Lecture 3 of the

# MLArchSys Seminar

Instructor: Thaleia Dimitra Doudali

*Assistant Professor at IMDEA Software Institute*

Universidad Politécnica de Madrid (UPM)

March 2023

# Outline of Today's Lecture

Systems Software ← ML *for* Systems — Machine Learning

Today's Paper:

**Kleio: A Hybrid Memory Page Scheduler with Machine Intelligence**

Thaleia Dimitra Doudali
Georgia Institute of Technology
thdoudali@gatech.edu

Sergey Blagodurov
Advanced Micro Devices, Inc.
Sergey.Blagodurov@amd.com

Abhinav Vishnu
Advanced Micro Devices, Inc.
Abhinav.Vishnu@amd.com

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Sudhanva.Gurumurthi@amd.com

Ada Gavrilovska
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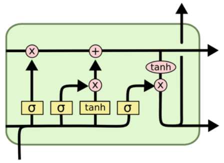

LSTMs

***for*** Hybrid Memory Management (HMem Management)

Lecture Outline:

| |
|---|
| Hybrid Memories |
| Hybrid Memory Management |
| How to Integrate ML? |
| System Design |
| Evaluation |
| Lessons Learned |

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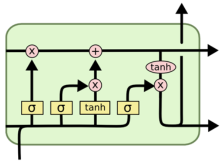

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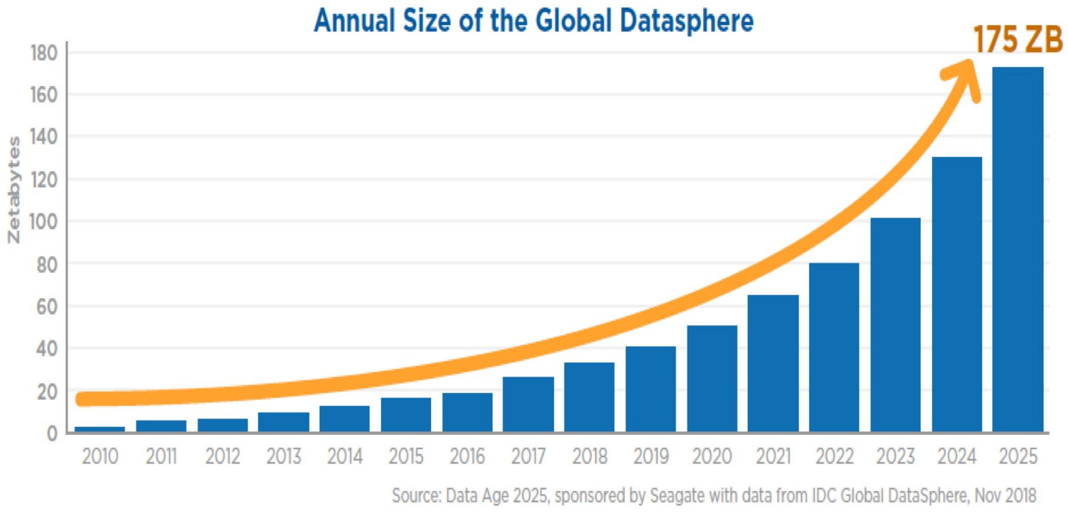
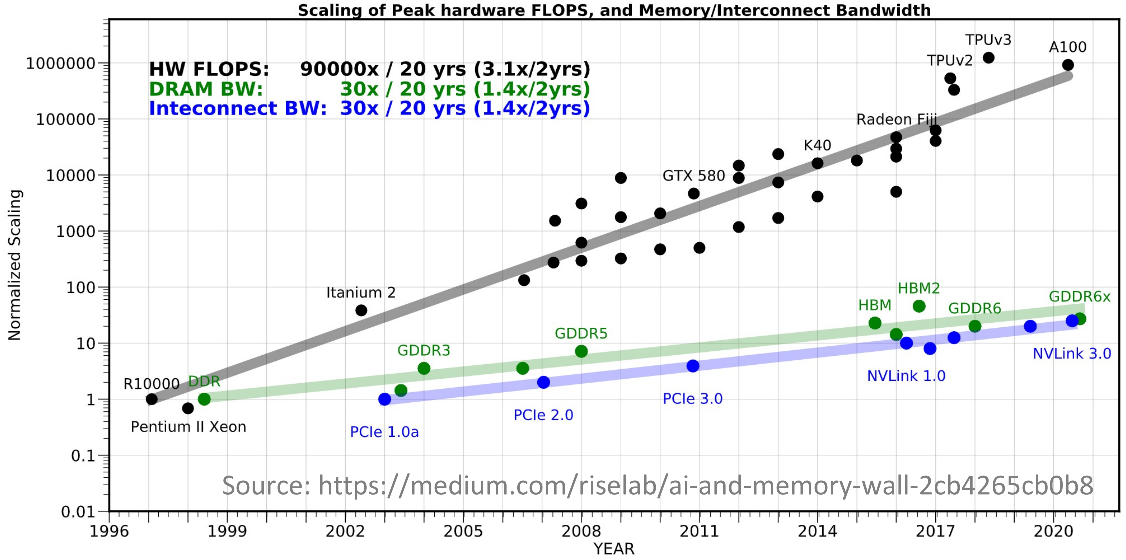
# Big Data hits the Memory Wall



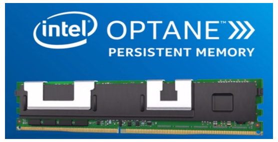




Applications generate huge amounts of data.

Processing speed grows faster than memory and data transfer speed.

Need for **larger** and **faster** memory configurations.

# New Memory Technologies

<table>
<tr><th>Characteristic</th><th>Technology</th><th>Vendors</th></tr>
<tr><td>Low Latency</td><td>MRAM</td><td>
</td></tr>
<tr><td>Uniform Latency</td><td>DRAM</td><td></td></tr>
<tr><td>High Bandwidth</td><td>HBM</td><td>
</td></tr>
<tr><td>Persistent / Non Volatile</td><td>PMEM / NVM</td><td>
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| | |
|---|---|
| Application Performance | 200 PF |
| Number of Nodes | 4,608 |
| Node performance | 42 TF |
| Memory per Node | 512 GB DDR4 + 96 GB HBM2 |
| NV memory per Node | 1600 GB |
| Total System Memory | >10 PB DDR4 + HBM2 + Non-volatile |
| Processors | 2 IBM POWER9™ 9,216 CPUs<br>6 NVIDIA Volta™ 27,648 GPUs |
| File System | 250 PB, 2.5 TB/s, GPFS™ |
| Power Consumption | 13 MW |
| Interconnect | Mellanox EDR 100G InfiniBand |
| Operating System | Red Hat Enterprise Linux (RHEL) version 7.4 |

Example Configuration of a Supercomputer.

We are in the era of **Hybrid Memory** Systems. A mix of different technologies at different speeds / capacities / costs.

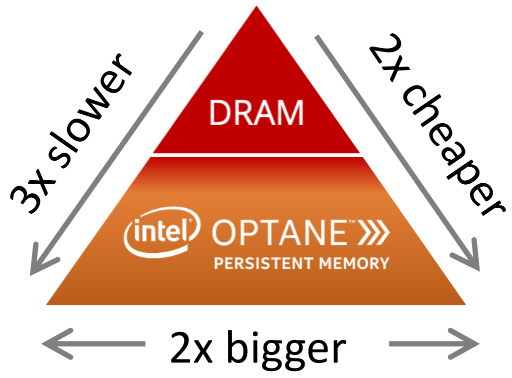
# Hybrid Memory Configurations

In today's paper we assume a hybrid memory system with **DRAM** and **NVM** (Non Volatile Memory).

The NVM actual product was released by Intel in 2019, after the paper was published.

So, the paper had to assume various possible configurations, e.g., capacity ratios.

Intel Optane is packaged together with DRAM.




Source: memverge.com

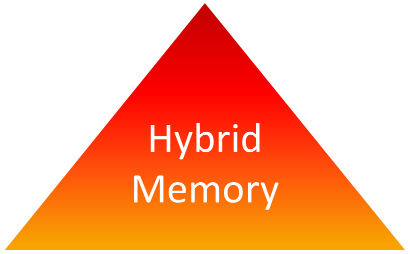
Guess what? The product got discontinued in 2022..

**Intel kills off Optane Memory, writes off $559 million inventory**

In a terrible quarter for the chip giant

July 29, 2022 By: Sebastian Moss 1 Comment

But this is not the end for hybrid memory configurations.
It is a mix of **any** number of **fast vs. slow**, **small vs. big** memories.



