Relational Algebra

Instructor: Shel Finkelstein

Reference:
A First Course in Database Systems,
3rd edition, Chapter 2.4 – 2.6, plus Query Execution Plans

Important Notices

- Lecture slides and other class information will be posted on Piazza (not Canvas).
  - Slides are posted under Resources→Lectures
  - Lecture Capture recordings are available to all students under Yuja.
    - That includes classes given over Zoom.
  - There's no Lecture Capture for Lab Sections.
- All Lab Sections (and Office Hours) normally meet In-Person, with rare exceptions announced on Piazza.
  - Some slides for Lab Sections have been posted on Piazza under Resources→Lab Section Notes
- Office Hours for TAs and me are posted in Syllabus and Lecture1, as well as in Piazza notice @7; that post also now includes hours for Group Tutors.
- Some suggestions about use (and non-use) of Generative AI systems such as ChatGPT were posted on Piazza in @41, with specific discussion about the Movies tables and the four Avatar queries in Lecture 4.

Important Notices

- CSE 180 Midterm was **on Wednesday, February 14.**
  - Midterm and Midterm answers were posted on Piazza under Resources→Exams on Wednesday, February 14.
  - Answers were discussed at the beginning of class on Friday, February 16.
- Midterm grades were unmuted on Tuesday, February 20.
  - Students can see submissions, scores and comments by accessing assignments on Canvas, which will take them to GradeScope.
- Median score was 83.5. There is no curve for the Midterm.
  - Maximum possible score was 101, but grades are treated as if out of 100. For example, 83.5 is 83.5/100 (83.5%), not 83.5/101.
- Ask your TA about your Midterm grade if you have questions about scoring, and then contact me if you still have questions.
  - You cannot request regrades within GradeScope.
  - Deadline for asking questions about Midterm grade is Monday, February 26.

Important Notices

- The Fourth Gradiance Assignment, CSE 180 Winter 2024 #2, was assigned on Friday, February 23.
  - You should have enough information to complete this Gradiance Assignment after the lecture on Friday, February 23.
  - It is due on Saturday, March 2, by 11:59pm (yes, on Saturday, not Sunday).
  - Some of the 9 Gradiance questions are difficult.
- The Winter 2024 CSE 180 Final is on Wednesday, March 20 from 8:00am – 11:00am in our usual classroom.

Important Notices

- Lab3 was posted on Piazza on Wednesday, February 14.
  - Lab3 is due on **Tuesday, February 27**.
    - Lab3 has many parts, and some parts of Lab3 are difficult.
    - You'll had enough information to do Lab3 after the class on on Friday, February 16.
      - You don’t need to use Triggers for Lab3.
  - You must use the Lab3 create file and load_lab3.sql file to do Lab3.
    - This original load data must be reloaded at multiple stages of Lab3.
    - The create_lab3.sql file was edited on Thursday, February 15 at about noon.
      - If you downloaded it before that, please download it again.
- To make Section 2.6.1 of Lab3 (createview.sql) simpler, I've modified the description of createview.sql on Tuesday, February 20 to include following line near the end:
  - For Lab3, you should assume that there's at least one role for every actor, so calculatedRowCount will be at least 1.

A Word to the Unwise

- This is a tough class for some students since it involves a combination of theory and practice.
  - The second half of CSE 180 is much harder than the first half of the course.
- Students who regularly attend Lectures and Lab Sections (and Office Hours and Tutoring) often do well; students who don't regularly attend often do poorly.
  - We don't take attendance; you're responsible for your own choices.
- After the course ends, your course grade will be determined by your scores on Exams, Labs and Gradiance, as described on the “Course Evaluation” and “Grading” Slides in the Syllabus.
  - You won't be able to do any additional work to improve your grade.

What is a Data Model?

- A *data model* is a mathematical formalism that consists of three parts:
  1. A notation for describing and representing data (structure of the data)
  2. A set of operations for manipulating data.
  3. A set of constraints on the data.

- What is the associated query language for the relational data model?

Two Query Languages

- Codd proposed two different query languages for the relational data model.
  - Relational Algebra
    - Queries are expressed as a sequence of operations on relations.
    - Procedural language.
  - Relational Calculus
    - Queries are expressed as formulas of first-order logic.
    - Declarative language.
- **Codd's Theorem**: The Relational Algebra query language has the same *expressive power* as the Relational Calculus query language.

Procedural vs. Declarative Languages

- **Procedural program**
  - The program is specified as a sequence of operations to obtain the desired the outcome. I.e., *how* the outcome is to be obtained.
  - E.g., Java, C, …
- **Declarative program**
  - The program specifies *what* is the expected outcome, and not *how* the outcome is to be obtained.
  - E.g., Scheme, Ocaml, …

SQL – Structured Query Language

- Is SQL a procedural or a declarative language?
  - SQL is usually described as declarative, but it's not fully declarative
  - However, relational database systems usually try to understand meaning of query, regardless of how query is expressed
    - There may be multiple equivalent ways to write a query

- SQL is the principal language used to describe and manipulate data stored in relational database systems.
  - Frequently pronounced as "Sequel", but formally it's "Ess Cue El"
  - Not the same as Codd's Relational Algebra or Relational Calculus

Some Properties of Good Database Query Languages and Database Systems

1. Physical database independence
   - Programmers should be able to write queries without understanding the mechanics of the physical layer
   - What was logical data independence?
2. Highly expressive
   - Programmers should be able to formulate simple and complex queries using the language.
3. Efficient execution
   - Systems should be able to compute answers to queries with “good” response time and throughput.

