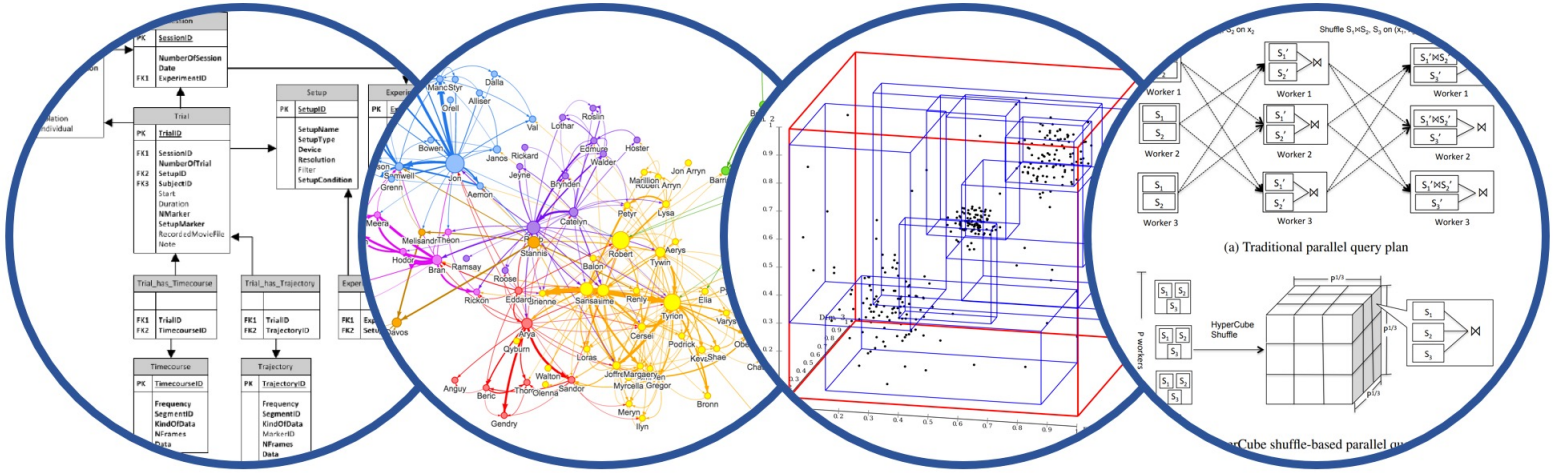


Introduction to Data Management

Cost Estimation

Paul G. Allen School of Computer Science and Engineering
University of Washington, Seattle

Announcements

- HW6:
  - Python of Java
  - Choose only one

- Part 1 due 5/17. No late days (for quick feedback)
- Part 2 due 5/24. Much more work than part 1

Agenda for this week

The query engine:

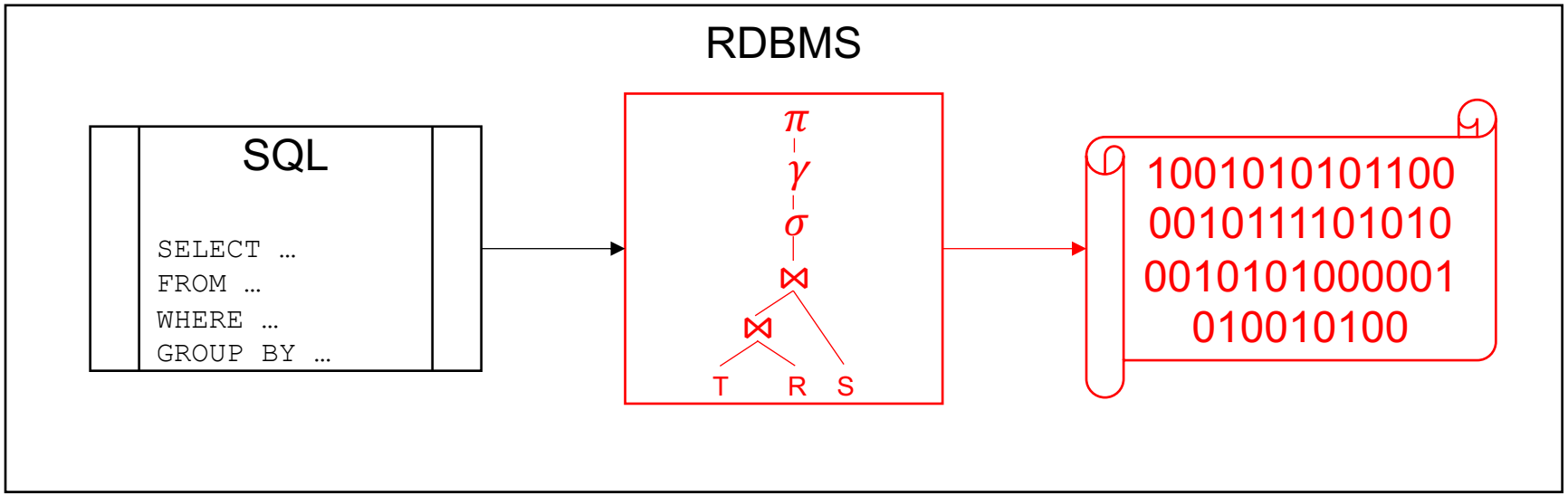
- Query execution

- Indexes and external memory
- Query optimization and cardinality estimation

Overview of the Query Engine

Logical vs Physical Plans

- SQL is translated into RA
- RA (logical plan) does not fully describe execution
- RA *with algorithms* (physical plan) is needed



Logical vs Physical Plans

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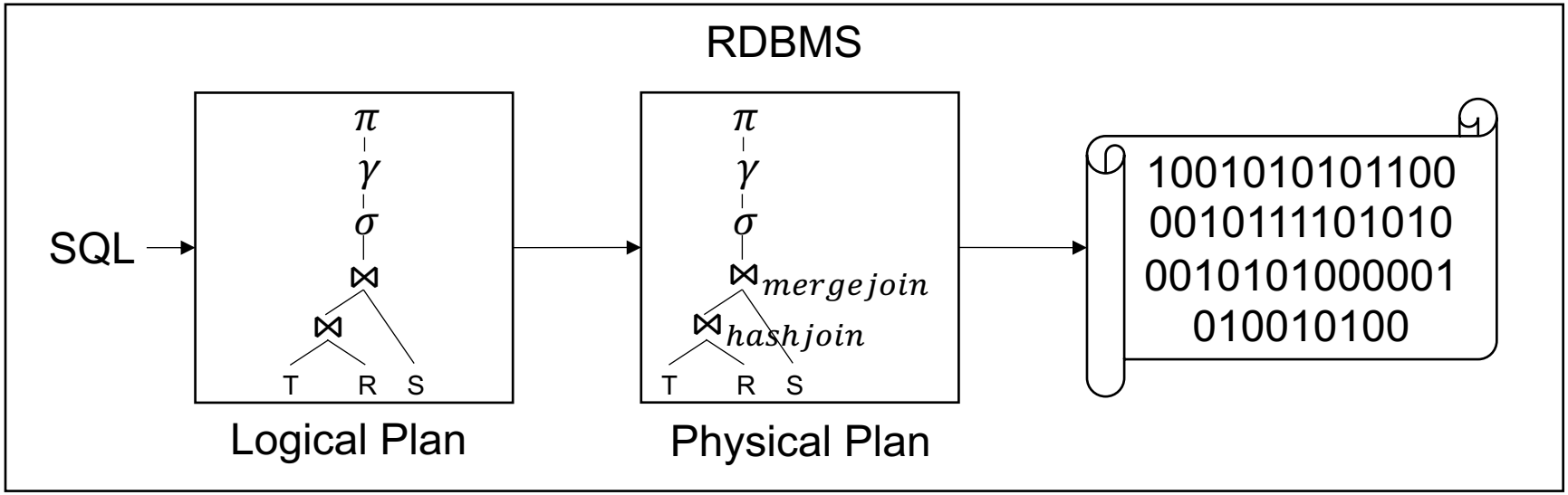


Plan Enumeration

RDBMS optimize by selecting the **least cost plan**

- SQL → RA
- RA → Set of equivalent RA
- Set of equivalent RA → Set of physical plans
- Set of physical plans → Least cost plan
- Execute least cost plan

Plan Enumeration

RDBMS

SQL

```
SELECT *
  FROM T, R, S
 WHERE …
```

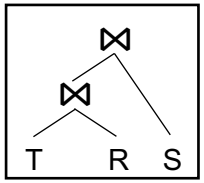
Plan Enumeration

RDBMS

SQL

```
SELECT *
  FROM T, R, S
 WHERE …
```

Logical Plan



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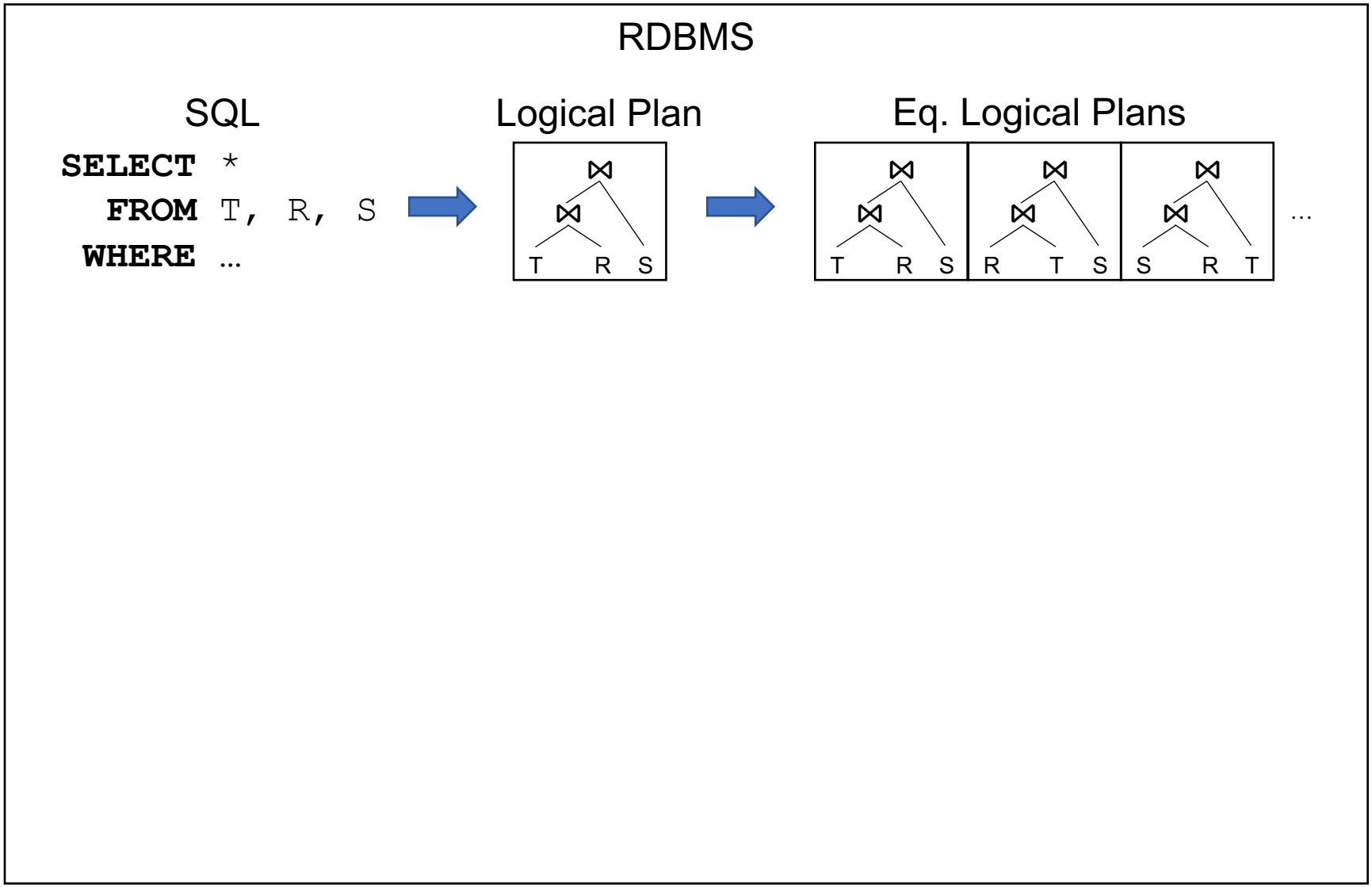

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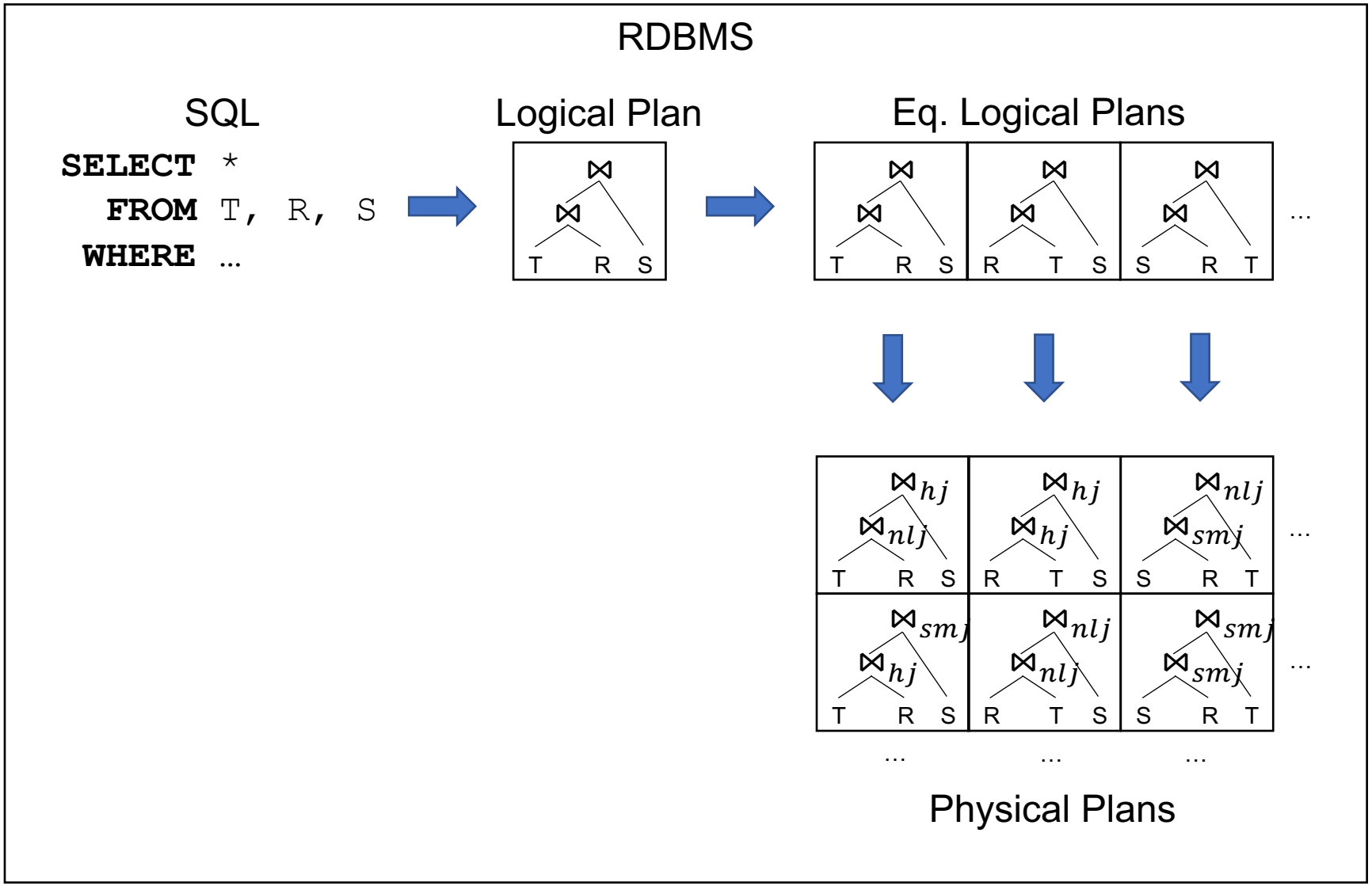

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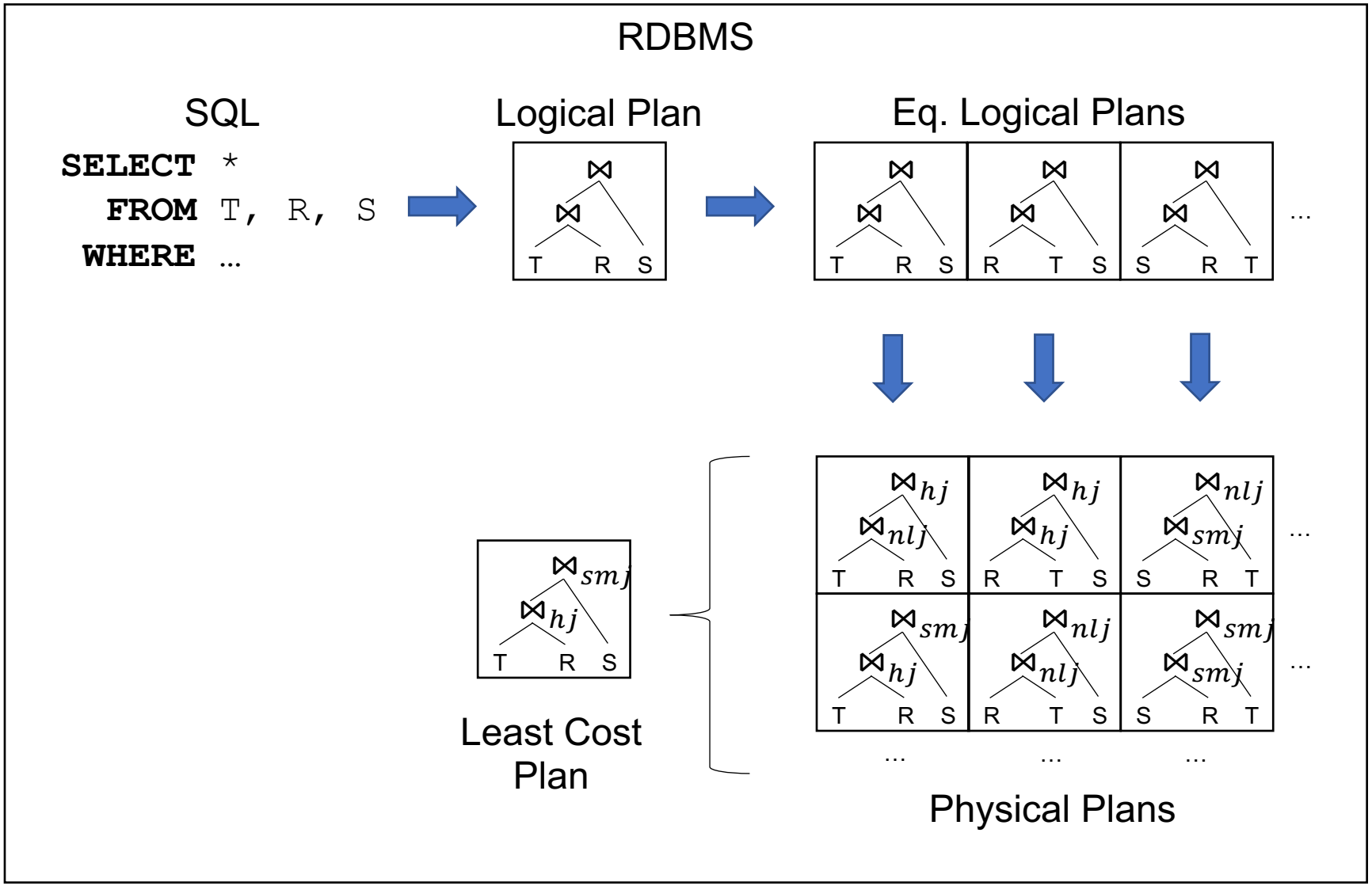

