CS 4440 A

Emerging Database Technologies

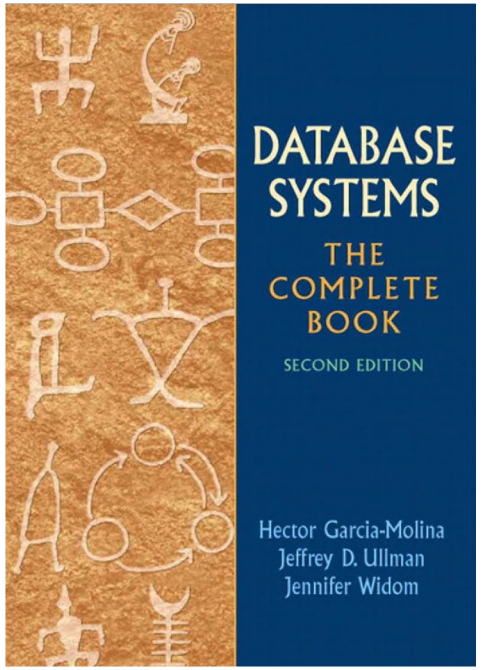
Lecture 2

01/08/25

Reading Materials

Database Systems: The Complete Book (2nd edition)

- Chapter 2.1: An Overview of Data Models
- Chapter 2.2: Basics of the Relation Model
- Chapter 2.4: An Algebraic Query Language



Acknowledgement: The following slides have been adapted from CS145 (Intro to Big Data Systems) taught by Peter Bailis.

Today's Class

1. Data Model
2. Relational Algebra: Basic Operators
3. Relational Algebra Pt. II

1. Data Model

Data models

- Relational → RDBMS

- Key/Value
- Graph
- Document (Semi-structured)
- Column-family

} NoSQL

- Array/Matrix → Machine Learning

- Hierarchical
- Network

} Obsolete

Data model

A notation for describing data or information.

The description generally consists of three parts:

- Structure of the data
- Operations on the data
- Constraints on the data

1st Part of the Model: Structure of the data

- Referred to as a “conceptual model” of the data
- Higher level than “physical data models” or data structures like arrays and lists

sid	name	gpa
001	Bob	3.2
002	Joe	2.8
003	Mary	3.8
004	Alice	3.5

Example: a relation consists of a schema, attributes, and tuples

The Relational Model: Schema

- Relational Schema:

Relation name

String, float, int, etc. are the domains of the attributes

Attributes

The Relational Model: Data

An attribute (or column) is a typed data entry present in each tuple in the relation

Student

sid	name	gpa
001	Bob	3.2
002	Joe	2.8
003	Mary	3.8
004	Alice	3.5

The number of attributes is the arity of the relation

The Relational Model: Data

Student

sid	name	gpa
001	Bob	3.2
002	Joe	2.8
003	Mary	3.8
004	Alice	3.5

The number of tuples is the cardinality of the relation

A tuple or row (or record) is a single entry in the table having the attributes specified by the schema

The Relational Model: Data

Student

sid	name	gpa
001	Bob	3.2
002	Joe	2.8
003	Mary	3.8
004	Alice	3.5

Note: In practice DBMSs relax the set requirement, and use multisets.

A relational instance is a set of tuples all conforming to the same schema

Equivalent representations of a relation

- A relation is a set of tuples (not a list)
- A schema is a set of attributes (not a list)
- Hence, the order of tuples or attributes of a relation is immaterial

sid	name	gpa
001	Bob	3.2
002	Joe	2.8
003	Mary	3.8
004	Alice	3.5

name	sid	gpa
Joe	002	2.8
Mary	003	3.8
Alice	004	3.5
Bob	001	3.2

In-class exercise

How many ways are there to represent this relation?

sid	name	gpa
001	Bob	3.2
002	Joe	2.8
003	Mary	3.8
004	Alice	3.5

To Reiterate

- A *relational schema* describes the data that is contained in a *relational instance*

Let $R(f_1:Dom_1,\ldots,f_m:Dom_m)$ be a relational schema then, an instance of R is a subset of $Dom_1 \times Dom_2 \times \ldots \times Dom_n$

