CLOCK-Pro+: Improving CLOCK-Pro Cache Replacement with Utility-Driven Adaptation

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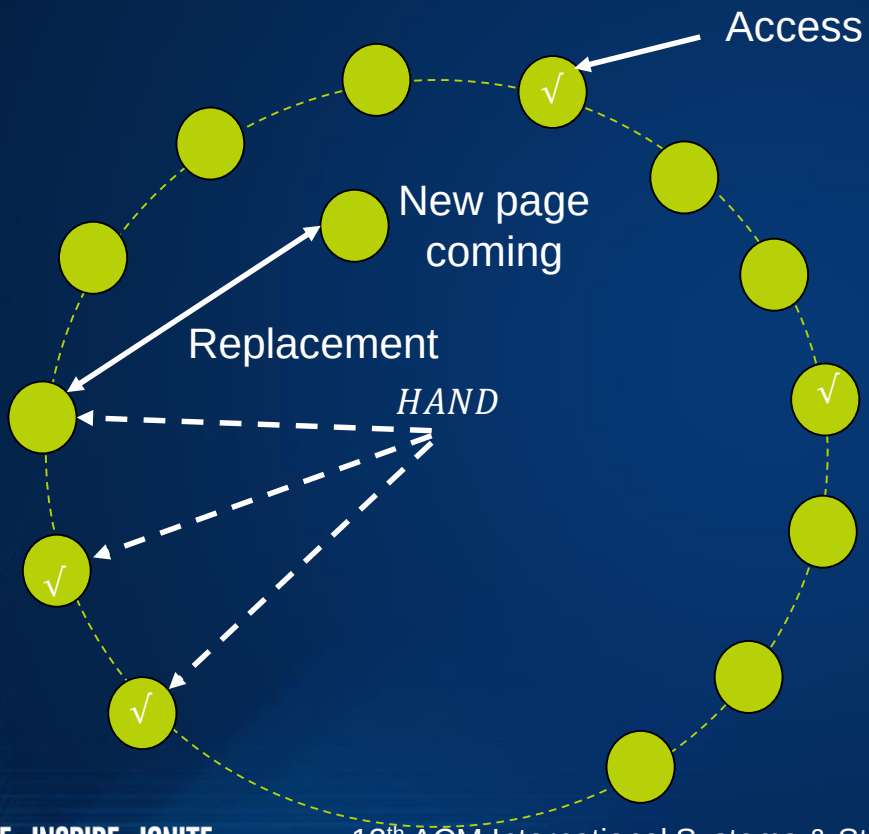
Outline

- Introduction: Cache & Page Replacement
- Background: CLOCK-Pro & CLOCK for Adaptive Replacement
- The New Policy w/ Utility-Driven Adaptation: CLOCK-Pro+
- Experimental Results
- Conclusion

Introduction

- **Buffer Cache Replacement**
  - Determine the victim to be replaced given a new data block to be loaded
  - Many policies proposed, e.g., LRU, ARC, LIRS, etc.
- **CLOCK**
  - Data manipulation w/ a hit → lock contention problem in low hit latency scenario
    - ✓ Page replacement in virtual memory management

CLOCK

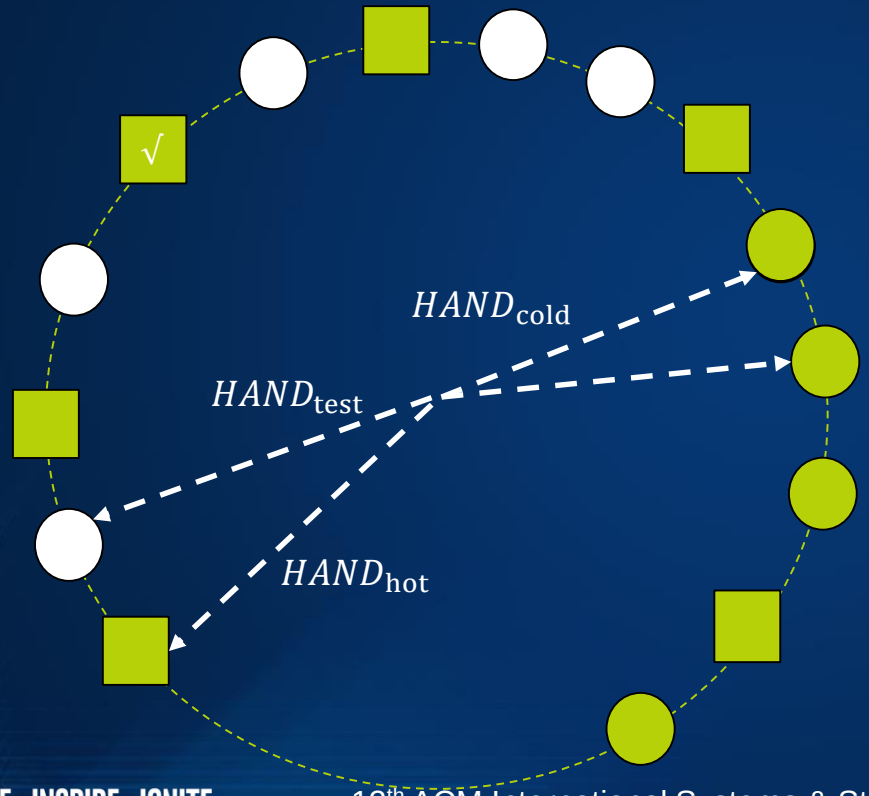


√ Referenced

CLOCK-Pro

- **Reuse Distance**
  - Distance of a referenced page away from the top
  - Page w/ a low reuse distance → more likely to be accessed in the future
- **CLOCK-Pro**
  - Efficiently discriminate hot pages (low reuse distances) from cold pages (high reuse distances)
    - ✓ Approximating LIRS policy
    - ✓ Adapting to LRU-friendly workloads