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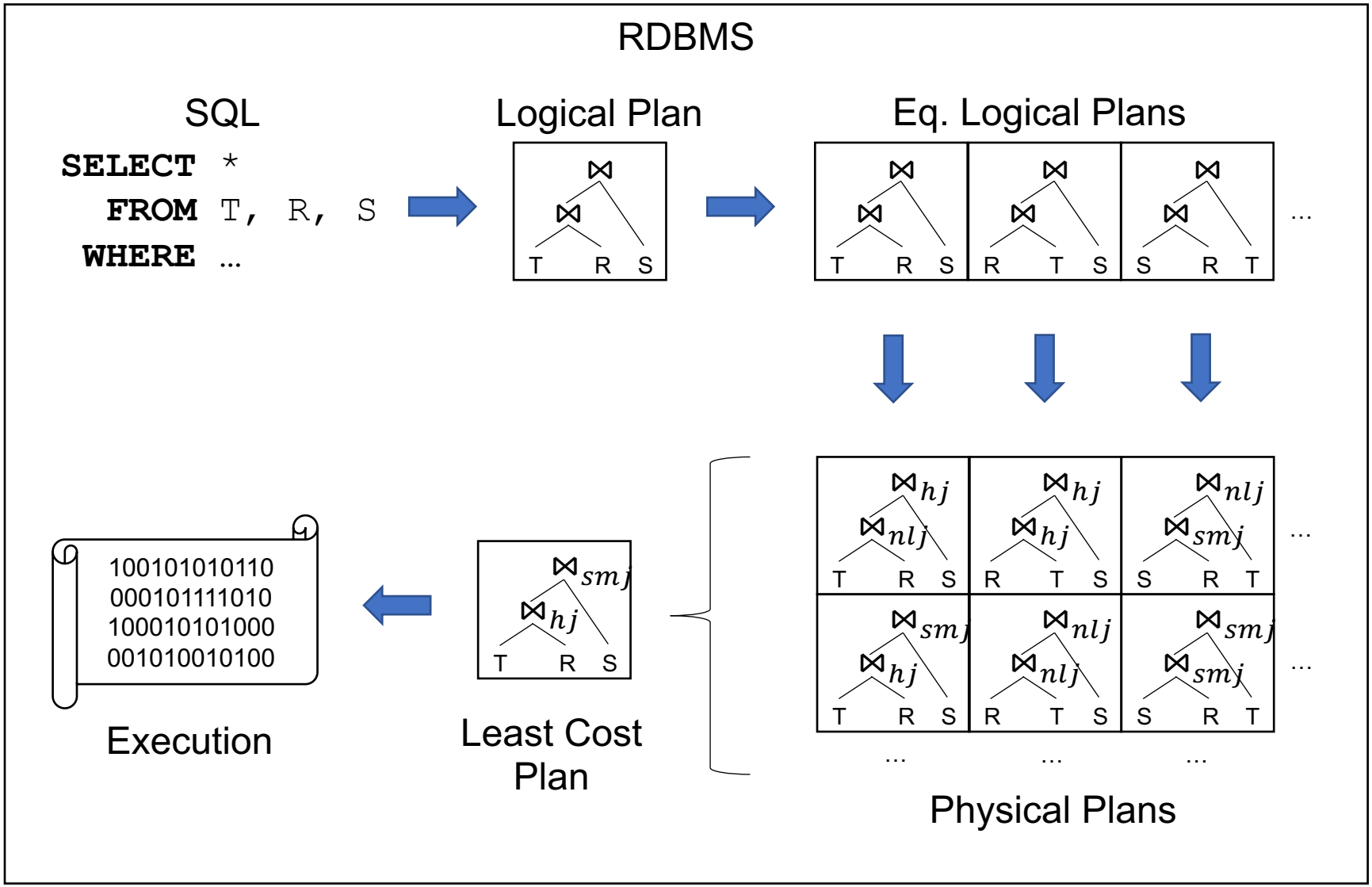

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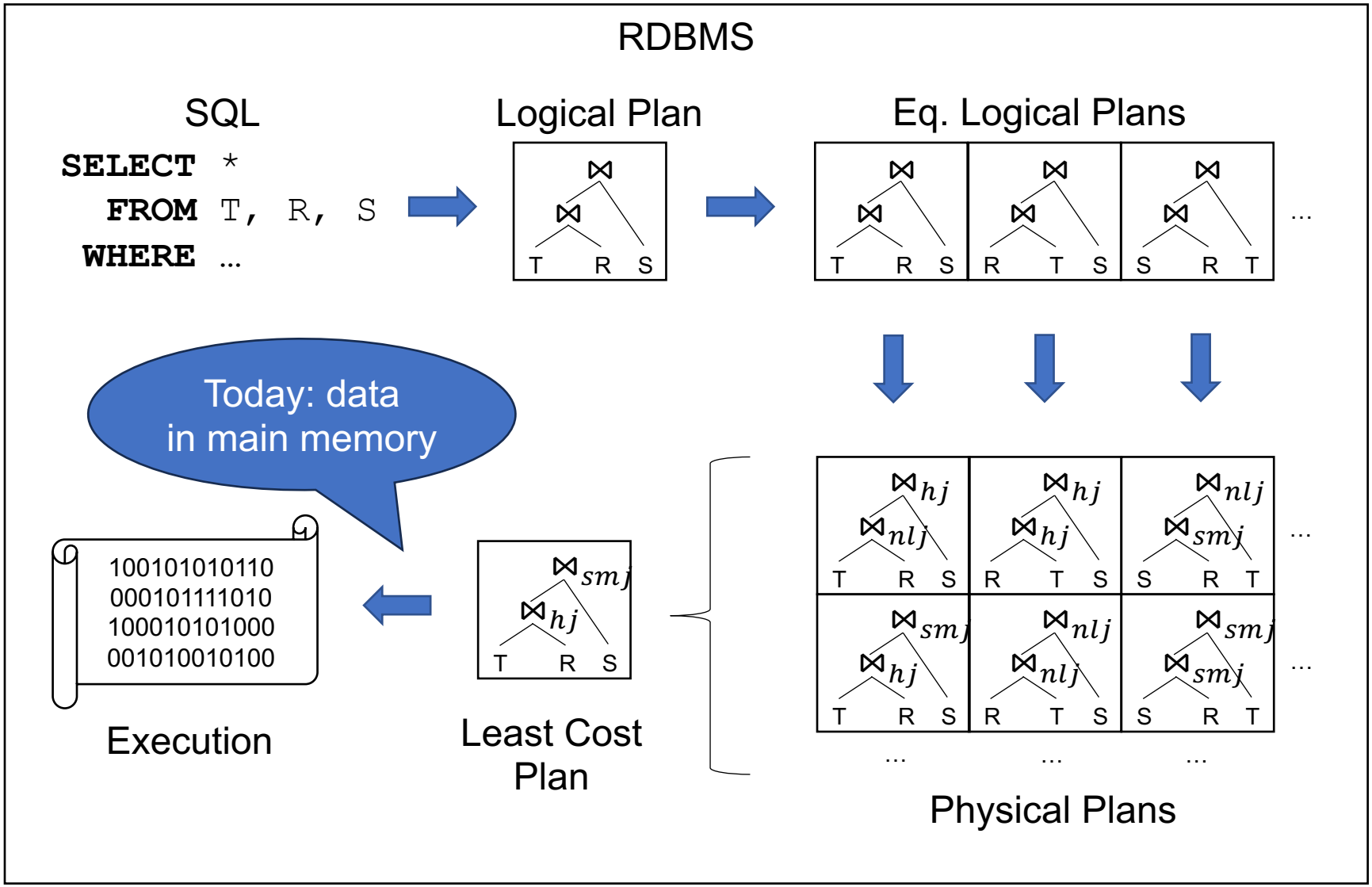

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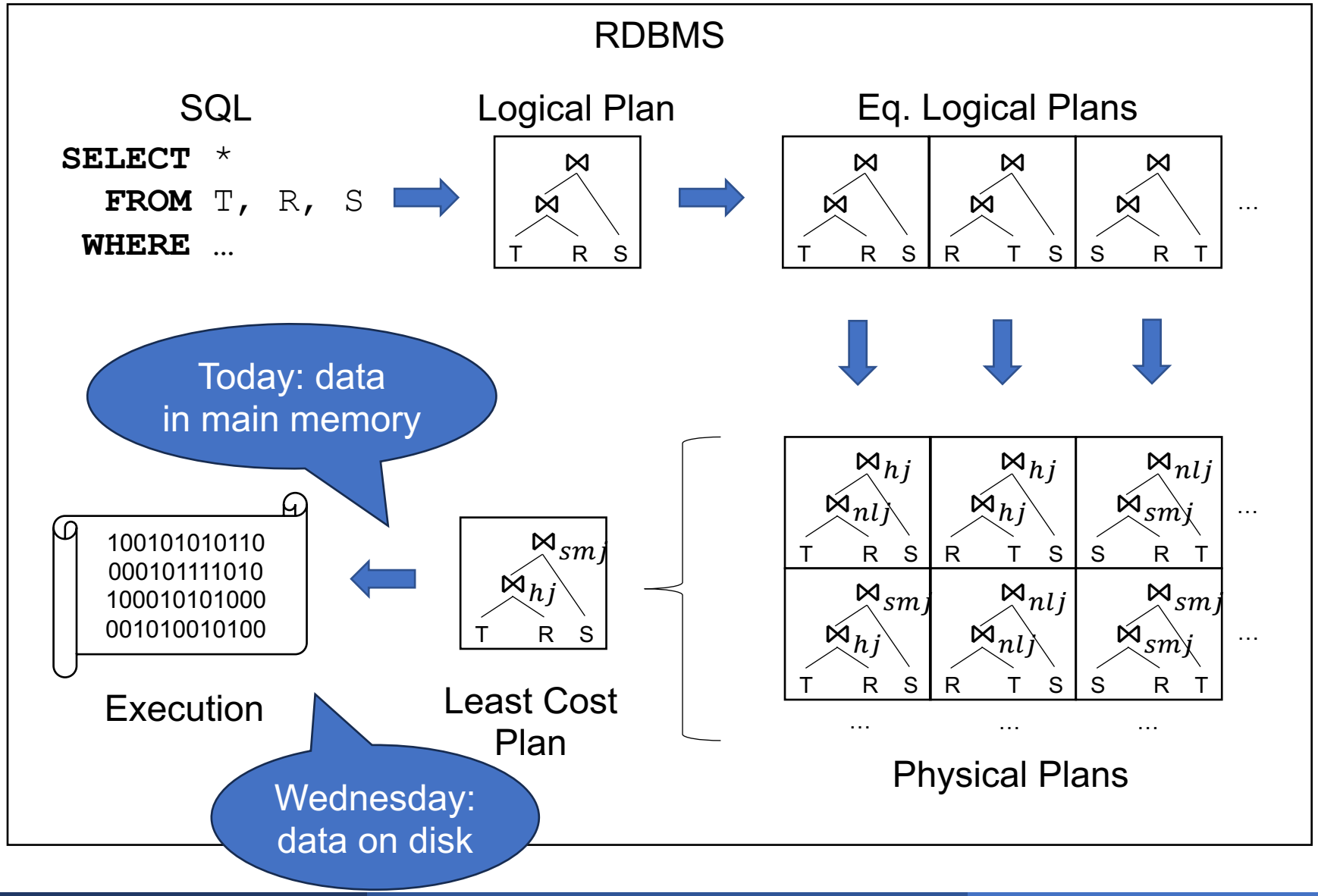
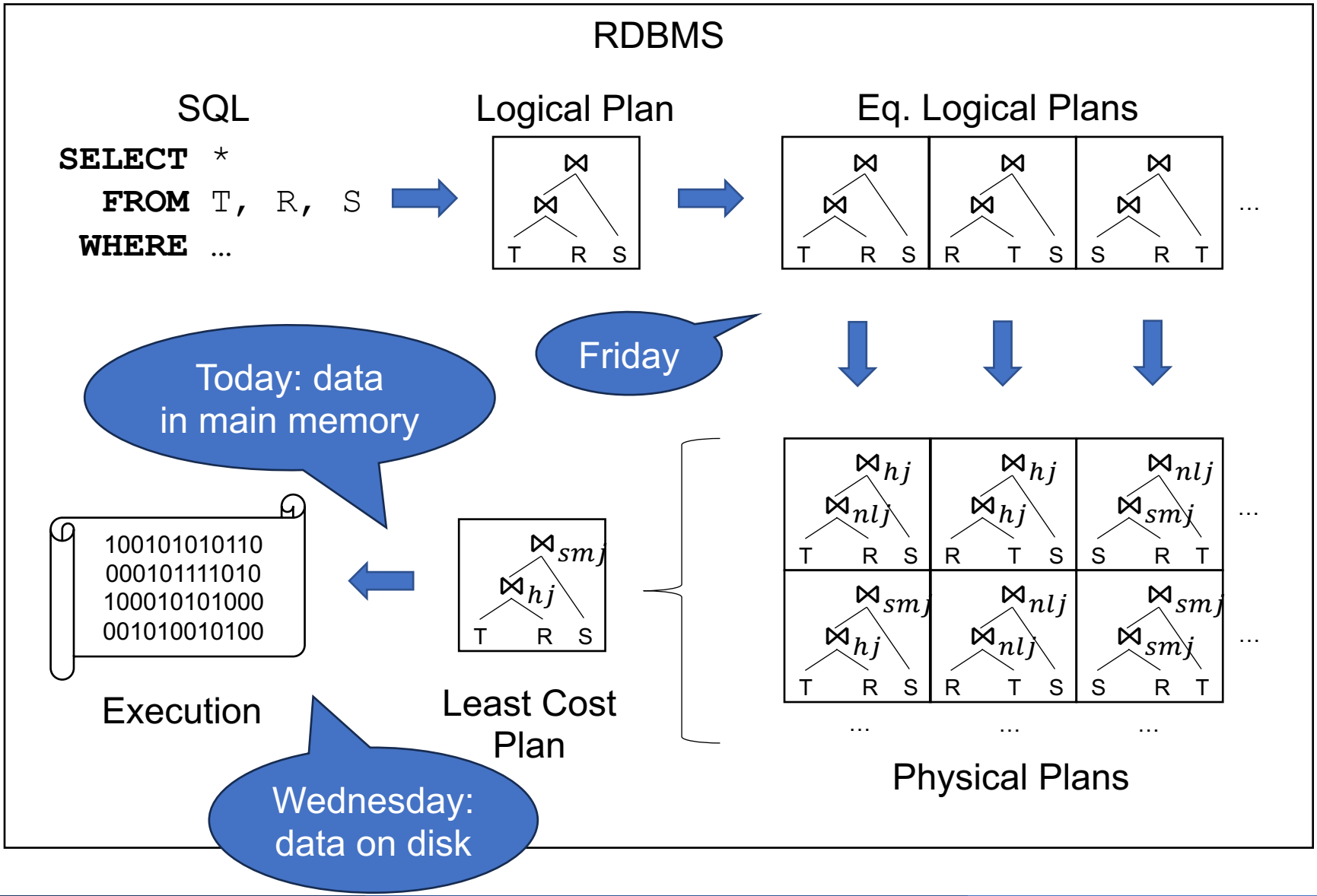


Plan Enumeration



Physical Operators

Physical Operators

- Relational Algebra consists of logical operators:
  - Selection, projection, join, union, group-by, …
- An algorithm for each is called a physical operator
  - Merge-join
  - Sort-based group-by
  - …
- Can be a main-memory, or disk-based algorithm

Join Algorithms

For each employee, find the cars that they drive

```
SELECT P.Name, R.Car
FROM Payroll AS P, Regist AS R
WHERE P.UserID = R.UserID;
```

Name	Car
Jack	Charger
Magda	Civic
Magda	Pinto

Payroll

UserID	Name	Job	Salary
123	Jack	TA	50000
345	Allison	TA	60000
567	Magda	Prof	90000
789	Dan	Prof	100000

Regist

UserID	Car
123	Charger
567	Civic
567	Pinto

Join Algorithms

$$\text{Payroll} \bowtie_{\text{UserID=UserID}} \text{Regist}$$

```
Payroll(UserID,Name,Job,Salary)
Regist(UserID,Car)
```

Join Algorithms

$$\text{Payroll} \bowtie_{\text{UserID=UserID}} \text{Regist}$$

```
Payroll(UserID,Name,Job,Salary)
Regist(UserID,Car)
```

How would you compute the join?

Join Algorithms

$$\text{Payroll} \bowtie_{\text{UserID=UserID}} \text{Regist}$$

```
Payroll(UserID,Name,Job,Salary)
Regist(UserID,Car)
```

How would you compute the join?

Three physical operators:

1. Nested Loops
2. Hash-join
3. Merge-join

Join Algorithms

$$\text{Payroll} \bowtie_{\text{UserID=UserID}} \text{Regist}$$

Outer table

Inner table

```
Payroll(UserID,Name,Job,Salary)
Regist(UserID,Car)
```

How would you compute the join?

