FSort: External Sorting on Flash-based Sensor Devices

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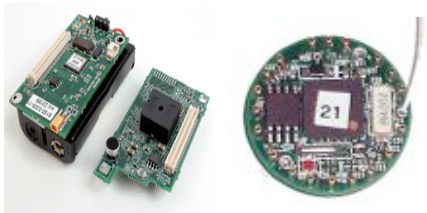
Motivation

- Wireless Sensor Devices have evolved from **primitive devices** into **powerful computing devices**.
- More **Computation Power** and More **Storage!**

2002

Applications: Remote Logging / Environmental Monitoring



Mica2 / Mica2Dot:

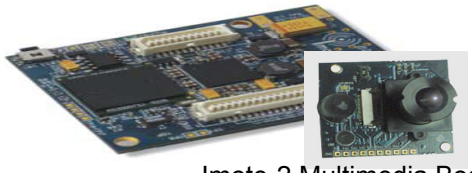
128KB Flash

2005

Applications: Digital Image Processing, etc.

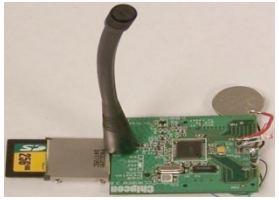
SunSpot:

4MB Flash



Imote-2 Multimedia Board

Imote-2: 32MB Flash



RISE: 1GB Flash

2009

Applications: People-Centric Sensing (sensing data by people for people)

IPhone:

32GB Flash

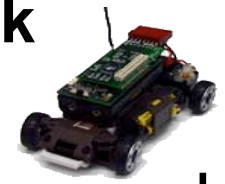
(GPS, camera, mic ambient light, 3-axis accelerometer, digital compass, …)

HTC Magic

512MB Flash

Motivation

- As **data storage mediums** continue to grow, **Sensor Device Developers** tend to **store more data in-situ**, e.g.,
  - To increase the **Sensing Fidelity**
    - Capture data locally, preprocess it, then transmit the useful information over to the sink, e.g., sound detection application
  - To overcome the problem of a **Distant Sink**
    - Applicable in Mobile Sensor Networks

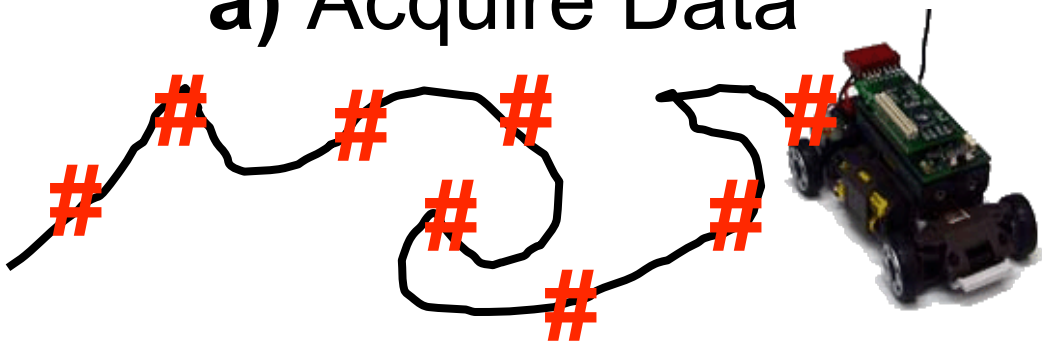


MilliBots (CMU)

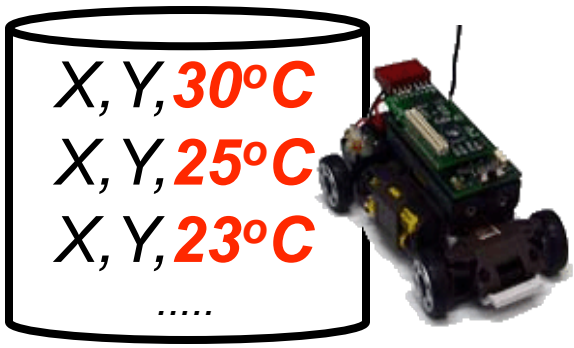
- Storing large quantities of data locally on each sensor calls for **database techniques …**
  - Indexing (e.g., “MicroHash”, In USENIX FAST’05)
  - Architectures (e.g., FlashDB, In IPSN’07)
  - External Sorting (e.g., FSort, In DMSN’09)
  - ….

