

Corey: An Operating System for Many Cores

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What this talk is about

- **New OS interfaces** that help applications scale with the number of cores.
- Target applications: Web servers, MapReduce, mail servers, ...

Many applications spend time in the kernel

- Serving static web pages
 - Directory lookups and TCP processing
- Even applications implemented with multicore MapReduce spend time in the kernel
 - 30% of execution time spent growing address space on 16 cores
- Fraction of time in OS increases with the number of cores
 - OS becomes a bottleneck

The bottleneck is shared OS data structures

- Contention on shared data structures is costly:
 - serialization
 - moving data between caches
- Why does the OS need shared data structures?
 - OS semantics requires it
 - Simplifies resource management

Current practice for scaling the OS

- Redesign and reimplement kernel subsystems
 - Fine grained locking, RCU, etc.
- Lots of work: continuous redesign to increase concurrency
 - Linux changes: page cache, scheduler, RCU, memory management, ...
- Existing interfaces constrain designers
 - Even a small amount of shared kernel data limits performance with many cores

Our solution: change OS interface

- Applications don't always need to share all the data structures that existing interfaces share
- Allow applications to control how cores share kernel data structures
 - Avoid contention over kernel data structures
- We propose three interface changes
 - shares, address ranges, kernel cores
- Implemented in Corey OS
 - Partially implemented in Linux

New OS interfaces

- **Shares** control the kernel data used to resolve application references.
- **Address ranges** control page tables and the kernel data used to manage them.
- **Kernel cores** allow applications to dedicate cores to running particular kernel functions.
- Improve scalability of some applications by avoiding kernel bottlenecks

Idea #1: Shares

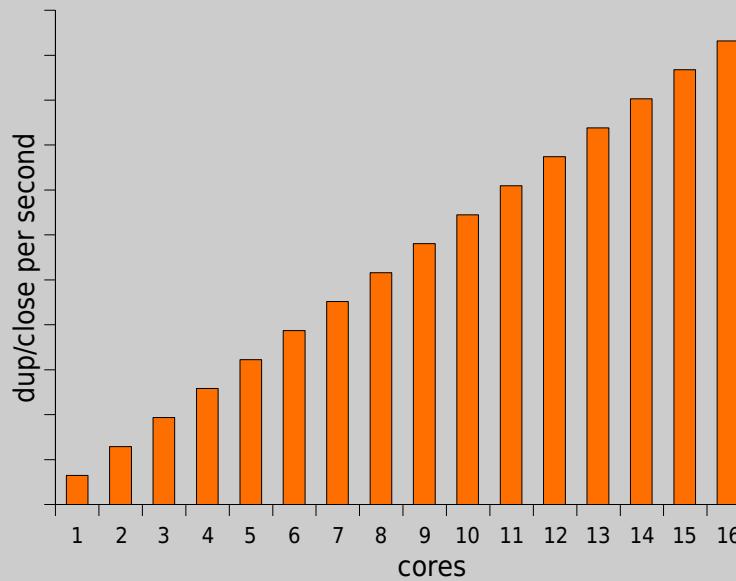
Object naming in an OS

- Kernel must map an application-visible reference into address of kernel object
 - Typically via per-process or global tables
 - Cores contend for shared data

Motivating example: file descriptors

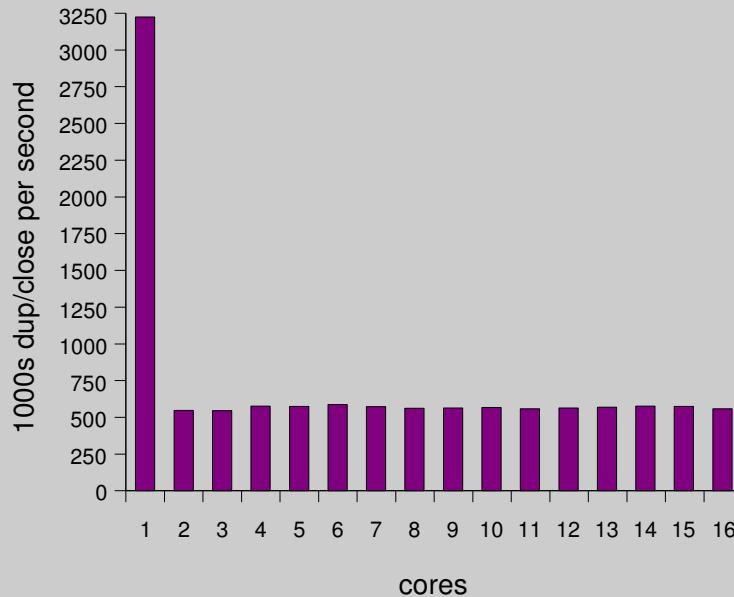
- Shared kernel data structure: file descriptor table
- Measure the cost of using FD table
 - Threads dup-and-close a per-thread FD
 - 16 core AMD Opteron running a Linux 2.6.27

Ideal FD performance graph



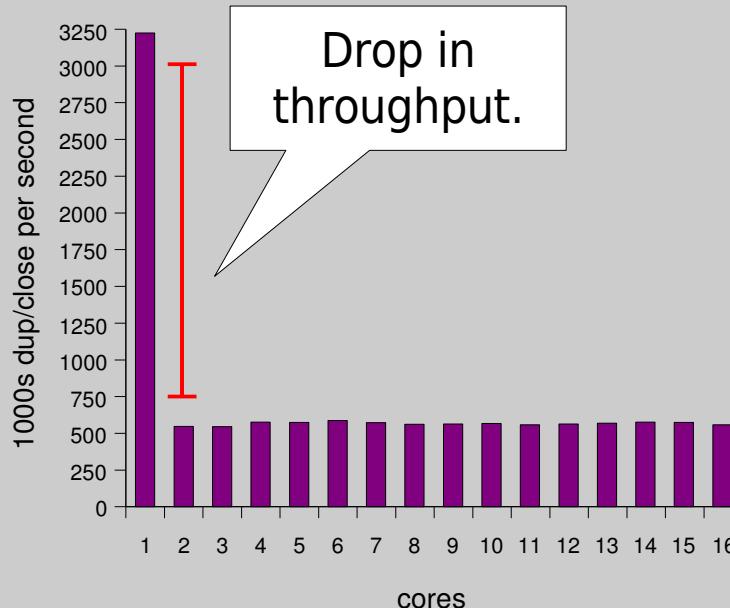
- Expect throughput to scale linearly

Actual FD performance



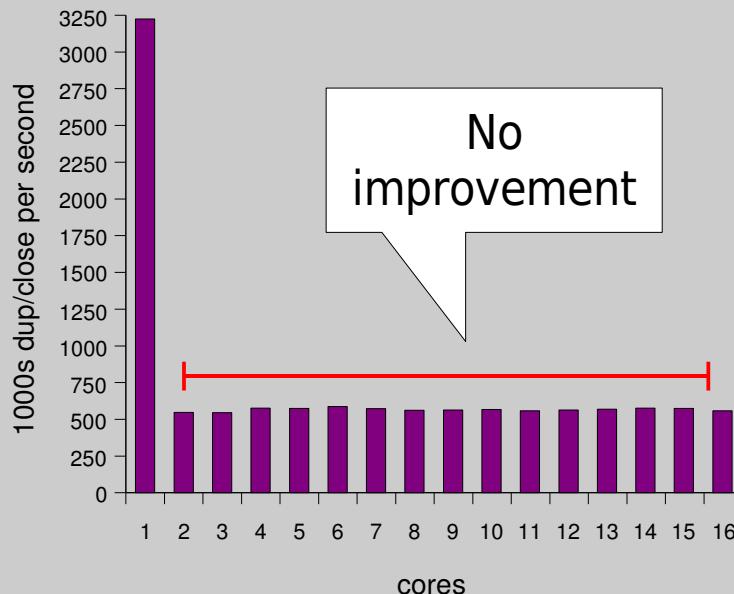
- Notice two things:

Actual FD performance



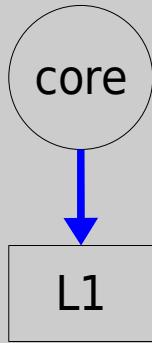
- Notice two things:
 - Drop in throughput.
 - No improvement in throughput.

Actual FD performance



- Notice two things:
 - Drop in throughput.
 - No improvement in throughput.

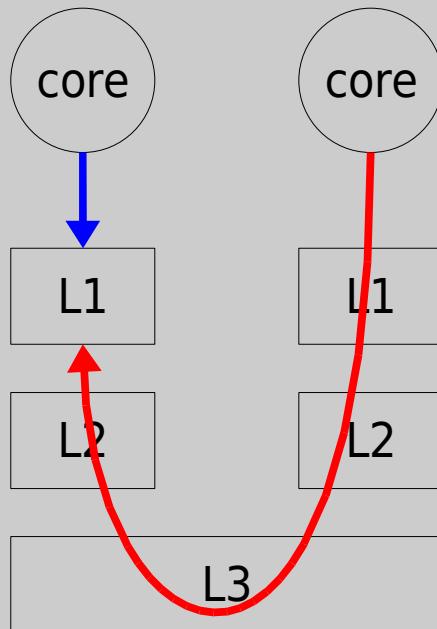
Why throughput drops?



```
fd_alloc(void) {  
    lock(fd_table);  
    fd = get_free_fd();  
    set_fd_used(fd);  
    fix_smallest_fd()  
    unlock(fd_table);  
}
```

- Load `fd_table` data from L1 in 3 cycles.

Why throughput drops?



```
fd_alloc(void) {  
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    fix_smallest_fd()  
    unlock(fd_table);  
}
```

- Load `fd_table` data from L1 in 3 cycles.
- Now it takes 121 cycles!

Why no improvement?

```
fd_alloc(void) {  
    lock(fd_table);  
    fd = get_free_fd();  
    set_fd_used(fd);  
    fix_smallest_fd()  
    unlock(fd_table);  
}
```

- Shared FD table is a bottleneck
 - A lock serializes updates to `fd_table`

Can the performance be better?

- For some applications the OS shares kernel data structures unnecessarily
 - Should be able to improve performance
- Challenge: how should the OS figure out when to share and when not to?
 - More difficult if application has a mixture

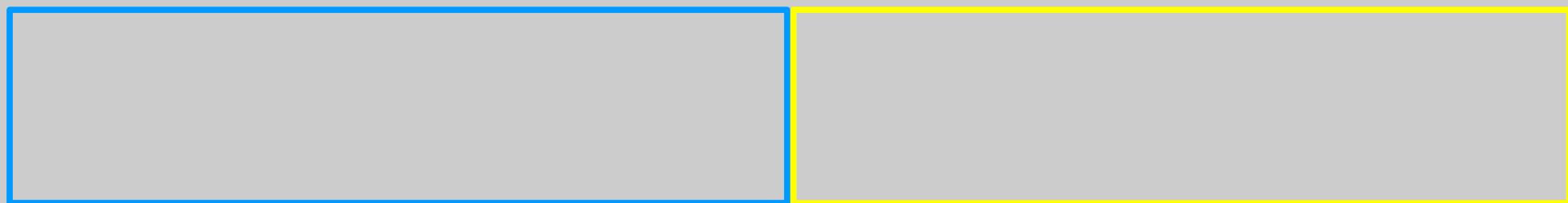
Our solution: shares

- **Shares** allow applications to control how cores share the kernel data structures used to do lookups
- Applications specify when they need sharing, for example:
 - shared FDs allocated in shared table
 - private FDs allocated in private table
- Corey kernel uses shares for all lookup tables

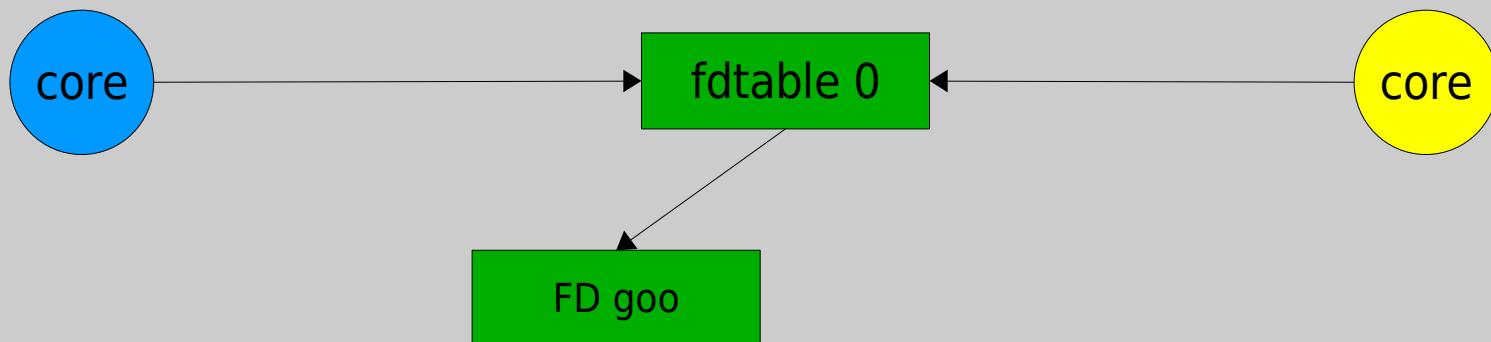
Adding shares to Linux

- With minimal changes can add a share-like interface for FDs.
- FD system calls (`sys_open`, `sys_dup`, ...) take an optional shareid/fdtableid argument.

Linux FD share example

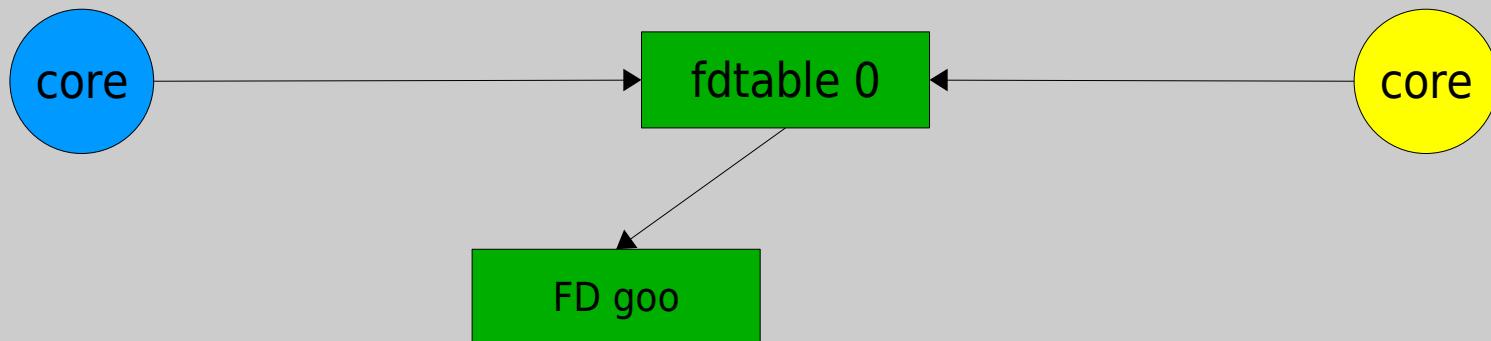


Linux FD share example



```
fd2 = open("goo");
```

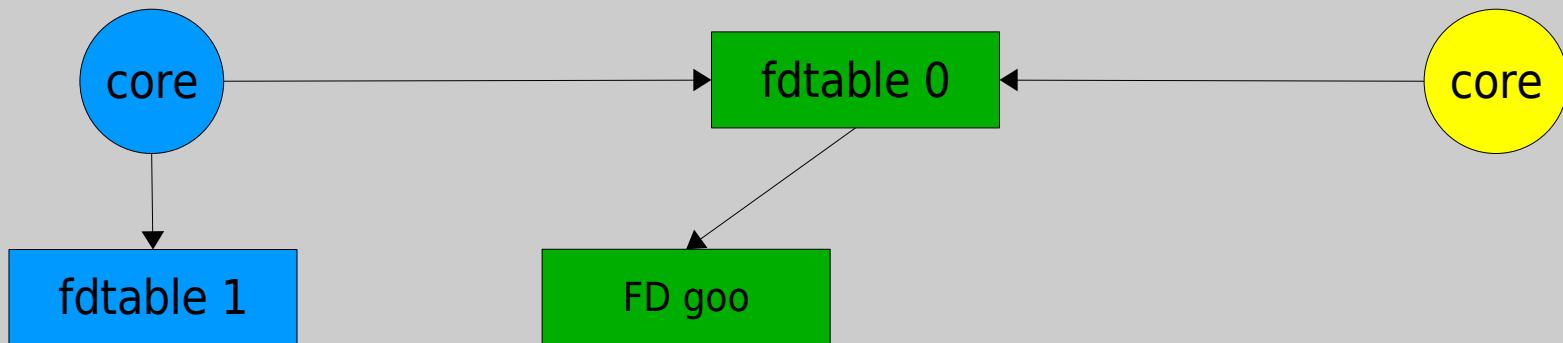
Linux FD share example



```
fd2 = open("goo");
```

```
write(fd2, buf, 128);
```

