Model Checking Cache Coherence in System-Level Code

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June 2016

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Program Agenda

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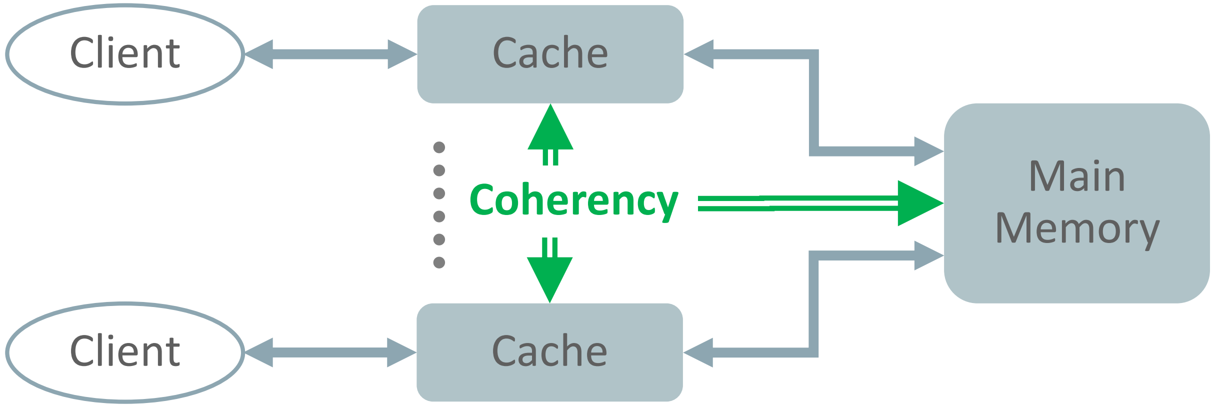
Cache Coherence Issue

- A shared memory multiprocessor system with a separate cache for each processor.
- Multiple copies for the same data in both main memory and caches.
- Coherence defines the proper access behaviors to the same memory location.



Cache Coherence Issue

- No cache coherence guarantee in hardware level.
- Must be dealt with explicitly in software by programmers.
  - Writing back data from the cache into the memory if the cacheline is “dirty”.

    flush(void addr, size_t size)*

  - Invalidating a cacheline in a cache such that the next load has to fetch data from memory.

    Invalidate(void addr, size_t size)*

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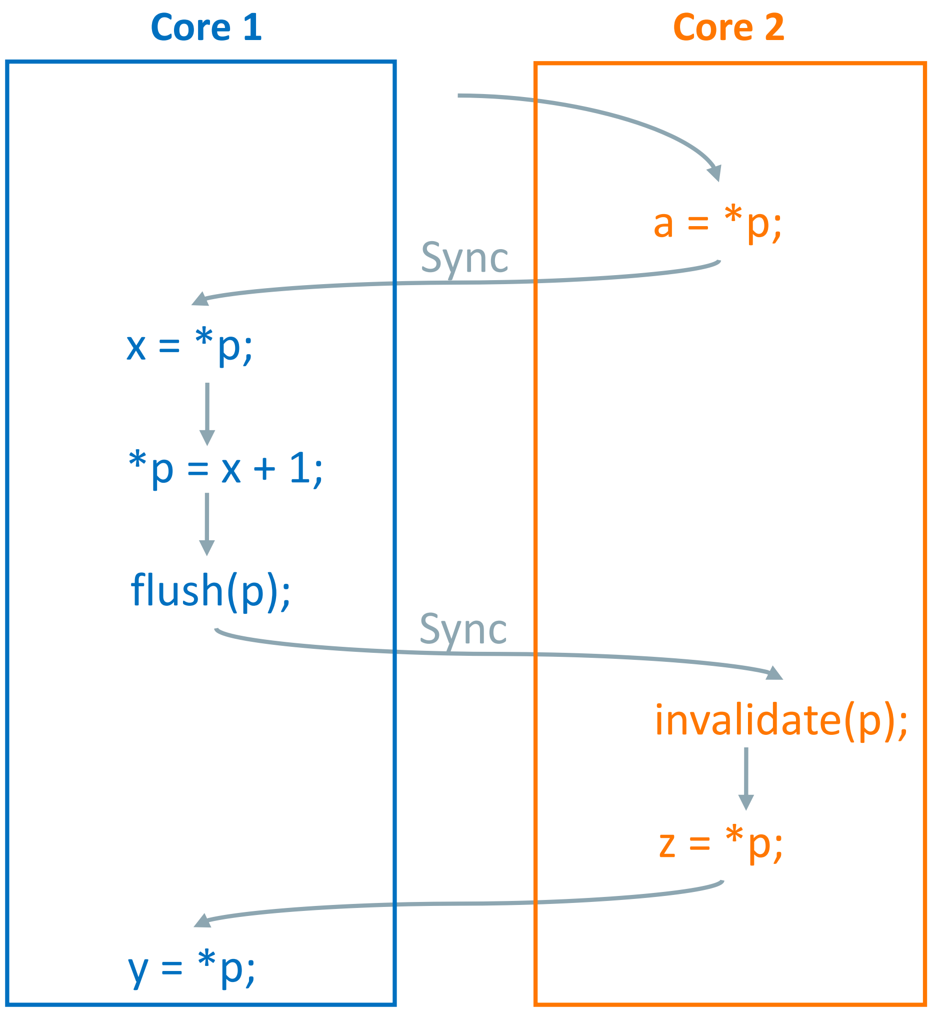
Cache Coherence Issue



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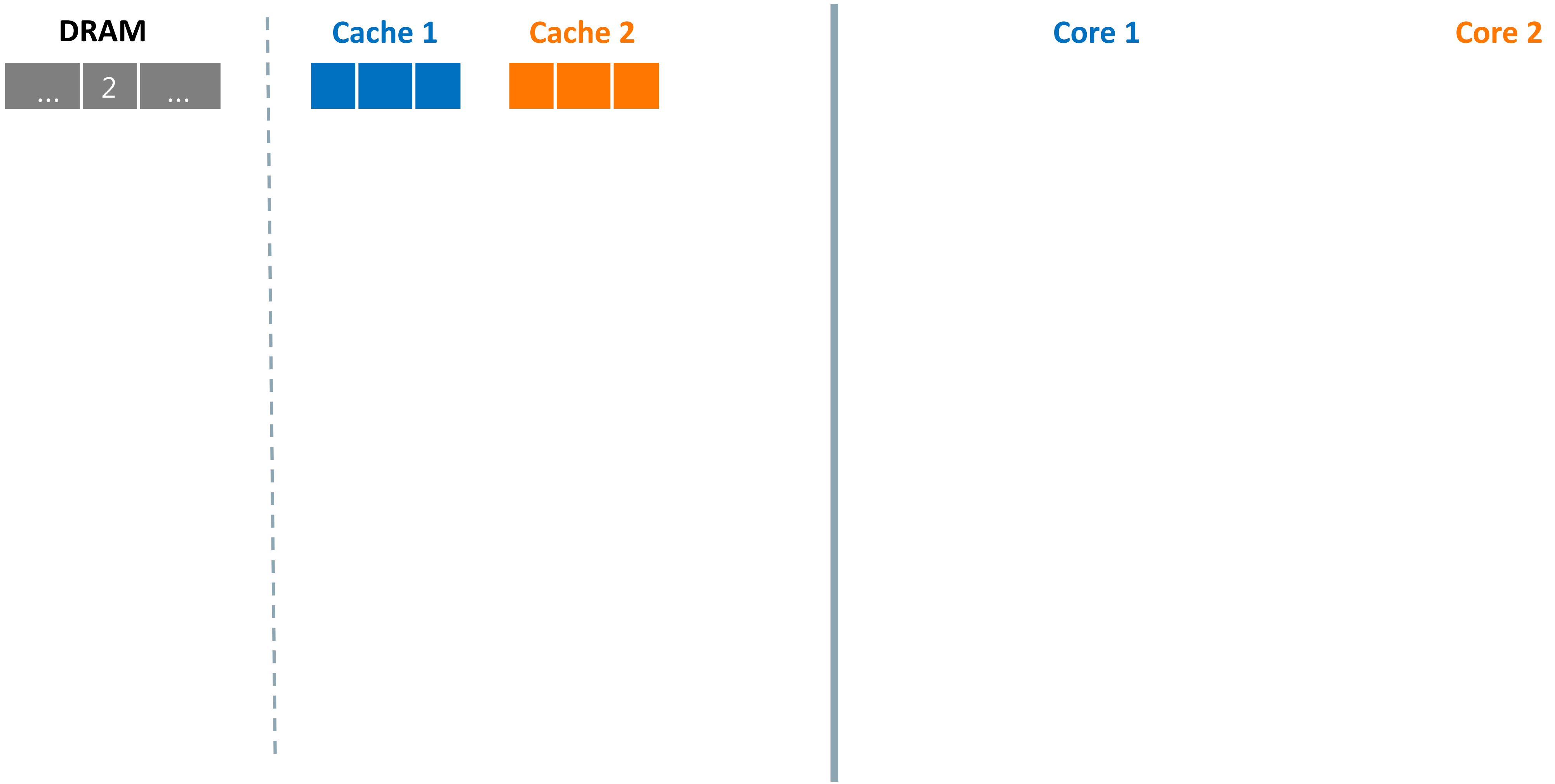

