FROM DATABASES
TO ARCHITECTURES FOR BIG DATA MANAGEMENT

DATABASE FUNDAMENTALS
(RECALL/CRASH COURSE)

DATABASE FUNDAMENTALS (RECALL/INTRODUCTION)

Database internals

(We illustrate for relational databases, as they are the most mature)

What's in a database?

SQL

Database

Results

select driver.name
from driver, car
where
driver.ID=car.driver
and
car.licese='123AB'.

name
Julie

What's in a database?

Driver

name	ID
Julie	1
Damien	2

Car

driver	license
1	‘123AB’
2	‘171KZ’

1. Load

2. SQL

select driver.name
from driver, car
where
driver.ID=car.driver
and
car.license=‘123AB’

Database

3. Results

name
Julie

What's in a database?

Driver

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Car

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1	‘123AB’
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1. Load

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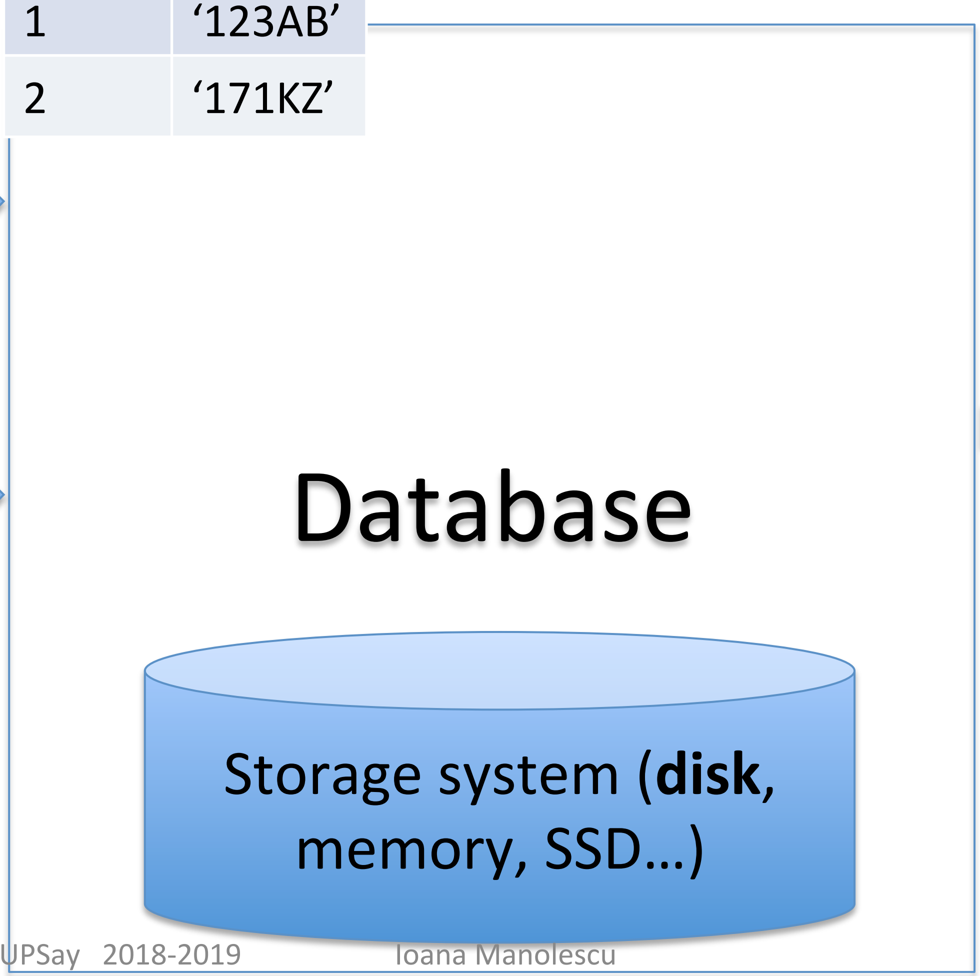
select driver.name
from driver, car
where
driver.ID=car.driver
and
car.license=‘123AB’



3. Results

name
Julie

What's in a database?

1. Load

2. SQL

select driver.name
from driver, car
where
driver.ID=car.driver
and
car.license='123AB'

Database

Driver

name	ID
Julie	1
Damien	2

Car

driver	license
1	'123AB'
2	'171KZ'

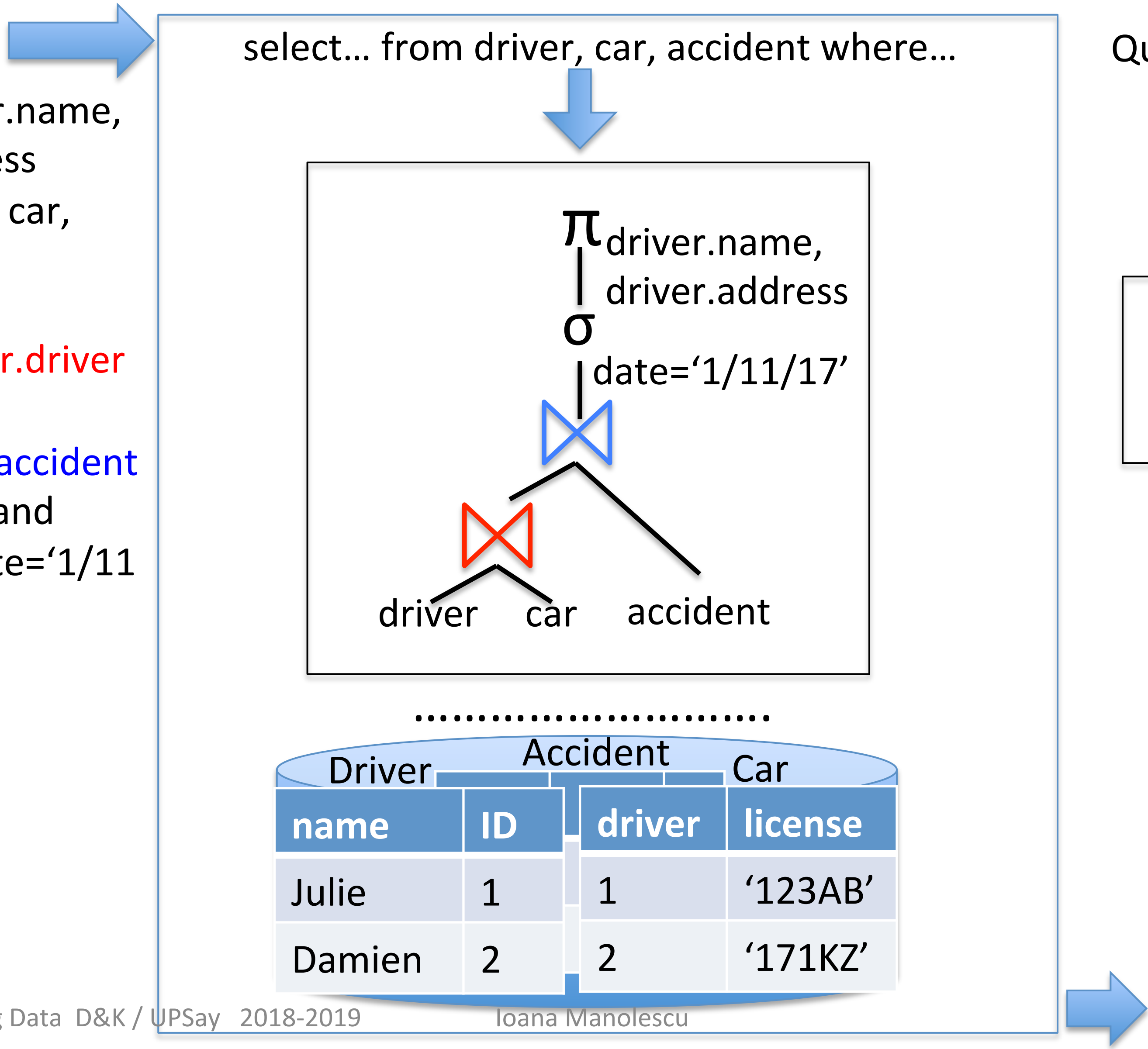
3. Results

name
Julie

What's in a database?

