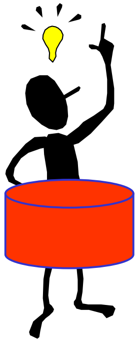
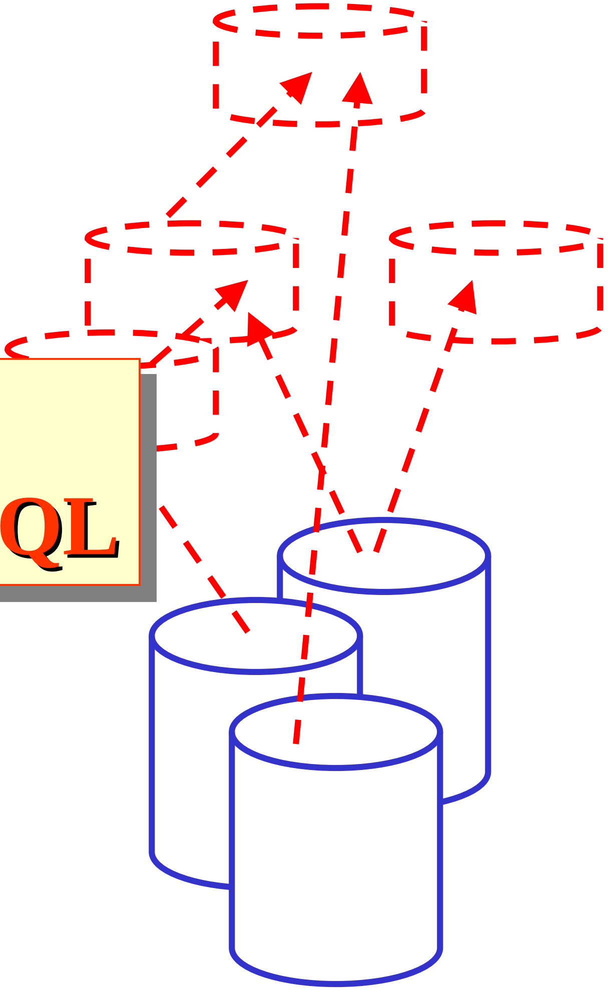
Intelligent Information Systems

