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

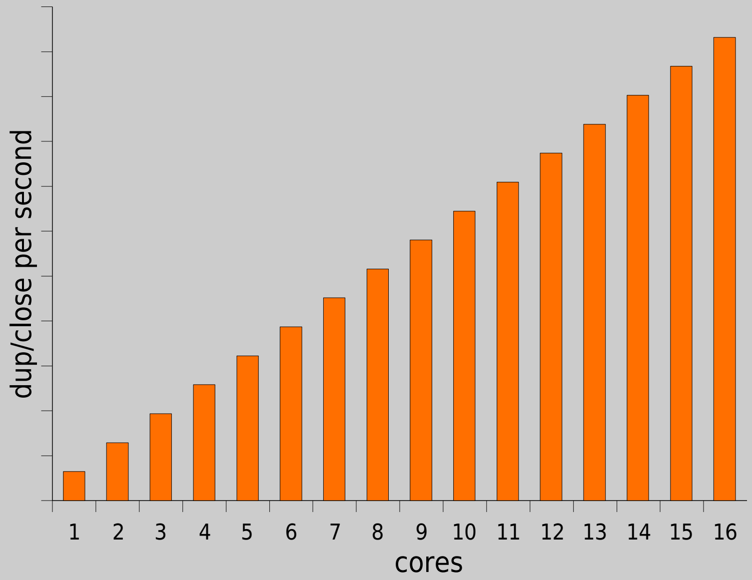
Object naming in an OS

- 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

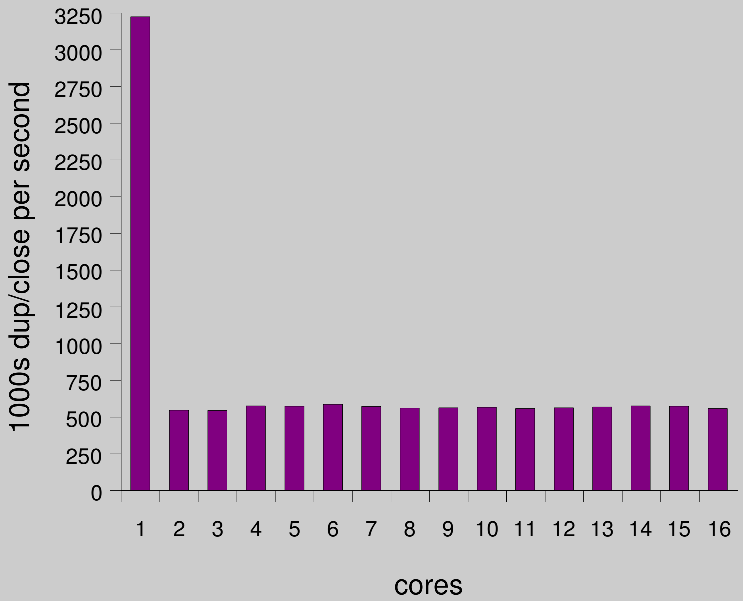
- Shared kernel data structure: file descriptor table
- Measure the cost of using FD table
  - Threads dup-and-close a per-thread FD
  - 16 core AMD Opteron running a Linux 2.6.27

Ideal FD performance graph



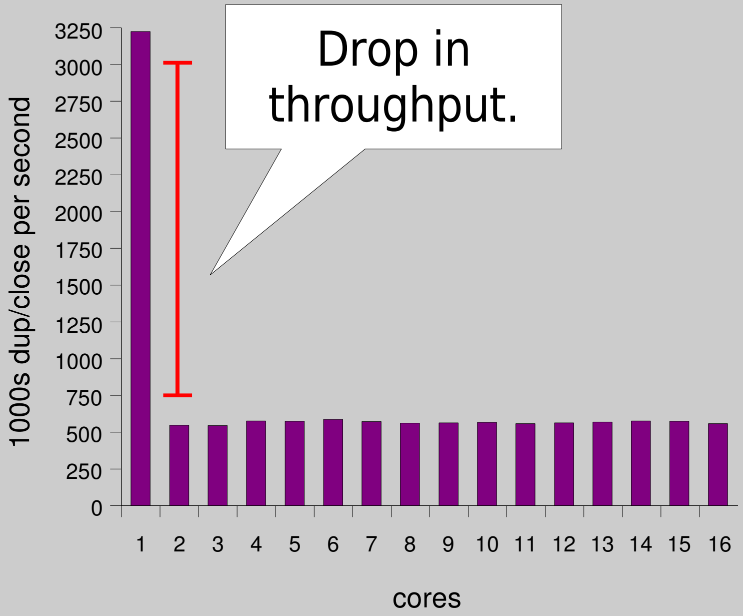
- Expect throughput to scale linearly

Actual FD performance



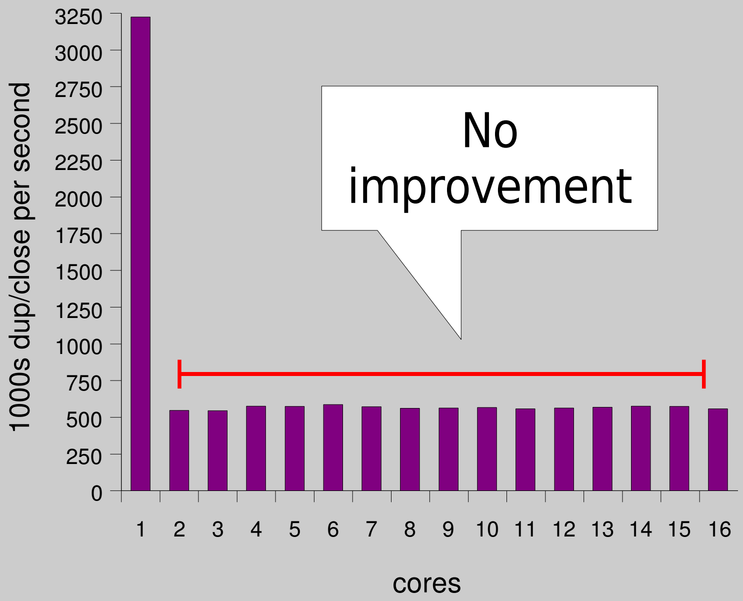
- Notice two things:

Actual FD performance



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

Actual FD performance



- Notice two things:
  - Drop in throughput.
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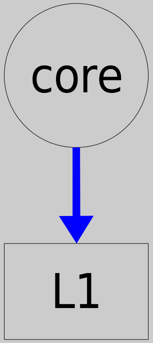
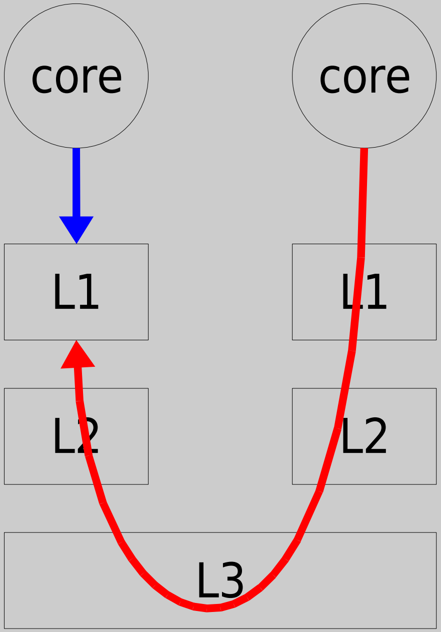
Why throughput drops?




```
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?

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}
```

- 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 is application has a mixture

