Back to the Future: Leveraging Belady's Algorithm for Improved Cache Replacement

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Cache Replacement

- On a cache miss, which line should we evict?
  - Well-studied problem

- Belady provided an optimal solution in 1966

Belady's Optimal Algorithm (OPT)

- Evict the line that is accessed *farthest in the future*
  - Impractical

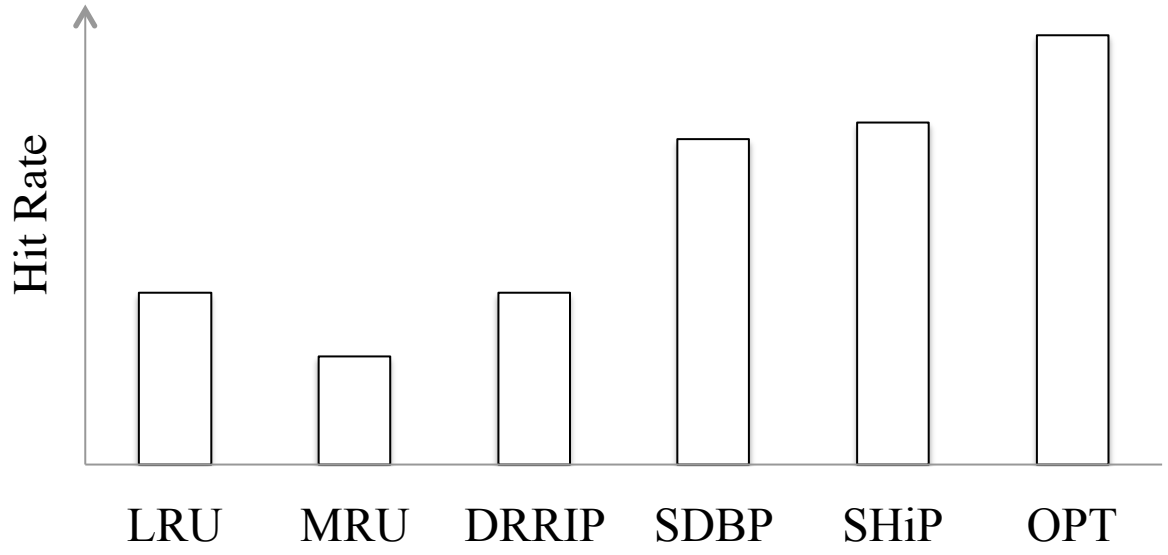
Existing Solutions

- Rely on heuristics that make *assumptions about the underlying access pattern*
  - LRU assumes recency-friendly accesses
  - MRU assumes thrashing accesses
  - Recent solutions use more sophisticated heuristics

- Problem: Heuristics don't work well when their assumptions don't hold

Example: Matrix Multiplication

A	*	B	=	C
Medium-term Reuse		Long-term Reuse		Short-term Reuse



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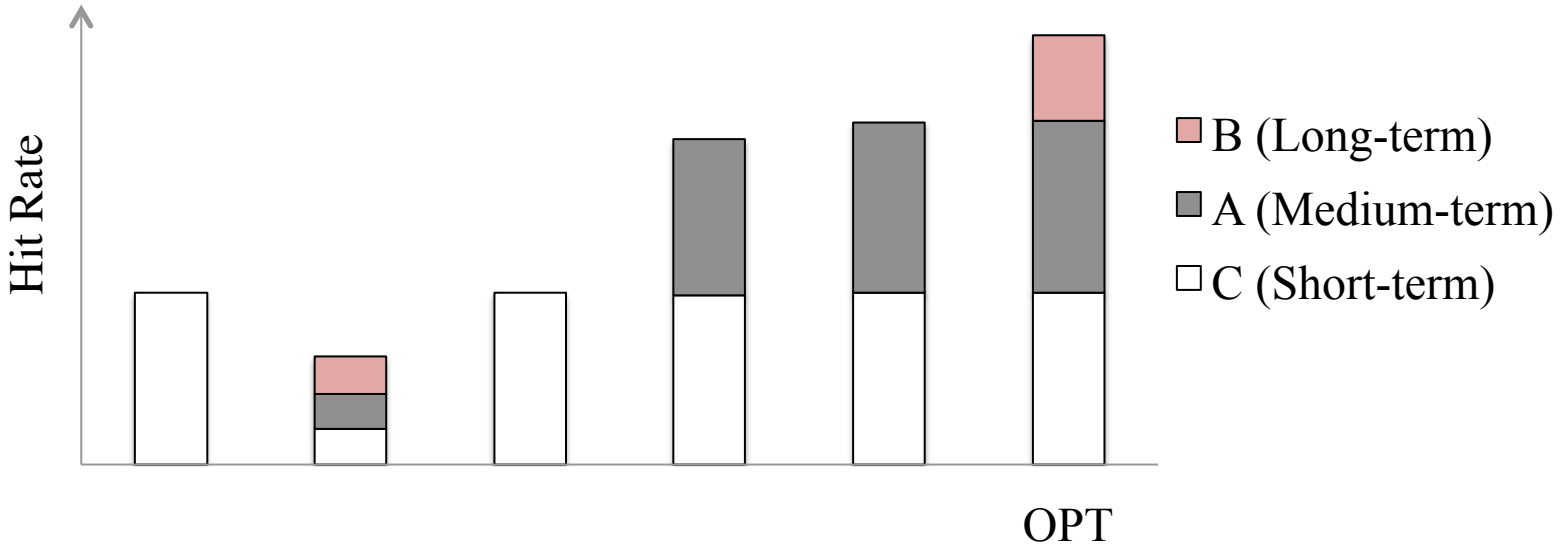
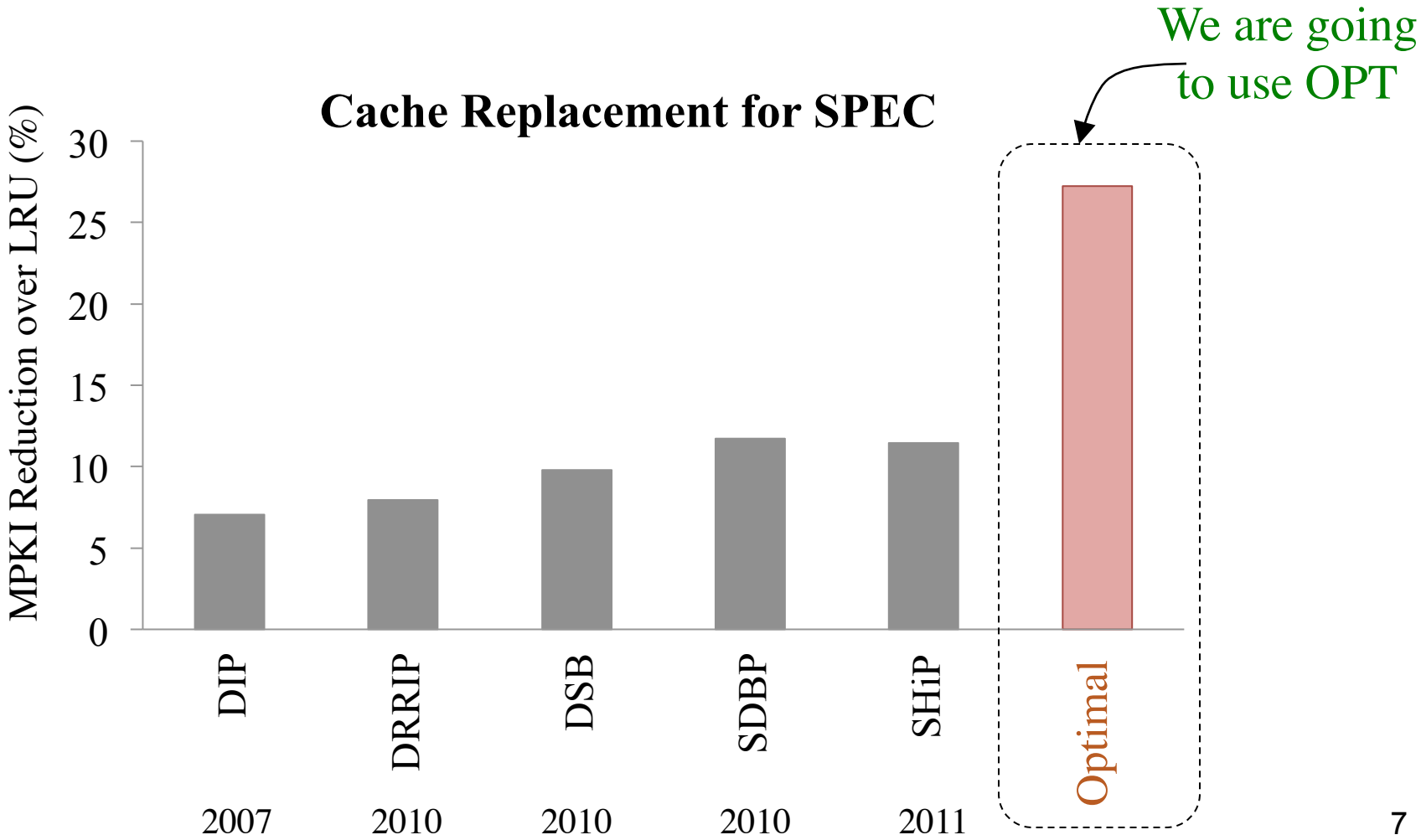
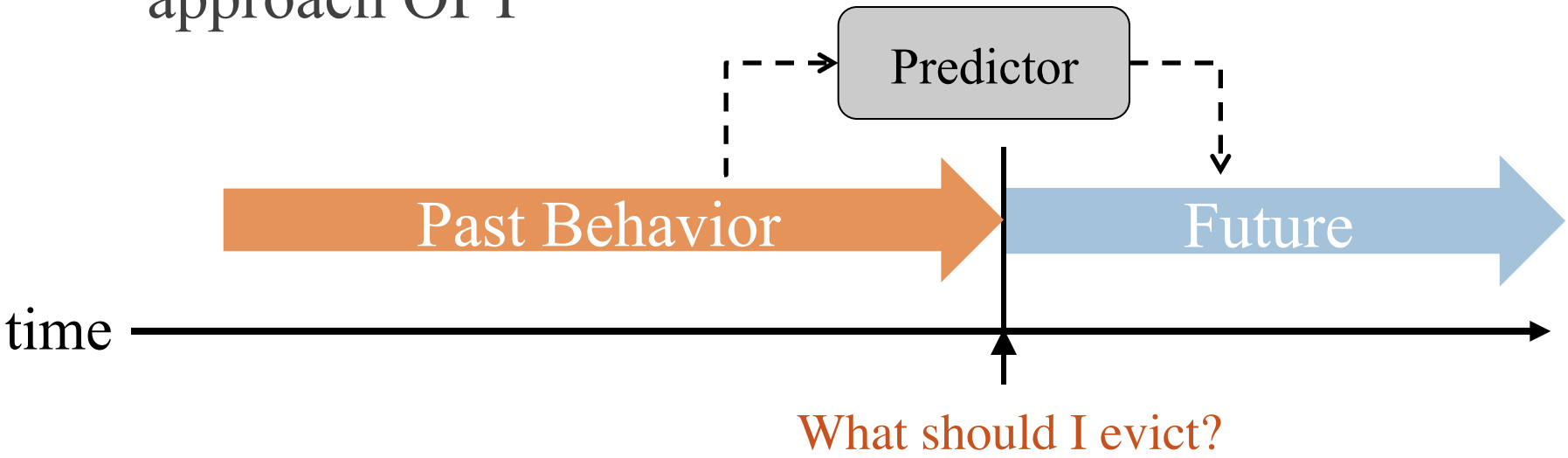