WS 2018/19

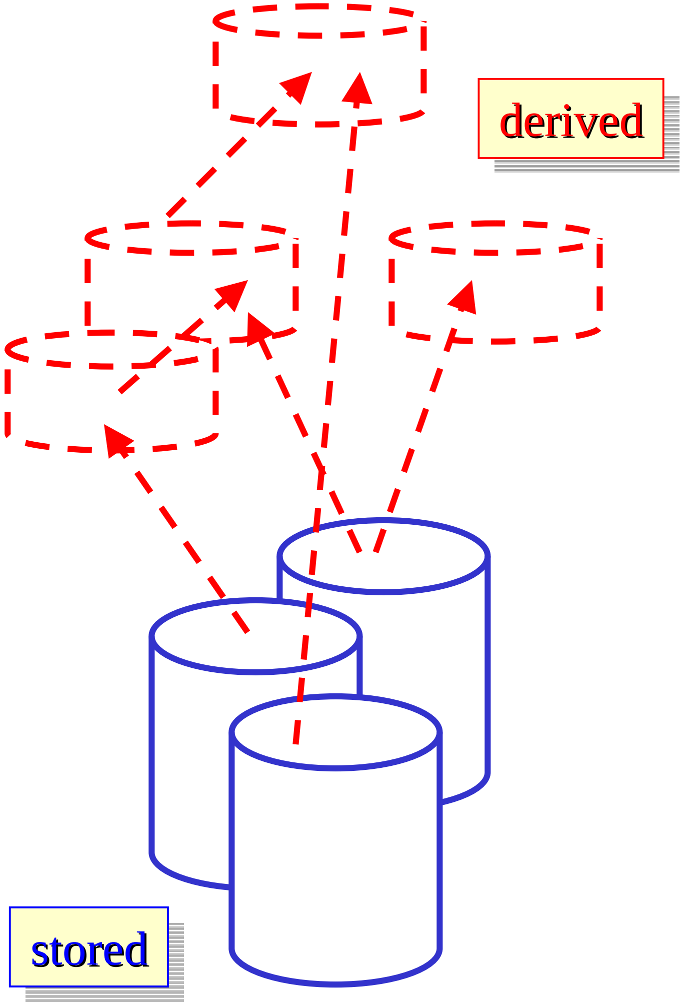
Deduction in Datalog and SQL

Chapter 2



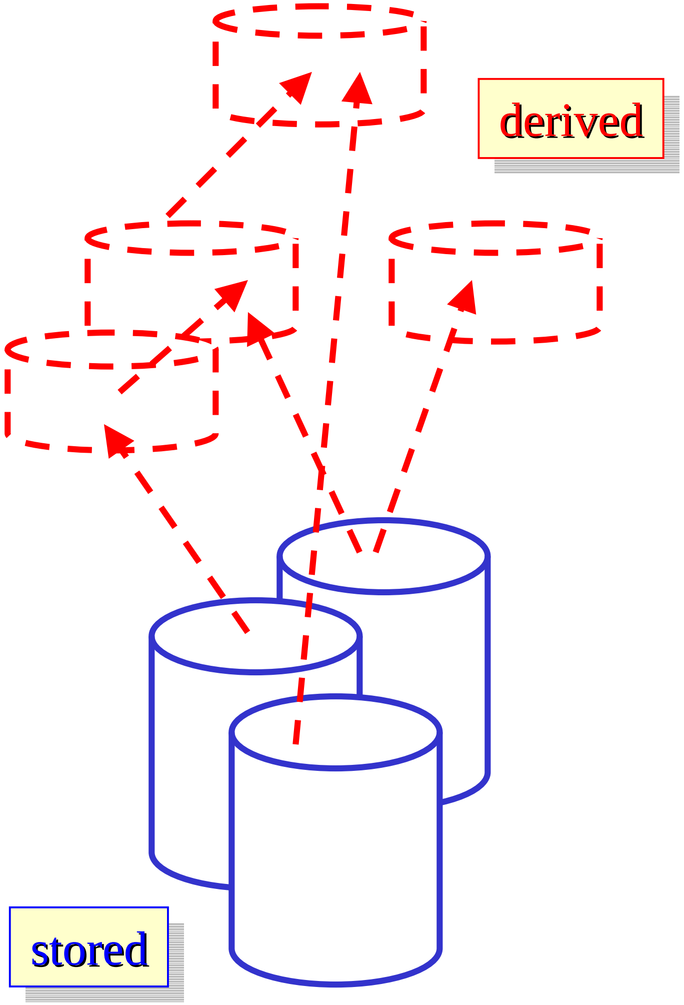


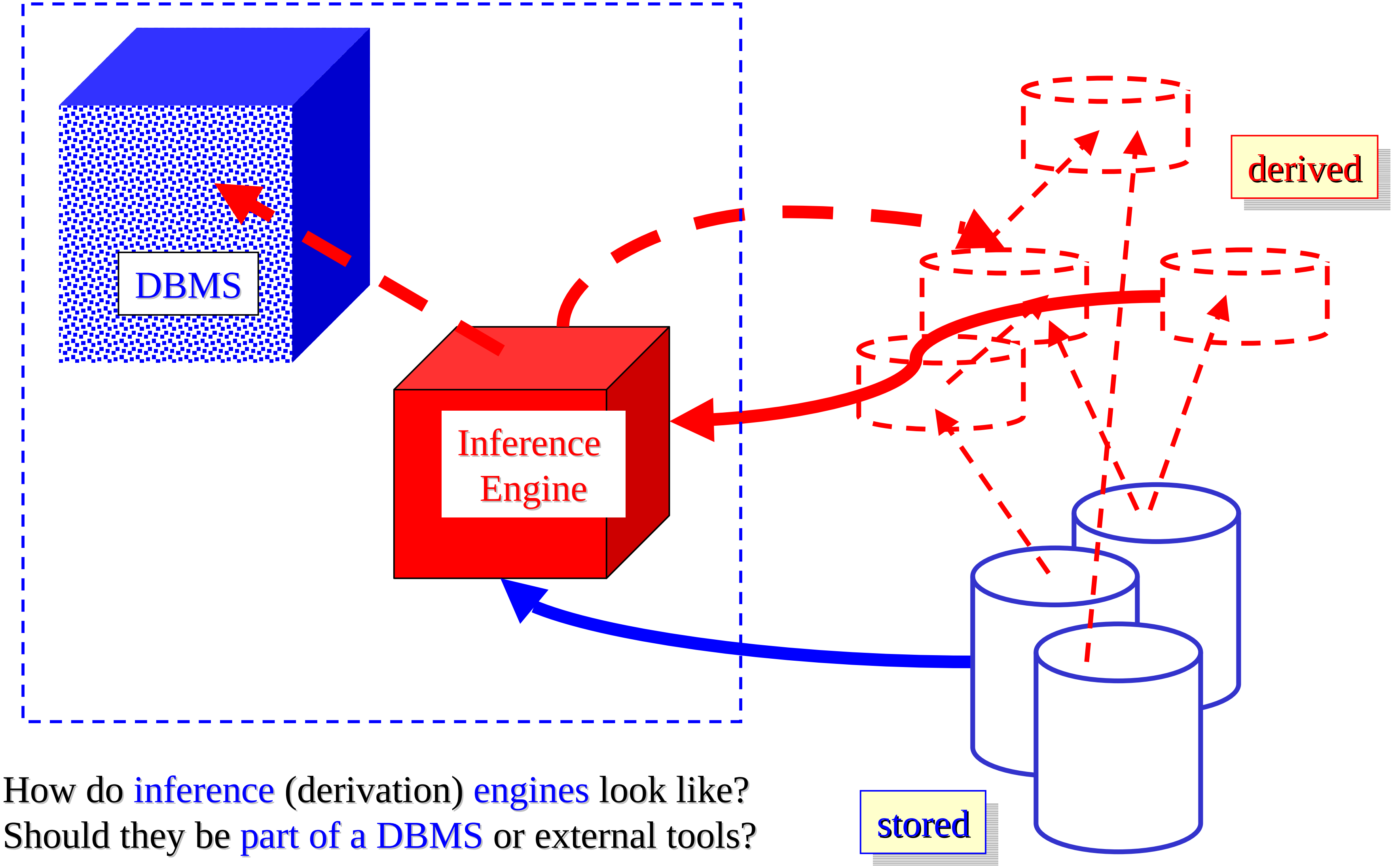
- The essential topic of this lecture is to understand the importance of the idea of using the concept of derived data (and of the corresponding technology).
- We already learnt last week, that databases „containing“stored as well as derived data are called deductive databases in scientific terminology.
- In order to manage derived data, we need special abilities of our DBMS that turn it into a deductive DBMS.
- Managing derived data means
  - designing a deductive DB schema
  - incl. specifying derivation rules
  - evaluating queries over derived data
- controlling consequences of changes of derived data



Stored or Derived (or both?)

- Storing data is the „normal“ way of keeping data (in some storage device).
- Every data element can be stored (in principle).
- But there are data elements that do not (necessarily) have to be stored, but (possibly) can be computed from stored (or other) derived data elements instead. We call such pieces of data „derived“ data (elements).
- It would be more precise to speak about „derivable“ data, because may be a derivable piece of data is actually never derived later on (or has never been derived up till now). We will use the term „derived“ data nevertheless.
- Part of the derivable data can redundantly be stored (after having been derived first) in order to avoid costly rederivation. We call such data materialized (derived) data.





How do inference (derivation) engines look like?
Should they be part of a DBMS or external tools?

We follow a specific approach in IIS!

Intelligent Information Systems

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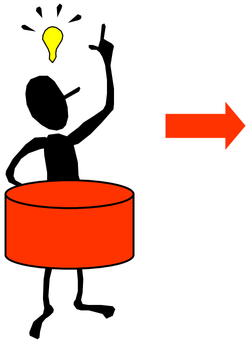
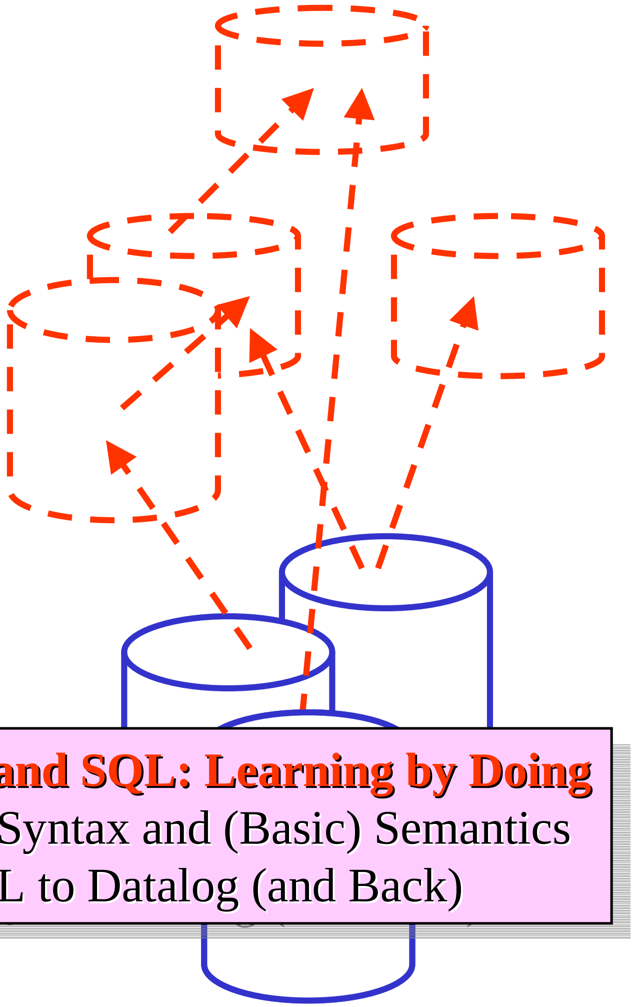
2. Datalog and SQL





