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Learning Cache Replacement with CACHEUS [1]

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(In Speaking Order)

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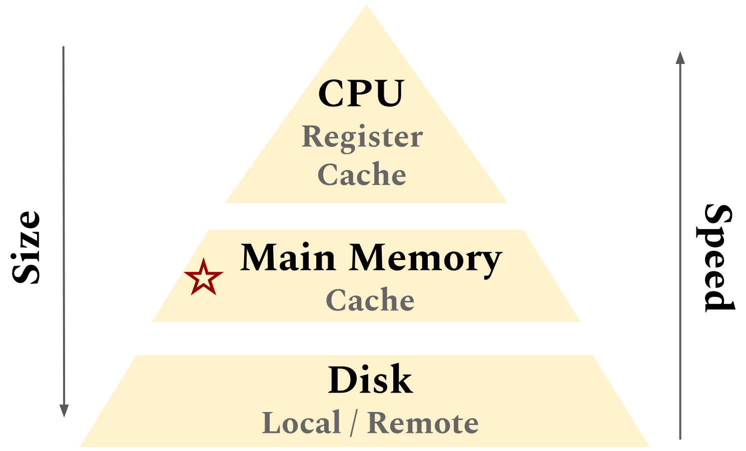
Introduction

- Memory System:
  - Cache:

    Fast but relatively small in capacity;
  - Permanent storage:

    Large but relatively slow in speed;
- Machine Learning (ML):
  - Improves decision making;
- Cache Management + Machine Learning:
  - Improves performance.



Workload Primitives

- LRU-Friendly
  - Best handled by the least recently used (**LRU**) caching algorithm;
- LFU-friendly
  - Best handled by the least frequently used (**LFU**) caching algorithm;
- Scan
  - A subset of stored items are accessed **exactly once;**
- Churn
  - **Repeated accesses** to a subset of stored items with equal probability.

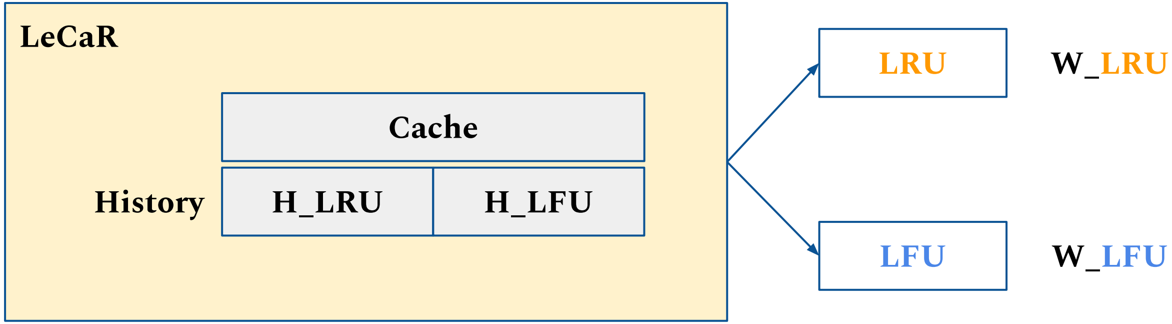
Workload Primitives

- Caching algorithms handling of workload primitive types:

Algorithm	Churn	Scan	LRU	LFU
ARC [3]	✗	✓	✓	✗
LIRS [4]	✗	✓	✗	✗
DLIRS [5]	✗	✓	✓	✗
LeCaR [2]	✓	✗	✓	✓

LeCaR: Introduction

- ML-Based: Reinforcement **Le**arning On **Ca**che **R**eplacement [2]
  - Simple: LRU, LFU as experts;
  - Adaptive: Update weights;
  - Outperforms state-of-the-art: Small cache sizes.