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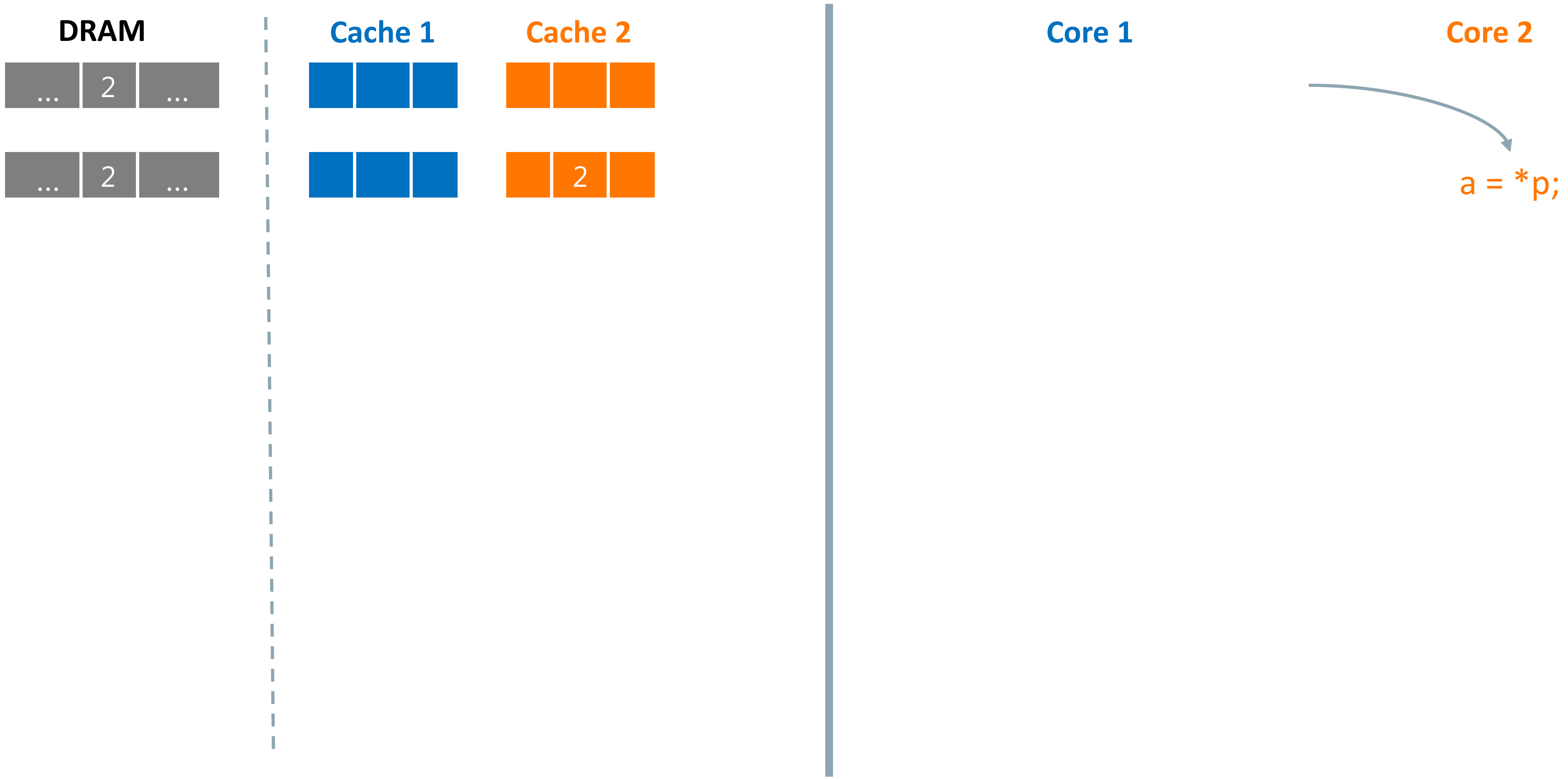

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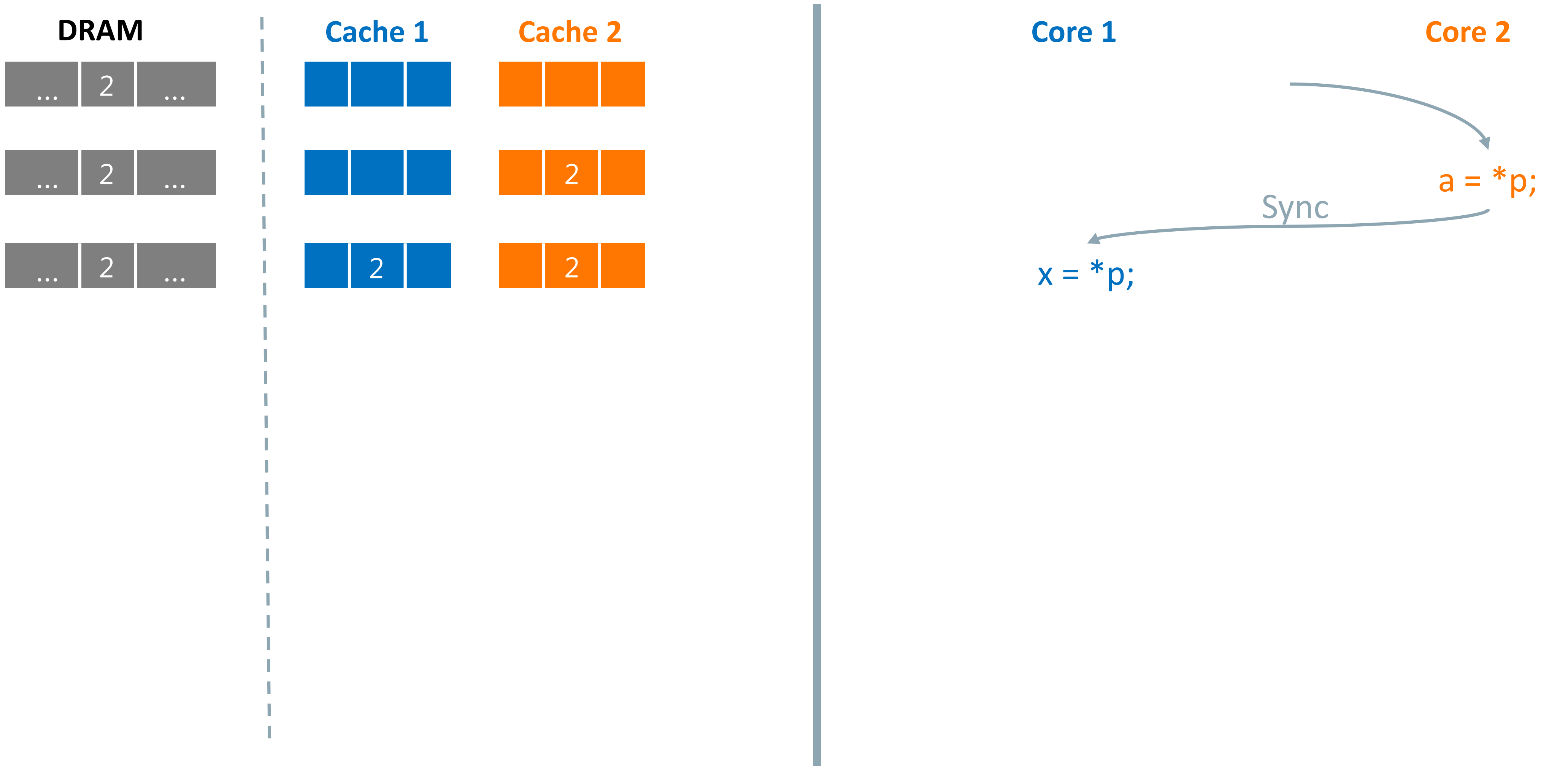

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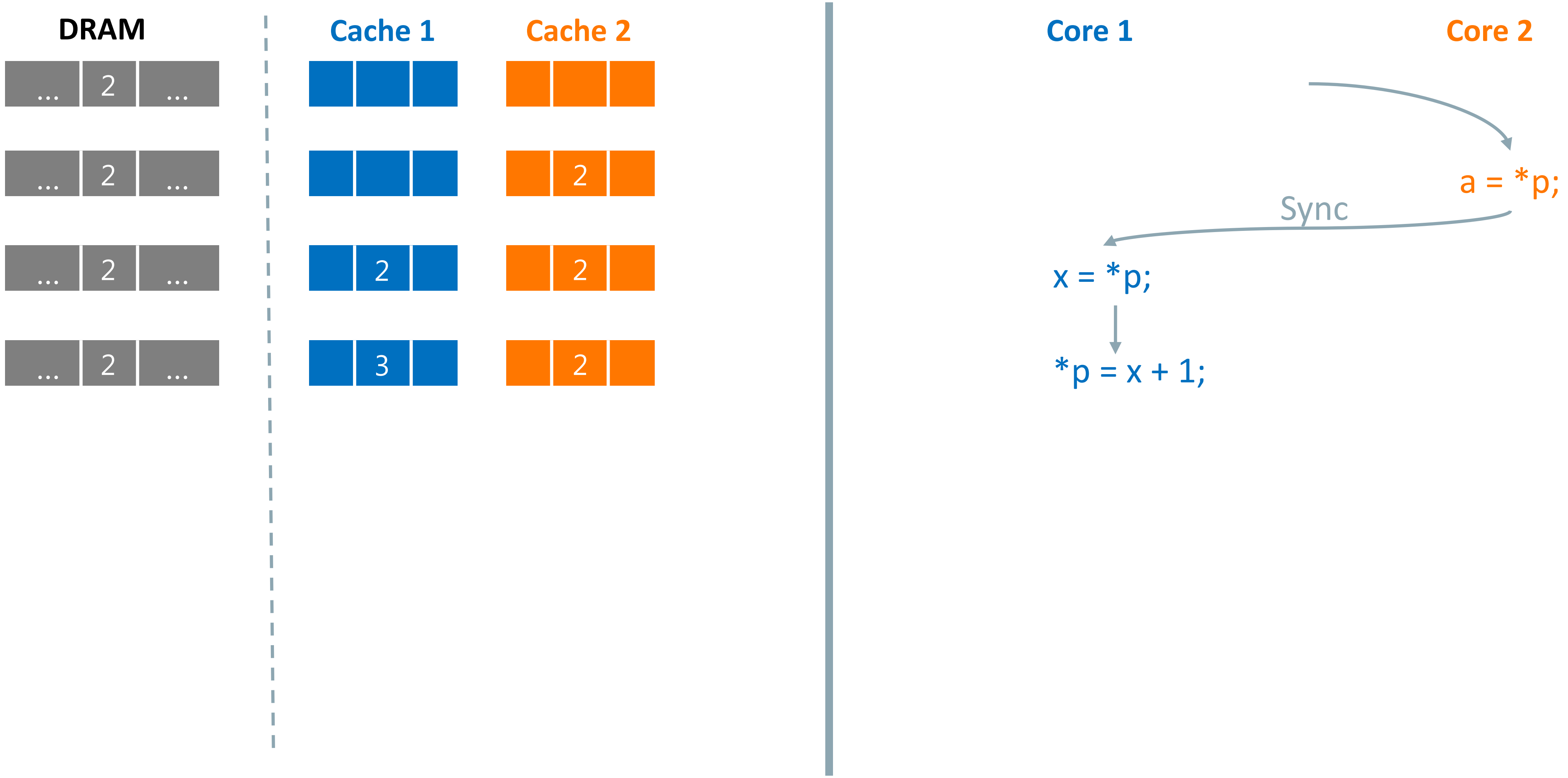

