Practical, transparent operating system support for superpages

Juan Navarro • Sitaram Iyer
Peter Druschel • Alan Cox

Rice University

https://dl.acm.org/citation.cfm?id=844138

OSDI 2002

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
- This talk: a practical and transparent solution to support superpages

Translation look-aside buffer

- TLB caches virtual-to-physical address translations

- TLB coverage
  - amount of memory mapped by TLB
  - amount of memory that can be accessed without TLB misses

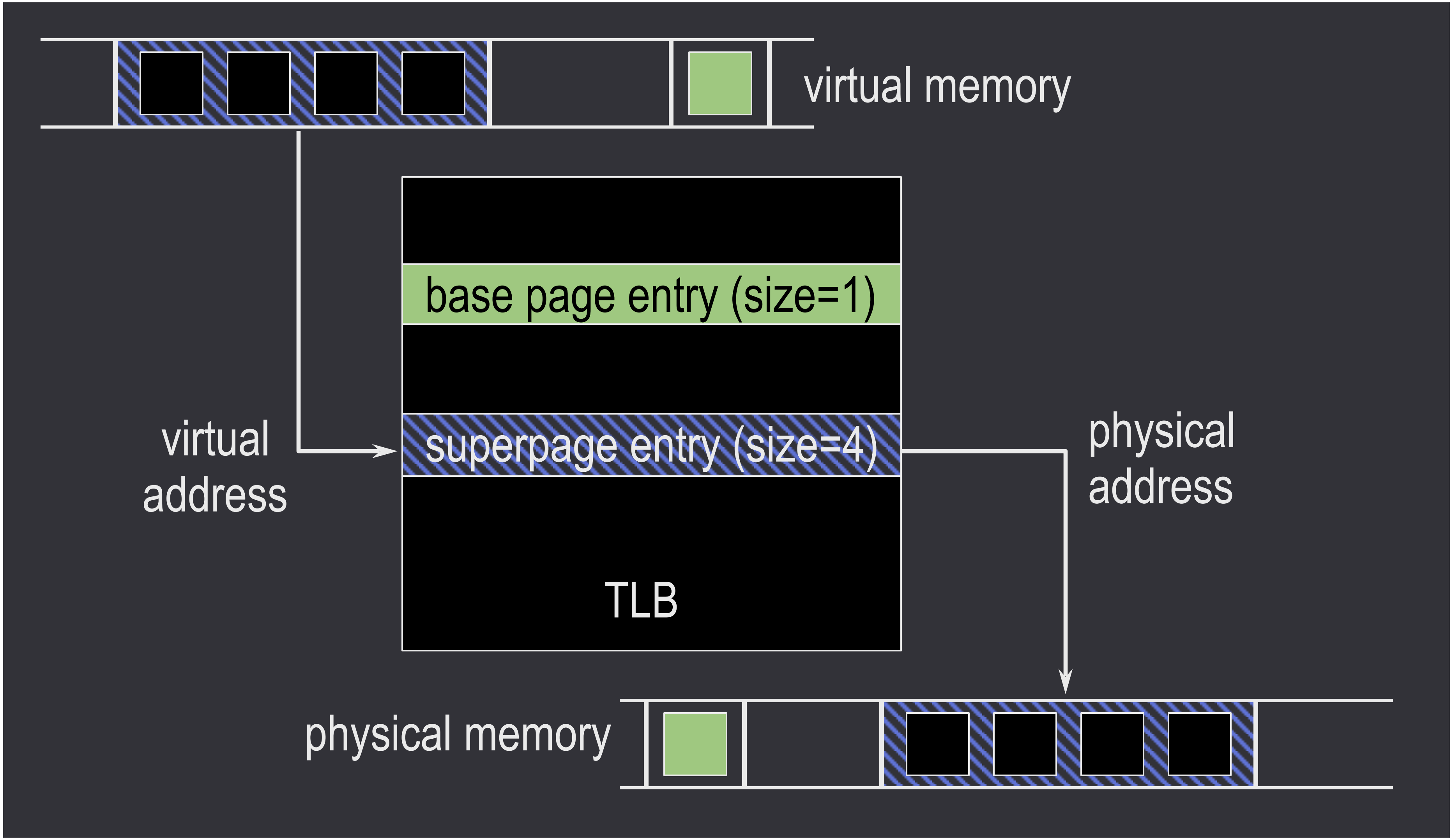
How to increase TLB coverage

- Typical TLB coverage ≈ 1 MB
- Use superpages!
  - large and small pages
  - Increase TLB coverage
  - no increase in TLB size