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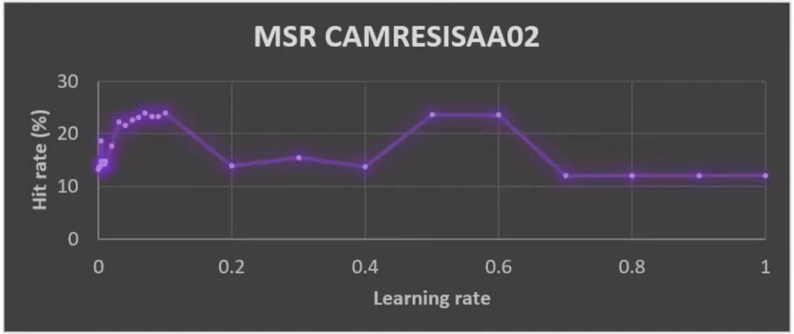
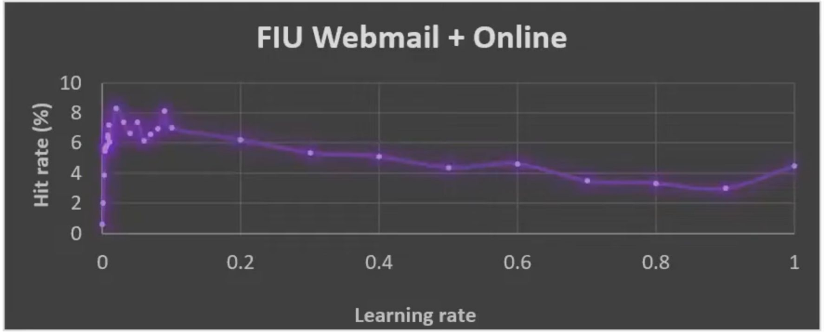
LeCaR: Limitations

- Fixed Learning Rate:
  - Empirically chosen: 0.45.





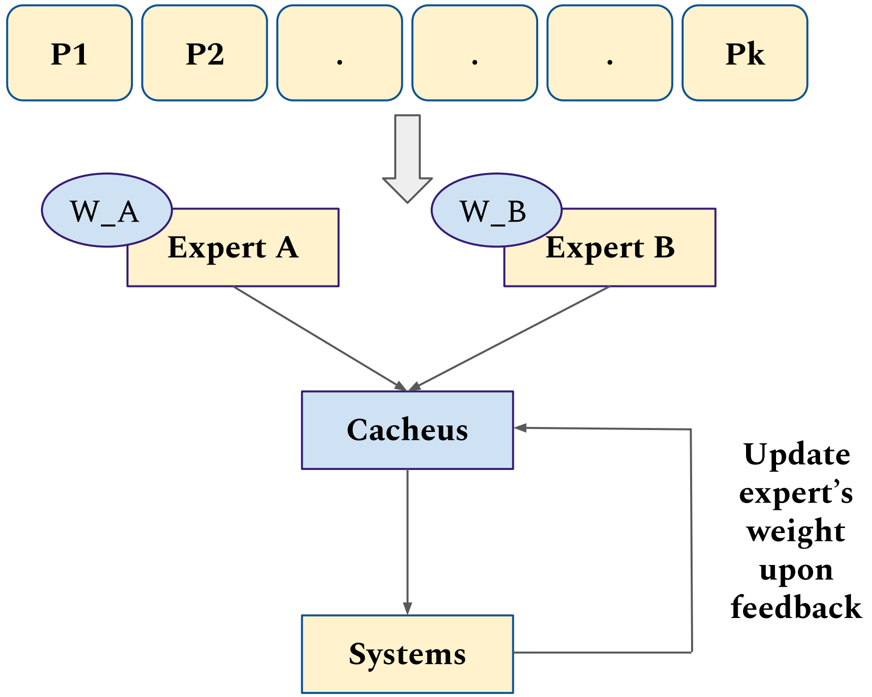
LeCaR: Limitations

- Cannot Handle Scan:

Algorithm	Churn	Scan	LRU	LFU
ARC	✗	√	√	✗
LIRS	✗	√	✗	✗
DLIRS	✗	√	√	✗
LeCaR	√	✗	√	√