Sorting on Sensors: Why is it Necessary?

a) Acquire Data



b) Store it Locally



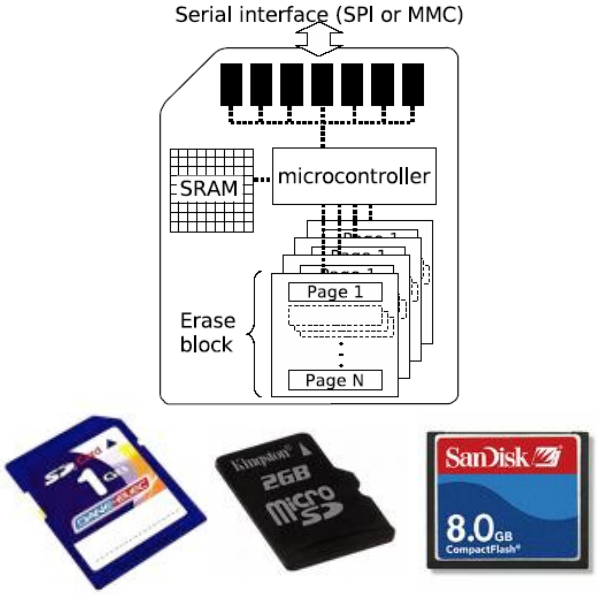
C) *"Find GPS locations where the temperature is in the range A to B"*

- ***Problem:*** *Temperature Data needs be* ***sorted on the given attribute*** *or some* ***index structure*** *might be necessary (e.g., B+tree)*
- **Other Examples: JOIN** the readings of two sensors, **Sort** local Images, **Remove** duplicates, .

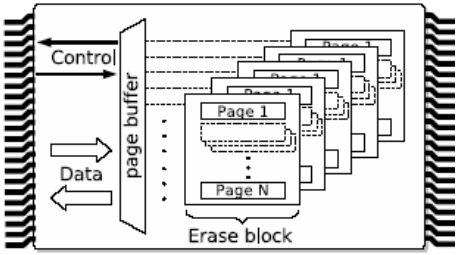
Background: Flash Memory

- The most prevalent storage medium used for Sensor Devices is **Flash Memory** (NAND Flash)
- Fastest Growing Memory Market (‘05 $8.7B, ’06 $11B)

Removable Flash

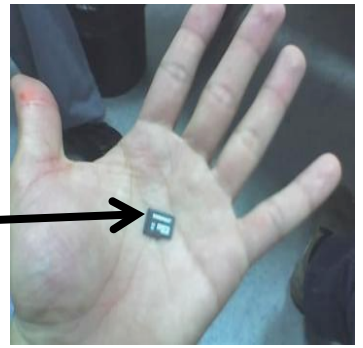


Surface Mount Flash



Background: Flash Memory

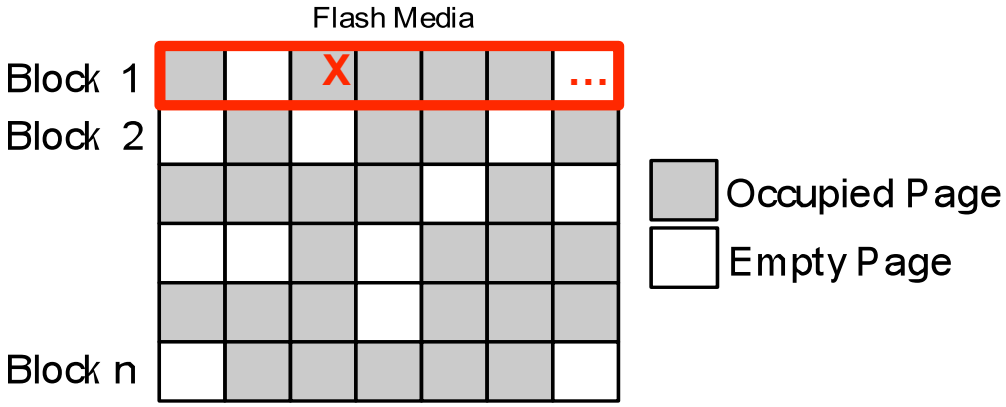
- **Simple Cell Architecture**
  - ➔ High capacity in a **small surface**
  - ➔ Economical Reproduction



- **Fast Random Access** (50-80 µs) compared to 10-20ms in Magnetic Disks

- **Shock Resistant & Power Efficient**
  - ➔ Appropriate for Sensor and Mobile Devices