- Physical data independence is achieved by most query languages today.
- Increased expressiveness may come at the expense of not-so-good performance on some complex queries

Relational Algebra

- Relational Algebra: a query language for manipulating data in the relational data model.
  - Not used directly as a query language

- Internally, Relational Database Systems transform SQL queries into trees/graphs that are similar to relational algebra expressions.
  - Query analysis, transformation and optimization are performed based on these relational algebra expression-like representations.
  - Relational Databases use multi-sets/bags, but Relational Algebra is based on sets.
    - There are multi-set variations of Relational Algebra that permit duplicates, and that's more realistic for Relational Database …
    - … but we'll only discuss set-based Relational Algebra.

Composition

- Each Relational Algebra operator is either a unary or a binary operator.
- A complex Relational Algebra expression is built up from basic ones by composing simpler expressions.
- This is similar to SQL queries and views.

Relation Algebra Operators

- Queries in relational algebra are composed using basic operations or functions.
  - Selection (σ)
  - Projection (π)
  - Set-theoretic operations:
    - Union ($\cup$)
    - Set-difference (-)
    - Cross-product (x)
    - Intersection ($\cap$)
  - Renaming (ρ) and Assignment ($\leftarrow$)
  - Natural Join ($\bowtie$), Theta-Join ($\bowtie_\theta$)
  - Division (/ or $\div$)

Relation Algebra Operators

- Codd proved that the relational algebra operators (σ , π , x , U , -) are independent of each other. That is, you can't define any of these operators using the others.

- However, there are other important operators that can be expressed using (σ , π , x , U , -)
  - Theta Join, Join, Natural Join, Semi-Join
  - Set Intersection
  - Division (/ or ÷)
  - Outer Join (sections 5.2.7 and 6.3.8), which we'll discuss when we get to OLAP, On-Line Analytic Processing (section 10.6)

Selection: $\sigma_{condition}(R)$

- Unary operation
  - Input: Relation with schema $R(A_1, \ldots, A_n)$
  - Output: Relation with attributes $A_1, \ldots, A_n$
  - Meaning: Takes a relation R and extracts only the rows from R that satisfy the *condition*
  - Condition is a logical combination (using AND, OR, NOT) of expressions of the form:

    <expr> <op> <expr>

    where <expr> is an attribute name, a constant, a string, and op is one of (=, ≤, ≥, <, >, <>)
    - E.g., "age > 20 OR height < 6",
    - "name LIKE 'Anne%' AND salary > 200000"
    - "NOT (age > 20 AND salary < 100000)"

Example of σ

- $\sigma_{rating > 6}$ (Hotels)

Hotels

name	address	rating	capacity
~~Windsor~~	~~54th ave~~	~~6.0~~	~~135~~
Astoria	5th ave	8.0	231
BestInn	45th st	6.7	28
~~ELodge~~	~~39 W st~~	~~5.6~~	~~45~~
~~ELodge~~	~~2nd E st~~	~~6.0~~	~~40~~

name	address	rating	capacity
Astoria	5th ave	8.0	231
BestInn	45th st	6.7	28

Example of σ with AND in Condition

- $\sigma_{\text{rating} > 6 \text{ AND capacity} > 50}$ (Hotel)

name	address	rating	capacity
Windsor	54th ave	6.0	135
Astoria	5th ave	8.0	231
BestInn	45th st	6.7	28
ELodge	39 W st	5.6	45
ELodge	2nd E st	6.0	40

name	address	rating	capacity
Astoria	5th ave	8.0	231

- Is $\sigma_{C1}(\sigma_{C2}(R)) = \sigma_{C1 \text{ AND } C2}(R)$?
- Prove or give a counter-example.

- Is $\sigma_{C1}(\sigma_{C2}(R)) = \sigma_{C2}(\sigma_{C1}(R))$?
- Prove or give a counter-example.

Projection: $\pi_{<attribute\ list>}(R)$

- Unary operation
  - Input : Relation with schema $R(A_1, \ldots, A_n)$
  - Output: Relation with attributes in *attribute list,* which must be attributes of R
  - Meaning: For every tuple in relation R, output only the attributes appearing in *attribute list*
- May be duplicates; for Codd's Relational Algebra, duplicates are always eliminated (set-oriented semantics)
  - Reminder: For relational database, duplicates matter.
  - Why?

Example of π

- $\pi_{name,\ address}$ (Hotels)

name	address
Windsor	54th ave
Astoria	5th ave
BestInn	45th st
ELodge	39 W st
ELodge	2nd E st

- Suppose that name and address form the key of the Hotels relation. Is the cardinality of the output relation the same as the cardinality of Hotels? Why?

Example of π

- π_{name} (Hotel)

name
Windsor
Astoria
BestInn
ELodge

- Note that there are no duplicates.

Set Union: R ∪ S

- Binary operator
  - Input: Two relations R and S which must be union-compatible
    - They have the same arity, i.e., the same number of columns.
    - For every column i, the i'th column of R has the same type as the i'th column of S.
    - Note that field names are not used in defining union-compatibility.
      - We can think of relations R and S as being union-compatible if they are sets of records having the same record type.
  - Output: Relation that has the same type as R (or same type as S).
  - Meaning: The output consists of the set of all tuples in either R or S (or both)

The schema in this example is prehistoric, … but it demonstrates Relational Operators, so I haven't updated it.