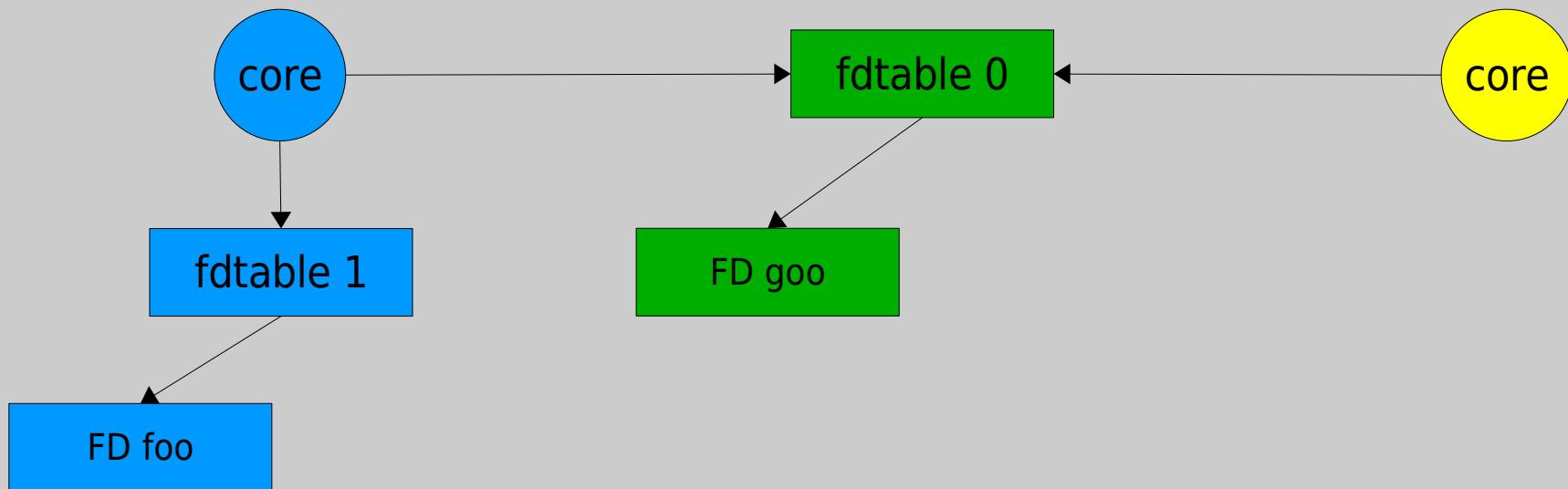
Linux FD share example



```
fd2 = open("goo");
fdtable1 = share_alloc();
```

```
write(fd2, buf, 128);
```

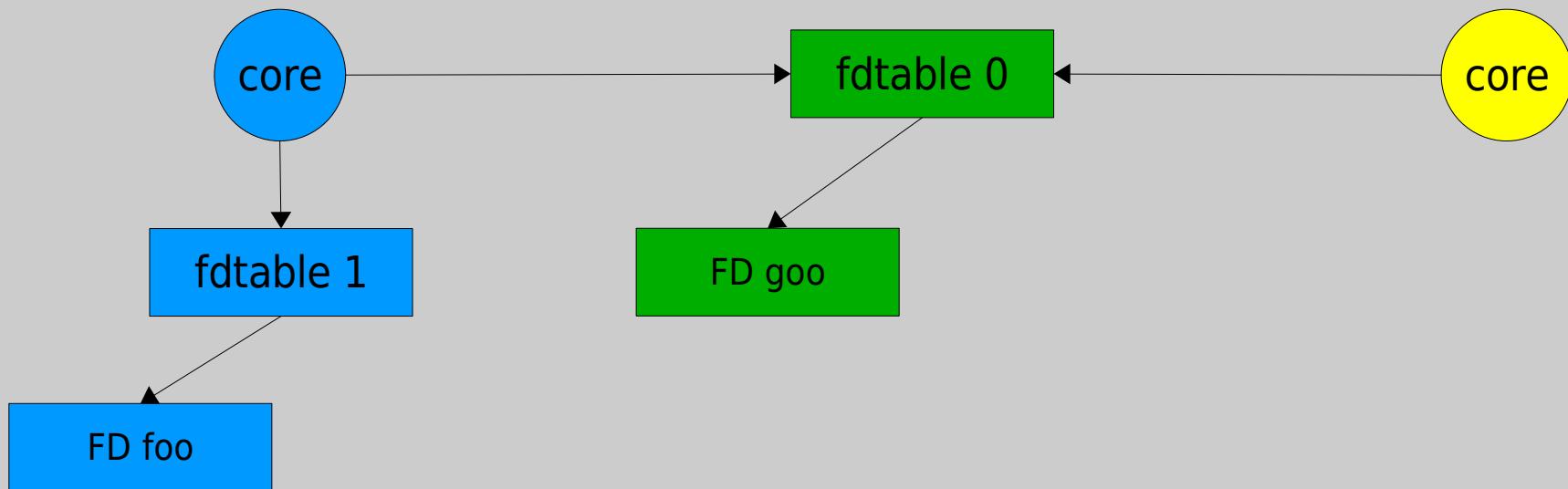
Linux FD share example



```
fd2 = open("goo");
fdtable1 = share_alloc();
fd0 = open("foo", share1);
```

```
write(fd2, buf, 128);
```

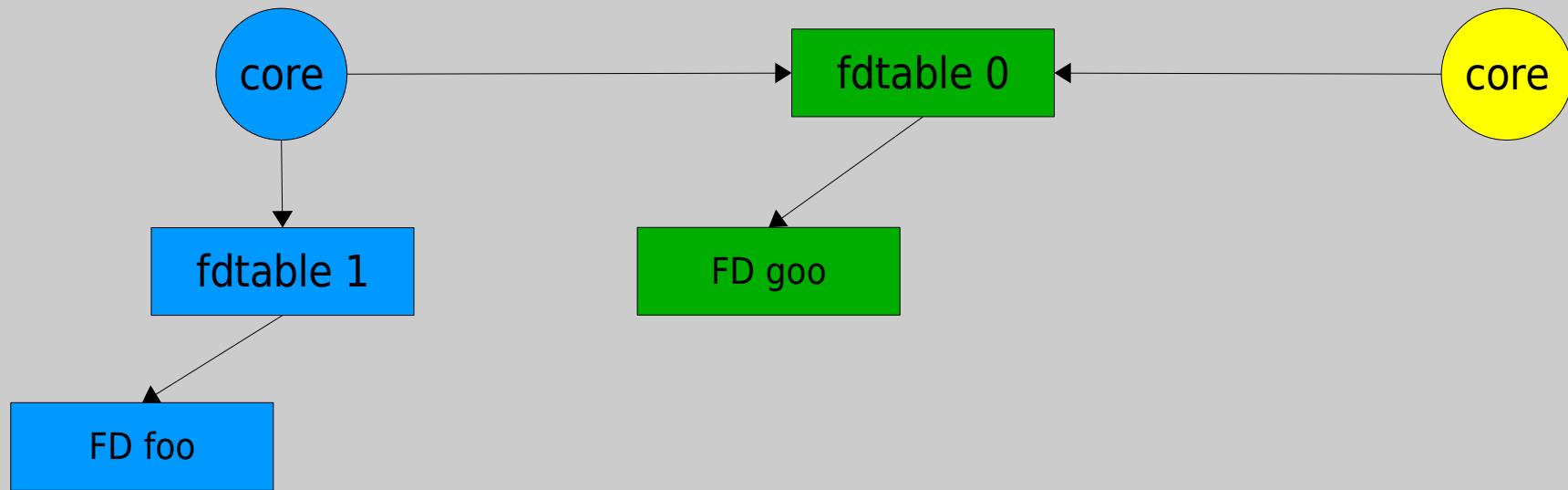
Linux FD share example



```
fd2 = open("goo");
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fd0 = open("foo", share1);
write(fd0, buf, 128, share1);
```

```
write(fd2, buf, 128);
```

Linux FD share example

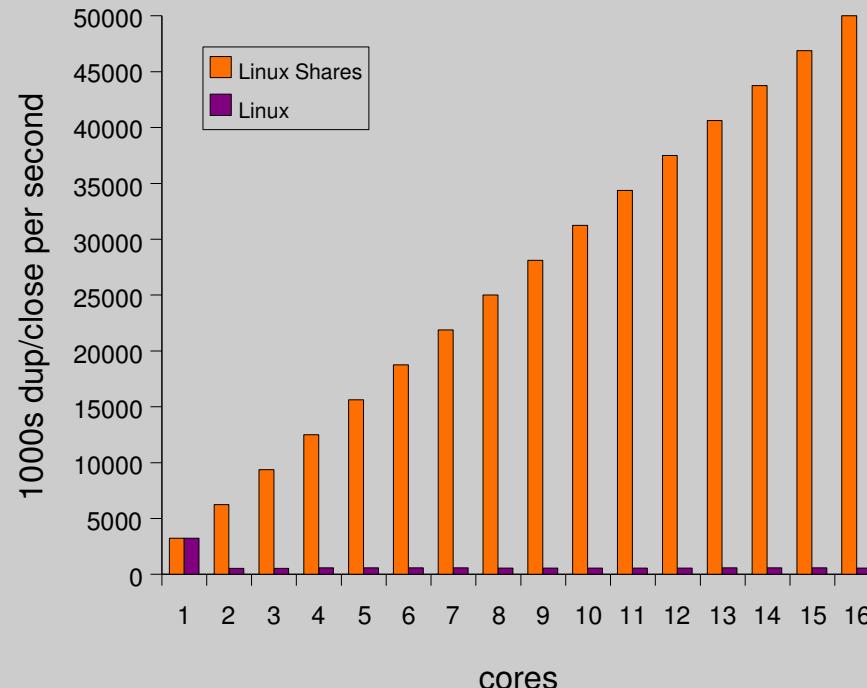


```
fd2 = open("goo");
fdtable1 = share_alloc();
fd0 = open("foo", share1);
write(fd0, buf, 128, share1);
```

```
write(fd2, buf, 128);
```

- Cores manipulate FDs without contending for kernel data structures

Performance is now ideal



- Avoid contention on shared FD table:
 - No drop in throughput (no L1 misses)
 - Scales linearly (no serialization)

Benefit of shares

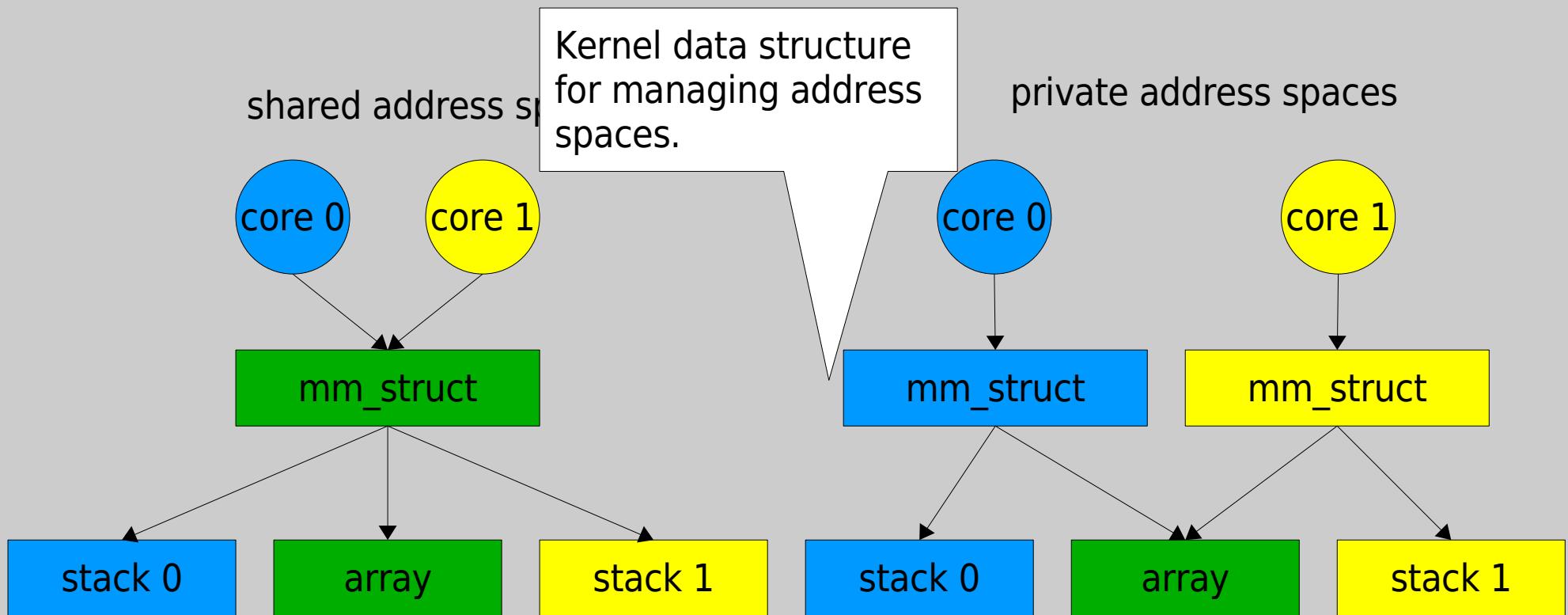
- Able to avoid unnecessary contention on kernel data structures
 - For example when application threads do not share FDs
- Applications can control how cores share internal kernel data structures
- Few kernel and application modifications to get scalability

Idea #2: Address ranges

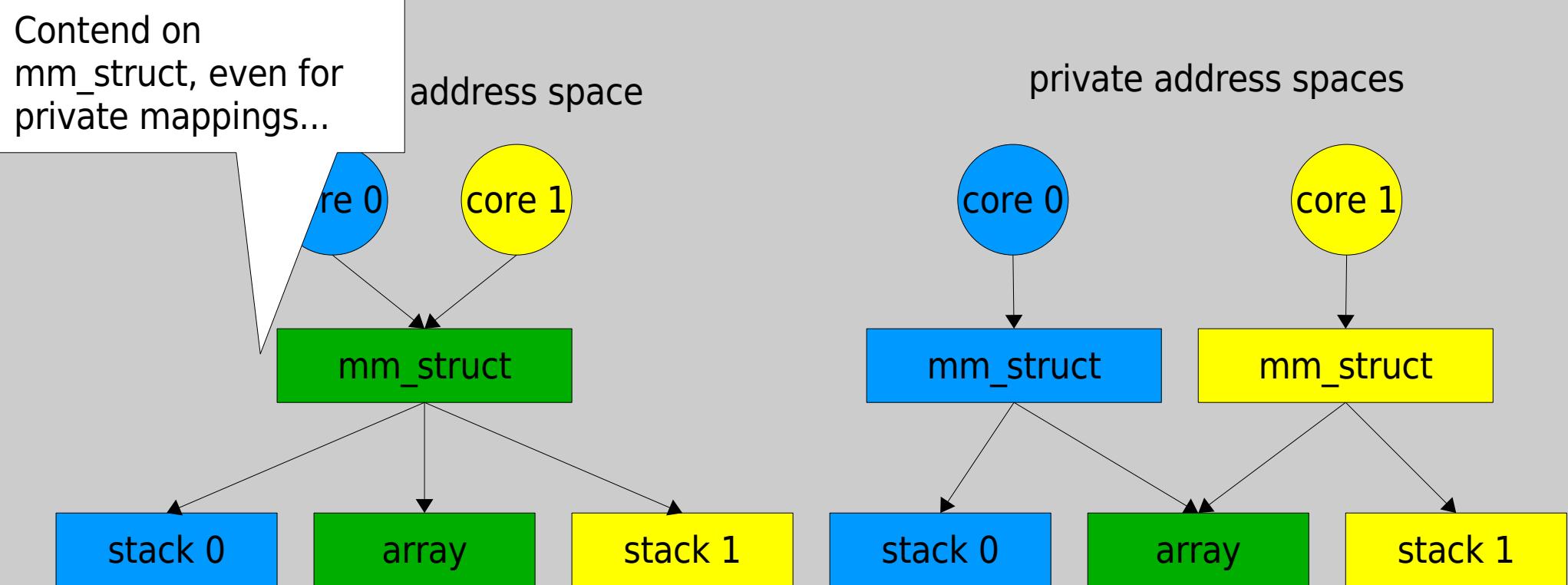
Two options for multiprocessor shared-memory application

- Shared address space
 - Implemented with multiple threads
- Private address spaces
 - Implemented with multiple processes
 - Share memory with `mmap(MAP_SHARED)`

Cost of two options



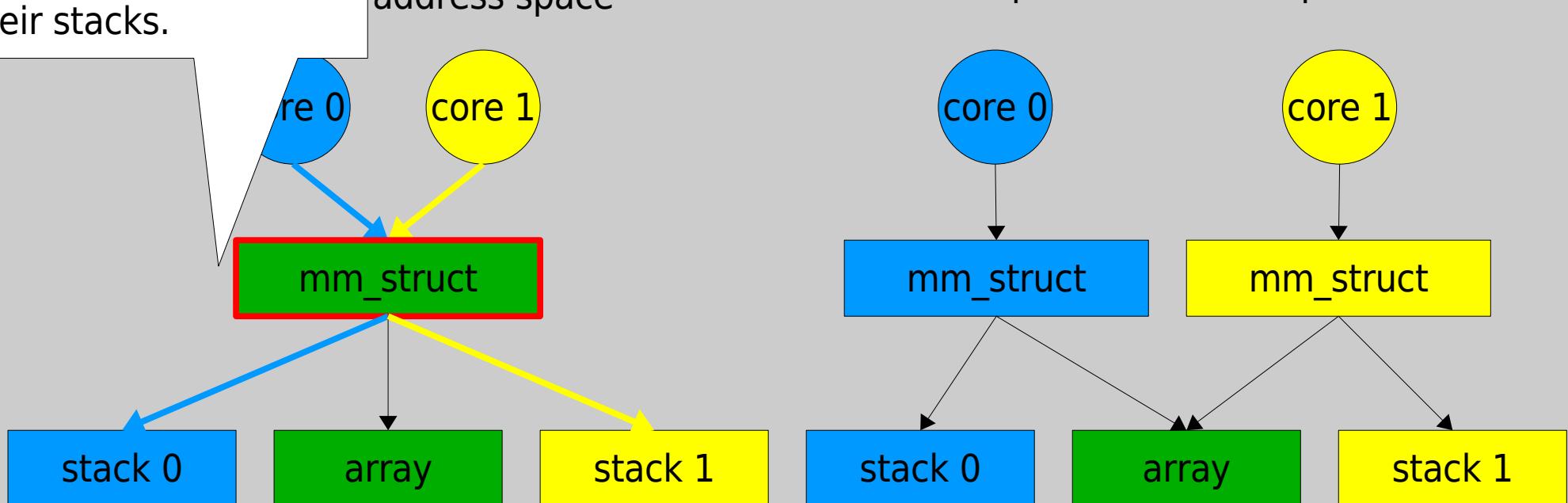
Cost of two options



- Contend on mm_struct:
locks, counters, lists...