Significant Headroom



Our Solution: Key Idea

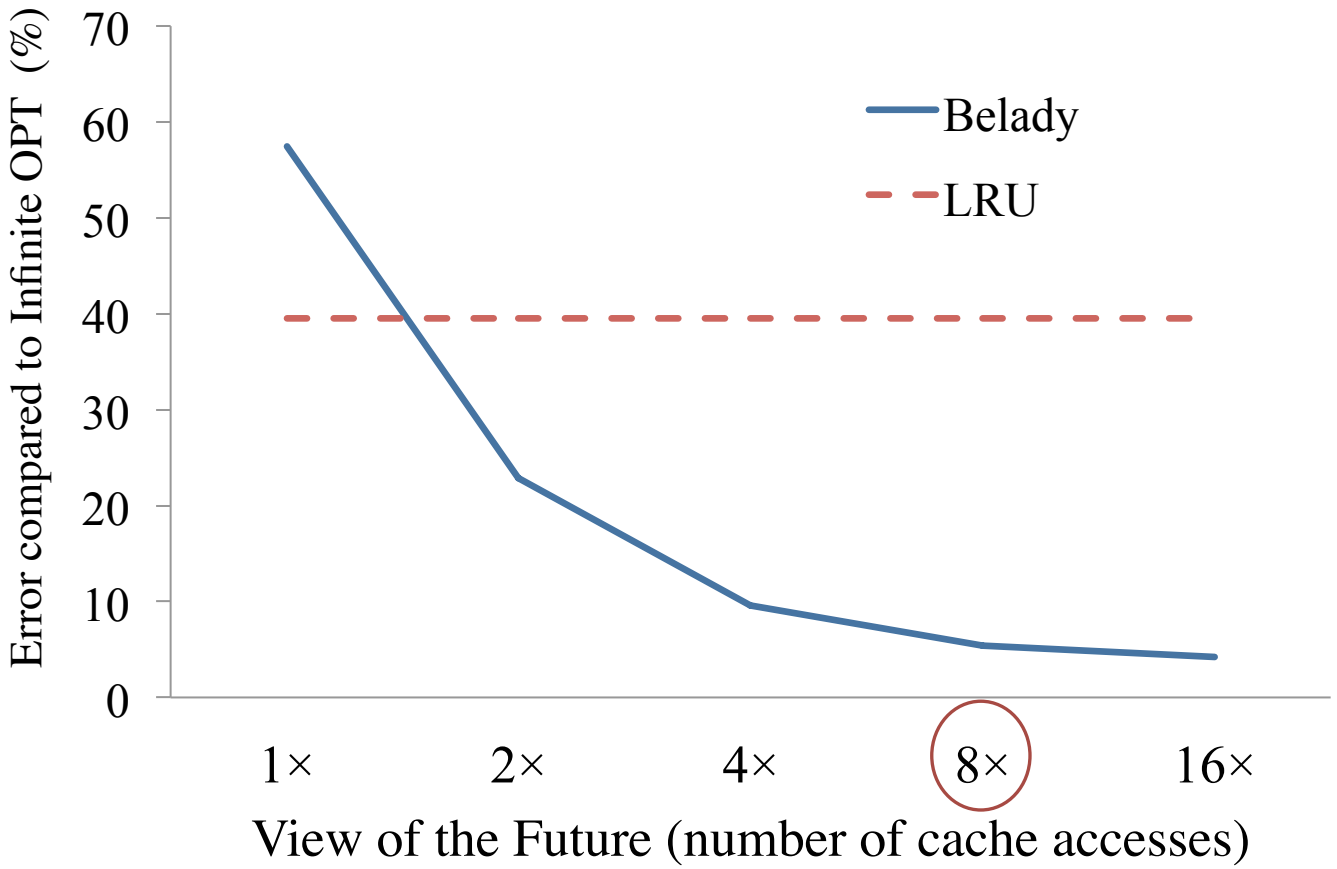
- We cannot look into the future
- But *we can apply the OPT algorithm to past events* to learn how OPT behaves
- If past predicts the future, then this solution should approach OPT



Complication

- OPT looks arbitrarily far into the future
  - We might need an arbitrarily long history

How far in the future does OPT need to look?



History length not unbounded, but we need to track past 8× cache accesses

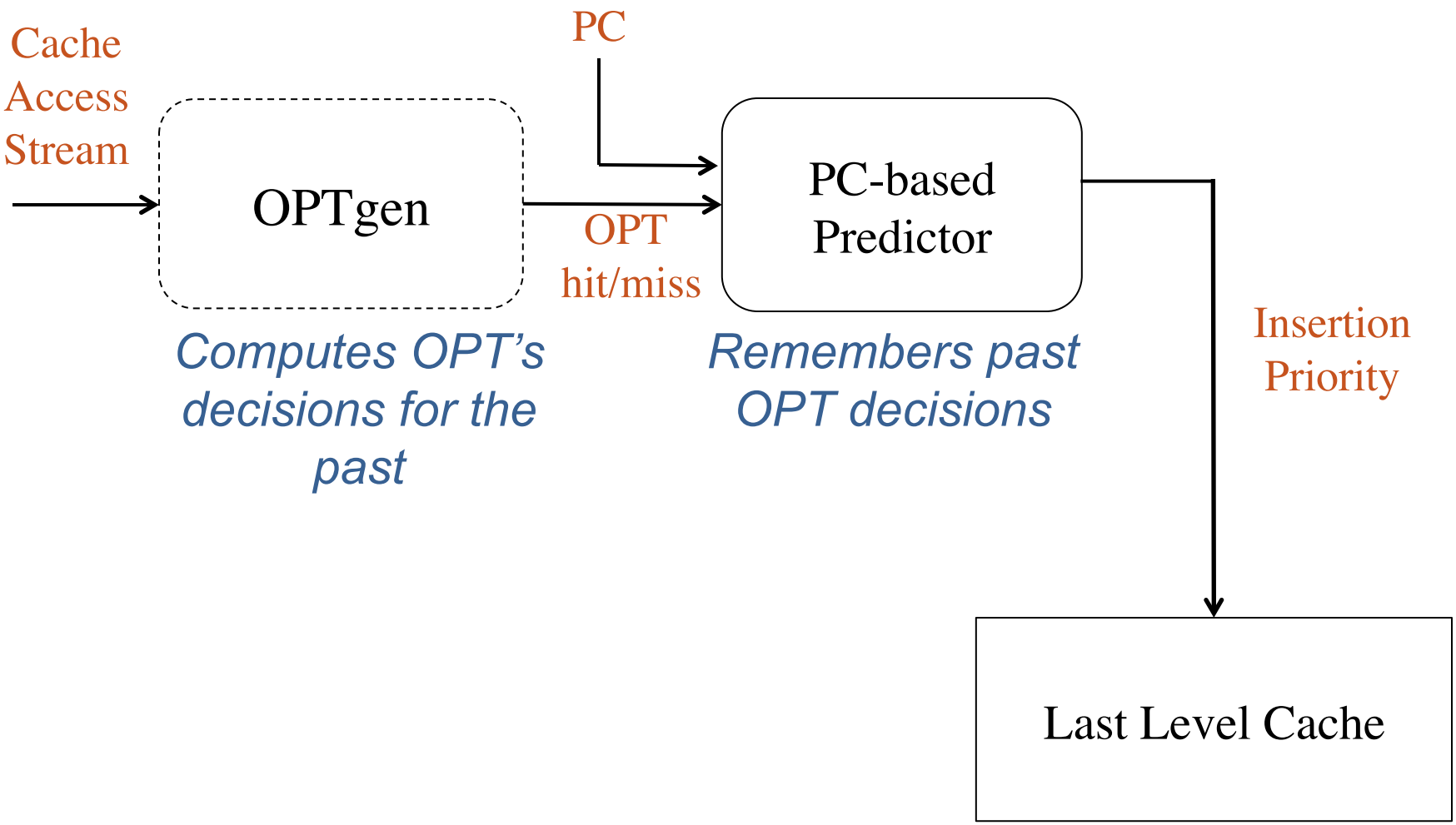
Our Solution

- Hawkeye Cache Replacement (Hawkeye)
  - Hawks can see 8× farther than the best humans

Hawkeye: Challenges

- Need to look at a *long history* (8× the cache size)
- Need to *efficiently compute the OPT solution* for a long history of past references
- New algorithm called ***OPTgen***
  - Online (linear time)
  - Sampling (12KB overhead for 2MB cache)

