TU Graz

SCIENCE
PASSION
TECHNOLOGY

Database Systems
04 Relational Algebra

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Last update: Mar 25, 2019

ISDS

Announcements/Org

- **#1 Video Recording**
  - Since last week, video/audio recording
  - Link in **TeachCenter** & **TUbe** (but not public yet)
- **#2 Exercise Submission**
  - Submission through **TeachCenter** (max 5MB, draft possible)
  - **Starting today** (deadline **Apr 02, 12.59pm**)

→ **Nobody left behind** (if problems, contact us via newsgroup or email)

Recap: Relations and Terminology

- **Domain D (value domain): e.g., Set S, INT, Char[20]**
- **Relation R**
  - **Relation schema** RS:
    Set of k attributes $\{A_1,\ldots,A_k\}$
  - **Attribute** A_j: value domain $D_j = dom(A_j)$
  - **Relation:** subset of the Cartesian product over all value domains D_j
    $\mathbf{R \subseteq D_1 \times D_2 \times \ldots \times D_k,\ k \geq 1}$

Attribute

A1 INT	A2 INT	A3 BOOL
3	7	T
1	2	T
3	4	F
1	7	T

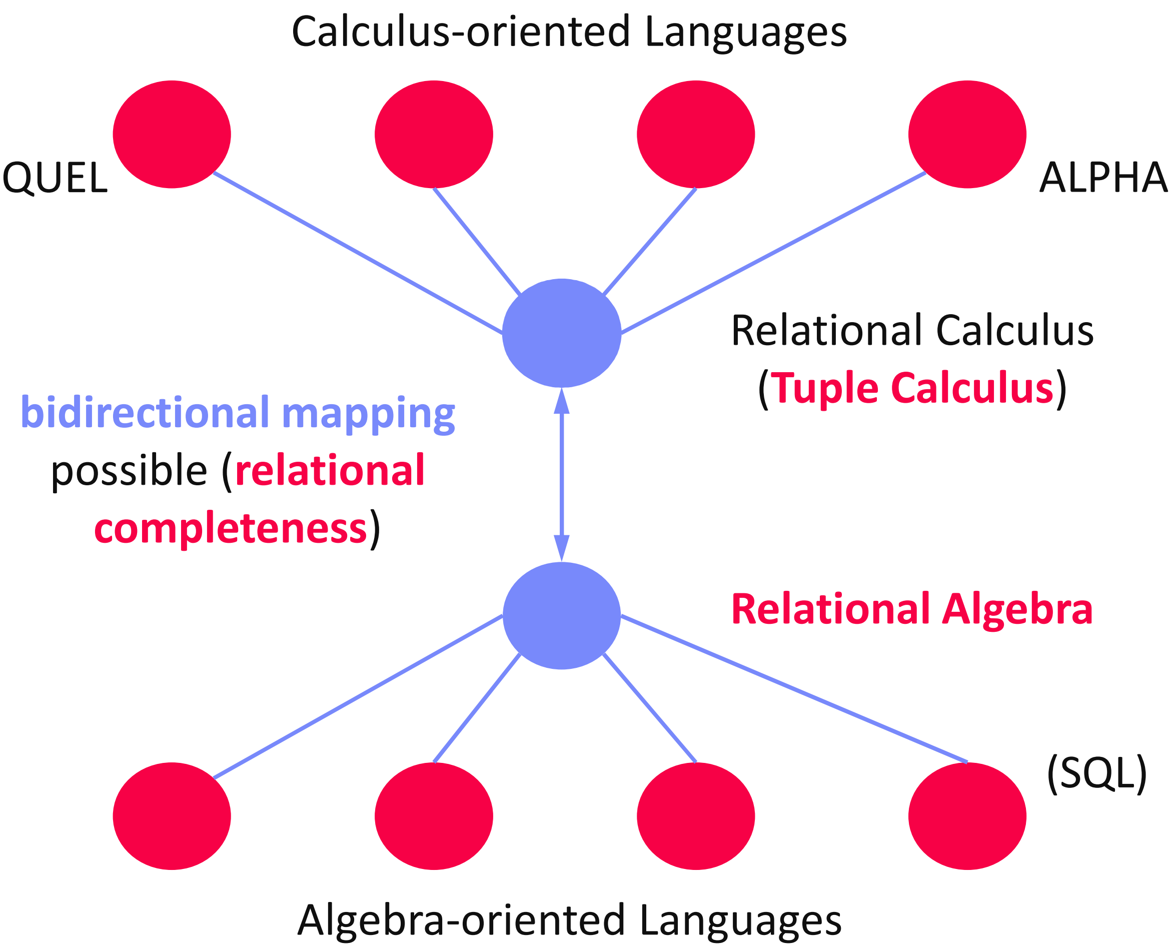
Tuple

cardinality: 4
rank: 3

- **Additional Terminology**
  - **Tuple**: row of k elements of a relation
  - **Cardinality** of a relation: number of tuples in the relation
  - **Rank** of a relation: number of attributes
  - **Semantics:** Set := no duplicate tuples (in practice: Bag := duplicates allowed)
  - **Order of tuples and attributes is irrelevant**