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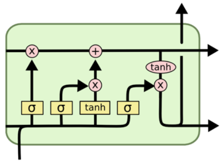

LSTMs

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- **Hybrid Memory Management**
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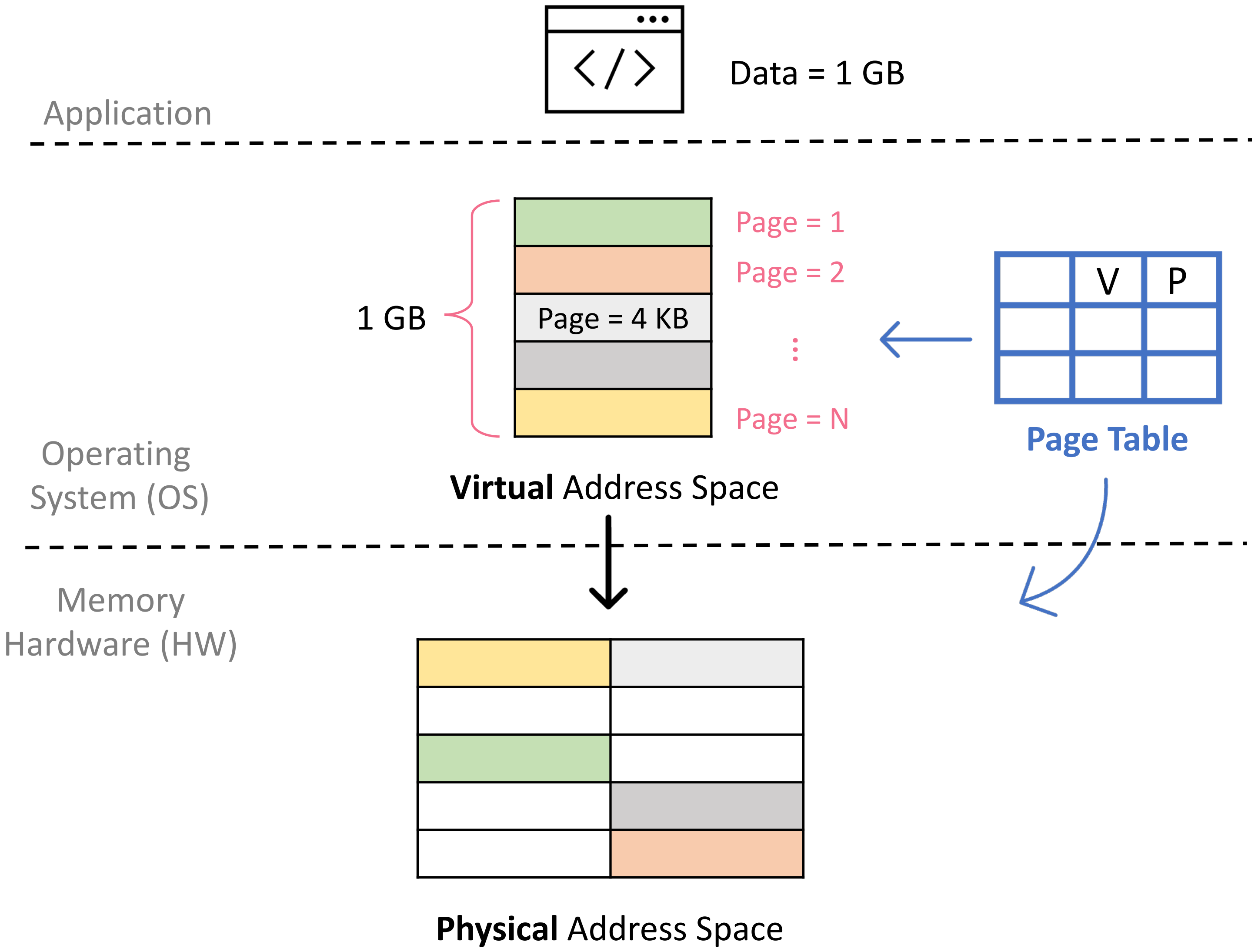
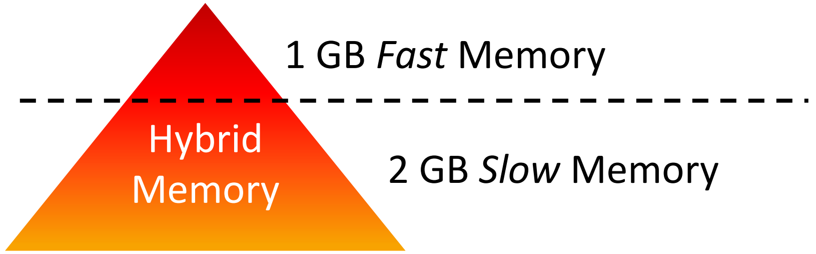
# OS-level Memory Management

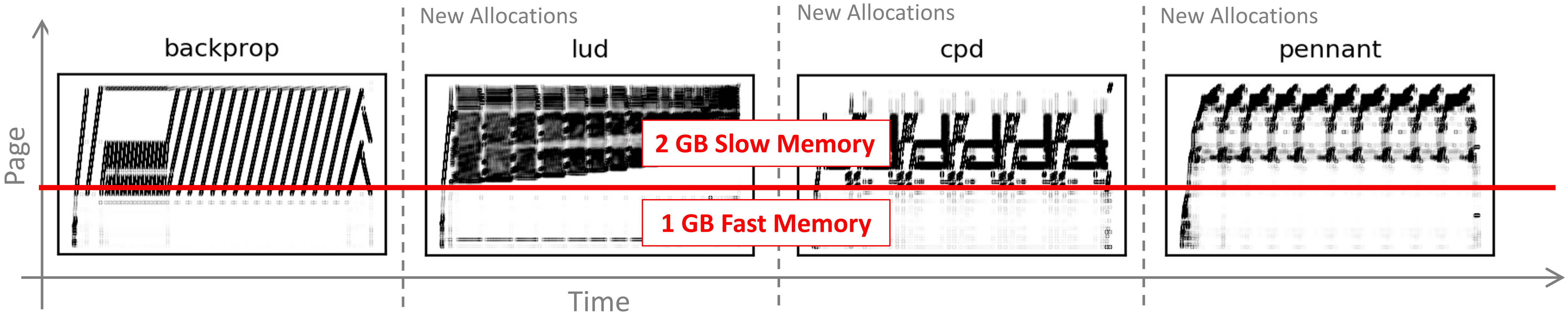


# Hybrid Memory Page Allocation

Example: Let's assume each application uses 3 GB. And hybrid memory consists of:



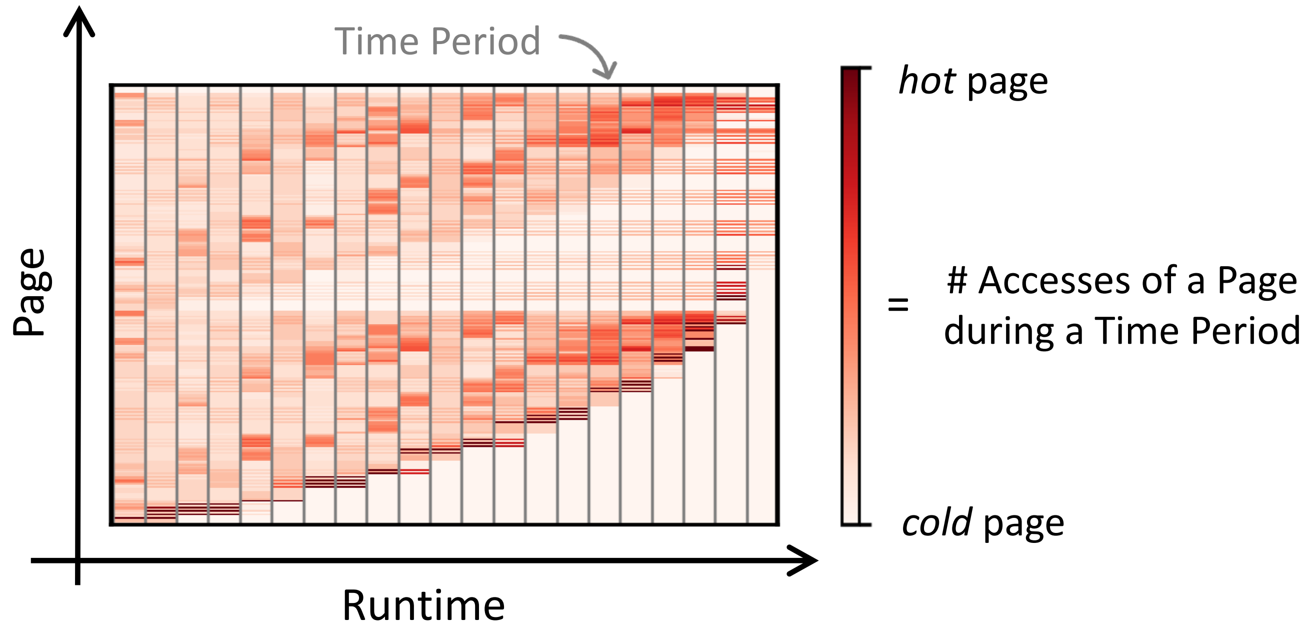

The OS allocates the pages in memory using the **"first touch"** policy.

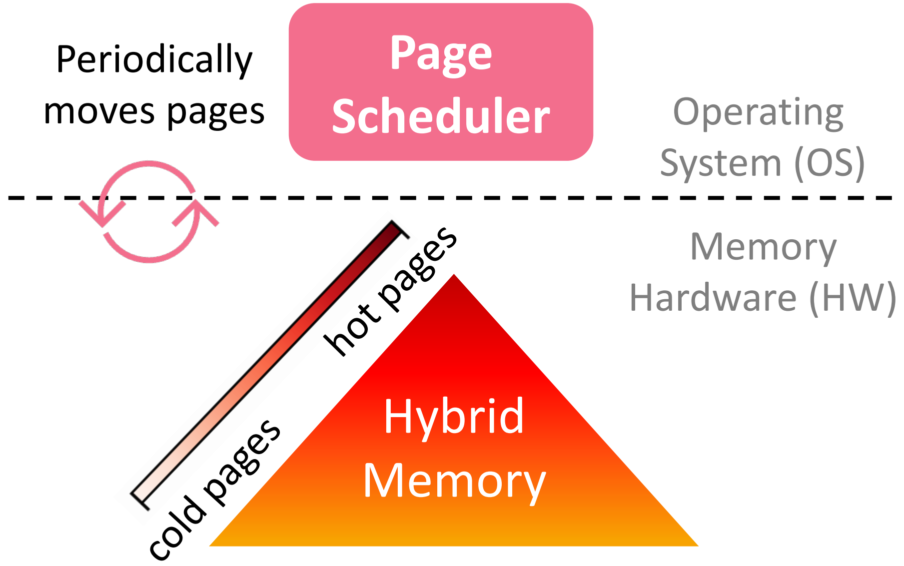



If the memory allocation doesn't change throughout time, then we get no use out of the *fast* memory.

