Transparent Hugepage Support

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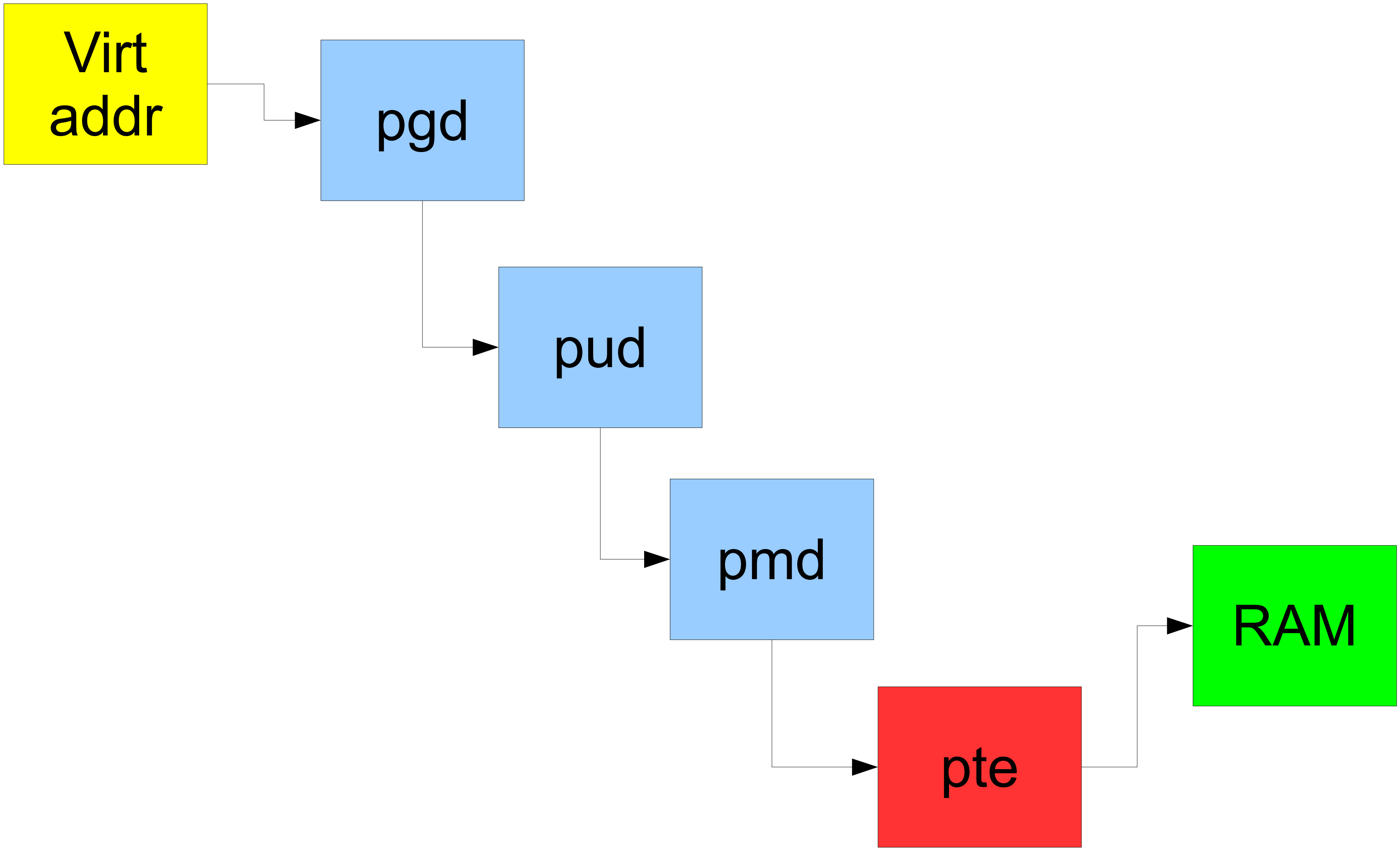
Benefit of hugepages

- **Boost CPU computing performance**
  - **Enlarge TLB size**
    - TLB is also separate for 4k and 2m pages
  - **Speed up TLB miss**
    - Need 3 accesses to memory instead of 4 to refill the TLB
  - Faster to allocate memory initially (minor)
  - Page colouring inside the hugepage (minor)
- Cons
  - clear_page/copy_page less cache friendly
  - Slightly higher memory footprint in some case

