RadixVM

Scalable address spaces for multithreaded applications

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Nickolai Zeldovich

Presented by Simon Pratt

February 12, 2016

Abstract

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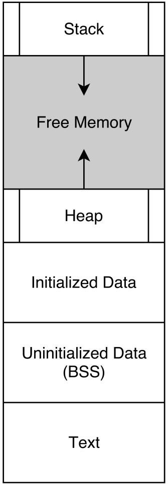
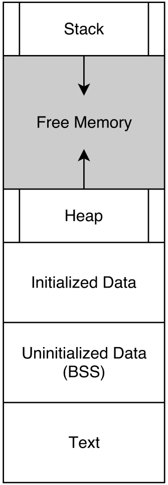
But first, some background...

Background: `malloc` and `mmap`



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

Background: `malloc` and `mmap`



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  - Actually allocates/frees space in virtual memory

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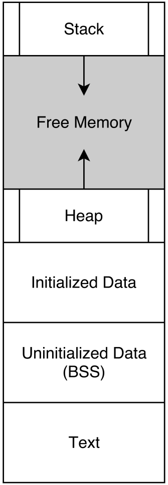

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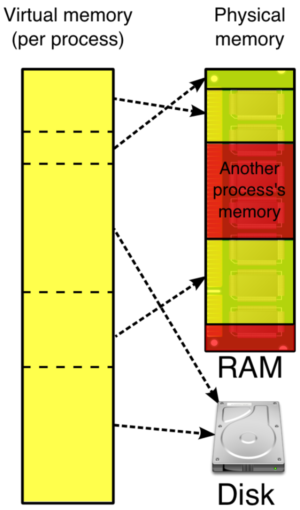
  - System calls
  - Actually allocates/frees space in virtual memory
- So what is virtual memory?

Background: Virtual Memory



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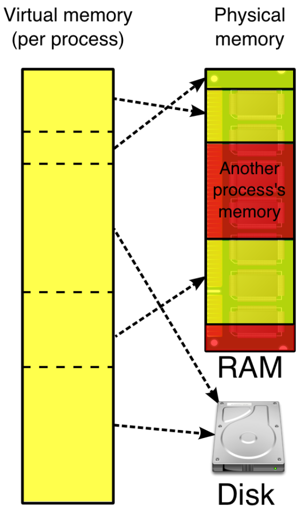
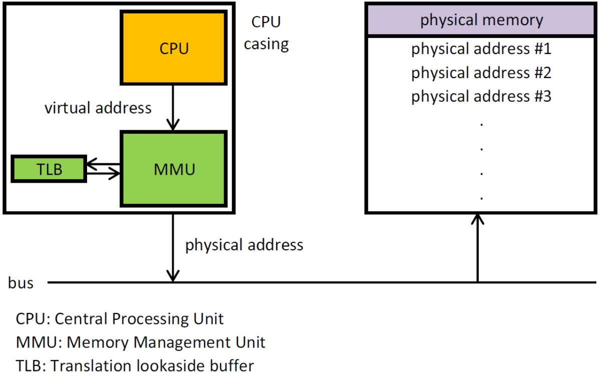


- (on x86) Instructions operate on virtual addresses
- Data may be stored:
  - In physical memory
  - On disk

Background: Virtual Memory



- Hardware, memory management unit (MMU)
  - Performs the translation
  - Keeps a cache (TLB) of virtual → physical mappings
  - No entry in TLB → page fault

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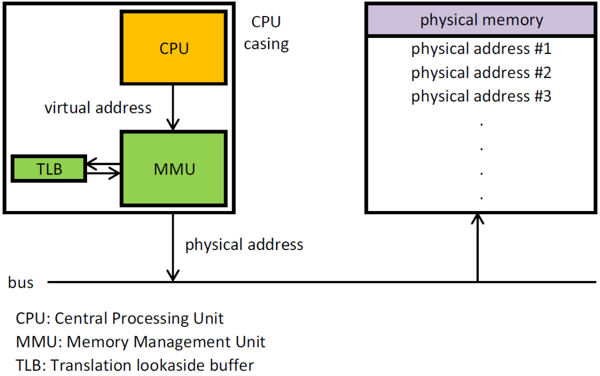

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  - Maintains the mapping (per process)
  - Handles page faults

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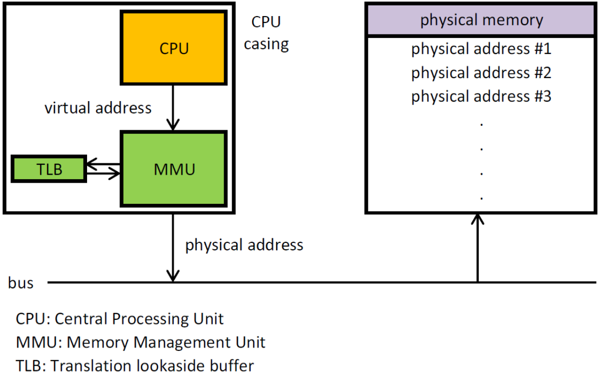

