KVM/ARM at Scale

Improvements to the MMU in the face of hardware growing pains

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Google Cloud

Introduction

Google Cloud has recently announced the T2A family of VMs, the first product built with the Arm architecture

- Ampere Altra SoC
- KVM-based virtualization stack
- Close-to-upstream “Icebreaker” kernel (presented at OSS 2021)

Dirty Tracking on Arm

- MMU lock contention was the bounding issue
- Write protection is the name of the game
    - No feature like Intel's PML
- High frequency of stage-2 aborts
- Dirty state tracked at PTE granularity

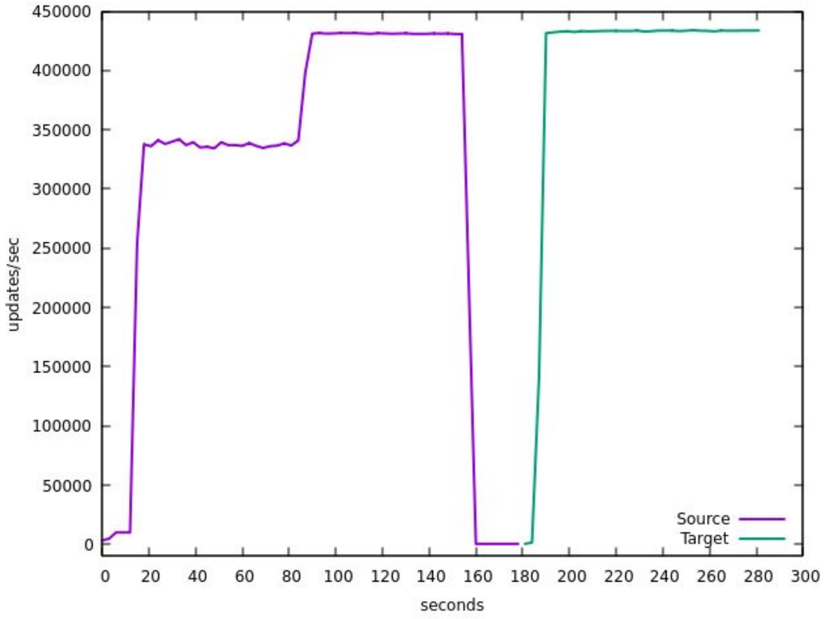
Test Workload

Theoretical worst case scenario:

- t2a-standard-48 (48 vCPUs, 192 GiB RAM)
- Backed with 2M HugeTLB
- Guest userspace strides memory with 100% write accesses
- After some time VMM enables dirty logging

“Live” Migration

- >99% performance degradation when dirty logging is enabled
- Guest starved of CPU for nearly 30 seconds



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Here we go again...

At first glance, the problems are similar to x86:

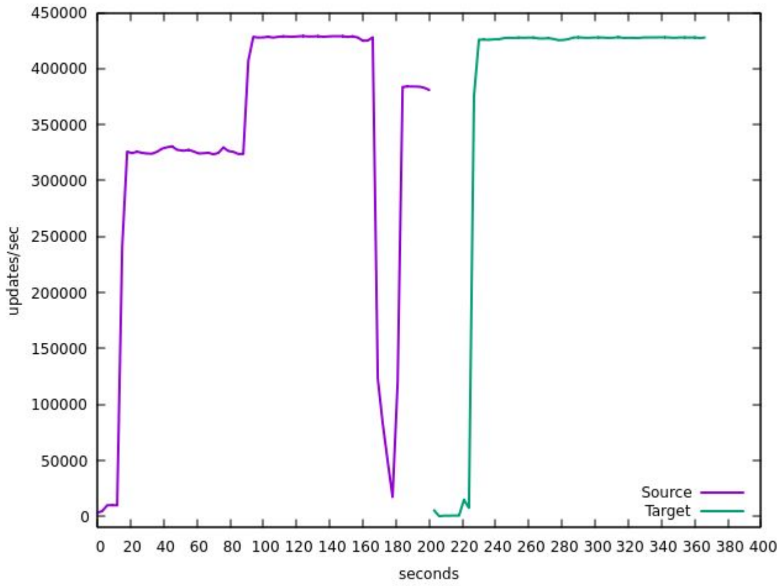
- MMU guarded with a spinlock
- When dirty logging, blocks are split into tables lazily