TLB miss cost 4k pages



TLB miss cost is 4 memory access

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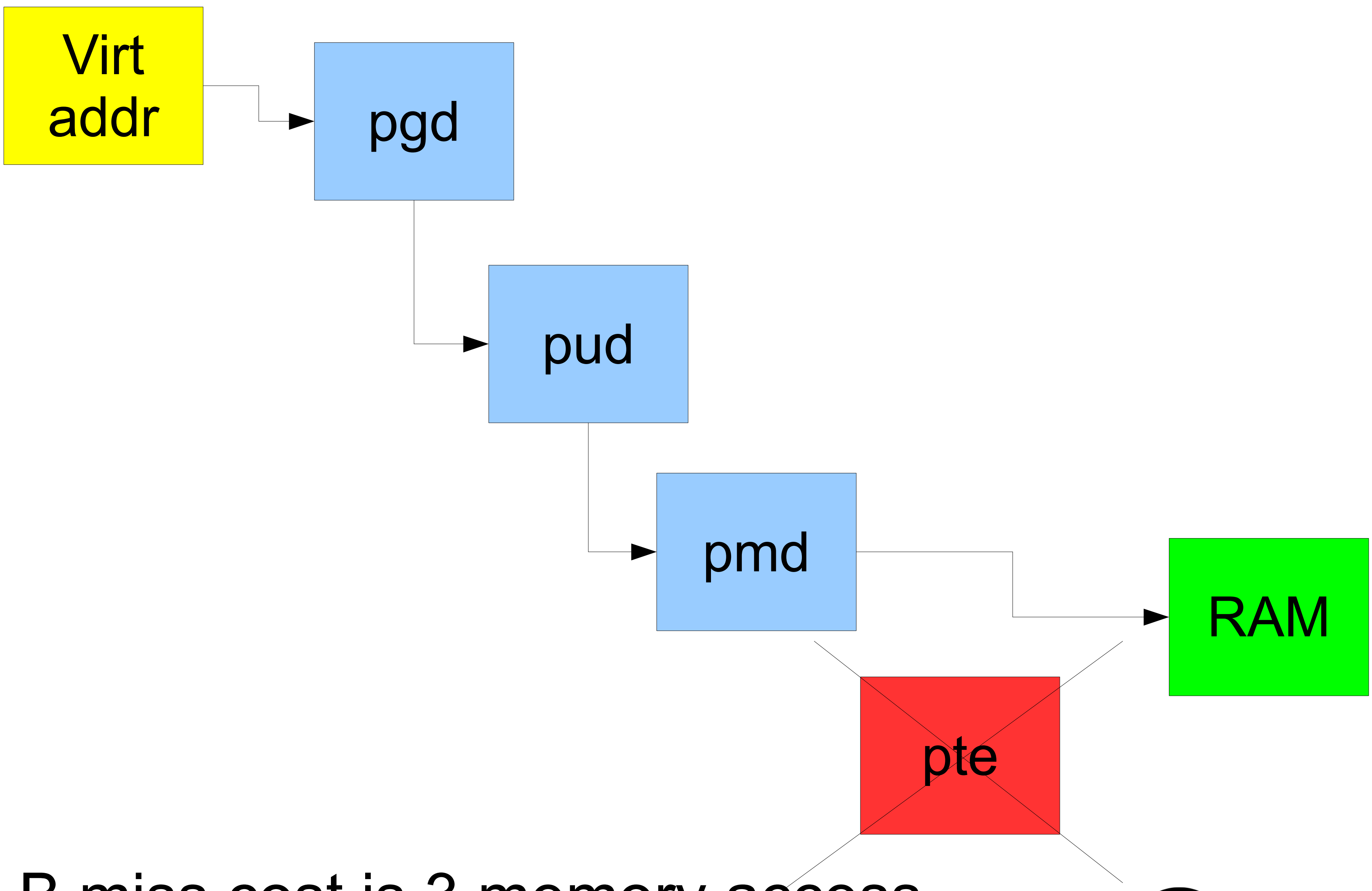
TLB miss cost 2M pages