Relational Algebra vs Tuple Calculus

- **Comparison Scheme for Data Sub Languages**



Calculus-oriented Languages

QUEL

ALPHA

Relational Calculus (**Tuple Calculus**)

bidirectional mapping possible (**relational completeness**)

Relational Algebra

(SQL)

Algebra-oriented Languages

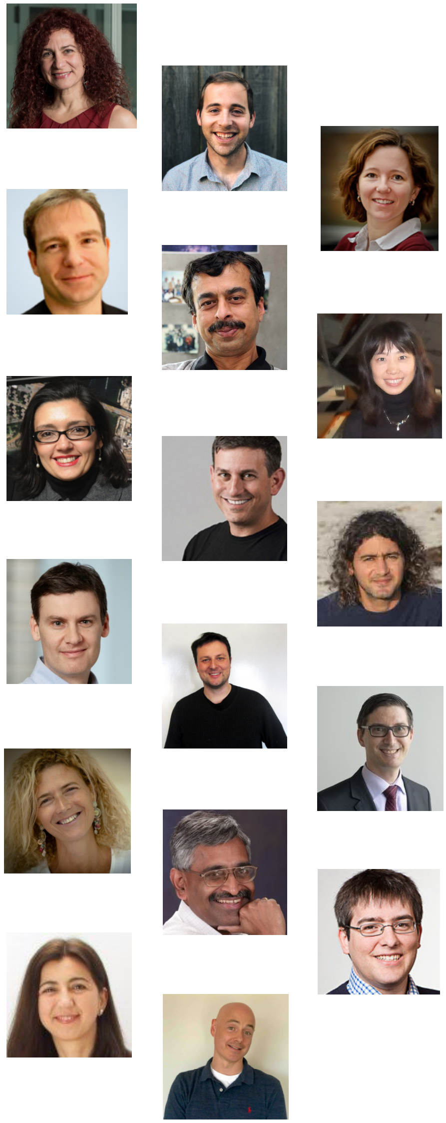
[E. F. Codd: Relational Completeness of Data Base Sublanguages. IBM Research Report RJ987, **1972**]

Agenda

- **Relational Algebra**
- **Tuple Calculus**
- **Physical Operators** (Preview Lecture 08)

Database Research Self-Assessment 2018

<u>PID</u>	Firstname	Lastname	Affiliation	LID
102	Anastasia	Ailamaki	EPFL	1
104	Peter	Bailis	Stanford	
105	Magdalena	Balazinska	U Washington	3
107	Peter	Boncz	CWI	2
108	Surajit	Chaudhuri	MS Research	3
111	Luna	Dong	Amazon	3
113	Juliana	Freire	NYU	5
115	Joe	Hellerstein	UC Berkley	6
116	Stratos	Idreos	Harvard	7
117	Donald	Kossman	MS Research	
118	Tim	Kraska	MIT	7
120	Volker	Markl	TU Berlin	8
122	Tova	Milo	Tel Aviv University	9
123	C.	Mohan	IBM Research	10
124	Thomas	Neumann	TU Munich	11
126	Fatma	Ozcan	IBM Research	10
130	Christopher	Re	Stanford	4



Database Research Self-Assessment 2018, cont.

