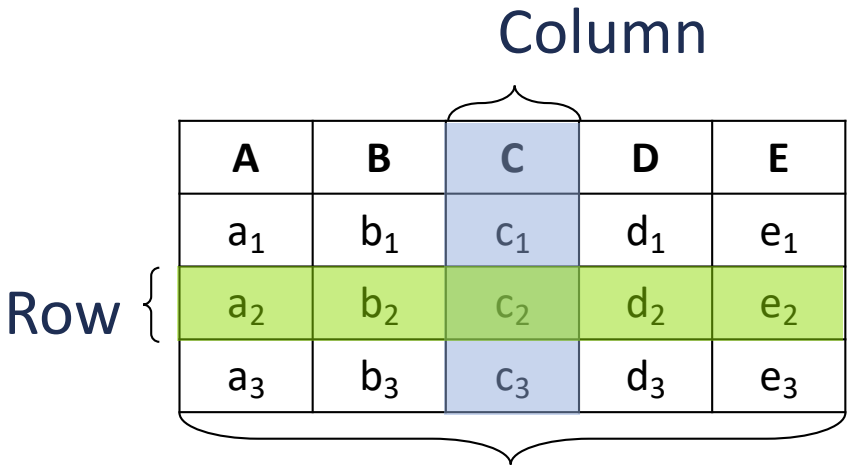
Relational Memory:

Native In-Memory Accesses on Rows and Columns

Ju Hyoung Mun

Relational Databases are everywhere



SQLite

MySQL

ORACLE DATABASE

PostgreSQL

Microsoft SQL Server

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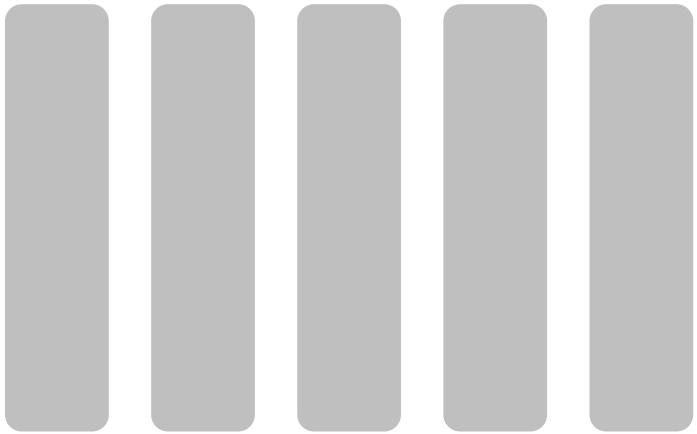
Data Layouts

row-stores

column-stores



Transactional

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Data Layouts

row-stores

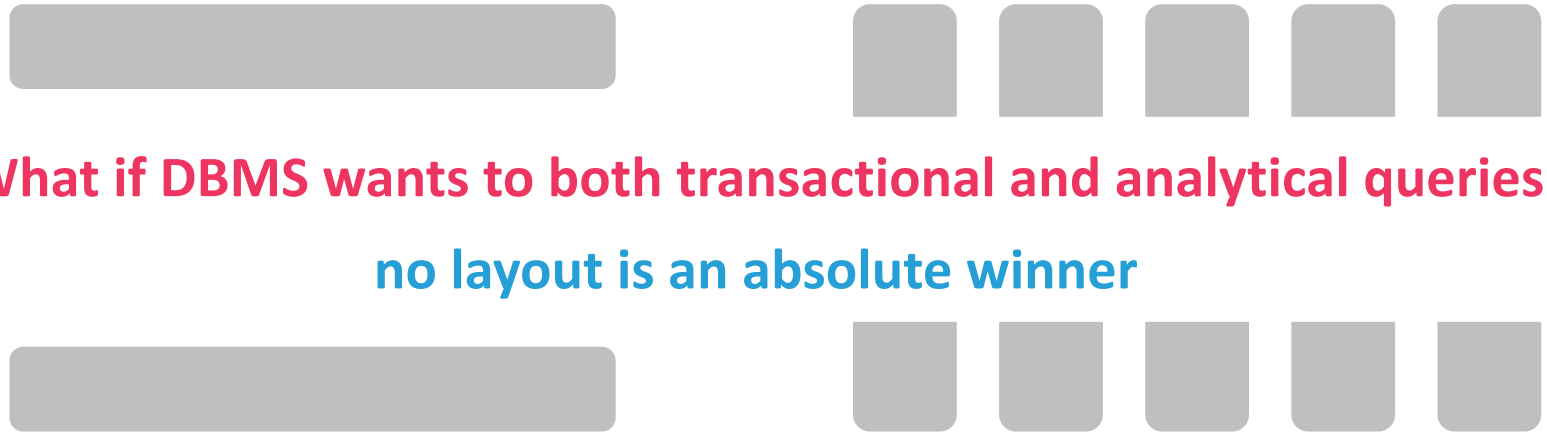
column-stores

Analytical

Data Layouts

row-stores

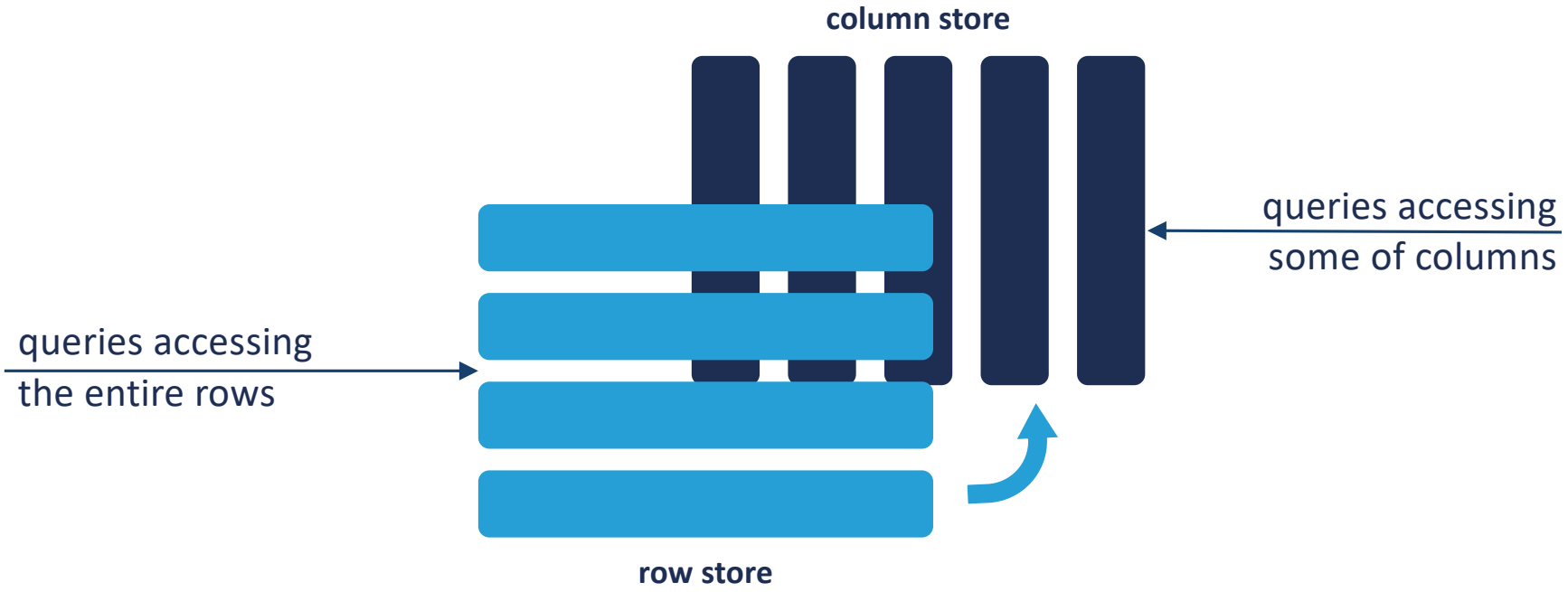
column-stores



What if DBMS wants to both transactional and analytical queries?

no layout is an absolute winner

What are the disadvantages of the adaptive layout?



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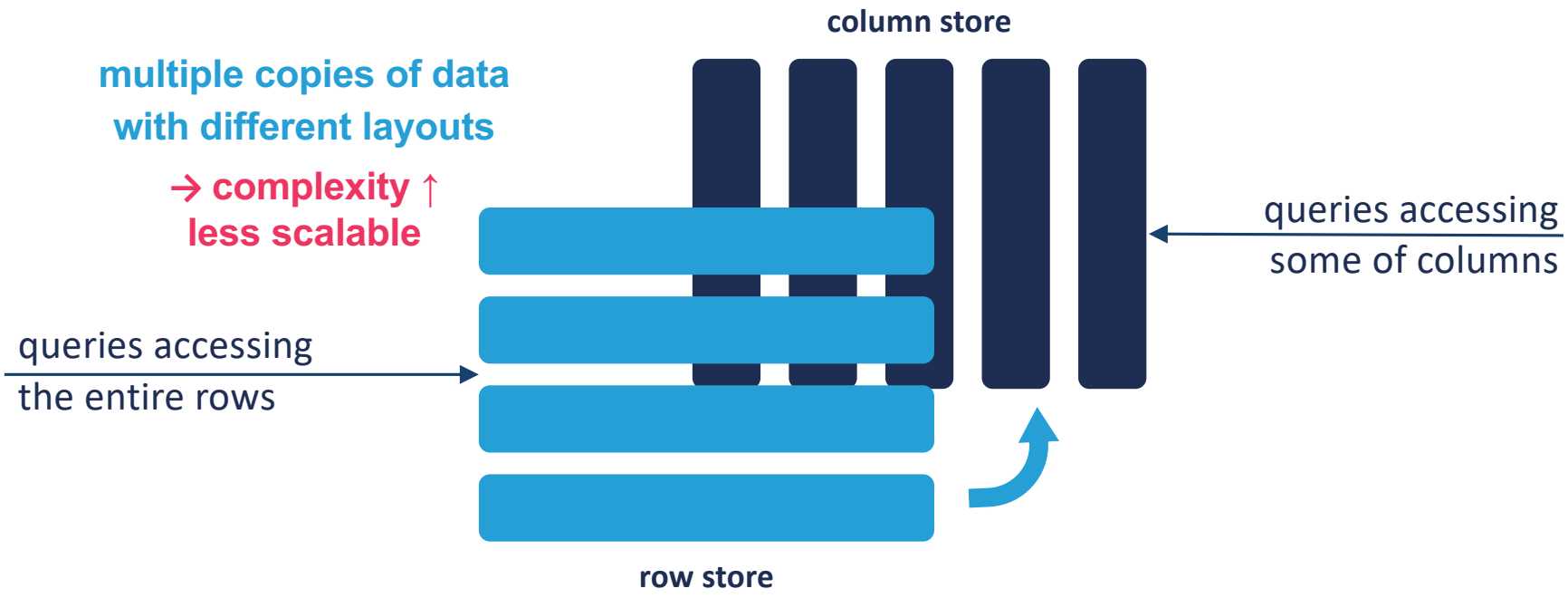
E.g., H2O (ACM SIGMOD, 2014), HyPer (IEEE ICDE , 2011), Peloton (ACM SIGMOD, 2016), OctopusDB (CIDR, 2011)

Adaptive layout



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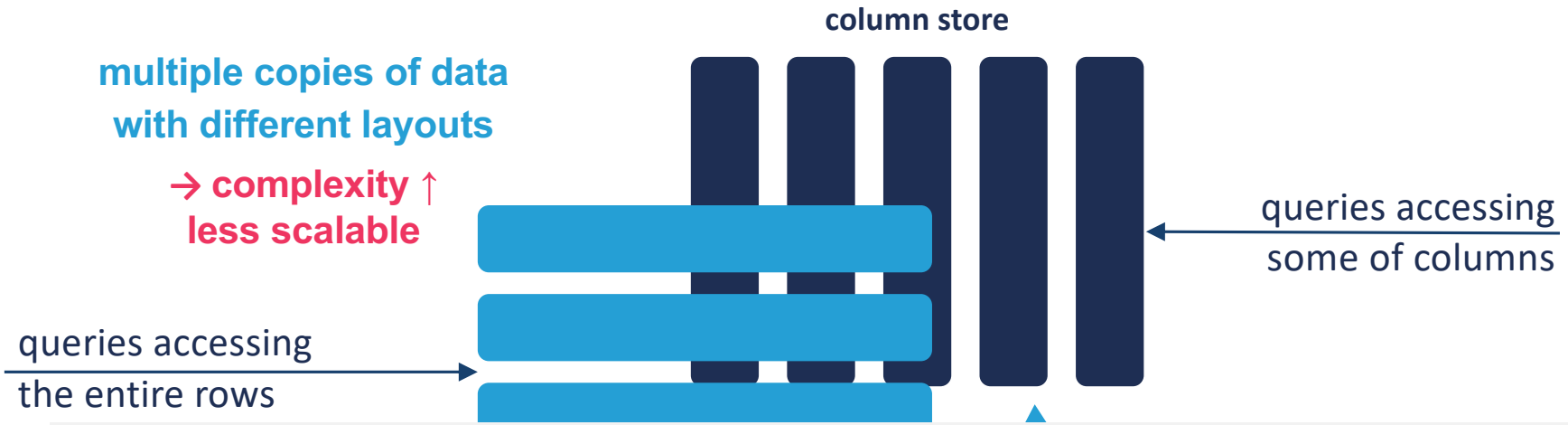
Adaptive layout



What if there is a shift over columns?

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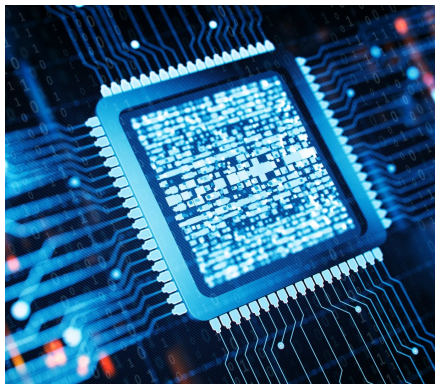
E.g., H2O (ACM SIGMOD, 2014), HyPer (IEEE ICDE , 2011), Peloton (ACM SIGMOD, 2016), OctopusDB (CIDR, 2011)

How can we access
only the desired columns
without storing or maintaining
multiple copies of data?

a novel hardware design
for data transformation

Relational Memory



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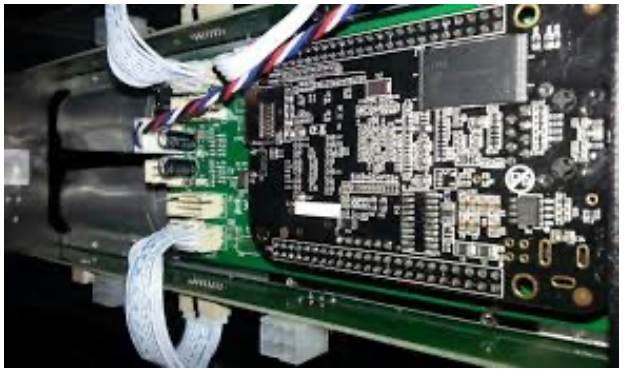
What is
Hardware?