TLB miss cost is 3 memory access

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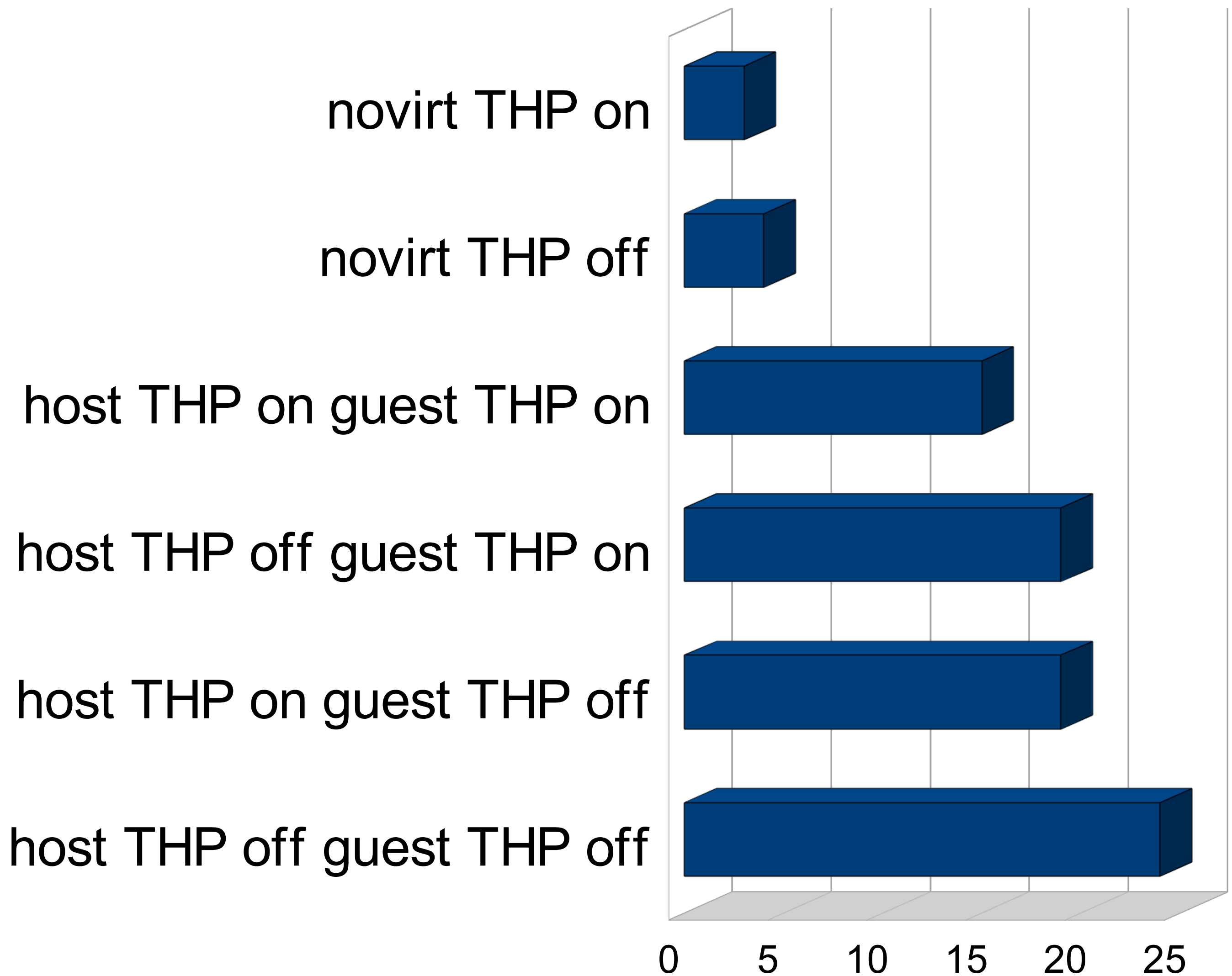
NPT/EPT TLB miss cost: number of accesses to memory



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Cache effect

- To access **16G of memory** the CPU has to read
  - **32MBytes worth of ptes with 4k pages** (not counting pmd/pud/pgd)
  - With hugepages the CPU will read only **64KBytes of hugepmd with hugepages**
- 64KBytes
  - fit into CPU cache
- 32MBytes
  - don't fit into CPU cache

Limit of hugetlbfs

- Hugepages can be used with hugetlbfs
  - They can't be **swapped** out
  - They better be **reserved** at boot
  - Hugepages and regular pages can't be mixed in the same vma (**only userland fallback**)
  - If reservation is not used and dynamic allocation fails things go bad in KVM
  - **Requires admin privilege** and libhugetlbfs
  - Hugetlbfs is **growing like a second but inferior Linux VM** with its own paths, as people add more features to hugetlbfs to behave more like tmpfs

Hugetlbfs for database

- Reservation at boot time may not be big deal with database
  - 1 database
  - 1 machine
  - 1 database cache
  - 1 database cache size set in config file or GUI
  - 1 reservation of hugepages with known size
  - Swapping is still missing (some DBMS want to swap its shared memory)
- **Hugetlbfs is usually ok <u>only</u> for database**

Hypervisors and hugetlbfs

- Hugetlbfs is not good for KVM
  - **Unknown number** of virtual machines
  - **Unknown amount of memory** used by virtual machines
  - We **want to use as many hugepages as available** to back guest physical memory (especially with NPT/EPT)
  - Virtual machines are **started, shutdown, migrated on demand** by user or RHEV-M
  - We need **overcommit (and KSM)** as usual
  - We want all memory not allocated by the guest available to the host for caching

Hugetlbfs userbase

- Not many are using hugetlbfs on laptop/workstation/server
  - Too many complications (not transparent)
  - Too many disadvantages/limitations
- As opposed: **even** the **OpenOffice** used to prepare this presentation **is backed by some Transparent Hugepage**...

Transparent Hugepage design

- Any Linux process will receive 2M pages
  - if the **mmap region is 2M naturally aligned**
- Hugepages are **only mapped by huge pmd**
- When VM pressure triggers the hugepage are split
  - Then they can be **swapped out as 4k pages**
- Tries to **modify as little code as possible**
- Entirely **transparent to userland**
- Already working with **KVM with NPT/EPT and shadow MMU**
- Boost for page faults too and later the CPU accesses memory faster

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THP on anonymous memory

- Current implementation **only covers anonymous** memory (MAP_ANONYMOUS, i.e. malloc())
  - KVM guest physical memory is incidentally backed by anonymous memory...
  - In the future database may require tmpfs to use transparent hugepages too if they want to swap
    - database main painful limit of hugetlbfs is the lack of swapping

