An Analysis of HPC Benchmarks in Virtual Machine Environments

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European Conference on Parallel and Distributed Computing (Euro-Par)
Workshop on Virtualization in High-Performance Cluster and Grid Computing (VHPC)
Las Palmas de Gran Canaria, Spain, August 26, 2008

Outline

- **Background and motivation**
- **Prior work and presented contribution**
- **Experimental setup and results**
- **Observations and conclusion**
- **Topics for discussion and future work**

Our Systems and Applications

- **We are the largest multi-purpose science laboratory within the US Department of Energy**
  - **Over $1 billion budget, over 4000 employees**
- **Oak Ridge National Laboratory has the 2^{nd} largest open scientific computing facility within the US**
  - **Jaguar, a 260 TFlop/s Cray XT4 with 7744 2.1GHz quad-core AMD processors and 60.5 TB total RAM**
- **Upgrade to petascale computing facility 2008/9**
- **Computationally and data intensive applications**
  - **Climate, astrophysics, fusion, nanotechnology, …**

Our Usage Model and System Software

- **Usage model: Capability computing**
  - **Single jobs occupy the entire system or large parts**
  - **Allocations range from days to weeks and months**
  - **Nation-wide resource with competitive process for allocation awards (DOE INCITE)**
- **Production-type system software stack**
  - **Compute node Linux (CNL), a Linux variant with modifications by Cray (drivers and scalability)**
  - **MPI, Open MP, Global Arrays, scientific libraries, ...**
  - **No virtualization solution (still considered research)**

Why Virtualization in HPC?

- **Virtual system environments**
  - **Configurable ‘sandbox’ for system software and scientific application development and deployment**
  - **Simplified application porting through virtualization**
  - **On-demand OS deployment on virtualized systems**
  - **On-demand deployment of isolated virtual testbeds**
- **Lowest-level layer for capturing state**
  - **Transparent VM checkpoint/restart (reactive FT)**
  - **Transparent VM migration (proactive FT)**

Impact of Virtualization on Applications

- Virtual environments are inherently complex
- Certain unpredictability of performance
- Performance impact is application depended
- Measuring the overall performance penalty
  – Can hide important performance differences/details
- Similar applications, but dissimilar code profiles
  – User, library and system code
- Missing knowledge about specific events
  – ITLB, DTLB and L2 cache misses

The Big Question

- **Is there a generalization for performance of compute-intensive applications in virtual environments?**
  - **Yes (results allow for a performance model)**
  - **No (unpredictable performance, no fitting model)**
  - **Can't say (inconclusive results)**
- **Need to investigate the impact of virtualization on HPC application performance in more detail**