Example of ∪

Dell_Desktops ∪ HP_Desktops

Dell_Desktops

Harddisk	Speed	OS
20G	500Mhz	Windows
30G	1.0Ghz	Windows
20G	750Mhz	Linux

HP_Desktops

Harddisk	Speed	OS
30G	1.2Ghz	Windows
20G	500Mhz	Windows

All tuples in R occurs in R ∪ S.
All tuples in S occurs in R ∪ S.
R ∪ S contains tuples that either occur in R or S (or both).

Harddisk	Speed	OS
20G	500Mhz	Windows
30G	1.0Ghz	Windows
20G	750Mhz	Linux
30G	1.2Ghz	Windows

Properties of ∪

Dell_Desktops ∪ HP_Desktops

R ∪ S = S ∪ R (commutativity)
(R ∪ S) ∪ T = R ∪ (S ∪ T) (associativity)

Dell_Desktops

Harddisk	Speed	OS
20G	500Mhz	Windows
30G	1.0Ghz	Windows
20G	750Mhz	Linux

HP_Desktops

Harddisk	Speed	OS
30G	1.2Ghz	Windows
20G	500Mhz	Windows

Harddisk	Speed	OS
20G	500Mhz	Windows
30G	1.0Ghz	Windows
20G	750Mhz	Linux
30G	1.2Ghz	Windows

Set Difference: R - S

- Binary operator.
  - Input: Two relations R and S which must be union-compatible
  - Output: Relation with the same type as R (or same type as S)

  - Meaning: Output consists of all tuples in R but not in S

Example of -

- Dell_Desktops - HP_Desktops

Dell_Desktops

Harddisk	Speed	OS
20G	500Mhz	Windows
30G	1.0Ghz	Windows
20G	750Mhz	Linux

HP_Desktops

Harddisk	Speed	OS
30G	1.2Ghz	Windows
20G	500Mhz	Windows

Dell_Desktops – HP_Desktops

Harddisk	Speed	OS
30G	1.0Ghz	Windows
20G	750Mhz	Linux

Properties of -

- HP_Desktops – Dell_Desktops

Dell_Desktops

Harddisk	Speed	OS
20G	500Mhz	Windows
30G	1.0Ghz	Windows
20G	750Mhz	Linux

HP_Desktops

Harddisk	Speed	OS
30G	1.2Ghz	Windows
20G	500Mhz	Windows

HP_Desktops – Dell_Desktops

Harddisk	Speed	OS
30G	1.2Ghz	Windows

Is it commutative?
Is it associative?

Product: R x S

- Binary operator
  - Input: Two relations R and S, where R has relation schema $R(A_1, \ldots, A_m)$ and S has relation schema $S(B_1, \ldots, B_n)$.
  - Output: Relation of arity m+n
  - Meaning:

    $R \times S = \{ (a_1, \ldots, a_m, b_1, \ldots, b_n) \mid (a_1, \ldots, a_m) \in R \text{ and } (b_1, \ldots, b_n) \in S) \}$.
    - Read "|" as "such that"
    - Read "$\in$" as "belongs to"

Example and Properties of Product

R

A	B	C
a_1	b_1	c_1
a_2	b_2	c_2

S

D	E
d_1	e_1
d_2	e_2
d_3	e_3

R x S

A	B	C	D	E
a_1	b_1	c_1	d_1	e_1
a_1	b_1	c_1	d_2	e_2
a_1	b_1	c_1	d_3	e_3
a_2	b_2	c_2	d_1	e_1
a_2	b_2	c_2	d_2	e_2
a_2	b_2	c_2	d_3	e_3

- Is x commutative?
- Is x associative?
- Is x distributive across ∪? That is, does R x (S ∪ T) = (R x S) ∪ (R x T) ?

Product and Common Attributes

- What happens when we compute the Product of R and S if R and S contain common attributes, e.g., for R(A,B,C) and S(A,E)?

R.A	B	C	S.A	E
a_1	b_1	c_1	d_1	e_1
a_1	b_1	c_1	d_2	e_2
a_1	b_1	c_1	d_3	e_3
a_2	b_2	c_2	d_1	e_1
a_2	b_2	c_2	d_2	e_2
a_2	b_2	c_2	d_3	e_3

Derived Operators

- So far, we have learned:
  - Selection
  - Projection
  - Product
  - Union
  - Difference

- Some other operators can be derived by composing the operators we have learned so far:
  - Theta-Join, Join, Natural Join, Semi-Join
  - Set Intersection
  - Division/Quotient
  - Outer Join (to be discussed when we get to OLAP)

Theta-Join: $R \bowtie_\theta S$

- Binary operator
  - Input: $R(A_1, \ldots, A_m)$, $S(B_1, \ldots, B_n)$
  - Output: Relation consisting of all attributes $A_1, \ldots, A_m$ and all attributes $B_1, \ldots, B_n$. Identical attributes in R and S are disambiguated with the relation names.
  - Meaning of $R \bowtie_\Theta S$: The θ-Join outputs those tuples from R x S that satisfy the condition θ.
    - Compute R x S, then keep only those tuples in R x S that satisfy θ.
    - Equivalent to writing $\sigma_\theta(R \times S)$
- If θ always evaluates to TRUE, then $R \bowtie_\Theta S = \sigma_\theta(R \times S) = R \times S$.