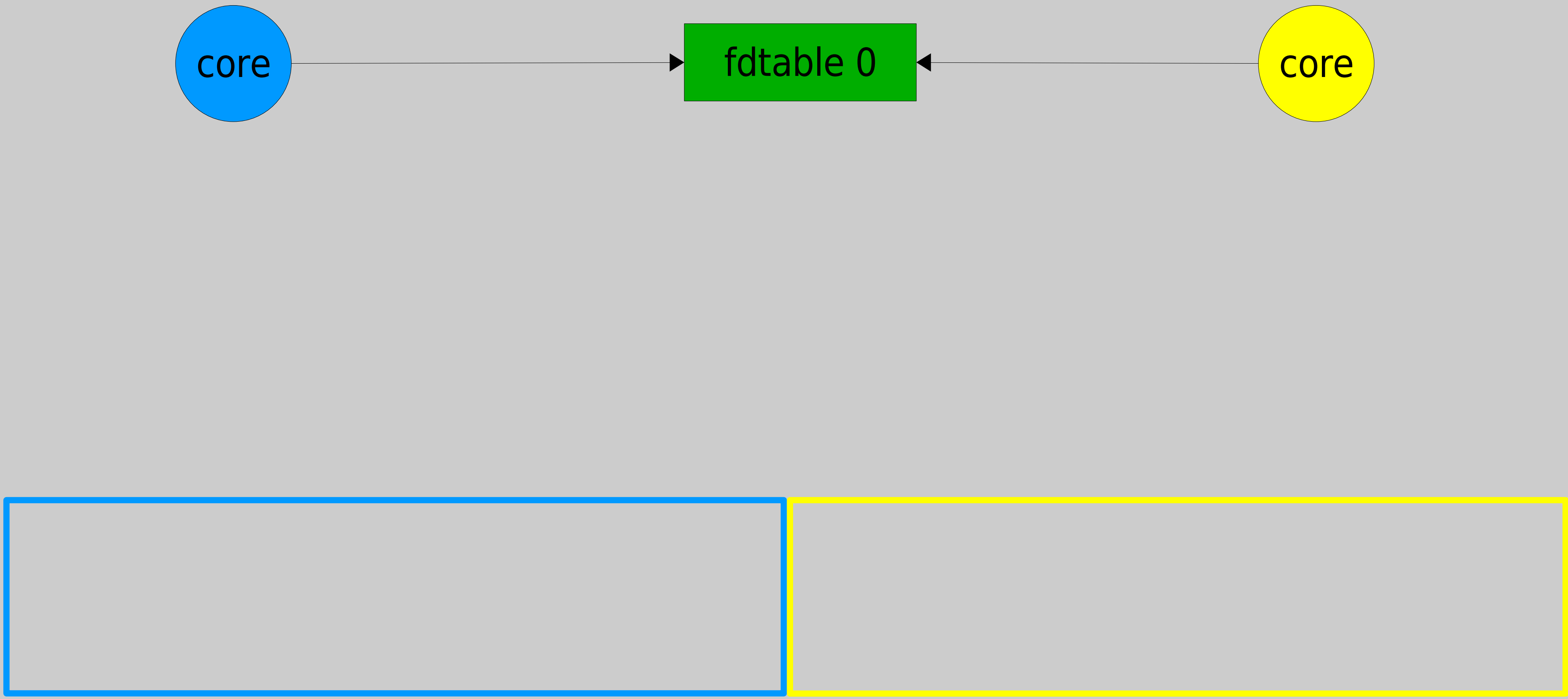
Our solution: shares

- **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

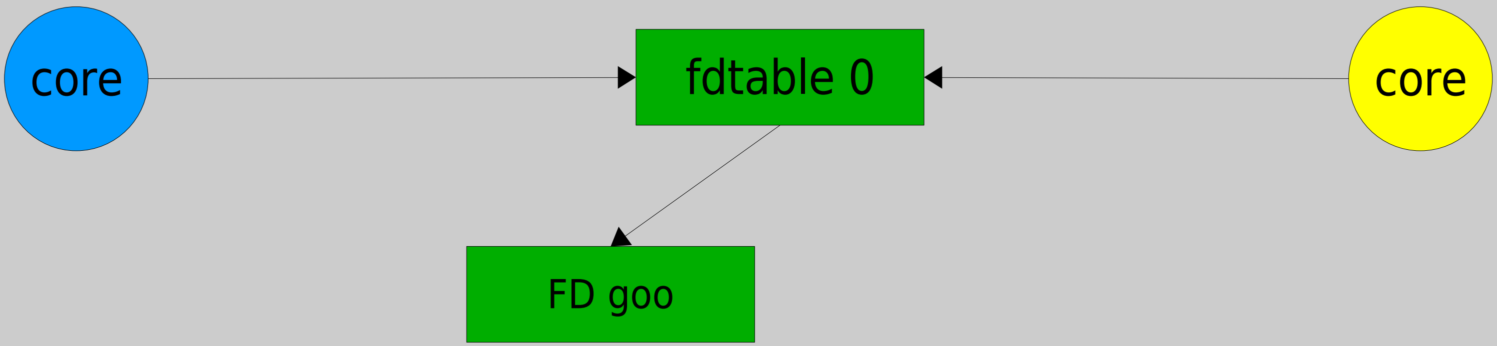
Adding shares to Linux

- 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

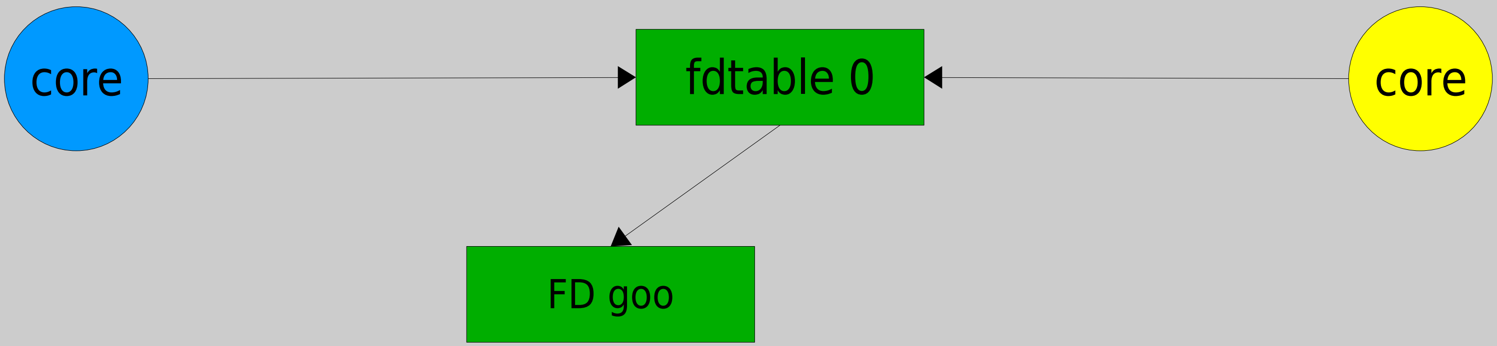


Linux FD share example




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

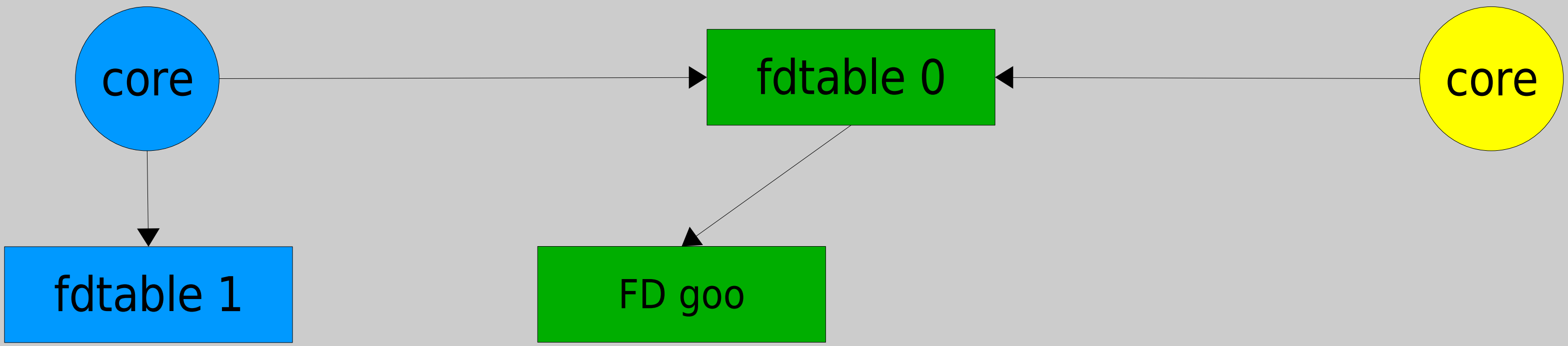
Linux FD share example




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

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

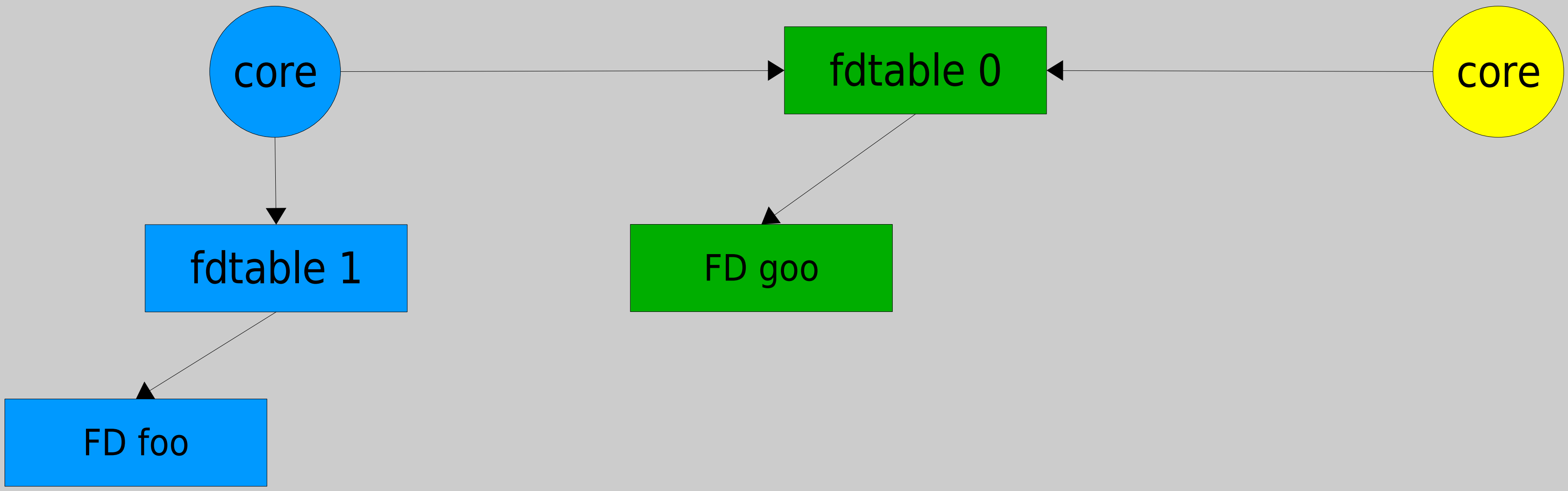
Linux FD share example




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

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

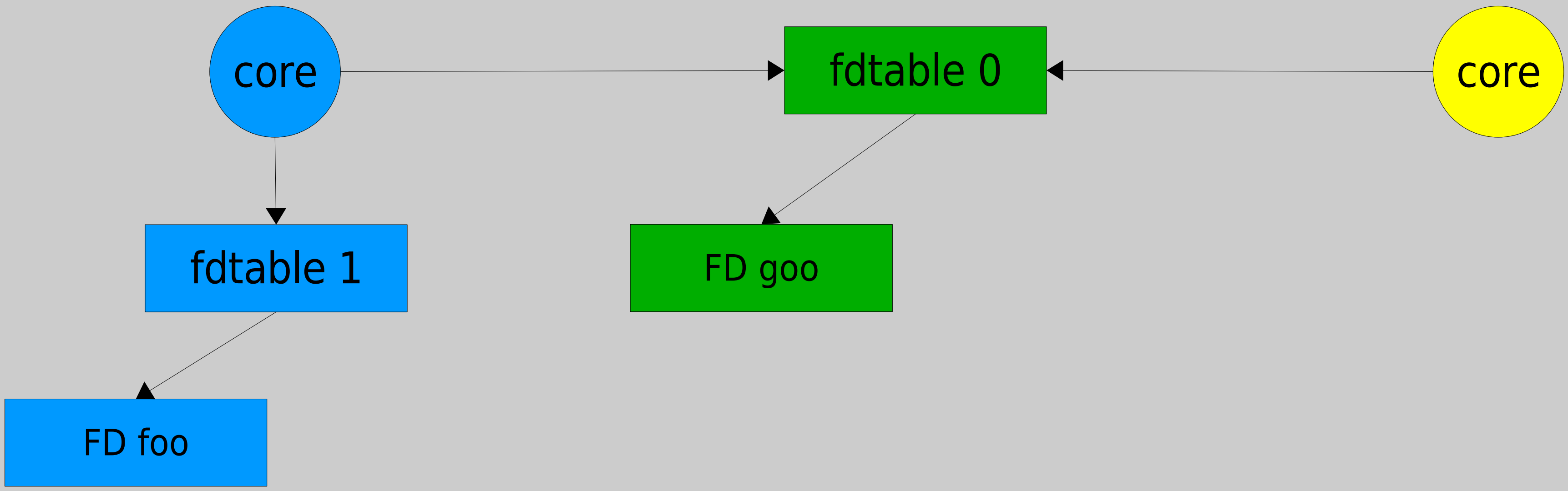
Linux FD share example




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

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

Linux FD share example

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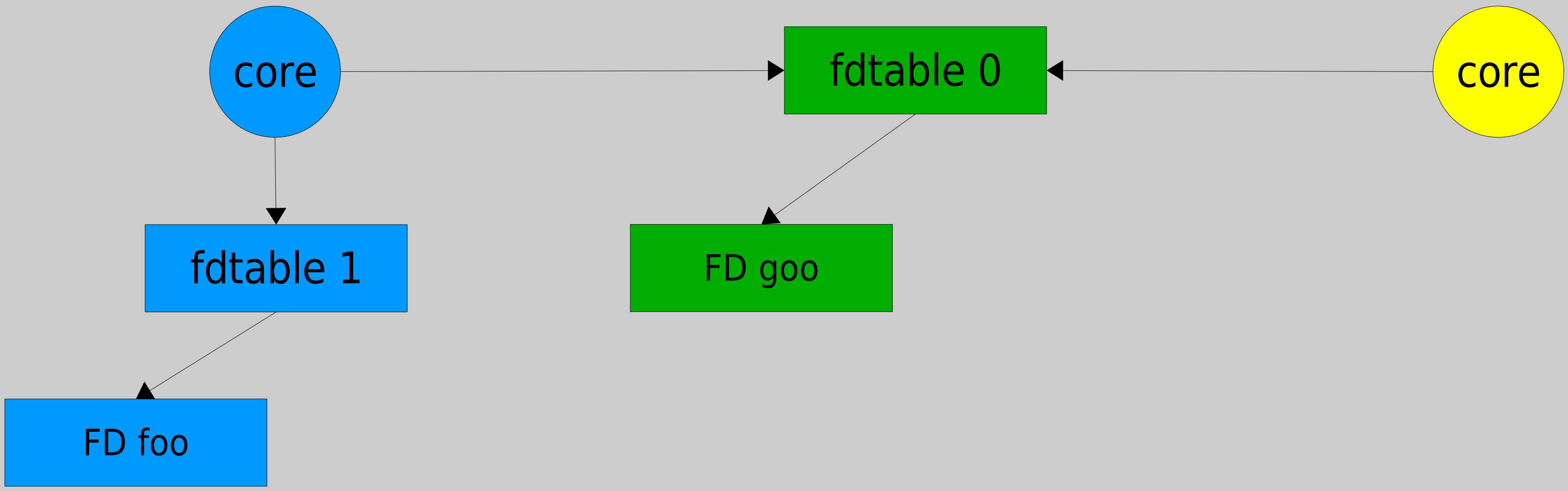


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```
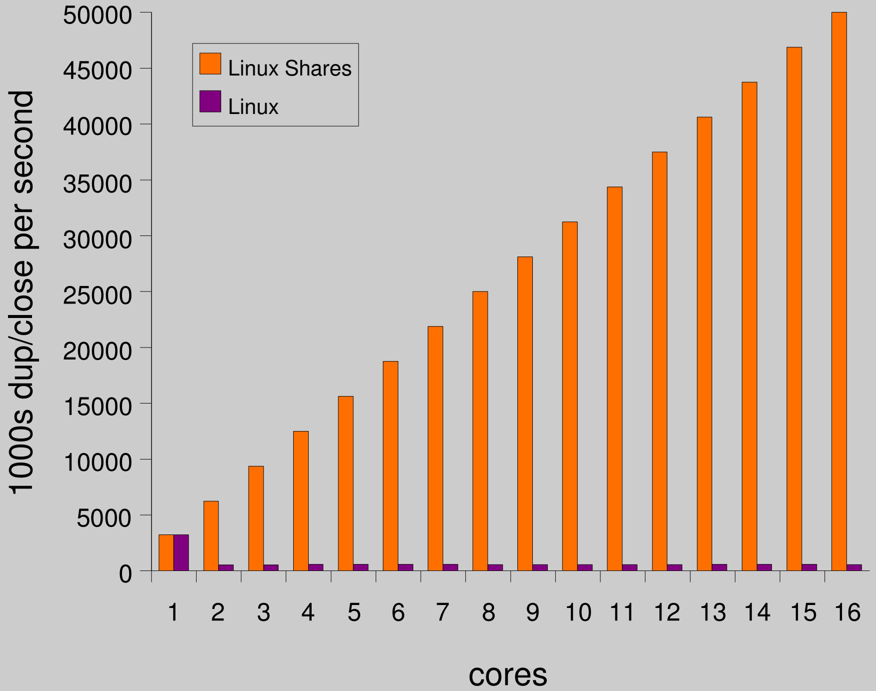

```
write(fd2, buf, 128);
```

- 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

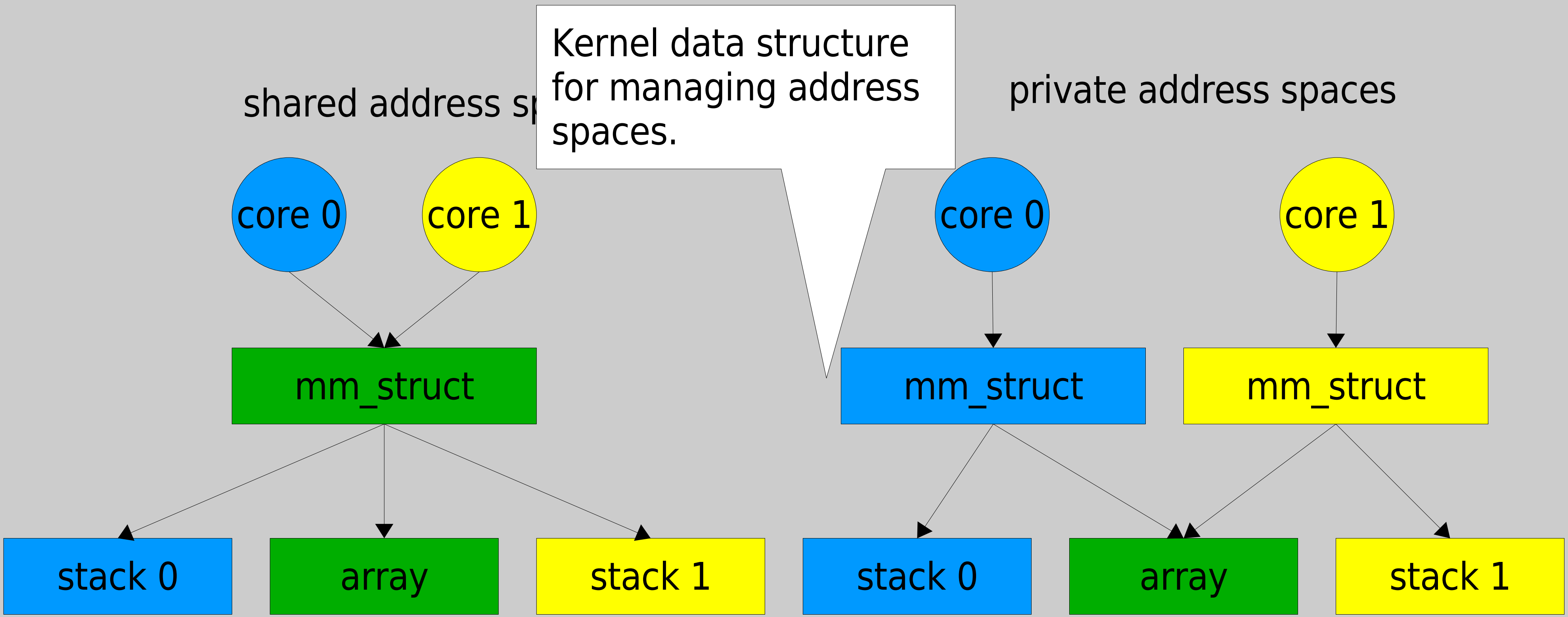
- Able to avoid unnecessary contention on kernel data structures
  - For example when application threads do not share FDs
- Applications can control how cores share internal kernel data structures
- Few kernel and application modifications to get scalability

Idea #2: Address ranges

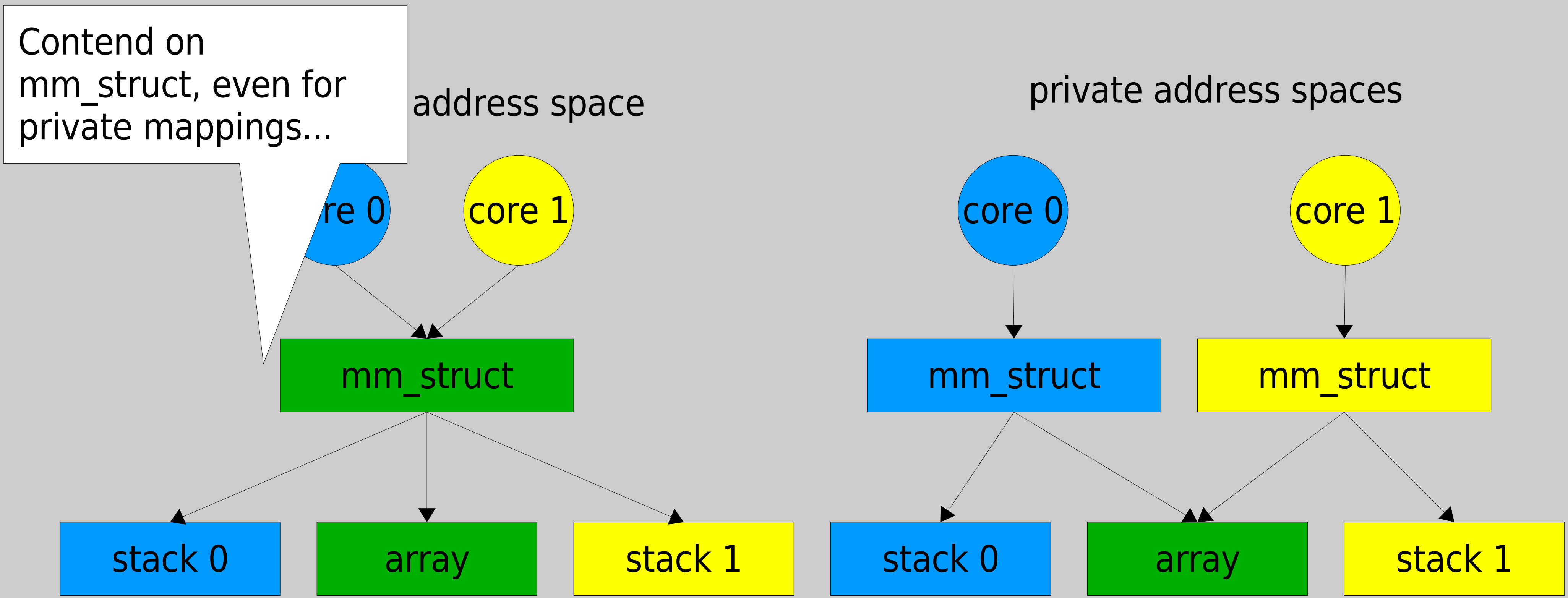
Two options for multiprocessor shared-memory application