Hawkeye: Overall Design



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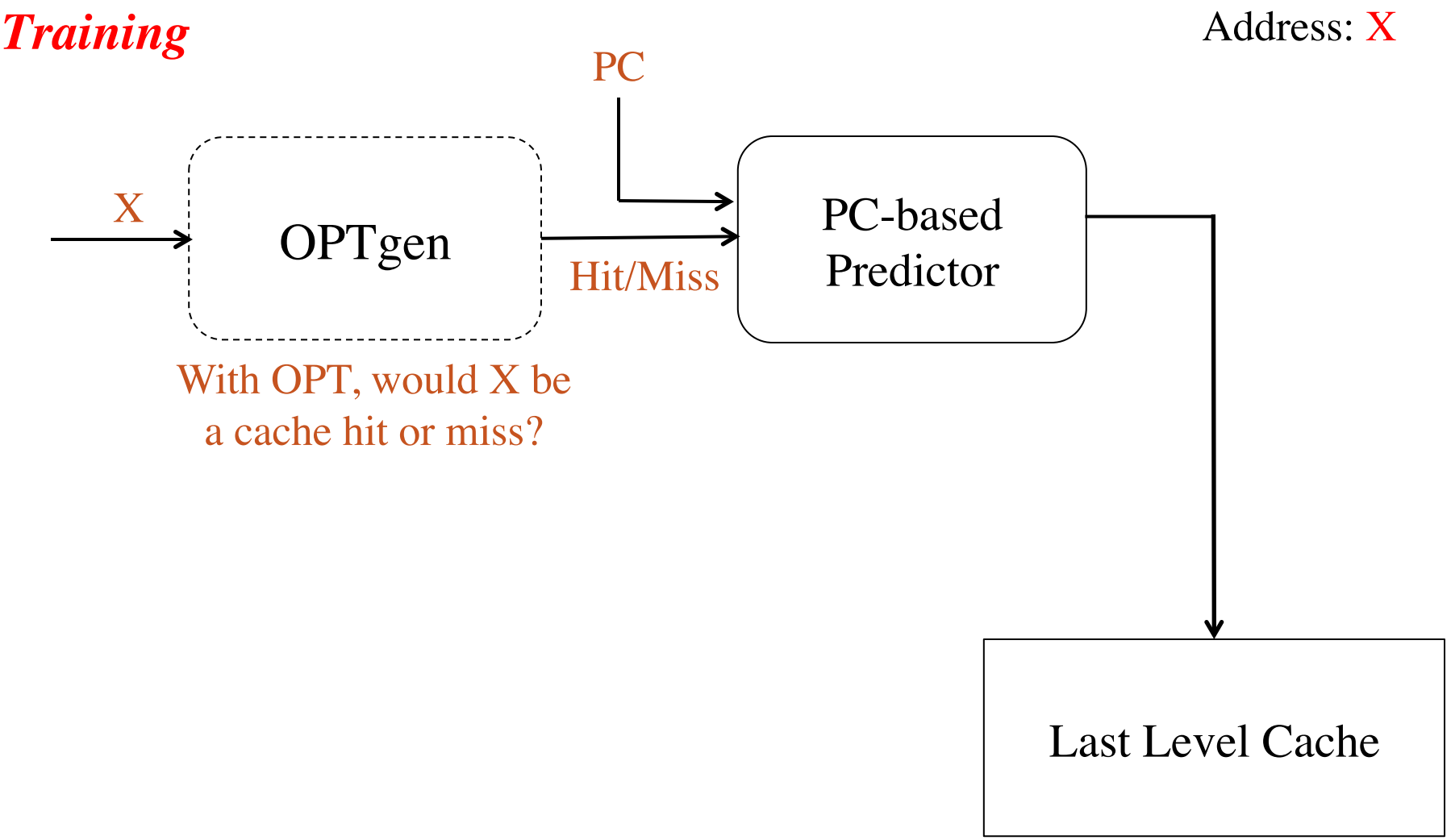

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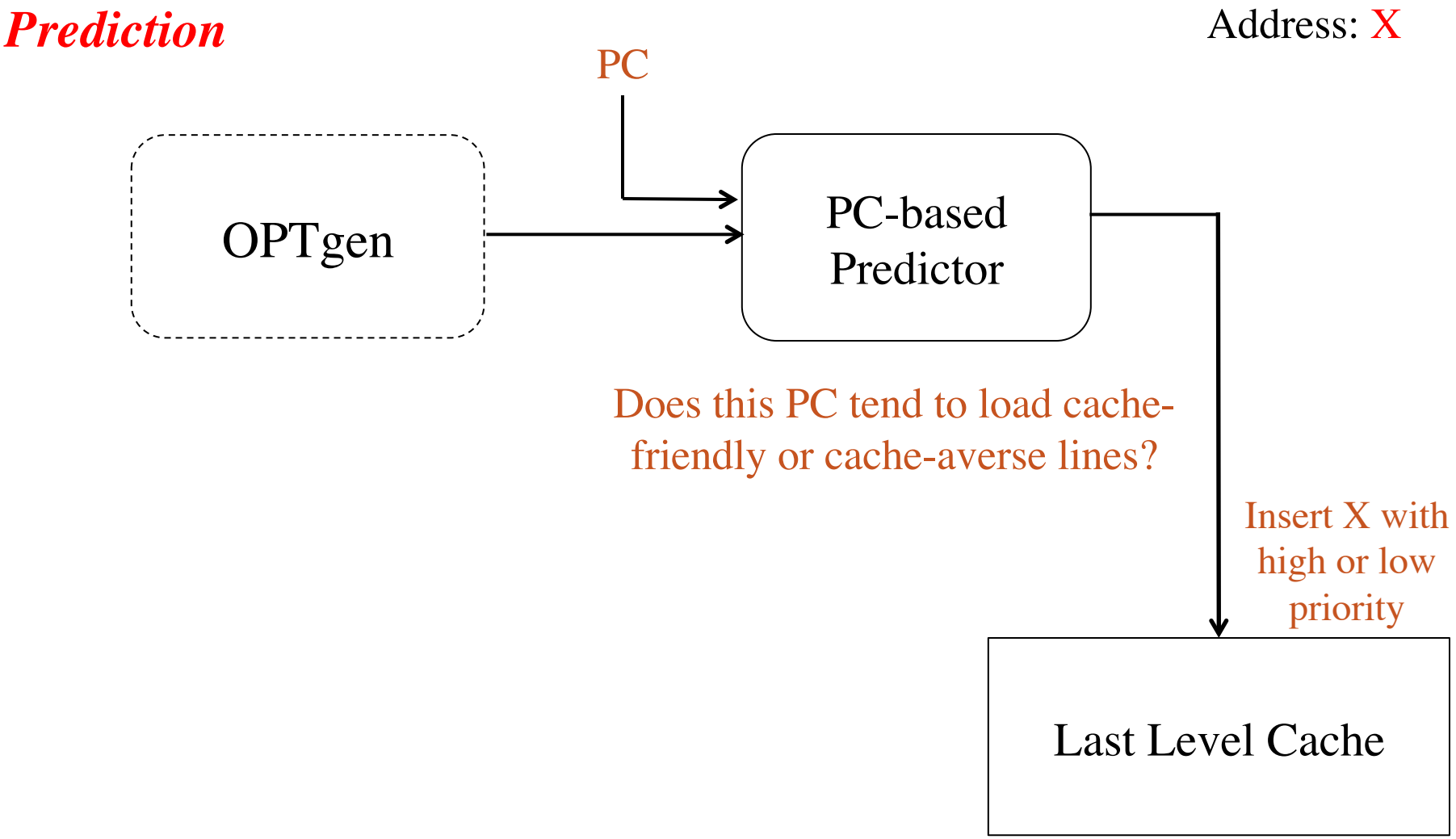
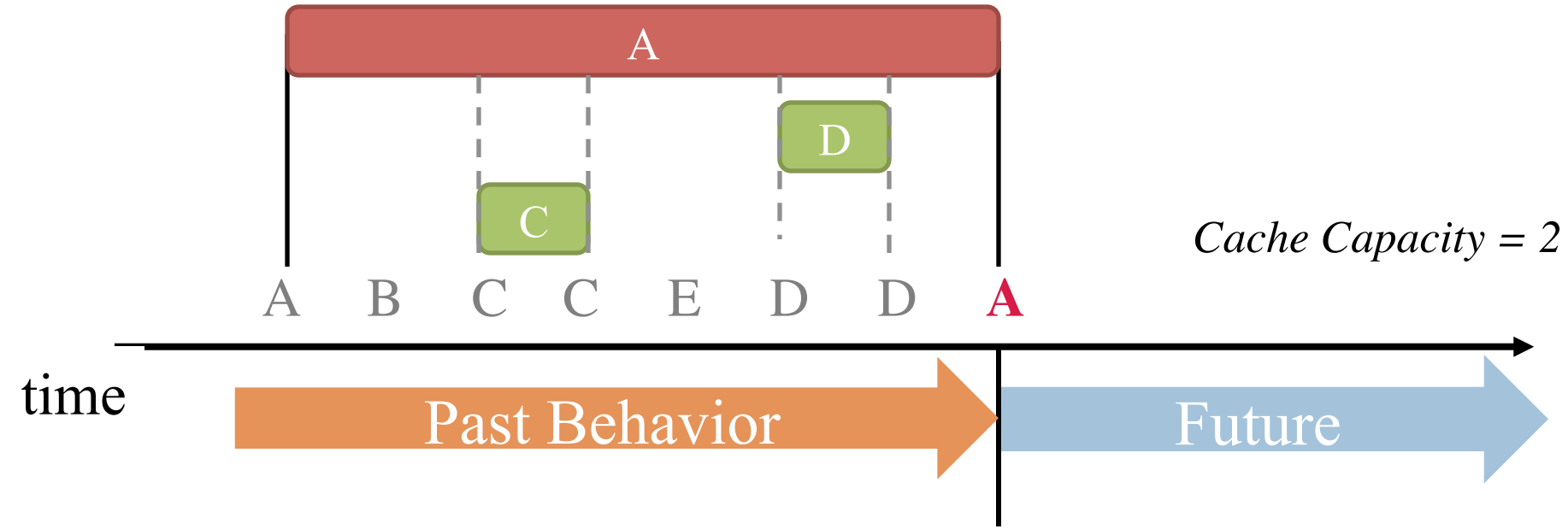


OPTgen

- Simple online algorithm that reproduces OPT's solution for the past
- Inspired from Belady's insight
  - Lines that are reused first have higher priority
- OPTgen also gives higher priority to lines that are reused first

OPTgen

- For each line, we ask if this line would have been a hit or miss with OPT.