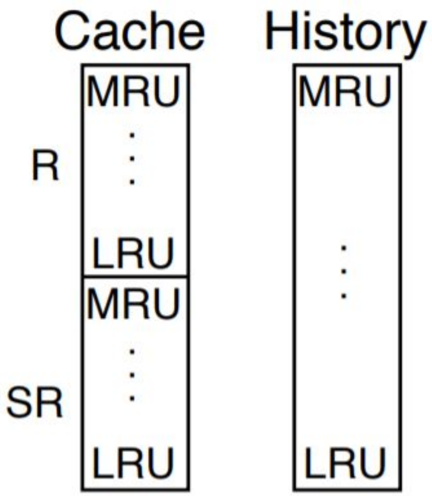
CACHEUS: Solutions

- Adaptive learning rate;
- Improve experts:
  - Introduce scan resistance
    - Replace LRU: ARC/LIRS/DLIRS -> Failed
    - **Scan resistant LRU: SR-LRU**
  - Improve churn resistance
    - **Churn resistant LFU: CR-LFU**



SR-LRU: Cache Partitioning

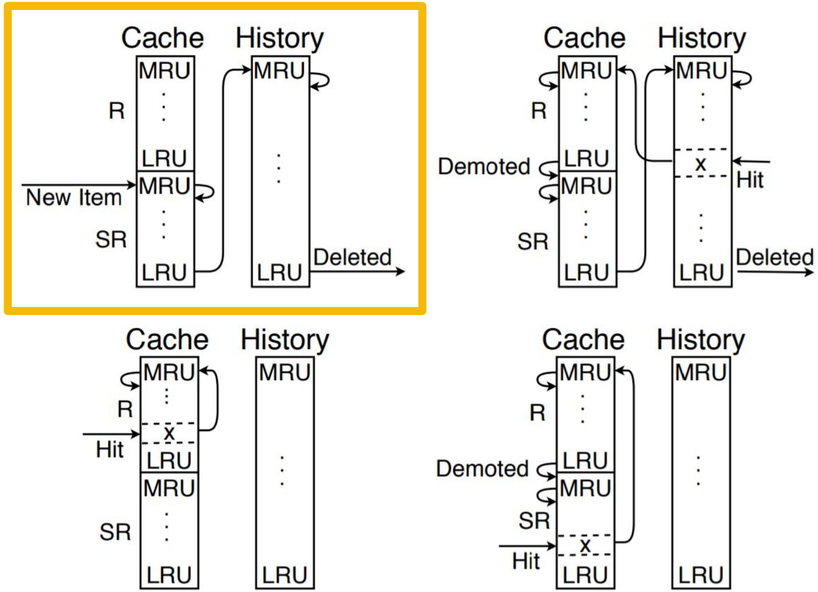
- Cache partitioning: similar to ARC and LIRS.
  - Partition Reuse (R):
    - Items with multiple accesses;
  - Partition Scan Resistance (SR):
    - Single access items;
    - Older items with multiple accesses.
- Why Partition SR?
  - MRU evicts the previously inserted page placed at the top of the stack;
  - SR Houses new items so that they don't affect important items in R;
  - SR allows SR-LRU to be scan resistant.



MRU: Most Recently Used
LRU: Least Recently Used

SR-LRU: Algorithm Explained

- **Miss in Cache + Miss in History:**
  - **Insert new item to the MRU position of SR;**
- Miss in Cache + Hit in History:
  - Move x to the MRU position of R;
- Hit in Cache R:
  - Move x to the MRU position of R;
- Hit in Cache SR:
  - Move x to the MRU position of R;



