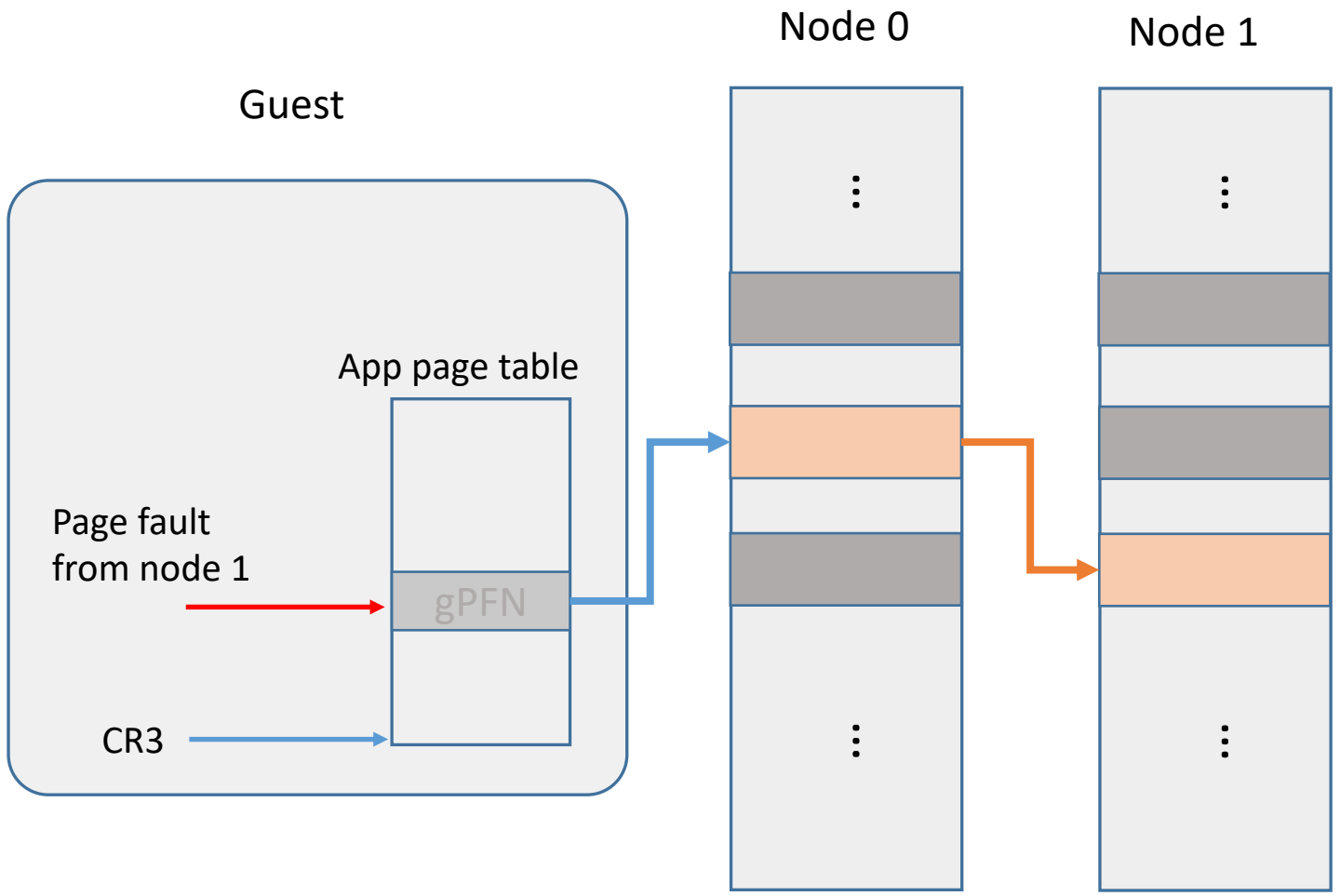

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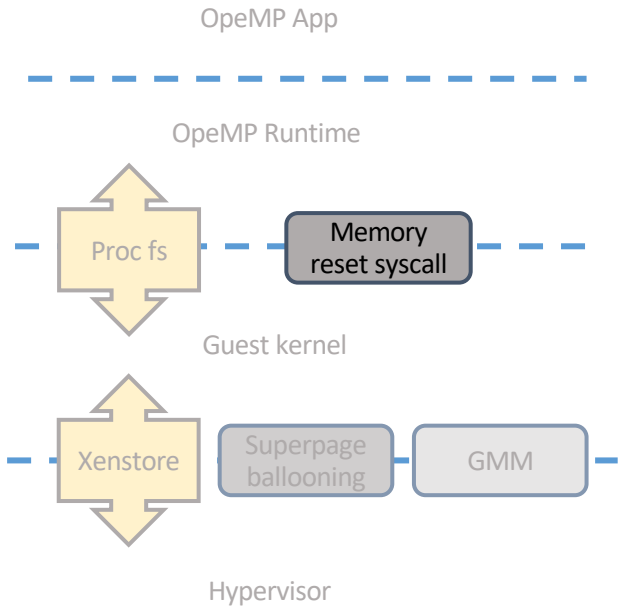