Prior Work

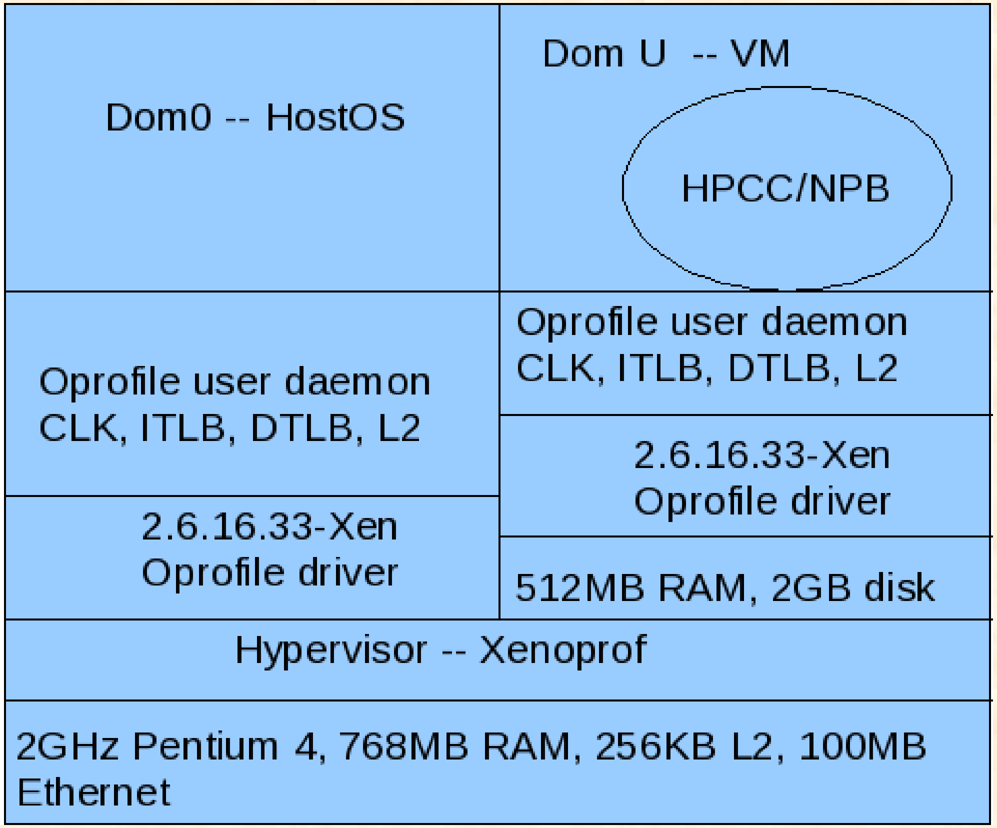
- Xenoprof tool
  - Investigation of performance overheads
  - Primarily used for diagnosing application bugs
- TLB behavior study of scientific applications
  - SPEC CPU and HPCC suites reflect cache behavior of HPC applications, but not TLB behavior
- Memory hierarchy study in virtualized systems
  - Xenoprof data shows near-native performance
- Real HPC applications != HPC kernel benchmarks
- Studies on Xen's impact on HPC applications
  - Small performance overheads, no generalization

Presented Contribution

- Investigation of performance penalties for
  - HPC Challenge (HPCC) Benchmark
    - High-Performance Linpack (HPL) Benchmark
  - NAS Parallel Benchmark (NPB)
    - Pentadiagonal Solver (SP) Benchmark (Class C)
- Study of HPL and SP on
  - Native environment
  - Host OS (Dom0) environment
  - Virtual machine (DomU) environment
- Comparative breakdown for HPL and SP of
  - Events: Clock cycles, DTLB, ITLB and L2 cache
  - Code: User, system, hypervisor, library, modules

Experimental Setup

- **16-node cluster**
- **Linux on Xen 3.0.4**
- **Oprofile 0.9.1**
  - **Frequency: 10,000**
  - **Native|Dom0|DomU**
- **Problem sizes**
  - **HPCC HPL: 6000**
  - **NAS SP: 162**
- **Parallel runs**



Overall Performance Penalty

	HostOS penalty %			VM penalty %		
	Wall clock time	No. of samples	Instructions executed	Wall clock time	No. of samples	Instructions executed
HPCC- HPL	2	8	2	12	$11 + \delta$	5
NPB - SP	1	5	9	18	$9 + \gamma$	11

Table 1. Performance penalty as compared to native

- **All numbers are relative to Native**
- **Wall clock time != # of samples**
  - **Clock-unhalted event is a measure of CPU active time**
  - **Does not account for time when CPU is idle, e.g., for I/O**
- **VM samples are DomU only (Xenoprof limitiation)**
- **δ and γ represent Dom0 (Host OS) samples of VM execution**