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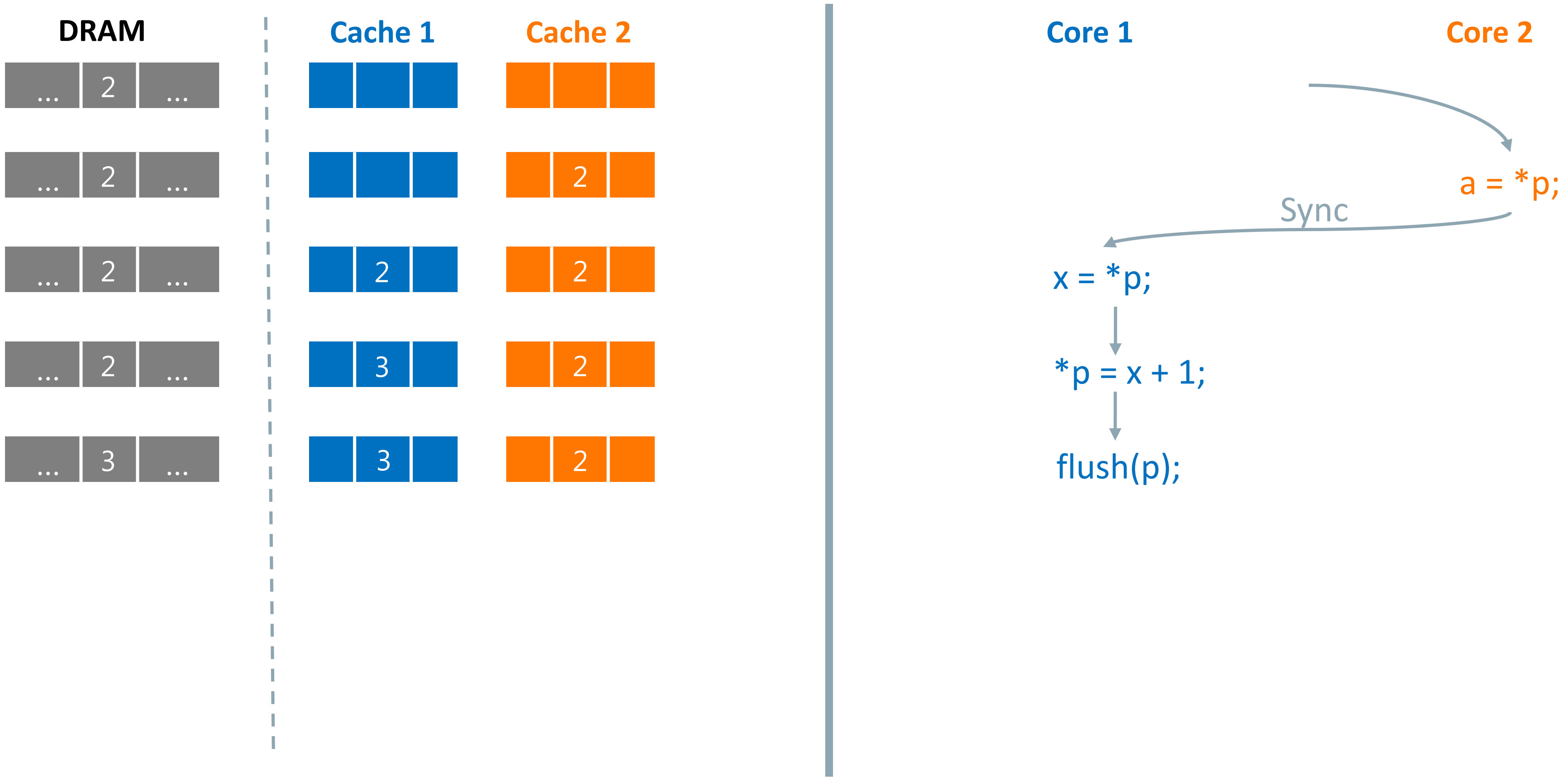

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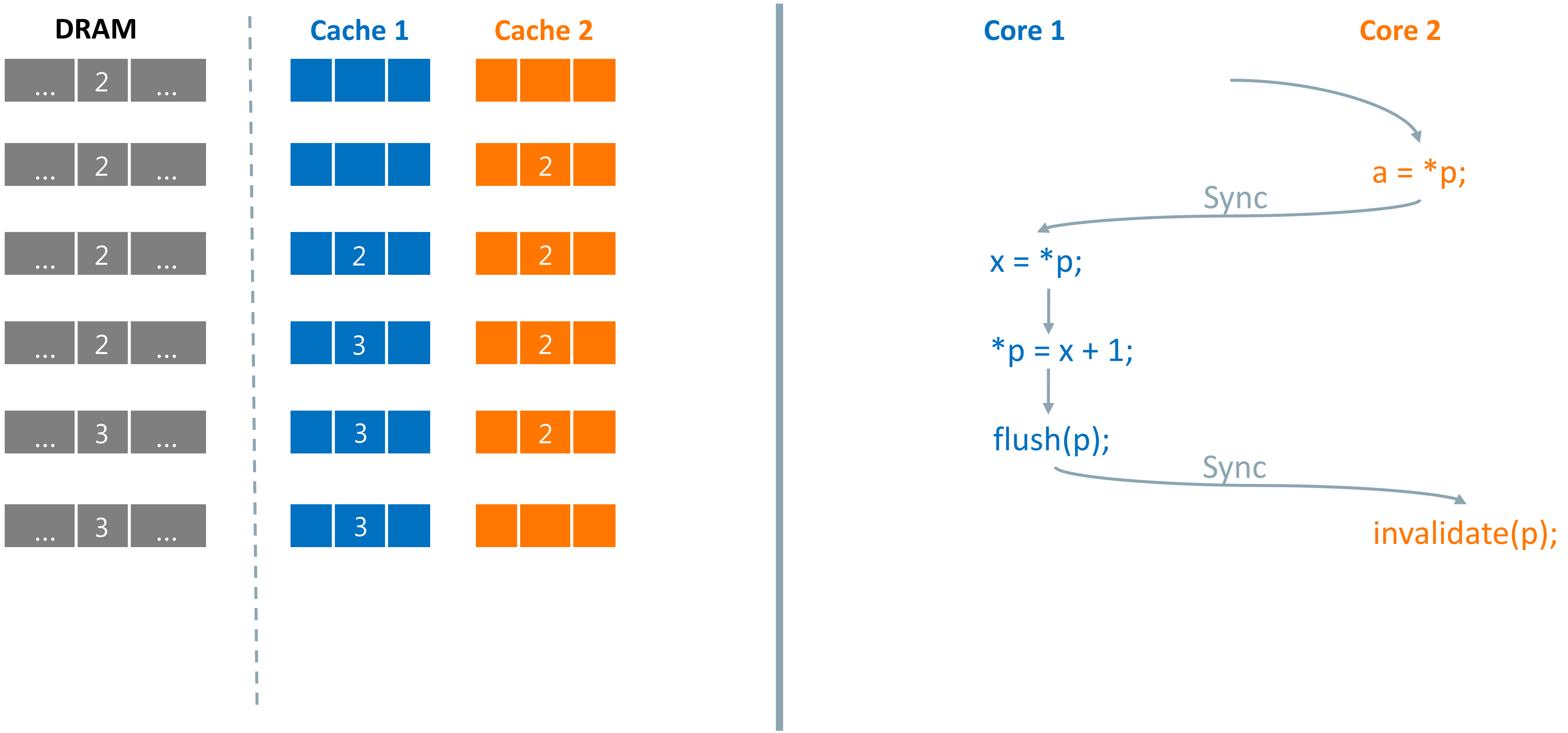

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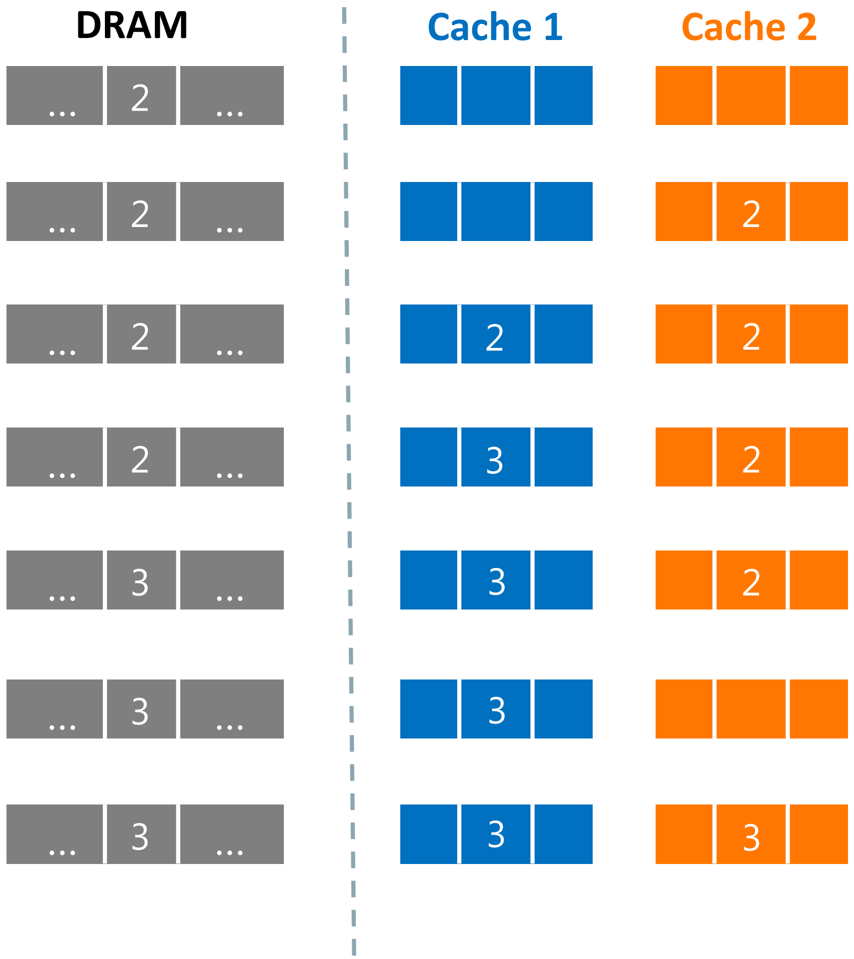