PID	…	Affiliation	LID
102		EPFL	1
104		Stanford	
105		U Washington	3
107		CWI	2
108		MS Research	3
111		Amazon	3
113		NYU	5
115		UC Berkley	6
116		Harvard	7
117		MS Research	
118		MIT	7
120		TU Berlin	8
122		Tel Aviv University	9
123		IBM Research	10
124		TU Munich	11
126		IBM Research	10
130		Stanford	4

LID	Location
1	Lausanne, SUI
2	Amsterdam, NLD
3	Seattle, USA
4	Stanford, USA
5	New York, USA
6	Berkley, USA
7	Cambridge, USA
8	Berlin, GER
9	Tel Aviv, ISR
10	San Jose, USA
11	Munich, GER

Relational Algebra

Core Relational Algebra

- **Relational Algebra**
  - **Operands: relations** (normalized, variables for computing new values)
  - **Operators**: traditional **set operations** and specific **relational operations**
- **Basic Operations** (minimal)
  - Cartesian product $R \times S$
  - Union $R \cup S$
  - Difference $R - S$
  - Projection $\pi_{i_1, \dots, i_m}(R)$
  - Selection $\sigma_F(R)$
- **Derived Operations**
  - Intersection $R \cap S$
  - Join $R \bowtie S$
  - Division $R \div S$
- **Rename $\rho_S(R)$**

	Traditional **Set Operations**	Specific **Relational Operations**
Basic Operations	$R \times S$ $R \cup S$ $R - S$	$\pi_{i_1, \dots, i_m}(R)$ $\sigma_F(R)$
Derived Operations	$R \cap S$	$R \bowtie S$ $R \div S$

Extended Relational Algebra

- **Extended Relational Algebra**
  - Relational algebra introduced with **set semantics** (no duplicate tuples)
  - SQL with **bag semantics** (more flexibility and performance)
  - **Codd'72:** *In a practical environment it would need to be augmented by a counting and summing capability, together with […] library functions […].*
- **Additional Operations (Ext)**
  - Duplicate elimination $\delta(R)$
  - Grouping $\gamma_{A,f(B)}R$
  - Sorting $\tau_A(R)$

- **Bag (aka Multiset) Terminology**
  - Multiplicity: # occurrences of an instance
  - Cardinality: # tuples (i.e., # instances weighted by multiplicity)

A	B
a	b
b	c
a	b

Cartesian Product

Basic
Derived
Ext

- **Definition:** **R×S := {(r,s) | r ∈ R, s ∈ S}**
  - Set of all pairs of inputs (equivalent in **set**/**bag**)

- **Example**

PID	Firstname	Lastname	Affiliation	LID
104	Peter	Bailis	Stanford	
130	Christopher	Re	Stanford	4

×

SF Bay Area

LID	Location
4	Stanford, USA
6	Berkley, USA
10	San Jose, USA

PID	Firstname	Lastname	Affiliation	LID	LID	Location
104	Peter	Bailis	Stanford		4	Stanford, USA
130	Christopher	Re	Stanford	4	4	Stanford, USA
104	Peter	Bailis	Stanford		6	Berkley, USA
130	Christopher	Re	Stanford	4	6	Berkley, USA
104	Peter	Bailis	Stanford		10	San Jose, USA
130	Christopher	Re	Stanford	4	10	San Jose, USA

Union

Basic Derived Ext

- **Definition:** **R∪S := {x | x ∈ R ∨ x ∈ S}**
  - **Set:** set union with duplicate elimination (idempotent: **S∪S = S**)
  - **Bag:** bag union (commutative but not idempotent)
- **Example w/ set semantics**

Firstname	Lastname	Affiliation
Anastasia	Ailamaki	EPFL
Peter	Boncz	CWI
Volker	Markl	TU Berlin
Thomas	Neumann	TU Munich

Firstname	Lastname	Affiliation
Anastasia	Ailamaki	EPFL
Magdalena	Balazinska	U Washington
Juliana	Freire	NYU
Tova	Milo	Tel Aviv University

Firstname	Lastname	Affiliation
Anastasia	Ailamaki	EPFL
Peter	Boncz	CWI
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Thomas	Neumann	TU Munich
Magdalena	Balazinska	U Washington
Juliana	Freire	NYU
Tova	Milo	Tel Aviv University

Union requires
compatible schema

Difference

Basic
Derived
Ext

- **Definition:** **R–S := {x | x ∈ R ∧ x ∉ S}** (sometimes \)
  - **Set:** set difference
  - **Bag:** element multiplicity of R minus multiplicity min(R,S)

- **Example w/ bag semantics**

Affiliation
Stanford
U Washington
MS Research
Amazon
NYU
UC Berkley
Harvard
MIT
IBM Research