SR-LRU: Algorithm Explained

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- **Miss in Cache + Hit in History:**
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- Hit in Cache R:
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- Hit in Cache SR:
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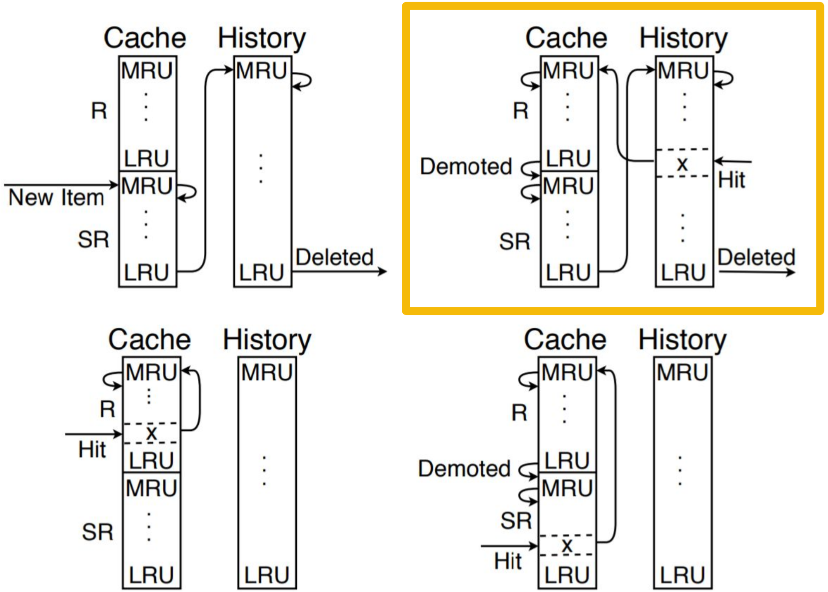
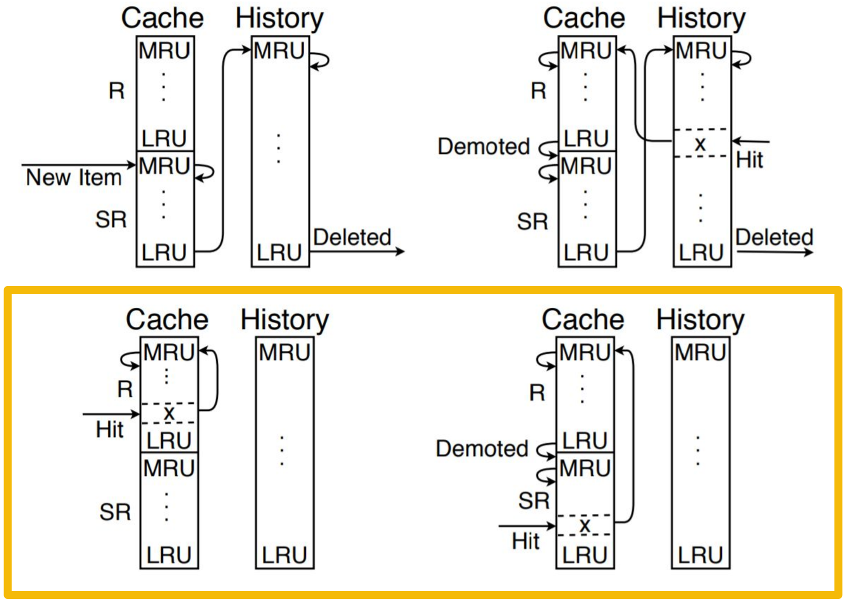


SR-LRU: Algorithm Explained

- Miss in Cache + Miss in History:
  - Insert new item to the MRU position of SR;
- Miss in Cache + Hit in History:
  - Move x to the MRU position of R;
- **Hit in Cache R:**
  - **Move x to the MRU position of R;**
- **Hit in Cache SR:**
  - **Move x to the MRU position of R;**



