Reaching "EPYC" Virtualization Performance

Case Study: Tuning VMs for Best Performance on AMD EPYC 7002 / 7742 Processor Series Based Servers

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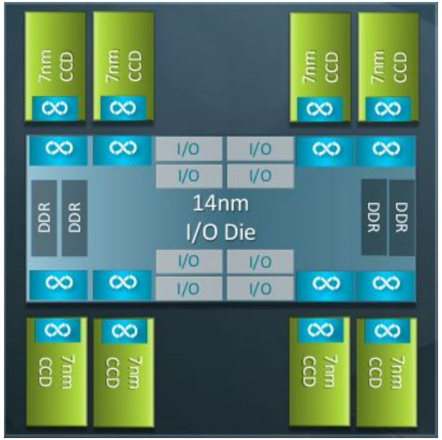
https://twitter.com/DarioFaggioli (@DarioFaggioli)

A.K.A.: Pinning the vCPUs is enough, right?

AMD EPYC 7002 Series ("EPYC2")



AMD64 SMP SoC, EPYC family

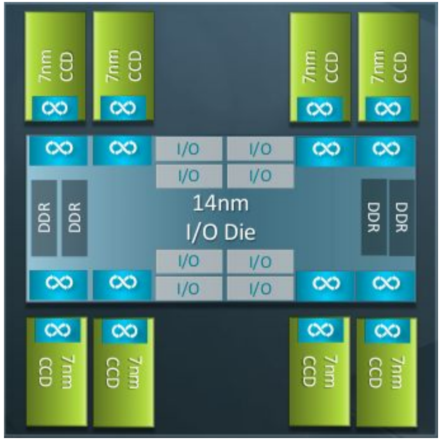
Multi-Chip Module, 9 dies:

- 1 I/O die, off-chip communications (memory, other sockets, I/O)
- 8 "compute" dies (CCDs)
  - Core CompleX (CCX) → 4 cores (8 threads), its own L1-L3 cache hierarchy
  - Core Complex Die (CCD) == 2 CCXs: 8 cores (16 threads) + dedicated Infinity Fabric link to IO die

64 cores (128 threads), 2 socket, 8 memory channels per socket

https://documentation.suse.com/sbp/all/html/SBP-AMD-EPYC-2-SLES15SP1/index.html#sec-epyc-architecture

AMD EPYC 7002 Series ("EPYC2")



AMD64 SMP SoC, EPYC family

Multi-Chip Mo

- 1 I/O die, o other sockets, I/O)
- 8 "compute
  - Core C), its own L1-L3 cache h
  - Core C es (16 threads) + dedicated

More info at:

AMD Documentations

WikiChip, AMD EPYC 7742

WikiChip, EPYC Family

64 cores (128 threads), 2 socket, 8 memory channels per socket

https://documentation.suse.com/sbp/all/html/SBP-AMD-EPYC-2-SLES15SP1/index.html#sec-epyc-architecture

AMD EPYC2 On SUSE's SLE15.1 Tuning Guide

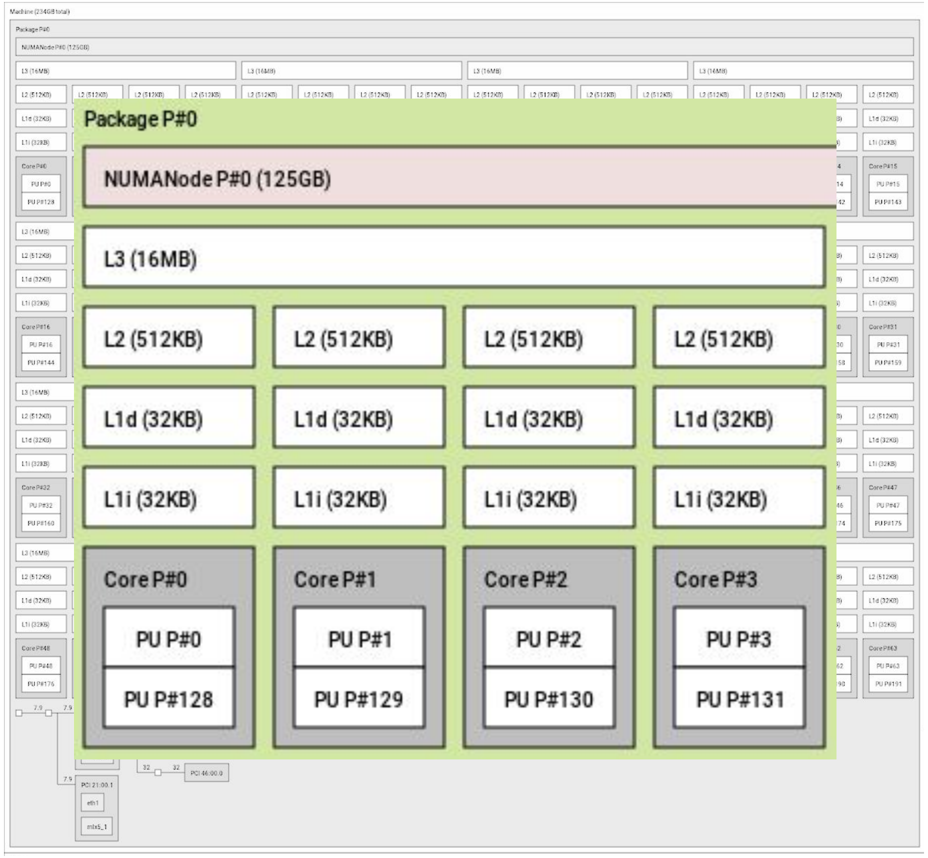
Joint effort by SUSE and AMD

- How to achieve the best possible performance when running SUSE Linux Enterprise Server on an AMD EPYC2 based platform?
- Covers both "baremetal" and virtualization
- "Optimizing Linux for AMD EPYC™ 7002 Series Processors with SUSE Linux Enterprise 15 SP1"

(Done for SLE12-SP3 AMD first gen. EPYC platforms too here)

“Our” EPYC Processor (7742)

“Our” EPYC Processor (7742)



Each CCX has it own LLC:

- NUMA at the socket level (unlike EPYC1)
- More than 1 (16!!) LLCs per NUMA node (unlike most others)

Tuning == Static Resource Partitioning

Virtualization + Resource partitioning: still makes sense?

- Server consolidation, as EPYC2 servers are very big
- Ease/Flexibility of management, deployment, etc.
- High Availability

What Resources?

- CPUs
- Memory
- ~~I/O~~ (will focus on CPU and memory here)

Host vs Guest(s)

Leave some CPUs and some Memory to the host (Dom0, if on Xen)

- For “host stuff” (remote access, libvirt, monitoring, ...)
- For I/O (e.g., IOThreads)

Recommendations:

- At least 1 core per socket
  - Better, if possible: 1 CCX (4 cores) ⇒ 1 “LLC domain”
  - What about 1 CCD (8 cores) ? Too much?
- RAM, depends. Say ~50GB

https://documentation.suse.com/sbp/all/html/SBP-AMD-EPYC-2-SLES15SP1/index.html#sec-allocating-resources-hostos

https://documentation.suse.com/sbp/all/html/SBP-AMD-EPYC-2-SLES15SP1/index.html#sec-allocating-resources-hostos-kvm

https://documentation.suse.com/sbp/all/html/SBP-AMD-EPYC-2-SLES15SP1/index.html#sec-allocating-resources-hostos-xen

Huge Pages and Auto-NUMA Balancing

At host level, statically partition:

- Static, pre-allocated at boot
- No balancing

Kernel command line:
numa_balancing=disable

Live system:
echo 0 > /proc/sys/kernel/numa_balancing

In guests: workload dependant

Kernel command line:

```
transparent_hugepage=never
default_hugepagesz=1GB hugepagesz=1GB
hugepages=200
```

Libvirt:

```
<memoryBacking>
  <hugepages>
    <page size='1048576' unit='KiB'/>
  </hugepages>
  <nosharepages/>
</memoryBacking>
```

https://documentation.suse.com/sbp/all/html/SBP-AMD-EPYC-2-SLES15SP1/index.html#sec-trasparent-huge-pages

https://documentation.suse.com/sbp/all/html/SBP-AMD-EPYC-2-SLES15SP1/index.html#sec-automatic-numa-balancing

Power Management

For improved consistency/determinism of benchmarks:

- Avoid deep sleep states
- Use `performance` CPUFreq governor

(At host level, of course! :-P)

If saving power is important, re-assess tuning with desired PM configuration

https://documentation.suse.com/sbp/all/html/SBP-AMD-EPYC-2-SLES15SP1/index.html#sec-services-daemons-power

VM Placement: vCPUs

vCPU pinning

- Pin, if possible, to CCDs:
  - VMs will not share Infinity Link to the I/O die
  - EPYC2: up to 14 (or 16) VMs, 16 vCPUs each
- If not, pin to CCXs:
  - VMs will not share L3 caches
  - EPYC2: up to 30 (or 32) VMs, 8 vCPUs each
- At worst, pin at least to Cores
  - VMs share Inf. Link and L3
  - At least VMs will not share L1 and L2 caches

Libvirt:

```
<vcpu placement='static'
cpuset='108-127,236-255'>40</vcpu>
  <cputune>
    <vcpupin vcpu='0' cpuset='108'/>
    <vcpupin vcpu='1' cpuset='236'/>
    <vcpupin vcpu='2' cpuset='109'/>
    <vcpupin vcpu='3' cpuset='237'/>
    ...
```

https://documentation.suse.com/sbp/all/html/SBP-AMD-EPYC-2-SLES15SP1/index.html#sec-placement-vms

VM Placement: Memory

Put the VM in least possible number of NUMA nodes

Pin the memory to NUMA nodes:

- If the VM spans both nodes
- If the VM fist on one node

Libvirt:

```
<numatune>
  <memory mode='strict' nodeset='0-1'/>
  <memnode cellid='0' mode='strict' nodeset='0'/>
  <memnode cellid='1' mode='strict' nodeset='1'/>
</numatune>
```

Libvirt:

```
<numatune>
  <memory mode='strict' nodeset='0'/>
  <memnode cellid='0' mode='strict' nodeset='0'/>
</numatune>
```

https://documentation.suse.com/sbp/all/html/SBP-AMD-EPYC-2-SLES15SP1/index.html#sec-placement-vms

VM Enlightenment

Give the VMs a (sensible!) virtual NUMA topology

Libvirt:

```
<numa>
  <cell id='0' cpus='0-119' memory='104857600' unit='KiB'>
    <distances>
      <sibling id='0' value='10'/>
      <sibling id='1' value='32'/>
    </distances>
  </cell>
  ...
```

Give the VMs a (sensible!) virtual CPU topology & CPU model

- Not Passthrough? See later...

Libvirt:

```
<cpu mode="host-model" check="partial">
  <model fallback="allow"/>
  <topology sockets='1' cores='60' threads='2'/>
  ...
```

https://documentation.suse.com/sbp/all/html/SBP-AMD-EPYC-2-SLES15SP1/index.html#sec-enlightment-vms

https://documentation.suse.com/sbp/all/html/SBP-AMD-EPYC-2-SLES15SP1/index.html#sec-CPU-topology-vm

AMD Secure Encrypted Virtualization (SEV)

Encrypts memory

- per-VM keys
- Completely transparent

Requires setup both at host and guest level:

SUSE AMD SEV Instructions
Libvirt AMD SEV Instructions

https://documentation.suse.com/sbp/all/html/SBP-AMD-EPYC-2-SLES15SP1/index.html#sec-sev-host

Security Mitigations

Meltdown, Spectre, L1TF, MDS, ...