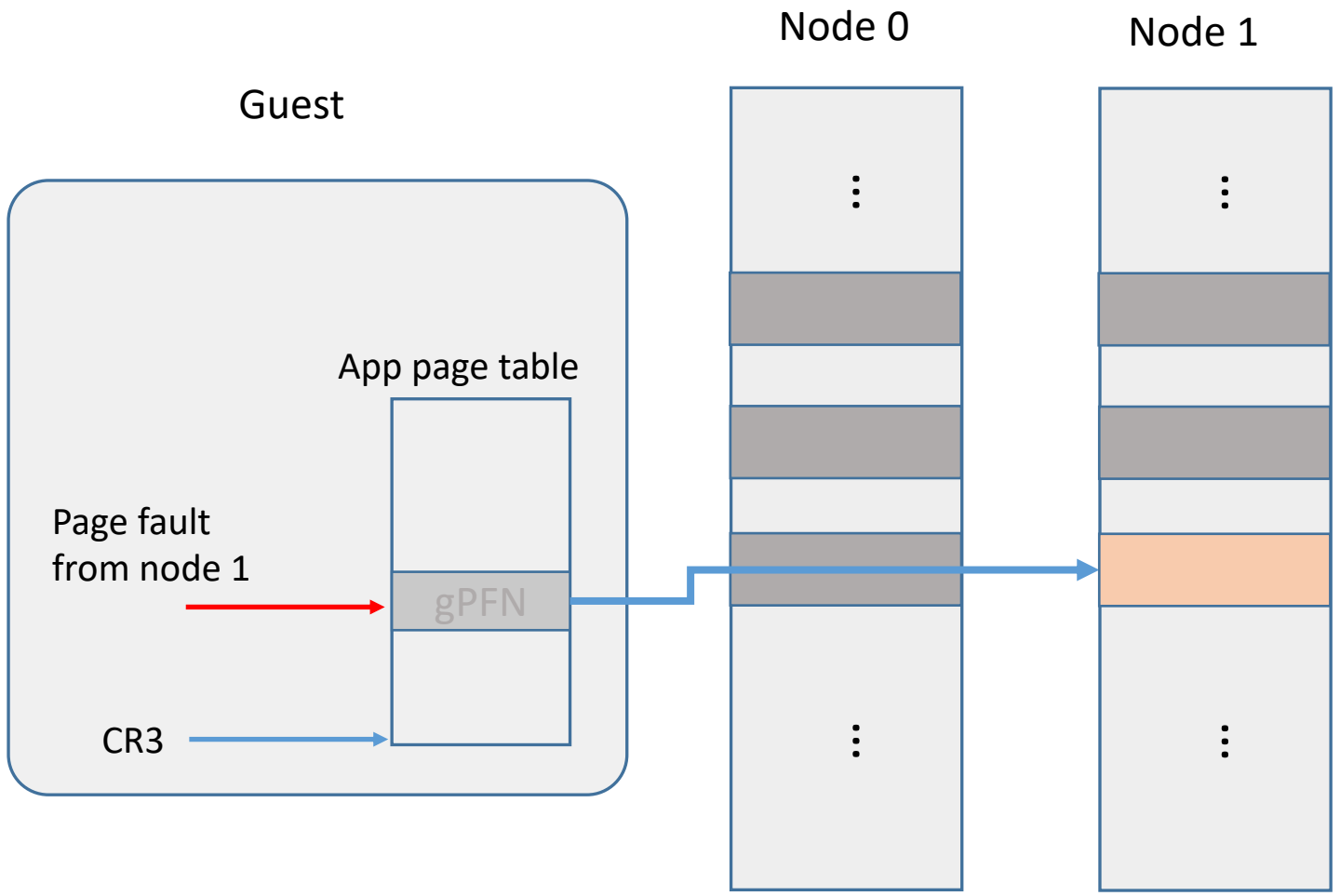

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