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

Cost of two options

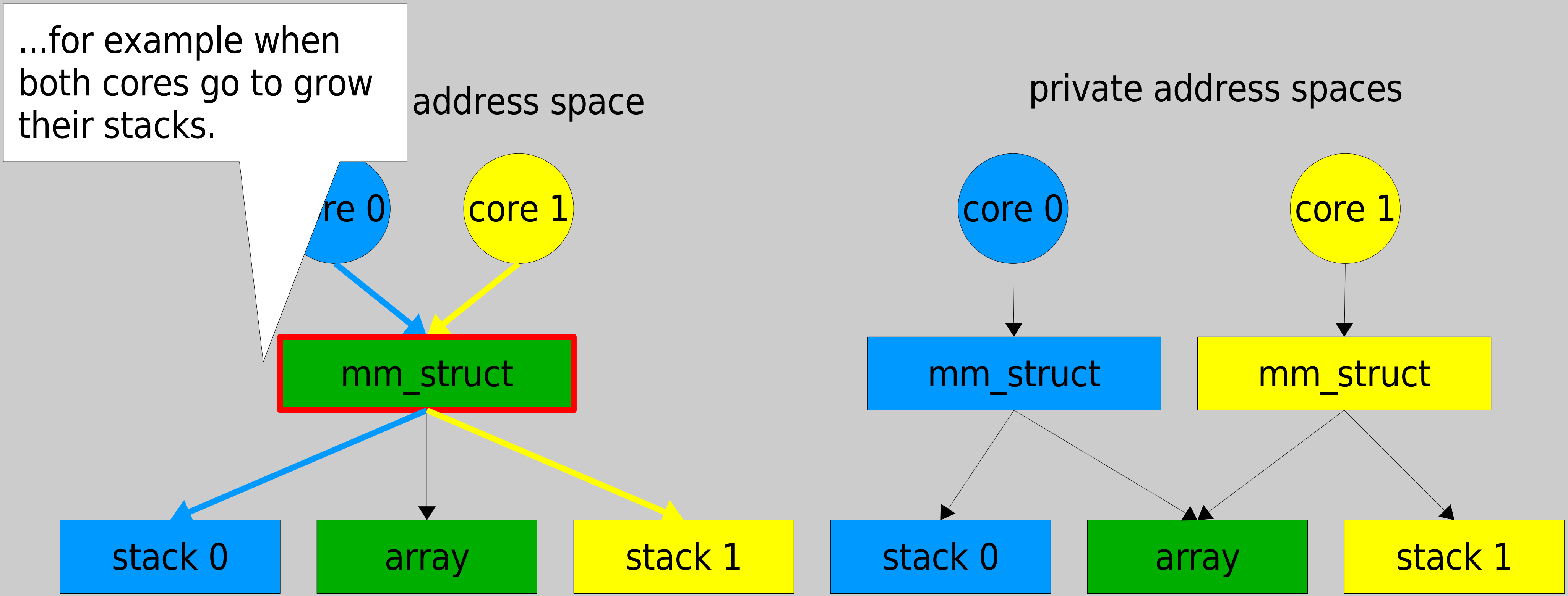


Cost of two options



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

Cost of two options



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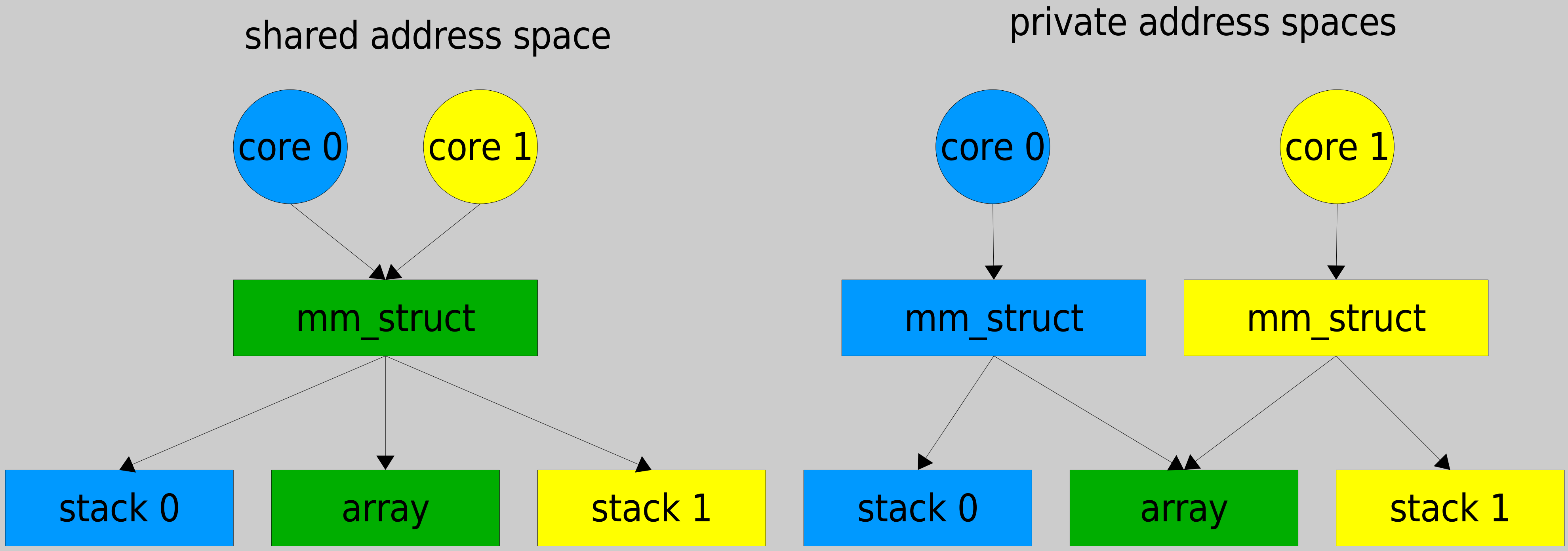
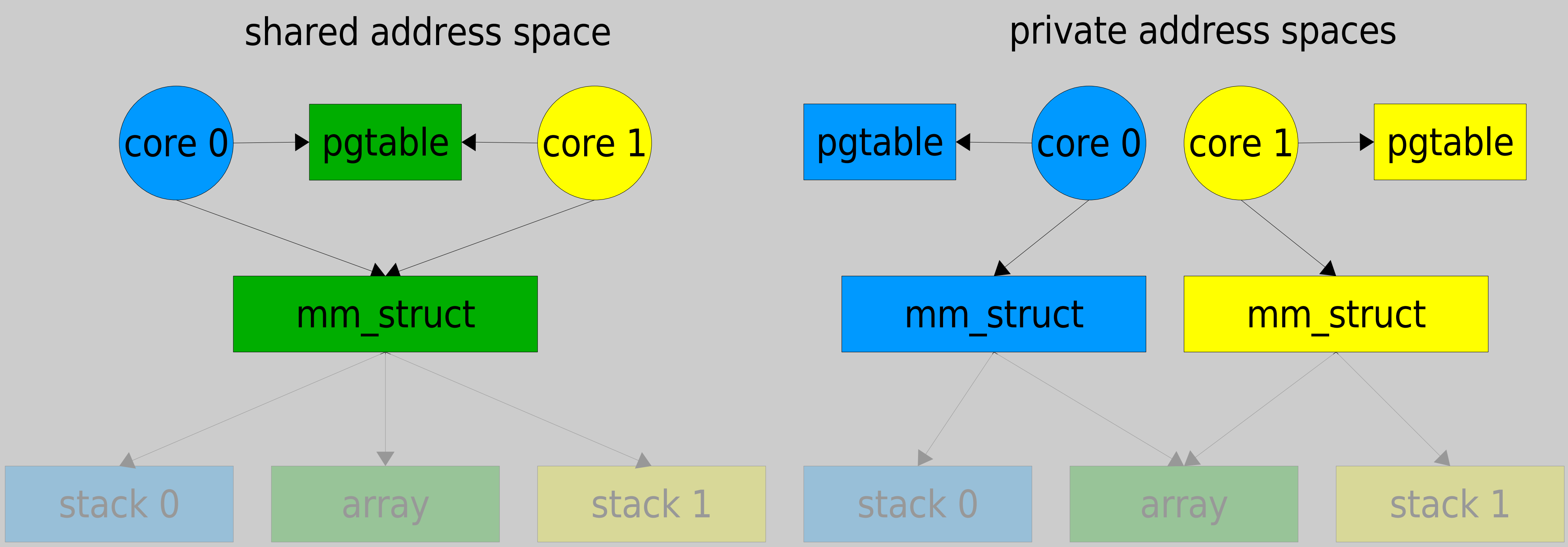


- Contend on mm_struct: locks, counters, lists...
- No contention on mm_struct

More costs: soft page faults

- Linux lazily instantiates page tables



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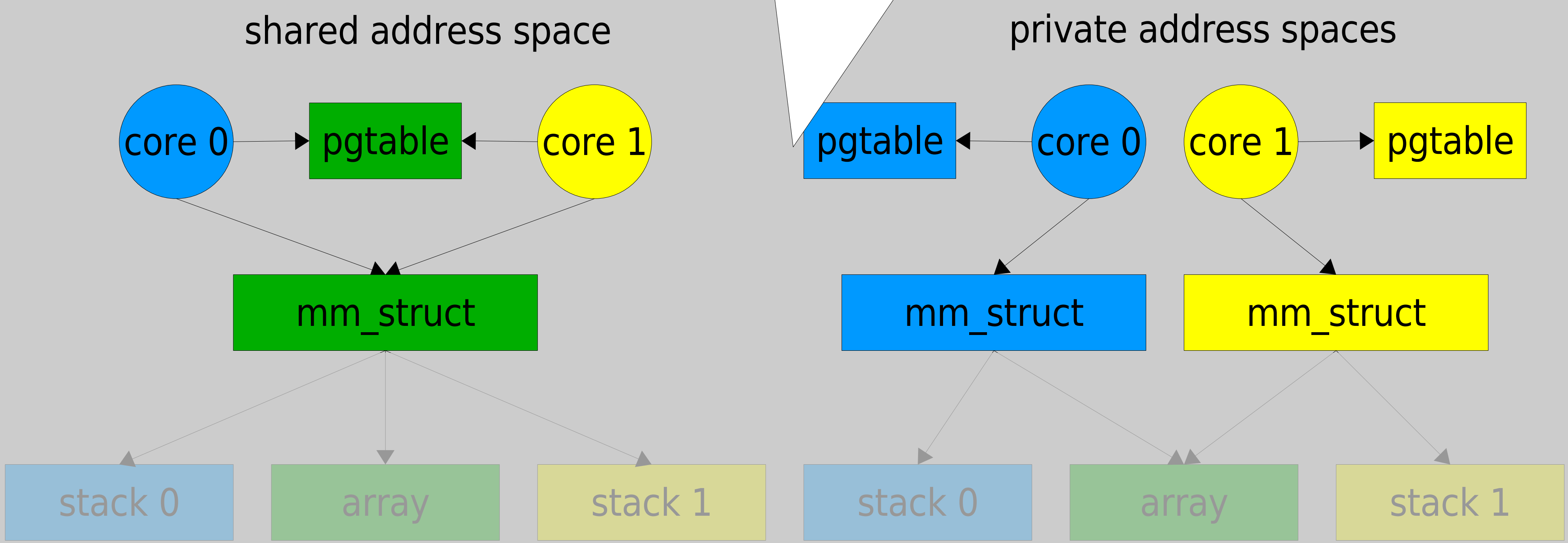
Hardware page table associated with the mm_struct of the same color.



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

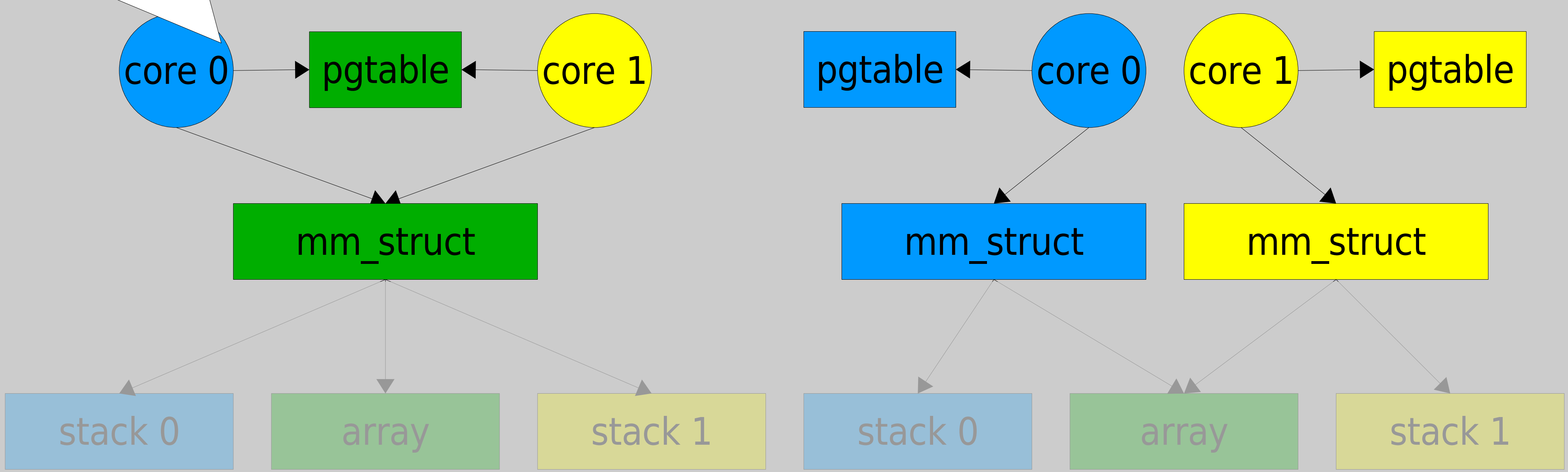
More costs: soft page faults

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

tantiates page tables

pace

private address spaces

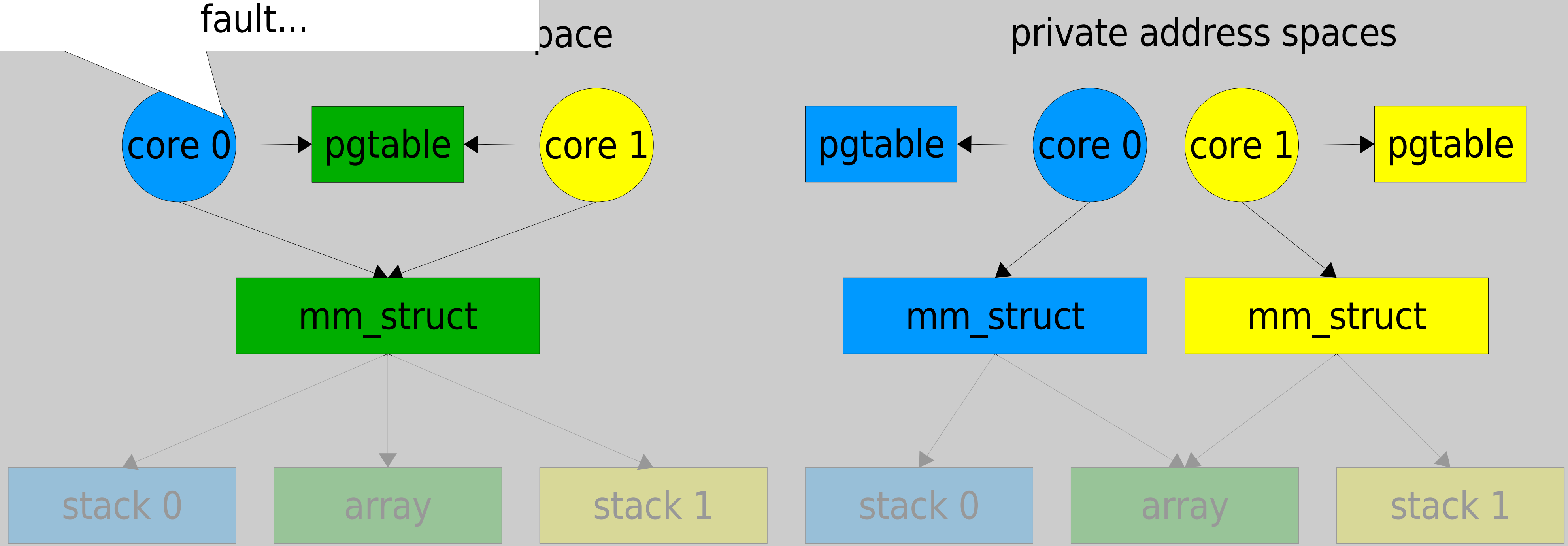


- Contend on mm_struct: locks, counters, lists…
- No contention on mm_struct

More costs: soft page faults

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

tantiates page tables



- Contend on mm_struct: locks, counters, lists...
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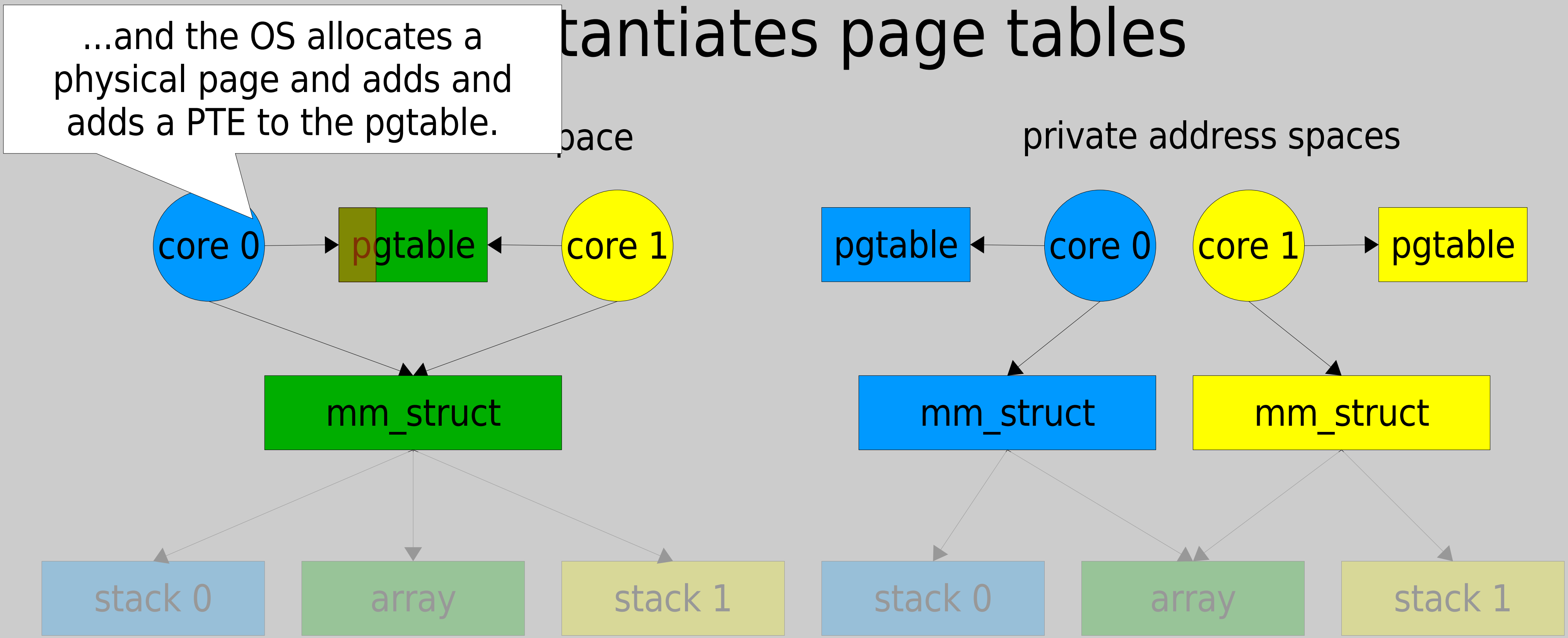
More costs: soft page faults