SQL

select driver.name, driver.address
from driver, car, accident
where driver.ID=car.driver and car.license=accident.carLicense and accident.date='1/11/17'



Query language

Logical plan

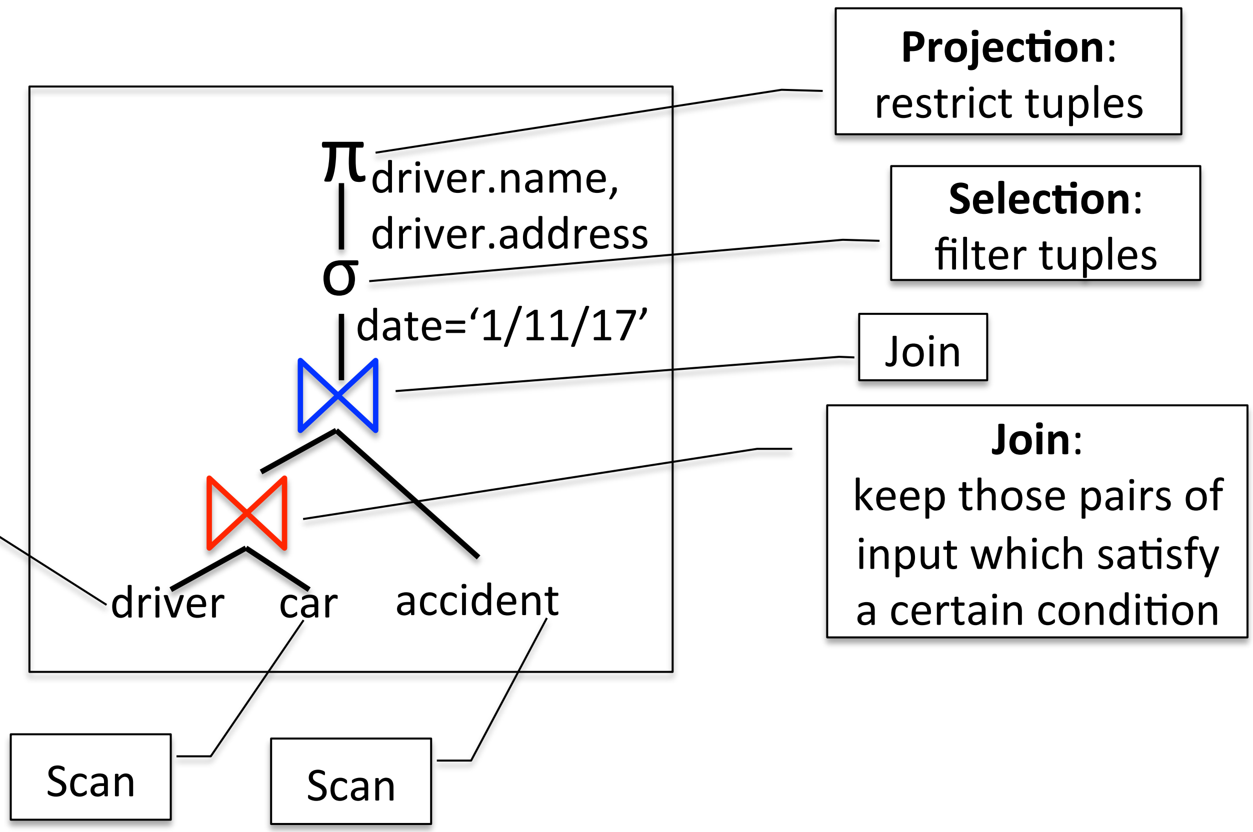
Results

Logical query plans

- Trees made of logical operators, each of which specializes in a certain task

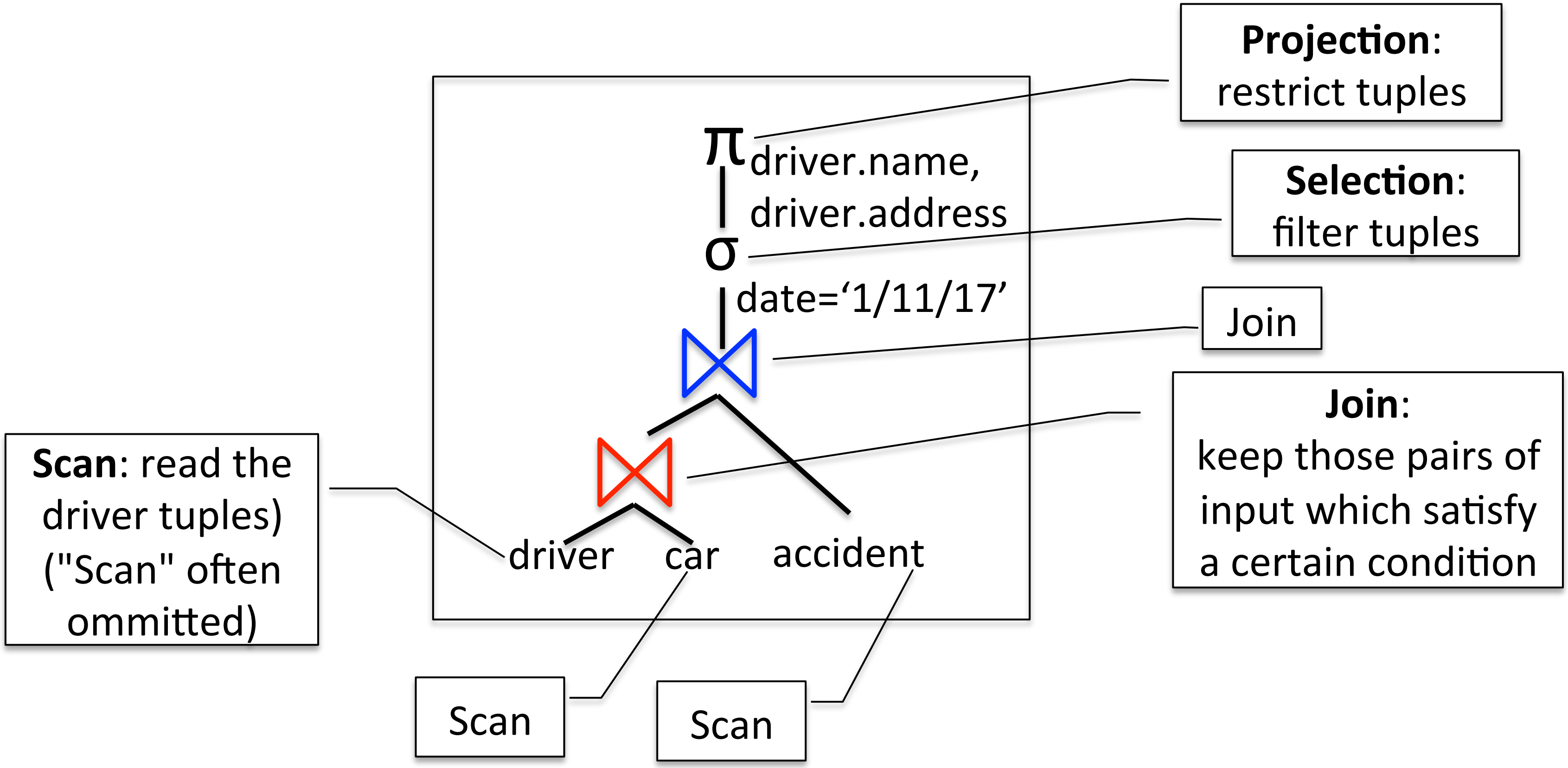
SQL:
select driver.name, driver.address
from driver, car, accident
where
driver.ID=car.driver and
car.license=accident.carLicense and
accident.date='1/11/17'

Scan: read the driver tuples) ("Scan" often ommitted)



Logical query plans

- Trees made of logical operators, each of which specializes in a certain task
- Logical operators: they are defined by their result, not by an algorithm
- Physical operators (see next) implement actual algorithms



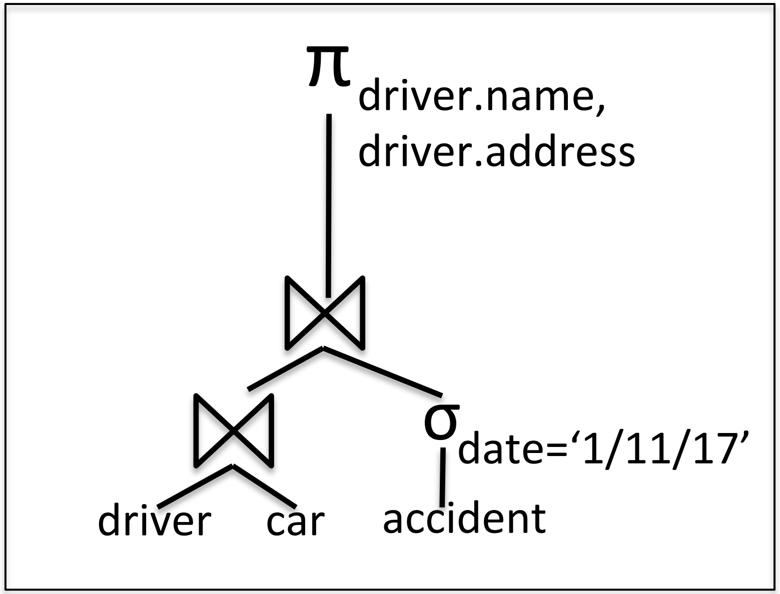
What's in a database?