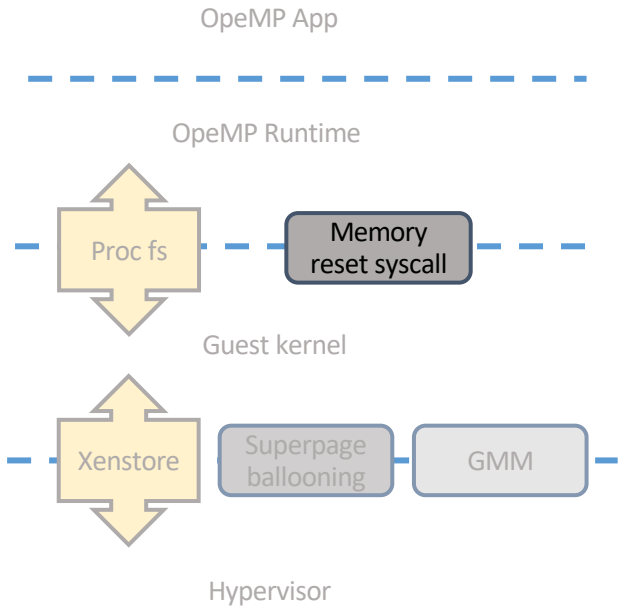
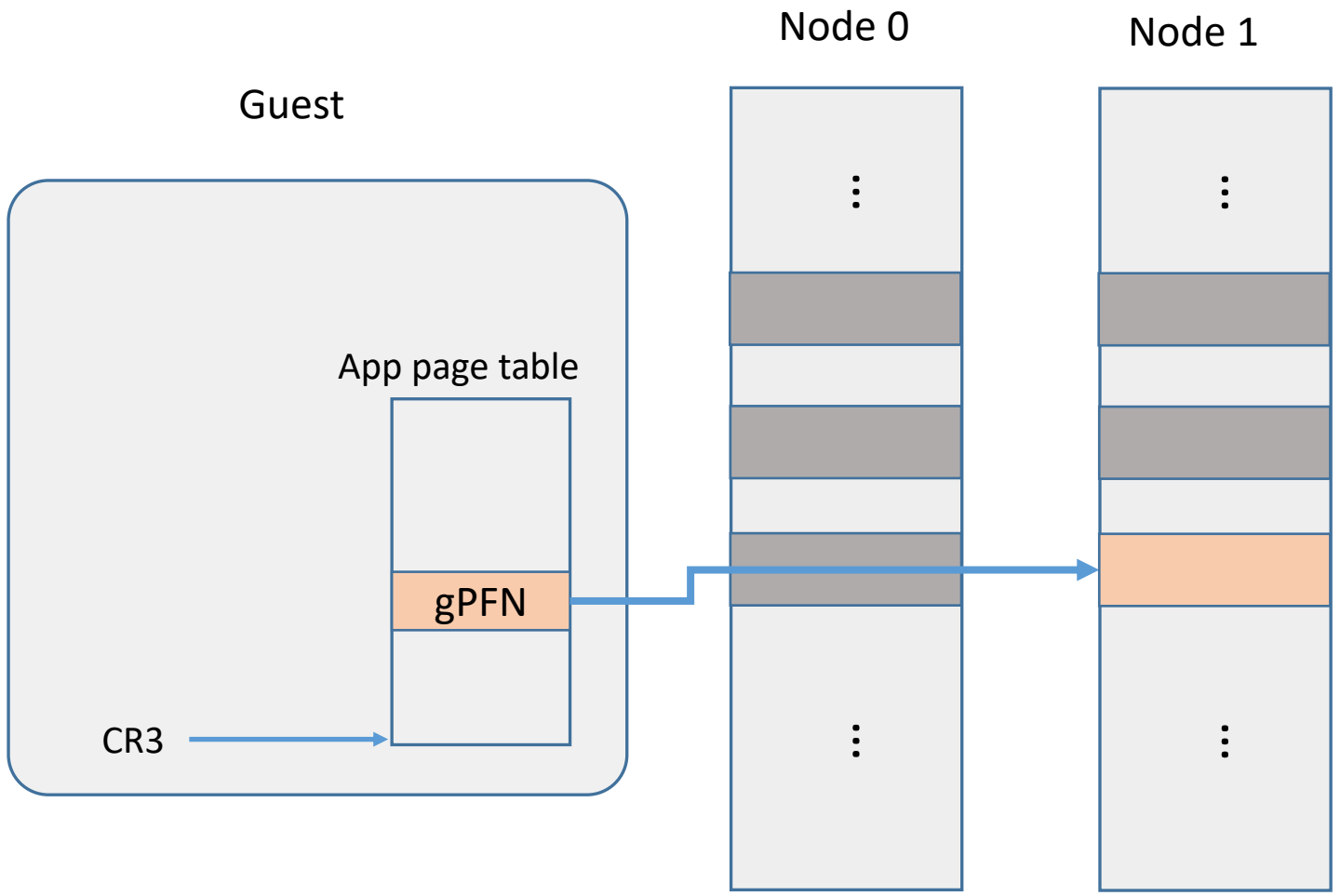