- AMD EPYC2 is immune to most of them
- Impact of mitigations is **rather small**, compared to other platforms

```
itlb_multihit:Not affected
l1tf:Not affected
mds:Not affected
meltdown:Not affected
spec_store_bypass:Mitigation: Speculative Store Bypass disabled via prctl and seccomp
spectre_v1:Mitigation: usercopy/swapgs barriers and __user pointer sanitization
spectre_v2:Mitigation: Full AMD retpoline, IBPB: conditional, IBRS_FW, STIBP: conditional, RSB filling
tsx_async_abort:Not affected
```

https://documentation.suse.com/sbp/all/html/SBP-AMD-EPYC-2-SLES15SP1/index.html#sec-security- mitigations

Benchmarks: STREAM

Memory intensive benchmark

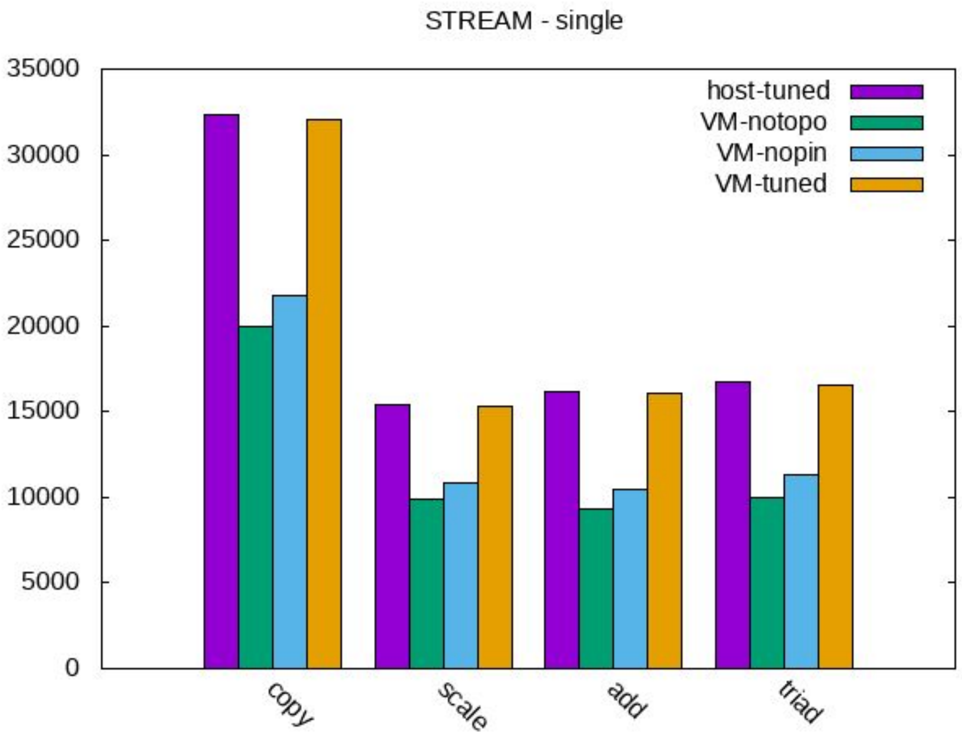
- Operations on matrices
  a. In one single thread
  b. In multiple threads, with OpenMP

OpenMP

- OMP_PROC_BIND=SPREAD
  OMP_NUM_THREADS=16 or 32 (on baremetal)
- 1 thread per memory channel / 1 thread per LLC
  (both on baremetal and in VMs)

https://documentation.suse.com/sbp/all/html/SBP-AMD-EPYC-2-SLES15SP1/index.html#sec-virtualization-test-workload-stream

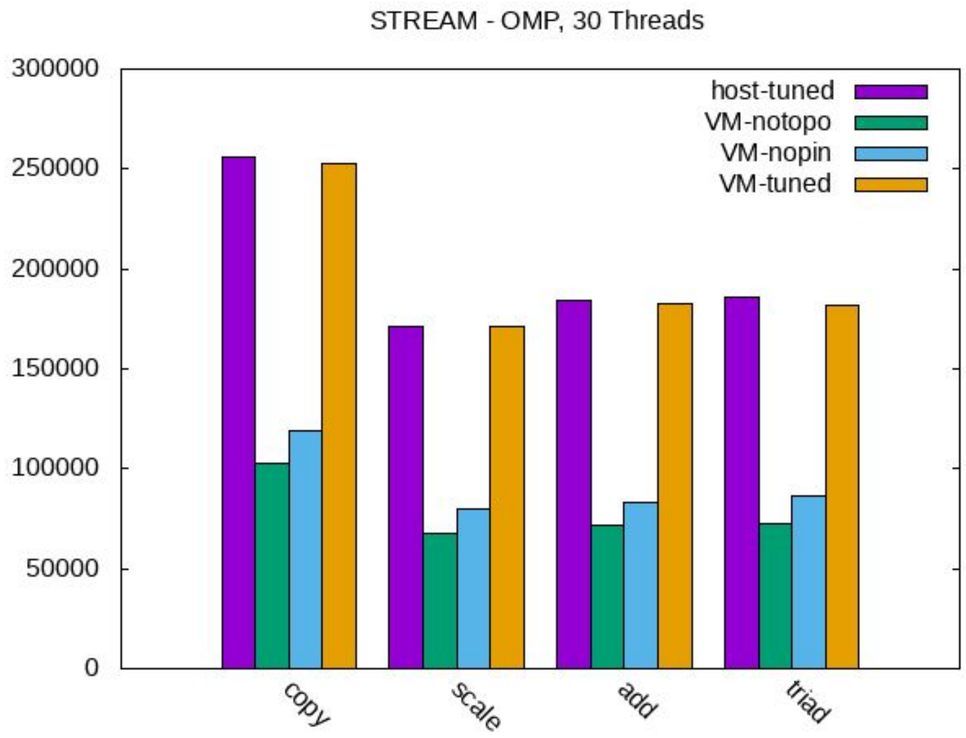
Benchmarks: STREAM, 1 VM, single thread



With full tuning, we reach the same level of performance we achieved on the host (look at **purple** and … **what colour is this?**)

https://documentation.suse.com/sbp/all/html/SBP-AMD-EPYC-2-SLES15SP1/index.html#sec-virt-test-stream-onevm

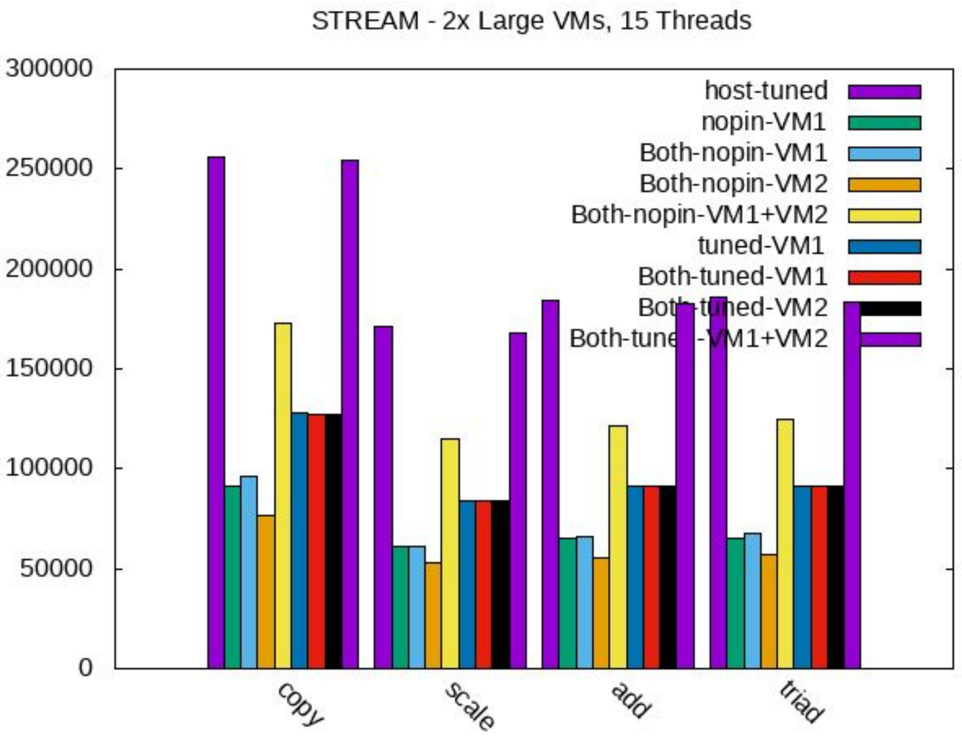
Benchmarks: STREAM, 1 VM, 30 threads



With full tuning, we reach the same level of performance we achieved on the host (look at **purple** and … **what colour is this?**)

https://documentation.suse.com/sbp/all/html/SBP-AMD-EPYC-2-SLES15SP1/index.html#sec-virt-test-stream-onevm

Benchmarks: STREAM, 2 VM, 15 threads (each)

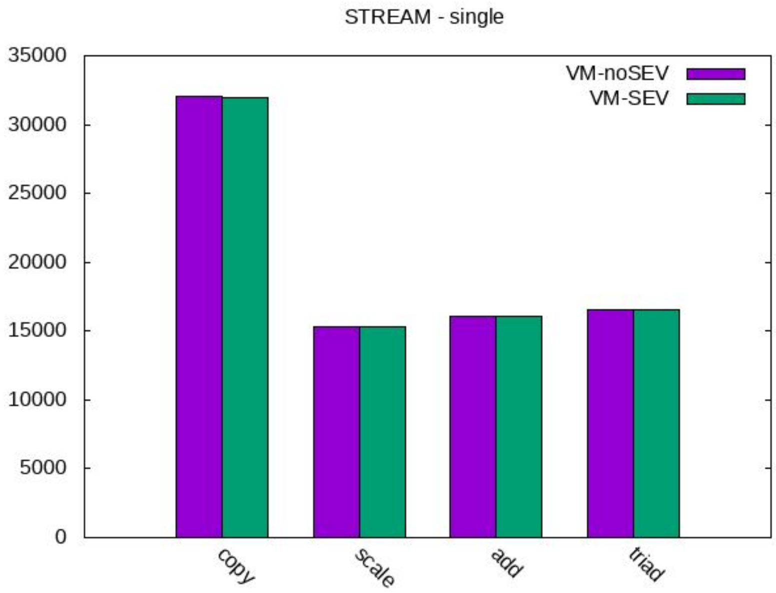


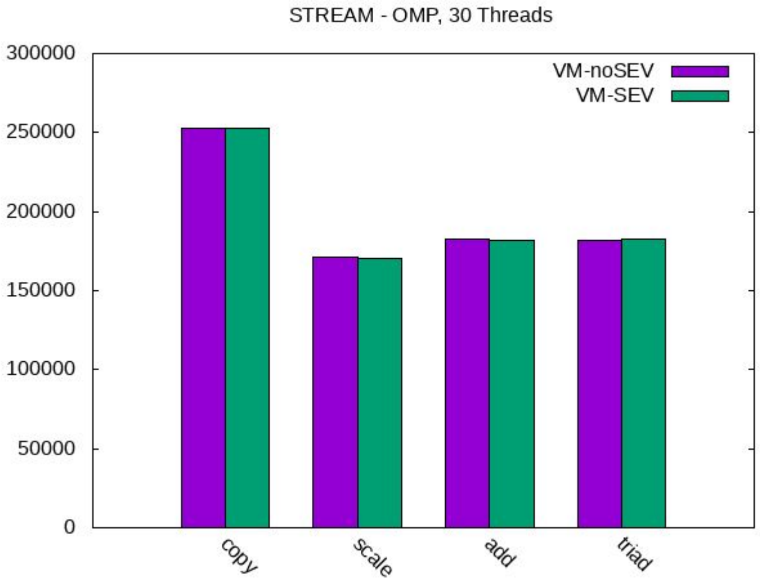
With full tuning

- Performance of the 2 VMs is consistent (look at **red** and **black**)
- Cumulative performance of the 2 VMs matches numbers of the host (look at the **purples**)

https://documentation.suse.com/sbp/all/html/SBP-AMD-EPYC-2-SLES15SP1/index.html#sec-virt-test-stream-twovm-all