Application-**S**pecific **I**ntegrated **C**ircuits (ASICs)

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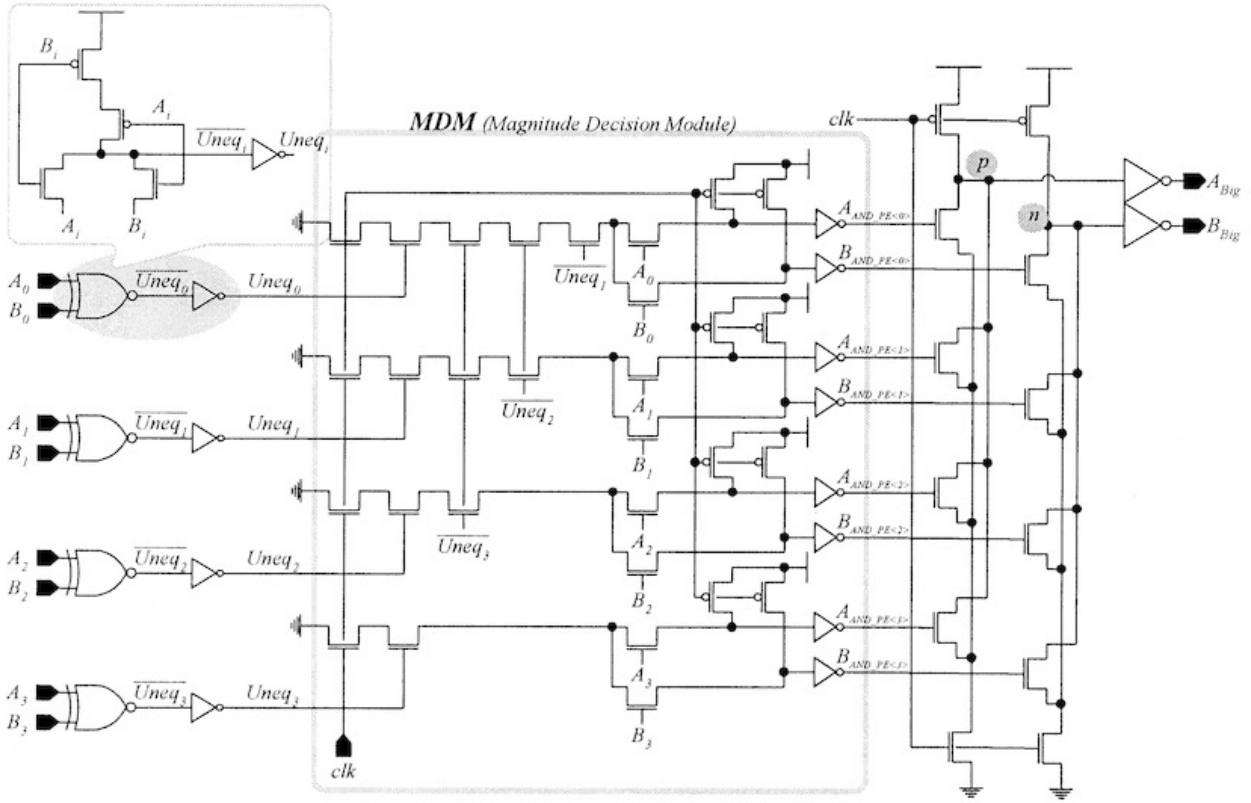
Integrated Circuits



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Hardware Accelerators

Advantages

- **Speedup**
- Reduced **power consumption**
- Lower **latency**
- Increased parallelism and bandwidth
- Better utilization of **area** and functional components available on an integrated circuit

Disadvantages

- Lower **flexibility**
- **Higher costs** of functional verification and times to market

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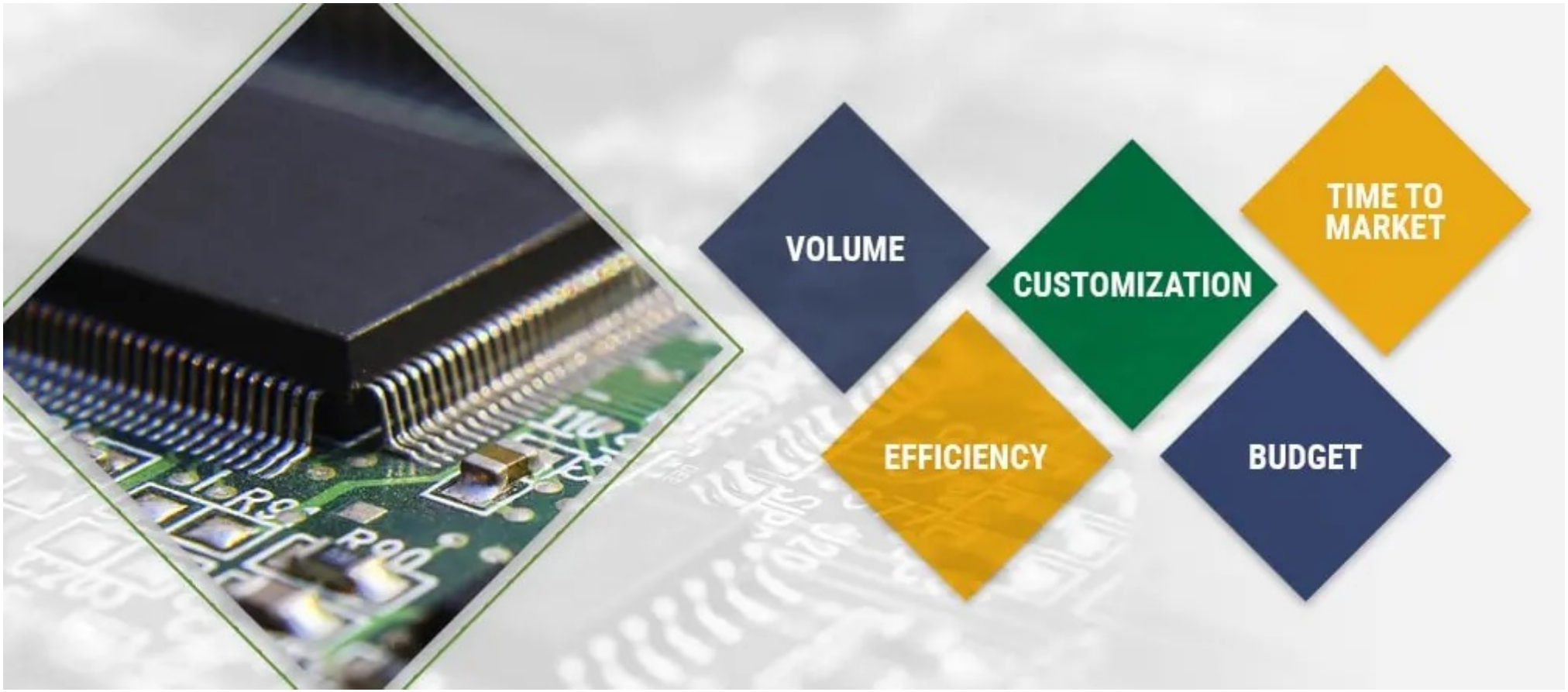
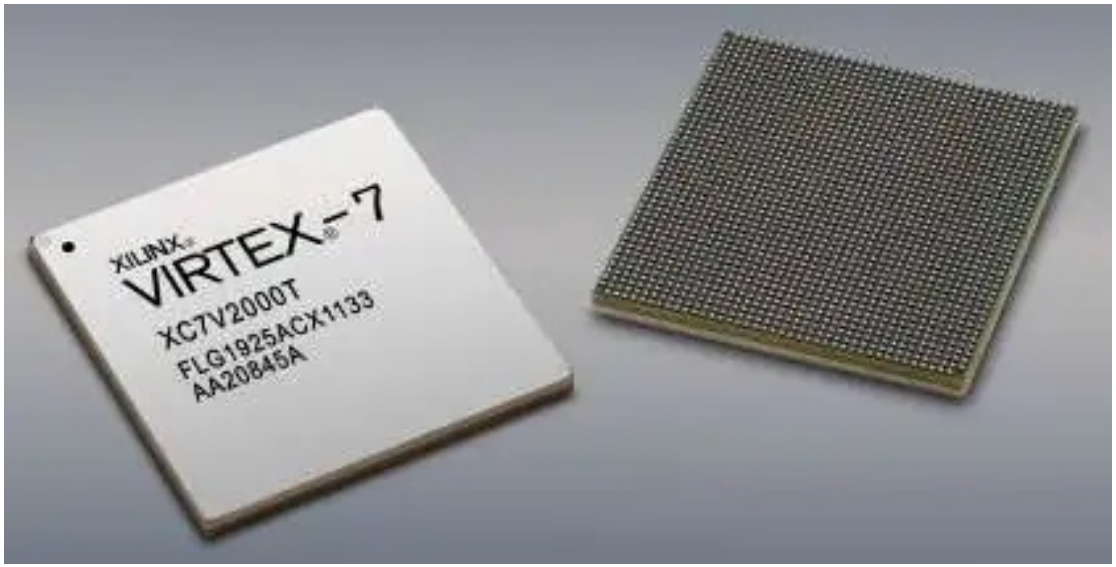
ASICs



Programmable Logic

Field Programmable Gate Arrays (FPGAs)



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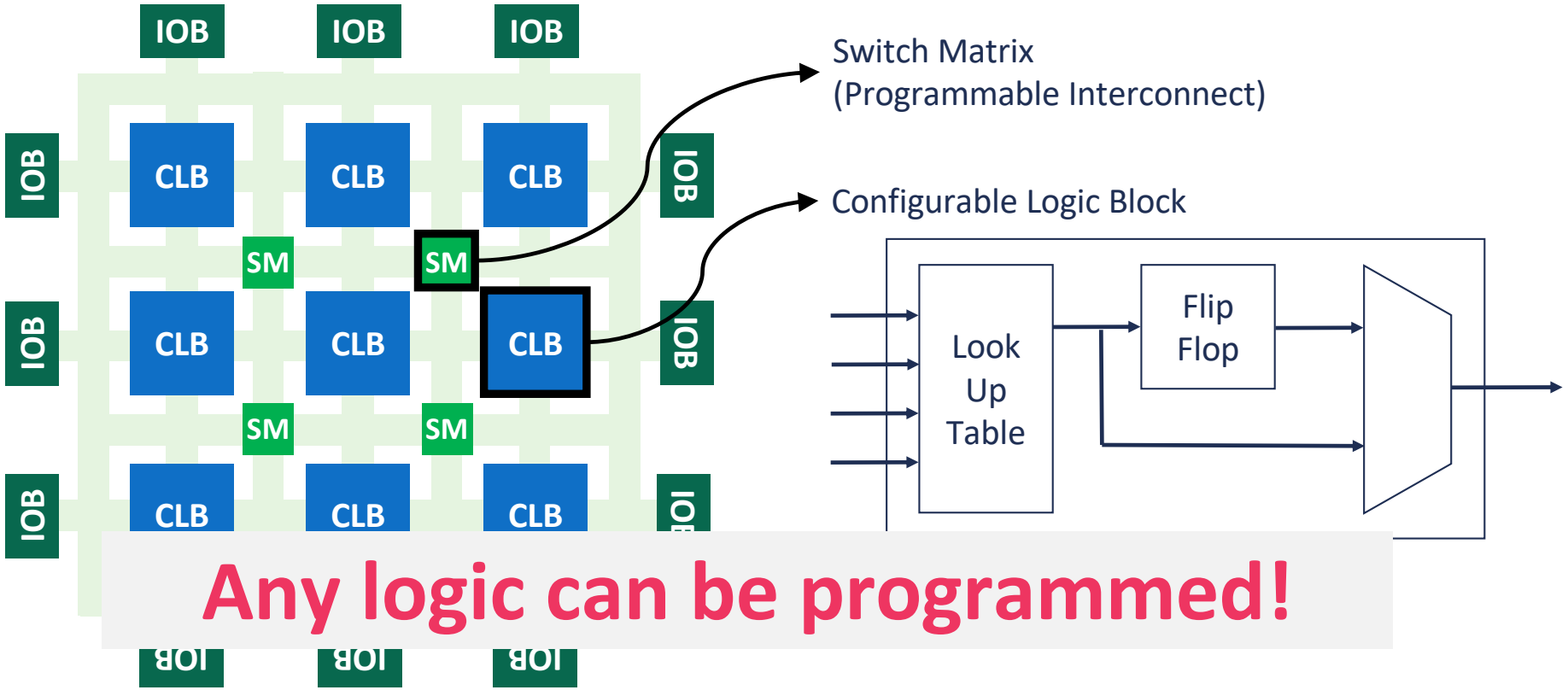
Architecture of Programmable Logic



Any logic can be programmed!

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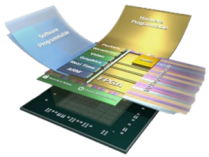
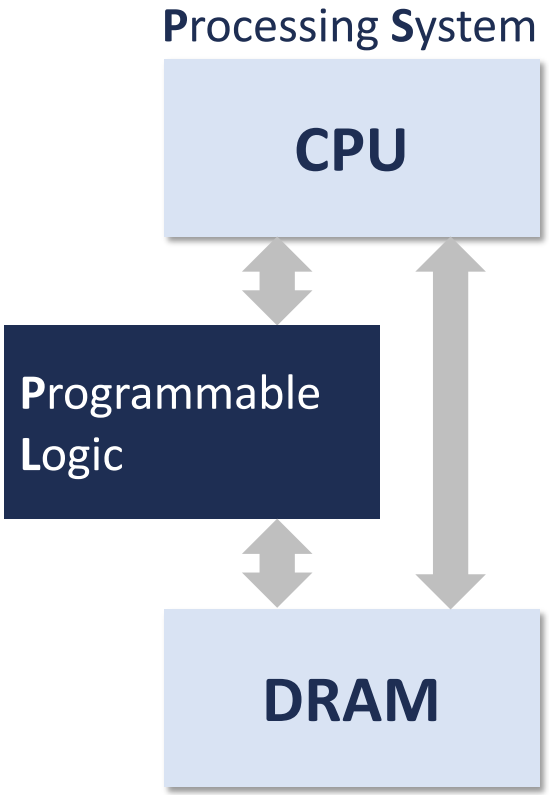


AMD XILINX UltraScale+ ENZIAN intel AGILEX

PS-PL Platforms



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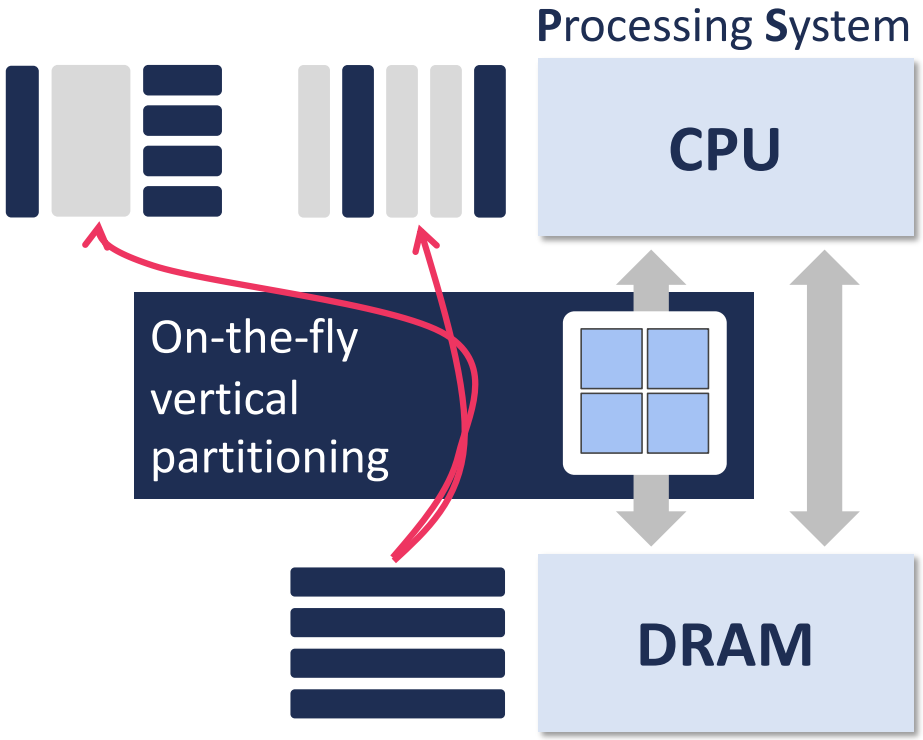
Relational Memory Engine



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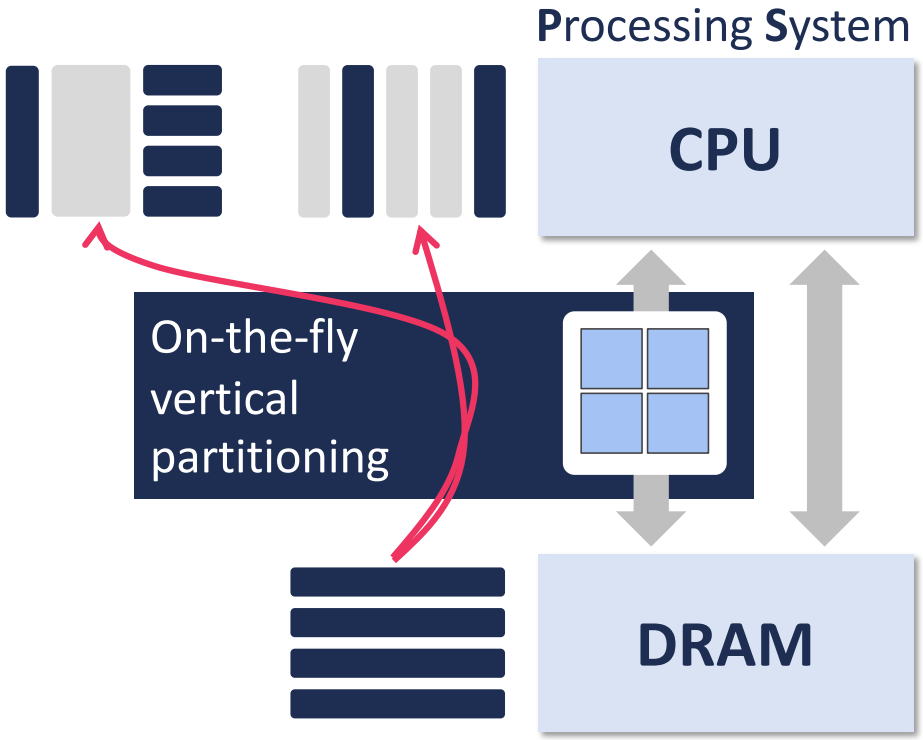
Q1: how to build?