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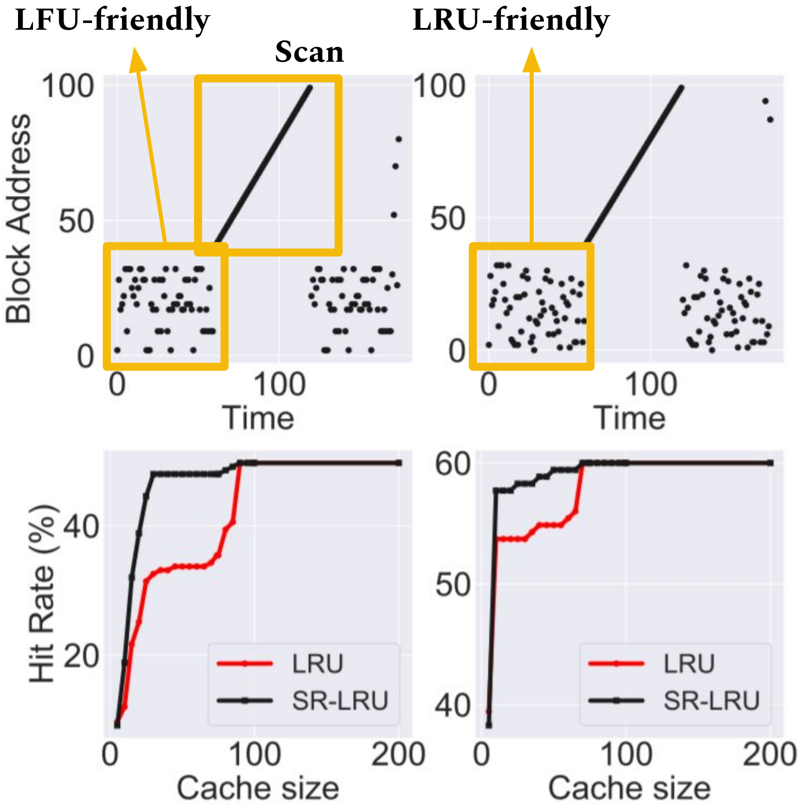
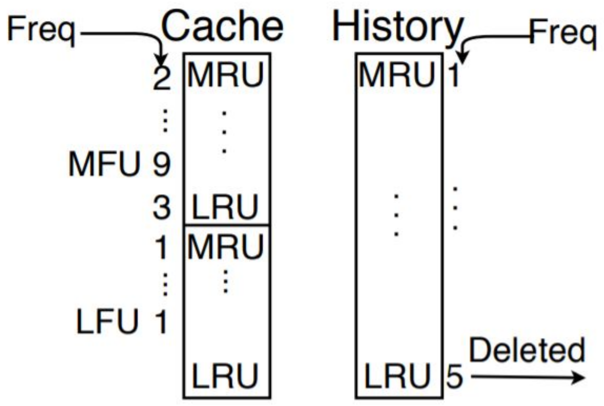
SR-LRU: Evaluation

- Scan + **LFU**-Load: Left;
  - A performance increase in small cache sizes;
- Scan + **LRU**-Load: Right.
  - A performance increase in small cache sizes;



CR-LFU: Cache Partitioning

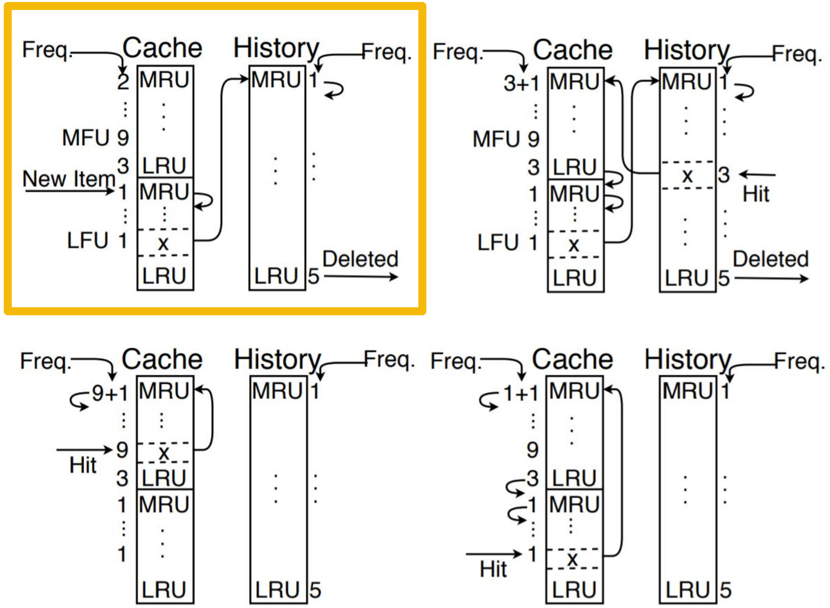
- Cache partitioning:
  - Partition by Frequency (MFU/LFU):
    - Cache partitioned by frequency of use;
  - Ordered by Recency (MRU/LRU):
    - Each partition maintaining recent uses.
- Why Frequency + Recency?
  - LRU repeatedly inserted and evicted items into/from the cache if #accessed > cache size;
  - LFU assigns equal importance to all items with the same frequency;
  - CR-LFU Chooses the MRU item to break ties when several LFU.