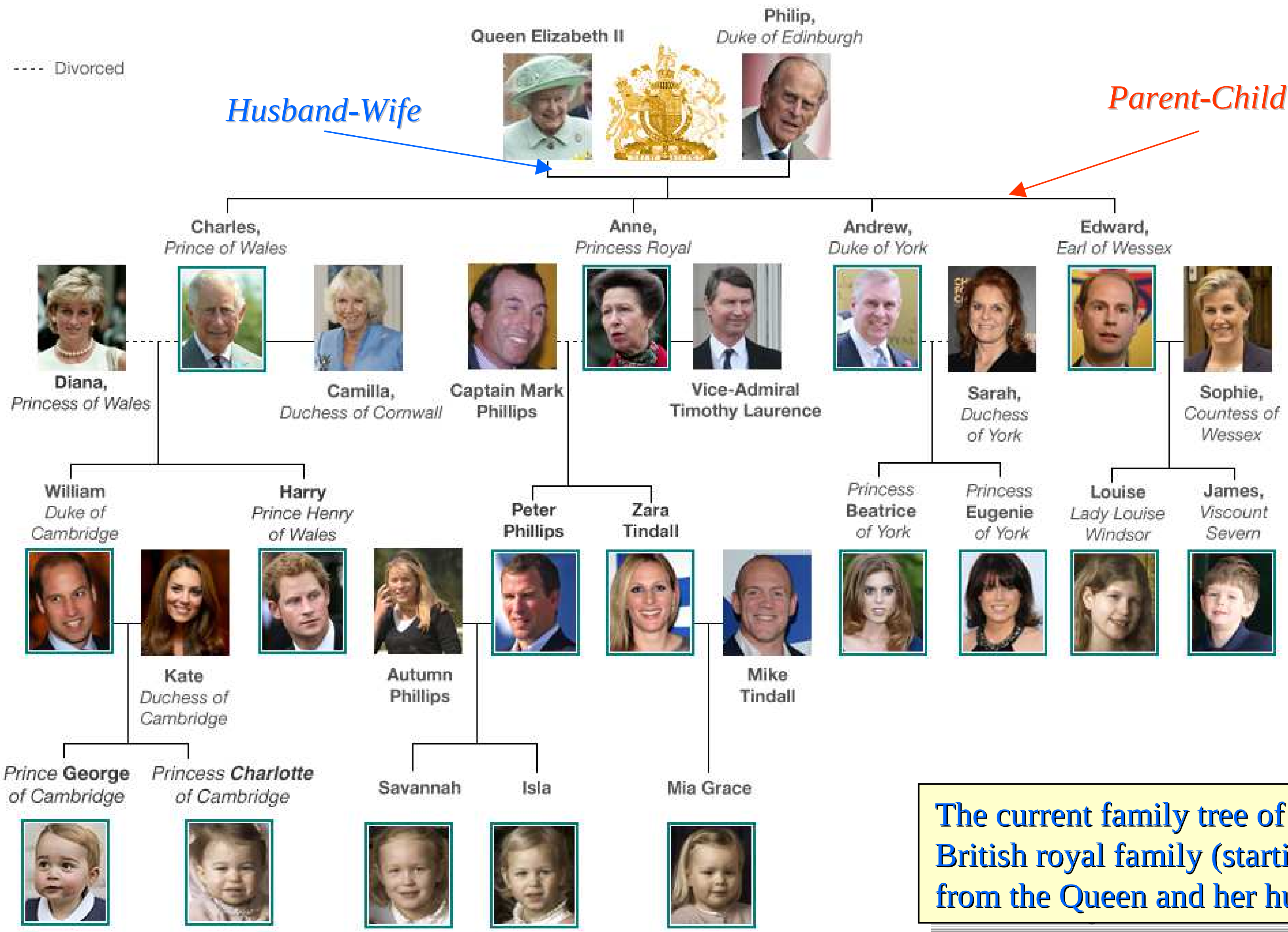
2.1 Datalog and SQL: Learning by Doing

2.2 Datalog: Syntax and (Basic) Semantics

2.3 From SQL to Datalog (and Back)

A case study on using derived data will give us a concrete start into using the techniques of Deductive Database technology: A Genealogical Database

The Royal Family Tree: Our Example Application Domain

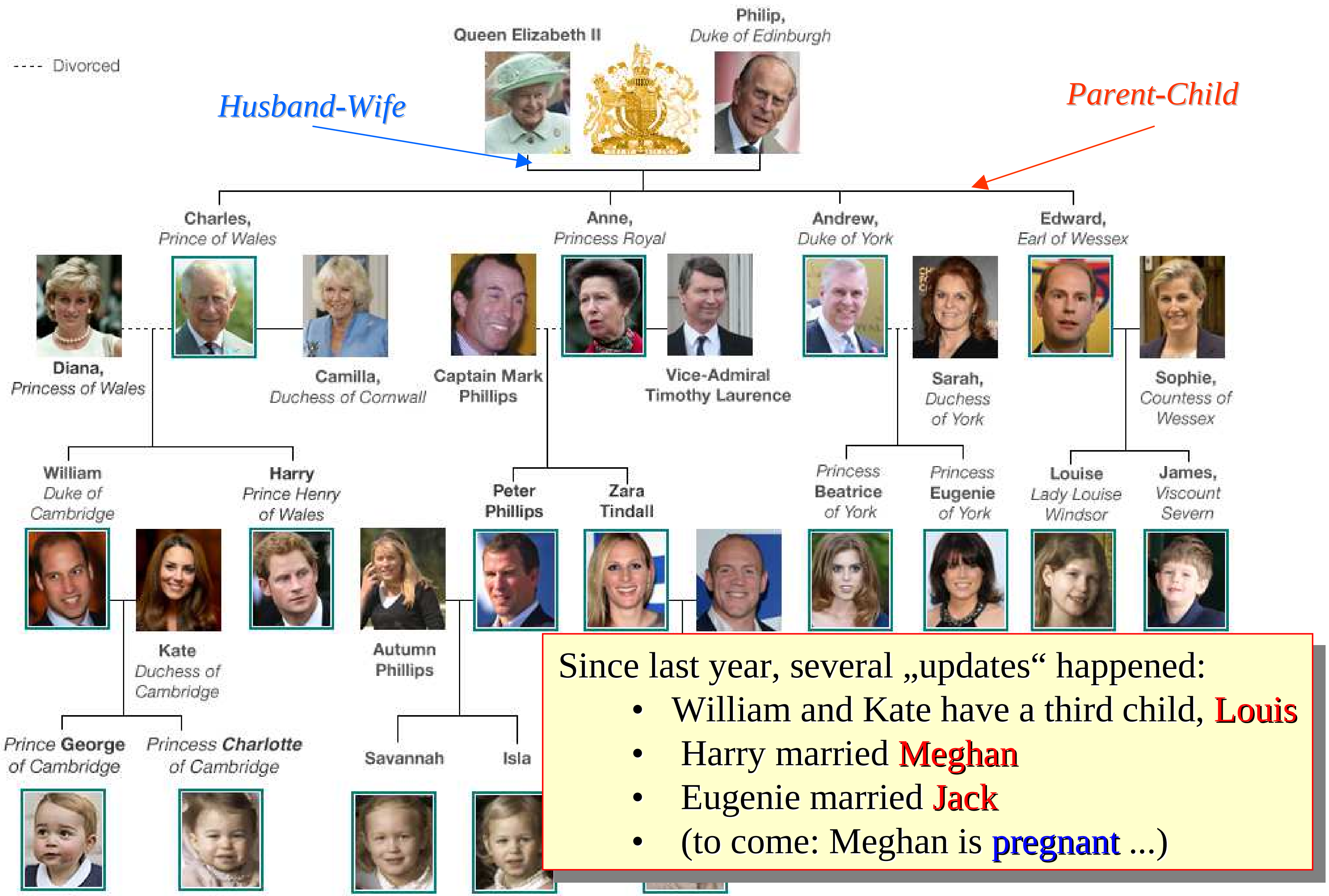


Husband-Wife

Parent-Child

The current family tree of the British royal family (starting from the Queen and her husband)