# Hybrid Memory Page Scheduling

The OS should move pages dynamically across hybrid memory to maximize the efficiency.

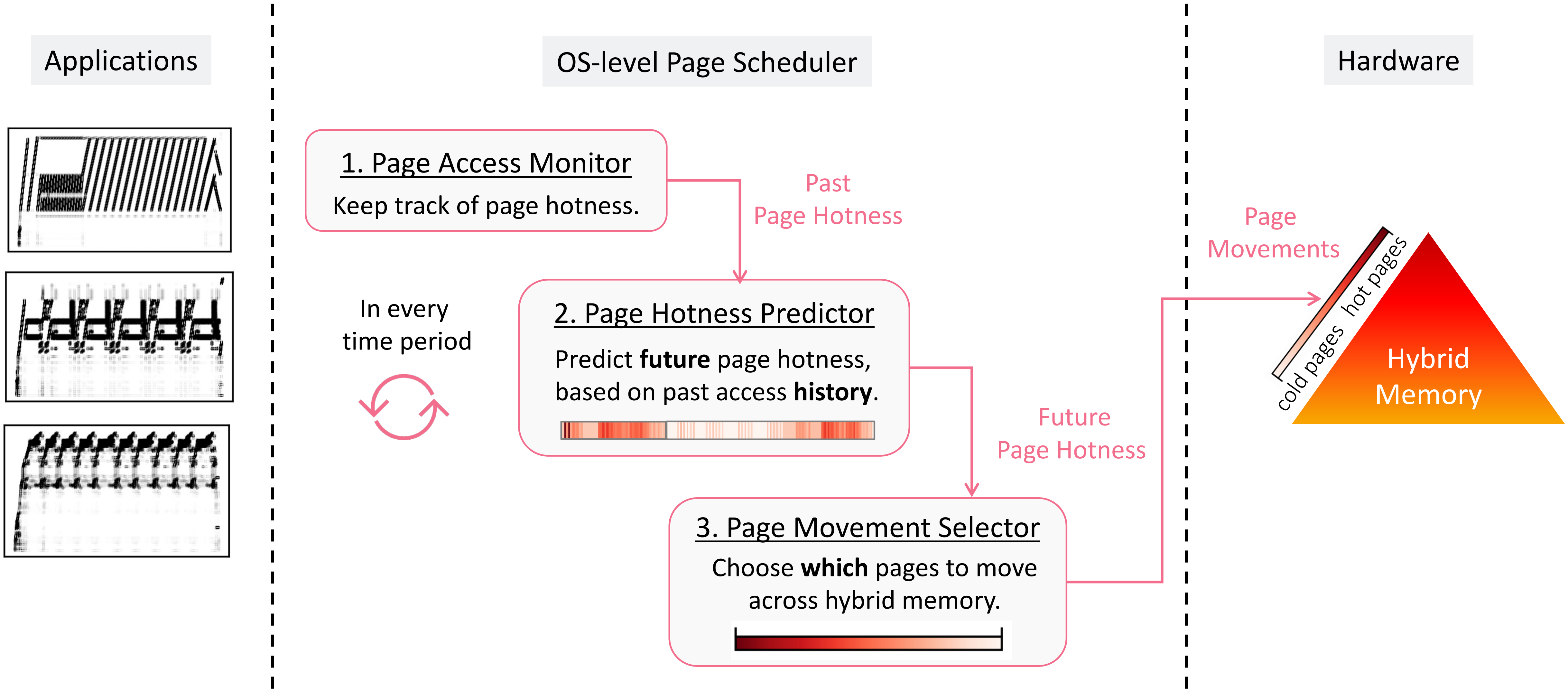



The page *hotness* changes through time.

Keep the hot pages in fast memory through time.

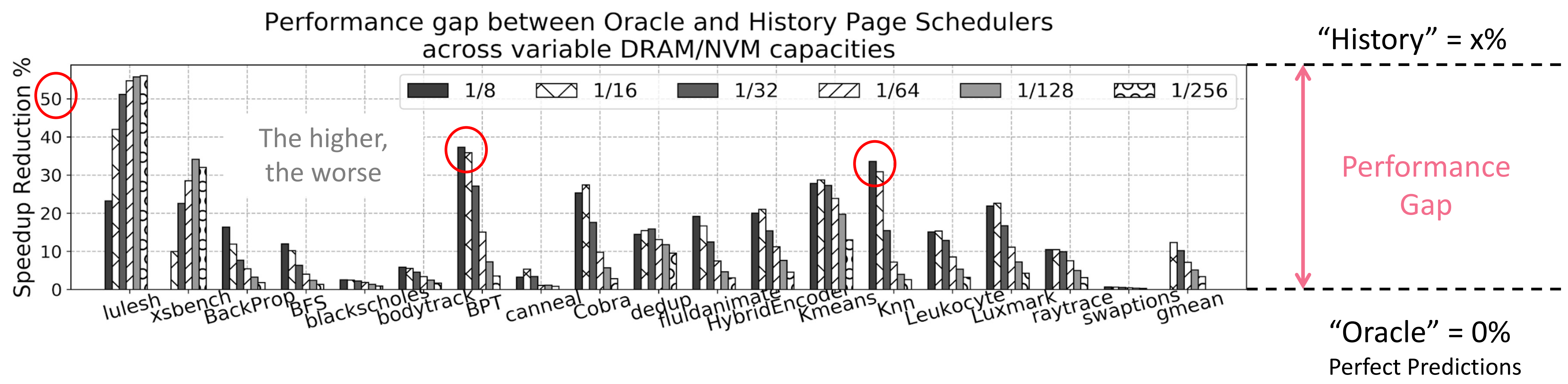
# Page Scheduling as a Prediction Problem



# Existing Predictors

OS uses a very simple **history**-based predictor, to minize operational overheads.

Predicts for all pages that page hotness at period $p_N$ = page hotness at period $p_{N+1}$




Need something more clever, to close this big gap.. How effective would Machine Learning be?

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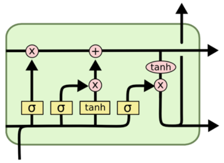