CLOCK-Pro



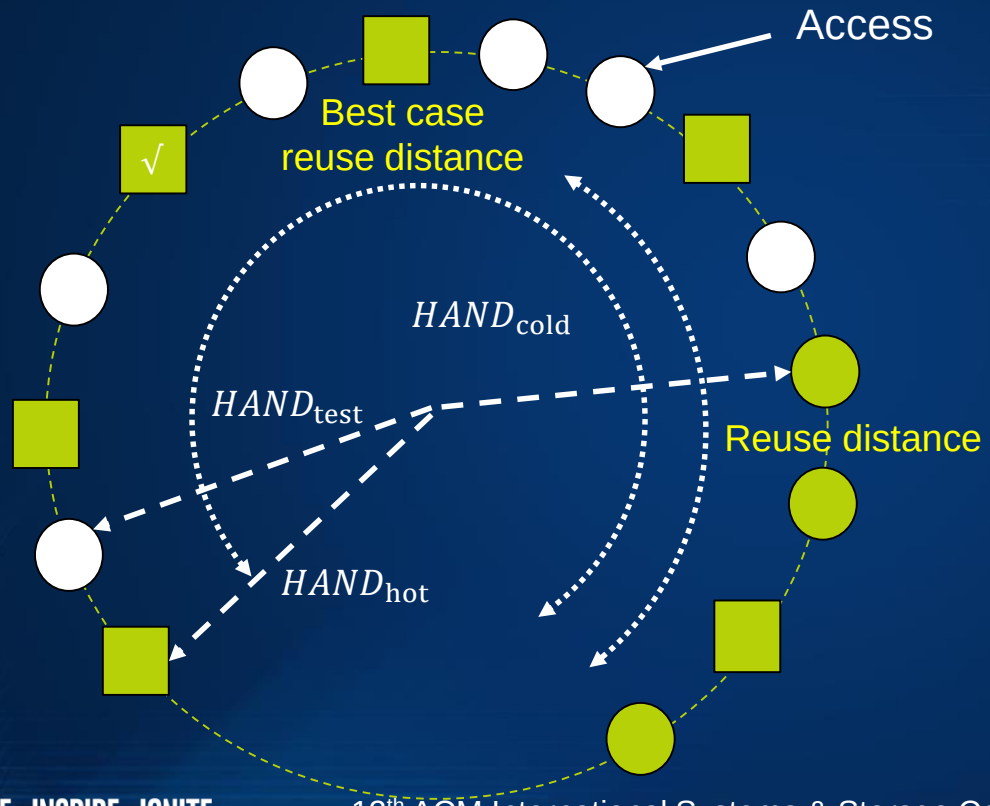
Hot page

Resident cold page

Non-resident cold page

√ Referenced

CLOCK-Pro



Hot page

Resident cold page

Non-resident cold page

√ Referenced

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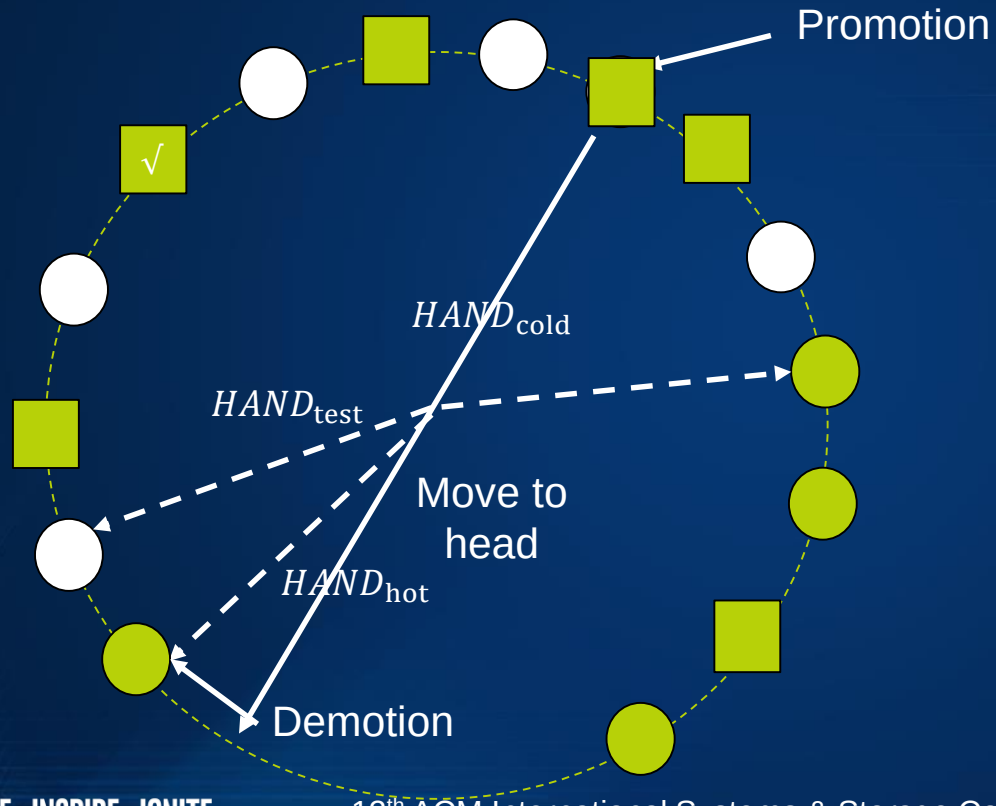
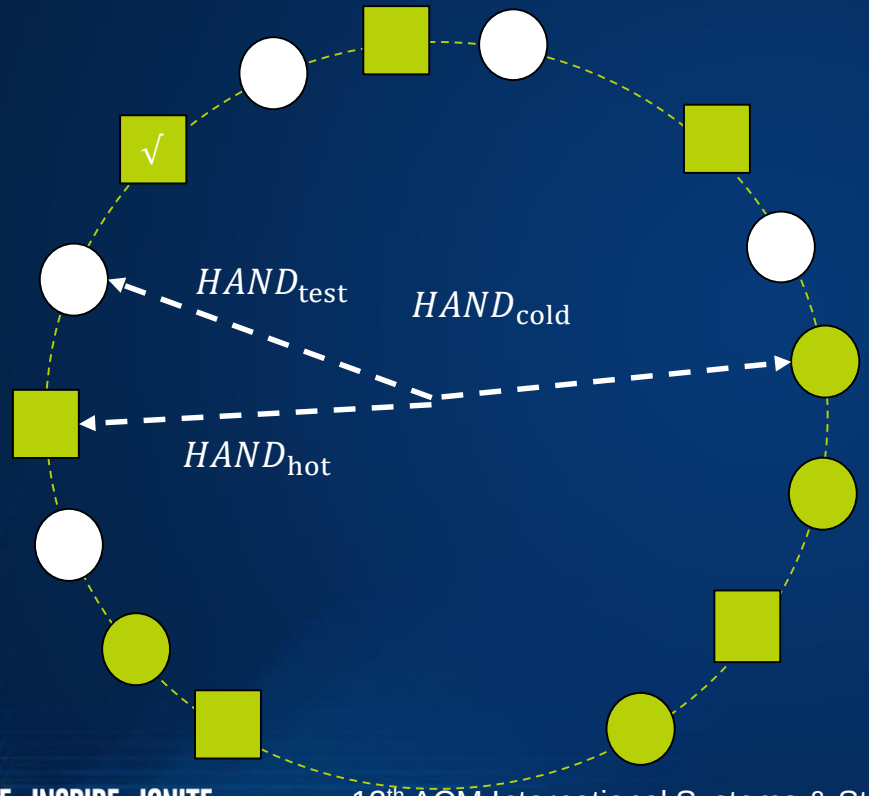
CLOCK-Pro