Three physical operators:

1. Nested Loops
2. Hash-join
3. Merge-join

1. Nested-Loop Join

1. Nested Loop Join

$$\text{Payroll} \bowtie_{\text{UserID=UserID}} \text{Regist}$$

```
Payroll(UserID,Name,Job,Salary)
Regist(UserID,Car)
```

```
for x in Payroll
  for y in Regist
    if x.UserID = y.UserID
       output(x,y)
```

1. Nested Loop Join

$$\text{Payroll} \bowtie_{\text{UserID=UserID}} \text{Regist}$$

```
Payroll(UserID,Name,Job,Salary)
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If |Payroll| = |Regist| = n, what is the runtime?

1. Nested Loop Join

$$\text{Payroll} \bowtie_{\text{UserID=UserID}} \text{Regist}$$

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Payroll(UserID,Name,Job,Salary)
Regist(UserID,Car)
```

```
for x in Payroll
  for y in Regist
    if x.UserID = y.UserID
       output(x,y)
```

If |Payroll| = |Regist| = n, what is the runtime?

Runtime = $O(n^2)$

Discussion

- Nested loop join: simplest implementation of join
- Works reasonably well when relation1 << relation2
  - O(mn) → O(n) when m << n
- Variations/improvements:
  - Index join: we have an index on inner table (later)
  - Block nested loop join (for data stored on disk)
- Before hash-join and merge-join: a quick review…

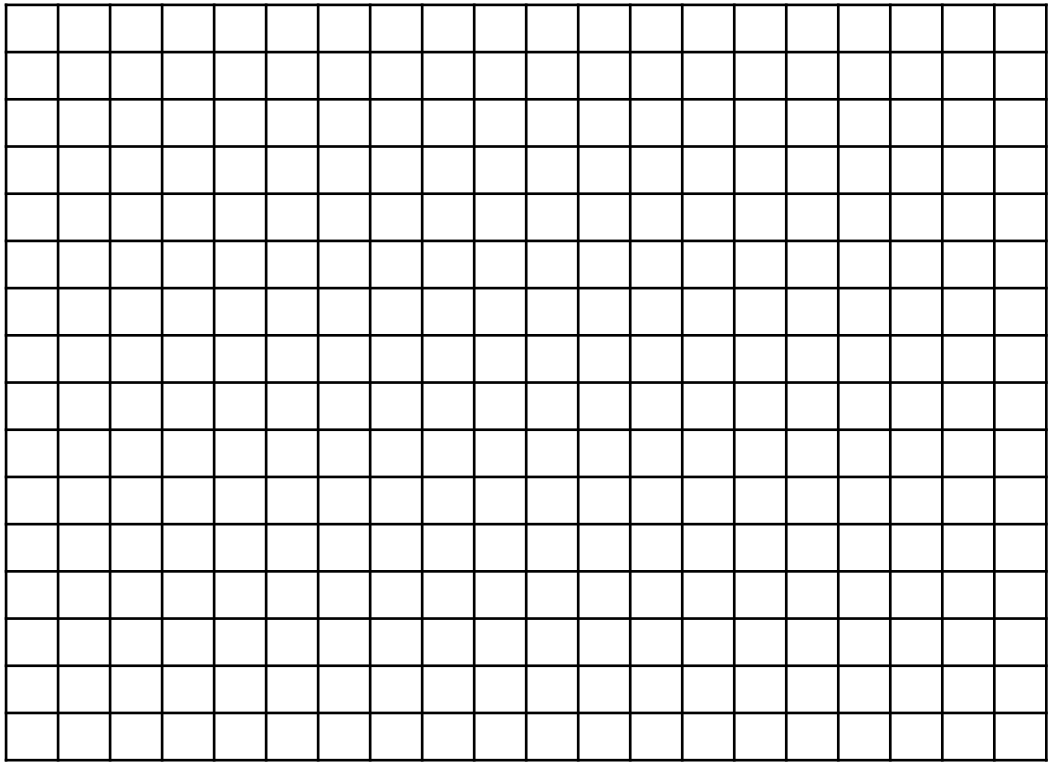
Review: Hash Tables, Sorting

How the Main Memory Works

Disk

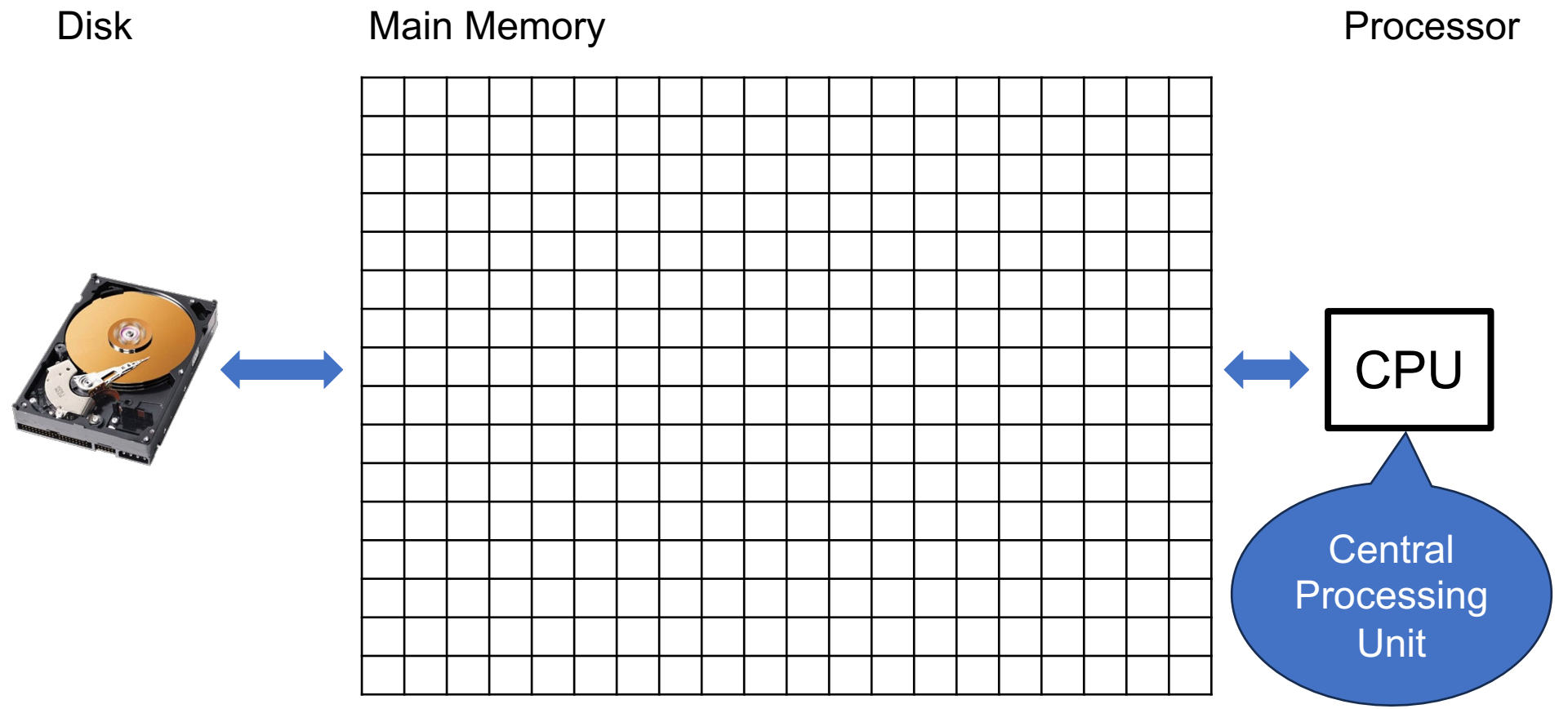
Main Memory

Processor



CPU

How the Main Memory Works



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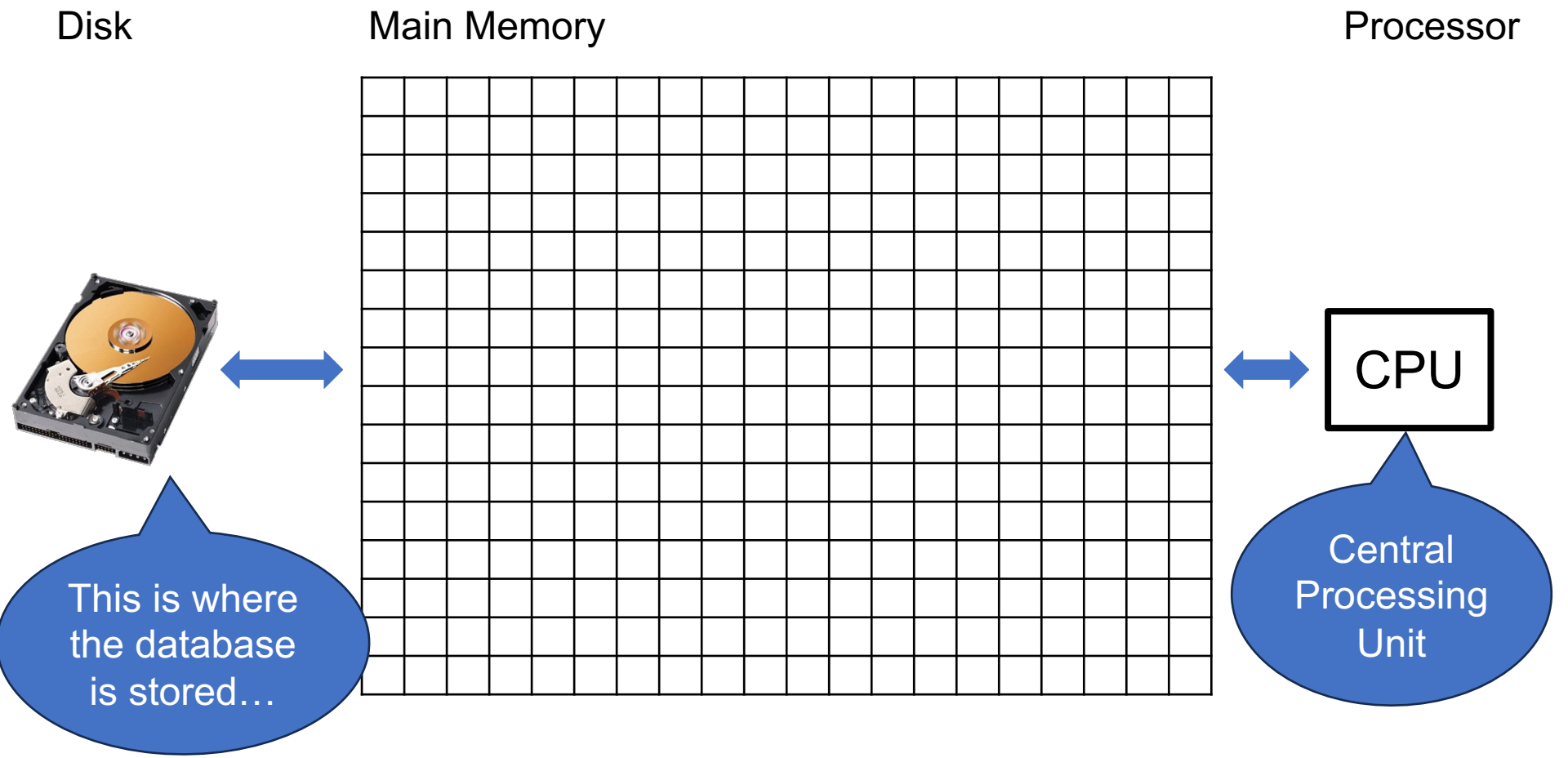

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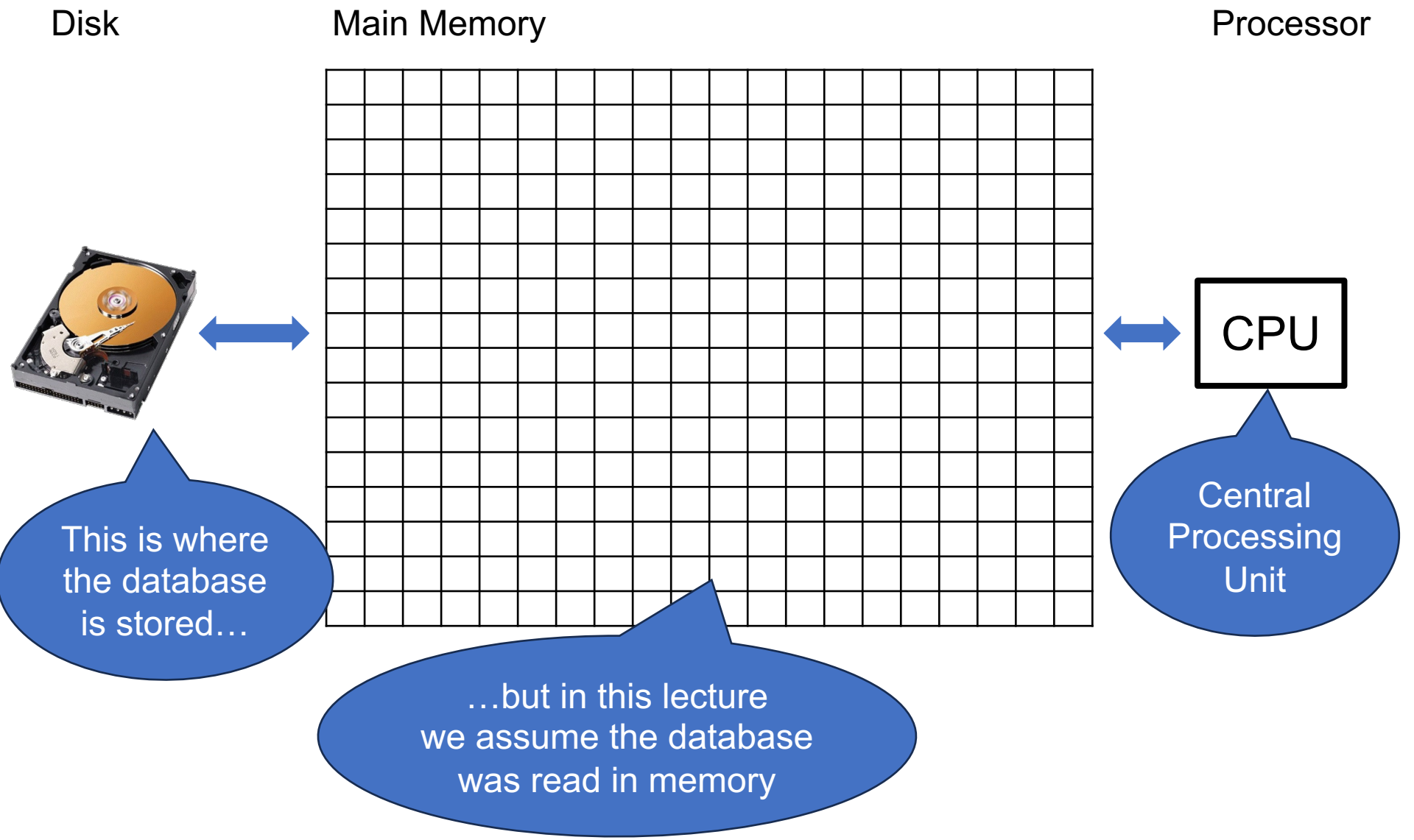

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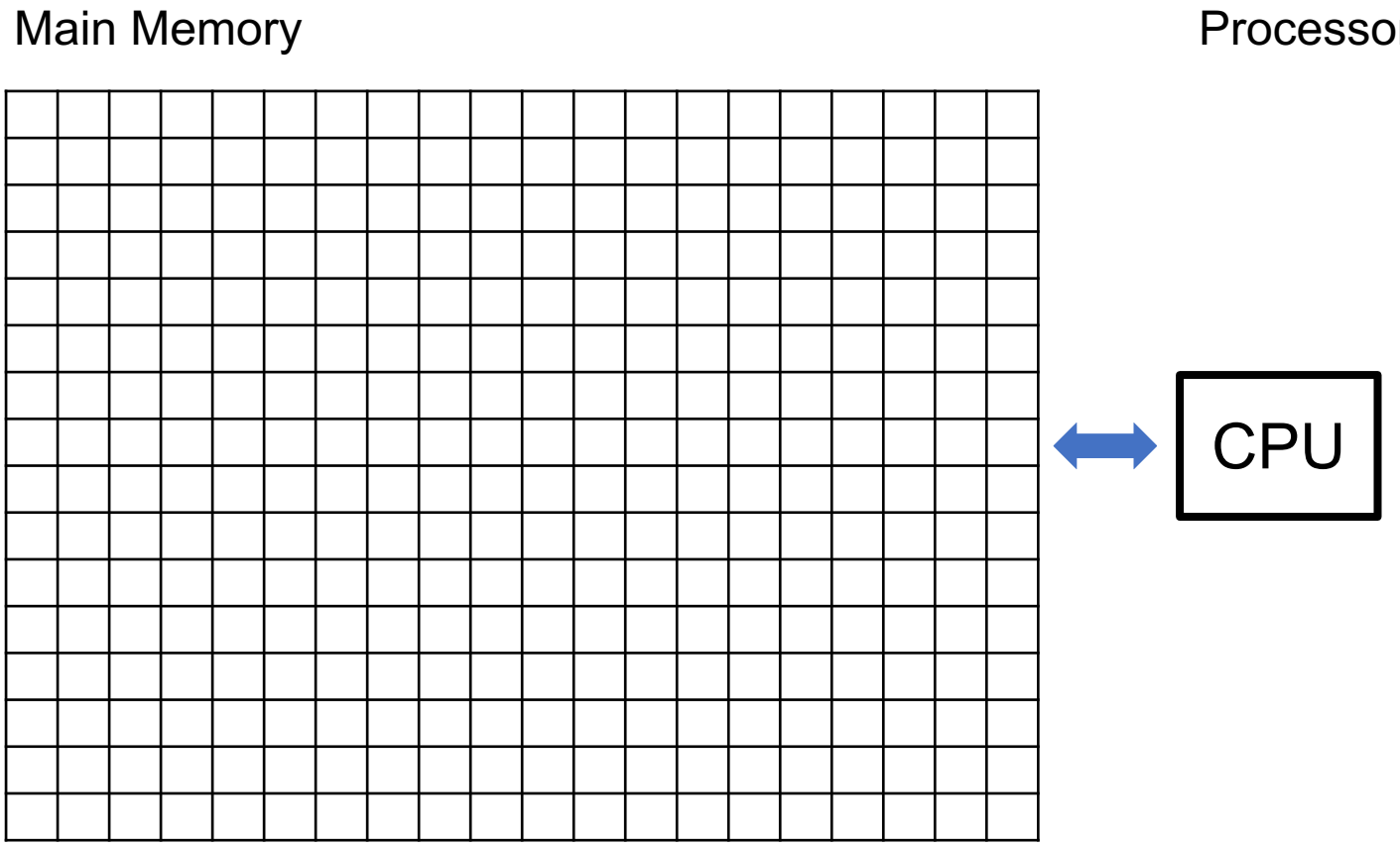