Benchmarks: STREAM, 1 VM, with SEV





On EPYC2, the impact of enabling SEV,
for this workload, is **very small** (less than 1%)

https://documentation.suse.com/sbp/all/html/SBP-AMD-EPYC-2-SLES15SP1/index.html#sec-virt-test-stream-sev

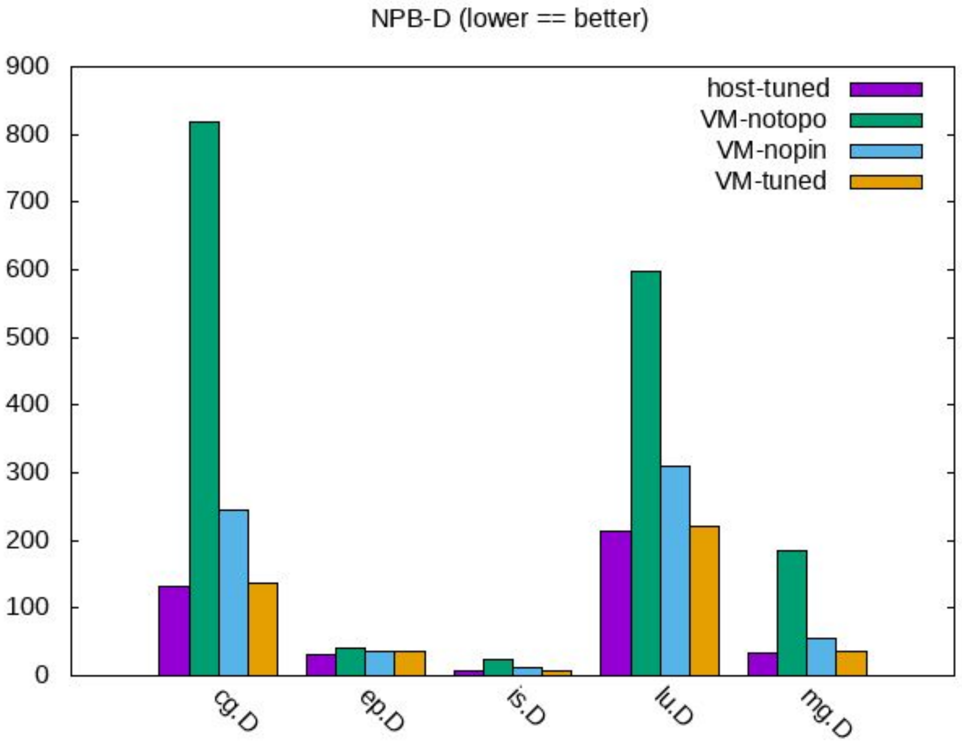
Benchmark: NAS-PB

CPU intensive benchmark

- Fluid-dynamics computational kernel
- openMPI

https://documentation.suse.com/sbp/all/html/SBP-AMD-EPYC-2-SLES15SP1/index.html#sec-virtualization-test-workload-npb

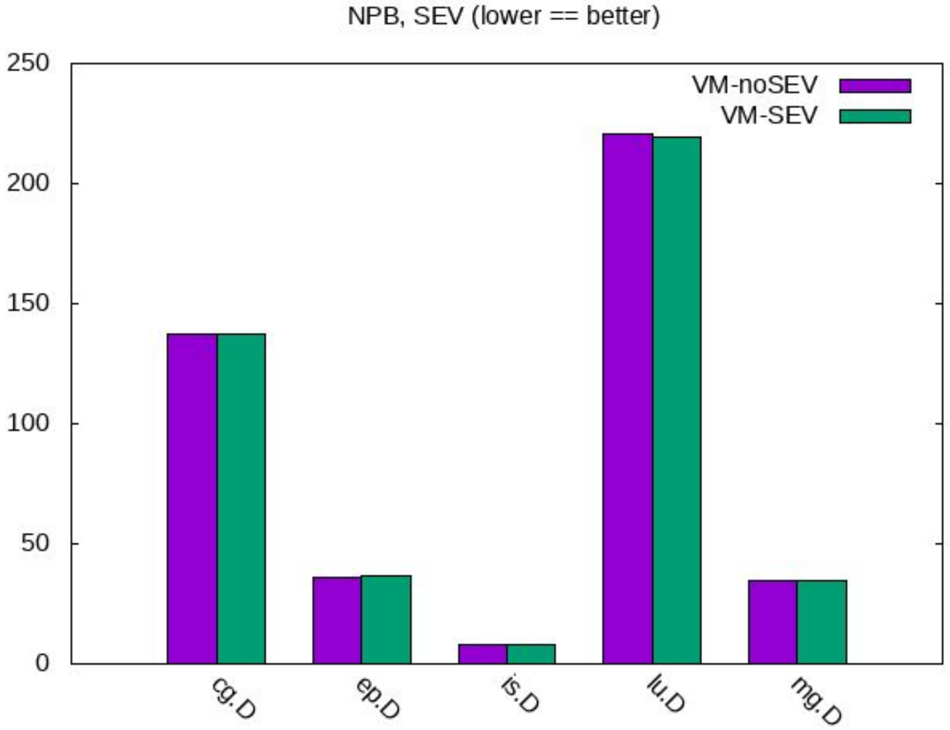
Benchmark: NAS-PB, 1 VM



With full tuning, we reach performance close to the one of the host (look at **purple** and … **Again!?!?**)

https://documentation.suse.com/sbp/all/html/SBP-AMD-EPYC-2-SLES15SP1/index.html#sec-virt-test-npb-onevm

Benchmark: NAS-PB, SEV



On EPYC2, the impact of enabling SEV, for this workload, is again **very small** (less than 1%)

https://documentation.suse.com/sbp/all/html/SBP-AMD-EPYC-2-SLES15SP1/index.html#sec-virt-test-npb-sev

Caveat: CPU Model

On SUSE Linux Enterprise 15.1

- EPYC2 CPU Model not available (QEMU/Libvirt versions)
- XPU Model = `host-passthrough` giving “strange” results

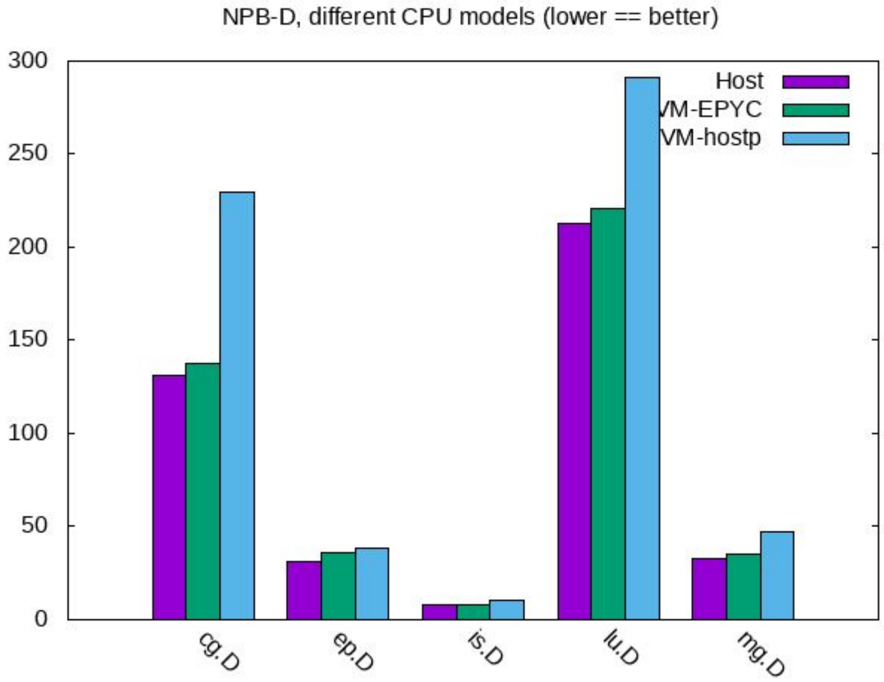
```
Thread(s) per core:   1
Core(s) per socket:   120
Socket(s):            2
NUMA node(s):         2
```

- EPYC (the model for *1st generation* EPYC processors) gives more sensible results

```
Thread(s) per core:   1
Core(s) per socket:   120
Socket(s):            2
NUMA node(s):         2
```

- (On newer distros, you’ll find the EPYC2 model)

~~Caveat: CPU Model~~
Always Double Check, Run Benchmarks!



Host-passthrough, on older QEMU, by not correctly exposing threads, was causing bad performance

https://documentation.suse.com/sbp/all/html/SBP-AMD-EPYC-2-SLES15SP1/index.html#sec-virt-test-npb-cpumod

More STREAM Benchmarks

Rerun of the STREAM benchmarks

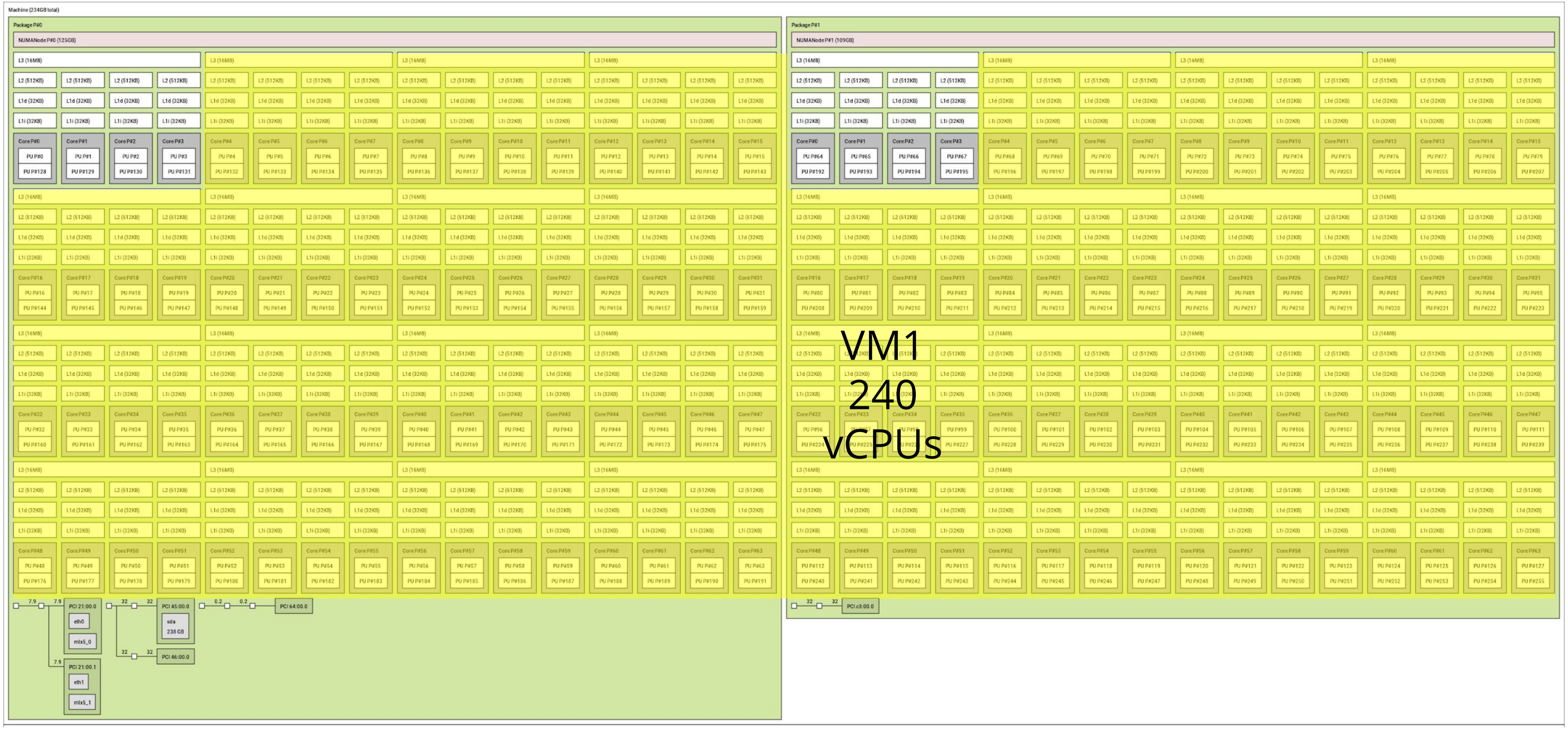
- With Mitigations enabled (were disabled for the Tuning Guide)
- (Much!) More VMs
- Varying pinning of VMs