The Royal Family Tree: More Recent Updates

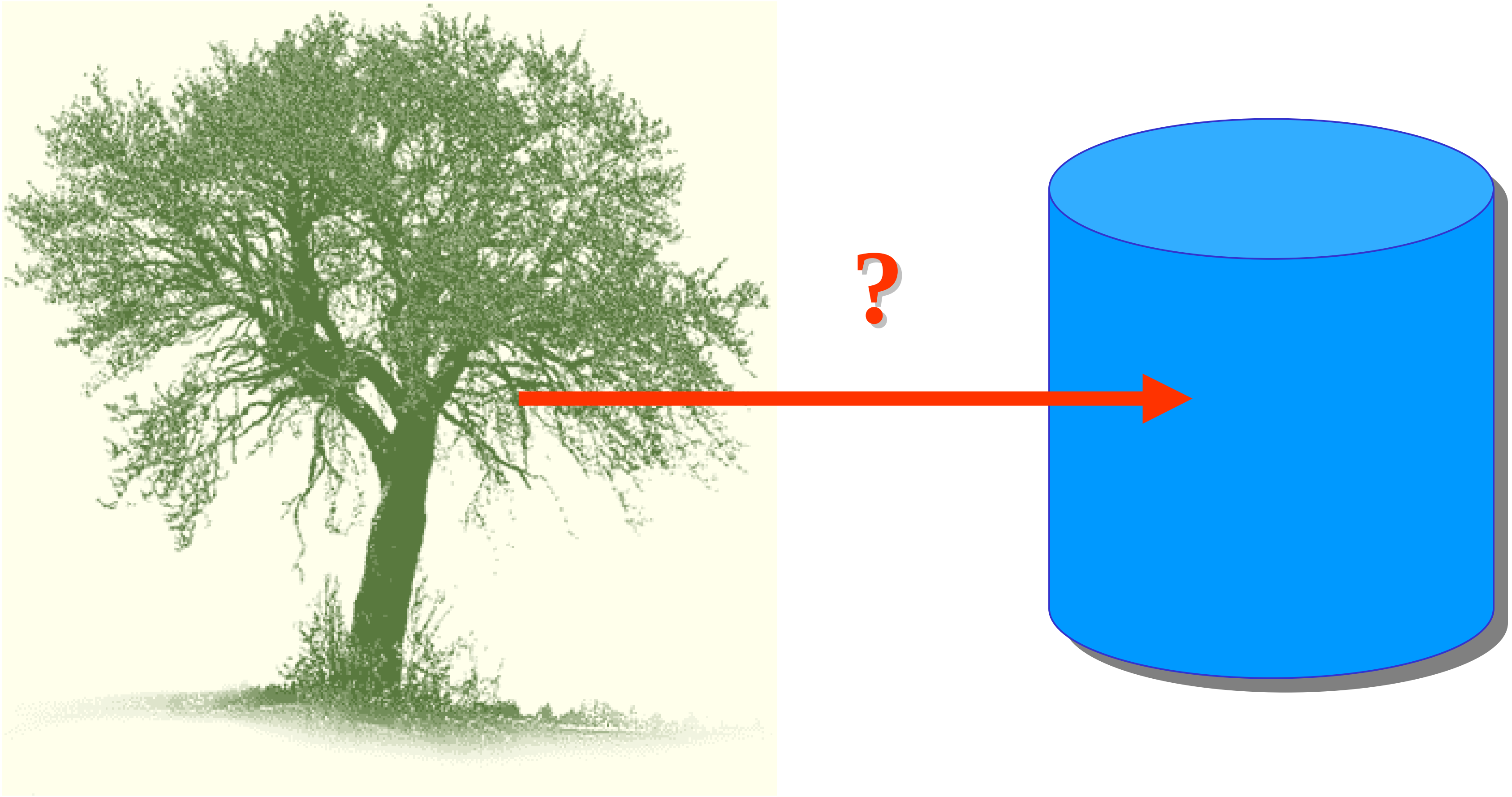

---- Divorced
Queen Elizabeth II
Philip, Duke of Edinburgh
Charles, Prince of Wales
Anne, Princess Royal
Andrew, Duke of York
Edward, Earl of Wessex
Diana, Princess of Wales
Camilla, Duchess of Cornwall
Captain Mark Phillips
Vice-Admiral Timothy Laurence
Sarah, Duchess of York
Sophie, Countess of Wessex
William Duke of Cambridge
Harry Prince Henry of Wales
Peter Phillips
Zara Tindall
Princess Beatrice of York
Princess Eugenie of York
Louise Lady Louise Windsor
James, Viscount Severn
Kate Duchess of Cambridge
Autumn Phillips
Prince George of Cambridge
Princess Charlotte of Cambridge
Savannah
Isla

Husband-Wife

Parent-Child

Since last year, several „updates“ happened:

- William and Kate have a third child, Louis
- Harry married Meghan
- Eugenie married Jack
- (to come: Meghan is pregnant ...)

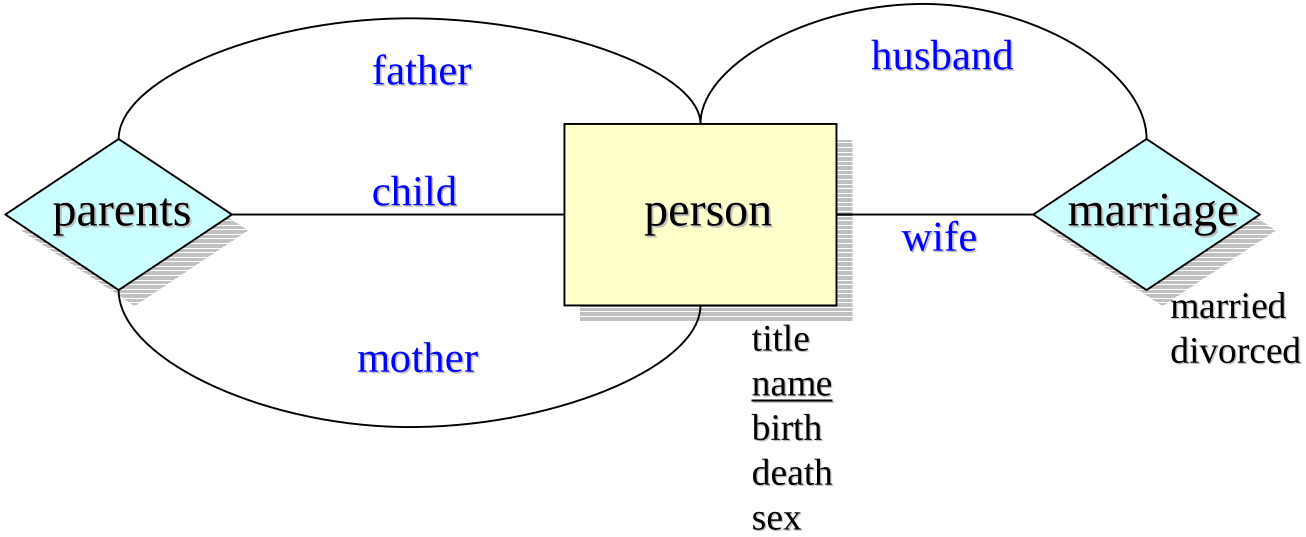


How to „put a family tree into a (relational) database"?

(i.e., how to design a basic genealogical database)

- Traditional way of designing a relational DB:
  Start by conceptually modelling the resp. application domain

- Corresponding ER diagram (Entity-Relationship approach):

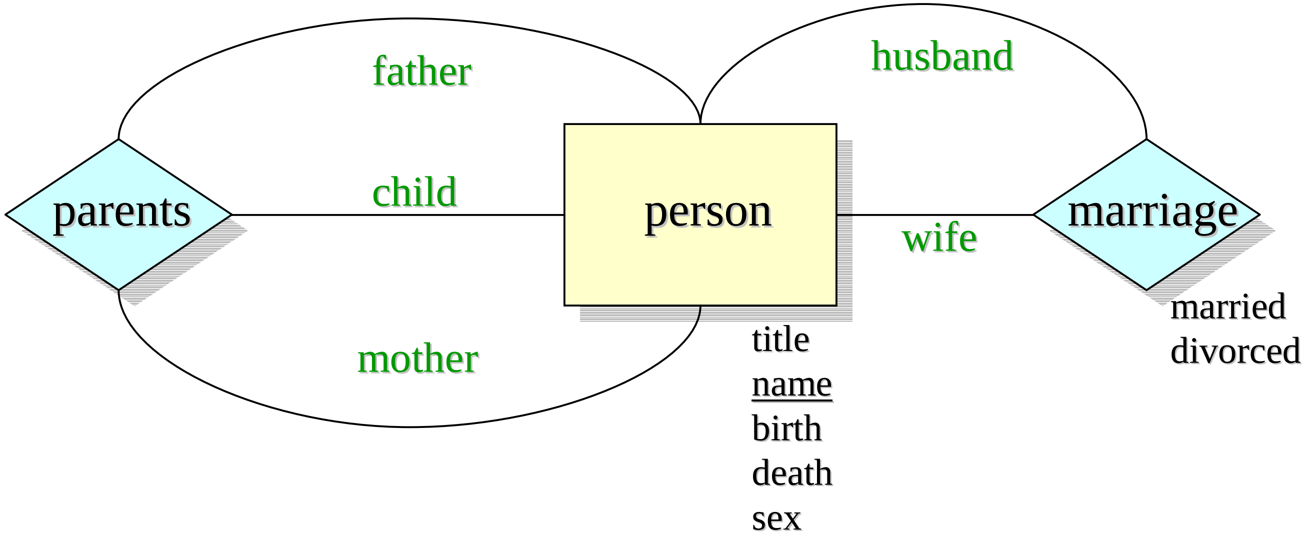


- Basic technique for logical design: deriving a relational DB schema from an ER diagram
  - per entity type one table: Each attribute of the E-type turned into attribute of table
  - per relationship type on table, too: Each attribute of the R-type into attribute of corr. table, plus key attributes of of participating E-types (as foreign keys)

Logical Modeling of the Family Tree DB (1)

