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-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

Best case reuse distance

$\text{HAND}_{\text{cold}}$

$\text{HAND}_{\text{hot}}$

$\text{HAND}_{\text{test}}$

Access

Hot page

 Resident cold page

Non-resident cold page

Referenced

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CLOCK-Pro

Cold page promotion & hot page demotion

Move to head

Demotion

Promotion

$\text{HAND}_{\text{hot}}$

$\text{HAND}_{\text{test}}$

$\text{HAND}_{\text{cold}}$
CLOCK-Pro

HAND_{\text{test}} & HAND_{\text{cold}} & HAND_{\text{hot}}

HAND_{\text{hot}} & \textit{HAND}_{\text{test}} \text{ move}

Test period terminates & non-resident page discarded
Many new pages come.

Limit clock size by terminating test pages with $H\!A\!N\!D_{\text{test}}$. 
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 with at most 1 recent access only

Recency CLOCK $T_1$

Recency shadow list $B_1$

Frequency pages: pages with at least 2 recent accesses

Frequency CLOCK $T_2$

Frequency shadow list $B_2$
CAR

Recency pages: pages w/ 1 recent accesses only

Frequency pages: pages w/ at least 2 recent accesses

Recency shadow list $B_1$ → growing $T_1$

Access recency shadow list $\rightarrow$ growing $T_1$

Incremental utility quantified as $P_1 = 1/|B_1|$

Frequency shadow list $B_2$ → growing $T_2$

Access frequency shadow list $\rightarrow$ growing $T_2$

Incremental utility quantified as $P_2 = 1/|B_2|$
CAR

Recency pages: pages w/ 1 recent accesses only

Frequency pages: pages w/ at least 2 recent accesses

Recency CLOCK $T_1$

Frequency CLOCK $T_2$

Recency shadow list $B_1$

Frequency shadow list $B_2$

Adjustment given a $B_1$ access:

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

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)

<table>
<thead>
<tr>
<th>Trace (cache size)</th>
<th>CLOCK-Pro</th>
<th>CAR</th>
</tr>
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<tbody>
<tr>
<td>WebSearch1 (131072)</td>
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No consistent winner

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CLOCK-Pro outperforms CAR
CAR outperforms CLOCK-Pro
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
Adaptation in CLOCK-Pro+

Grow resident cold page size
Utility quantified as $P_{\bar{n}} = 1/C_n$
Adaptation in CLOCK-Pro+

Growing hot page size
Utility quantified as $P_{\bar{d}} = 1/C_d$
Adaptation in CLOCK-Pro+

\[ \text{HAND}_{\text{test}} \rightarrow \text{HAND}_{\text{hot}} \rightarrow \text{HAND}_{\text{cold}} \rightarrow \text{Access} \]

Grow resident cold page size by \( \max\{1, \frac{P_{\bar{m}}}{P_{\bar{d}}}\} \)
Adaptation in CLOCK-Pro+

Grow hot page size by
\[ \max\{1, \frac{P_{\bar{d}}}{P_{\bar{n}}}\} \]

Observe a hit

\[ HAND_{\text{cold}} \]

\[ HAND_{\text{test}} \]

\[ HAND_{\text{hot}} \]
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

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

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
## Ablation Study

Sometimes CLOCK-Pro improves the performance.

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$^1$ CLOCK-Pro w/o adaptation

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

Sometimes it does not.

CLOCK-Pro+ consistently improves the performance.
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 & WebSearch2

- CLOCK
- CAR
- CLOCK-Pro
- CLOCK-Pro+

Hit ratio vs. # of pages cached

12th ACM International Systems & Storage Conference (SYSTOR 2019)
Full Results: WebSearch3 & Financial1
Full Results: Financial2 & SDD