Q2: how to use?

Relational Memory Engine



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ephemeral variable

a simple, lightweight programming abstraction

to use Relational Memory

leads to normal memory accesses

```
struct row table[ ];
[[ephemeral]] struct col_group cg[ ];
```

fake address that CPU thinks it exists

intercepted by RME

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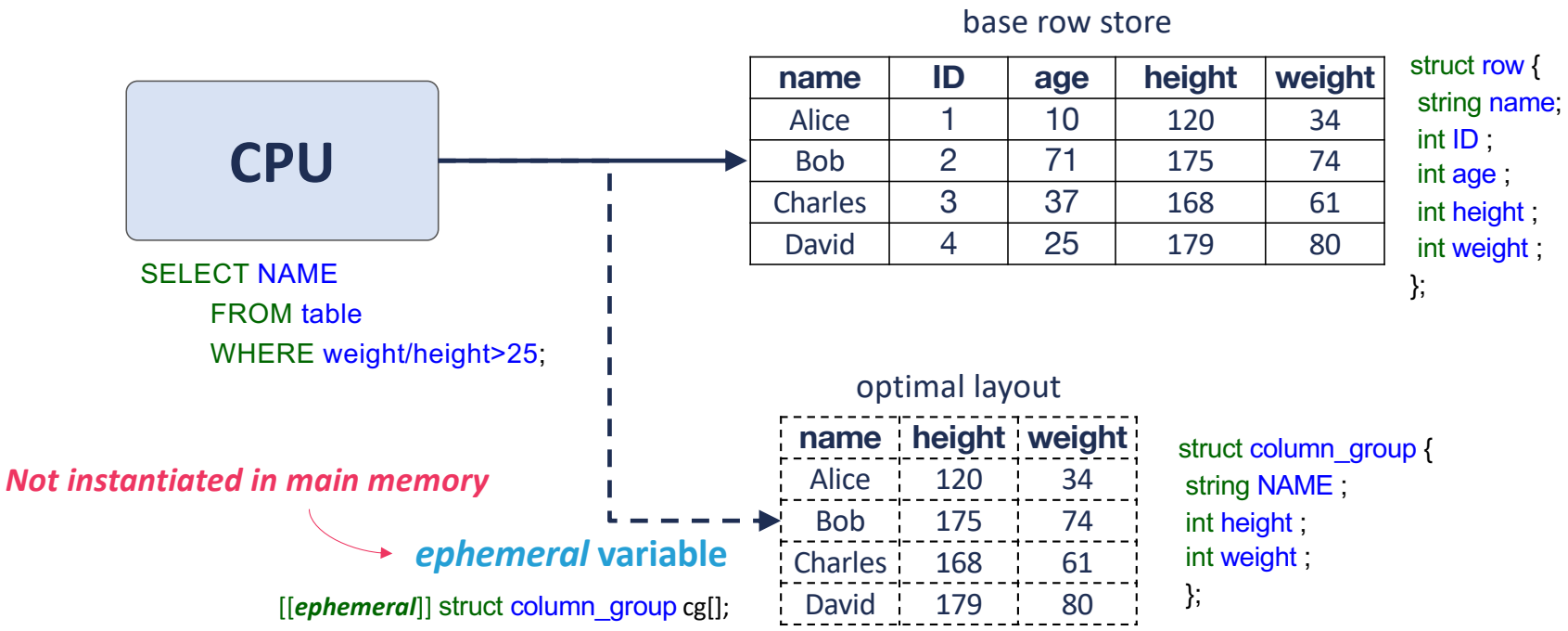
base row store
CPU
name ID age height weight
Alice 1 10 120 34
Bob 2 71 175 74
Charles 3 37 168 61
David 4 25 179 80
struct row {
string name;
int ID ;
int age ;
int height ;
int weight ;
};
SELECT NAME
FROM table
WHERE weight/height>25;
optimal layout
Not instantiated in main memory
ephemeral variable
[[ephemeral]] struct column_group cg[];
name height weight
Alice 120 34
Bob 175 74
Charles 168 61
David 179 80
struct column_group {
string NAME ;
int height ;
int weight ;
};

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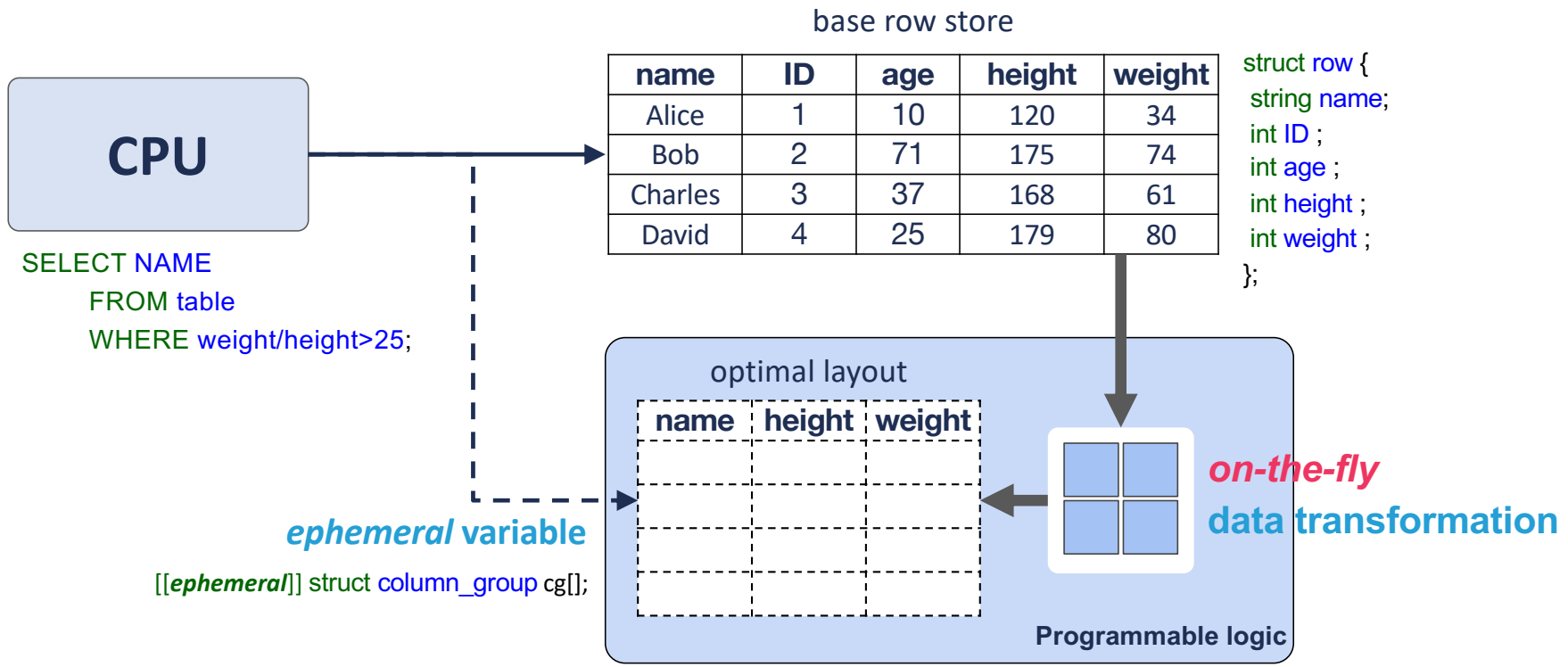
base row store
CPU
name
ID
age
height
weight
Alice
1
10
120
34
Bob
2
71
175
74
Charles
3
37
168
61
David
4
25
179
80
struct row {
string name;
int ID ;
int age ;
int height ;
int weight ;
};
SELECT NAME
FROM table
WHERE weight/height>25;
optimal layout
name
height
weight
ephemeral variable
[[ephemeral]] struct column_group cg[];
on-the-fly
data transformation
Programmable logic

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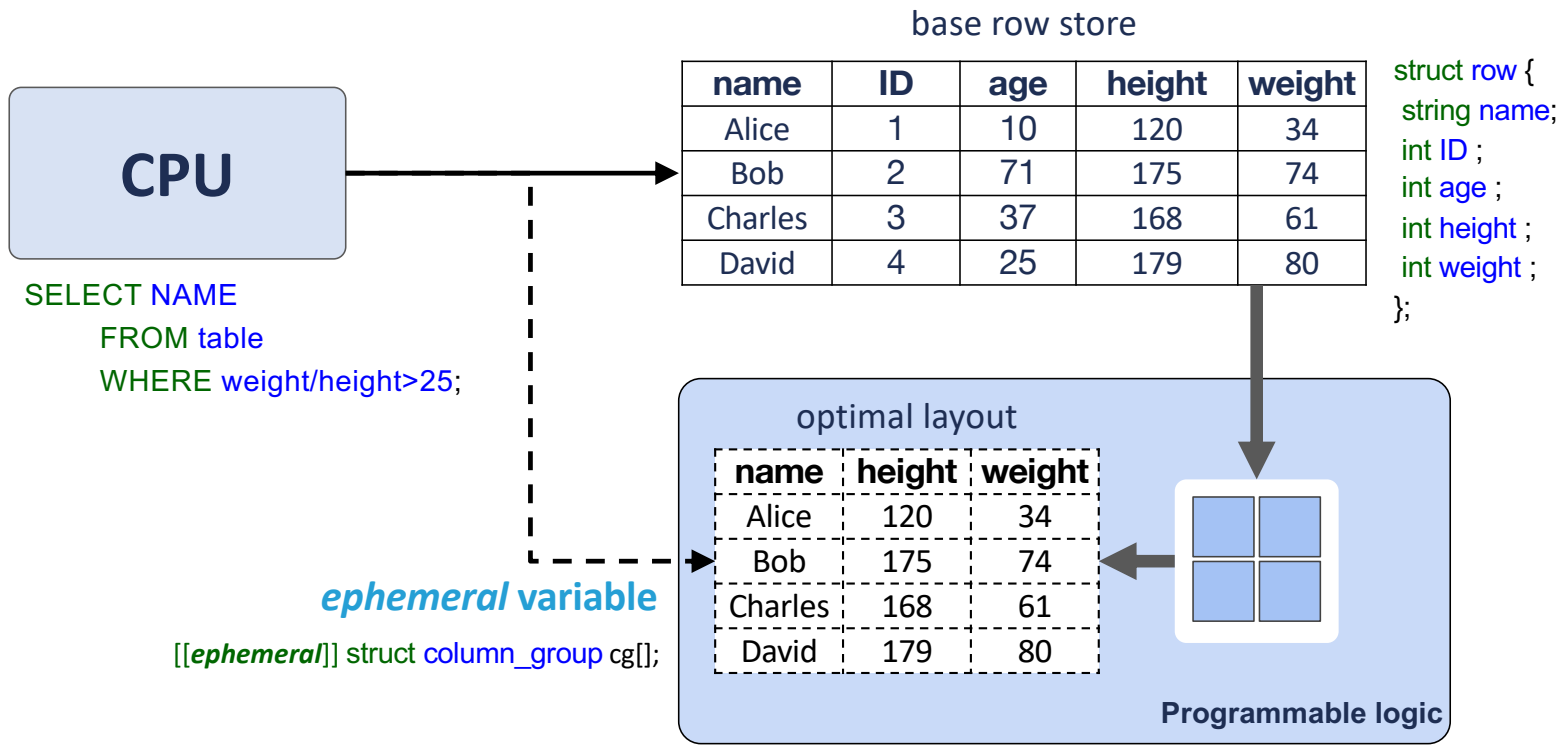
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Programmable logic
ephemeral variable
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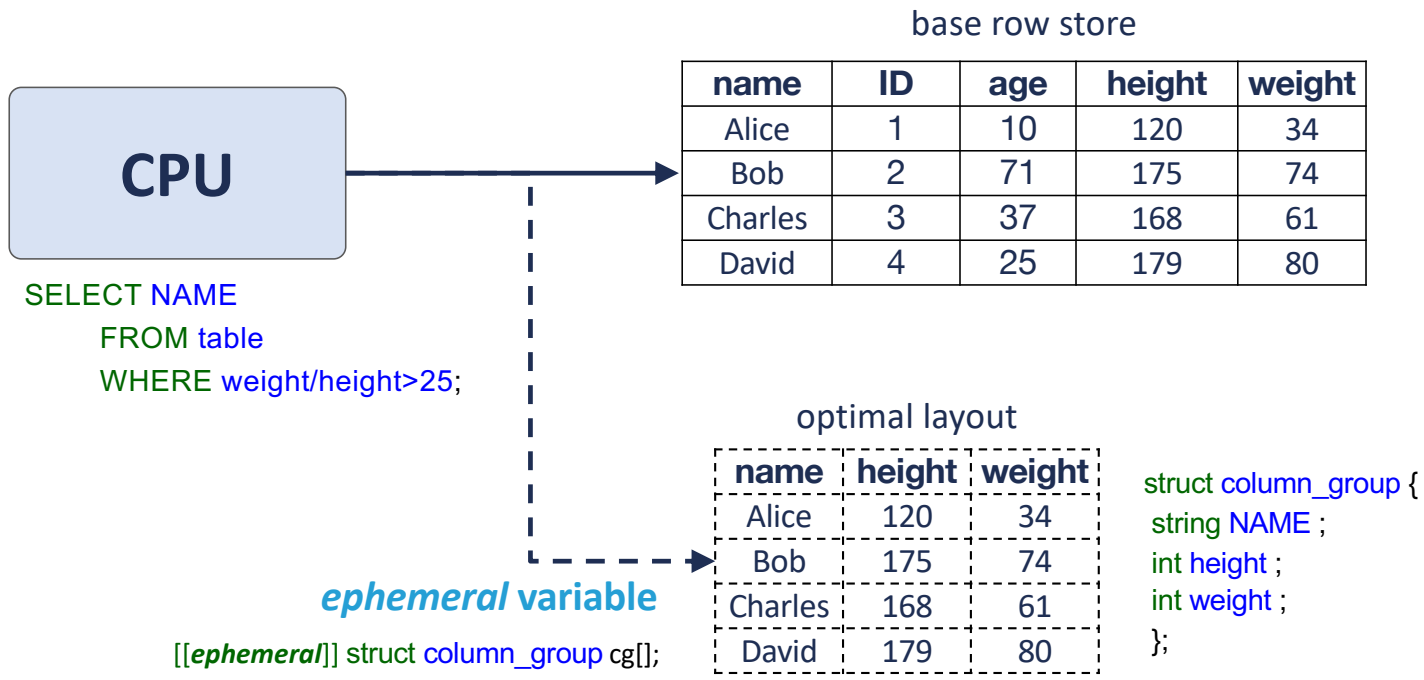
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Charles 3 37 168 61
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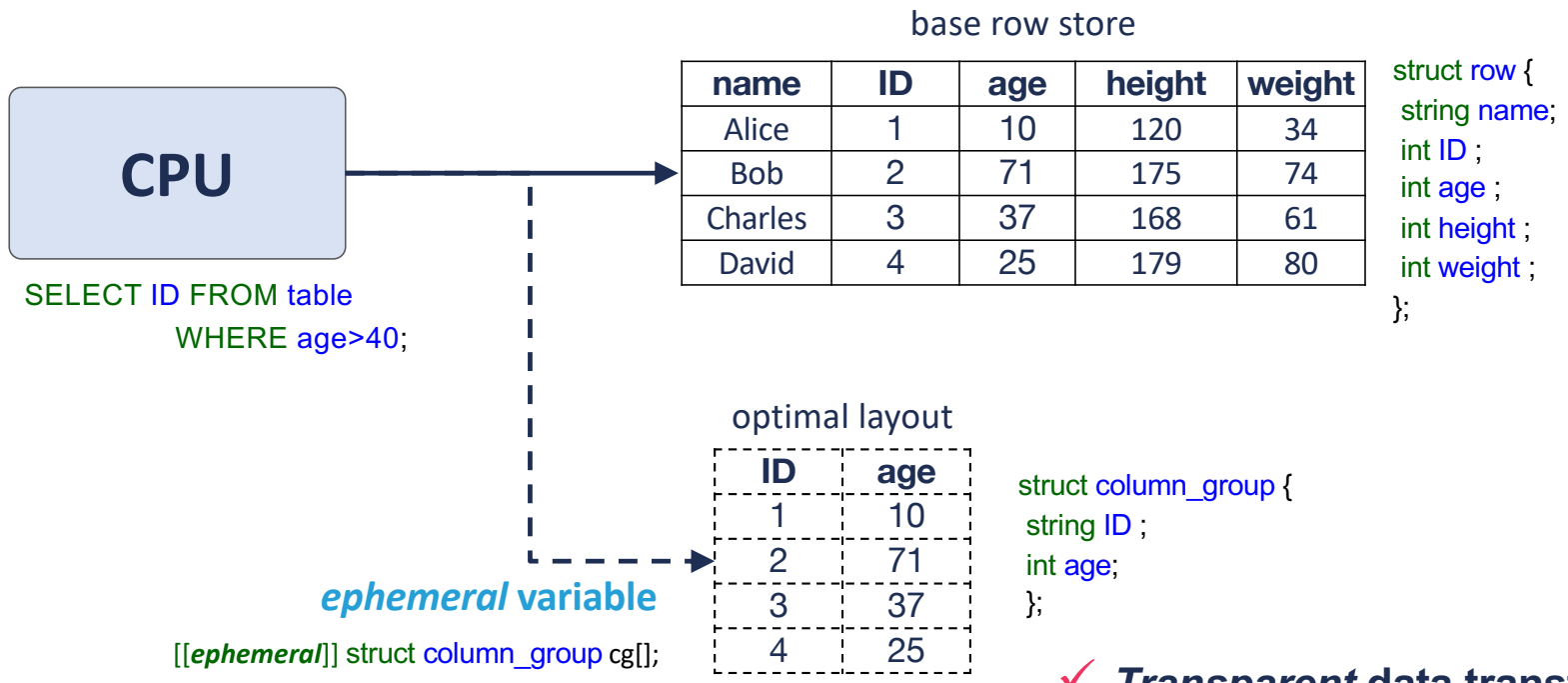