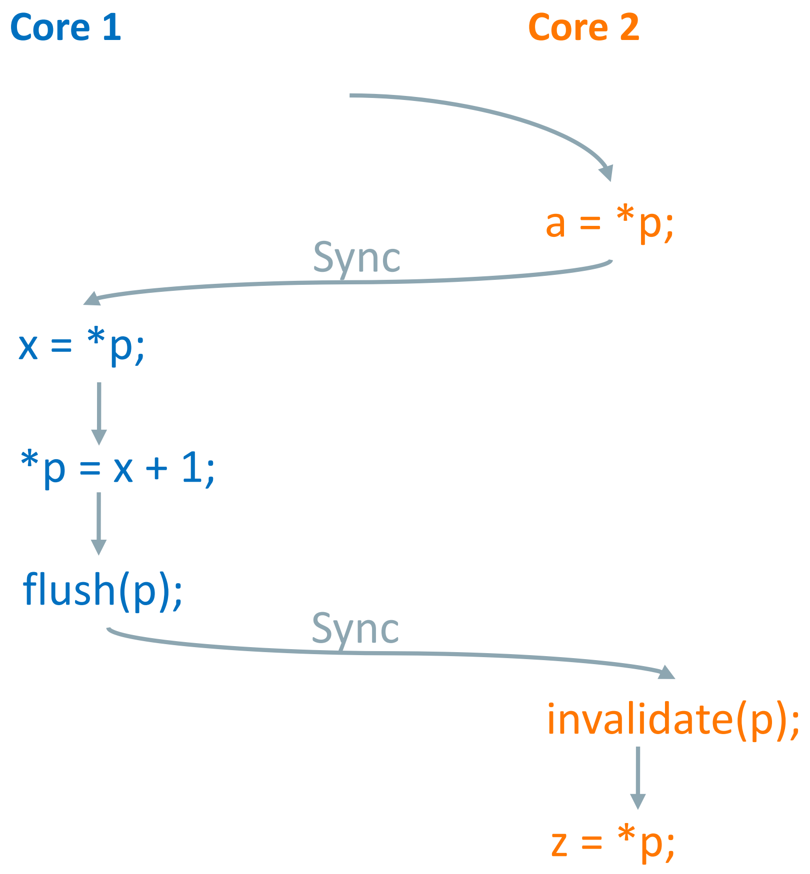

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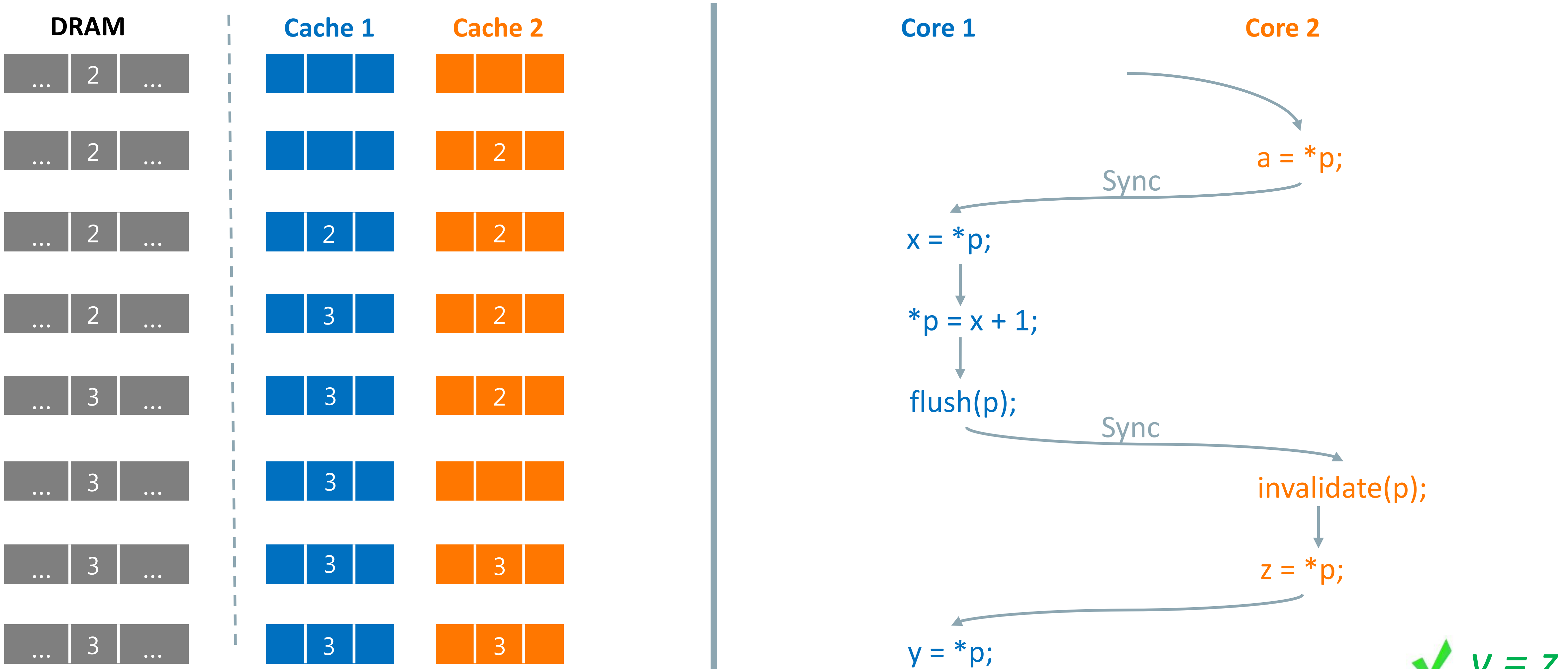

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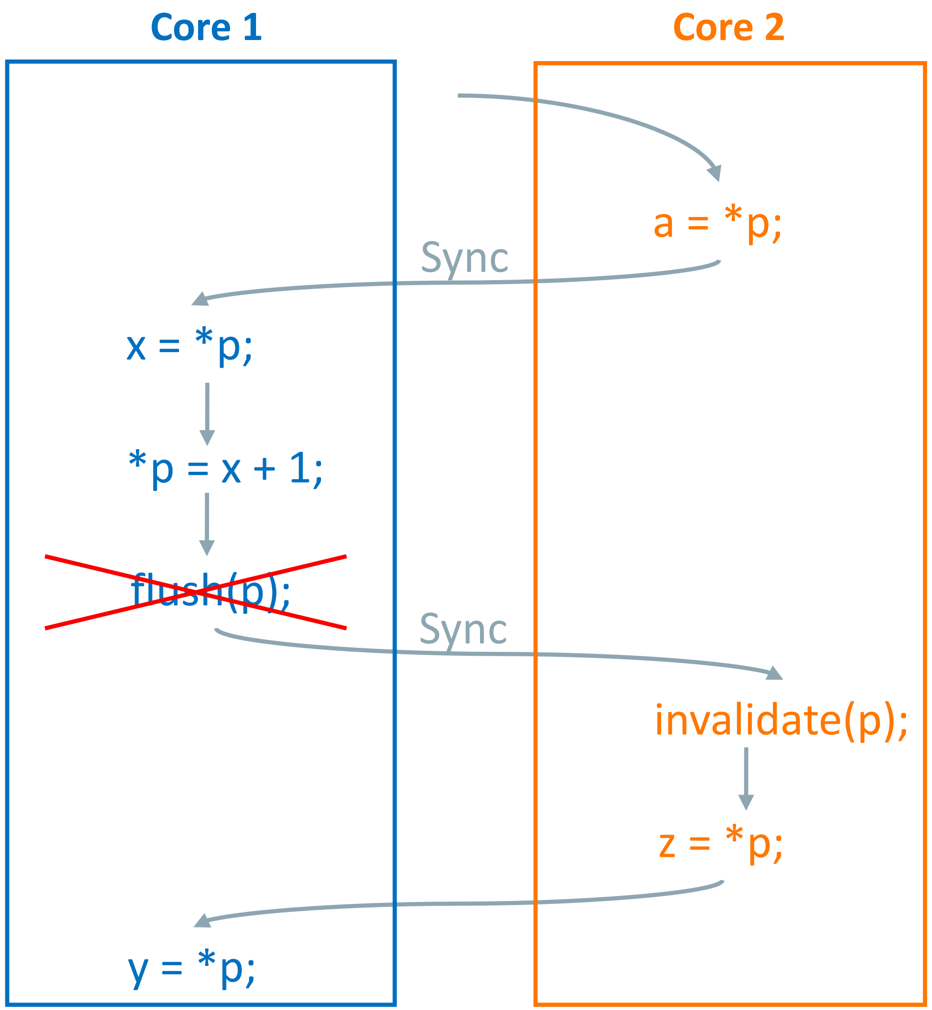

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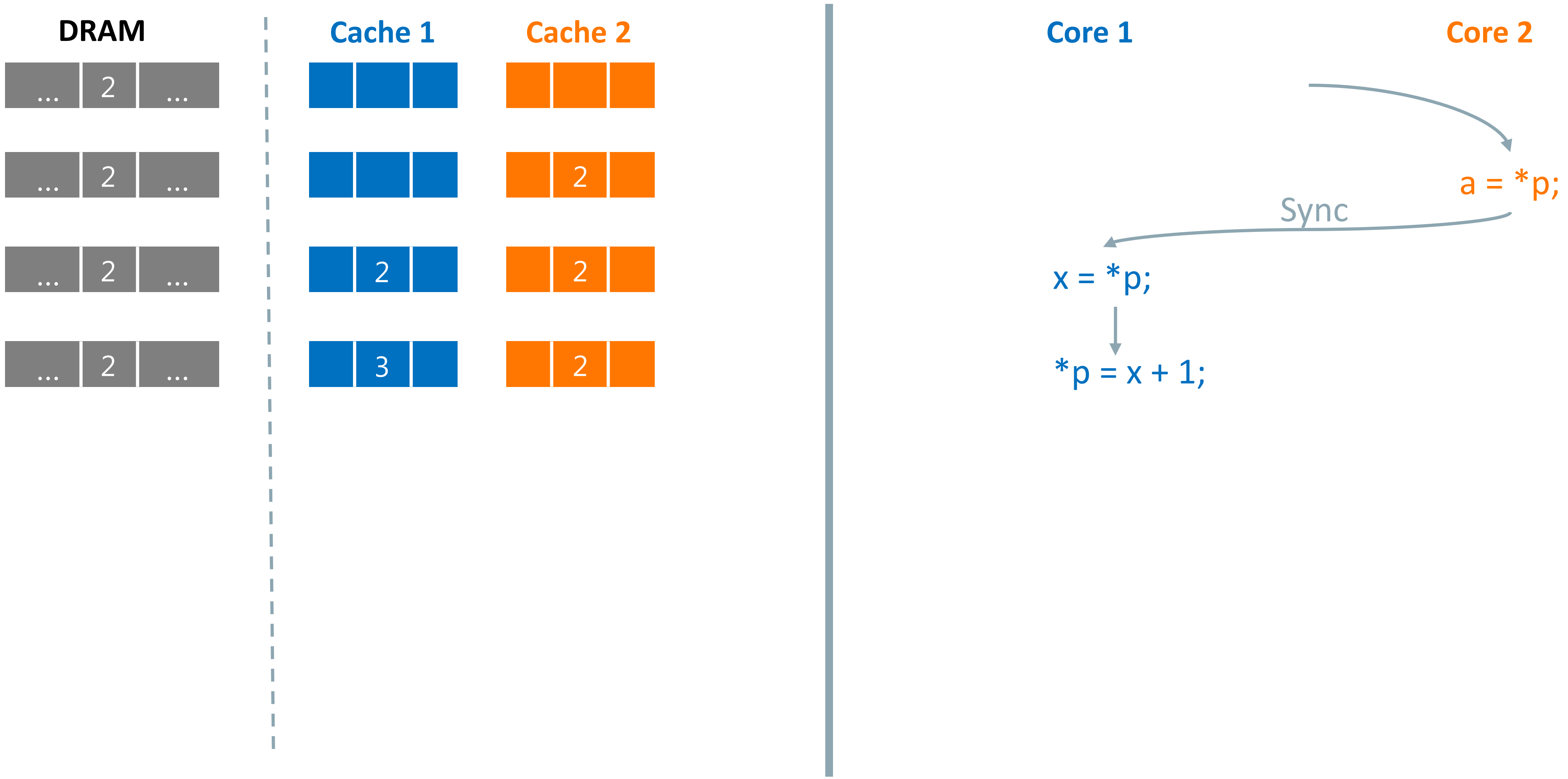

