Lecture 14: Practical, transparent operating system support for superpages

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(slides adapted from OSDI 2002 presentation)

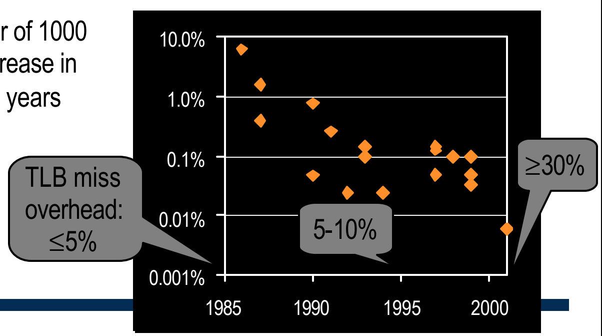
Overview

- Increasing cost in TLB miss overhead
  - growing working sets
  - TLB size does not grow at same pace
- Processors now provide superpages
  - one TLB entry can map a large region
- OSs have been slow to harness them
  - no transparent superpage support for apps

TLB coverage trend

TLB coverage as percentage of main memory

Factor of 1000 decrease in 15 years

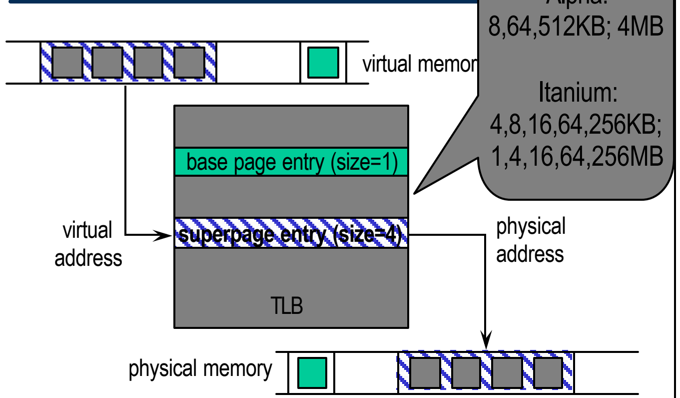


How to increase TLB coverage

- Typical TLB coverage ≈ 1 MB
- Use superpages!
  - Both large and small pages – power-of-2 size
  - 1 TLB entry per superpage
  - Contiguous, and virtually and physically aligned
  - Uniform attributes (protection, valid, ref, dirty)
- Benefit: Increase TLB coverage
  - no increase in TLB size
  - no internal fragmentation

If only large pages:
larger working sets, more I/O.

A superpage TLB



Why multiple superpage sizes

bench	64KB	512KB	4MB	All
FFT	1%	0%	**55%**	55%
galgel	**28%**	**28%**	1%	29%
mcf	24%	31%	22%	**68%**

- Different apps have different "best" size
  - Different data structures in a single app have different "best" size

Previous research approaches

- Reservations
  - Talluri & Hill "Surpassing the TLB performance of superpages with less operating system support"
  - one superpage size only, designed to work with proposed partial sub-block TLBs
- Relocation
  - move pages at promotion time
  - must recover copying costs
  - E.g. Romer, et al. "Reducing TLB and memory overhead using online superpage promotion".
- Not known to be implemented in non-research OS

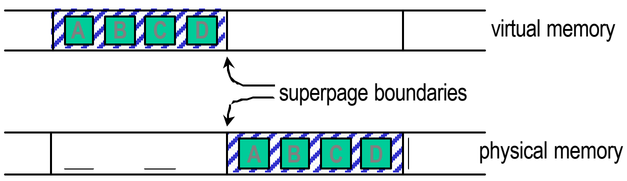
Prior commercial OS approaches

- Eager superpage creation (IRIX, HP-UX)
  - Superpage is allocated at page fault time
  - Size specified by user: non-transparent
    - IRIX
      - can select different page size for any suitably-aligned range of the virtual address space
      - OS maintains list of free pages of each size, coalescing daemon periodically tries to refresh
      - Large pages can be demoted under memory pressure
    - HP-UX
      - Can select different sizes for text and data segment only
      - Hint is associated with binary, not selectable at run-time

The Superpage Problem

- Main Issues
  - Allocation
  - Promotion
  - Demotion
  - Fragmentation

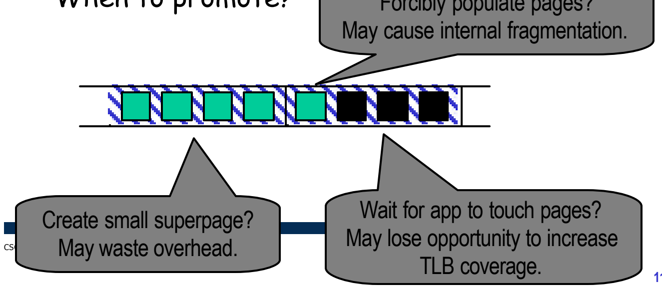
Issue 1: superpage allocation



- How / when / what size to allocate?

Issue 2: promotion

- Promotion: create a superpage out of a set of smaller pages
  - mark page table entry of each base page
- When to promote?