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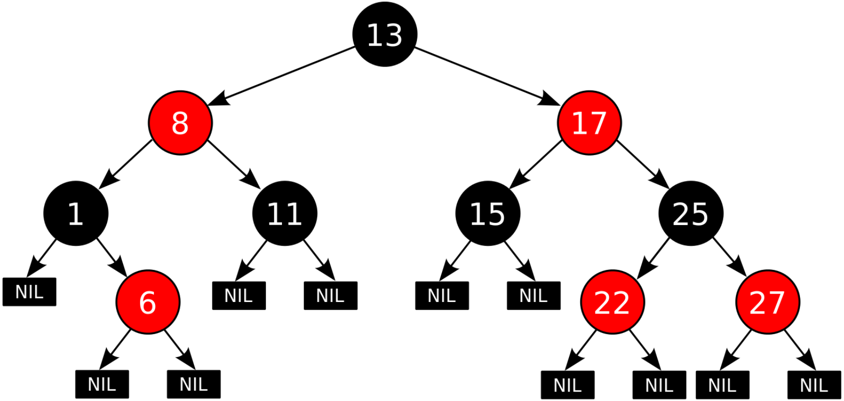
- So how does the OS store this?

Background: Linux Virtual Memory



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

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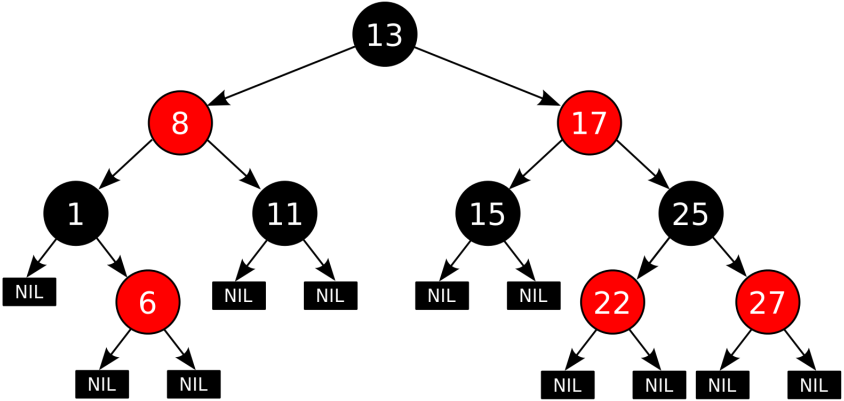
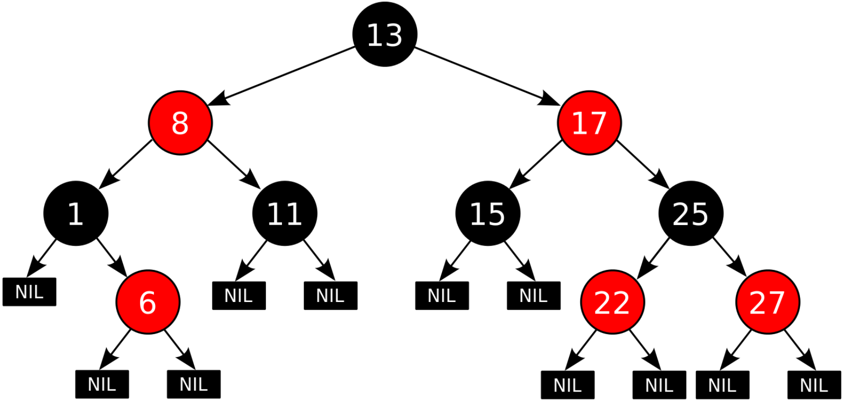


- Red-black tree
- Allows the kernel to search for memory area covering a virtual address
- Problem: A single lock per address space!

Problem 1: Multithreaded Address Space Scaling



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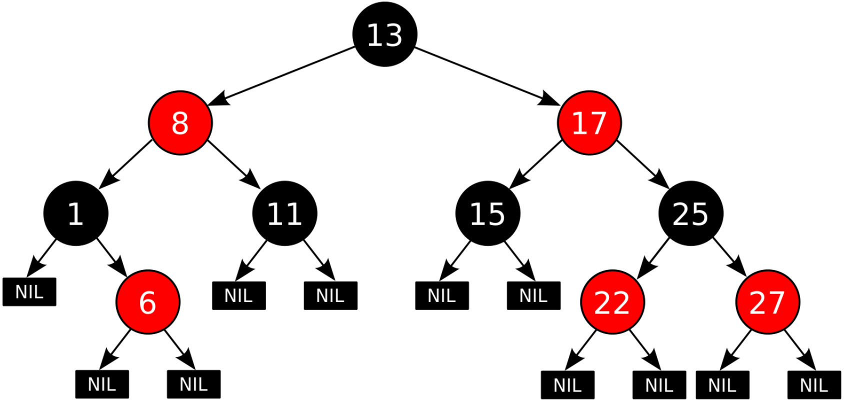

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- Aside: prwlock paper notes that Psearchy is `mmap`-intensive