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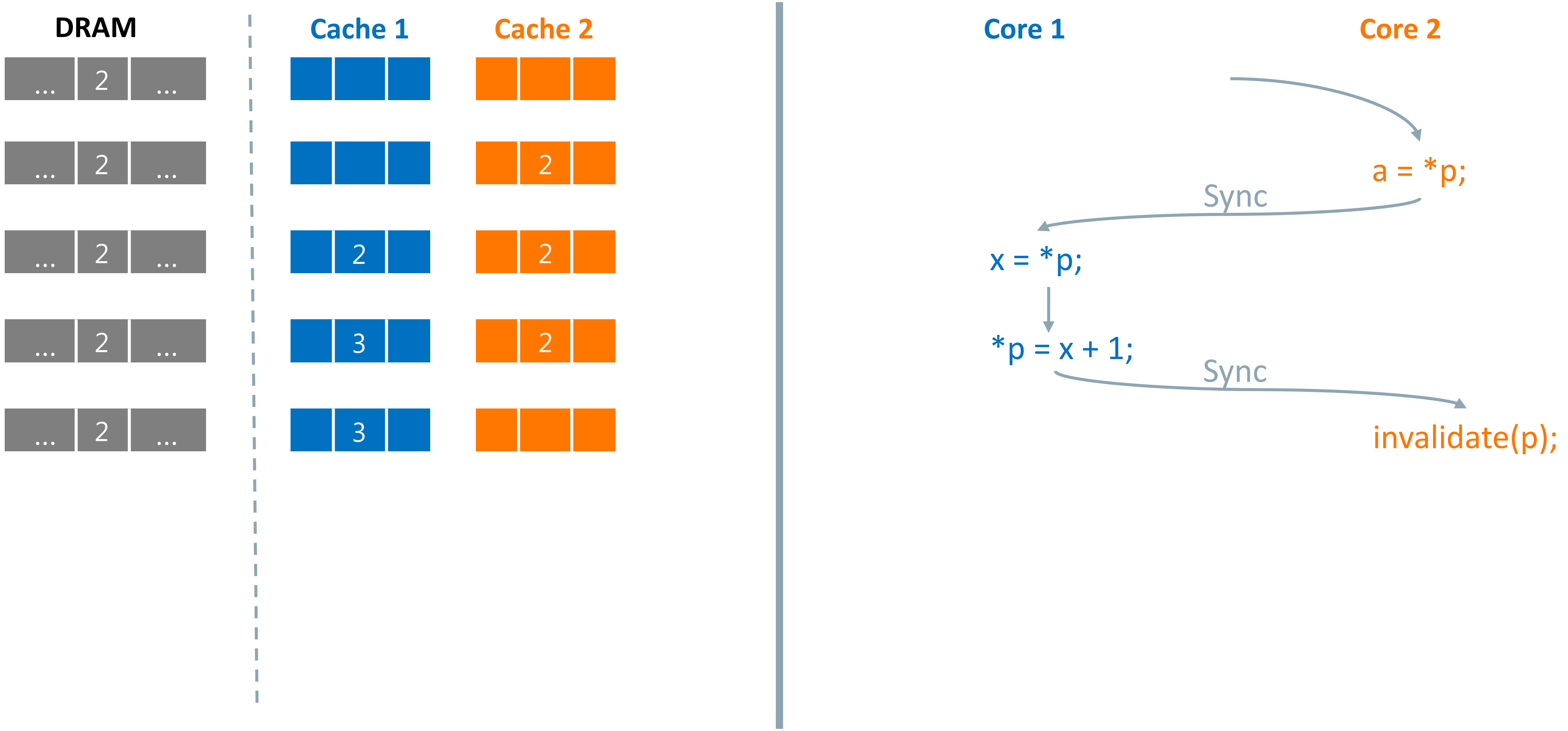

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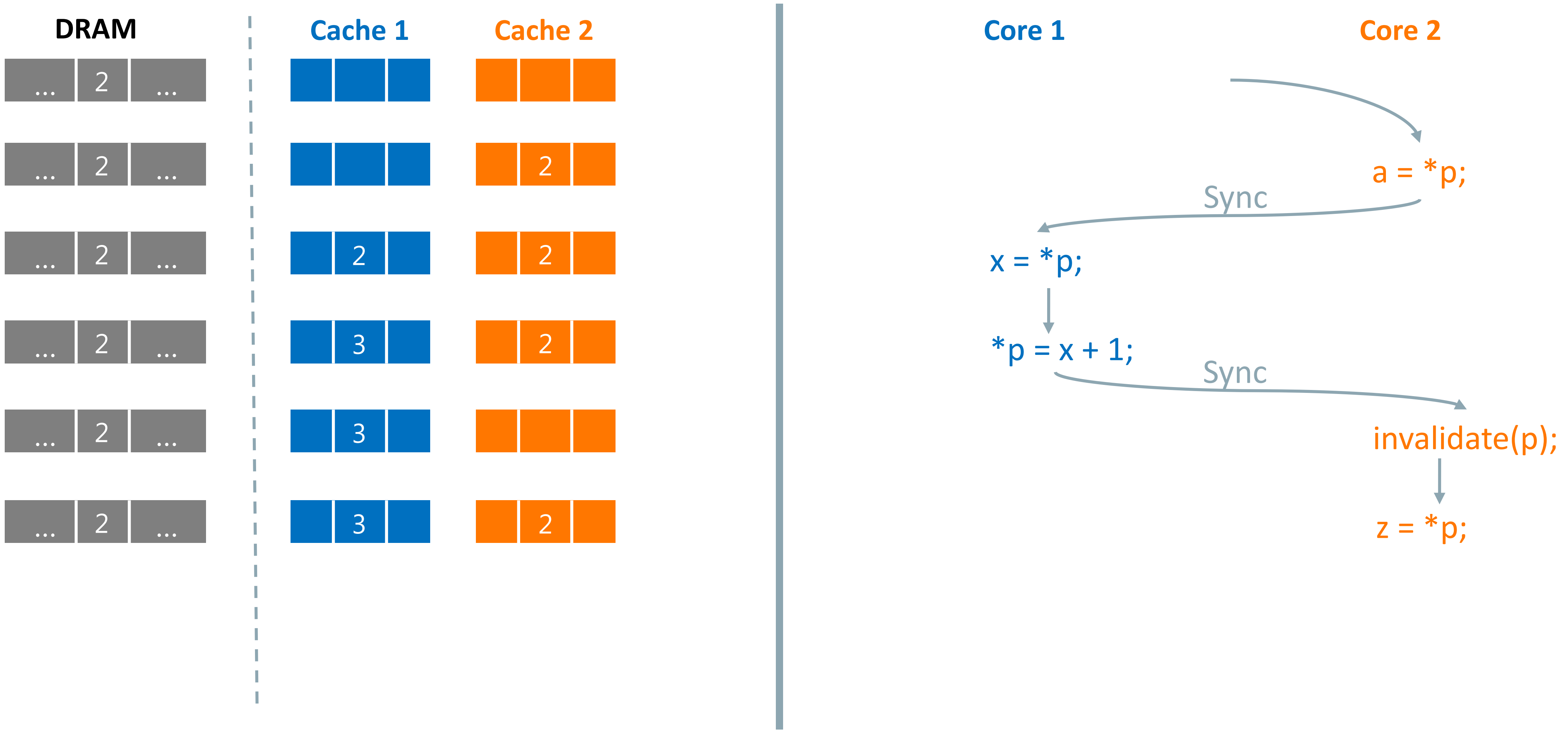

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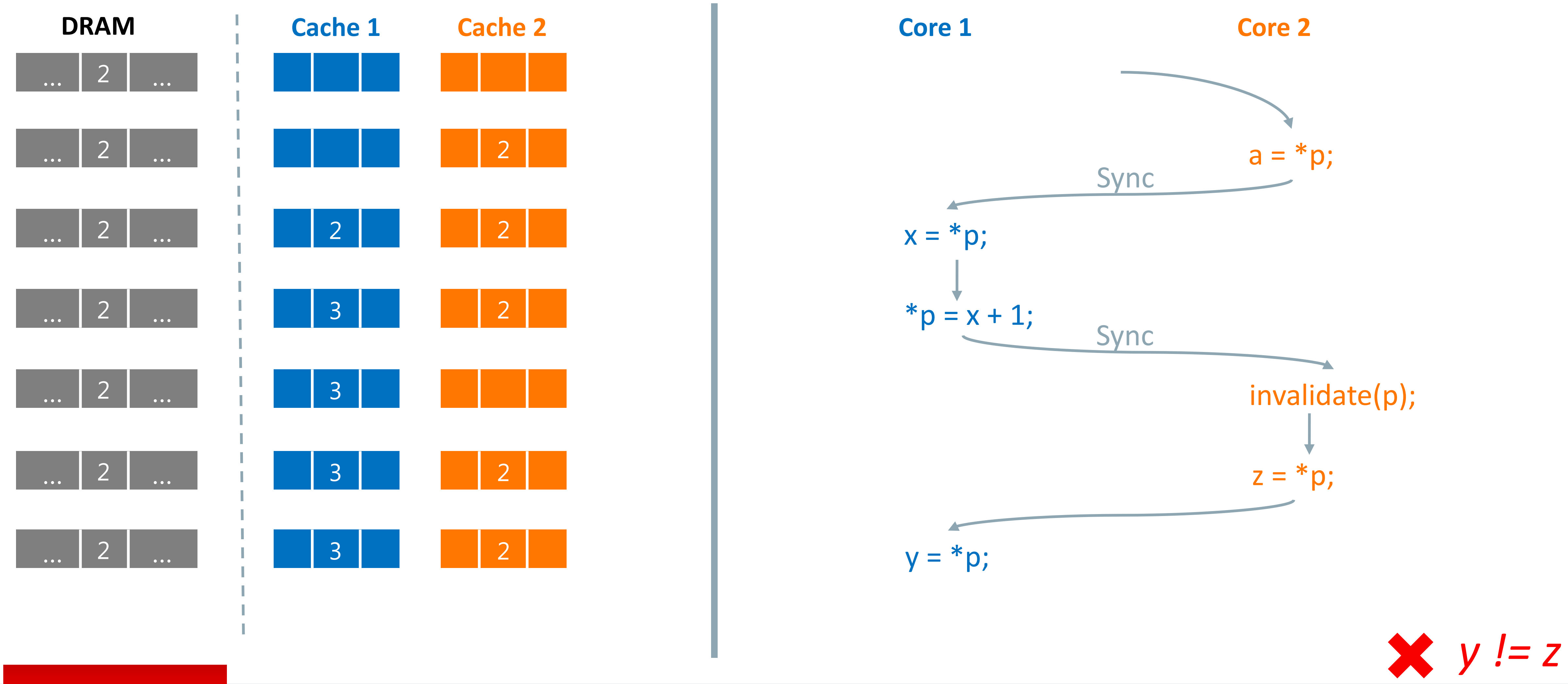

Cache Coherence Issue

- Hardware
  - 32 Cores
  - 8 GB DRAM
- Software
  - ~50,000 lines of C code
- Approach
  - Investigate software model checking to verify cache coherence

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Model Checking

- A formal technique which automatically verifies the desired behavioral properties ***p*** of a given system , on the basis of a user-defined model ***M*** and initial state ***s***.

$$M, s \models p$$

- Verification procedure is an exhaustive search of the state space of the design.
  - No proofs
  - Counterexamples
  - State-space explosion

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Model Checking Tools

- Initial investigation suggests SPIN is the best choice.