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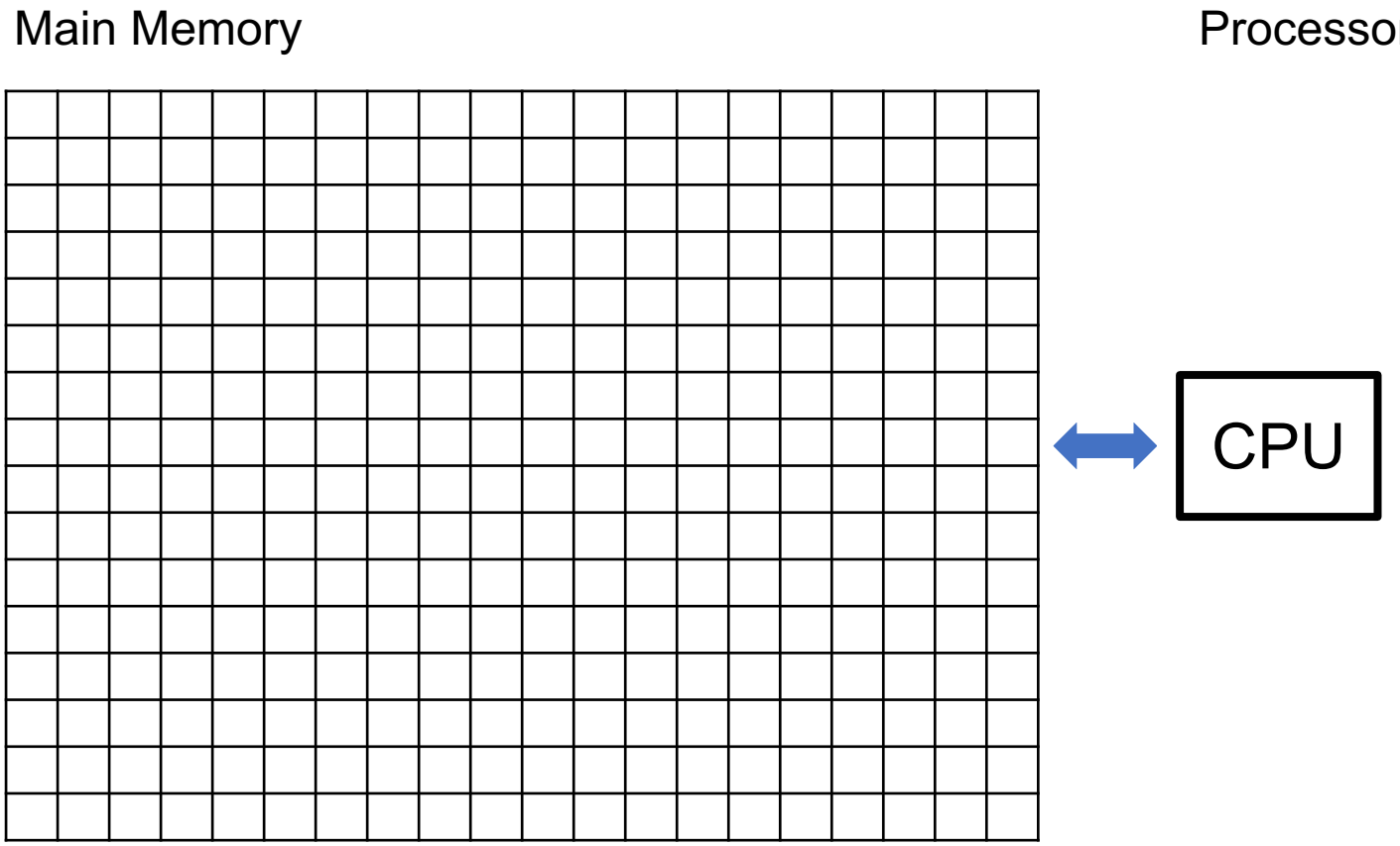
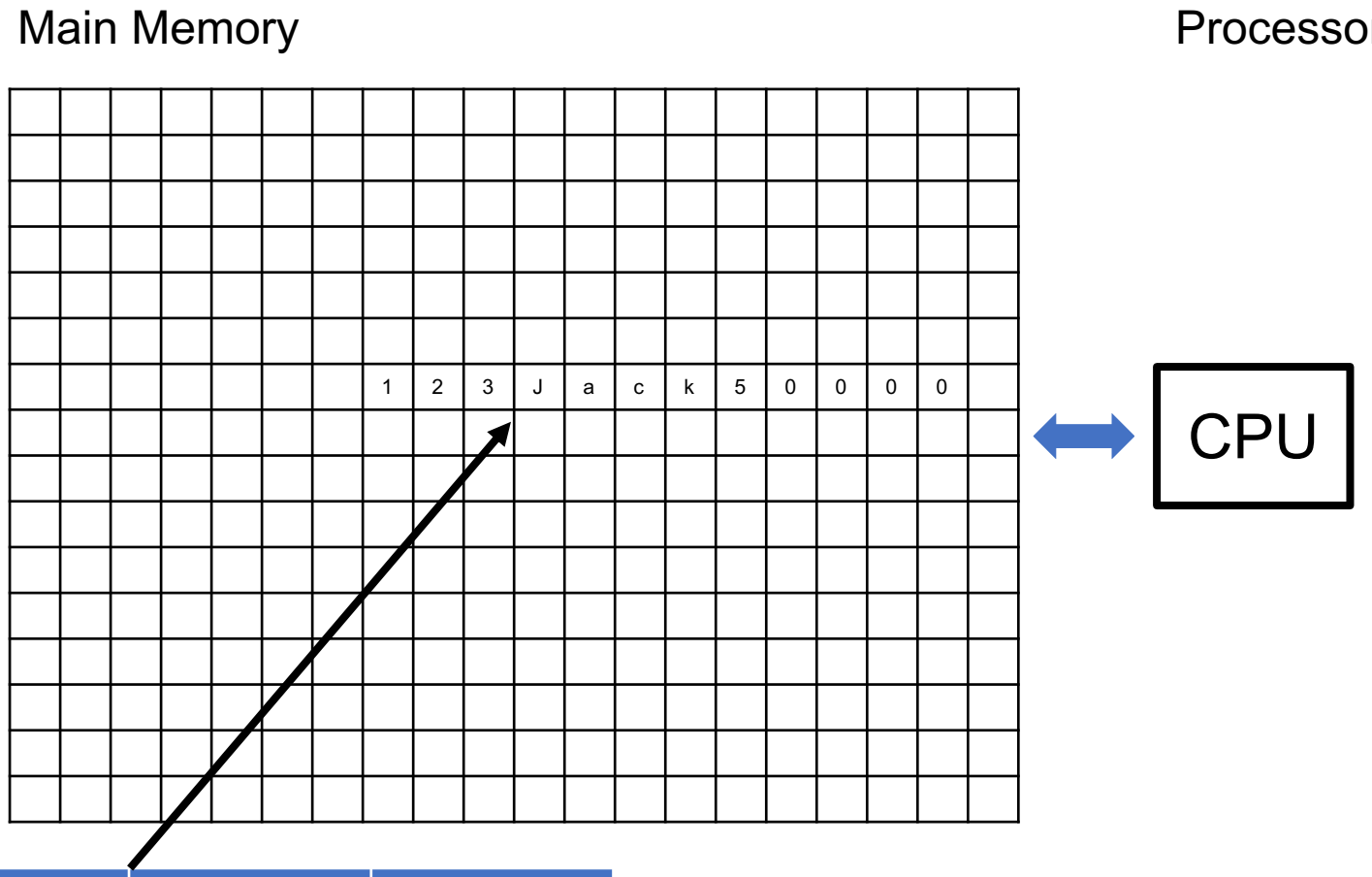


UserID	Name	Job	Salary
123	Jack	TA	50000
	…		

How the Main Memory Works



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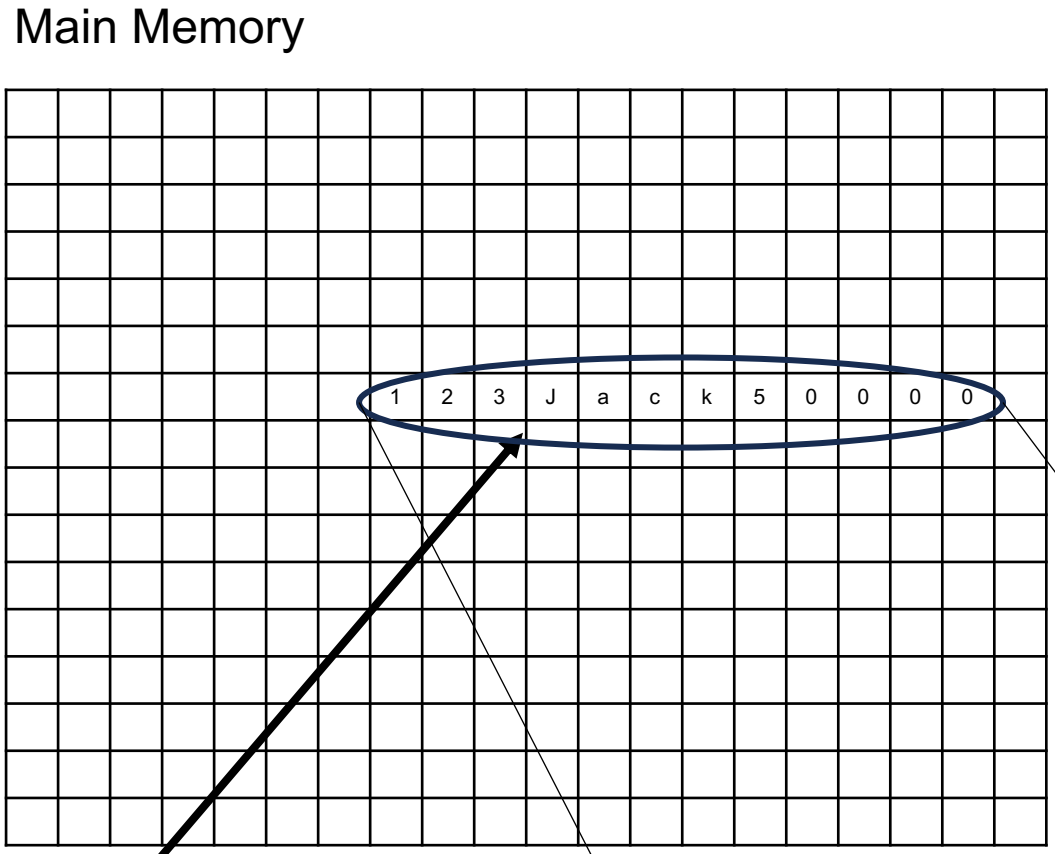
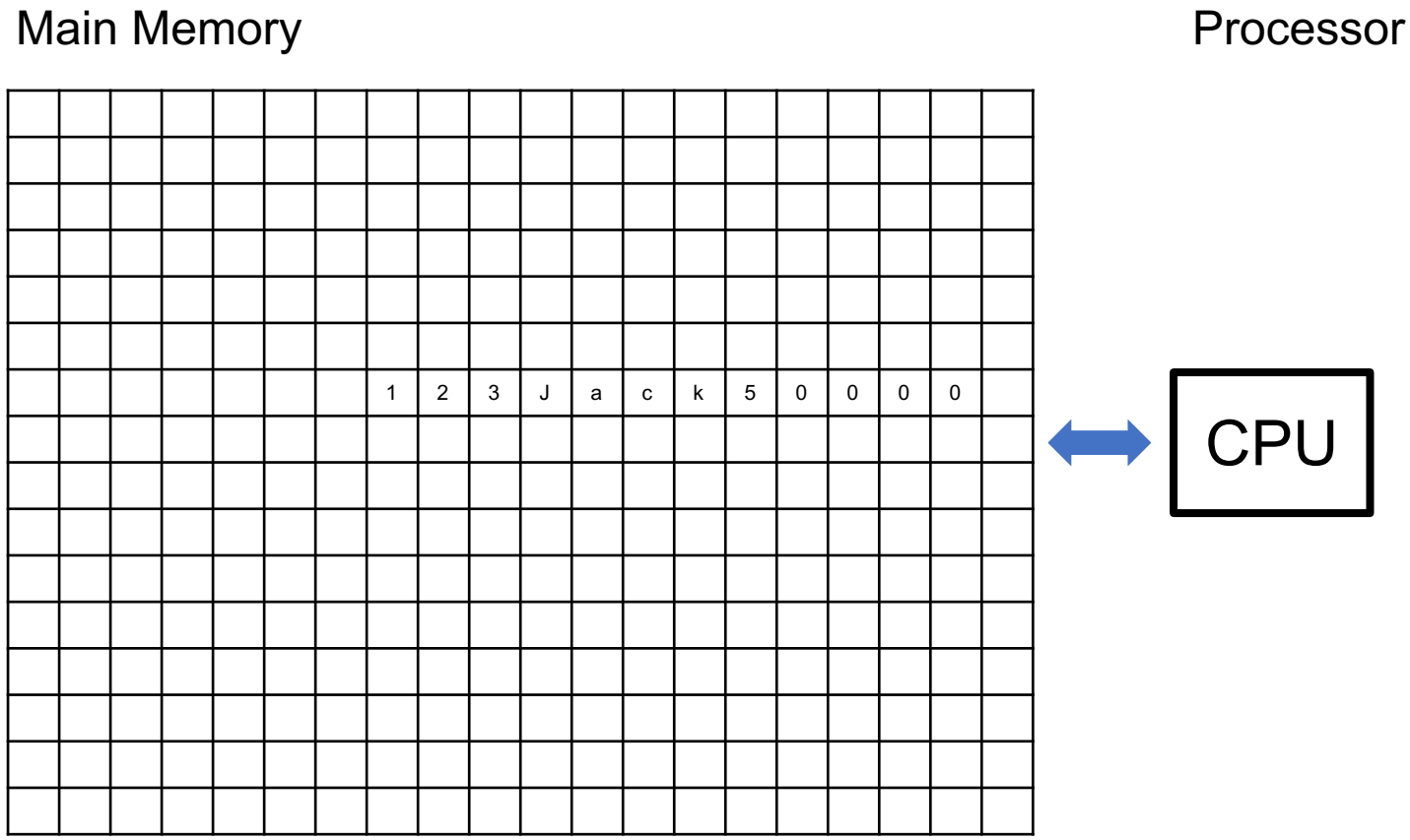