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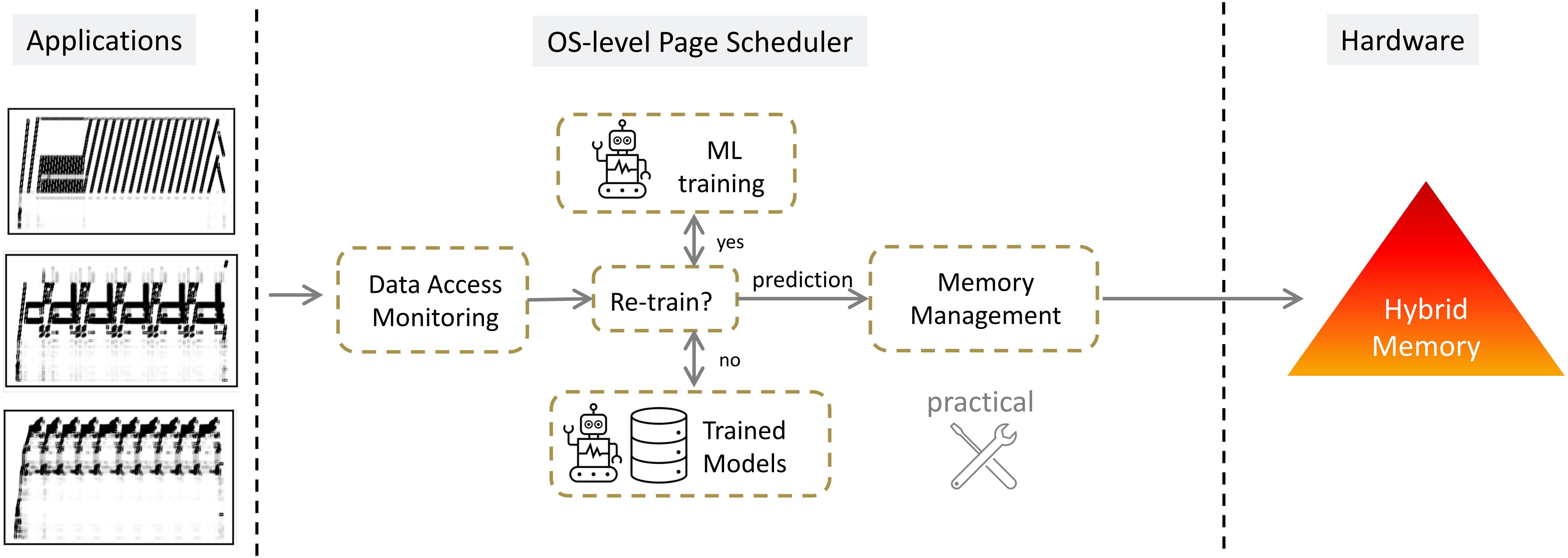
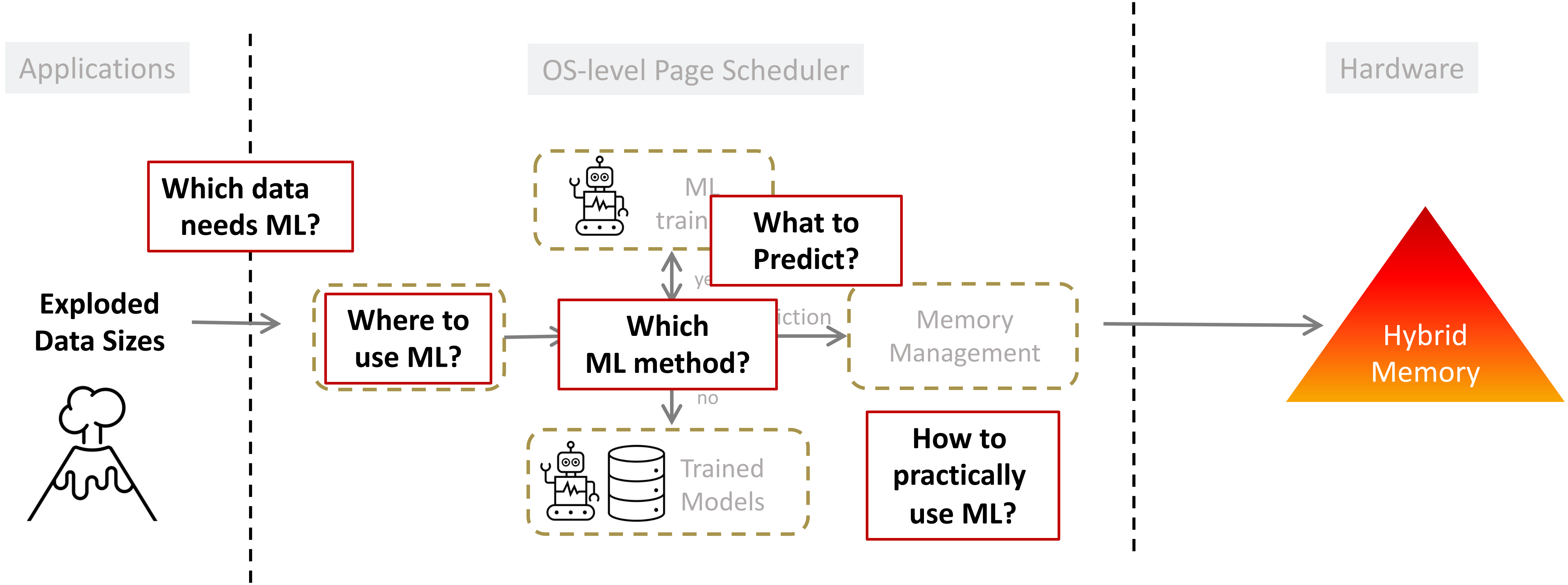
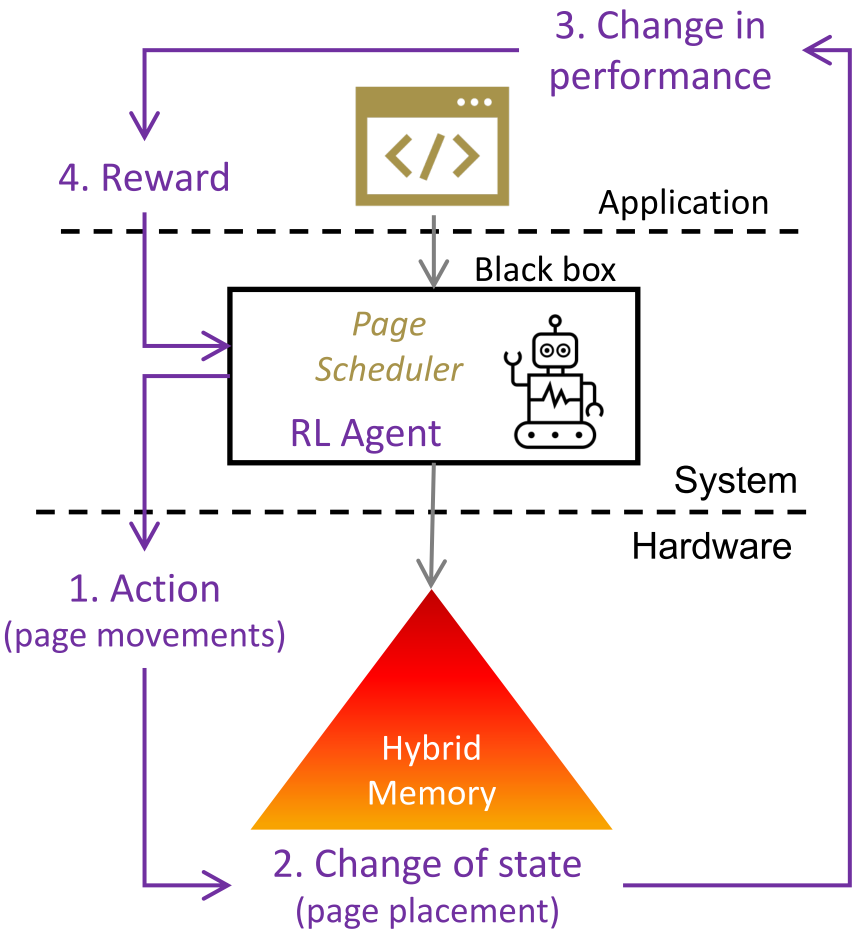
# The Vision: Integrate ML in Page Sceduling



# Toward Realizing the Vision: Questions to Ask



# Where to Use ML? (1)




**Replace** the Page Scheduler with a Reinforcement Learning (RL) agent.

**Learn the Action:** Learn from moving pages across hybrid memory.

Learn from mistakes (e.g., cold pages in DRAM).

**Why it is not a good fit:**

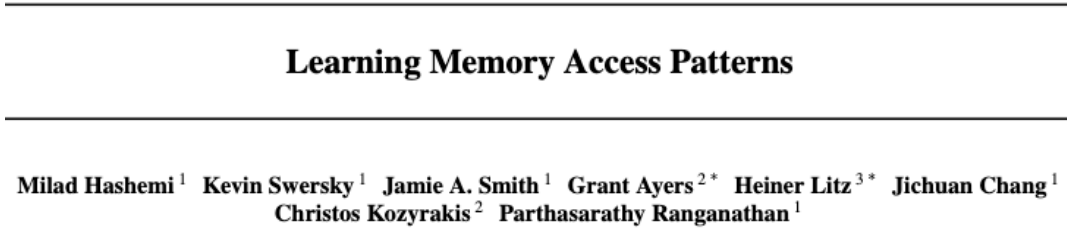
- Exponential Action Space = $2^N$, when moving N pages across 2 memories.
- Need to re-train if configuration of hybrid memory changes.
  - Number of memory units.
  - Difference in access speeds / capacities.

Not practical / scalable.

Don't learn the action!

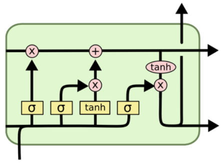
# Learning Memory Access Patterns

Don’t learn the action.. Learn the memory access pattern?



**Learning Memory Access Patterns**

Milad Hashemi [1] Kevin Swersky [1] Jamie A. Smith [1] Grant Ayers [2*] Heiner Litz [3*] Jichuan Chang [1]
Christos Kozyrakis [2] Parthasarathy Ranganathan [1]




LSTMs

***for*** Cache Prefetching

Memory Access Trace

```
0x40001ee0: R 0xbfffe798
0x40001efd: W 0xbfffe7d4
0x40001f09: W 0xbfffe7d8
0x40001f20: W 0xbfffe864
0x40001f20: W 0xbfffe868
```

PC Physical address

**input**

PC $t_N$,
Address Delta($t_N$, $t_{N-1}$)

→ LSTM-based Deep Neural Network →

**output**

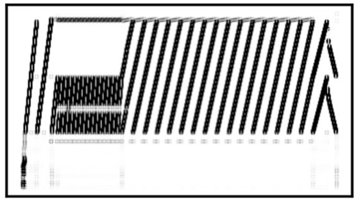
Delta($t_{N+1}$, $t_N$)

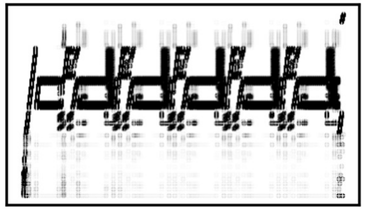
LSTMs (Long Short Term Memory) Networks are used in timeseries forecasting.

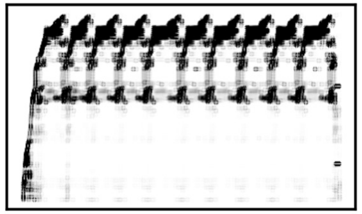
Can we do something similar?