–

Affiliation
Stanford
U Washington
NYU
UC Berkley
Harvard
MIT
TU Berlin
Stanford

➡

Affiliation
MS Research
Amazon
IBM Research

Difference requires **compatible schema**

Projection and Selection

Basic | Derived | Ext

- **Projection $\pi_{i_1, \ldots, i_m}(R)$**
  - **Set:** selection of attributes with duplicate elimination
  - **Bag:** selection of attributes
- **Extended Projection**
  - Arithmetic expressions: $\pi_{A,A*B}(R)$
  - Duplicate occurrences: $\pi_{A,A,B}(R)$
- **Selection (restriction) $\sigma_F(R)$**
  - Selection of tuples satisfying the predicate F (equivalent in **set**/**bag**)
  - Example: $\sigma_{Affiliation=‘IBM Research‘}(R)$

PID	Firstname	Lastname	Affiliation	LID
123	C.	Mohan	IBM Research	10
126	Fatma	Ozcan	IBM Research	10

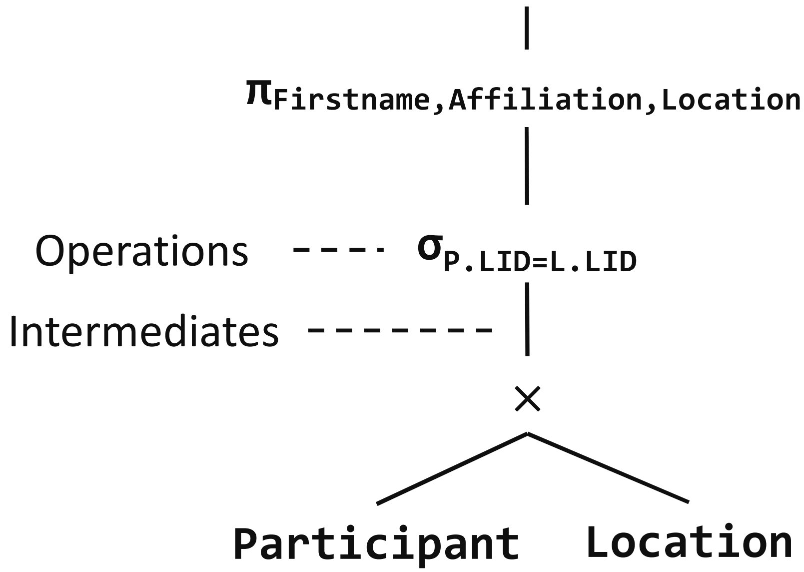
Example:

$\pi_{Affiliation}(R)$ w/ set semantics

Affiliation
EPFL
Stanford
U Washington
CWI
MS Research
Amazon
NYU
UC Berkley
Harvard
MIT
TU Berlin
Tel Aviv University
IBM Research
TU Munich

Query Trees

- **Composition of Complex Queries**
  - Relational algebra expressions → **data flow graph (tree)**
  - Leaf nodes represent base relations; root node represent result
- **Example** $\pi_{\texttt{Firstname,Affiliation,Location}}($
  $\sigma_{\texttt{P.LID=L.LID}}(\texttt{Participant} \times \texttt{Location}))$



Firstname	Affiliation	Location
Anastasia	EPFL	Lausanne, SUI
Magdalena	U Washington	Seattle, USA
Peter	CWI	Amsterdam, NLD
Surajit	MS Research	Seattle, USA
…	…	…

Intersection

Basic | Derived | Ext

- **Definition R∩S := $\boxed{R - (R - S)}$** (derived from basic operations)
  - **Set:** set intersection derived from difference
  - **Bag:** bag intersection, with element multiplicity min(R,S)
- **Example**

Firstname	Lastname	Affiliation
Anastasia	**Ailamaki**	**EPFL**
Peter	Boncz	CWI
Volker	Markl	TU Berlin
Thomas	Neumann	TU Munich

Firstname	Lastname	Affiliation
Anastasia	**Ailamaki**	**EPFL**
Magdalena	Balazinska	U Washington
Juliana	Freire	NYU
Tova	Milo	Tel Aviv University

→

Firstname	Lastname	Affiliation
Anastasia	Ailamaki	EPFL

Intersection requires **compatible schema**

Division

Basic | Ext
Derived

- **Definition** $R \div S := \pi_{R-S}(R) - \pi_{R-S}((\pi_{R-S}(R) \times S) - R)$
  - Find instances in R that satisfy S (e.g., **which students took ALL DB course**)
  - $R \div S := \{(a_1, ..., a_{r-s}) \mid \forall (b_1, ..., b_s) \in S : (a_1, ..., a_{r-s}, b_1, ..., b_s) \in R\}$

- **Example**

R

A	B	C	D
a	b	c	d
a	b	e	f
b	c	e	f
e	d	e	f
e	d	c	d
a	b	d	e

S

C	D
c	d
e	f

(many-to-one
set containment test)