UserID	Name	Job	Salary
123	Jack	TA	50000
	…		

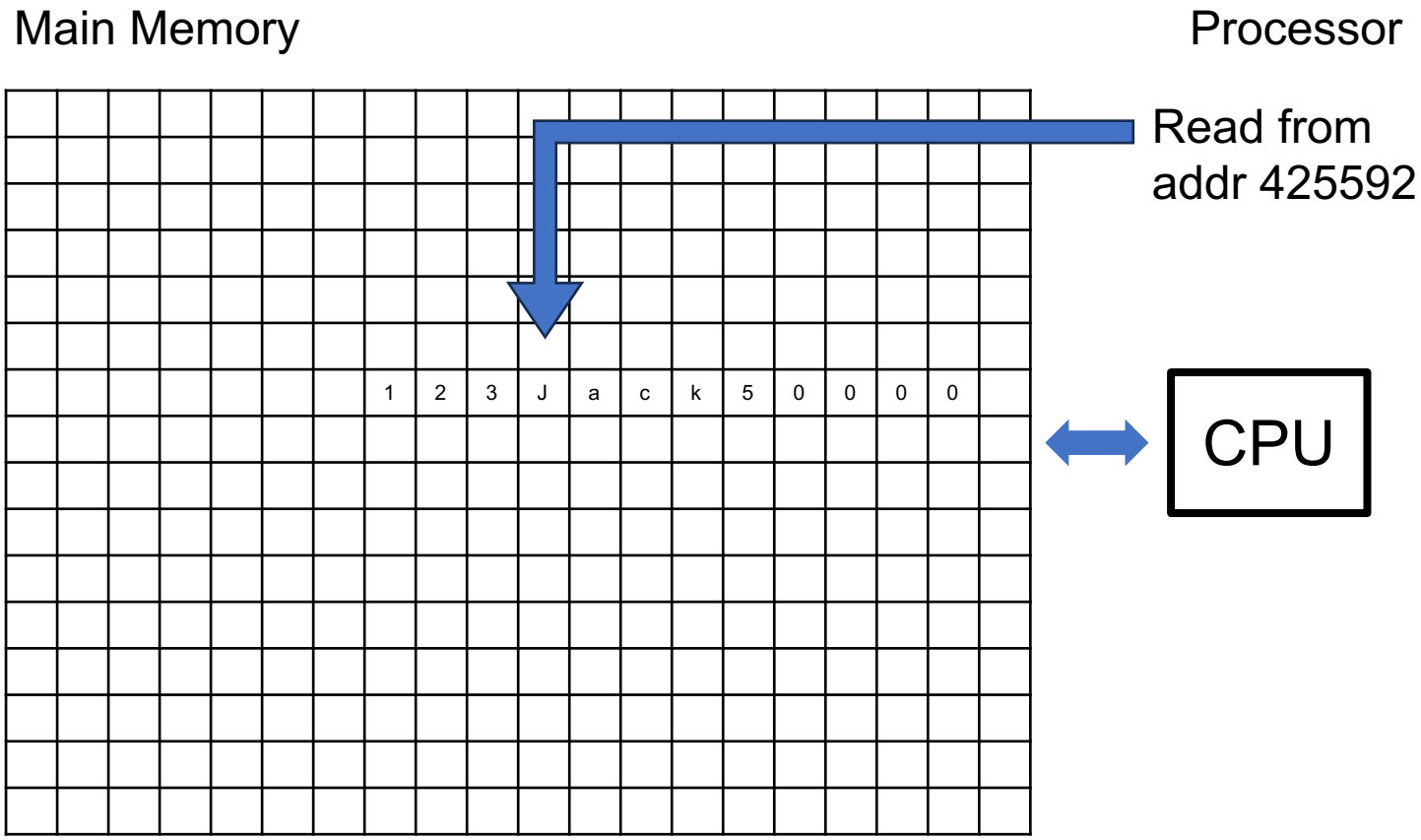
1	2	3	J	a	c	k	5	0	0	0	0

How the Main Memory Works



To read from Main Memory, the CPU needs to know the address

How the Main Memory Works



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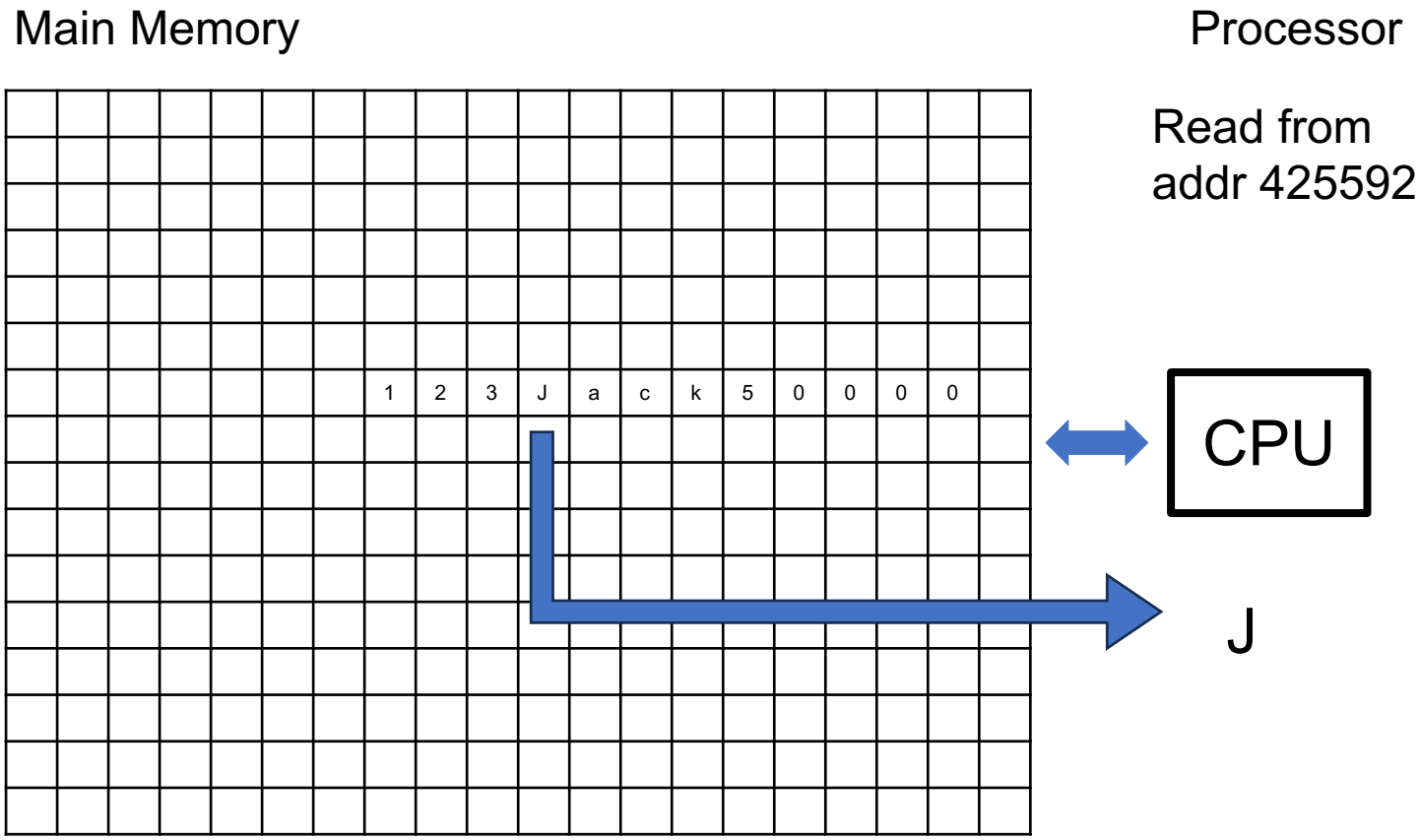

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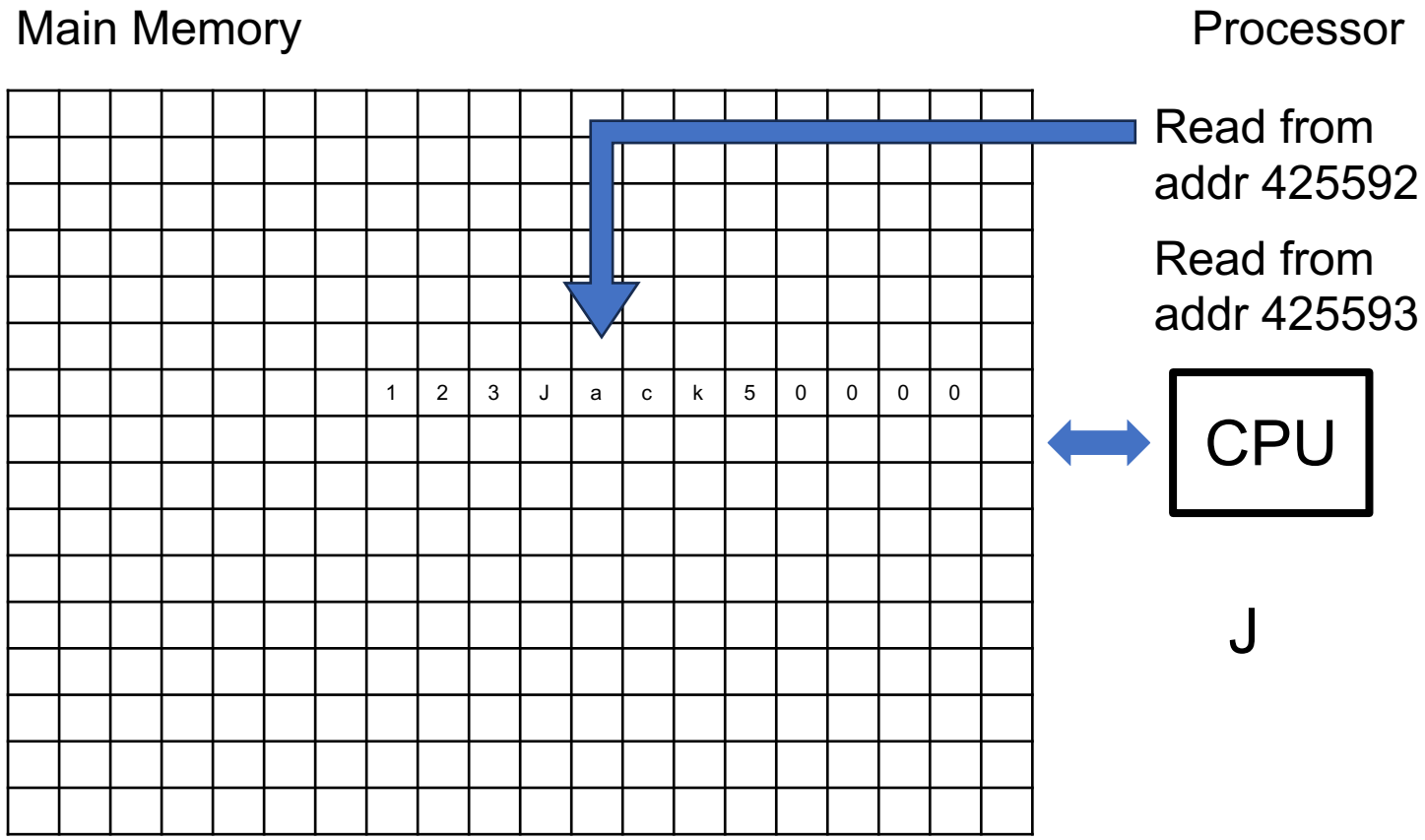

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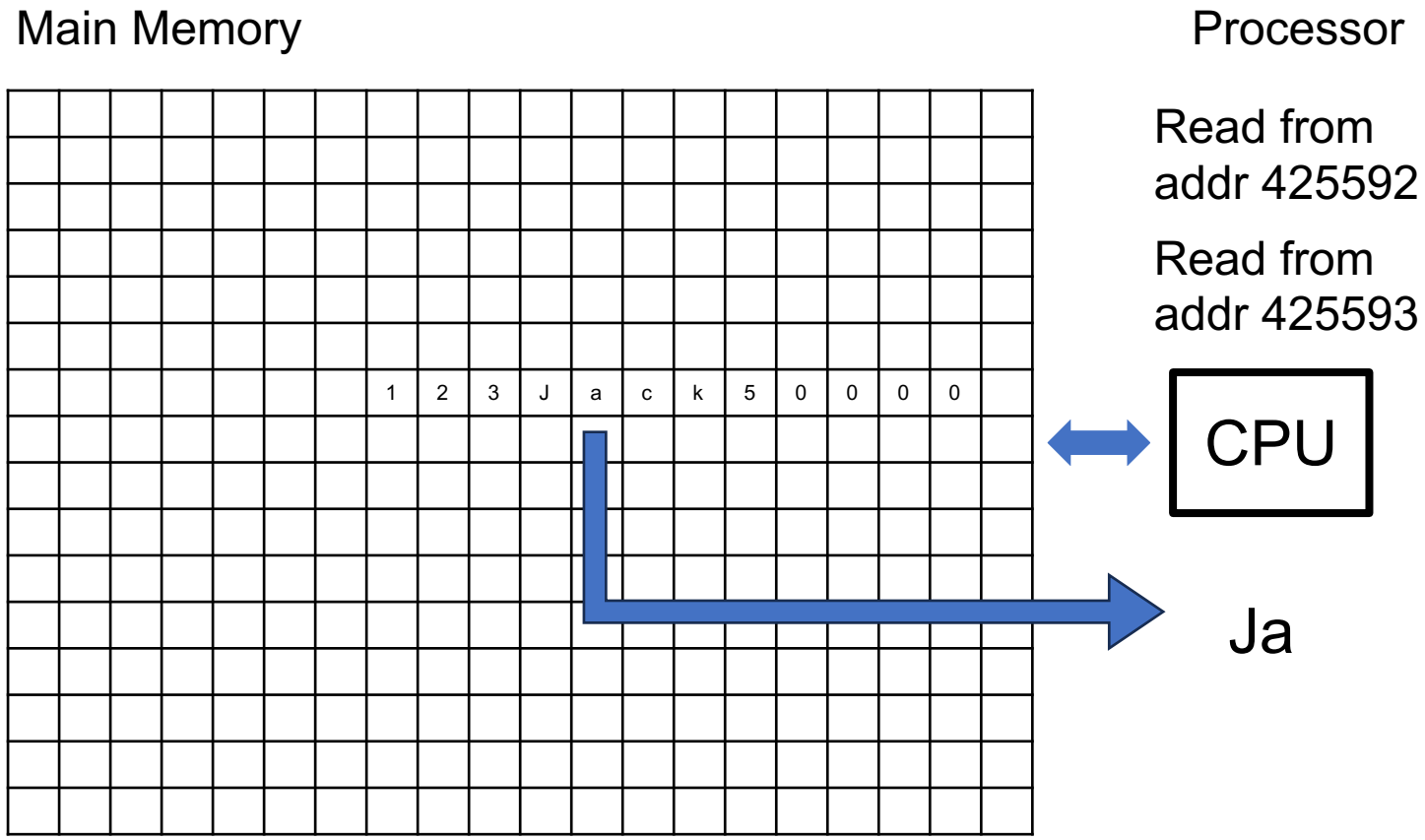

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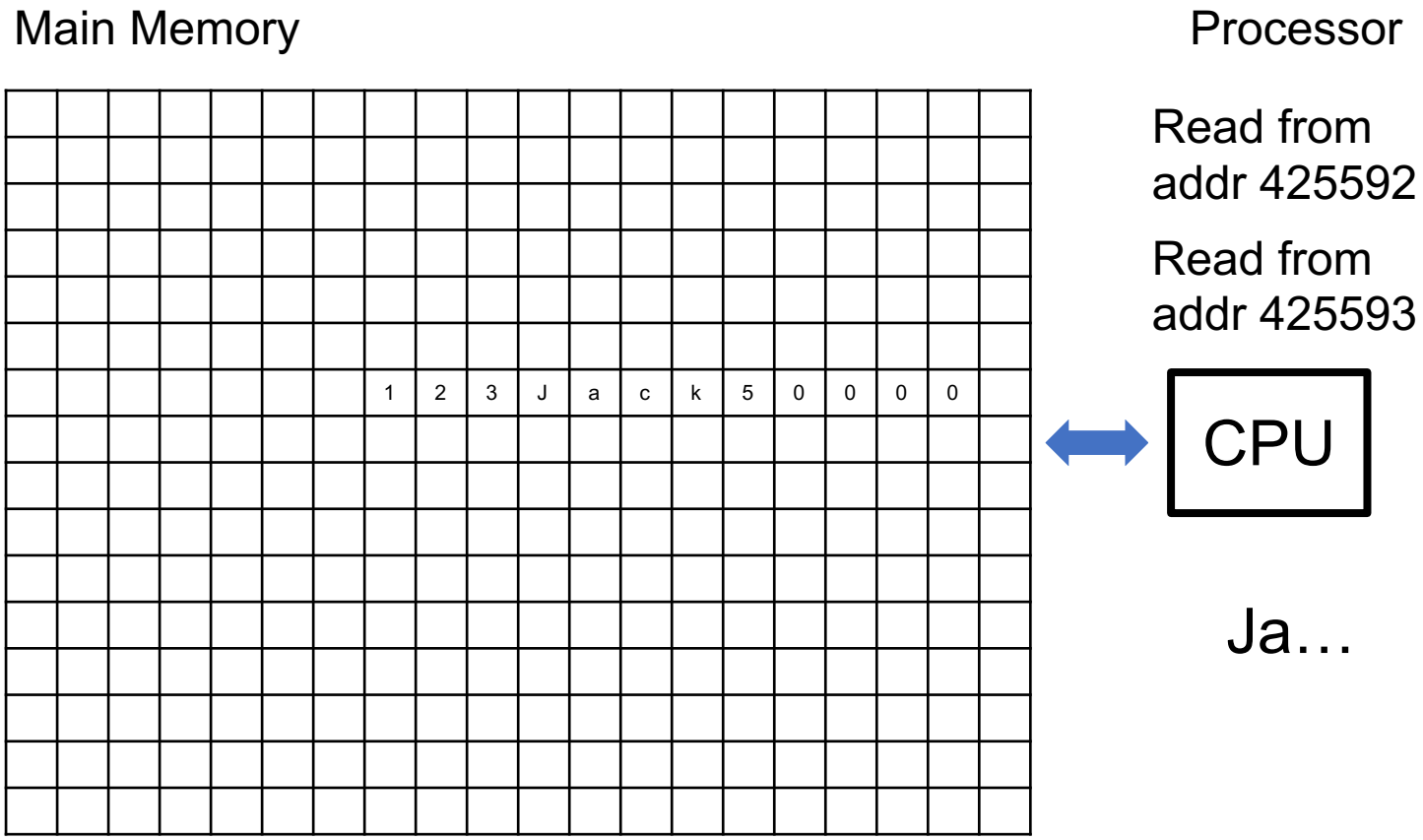

To read from Main Memory, the CPU needs to know the address

Hash Tables

Array: map indices to memory locations

- A[0], A[1], A[2], … sequential in memory
- To read A[5262]: read from [address of A] + 5262

Hash Tables

Array: map indices to memory locations

- A[0], A[1], A[2], … sequential in memory
- To read A[5262]: read from [address of A] + 5262

How to map strings to memory locations?

- A[“alice”], A[“bob”],A[“carl”]…???
- How do we read A[“jack”]?

Hash Tables

Array: map indices to memory locations

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How to map strings to memory locations?

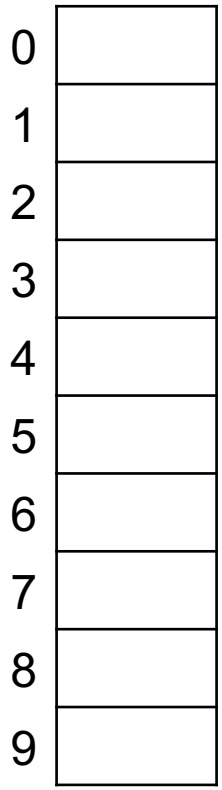
- A[“alice”], A[“bob”],A[“carl”]…???
- How do we read A[“jack”]?