Re-interleave

- Relocate interleaved memory pages to the new set of available nodes after topology change in a round-robin way.
- Does not requires page fault to initiate the migration
- Two versions available, serial version and parallel version

Evaluation

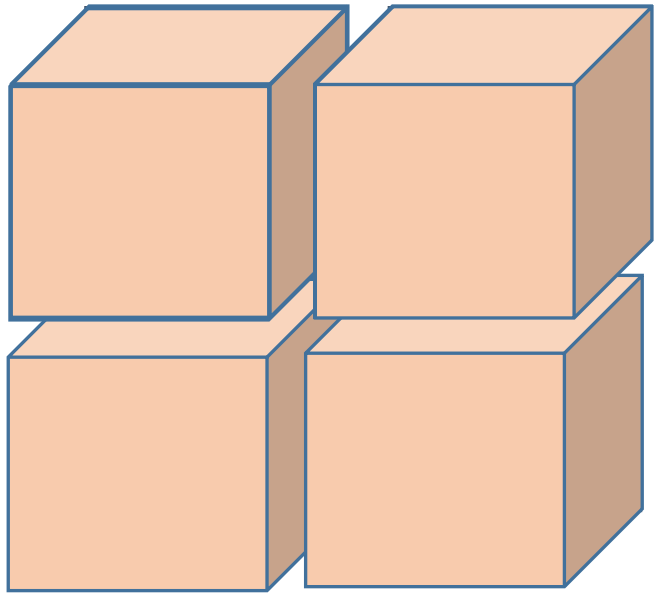
Experiment setup

- Environment:
  - AMD EPYC 7551p, 32 cores, 64 hardware threads
  - 4 NUMA nodes
  - Each node has 2666 MHz DDR4 channels with 16GB of memory
  - AMD’s Infinity Fabric max bandwidth of 21.325 GB/s
  - Xen 4.11 and Linux 4.18 with GCC 7.3