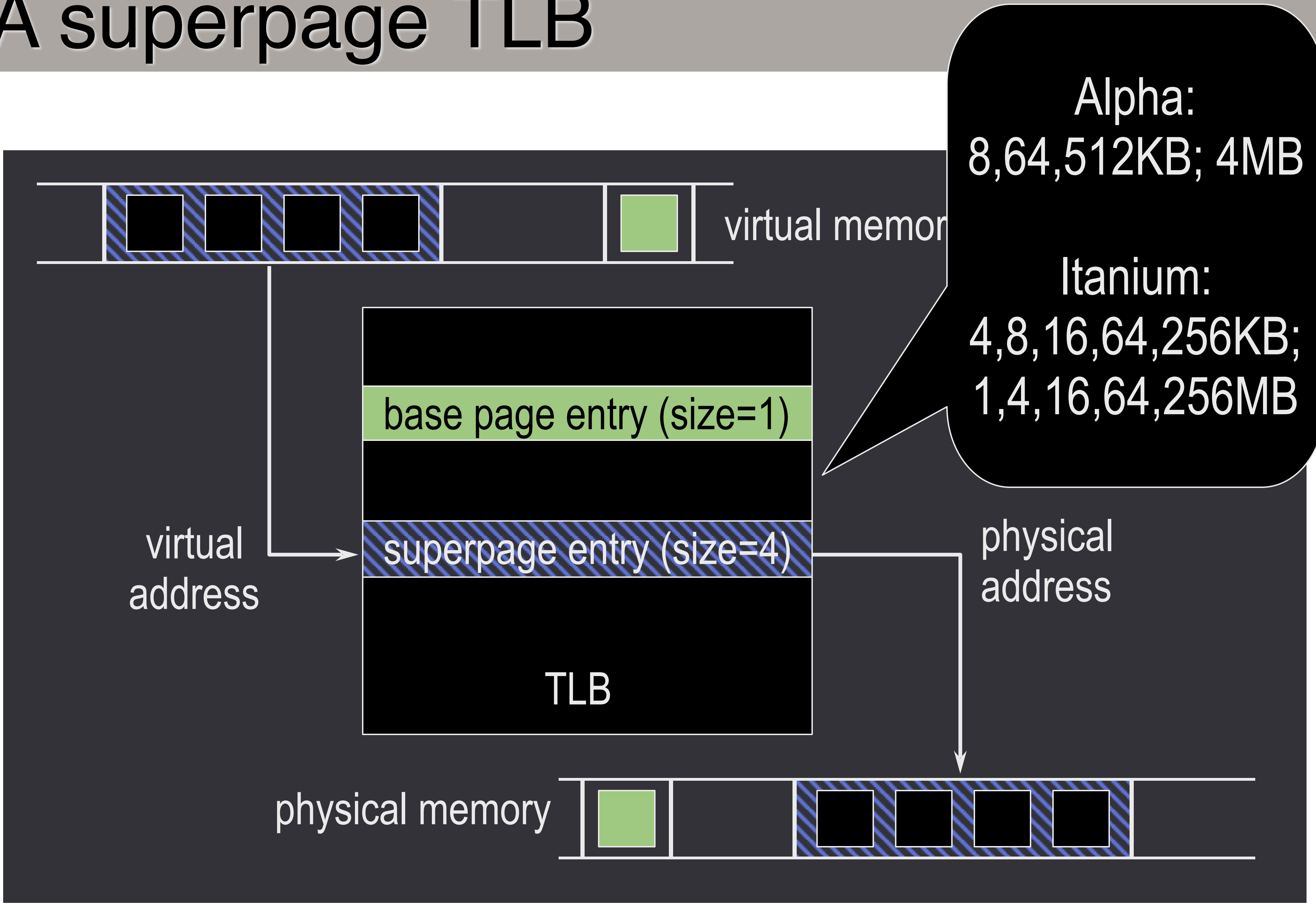
What are these superpages anyway?

- Memory pages of larger sizes
  - supported by most modern CPUs
- Otherwise, same as normal pages
  - power of 2 size
  - use only one TLB entry
  - contiguous
  - aligned (physically and virtually)
  - uniform protection attributes
  - one reference bit, one dirty bit