✓ ***Transparent*** **data transformation**

✓ ***Optimal layout***

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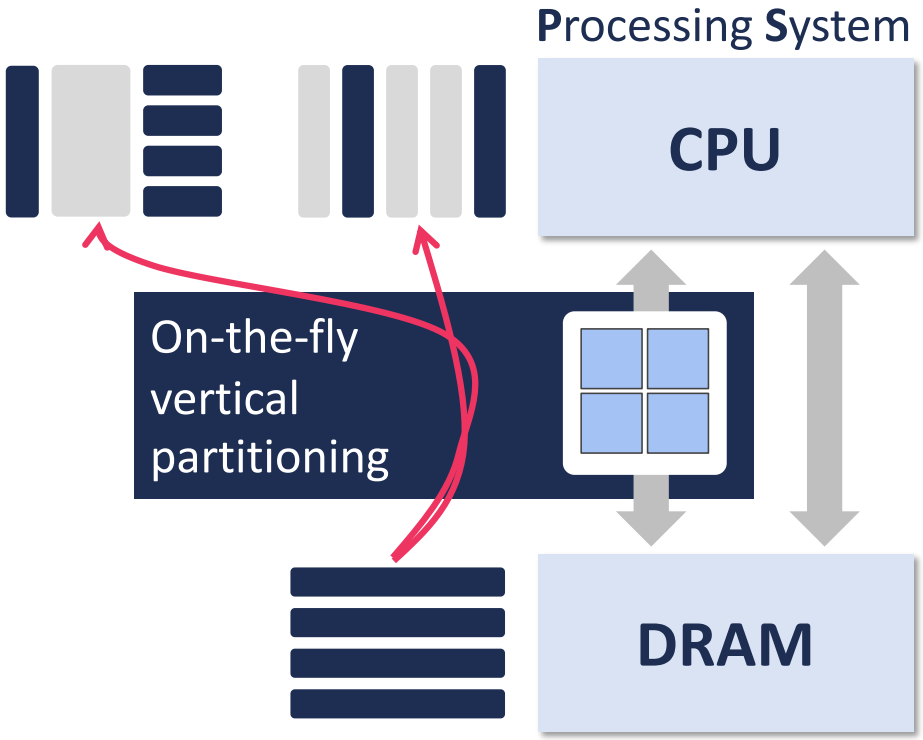
Q1: how to build?

Q2: how to use?

Relational Memory Engine



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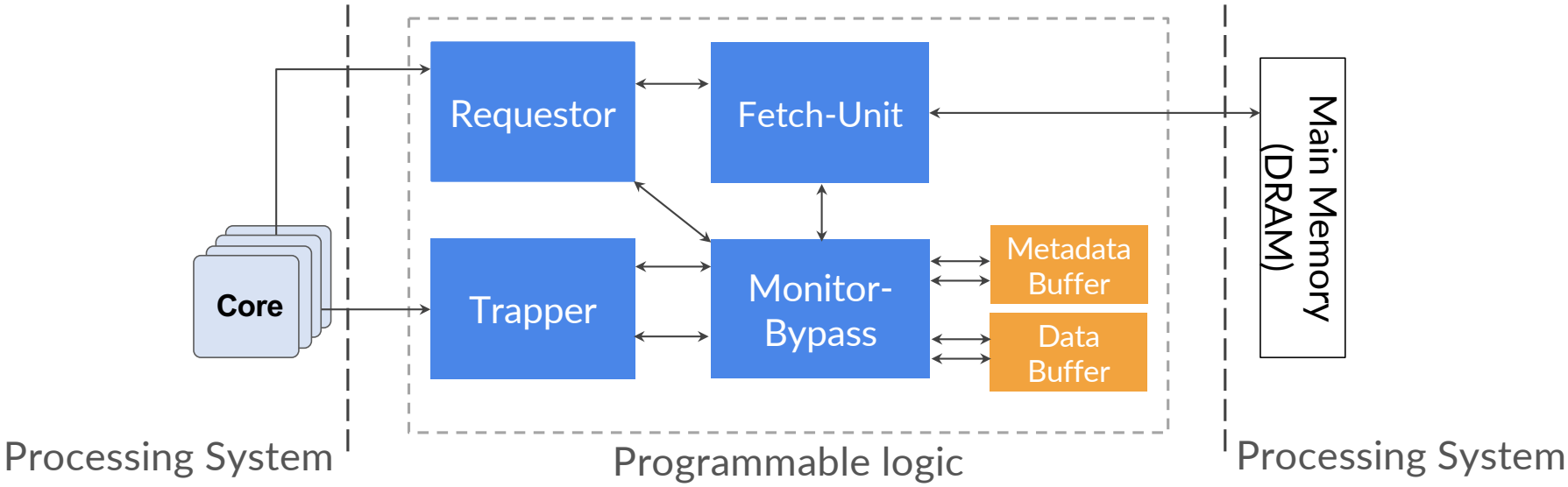
Relational Memory Engine



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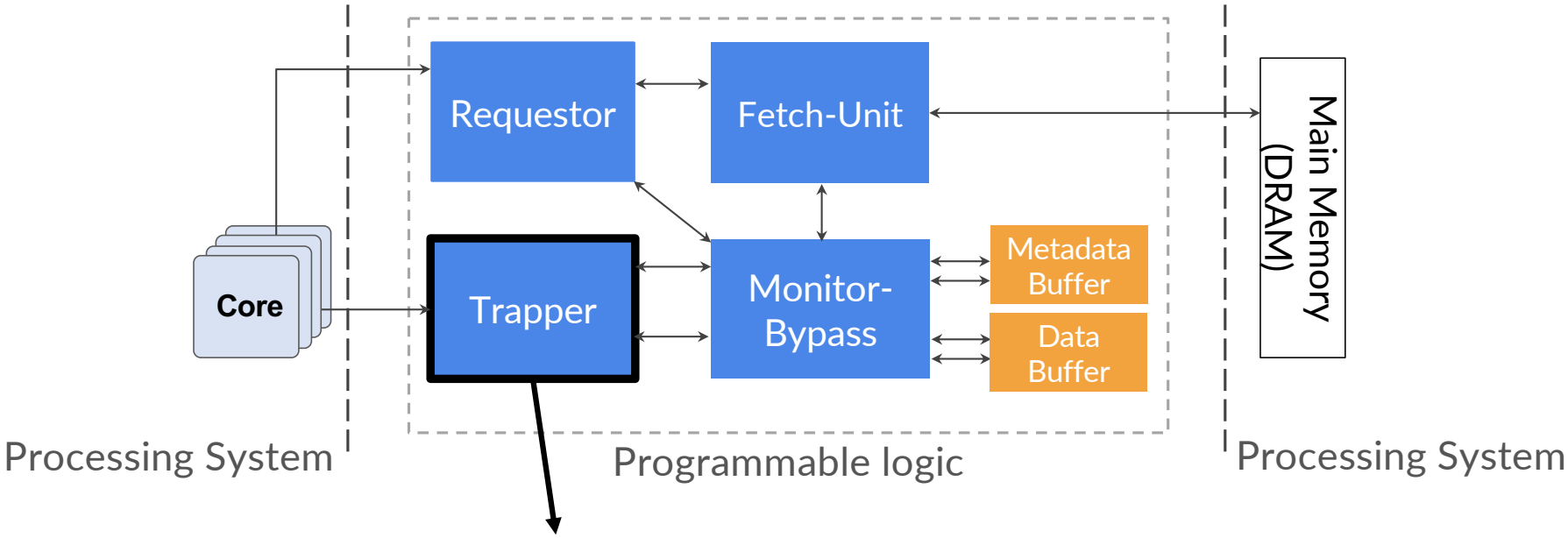
Relational Memory Engine



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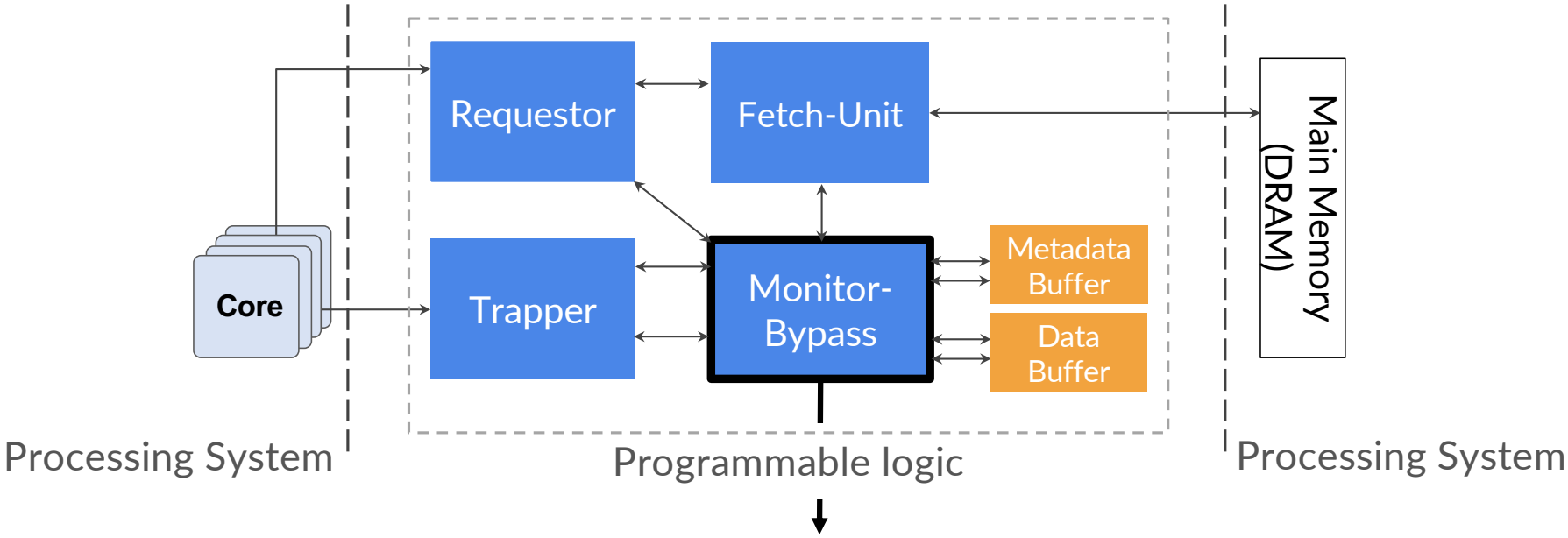
Relational Memory Engine