Experiment setup

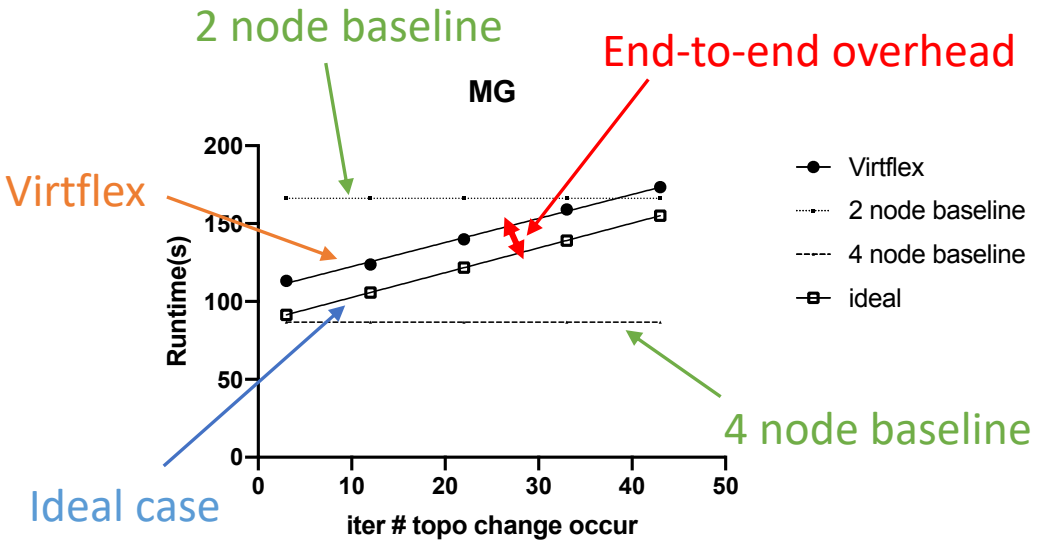
- Benchmarks:
  - NPB 3.3.1, Parsec 3.0, HPC Challenge's RandomAccess ("GUPS")
- Two scenarios
  - Adding node
  - Removing node

End-to-end experiment (topology expansion)



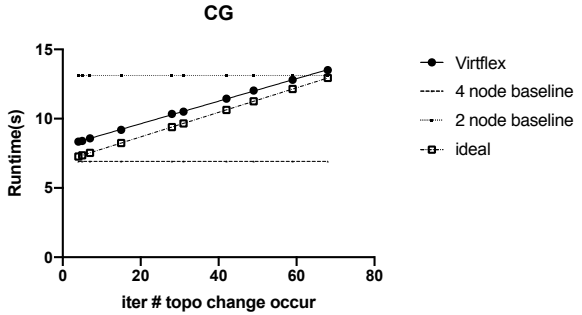
- VM booted up 2 NUMA nodes
- Application starts
- Expand topology, 2 other nodes are populated

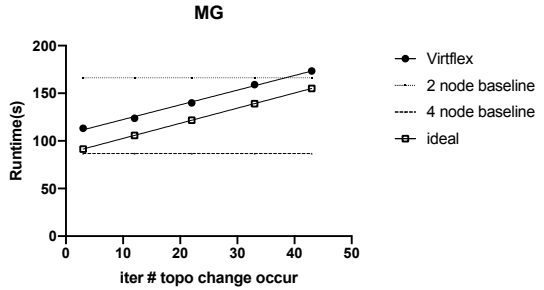
Evaluation (adding nodes)

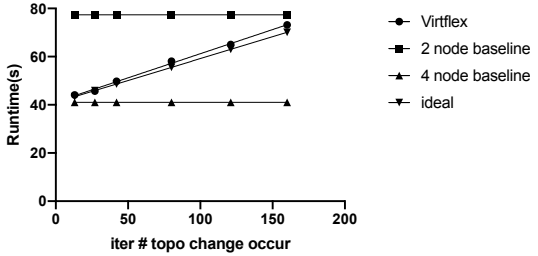


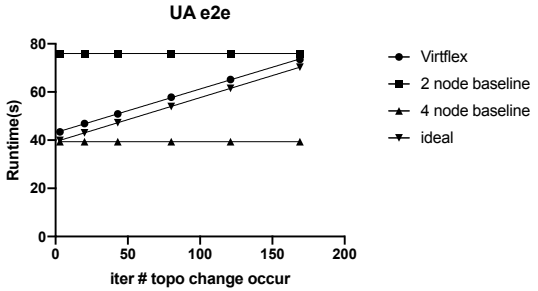
- End-to-end topology change adaptation overhead is on average 7.27%