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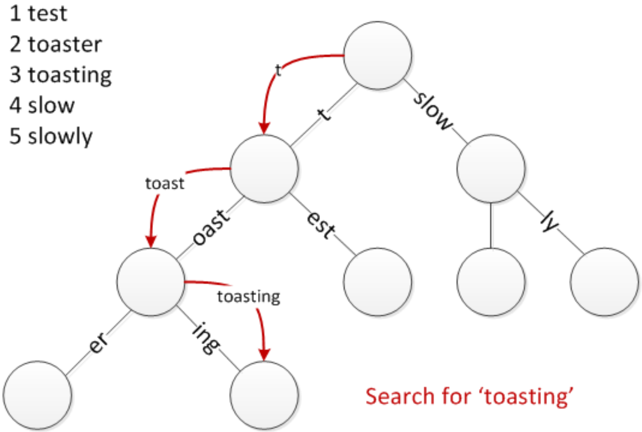

- A.K.A. prefix tree

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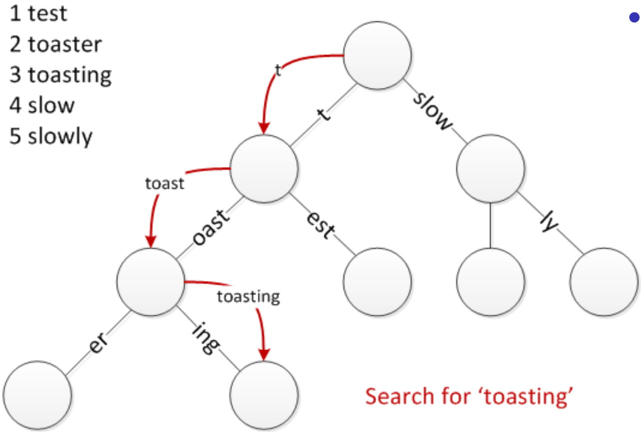

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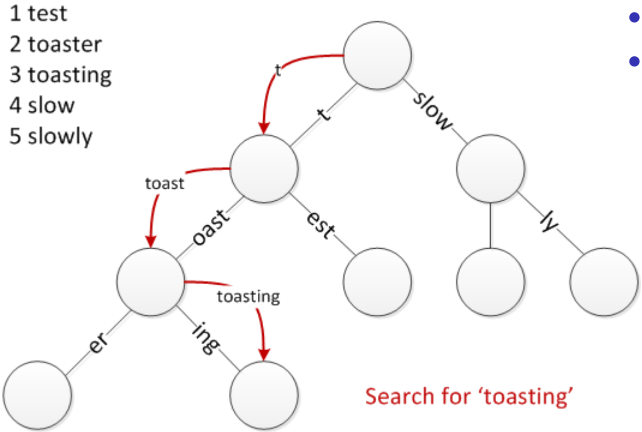

- A.K.A. prefix tree
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- Concatenation of edge labels along root$\rightarrow$node path gives a string

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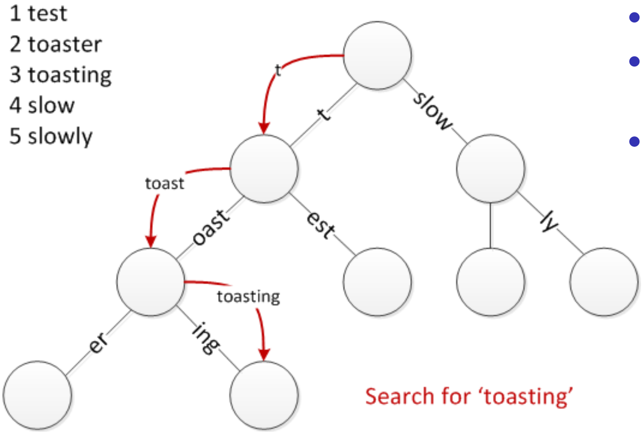
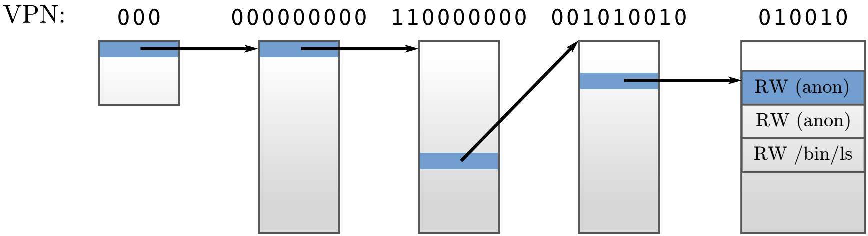


- A.K.A. prefix tree
- Edges labeled
- Concatenation of edge labels along root→node path gives a string
- In OSes, usually strings of bits

Design: RadixVM Data Structure



- Pretty much a page table

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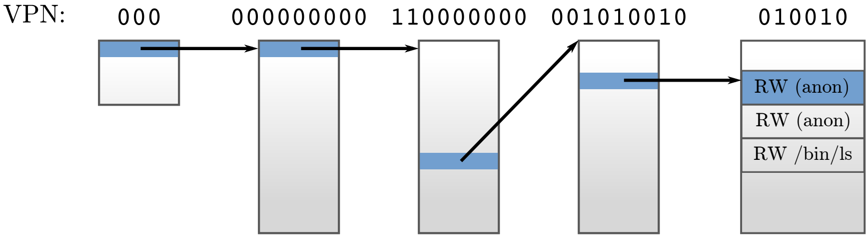