In this way, a relational schema R is a total function from attribute names to types

A relational database

- A *relational database schema* is a set of relational schemata, one for each relation

- A *relational database instance* is a set of relational instances, one for each relation

Two conventions:
1. We call relational database instances as simply **databases**
2. We assume all instances are valid, i.e., satisfy the domain constraints

2nd Part of the Model: Operations on the data

Usually a limited set of operations that can be performed

- Queries (operations that retrieve information)
- Modifications (operations that change the database)

This is a strength, not a weakness

- Programmers can describe operations at a very high level
- The DBMS implements them efficiently
- Not easy to do when coding in C

The Relational Model: Operations

"Find names of all students with GPA > 3.5"

```
SELECT S.name
FROM Students S
WHERE S.gpa > 3.5;
```

We specify how or where to get the data - just what we want, i.e., Querying is declarative

To make this happen, we need to translate the declarative query into a series of operators…

The operations normally associated with the relational model forms relational algebra

Comparison: the relational model

Structure
- Based on tables (relations)

Operations
- Relational Algebra

Constraints
- Key constraints, referential integrity constraints

sid	name	gpa
001	Bob	3.2
002	Joe	2.8
003	Mary	3.8
004	Alice	3.5

Comparison: the key-value model

Structure
- (key, value) pairs
- Key is a string or integer
- Value can be any blob of data

Operations
- get (key), put(key, value)
- Operations on values not supported

Constraints
- e.g., key is unique, value is not NULL

key	value
1000	(Bob, 3.2)
1001	(Joe, 2.8)
1002	(Mary, 3.8)
1003	(Alice, 3.5)

Comparison of data models

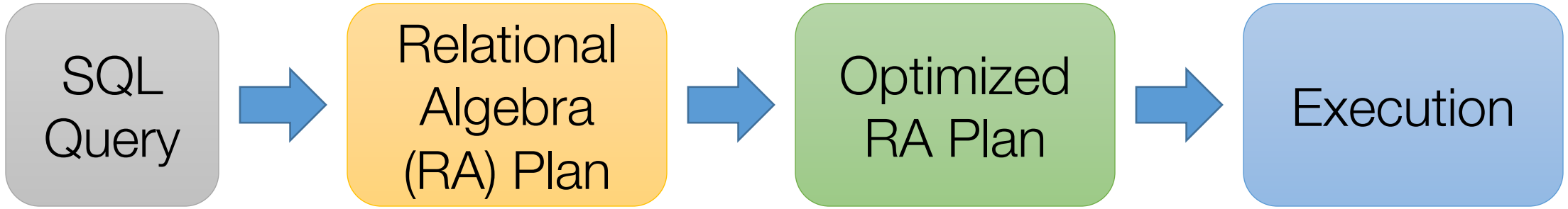
Let's compare the relational model and the key-value model in the following aspects. Which one is better?

- Flexibility? Key-value
- Queryability? Relational
- Performance? Relational

2. Relational Algebra

The big picture: RDBMS Architecture

How does a SQL engine work ?



Declarative query (from user)

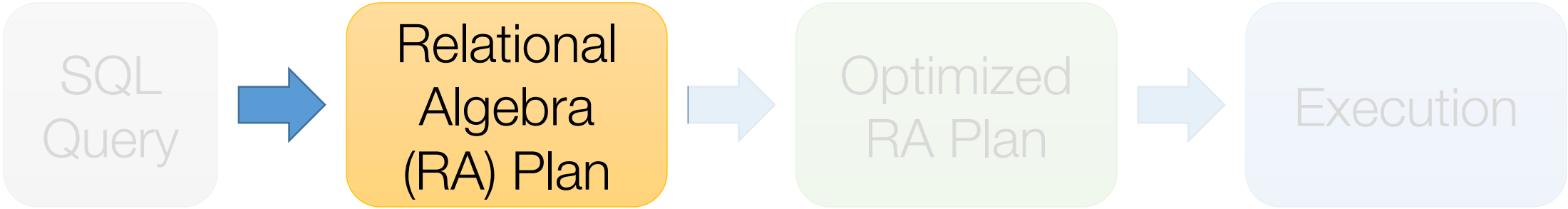
Translate to relational algebra expression

Find logically equivalent- but more efficient- RA expression

Execute each operator of the optimized plan!