-- Still work in pogress --

-- Benchmarks still running --

-- Data Set not complete yet --

STREAM, 1 VM

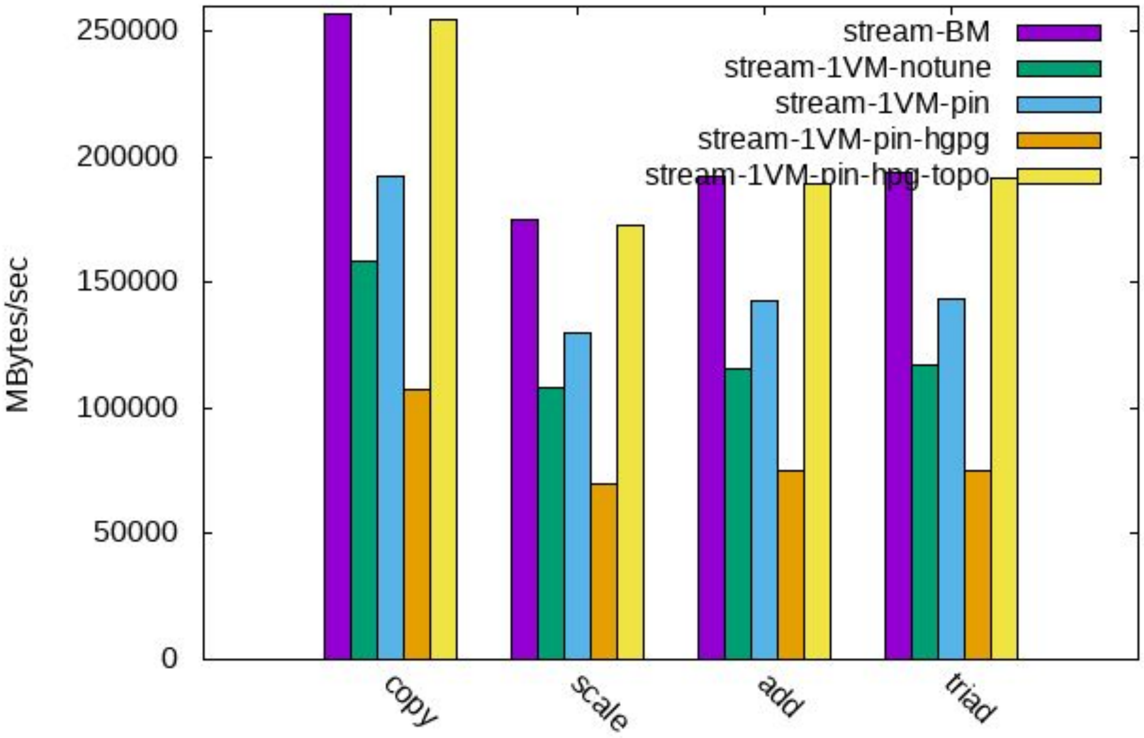

Machine (234GB total)
Package P#0
NUMANode P#0 (125GB)
Package P#1
NUMANode P#1 (109GB)
VM1
240
vCPUs
PCI 21:00.0
eth0
mlx5_0
PCI 21:00.1
eth1
mlx5_1
PCI 45:00.0
sda
238 GB
PCI 46:00.0
PCI 64:00.0
PCI c3:00.0

STREAM, 1 VM

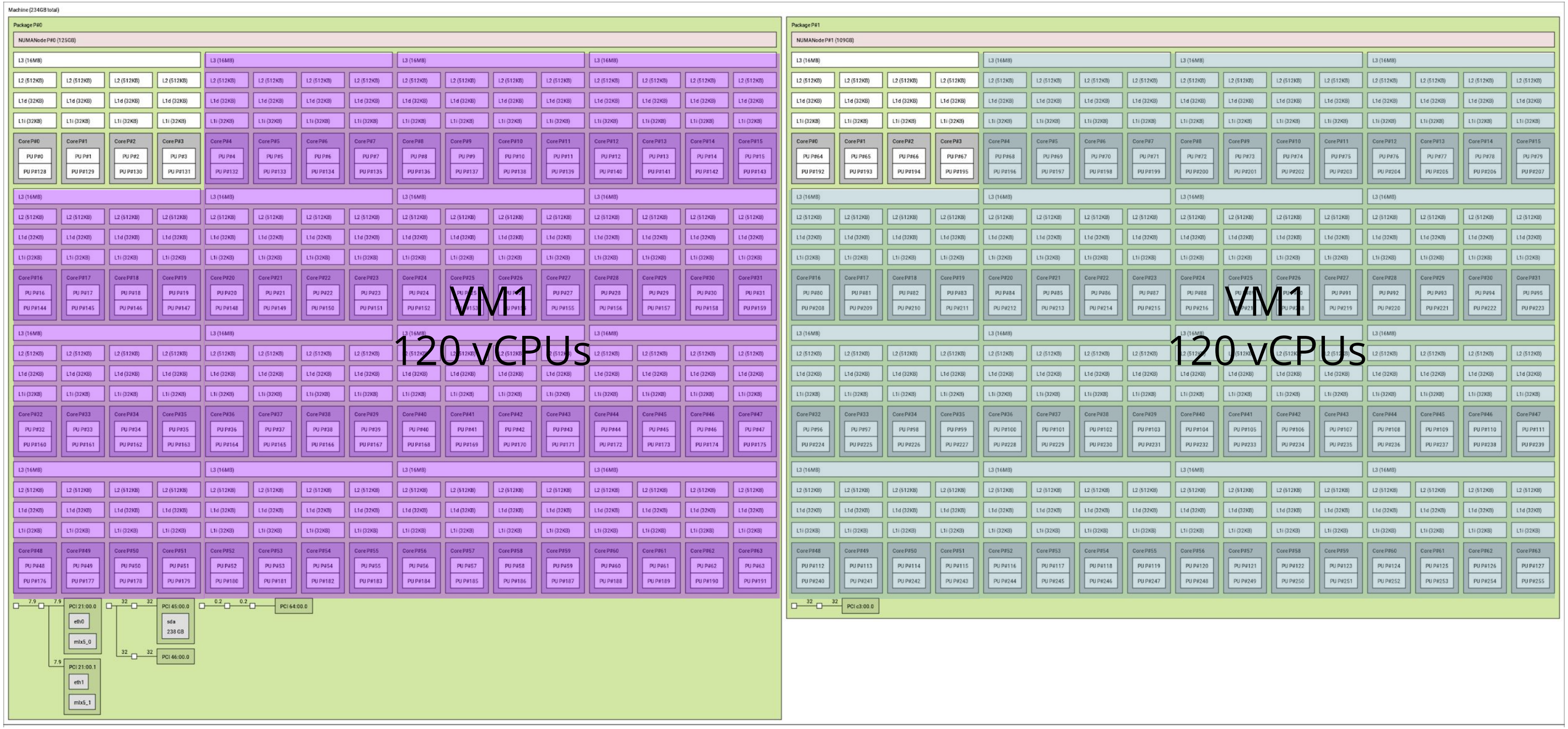
Baremetal:

```
MB/sec copy     256221.30
MB/sec scale    173231.56
MB/sec add      181804.68
MB/sec triad    183952.20
```

We expect ~Baremetal (with full tuning, look at **purple** and **yellow**)



STREAM, 2 VMs


Machine (234GB total)
Package P#0
NUMANode P#0 (125GB)
VM1
120 vCPUs
Package P#1
NUMANode P#1 (109GB)
VM1
120 vCPUs

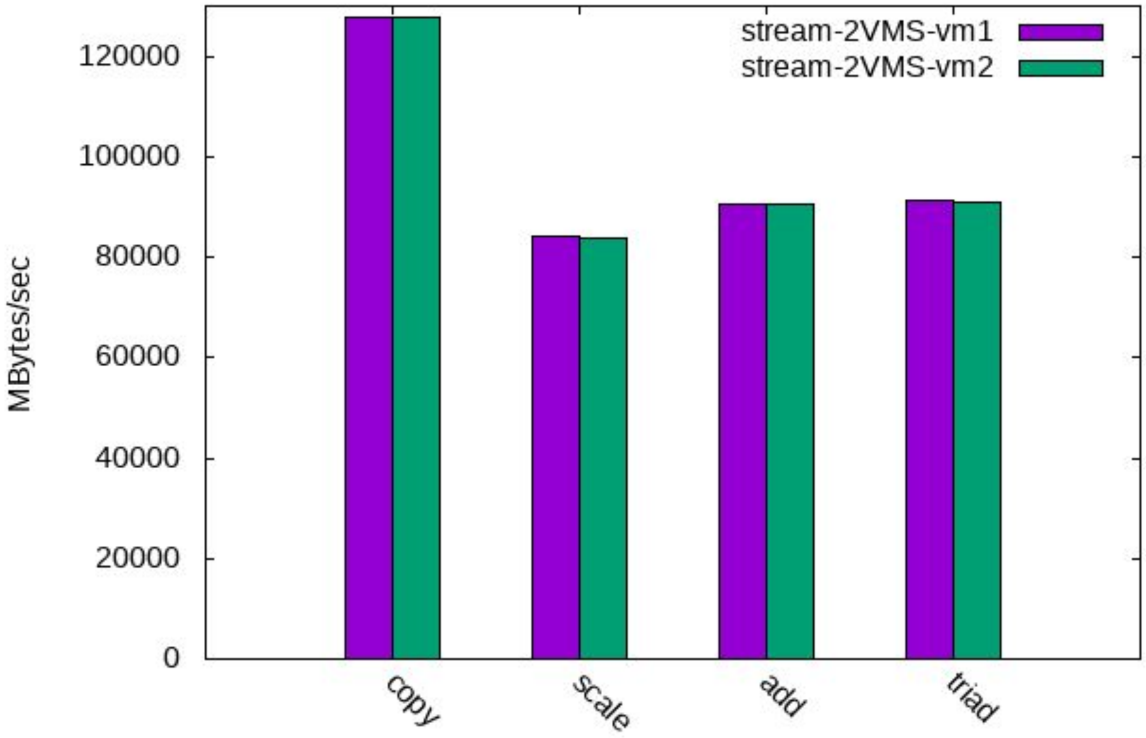
STREAM, 2 VMs

Baremetal:

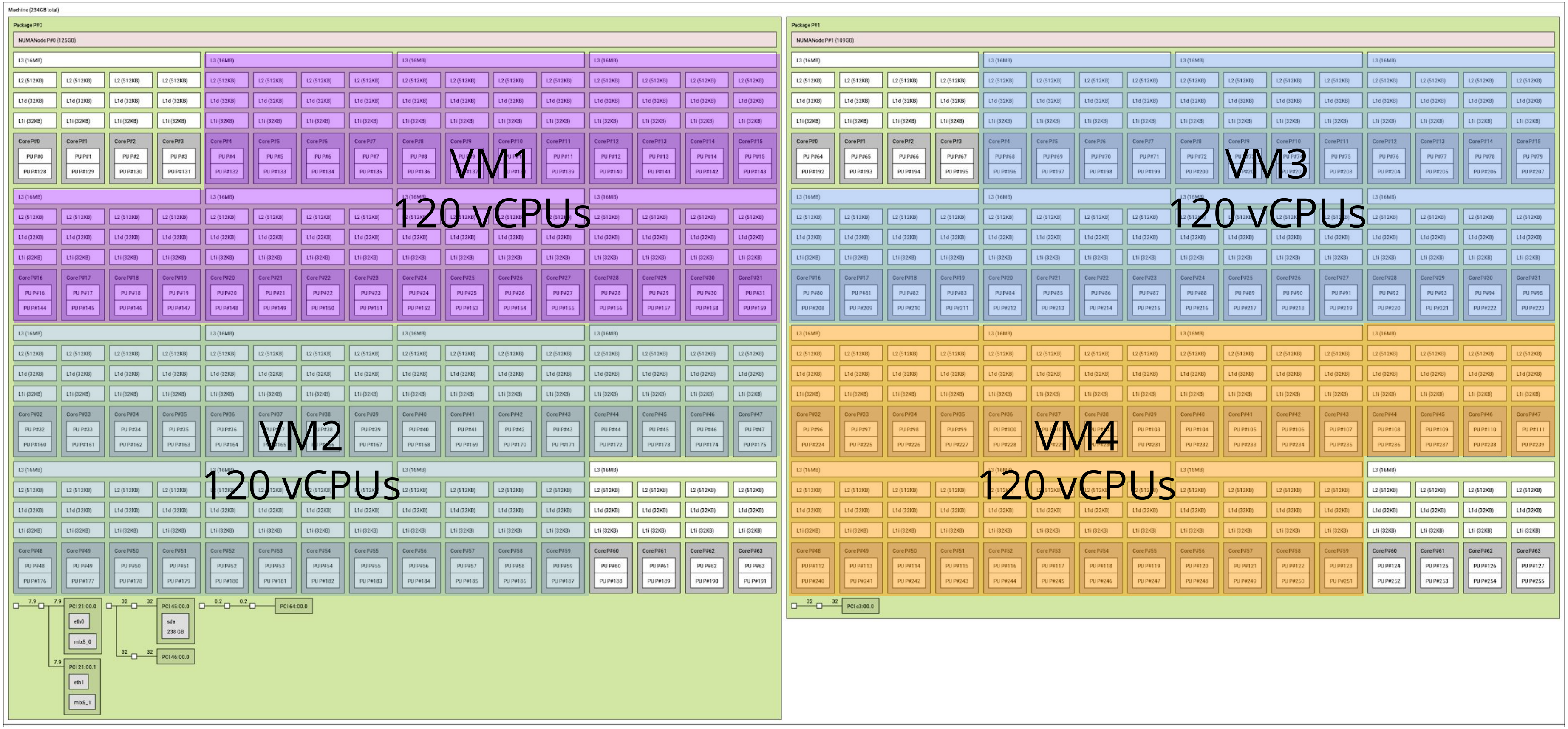
```
MB/sec copy     256221.30
MB/sec scale    173231.56
MB/sec add      181804.68
MB/sec triad    183952.20
```

We expect ~Baremetal/2

```
MB/sec copy     128110.65
MB/sec scale     86615.78
MB/sec add       90902.34
MB/sec triad     91976.10
```



STREAM, 4 VMs


Machine (234GB total)
Package P#0
NUMANode P#0 (125GB)
Package P#1
NUMANode P#1 (109GB)
VM1
120 vCPUs
VM2
120 vCPUs
VM3
120 vCPUs
VM4
120 vCPUs

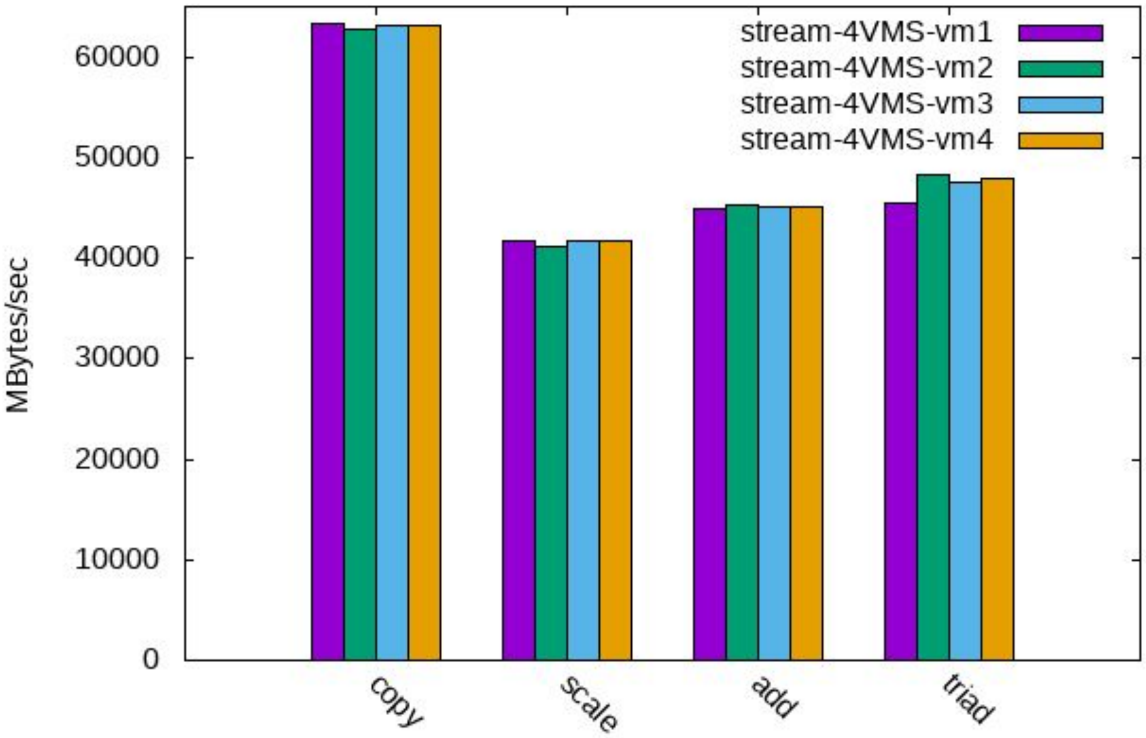
STREAM, 4 VMs

Baremetal:

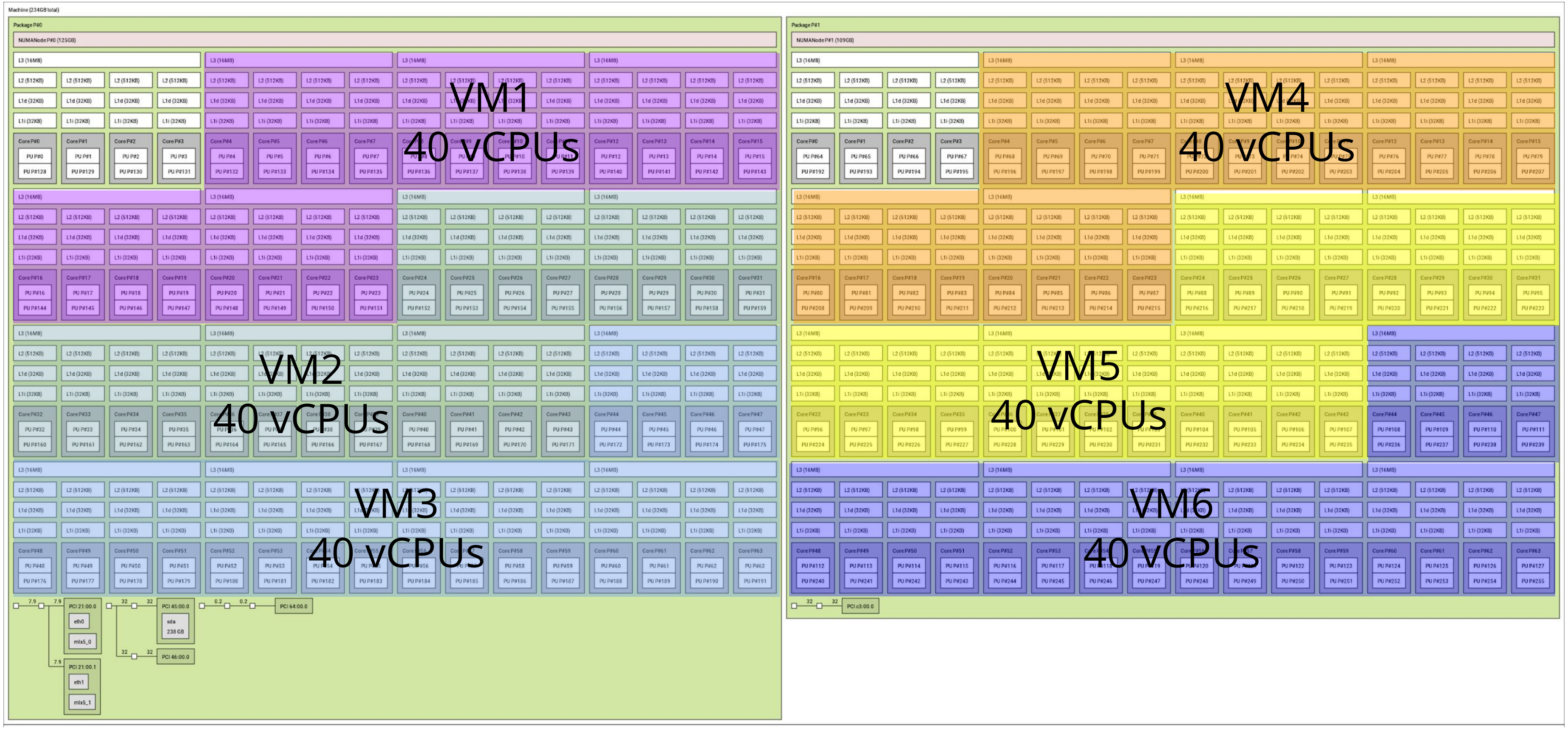
MB/sec copy	256221.30
MB/sec scale	173231.56
MB/sec add	181804.68
MB/sec triad	183952.20

We expect Baremetal/4

MB/sec copy	64055.32
MB/sec scale	43307.89
MB/sec add	45451.17
MB/sec triad	45988.05