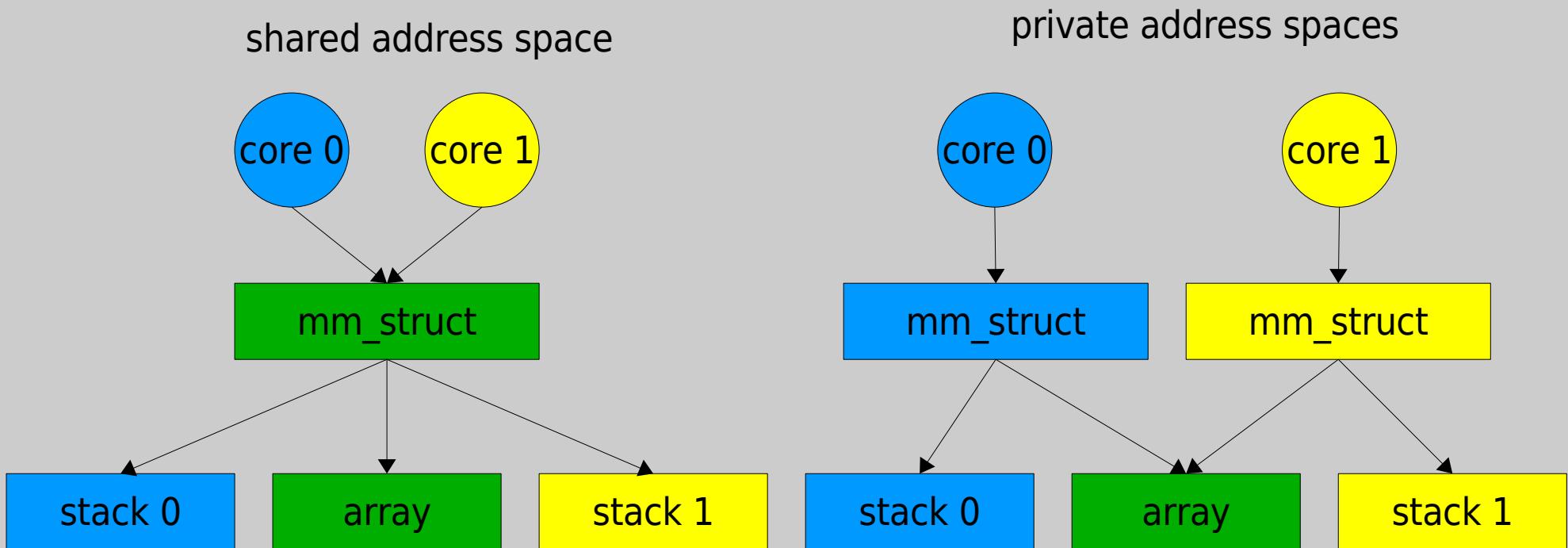
Cost of two options

...for example when both cores go to grow their stacks.



- Contend on **mm_struct**: locks, counters, lists...

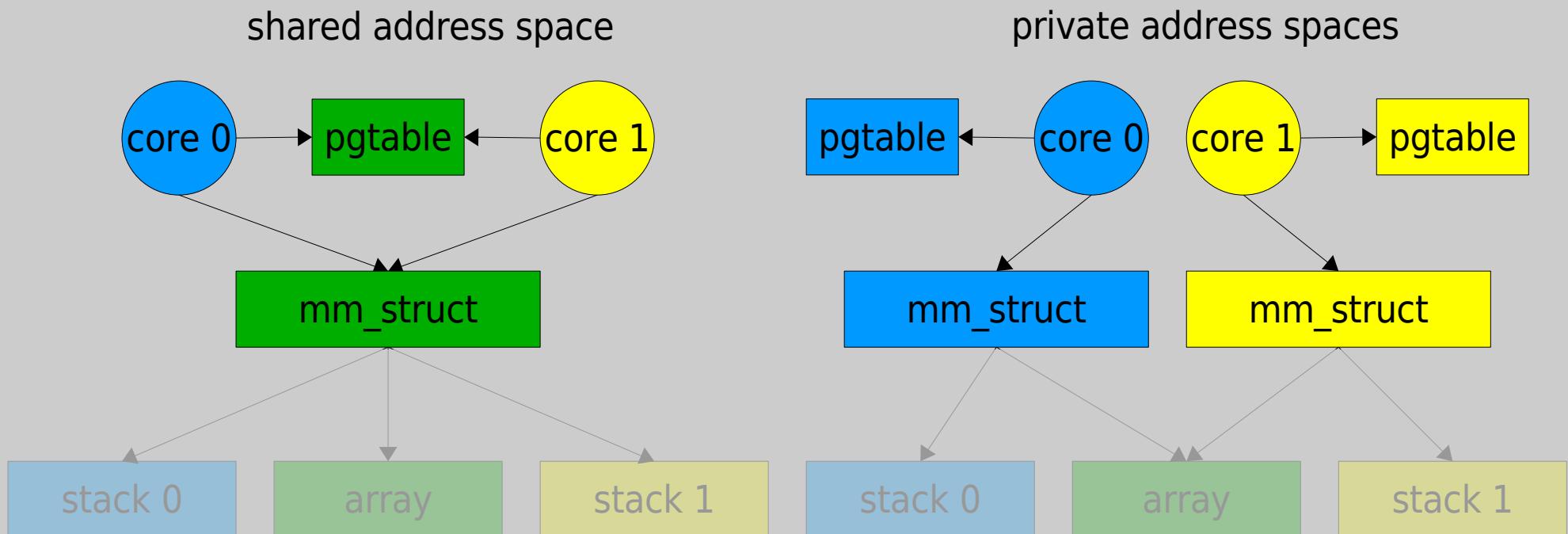
Cost of two options



- Contend on mm_struct: locks, counters, lists...
- No contention on mm_struct

More costs: soft page faults

- Linux lazily instantiates page tables

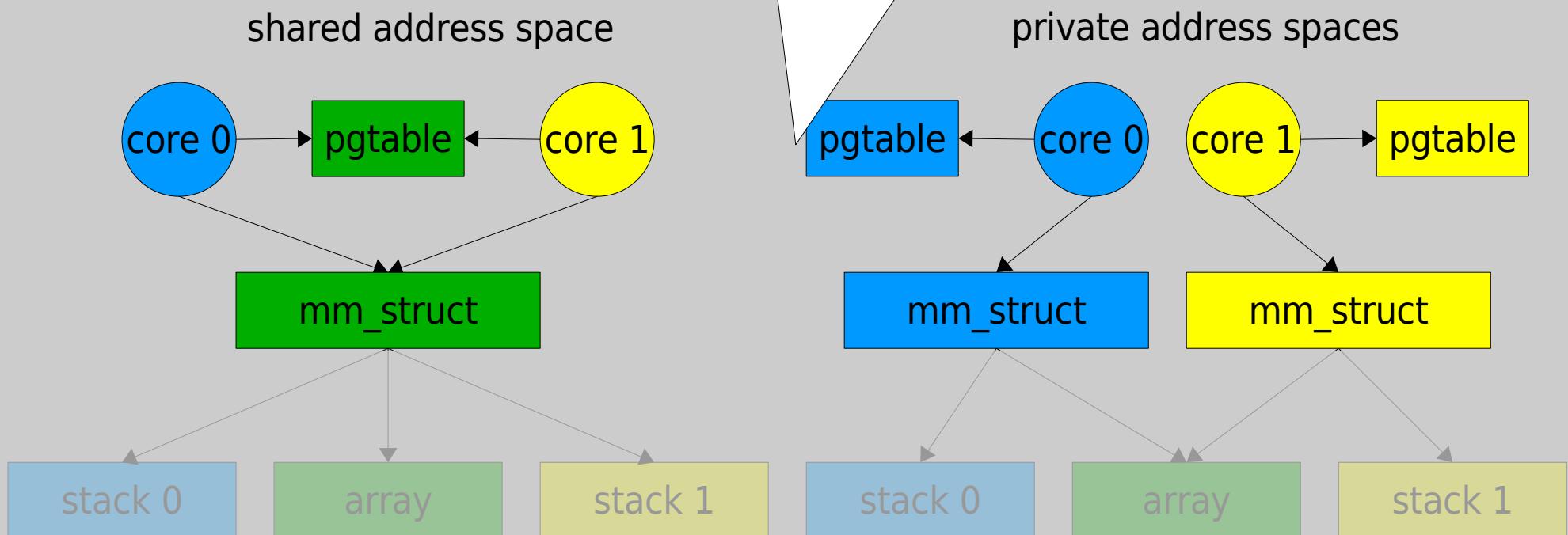


- Contend on mm_struct: locks, counters, lists...
- No contention on mm_struct

More costs: soft page faults

- Linux lazily initializes tables

Hardware page table associated with the mm_struct of the same color.



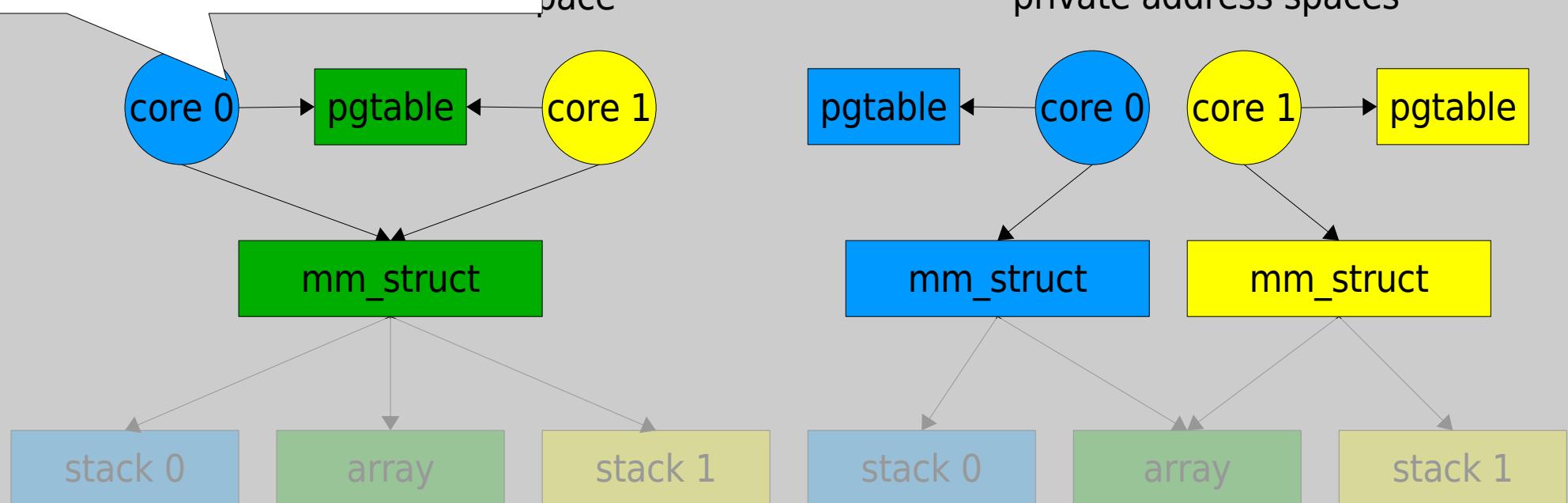
- Contend on mm_struct: locks, counters, lists...

- No contention on mm_struct

More costs: soft page faults

When an application allocates memory the OS doesn't actually fill in the PTEs.

instantiates page tables



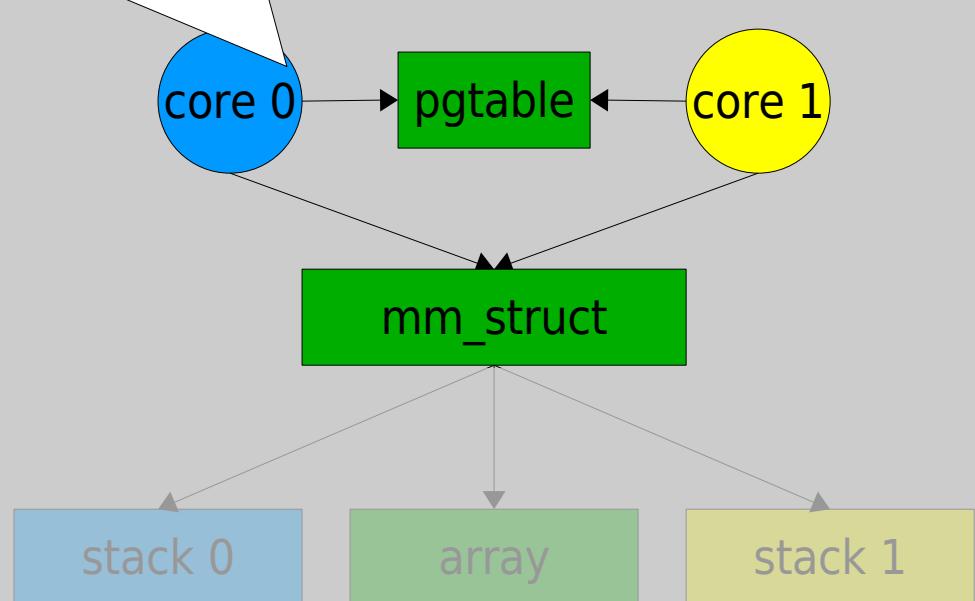
- Contend on `mm_struct`: locks, counters, lists...
- No contention on `mm_struct`

More costs: soft page faults

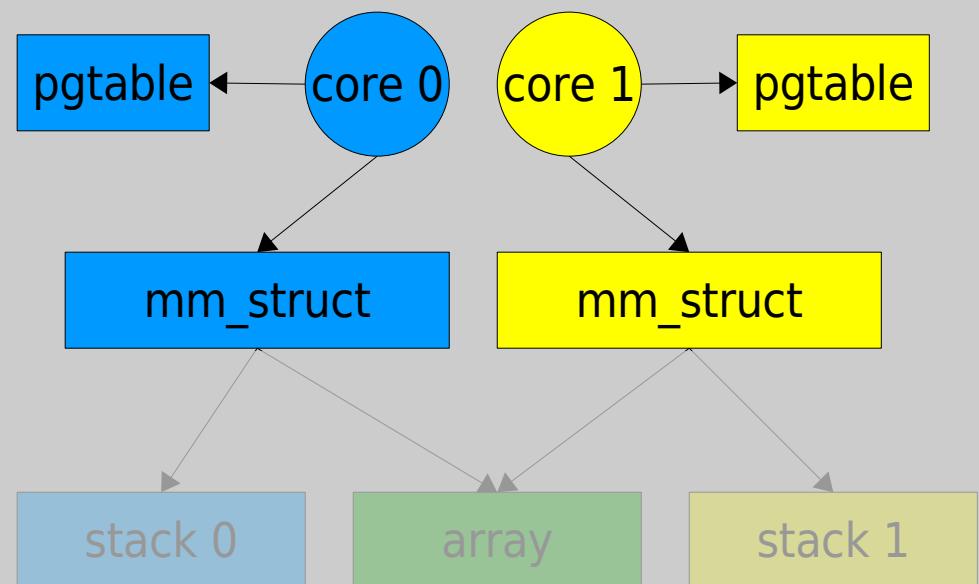
The first time a page is touched
the core will signal a memory
fault...

instantiates page tables

space



private address spaces



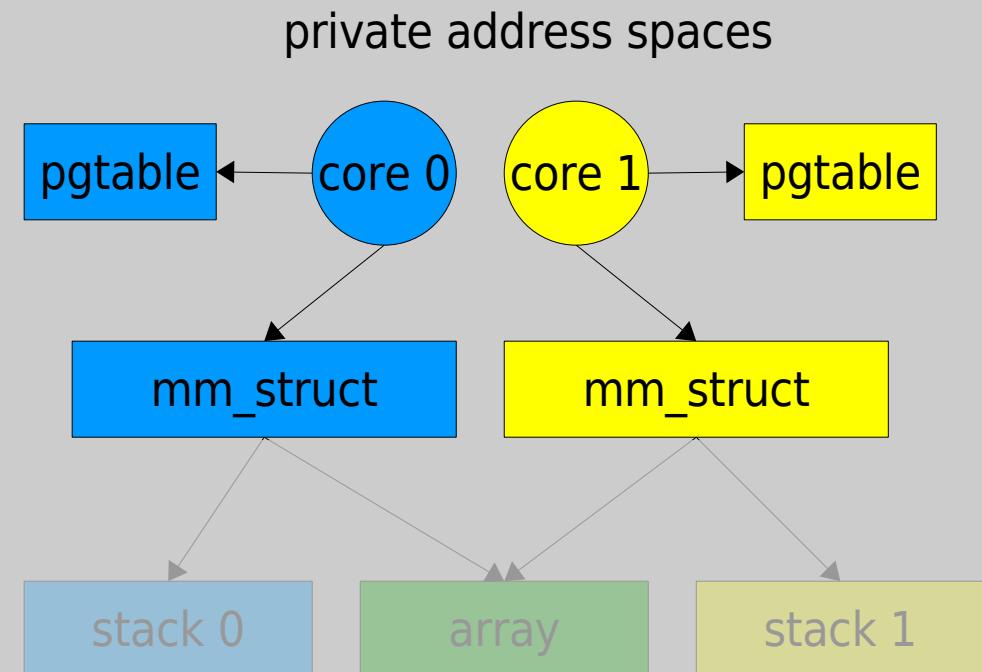
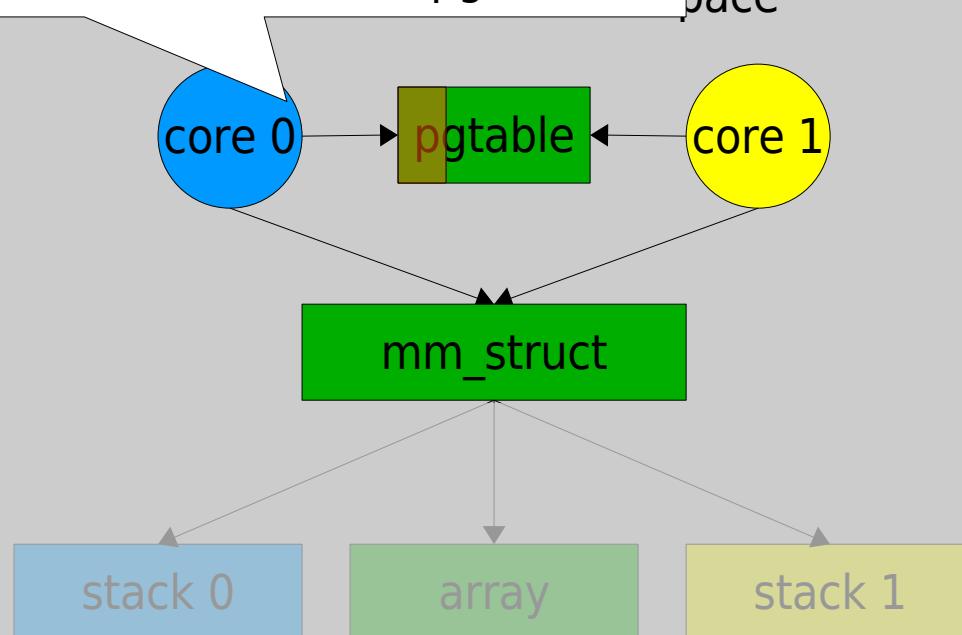
- Contend on mm_struct:
locks, counters, lists...