The big picture: RDBMS Architecture

How does a SQL engine work ?



Relational Algebra allows us to translate declarative (SQL) queries into precise and optimizable expressions!

Relational Algebra (RA)

- Five **basic** operators:
  1. Selection: σ
  2. Projection: Π
  3. Cartesian Product: $\times$
  4. Union: $\cup$
  5. Difference: -
- Derived or auxiliary operators:
  - Intersection, complement
  - Joins (natural, equi-join, theta join, semi-join)
  - Renaming: ρ
  - Grouping: γ

We'll look at these first!

And also at one example of a derived operator (natural join) and a special operator (renaming)

Note: RA operates on sets!

- RDBMSs use *multisets*, however in relational algebra formalism we will consider **sets!**

- Also: we will consider the ***named perspective***, where every attribute must have a unique name
  - →attribute order does not matter…

Now on to the basic RA operators…

1. Selection (σ)

- Returns all tuples which satisfy a condition
- Notation: $\sigma_c(R)$
- Examples
  - $\sigma_{\text{Salary} > 40000}$ (Employee)
  - $\sigma_{\text{name} = \text{“Smith”}}$ (Employee)
- The condition c can be =, <, ≤, >, ≥, <>

```
Students(sid,sname,gpa)
```

SQL:

```
SELECT *
FROM Students
WHERE gpa > 3.5;
```

RA:

$$\sigma_{gpa>3.5}(Students)$$

Another example:

SSN	Name	Salary
1234545	John	200000
5423341	Smith	600000
4352342	Fred	500000

$\sigma_{Salary > 40000}$ (Employee)

SSN	Name	Salary
5423341	Smith	600000
4352342	Fred	500000

2. Projection (Π)

- Eliminates columns, then removes duplicates
- Notation: $\Pi_{A1,\ldots,An}(R)$
- Example: project social-security number and names:
  - $\Pi_{SSN,\ Name}$ (Employee)
  - Output schema: Answer(SSN, Name)

```
Students(sid,sname,gpa)
```

SQL:

```
SELECT DISTINCT
   sname,
   gpa
FROM Students;
```

RA:

$$\Pi_{sname,gpa}(Students)$$

Another example:

SSN	Name	Salary
1234545	John	200000
5423341	John	600000
4352342	John	200000

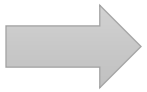
$\Pi_{\text{Name,Salary}}$ (Employee)

Name	Salary
John	200000
John	600000

Note that RA Operators are Compositional!

```
Students(sid,sname,gpa)
```

```
SELECT DISTINCT
   sname,
   gpa
FROM Students
WHERE gpa > 3.5;
```



$$\Pi_{sname,gpa}(\sigma_{gpa>3.5}(Students))$$

$$\sigma_{gpa>3.5}(\Pi_{sname,gpa}(Students))$$

How do we represent this query in RA?

Are these logically equivalent?

3. Cross-Product (×)

- Each tuple in R1 with each tuple in R2
- Notation: R1 × R2
- Example:
  - Employee × Dependents
- Rare in practice; mainly used to express joins

```
Students(sid,sname,gpa)
People(ssn,pname,address)
```

SQL:

```
SELECT *
FROM Students, People;
```

RA:

$$Students \times People$$

Another example:

People

ssn	pname	address
1234545	John	216 Rosse
5423341	Bob	217 Rosse

$\times$

Students

sid	sname	gpa
001	John	3.4
002	Bob	1.3

$$Students \times People$$

ssn	pname	address	sid	sname	gpa
1234545	John	216 Rosse	001	John	3.4
5423341	Bob	217 Rosse	001	John	3.4
1234545	John	216 Rosse	002	Bob	1.3
5423341	Bob	216 Rosse	002	Bob	1.3

Renaming (ρ)

- Changes the schema, not the instance
- A 'special' operator- neither basic nor derived
- Notation: $\rho_{B1,\ldots,Bn}(R)$