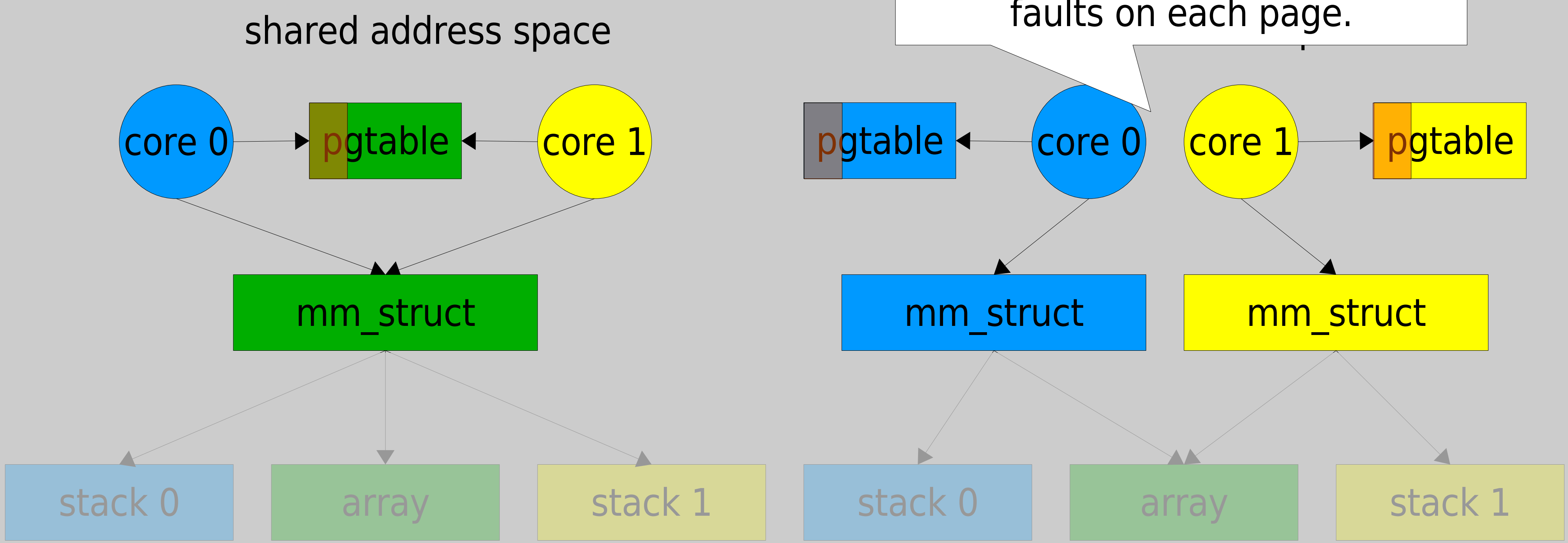


- Contend on mm_struct: locks, counters, lists...
- One soft page fault per page
- No contention on mm_struct

More costs: soft page faults

- Linux lazily instantiates pa

Each mm_struct has a different pgtable, so each core soft page faults on each page.



- 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

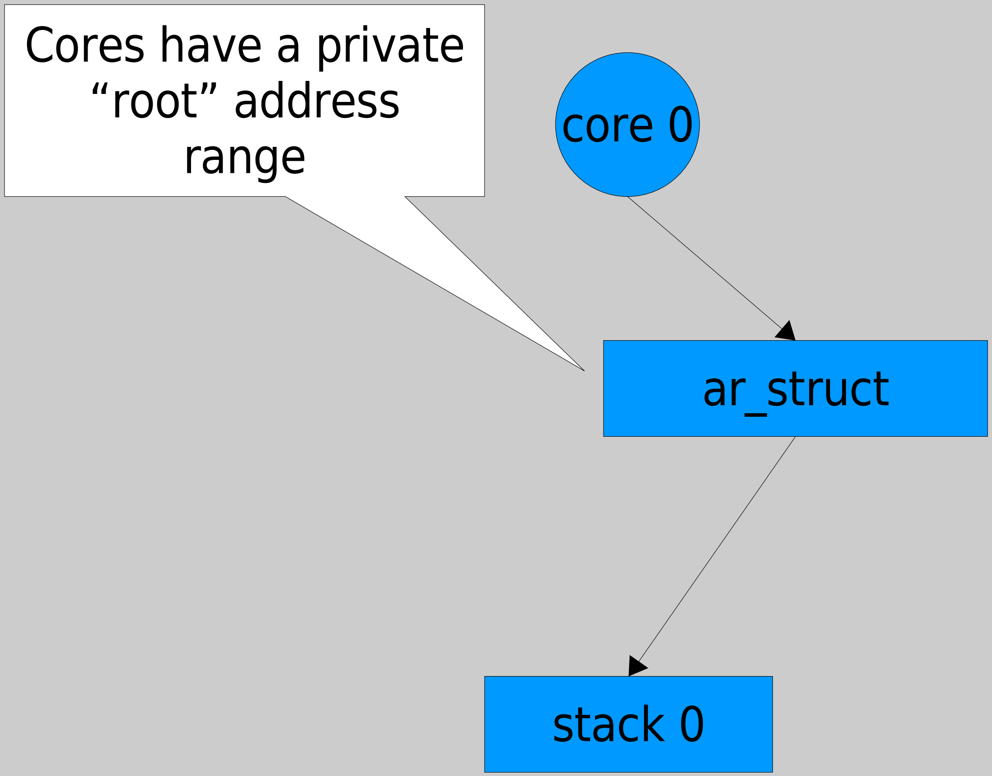
The problem

- 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

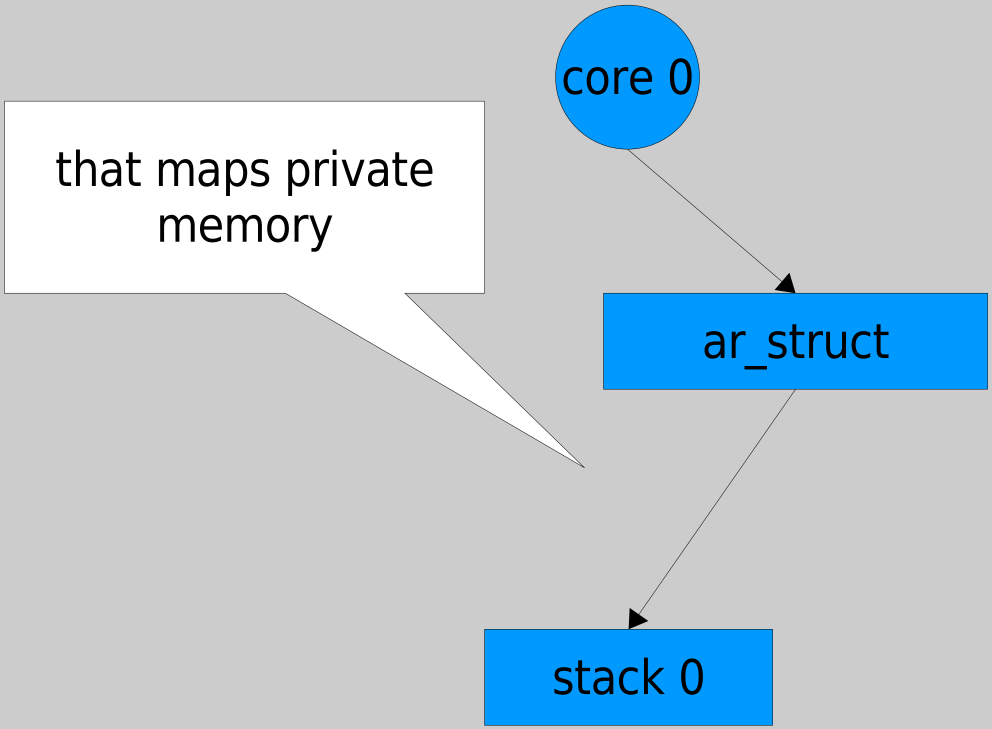
Our solution: address ranges

- **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



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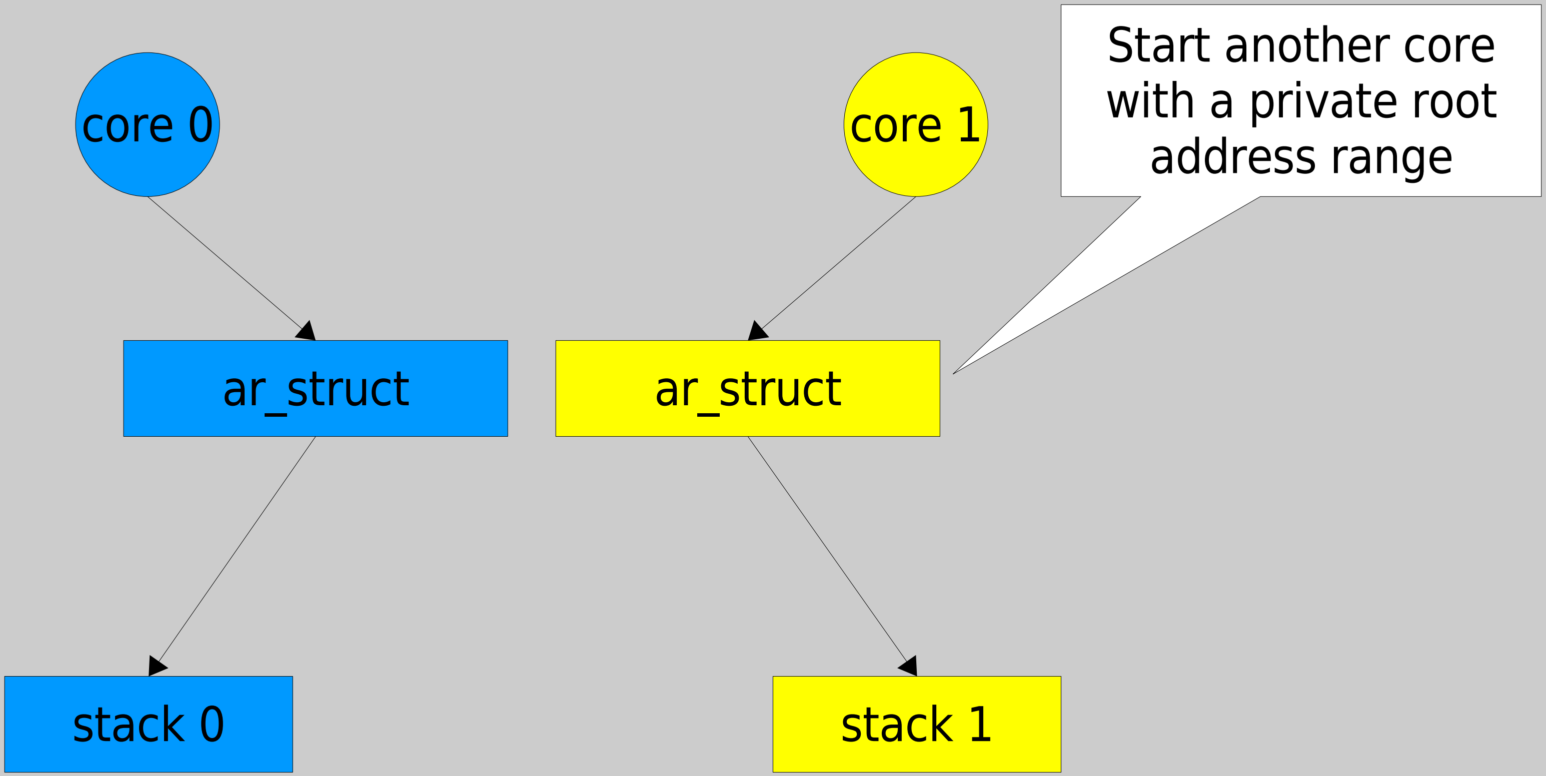

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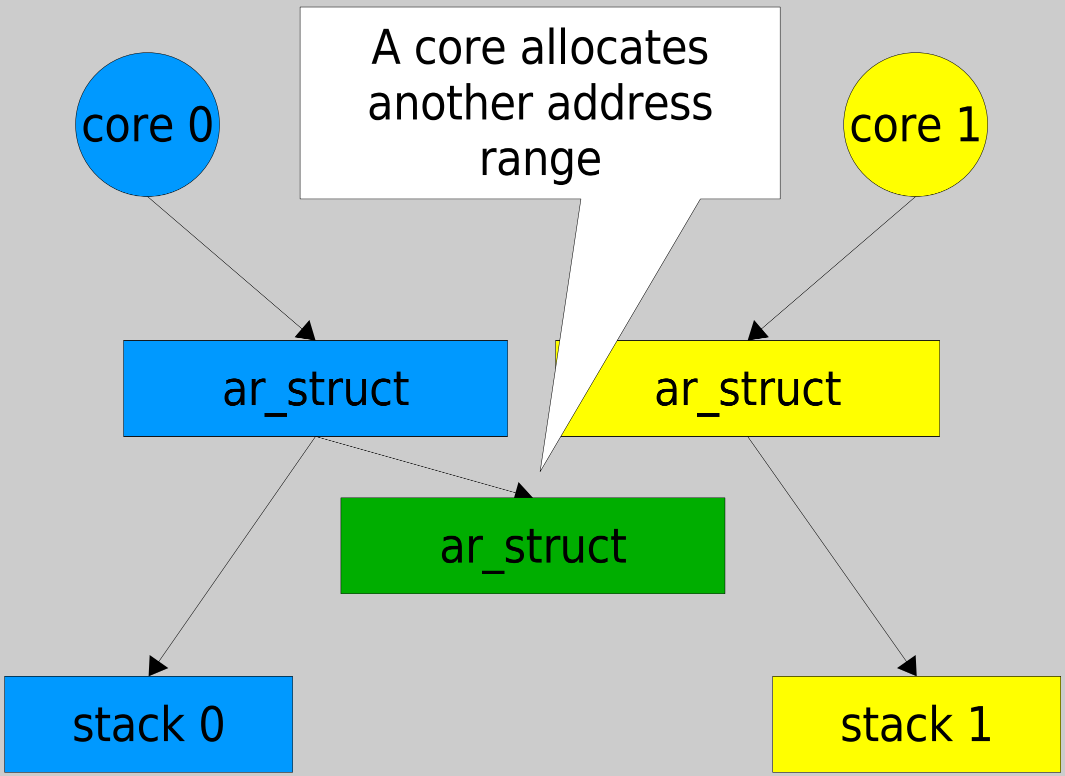

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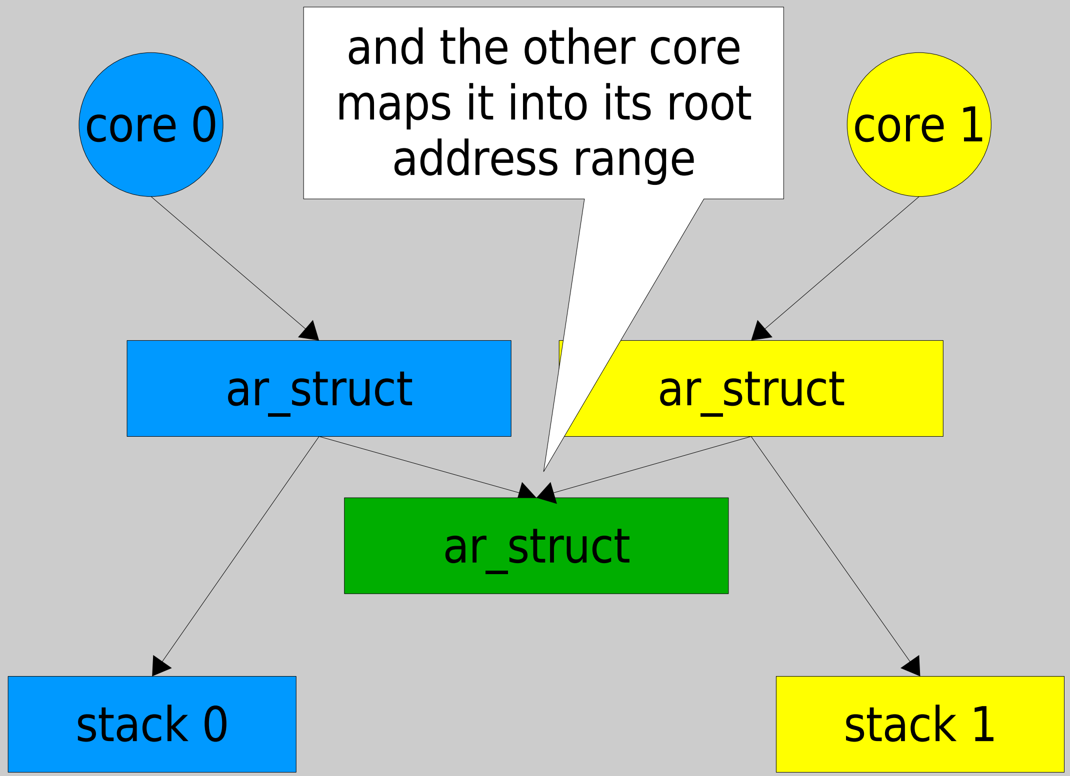