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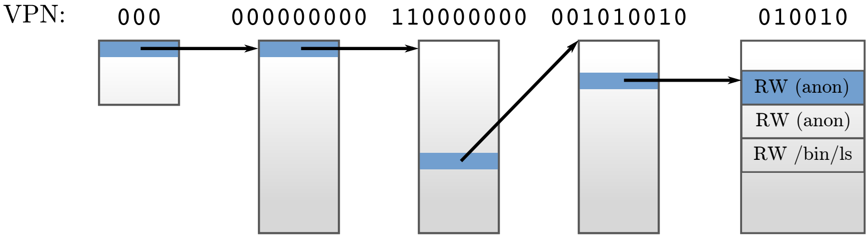

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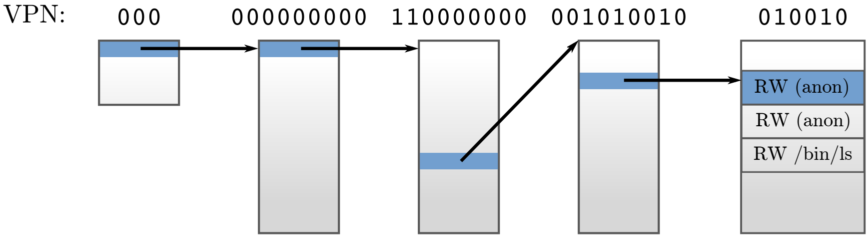

- Pretty much a page table
- Each level indexed by up to 9 bits
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- Lazy expansion/collapsing

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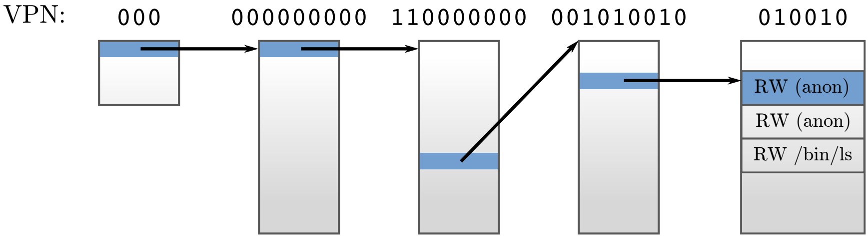

- Minimizes cache-line contention

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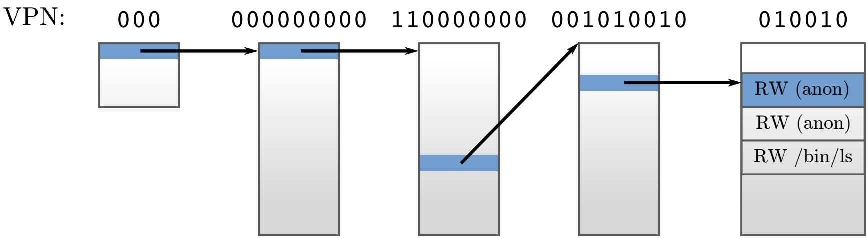
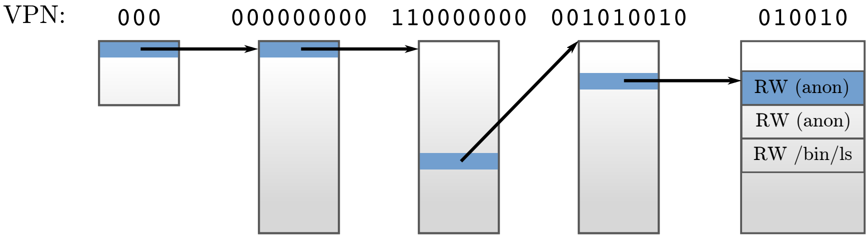


- Minimizes cache-line contention
- Supports precise range locking

Problem 1.1: When to Free



- How do we know when we can free the underlying pages?

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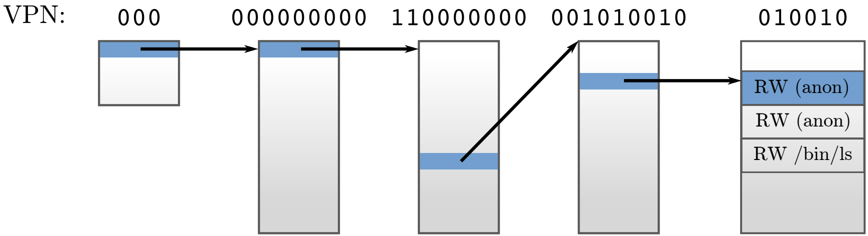

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- Reference counting!

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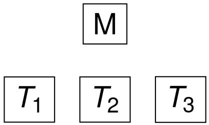
Background: Reference Counting

- 3 operations: inc, dec, zero?