Background: Characteristics of Flash



1. Delete-Constrain: **Erasure of a page can only be performed at a block granularity (i.e. 8KB~64KB)**
2. Write-Constrain: Data is written to flash on a **page granularity** (256B~512B) to an **empty page** (delete page if necessary).
3. Wear-Constrain: **Each page can only be written a limited number of times (typically 10,000-100,000)**
4. Asymmetric Read/Write: **Reading Faster (Cheaper) than Writing (23mJ vs. 763mJ on the RISE sensor)**

Presentation Outline

1. Motivation and Background

2. **Overview of Sorting on Sensor Devices**

3. The FSort External Sorting Algorithm

4. Experimental Evaluation

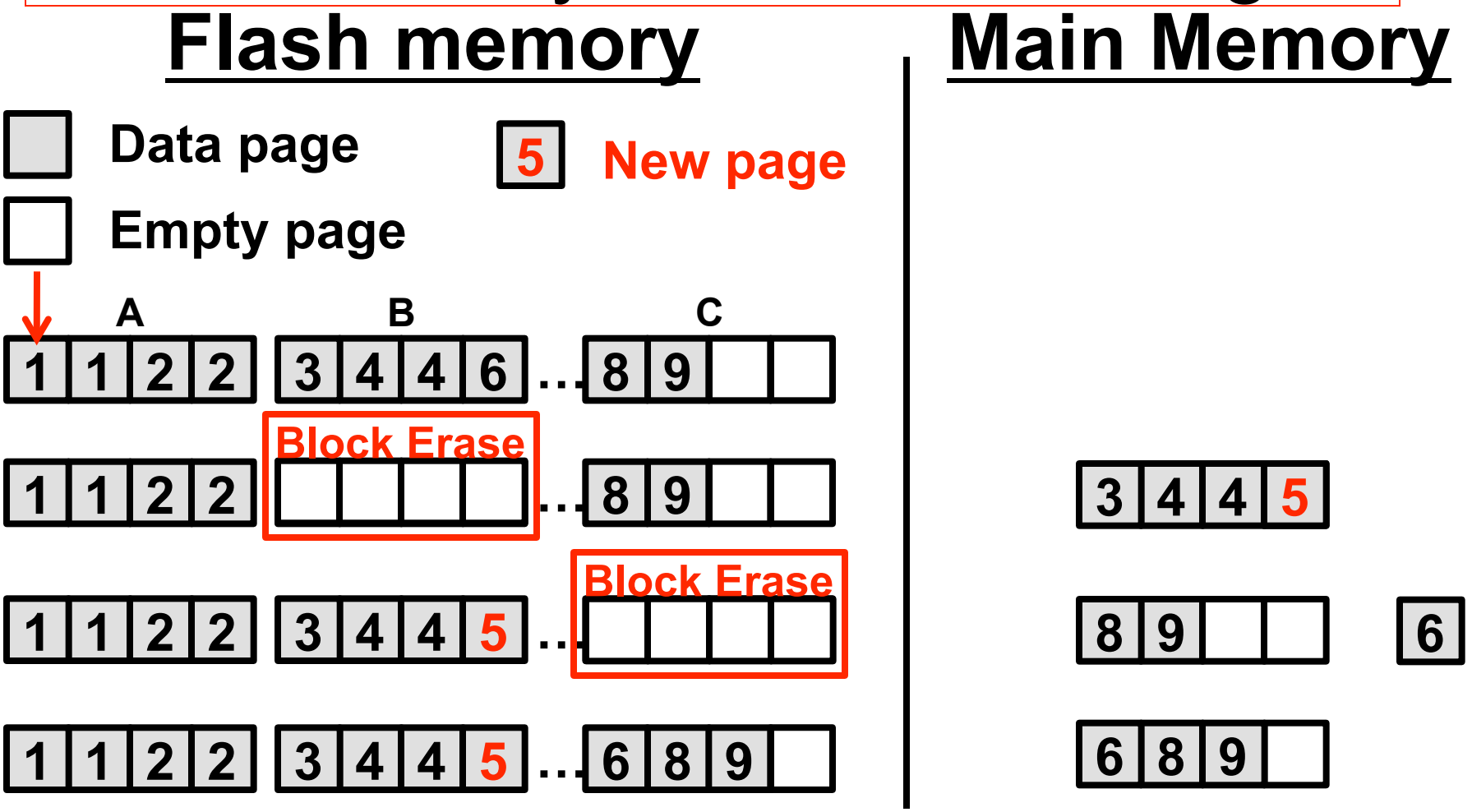
5. Conclusions and Future Work

Sorting on Sensor Devices

Sorting can be performed in two modes:

- **Online Sorting**
  - Keep a target sequence **sorted at all times**.
  - i.e., upon reception of a **new data record (e.g., after data acquisition)**, sort sequence using the **InsertionSort** idea.
- **Offline Sorting**
  - Log data records in an **Unsorted File** until **Sorting function** is requested.
  - **Problem:** Unsorted File might be too large to fit in main memory, thus In-Memory Sorting (using quicksort, mergesort, etc) is not feasible
  - **Solution:** Use an External Sorting Algorithm

Inefficiency of Online Sorting



Online Sorting is Inefficient! For 1 write it took us:

6 Reads + 7 Writes + 2 Block Erases

Decreased Performance + Decreased Lifetime

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3. **FSort External Sorting Algorithm**
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FSort Algorithm

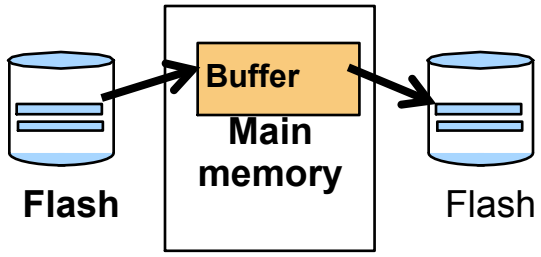
- **FSort** is an **external sorting** algorithm appropriate for flash-media on sensor devices

Characteristics

- **Offline External Sorting Algorithm**
  - It sorts on-demand, **arbitrary large sequences** with a **fixed-sized (**main) memory.
- **Appropriate for Sensor Devices**
  - Its performance is boosted by the **temporal coherence** in sensor readings (i.e., values that don't change quickly over time).
- **Designed for Flash**
  - It deletes blocks sequentially
  - It minimizes read/write/block erase operations.

FSort: Outline of Operation

FSort consists of two phases:



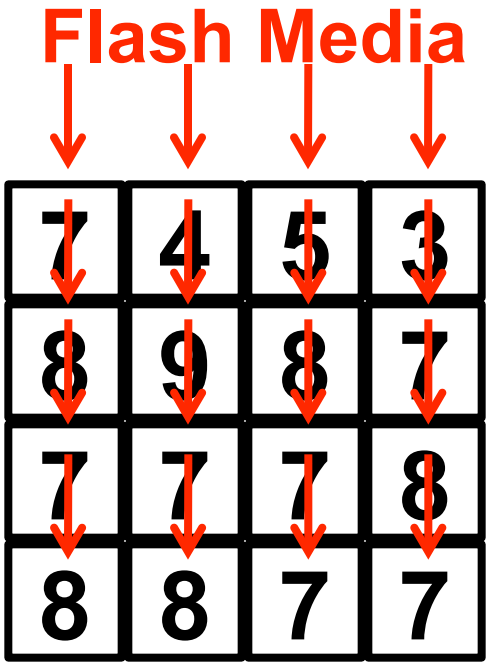
- **Sorting phase:**
  - Perform a Scan of the Flash media using **M block iterators.**
  - Use the **Replacement-Selection** concept to produce **Sorted Runs (Sequences)**
  - **Append** the Sorted Runs to the **end of the Flash Media**
- **Merging phase**
  - **Merge the sorted runs** recursively until a **single sorted output is produced.**