- No contention on mm_struct

More costs: soft page faults

...and the OS allocates a physical page and adds and adds a PTE to the pgtable.

instantiates page tables

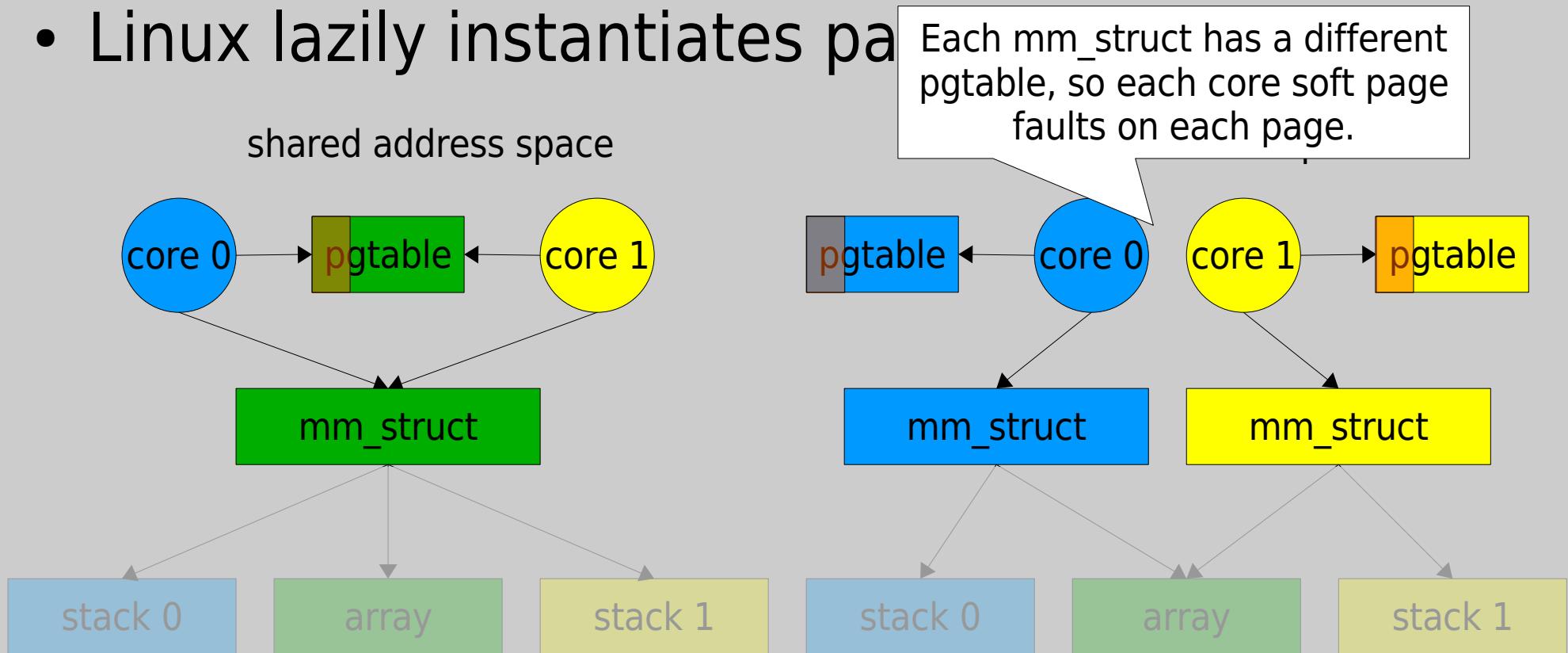


- Contend on mm_struct: locks, counters, lists...
- One soft page fault per page

- No contention on mm_struct

More costs: soft page faults

- Linux lazily instantiates pa



- Contend on **mm_struct**: locks, counters, lists...
- One page fault per page

- No contention on **mm_struct**
- Each core soft page faults on each page

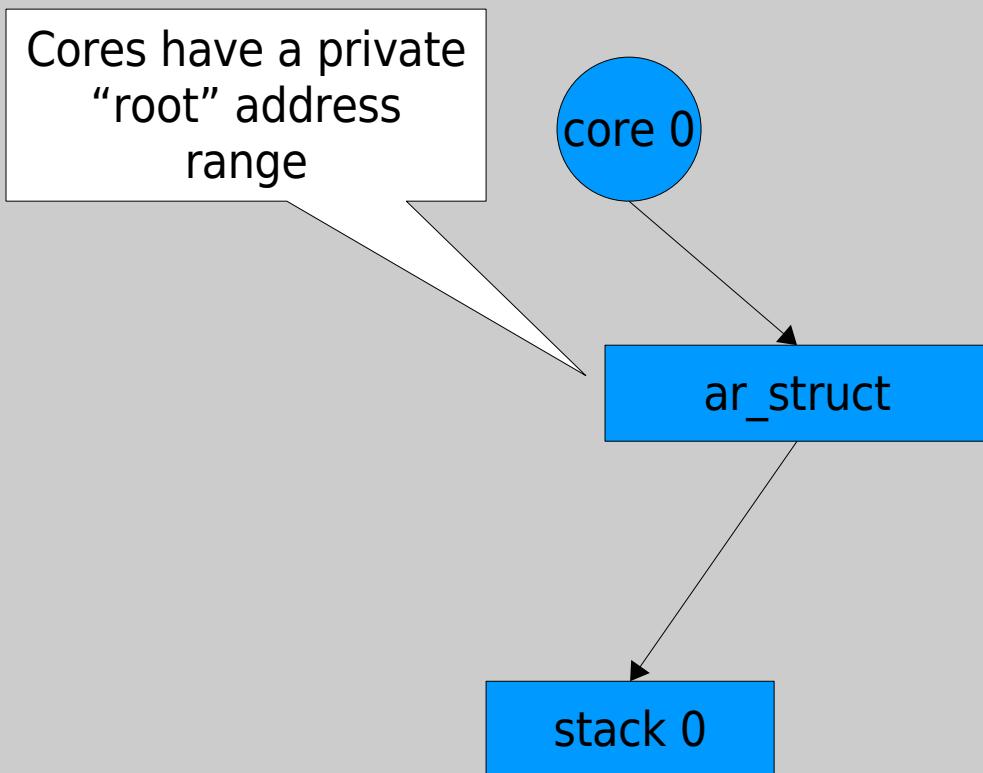
The problem

- Neither option accurately represents how the application is using kernel data structures:
 - shared address spaces – the `mm_struct` is global
 - contention
 - unnecessary for private memory
 - private address spaces – the `mm_struct` is private
 - extra soft page faults, because no PTE sharing

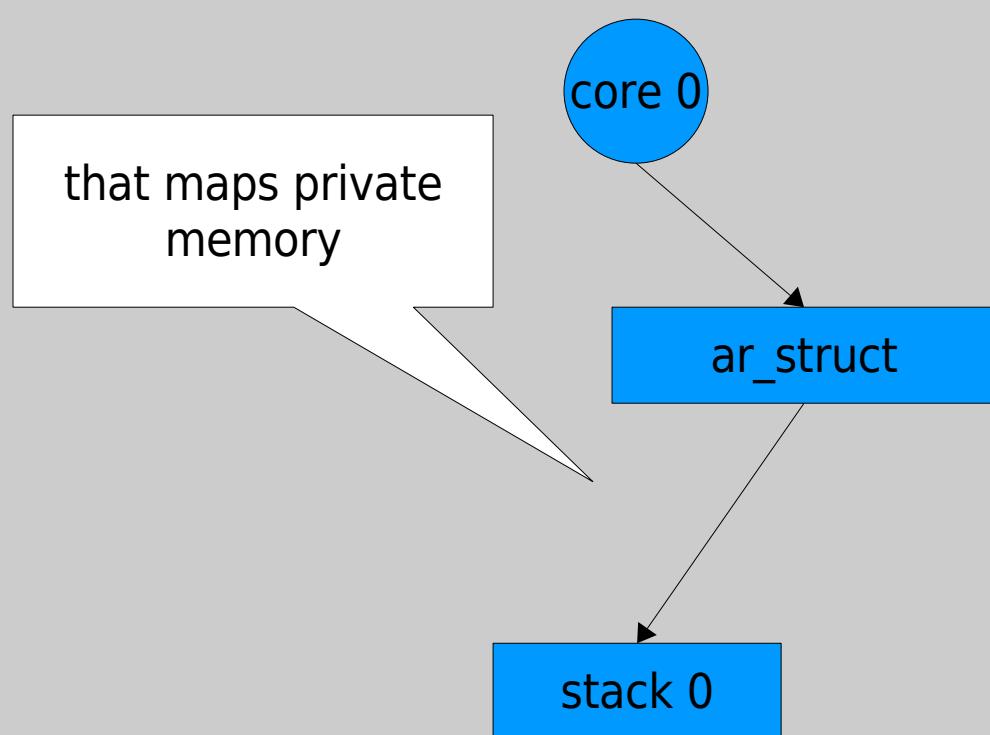
Our solution: address ranges

- **Address ranges** provide benefits of both shared and private address spaces:
 - avoid contention for private memory
 - share PTEs for shared memory