Cold page promotion & hot page demotion

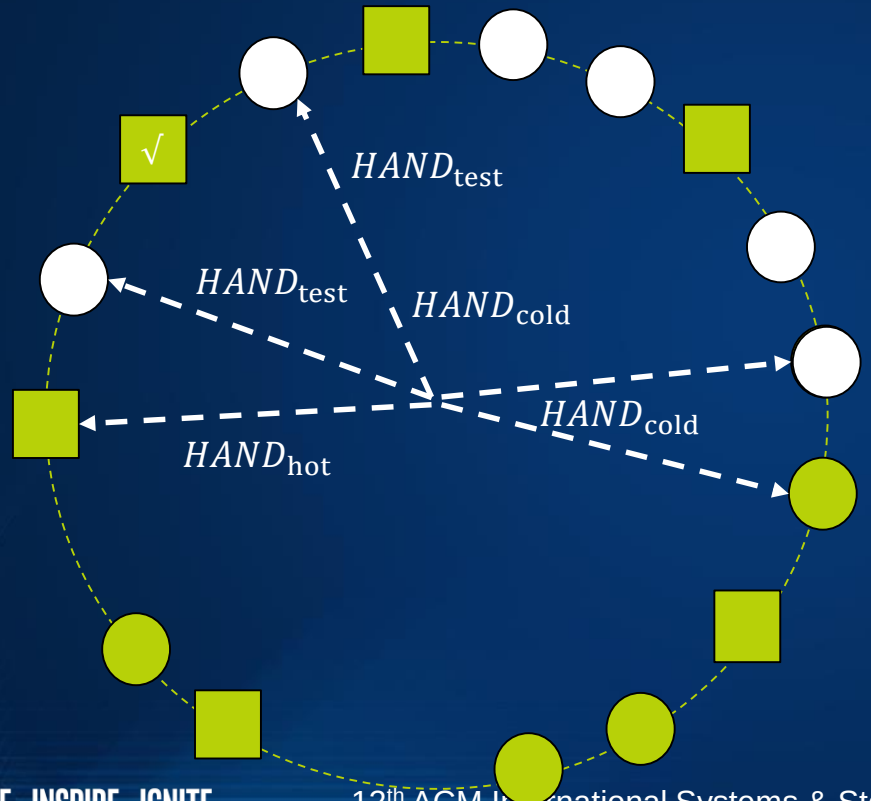
CLOCK-Pro



$HAND_{\text{hot}}$ & $HAND_{\text{test}}$ move

Test period terminates & non-resident page discarded

CLOCK-Pro



Many new pages come

Limit clock size by terminating test pages with $HAND_{\text{test}}$

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Weakness w/o Adaptation

- **Static Cache Space Allocation**
  - Small number of resident cold pages close to head position
  - Non-resident cold pages interleaved w/ hot pages
- **When Reuse Distance Is not a Good Predictor (or does not Exist)**
  - Frequent accesses to close-to-head non-resident cold pages result in misses
    - ✓ Can be captured with a basic CLOCK policy
    - ✓ Example: stack depth distribution (SDD) workload

CLOCK-Pro w/o adaptation is not good enough

CLOCK-Pro w/ Adaptation

- **Idea**
  - Cold page access → LRU friendly
  - Test period expiration → need more hot pages to extend test period
- **Issue**
  - Simple heuristics w/o utility analysis, e.g.,
    - ✓ Resident cold page accesses → not necessary to increase cold page number
    - ✓ Many test pages expire → more hot pages may not help