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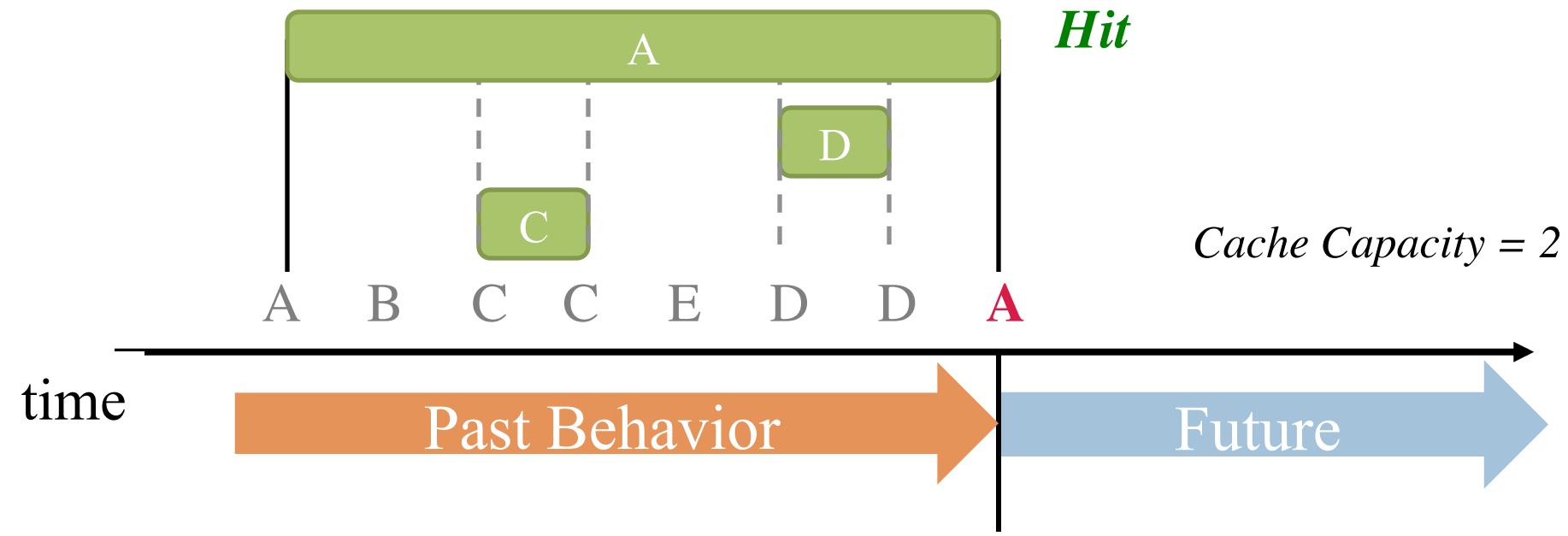

OPTgen

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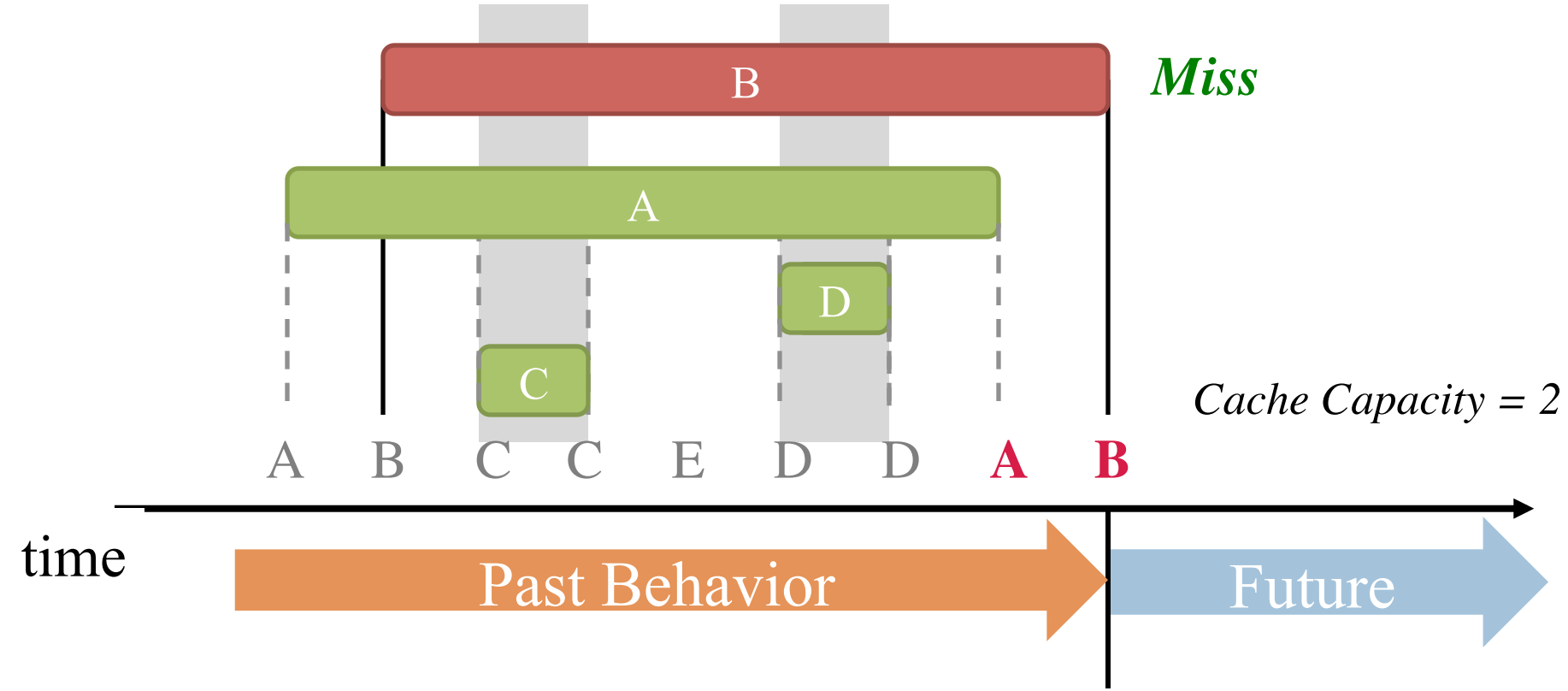


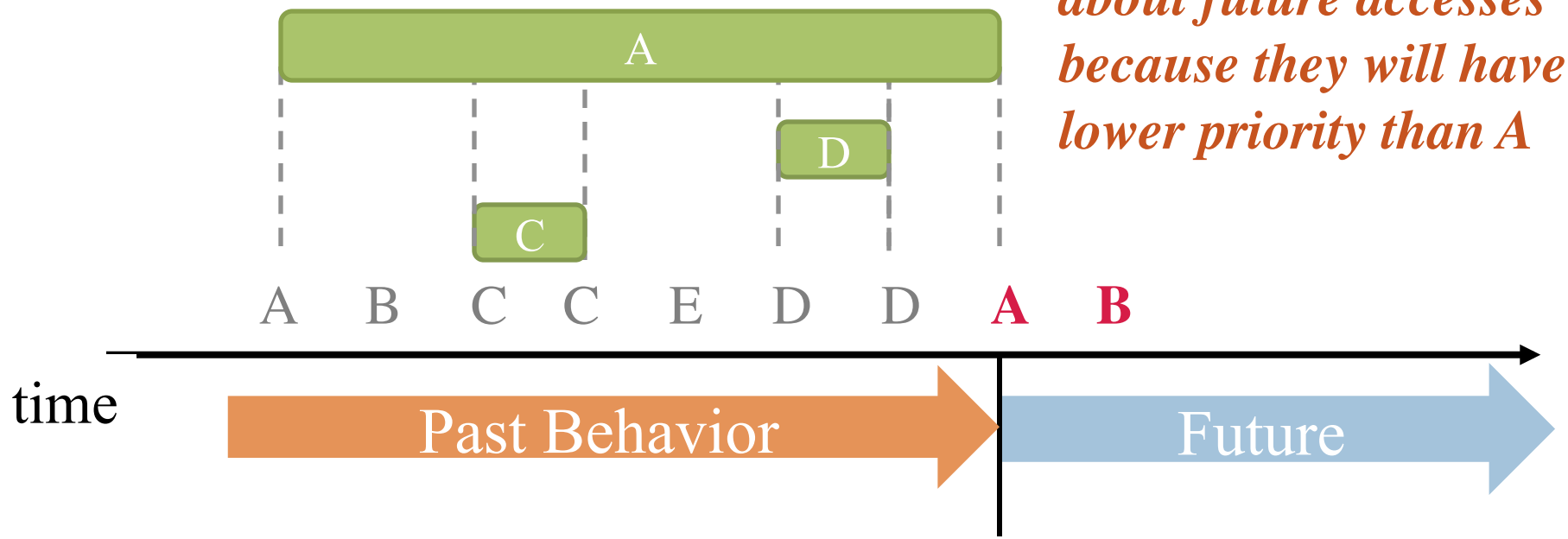
OPTgen is equivalent to OPT

- 100% accuracy with unlimited history
  - 95.5% accuracy with 8× history (for SPEC 2006)