Monitors the completion of each reorganized cache line

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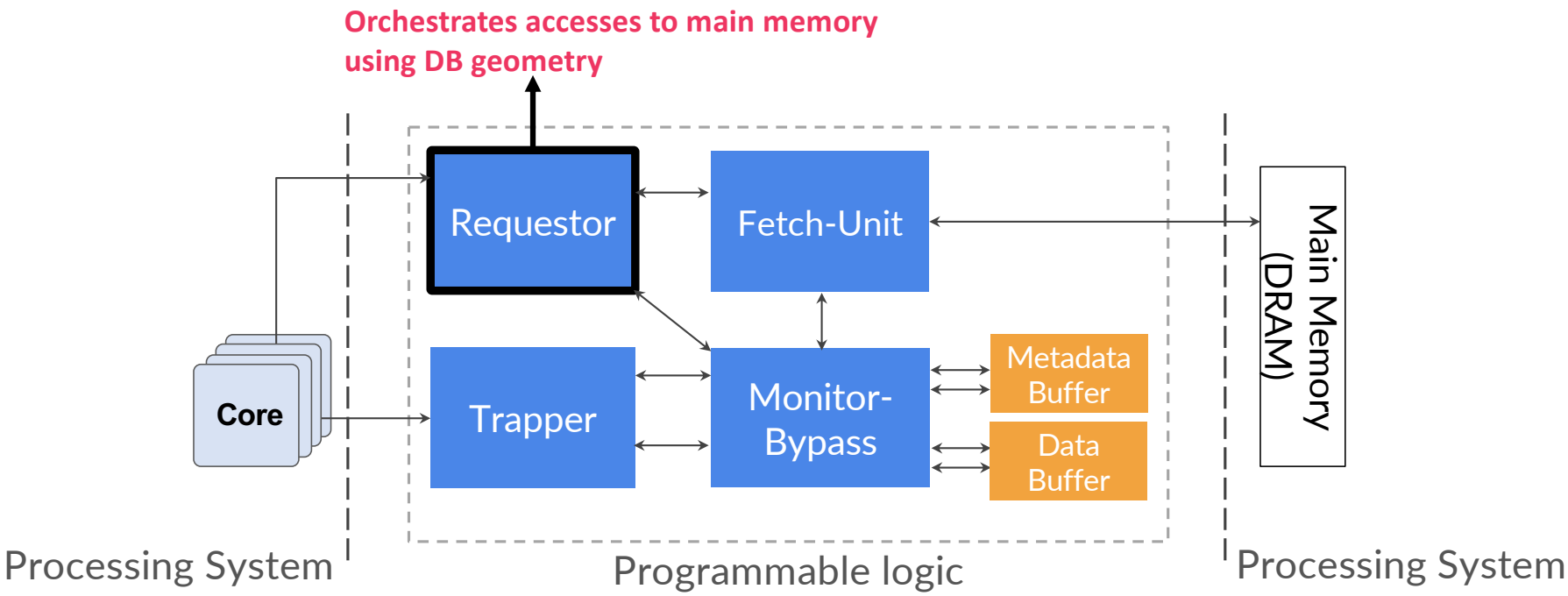
Relational Memory Engine



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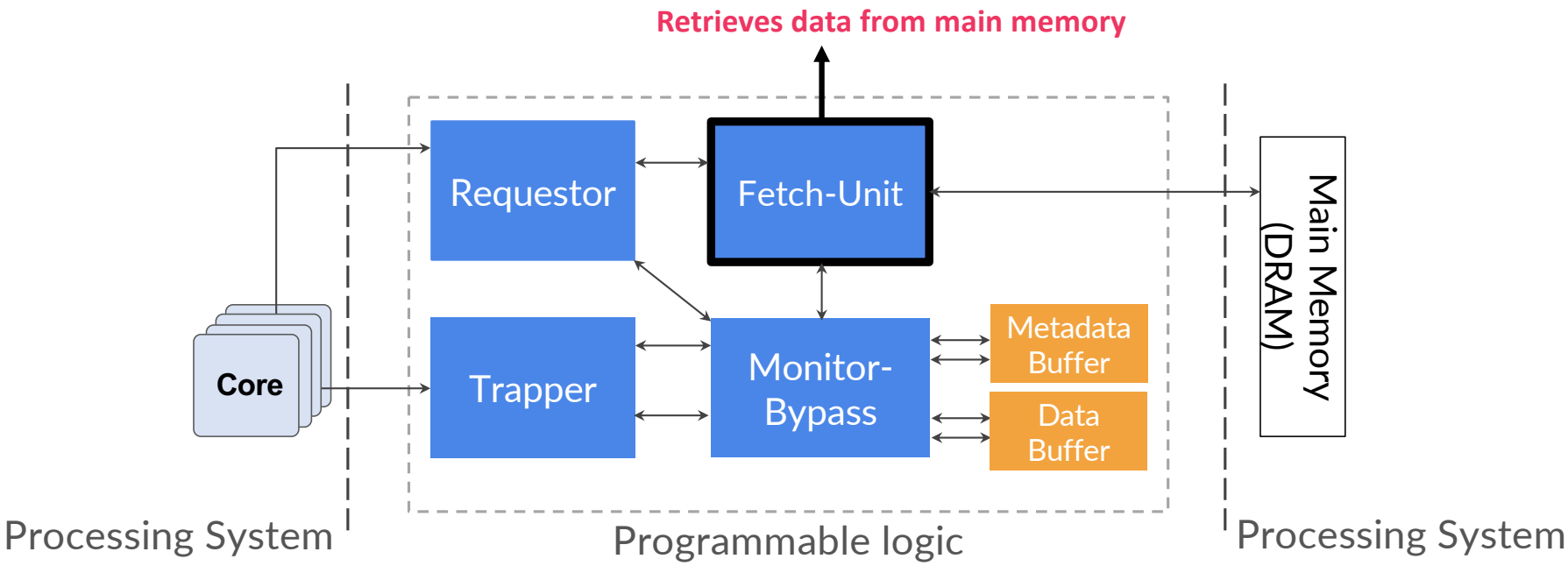

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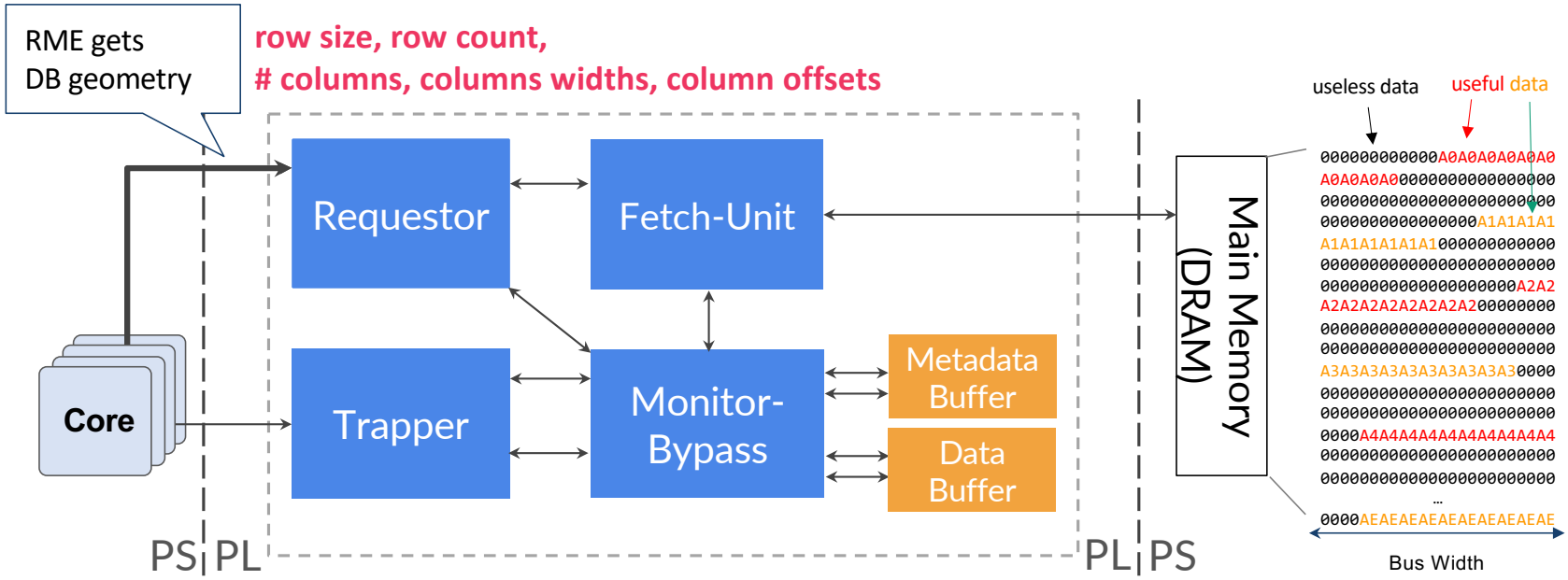
Relational Memory Engine



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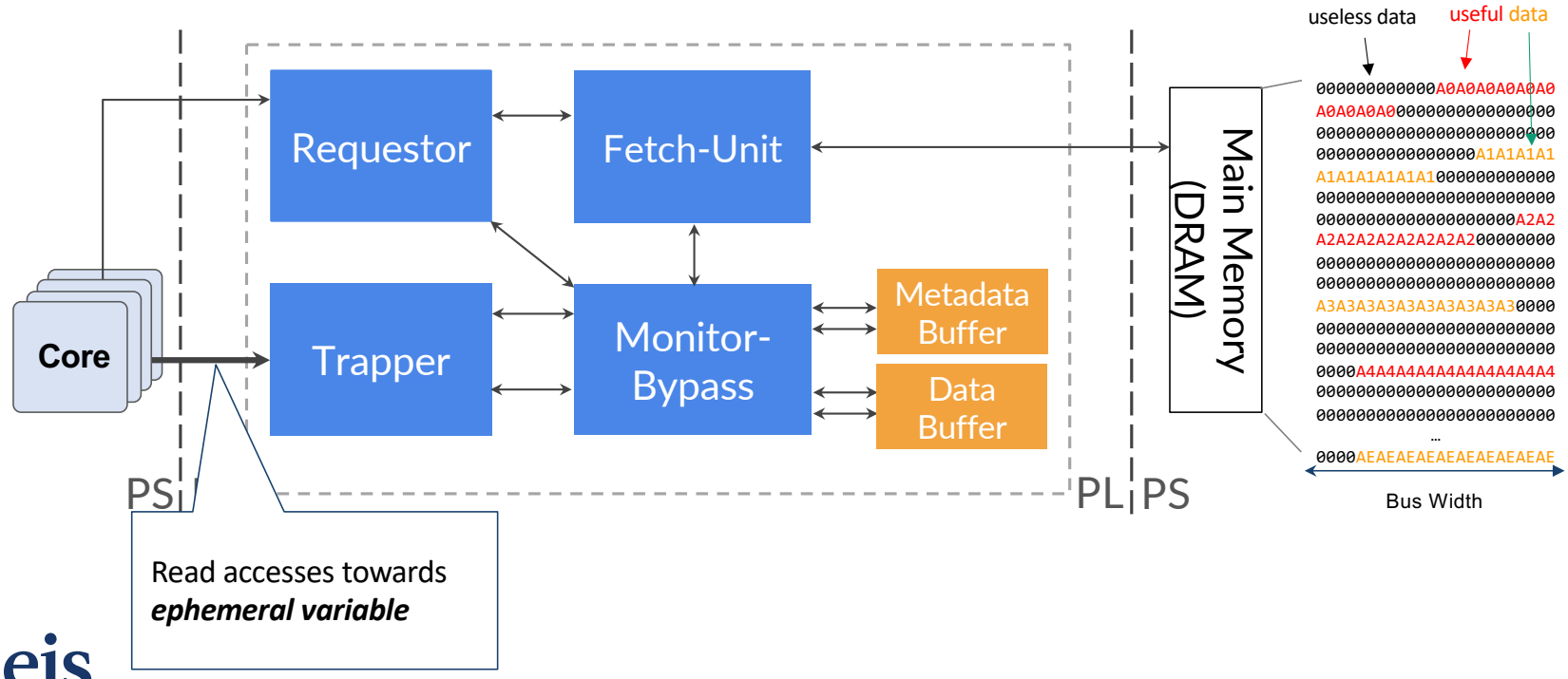
Relational Memory Engine



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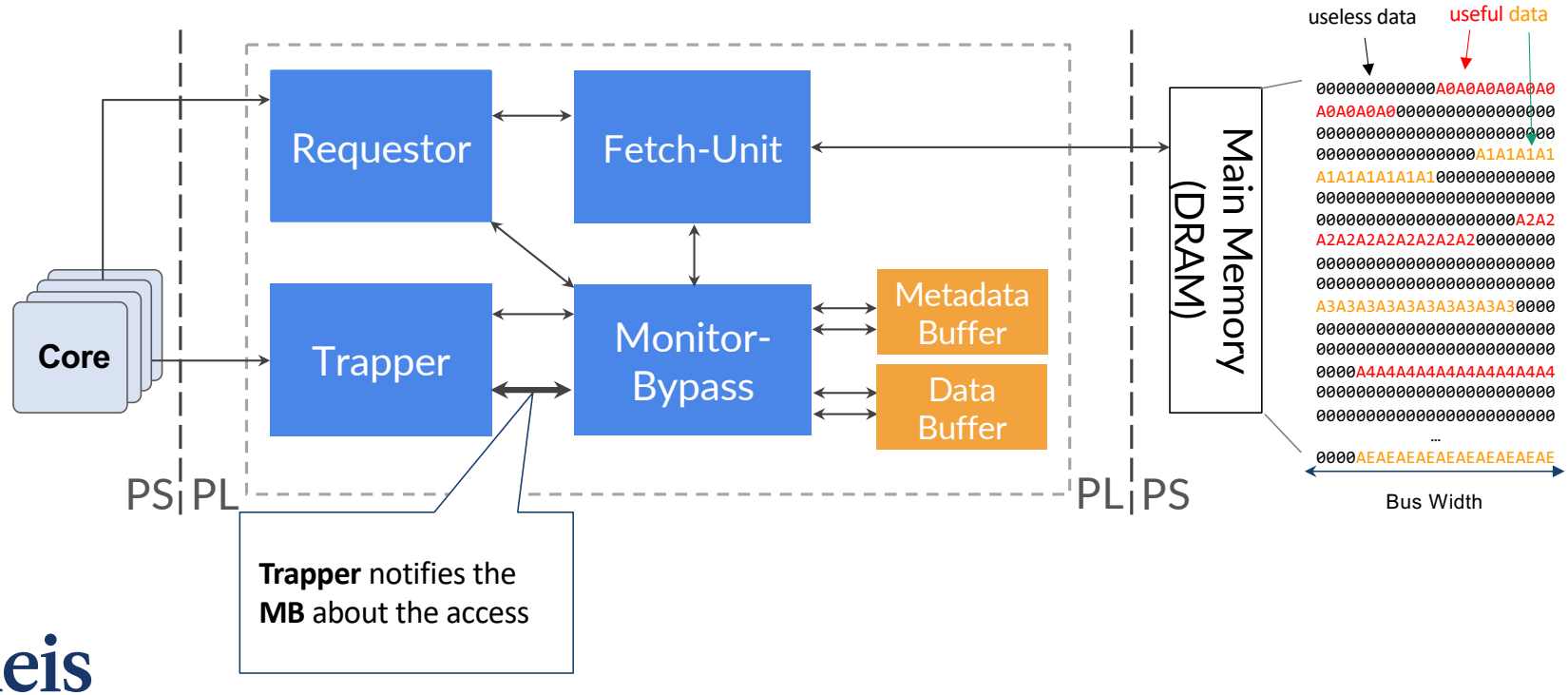