	Model Language	Properties Language	Concurrency Support	Scalability
SPIN	Promela (C-like)	LTL User assertions	Yes	Multi-core, State compression, Partial order reduction
CBMC / LLBMC	C/C++	Built-in options User assertions	Partial	SAT-solver/ SMT-solver Bounded checking
NuSMV / NuSMV2	SMV	LTL and CTL	Yes	SAT-solver
BLAST / CPAChecker	C	Program instrumentation	No	Counterexample-driven, Refinement
CADP / FDR2	LOTOS / CSP	Automata / User assertions	Yes	Compressing states

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Cache Coherence Model in Promela

- Model the main memory
  - Accurate
  - Flat memory: an array of bytes

```
byte    DRAM[MAX_ELEMENT];
```

    - Each C language pointer in Promela is an integer, which is used to index the `DRAM` array.
- Model the cache
  - For each particular memory location, it has 4 possible states (U/I/S/M) at all `N` cores.

```
typedef CACHE {
            State state[N];
}
CACHE   cache[MAX_ELEMENT];
```

U: Unknown
I: Invalid
S: Shared
M: Modified

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Cache Coherence Model in Promela

- State Transition Diagram
  - Operations: LOAD, STORE, MALLOC, FREE, FLUSH and INVALIDATE

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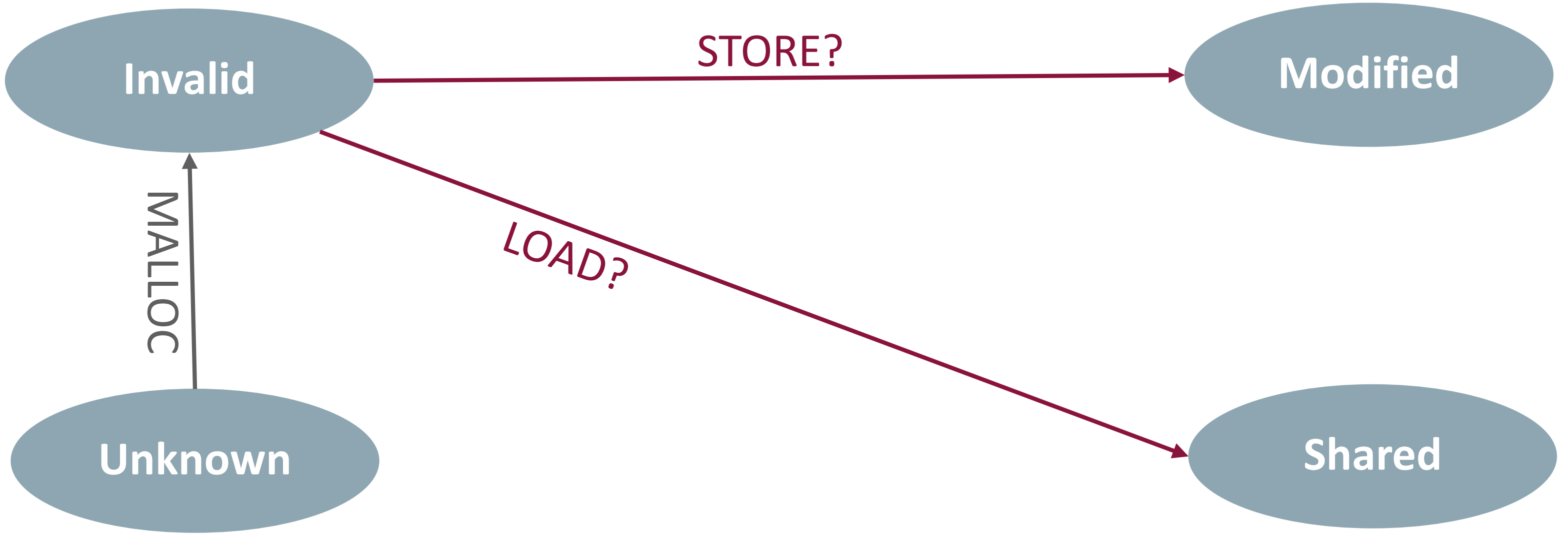

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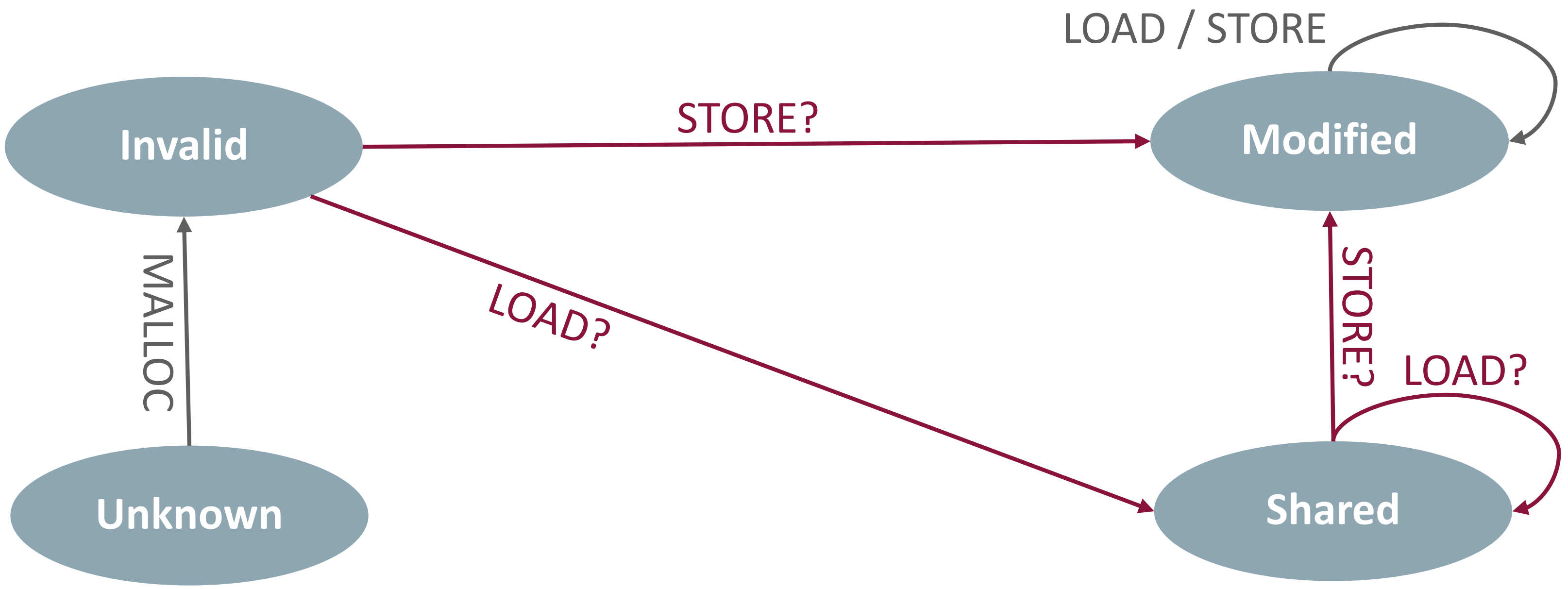

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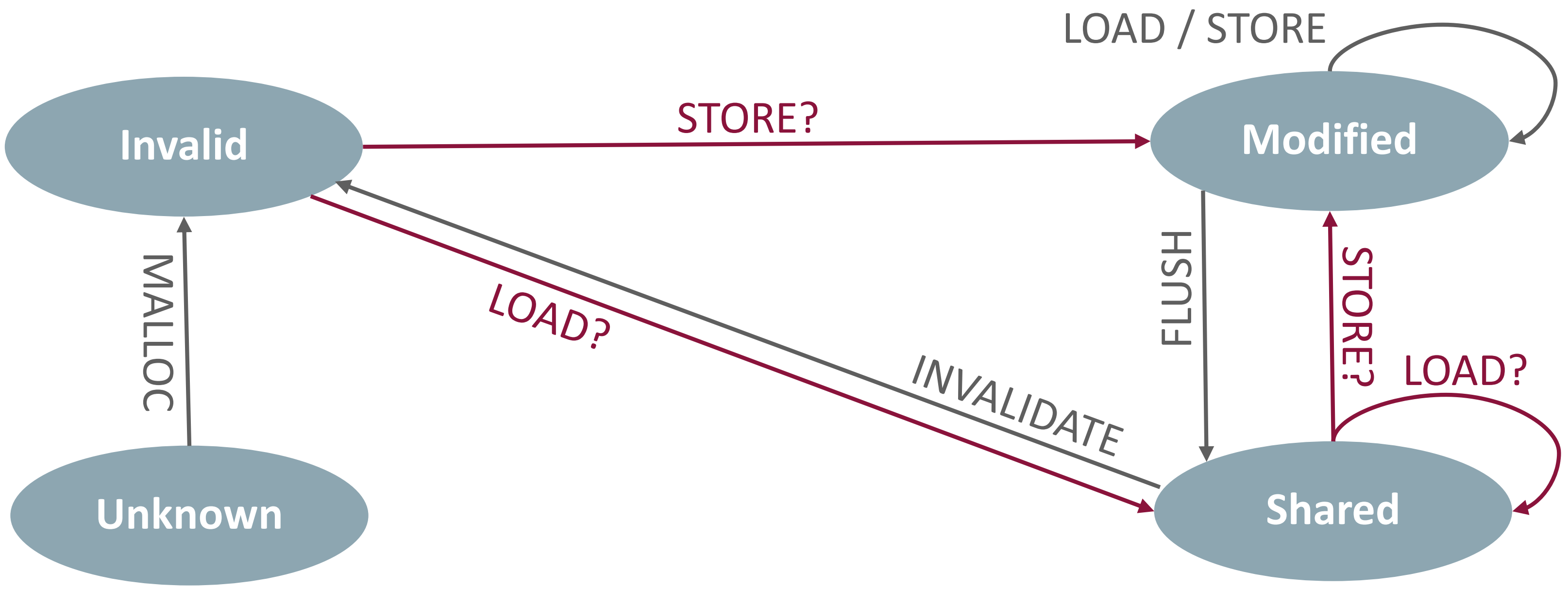

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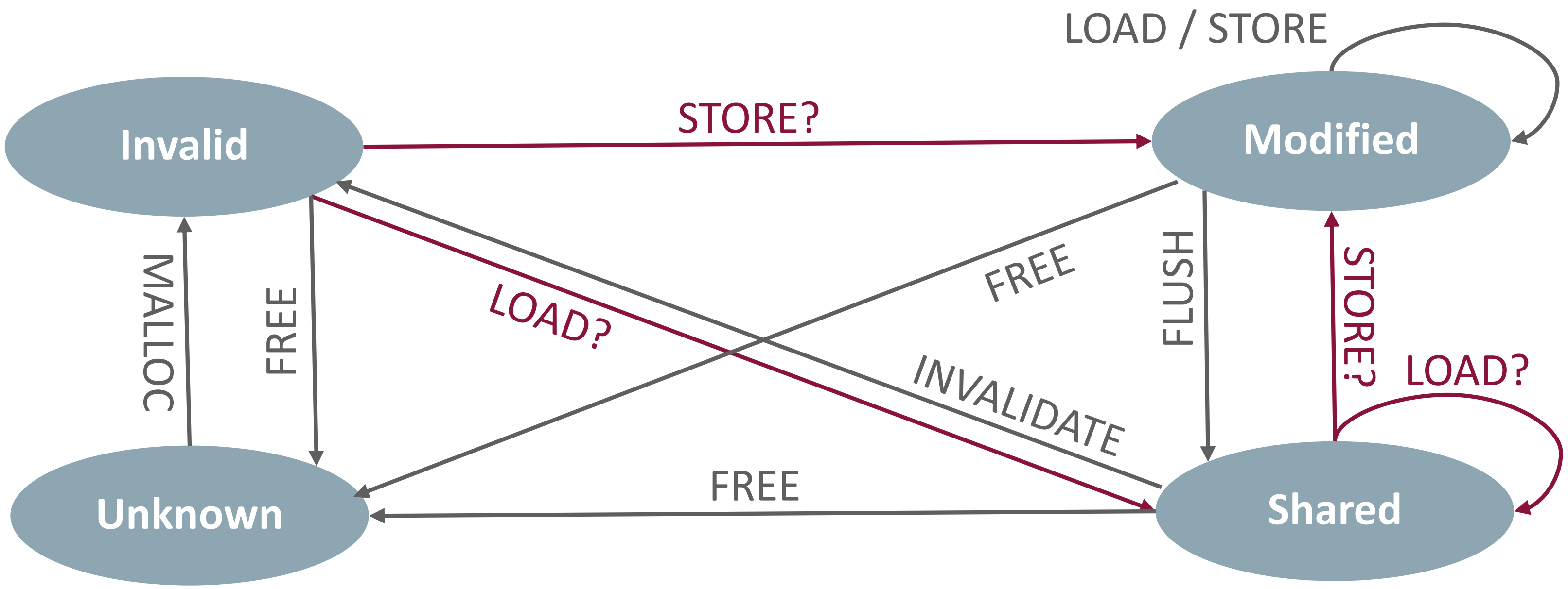