FSort: Sorting Phase

a) Initialize **B-1 Block Iterators.**

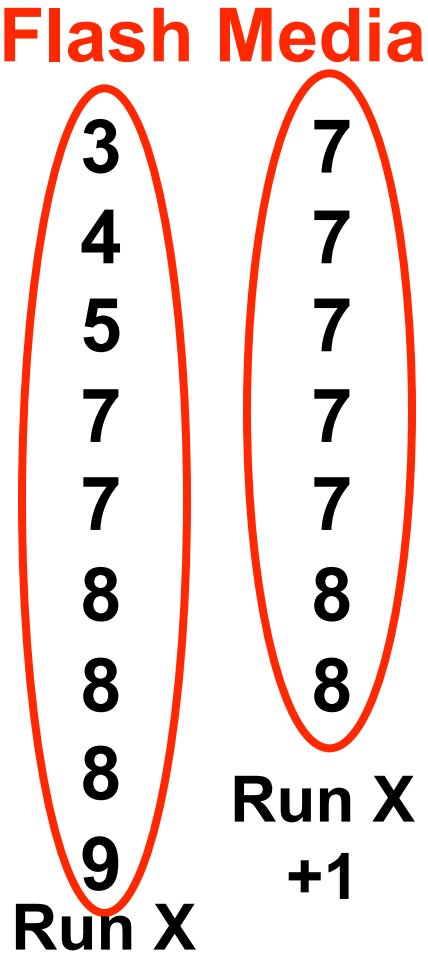
b) Write **next smallest elem. >=** current elem. to run **X**

- If above not possible, output next elem. to run **X+1**



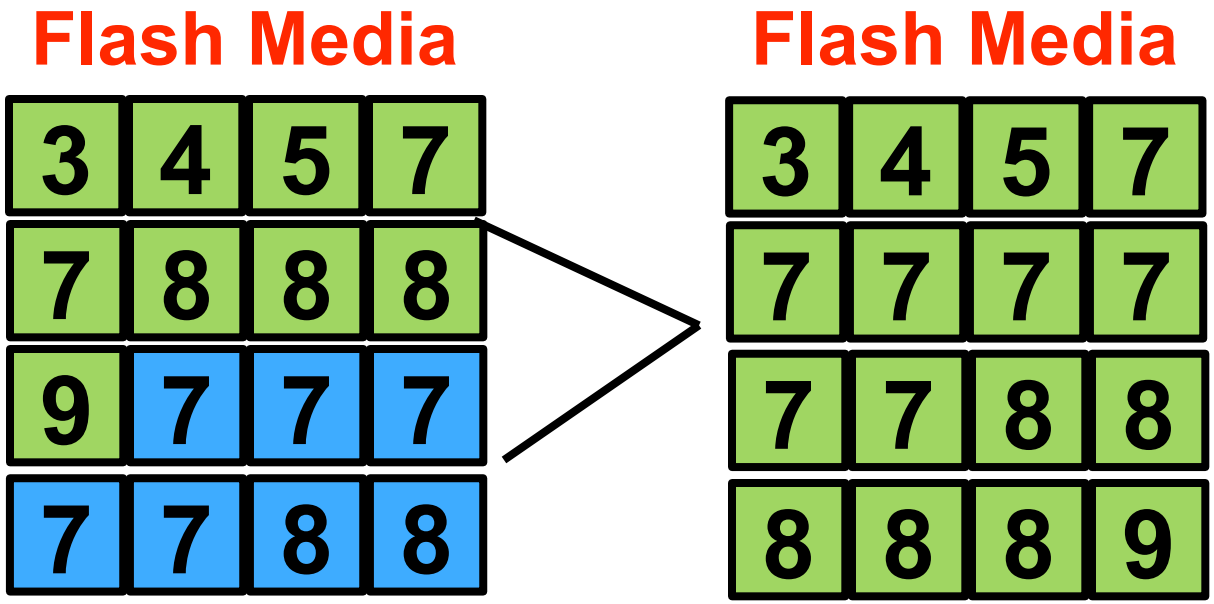
Main Memory

7	4	5	3



FSort: Merging Phase

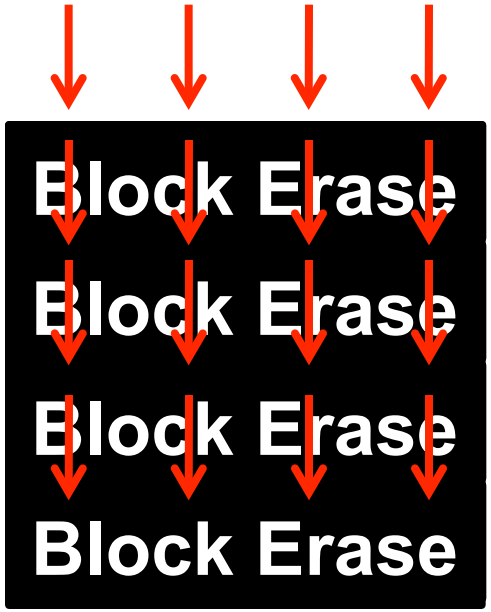
Example: B Buffer Pages (Input: B-1, Output: **1**)