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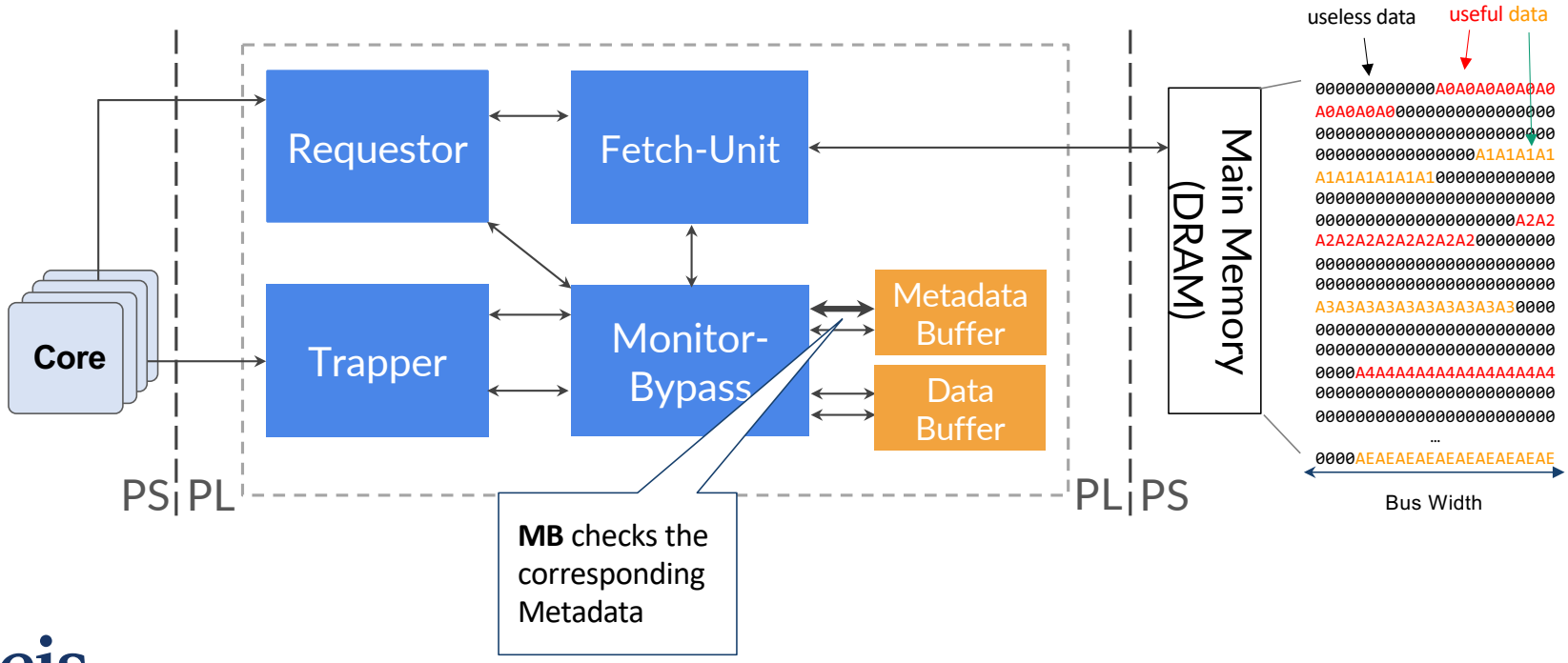
Relational Memory Engine



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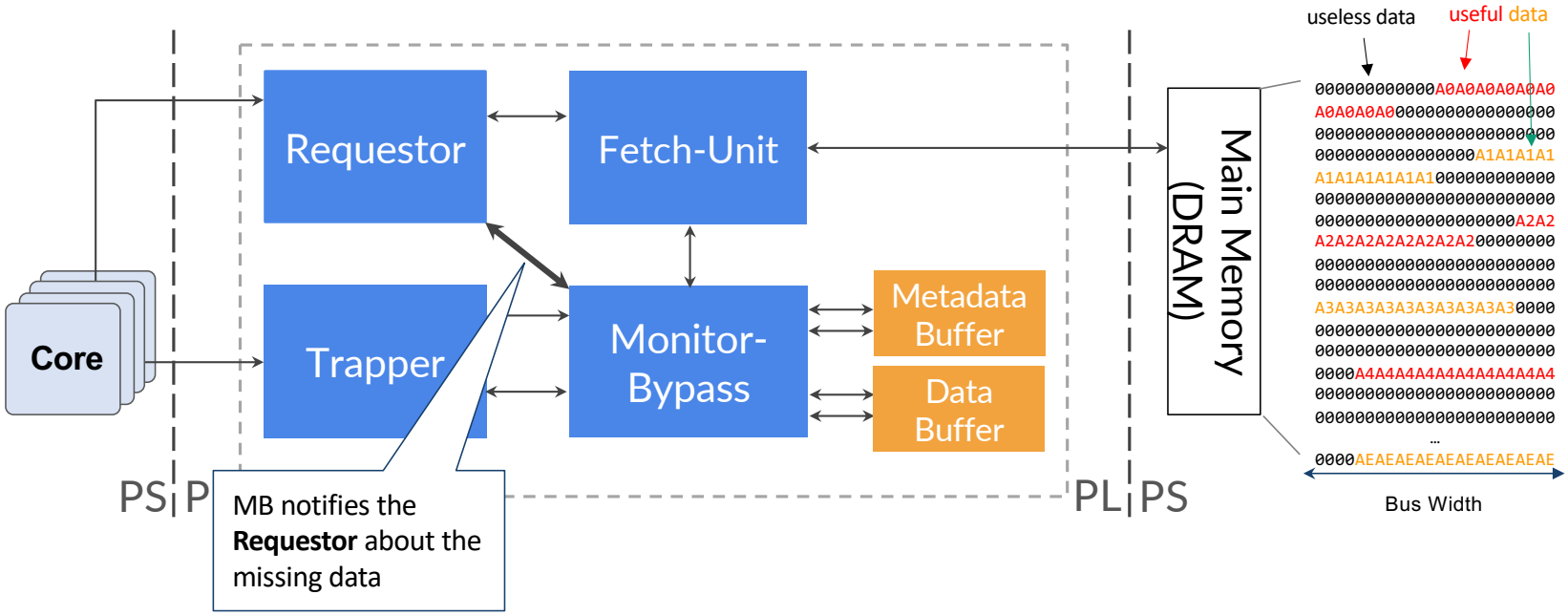
Relational Memory Engine

When the data is not in Data Buffer



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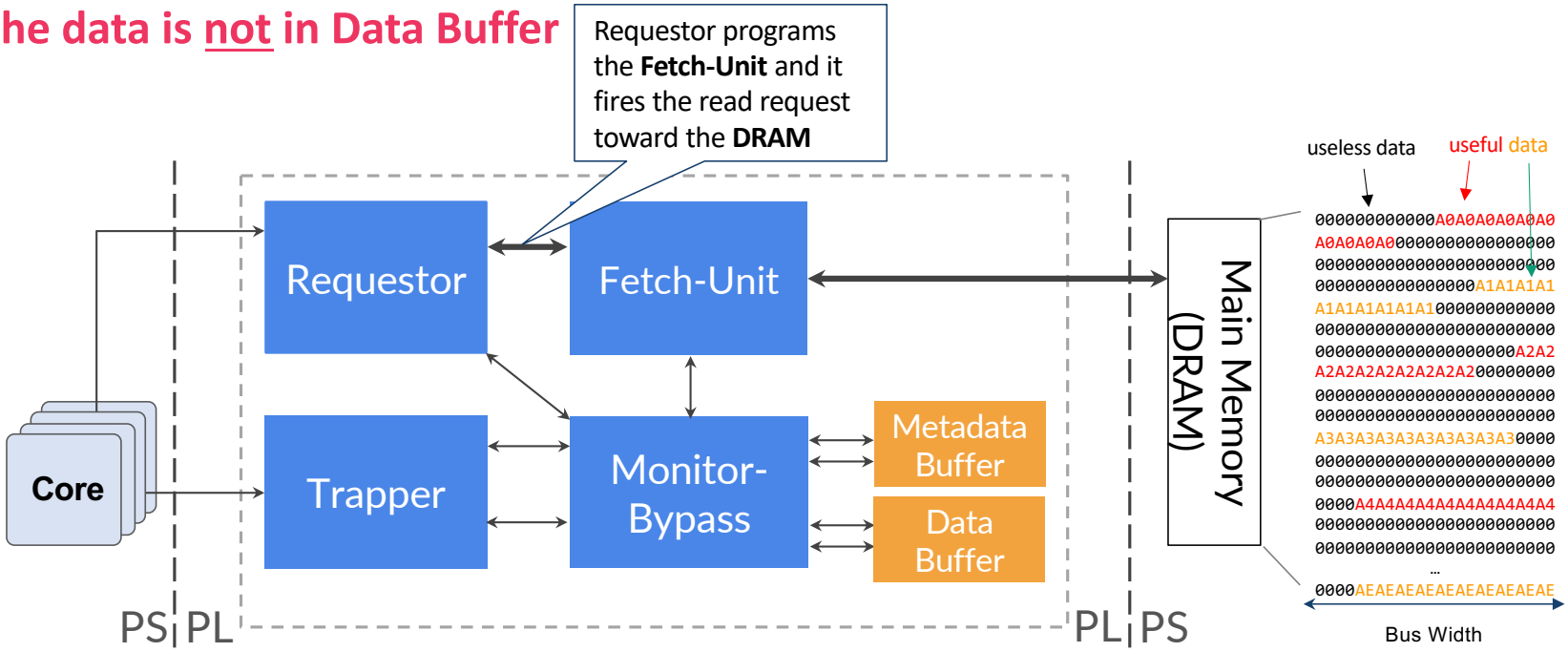

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Relational Memory Engine

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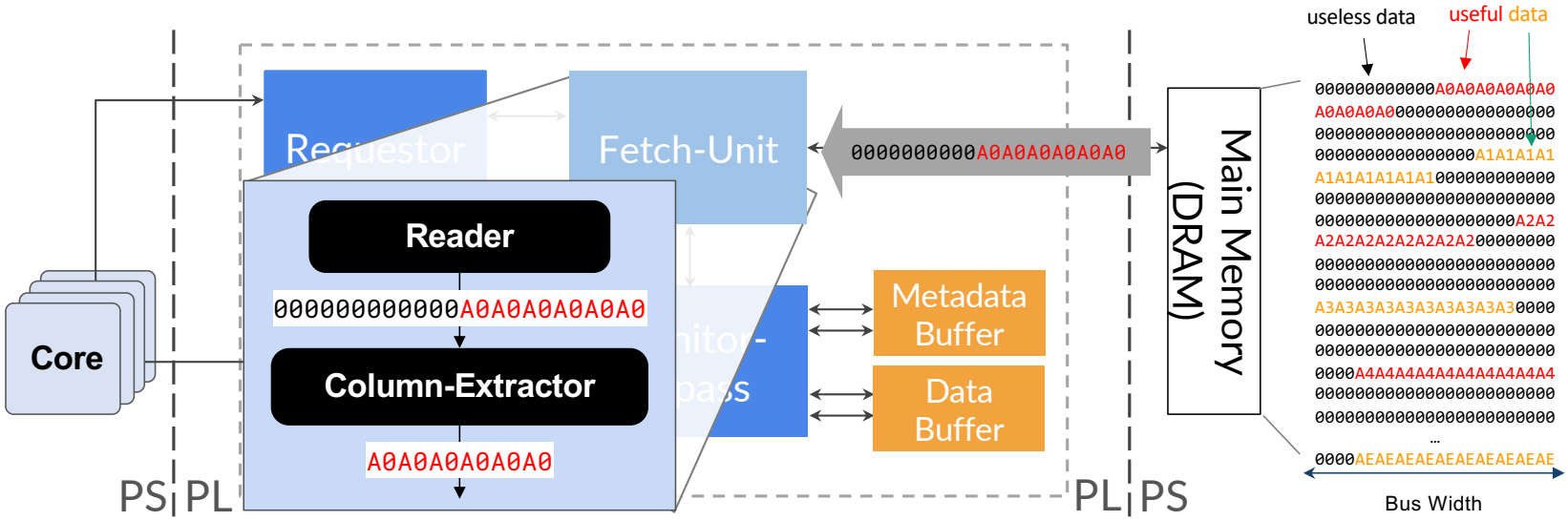

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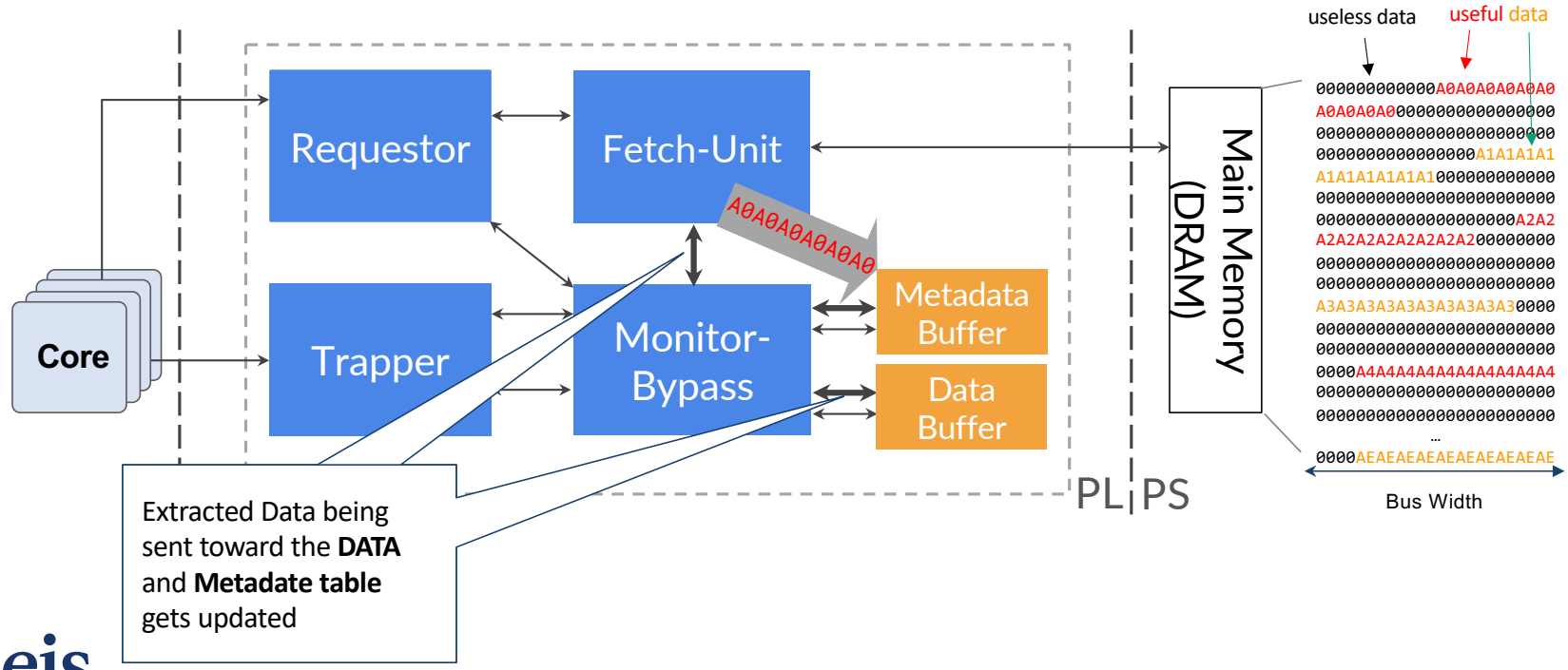