MRU: Most Recently Used
LRU: Least Recently Used
MFU: Most Frequently Used
LFU: Least Frequently Used

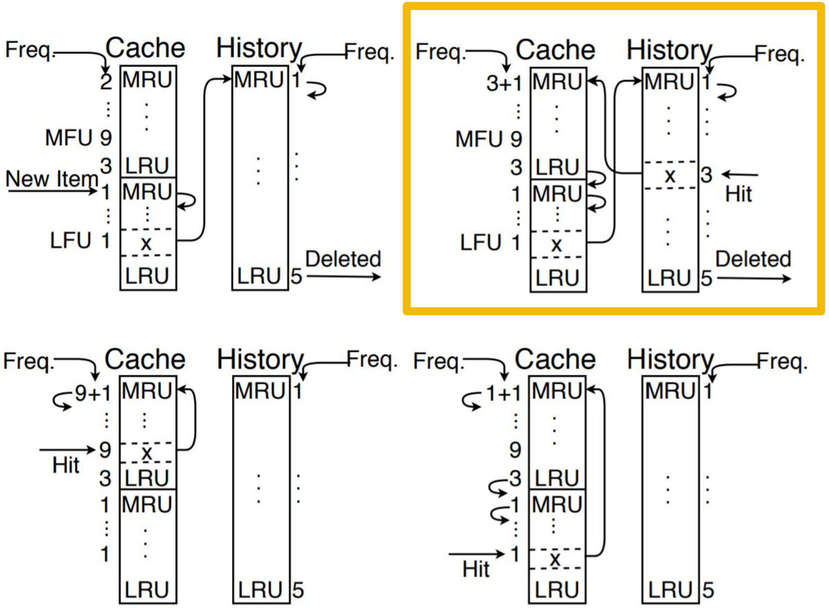
CR-LFU: Algorithm Explained

- **Miss in Cache + Miss in History:**
  - **Evict x at the MRU position of LFU;**
- Miss in Cache + Hit in History:
  - Move x to the MRU position of MFU;
- Hit in Cache MFU:
  - Move x to the MRU position of MFU;
- Hit in Cache LFU:
  - Move x to theMRU position of MFU;



CR-LFU: Algorithm Explained

- Miss in Cache + Miss in History:
  - Insert new item to the MRU position of LFU;
- **Miss in Cache + Hit in History:**
  - **Move x to the MRU position of MFU;**
- Hit in Cache MFU:
  - Move x to the MRU position of MFU;
- Hit in Cache LFU:
  - Move x to theMRU position of MFU;



CR-LFU: Algorithm Explained

- Miss in Cache + Miss in History:
  - Insert new item to the MRU position of LFU;
- Miss in Cache + Hit in History:
  - Move x to the MRU position of MFU;
- **Hit in Cache MFU:**
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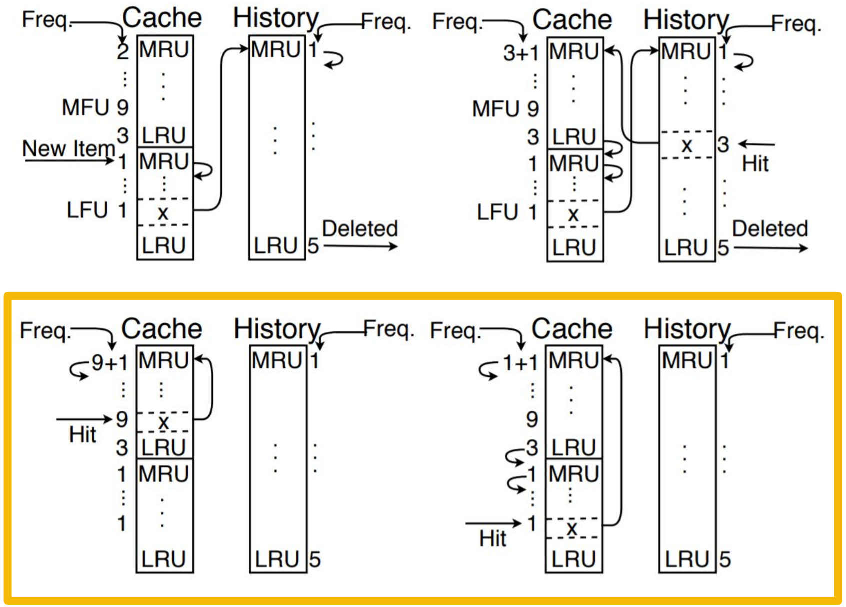