Distribution of Clock Cycles

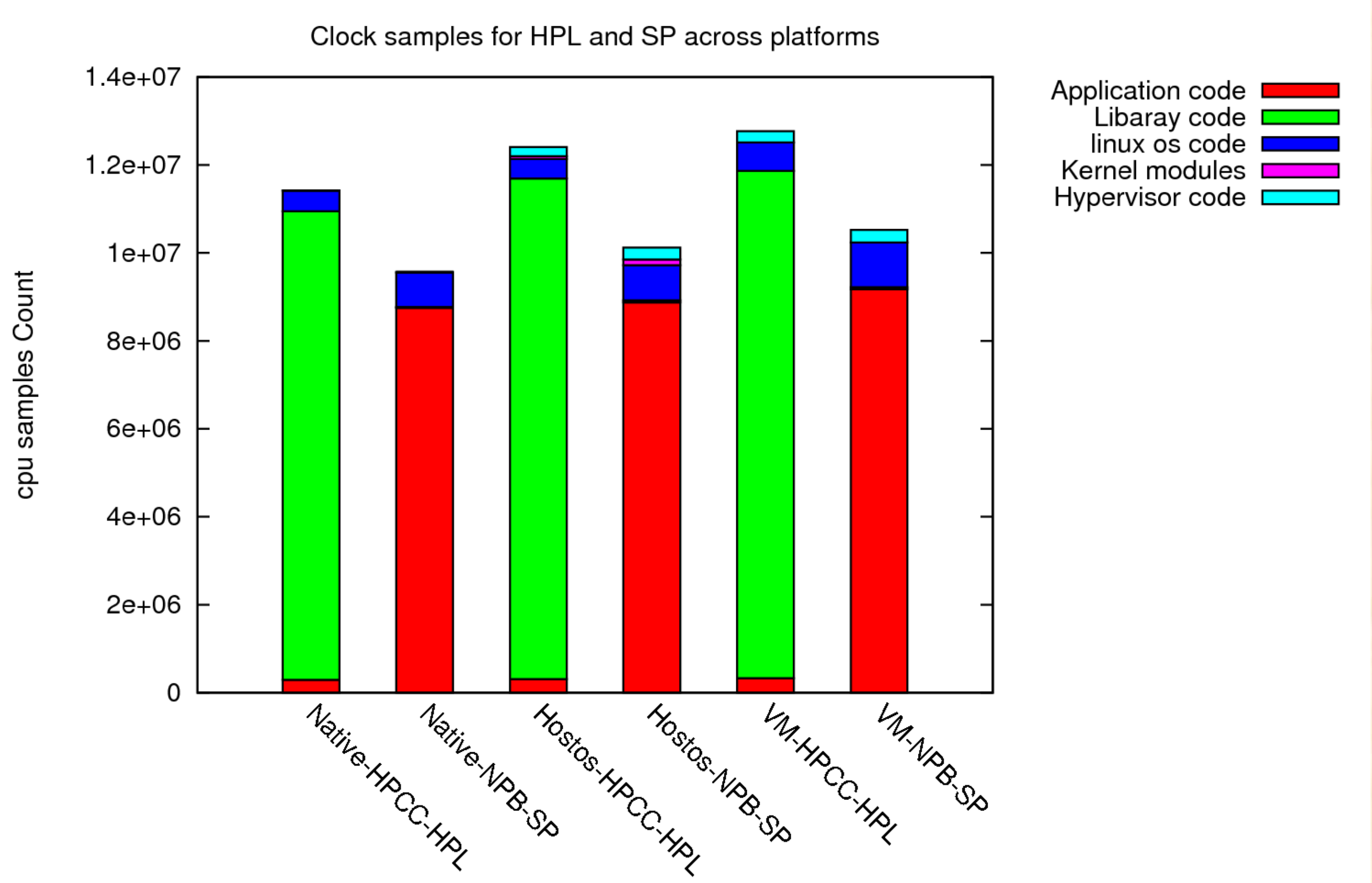


Fig. 1. Comparison of breakdown of CPU samples for HPL and SP across platforms - Results for VM do not contain Dom0 samples

Breakdown for Clock Samples

	HPL-App	SP-App	HPL-Lib	SP-Lib	HPL-Sys	SP-Sys
HostOS penalty%	5	1	6	138	50	49
VM penalty %	13	4	8	118	88 + δ_{clk}	62 + γ_{clk}

Table 2. Breakdown of performance penalty for clock samples as compared to native - δ_{clk} and γ_{clk}: Dom0 part of HPL and SP respectively

- **All numbers are relative to Native**
- **δ_{clk} and γ_{clk} represent Dom0 samples of VM execution**
- **Overall SP-library and HPL-application sample count is tiny**
- **Application code penalties for HPL and SP**
  - **Host OS: penalty (HPL-app.) > penalty (SP-app.)**
  - **VM: penalty (HPL-app.) > penalty (SP-app.)**