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Relational Memory Engine

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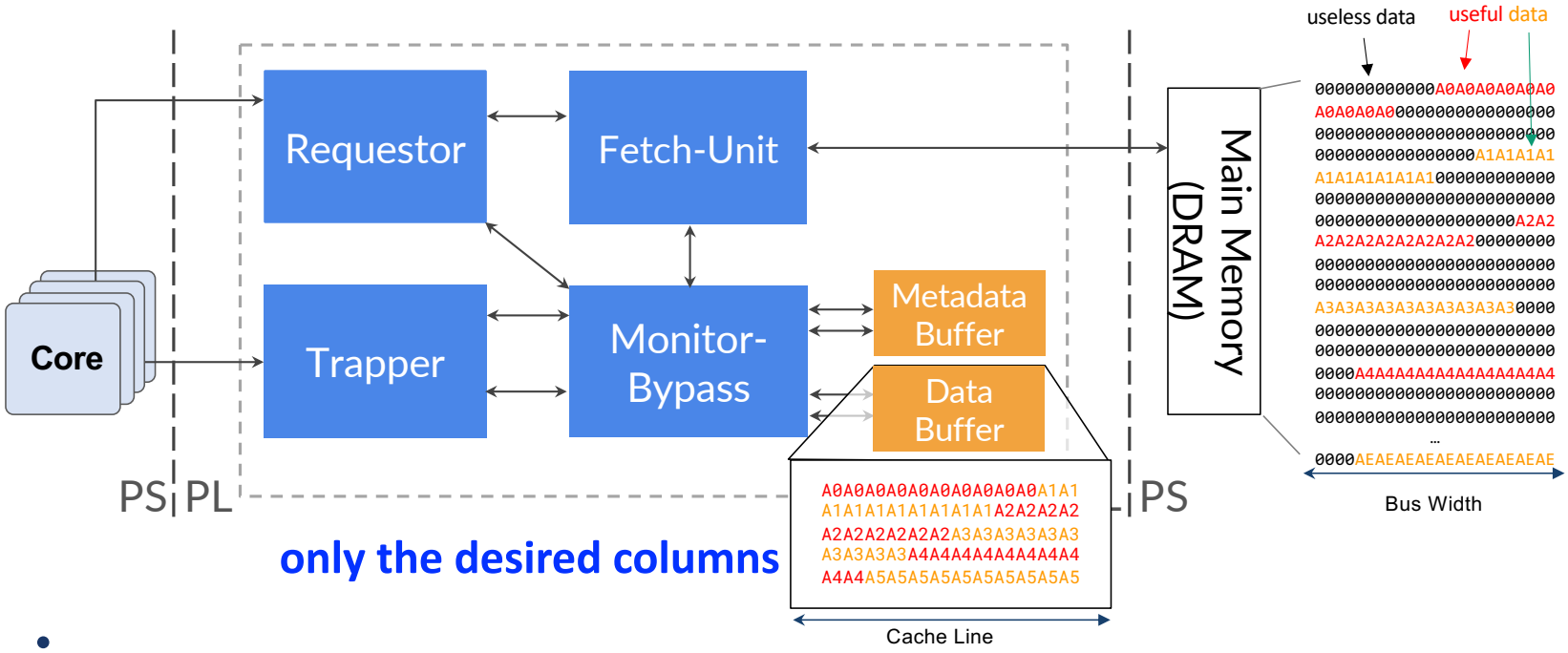

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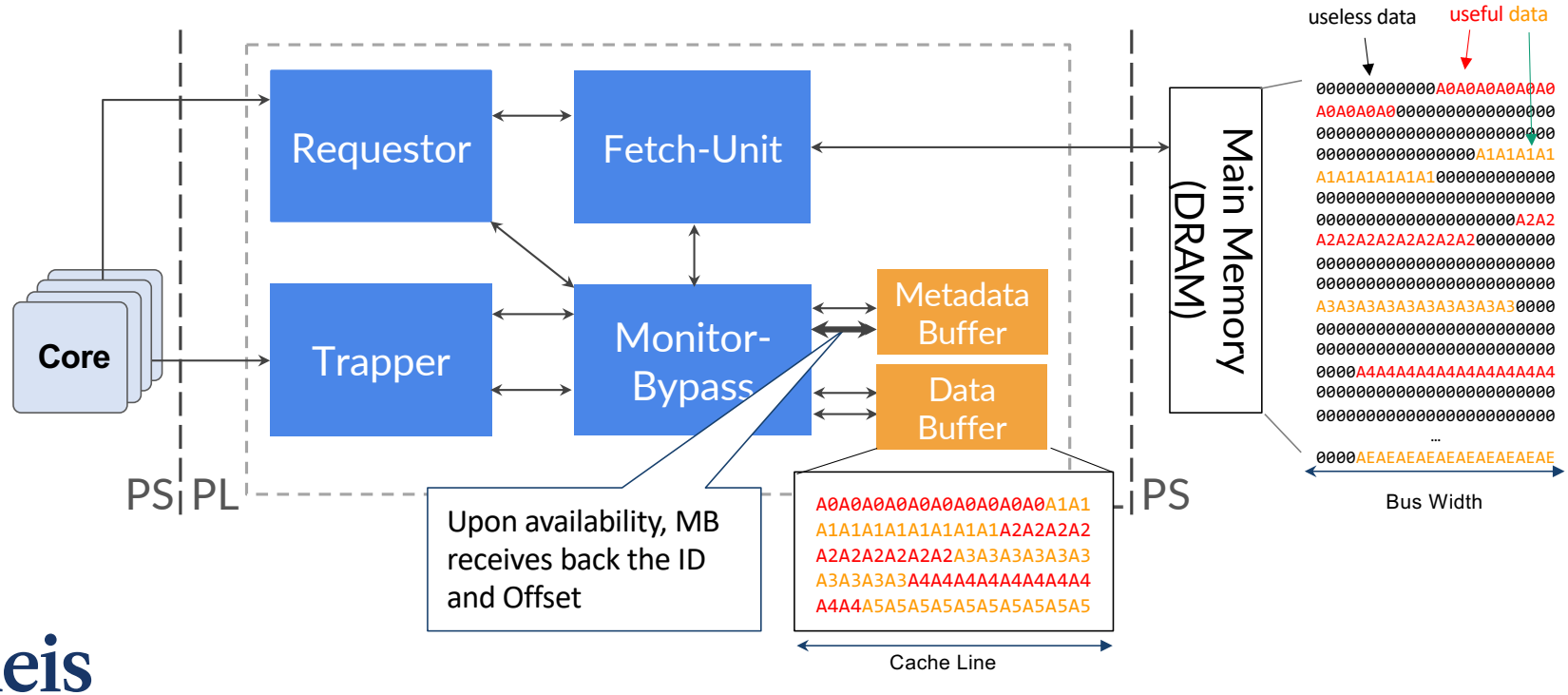
Relational Memory Engine

When the data is already in Data Buffer



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Relational Memory Engine

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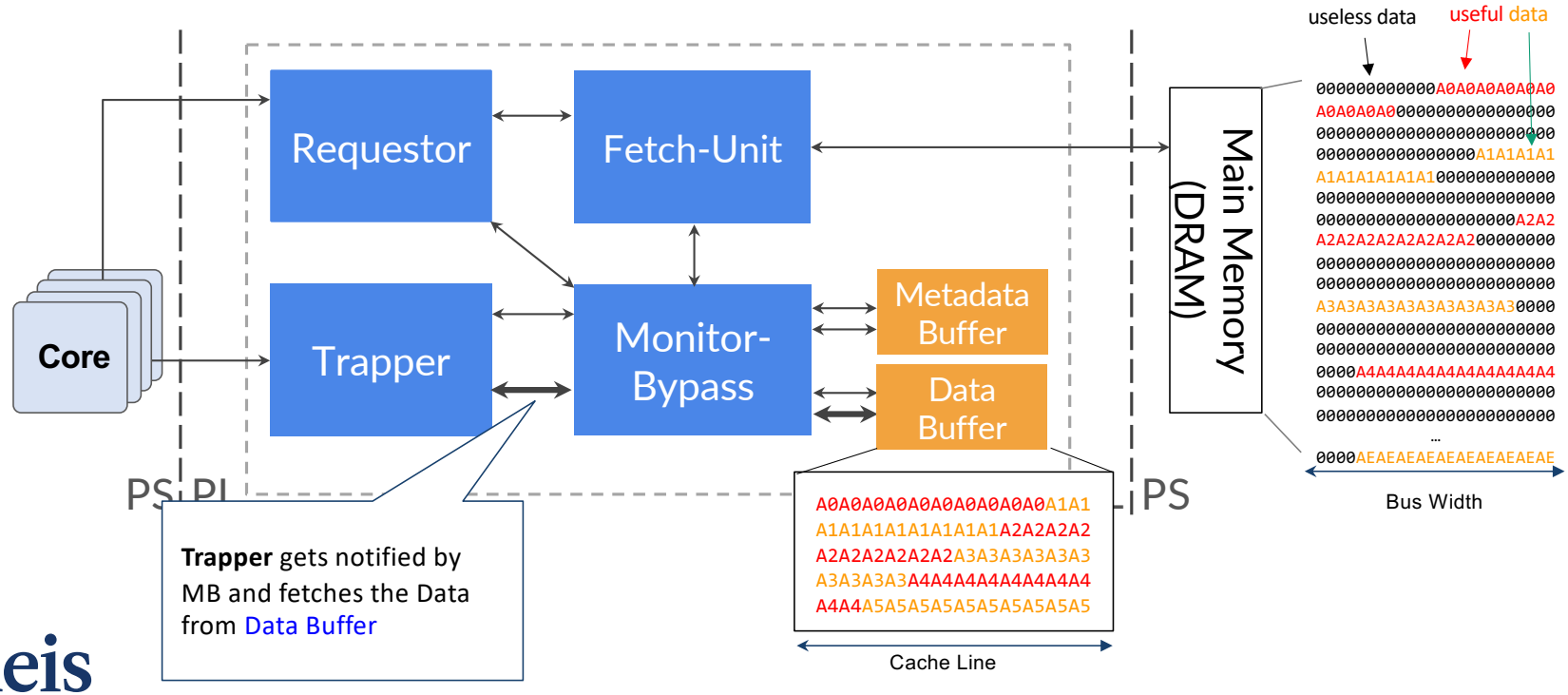

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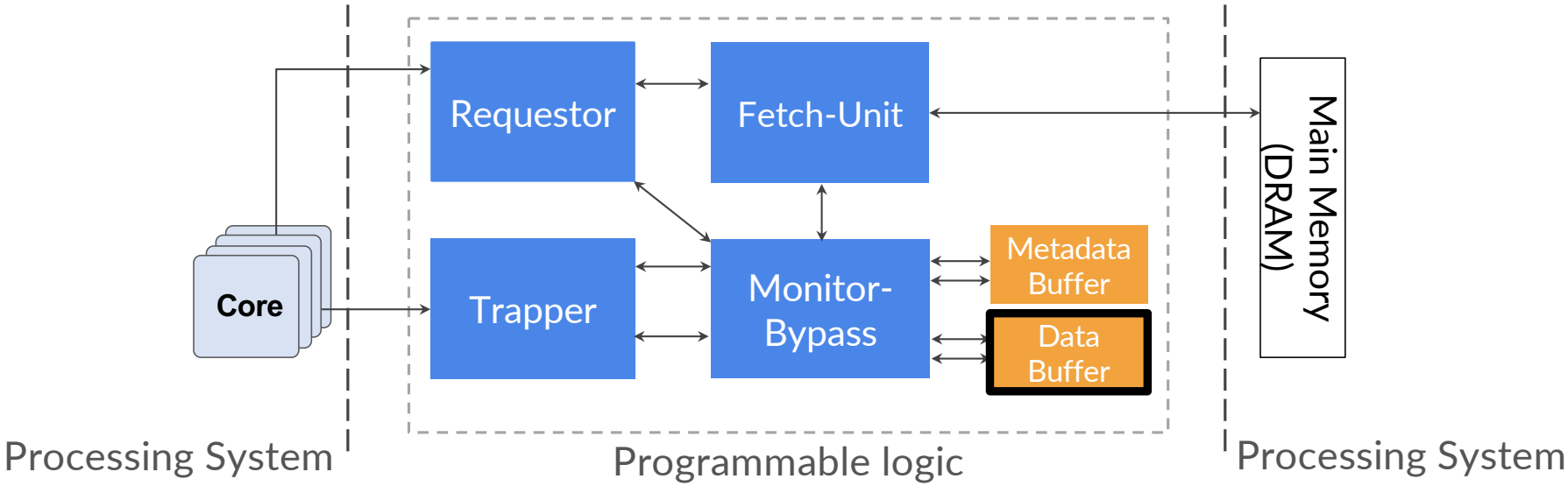
Relational Memory Engine



2MB << Data size

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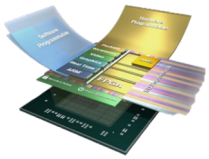
Target Platform

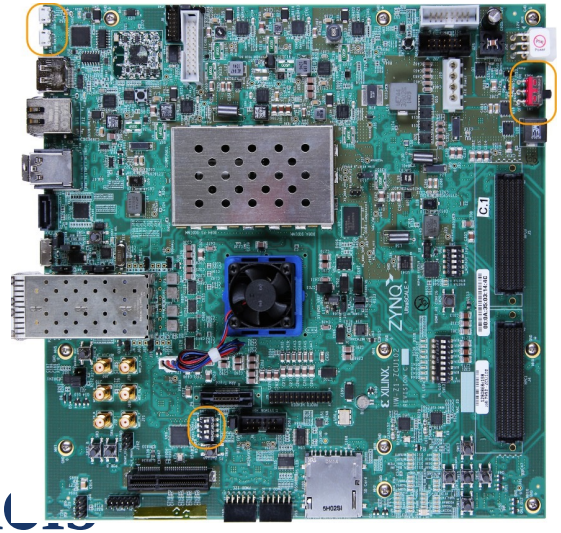


AMD XILINX

UltraScale+

ZCU102 platform

- CPUs : 4x ARM Cortex-A53
- L1/L2 Cache : 32+32KB I+D / 1 MB
- PS Frequency : 1.5 GHz
- PL Frequency : 100MHz



Resources	Utilization (%)
LUT	2.78
FF	0.68
DSP	0.08
BRAM	60.69

area utilization less than 3%

Relational Memory Benchmark

Q1: SELECT A1 , A2 , ... , Ak FROM S; ⇒ projection

Q2: SELECT A1 , A2 , ... , Ak FROM S WHERE C1, C2, … ,Ci; ⇒ both projection & selection

Q3: SELECT AVG (A1) FROM S WHERE A3 < k GROUP BY A2; ⇒ group by

Q4: SELECT S.A1 , R.A3 FROM S JOIN R ON S.A2 = R.A2; ⇒ join over two tables

Approach tested

ROW : Direct row-wise access

COL : Direct columnar access

} **Processing System**

RME : using Relational Memory Engine → **Slow FPGA** (100MHz)

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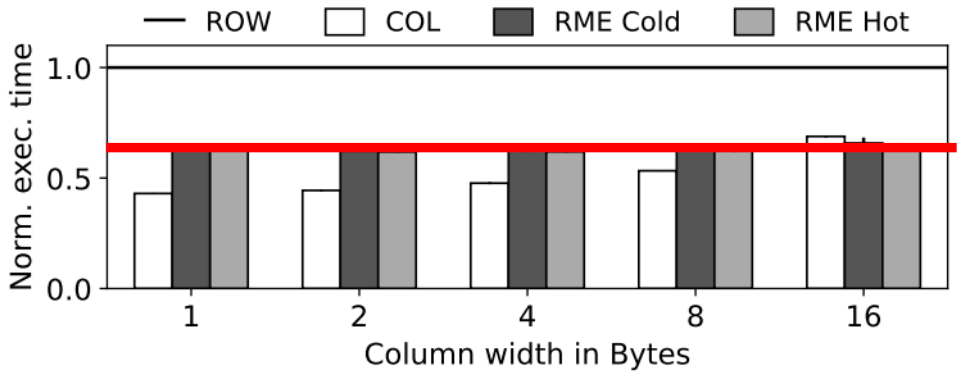
How big is the overhead of fetching the data?

RME Cold vs. Hot

SELECT A1, A3, A5 FROM S;



RME is comparable with directly accessing a single column!

RME Cold has virtually the same performance as RME Hot!