Number of Passes over Data? 2 times

FSort and the Delete Constrain

- A block is **deleted** only whenever **all pages** within the given **block are empty**
  - This satisfies the Flash Delete Constrain



Additionally, due to **temporal coherence** (i.e., values within a block are similar) **blocks are usually freed up quickly.**

Presentation Outline

1. Motivation and Background
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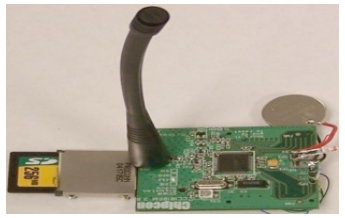
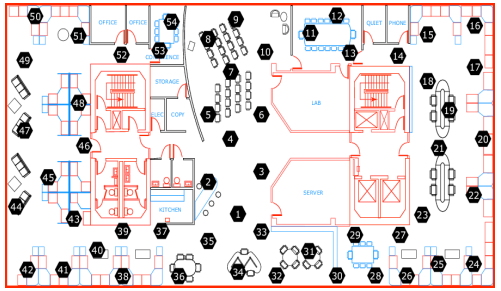
3. FSort External Sorting Algorithm
4. **Experimental Evaluation**
5. Conclusions and Future Work

Experimental Evaluation

- **Testbed: Trace-driven Simulator**
  - Written in C++ (idea also prototyped in LiteOS/C on IRIS Sensor)
  - Emulates Flash (Page=512B, Block=16KB)
  - Measures:
    - # of read (1.17mA), write (37mA), erases (18mA)
    - Energy Consumption Energy = Volts x Amperes x Seconds



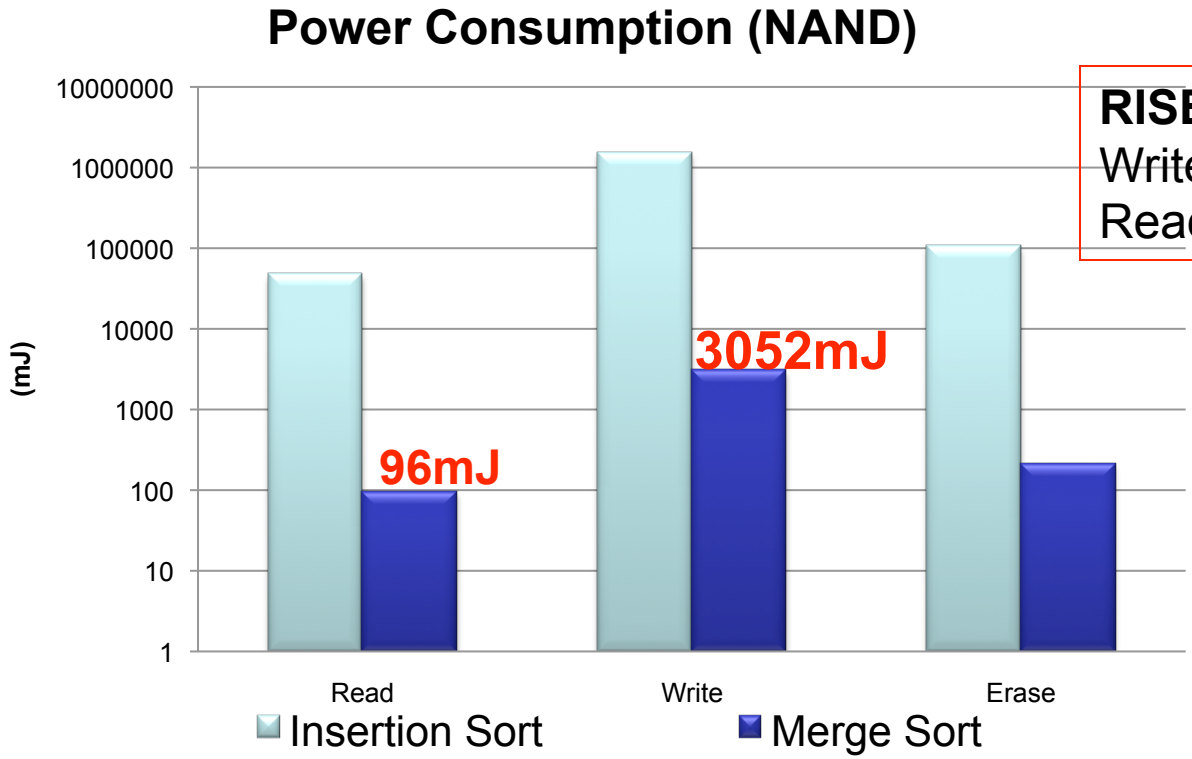
- **Dataset:** Intel Research Berkeley
  - Temperature, Humidity, Light, Vol, etc.
  - 2.3 million readings