- Note: this is shorthand for the proper form (since names, not order matters!):
  - $\rho_{A1 \rightarrow B1,\ldots,An \rightarrow Bn}(R)$

```
Students(sid,sname,gpa)
```

SQL:

```
SELECT
   sid AS studId,
   sname AS name,
   gpa AS gradePtAvg
FROM Students;
```

RA:

$$\rho_{studId,name,gradePtAvg}(Students)$$

Another example:

Students

sid	sname	gpa
001	John	3.4
002	Bob	1.3

$\rho_{studId,name,gradePtAvg}(Students)$

Students

studId	name	gradePtAvg
001	John	3.4
002	Bob	1.3

Natural Join (⋈)

- $R_1 \bowtie R_2$: Joins R_1 and R_2 on *equality of all shared attributes*
  - If R_1 has attribute set A, and R_2 has attribute set B, and they share attributes A ⋂ B = C, can also be written: $R_1 \bowtie_C R_2$

- Our first example of a *derived* RA operator:
  - $R_1 \bowtie R_2 = \Pi_{A \cup B}(\sigma_{C=D}(\rho_{C \to D}(R_1) \times R_2))$
  - Where:
    - The rename $\rho_{C \to D}$ renames the shared attributes in one of the relations
    - The selection $\sigma_{C=D}$ checks equality of the shared attributes
    - The projection $\Pi_{A \cup B}$ eliminates the duplicate common attributes

```
Students(sid,name,gpa)
People(ssn,name,address)
```

SQL:

```
SELECT DISTINCT
  ssid, S.name, gpa,
  ssn, address
FROM
  Students S,
  People P
WHERE S.name = P.name;
```

RA:

$$Students \bowtie People$$

Another example:

Students S

sid	S.name	gpa
001	John	3.4
002	Bob	1.3

$\bowtie$

People P

ssn	P.name	address
1234545	John	216 Rosse
5423341	Bob	217 Rosse

$$Students \bowtie People$$

sid	S.name	gpa	ssn	address
001	John	3.4	1234545	216 Rosse
002	Bob	1.3	5423341	216 Rosse

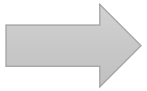
In class exercise

- Given schemas R(A, B, C, D), S(A, C, E), what is the schema of R ⋈ S ?
- Given R(A, B), S(A, B), what is R ⋈ S ?
- Given R(A, B, C), S(D, E), what is R ⋈ S ?

Example: Converting SFW Query -> RA

```
Students(sid,name,gpa)
People(ssn,name,address)
```

```
SELECT DISTINCT
   gpa,
   address
FROM Students S,
      People P
WHERE gpa > 3.5 AND
    S.name = P.name;
```



$$\Pi_{gpa,address}(\sigma_{gpa>3.5}(S \bowtie P))$$

How do we represent this query in RA?

2. Relational Algebra Pt. II

Relational Algebra (RA)

- Five **basic** operators:
  1. Selection: σ
  2. Projection: Π
  3. Cartesian Product: $\times$
  4. Union: $\cup$
  5. Difference: -

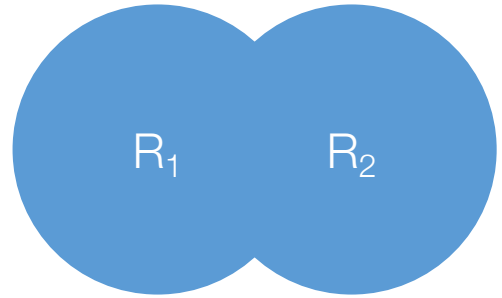
We'll look at these

- Derived or auxiliary operators:
  - Intersection, complement
  - Joins (natural, equi-join, theta join, semi-join)
  - Renaming: ρ
  - Grouping: γ

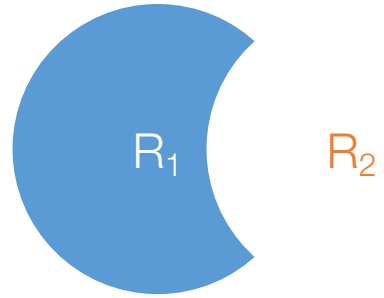
And also at some of these derived operators

Union (∪) and 2. Difference (–)