OPTgen Algorithm: Insight 1

- OPT hit/miss can be determined at the time of reuse

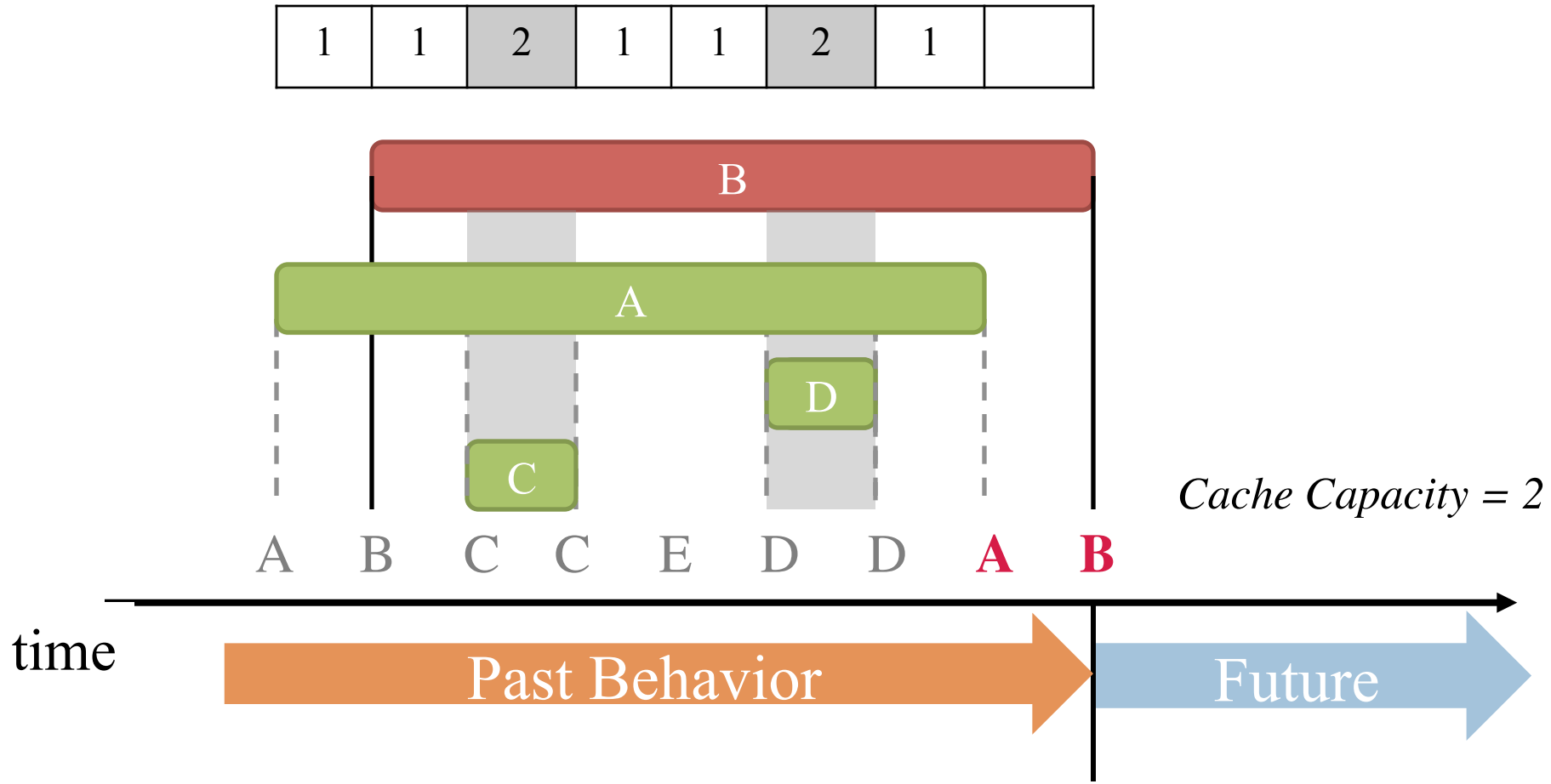
Don't need information about future accesses because they will have lower priority than A



OPTgen Algorithm: Insight 2

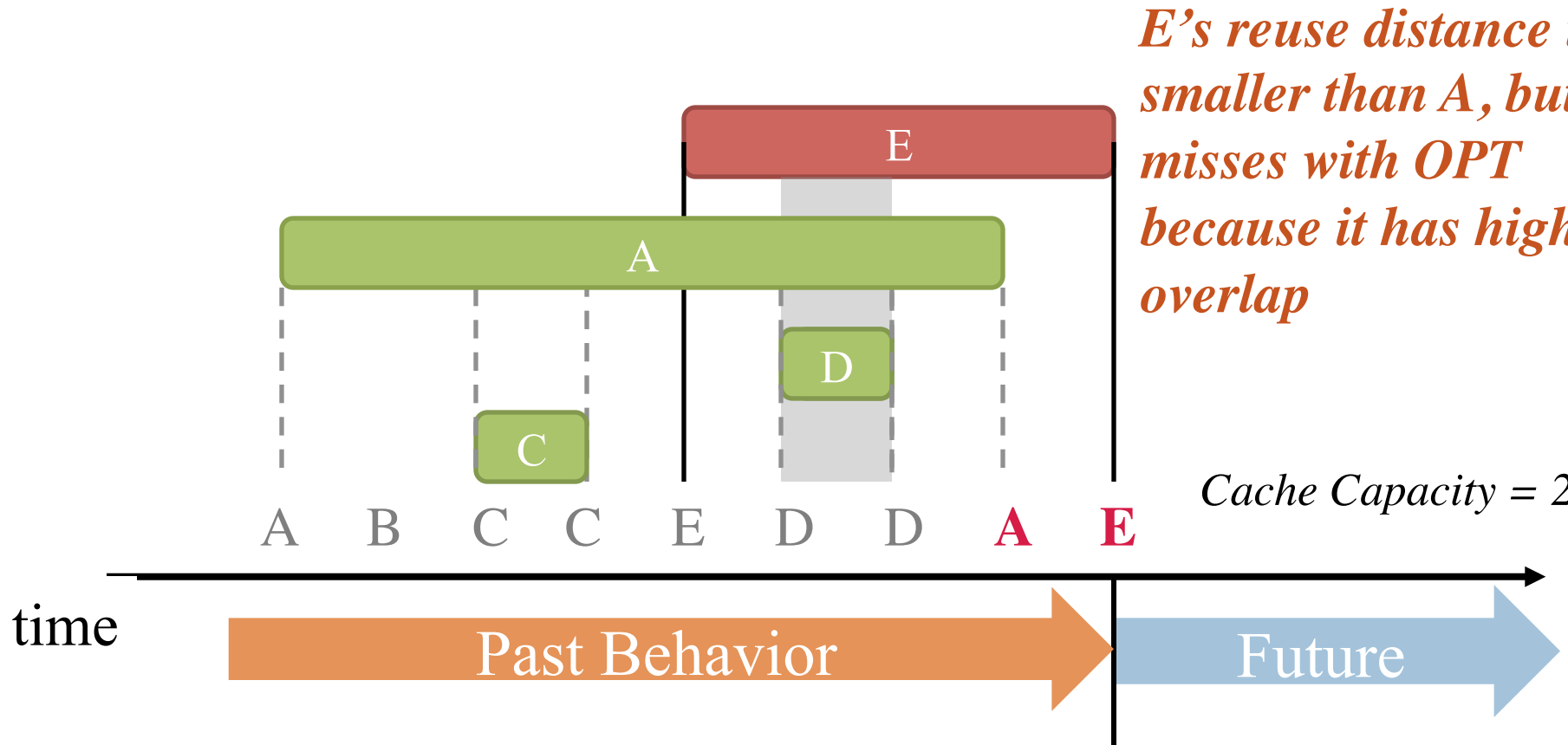
- OPT solution can be reproduced by tracking occupancy rather than cache contents

OPTgen Algorithm: Insight 2



OPTgen Algorithm: Insight 3

- OPT considers both reuse distances and their overlap

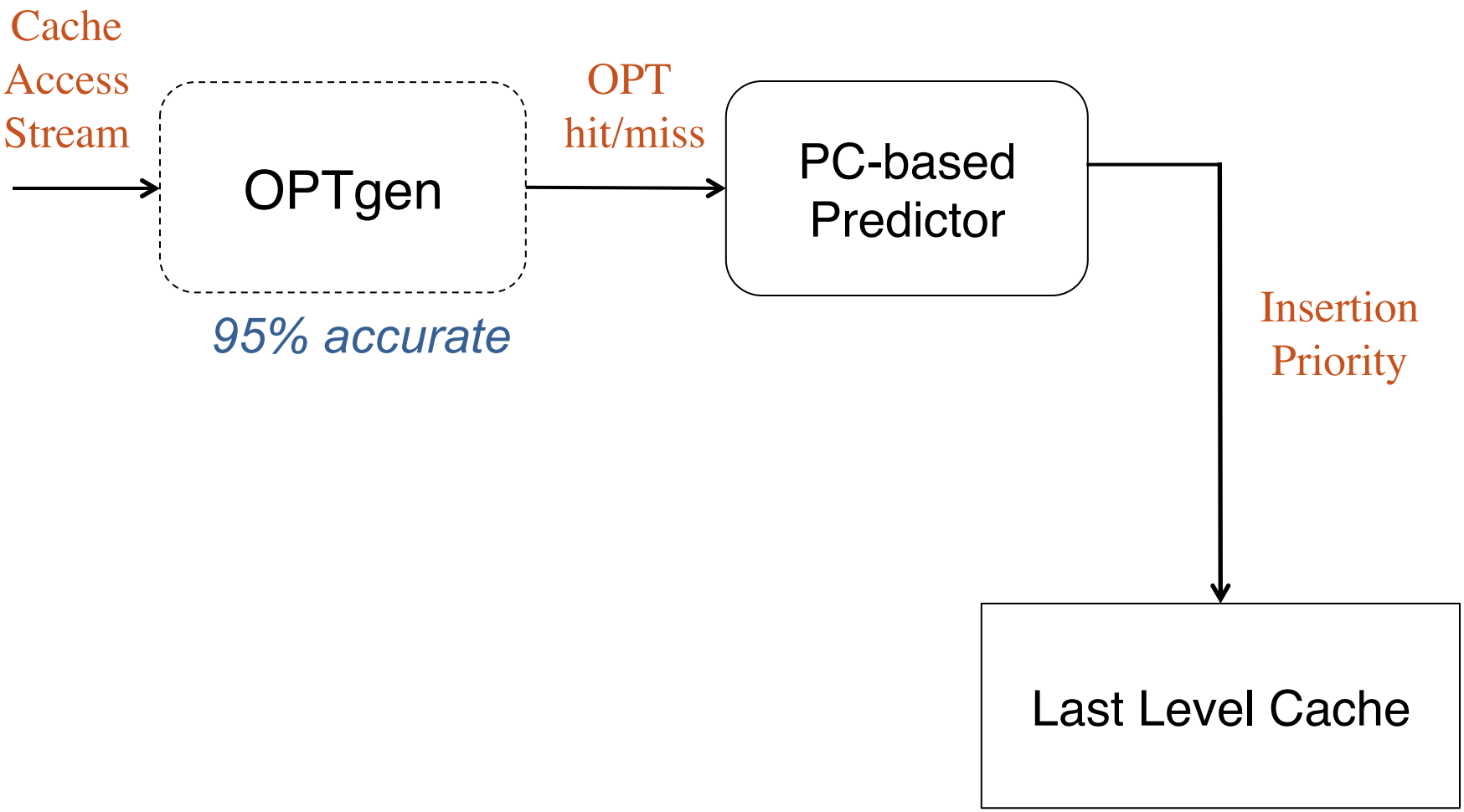


E's reuse distance is smaller than A, but it misses with OPT because it has higher overlap

Sampling for OPTgen

- 8× history for a 2MB cache
  - 100K entries (> 0.5MB)
- Set Dueling [Qureshi et al., ISCA 07]
  - Sample the behavior of a few cache sets
  - 64 sampled sets
- Set Dueling with OPTgen
  - Apply OPTgen to 64 sampled sets
  - 2.5K entries (12KB)
  - 95% accuracy in estimating miss rate