STREAM, 6 VMs


VM1
40 vCPUs
VM2
40 vCPUs
VM3
40 vCPUs
VM4
40 vCPUs
VM5
40 vCPUs
VM6
40 vCPUs

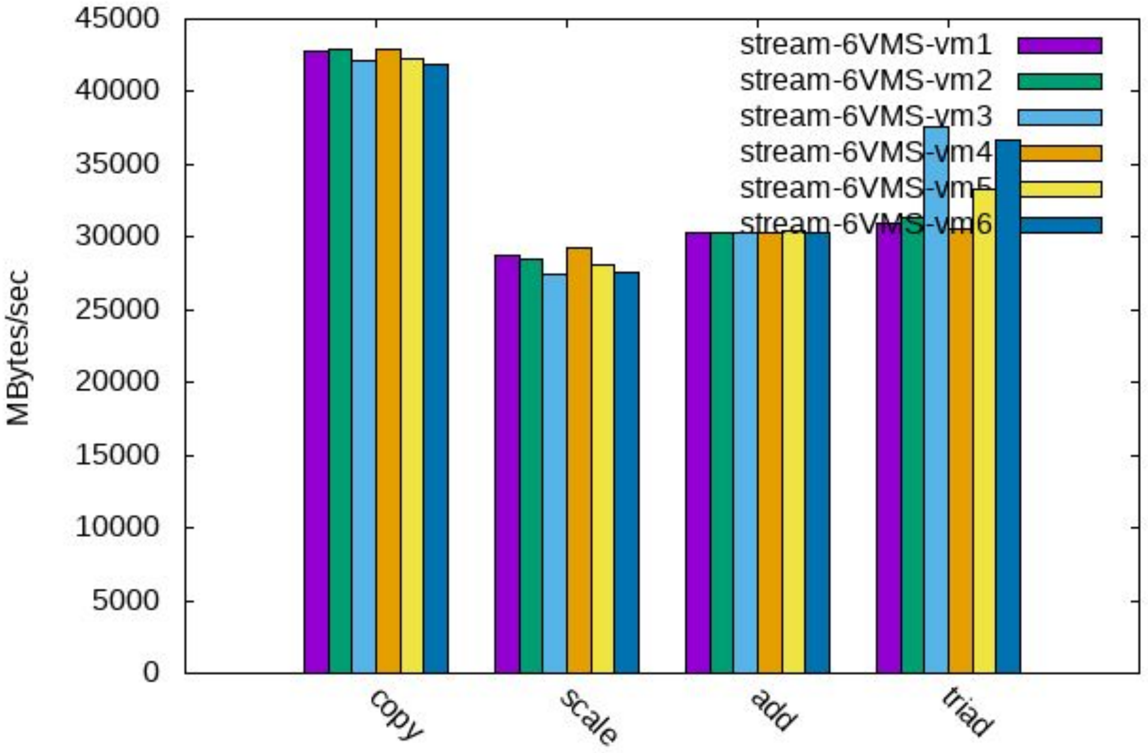
STREAM, 6 VMs

Baremetal:

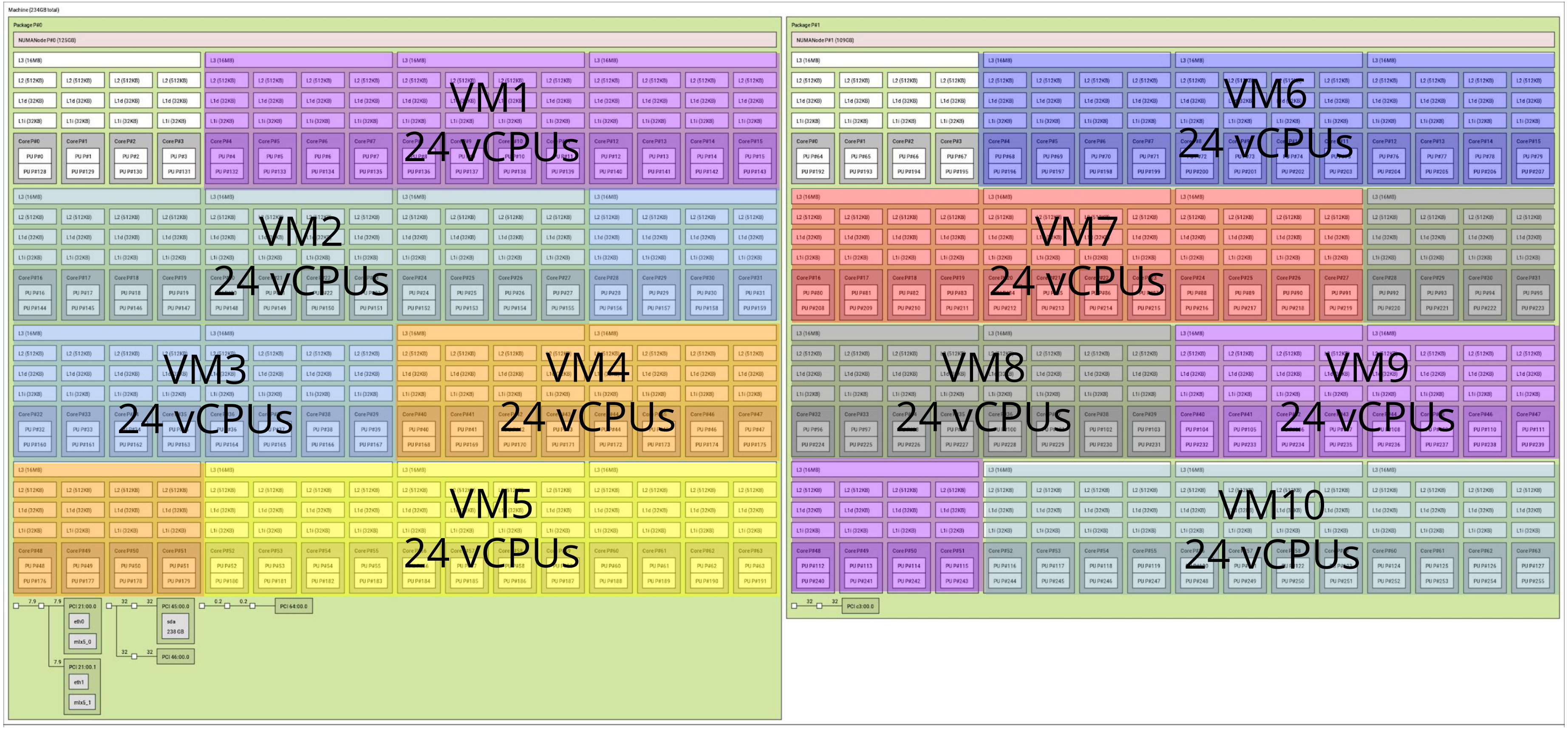
```
MB/sec copy     256221.30
MB/sec scale    173231.56
MB/sec add      181804.68
MB/sec triad    183952.20
```

We expect ~Baremetal/X

```
MB/sec copy      42703.55
MB/sec scale     28871.92
MB/sec add       30300.78
MB/sec triad     30658.70
```



STREAM, 10 VMs



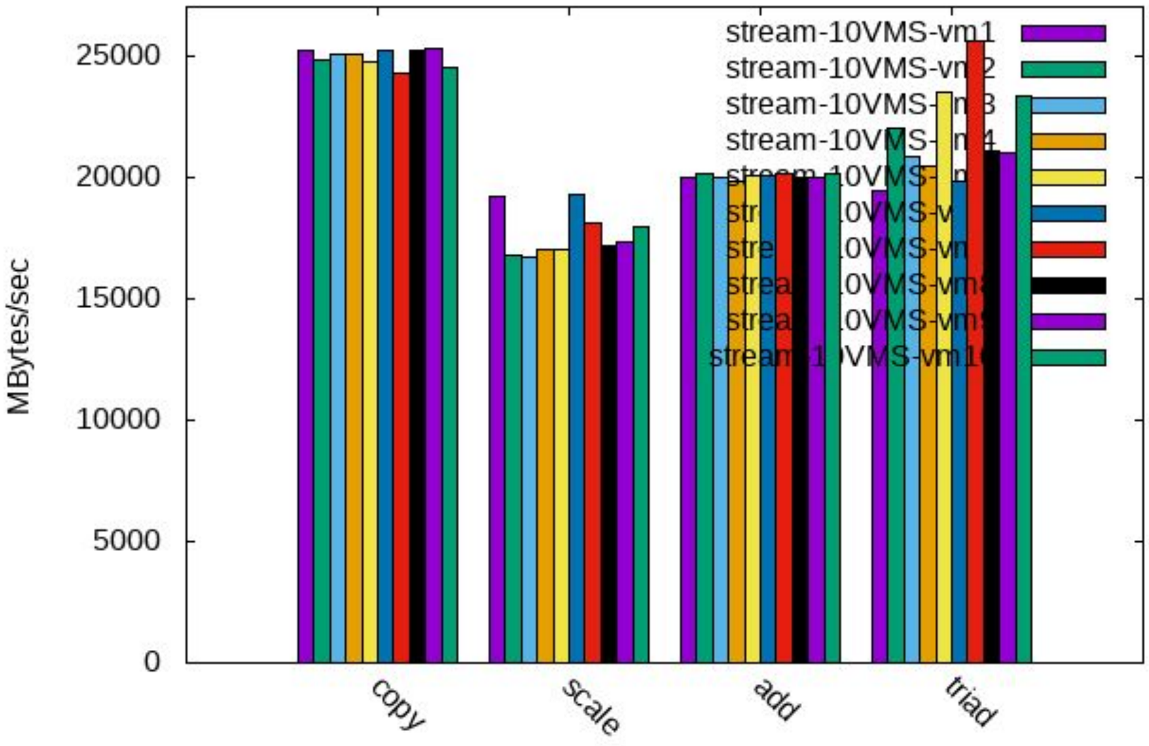
STREAM, 10 VMs

Baremetal:

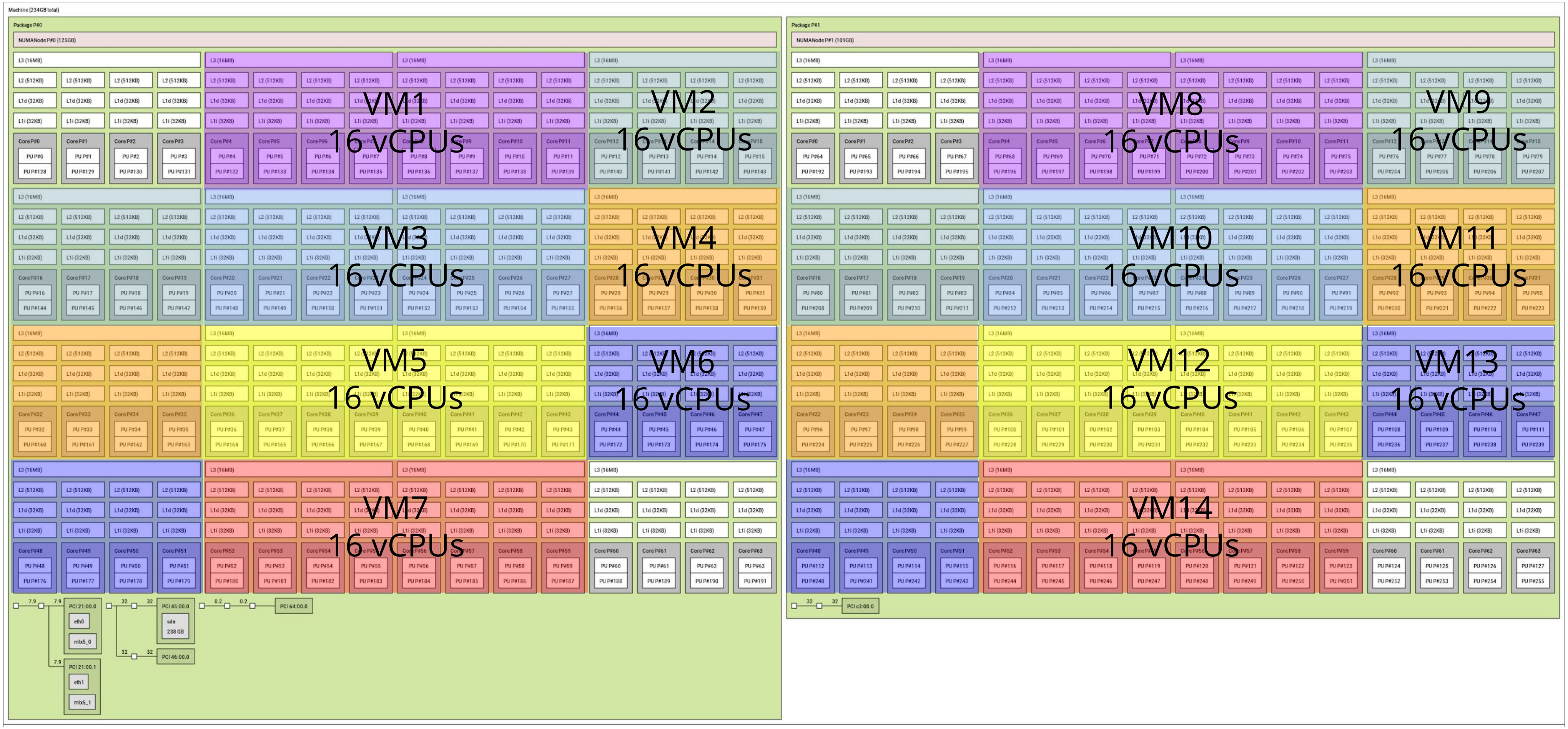
```
MB/sec copy     256221.30
MB/sec scale    173231.56
MB/sec add      181804.68
MB/sec triad    183952.20
```