Hash table: simulates an array indexed by strings

Hash Tables

A (naïve!!) hash function:

h(“abc”) = (‘a’+’b’+’c’) mod 10



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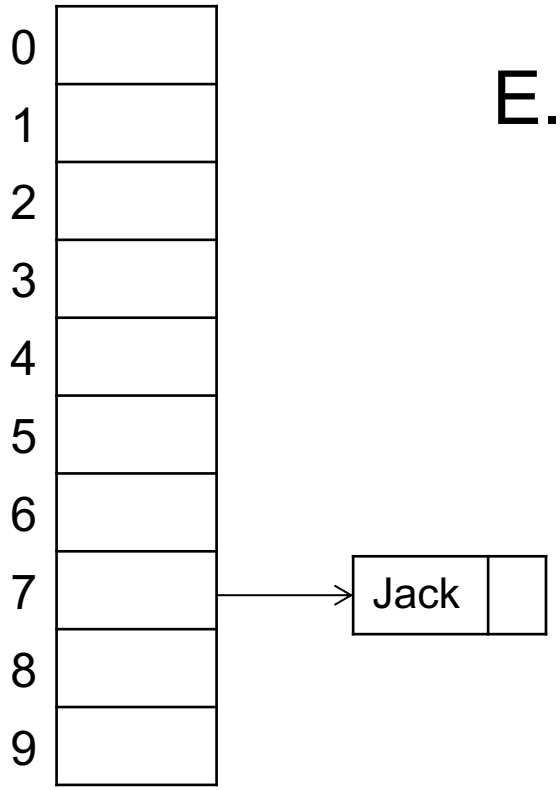

E.g. h(“Jack”) = (‘J’+’a’+’c’+’k’) mod 10
= (74+97+99+107) mod 10
= 377 mod 10 = 7

Hash Tables

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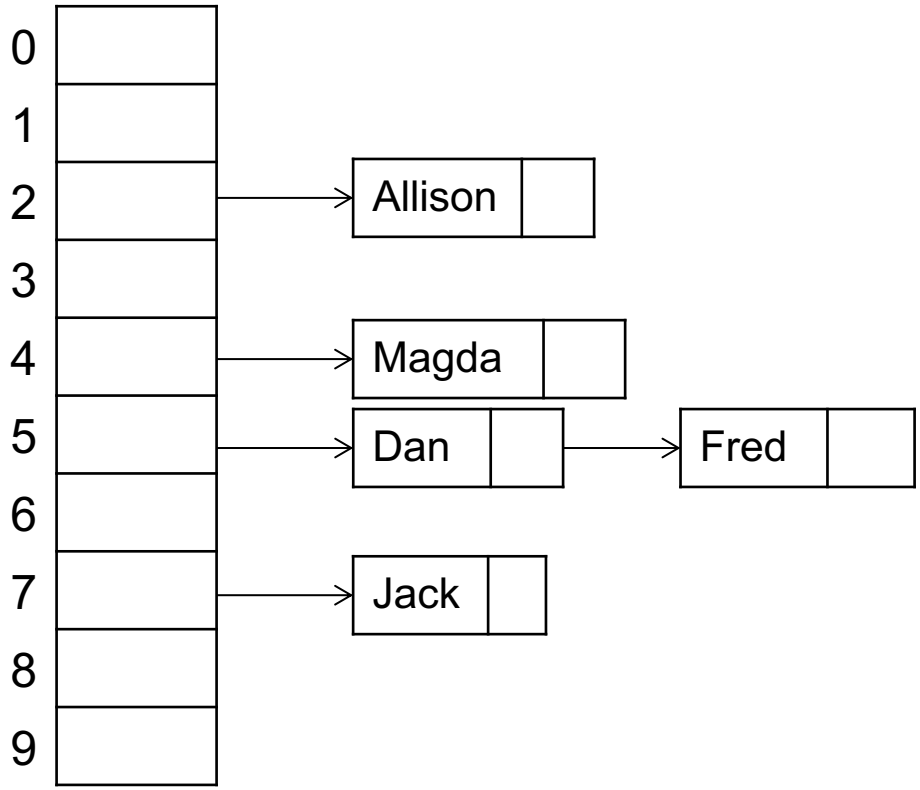

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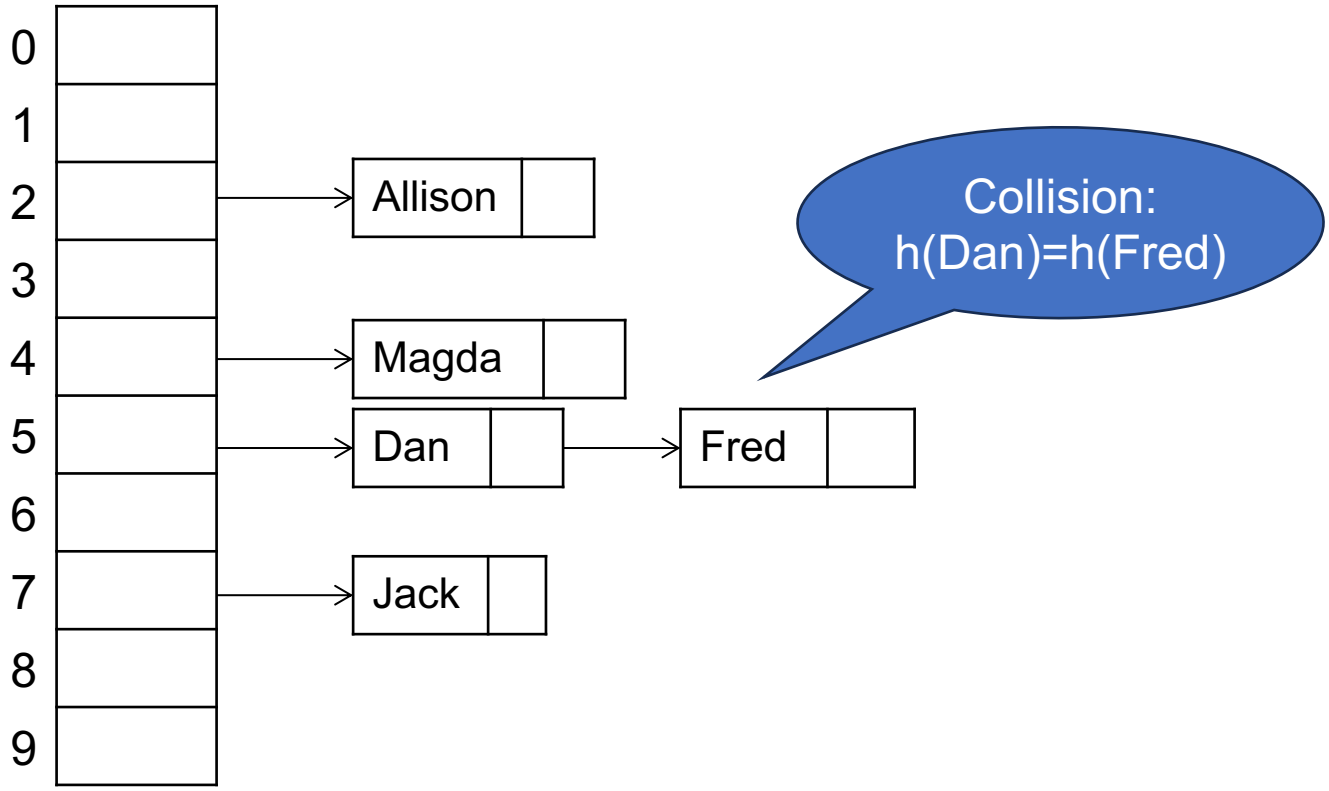

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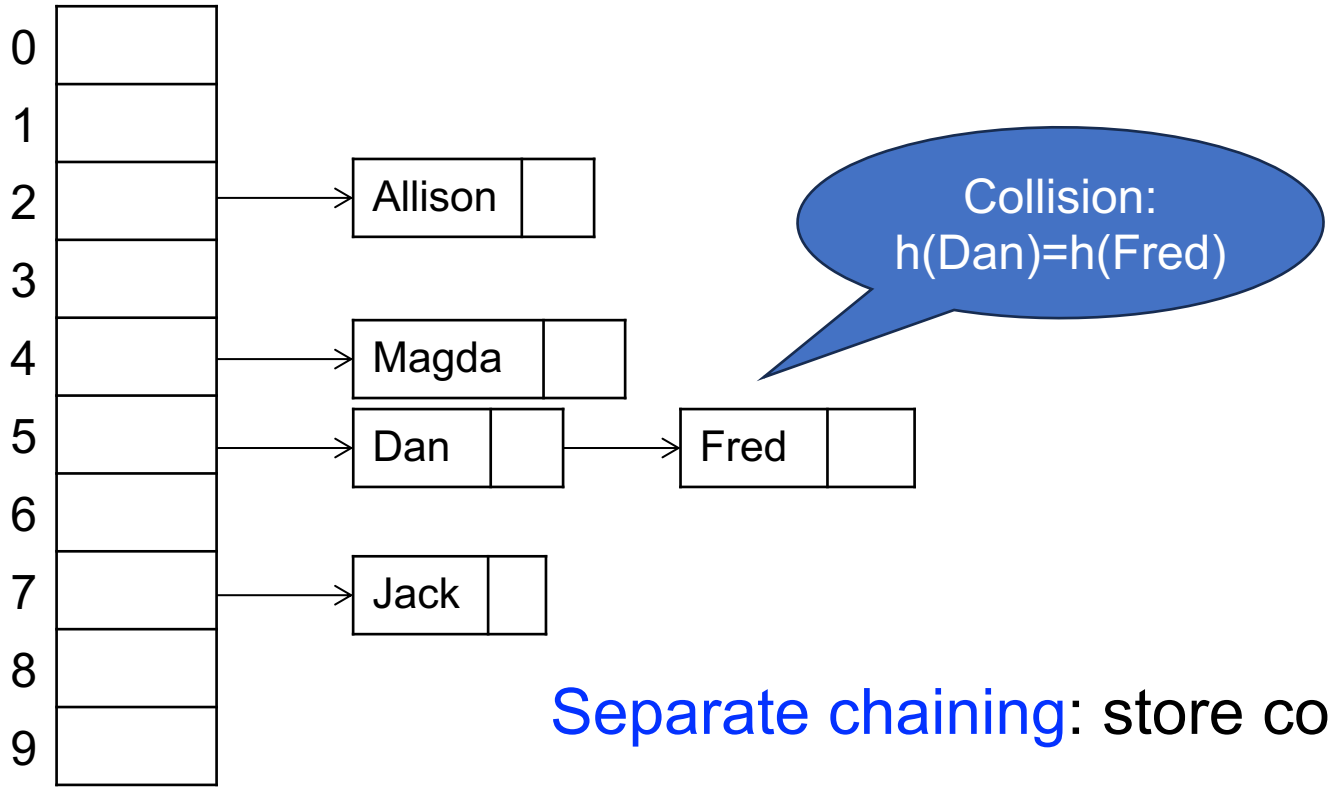

Separate chaining: store collisions in a list

Hash Tables

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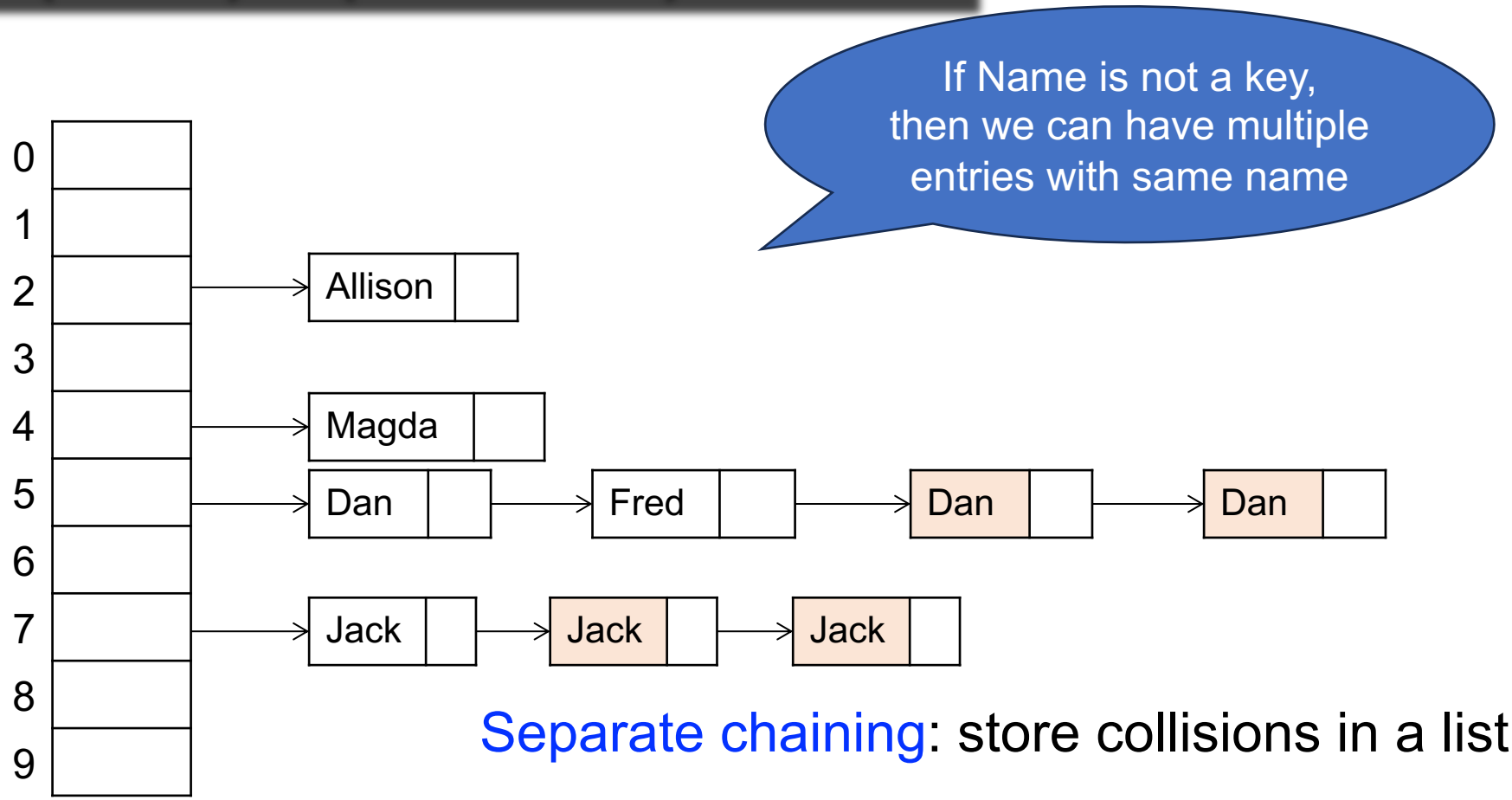

Separate chaining: store collisions in a list

Hash Tables

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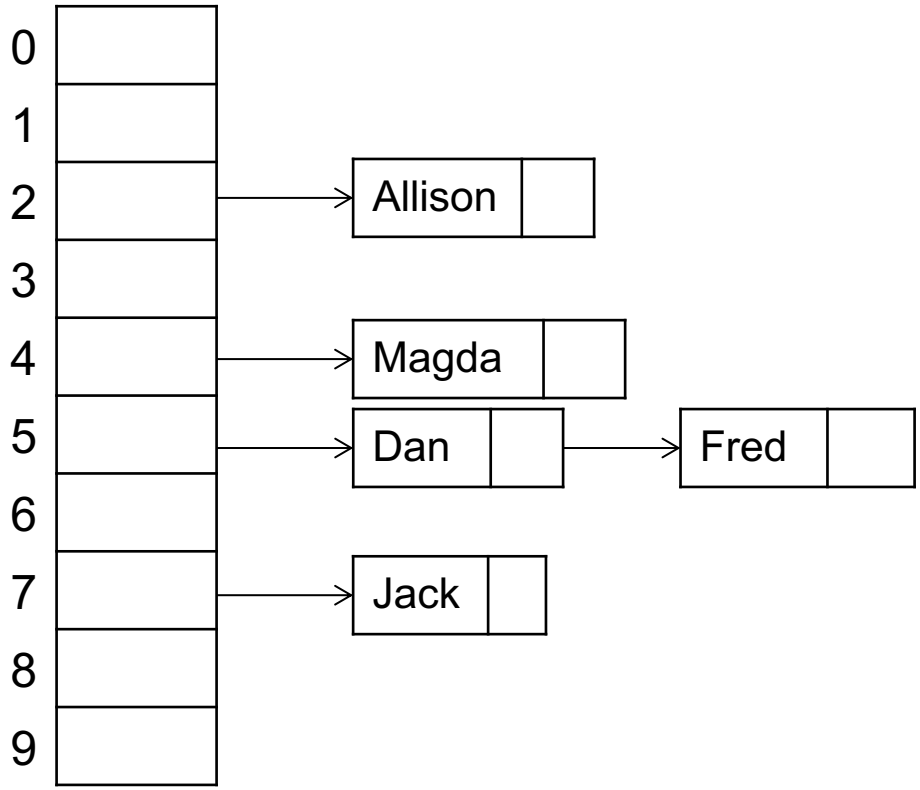
h(“abc”) = (‘a’+’b’+’c’) mod 10

find(“Magda”)



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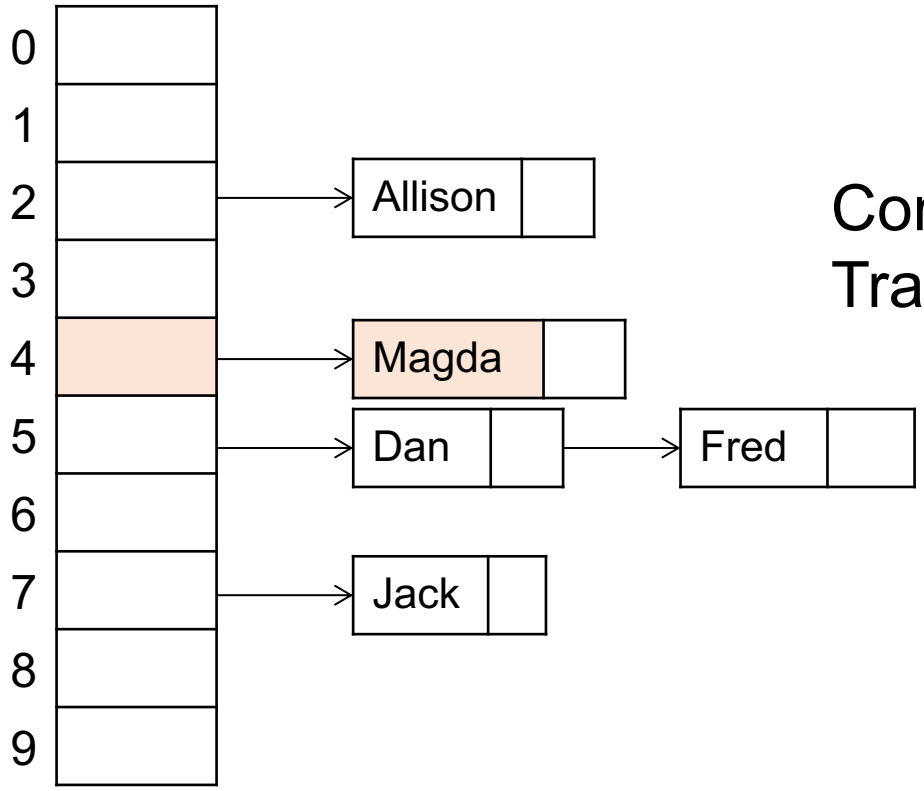