- R1 ∪ R2
- Example:
  - ActiveEmployees ∪ RetiredEmployees

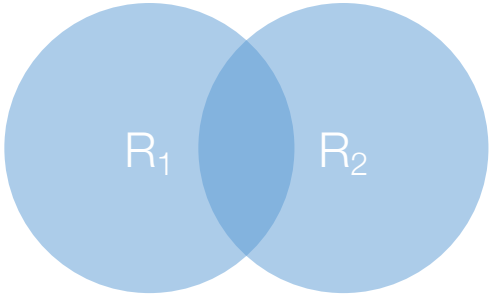


- R1 – R2
- Example:
  - AllEmployees -- RetiredEmployees



What about Intersection (∩) ?

- It is a derived operator
- R1 ∩ R2 = R1 – (R1 – R2)
- Also expressed as a join!
- Example
  - UnionizedEmployees ∩ RetiredEmployees



Theta Join ($\bowtie_\theta$)

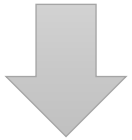
- A join that involves a predicate
- R1 $\bowtie_\theta$ R2 $= \sigma_\theta$ (R1 $\times$ R2)
- Here θ can be any condition

Note that natural join is a theta join + a projection.

```
Students(sid,sname,gpa)
People(ssn,pname,address)
```

SQL:

```
SELECT *
FROM
  Students,People
WHERE θ;
```



RA:

$$Students \bowtie_\theta People$$

Equi-join ($\bowtie_{A=B}$)

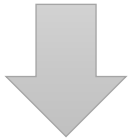
- A theta join where θ is an equality
- $R1 \bowtie_{A=B} R2 = \sigma_{A=B}(R1 \times R2)$
- Example:
  - Employee $\bowtie_{SSN=SSN}$ Dependents

Most common join in practice!

```
Students(sid,sname,gpa)
People(ssn,pname,address)
```

SQL:

```
SELECT *
FROM
  Students S,
  People P
WHERE sname = pname;
```



RA:

$$S \bowtie_{sname=pname} P$$

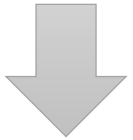
Semijoin (⋉)

- $R \ltimes S = \Pi_{A1,\ldots,An} (R \bowtie S)$
- Where $A_1, \ldots, A_n$ are the attributes in R
- Example:
  - Employee ⋉ Dependents

```
Students(sid,sname,gpa)
People(ssn,pname,address)
```

SQL:

```
SELECT DISTINCT
   sid,sname,gpa
FROM
   Students,People
WHERE
   sname = pname;
```