CLOCK-Pro w/ adaptation is still not good enough

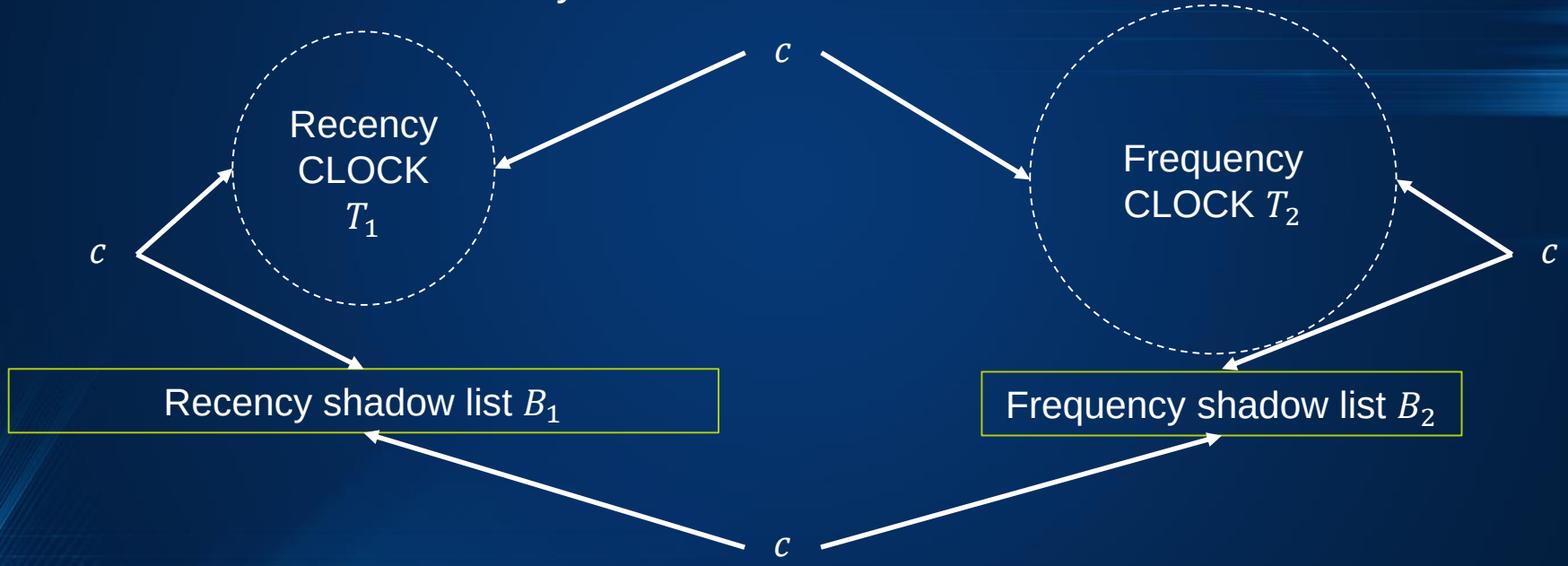
CLOCK w/ Adaptive Replacement (CAR)

- **Recency vs. Frequency**
  - Varying & requiring dynamic adaptation
- **CAR (Approximation of ARC)**
  - Maintain 2 different CLOCKs & 2 different shadow lists
    - ✓ 1 CLOCK & 1 shadow list for recency (1 recent access)
    - ✓ 1 CLOCK & 1 shadow list for frequency (at least 2 recent accesses)
  - Utility-driven adaptation to dynamically adjust the 2 CLOCKs

CAR

Recency pages: pages w/ 1 recent accesses only

Frequency pages: pages w/ at least 2 recent accesses



CAR

Recency pages: pages w/ 1 recent accesses only

Frequency pages: pages w/ at least 2 recent accesses

Access recency shadow list → growing T_1
Incremental utility quantified as $P_1 = 1/|B_1|$

Access frequency shadow list → growing T_2
Incremental utility quantified as $P_2 = 1/|B_2|$

CAR

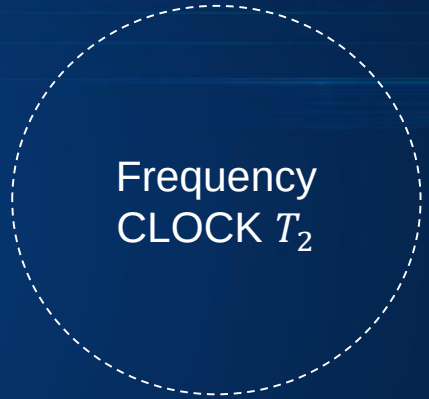
Recency pages: pages w/ 1 recent accesses only

Recency shadow list B_1

Adjustment given a B_1 access:

$|T_1| \leftarrow |T_1| + \max\{1, P_1 / P_2\}$

Frequency pages: pages w/ at least 2 recent accesses



Frequency shadow list B_2

Adjustment given a B_2 access:

$|T_2| \leftarrow |T_2| + \max\{1, P_2 / P_1\}$

CAR (cont.)

- **Frequency CLOCK & Shadow List**
  - Contain less granular information
- **Without a Fine-Grained Metric like Reuse Distance**
  - Less capable in capturing repeated accesses w/ relatively long temporal distances (weak locality)

CAR is not good enough as well

CLOCK-Pro vs CAR (a Glance)

CLOCK-Pro outperforms CAR

CAR outperforms CLOCK-Pro

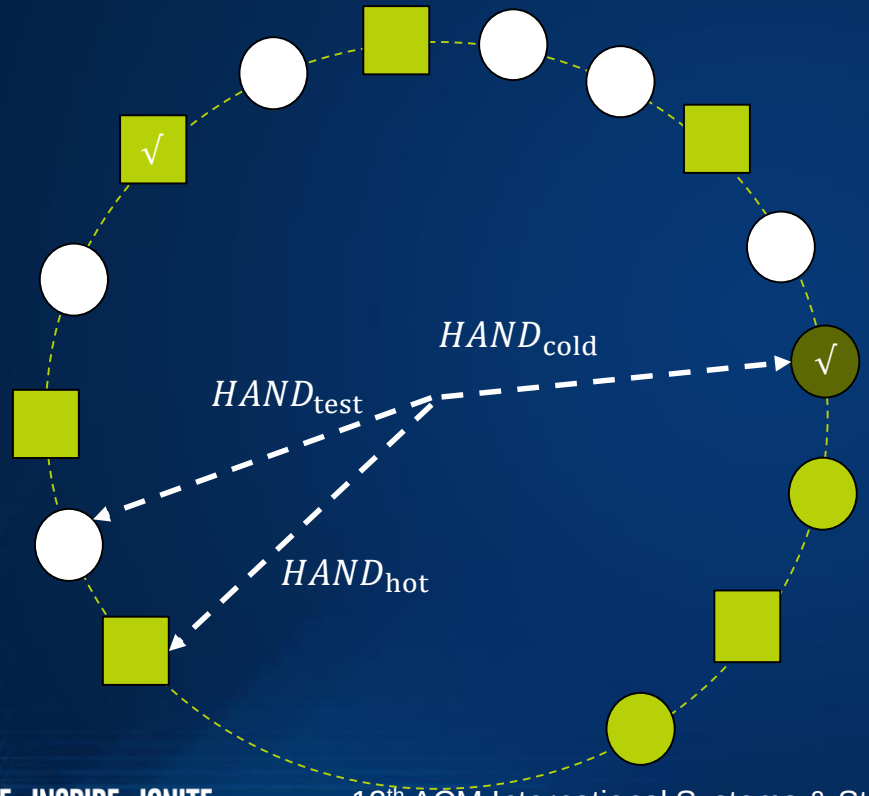
Trace (cache size)	CLOCK-Pro	CAR
WebSearch1 (131072)	**13.10%**	8.32%
WebSearch1 (262144)	**24.91%**	14.90%
WebSearch1 (524288)	**40.36%**	32.78%
WebSearch2 (262144)	**29.80%**	26.94%
WebSearch2 (524288)	**48.35%**	41.72%
WebSearch3 (262144)	**29.66%**	26.68%
WebSearch3 (524288)	**48.21%**	41.40%
Financial1 (512)	17.78%	**23.17%**
Financial1 (1024)	20.62%	**26.02%**
Financial1 (2048)	24.16%	**29.38%**
Financial1 (4096)	27.58%	**32.61%**
Financial1 (8192)	31.31%	**35.72%**
SDD (256)	17.10%	**20.40%**
SDD (512)	31.60%	**36.75%**