# Where to Use ML? (2)

## Applications







## OS-level Page Scheduler

**1. Page Access Monitor**
Keep track of page hotness.

Past Page Hotness

In every time period

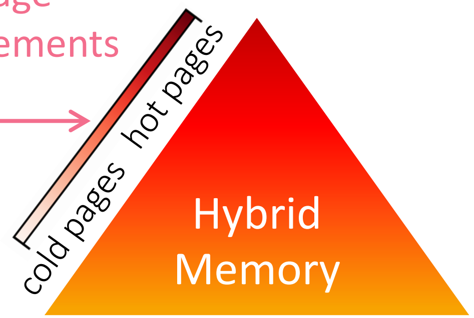
**2. Page Hotness Predictor**
Use **LSTMs** to predict **which** pages will be accessed in the next period. Then, calculate page hotness.

Future Page Hotness

**3. Page Movement Selector**
Choose **which** pages to move across hybrid memory.

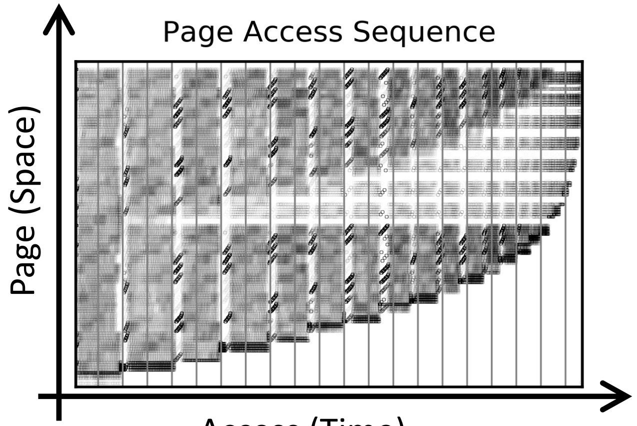
## Hardware

Page Movements



# Learning the Page Access Sequence

Learn **which** pages will be accessed in the next period of time, given a window of history.




**input**

Page ID $t_{N-1}$,
Page ID $t_{N-2}$,
...
Page ID $t_{N-h}$

→ LSTM-based Deep Neural Network →

**output**

Page ID $t_N$

| No. models | Overheads | Accuracy |
|---|---|---|
| 1 per app | Huge Memory Trace Files. Days to train. Months to fine-tune. | Low, because millions of pages. Top-k predictions not useful. |

Can we learn something else?

# Learning the Page Hotness

Learn **how hot** a page will be in the next period of time, given a window of history.

Flip the way you look at a problem!


Page Access Hotness per Period

**input**

Page Hotness $t_{N-1}$,
Page Hotness $t_{N-2}$,
...
Page Hotness $t_{N-h}$

→ LSTM-based Deep Neural Network →

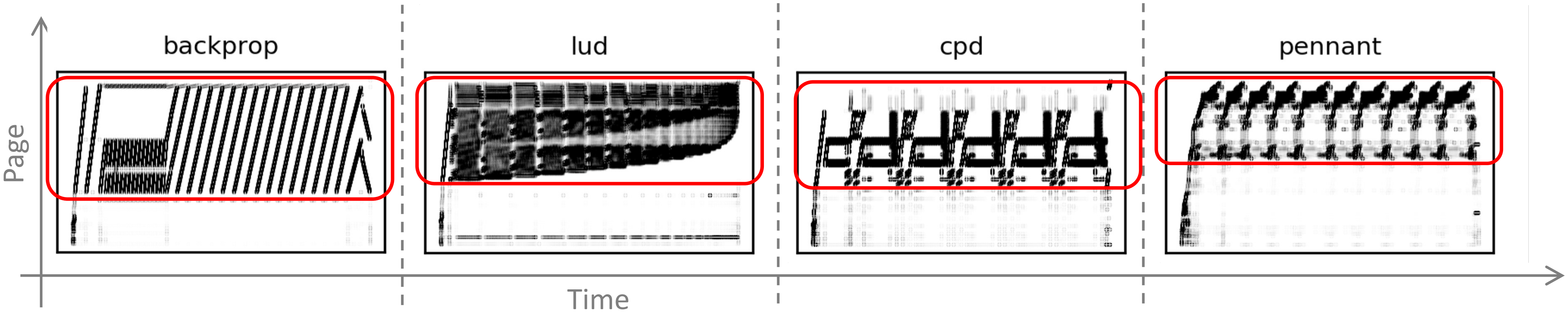
**output**

Page Hotness $t_N$

| No. models | Overheads | Accuracy |
|---|---|---|
| Many per app.<br>1 per page. | Smaller models.<br>Parallel Training.<br>Faster to train and fine-tune. | High, because hotness value is smaller, depending on the period length. |

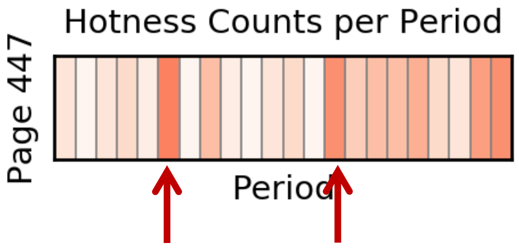
Challenge: 1 model per page, means millions of models..

# Do all Pages Need ML?




Probably the pages that are part of a pattern, need ML-based management.
For the rest, the simple *history* page scheduler works well (page hotness at period $p_N$ = page hotness at period $p_{N+1}$).

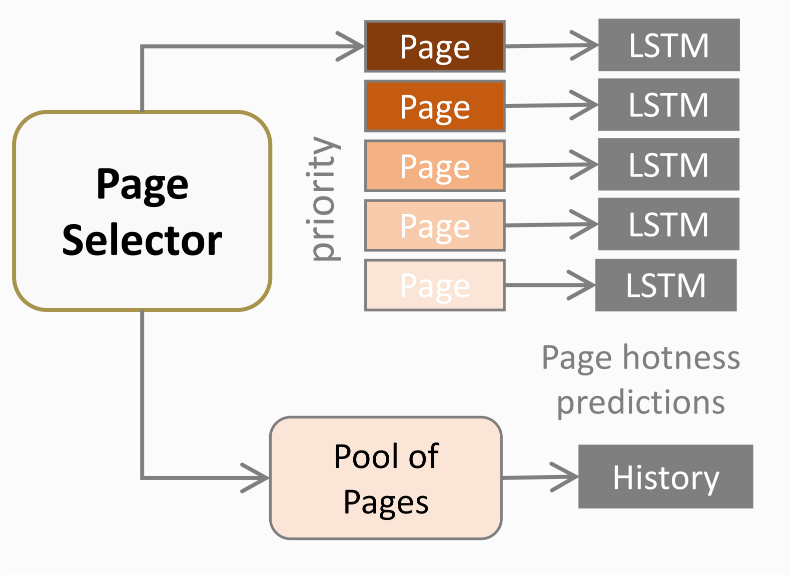
Which pages **really** need ML?




Page suddenly becomes very **hot**.
History scheduler will **misplace** it (not in DRAM when hot).

Use ML for subset of pages, and the existing *history* scheduler for the rest.

# Proposed ML Integration




Apply ML on a small page subset.

Foundations for practical use of ML.

Carefully select pages for ML.

Application performance boost.

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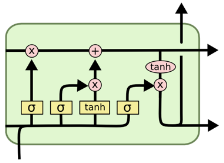


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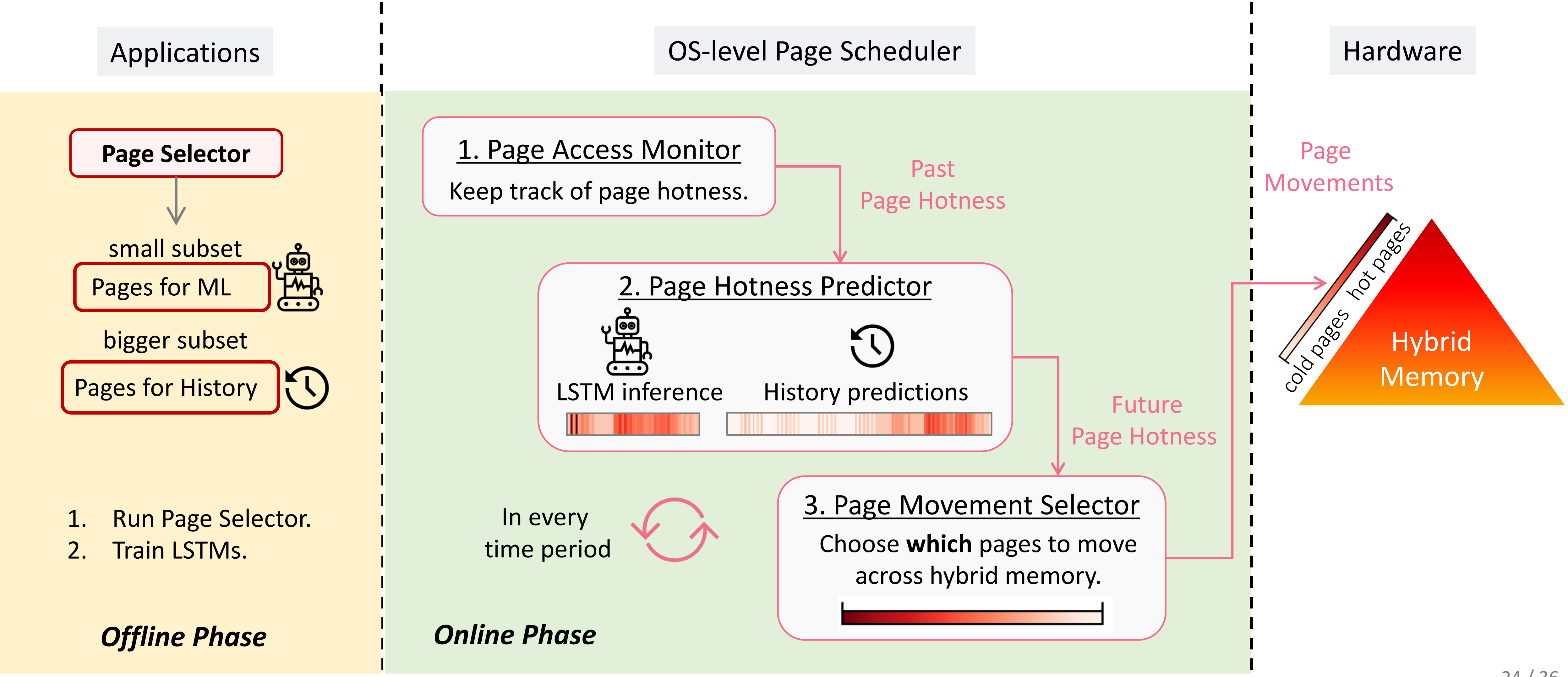
# System Design of Kleio