➡

R÷S

A	B
a	b
e	d

- **Example Derivation**

$\pi_{R-S}(R)$

A	B
a	b
b	c
e	d

$\pi_{R-S}(R) \times S$

A	B	C	D
a	b	c	d
a	b	e	f
b	c	c	d
b	c	e	f
e	d	c	d
e	d	e	f

$(\pi_{R-S}(R) \times S) - R$

A	B	C	D
b	c	c	d

$\pi_{R-S}((\pi_{R-S}(R) \times S) - R)$

A	B
b	c

$\pi_{R-S}(R) - \pi_{R-S}((\pi_{R-S}(R) \times S) - R)$

A	B
a	b
e	d

Join

Basic
Derived
Ext

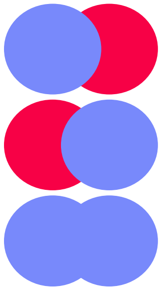
- **Definition $R \bowtie S := \pi... (\sigma_F (R \times S))$**
    - Selection of tuples (and attributes) from the catesian product $R \times S$ (equivalent in set/bag); **beware of NULLs:** do never match
    - **Theta Join:** $R \bowtie_\Theta S := \sigma_\Theta (R \times S)$; arbitrary condition e.g., $\Theta \in \{=, \neq, <, \leq, >, \geq\}$
    - **Natural Join:** $R \bowtie S$; **equi join** (Θ is =) w/ shared attributes appearing once

- **Example Natural Join Participant $\bowtie$ Location**

PID	Firstname	Lastname	Affiliation	LID
102	Anastasia	Ailamaki	EPFL	1
104	Peter	Bailis	Stanford	
105	Magdalena	Balazinska	U Washington	3

PID	Firstname	Lastname	Affiliation	LID	Location
102	Anastasia	Ailamaki	EPFL	1	Lausanne, SUI
105	Magdalena	Balazinska	U Washington	3	Seattle, USA

Types of Joins



- **Outer Joins**
  - Left outer join ⟕ (tuples of lhs, NULLs for non-existing rhs)
  - Right outer join ⟖ (tuples of rhs, NULLs for non-existing lhs)
  - Full outer join ⟗ (tuples of lhs/rhs, NULLs for non-existing lhs/rhs)
  - Example

Participant ⟕ Location

PID	Firstname	Lastname	Affiliation	LID	LID	Location
102	Anastasia	Ailamaki	EPFL	1	1	Lausanne, SUI
104	Peter	Bailis	Stanford	NULL	NULL	NULL
105	Magdalena	Balazinska	UW	3	3	Seattle, USA

- **Semi Join**
  - Left semi join $\ltimes := \pi_R(R \bowtie S)$ (filter lhs)
  - Right semi join $\rtimes$ (filter rhs)
  - Example Participant $\ltimes\ \sigma_{GER}$ (Location)

PID	Firstname	Lastname	Affiliation	LID
120	Volker	Markl	TU Berlin	8
124	Thomas	Neumann	TU Munich	11

- **Anti Join**
  - Left anti join $R \triangleright S := R - R \ltimes S$ (**complement of left semi join**)
  - Right anti join (complement of right semi join)

Deduplication, Sorting, and Renaming

Basic Derived Ext

- **Duplication Elimination δ(R)**
  - Convert a bag into a **set** by removing all duplicate instances
  - SQL: use **ALL** or **DISTINCT** to indicate w/ or w/o duplicate elimination

- **Sorting $\tau_A(R)$**
  - Convert a bag into a **sorted list** of tuples; order lost if used in other ops
  - SQL: sequence of attributes with ASC (ascending) or DESC (descending) order
  - Example: $\tau_{\text{Firstname ASC, Lastname ASC}}(\text{Participant})$

- **Rename $\rho_S(R)$**
  - Define new schema (attribute names), but keep tuples unchanged
  - **Example:** $\rho_{\text{ID, Given Name, Family Name, Affiliation, LID}}(\text{Participant})$

Grouping and Aggregation

Basic
Derived
Ext

- **Definition $\gamma_{A,f(B)}R$**
  - Grouping: group input tuples R according to unique values in A
  - Aggregation: compute aggregate f(B) per group of tuples (aggregation w/o grouping possible)
- **Example $\gamma_{Affiliation,COUNT(*)}Participant$**