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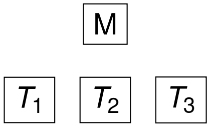

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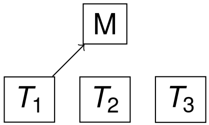

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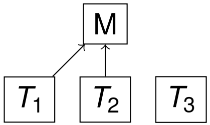

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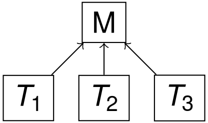

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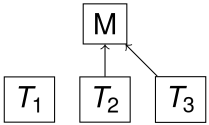

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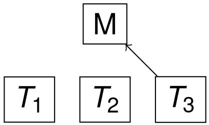

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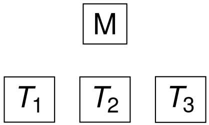

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Background: Reference Counting

T_1 T_2 T_3

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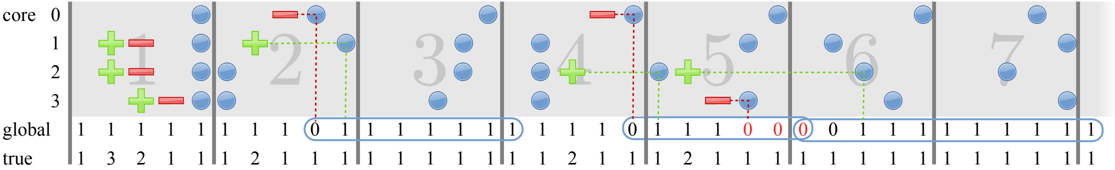
- But: single counter $\rightarrow$ contention

Design: Refcache



- Per-core lazy counting

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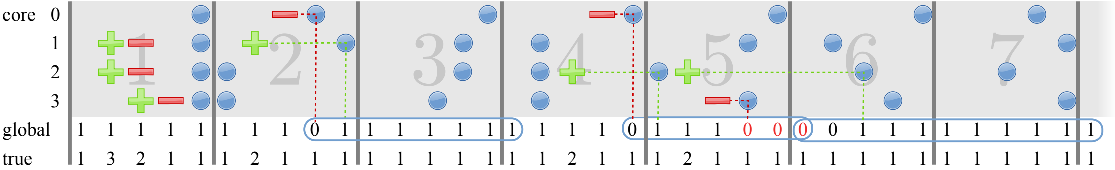

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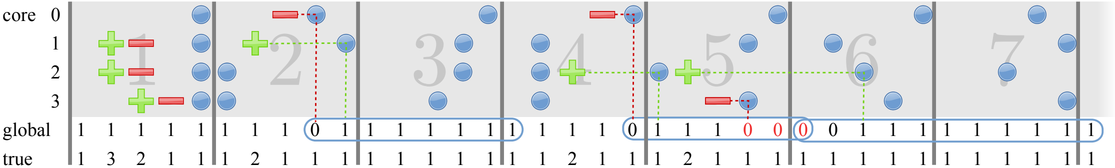

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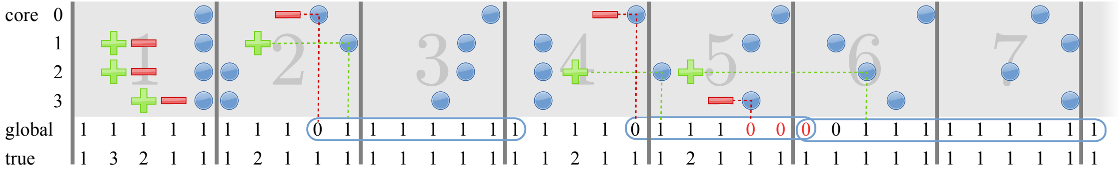

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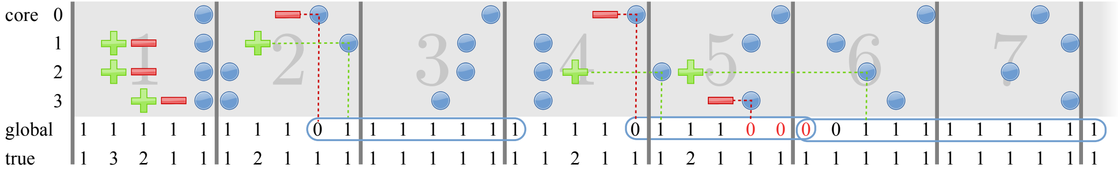

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- Divides time into epochs
- Ref. count zero for an entire epoch → free

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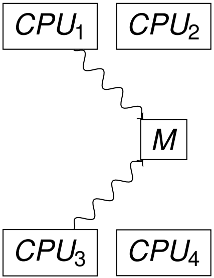

- Processes on CPU_1 and CPU_3 share memory area M

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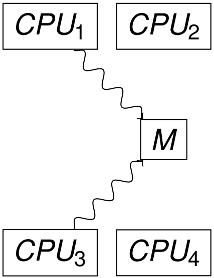

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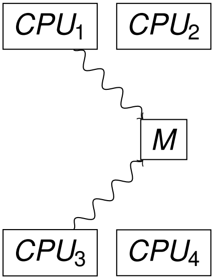

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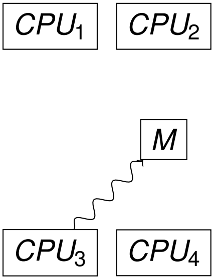