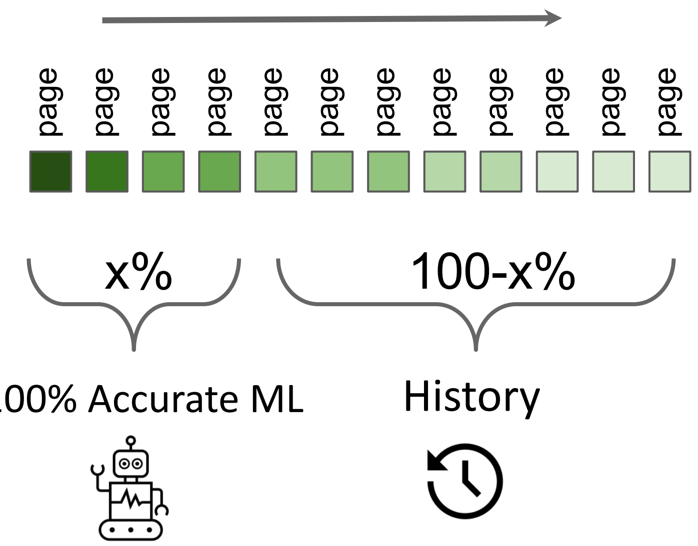
**Greek Trivia:** According to the ancient Greek mythology, Kleio was the muse of history, daughter of Mnemosyne, goddess of memory.



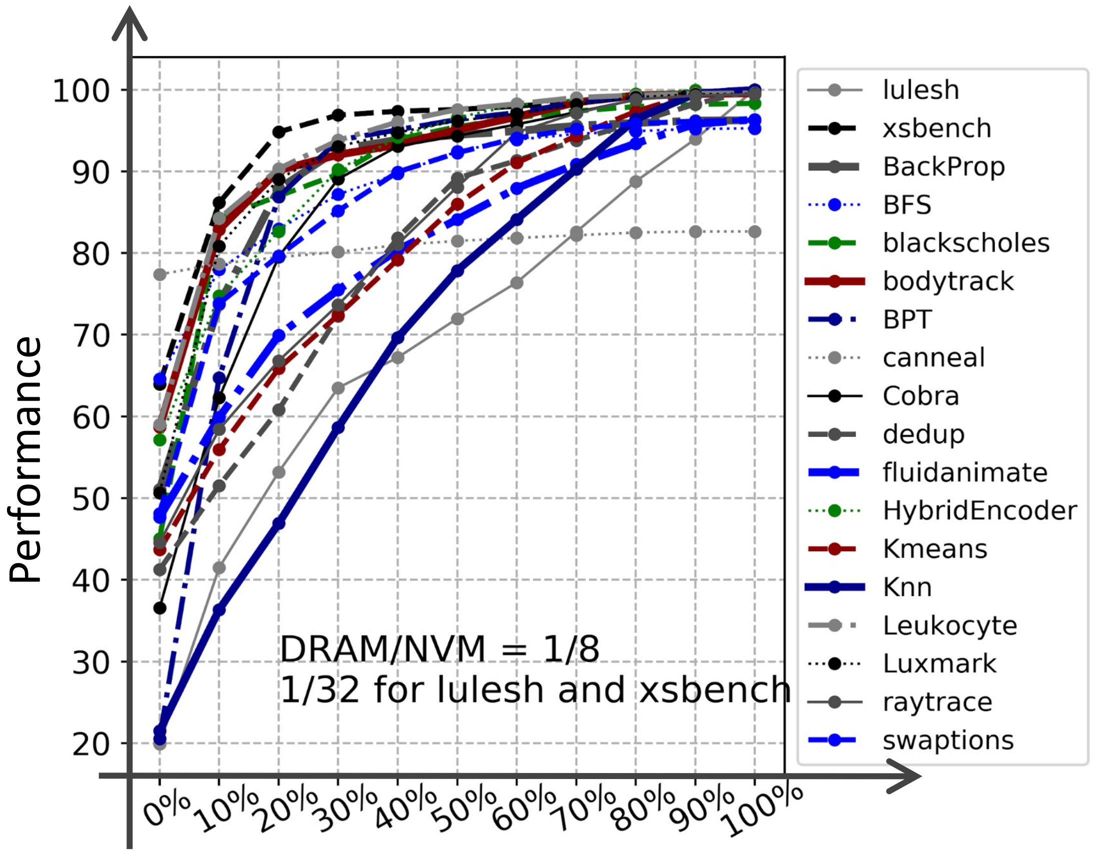
# Which Pages to Select?

Need to create a metric to select pages.

Per Page Benefit Factor
**benefit = # accesses x # misplacements**



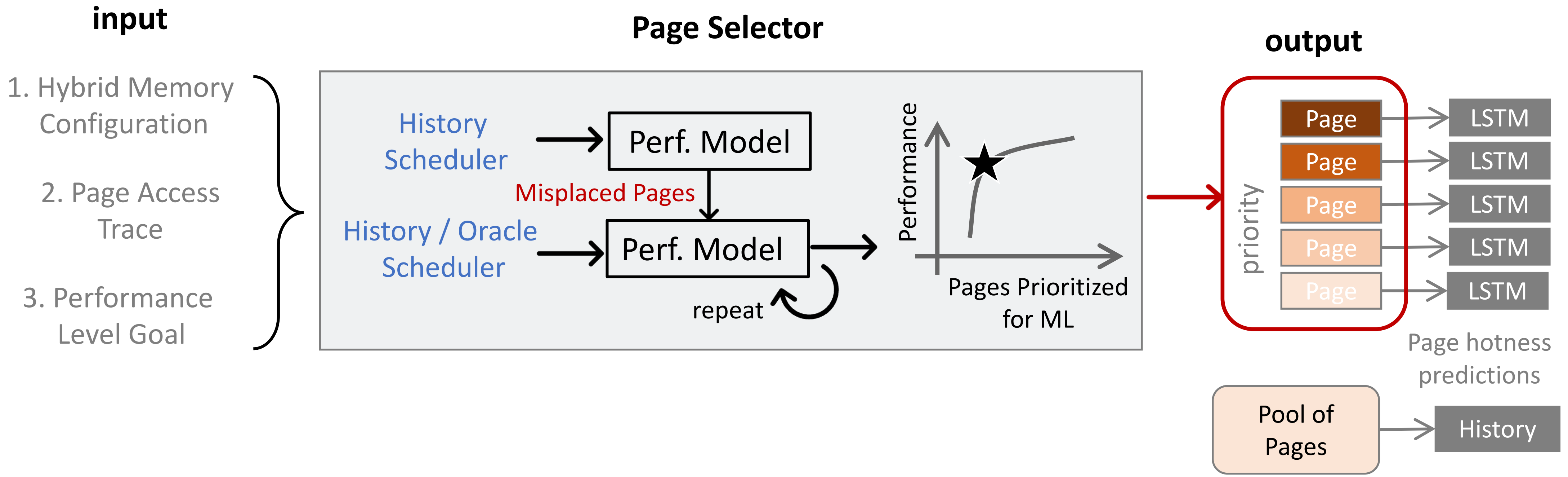

*Page Hotness Prediction*




Select a **small subset** of pages in the **order** that brings the desired **performance** level.

# Page Selector Design

Page Selector calculates internally the perfomance curve, using a performance estimate analytical model.




It is not a lightweight process, but necessary to deliver the desired application performance levels.