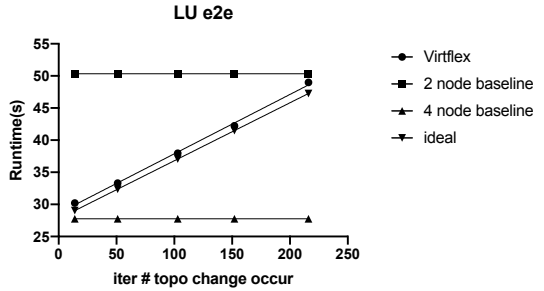
More results

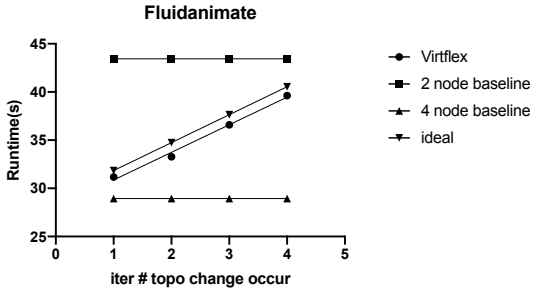




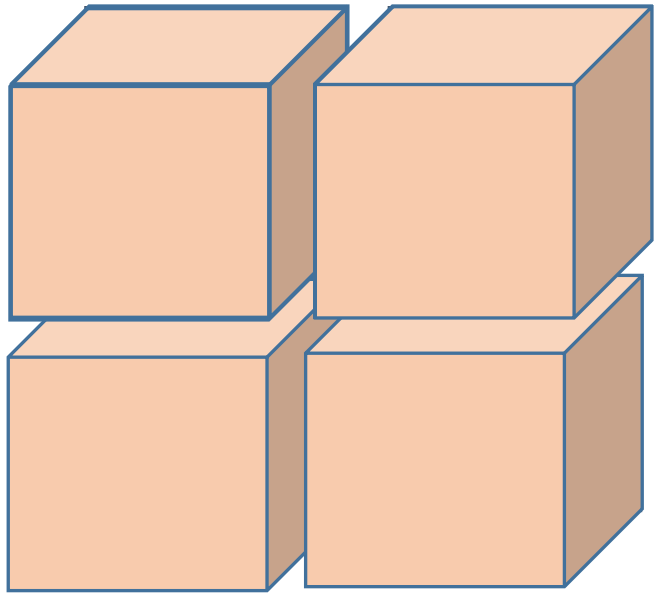








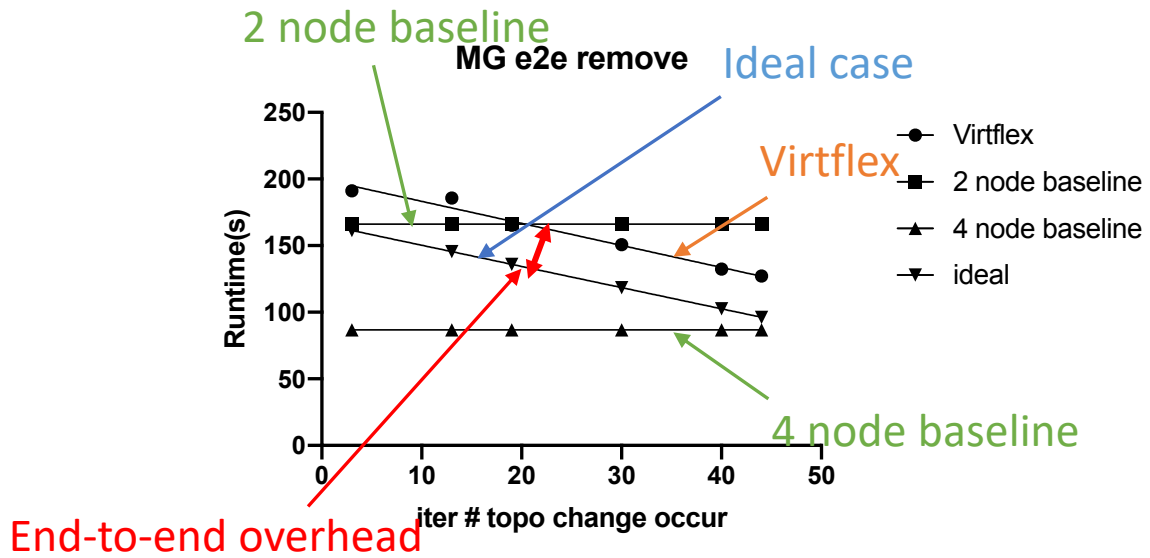
End to end experiment (topology shrinking)