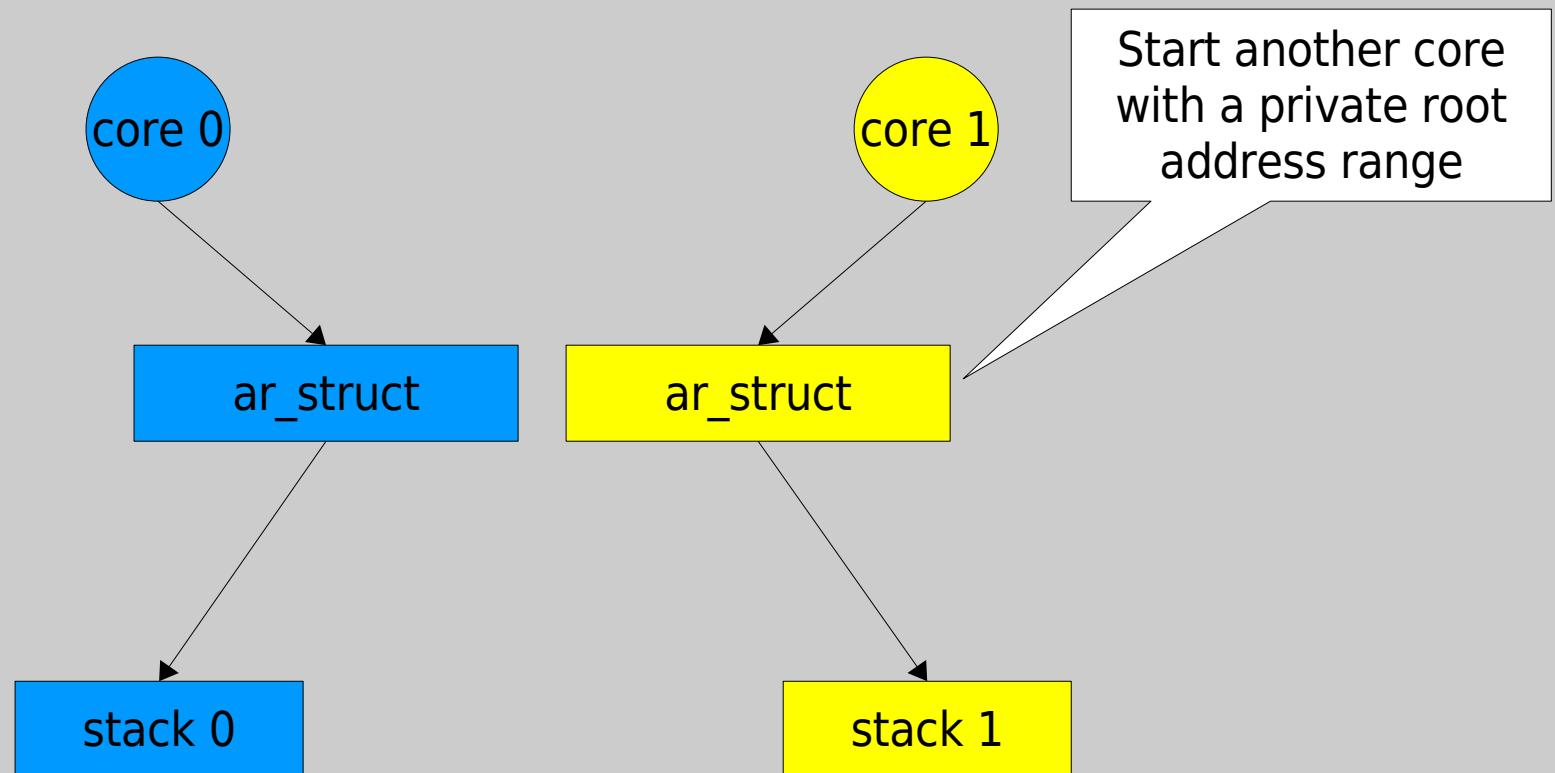
Address ranges: avoid contention



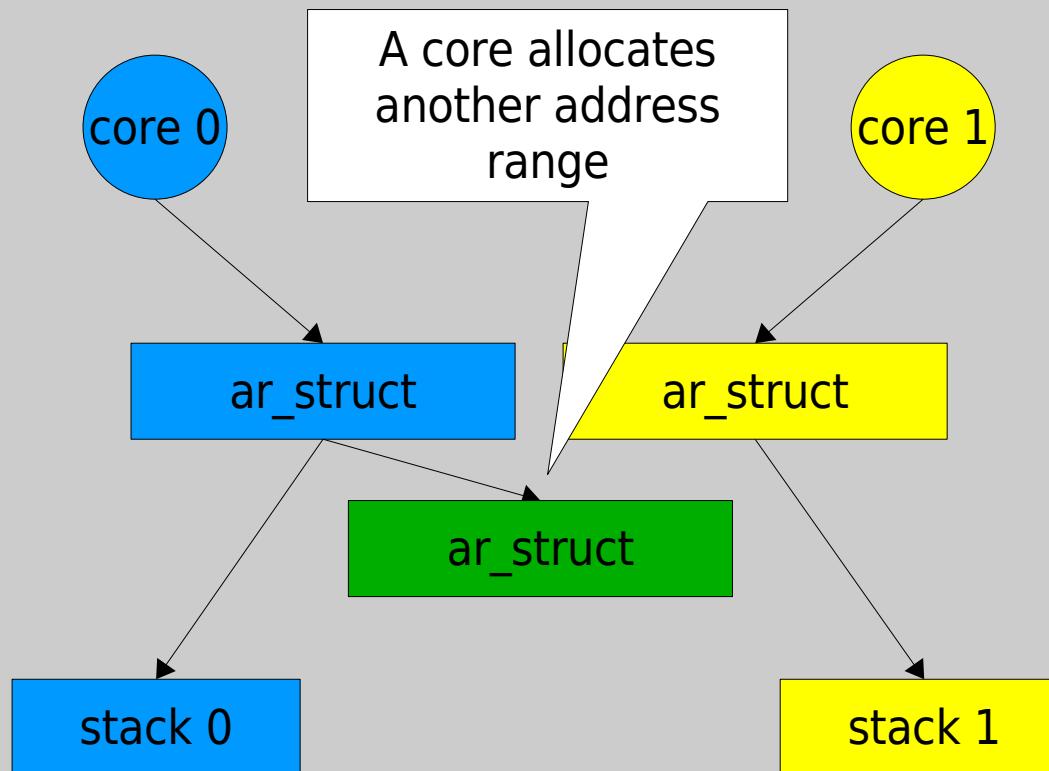
Address ranges: avoid contention



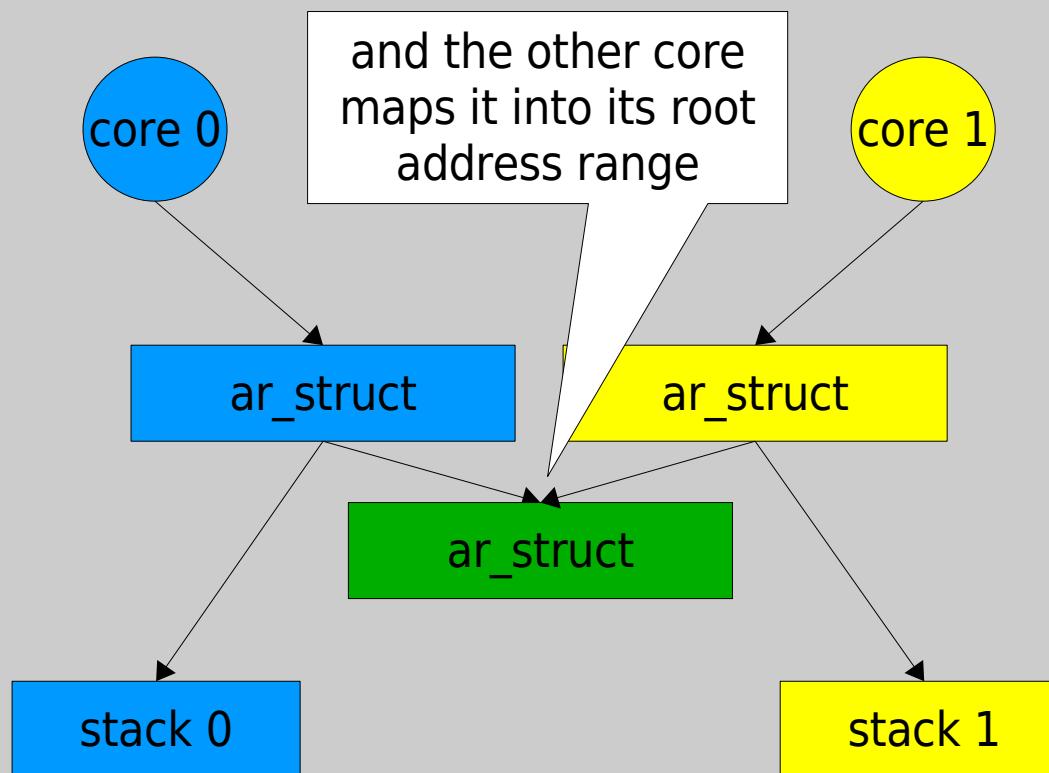
Address ranges: avoid contention



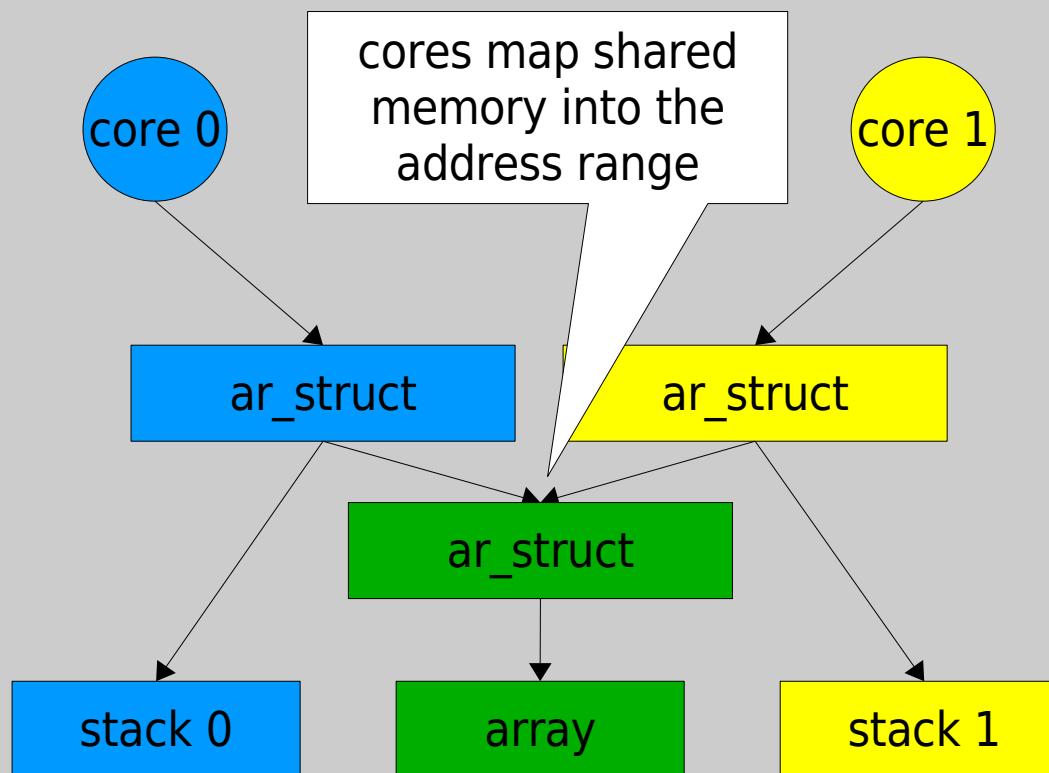
Address ranges: avoid contention



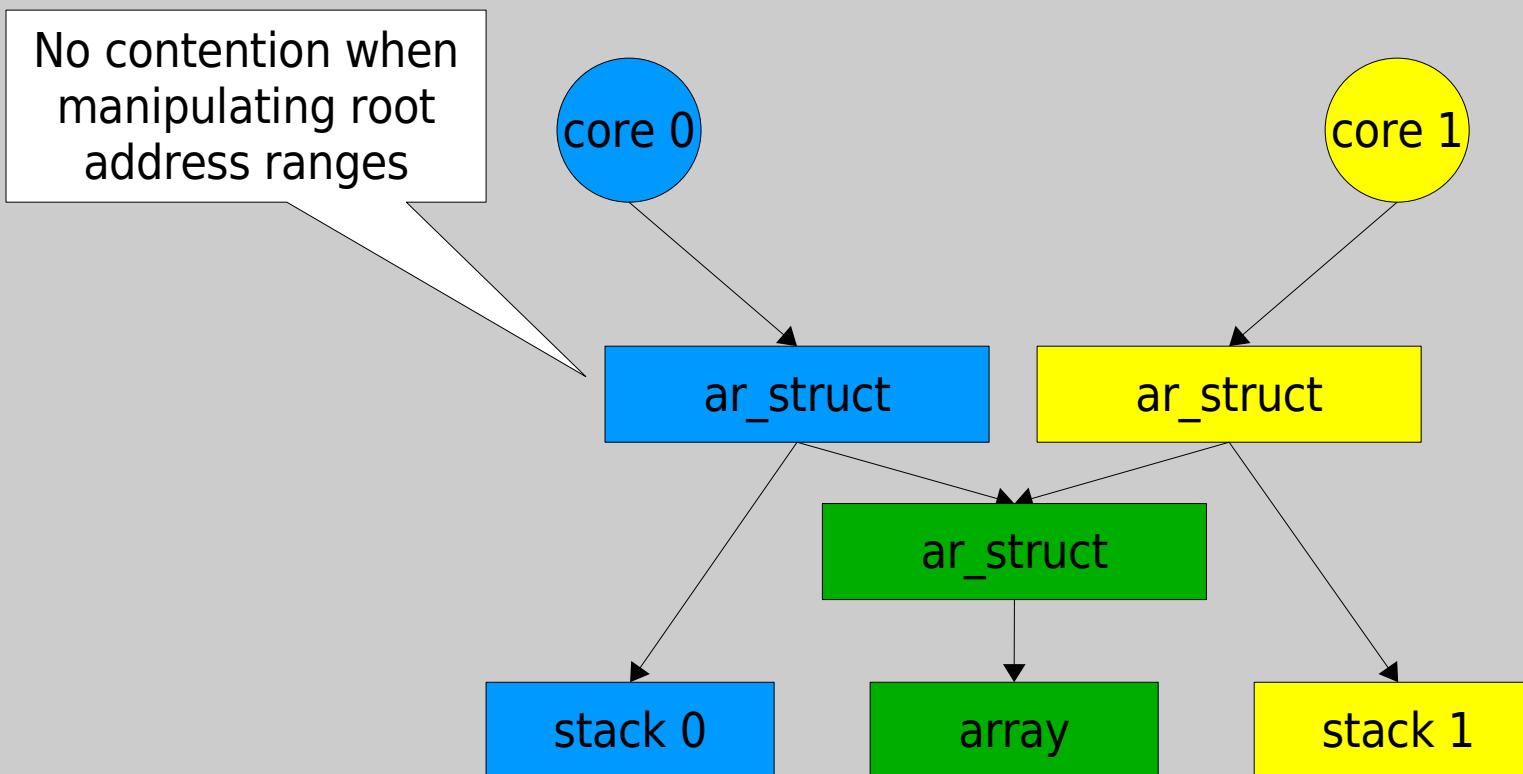
Address ranges: avoid contention



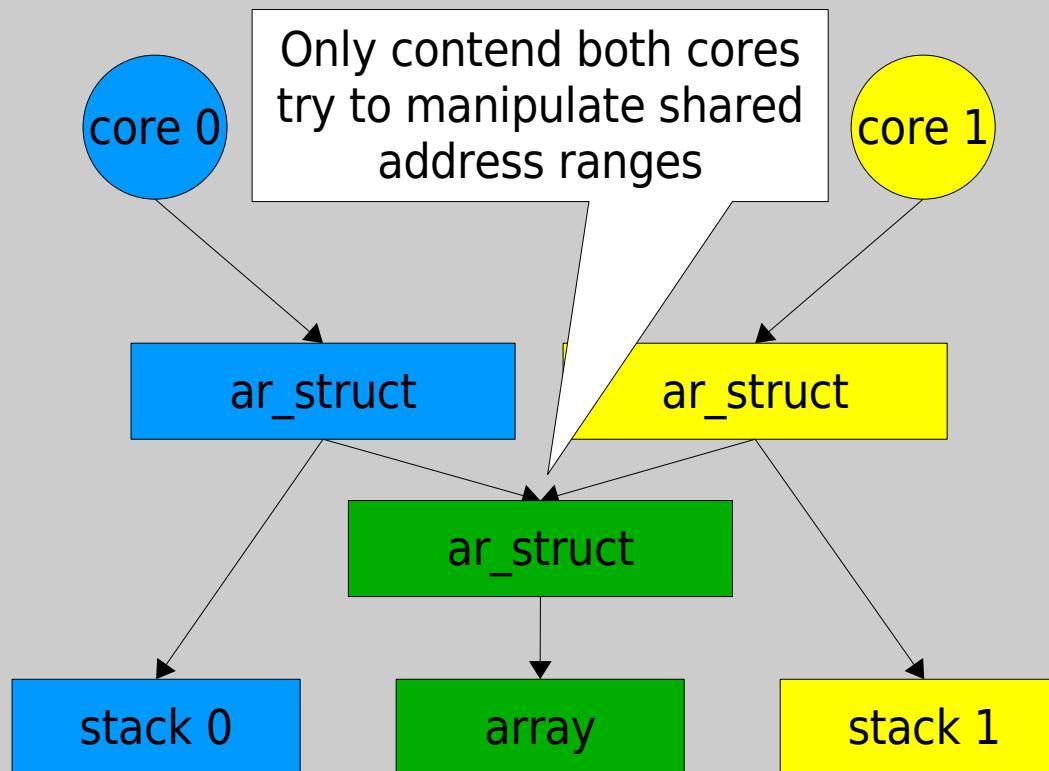
Address ranges: avoid contention



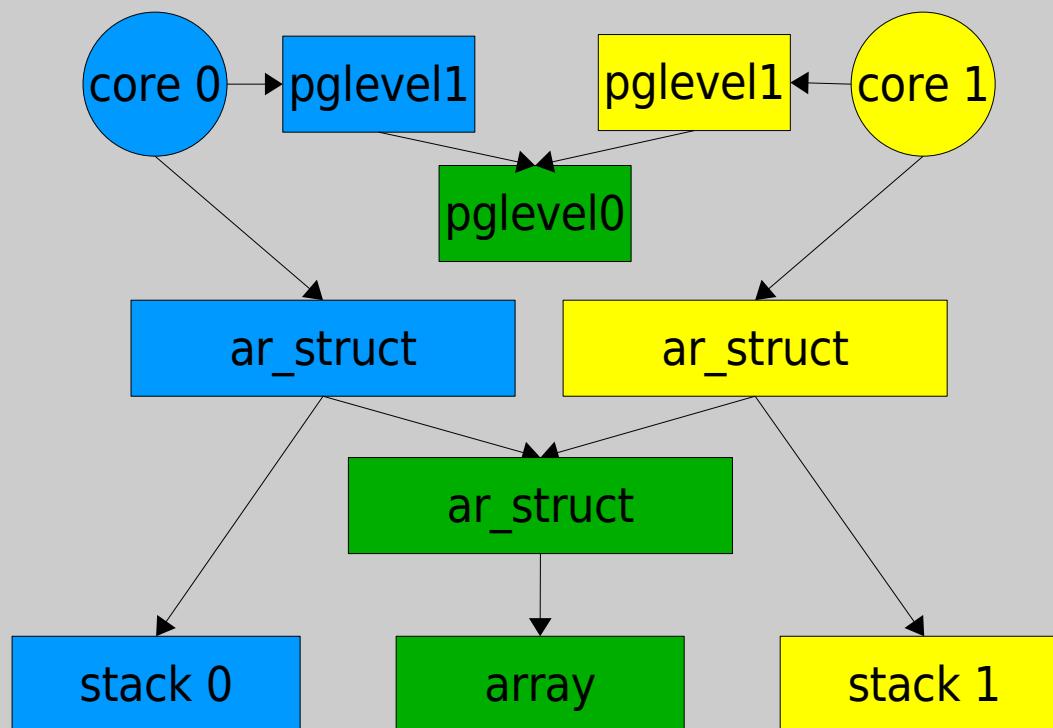
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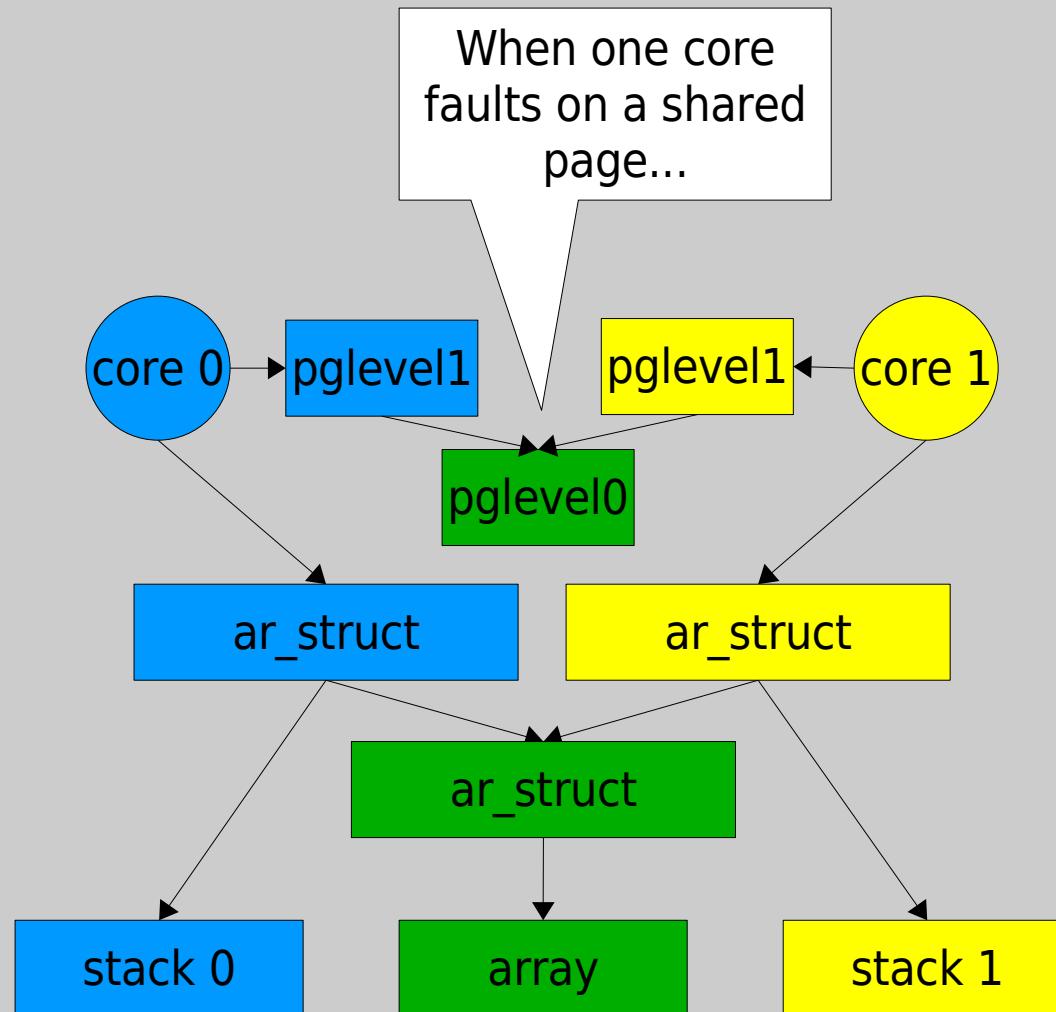
Address ranges: avoid contention