No consistent winner

Idea of CLOCK-Pro+

- **Idea Inspired by CAR**
  - Dynamic adaptation in CLOCK-Pro using a CAR-style utility evaluation
    - ✓ When reuse distance is a good predictor, more space allocated to hot pages
    - ✓ When reuse distance is not a good predictor, more space allocated to cold pages
- **Determining Predictor Goodness**
  - Accessing non-resident cold pages
  - Inappropriately demoting hot pages (hit shortly after demotion)

Adaptation in CLOCK-Pro+



Resident cold pages demoted from hot pages

C_n: current number of non-resident pages

C_d: current number of resident cold pages demoted from hot pages

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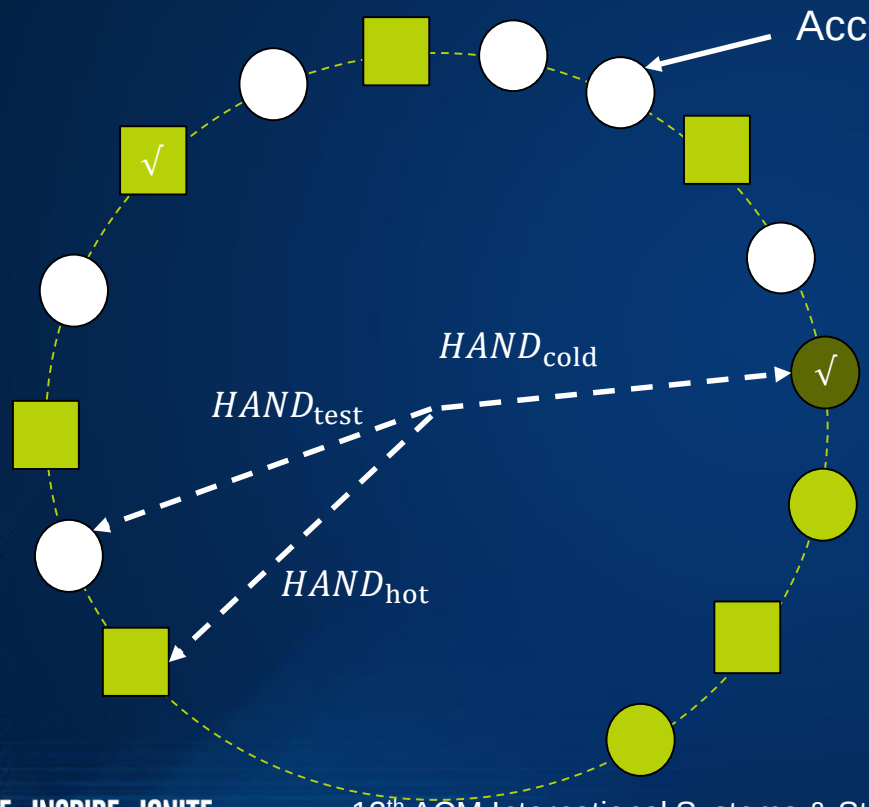
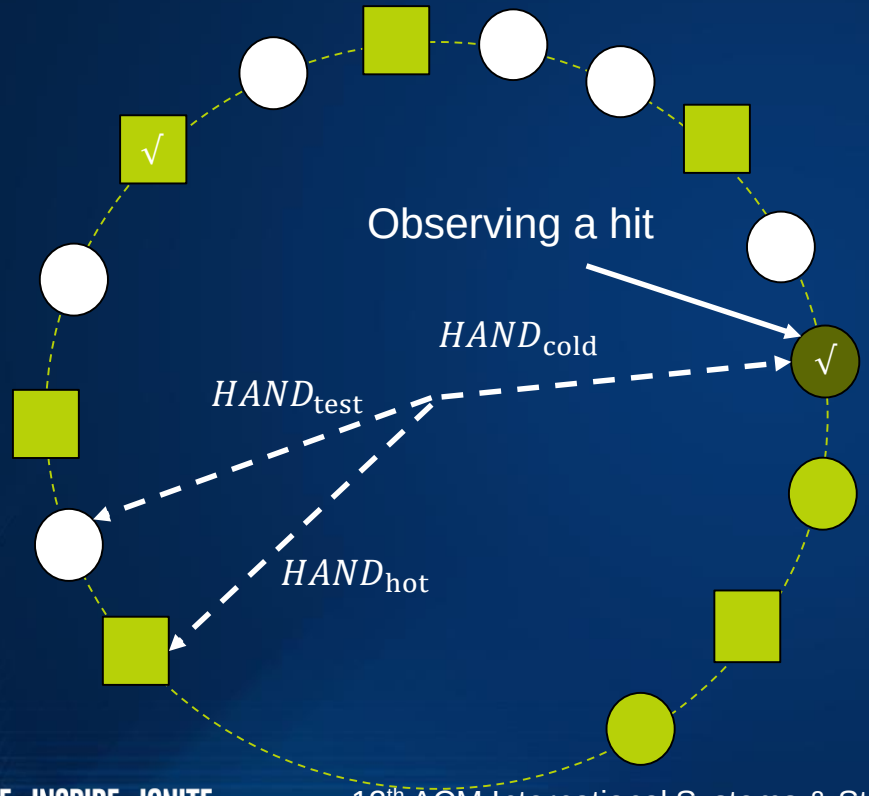
Adaptation in CLOCK-Pro+



