RadixVM

Scalable address spaces for multithreaded applications

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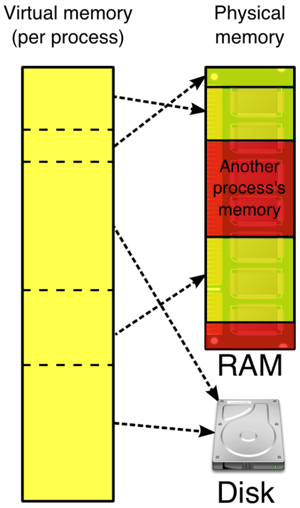
Nickolai Zeldovich

Presented by Simon Pratt

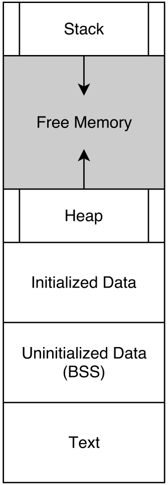
February 12, 2016

Background: Virtual Memory



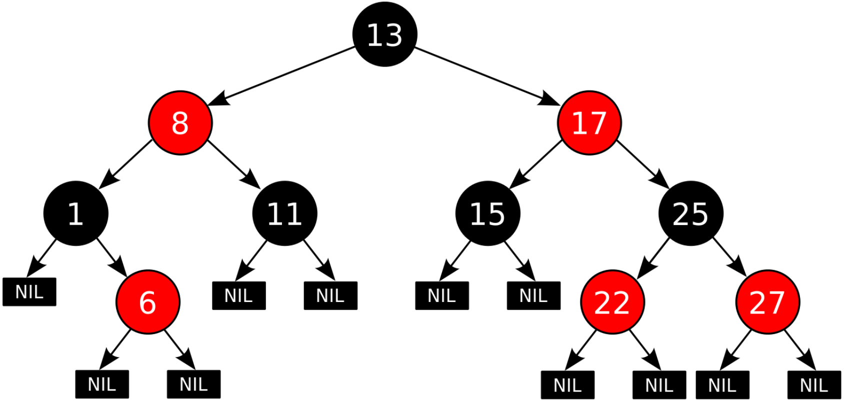
- Maps a contiguous virtual address space to:
  - physical memory (frames)
  - disk (swap)
- Translation Lookaside Buffer (TLB): hardware that caches virtual to physical address mappings
- Virtual address not in TLB $\rightarrow$ page fault
  - “Soft” page fault: page loaded in memory
  - “Hard” page fault: page swapped out, must be loaded into memory

Background: `malloc` and `mmap`



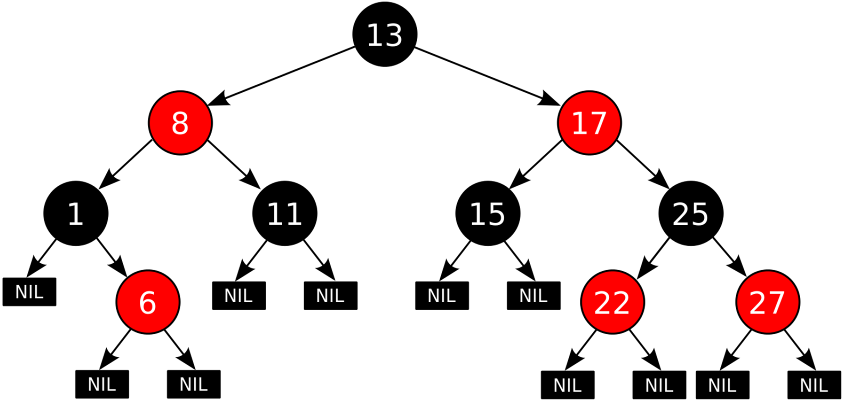
- `malloc` and `free`
  - User-level library function
  - Allocates/frees space in virtual memory
  - Often implemented using `mmap` and `munmap`
- `mmap` and `munmap`
  - System calls
  - Actually allocates/frees space in virtual memory