Example of Theta-Join

Enrollment(esid, ecid, grade)

Course(cid, cname, instructor-name)

Please give me an example of a Theta-Join to write on the board where ecid in Enrollment equals cid in Course.

- Joins involving equality predicates (usually just called Joins or Equi-Joins) are very common in database; other joins are less common.
  - Enrollment $\bowtie_{\theta}$ Course, where θ could be:
    "Enrollment.ecid = Course.cid"

- Could write <u>any</u> condition involving attributes of Enrollment and Course as θ, just as with σ.

Natural Join: R ⋈ S

- Often a query over two relations can be formulated using Natural Join.
- Binary operator:
  - Input: Two relations R and S where $\{ A_1, \ldots, A_k \}$ is the set of common attributes (column names) between R and S.
  - Output: A relation where its attributes are attr(R) U attr(S). In other words, the attributes consists of the attributes in R x S without repeats of the common attributes $\{ A_1, \ldots, A_k \}$

- Meaning:

  $R \bowtie S = \pi_{(attr(R) \cup attr(S))} (\sigma_{R.A1=S.A1 \text{ AND } R.A2 = S.A2 \text{ AND } \ldots \text{ AND } R.Ak=S.Ak} (R \times S))$

1. Compute R x S
2. Keep only those tuples in R x S satisfying:
   R.A1=S.A1 AND R.A2 = S.A2 AND … AND R.Ak=S.Ak
3. Output is projection on the set of attributes in R U S (without repeats of the attributes that appear in both)

Example of Natural Join

Enrollment(sid, cid, grade)

Course(cid, cname, instructor-name)

cid is the only common attribute appearing in both relations.

- Want the Natural Join of Enrollment and Course, which computes:
  StudentCourseGrade(sid, cid, grade, cname, instructor-name)

$$\pi_{(\text{sid, cid, grade, cname, instructor-name})} (\sigma_{\text{Enrollment.cid=Course.cid}} (\text{Enrollment x Course}))$$

- What 's the Natural Join when R and S have no common attributes?
- What 's the Natural Join when R and S have only common attributes?

Semi-Join: R ⋉ S

- Meaning: $R \ltimes S = \pi_{attr(R)} (R \bowtie S)$

1. Compute Natural Join of R and S
2. Output the projection of that on just the attributes of R

- Find all courses that have some enrollment:
  Course ⋉ Enrollment
- Find all faculty who are advising at least one student:
  Faculty ⋉ Student

- How does Semi-Join relate to EXISTS in SQL?

Set Intersection: R∩S

Find all desktops sold by both Dell and HP.

Dell_Desktops ∩ HP_Desktops

Dell_Desktops

Harddisk	Speed	OS
20G	500Mhz	Windows
30G	1.0Ghz	Windows
20G	750Mhz	Linux

HP_Desktops

Harddisk	Speed	OS
30G	1.2Ghz	Windows
20G	500Mhz	Windows

Harddisk	Speed	OS
20G	500Mhz	Windows

- Is Intersection Commutative?
- Is Intersection Associative?

Intersect

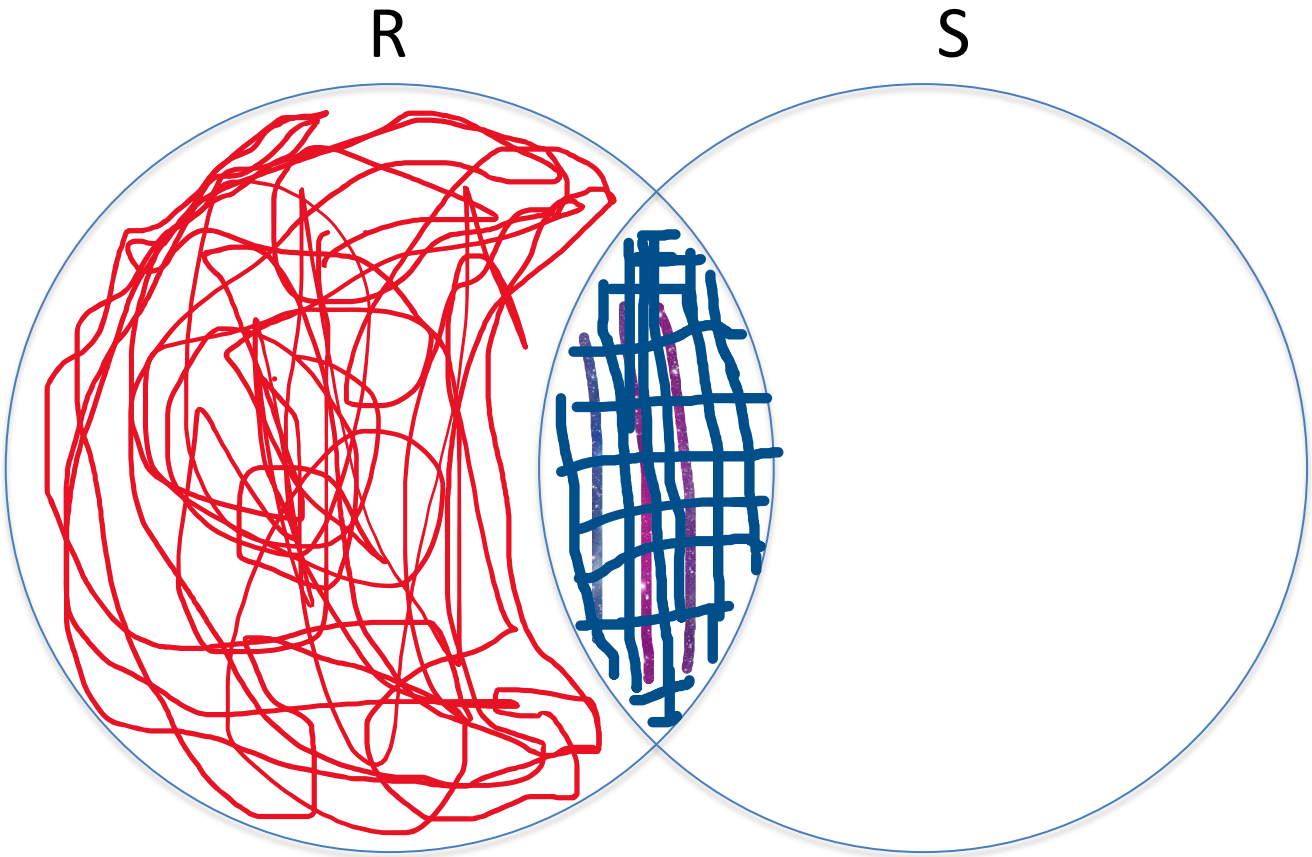
- How would you write Dell_desktops ∩ HP_desktops in SQL?

```
SELECT *
FROM Dell_desktops

INTERSECT

SELECT *
FROM HP_desktops;
```