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split_huge_page

- Low code impact
- Try to stay **self contained**
  - If the code is not THP aware it's enough to call split_huge_page() to make it THP aware
    - then it's business as usual
- **1 liner trivial change vs >100 lines of non trivial code**
- Over time we need to minimize the use of split_huge_page
- **Like the big kernel lock** (lock_kernel() going away over time where avoidable)

collapse_huge_page/khugepaged

- "khugepaged" scans the virtual address space
  - it collapses 512 4k pages in one 2M page
  - it converts the 512 ptes to a huge pmd
- "khugepaged" can undo the effect of split_huge_page
  - Like after swapin

THP sysfs enabled

- /sys/kernel/mm/transparent_hugepage/enabled
  - **[always]** madvise never
    - Try to use THP on every big enough vma to fit 2M pages
  - always **[madvise]** never
    - Only inside MAD_HUGEPAGE regions
      - Applies to khugepaged too
  - always madvise **[never]**
    - Never use THP
    - khugepaged quits
- Default selected at build time (**enabled|madvise**)

THP kernel boot param

- To alter the default build time setting
  - transparent_hugepage=**always**
  - transparent_hugepage=**madvise**
  - transparent_hugepage=**never**
    - khugepaged isn't even started

khugepaged sysfs

- /sys/kernel/mm/transparent_hugepage/**khugepaged**
  - **pages_to_scan** (default 4096 = 16MB)
    - Number of pages to scan at each wakeup
  - **scan_sleep_millisecs** (default 10000 = 10sec)
    - How long before khugepaged is waken up to scan "pages_to_scan" virtual pages
      - 0 value run khugepaged at 100% load
  - **alloc_sleep_millisecs** (default 60000 = 60sec)
    - How long to wait before trying again allocating an hugepage in case of fragmentation

THP monitoring

```
$ grep Anon /proc/meminfo
AnonPages:       15719600 kB
AnonHugePages:   14436352 kB
$ cat /proc/`pgrep mutt`/smaps|grep Anon
Anonymous:              0 kB
AnonHugePages:          0 kB
Anonymous:              4 kB
AnonHugePages:          0 kB
Anonymous:             20 kB
AnonHugePages:          0 kB
Anonymous:             20 kB
AnonHugePages:          0 kB
Anonymous:          69400 kB
AnonHugePages:      67584 kB
[..]
```

THP vmstat

```
$ grep thp /proc/vmstat #during heavy swap
thp_fault_alloc 66608
```

- Transparent Hugepages allocated in page faults
  - The higher the better

```
thp_fault_fallback 546
```

- Failure in allocating hugepage in fault → fallback to 4k
  - The lower the better

```
thp_collapse_alloc 113
```

- Transparent Hugepages collapsed by khugepaged

```
thp_collapse_alloc_failed 5
```

- Failure in allocating hugepage in khugepaged

```
thp_split 22608
```

- Number of split_huge_page()
  - The lower the better

Optimizing apps for THP

- Not really required
  - Mutt example → unmodified:
    - `Anonymous:          69400 kB`
    - **`AnonHugePages:      67584 kB`**
- posix_memalign(&ptr, 2M, (size+2M-1) & ~(2M-1))
  - Allows max 2 more THP allocated per mapping
    - Generally not very important
    - Only KVM requires this: gfn → hva → pfn
- **Glibc could learn** to auto-align large mappings
- 4M for x86 32bit noPAE

madvise(MADV_HUGEPAGE)

- To use hugepages only in specific regions
  - To avoid altering the memory footprint
    - **Embedded systems** want to use it
- Makes a difference **only** when *"/sys/kernel/mm/transparent_hugepage/enabled"* is set to "madvise"
- Better than libhugetlbfs for embedded:
  - swap enabled
  - full userland transparency
  - no root privilege
  - no library dependency