- **Compared Algorithms**
  - **Online vs. Offline Sorting**
    - InsertionSort vs. External Merge Sort
  - **Comparison of Offline Sorting**
    - External Merge Sort vs. FSort

Online vs. Offline Sorting

Sorting 1000 records (1 record / page)



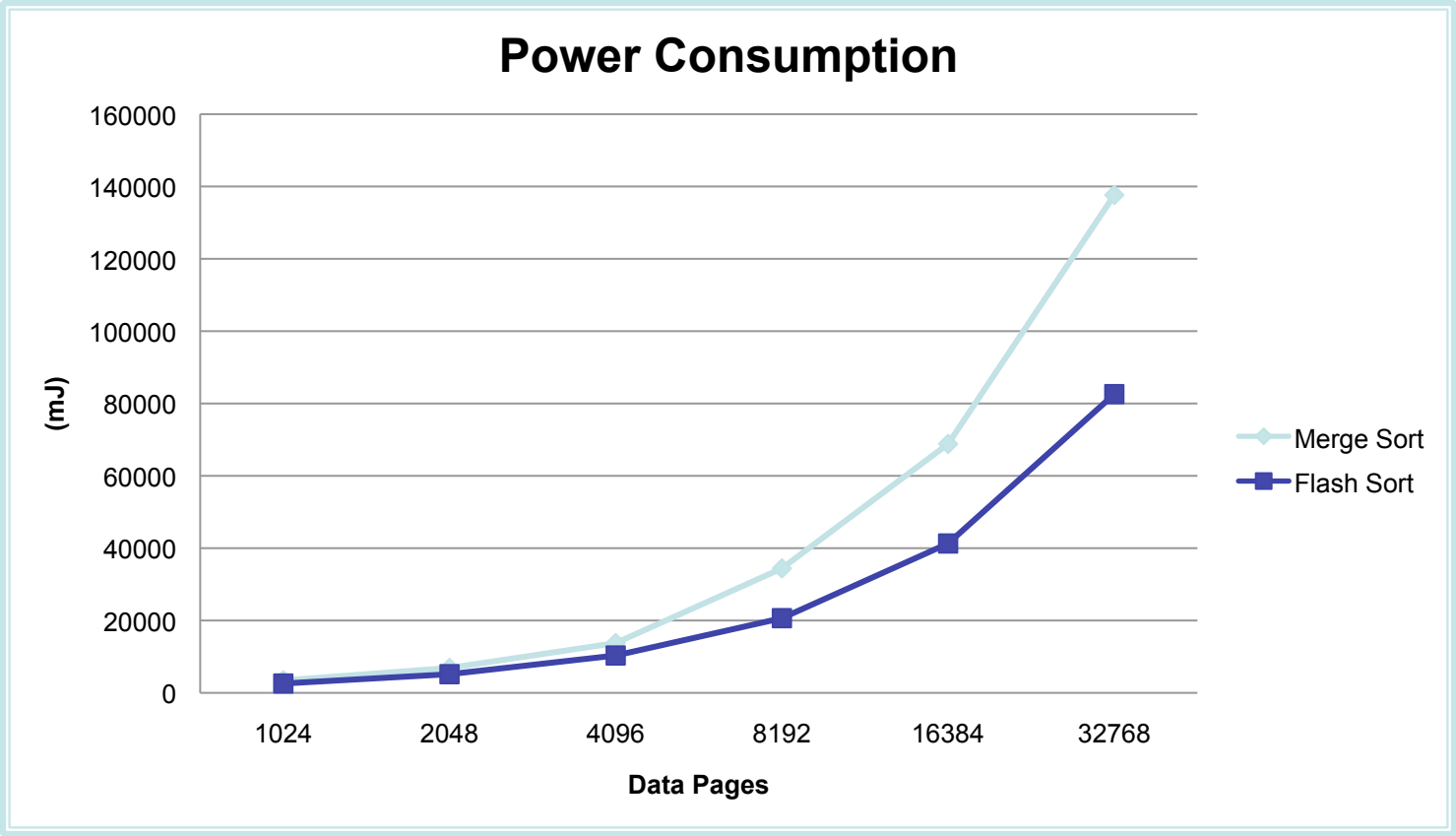
RISE Energy Model
Write: 37mA
Read: 1.17mA

a) **Online Sorting** is 2 Orders **slower** (less efficient) than **Offline Sorting**

b) **Same** number of **Read/Write** operations**, yet** writing is overall **more Expensive**