A superpage TLB

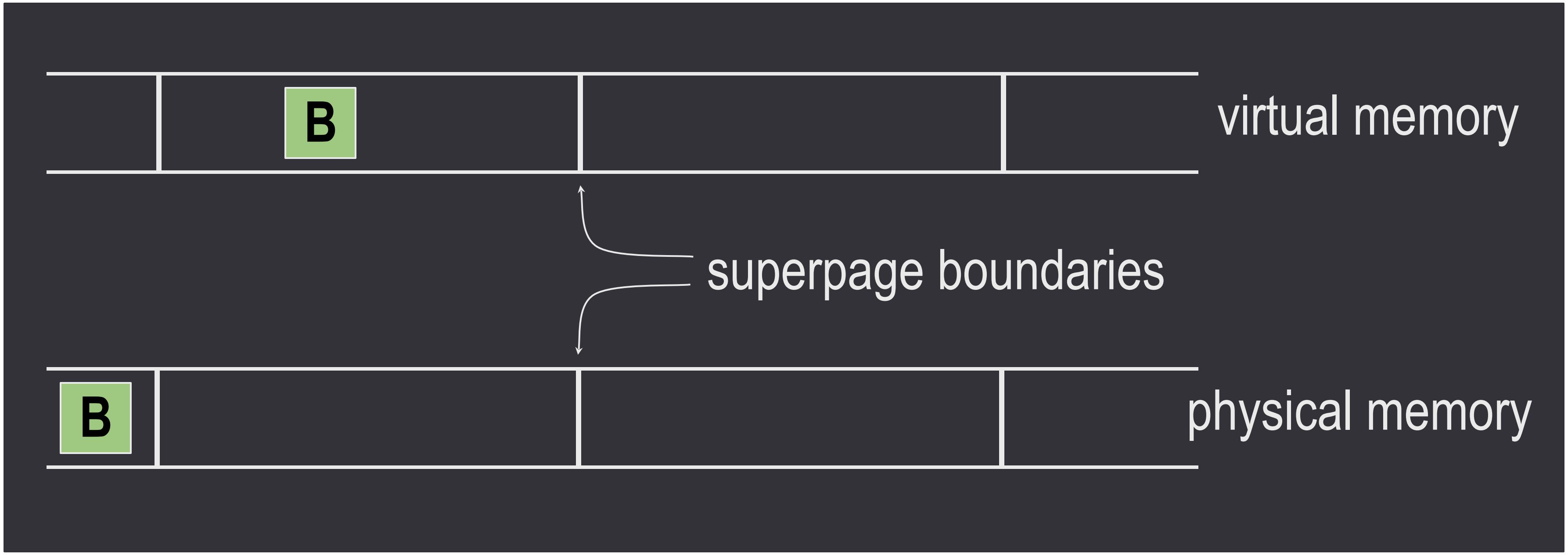


A superpage TLB



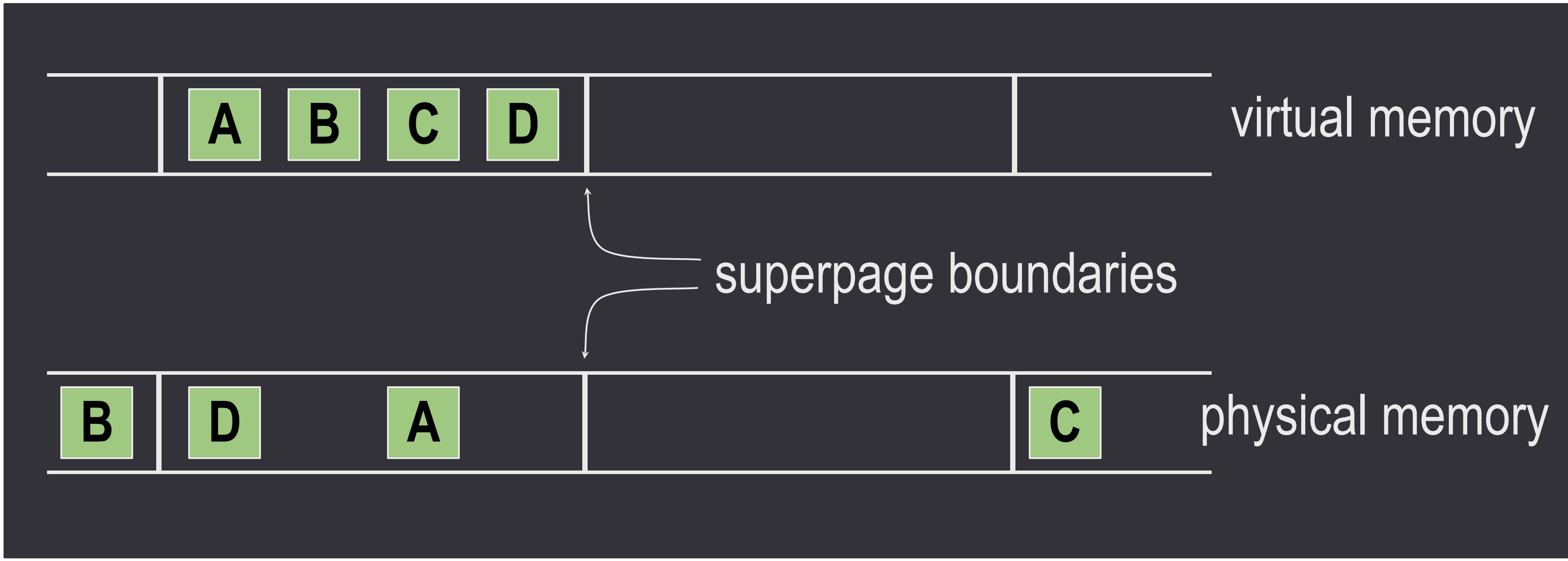
II
The superpage problem

Issue 1: superpage allocation



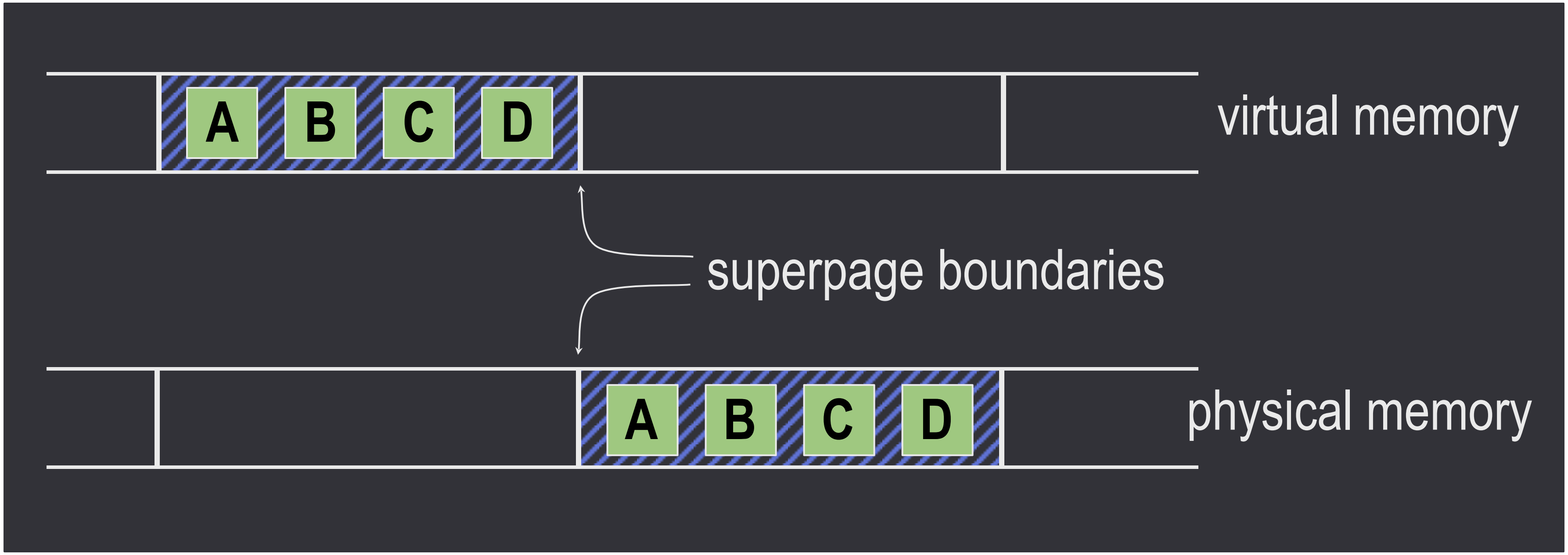
- How / when / what size to allocate?