SQL

select driver.name, driver.address
from driver, car, accident
where driver.ID=car.driver and car.license=accident.carLicense and accident.date='1/11/13'

select… from driver, car, accident where…

Query language



Logical plan 1

Logical plan 2

…………………………

Driver Accident Car

name	ID
Julie	1
Damien	2

driver	license
1	'123AB'
2	'171KZ'

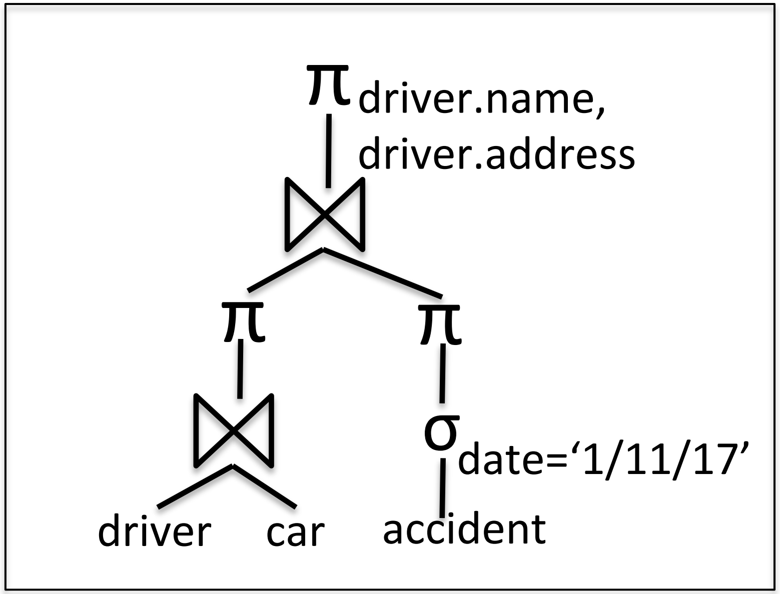
Results

What's in a database?

SQL

select driver.name, driver.address
from driver, car, accident
where driver.ID=car.driver and car.license=accident.carLicense and accident.date='1/11/17'

select… from driver, car, accident where…



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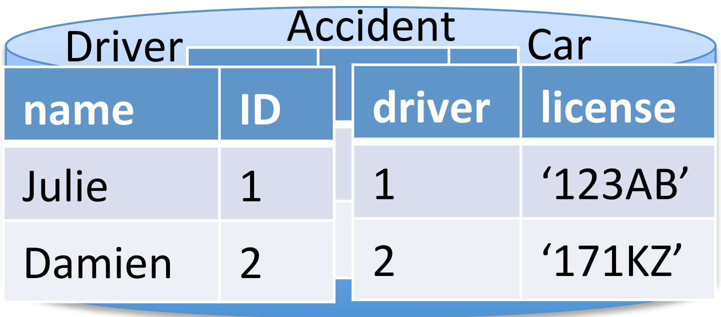


Query language

Logical plan 1

Logical plan 2

Logical plan 3

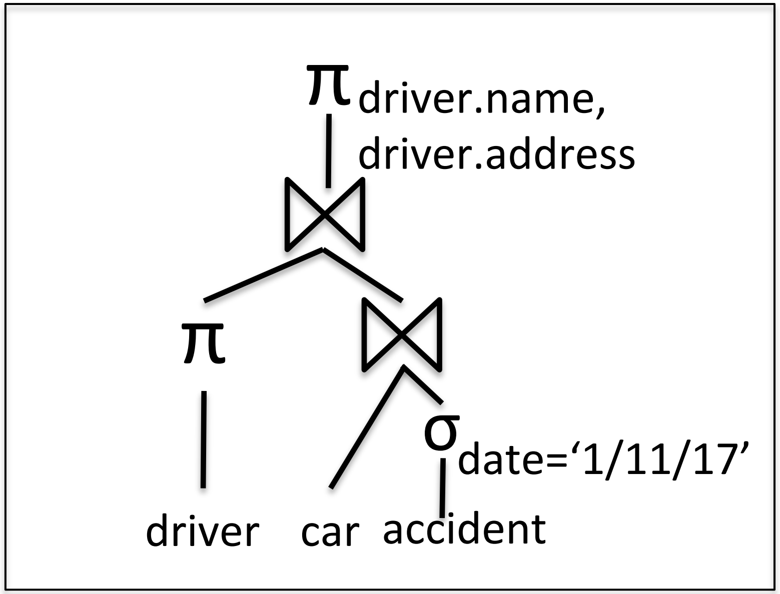
Results

What's in a database?

SQL

select driver.name, driver.address
from driver, car, accident
where driver.ID=car.driver and car.license=accident.carLicense and accident.date='1/11/17'

select… from driver, car, accident where…



……………………………

Driver

name	ID
Julie	1
Damien	2

Accident

Car

driver	license
1	'123AB'
2	'171KZ'

Query language

Logical plan 1

Logical plan 2

Logical plan 3

Logical plan 4

Results

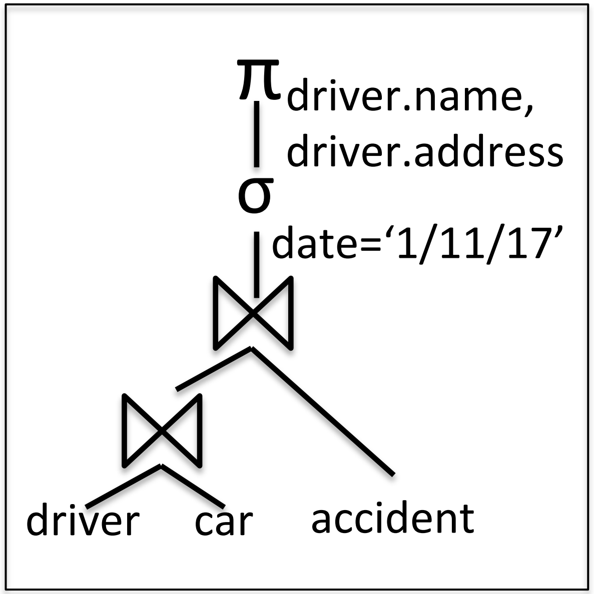
Logical query optimization

- Enumerates logical plans
- All logical plans compute the query result
  - They are **equivalent**
- Some are (much) more **efficient** than others
- **Logical optimization**: moving from a plan to a more efficient one
  - Pushing selections
  - Pushing projections
  - Join reordering: most important source of optimizations

Logical query optimization example

1.000.000 cars, 1.000.000 drivers, 1.000 accidents, 2 cars per accident, 10 accidents on 1/11/17

« Name and address of drivers in accidents on 1/11/2017? »



Cost of an operator: depends on the number of tuples (or tuple pairs) which it must process

e.g. c_disk x number of tuples read from disk

e.g. c_cpu x number of tuples compared

Cardinality of an operator's output: how many tuples result from this operator

The cardinality of one operator's output determines the cost of its parent operator

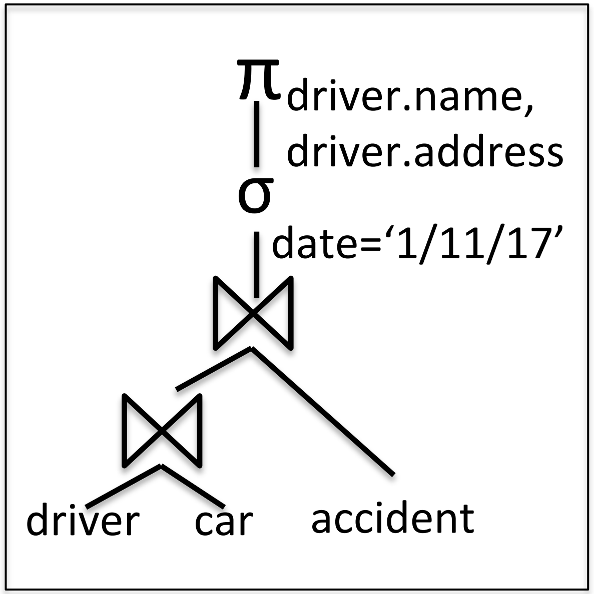
Plan **cost** = the sum of the costs of all operators in a plan

Logical query optimization example

1.000.000 cars, 1.000.000 drivers, 1.000 accidents, 2 cars per accident, 10 accidents on 1/11/17

« Name and address of drivers in accidents on 1/11/2017? »

Pessimistic (worst-case) estim.