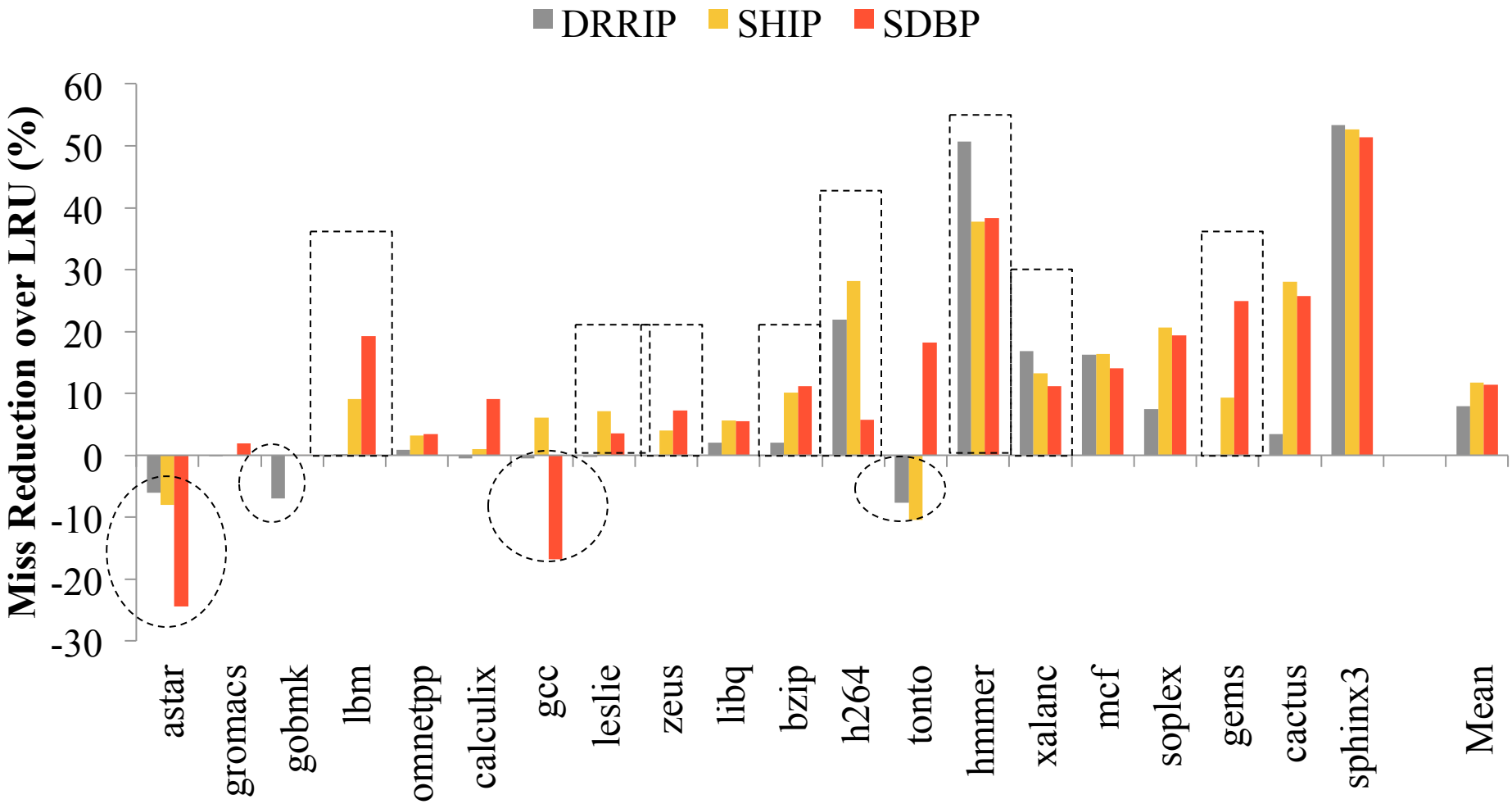
Hawkeye: Overall Design



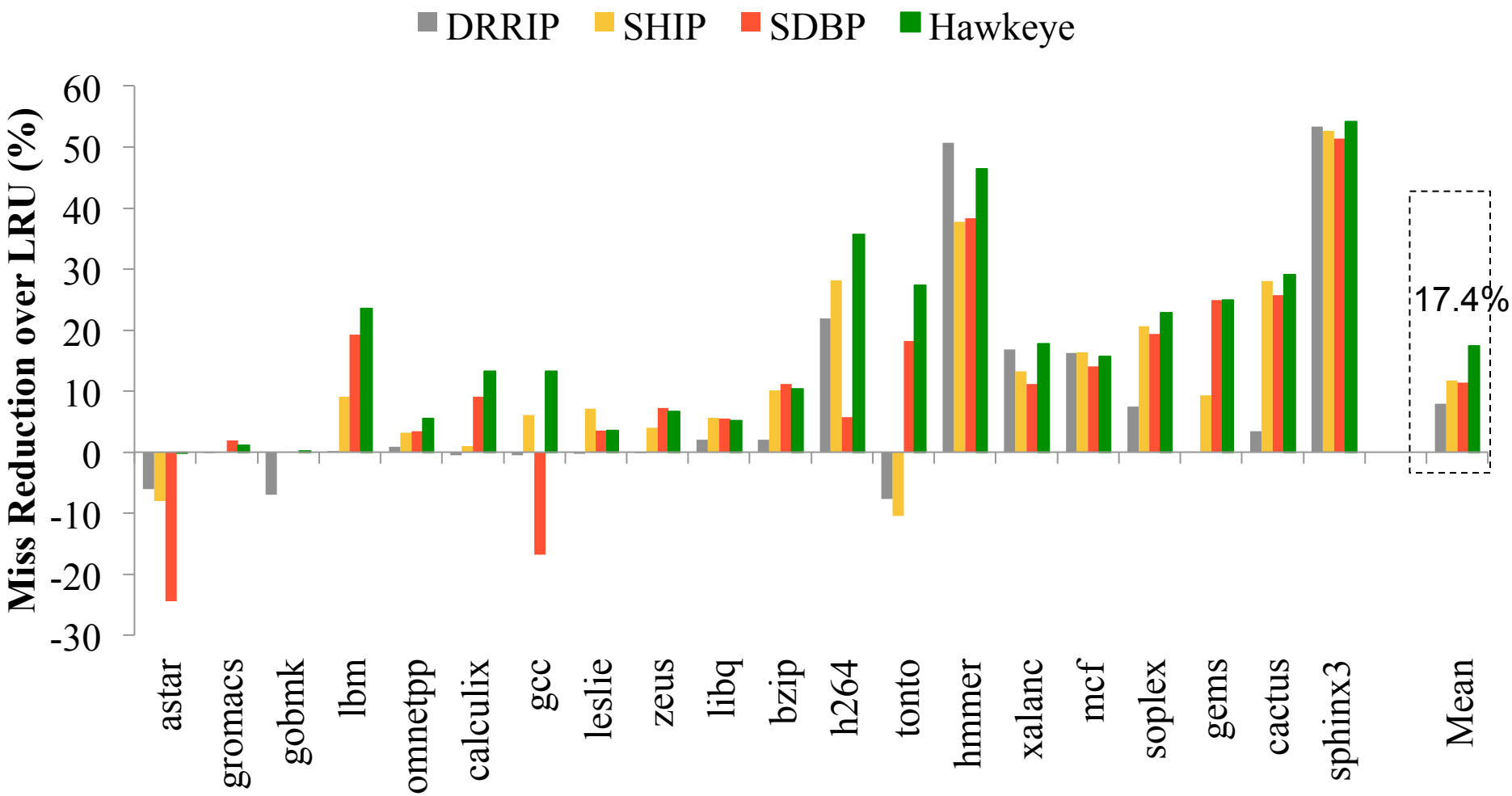
Evaluation

- Cache Replacement Championship Simulator (CRC)
- Benchmarks: Memory-intensive SPEC 2006
- Hardware Configurations
  - Single Core: Last-level Cache: 16-way, 2MB LLC
  - Multi-core: Shared Cache: 16-way, 4MB & 8MB LLC
- Replacement policies
  - Baseline: LRU
  - DRRIP [2010]
  - SDBP [2011]
  - SHiP [2012]