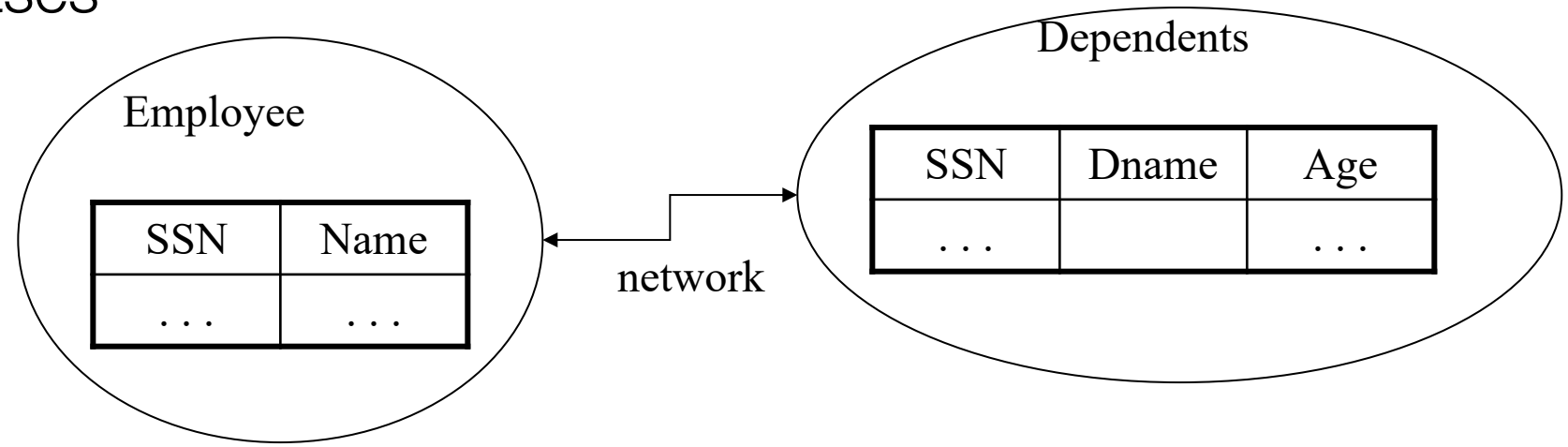


RA:

$$Students \ltimes People$$

Semijoins in Distributed Databases

- Semijoins are often used to compute natural joins in distributed databases



Send less data to reduce network bandwidth!

$$\text{Employee} \bowtie_{ssn=ssn} (\sigma_{age>71} (\text{Dependents}))$$

$$T = \Pi_{SSN} (\sigma_{age>71} (\text{Dependents}))$$

$$R = \text{Employee} \ltimes T$$

$$\text{Answer} = R \bowtie \text{Dependents}$$

Grouping (γ)

- The grouping operator γ consists of
  - Grouping attributes: attributes to group by
  - Aggregation attributes: attributes to which aggregation operations are applied
    - SUM, AVG, MIN, MAX, COUNT

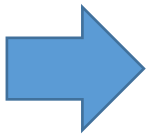
R

A	B	C
1	1	1
1	2	3
2	3	5

$\gamma_{\text{A, MIN(B)->minB, AVG(C)->avgC}}(R)$

Grouping attribute

Aggregation attributes



A	minB	avgC
1	1	2
2	3	5

Combining operations to form queries

- RA expressions can be arbitrarily complicated by applying operations to other results
- Multiple RA expressions may be equivalent

$$\Pi_{A,D}(\sigma_{A<10}(T \bowtie (R \bowtie S)))$$

R(A,B) S(B,C) T(C,D)

=

$$\Pi_{A,D}\left(T \bowtie \Pi_{A,C}(\sigma_{A<10}(R) \bowtie S)\right)$$

Which version is more efficient?

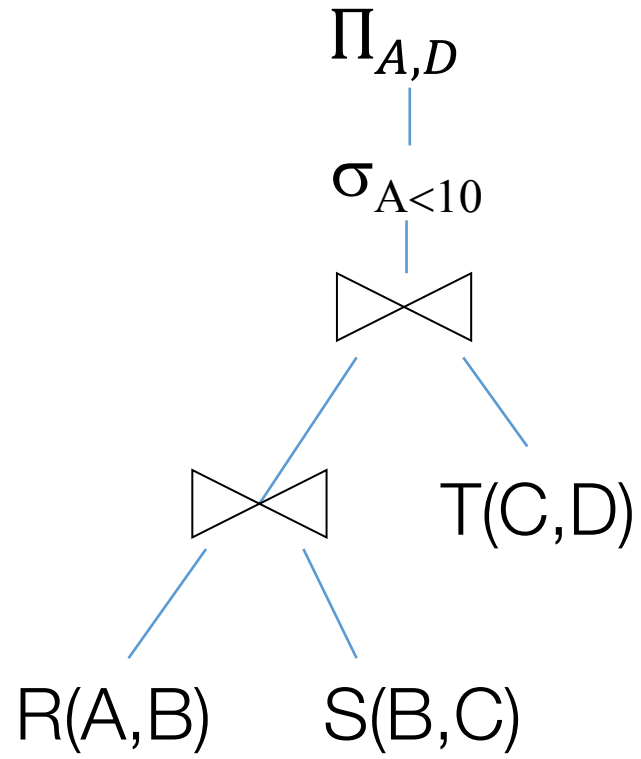
Logical optimization (will cover later): Find equivalent RA expressions that are more efficient