We expect ~Baremetal/10

```
MB/sec copy      25622.13
MB/sec scale     17323.15
MB/sec add       18180.46
MB/sec triad     18395.22
```



STREAM, 14 VMs



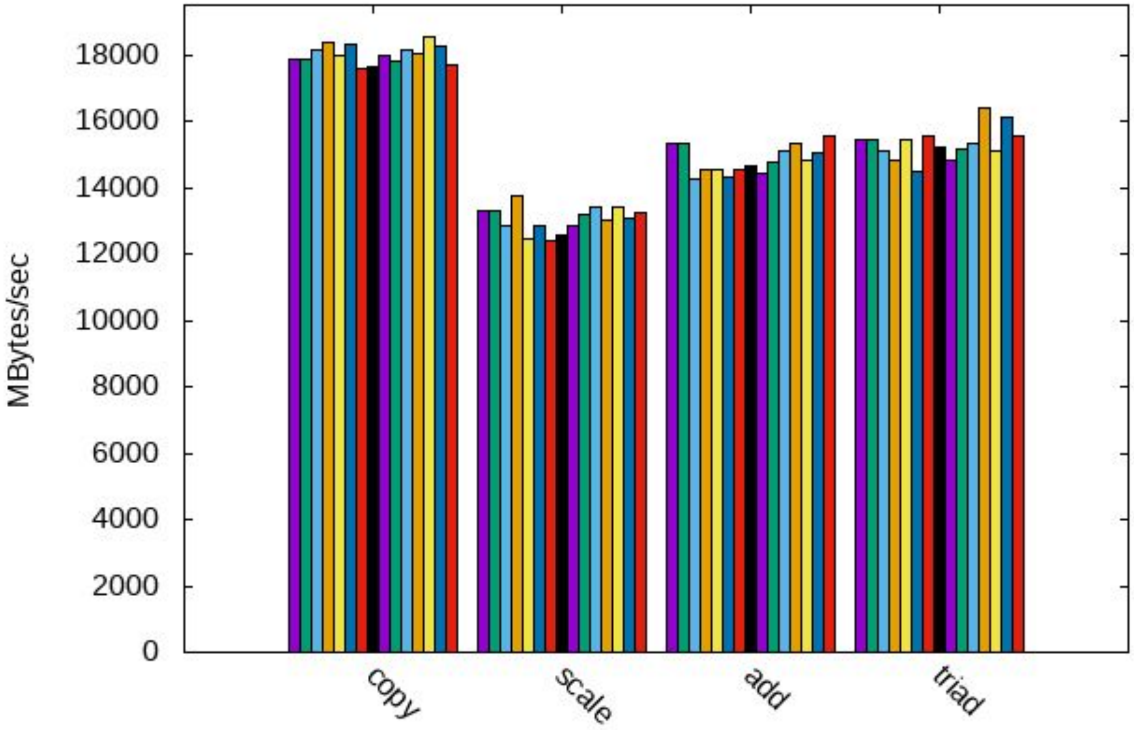
STREAM, 14 VMs

Baremetal:

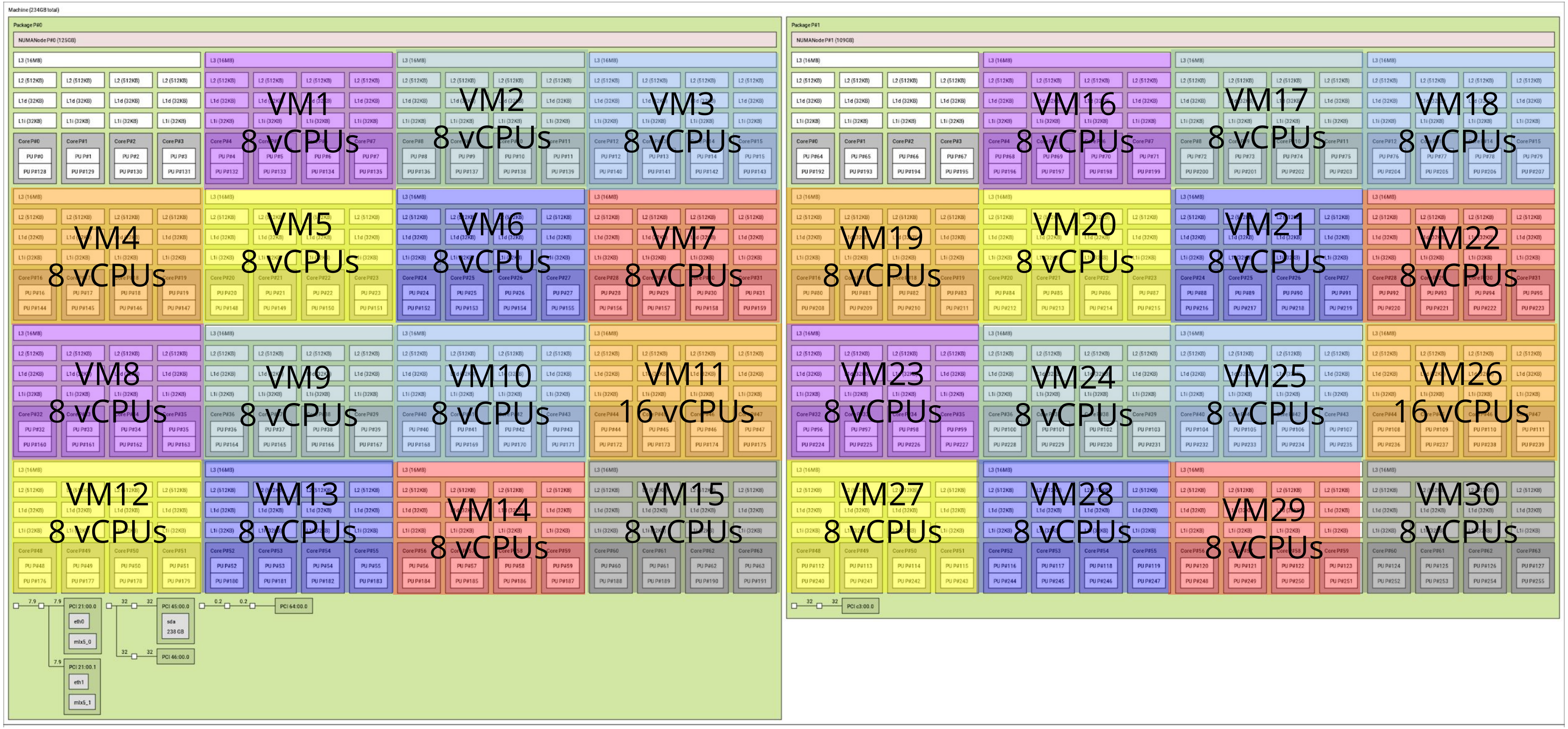
```
MB/sec copy     256221.30
MB/sec scale    173231.56
MB/sec add      181804.68
MB/sec triad    183952.20
```

We expect ~Baremetal/14

```
MB/sec copy      18301.52
MB/sec scale     12373.68
MB/sec add       12986.04
MB/sec triad     13139.44
```



STREAM, 30 VMs



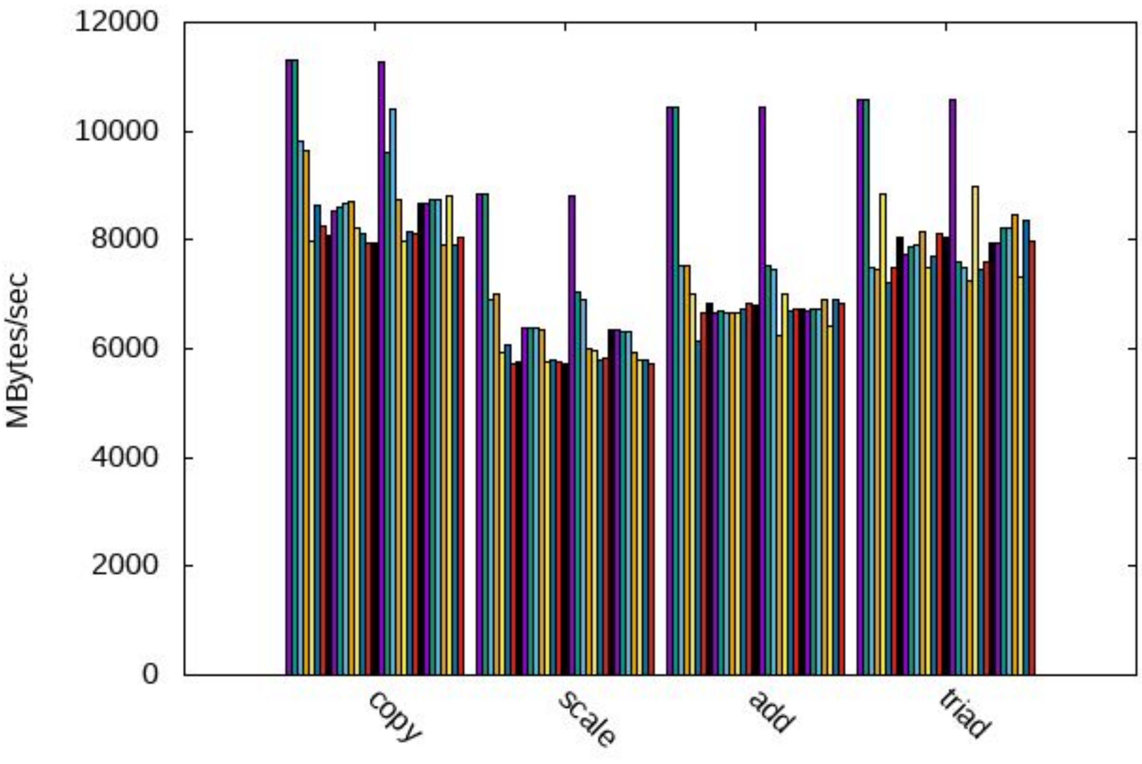
STREAM, 30 VMs

Baremetal:

```
MB/sec copy     256221.30
MB/sec scale    173231.56
MB/sec add      181804.68
MB/sec triad    183952.20
```

We expect ~Baremetal/30

```
MB/sec copy       8540.71
MB/sec scale      5774.38
MB/sec add        6060.15
MB/sec triad      6131.74
```



Conclusions

- Achieving close to host performance in VMs is possible:
  - (In the analyzed workloads)
  - Via resource partitioning
- With KVM, QEMU and Libvirt, on SUSE Linux Enterprise Server 15.1, we can effectively partition the resources to achieve such result
    - With Xen, lacking virtual topology enlightenment for guests
- AMD EPYC2 processor based platforms (especially as far as memory bandwidth is concerned):
  - Guarantees great scalability
  - Offers Memory Encryption with really low overhead
  - Mitigations for hardware vulnerabilities have limited performance impact

About Myself

- Ph.D on Real-Time Scheduling, `SCHED_DEADLINE`
- 2011, Sr. Software Engineer @ Citrix
  The Xen-Project, hypervisor internals,
  Credit2 scheduler, Xen scheduler maintainer
- 2018, Virtualization Software Engineer @ SUSE
  Still Xen, but also KVM, QEMU, Libvirt;
  Scheduling, VM's virtual topology,
  performance evaluation & tuning
- Spoke at XenSummit, Linux Plumbers, FOSDEM,
  LinuxLab, OSPM, KVM Forum, ...