Compute h(“Magda”)=4
Traverse the short list at offset 4

Hash Tables

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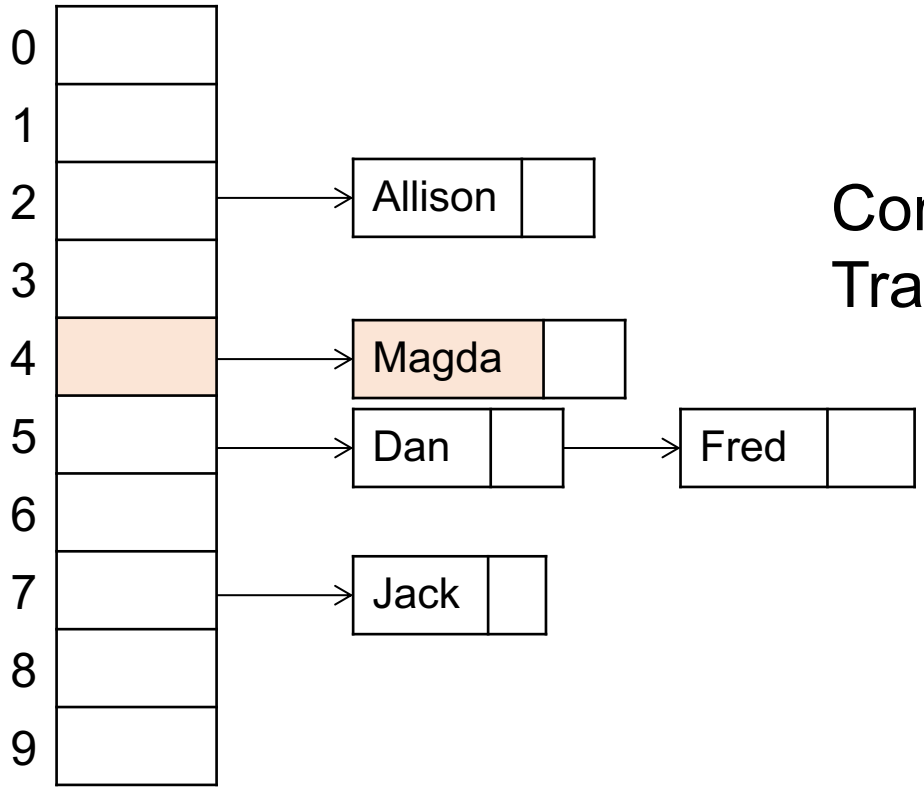

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Time = O(1)

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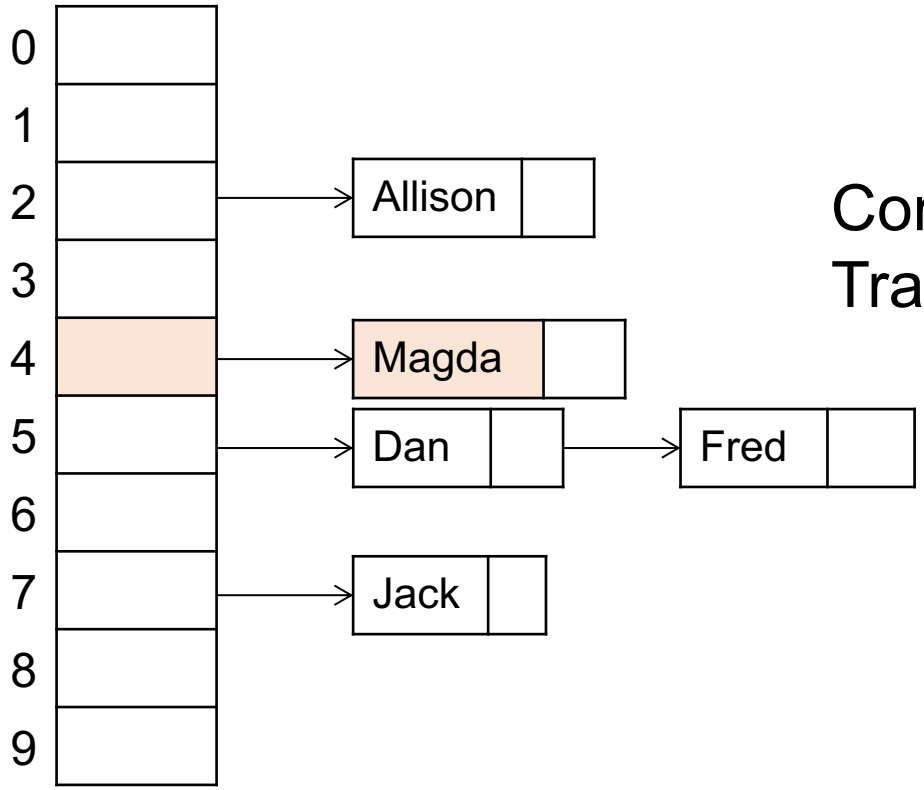

find(“Magda”)

Compute h(“Magda”)=4
Traverse the short list at offset 4

Time = O(1)

…but can becomes O(n)
if the collision list is long

Hash Tables

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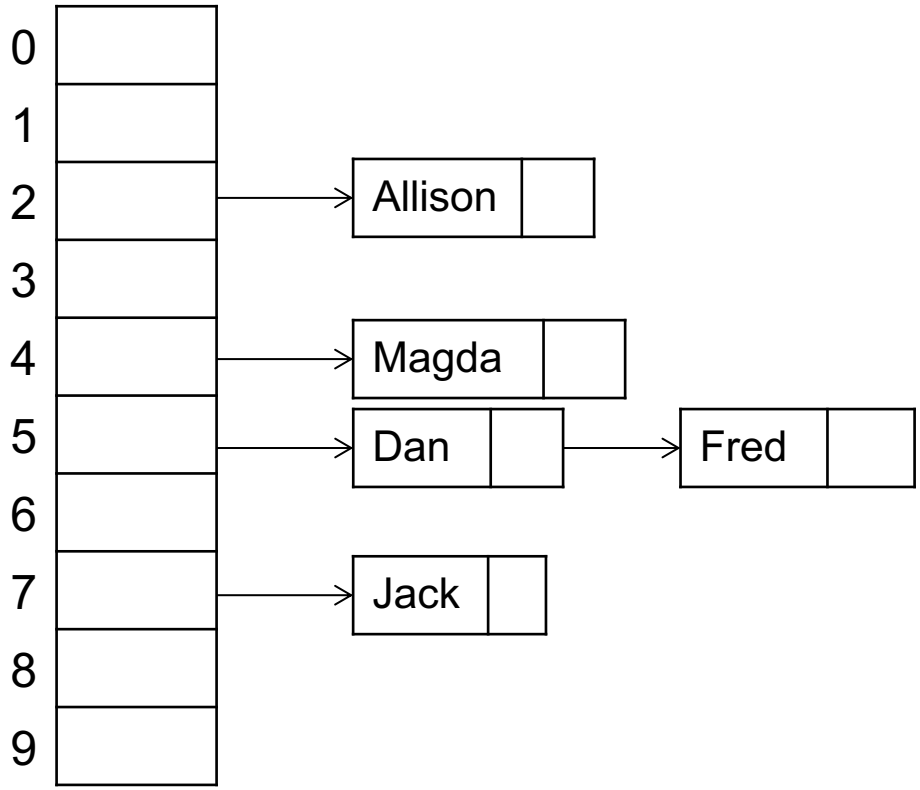

find(“Magda”)

insert(“Jane”)

Hash Tables

A (naïve!!) hash function:

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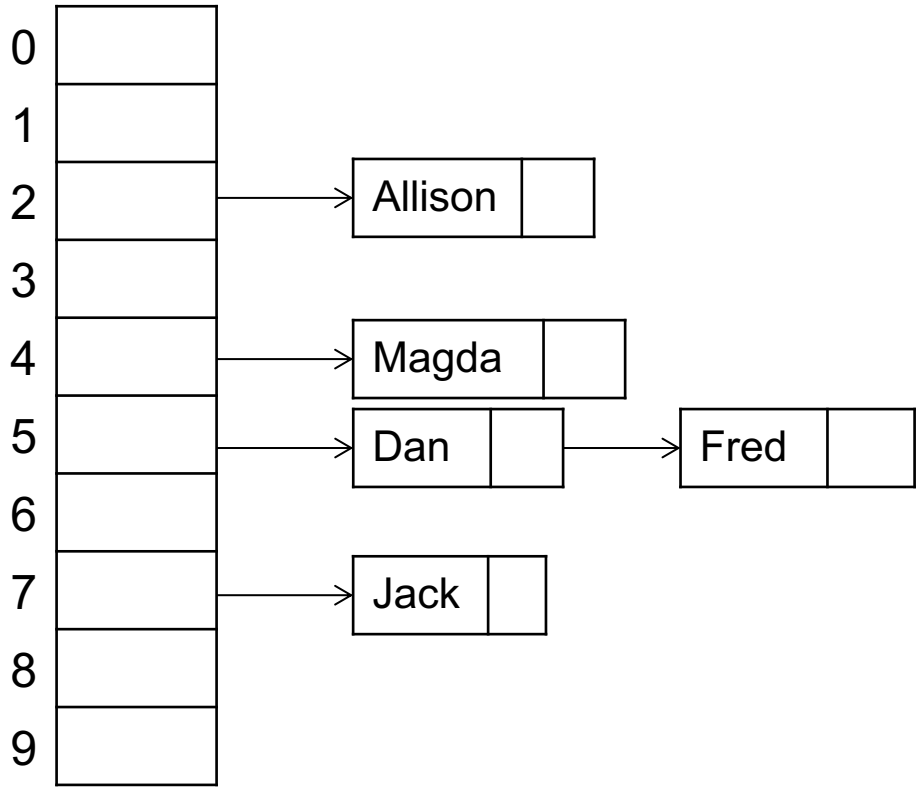

find(“Magda”)

insert(“Jane”)

Compute h(“Jane”)=2
Insert into that list.
Easiest: insert at beginning

Hash Tables

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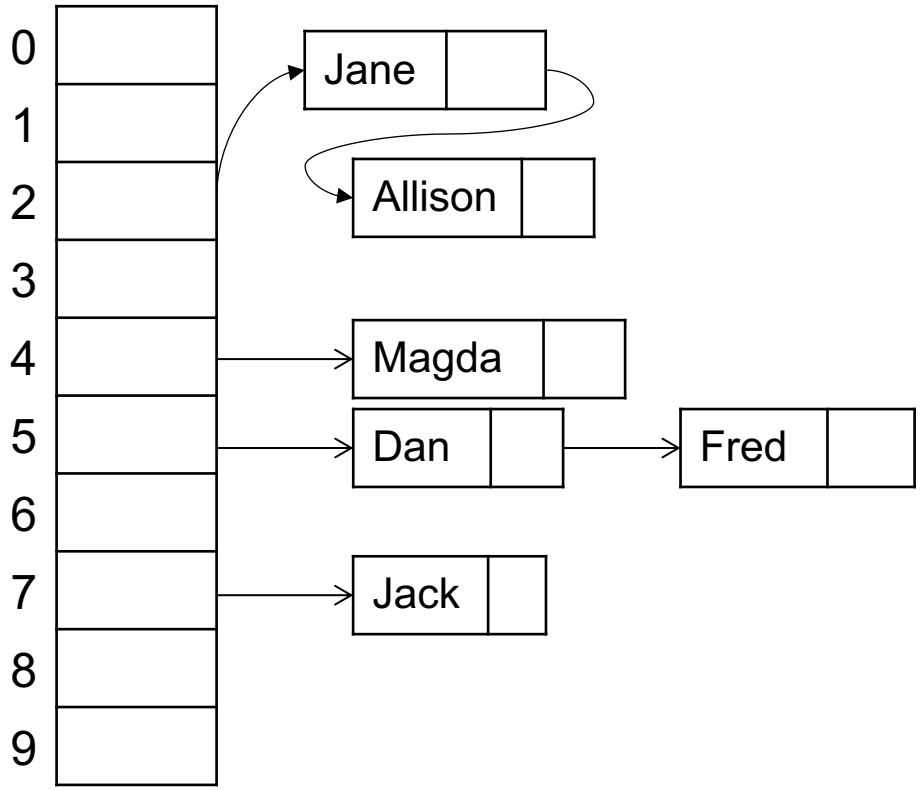

find(“Magda”)

insert(“Jane”)

Compute h(“Jane”)=2
Insert into that list.
Easiest: insert at beginning

Hash Table Takeaways

- Use good hash function, never your own. E.g. https://15445.courses.cs.cmu.edu/fall2023/slides/07-hashtables.pdf
  - Low probability of collision
- Don't use a cryptographic hash function! Why?
- The vector needs to be pre-allocated:
  - Too big: waste space
  - To small: long chains
  - Reallocation (java, python, …): expensive
- If one value occurs much more than average, we say that the data is skewed:
  - O(1)→O(N)

Sorting

- Given an array, sort it in increasingly

74	7	45	99	2	90	19	87	61	82

Sorting

- Given an array, sort it in increasingly

74	7	45	99	2	90	19	87	61	82

2	7	19	45	61	74	82	87	90	99

Sorting

- Given an array, sort it in increasingly

74	7	45	99	2	90	19	87	61	82

2	7	19	45	61	74	82	87	90	99

Simple algorithms: $O(N^2)$
Quicksort: O(N log N)
Mergesort: O(N log N)

2. Hash-Join

2. Hash Join

$$\text{Payroll} \bowtie_{\text{UserID=UserID}} \text{Regist}$$

```
Payroll(UserID,Name,Job,Salary)
Regist(UserID,Car)
```

2. Hash Join

$$\text{Payroll} \bowtie_{\text{UserID=UserID}} \text{Regist}$$

```
Payroll(UserID,Name,Job,Salary)
Regist(UserID,Car)
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```
for x in Payroll
    insert(x.UserID,x)
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2. Hash Join

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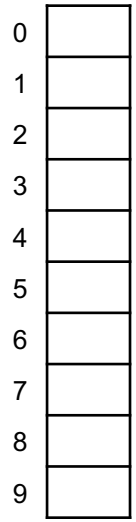


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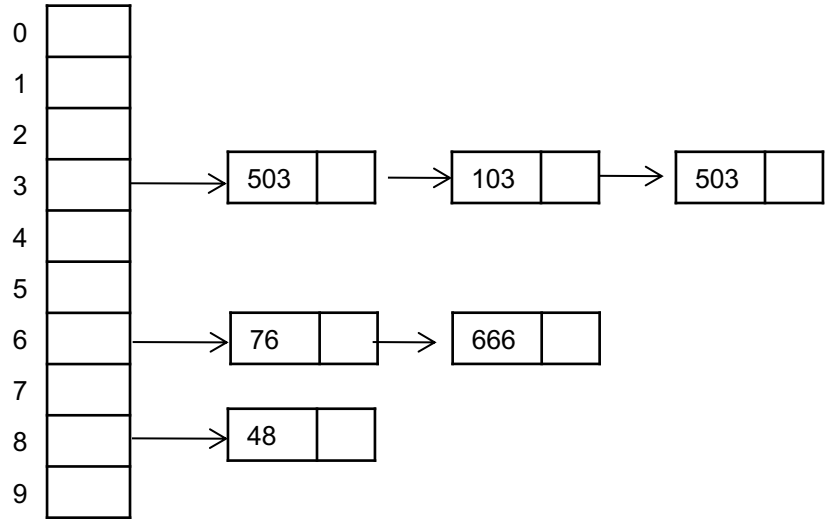


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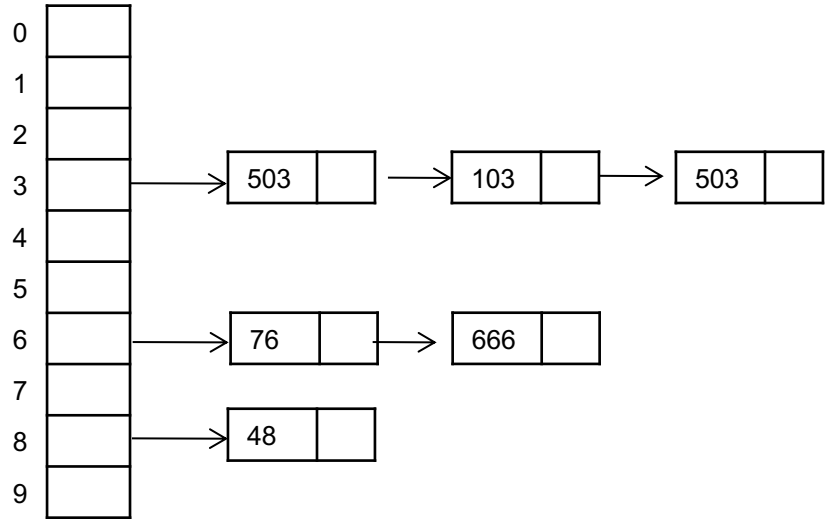


```
for x in Payroll
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    x = find(y.UserId)
    output(x,y)
```

2. Hash Join

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```
Payroll(UserID,Name,Job,Salary)
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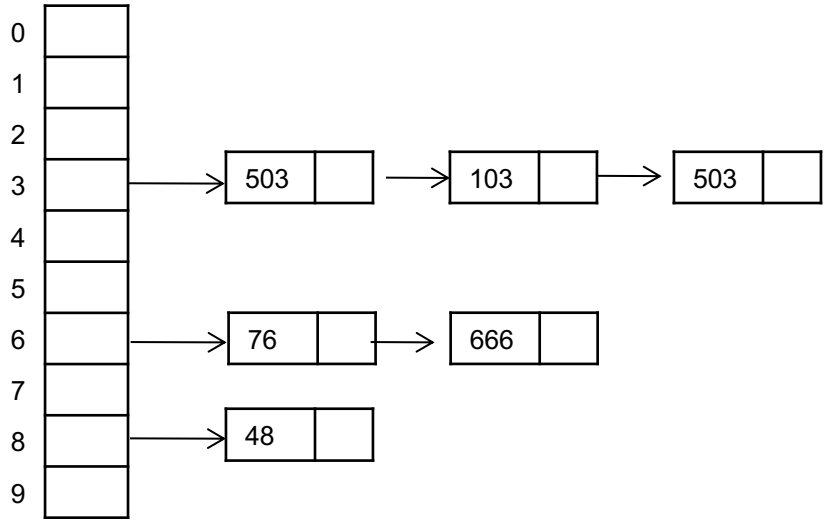


”Build phase”

```
for x in Payroll
    insert(x.UserID,x)

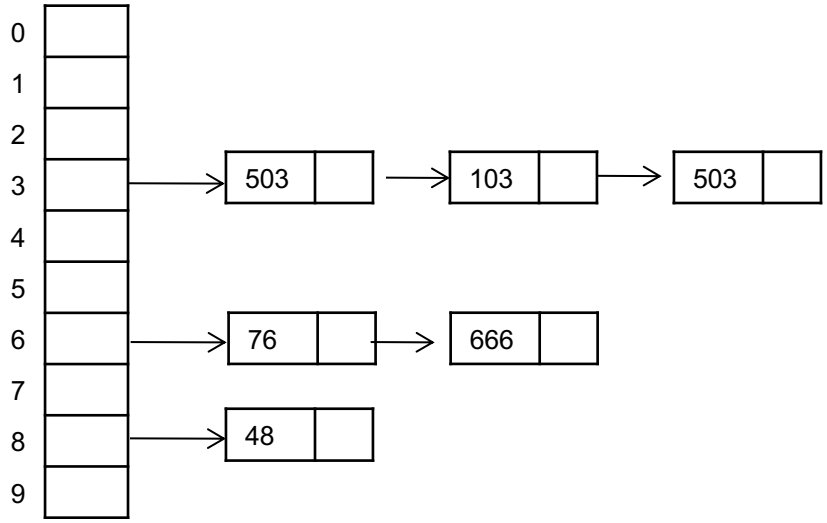
for y in Regist
    x = find(y.UserId)
    output(x,y)
```

”Probe phase”

2. Hash Join

$$\text{Payroll} \bowtie_{\text{UserID=UserID}} \text{Regist}$$