Distribution of Clock Cycles

- Library code penalties for HPL and SP
  - Host OS: penalty (HPL-library) << penalty (SP-library)
  - VM: penalty (HPL-library) << penalty (SP-library)
- System code penalties for HPL and SP
  - Host OS: penalty (HPL-system) ≈ penalty (SP-system)
  - VM: penalty (HPL-system) > penalty (SP-system)
- System code distribution (HPL 5%, SP 10% of overall code)

	% Hypervisor		% Kernel Core		% Kernel Modules	
	HPL	SP	HPL	SP	HPL	SP
Host OS	29	24	62	66	9	10
VM	28	23	72	77	N/A	N/A

Distribution of DTLB Miss Samples

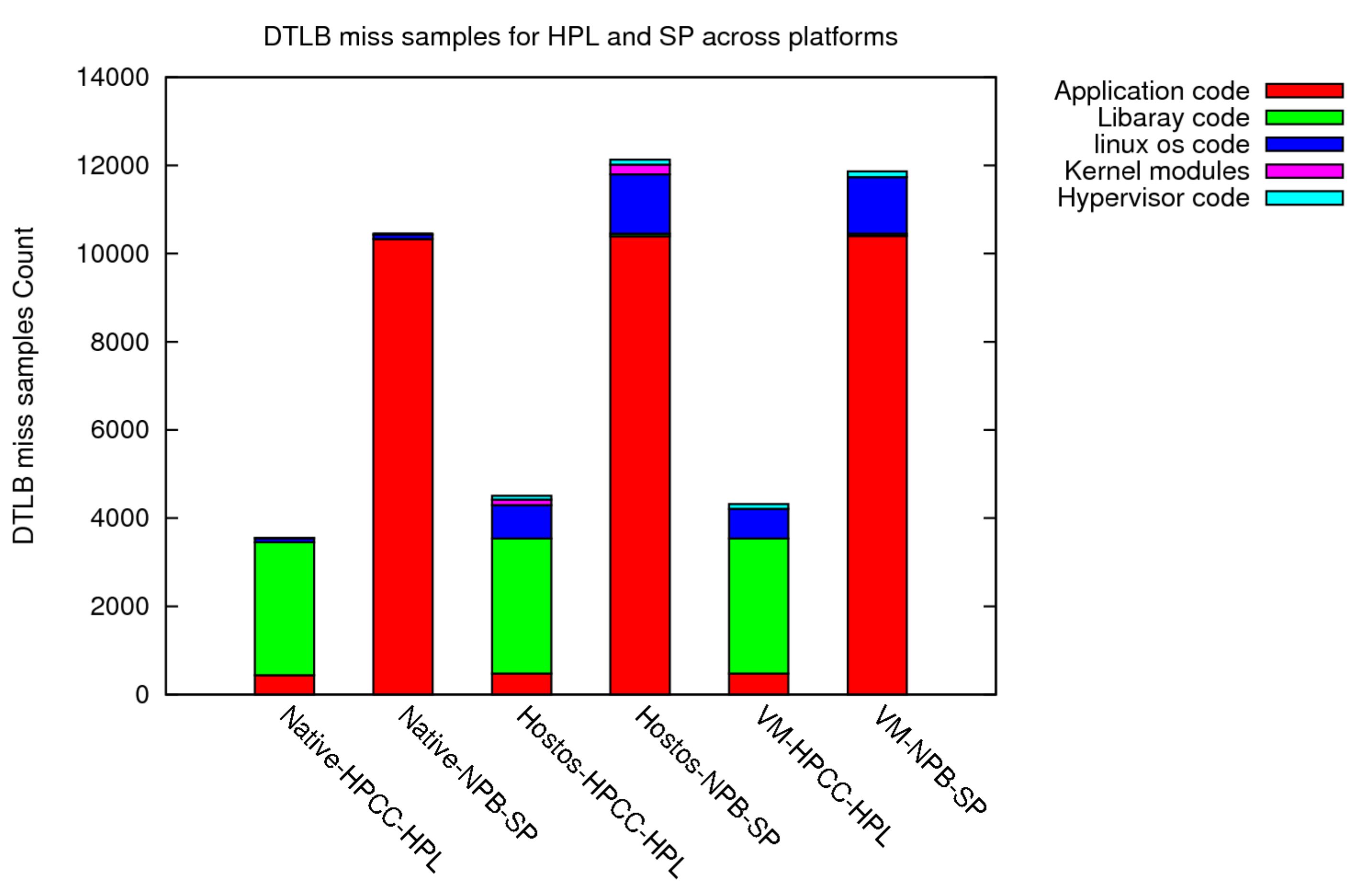


Fig. 2. Comparison of breakdown of DTLB Miss samples for HPL and SP across platforms - Results for VM do not contain Dom0 samples