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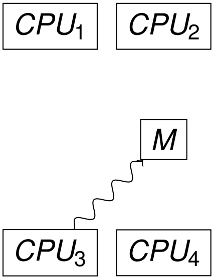

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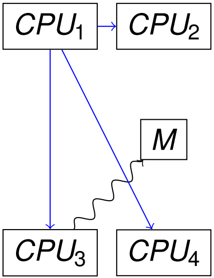

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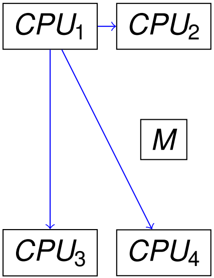

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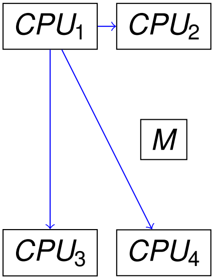

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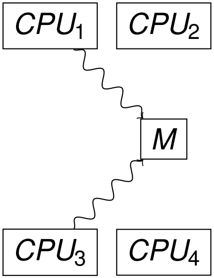
- This is expensive!

Design: Targeted TLB Shootdowns



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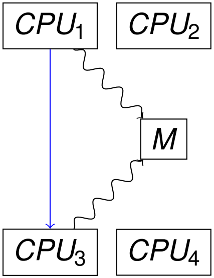

- Store metadata on which cores may have address in TLB
- Only flush TLBs on cores which may share that memory

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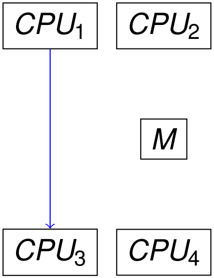

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Implementation

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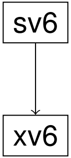
  - Too complicated

Implementation

sv6

- *Not* implemented on Linux
  - Too complicated
- Implemented on sv6 (C++)

Implementation



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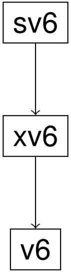

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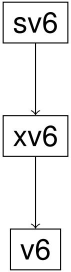

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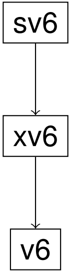

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  - `https://github.com/aclements/sv6`

Comparison

- Compared against:

Comparison

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    - Default Linux

Comparison

- Compared against:
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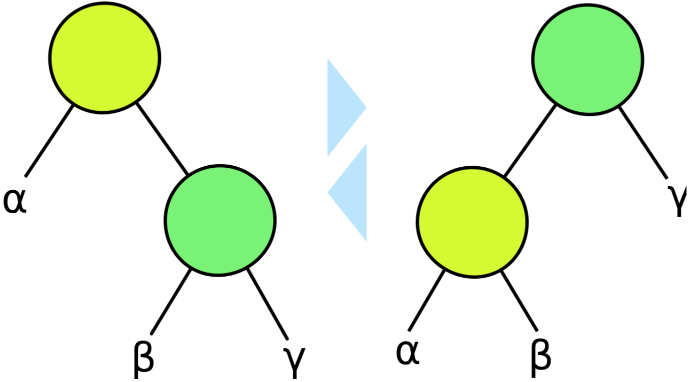
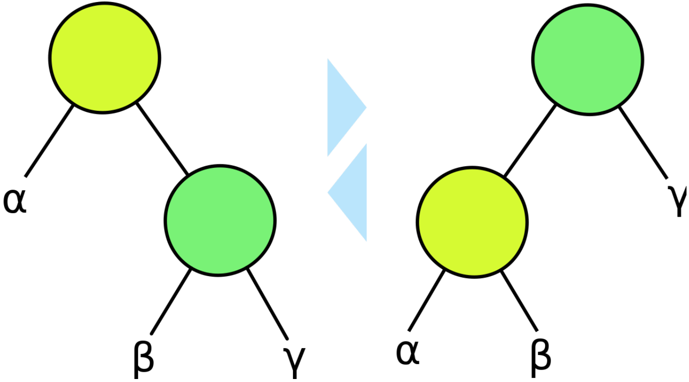
    - “Bonsai”

Background: Bonsai



- Designed by the same authors

Background: Bonsai



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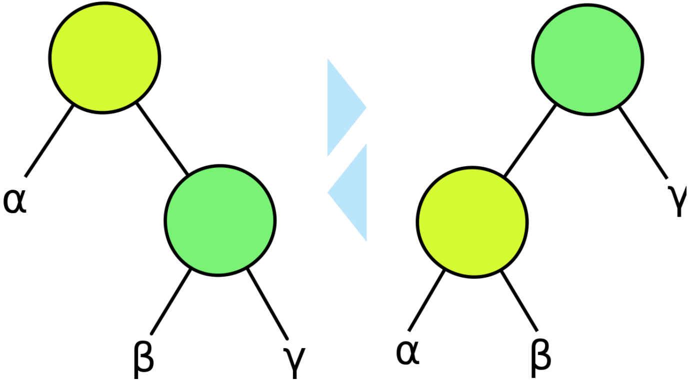