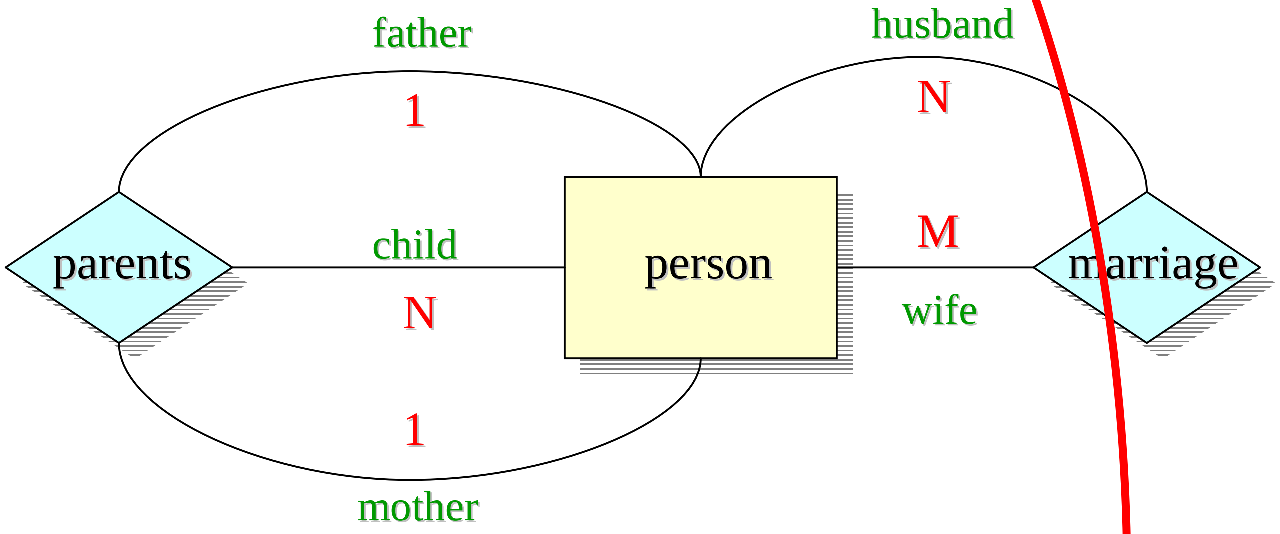
- The basic relational schema for this ER diagram looks as follows:
  - person (title, <u>name</u>, birth, death, sex)
  - parents (father, mother, <u>child</u>)
  - marriage (<u>husband</u>, <u>wife</u>, <u>married</u>, divorced)

- Roles in R-types are turned into attributes of the corr. R-table.



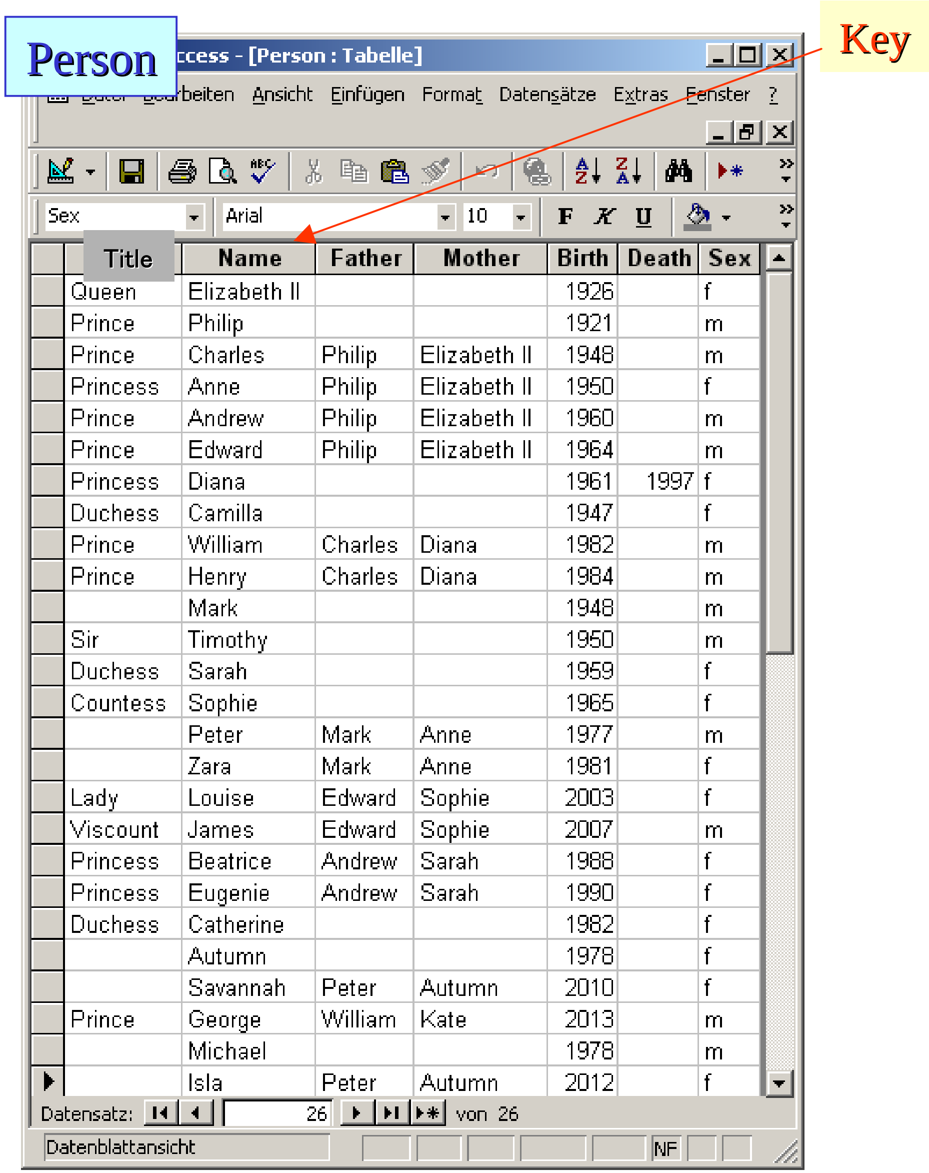
- person (title, name, birth, death, sex)
- parents (father, mother, child)
- marriage (husband, wife, married, divorced)

The initial design can be improved by integrating certain relationship tables into entity tables in case of 1:N functionalities :



- person (title, name, birth, death, sex, father, mother)
- marriage (husband, wife, married, divorced)

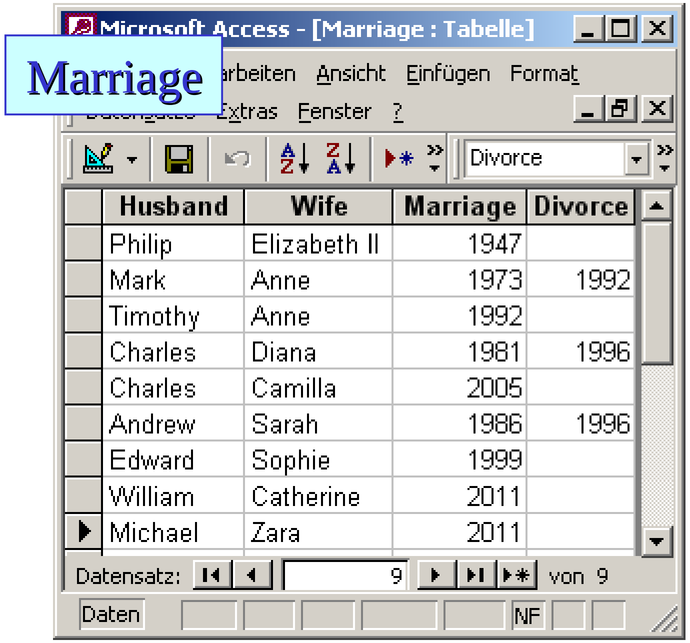
Corresponding Genealogical Database


Person
Key
ccess - [Person : Tabelle]
Datei Bearbeiten Ansicht Einfügen Format Datensätze Extras Fenster ?
Sex
Arial
10
F K U
Datenblattansicht
NF

Title	Name	Father	Mother	Birth	Death	Sex
Queen	Elizabeth II			1926		f
Prince	Philip			1921		m
Prince	Charles	Philip	Elizabeth II	1948		m
Princess	Anne	Philip	Elizabeth II	1950		f
Prince	Andrew	Philip	Elizabeth II	1960		m
Prince	Edward	Philip	Elizabeth II	1964		m
Princess	Diana			1961	1997	f
Duchess	Camilla			1947		f
Prince	William	Charles	Diana	1982		m
Prince	Henry	Charles	Diana	1984		m
	Mark			1948		m
Sir	Timothy			1950		m
Duchess	Sarah			1959		f
Countess	Sophie			1965		f
	Peter	Mark	Anne	1977		m
	Zara	Mark	Anne	1981		f
Lady	Louise	Edward	Sophie	2003		f
Viscount	James	Edward	Sophie	2007		m
Princess	Beatrice	Andrew	Sarah	1988		f
Princess	Eugenie	Andrew	Sarah	1990		f
Duchess	Catherine			1982		f
	Autumn			1978		f
	Savannah	Peter	Autumn	2010		f
Prince	George	William	Kate	2013		m
	Michael			1978		m
	Isla	Peter	Autumn	2012		f

Datensatz: 26 von 26

One possible (initial) relational format for family trees: just two tables!