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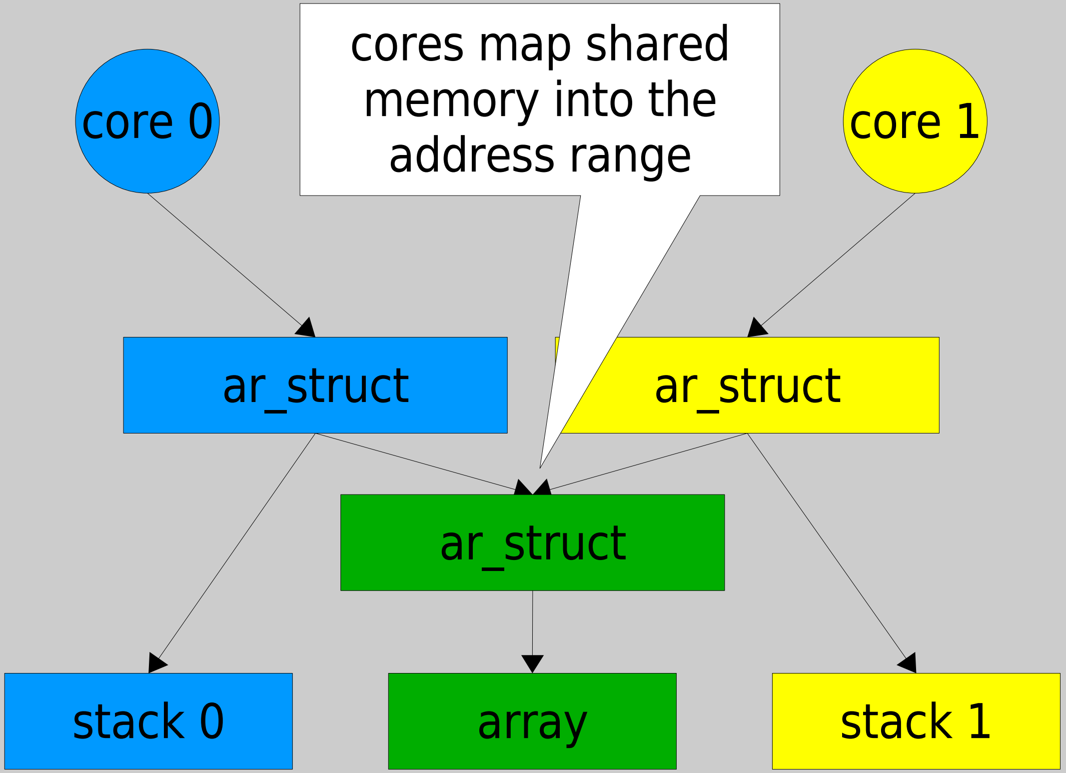

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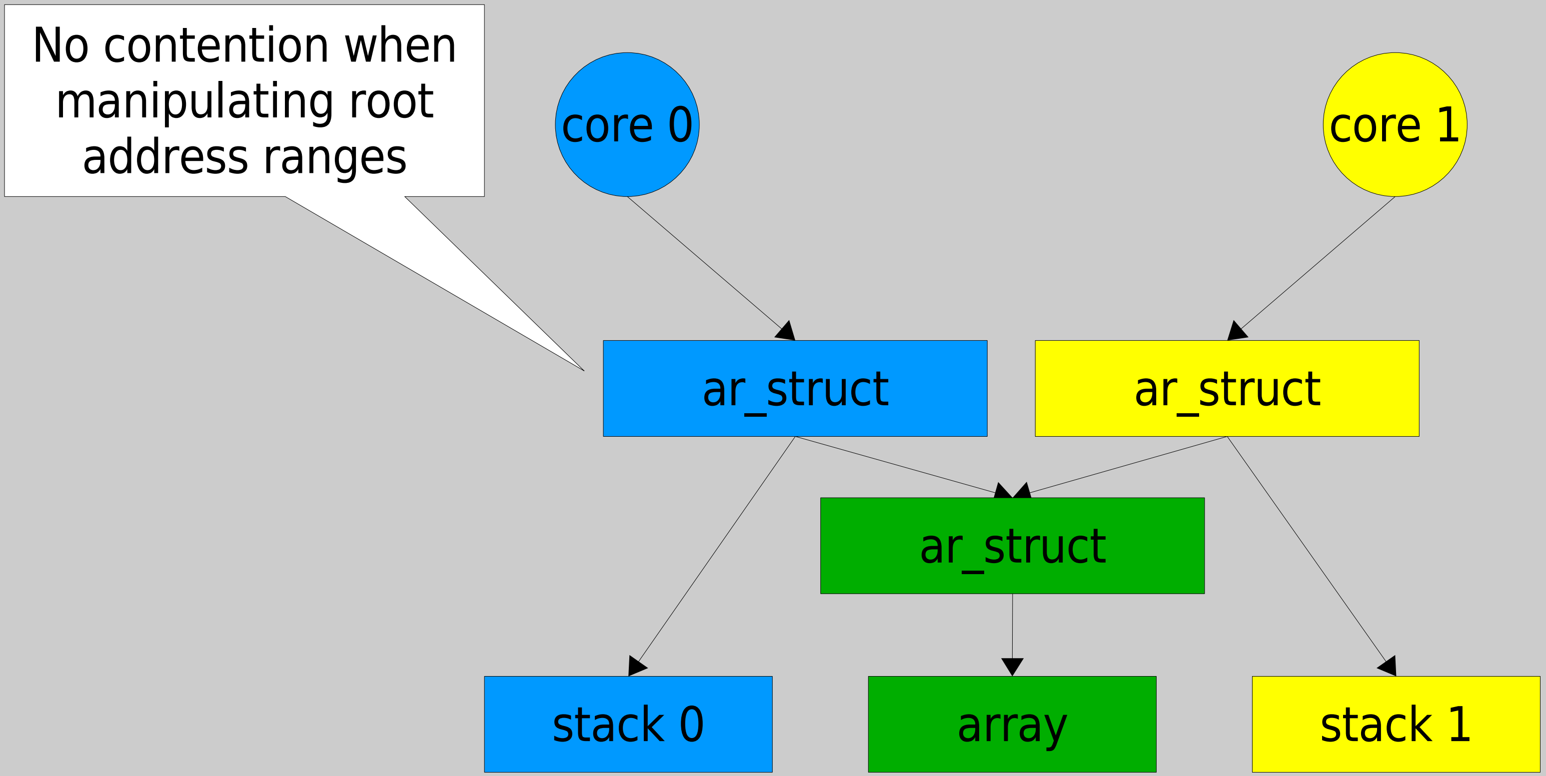

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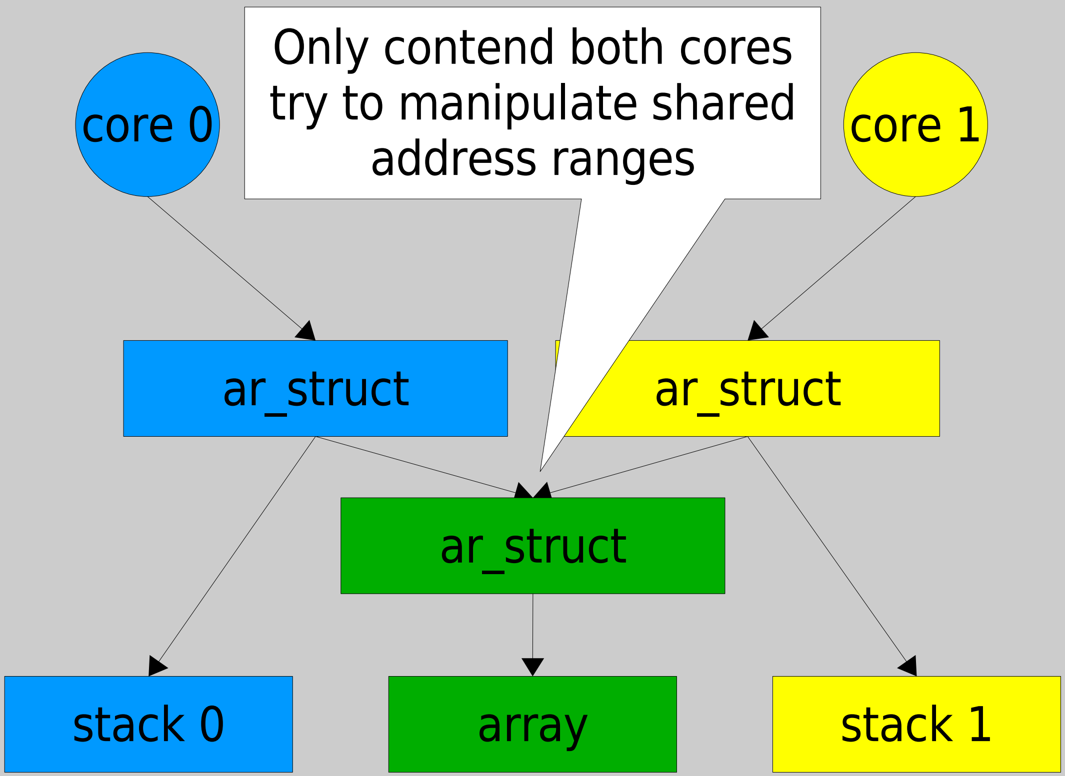
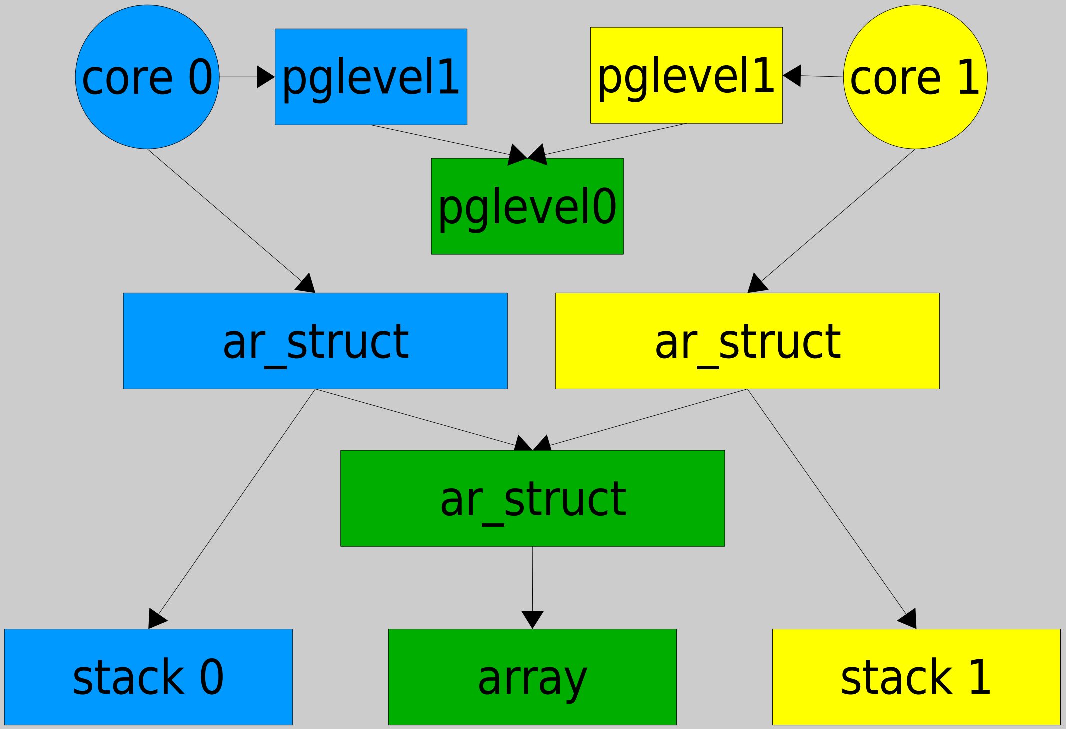


Address ranges: share PTEs



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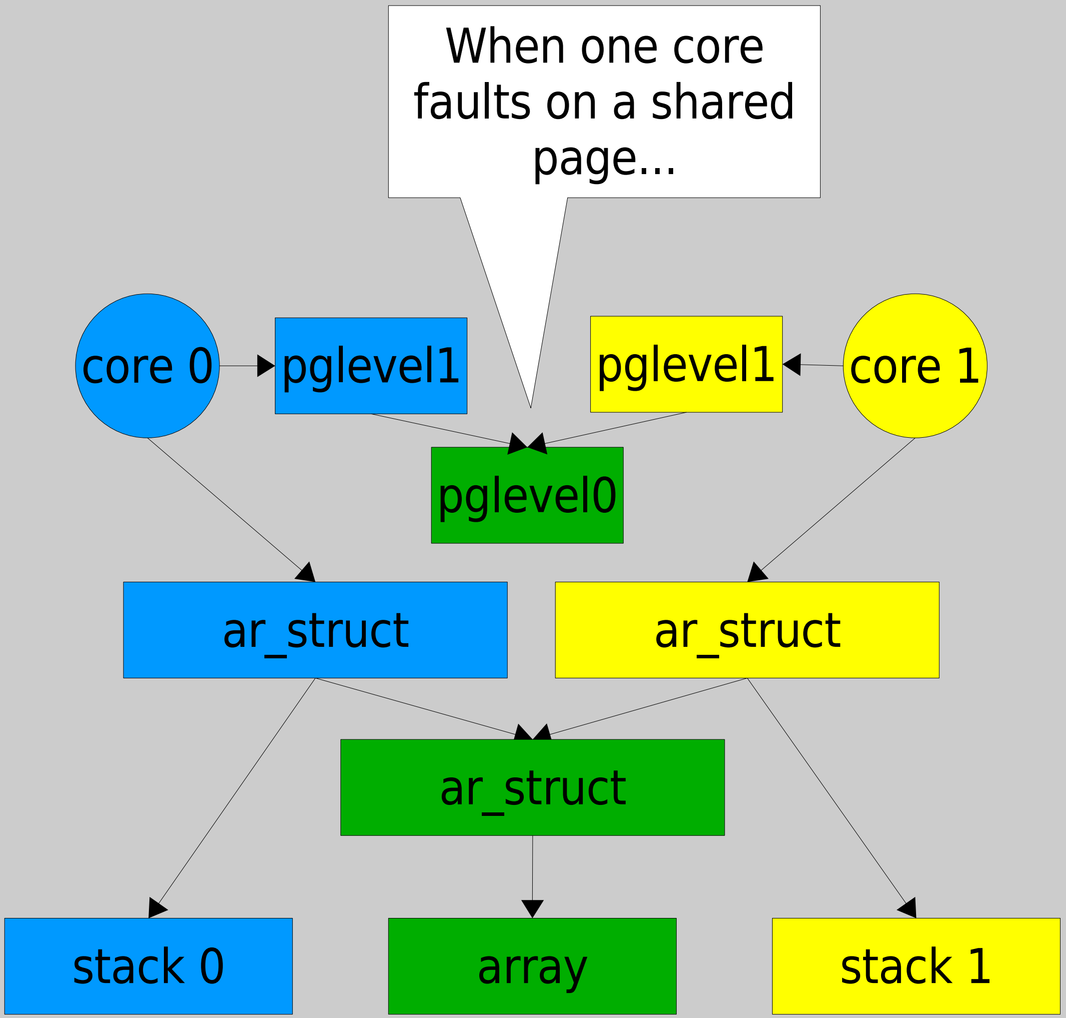