Affiliation	COUNT
EPFL	1
Stanford	**2**
U Washington	1
CWI	1
MS Research	**2**
Amazon	1
…	…
IBM Research	**2**
TU Munich	1

- **Classification of Aggregates f(B)**
  - Additive aggregation functions (SUM, COUNT)
  - Semi-additive aggregation functions (MIN, MAX)
  - Additively computable aggregation functions (AVG, STDDEV, VAR)
  - Aggregation functions (MEDIAN, QUANTILES)

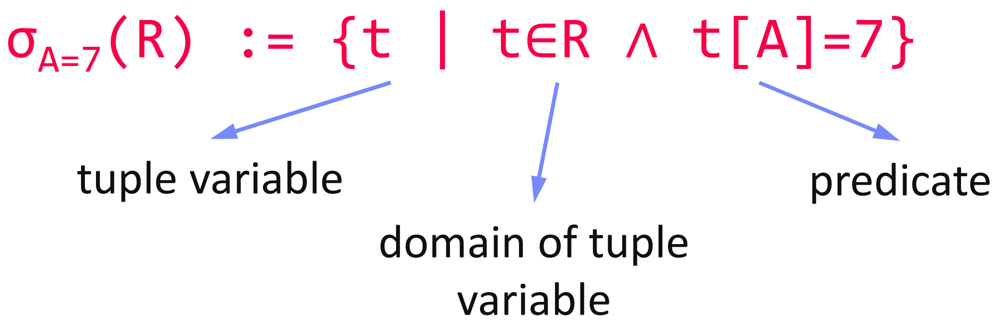
Tuple Calculus

Overview Tuple Calculus

- **Relational Calculus**
  - Tuple Calculus – tuple relational calculus: {T | p(T)} (tuple → set)
    ➔ **examples:** see definition of relational algebra
  - (Domain Calculus – domain relational calculus: attribute → set)

- **Characteristics Tuple Calculus**
  - Calculus expression **does not specify order of operations**
  - Calculus expressions consist of variables, constants, comparison operators, logical concatenations, and quantifiers
  - Expressions are formulas, free formal variables → result

- **Example Selection**



$$\sigma_{A=7}(R) := \{t \mid t \in R \wedge t[A]=7\}$$

Quantifiers

- **Variables**
  - Free: unbound variables define the result
  - Bound: existential quantifier **$\exists x$** and universal quantifier **$\forall x$** bind a variable x

- **Example Projection**

$$\pi_{A,B}(R) := \{\underset{\text{free variable}}{\underset{\downarrow}{t}} \mid \underset{\text{bound variable}}{\underset{\searrow}{\exists r}} \in R(t[A]=r[A] \wedge t[B]=r[B])\}$$

(relation T defined with two attributes A and B)

- **Safe Queries**
  - **Guarantees finite number of tuples** (otherwise, unsafe)
  - Example unsafe query: **$\{t \mid t \notin R\}$**
  - **Relational completeness:** Every safe query expressible in RA and vice versa

Relational Algebra vs Tuple Calculus Revisited

- **E. F. Codd argued for Tuple Calculus**
  - **Criticism RA:** operator-centric
  - Ease of Augmentation (w/ lib functions)
  - Scope for Search Optimization
  - Authorization Capabilities
  - Closeness to Natural Language

➔ focus on query language

[E. F. Codd: Relational Completeness of Data Base Sublanguages. IBM Research Report RJ987, **1972**]

- **System R Team used SEQUEL + RA**
  - **Criticism Tuple Calculus:** too complex
  - Iterating over tuples (not set-oriented)
  - Quantifiers and bound variables
  - Join over all variable attributes and result mapping

[Donald D. Chamberlin, Raymond F. Boyce: SEQUEL: A Structured English Query Language. SIGMOD Workshop **1974**]

- **Equivalent expressiveness + simplicity of RA + use as IR**
  ➔ **Relational Algebra as basis for SQL und DBMS in practice**

Excursus: The History of System R and SQL

Gem: "The Birth of SQL – Prehistory / System R" (SQL Reunion 1995)

- https://www.mcjones.org/System_R/SQL_Reunion_95/sqlr95-Prehisto.html
- https://www.mcjones.org/System_R/SQL_Reunion_95/sqlr95-System.html