Issue 1: superpage allocation



- How / when / what size to allocate?

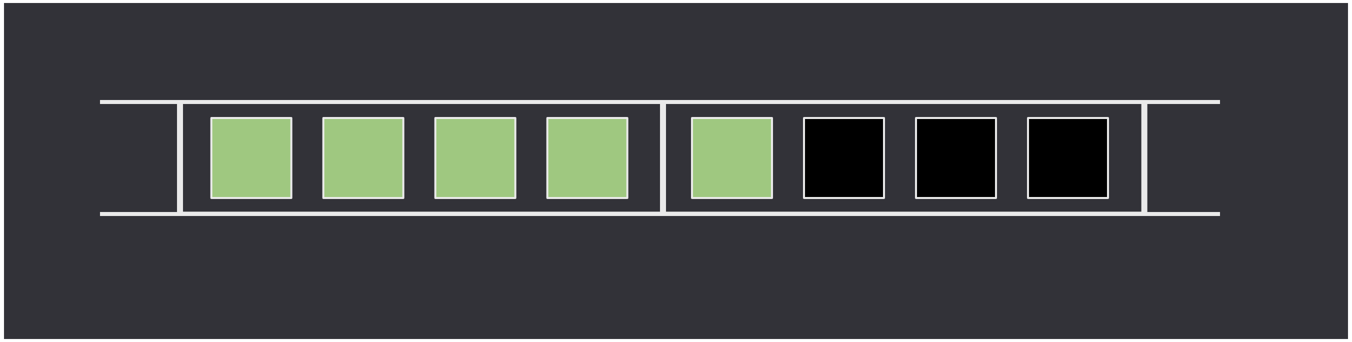
Issue 1: superpage allocation



- How / when / what size to allocate?