Background: Linux Virtual Memory



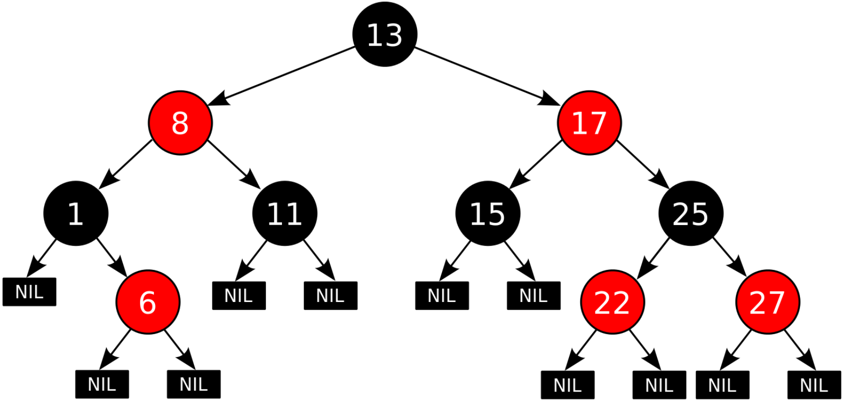
- Red-black tree
- Allows the kernel to search for memory area covering a virtual address

Background: Linux Virtual Memory



- Red-black tree
- Allows the kernel to search for memory area covering a virtual address
- Problem: A single lock per address space!

Aside: Psearchy



- A single lock on this structure → `mmap` within a single process is serialized
- This is probably why the prwlock paper notes that Psearchy is `mmap`-intensive

Design: High-level

RadixVM has 3 parts:

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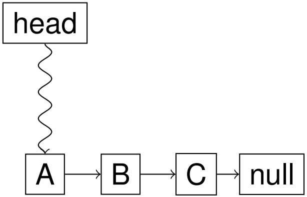
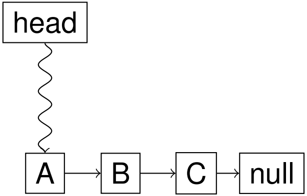


- Process P_1 reads value at A in order to pop A

Background: ABA Problem



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- P_1 is preempted

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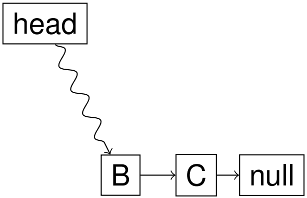

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- P_2 pops (and frees) A, sets head to B

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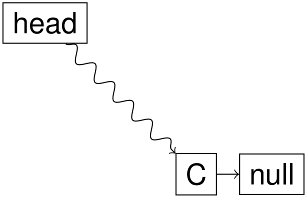

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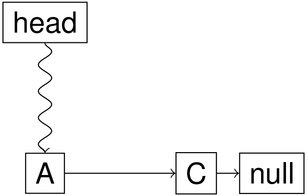

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  - Important: this new A has the same location as the old A

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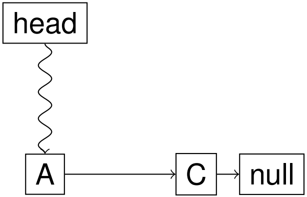

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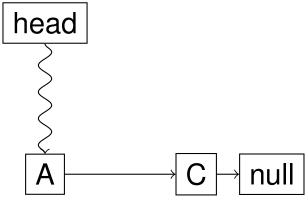

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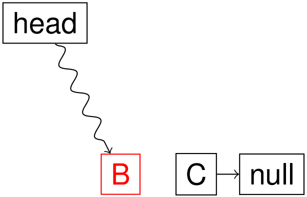