Issue 3: demotion

Demotion: convert a superpage into smaller pages

- when page attributes of base pages of a superpage become non-uniform
- during partial pageouts

Issue 4: fragmentation

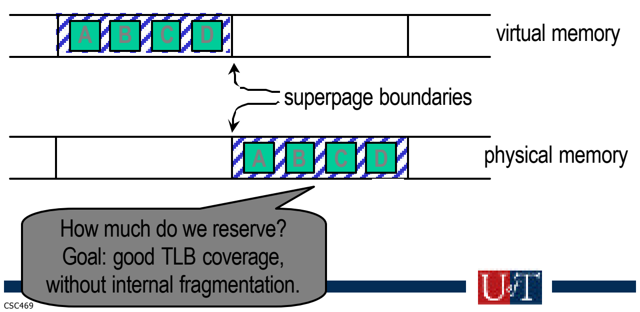
- Memory becomes fragmented due to
  - use of multiple page sizes
  - persistence of file cache pages
  - scattered wired (non-pageable) pages
- Contiguity: contended resource
- OS must
  - use contiguity restoration techniques
  - trade off impact of contiguity restoration against superpage benefits

Design

- Now look in detail at Navarro et al.'s design decisions for
  - Allocation
  - Promotion
  - Demotion
  - Fragmentation control

Superpage allocation

Use preemptible reservations



Key observation

Once an application touches the first page of a memory object then it is likely that it will quickly touch every page of that object

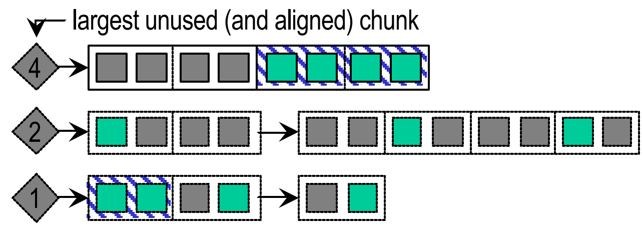
- Example: array initialization
- Opportunistic policies
  - superpages as large and as soon as possible
  - as long as no penalty if wrong decision
- Q: What is a memory object to the OS?

Allocation: reservation size

Opportunistic policy

- Go for biggest size that is no larger than the memory object (e.g., file)
- If size not available, try preemption before resigning to a smaller size
  - preempted reservation had its chance

Allocation: managing reservations



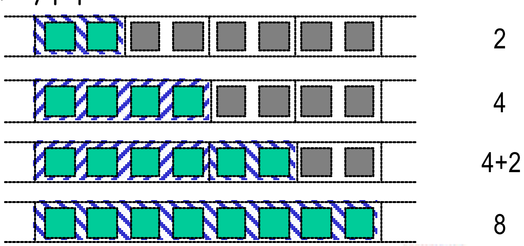
best candidate for preemption at front:

- reservation whose most recently populated frame was populated the least recently

Incremental promotions

Promotion policy: opportunistic

- Superpage is created whenever any superpage-sized and aligned extent within a reservation is fully populated.

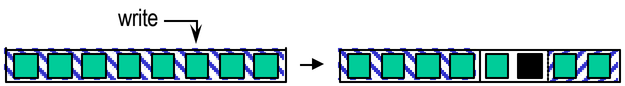


Speculative demotions

- One reference bit per superpage
  - How do we detect portions of a superpage not referenced anymore?
- On memory pressure, demote superpages when resetting ref bit
- Re-promote (incrementally) as pages are referenced

Demotions: dirty superpages

- One dirty bit per superpage
  - what's dirty and what's not?
  - page out entire superpage
- Demote on first write to clean superpage



- Re-promote (incrementally) as other pages are dirtied

Fragmentation control

- Low contiguity: modified page daemon
  - restore contiguity
    - move clean, inactive pages to the free list
  - minimize impact
    - prefer pages that contribute the most to contiguity
    - keep contents for as long as possible (even when part of a reservation: if reactivated, break reservation)
- Cluster wired pages

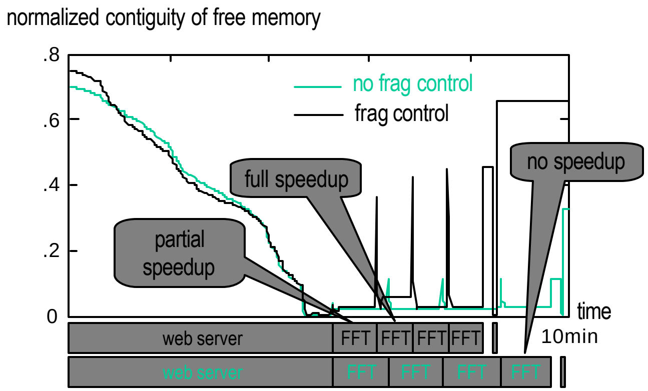
Experimental setup

- FreeBSD 4.3
- Alpha 21264, 500 MHz, 512 MB RAM
- 8 KB, 64 KB, 512 KB, 4 MB pages
- 128-entry DTLB, 128-entry ITLB
- Unmodified applications

Best-case benefits

- TLB miss reduction usually above 95%
- SPEC CPU2000 integer
  - 11.2% improvement (0 to 38%)
- SPEC CPU2000 floating point
  - 11.0% improvement (-1.5% to 83%)
- Other benchmarks
  - FFT (200^3 matrix): 55%
  - 1000x1000 matrix transpose: 655%
- 30%+ in 8 out of 35 benchmarks

Fragmentation control



Conclusions

- Superpages: 30%+ improvement
  - transparently realized; low overhead
- Contiguity restoration is necessary
  - sustains benefits; low impact
- Multiple page sizes are important
  - scales to very large superpages
- Source code and more info at:
  - www.cs.rice.edu/~jnavarro/superpages