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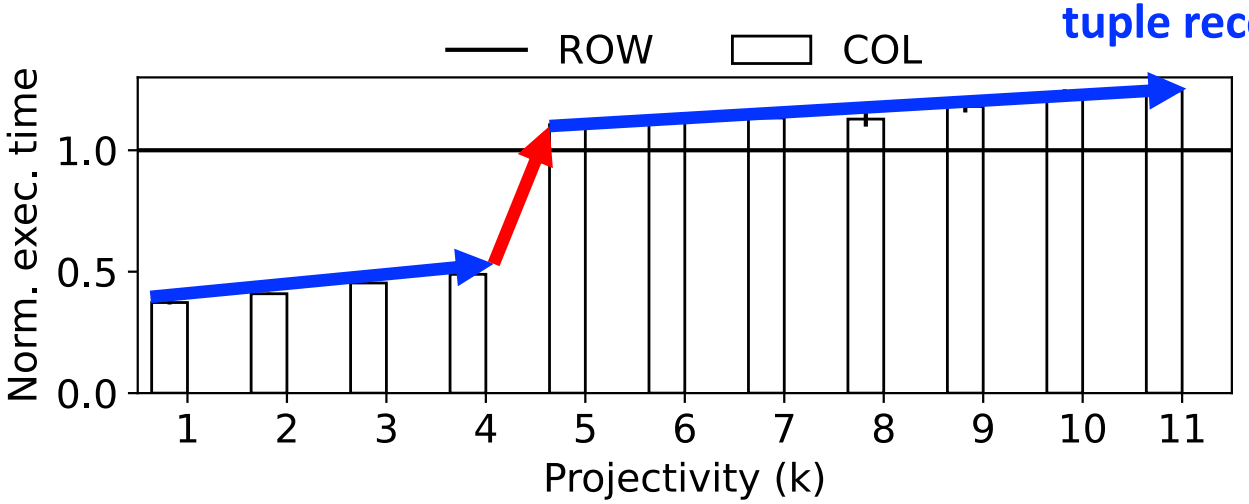
Row size: 64 Bytes

Queries Varying Projectivity

Q1: SELECT A1 , A2 , … , Ak FROM S;



tuple reconstruction cost

prefetcher supports up to four parallel streams

Row size: 64 Bytes, Column size: 4 Bytes

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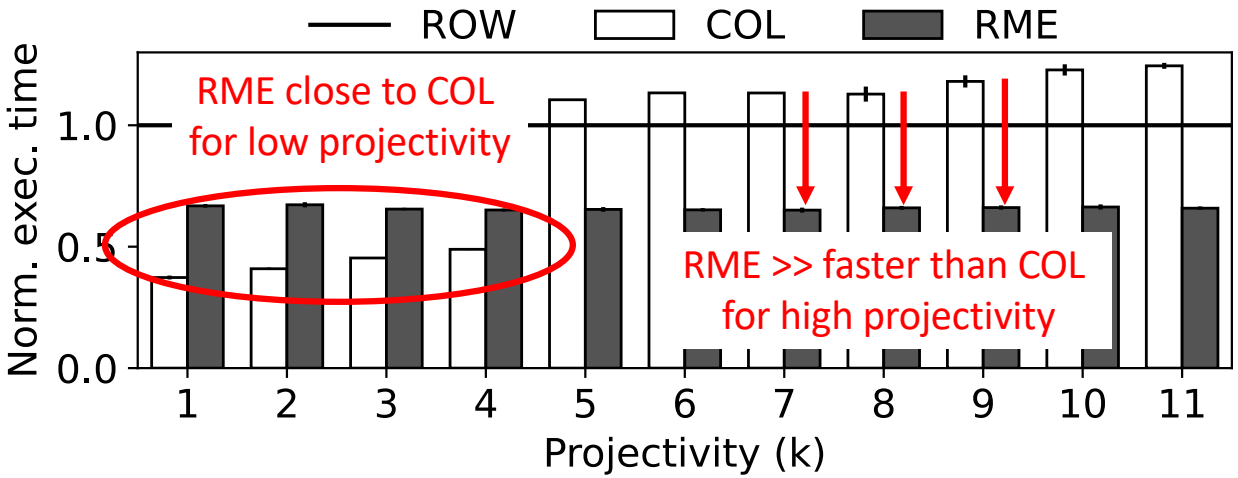
Queries Varying Projectivity

Q1: SELECT A1 , A2 , … , Ak FROM S;



RME provides stable performance irrespectively of projectivity

Row size: 64 Bytes, Column size: 4 Bytes

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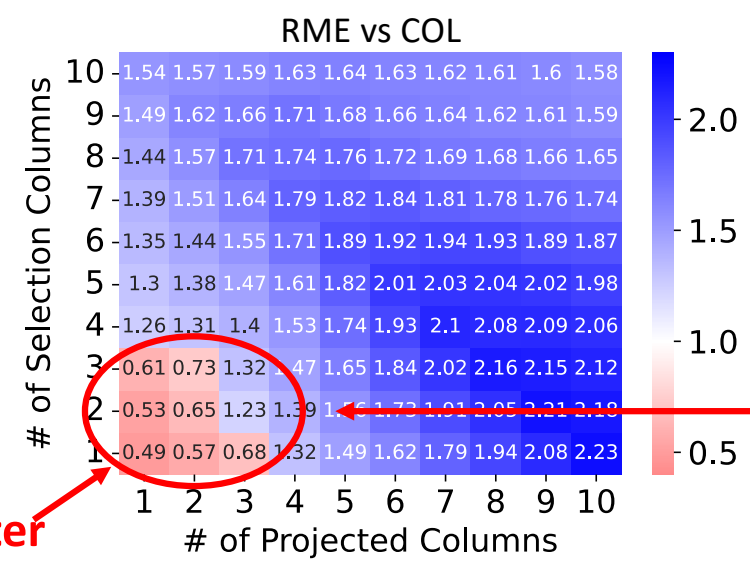
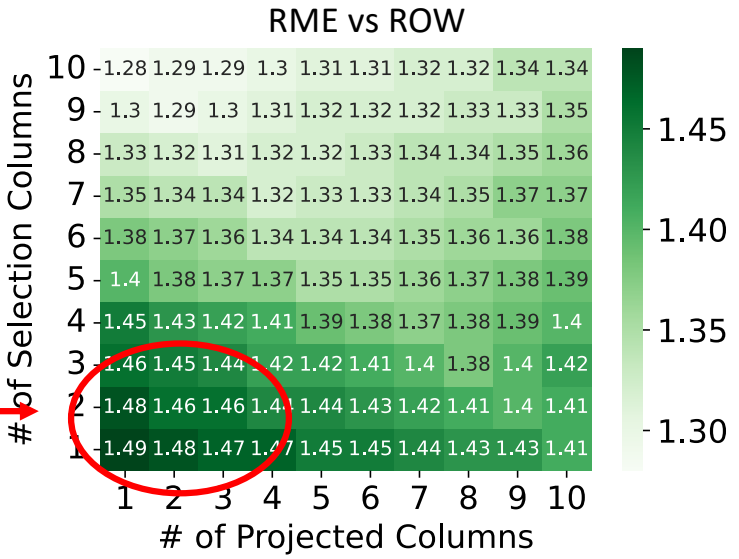
RME for Multiple Selection and Projection Attributes

Q3: SELECT A1 , A2 , ... , Ak FROM S WHERE C1, C2, ... ,Ci; Row size: 64 Bytes, Column size: 4 Bytes





COL faster

RME can be up to 2.23× faster than columnar access

RME *always* outperforms row access by being 1.3 – 1.5× faster

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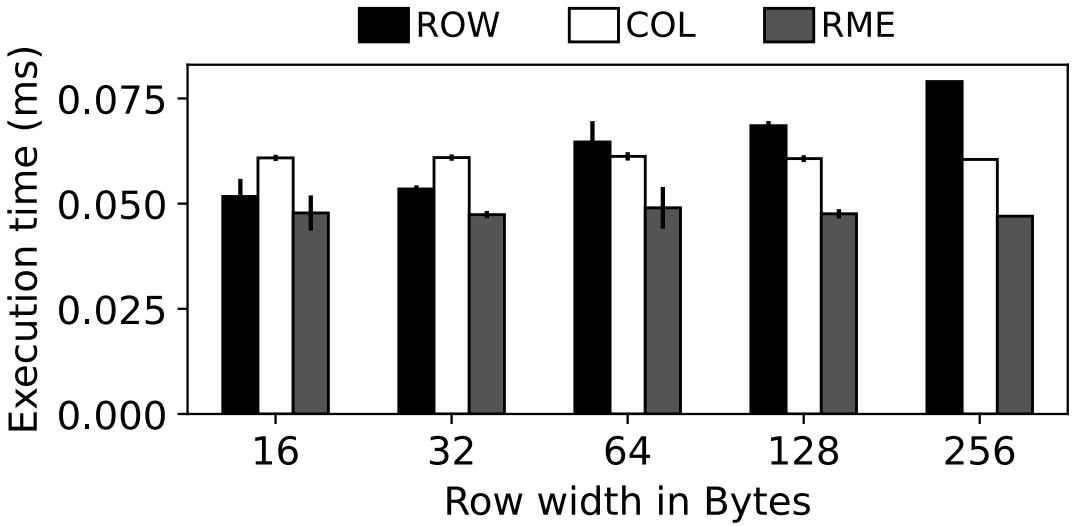
Group by

Q4: SELECT AVG (A1) FROM S WHERE A3 < k GROUP BY A2; Selectivity: 10%



RME outperforms both ROW and COL

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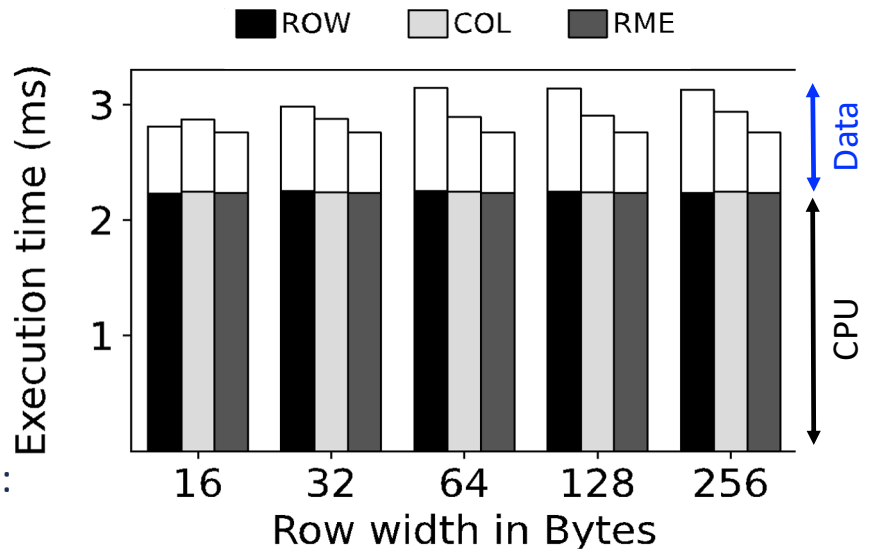
Column size: 4 Bytes

Join Over Two Tables

Q4: SELECT S.A1 , R.A3 FROM S JOIN R ON S.A2 = R.A2;



Column size:

RME reduces data movement up to 41%

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RME Scales with Data Size

TPC-H Q1

```
SELECT l_returnflag, l_linestatus,
   SUM(l_quantity), SUM(l_extendedprice),
   SUM(l_extendedprice*(1-l_discount)),
   SUM(l_extendedprice*(1-l_discount)*(1+l_tax)),
   AVG(l_quantity), AVG(l_extendedprice),
   AVG(l_discount),
   COUNT(*)
FROM lineitem
WHERE
   l_shipdate <= '1998-12-01' - '[DELTA]' day (3)
GROUP BY l_returnflag, l_linestatus
ORDER BY l_returnflag, l_linestatus;
```

Selectivity: 95%, projectivity: 24%

TPC-H Q6

```
SELECT
   SUM(l_extendedprice*l_discount)
FROM lineitem
WHERE
   l_shipdate >= '[DATE]' and
   l_shipdate < '[DATE]' + 1 year and
   l_discount > [DISCOUNT] - 0.01 and
   l_discount < [DISCOUNT] + 0.01 and
   l_quantity < [QUANTITY];
```

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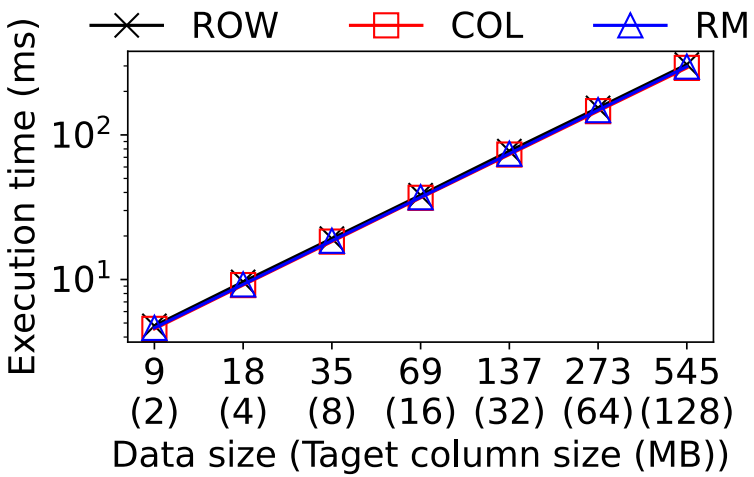
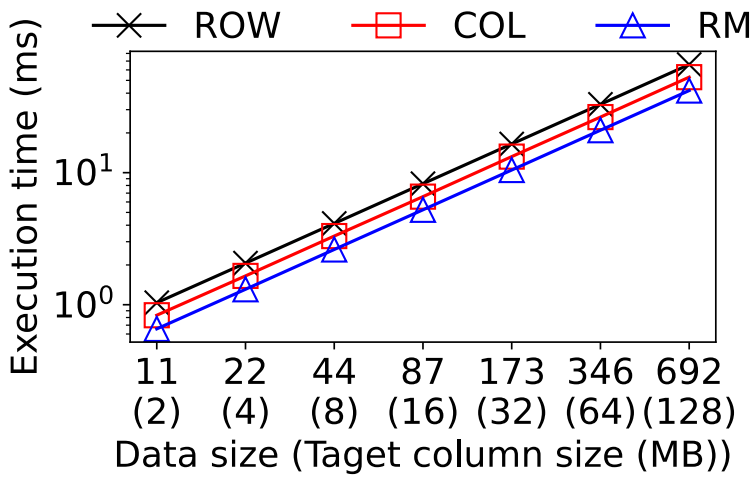
RME Scales with Data Size

TPC-H Q1 CPU-bound (sort, group by)



CPU overhead dominates data movement cost

TPC-H Q6 IO-bound



RME benefits regardless of data size

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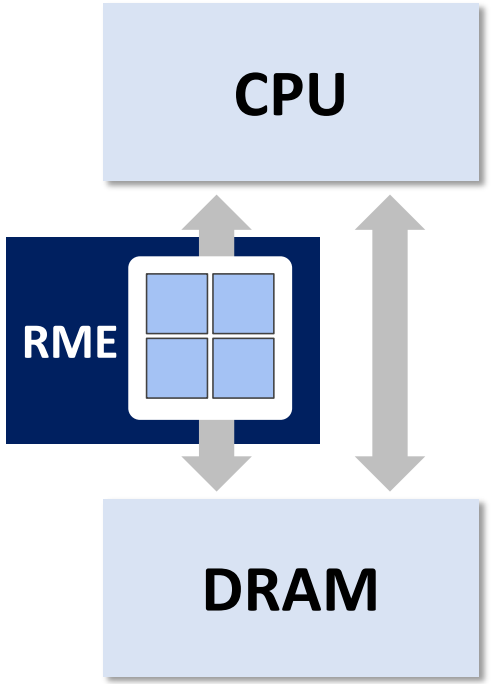
Summary

- **Relational Memory**
  - a novel SW/HW co-design paradigm
  - every query always has access to the optimal data layout
- ***ephemeral variables***
  - a simple and lightweight abstraction to use RM
- Relational Memory enables opportunities for innovation across the data system architecture.



Relational Fabric, ICDE '23

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Future Work

Data Transformation for ML workloads

Matrix and tensor slicing

Integrating with Real DBMS

Exploring query optimization

DRAM Controller Augmentation

Utilizing bank interleaving and parallelism

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Thank you

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