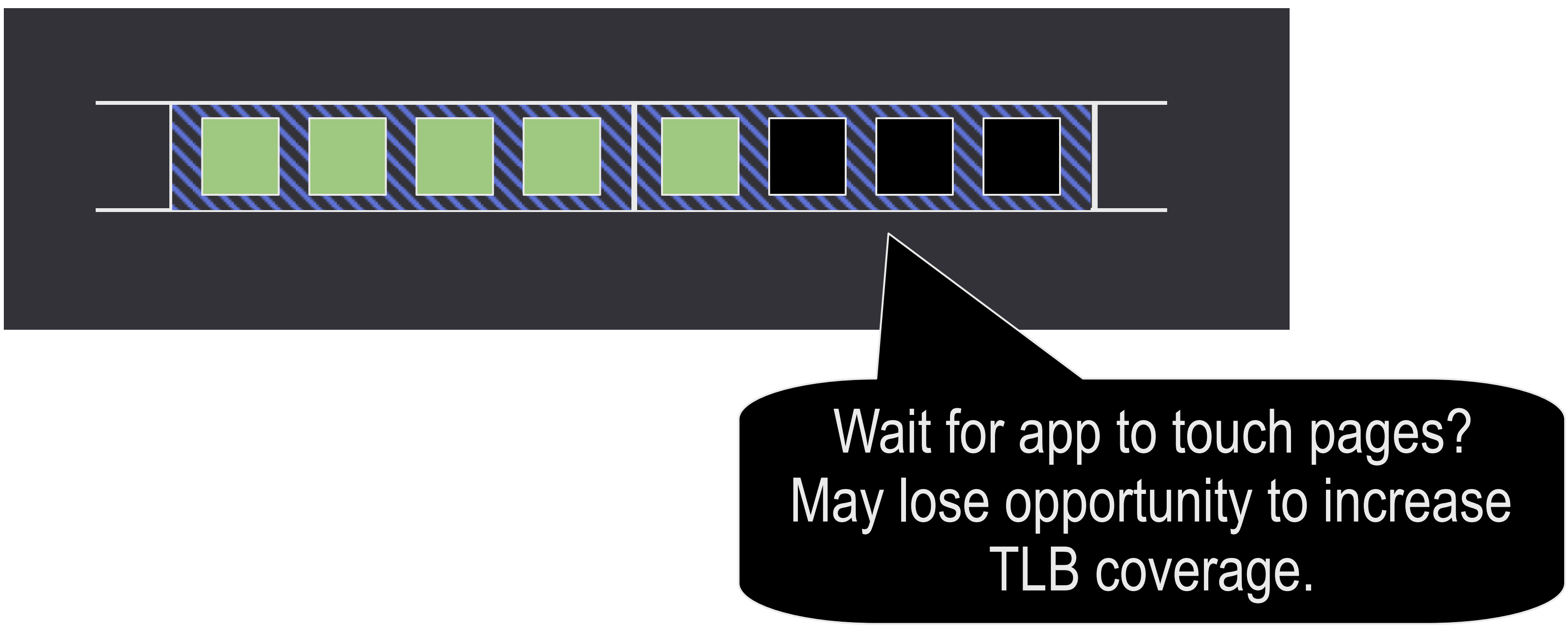
Issue 2: promotion

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



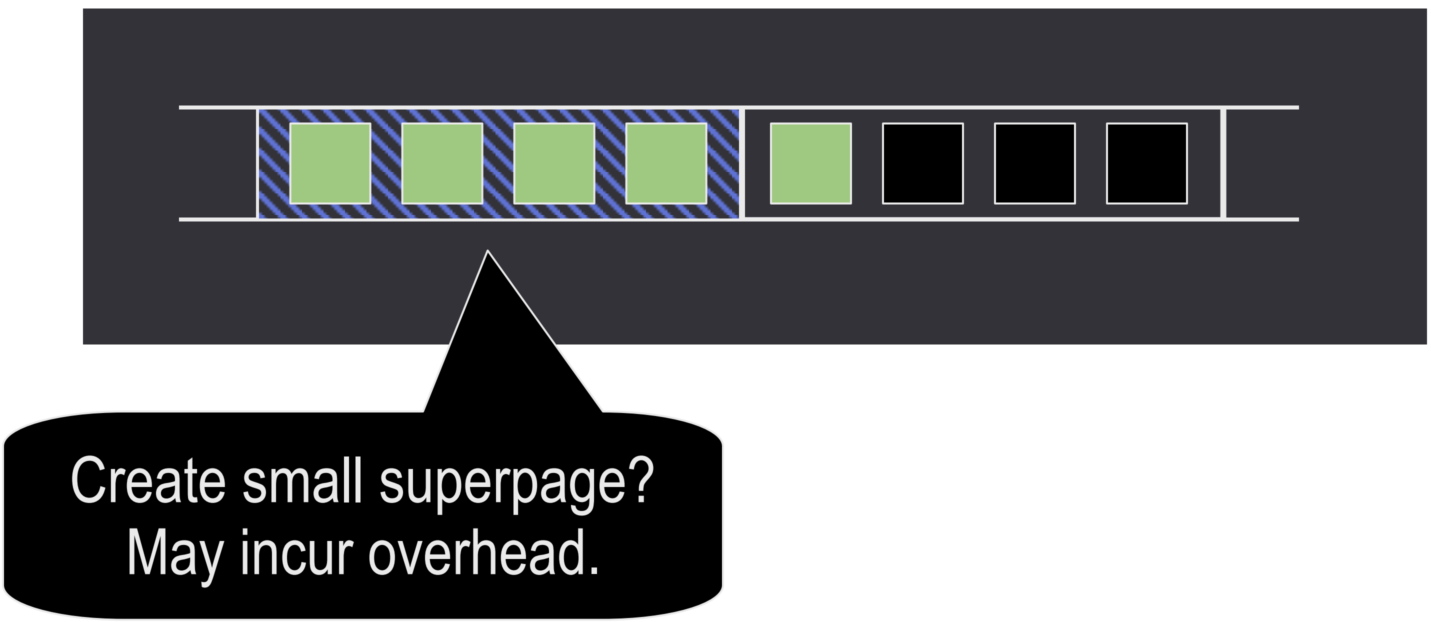
Issue 2: promotion

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



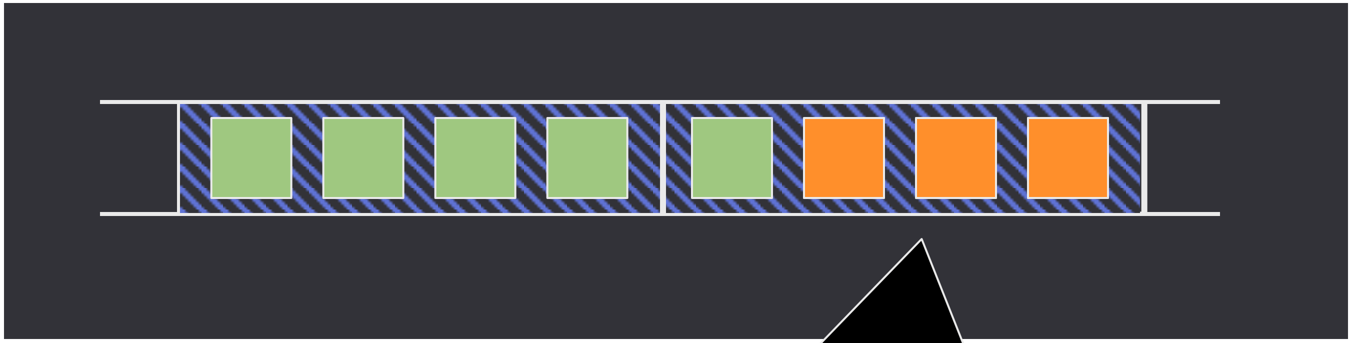
Issue 2: promotion

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



Issue 2: promotion

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



Forcibly populate pages?
May incur I/O cost or increase internal fragmentation.