External MergeSort vs. FSort

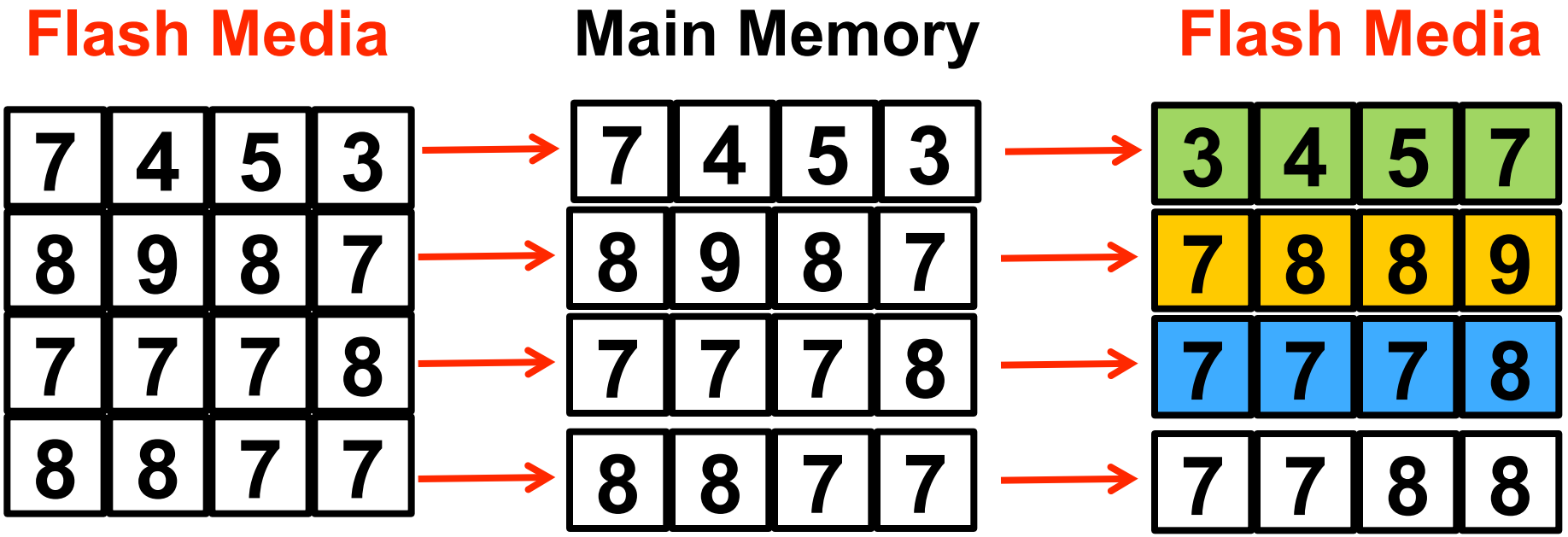
Task: Sort records (on temperature) after adding 1000 measurement to local flash media.



FSort is 25-40% more efficient than External MergeSort.

External Merge Sort

Example: B Buffer Pages (Input: B-1, Output: **1**)



Drawback of External Merge Sort: Small Runs

➔ Here **4** rather than **~8 (Fsort)**,

➔ In our experiments we found that they are **2-3 times smaller** than FSort

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4. FSort Experimental Evaluation
5. **Conclusions and Future Work**

Conclusions and Future Work

- We have shown that FSort improves **response time** and **energy consumption** for sorting **by 25 - 40%** compared to EMS.
- **In the future we plan to:**
  - Formally **analyze** the **performance** of the FSort algorithm.
  - **Empirically assess its performance** on real **devices** and **storage** mediums (External Flash cards, Smart-phones, SSDs, …)
  - Study the utilization of **complementary structures** for sorting (e.g., indexes)

FSort: External Sorting on Flash-based Sensor Devices

Thank you!

Questions?

This presentation will be available at:
http://www.cs.ucy.ac.cy/~dzeina/