Breakdown for DTLB Miss Samples

	HPL-App	SP-App	HPL-Lib	SP-Lib	HPL-Sys	SP-Sys
HostOS penalty%	7	0.6	1	1900	800	1300
VM penalty %	7	0.6	1.6	1500	$700 + \delta_{dtlb}$	$1150 + \gamma_{dtlb}$

Table 3. Breakdown of performance penalty for DTLB miss samples as compared to native

- **All numbers are relative to Native**
- **δ_{dtlb} and γ_{dtlb} represent Dom0 samples of VM execution**
- **DTLB overhead (host OS) ≈ DTLB overhead (VM)**
- **Large DTLB overheads for HPL- and SP-system code**
- **Small DTLB overheads for HPL- and SP-application code**
- **DTLB overheads for HPL-library code are small**
- **DTLB overheads for SP-library code are huge**

Distribution of ITLB Miss Samples

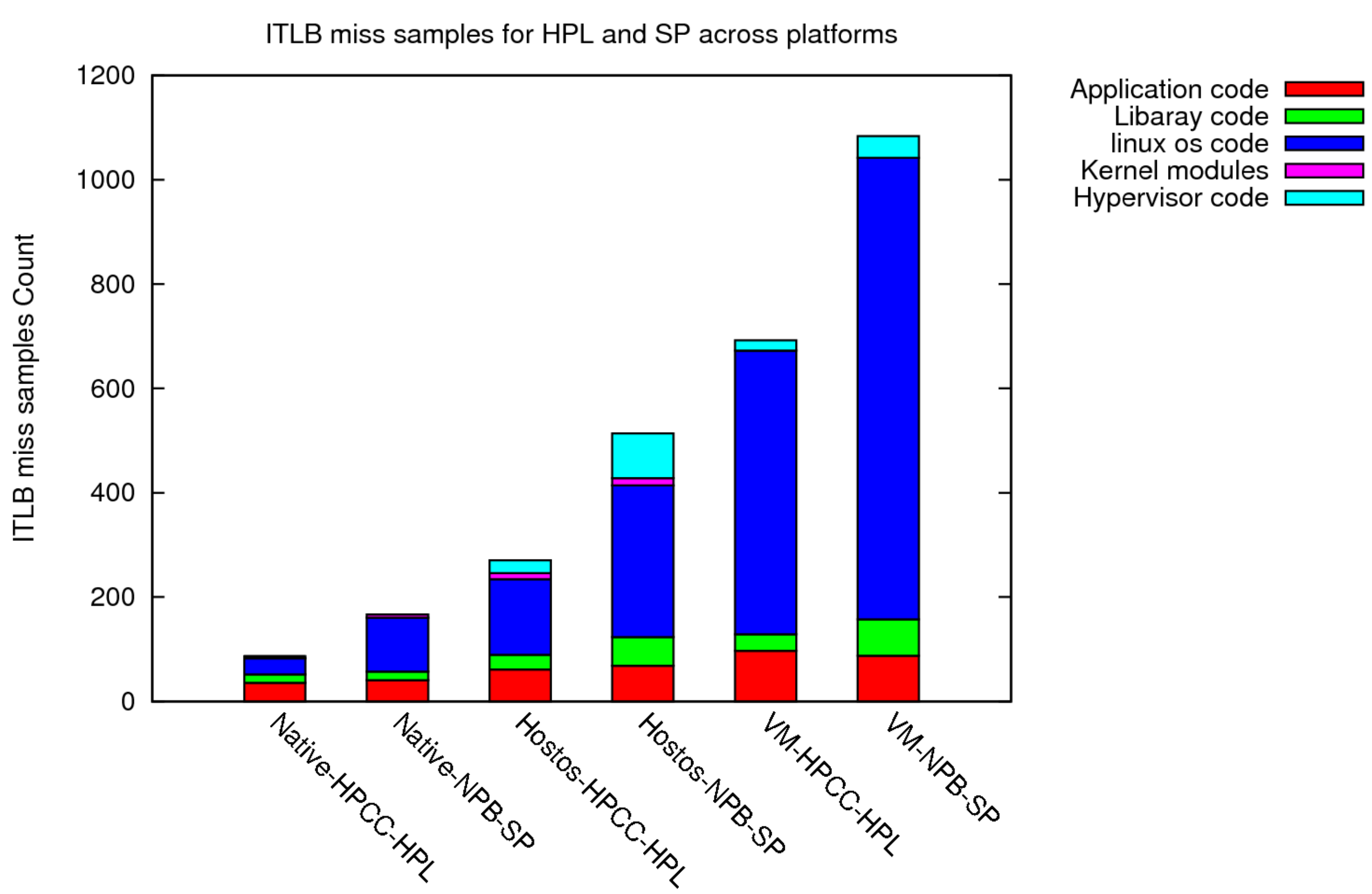


Fig. 3. Comparison of breakdown of ITLB miss samples for HPL and SP across platforms - Results for VM do not contain Dom0 samples

Breakdown for ITLB Miss Samples

	HPL-App	SP-App	HPL-Lib	SP-Lib	HPL-Sys	SP-Sys
HostOS penalty %	74	70	74	243	417	257
VM penalty %	177	117	93	331	$1500 + \delta_{itlb}$	$750 + \gamma_{itlb}$

Table 4. Breakdown of performance penalty for ITLB miss samples as compared to native - δ_{itlb} and γ_{itlb}: Dom0 part of HPL and SP respectively

- **All numbers are relative to Native**
- **δ_{itlb} and γ_{itlb} represent Dom0 samples of VM execution**
- **ITLB overhead (host OS) << ITLB overhead (VM)**
- **ITLB overhead (user) << ITLB overhead (system)**
- **ITLB overhead (SP-system) << ITLB overhead (HPL-system)**
- **ITLB overheads for SP-library code are big**