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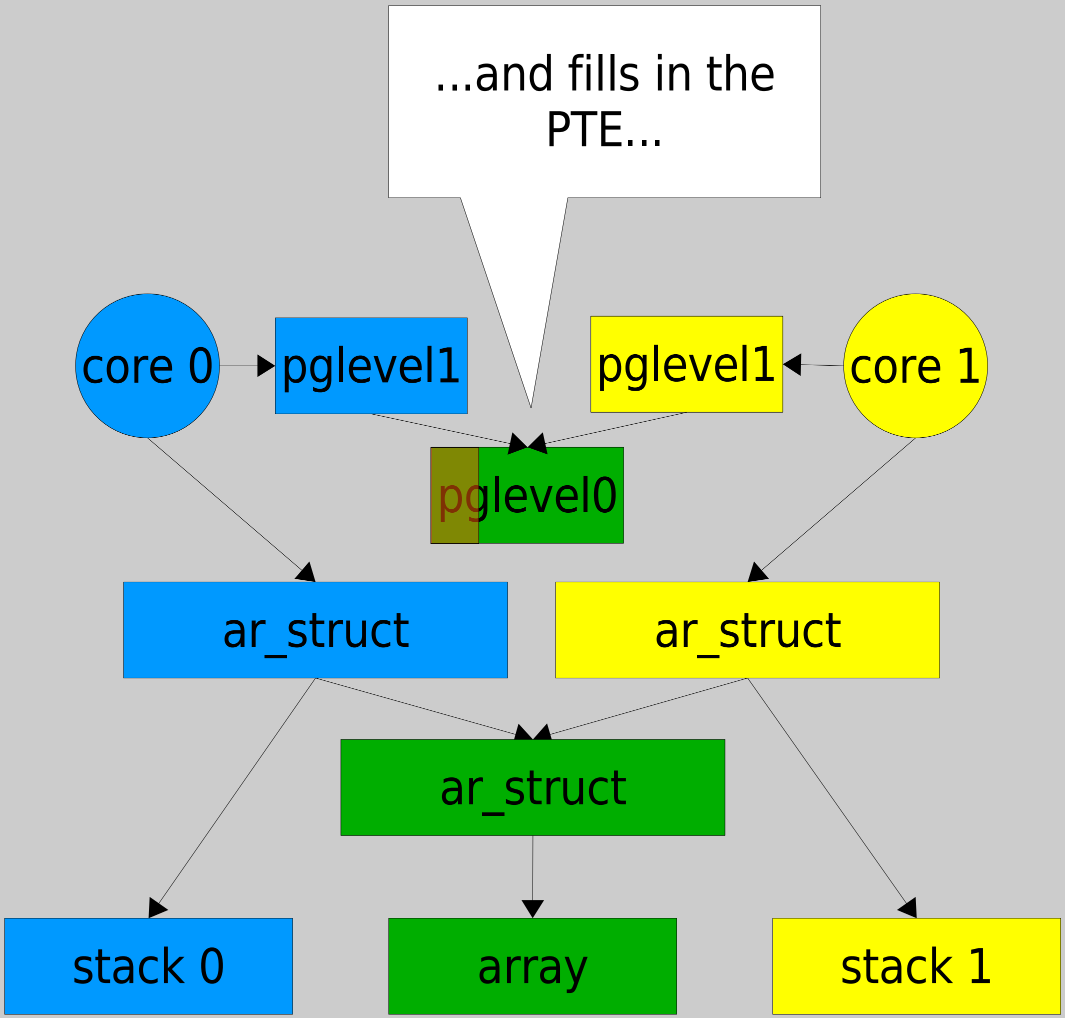

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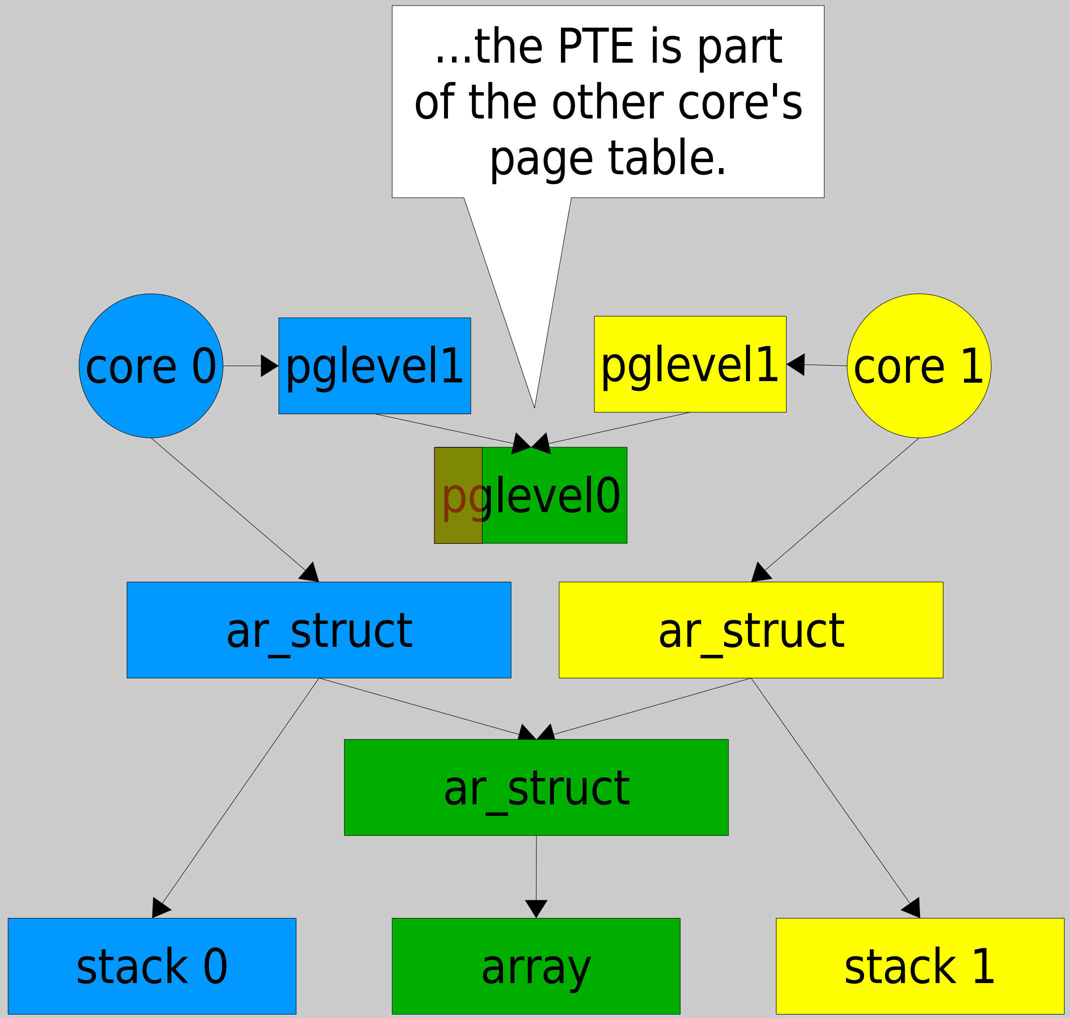
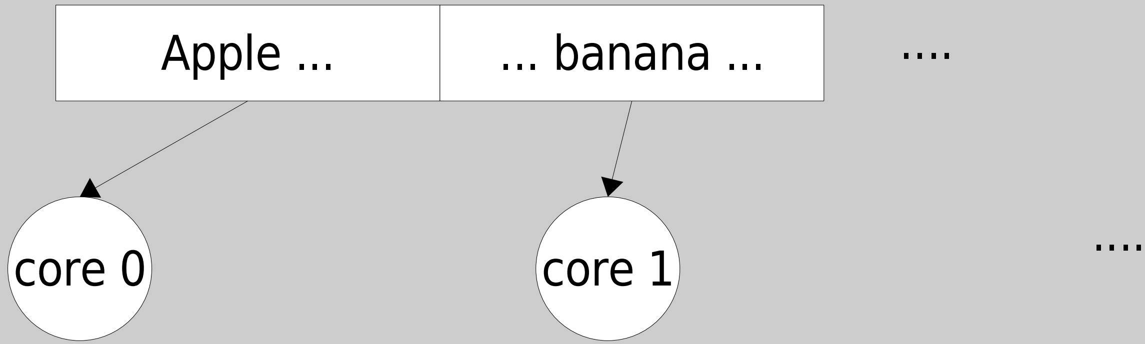


Address ranges good for complex memory sharing patterns

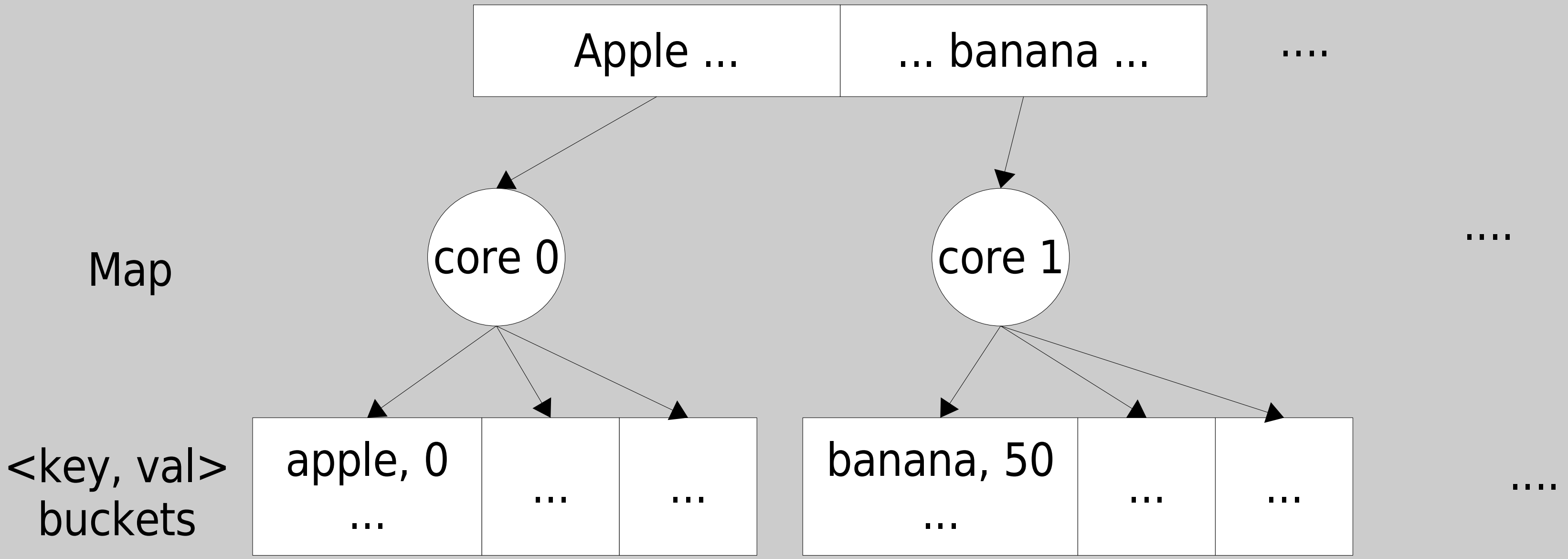
- Typical applications have more complex memory sharing patterns
  - Not just global or private
  - Example: MapReduce library designed for multicore