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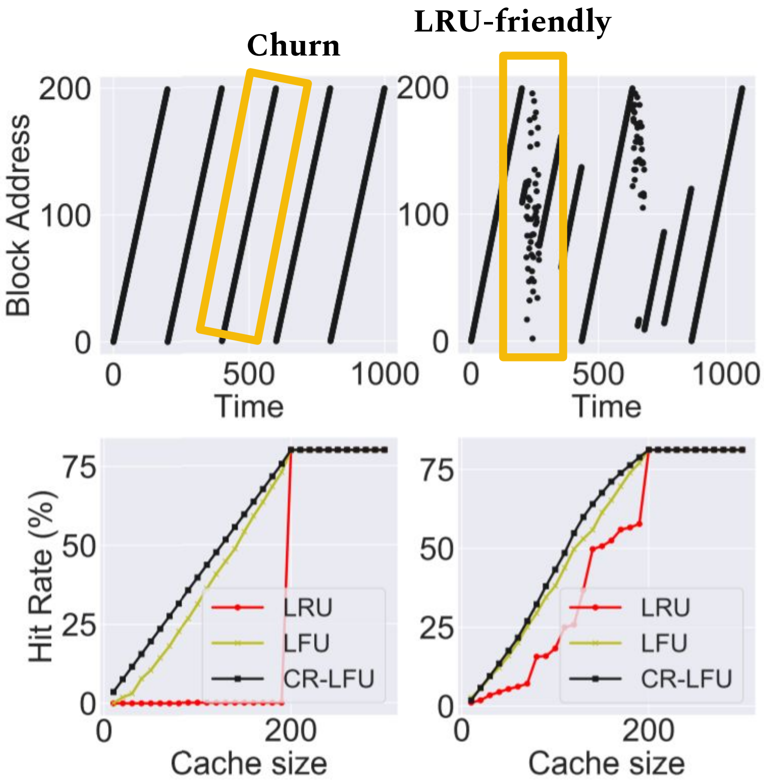
CR-LFU: Evaluation

- Pure Churn: Left;
  - Avg Performance Increase: 8.67%;
- Churn + **LRU**-Load: Right.
  - Avg Performance Increase: 3.83%;



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Experiments

- Datasets: 5 different sources;
- Cache size: 0.05, 0.1, 0.5, 1,5, 10%;
- Comparison:
  - 3 CACHEUS variants:
    - (ARC, LFU)
    - (LIRS, LFU)
    - (SR-LRU, CR-LFU)
  - 6 baselines:
    - LRU, LFU, ARU, LIRS, LeCaR, DLIRS
- Total experiments: 17,766

Dataset	#Traces
FLU	**184**
MSR	**22**
CloudPhysics	**99**
CloudVPS	**18**
CloudCache	**6**
Total	**329**

CACHEUS: Evaluation

- Paired t-test analysis;
- Significance:
  - P-value: threshold of 0.05;
  - **Green**: CACHEUS variant significantly better;
  - **Red**: CACHEUS variant significantly worse;
  - **Gray**: no significant difference;
- Effective size:
  - Cohen's d-measure;
  - Bright color: high effective size.