Distribution of L2 Cache Miss Samples

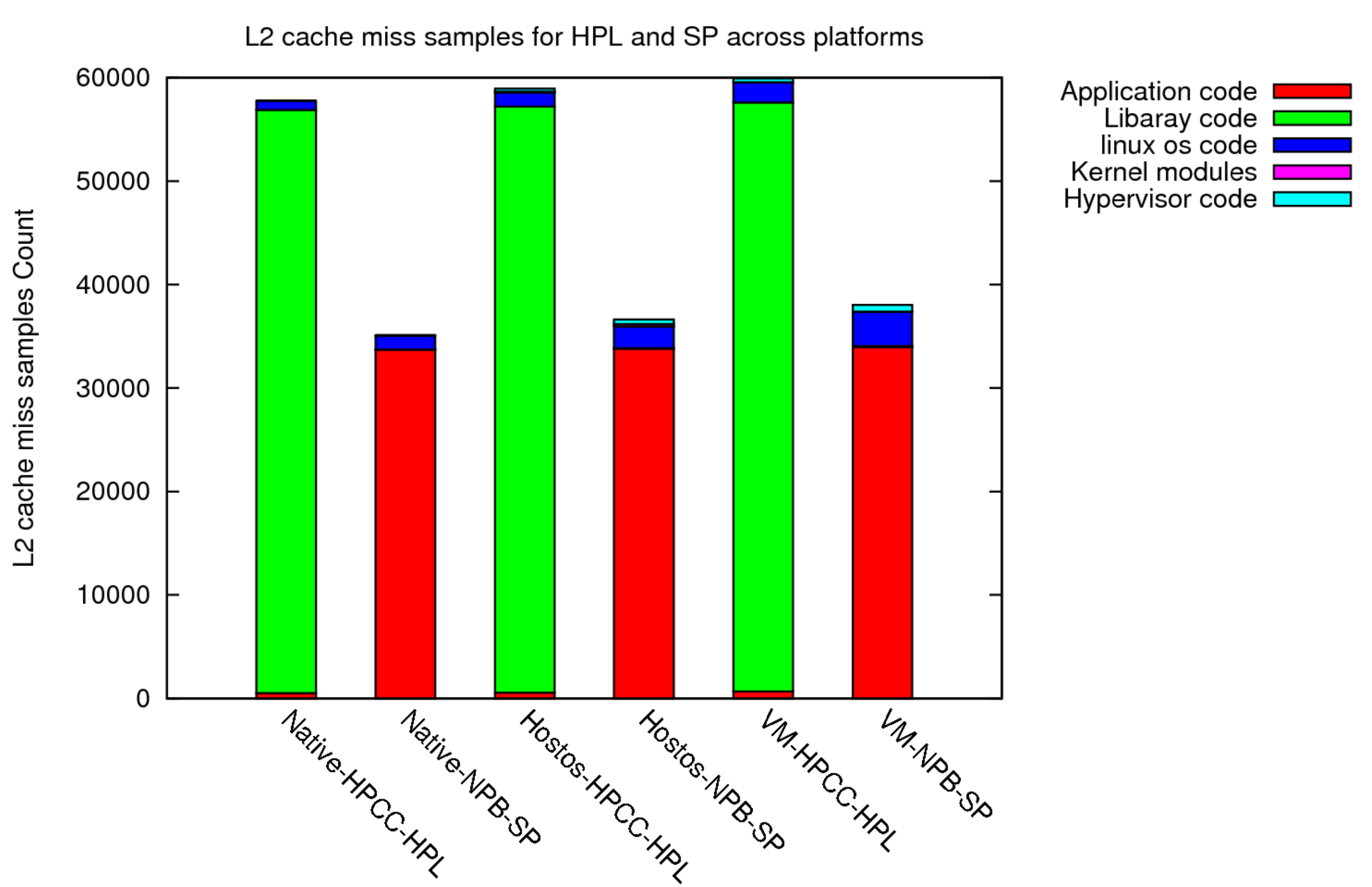


Fig. 4. Comparison of breakdown of L2 miss samples for HPL and SP across platforms - Results for VM do not contain Dom0 samples

Breakdown for L2 Cache Miss Samples

	HPL-App	SP-App	HPL-Lib	SP-Lib	HPL-Sys	SP-Sys
HostOS penalty%	10	0.2	0.4	130	104	101
VM penalty %	30	0.7	0.9	500	171 + δ_{l2}	186 + γ_{l2}

Table 5. Breakdown of performance penalty for L2 cache samples as compared to native - δ_{l2} and γ_{l2}: Dom0 part of HPL and SP respectively

- **All numbers are relative to Native**
- **δ_{l2} and γ_{l2} represent Dom0 samples of VM execution**
- **L2 cache overhead (host OS) << L2 cache overhead (VM)**
- **L2 cache overheads for HPL-library code are tiny**
- **L2 cache overheads for SP-library code are large**

Observations

- **Xen impacts HPL and SP differently**
  - **Other applications may be impacted differently**
- **Large impact parts are too small in code weight**
  - **No influence on final performance penalty %**
- **System code penalty >>> User code penalty**
- **Host OS impact not same as VM impact**
- **Missing Dom0 samples could explain the difference of HPL and SP behaviour in VM**
  - **Better tools and more investigation needed**

Conclusion

- **Based on our analysis of HPCC HPL and NAS SP, it is difficult to answer whether performance generalization in virtual environments is possible**
  - Yes (results allow for a performance model)
  - No (unpredictable performance, no fitting model)
  - **Can’t say (inconclusive results)**

Topics for Discussion and Further Work

- **General profiling issues**
  - **I/O, DMA, task accountability**
- **Oprofile/XenOprofile characteristics**
  - **Wall clock time vs. sample count**
  - **Sample frequency**
  - **Interference**
- **Xen's Dom0**
  - **Xentrace and event tracing**
  - **With/without profile comparing**
- **Performance isolation**

Questions or comments?