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
  - scattered *wired* (non-pageable) pages
- Contiguity: contended resource
- OS must
  - use contiguity restoration techniques
  - trade off impact of contiguity restoration against superpage benefits

Previous approaches

- Reservations
  - one superpage size only
- Relocation
  - move pages at promotion time
  - must recover copying costs
- Eager superpage creation (IRIX, HP-UX)
  - size specified by user: non-transparent
- Hardware support
  - Contiguous virtual superpage mapped to discontiguous physical base pages
- Demotion issues not addressed
  - large pages partially dirty/referenced

III
Design

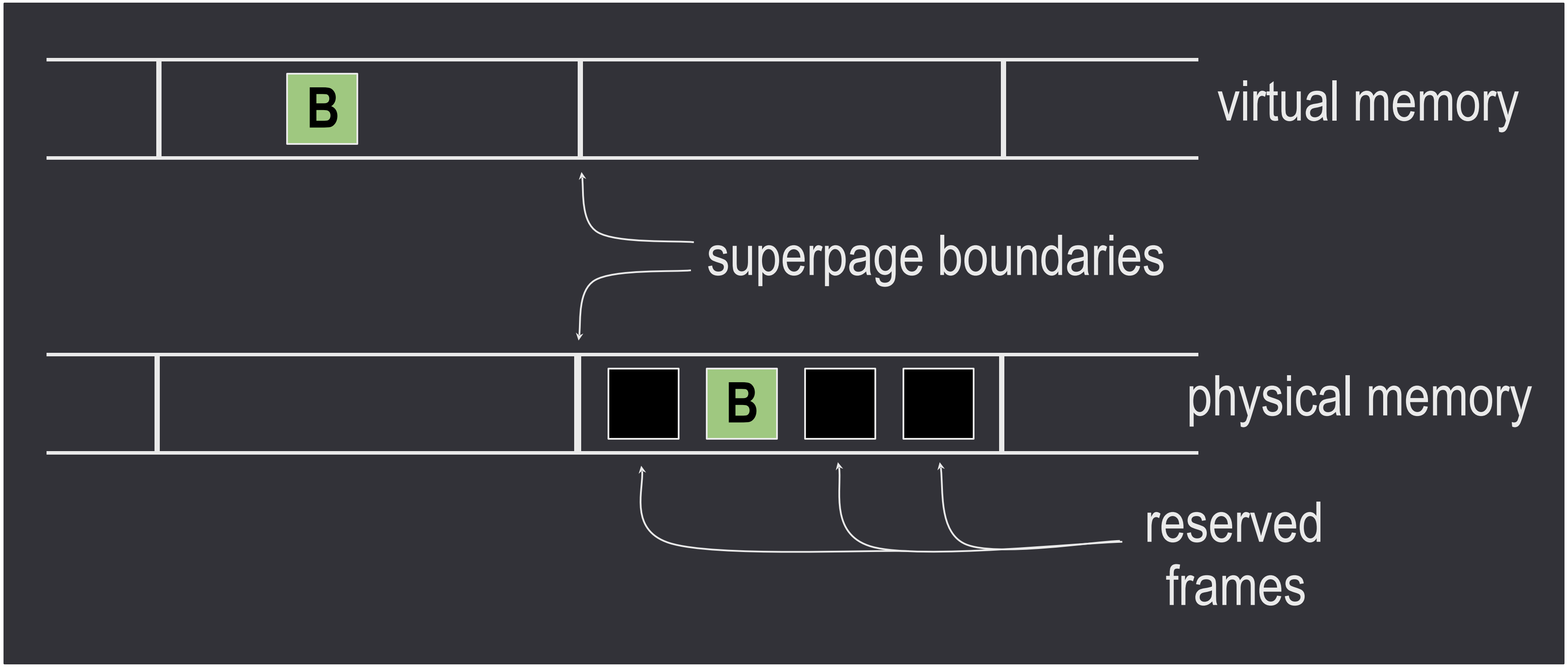
Key observation