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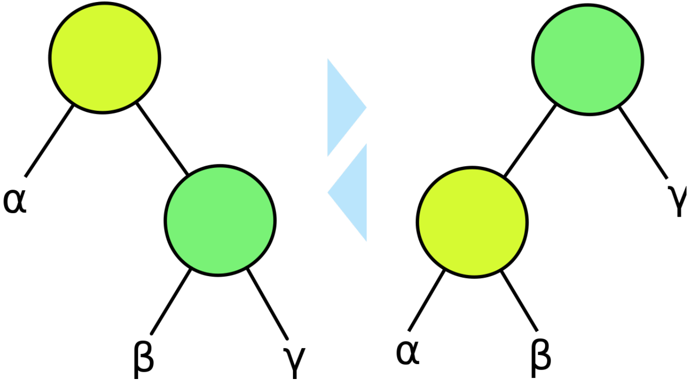

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- Maintains bounded balance rather than strict balance (this means fewer rotations)
- Rotations construct a new subtree rather than mutate the old one

Application: Metis

- MapReduce Library

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- Single-server

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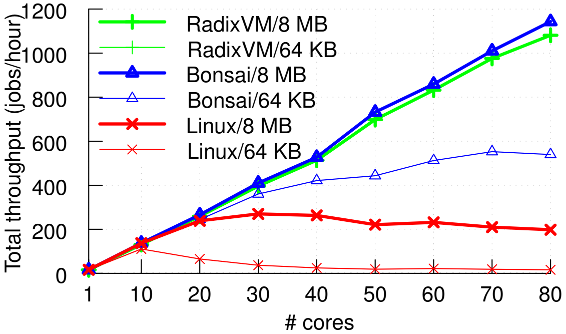

Microbenchmark: Local

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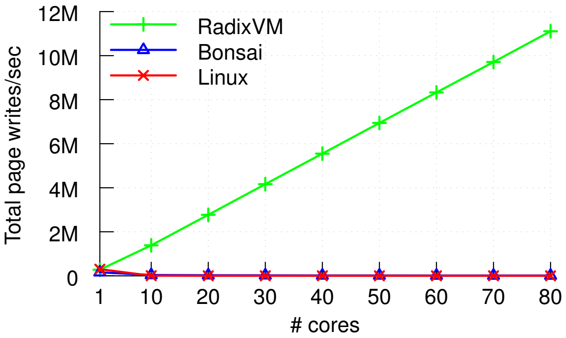

Microbenchmark: Pipeline

- Each thread `mmap` a region

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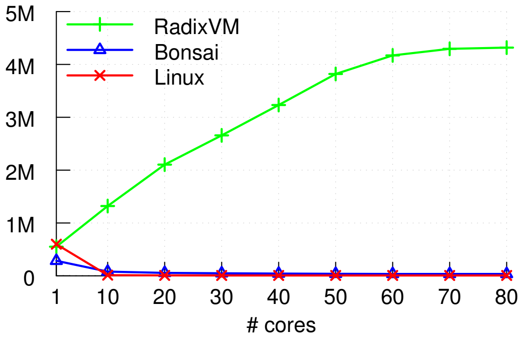

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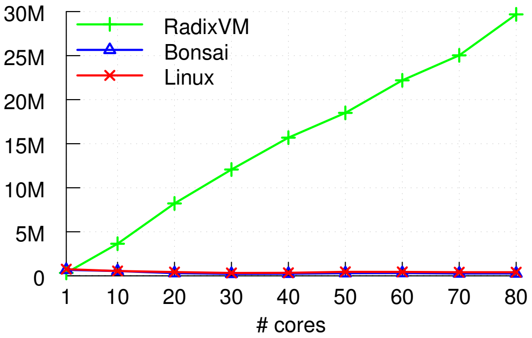
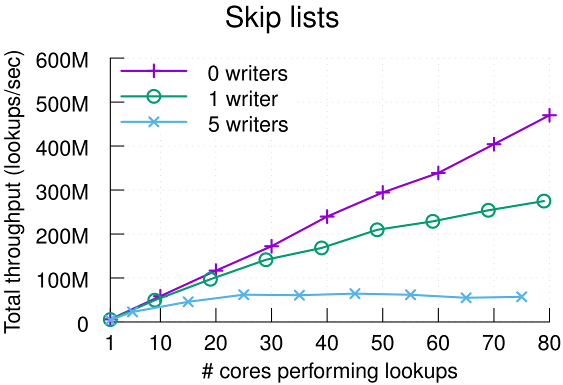


Question

Do we really need all 3 pieces?

- Radix trees
- Refcache
- Targeted TLB shootdown

Question: Do we need radix trees?