Scan costs: cs x (10^6+10^6 +10^3)
Scan cardinality estimations: 10^6, 10^6, 10^3

Driver-car join cost estimation: cj x (10^6 x 10^6 =10^{12})

Driver-car join cardinality estimation: 10^9

Driver-car-accident join cost estim.: cj x (10^9 x 10^3= 10^{12})
Driver-car-accident join cardinality estimation: 2 x 10^3

Selection cost estimation: cf x (2 x 10^3)
Selection cardinality estimation: 10

Projection (similar), negligible

cs, cj, cf constant

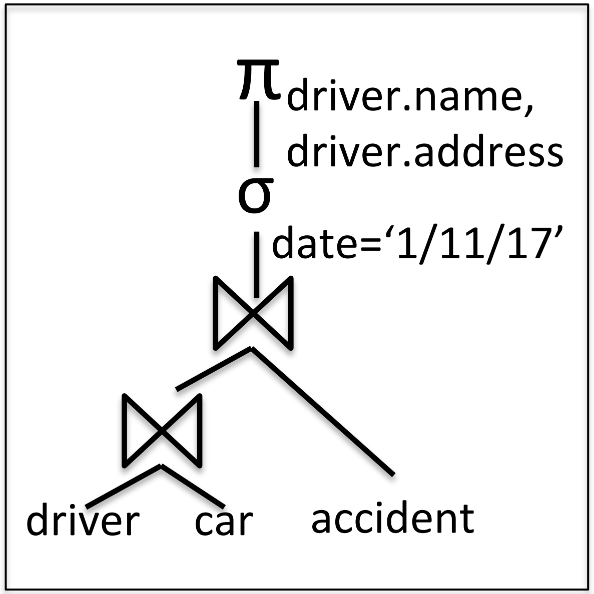
Total cost estimation: 10 + 3x10^3+2x10^6 +10^{12} ~ 10^{12}

Logical query optimization example

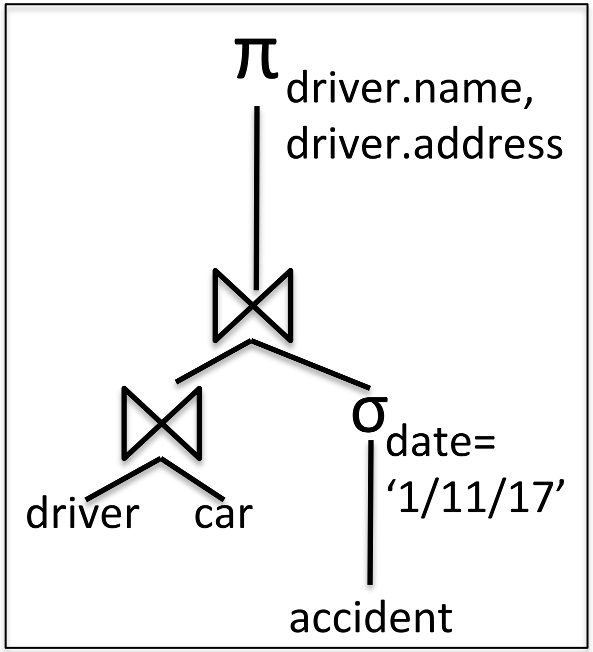
1.000.000 cars, 1.000.000 drivers, 1.000 accidents, 2 cars per accident, 10 accidents on 1/11/17

« Name and address of drivers in accidents on 1/11/2017? »

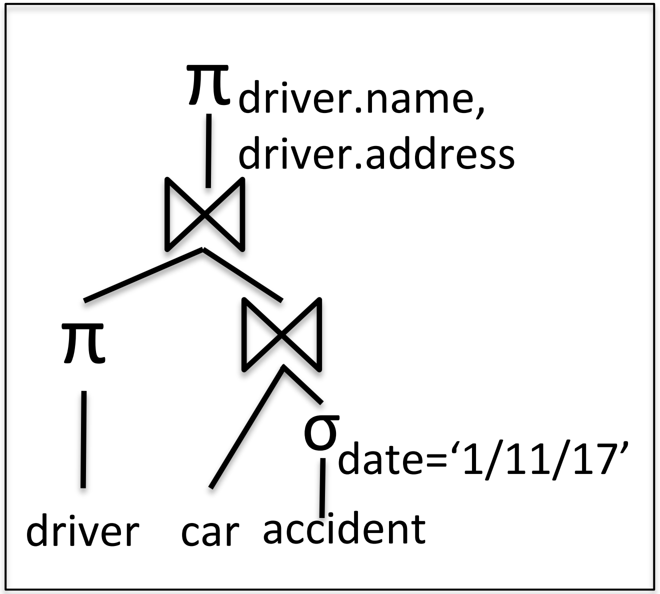
Three plans, same scan costs (neglected below); join costs dominant



$10^9 + 10^{12} \sim \mathbf{10^{12}}$



$10^9 + 10^7 \sim \mathbf{10^9}$



$10^7 + 2*10^7 \sim \mathbf{3*10^7}$

Logical query optimization example

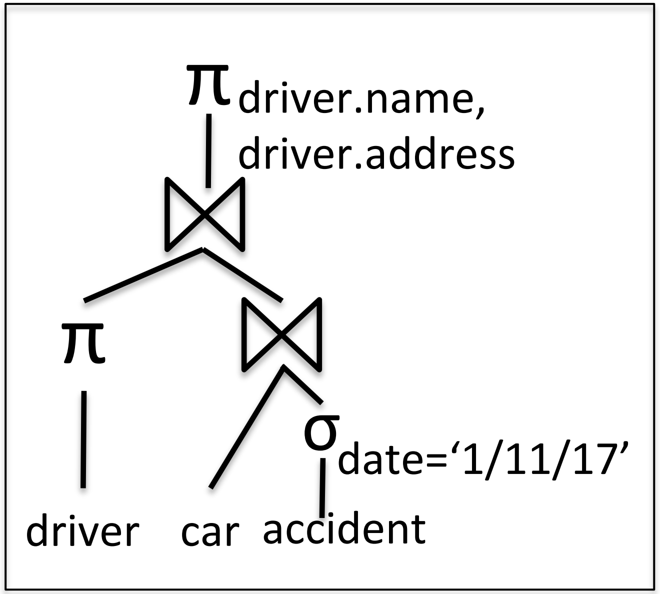
1.000.000 cars, 1.000.000 drivers, 1.000 accidents, 2 cars per accident, 10 accidents on 1/11/17

« Name and address of drivers in accidents on 1/11/2017? »

Three plans, same scan costs (neglected below); join costs dominant

The best plan reads only the accidents that have to be consulted

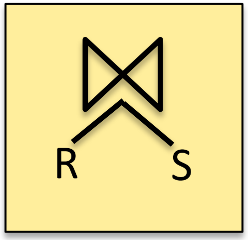
- **Selective data access**
- Typically supported by an **index**
  - Auxiliary data structure, built on top of the data collection
  - Allows to access directly objects satisfying a certain condition



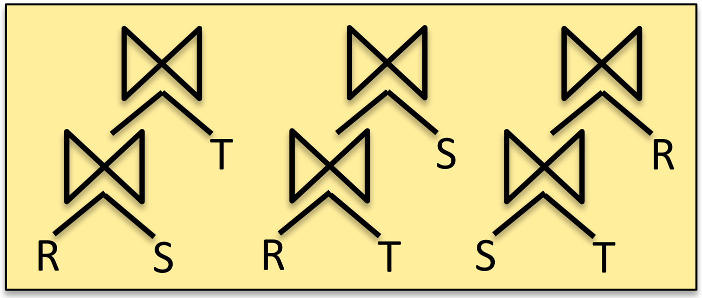
$10^7 + 2*10^7 \sim \mathbf{3*10^7}$

Join ordering is the main problem in logical query optimization

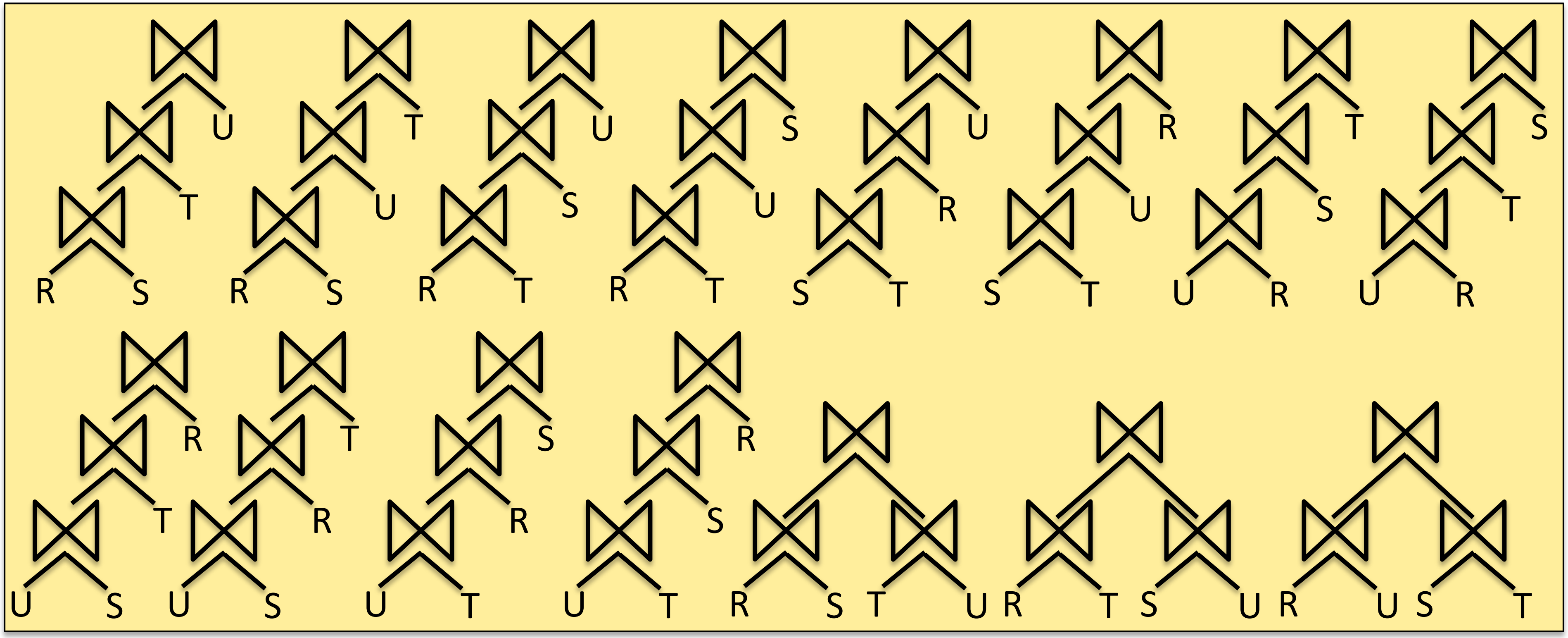
N=2:



N=3:



N=4:



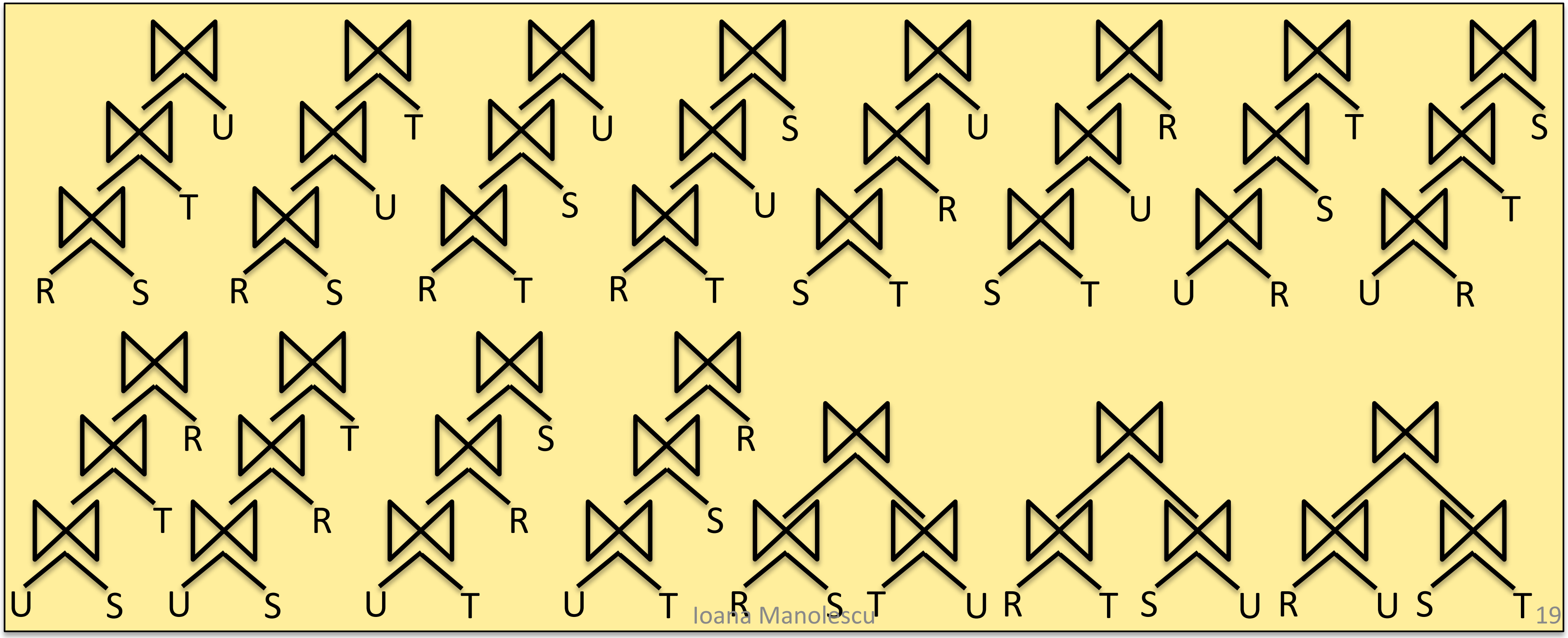
Join ordering is the main problem in logical query optimization

$$Plans(n+1) = (n+1) * Plans(n) + \frac{1}{2} * \Sigma_{i=1}^{(n/2)} Plans(i)*Plans(n+1-i)$$

High (exponential) complexity → many heuristics

- Exploring only left-linear plans etc.

N=4:



Logical query optimization needs statistics

Exact statistics (on base data):

- 1.000.000 cars, 1.000.000 drivers, 1.000 accidents

Approximate / estimated statistics (on intermediary results)

- "1.75 cars involved in every accident"

Statistics are gathered

- When **loading** the data: take advantage of the scan
- **Periodically** or upon **request** (e.g. `analyze` in the Postgres RDBMS)
- At **runtime**: modern systems may do this to change the data layout

Statistics on the base data vs. on results of operations not evaluated (yet):

- « On average 2 cars per accident »

- For each column R.a, store:
  |R|, |R.a| (number of distinct values), min{R.a}, max{R.a}
- Assume **uniform distribution** in R.a
- Assume **independent distribution**
  - of values in R.a vs values in R.b; of values in R.a vs values in S.c
- + simple probability computations

More on statistics

- For each column R.a, store:
  |R|, |R.a| (number of distinct values), min{R.a}, max{R.a}
- Assume **uniform distribution** in R.a
- Assume **independent distribution**
  - of values in R.a vs values in R.b; of values in R.a vs values in S.c

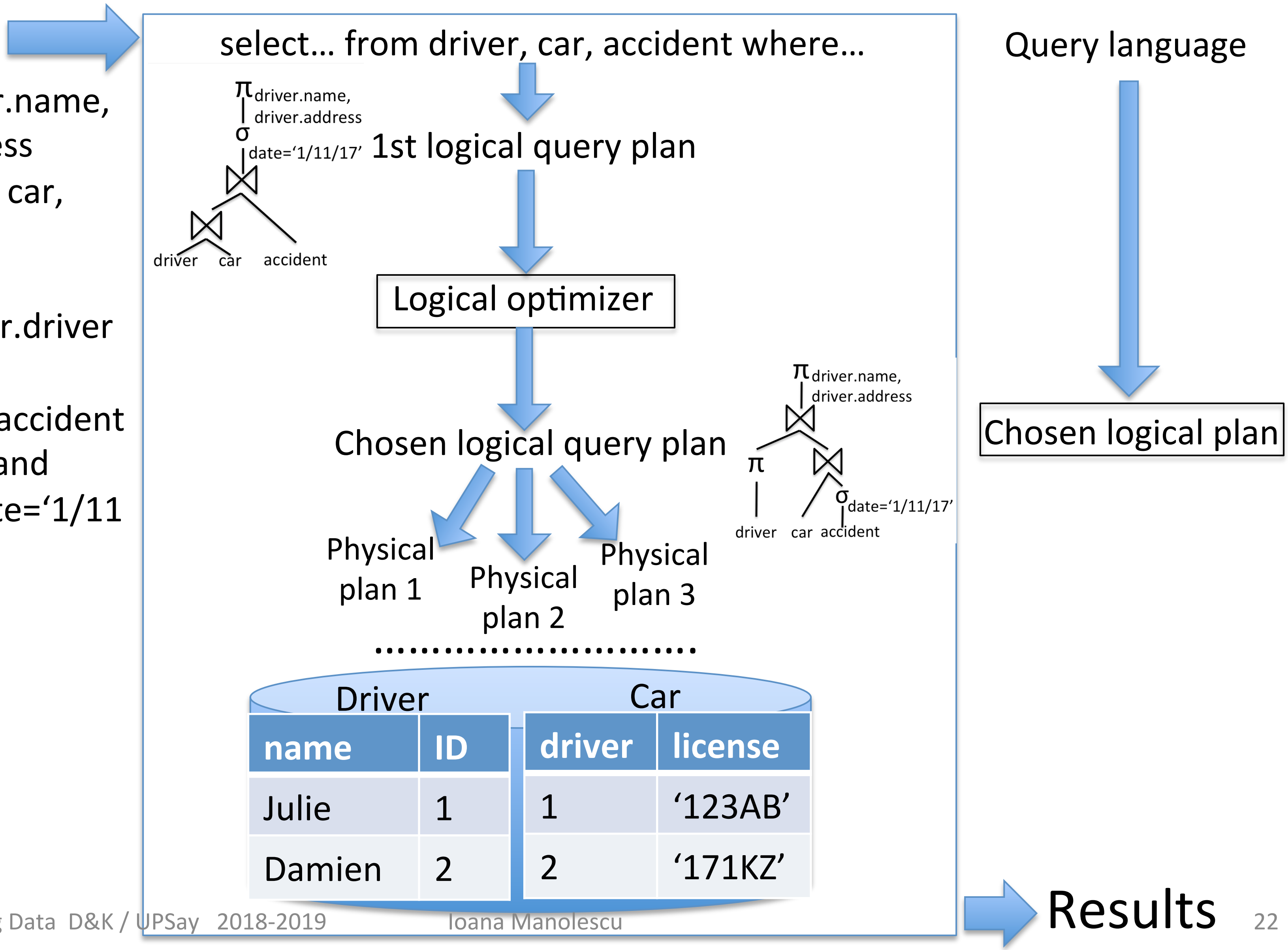
- The **uniform distribution** assumption is frequently wrong
  - Real-world distribution are skewed (popular/frequent values)
- The **independent distribution** assumption is sometimes wrong
  - « Total » counter-example: *functional dependency*
  - Partial but strong enough to ruin optimizer decisions: *correlation*