```
Payroll(UserID,Name,Job,Salary)
Regist(UserID,Car)
```



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”Probe phase”

If |Payroll| = |Regist| = n, what is the runtime?

2. Hash Join

$$\text{Payroll} \bowtie_{\text{UserID=UserID}} \text{Regist}$$

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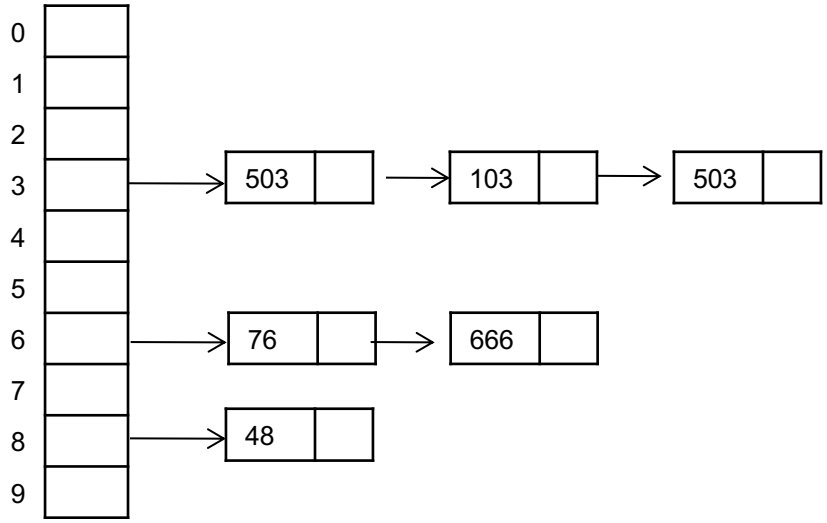

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```

”Probe phase”

If |Payroll| = |Regist| = n, what is the runtime?

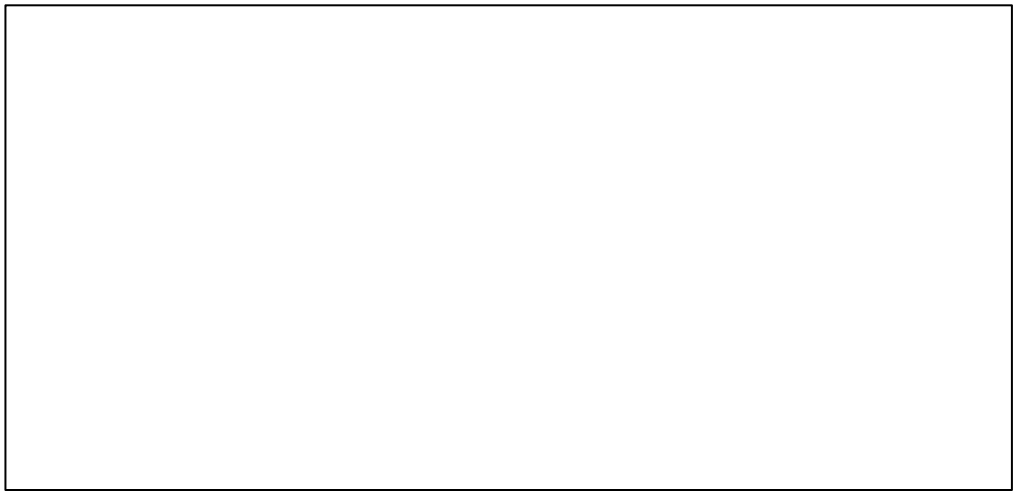
O(n)

2. Hash Join

$\text{Regist} \bowtie_{\text{UserID=UserID}} \text{Payroll}$

```
Payroll(UserID,Name,Job,Salary)
Regist(UserID,Car)
```

Switch join order



2. Hash Join

$$\text{Regist} \bowtie_{\text{UserID=UserID}} \text{Payroll}$$

```
Payroll(UserID,Name,Job,Salary)
Regist(UserID,Car)
```


```
for y in Regist
    insert(y.UserID,x)
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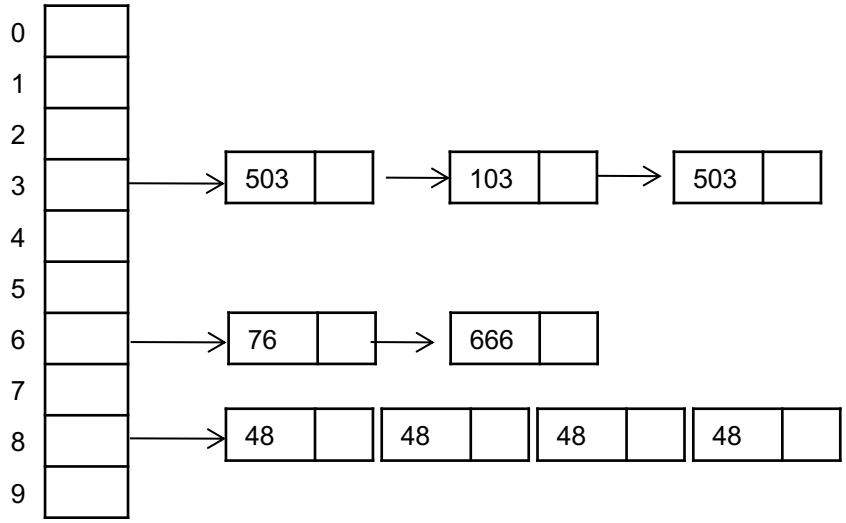


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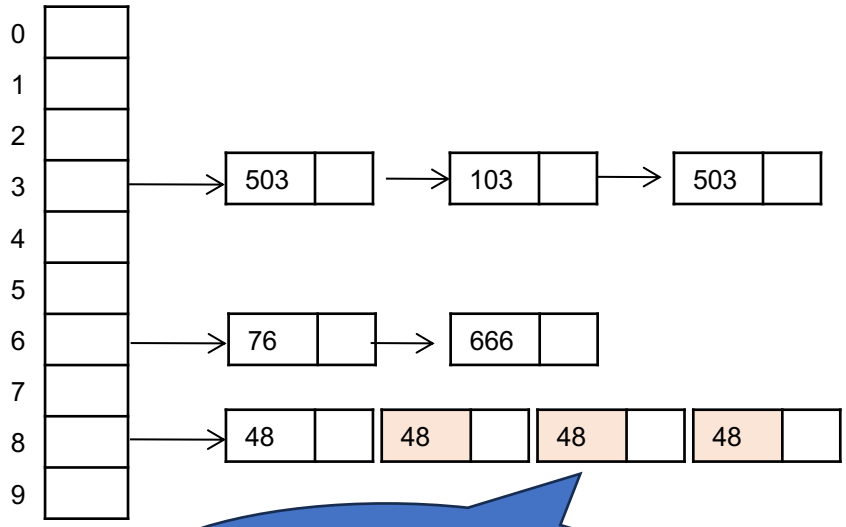


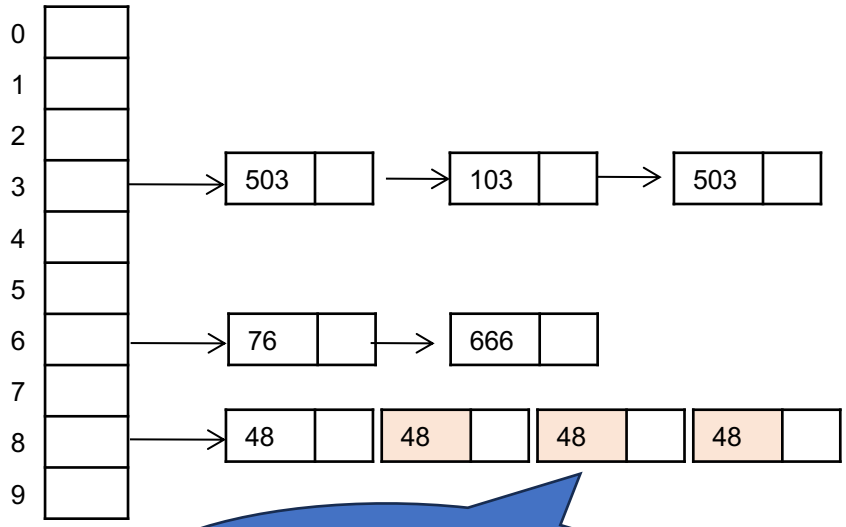
Duplicates of UserID in Regist

2. Hash Join

$$\text{Regist} \bowtie_{\text{UserID=UserID}} \text{Payroll}$$

```
Payroll(UserID,Name,Job,Salary)
Regist(UserID,Car)
```

Switch join order



Duplicates of UserID in Regist

```
for y in Regist
    insert(y.UserID,x)

for x in Payroll
   for y in find(y.UserId)
       output(x,y)
```

2. Hash Join

$$\text{Regist} \bowtie_{\text{UserID=UserID}} \text{Payroll}$$

```
Payroll(UserID,Name,Job,Salary)
Regist(UserID,Car)
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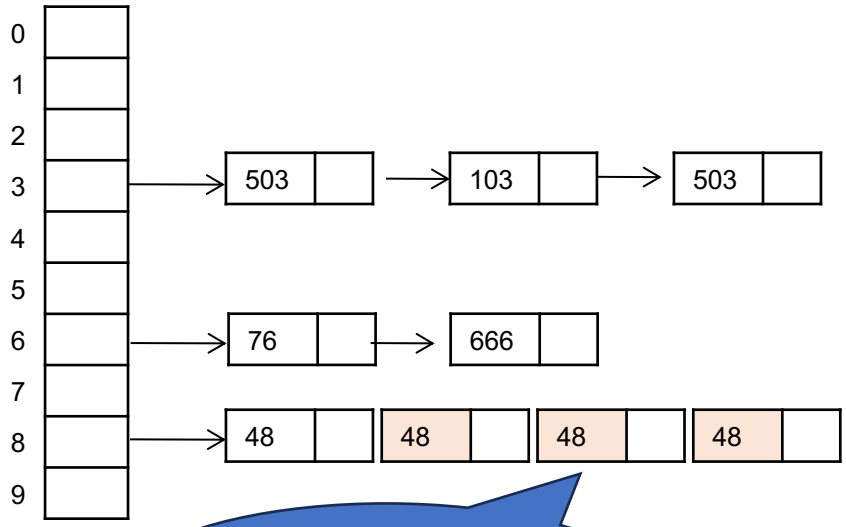
Switch join order



Duplicates of UserID in Regist

```
for y in Regist
    insert(y.UserID,x)

for x in Payroll
   for y in find(y.UserId)
      output(x,y)
```

Runtime: O(n)

But may be $O(n^2)$

2. Hash Join

$$\text{Regist} \bowtie_{\text{UserID=UserID}} \text{Payroll}$$

```
Payroll(UserID,Name,Job,Salary)
Regist(UserID,Car)
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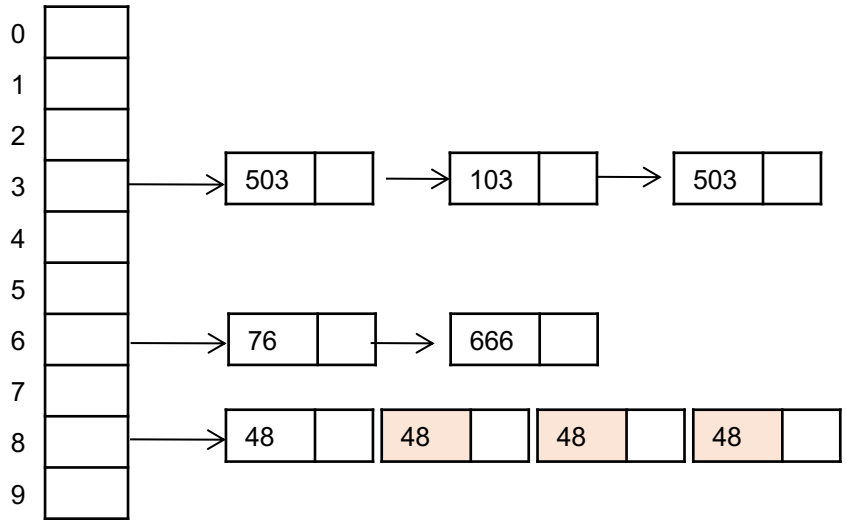
Switch join order




```
for y in Regist
    insert(y.UserID,x)

for x in Payroll
  for y in find(y.UserId)
      output(x,y)
```

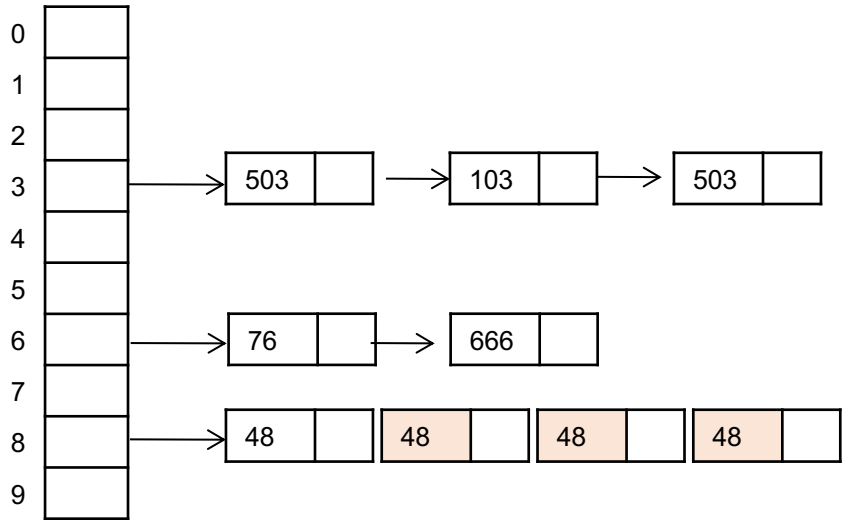
What could be the advantage of this join order?

2. Hash Join

$$\text{Regist} \bowtie_{\text{UserID=UserID}} \text{Payroll}$$

```
Payroll(UserID,Name,Job,Salary)
Regist(UserID,Car)
```

Switch join order




```
for y in Regist
    insert(y.UserID,x)

for x in Payroll
  for y in find(y.UserId)
      output(x,y)
```

What could be the advantage of this join order?

Is better than previous order when |Regist| << |Payroll|

Discussion

Hash-Join: very efficient, usually runs in time O(n)

Performance degrades when:

- Data is skewed, e.g. join on non-key
- Outer table (for which we build the hash table) does not fit in main memory

3. Merge-Join

3. Merge Join

$$\text{Payroll} \bowtie_{\text{UserID=UserID}} \text{Regist}$$

```
Payroll(UserID,Name,Job,Salary)
Regist(UserID,Car)
```

```
sort(Payroll); sort(Regist);
x = Payroll.first()
y = Regist.first()
```

3. Merge Join

$$\text{Payroll} \bowtie_{\text{UserID=UserID}} \text{Regist}$$

```
Payroll(UserID,Name,Job,Salary)
Regist(UserID,Car)
```

```
sort(Payroll); sort(Regist);
x = Payroll.first()
y = Regist.first()
while y!=NULL do:
```

3. Merge Join

$\text{Payroll} \bowtie_{\text{UserID=UserID}} \text{Regist}$

```
Payroll(UserID,Name,Job,Salary)
Regist(UserID,Car)
```

```
sort(Payroll); sort(Regist);
x = Payroll.first()
y = Regist.first()
while y!=NULL do:
  case:
    x.UserID < y.UserID: ??????
    x.UserID = y.UserID: ??????
    x.UserID > y.UserID: ??????
```

3. Merge Join

$$\text{Payroll} \bowtie_{\text{UserID=UserID}} \text{Regist}$$

```
Payroll(UserID,Name,Job,Salary)
Regist(UserID,Car)
```

```
sort(Payroll); sort(Regist);
x = Payroll.first()
y = Regist.first()
while y!=NULL do:
  case:
    x.UserID < y.UserID: x.next();
    x.UserID = y.UserID: ??????
    x.UserID > y.UserID: ??????
```

3. Merge Join

$\text{Payroll} \bowtie_{\text{UserID=UserID}} \text{Regist}$

```
Payroll(UserID,Name,Job,Salary)
Regist(UserID,Car)
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    x.UserID = y.UserID: output(x,y); y.next();
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3. Merge Join

$\text{Payroll} \bowtie_{\text{UserID=UserID}} \text{Regist}$

```
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3. Merge Join

$$\text{Payroll} \bowtie_{\text{UserID=UserID}} \text{Regist}$$

```
Payroll(UserID,Name,Job,Salary)
Regist(UserID,Car)
```

If |Payroll| = |Regist| = n
then runtime = O(n log n)

```
sort(Payroll); sort(Regist);
x = Payroll.first()
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while y!=NULL do:
  case:
    x.UserID < y.UserID: x.next();
    x.UserID = y.UserID: output(x,y); y.next();
    x.UserID > y.UserID: y.next();
```

Summary

Three join algorithms:

- Nested loop: always $O(n^2)$
- Hash join: usually $O(n)$, but can be $O(n^2)$
- Merge join: $O(n \log n)$

Other Physical Operators

Physical Operators

- Selection $\sigma_{pred}(R)$: iterate over R, return matches
- Projection $\Pi_{attrs}(R)$: iterate over R, return $attrs$
- Join $R \bowtie S$: we saw this
- Duplicate elimination δ or group by $\gamma_{attrs,agg}$
  - Nested loop, or
  - Hash-based, or
  - Sort-based
- Union $R \cup S$:
  - Bag semantics: concatenate R, S
  - Set semantics: concatenate, then eliminate duplicates
- Difference: like join, but more complicated

Final Comments

- Each operator can have several implementations
- Join = the most important and most complex: other operators use similar or simpler algorithms
- When data is on disk, specialized operators are needed
- The physical operator is chosen by the optimizer, not by the user