Miss Reduction

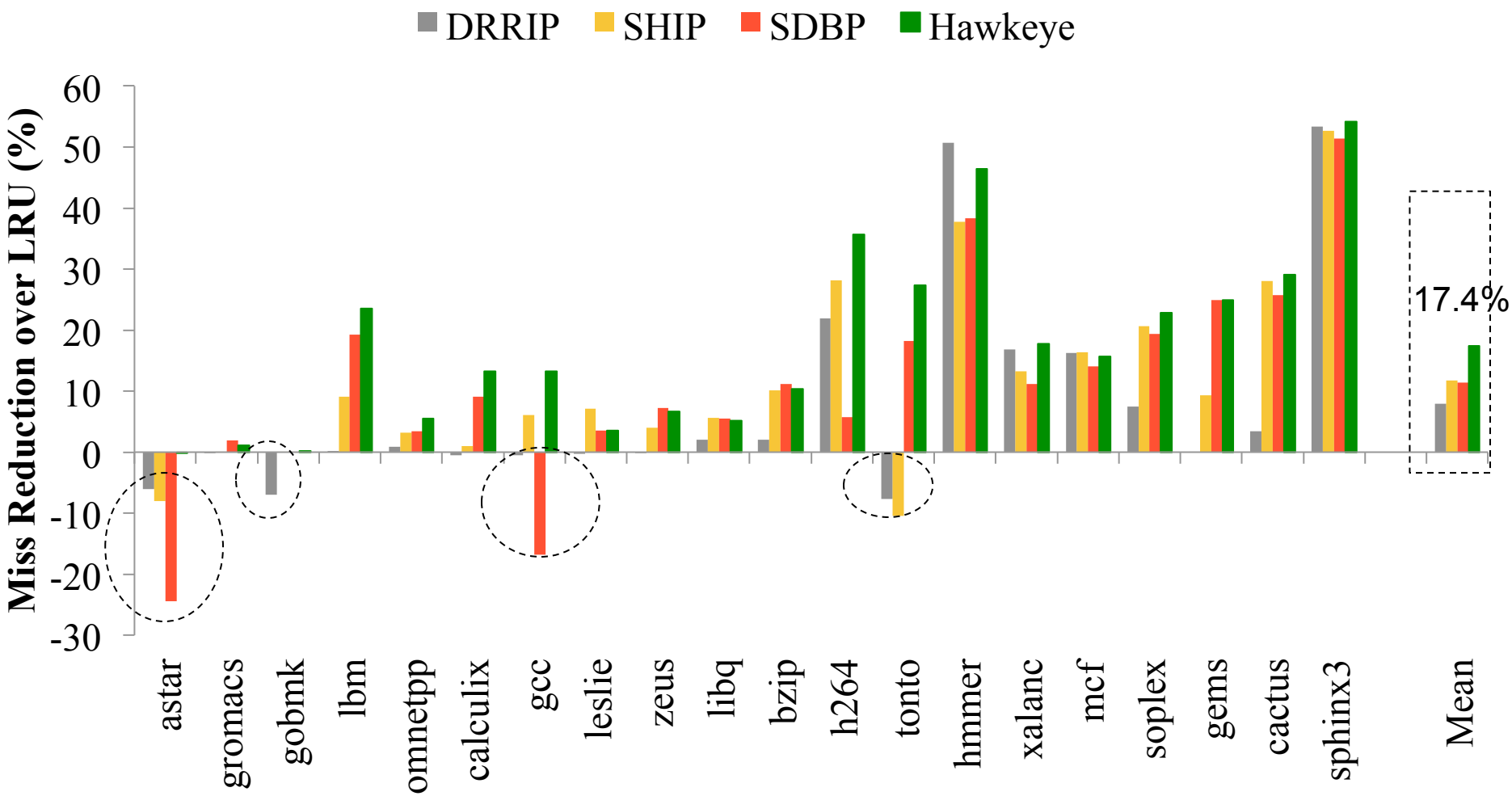


Miss Reduction



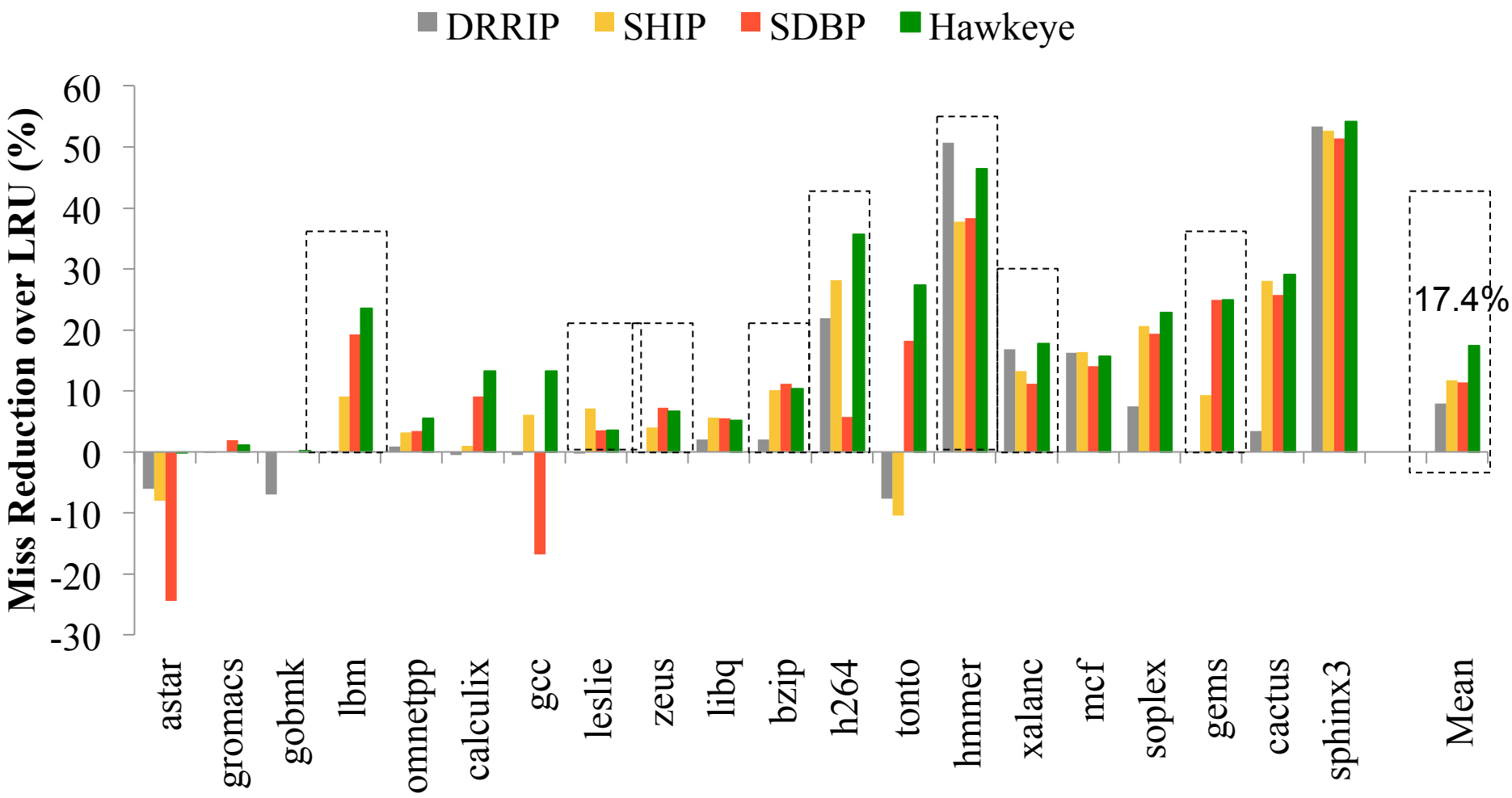
Hawkeye outperforms DRRIP, SDBP and SHiP

Miss Reduction



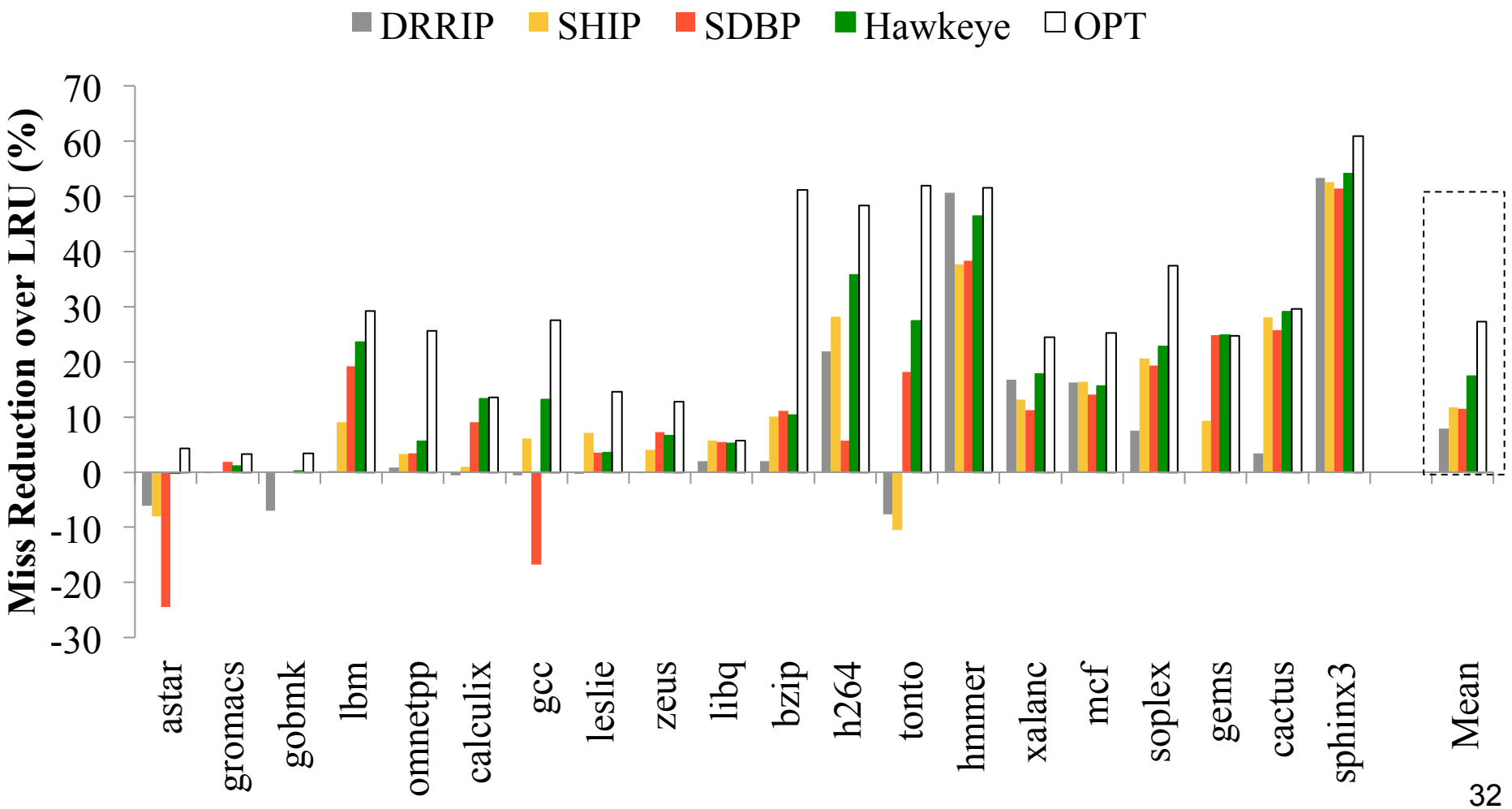
Hawkeye does not result in a slowdown for any benchmark