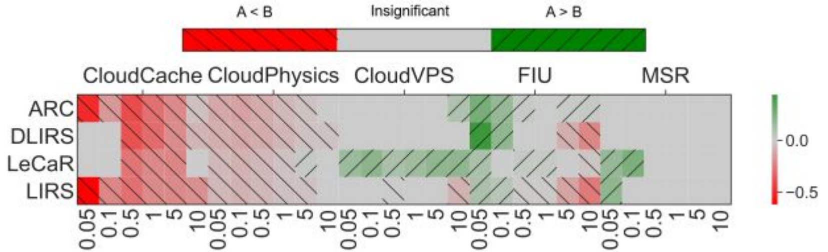


Figure: CACHEUS (ARC, LFU) vs.others

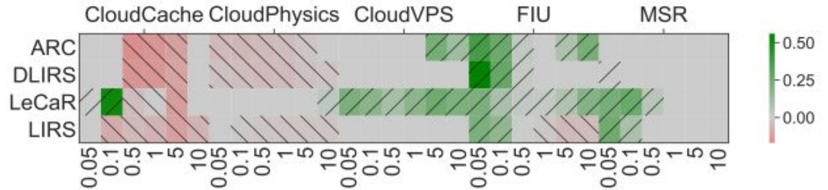


Figure: CACHEUS (LIRS,LFU) vs.others

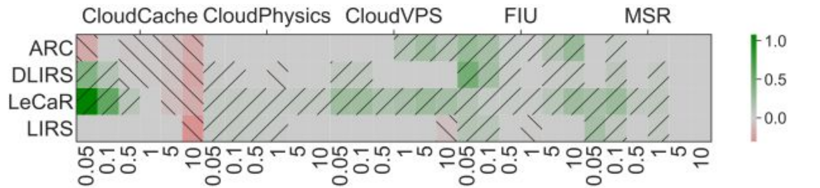
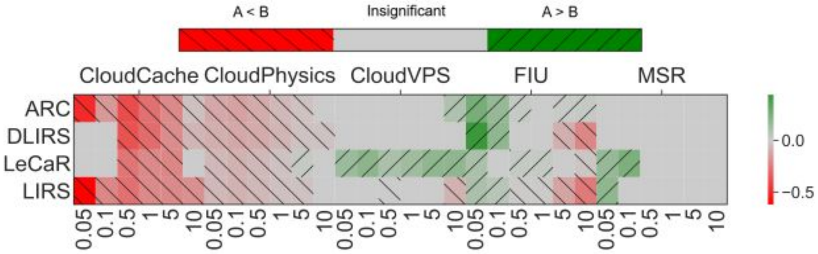


Figure: CACHEUS (SR-LRU,CR-LFU) vs.others

CACHEUS: Statistical Analysis

- CHACHEUS Variants:
  - (SR-LRU, CR-LFU) is distinctly the best;
- Results:
  - Best in **47%**;
  - Worse in **13%**;
  - Insignificant in **40%**;
  - Effective size `[-0.31, 1.08]`.



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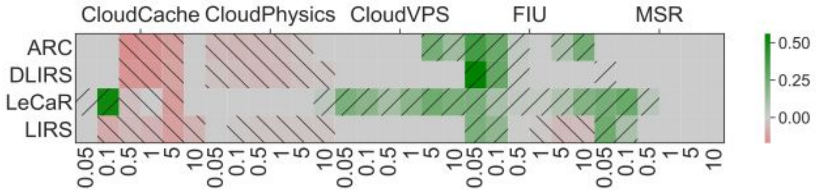

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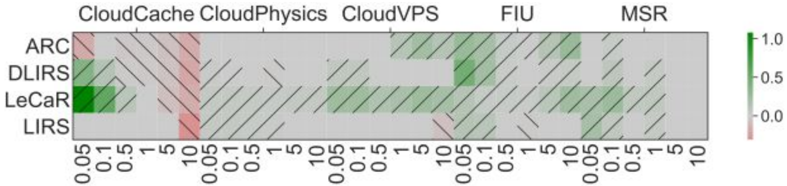

Figure: CACHEUS (SR-LRU,CR-LFU) vs.others

Conclusion

- Cache Management + Machine Learning:
    - Improves performance;
- Workload primitive types:
    - LRU-friendly, LFU-friendly, Churn, Scan;
- CACHEUS: Improved Cache replacement algorithm:
    - **Adaptive** learning rate;
    - Improved **experts**: SR-LRU and CR-LFU;
    - **Comprehensive** evaluations;
    - Outstanding **performance.**

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