- Actual optimizers use more sophisticated statistic informations
  - **Histograms**: equi-width, equi-depth
  - Trade-offs: size vs. maintenance cost vs. control over estimation error

Database internal: query optimizer

SQL

select driver.name, driver.address
from driver, car, accident
where driver.ID=car.driver and car.license=accident.carLicense and accident.date='1/11/17'



name	ID
Julie	1
Damien	2

driver	license
1	'123AB'
2	'171KZ'

Physical query plans

Made up of **physical operators** =

algorithms for implementing logical operators

Example: equi-join (R.a=S.b)

Nested loops join:

```
foreach t1 in R{
  foreach t2 in S {
    if t1.a = t2.b then output (t1 || t2)
  }
}
```

Merge join: // requires sorted inputs

```
repeat{
 while (!aligned) { advance R or S };
 while (aligned) { copy R into topR, S into topS };
 output topR x topS;
} until (endOf(R) or endOf(S));
```

Hash join: // builds a hash table in memory

```
While (!endOf(R)) { t ← R.next; put(hash(t.a), t); }
While (!endOf(S)) { t ← S.next;
                    matchingR = get(hash(S.b));
                    output(matchingR x t);
                  }
```

Physical query plans

Made up of **physical operators** =

algorithms for implementing logical operators

Example: equi-join (R.a=S.b)

Nested loops join: O(|R|x|S|)

```
foreach t1 in R{
  foreach t2 in S {
    if t1.a = t2.b then output (t1 || t2)
  }
}
```

Merge join: // requires sorted inputs O(|R|+|S|)

```
repeat{
  while (!aligned) { advance R or S };
  while (aligned) { copy R into topR, S into topS };
  output topR x topS;
} until (endOf(R) or endOf(S));
```

Hash join: // builds a hash table in memory

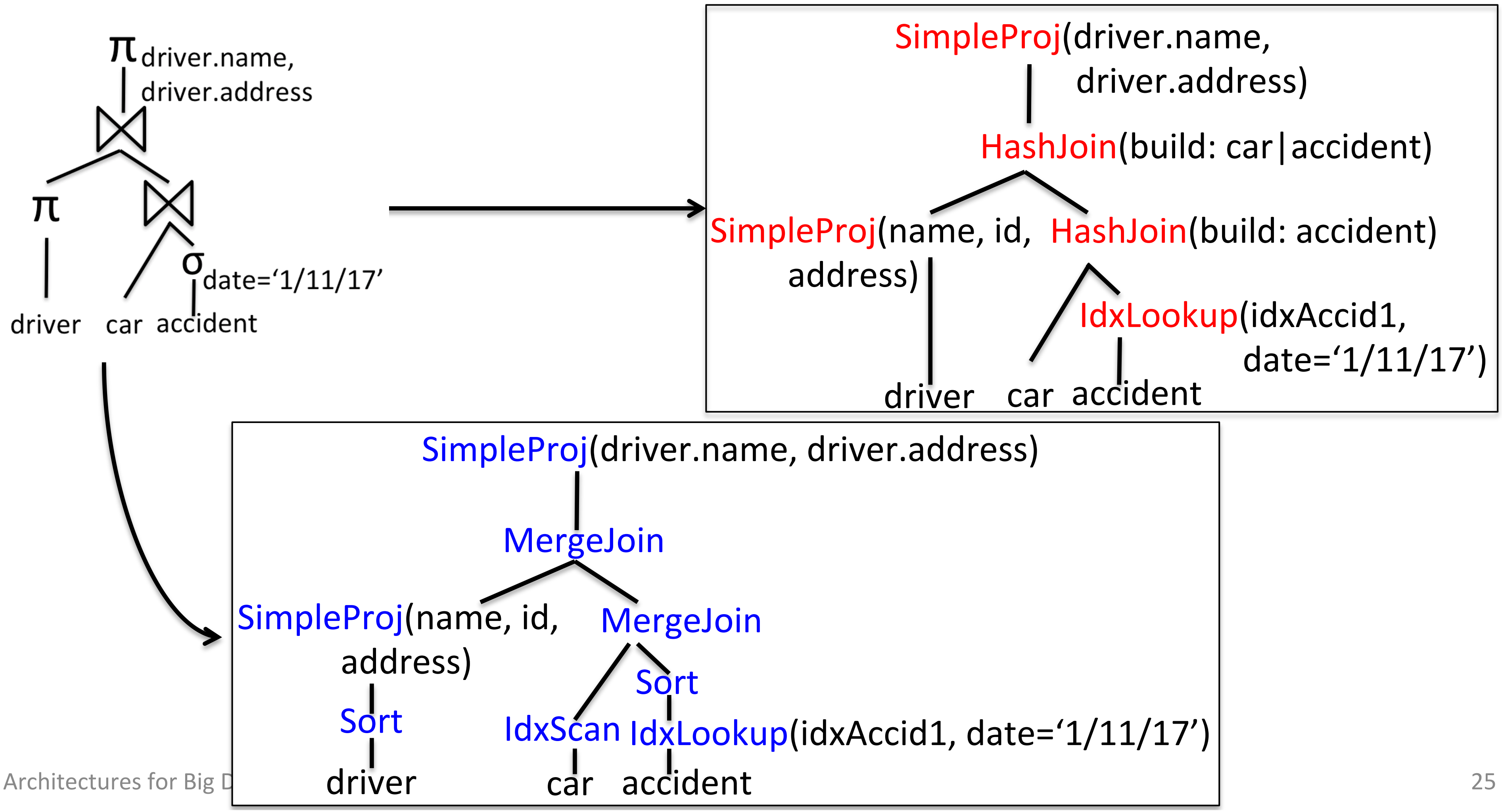
```
While (!endOf(R)) { t ← R.next; put(hash(t.a), t); }
While (!endOf(S)) { t ← S.next;
                    matchingR = get(hash(S.b));
                    output(matchingR x t);
                  }
```

O(|R|+|S|)

Also:
Block nested loops join
Index nested loops join
Hybrid hash join
Hash groups / teams
…

Physical optimization

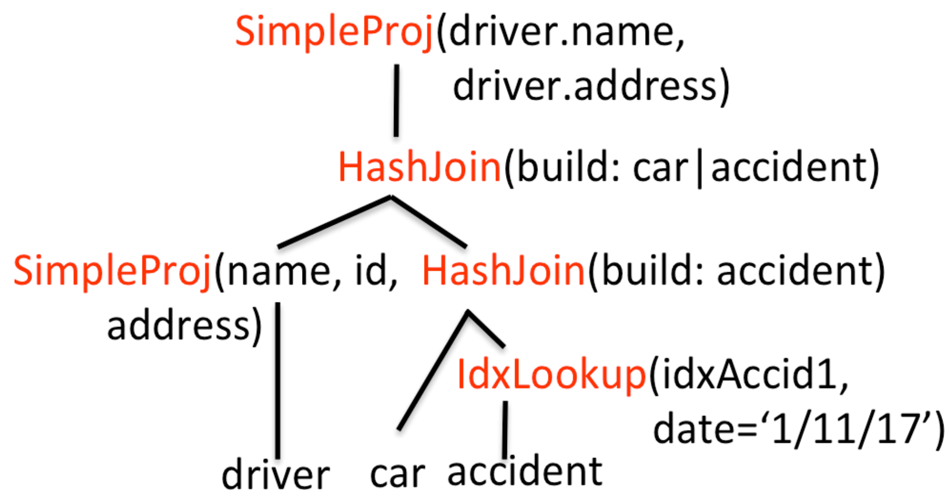
Possible physical plans produced by physical optimization for our sample logical plan:



Physical plan performance

Metrics characterizing a physical plan

- **Response time**: between the time the query starts running to the we know it's end of results
- **Work** (resource consumption)
  - How many **I/O** calls (blocks read)
    - Scan, IdxScan, IdxAccess; Sort; HybridHash (or spilling HashJoin)
  - How much **CPU**
    - All operators
  - Distributed plans: **network** traffic
- **Total work**: work made by all operators



Query optimizers in action

Most database management systems have an « explain » functionality → physical plans. Below sample Postgres output:

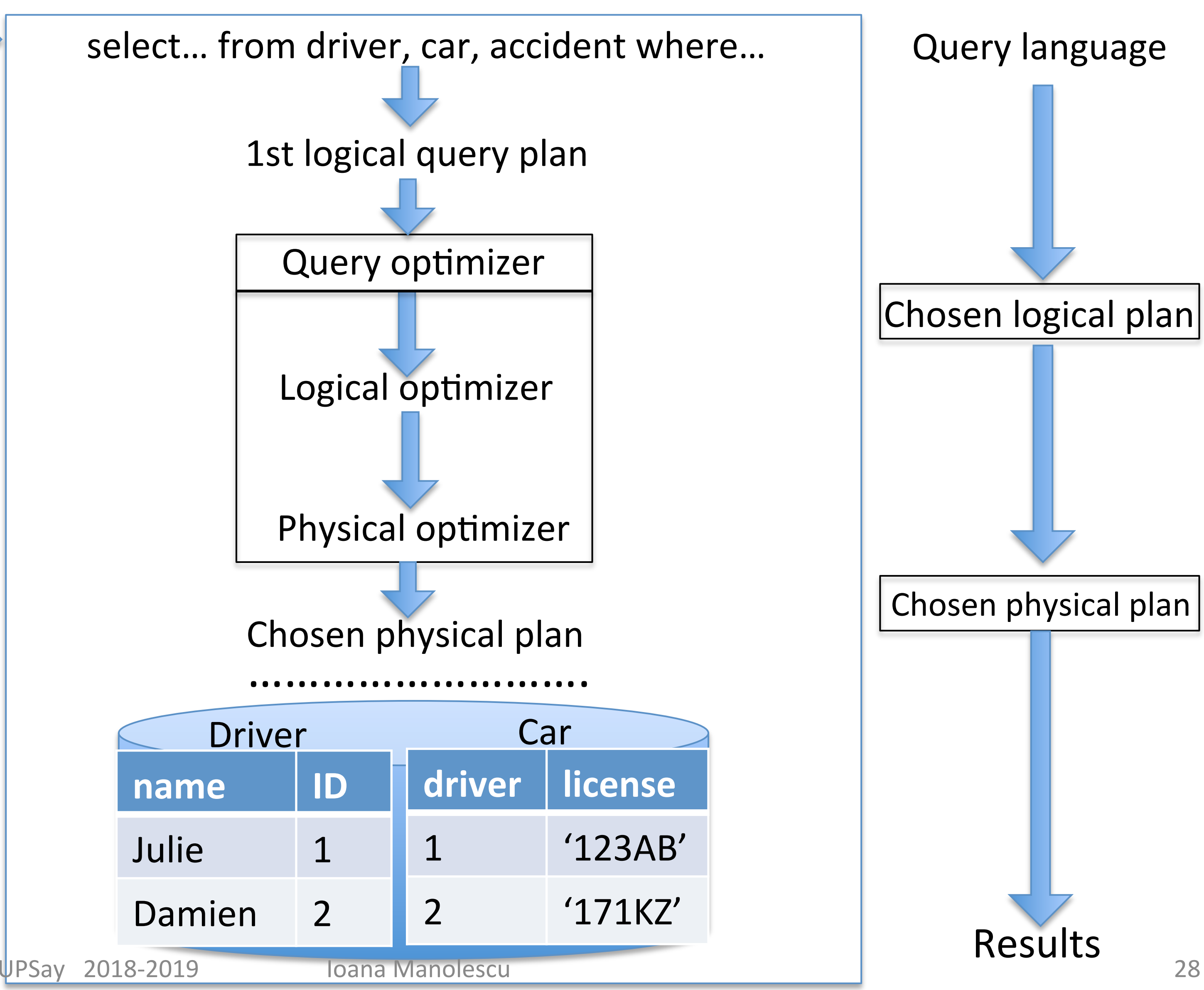
```
EXPLAIN SELECT * FROM tenk1;
                     QUERY PLAN
------------------------------------------------------------
Seq Scan on tenk1 (cost=0.00..458.00 rows=10000 width=244)
```

```
EXPLAIN SELECT * FROM tenk1 t1, tenk2 t2
WHERE t1.unique1 < 100 AND t1.unique2 = t2.unique2;
                                      QUERY PLAN
 --------------------------------------------------------------------------------------
Hash Join (cost=232.61..741.67 rows=106 width=488)
   Hash Cond: ("outer".unique2 = "inner".unique2)
   -> Seq Scan on tenk2 t2 (cost=0.00..458.00 rows=10000 width=244)
   -> Hash (cost=232.35..232.35 rows=106 width=244)
        -> Bitmap Heap Scan on tenk1 t1 (cost=2.37..232.35 rows=106 width=244)
        Recheck Cond: (unique1 < 100)
        -> Bitmap Index Scan on tenk1_unique1 (cost=0.00..2.37 rows=106 width=0)
             Index Cond: (unique1 < 100)
```

Database internal: physical plan

SQL

select driver.name
from driver, car
where
driver.ID=car.driver
and
car.license='123AB'



Driver

name	ID
Julie	1
Damien	2

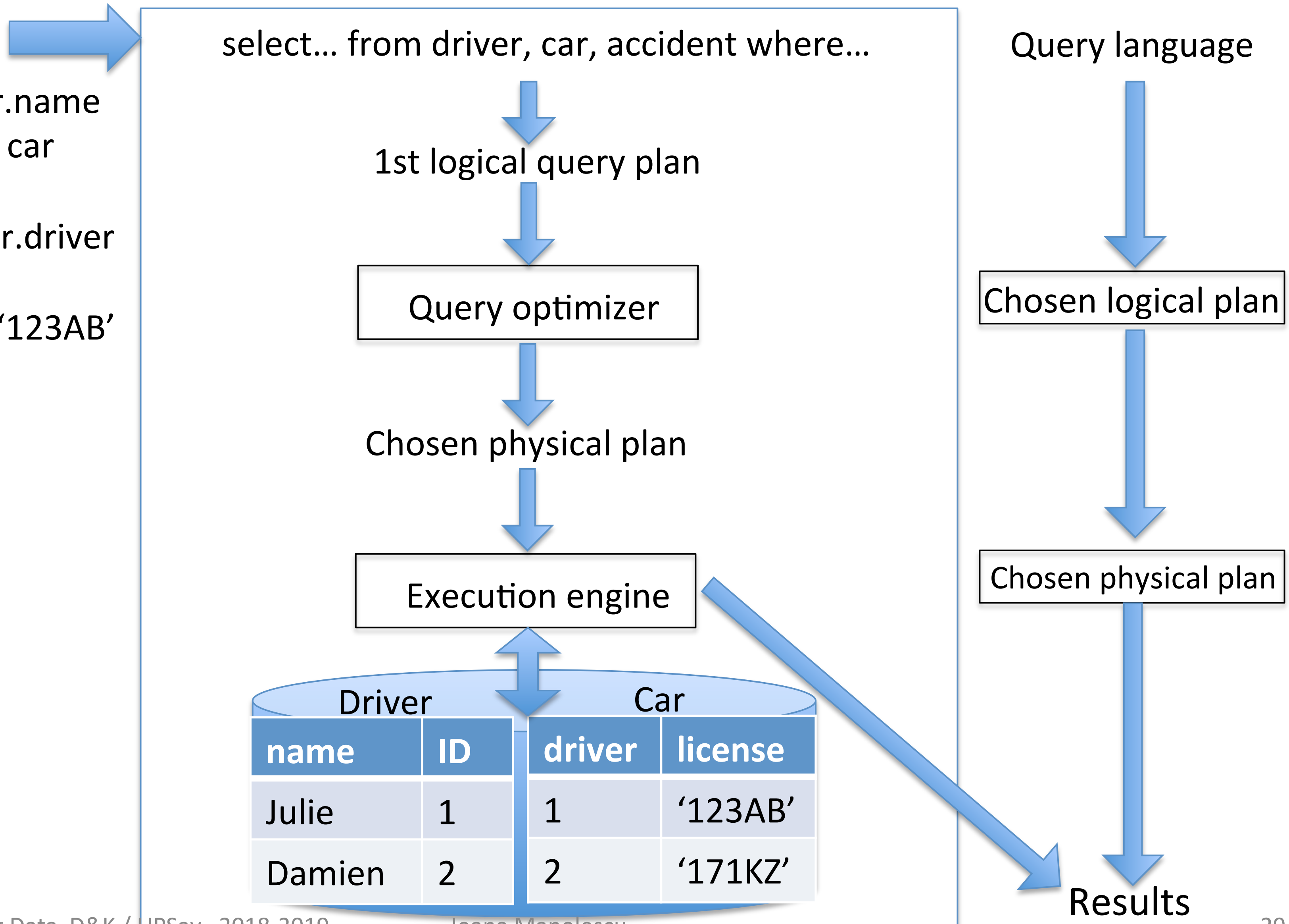
Car

driver	license
1	'123AB'
2	'171KZ'

Database internals: query processing pipeline

SQL

select driver.name
from driver, car
where
driver.ID=car.driver
and
car.license='123AB'