Marriage
Microsoft Access - [Marriage : Tabelle]
arbeiten Ansicht Einfügen Format
Extras Fenster ?
Divorce
Daten
NF

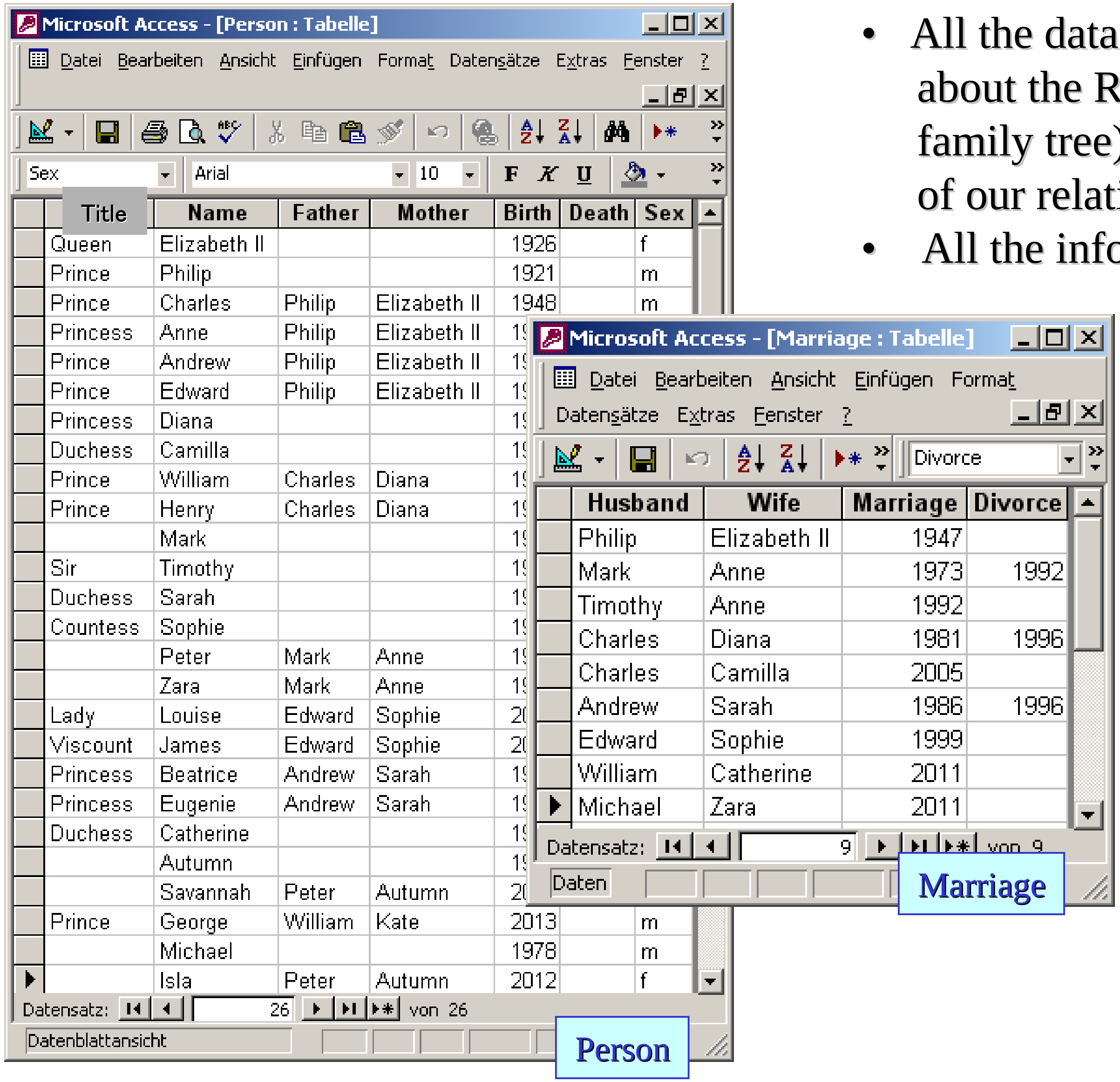
Husband	Wife	Marriage	Divorce
Philip	Elizabeth II	1947	
Mark	Anne	1973	1992
Timothy	Anne	1992	
Charles	Diana	1981	1996
Charles	Camilla	2005	
Andrew	Sarah	1986	1996
Edward	Sophie	1999	
William	Catherine	2011	
Michael	Zara	2011	

Datensatz: 9 von 9

The entire family tree is „in“ these two tables.

Disadvantage(?): Many empty cells („nulls“)

Just Stored Data in Our Genealogical DB – Up Till Now



Microsoft Access - [Person : Tabelle]

Title	Name	Father	Mother	Birth	Death	Sex
Queen	Elizabeth II			1926		f
Prince	Philip			1921		m
Prince	Charles	Philip	Elizabeth II	1948		m
Princess	Anne	Philip	Elizabeth II	19		
Prince	Andrew	Philip	Elizabeth II	19		
Prince	Edward	Philip	Elizabeth II	19		
Princess	Diana			19		
Duchess	Camilla			19		
Prince	William	Charles	Diana	19		
Prince	Henry	Charles	Diana	19		
	Mark			19		
Sir	Timothy			19		
Duchess	Sarah			19		
Countess	Sophie			19		
	Peter	Mark	Anne	19		
	Zara	Mark	Anne	19		
Lady	Louise	Edward	Sophie	20		
Viscount	James	Edward	Sophie	20		
Princess	Beatrice	Andrew	Sarah	19		
Princess	Eugenie	Andrew	Sarah	19		
Duchess	Catherine			19		
	Autumn			19		
	Savannah	Peter	Autumn	20		
Prince	George	William	Kate	2013		m
	Michael			1978		m
	Isla	Peter	Autumn	2012		f

Datensatz: 26 von 26

Datenblattansicht

Person

Microsoft Access - [Marriage : Tabelle]

Husband	Wife	Marriage	Divorce
Philip	Elizabeth II	1947	
Mark	Anne	1973	1992
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Charles	Diana	1981	1996
Charles	Camilla	2005	
Andrew	Sarah	1986	1996
Edward	Sophie	1999	
William	Catherine	2011	
Michael	Zara	2011	

Datensatz: 9 von 9

Daten

Marriage

Datei Bearbeiten Ansicht Einfügen Format Datensätze Extras Fenster ?
Sex
Arial
10
F K U
Divorce