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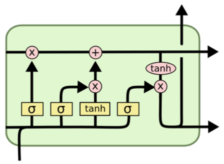

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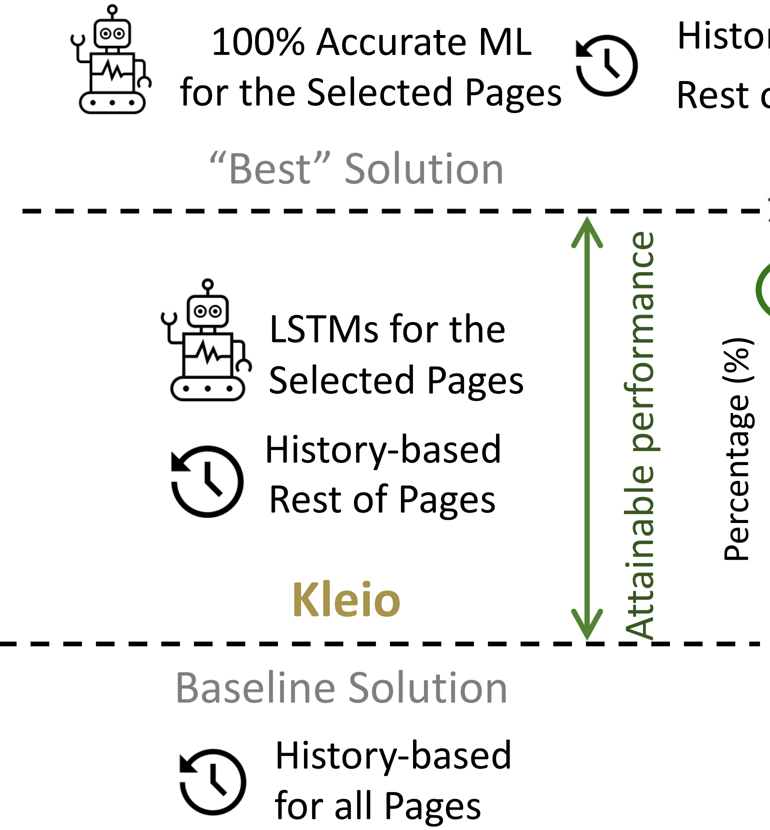
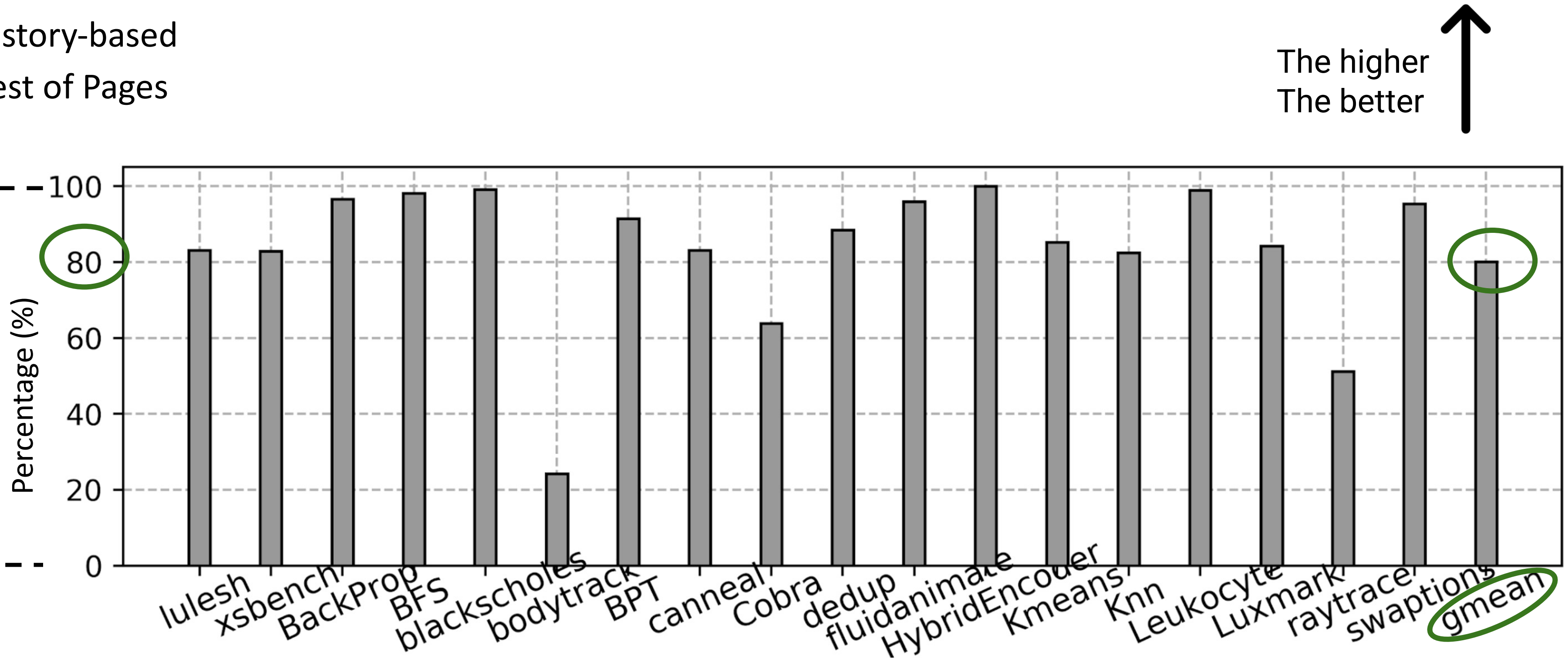
# Effect on Application Performance

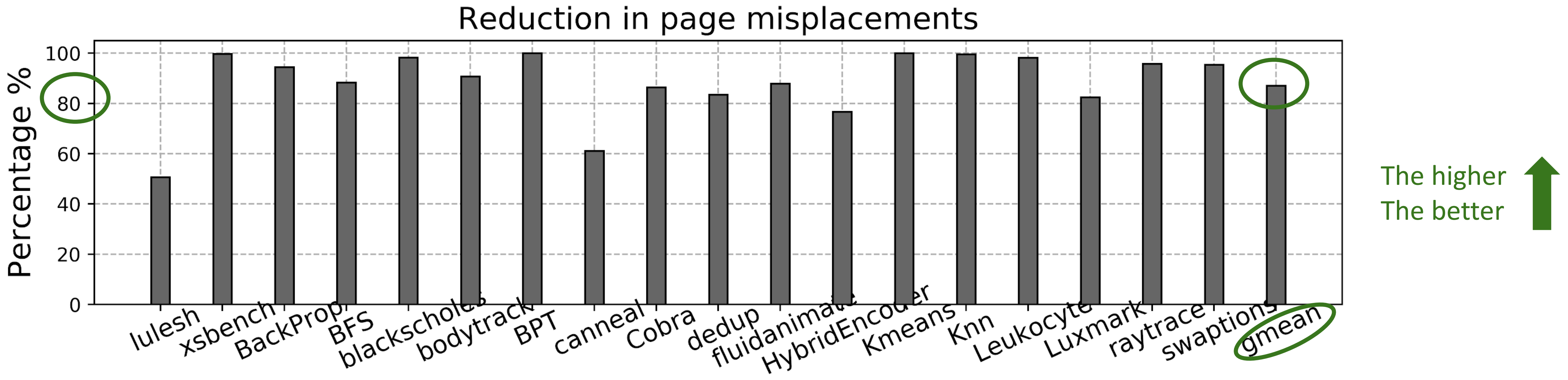



*For 100 selected pages.

For half of the applications, Kleio reaches **95%** the possible performance levels!

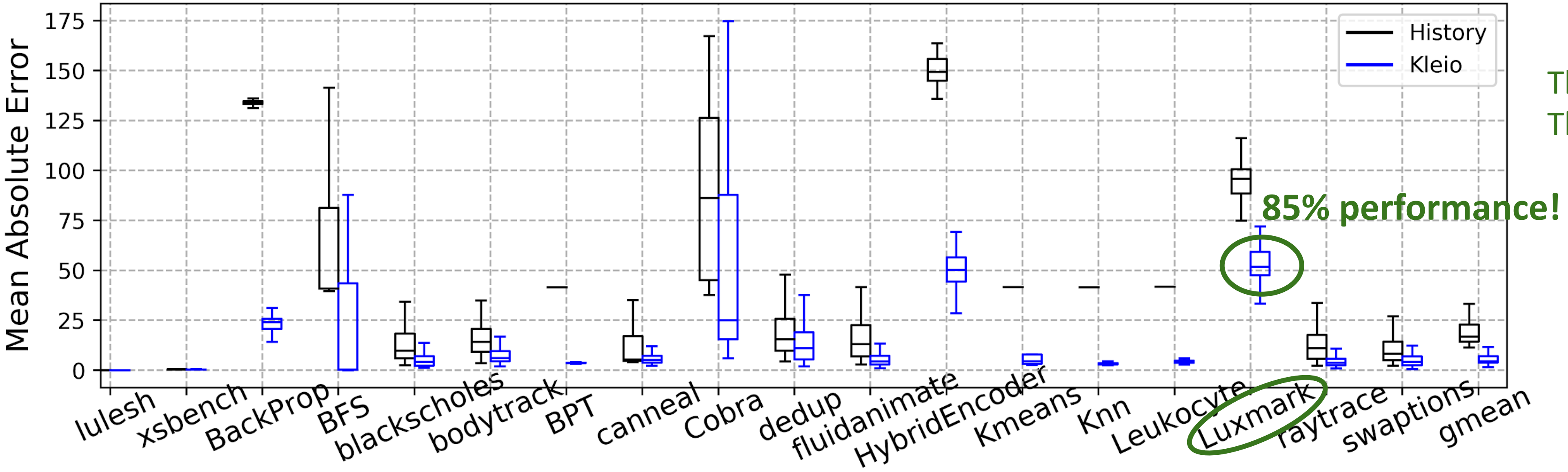
# Effect on Quality of Page Placement




For the pages managed with ML.

Kleio reduces more than 80% of the page misplacements, due to the improved **page movement decisions**, via the more **accurate** page hotness **predictions**.

# LSTM Prediction Accuracy




The lower
The better

e.g. MAE = 50 means that the RNN predicted on average 50 more accesses per scheduling epoch per page.

High prediction error **does not impact** application performance, when it does not affect the quality of page movement decision.