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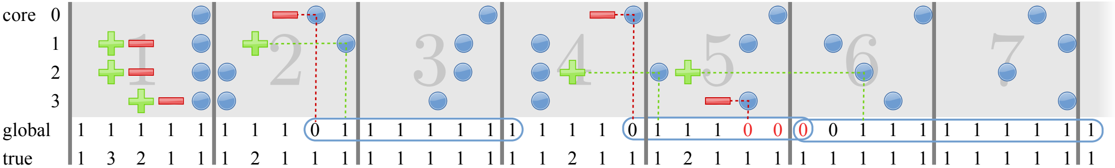
Design: Refcache



- Counts references to memory locations

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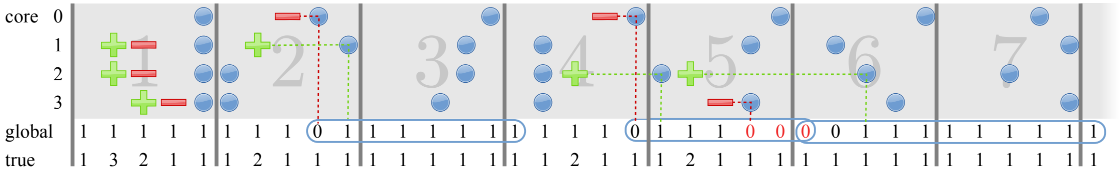

- Counts references to memory locations
  - Per-core lazy counting

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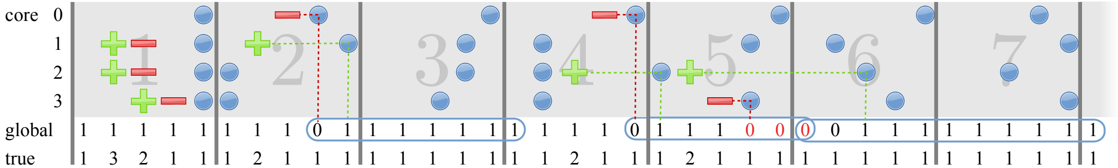

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- Divides time into epochs

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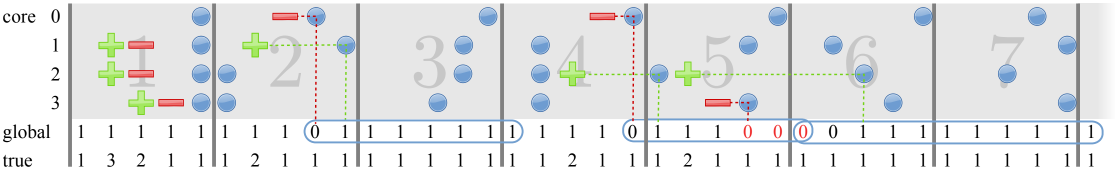

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- Ref. count zero for an entire epoch $\rightarrow$ free

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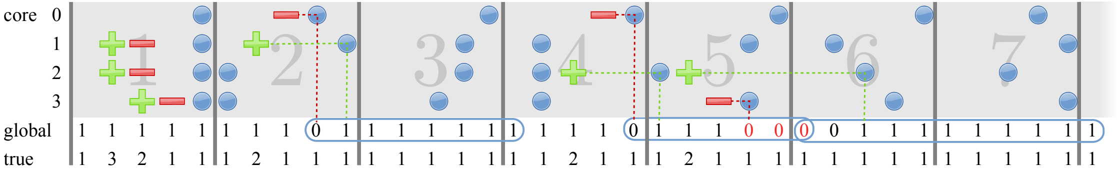

- Counts references to memory locations
  - Per-core lazy counting
- Divides time into epochs
- Ref. count zero for an entire epoch $\rightarrow$ free
- Solves the ABA problem

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RadixVM has 3 parts:

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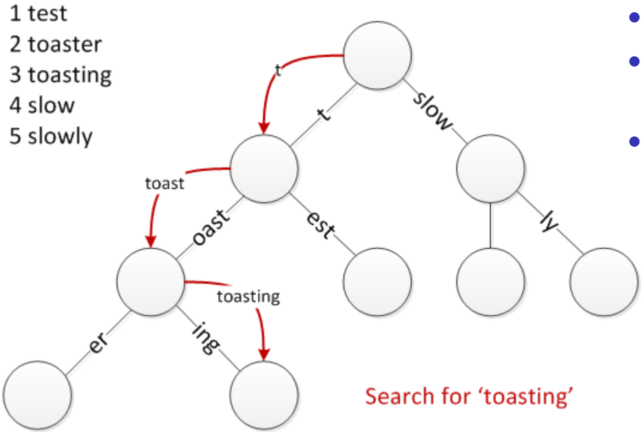
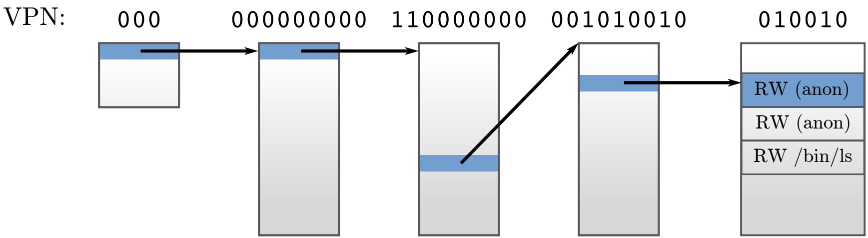
Background: Radix Tree



- A.K.A. prefix tree
- Edges labeled
- Concatenation of edge labels along root→node path gives a string
- In OSes, usually strings of bits

Design: RadixVM Data Structure



- Similar to a radix-tree/page table
- Really more of an implicit tree
- Fixed-height
- Each level indexed by up to 9 bits
- No balancing needed

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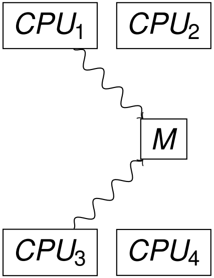
Background: Remote TLB Shootdowns



- Processes on CPU_1 and CPU_3 share memory area M

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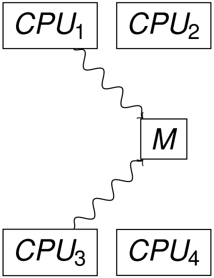

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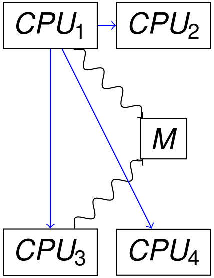

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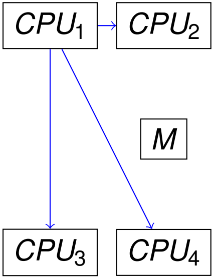

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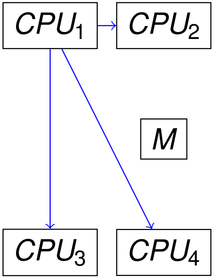
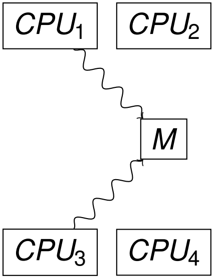


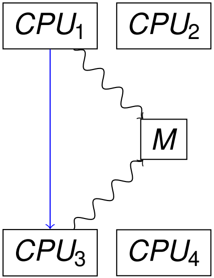
- Processes on CPU_1 and CPU_3 share memory area M
- A process on CPU_1 unmaps M
- The kernel sends a message to all CPU to flush their TLBs
- This is expensive!