Expression tree

RA expressions can be represented as expression trees

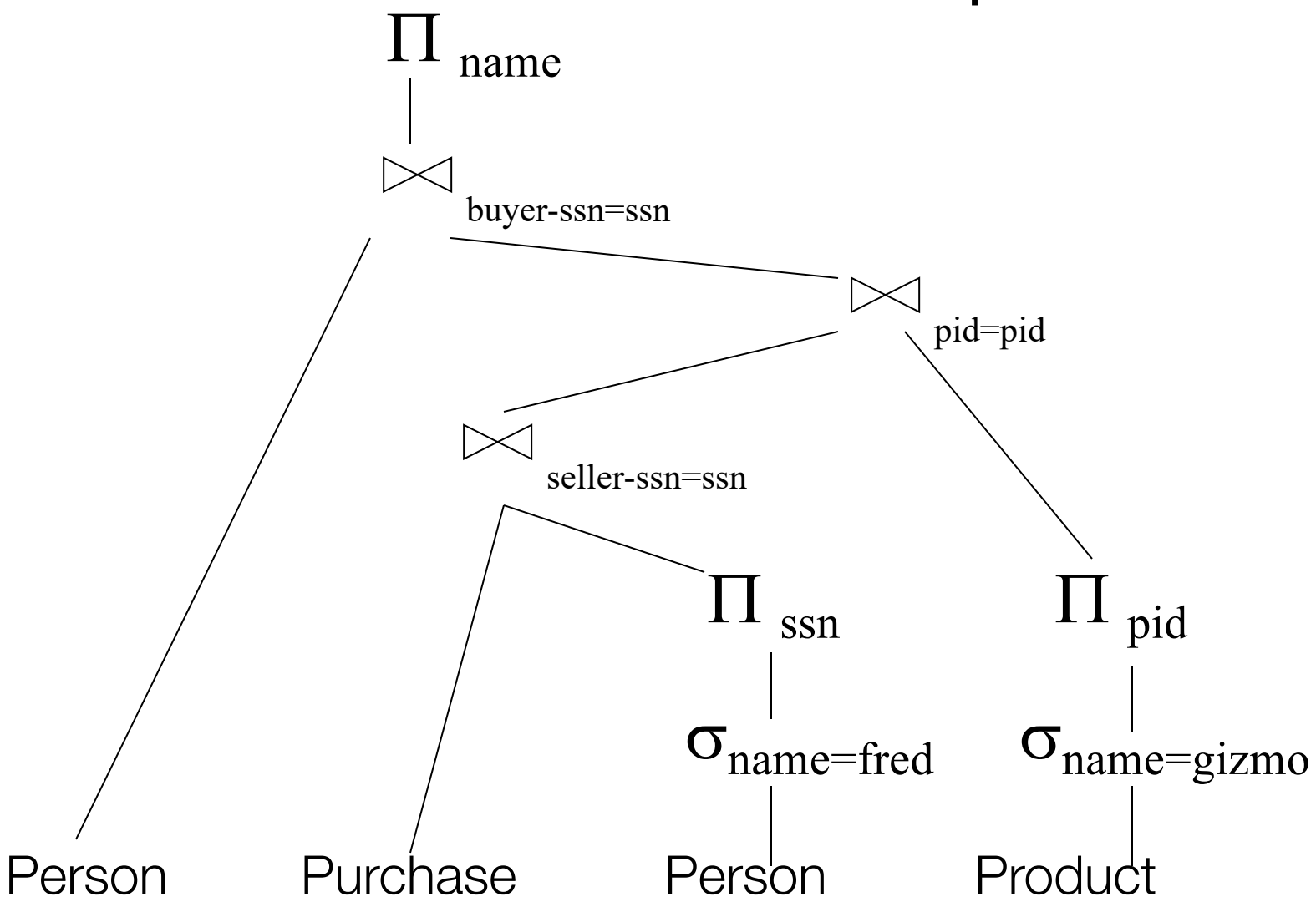
$$\Pi_{A,D}(\sigma_{A<10}(T \bowtie (R \bowtie S)))$$

=



Bottom-up tree traversal = order of operation execution!

RA Expressions Can Get Complex!



In class exercise

Suppose relations R and S have n and m tuples, respectively

What are the minimum / maximum number of tuples of the following expressions?

1. $R \cup S$
2. $R \bowtie S$
3. $\pi_L(R)$ – S, for some list of attributes L