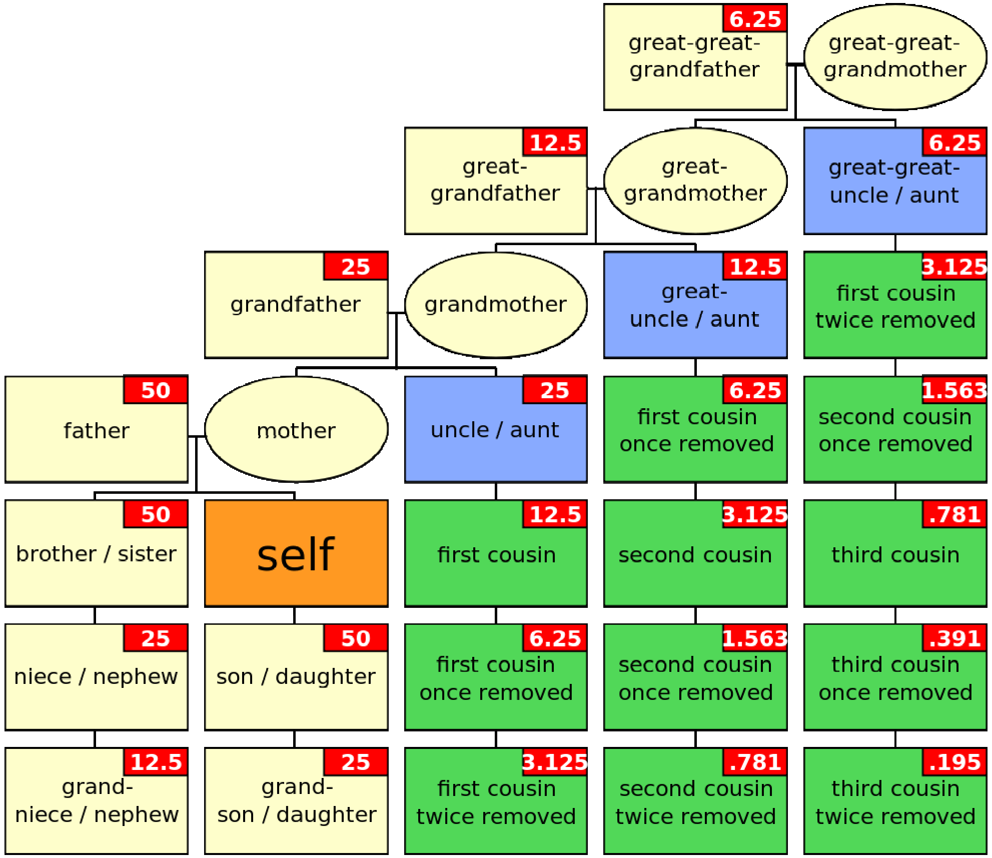
- All the data representing what we know about the Royal family members (in the family tree) have to be stored in tables of our relational DB.
- All the information in these two tables are „given“ data reported from the „real world“.
- None of this could have been derived from other parts of the database.

Can we turn this DB into a deductive DB by extending it with additional derived data?

How to do this, ...

...if we can?

Genealogical Terminology: Potential for Deduction



Blood relation (or: consanguinity) only!

Numbers indicate percentage of „common blood“

In this graph, relatives from the maternal side are given only – paternal relatives analogously.

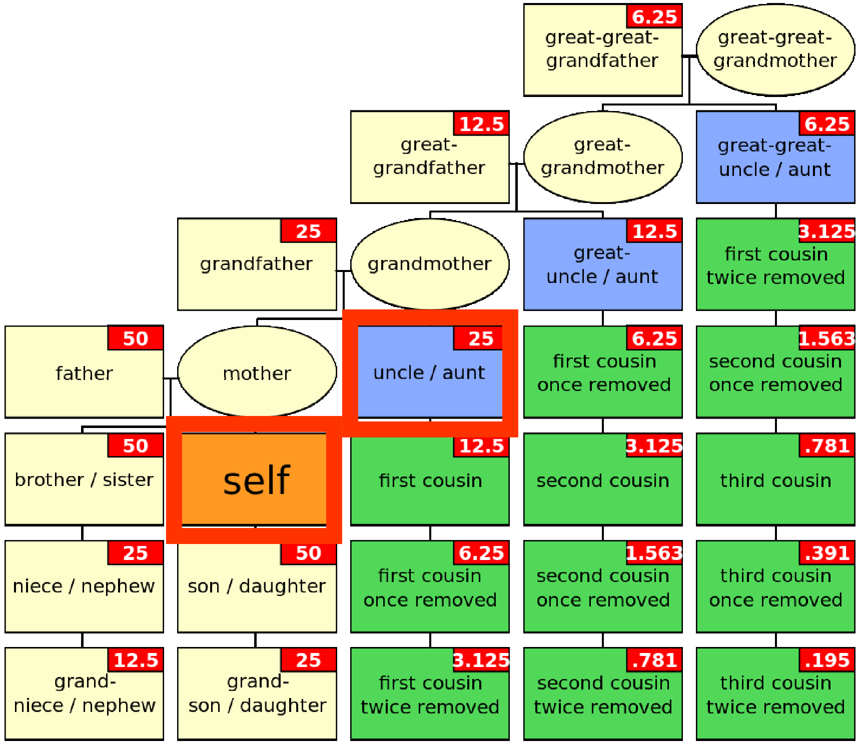
- Data about „existence“ (birth, death, sex, name etc.) cannot be derived, but have to be entered manually and stored in tables. The same applies to marriage and divorce.
- All other data about family relationships, however, are derivable from these stored data, provided we can express them using suitable derivation rules.

Example: Deriving Uncle Data from the Stored Family Tree Data

e.g.:

How to derive data about the uncles of a person?

(Aunts could be treated analogously.)

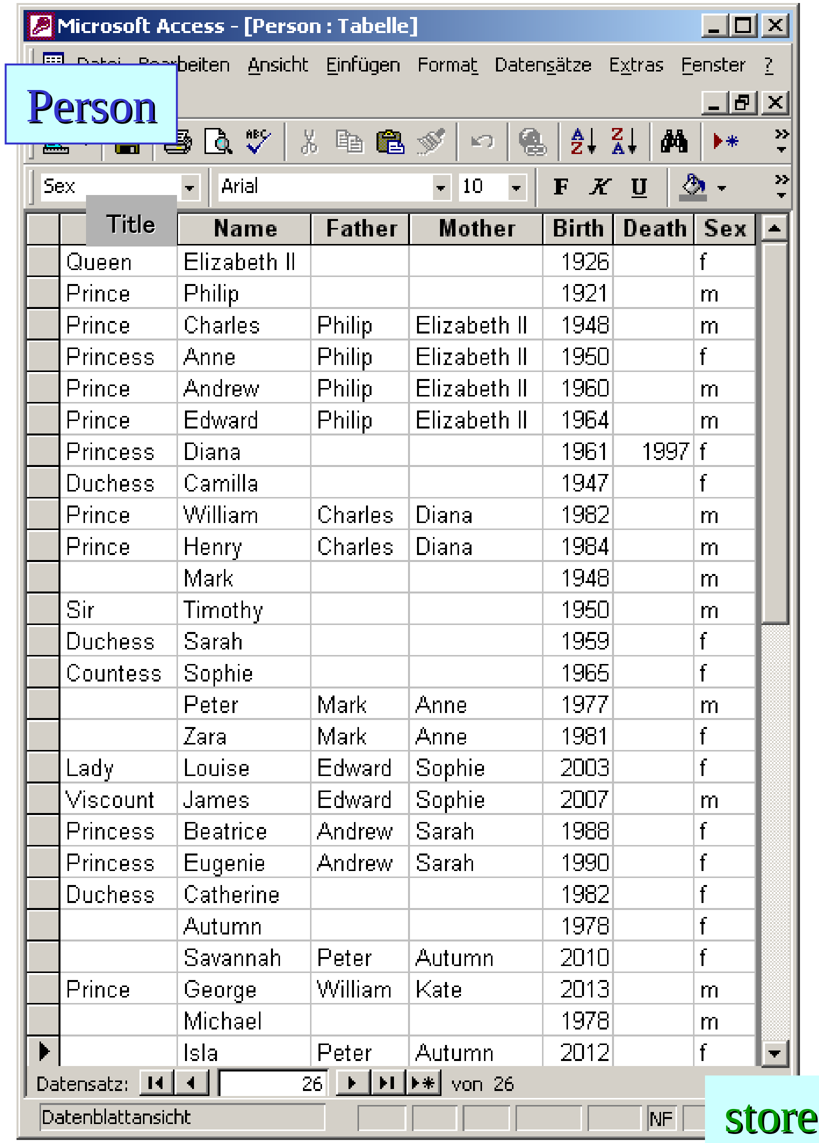

great-great-grandfather 6.25
great-great-grandmother
great-grandfather 12.5
great-grandmother
great-great-uncle / aunt 6.25
grandfather 25
grandmother
great-uncle / aunt 12.5
first cousin twice removed 3.125
father 50
mother
uncle / aunt 25
first cousin once removed 6.25
second cousin once removed 1.563
brother / sister 50
self
first cousin 12.5
second cousin 3.125
third cousin .781
niece / nephew 25
son / daughter 50
first cousin once removed 6.25
second cousin once removed 1.563
third cousin once removed .391
grand-niece / nephew 12.5
grand-son / daughter 25
first cousin twice removed 3.125
second cousin twice removed .781
third cousin twice removed .195