- **Don Chamberlin:** *We had this idea, that Codd had developed two languages, called the relational algebra and the relational calculus. […] The relational calculus was a kind of a strange mathematical notation with a lot of quantifiers in it. We thought that what we needed was a language that was* ***different from either one of those****, […].*
- **Don Chamberlin:** *Interestingly enough, Ted Codd didn't participate in that as much as you might expect. He got off into natural language processing […]. He really didn't get involved in the nuts and bolts of System R very much. I think he may have wanted to maintain a certain distance from it in case we didn't get it right. Which I think he would probably say we didn't.*
- **Mike Blasgen:** *Oh, he has said that, many times.*

Physical Operators

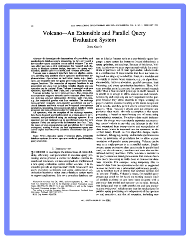
(Preview of Lecture 08 Query Processing)

Iterator Model

Scalable (small memory)
High CPI measures

- **Volcano Iterator Model**
  - **Pipelined & no global knowledge**
  - **Open-Next-Close** (ONC) interface
  - Query execution from root node (pull-based)

[Goetz Graefe: Volcano - An Extensible and Parallel Query Evaluation System. **IEEE Trans. Knowl. Data Eng. 1994**]

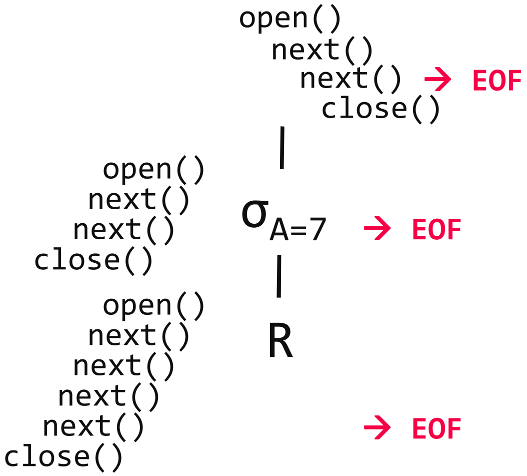


- **Example $\sigma_{A=7}(R)$**

```
void open() { R.open(); }

void close() { R.close(); }

Record next() {
  while( (r = R.next()) != EOF )
    if( p(r) ) //A==7
      return r;
  return EOF;
}
```

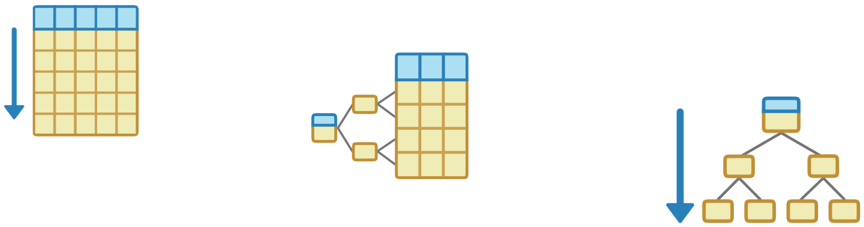


- **Blocking Operators**
  - Sorting, grouping/aggregation, build-phase of (simple) hash joins

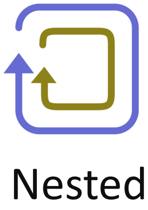
PostgreSQL: `Init()`, `GetNext()`, `ReScan()`, `MarkPos()`, `RestorePos()`, `End()`

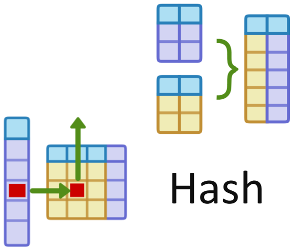
(Selected) Physical Operators in PostgreSQL

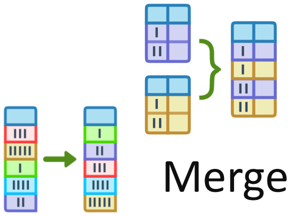
- **Physical Table Access Operators**
    - Seq Scan (table scan)
    - Index Scan
    - Index Only Scan



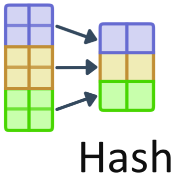
- **Physical Join Operators**
    - Nested Loop Join
    - Hash / Hash Join
    - Sort / Merge Join

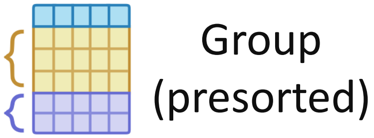






- **Physical Grouping Operators**
    - Hash Aggregate
    - Group Aggregate





[**Images:** PostgreSQL/11/pgAdmin 4/web/pgadmin/misc/static/explain/img]

ANALYZE and EXPLAIN

Note: SQL for table creation and insert in the pptx notes.