We went about fixing the problem the same way:

- 5.18: Take the read lock to write-unprotect a page
- RFC: Take the read lock for the other stage-2 faults

Signs of life

- Improvement over baseline
- Still, significant performance degradation at the beginning of dirty logging



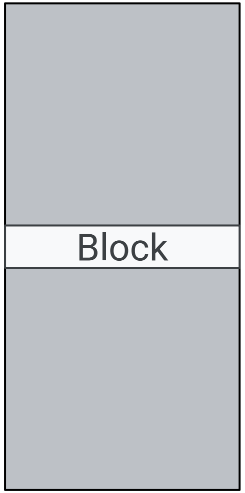
Where else are we serializing?

- Inspecting some traces, it appears a lot of time is spent in `__kvm_tlb_flush_vmid_ipa()`
- Called in the middle of page split because of break-before-make
- No software locking, so what gives?

Break-before-make

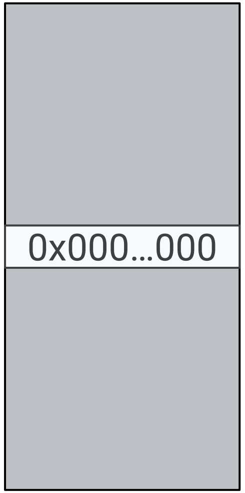
- Arm architecture more prescriptive than others (x86) on how software manipulates page tables
- Software must first make an invalid PTE (break) visible to hardware before another valid PTE (make)
- Prevents TLB conflicts
- Required for hugepage splitting

Break-before-make (cont’d)



```
WRITE_ONCE(*ptep, 0);

dsb(ishst);

tlbi(ipas2e1is, ipa);

dsb(ish);

tlbi(vmalle1is);

dsb(ish);

isb();

WRITE_ONCE(*ptep, new);
```

Break-before-make (cont’d)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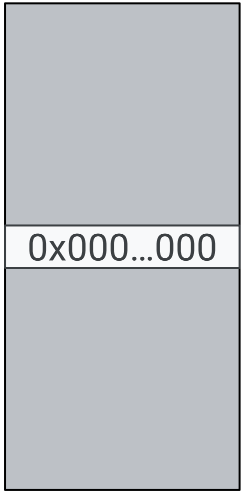
Break-before-make (cont’d)



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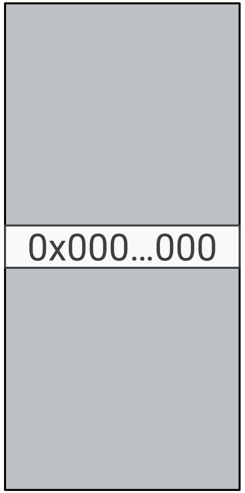
Break-before-make (cont'd)



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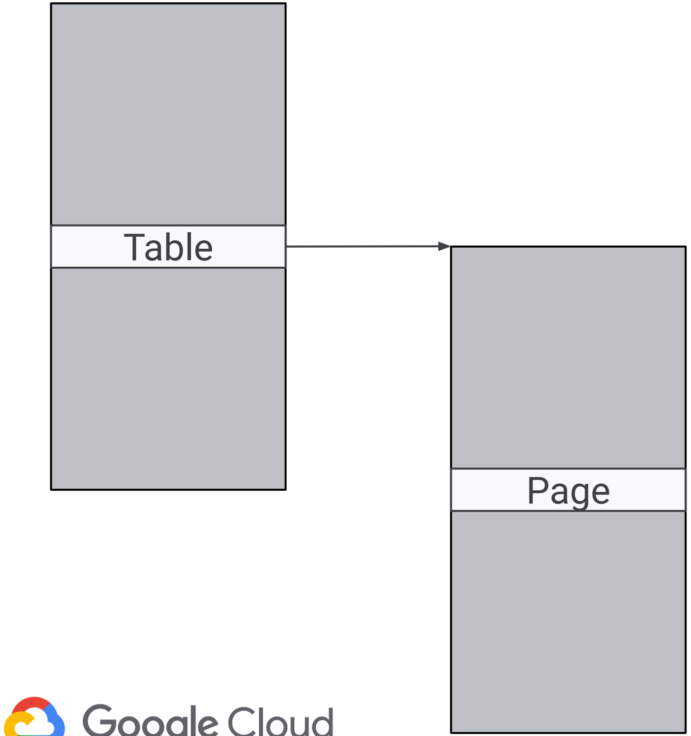