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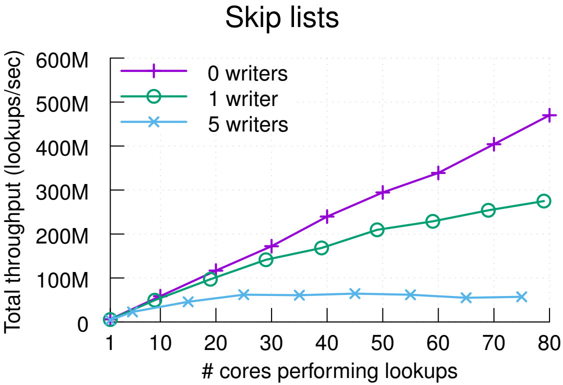
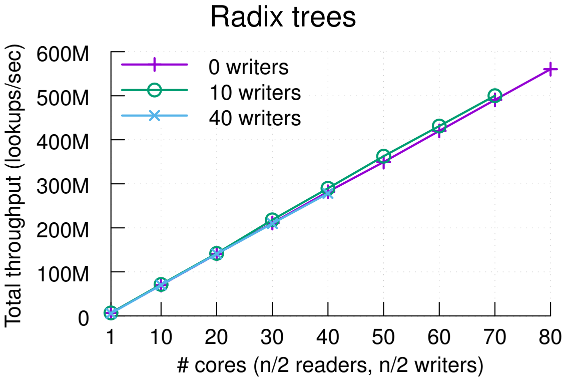
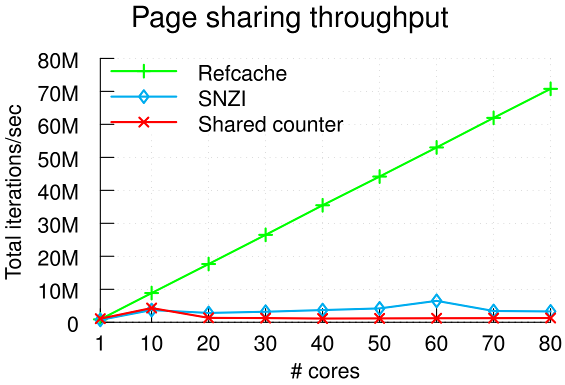


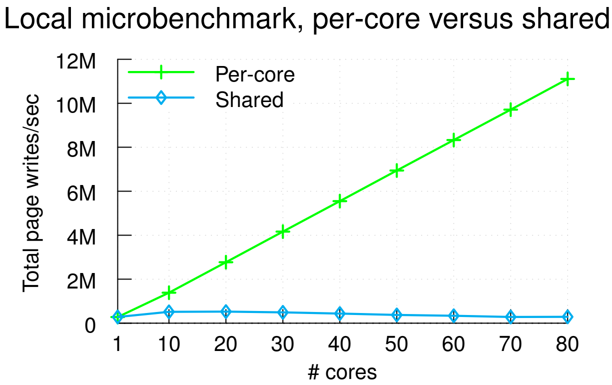


Question: Do we need Refcache?



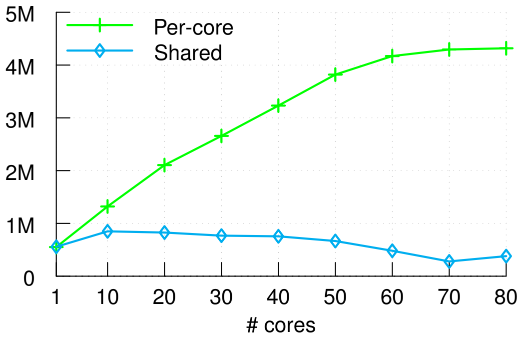
SNZI: Scalable Non-Zero Indicators

Question: Do we need targeted TLB shootdown?



Question: Do we need targeted TLB shootdown?

Pipeline microbenchmark, per-core versus shared



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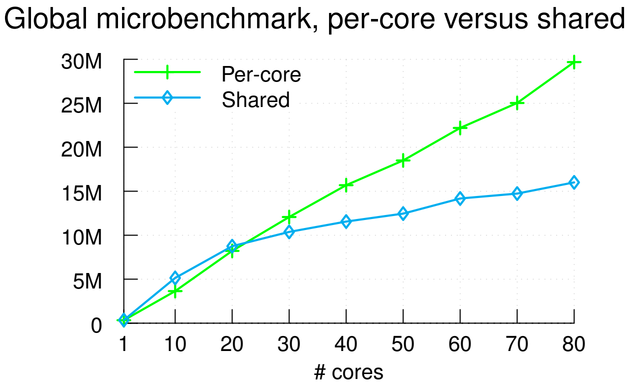
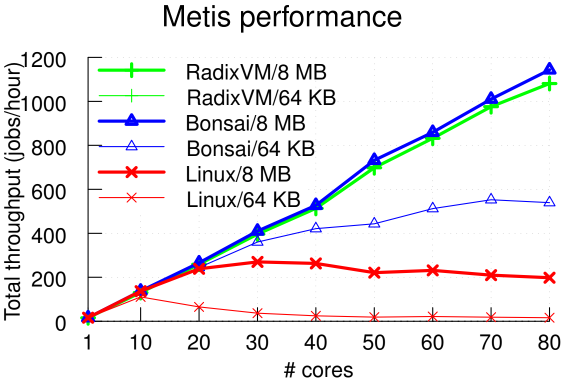


Issue: Memory Overhead

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

- 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

	RSS	Linux	Radix tree (rel. to Linux)
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References

- 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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