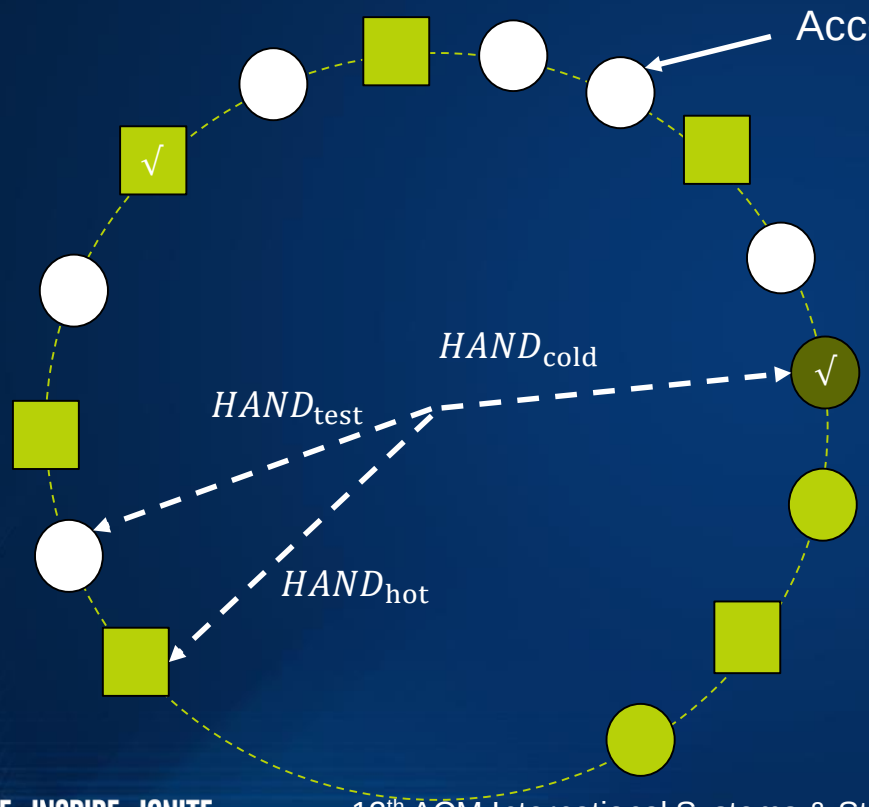
Grow resident cold page size
Utility quantified as $P_{\overline{n}} = 1/C_n$

Adaptation in CLOCK-Pro+



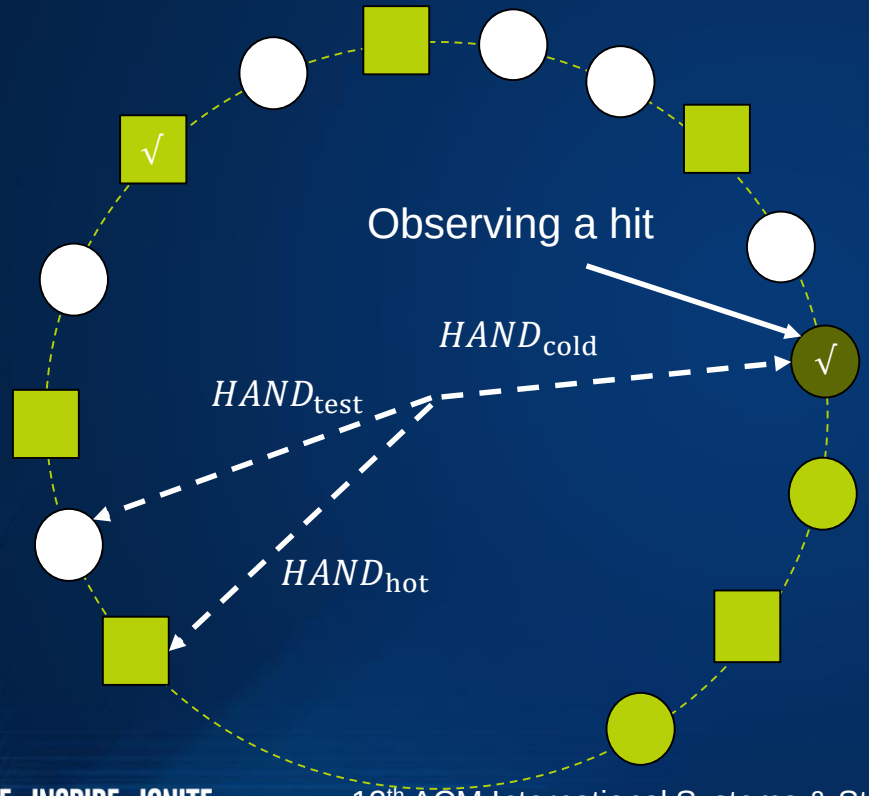
Grow hot page size
Utility quantified as $P_{\bar{d}} = 1/C_d$

Adaptation in CLOCK-Pro+



Grow resident cold page size by $\max\{1, P_{\bar{n}}/P_{\bar{d}}\}$

Adaptation in CLOCK-Pro+



Grow hot page size by $\max\{1, P_{\bar{d}}/P_{\bar{n}}\}$

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Experimental settings

- **Trace-Driven Simulation**
  - I/O traces from UMass Trace Repository
  - Synthetic trace drawn from a stack depth distribution
  - Cache size varies, & shadow entry number = cache entry number
- **Comparative Study on Hit Ratio**
  - CLOCK-Pro
  - CAR
  - CLOCK-Pro+