Driver

name	ID
Julie	1
Damien	2

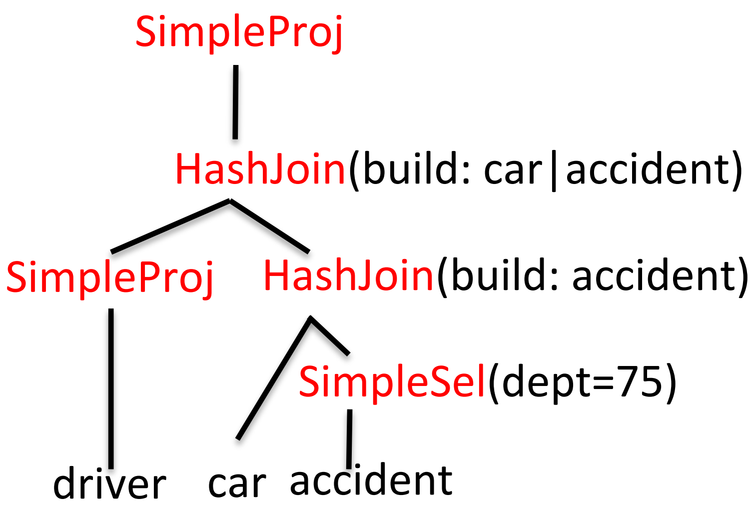
Car

driver	license
1	'123AB'
2	'171KZ'

Advanced query optimization techniques: Dynamic Query Optimization

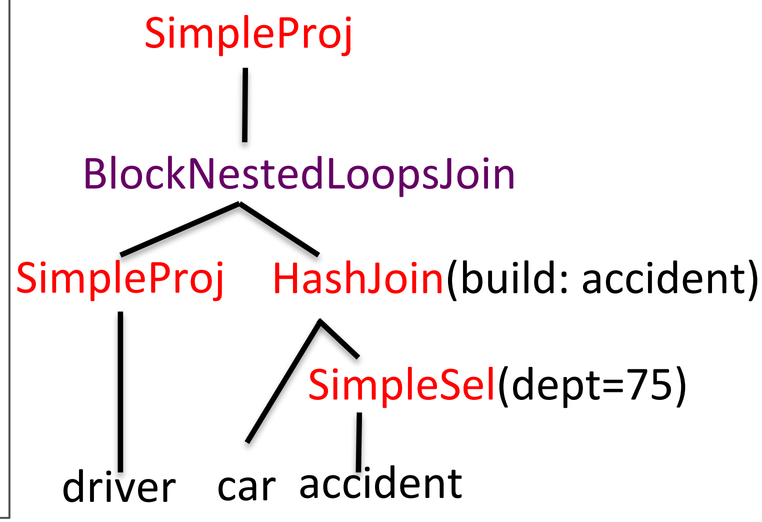
- Sizes (cardinalities) of intermediary results are estimated, which may lead to estimation errors
- A cardinality estimation error may lead to chosing a logical plan and a set of physical operators that perform significantly different from expectation (especially for the worse)

Initially chosen plan:



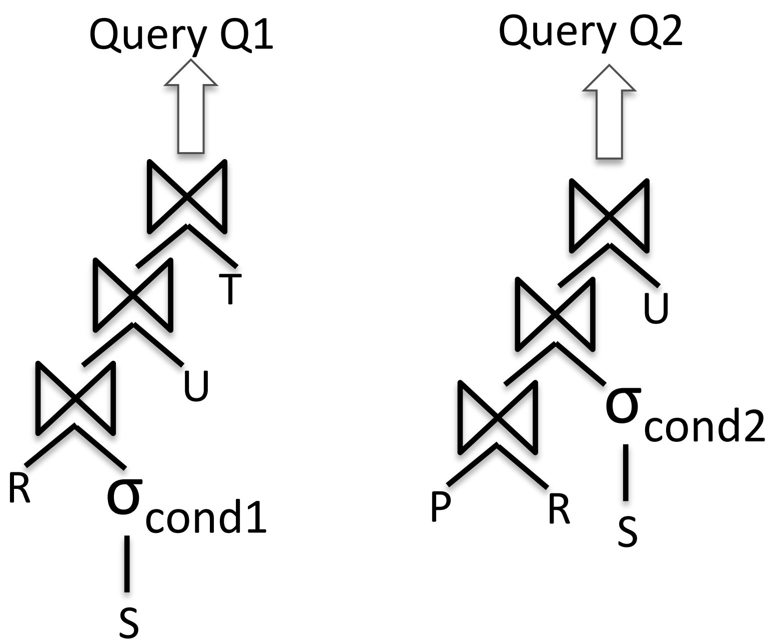
At execution time, we see that the lower HashJoin output is larger than expected: memory insuffi-cient to build

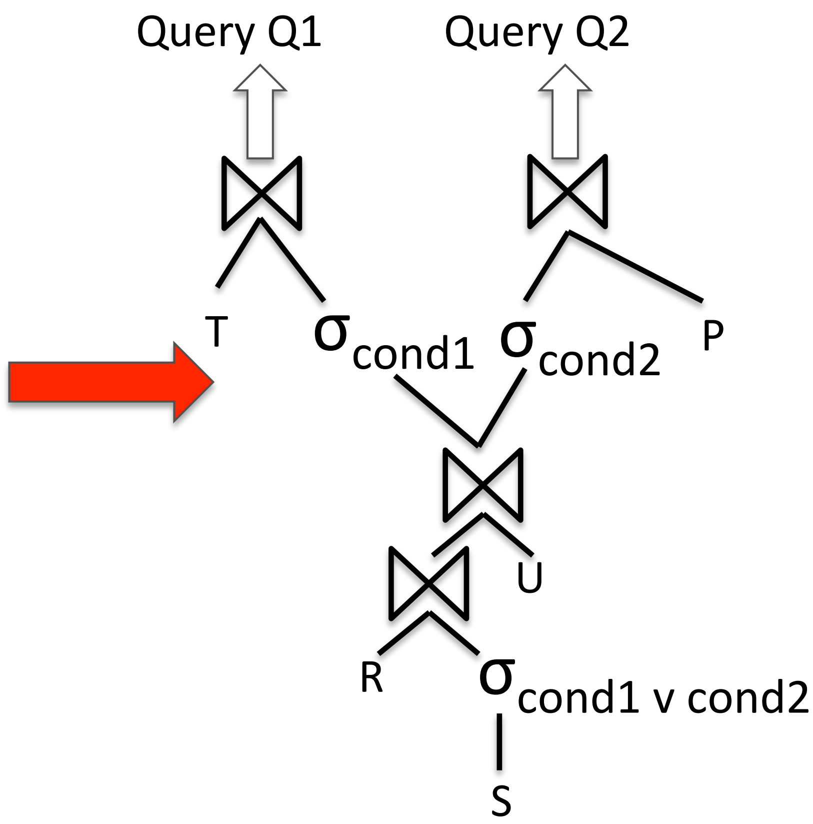
Modified plan:



Advanced query optimization techniques: Multi-Query Optimization

Multiple queries sharing sub-expressions can be optimized together into a single plan with **shared subexpressions**





followed by choice of physical operators

Assume join conditions are the same for R-S and S-U

What's in a database?

SQL update

insert into driver values ('Thomas', 3);
update car set driver=3 where license='123AB';

Database

Accident

Driver

name	ID
Julie	1
Damien	2

Car

driver	license
1	‘123AB’
2	‘171KZ’

Database

Accident

Driver

name	ID
Julie	1
Damien	2
Thomas	3

Car

driver	license
3	‘123AB’
2	‘171KZ’

Database updates

- A set of operations atomically executed (either all, or none) is called a **transaction**
- There may be some **dependencies** between the operations of a transaction
  - First read the bank account balance
  - Then write that value reduced by 50€
- A total order over the operations of several concurrent transaction is called a **scheduling**
- The DB component that receives all incoming transactions and decides what operation will be executed when (i.e., <u>global order</u> over the operations of all transactions) is called a **scheduler**

Database updates

- The scheduler is in charge of ordering all operations so that they will appear executed one after the other (serially)

```
T1: BEGIN   A=A+100,   B=B-100   END
T2: BEGIN   A=1.06*A,   B=1.06*B   END
```

```
T1:  A=A+100,  B=B-100,
T2:                              A=1.06*A,   B=1.06*B
```

```
T1:  A=A+100,                 B=B-100
T2:             A=1.06*A,              B=1.06*B
```

ARCHITECTURES FOR BIG DATA:

WHAT NEEDS TO CHANGE?

What is the impact of Big Data properties on database architectures?

- Volume requires **distribution**
  - Of the data storage; of query evalution
  - Distribution makes **ACID difficult** (CAP theorem) ✔
    - Complicates concurrency control
    - Replication, eventual consistency
  - Distribution requires efficient, easy-to-use **parallelism**
  - Distribution raises issues of **control** which can lead to single point of failure → **decentralization**
- Velocity requires efficient algorithms
  - Optimize for throughput (rather than response time)
  - Stream processing, in-memory architectures
  - Process-then-store (or process-then-discard)

What is the impact of Big Data properties on database architectures?

- Variety requires support for
  - **flexible data models**: key-values, JSON, graphs...
  - **different schemas**, and translation mechanisms between the schemas
    - Data integration
  - **several data models** being used together
    - Mediators, Data lakes
- Veracity requires support for reconciliation, data cleaning etc.
  - Similar to single-database setting, but adding source, source confidence, and provenance information

Roadmap for the rest of the course

1. Analysis of large-scale (in particular, distributed) Big Data platforms
   – Focus on: distribution of data and query processing, concurrency control
2. A selection of NoSQL platforms
   – Choice of most popular ones in their class
   – To illustrate variety of data models, and some distribution choices