Design: Targeted TLB Shootdowns



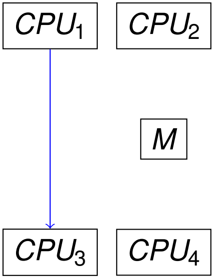
- Store metadata on which cores may have address in TLB

Design: Targeted TLB Shootdowns



- Store metadata on which cores may have address in TLB
- Only flush TLBs on cores which may share that memory

Design: Targeted TLB Shootdowns



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Implementation

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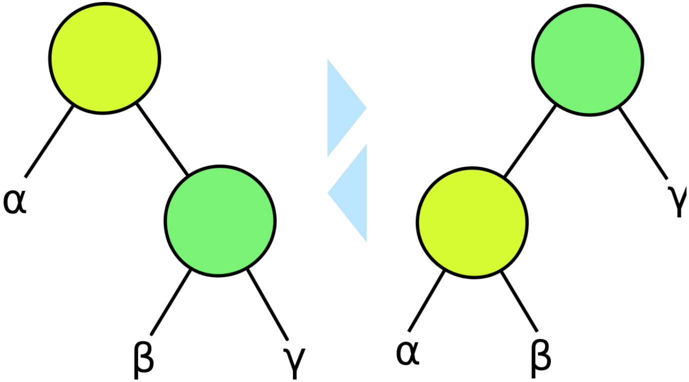
Implementation

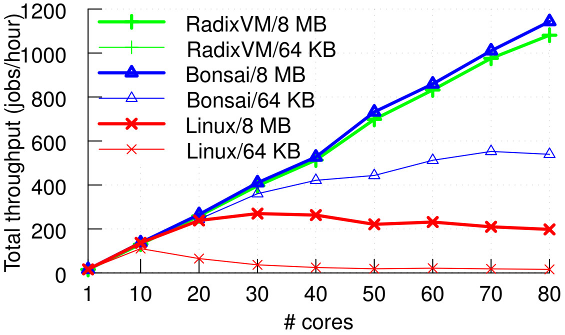
- *Not* implemented on Linux
  - Too complicated
- Implemented on sv6
  - Based on xv6
    - Academic OS
    - Based on v6 Unix
  - Largely rewritten in C++
  - `https://github.com/aclements/sv6`

Background: Bonsai



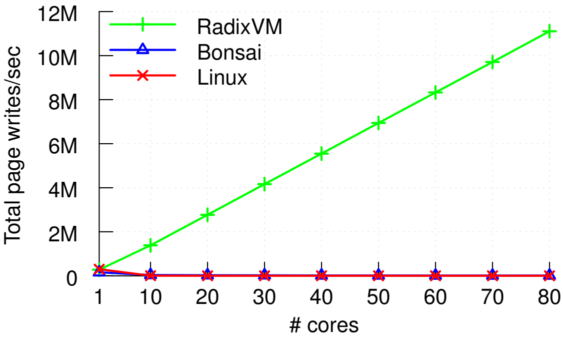
- Designed by the same authors
- "Soft" page faults happen in parallel using RCU
- Uses an RCU-based balanced binary tree
- Maintains bounded balance rather than strict balance (this means fewer rotations)
- Rotations construct a new subtree rather than mutate the old one

Application: Metis



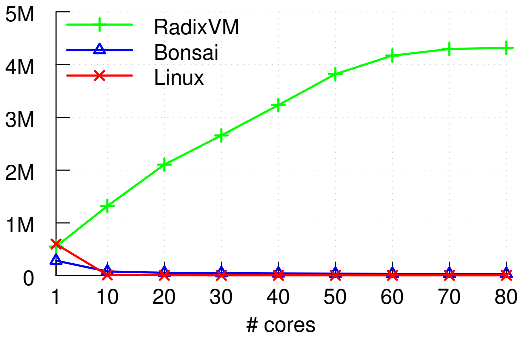
- MapReduce Library
- Single-server
- Multithreaded
- Stresses concurrent `mmap`s and `pagefault`s, but not concurrent `munmap`s
- Compiles on sv6 and linux

Microbenchmark: Local



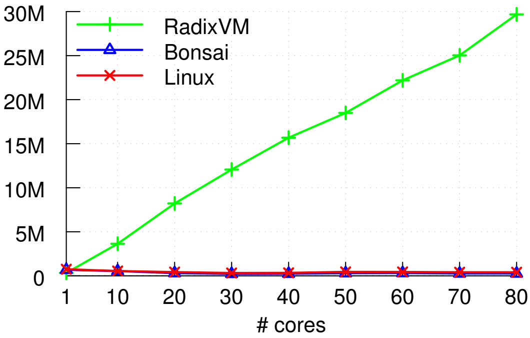
- `mmap` a private 4KB region in shared address space
- Write to every page in region
- `munmap` region