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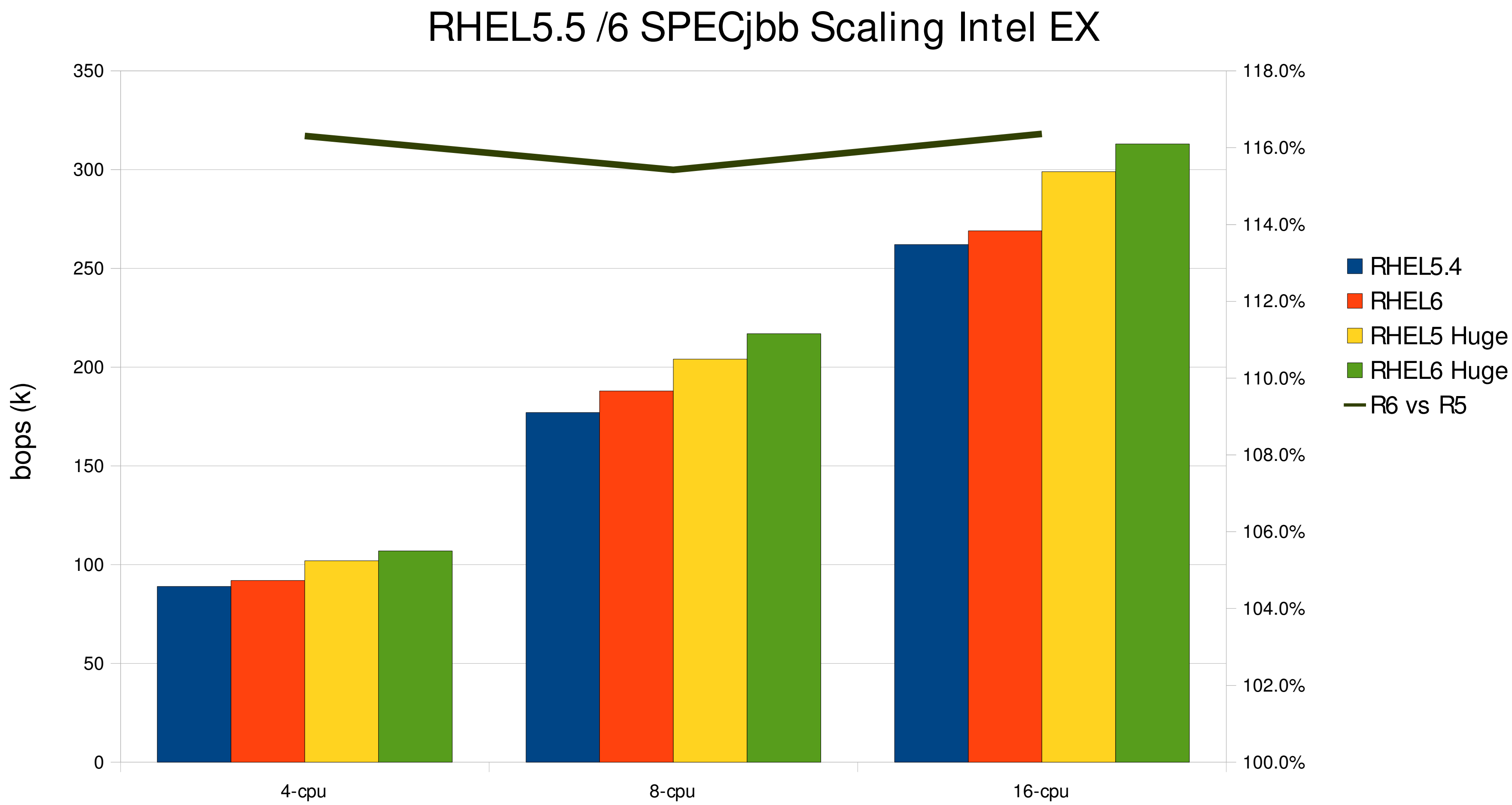
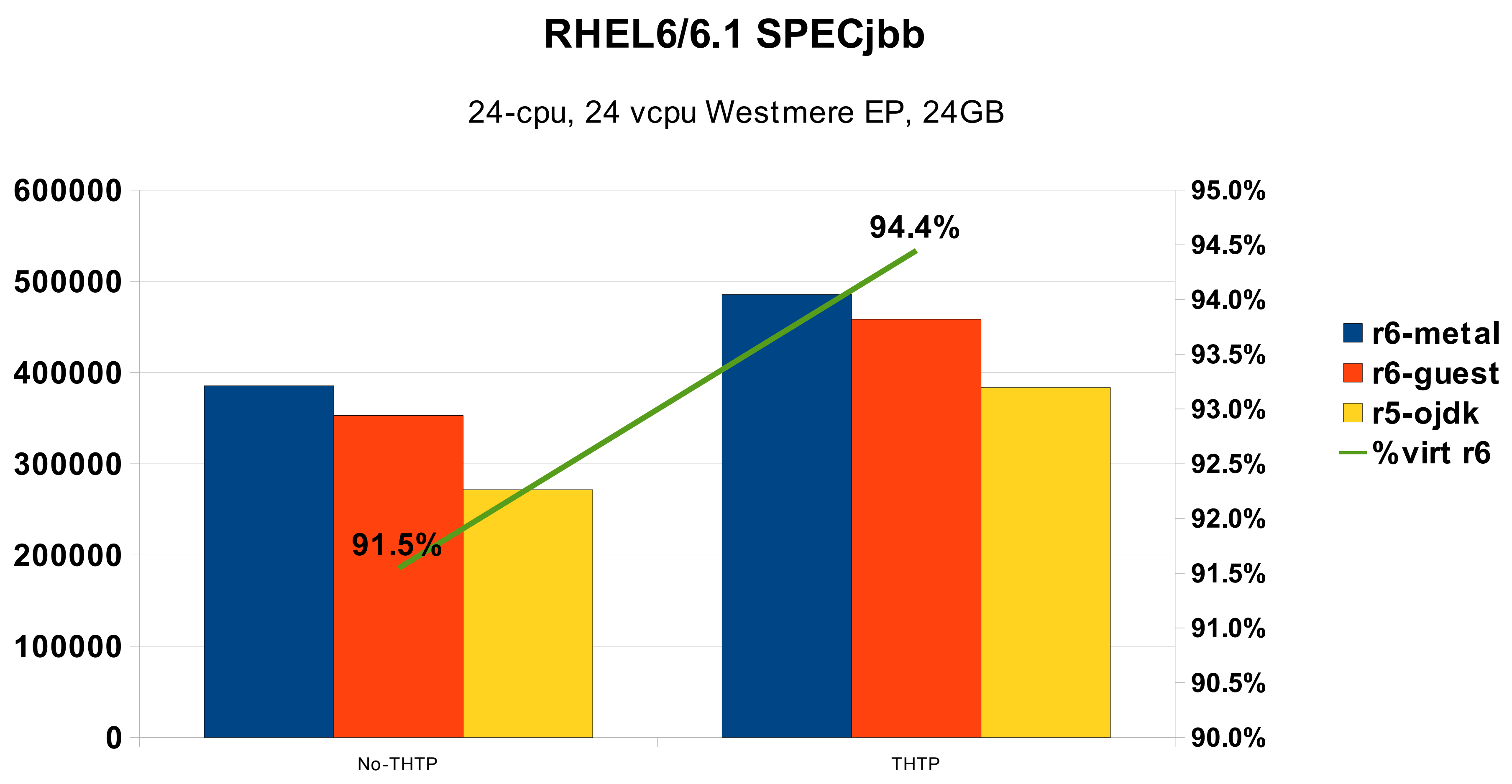
Transparent Hugepages and KVM