Experimental results

Retain CLOCK-Pro's strength

Trace (cache size)	CLOCK-Pro	CAR	CLOCK-Pro+
WebSearch1 (131072)	**13.10%**	8.32%	**12.96%**
WebSearch1 (262144)	**24.91%**	14.90%	**24.80%**
WebSearch1 (524288)	**40.36%**	32.78%	**41.66%**
WebSearch2 (262144)	**29.80%**	26.94%	**29.64%**
WebSearch2 (524288)	**48.35%**	41.72%	**48.50%**
WebSearch3 (262144)	**29.66%**	26.68%	**29.52%**
WebSearch3 (524288)	**48.21%**	41.40%	**48.41%**
Financial1 (512)	17.78%	**23.17%**	**22.69%**
Financial1 (1024)	20.62%	**26.02%**	**25.77%**
Financial1 (2048)	24.16%	**29.38%**	**29.15%**
Financial1 (4096)	27.58%	**32.61%**	**32.35%**
Financial1 (8192)	31.31%	**35.72%**	**35.65%**
Financial1 (16384)	34.33%	**38.35%**	**38.31%**
SDD (256)	17.10%	**20.40%**	**19.34%**
SDD (512)	31.60%	**36.75%**	**35.06%**

Experimental results

Overcome CLOCK-Pro's weaknesses, bringing its performance close to CAR

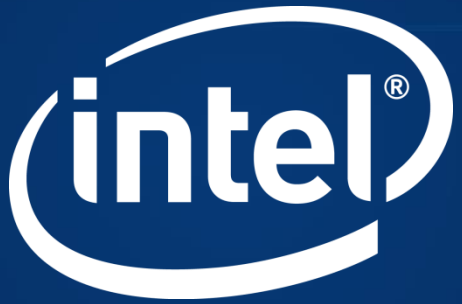
Trace (cache size)	CLOCK-Pro	CAR	CLOCK-Pro+
WebSearch1 (131072)	**13.10%**	8.32%	**12.96%**
WebSearch1 (262144)	**24.91%**	14.90%	**24.80%**
WebSearch1 (524288)	**40.36%**	32.78%	**41.66%**
WebSearch2 (262144)	**29.80%**	26.94%	**29.64%**
WebSearch2 (524288)	**48.35%**	41.72%	**48.50%**
WebSearch3 (262144)	**29.66%**	26.68%	**29.52%**
WebSearch3 (524288)	**48.21%**	41.40%	**48.41%**
Financial1 (512)	17.78%	**23.17%**	**22.69%**
Financial1 (1024)	20.62%	**26.02%**	**25.77%**
Financial1 (2048)	24.16%	**29.38%**	**29.15%**
Financial1 (4096)	27.58%	**32.61%**	**32.35%**
Financial1 (8192)	31.31%	**35.72%**	**35.65%**
SDD (256)	17.10%	**20.40%**	**19.34%**
SDD (512)	31.60%	**36.75%**	**35.06%**

CLOCK-Pro+ performs close to the winner between the two

Conclusion

- **Novel Improvement to CLOCK-Pro's Adaptation**
  - Borrowing idea from CAR
  - Utility-driven adaptation of cache space allocation
- **CLOCK-Pro+**
  - Enjoy the strengths of CLOCK-Pro & CAR
  - Overcome the weaknesses of CLOCK-Pro & CAR
  - Perform consistently close to the winner between the two

Q & A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Ablation Study

Sometimes CLOCK-Pro improves the performance

Trace (cache size)	CLOCK-LIRS[1]	CLOCK-Pro	CLOCK-Pro+
Financial1 (512)	15.80%	17.78%	**22.69%**
Financial1 (1024)	19.42%	20.62%	**25.77%**
Financial1 (2048)	25.36%	24.16%	**29.15%**
Financial1 (4096)	30.51%	27.58%	**32.35%**
Financial1 (8192)	34.24%	31.31%	**35.65%**
Financial1 (16384)	37.08%	34.33%	**38.31%**
SDD (256)	17.00%	17.10%	**19.34%**
SDD (512)	30.95%	31.60%	**35.06%**
SDD (1024)	51.55%	**58.08%**	**58.07%**