- **Step 1:** `EXPLAIN SELECT * FROM Participant AS R, Locale AS S WHERE R.LID=S.LID;`

```
Hash Join (.. rows=70 width=1592)
  Hash Cond:(s.lid = r.lid)
  ->  Seq Scan on locale s (.. rows=140 width=520)
  ->  Hash (.. rows=70 width=1072)
        ->  Seq Scan on participant r (.. rows=70 width=1072)
```

build side

- **Step 2:** `ANALYZE Participant, Locale;`

- **Step 3:** `EXPLAIN SELECT * FROM Participant AS R, Locale AS S WHERE R.LID=S.LID;`

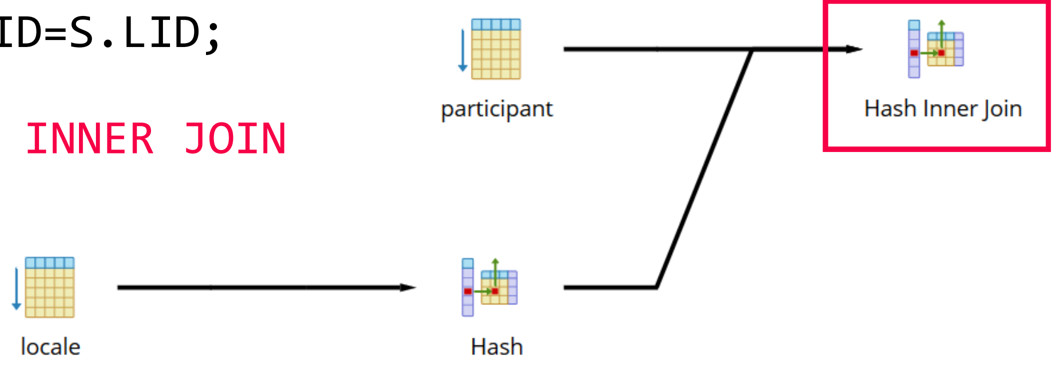
```
Hash Join (.. rows=17 width=47)
  Hash Cond:(r.lid = s.lid)
  ->  Seq Scan on participant r (.. rows=17 width=30)
  ->  Hash (.. rows=11 width=17)
        ->  Seq Scan on locale s (.. rows=11 width=17)
```

WHY?

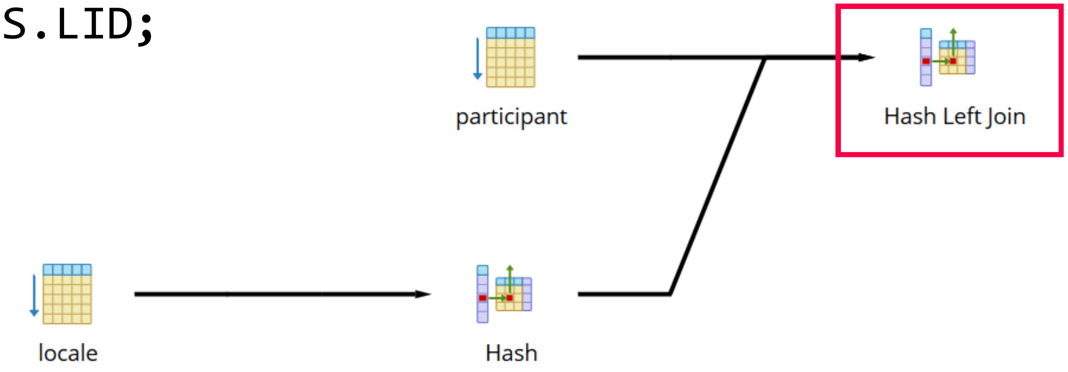
Visual EXPLAIN

- `SELECT * FROM Participant AS R, Locale AS S`
  `WHERE R.LID=S.LID;`

  $\sigma_F(R \times S)$ → INNER JOIN



- `SELECT * FROM Participant AS R LEFT JOIN Locale AS S`
  `ON R.LID=S.LID;`



Conclusions and Q&A

- **Summary**
  - **Fundamentals of relational algebra** and tuple calculus
  - Preview of query trees and physical operators

- **Exercise 1 Reminder**
  - All background to solve tasks 1.1-1.3 since last lecture
  - Submission: **starting today**, Deadline: **Apr 02 11.59pm**

- **Next Lectures**
  - Apr 01: **05 Query Languages (SQL)**, **incl. Exercise 2**
  - Apr 08: **06 APIs (ODBC, JDBC, OR frameworks)**