- We need THP in both guest and host
  - So the CPU can use the 2M TLB for the guest
- This shows the power of KVM design
  - same algorithm
  - same code
  - same kernel image
    - For both KVM hypervisor and guest OS

RHEL6 Linux Intel EP Specjbb Java Bare-Metal Huge/Transparent Huge Pages



RHEL6/6.1 KVM Linux Intel Westmere EP Specjbb transparent hugepages/unfair_spin



THP and kbuild

- GCC allocations are specially optimized (gcc isn't using glibc malloc)
  - Requires a small tweak to gcc
- Heavily parallel
- Heavily MMU intensive
- Worst case benchmark for THP, especially on bare metal
  - Small working set for each task
  - It even includes `make clean` etc...
- Phenom X4 kbuild (no virt)
  - 2.5% faster with THP

gcc patch (trivial)

```
@@ -450,6 +450,11 @@
 #define BITMAP_SIZE(Num_objects) \
   (CEIL ((Num_objects), HOST_BITS_PER_LONG) * sizeof(long))

+#ifdef __x86_64__
+#define HPAGE_SIZE (2*1024*1024)
+#define GGC_QUIRE_SIZE 512
+#endif
+
 /* Allocate pages in chunks of this size, to throttle calls to memory
    allocation routines.  The first page is used, the rest go onto the
    free list.  This cannot be larger than HOST_BITS_PER_INT for the
@@ -654,6 +659,23 @@
 #ifdef HAVE_MMAP_ANON
   char *page = (char *) mmap (pref, size, PROT_READ | PROT_WRITE,
                               MAP_PRIVATE | MAP_ANONYMOUS, -1, 0);
+#ifdef HPAGE_SIZE
+  if (!(size & (HPAGE_SIZE-1)) &&
+      page != (char *) MAP_FAILED && (size_t) page & (HPAGE_SIZE-1)) {
+        char *old_page;
+        munmap(page, size);
+        page = (char *) mmap (pref, size + HPAGE_SIZE-1,
+                              PROT_READ | PROT_WRITE,
+                              MAP_PRIVATE | MAP_ANONYMOUS, -1, 0);
+        old_page = page;
+        page = (char *) (((size_t)page + HPAGE_SIZE-1)
+                         & ~(HPAGE_SIZE-1));
+        if (old_page != page)
+                munmap(old_page, page-old_page);
+        if (page != old_page + HPAGE_SIZE-1)
+                munmap(page+size, old_page+HPAGE_SIZE-1-page);
+  }
+#endif
```

`perf` of kbuild (real life)

24-way SMP (12 cores, 2 sockets) 16G RAM host, 24-vcpu 15G RAM guest

```
====== build ======
#!/bin/bash
make clean >/dev/null; make -j32 >/dev/null
=====================
```