Miss Reduction

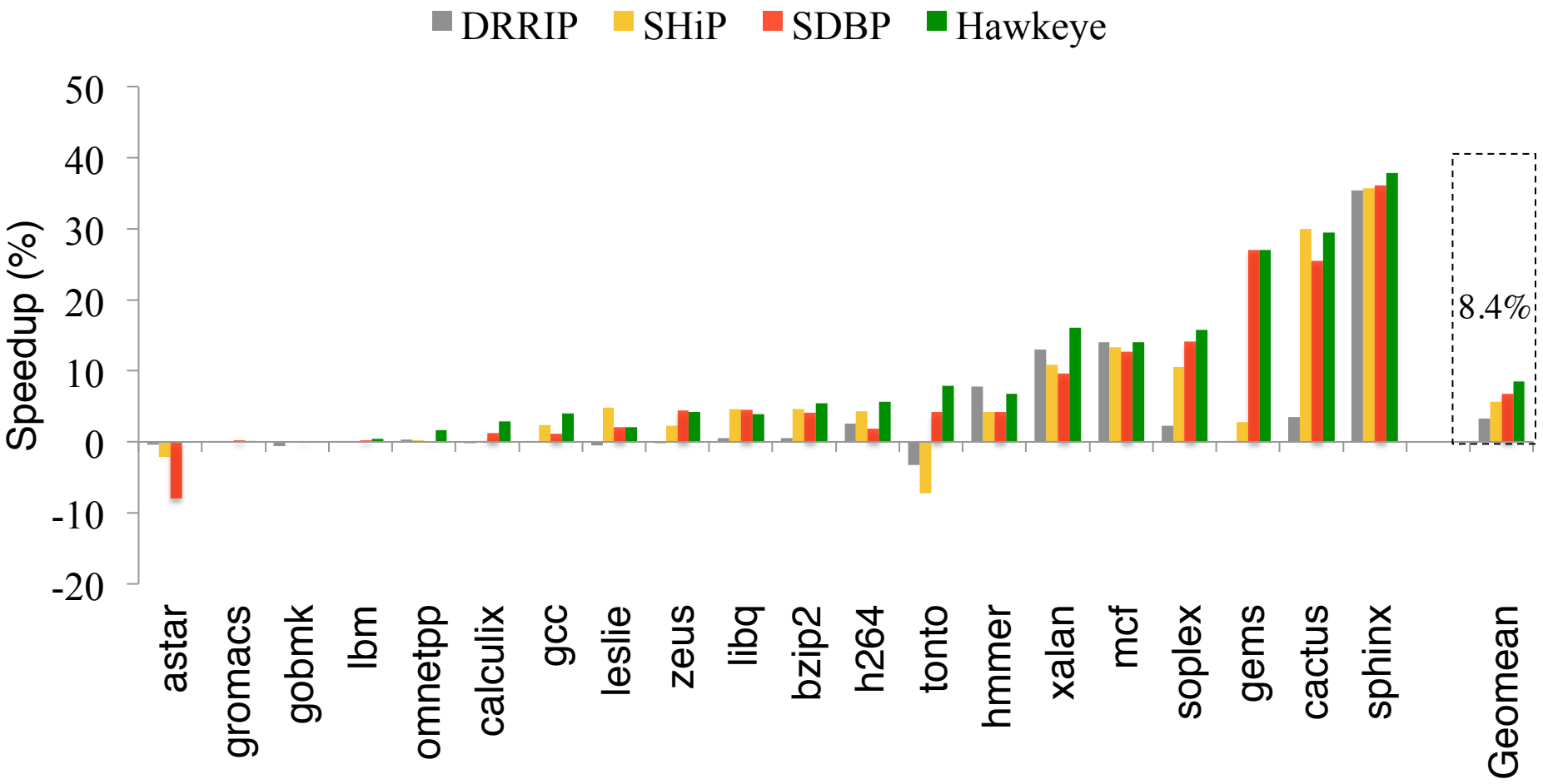


Hawkeye's performance gains are consistent across benchmarks

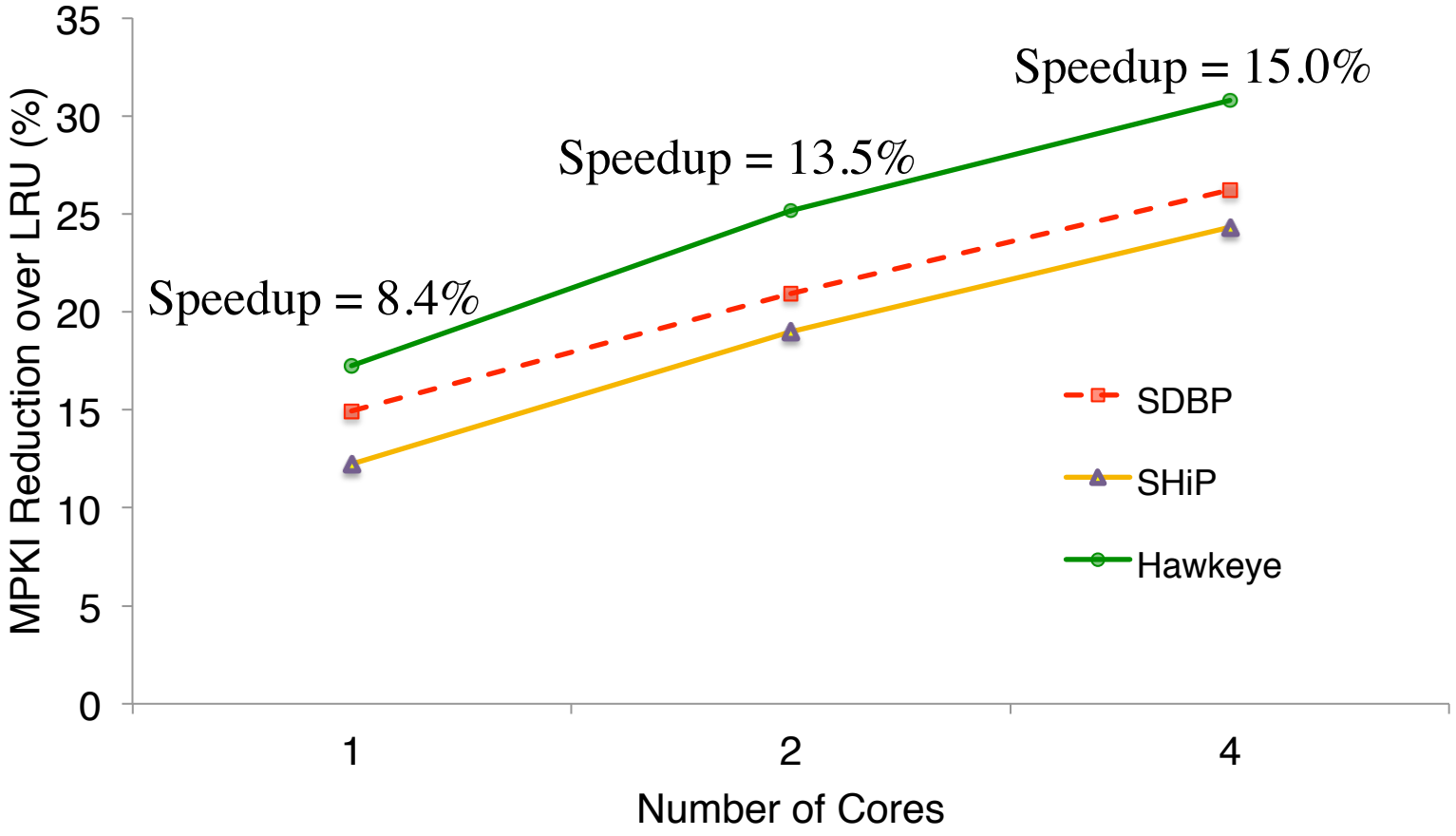
Miss Reduction



Speedup


DRRIP
SHiP
SDBP
Hawkeye
Speedup (%)
50
40
30
20
10
0
-10
-20
8.4%
astar
gromacs
gobmk
lbm
omnetpp
calculix
gcc
leslie
zeus
libq
bzip2
h264
tonto
hmmer
xalan
mcf
soplex
gems
cactus
sphinx
Geomean

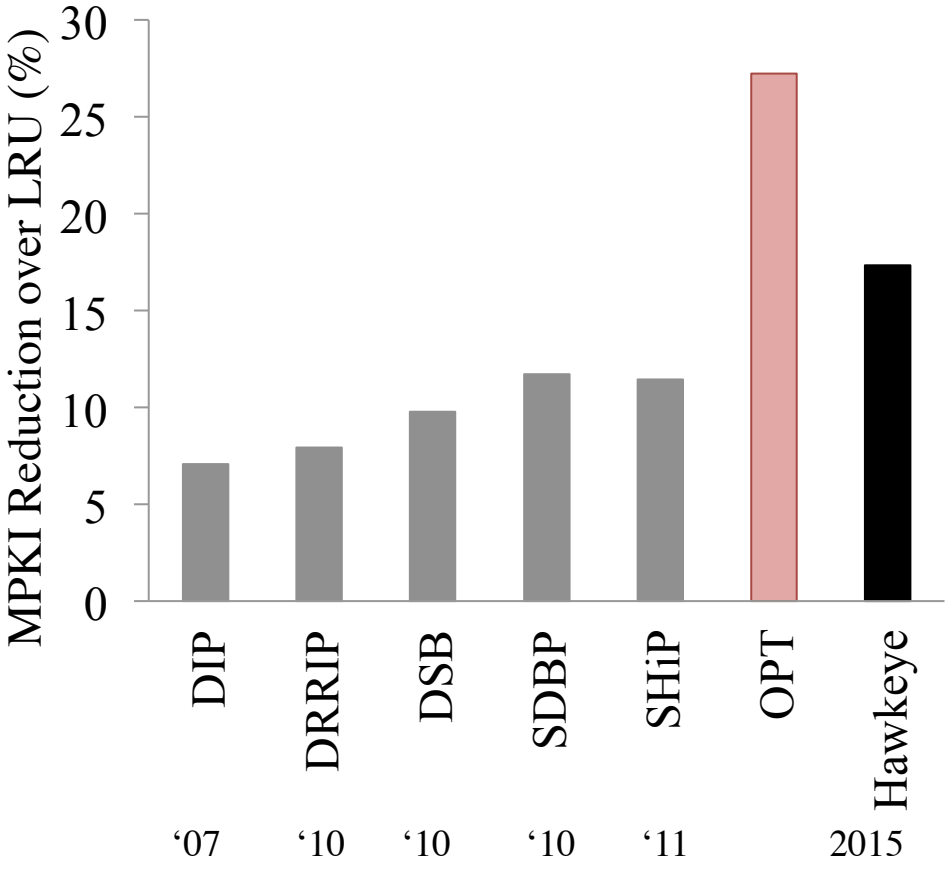
Multi-Core Results



Averaged across 100s of multi-programmed SPEC runs

Hawkeye: Summary

- New goal: learn from the OPT solution
- Not limited to specific access patterns
- Models both reuse distance and demand



Conclusions and Future Work

- Recent trend to view *cache replacement as a prediction problem*
  - Learn from the past to predict the future
- Hawkeye learns from an oracle
- Future Work: More sophisticated predictors to learn the OPT solution for the past