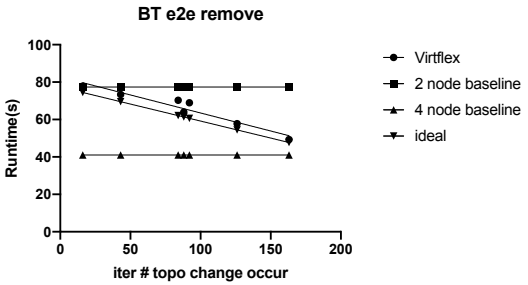
- VM booted up with 4 fully-blown nodes
- Application starts
- Shrinking topology, 2 nodes are de-populated

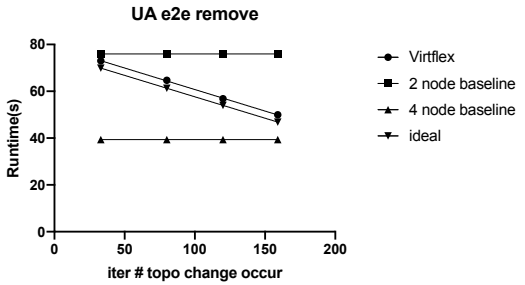
Evaluation (removing nodes)

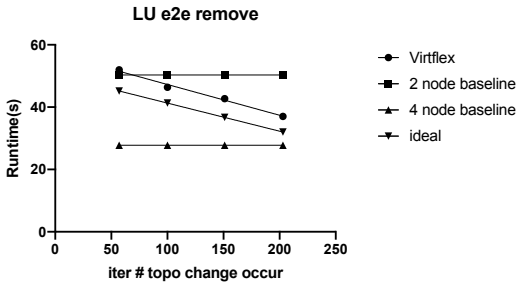
- The average overhead for the remove case is 19.39%.
  - Inflating balloon takes longer
  - There are less CPU cores doing the migration in the removing case

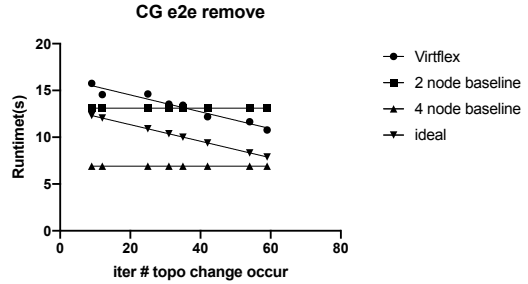


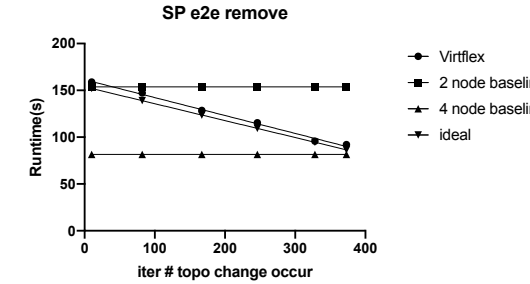
More results

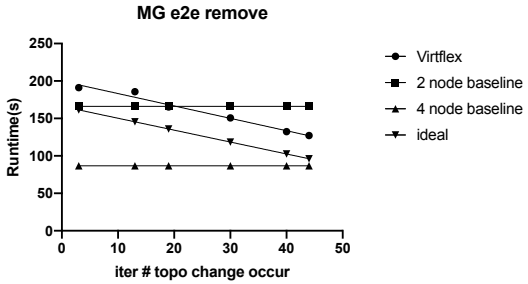












Conclusion

- Virtflex allows un-modified OpenMP applications to adapt automatically to NUMA topology changes with low overhead.
  - NUMA-aware Superpage ballooning changes topology fast
  - Guest memory migration changes topology completely
  - Memory reset syscall allow application to adapt with ease