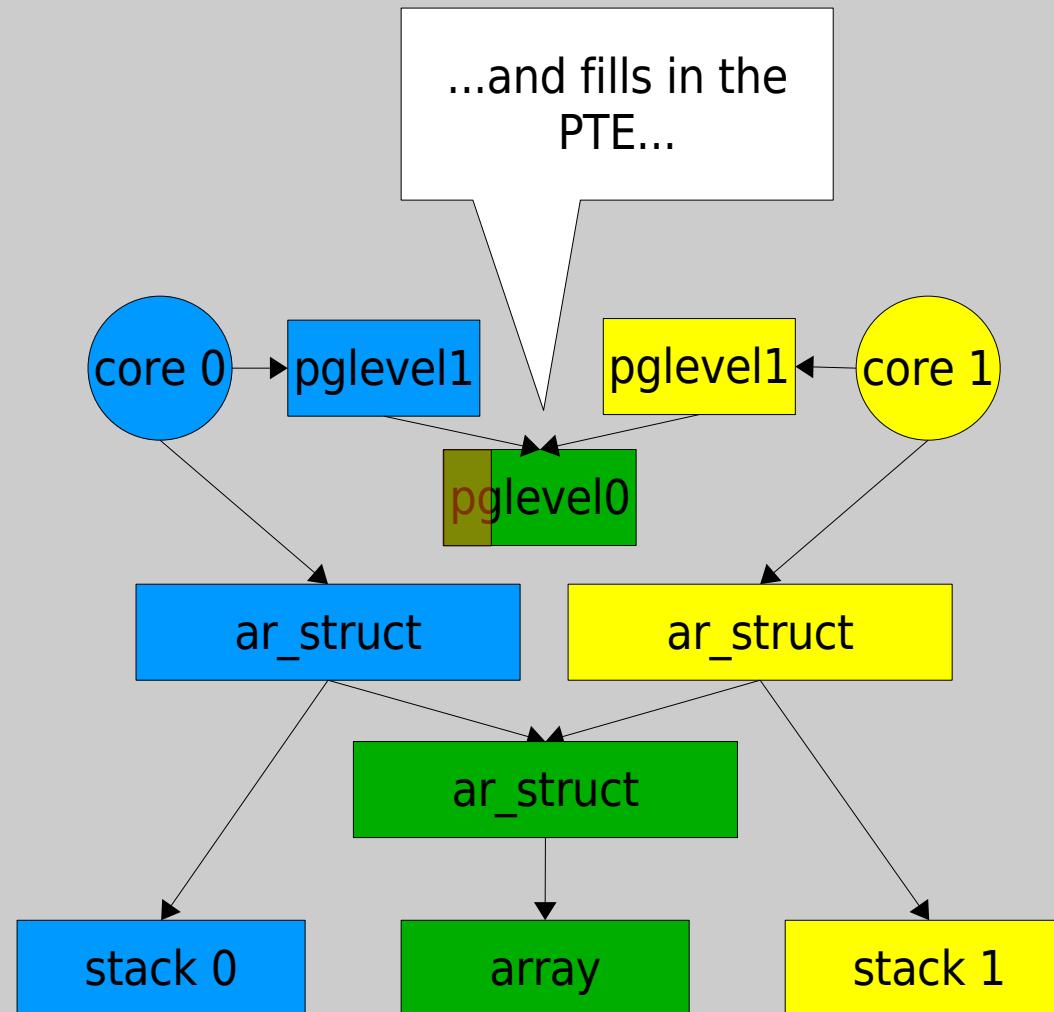
Address ranges: share PTEs



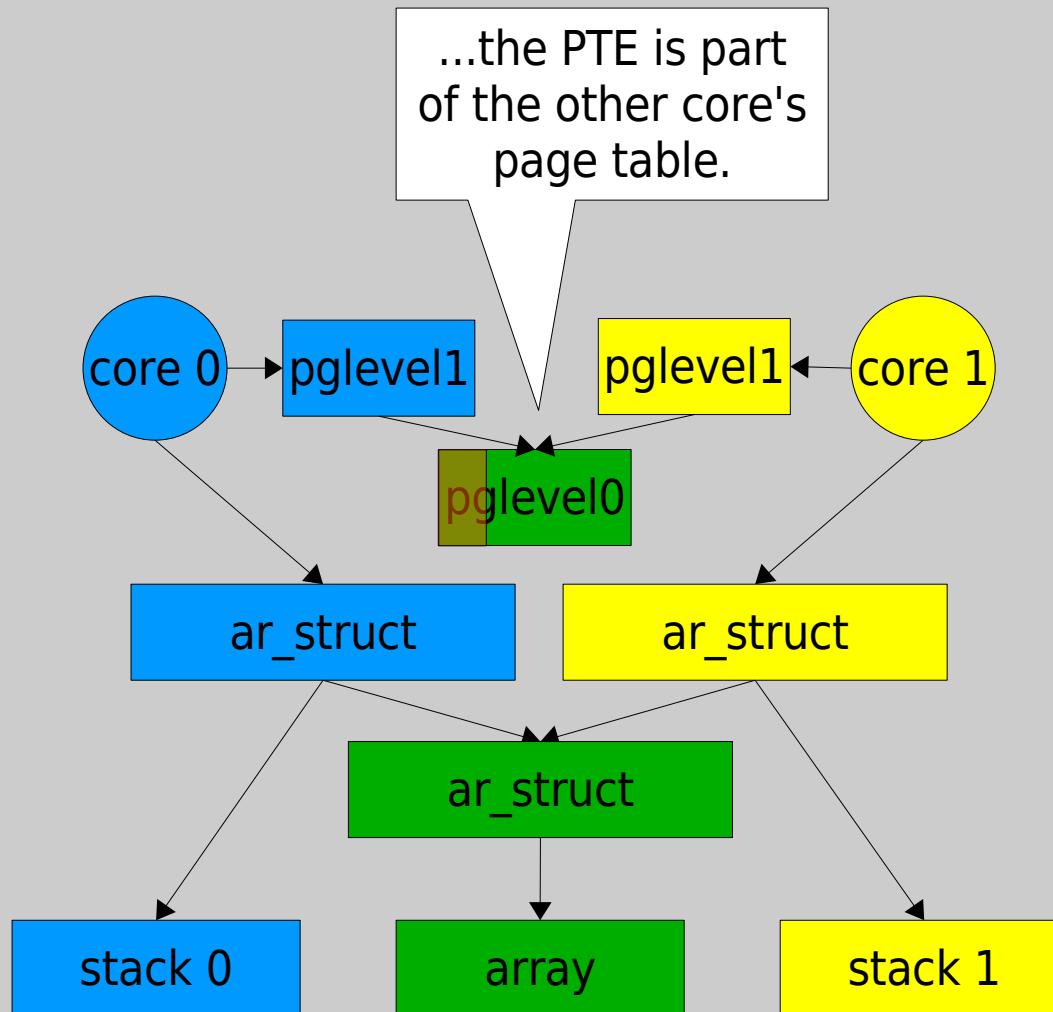
Address ranges: share PTEs



Address ranges: share PTEs



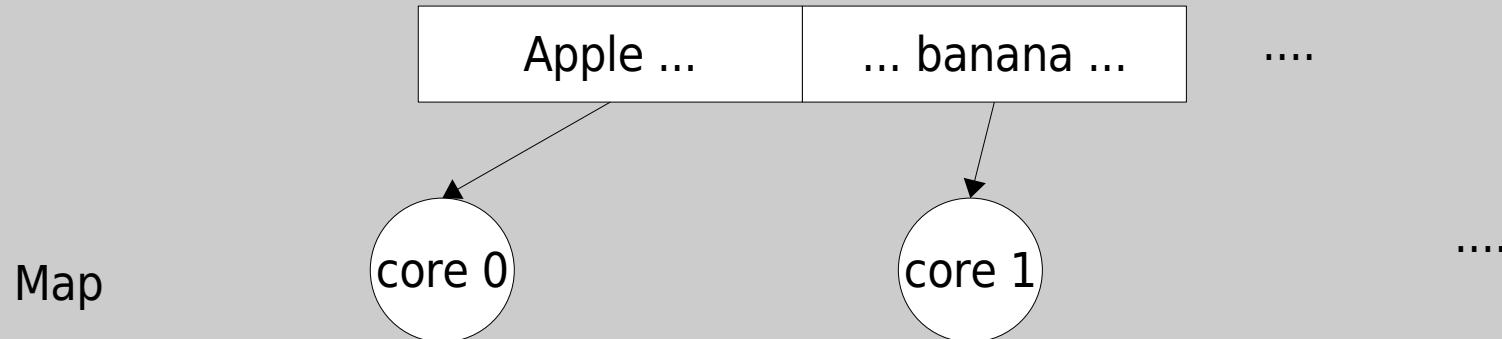
Address ranges: share PTEs



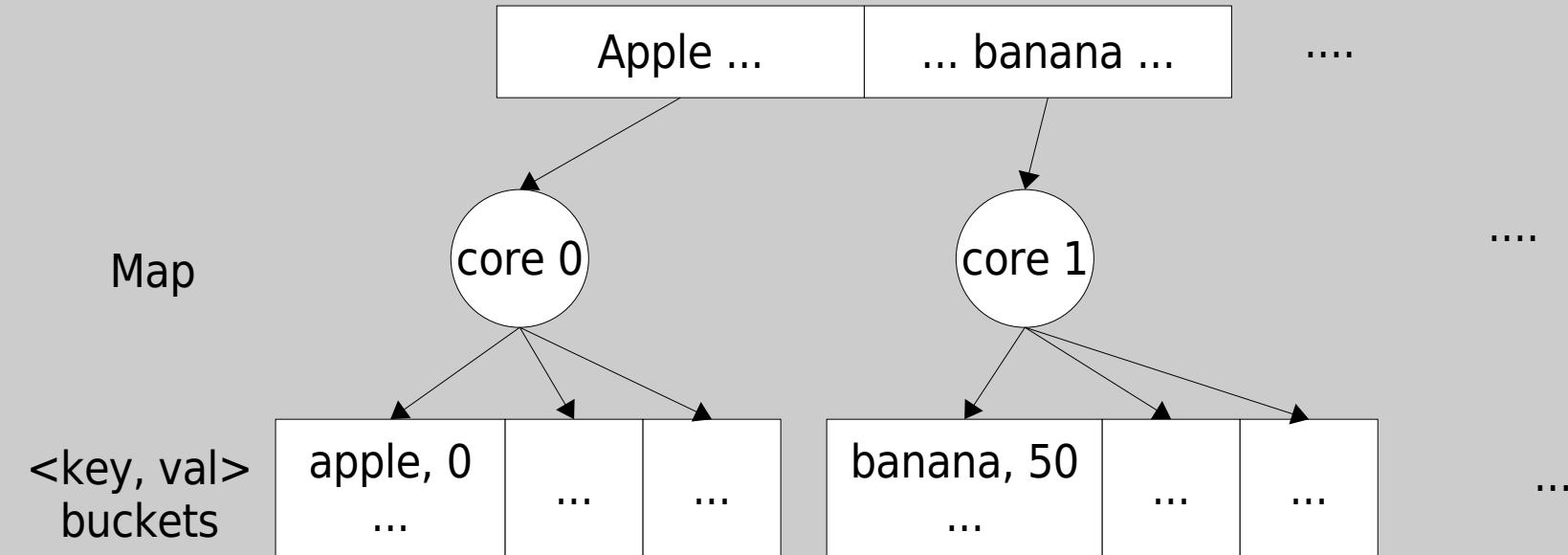
Address ranges good for complex memory sharing patterns

- Typical applications have more complex memory sharing patterns
 - Not just global or private
 - Example: MapReduce library designed for multicore