- Intersection is a Derived Operator in Relational Algebra:

$$R \cap S = R - (R - S)$$
$$= S - (S - R)$$

Intersection using Difference



The area squiggled in **RED** is R - S.
The area cross-hatched in **BLUE** is R – (R – S), which equals R ∩ S.
Can you see why S – (S –R) also equals R ∩ S?

Division: R ÷ S (also written R/S)

- Input: Two relations R and S, where both:
  - attr(S) ⊂ attr(R) and
  - attr(S) is non-empty
- Output: Relation whose attributes are in attr(R) – attr(S).

- Example: R(A,B,C,D), S(B,D).
  - Meaning: R ÷ S = { (a, c) | for <u>all</u> (b,d) ∈S, we have (a,b,c,d) ∈R }

- Example: Find the names of drinkers who like <u>all</u> beers
  - Likes(drinker, beer) ÷ π_{beer} (BeersInfo(beer, maker))

- The Quotient (or Division) R ÷ S is the relation consisting of all tuples $(a_1,\ldots,a_{r-s})$ such that:

  For <u>every</u> tuple $(b_1,\ldots,b_s)$ in S, the tuple $(a_1,\ldots,a_{r-s}, b_1,\ldots,b_s)$ is in R

Example of Division

Enrollment(sid, cid, grade)

Course(cid, cname, instructor-name)

- Find the sids of students who are enrolled <u>in all courses</u>

  $\pi_{sid,cid}(\text{Enrollment}) \div \pi_{cid}(\text{Course})$

- Find the sids of all students who are enrolled in <u>all courses taught by Ullman</u>

  $\pi_{sid,cid}(\text{Enrollment}) \div \pi_{cid}(\sigma_{\text{instructor-name='Ullman'}}(\text{Course}))$

Example of Division

R

A	B	C
a1	b1	c1
a1	b2	c2
a2	b1	c1
a1	b3	c3
a4	b2	c2
a3	b2	c2
a4	b1	c1

S

B	C
b1	c1
b2	c2

R ÷ S

A
a1
a4

Independence of Basic Operators

- Many interesting queries can be expressed using the five basic operators (σ , π , x , U , -)
- Can one of the five operators be derived by the other four operators?

Theorem (Codd):

The five basic operators are independent of each other. In other words, for each relational operator *o*, there is no relational algebra expression that is built from the rest that defines *o*.

- x
- U
- π
- σ
- -

Two “Housekeeping” Operations

- There are two “Housekeeping” operations that make Relational Algebra queries easier to write.
  - Assignment: $\leftarrow$
  - Rename: ρ
- You may use these operations when you write Relational Algebra queries.

Assignment

- It may be convenient to write a relational-algebra expression by assigning parts of it to temporary relation variables.
- The assignment operation is denoted by $\leftarrow$ and it works like assignment in common programming languages.
- Example: Find all Sailors who have rating 3 or whose age is at least 18.

$$R3Sailors \leftarrow \sigma_{rating = 3}(Sailors)$$
$$VotingSailors \leftarrow \sigma_{age >= 18}(Sailors)$$
$$R3Sailors \cup VotingSailors$$

- With the assignment operation, a query can be written as a sequential program, consisting of a series of assignments, ending with an expression whose value is displayed as the result of the query.

Renaming: $\rho_{S(A1, \ldots, An)}$ (R)

- To specify the attributes of a relational expression.
- Input: a relation, a relation symbol R, and a set of attributes {B1, … ,Bn}
- Output: the same relation with name S and attributes A1, …, An.

- Meaning: rename relation R to S with attributes A1, …, An.