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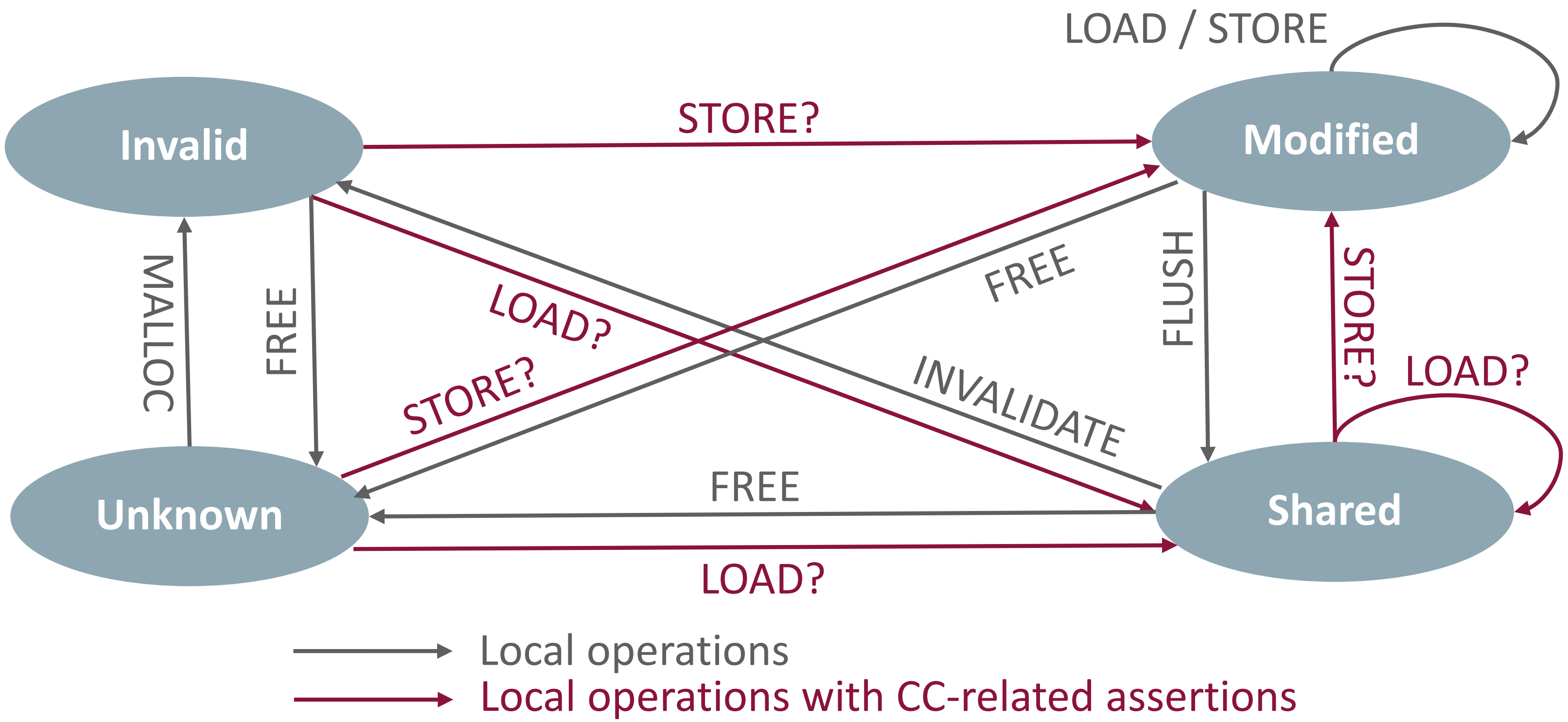

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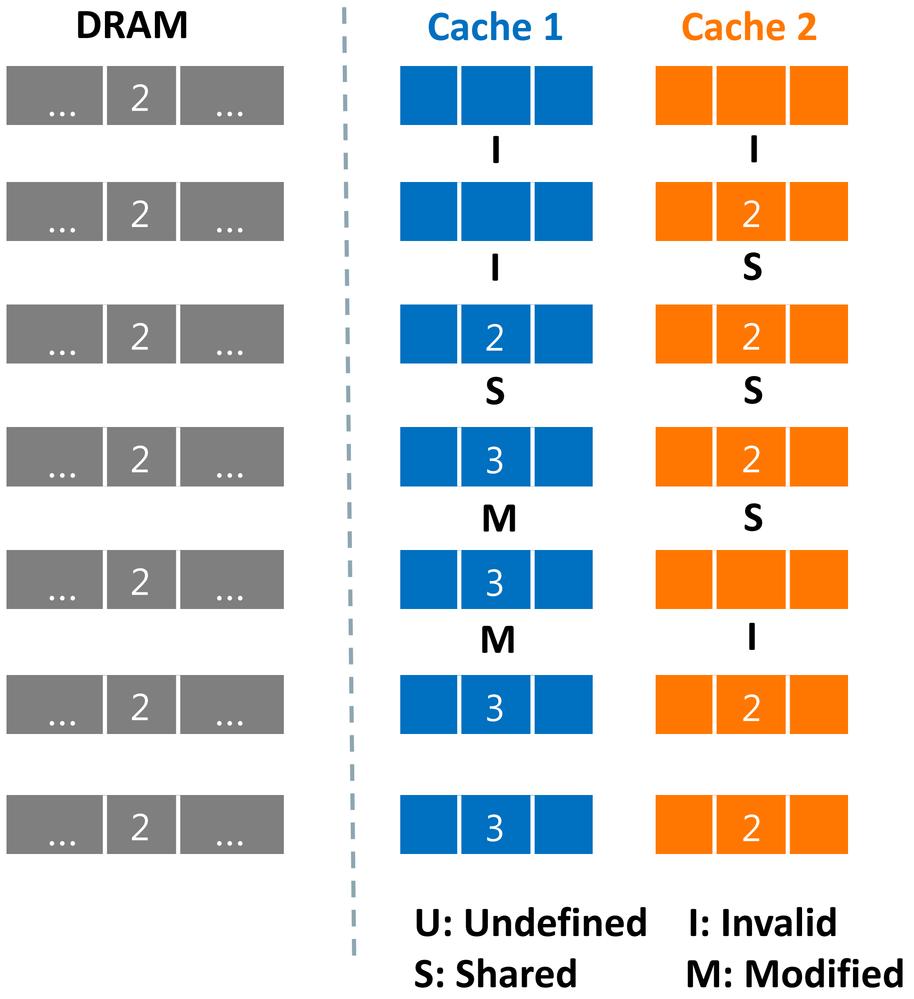
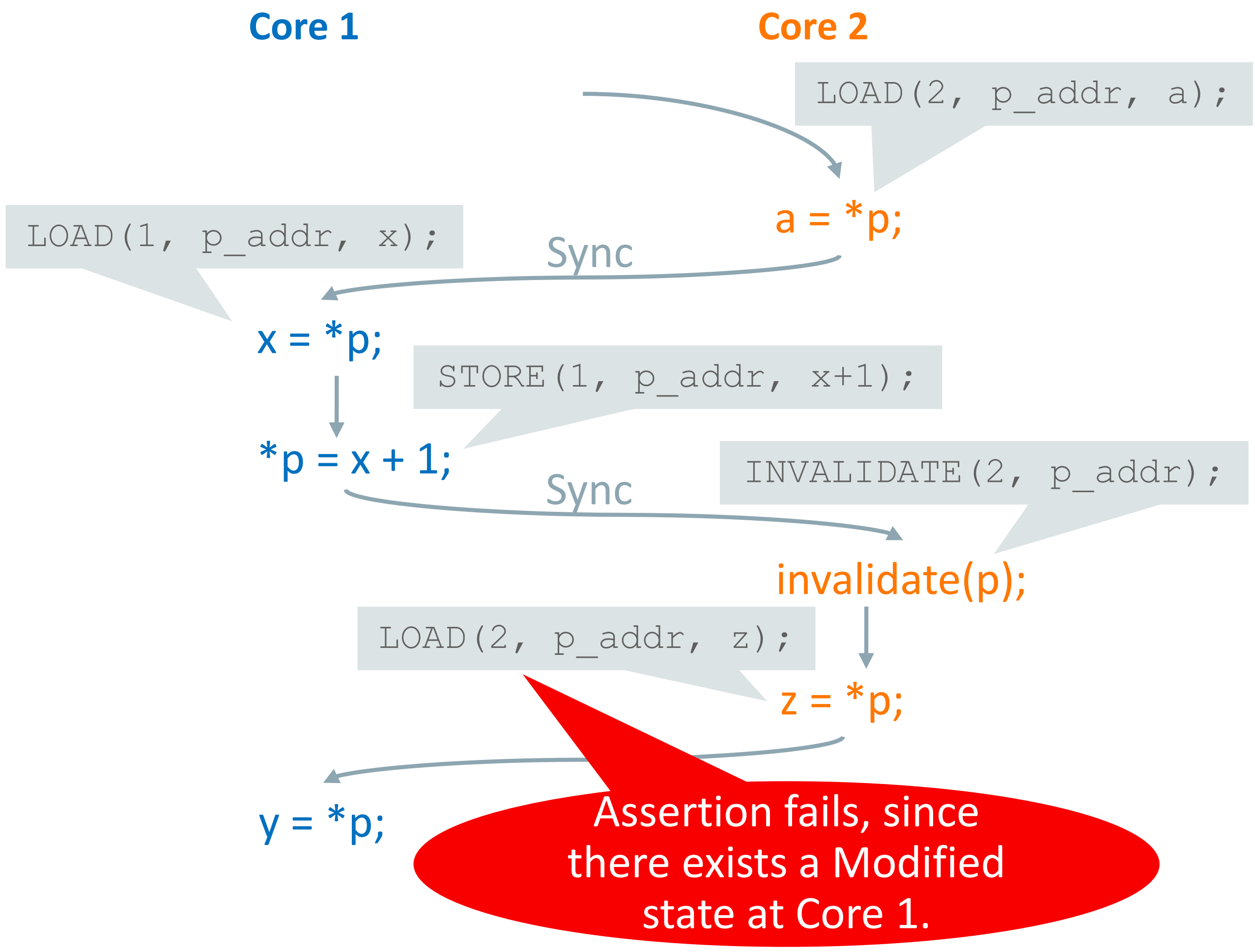
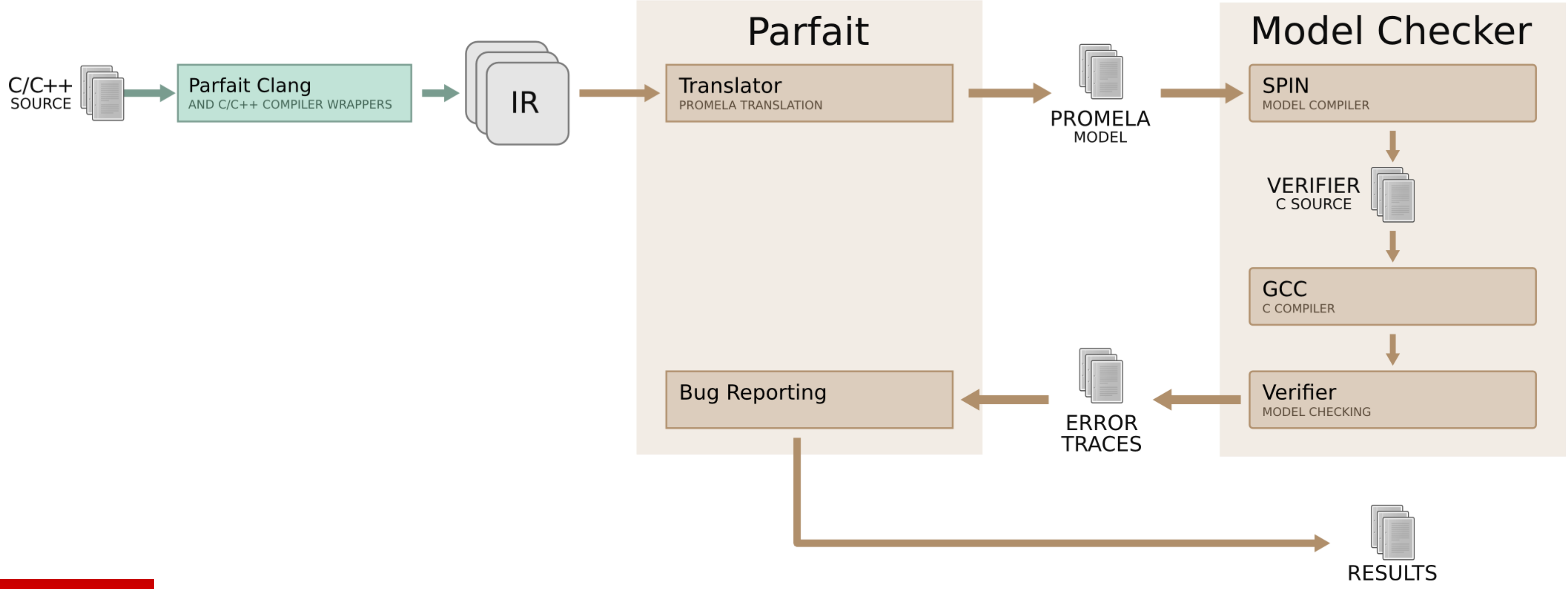