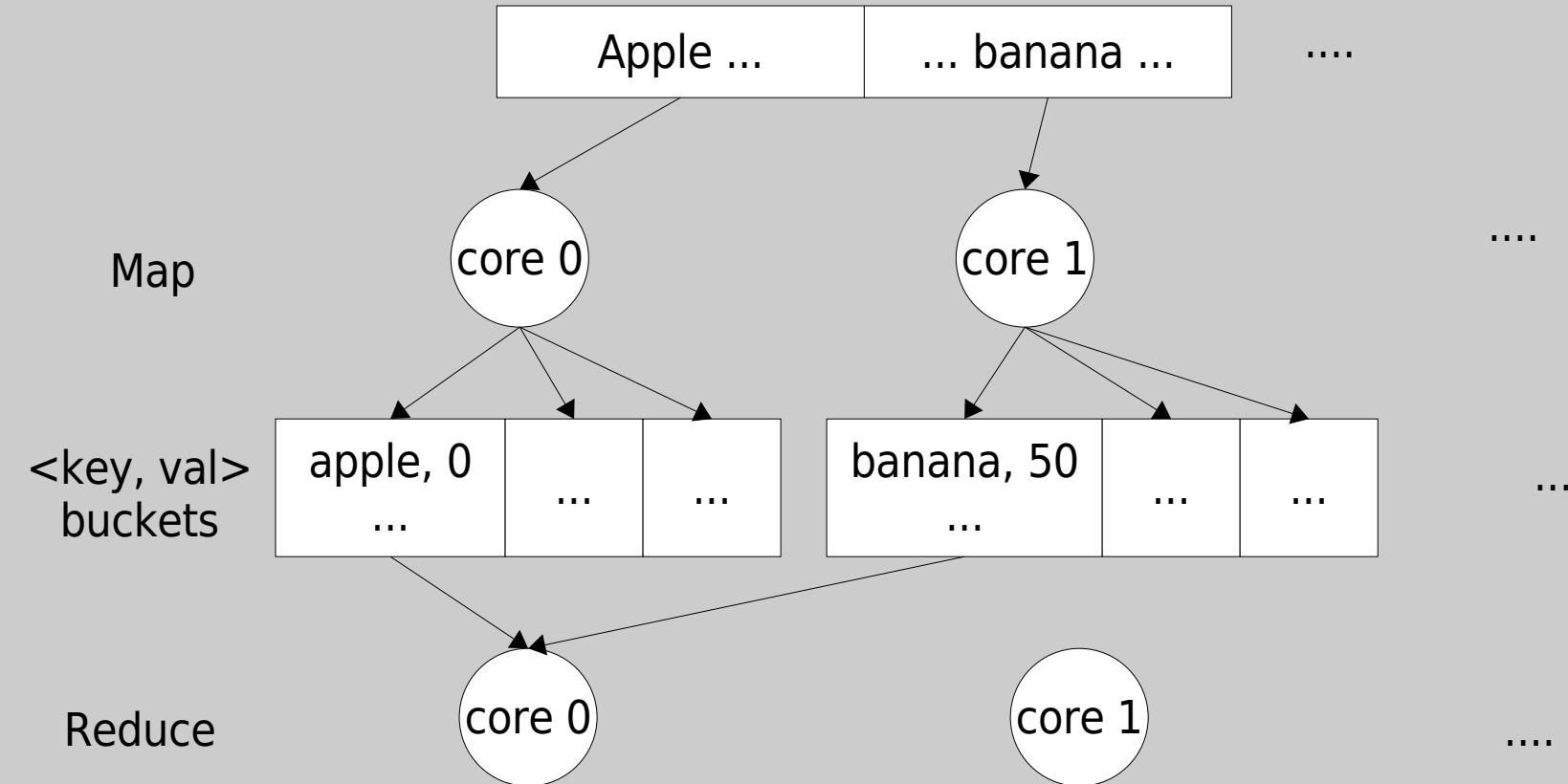
Inverted index with MapReduce



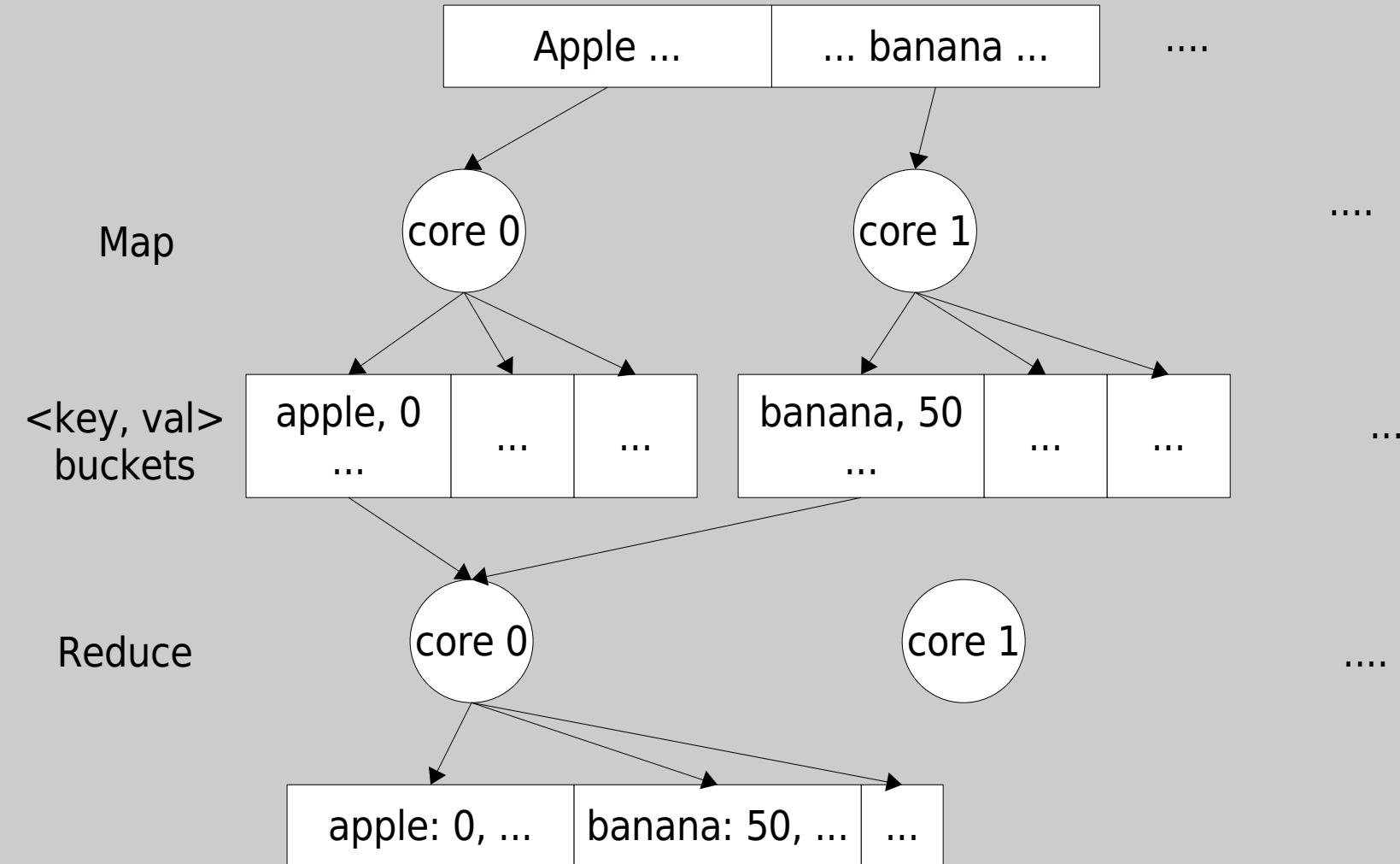
Inverted index with MapReduce



Inverted index with MapReduce



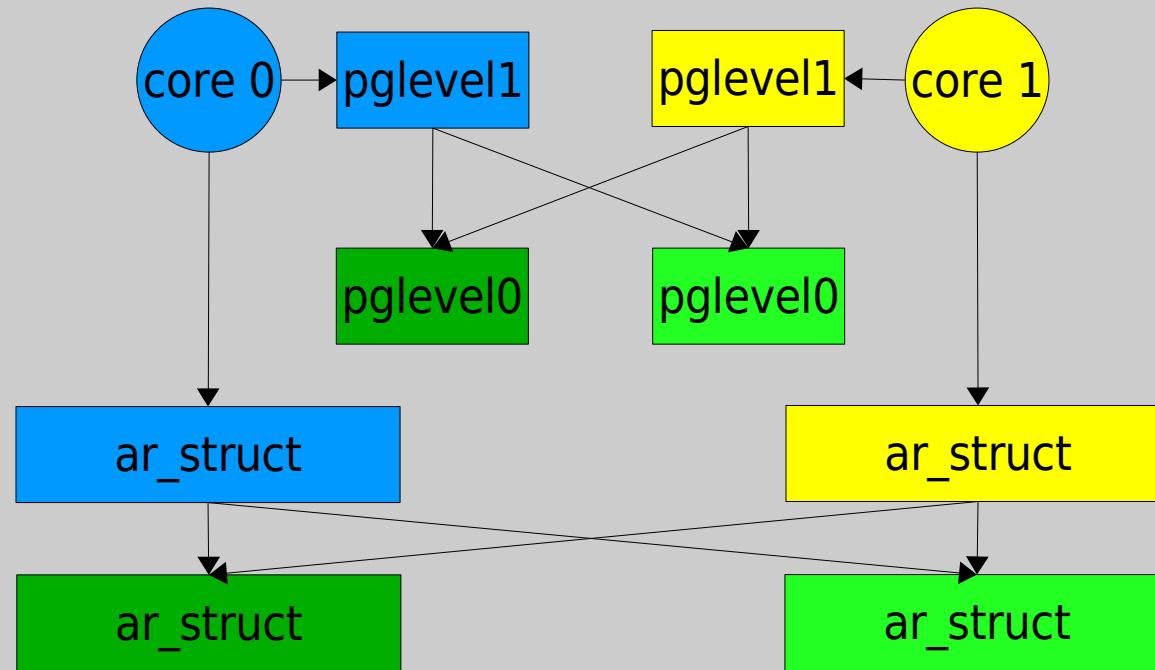
Inverted index with MapReduce



MapReduce sharing goals for kernel data structures

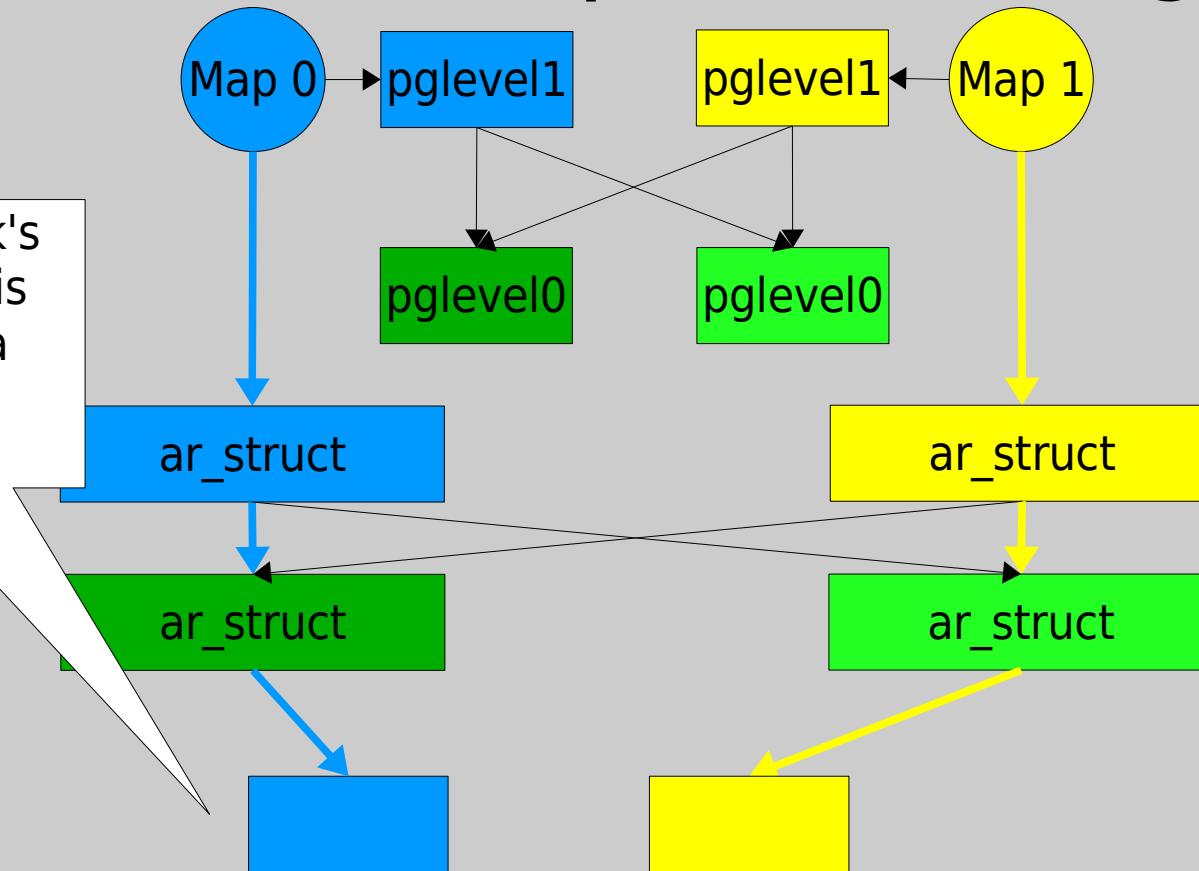
- No contention when growing the address space during Map
 - No contention in the mm_struct/ar_struct
- Share PTEs between Map and Reduce

Address ranges meet the goals



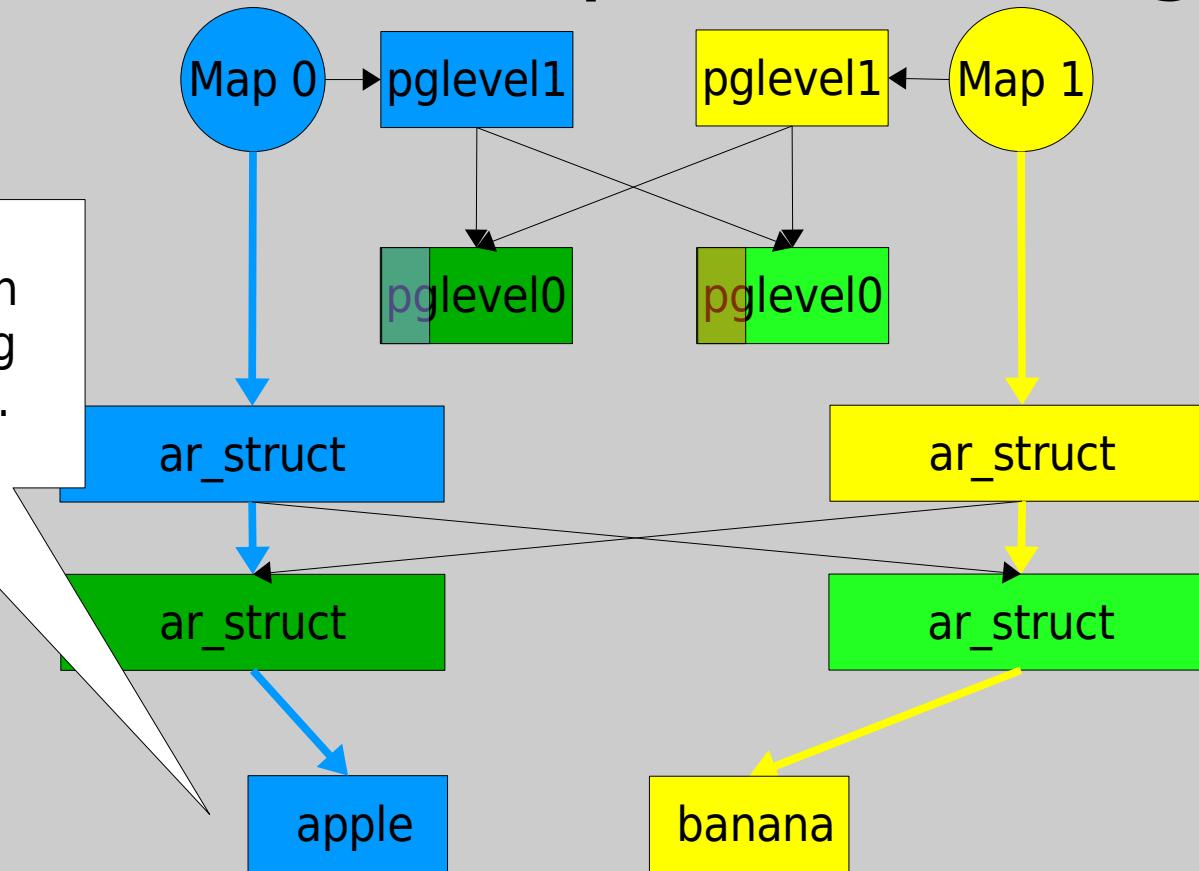
Avoids contention when growing the address space during Map

Each Map task's bucket array is mapped by a different ar_struct.



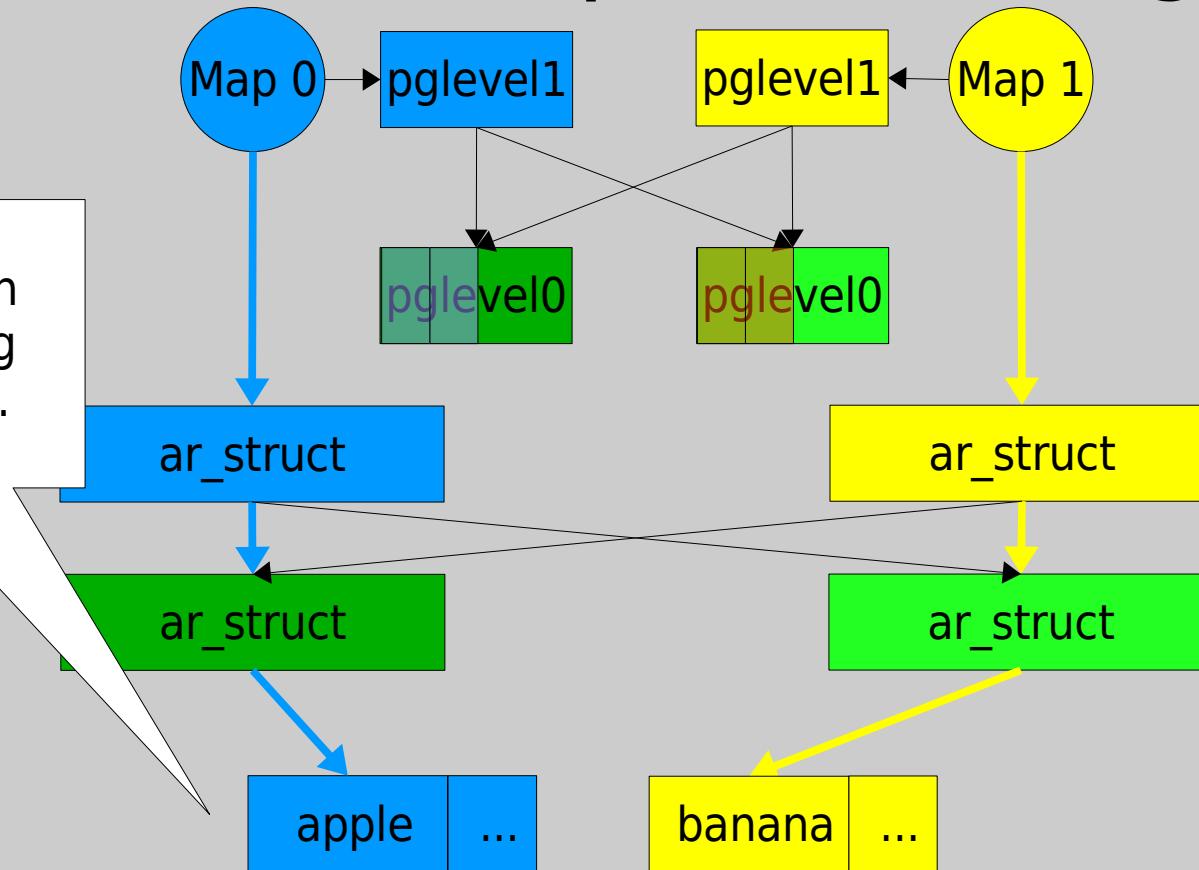
Avoids contention when growing the address space during Map

No contention while growing bucket array.



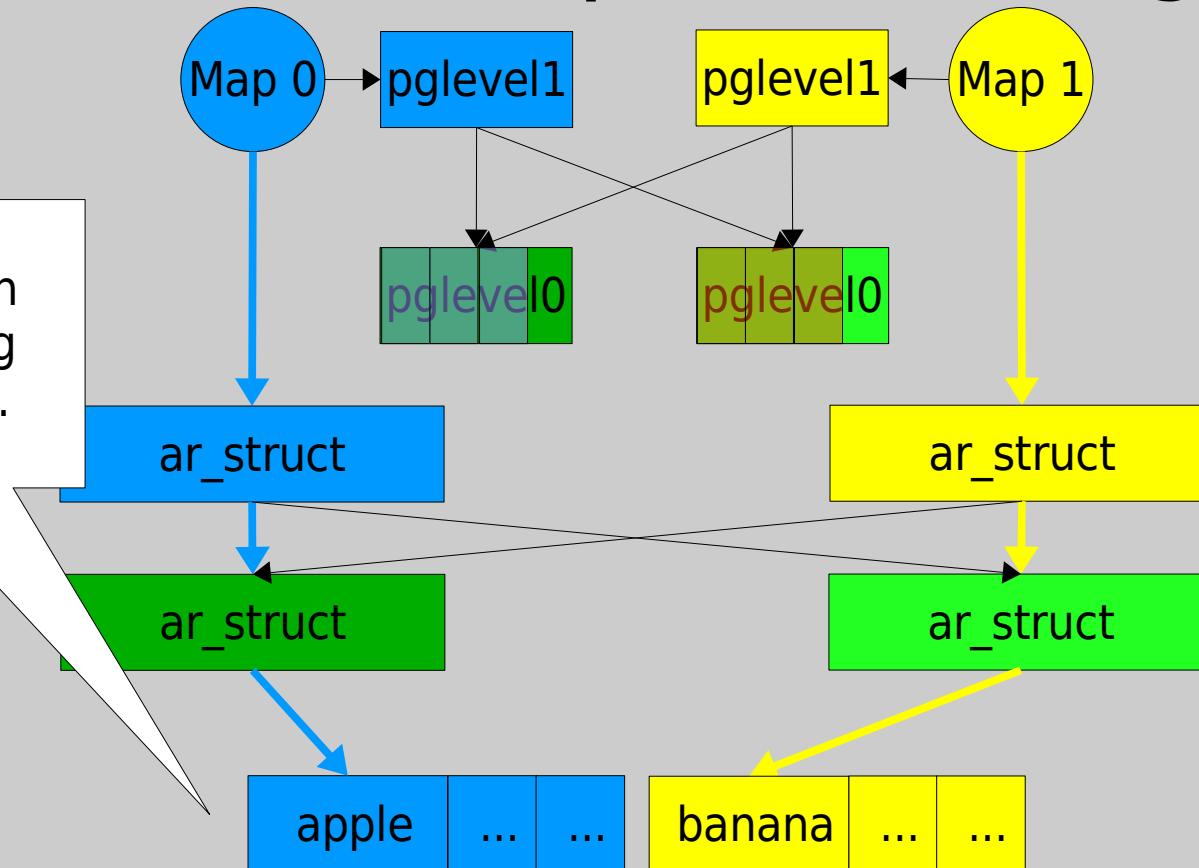
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No contention while growing bucket array.