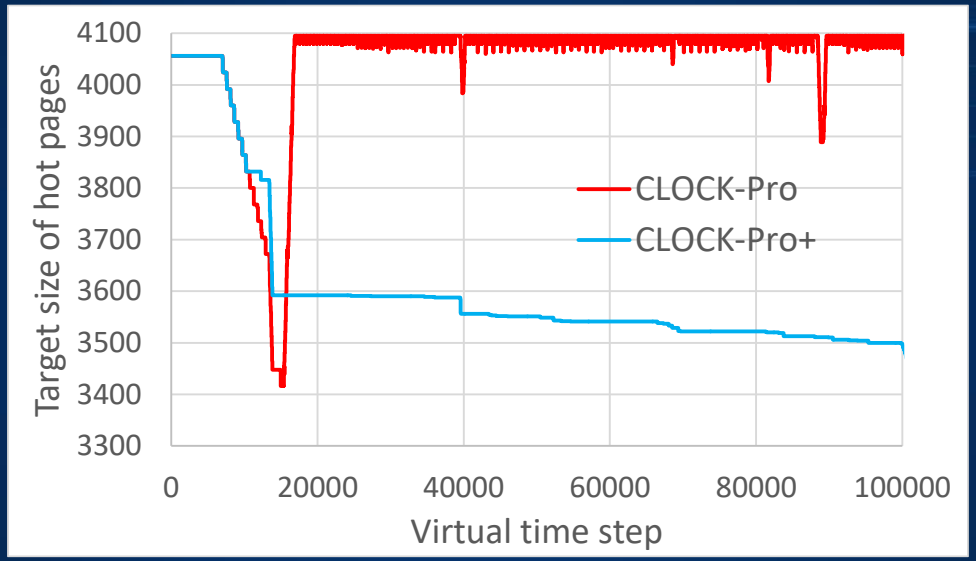
[1] CLOCK-Pro w/o adaptation

Sometimes it does not

CLOCK-Pro+ consistently improves the performance

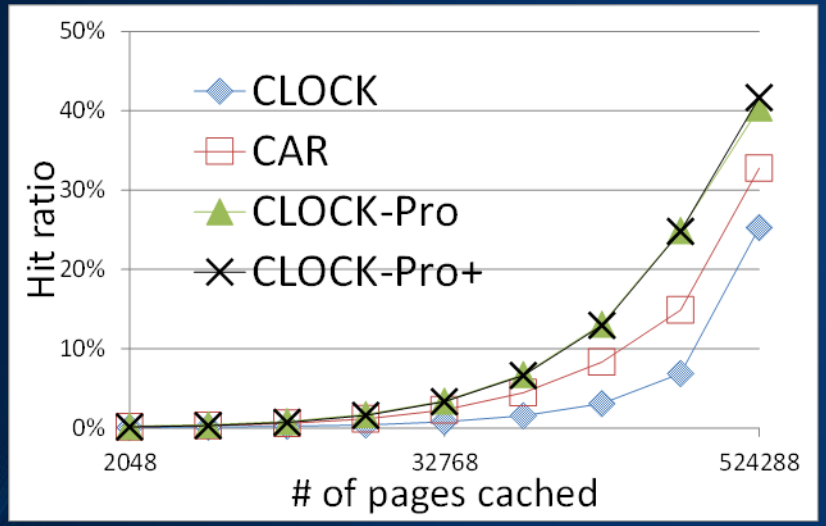
CLOCK-Pro performs unstably but CLOCK-Pro+ performs consistently

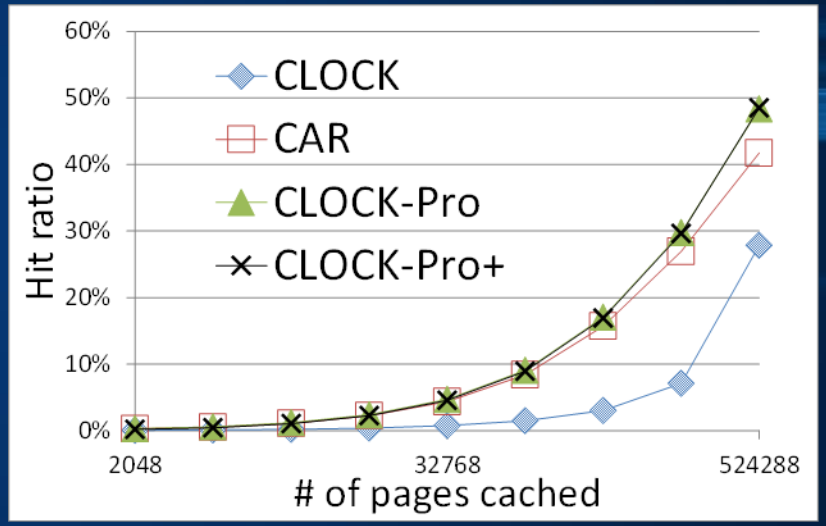
Case Study: Financial1 (4096)



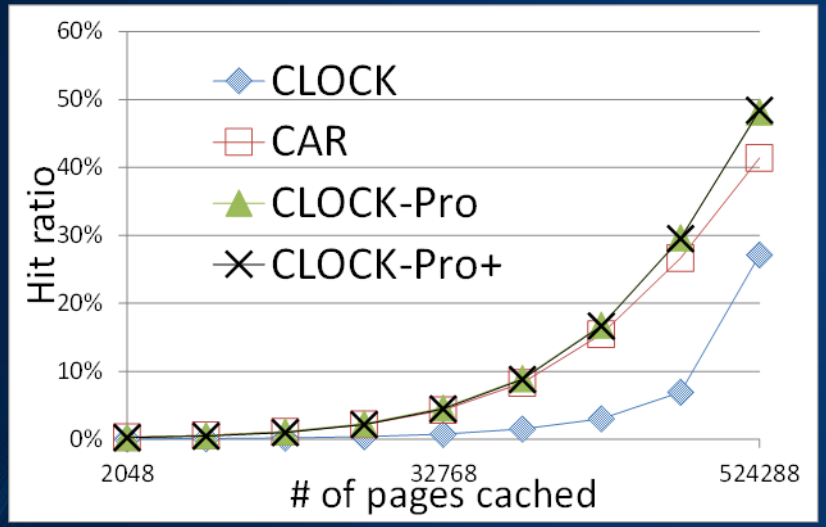
CLOCK-Pro: 382,543 non-resident cold page accesses, 111,244 resident cold page hits tracked, but **3,143,452** test pages expired;
CLOCK-Pro+: 102,804 non-resident cold page accesses & 3,780 demoted page hits

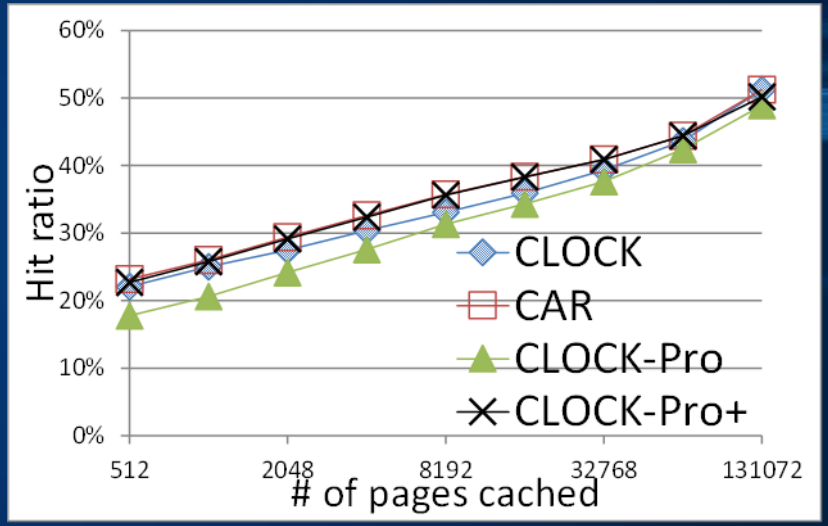
Full Results: WebSearch1 & Webserach2





Full Results: WebSearch3 & Financial1





Full Results: Financial2 & SDD