Automated Translation of C code to Model

- Translation of program from LLVM IR to Promela
- Generates Promela model with equivalent semantics to original program
  - With instrumentation added for each memory operation to check cache coherence



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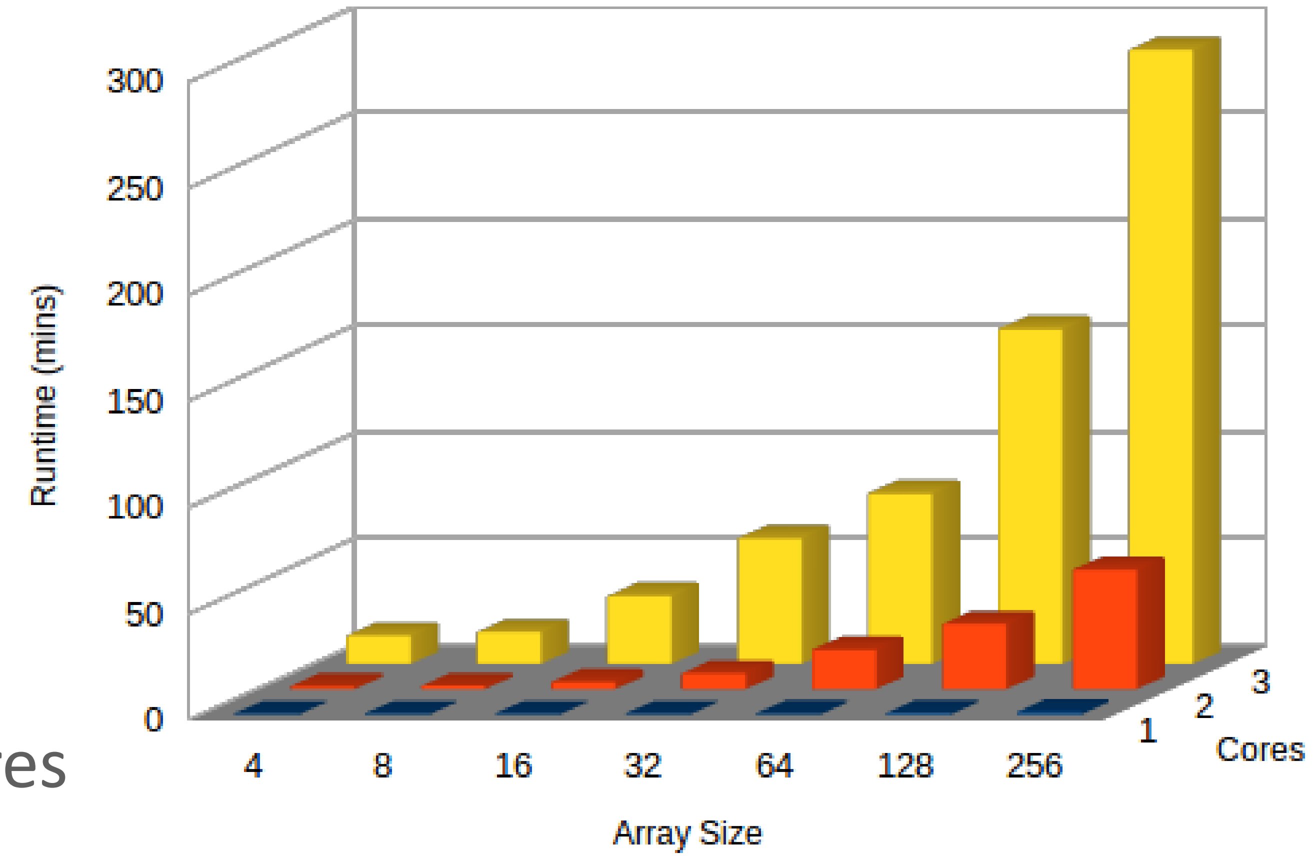
Automated Translation of C code to Model

- Optimisations
  - Group consecutive non-memory operations into atomic blocks
    - Avoids exploration of different interleavings of operations that cannot affect each other
    - 10x speedup in verification
  - Use SPIN's bounded context switch mode
    - *"Relatively low bounds on the number of context switches suffice for a model checker to visit all the reachable states of a model at least once." (Musuvathi, PLDI2007)*
    - Only explore execution paths with the number of preemptions less than a specified bound
    - 8x speedup in verification with a bound of 2

Results - Scalability

- Larger synthetic example: concurrent quicksort
  - ~200 lines of code
- Tested performance of model checking with different configurations
  - Number of concurrent cores
  - Number of elements to be sorted
- Largest test: 256 elements, 3 cores
  - Verification took ~5 hours



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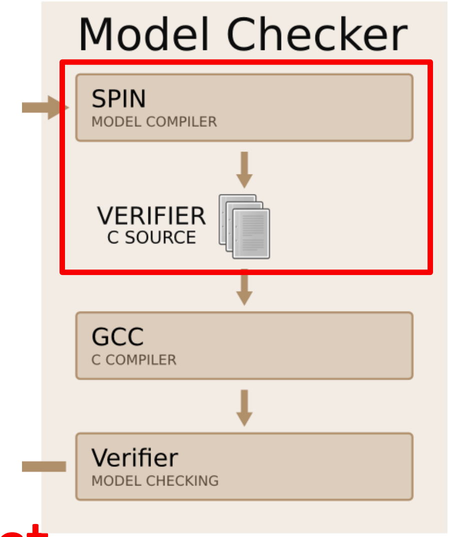
Results - Scalability

- Translated model for a C code base for about 50,000 LoC
  - ~6,000,000 lines of Promela (~1,150,000 with no function inlining)
- SPIN cannot process a model this large
  - Compiling the model did not terminate after 90 hours
- Optimisations implemented in SPIN
  - Compiling the model completes in 4 hours
  - Verifier code generated is 100,000,000 lines of C code
  - Compiling with gcc ran out of memory (64G)
- Current approach using SPIN does not scale for our project.



Further Investigation into Other Model Checkers

- More model checkers have been evaluated
  - Explicit State model checkers: Murphi/PReach, DIVINE
  - Symbolic model checkers: CBMC, LLBMC, ESBMC, SAL, Mocha, Alloy, SATABS, CSeq
  - Hybrid: LTSmin
- Initial experimental result
  - Many of them are designed for state transition systems, and only work well for algorithm verification.
  - Some of them use inlining to handle method calls and then exclude recursive calls.

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Further Investigation into Other Model Checkers

Model Checker	Concurrency	Recursion	Quicksort 8 elements, 1 core	Quicksort 32 elements, 1 core	Quicksort 8 elements, 2 cores
SPIN	Yes	Yes	38 s	42 s	112 s
LLBMC	No	Yes (bounded)	40 s	1500 s	N/A
CSeq	Yes	No	N/A	N/A	N/A
LTSMin	Yes	Yes	> 4 h	> 4 h	> 4 h
SATABS	Partial (doesn't support shared dynamic memory)	No (ignores recursion)	> 4 h	> 4 h	N/A
CBMC	Yes	Yes (bounded)	48 s	> 2 h	> 2 h

- SPIN still appears to be the best choice

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Conclusion

- Current approach of full software model checking for the verification of cache coherence will not scale for our 50k LoC codebase.
  - Accurate model of program memory and execution produces large models and causes state explosion

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Next Steps

- Reduce model size and complexity via abstraction of the program
  - No longer verification (may have false positives / negatives)
  - Use abstracted memory model (e.g. based on points-to analysis)
  - Use slicing to separate the program into multiple smaller parts involving a subset of cores and verify independently
    - May be applied to either accurate or abstracted memory models
  - Manually abstract some auxiliary functions
- Reduce the number of interleavings explored
  - Group successive operations that only have local effects as one atomic operation
    - Use static analysis to determine which memory accesses do not access shared memory
  - Partial Order Reduction

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