Questions ?

(Picture from FOSDEM 2013… I think)

Farewell,
Lars

Backup

Virtual VS. Real

(v)CPU Topology:

- vCPUs wander around among pCPUs:
- The hypervisor scheduler moves them!
  - at time t1 vCPU 1 and vCPU 3 run on pCPUs that are SMT-siblings
  - at time t2! = t1 … Not anymore!

Shall the guest have a (virtual) topology?

- Yes… if properly constructed, and …
- … if we can “rely” on it
- E.g., if the vCPUs are pinned/have hard affinity

Virtual VS. Real: L3-cache & task wakeups

Cache layout: does it affect guest scheduling (& performance)?

- ~~No~~ Yes!!
-

```
ttwu_queue(p, cpu)
if (cpus_share_cache(spm_processor_id(), cpu)) {
  rq_lock(cpu_rq(cpu))
  ttwu_do_activate(cpu_rq(cpu), p)
    ttwu_do_wakeup(cpu_rq(cpu), p)
      check_preempt_curr(cpu_rq(cpu), p)
        /* If cpu_rq(cpu)->curr higher prio *
         * no IPI to cpu                    */
  rq_unlock()
} else {
  ttwu_queue_remote()
  llist_add(cpu_rq(cpu)->wake_list)
  smp_send_reschedule(cpu)
  /* IPI to cpu */
}
```

kernel/sched/core.c:1875
kernel/sched/core.c:1869
kernel/sched/core.c:1730
kernel/sched/core.c:884
kernel/sched/fair.c:L7661
kernel/sched/core.c:1883
kernel/sched/core.c:1831
kernel/sched/core.c:1837
kernel/sched/core.c:1839

Virtual VS. Real: L3-cache & task wakeups

Cache layout: does i

- ~~No~~ Yes!!
- ttwu_queue(p, cpu)

```
if (cpus_sh                                 u)) {
  rq_lock(c
  ttwu_do_a
    ttwu_do
      check_preempt_curr(cpu_rq(cpu), p)
        /* If cpu_rq(cpu)->curr       gher prio *
         * no IPI to cpu                       */
  rq_unlock()
} else {
  ttwu_queue_remote()
  llist_add(cpu_
  smp_send_resch
  /* IPI to cpu
}
```

kernel/sched/core.c:1875
kernel/sched/core.c:1869
kernel/sched/core.c:1730
kernel/sched/core.c:884
kernel/sched/fair.c:L7661
kernel/sched/core.c:1883
kernel/sched/core.c:1831
re.c:1837
re.c:1839

VM cache layout (before QEMU commit git:9308401):

- No L3 cache at all

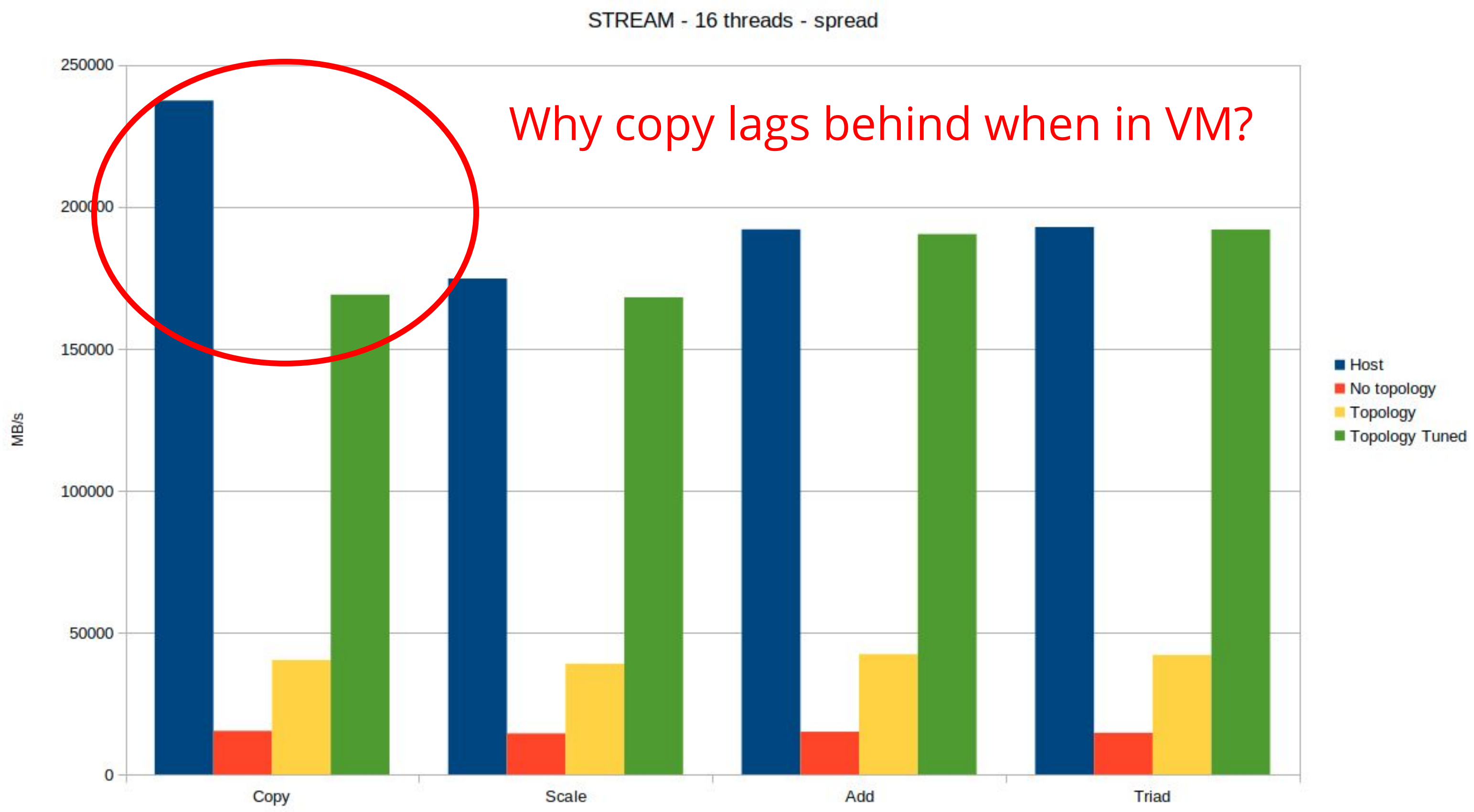
`cpus_share_cache()`,
always `false`

Always send IPI... TO ANOTHER _virtual_ CPU!
Difference shows!

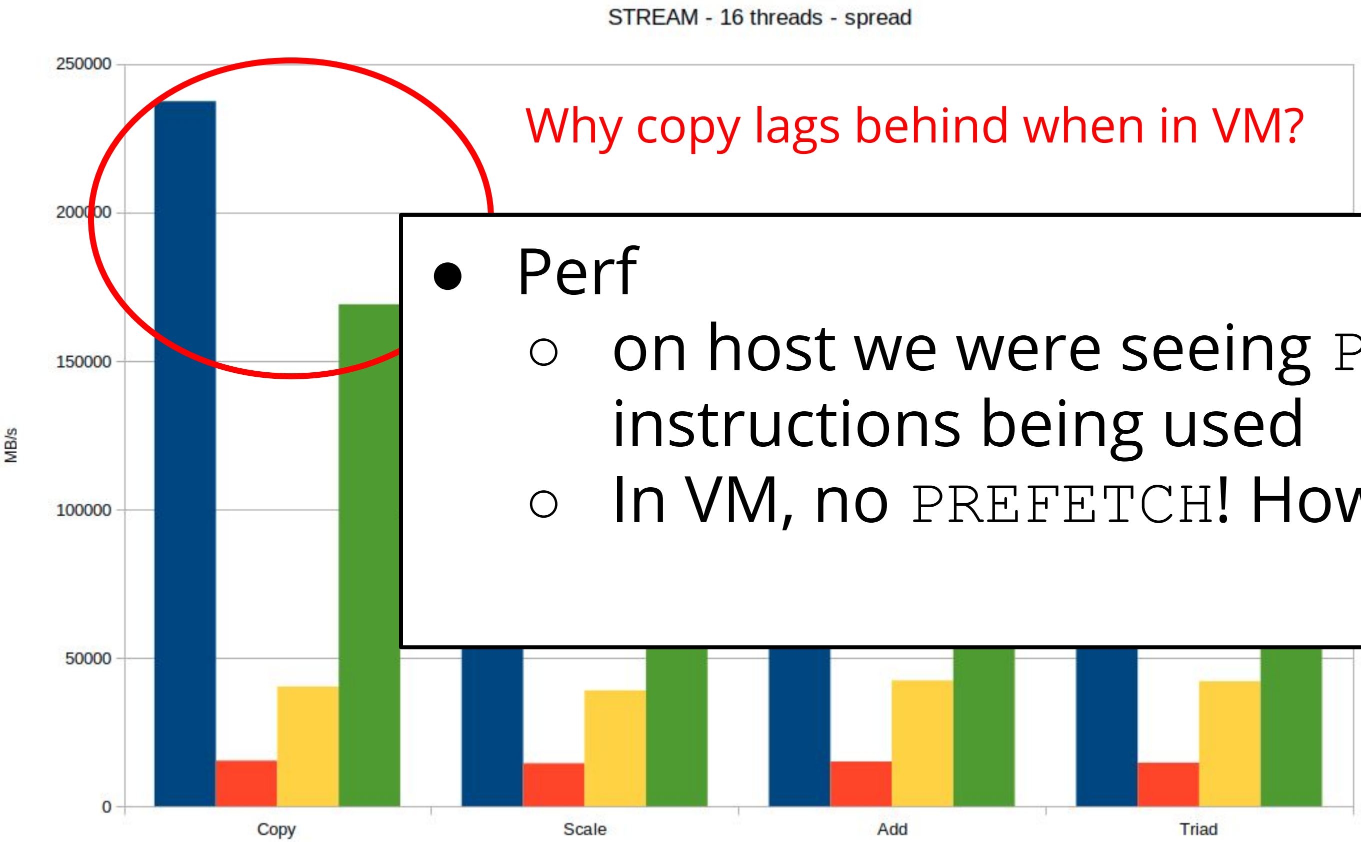
Virtual VS. Real: L3-cache size!

- STREAM benchmark
- AMD EPYC
- VM (KVM) tuned to match host perf

Virtual VS. Real: L3-cache size!



Virtual VS. Real: L3-cache size!



Why copy lags behind when in VM?

- Perf
  - on host we were seeing `PREFETCH` instructions being used
  - In VM, no `PREFETCH`! How so ?!?!

Virtual VS. Real: L3-cache size!

- *<<Let’s just expose to the VM whether vCPUs share an L3, no big deal how big such L3 the VM sees>>*
- Not quite:
  - Glibc heuristics for deciding whether or not memcpy uses non-temporal stores and `PREFETCH` instrs.
  - `thrs` = (L3 cache size / nr. threads sharing it) + L2 cache size
  - Don’t `PREFETCH` if amount of data mem-copied is smaller than `thrs`
- We need to expose the correct cache size to the VM
- (still working on it)