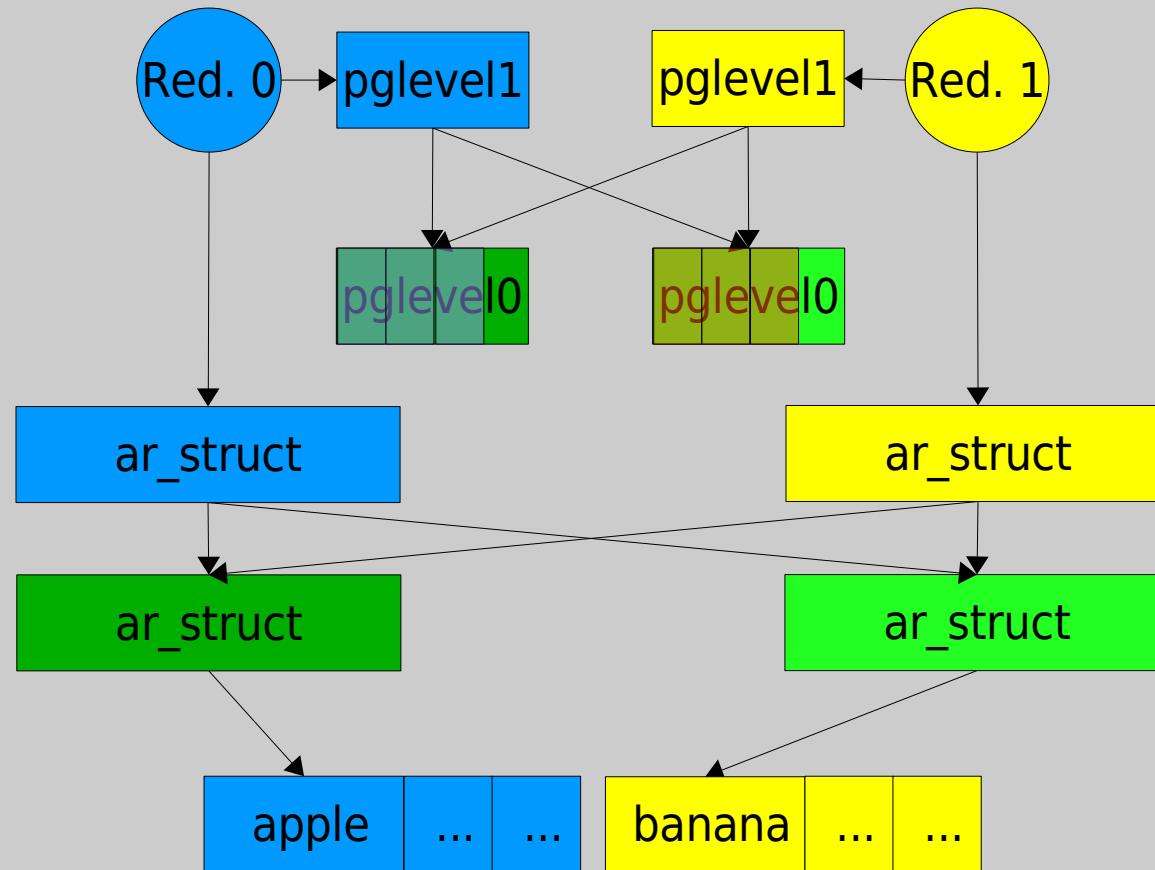


Avoids contention when growing the address space during Map

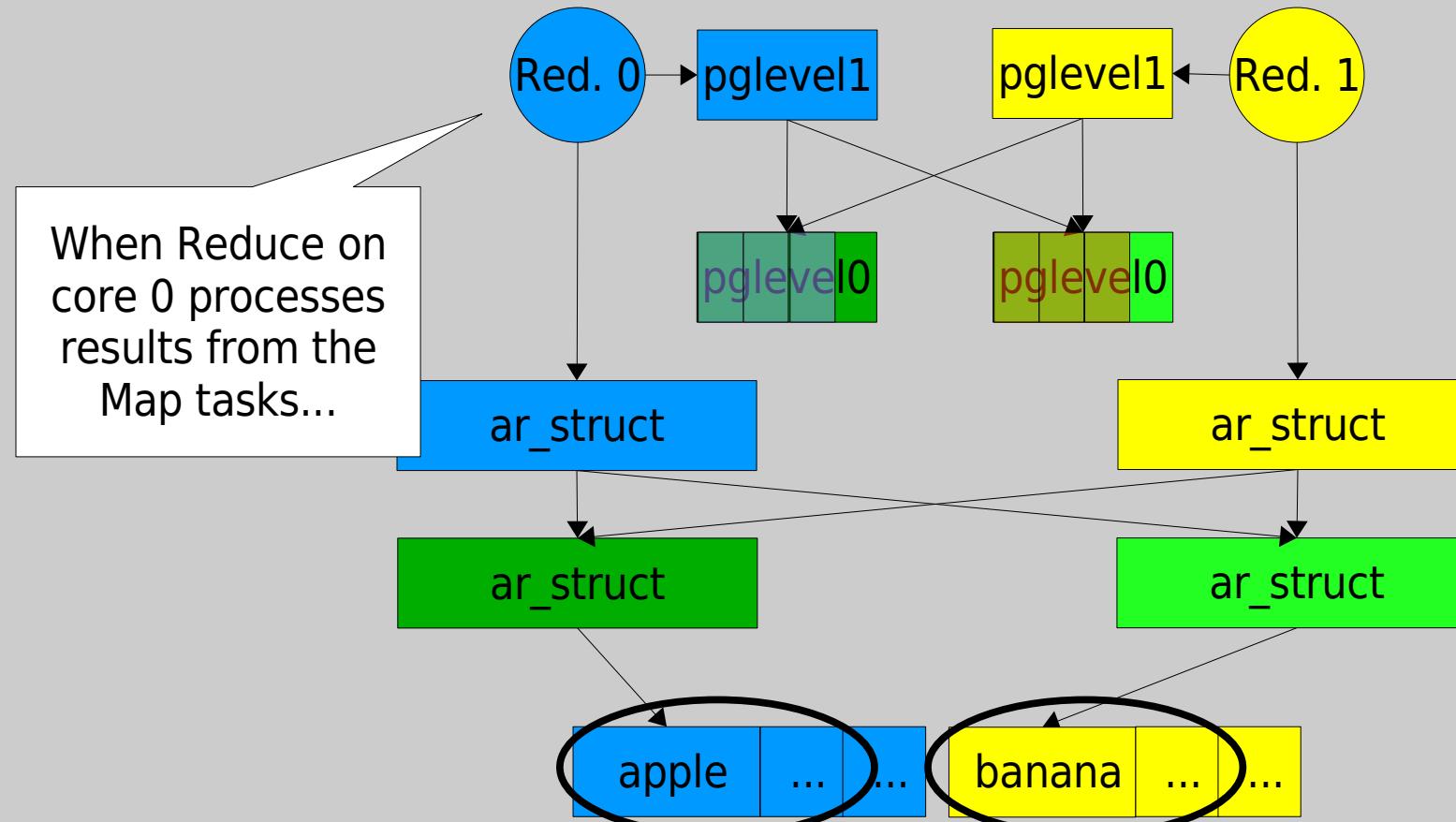
No contention while growing bucket array.



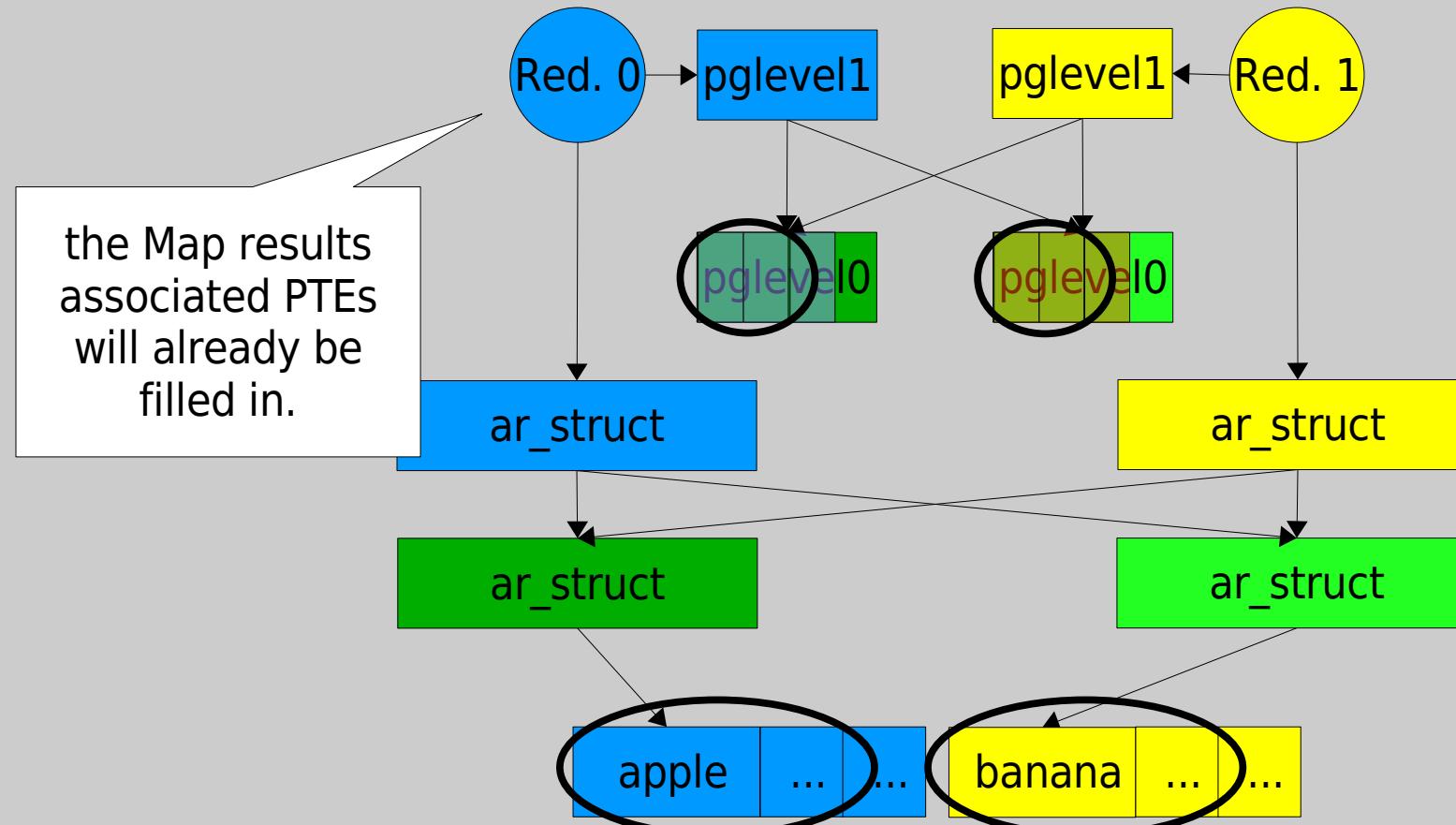
During Reduce PTEs are shared



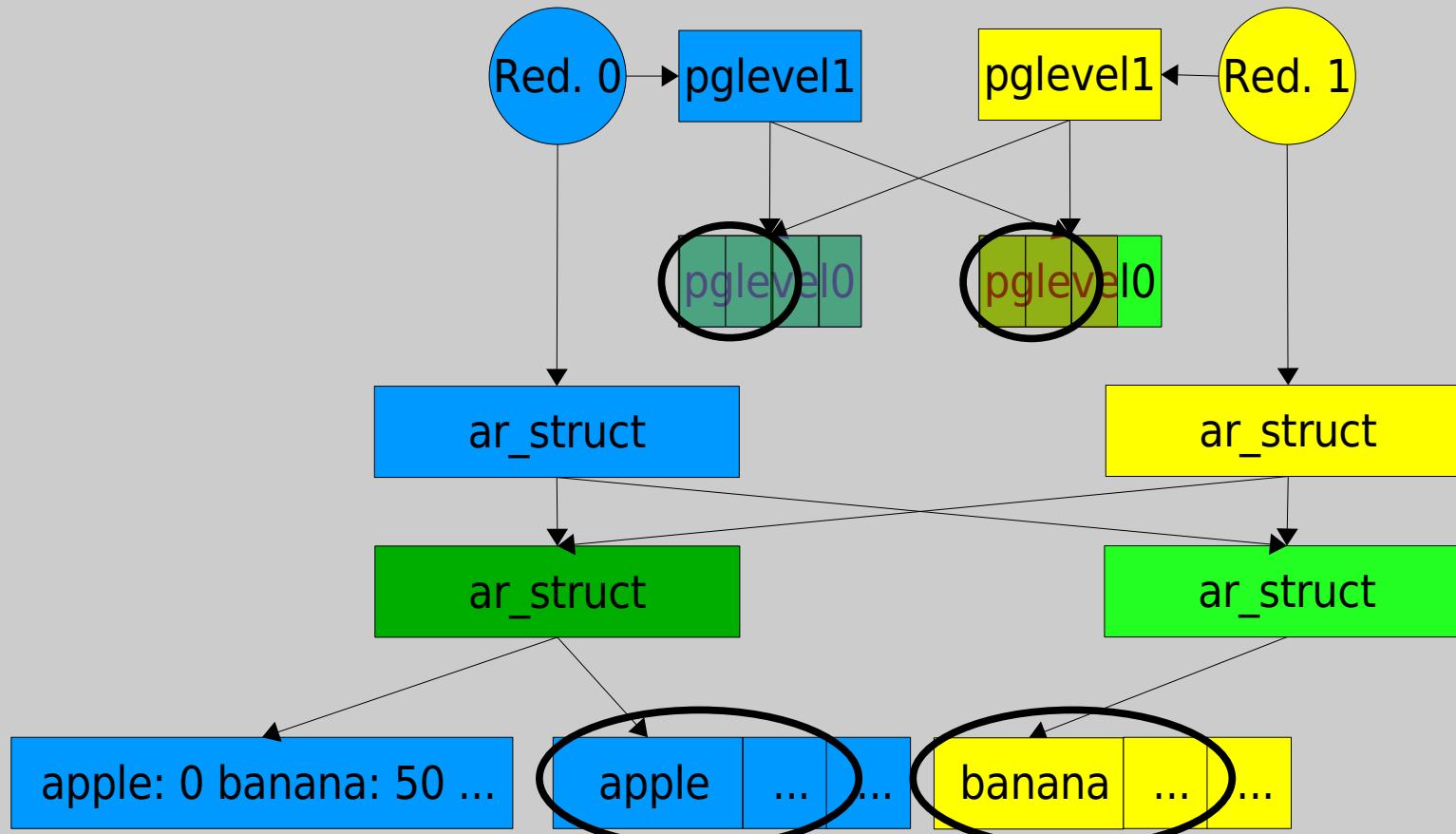
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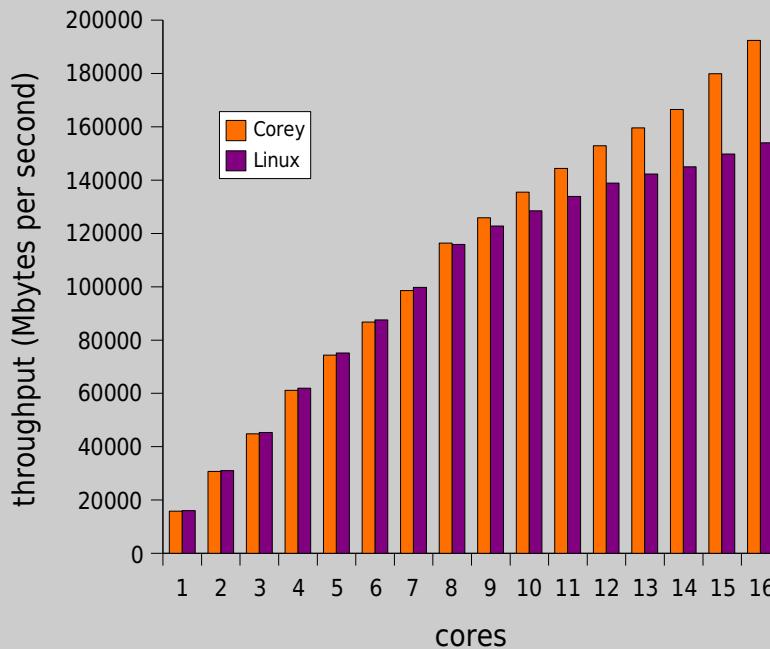
Address ranges in Corey

- Corey is a small experimental OS
- Low-level kernel interface for mapping memory and address ranges
- MapReduce uses Corey's user-level malloc

MapReduce application

- Word inverted index
- Measured the time to build the index of a 1Gbyte file
- For Linux, shared address space is faster than private address spaces
 - Fewer soft page faults

MapReduce reverse index results



- For Linux cores contend on `mm_struct`
 - Linux page fault handler is faster than Corey's
- With address ranges there is no contention

Benefit of address ranges

- Able to avoid contention, but able to share what is necessary
- Applications control how cores share internal OS data structures
- Few application modifications to improve scalability

Related work

- Research on NUMA operating systems.
 - K42 and Tornado: clustered objects
 - Disco and Cellular Disco on Flash: “distributed kernel”
- Research on multicore:
 - Linux performance studies
 - McRT
 - Barreelfish
 - Thread clustering, constructive caching
- KeyKOS segments

Future work

- Finish Linux interface changes
 - Other interface changes
 - Bigger workloads
 - How much does OS interface need to change?
- Use caches better
 - Reduce cost of manipulating shared data
 - Large aggregate cache, small per-core caches
 - Kernel cores help

Summary

- New OS interfaces that help applications scale with the number of cores
- Allow applications to control how cores share kernel data structures
 - Avoid contention from unnecessary sharing
 - Share state when its beneficial