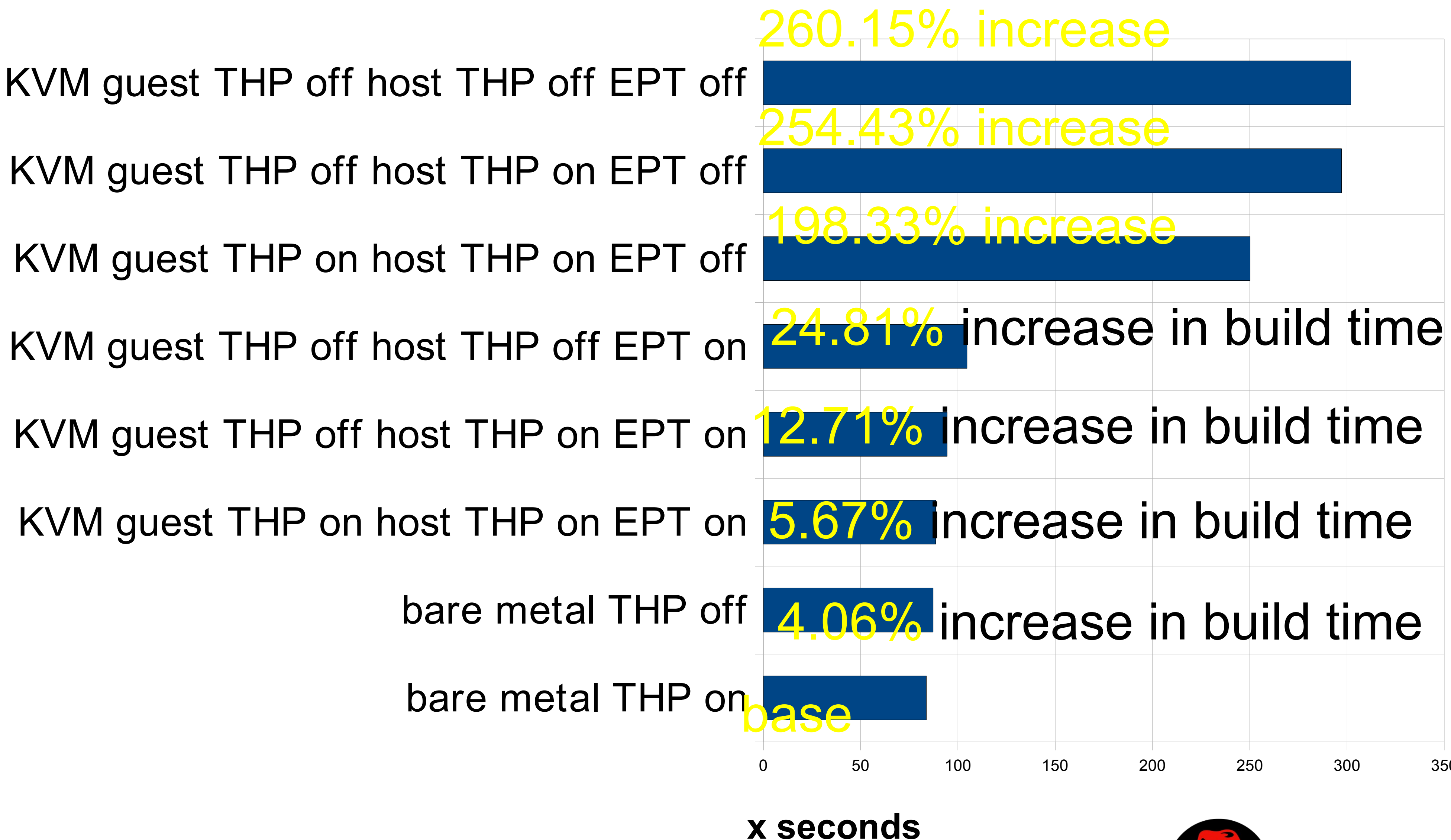
THP always host (base result)

```
 Performance counter stats for './build' (3 runs):

     4420734012848  cycles                    ( +-   0.007% )
     2692414418384  instructions              #      0.609 IPC     ( +-   0.000% )
      696638665612  dTLB-loads                ( +-   0.001% )
        2982343758  dTLB-load-misses          ( +-   0.051% )

      83.855147696  seconds time elapsed   ( +-   0.058% )
```

THP never host (slowdown 4.06%)

```
 Performance counter stats for './build' (3 runs):
     4599325985460  cycles                    ( +-   0.013% )
     2747874065083  instructions              #      0.597 IPC     ( +-   0.000% )
      710631792376  dTLB-loads                ( +-   0.000% )
        4425816093  dTLB-load-misses          ( +-   0.039% )

      87.260443531  seconds time elapsed   ( +-   0.075% )
```

kbuild bench
build time: lower is better



qemu-kvm translate.o

- Phenom X4 qemu-kvm translate.o build (no virt)
  - 10% faster with THP
  - this is a single gcc task running
    - Not parallel
    - no `make -jxx`
    - no `make clean`
- Will follow the result on 24-way SMP

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`perf` profiling of translate.o