Inverted index with MapReduce

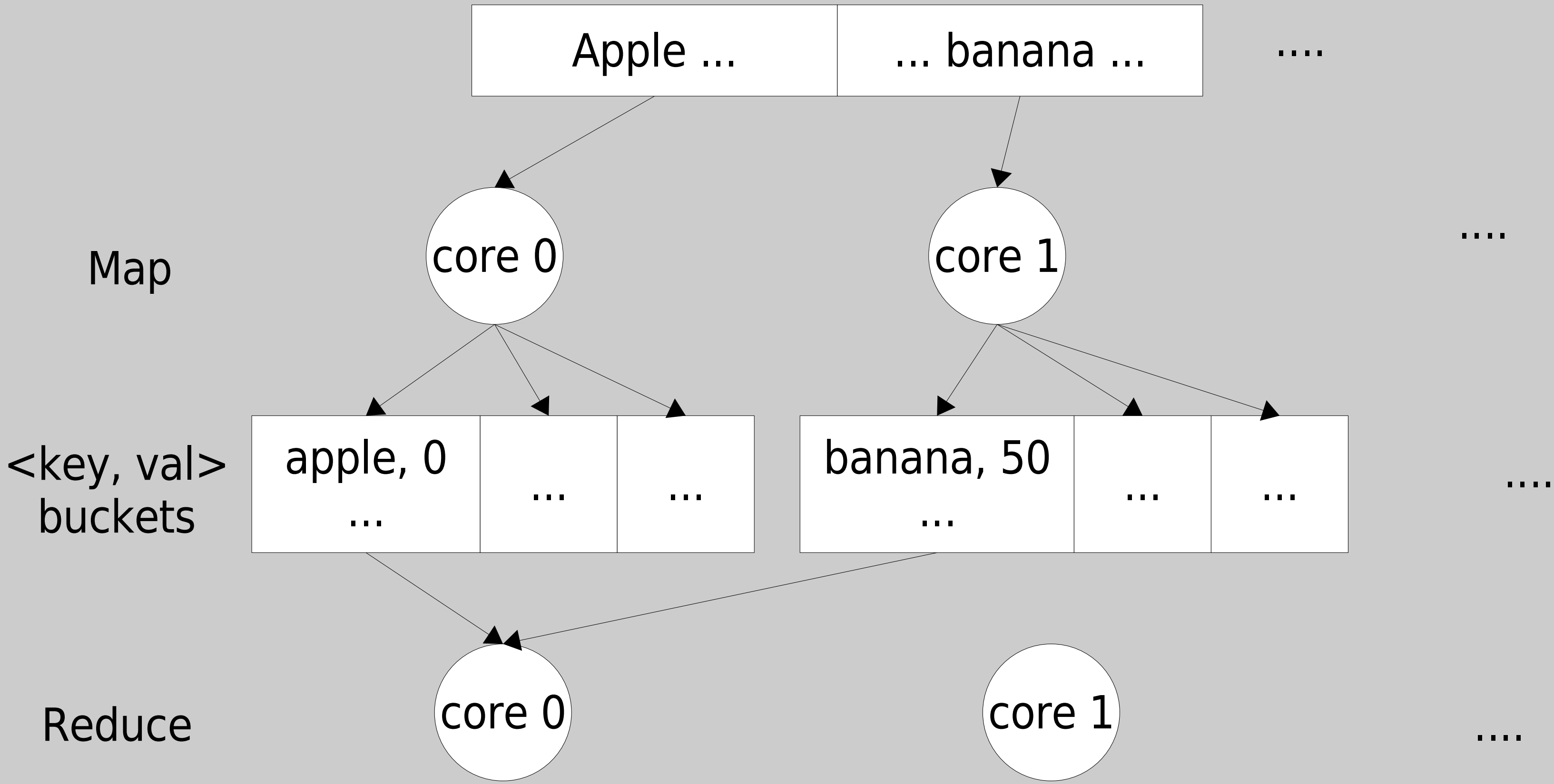


Map

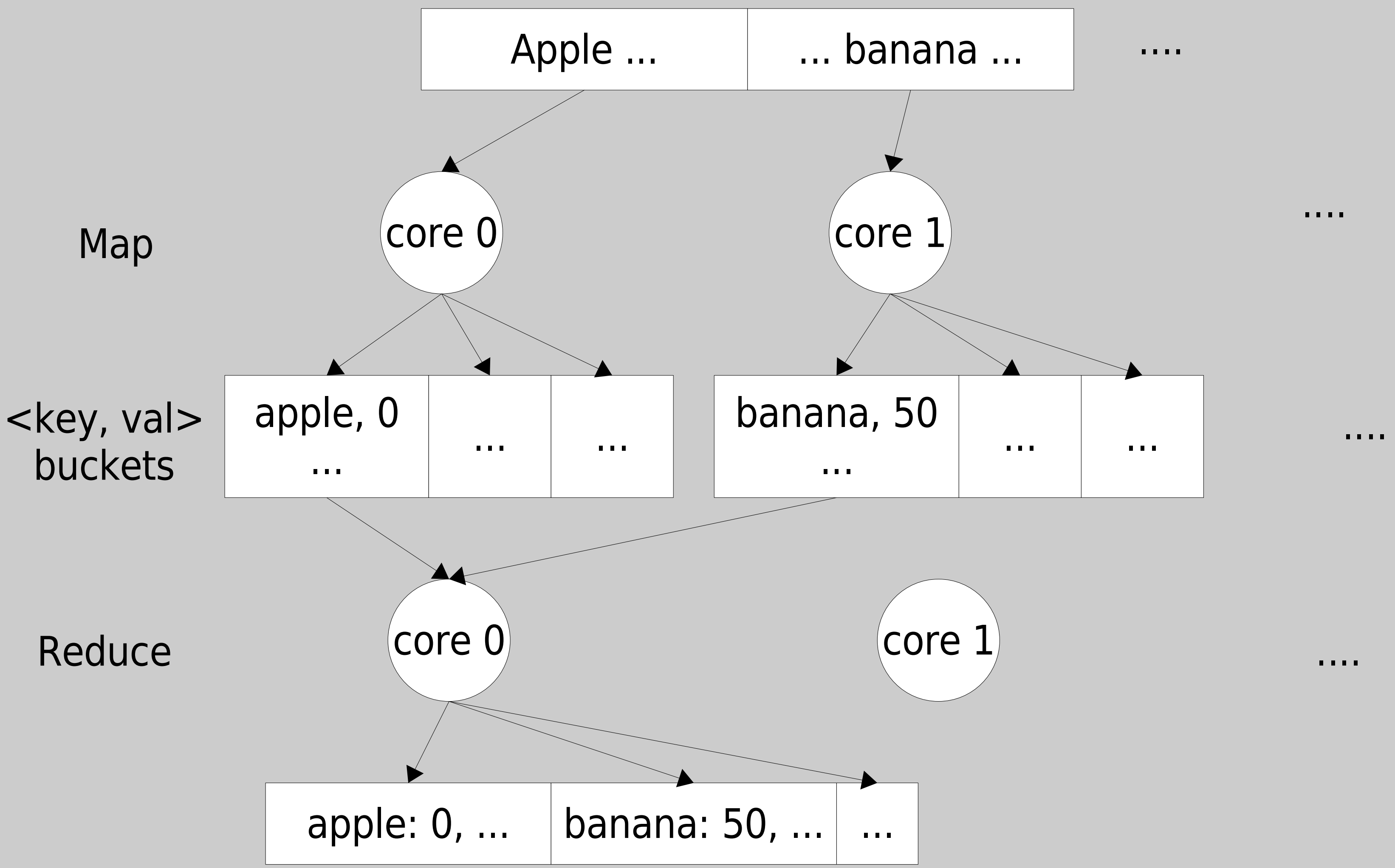
Inverted index with MapReduce



Inverted index with MapReduce



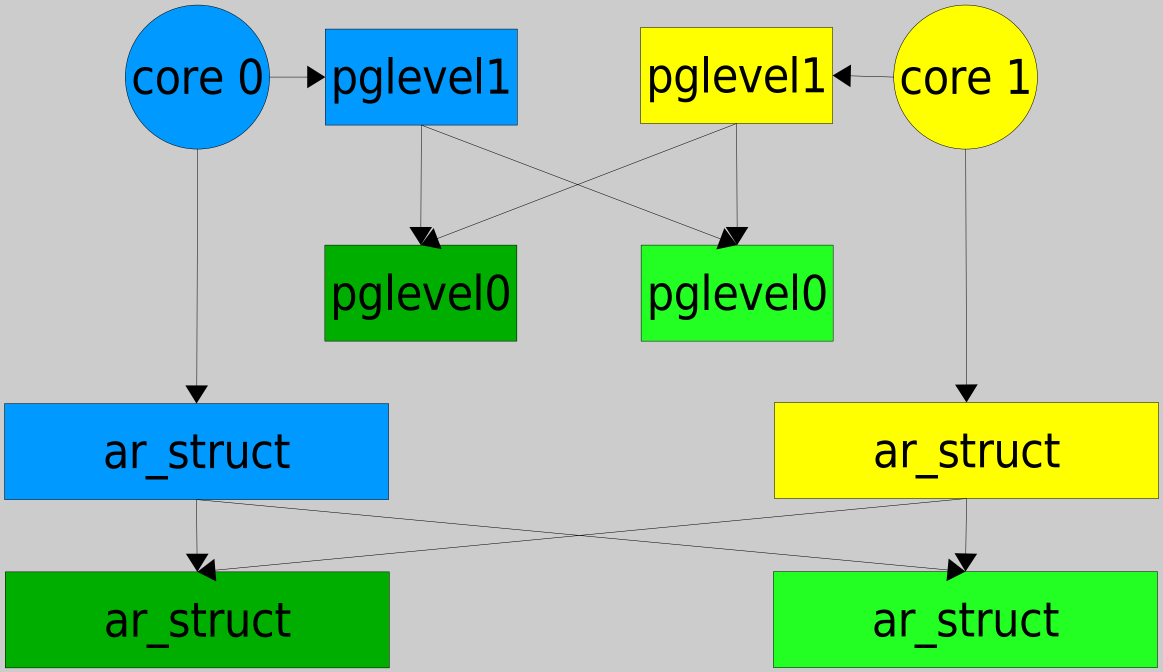
Inverted index with MapReduce



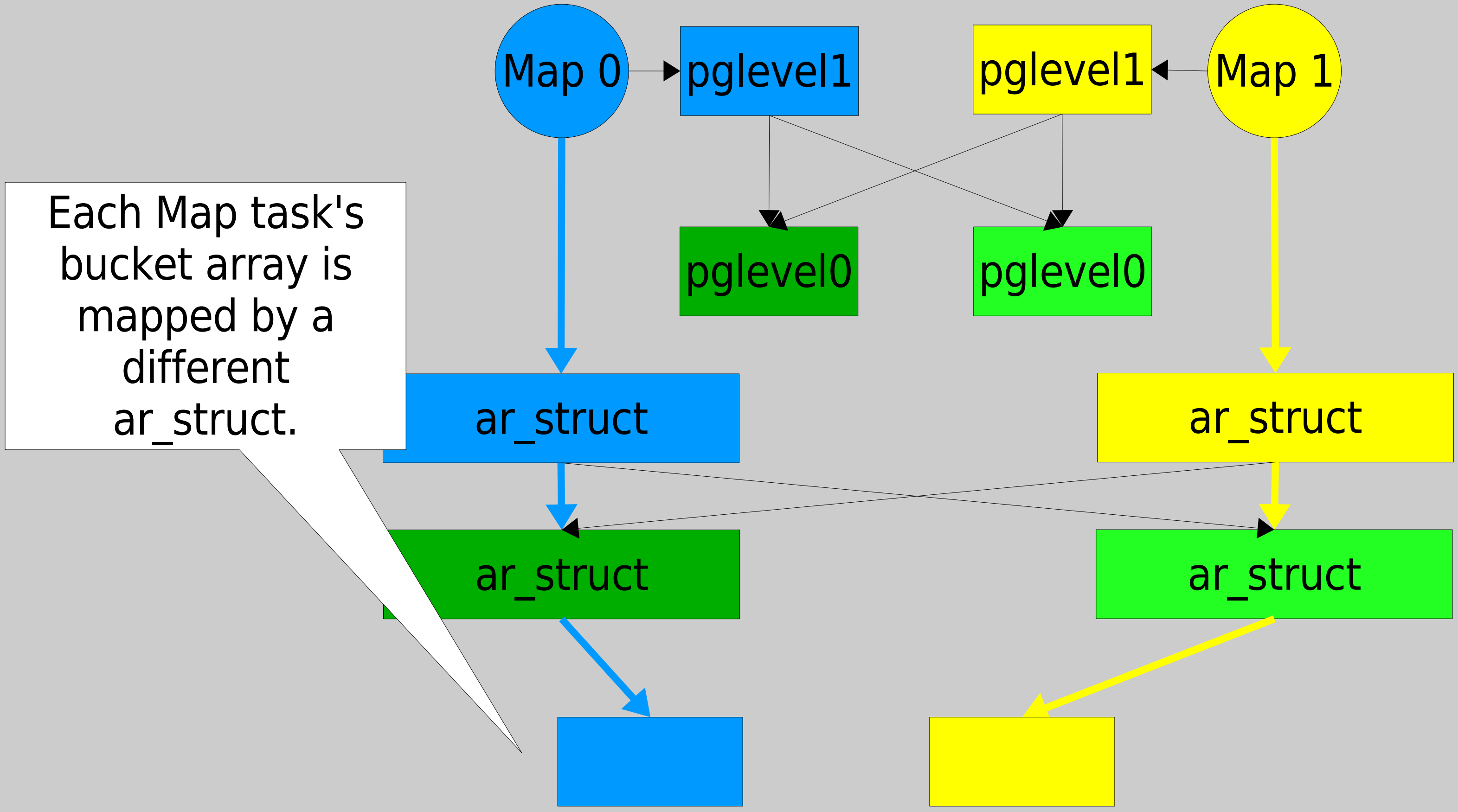
MapReduce sharing goals for kernel data structures

- 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



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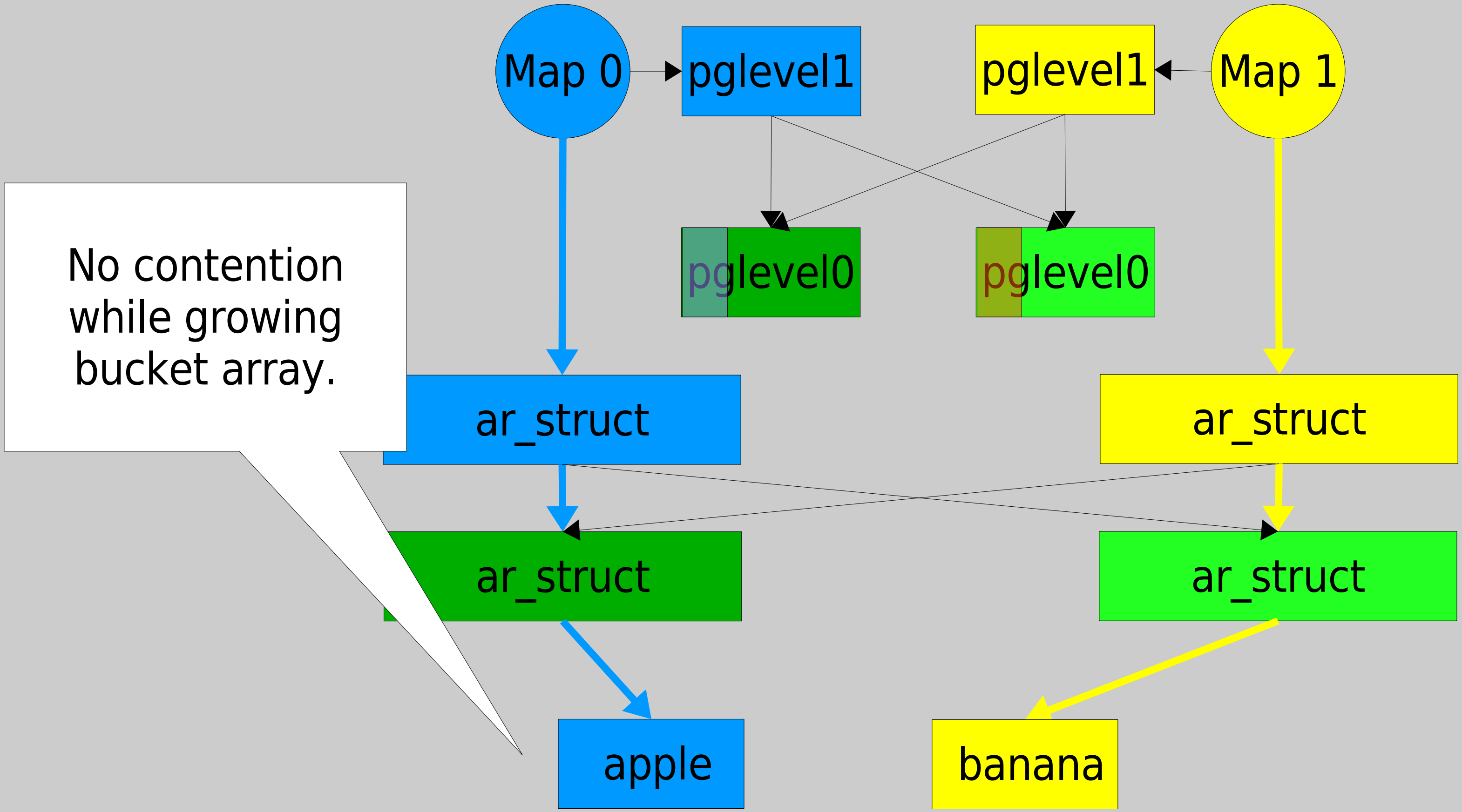

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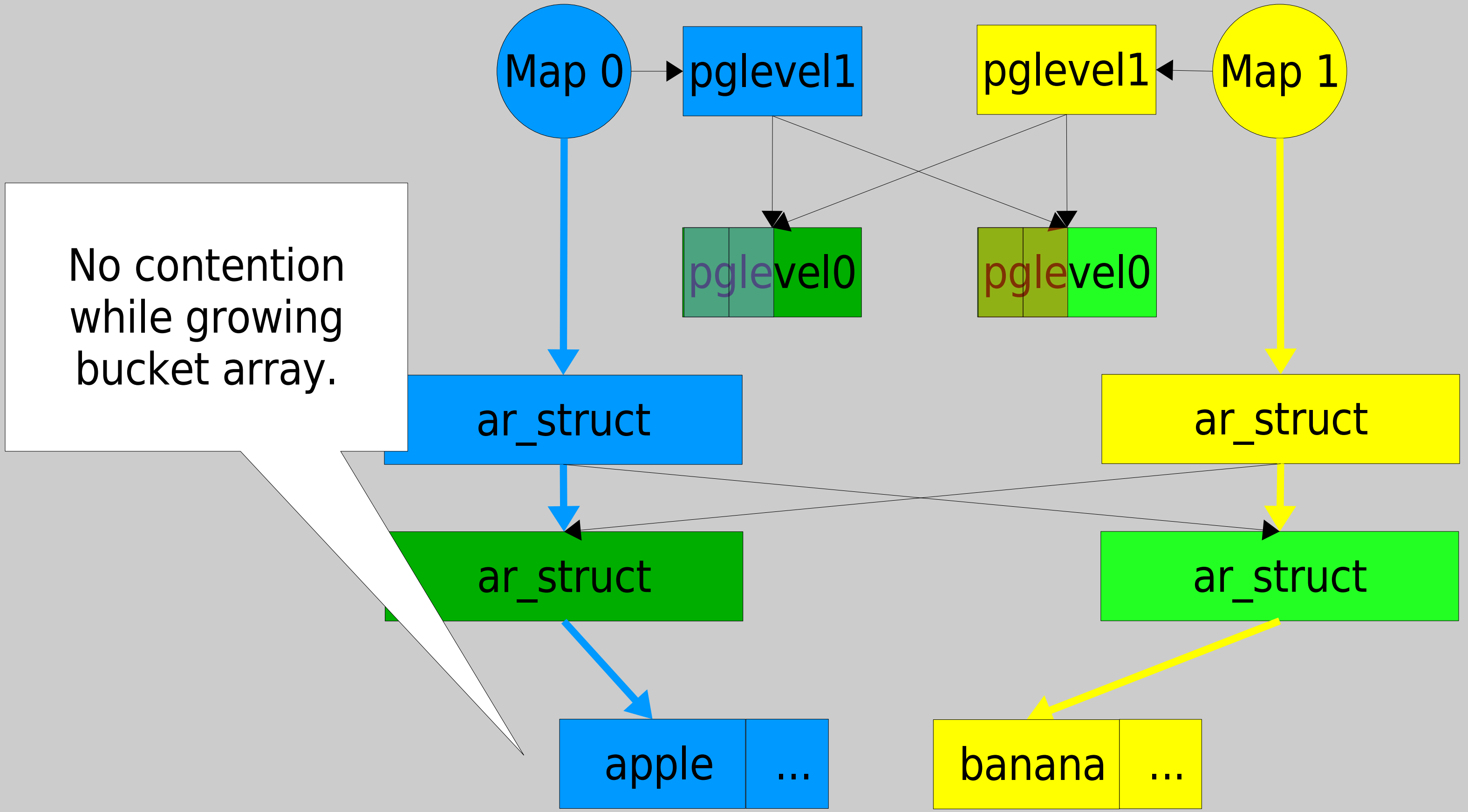