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Side effects of break-before-make

- TLB invalidations are broadcasted to Inner-Shareable domain
- DSB awaits the completion of *all* in flight invalidations on the Inner-Shareable domain
- Observation: on a loaded system, the sequence can take several **milliseconds** to complete
- Result: unacceptable vCPU fault latency

What if I elide break-before-make?

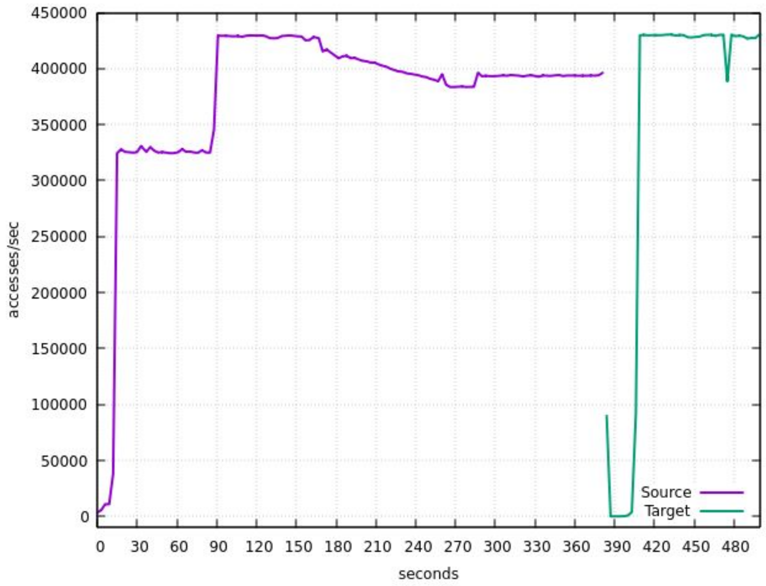
- Based on the implementation:
  - TLB conflict abort
  - TLB returns either of the duplicate entries
  - TLB returns an amalgamation of both entries
- Open season for all kinds of interesting failures, such as breaking:
  - Coherency
  - Single-copy atomicity
  - Ordering

Mitigating in software

- Eliminate unnecessary broadcasting of TLB invalidations
  - Relaxing write permissions falls outside the scope of break-before-make
  - Instead, invalidate only within the Non-Shareable domain (local)
- Spread out the necessary TLB invalidations over a longer period of time
- Solution: extend the KVM_CLEAR_DIRTY_LOG ioctl to split hugepages
  - Eager page splitting, with the ability to ratelimit in userspace

End result

- Page splitting throttled to minimize break-before-make overhead
- Gradual (and smaller) degradation in guest performance



Outlook

- Problem only gets worse with more cores in a system
  - Interconnect implementations need TLB snoop filters
- `FEAT_TLBIRANGE` - Software can target a range of memory with a single invalidation; allows batching without dropping all context
- `FEAT_BBM=2` - Relaxes the break-before-make requirements, allowing hugepage split/collapse without the sequence
  - Snag: software needs to deal with TLB conflict aborts. Only option is to flush everything when the abort occurs.

Acknowledgements

- Ricardo Koller: Eager splitting implementation
- David Matlack: Use CLEAR ioctl for split throttling
- Marc Zyngier: Non-Shareable TLB invalidations
- Jing Zhang: Parallel permission relaxation

Questions?

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