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

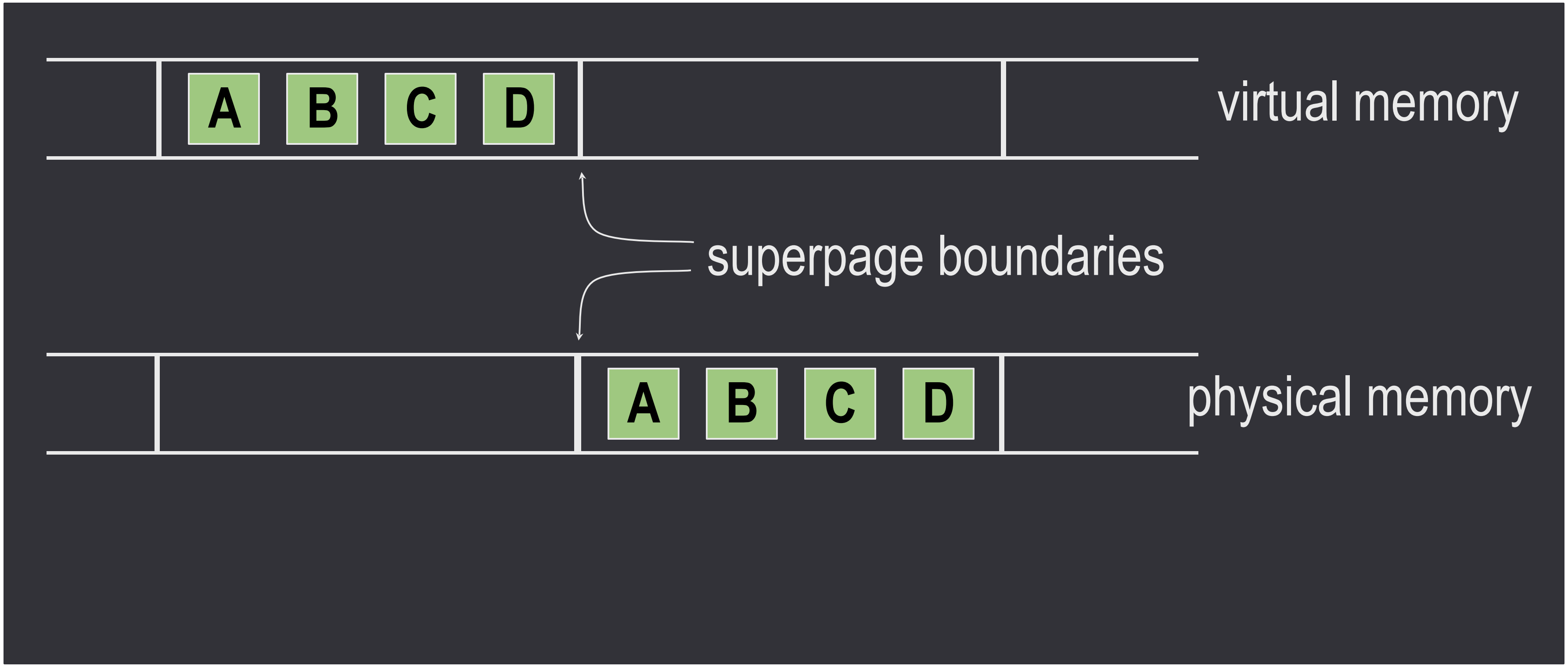
Superpage allocation

Preemptible reservations



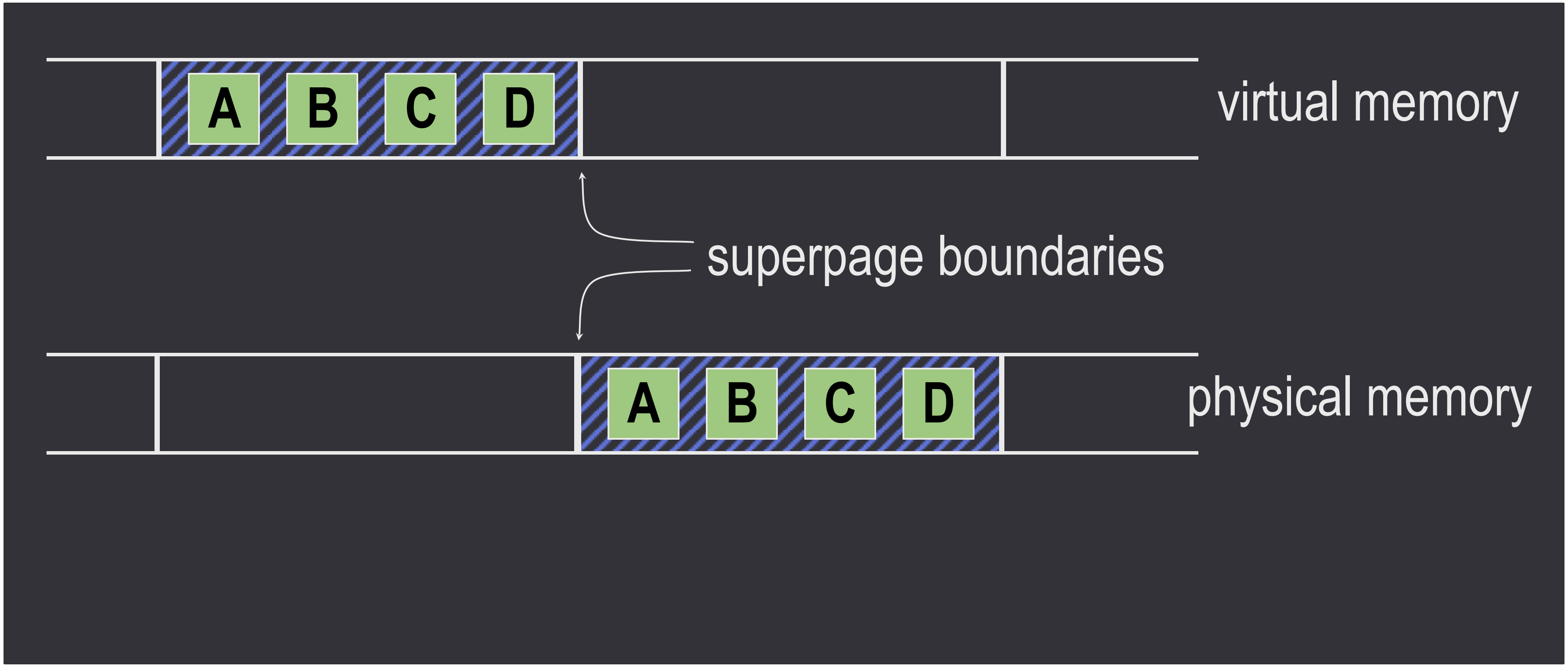
Superpage allocation

Preemptible reservations



Superpage allocation

Preemptible reservations

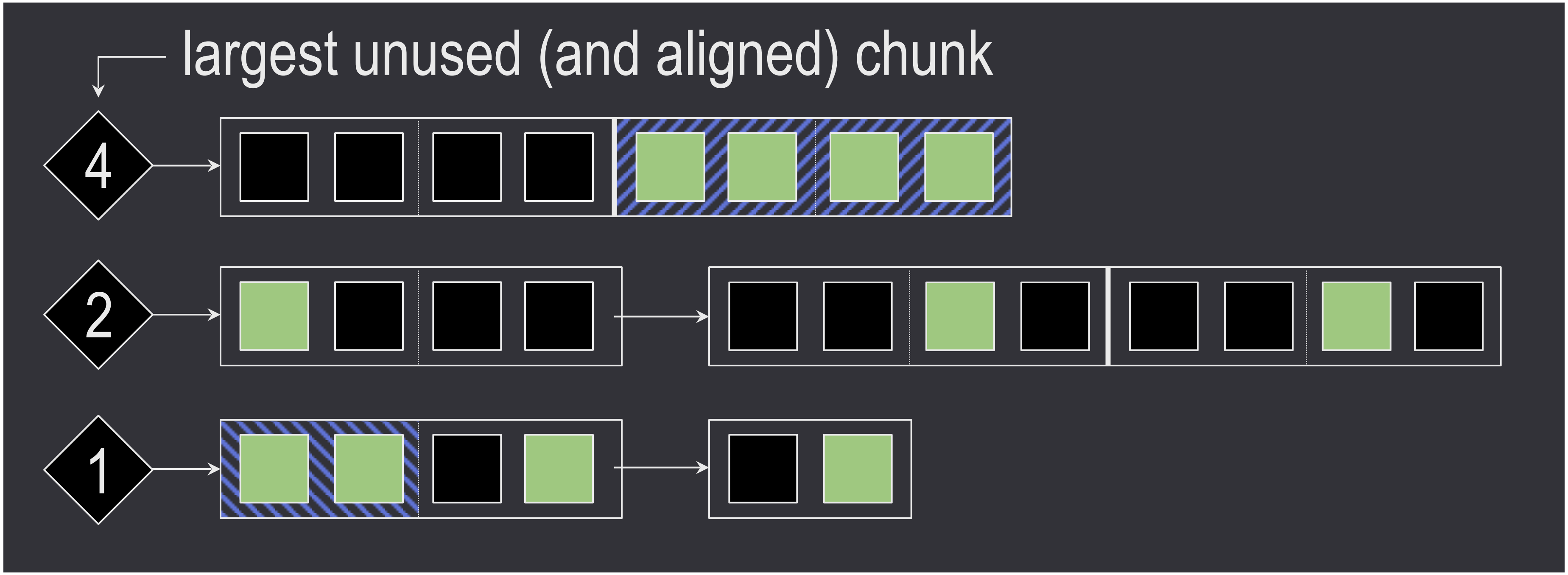


Allocation: reservation size

Opportunistic policy

- Go for biggest size that is no larger than the memory object (e.g., file)
- If required 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

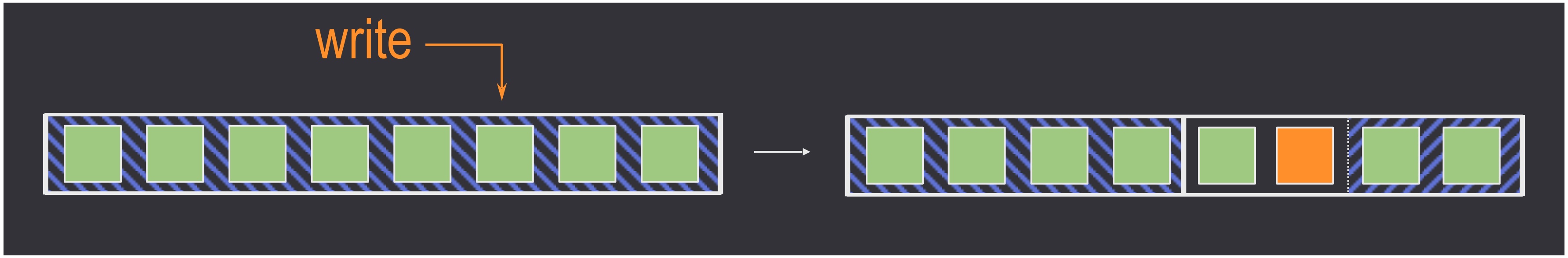
Promotion policy: opportunistic

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
- Demote also when the page daemon selects a base page as a victim page.

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 for victim selection
  - restore contiguity
    - move clean, inactive pages to the free list
  - minimize impact
    - prefer pages that contribute the most to contiguity
- Cluster wired pages

IV
Experimental evaluation

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

Why multiple superpage sizes

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

Improvements with only one superpage size vs. all sizes

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

More references:

- Multiple page sizes in different processors
  - https://en.wikipedia.org/wiki/Page_(computer_memory)#Multiple_page_sizes
- Linux Transparent Hugepages
  - https://lwn.net/Articles/423584/
-