Microbenchmark: Pipeline



- Each thread `mmap` a region
- Write to every page in region
- Pass region to next thread
- Write to every page in passed region
- `munmap` region

Microbenchmark: Global



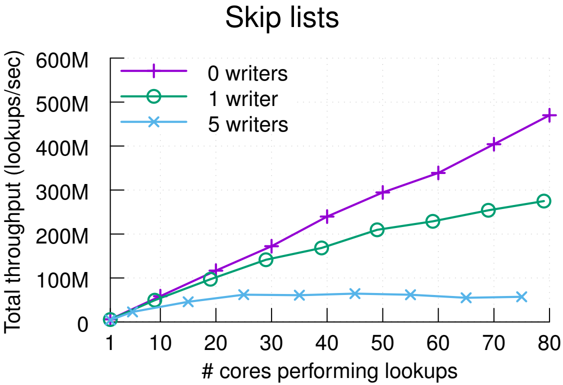
- Each thread `mmap` a 64KB region within a large region of memory
- All threads access all pages in random order

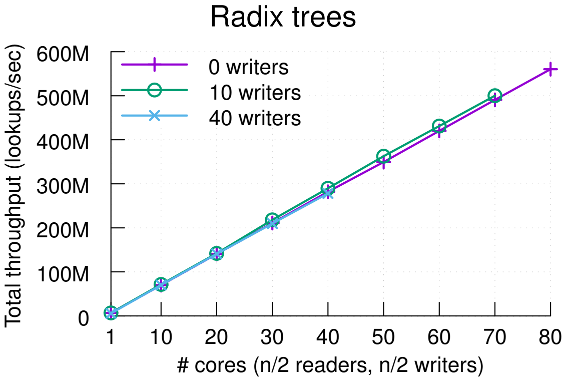
Question

Do we really need all 3 pieces?

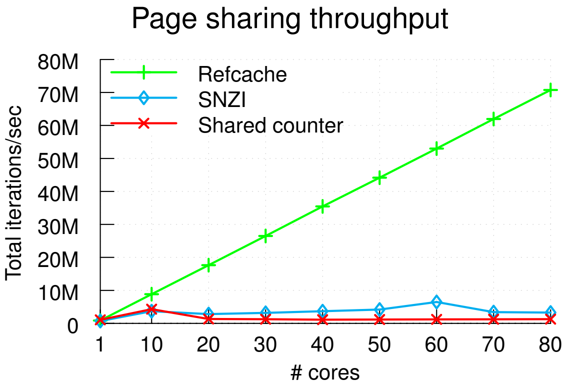
- Radix trees
- Refcache
- Targeted TLB shootdown

Question: Do we need radix trees?

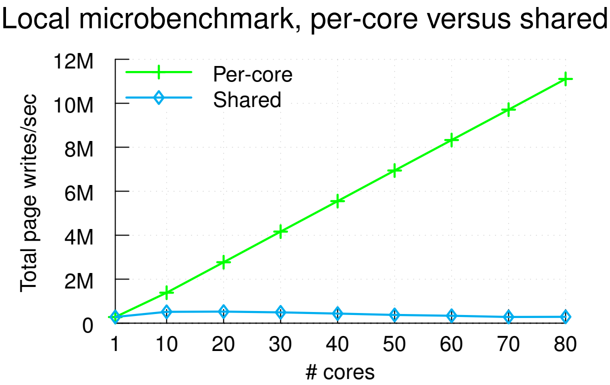




Question: Do we need Refcache?



Question: Do we need targeted TLB shootdown?