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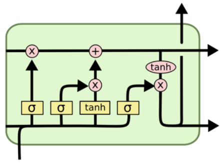
Georgia Institute of Technology
ada@cc.gatech.edu


LSTMs

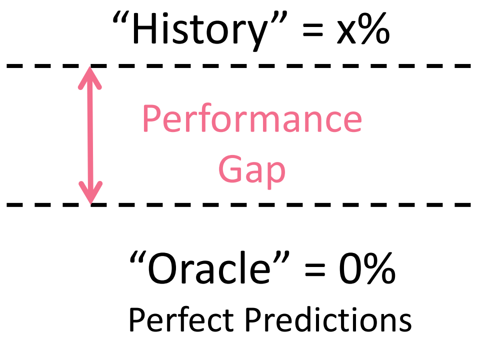
***for*** Hybrid Memory Management (HMem Management)

Lecture Outline:

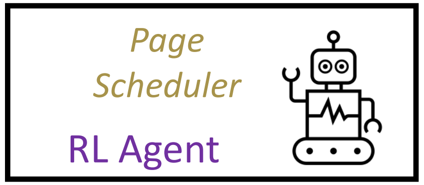
| |
|---|
| Hybrid Memories |
| Hybrid Memory Management |
| How to Integrate ML? |
| System Design |
| Evaluation |
| Lessons Learned |

# Lessons Learned

1. Understand what would be the benefit from using ML.



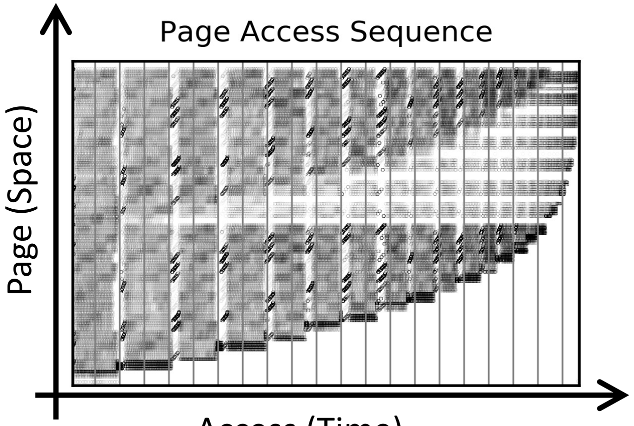

2. Learn the Behavior, not the Action, for the use case of hybrid memory management.

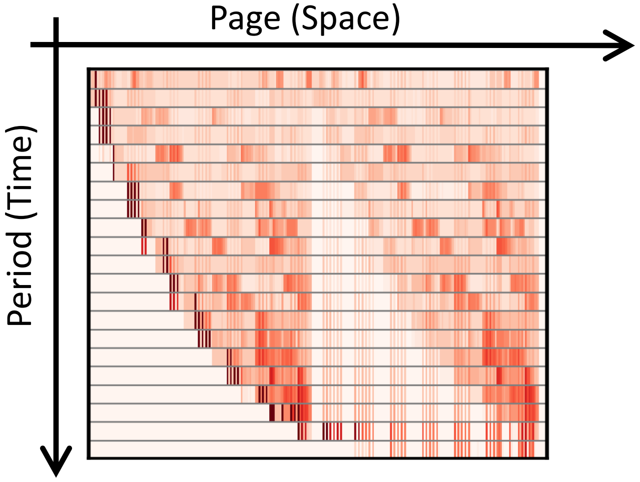



Replacing the Page Scheduler with an RL agent would not be practical, nor scalable.

# Lessons Learned

3. Look at the same problem from a different angle.




Page Access Hotness per Period

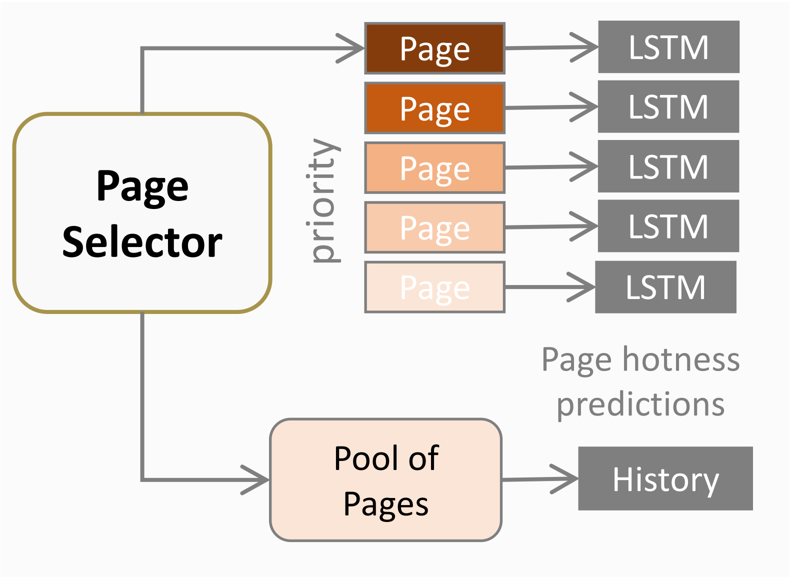
Learn **which** pages will be accessed next.

Learn **how hot** a page will be next.

4. High prediction error of page hotness **does not impact** application performance, when it does not affect the quality of page movement decision.

# Lessons Learned

5. Use existing solutions to the best of their ability, and deploy ML where necessary.



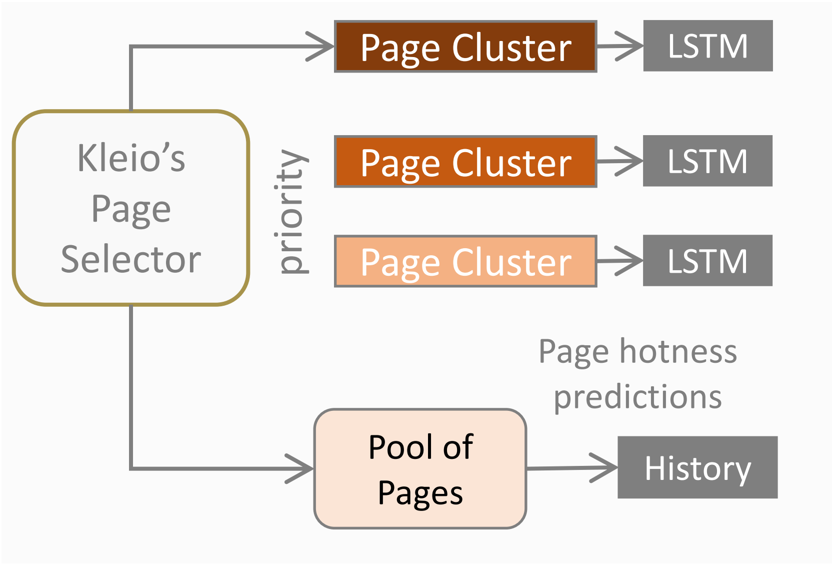

Apply ML on a small page subset.

↳ Foundations for practical use of ML.

Carefully select pages for ML.

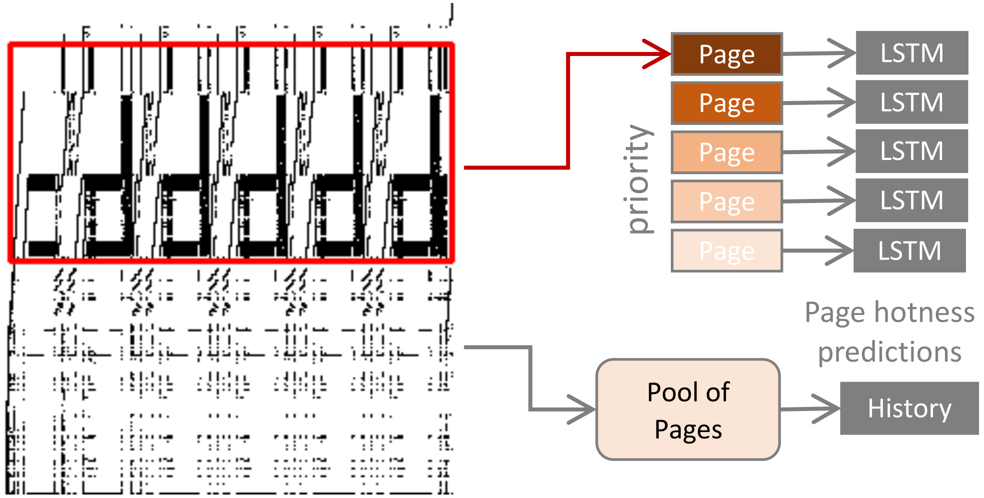
↳ Application performance boost.

# Improvements on Kleio




**Can we reduce the number of LSTMs via clustering?**

**Coeus:** Clustering (A)like Patterns for Practical Machine Intelligent Hybrid Memory Management. [CCGrid 2022]




**Can we accelerate the page selection process?**

**Cronus:** Computer Vision-based Machine Intelligent Hybrid Memory Management. [MEMSYS 2022]

# Report Due April 4 at 18.00

**Answer / expand upon these 4 questions:**

1. What problem is the paper addressing and why is it important?
2. How do they approach to solve the problem?
3. What are the main evaluation results?
4. What are 2 things you will remember from this paper?

## Contact

- Via email: `thaleia.doudali@imdea.org`

Website

https://thaleia-dimitradoudali.github.io/