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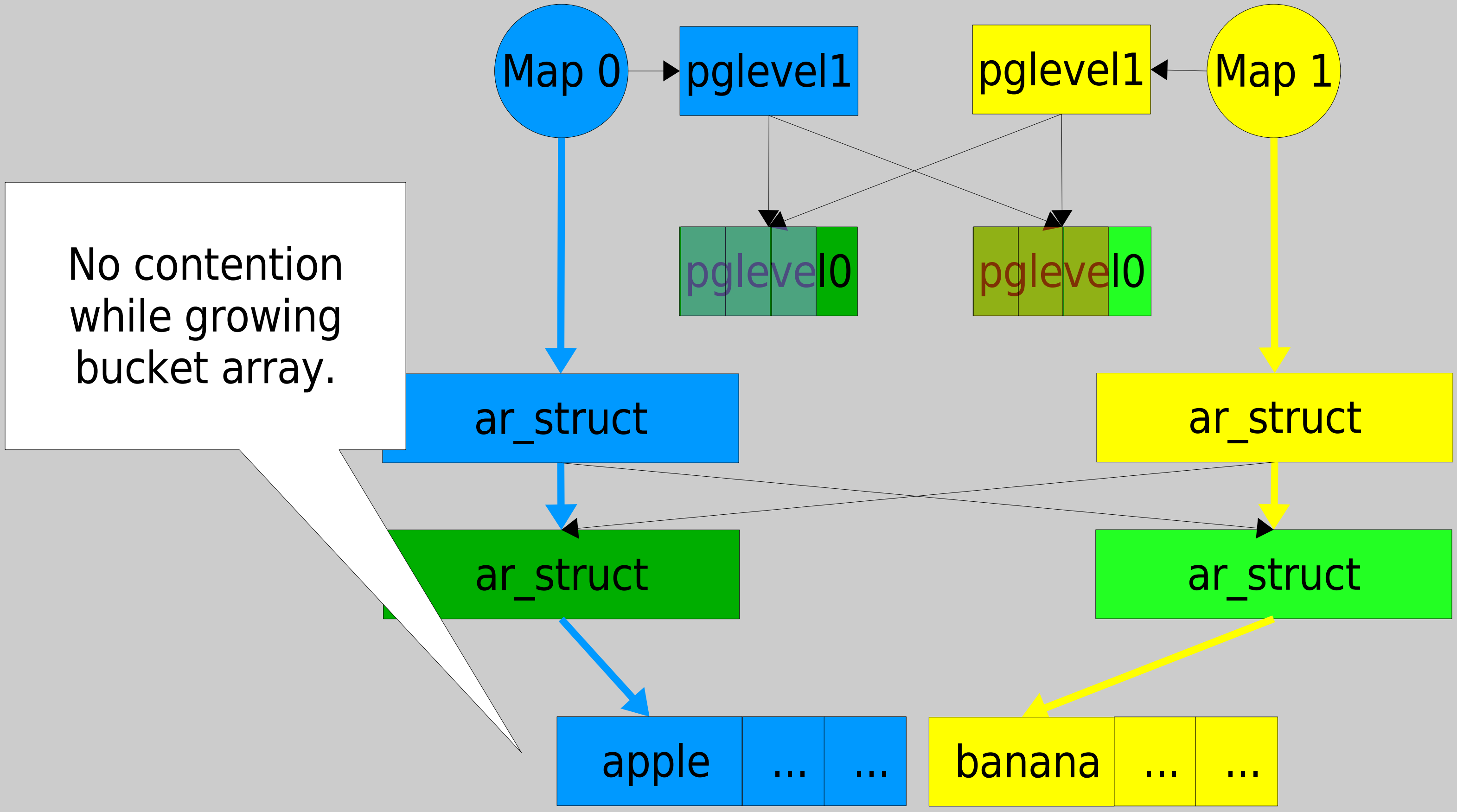
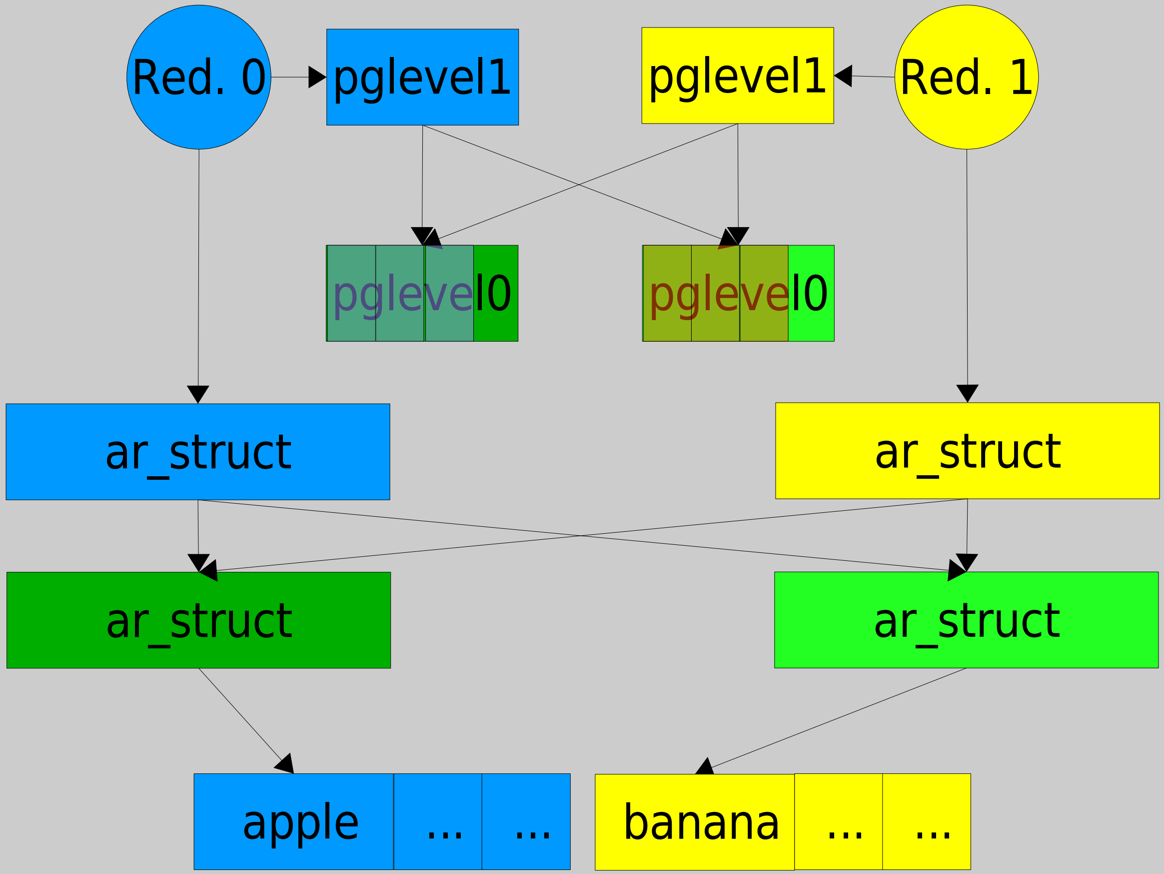


During Reduce PTEs are shared



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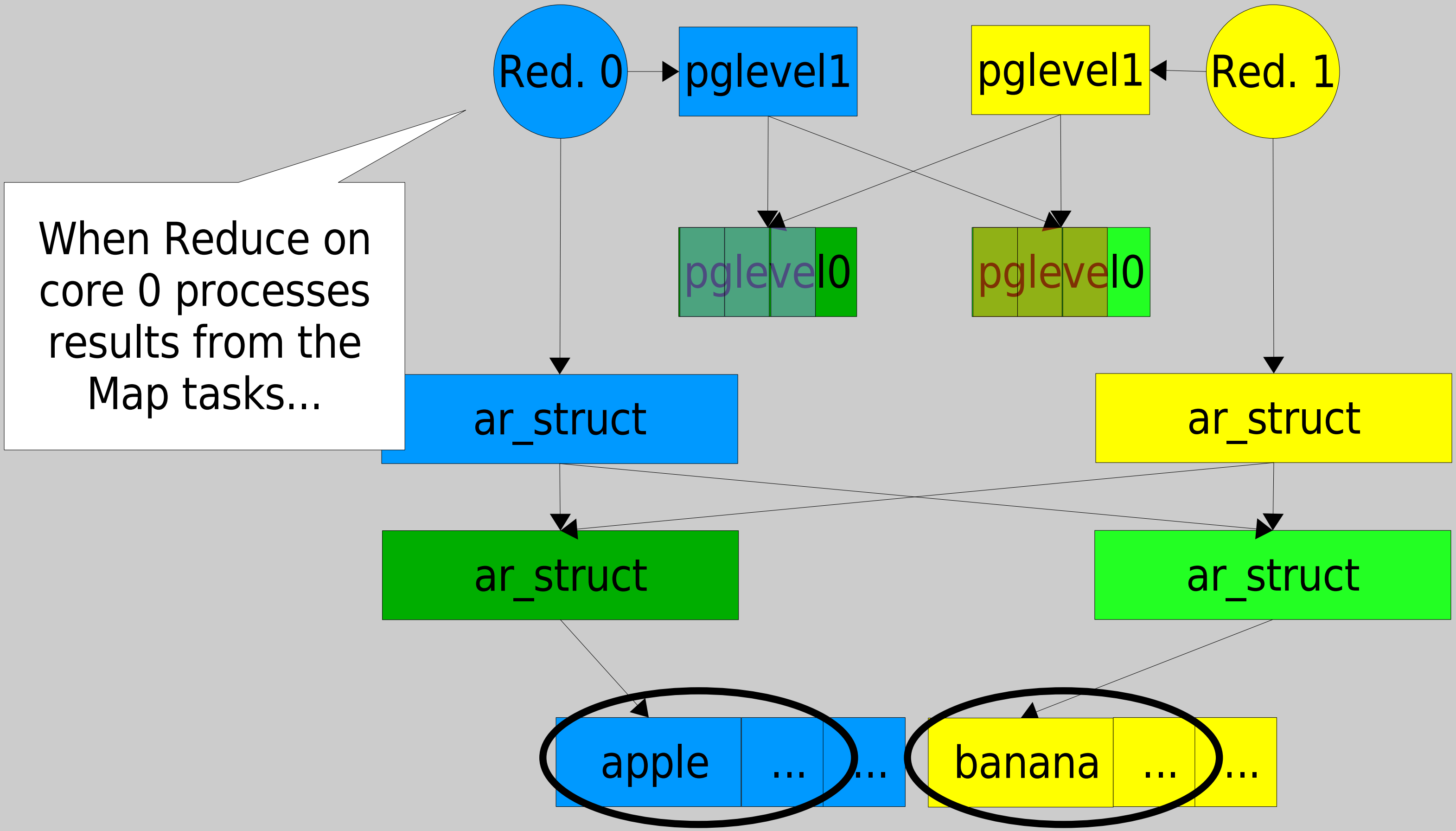

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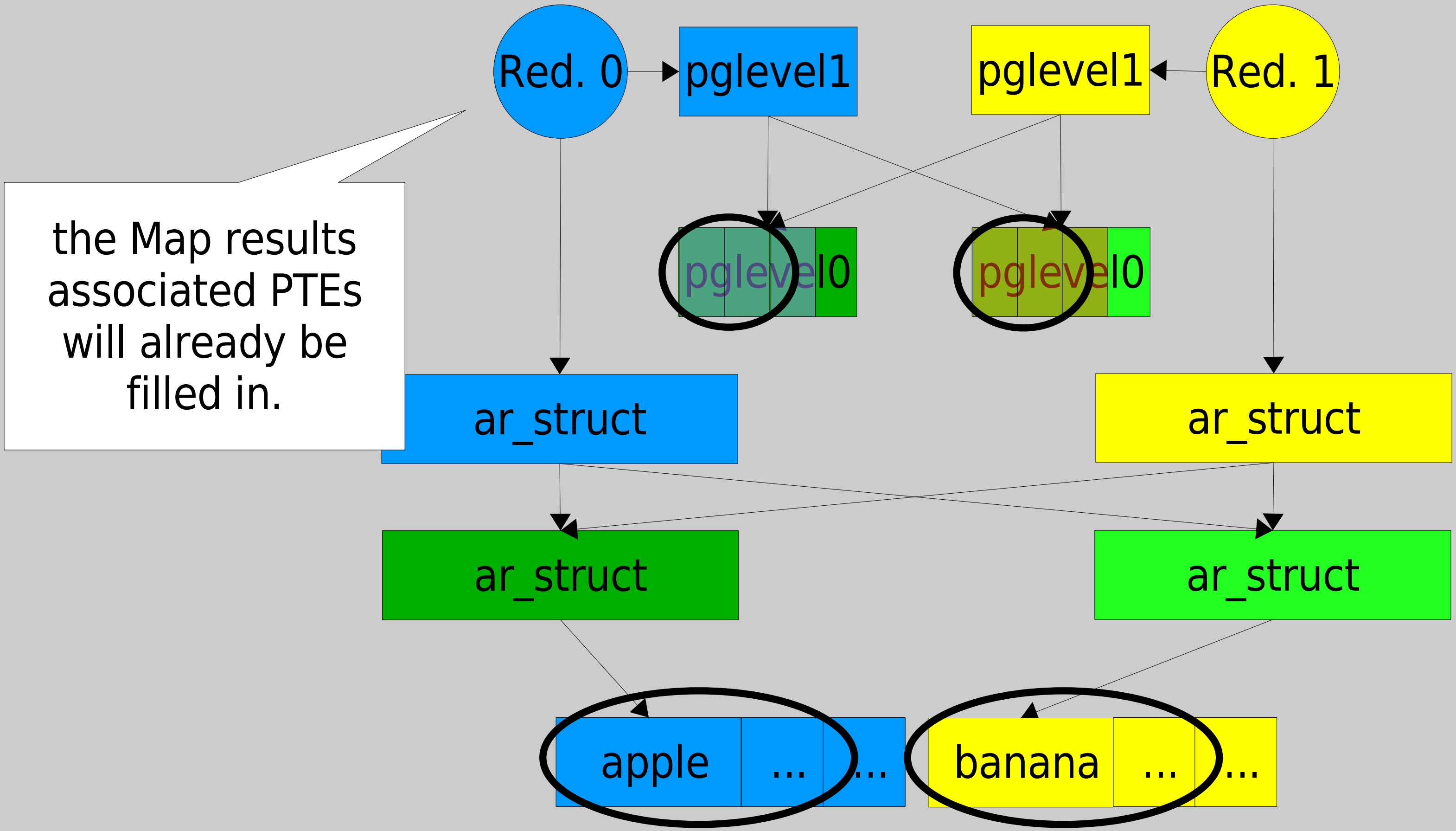

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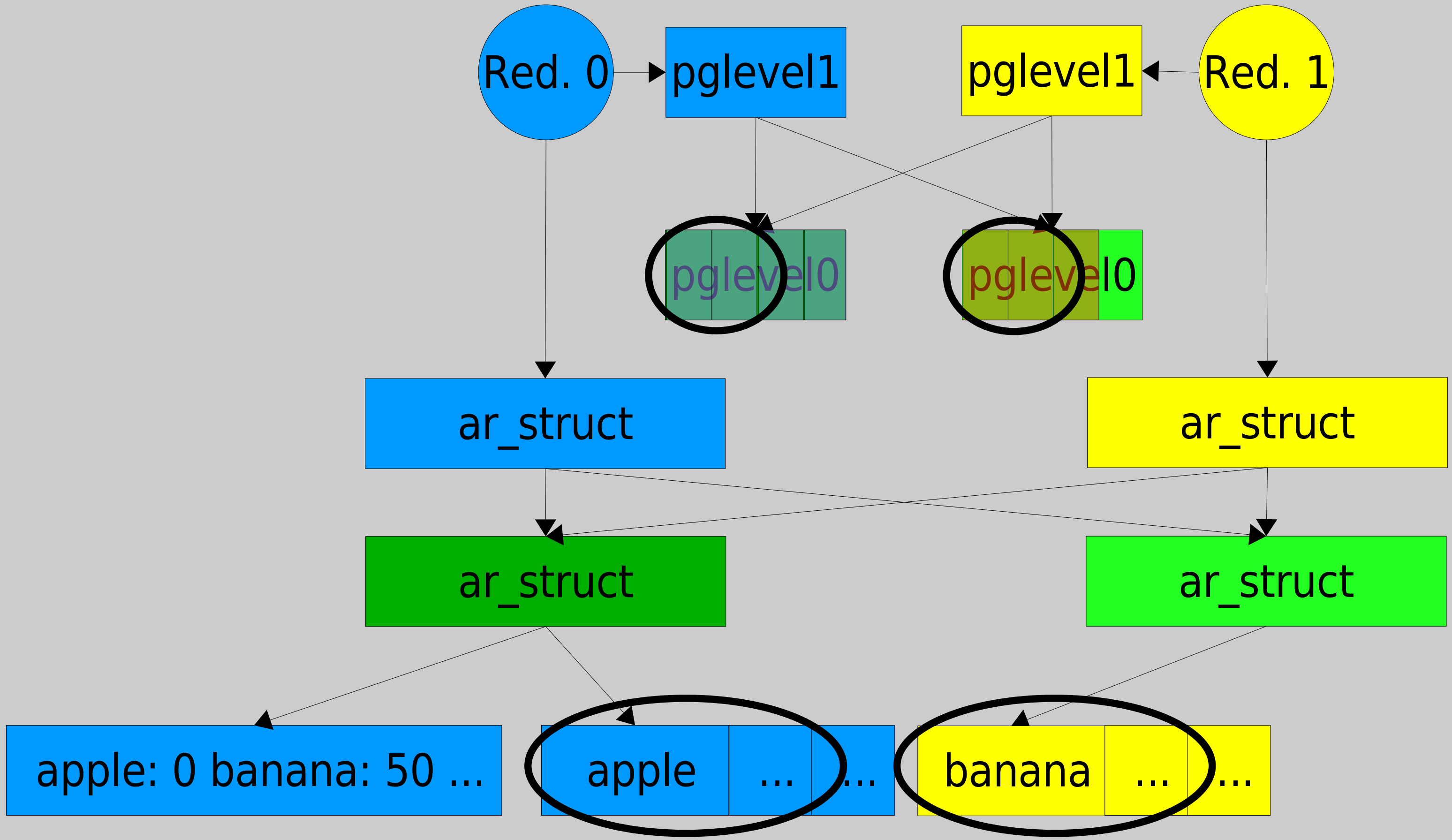


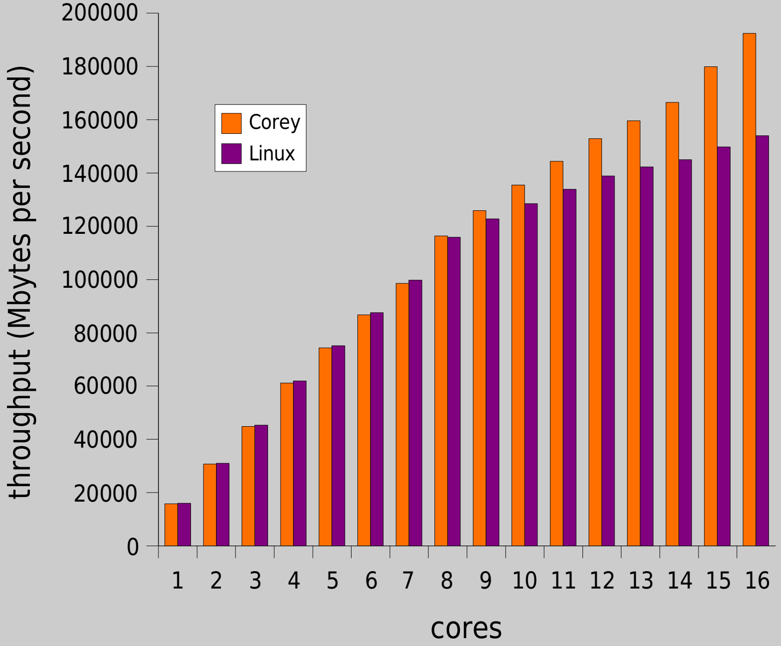
Address ranges in Corey

- 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
  - Barrelfish
  - 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