- Example: $\rho_{BeersInfo(beer,maker)}$ Beers(name, manuf)

Example

R

A	B	C
a_1	b_1	c_1
a_2	b_2	c_2

S

C	D
d_1	e_1
d_2	e_2
d_3	e_3

$R \times \rho_{T(X,D)} S$

A	B	C	X	D
a_1	b_1	c_1	d_1	e_1
a_1	b_1	c_1	d_2	e_2
a_1	b_1	c_1	d_3	e_3
a_2	b_2	c_2	d_1	e_1
a_2	b_2	c_2	d_2	e_2
a_2	b_2	c_2	d_3	e_3

More Complex Queries

- Relational operators can be composed to form more complex queries. We have already seen examples of this in SQL.

Enrollments(<u>esid, ecid</u>, grade)

Courses(<u>cid</u>, cname, instructor-name)

- Query 1: Find the student id, grade and instructor where the student had a grade that was more than 80 points in a course.

$$\sigma_{grade>80} (\pi_{esid,\ grade,\ instructor\text{-}name} (\sigma_{Enrollments.ecid = Courses.cid} (Enrollments \times Courses)))$$

Query 2

Enrollments(<u>esid, ecid</u>, grade)

Courses(<u>cid</u>, cname, instructor-name)

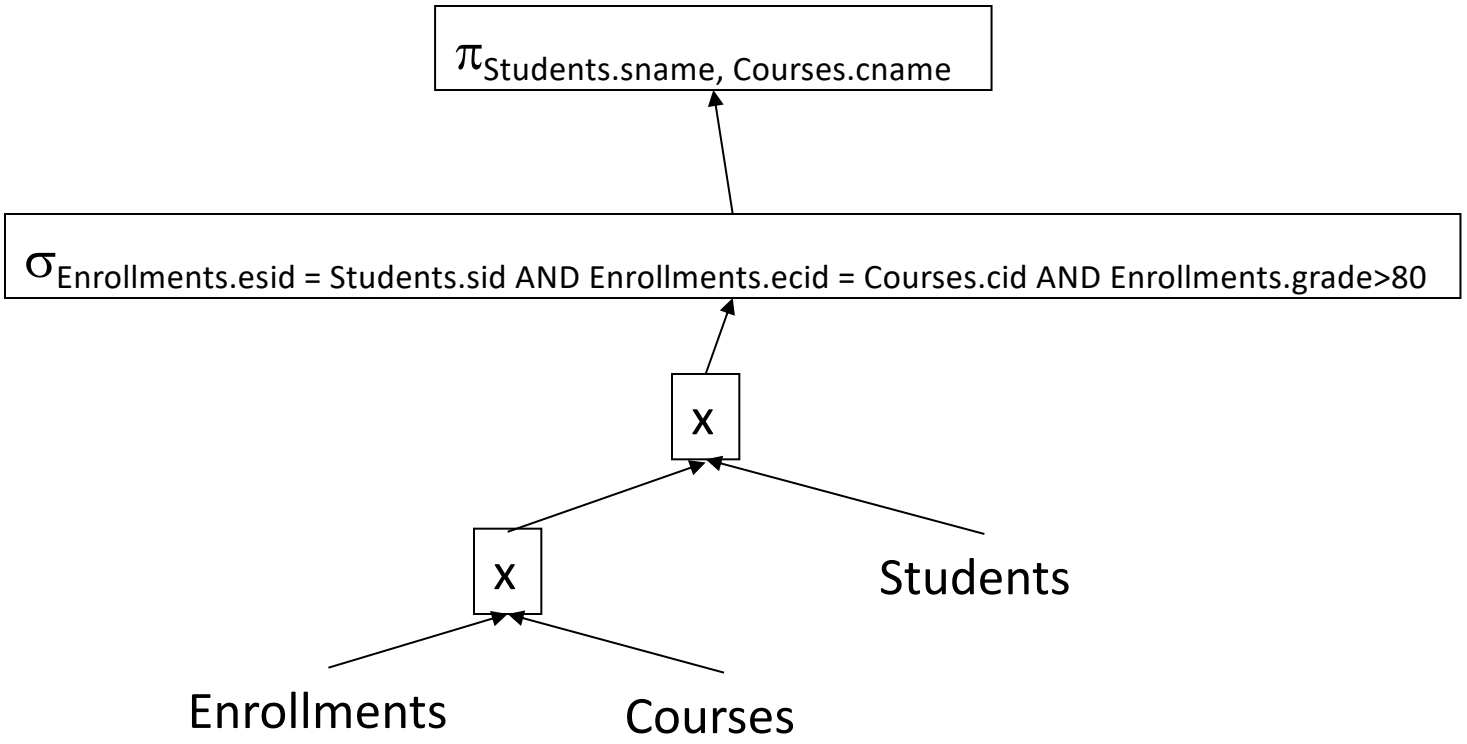
Students(<u>sid</u>, sname)

- Find the student name and course name where the student had a grade that was more than 80 points in a course.

$$\pi_{\text{Students.sname, Courses.cname}} \Big(\sigma_{\substack{\text{Enrollments.ecid = Courses.cid} \\ \text{AND Enrollments.esid = Students.sid} \\ \text{AND Enrollments.grade > 80}}} (\text{Enrollments} \times \text{Courses} \times \text{Students}) \Big)$$