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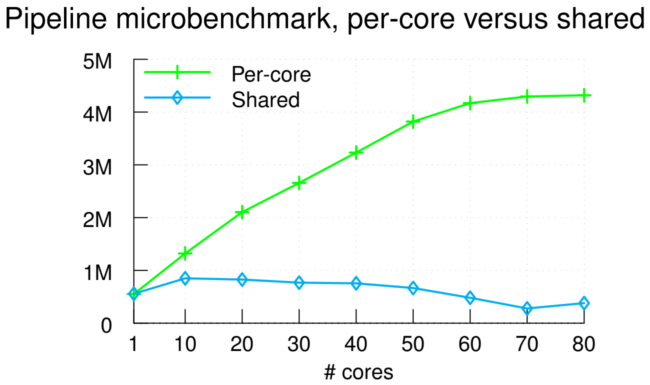
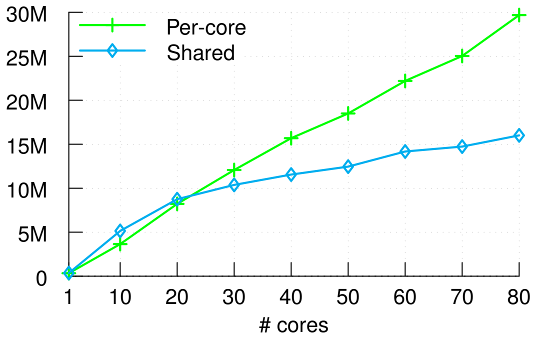


Question: Do we need targeted TLB shootdown?

Global microbenchmark, per-core versus shared

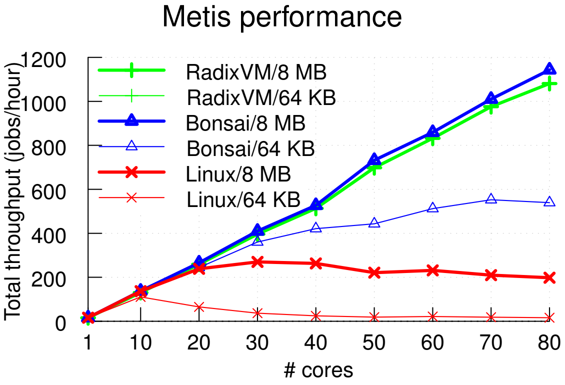


Memory Overhead

		Linux		Radix tree
	RSS	VMA tree	Page table	(rel. to Linux)
Firefox	352 MB	117 KB	1.5 MB	3.9 MB (2.4×)
Chrome	152 MB	124 KB	1.1 MB	2.4 MB (2.0×)
Apache	16 MB	44 KB	368 KB	616 KB (1.5×)
MySQL	84 MB	18 KB	348 KB	980 KB (2.7×)

- RSS
  - Resident Set Size
  - physical memory used by a process
- VMA
  - Virtual Memory Areas
  - stored in a red-black tree in Linux

Summary



- Good: Scales well on
  - Metis, real-world application
  - Microbenchmarks
- Bad: Increased memory overhead

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- Clements, Austin T., M. Frans Kaashoek, and Nickolai Zeldovich. "RadixVM: Scalable address spaces for multithreaded applications." In *Proceedings of the 8th ACM European Conference on Computer Systems*, pp. 211-224. ACM, 2013.
  - Revised version: `https://pdos.csail.mit.edu/papers/radixvm:eurosys13-2014-08-05.pdf`
- 6.828 Lecture on RadixVM: `https://www.youtube.com/watch?v=qlg7jqBtR4c`
- Clements, Austin T., M. Frans Kaashoek, and Nickolai Zeldovich. "Scalable address spaces using RCU balanced trees." *ACM SIGPLAN Notices* 47, no. 4 (2012): 199-210.
  - Available online: `https://pdos.csail.mit.edu/papers/rcuvm:asplos12.pdf`
- Linux VM info from: `http://duartes.org/gustavo/blog/post/how-the-kernel-manages-your-memory/`

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