CAUSE: Critical Application Usage-Aware Memory System using Non-volatile Memory for Mobile Devices

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User Experience in Mobile

User experience

Performance
- Processor speed

Memory bandwidth

Power
- Limited battery

Launching Process (Angry Birds Rio)
Mobile, Applications and DRAM

- **Limited DRAM capacity**
  - State of the art mobile phones e.g. 1G in iphone 6
  - 15% of applications close due to limited memory
  - Re-launching needs 10X slower [Wook et al. IEEE TECS14]

- **Problem caused by limited main memory**
  - Application termination
  - Launch time + energy overhead
  - Process service times

- **User experience degradation**
Swap and Mobile Device

- Swap Memory with Flash
  - Energy
  - Latency
  - Endurance of eMMC flash

- Emerging NVM technology
  - Efficient read operation
  - Denser than DRAM (PCM ~2-4X)
  - Low write performance!

Non-volatile Memory

- **STT-RAM**
  - Low leakage power
  - High endurance ($10^{10}$-$10^{15}$)
  - Very fast in read
  - Write latency and energy!
  - Low scalability

- **PCM**
  - Low leakage power
  - Very high density
  - Scalable
  - Write latency and energy!
  - Low endurance ($10^6$-$10^7$)

### Table

<table>
<thead>
<tr>
<th>Features</th>
<th>SRAM</th>
<th>eDRAM</th>
<th>STT-RAM</th>
<th>PCM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>Low</td>
<td>High</td>
<td>High</td>
<td>Very high</td>
</tr>
<tr>
<td>Speed</td>
<td>Very Fast</td>
<td>Fast</td>
<td>Fast for read; slow for write</td>
<td>Slow for read; very slow for write</td>
</tr>
<tr>
<td>Dynamic Power</td>
<td>Low</td>
<td>Medium</td>
<td>Low for read; very high for write</td>
<td>Medium for read; high for write</td>
</tr>
<tr>
<td>Power</td>
<td>Low</td>
<td>Medium</td>
<td>Low</td>
<td>Low</td>
</tr>
<tr>
<td>Non-volatility</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
</tbody>
</table>
Challenges of NVM Based Swap Memory

- **Software:**
  How to select apps which are good to be swapped?
  - Apps have different launching usage trends, resulting in distinct levels of criticality for user experience

- **Hardware:**
  How to design NVMs for swap?
  - Apps have different access characteristics according to their status, e.g., foreground app and background service
CAUSE

- Critical Application Usage-Aware Memory System
  - Fast app launch: Better user experience!
  - Better process service time: More memory space for foreground apps

- Optimized NVM for swap
  - Low leakage power
  - Fast as DRAM
Memory Systems with NVM

- **App management service:**
  - Recognizes applications launched by users
  - Tracks the applications recently launched in foreground
  - Sends the application information that is likely to be used in near future

- **Page characteristics:**
  - **Dormant:**
    - Foreground applications
    - Indeed not recently used
  - **Non-dormant:**
    - Likely to be accessed soon or periodically
    - Background applications and widget
Software:
Application Launching Usage Trend

- Collected logs for two weeks from 10 users
- **Re-launching interval**: the time interval between two application launches for a certain application.
- 80% of applications were reused within 100 minutes!

80% of app reused within 100 minutes!

Apps after 100min consider as inactive

Critical
CAUSE Management Policy

Active List Management

- Linux policy: balancing the number of active and inactive pages

Active List

Pa_1 Pa_2 Pa_3 Pa_4 \ldots Pa_{N-2} Pa_{N-1} Pa_N

Inactive List

In_1 In_2 In_3 In_4 \ldots In_{M-2} In_{M-1} In_M
CAUSE Management Policy

Freeing memory pages

Active List

\[\text{Pa}_1, \text{Pa}_2, \text{Pa}_3, \text{Pa}_4, \ldots, \text{Pa}_{N-1}, \text{Pa}_{N-1}, \text{Pa}_N\]

Inactive List

\[\text{In}_1, \text{In}_2, \text{In}_3, \text{In}_4, \ldots, \text{In}_{M-2}, \text{In}_{M-1}, \text{In}_M\]

Foreground

Dormant

Background

Non-dormant
Hardware: Buffer Optimization

Main Memory (DRAM)

- DRAM Buffer
  - NVMdormant
    - Relaxed NVM
  
  *Energy Optimized*

- DRAM Buffer
  - NVMnon-dormant
    - Relaxed NVM

  *Latency Optimized*

Area + Power

Read/write latency

Low access activity

High frequent access block
Retention Relaxation

- **STT-RAM retention** [Smullen et al, HPCA 2011]
  - 20% MTJ area relaxation
  - 83% write latency improvement
  - Retention time from 20 years to 1 month
  - Possibility of refresh

![Graph showing normalized retention time vs area relaxation]
Experimental Setup

- Qualcomm MSM8660 smartphone
  - Running Android 4.1 with Linux kernel 3.0.6
  - 1GB Main memory; 768MB DRAM; 64KB-256KB NVM

- HSPICE for circuit level simulation
  - Retention time relaxation
  - Circuit level optimization

- NVsim & NVmain simulators for energy estimation
  - DRAM buffer
  - Buffer design

- 10 users launch 20 apps for 2 weeks
  - Scale down the executed time to 20 mins
CAUSE Energy Consumption

- Comparison of energy consumption with different memory technologies
  - 90% and 44% energy savings for STT-RAM and PCM

![Energy Consumption Chart]

- Comparison of energy consumption with different memory technologies
- 90% and 44% energy savings for STT-RAM and PCM

![Energy Consumption Chart]
Launch Experience

- 32% launching time speed up
- Better user experience 😊

<table>
<thead>
<tr>
<th>User</th>
<th>Improved Restart Count</th>
<th>Improved Launching Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>User 1</td>
<td>40%</td>
<td>30%</td>
</tr>
<tr>
<td>User 2</td>
<td>30%</td>
<td>20%</td>
</tr>
<tr>
<td>User 3</td>
<td>25%</td>
<td>25%</td>
</tr>
<tr>
<td>User 4</td>
<td>20%</td>
<td>30%</td>
</tr>
<tr>
<td>User 5</td>
<td>15%</td>
<td>25%</td>
</tr>
<tr>
<td>Geo.Mean (10 Users)</td>
<td>24%</td>
<td>22%</td>
</tr>
</tbody>
</table>
Background Page Balancing

- 23% more background page migration
- Provides space for foreground applications
- Better process service time 😊

![Bar chart showing the ratio of background app. page (CAUSE vs Baseline) for different users and the geometric mean for 10 users.](chart.png)
Summary

- Addressed limited main memory capacity of mobile devices
- Proposed new swap architecture to save the inactive pages based on applications and users
- Proposed & optimized dormant and non-dormant memory components for background and foreground applications
- 23% more background migrations + better process service time
- 32% launching time speed up + better user experience