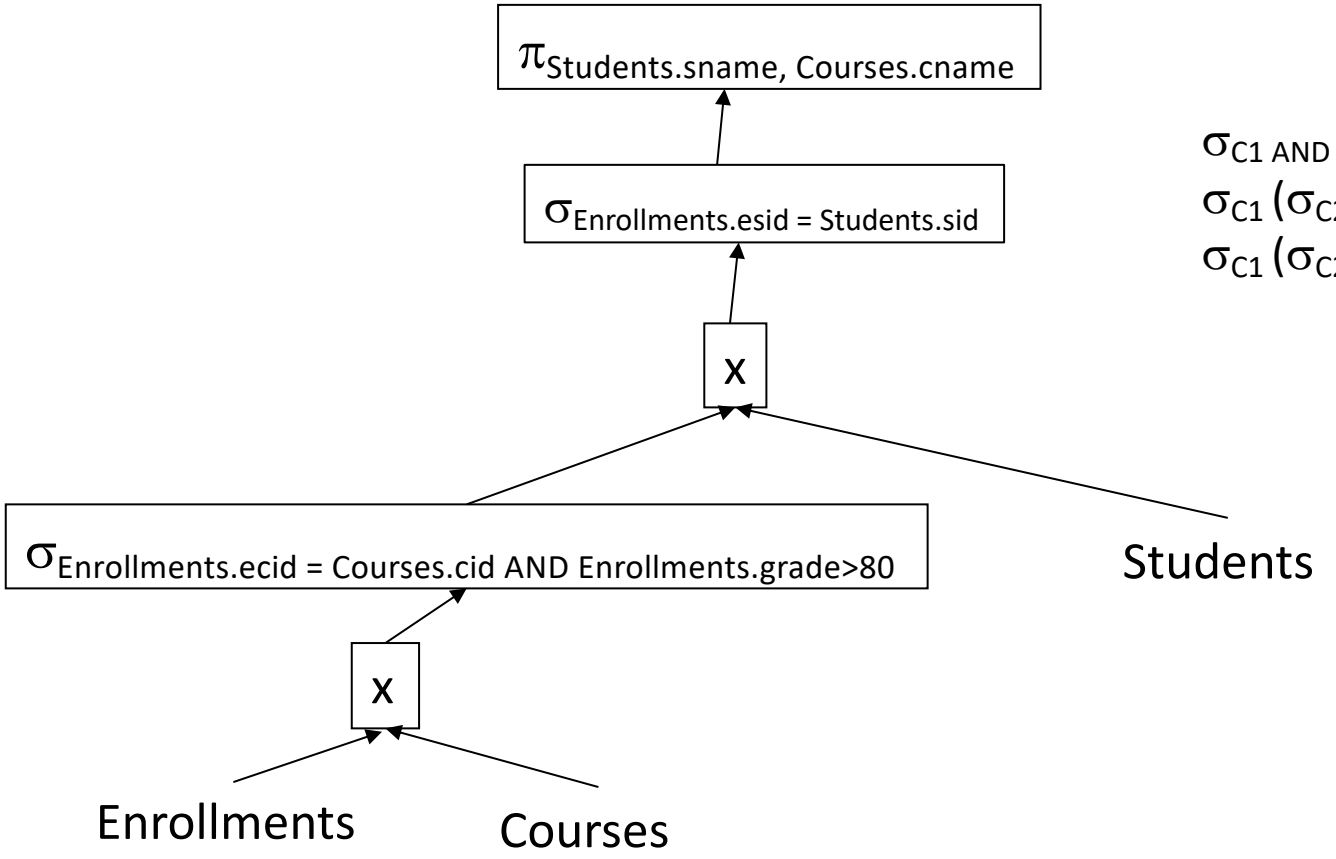
An Execution Plan for Query 2

- Find the student name and course name where the student had a grade more than 80 points in a course.



Another Execution Plan for Query 2

- Find the student name and course name where the student had a grade more than 80 points in a course.