24-way SMP (12 cores, 2 sockets) 16G RAM host, 24-vcpu 15G RAM guest

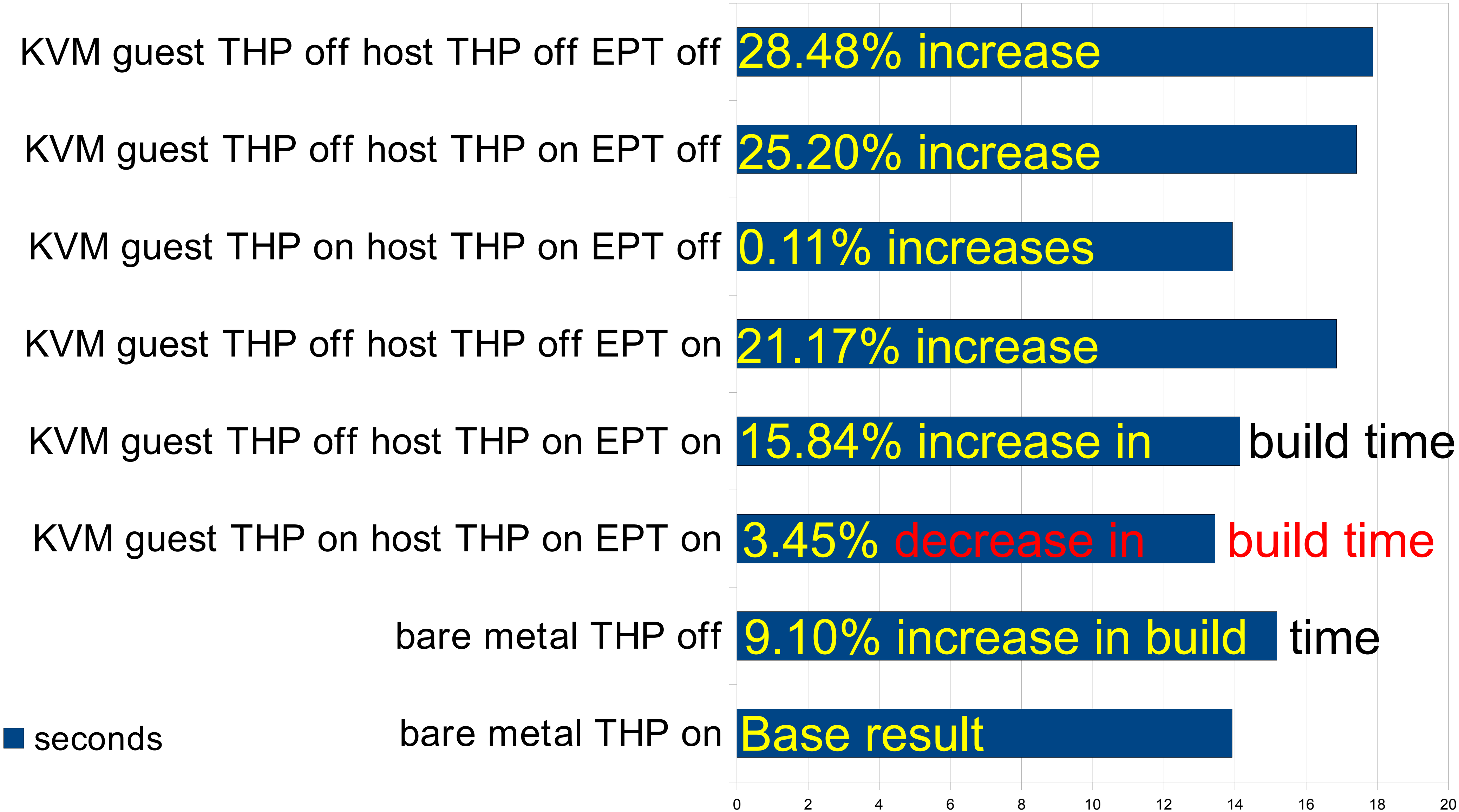
THP always bare metal (base result)

```
40746051351  cycles                 ( +-   5.597% )
36394696366  instructions           #     0.893 IPC     ( +-   0.007% )
 9602461977  dTLB-loads               ( +-   0.006% )
   45123574  dTLB-load-misses           ( +-   0.614% )

13.920436128  seconds time elapsed   ( +-   5.600% )
```

THP never bare metal (9.10% slower)

```
44492051930  cycles                 ( +-   5.189% )
36757849113  instructions           #     0.826 IPC     ( +-   0.001% )
 9693482648  dTLB-loads               ( +-   0.004% )
   63675970  dTLB-load-misses           ( +-   0.598% )

15.188315986  seconds time elapsed   ( +-   5.194% )
```

kbuild "EPT off" build time: lower is better



Phoronix test suite

- http://www.phoronix.com/scan.php?page=article&item=linux_transparent_hugepages&num=2
- IS.C test of NASA's OpenMP-based performance boost more than 20%
  - No virt
  - On thinkpad T16 notebook
    - Core 2 Duo T9300
    - 4GB of RAM
  - A bigger boost is expected on server/virt

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Other results

- "/usr/bin/sort -b 1200M /tmp/largerand" no virt
  - 6% faster with THP (reported on lkml)
- Vmware workstation SPECJBB with hugetlbfs in guest
  - 22% faster with THP (reported on lkml)

Transparent Hugepages status

- **Fully merged in 2.6.38 upstream**
- Memory compaction included in 2.6.35
  - Memory compaction motivated by THP
- THP enabled by default in RHEL6 (guest & host)
- KSM fully THP aware (2.6.38 and RHEL6.1)
  - Mix of PageKsm, PageTransHuge and regular anon pages in the same vma
    - All 3 kind of anonymous pages swappable
- mprotect/mincore/memcg THP support in 2.6.38
- /proc/<pid>/smaps support in 2.6.39-rc

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THP future optimizations

- mremap THP support + tlb boost ready for -mm
- Remove tlb flush in pmdp_splitting_flush_notify()
- Avoid some unnecessary split_huge_page:
  - migrate_pages()/move_pages() syscall
- More glibc awareness for automatic alignments of large mmap
- pagecache
  - tmpfs
  - swapcache (i.e. native THP swapping)
  - Maybe filebacked mappings?

Q/A

- You're very welcome!
- Latest development THP code
  - http://git.kernel.org and then search “aa.git”
- **First: git clone git://git.kernel.org/pub/scm/linux/kernel/git/andrea/aa.git**
- **Later: git fetch && git checkout -f origin/master**