Selected References

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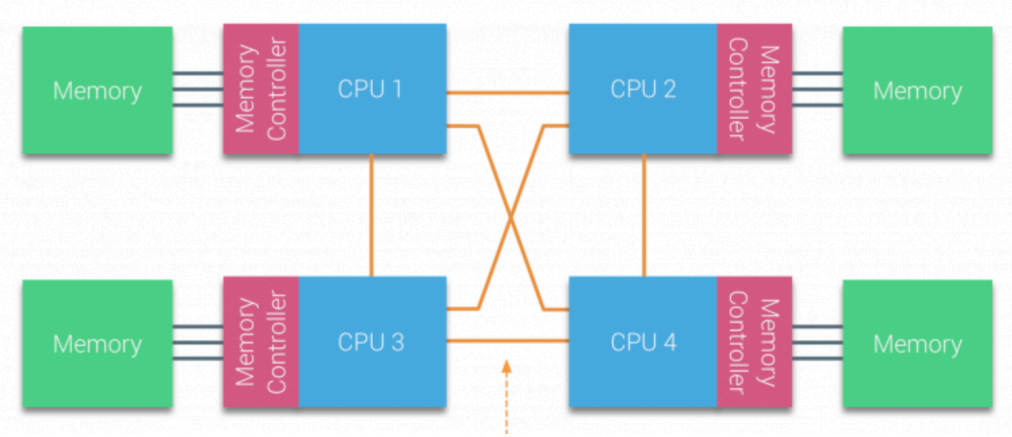
Extra slides.

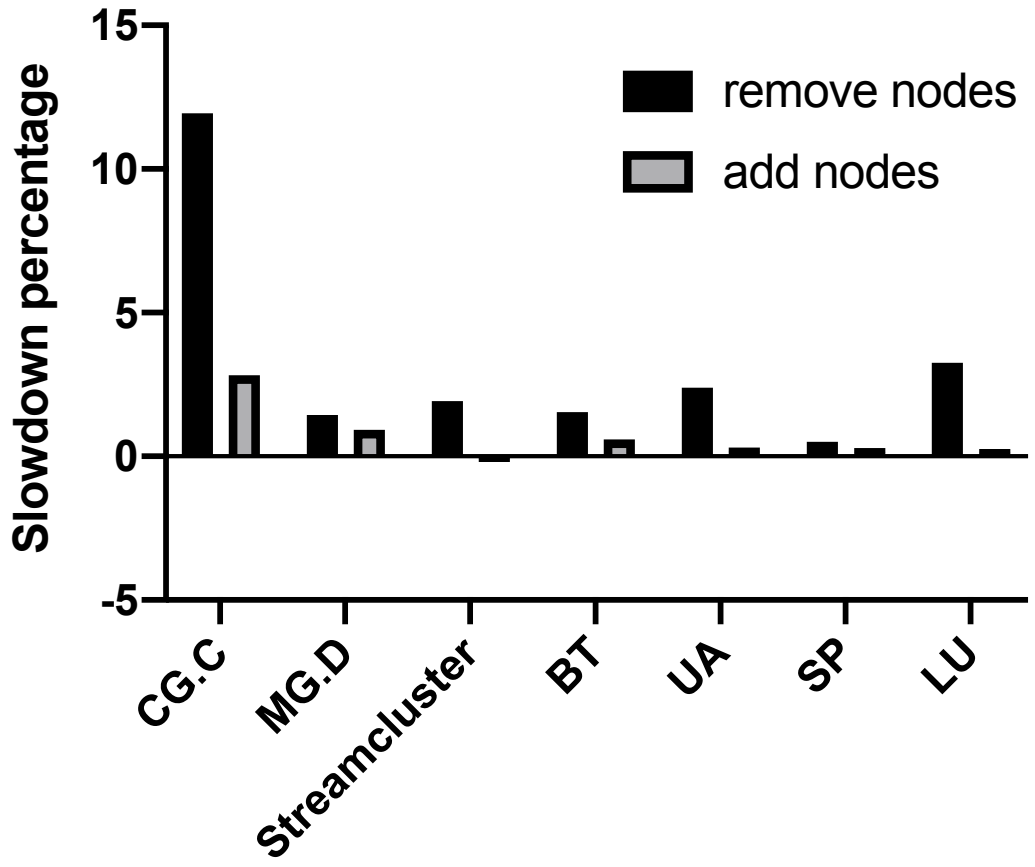
Non-Uniform Memory Access (NUMA) is and will be common

- NUMA is unavoidable
  - Chips become larger
  - Cross-chip/chiplet/racks communication cost becomes high
  - Memory has to be divided into different banks, complex topology
- Future rack-scale computers exhibits NUMA characteristics



https://frankdenneman.nl/2016/07/07/numa-deep-dive-part-1-uma-numa/

Evaluation (background topology change overhead)



- Removing nodes incurrs more overhead than adding nodes for most of the applications.
- The absolute overhead of the topology change on all applications is comparable to standalone ballooning time.