$\sigma_{C1 \text{ AND } C2 \text{ AND } C3}$ (E x C x S) =
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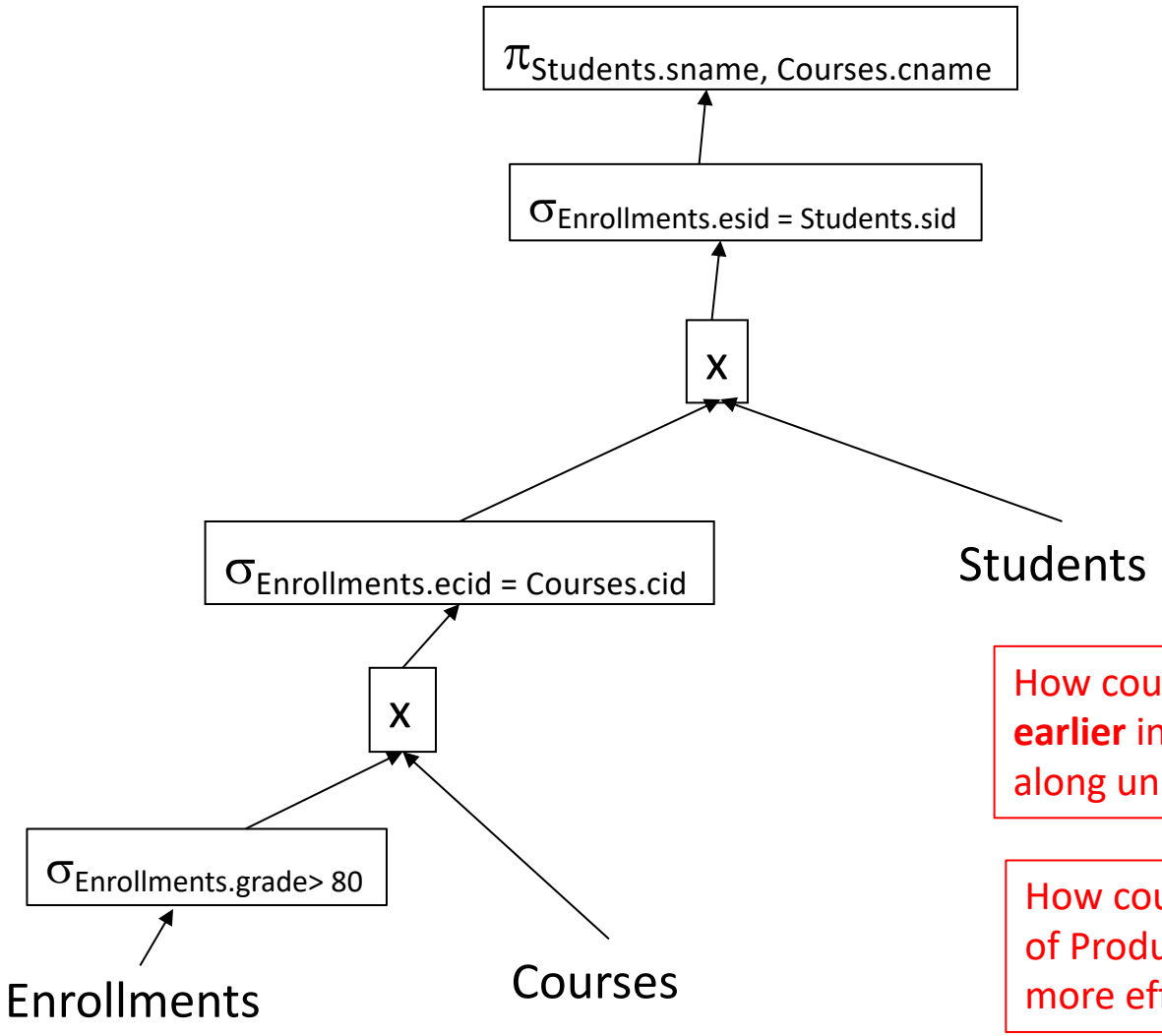
A Third Execution Plan for Query 2



How could we do projections **earlier** in plan to avoid carrying along unnecessary attributes?

How could we do **Joins**, instead of Products to make plan more efficient?

Query Transformations

- What were some of the query equivalences that we talked about earlier?

- What other query equivalences do you know about?

Execution Plans

- When do you do SELECTION?
  - Predicate pushdown is almost always a good idea.
- How do you access each table?
  - Scan, index (which index), hash, …
- What's the order in which you Join tables?
  - Join/Equi-join is common; avoid Cartesian product
  - But which table do you start with?
    - Predicates on indexed columns are often useful in picking first table, then next table, to join, …
- What join method do you use for each join?
  - Nested loop join, Merge join, Hash-join, …
- How much parallelism do you use?
  - How do you schedule tasks to hardware?
- Do you need to sort? If so, when do you sort?

Query Optimization

- Comparing Execution Plans and finding a “very good” (not necessarily best) plan
- Statistics that DBMS may keep to help calculate approximate query cost
  - Cardinality (number of rows) in table
  - Highest and lowest (non-null) value in column
  - Column cardinality (number of different values in column)
  - Number of appearances of the top 10 most frequent value in each column
  - Join cardinality between tables for a particular equi-join
    - May be calculated, not stored; not well-defined if there are conditions (predicates) on the tables
  - Many other statistics are calculated approximately
- How frequently are stored statistics updated?
- Cost: CPU? I/O? Network? How do these get combined to compare plans?

EXPLAIN Statement

- Shows information about query plan
  - Each DBMS that has EXPLAIN has its own variation
  - Try it with PostgreSQL
- You may want to try to rewrite query yourself to find better execution plan if Query Optimizer isn't smart enough to do so
- Should Optimizer take advice from users?

Practice Homework 5

Sailors(sid, sname, rating, age) // sailor id, sailor name, rating, age

Boats(bid, bname, color) // boat id, boat name, color of boat

Reserves(sid, bid, day) // sailor id, boat id, date that sid reserved bid.

- Use **Relational Algebra** to write the following **8 queries**.
- How might Database optimize execution of queries using ideas in this Lecture, per discussion in this Lecture about Execution Plans for Query 2?

1. Find the names of sailors who reserved boat 103.

2. Find the colors of boats reserved by Lubber.

3. Find the names of sailors who reserved at least one boat.

Practice Homework 5 (cont'd)

4. Find the names of sailors whose age > 20 and who have not reserved any boats.

5. Find the names of sailors who have reserved a red or a green boat.

6. Find the names of sailors who have reserved a red and a green boat.

7. Find the names of sailors who have reserved at least 2 different boats.

8. Find the names of sailors who have reserved exactly 2 different boats.

Solution to just the two Practice Homework 5 questions that are in **magenta** will be posted on Piazza soon.