Uncle (from Latin: *avunculus* "little grandfather", the diminutive of *avus* "grandfather") is a family relationship or kinship, between a person and his or her parent's brother, ~~parent's brother-in-law or parent's cousin.~~

(from: en/wikipedia)

(Here we restrict ourselves to uncle in the narrow sense)

„Uncle“ as a Derived Table


Microsoft Access - [Person : Tabelle]
Datei Bearbeiten Ansicht Einfügen Format Datensätze Extras Fenster ?
Sex
Arial
10
F K U
Datensatz: 26 von 26
Datenblattansicht
NF

Person

Title	Name	Father	Mother	Birth	Death	Sex
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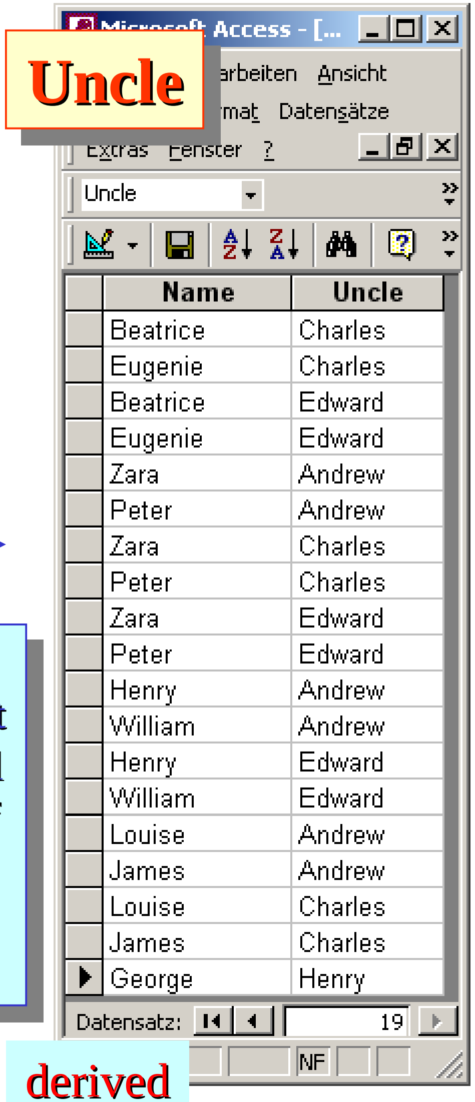
Prince	Philip			1921		m
Prince	Charles	Philip	Elizabeth II	1948		m
Princess	Anne	Philip	Elizabeth II	1950		f
Prince	Andrew	Philip	Elizabeth II	1960		m
Prince	Edward	Philip	Elizabeth II	1964		m
Princess	Diana			1961	1997	f
Duchess	Camilla			1947		f
Prince	William	Charles	Diana	1982		m
Prince	Henry	Charles	Diana	1984		m
	Mark			1948		m
Sir	Timothy			1950		m
Duchess	Sarah			1959		f
Countess	Sophie			1965		f
	Peter	Mark	Anne	1977		m
	Zara	Mark	Anne	1981		f
Lady	Louise	Edward	Sophie	2003		f
Viscount	James	Edward	Sophie	2007		m
Princess	Beatrice	Andrew	Sarah	1988		f
Princess	Eugenie	Andrew	Sarah	1990		f
Duchess	Catherine			1982		f
	Autumn			1978		f
	Savannah	Peter	Autumn	2010		f
Prince	George	William	Kate	2013		m
	Michael			1978		m
	Isla	Peter	Autumn	2012		f

stored

It would be nice to have the data about uncles in the Royal family in a table of its own – best in a derived table!

(If possible!)



Uncle

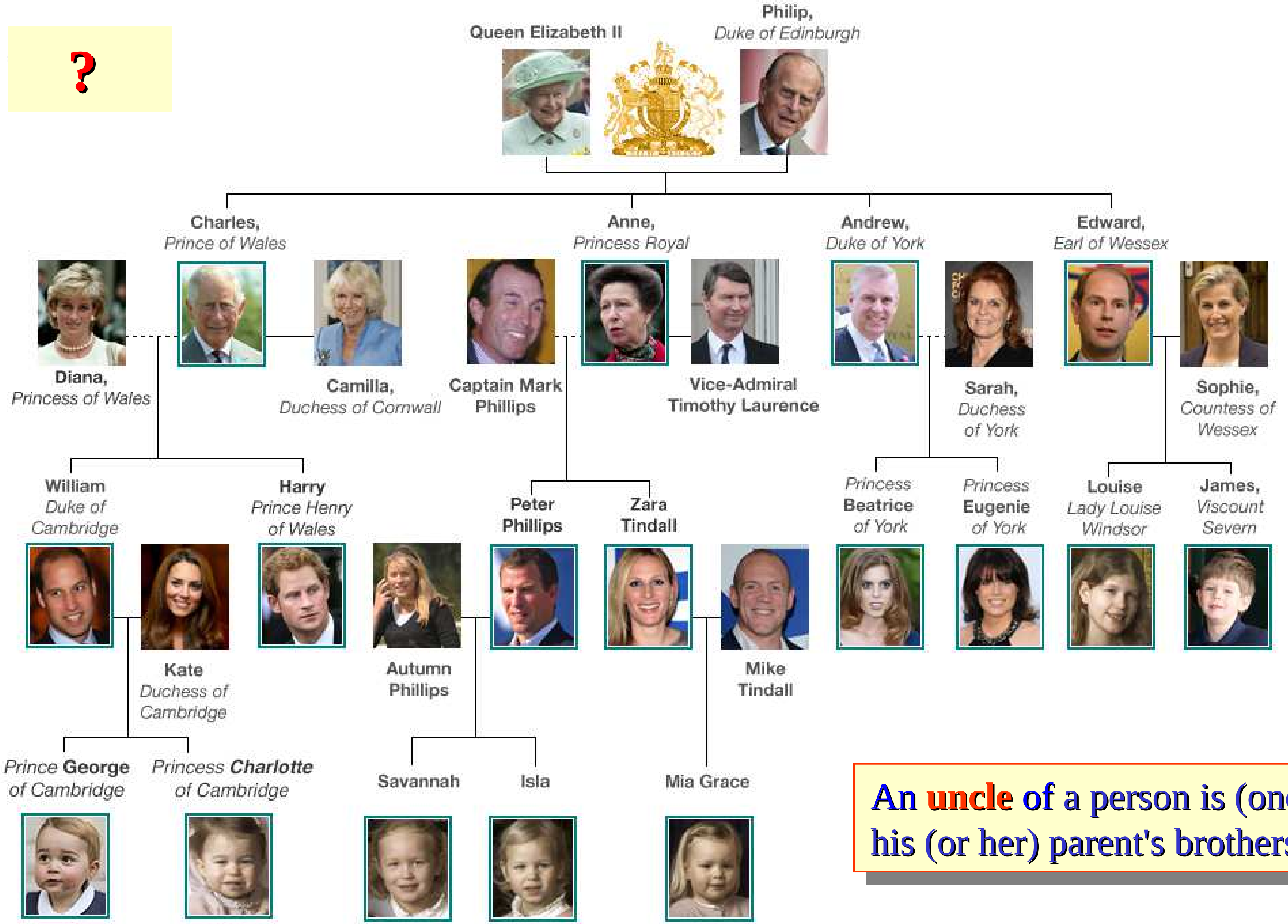
Name	Uncle
Beatrice	Charles
Eugenie	Charles
Beatrice	Edward
Eugenie	Edward
Zara	Andrew
Peter	Andrew
Zara	Charles
Peter	Charles
Zara	Edward
Peter	Edward
Henry	Andrew
William	Andrew
Henry	Edward
William	Edward
Louise	Andrew
James	Andrew
Louise	Charles
James	Charles
George	Henry

derived

(Uncles of Charlotte
and Mia still missing.)

Uncle Relationships in the Royal Family Tree?

?

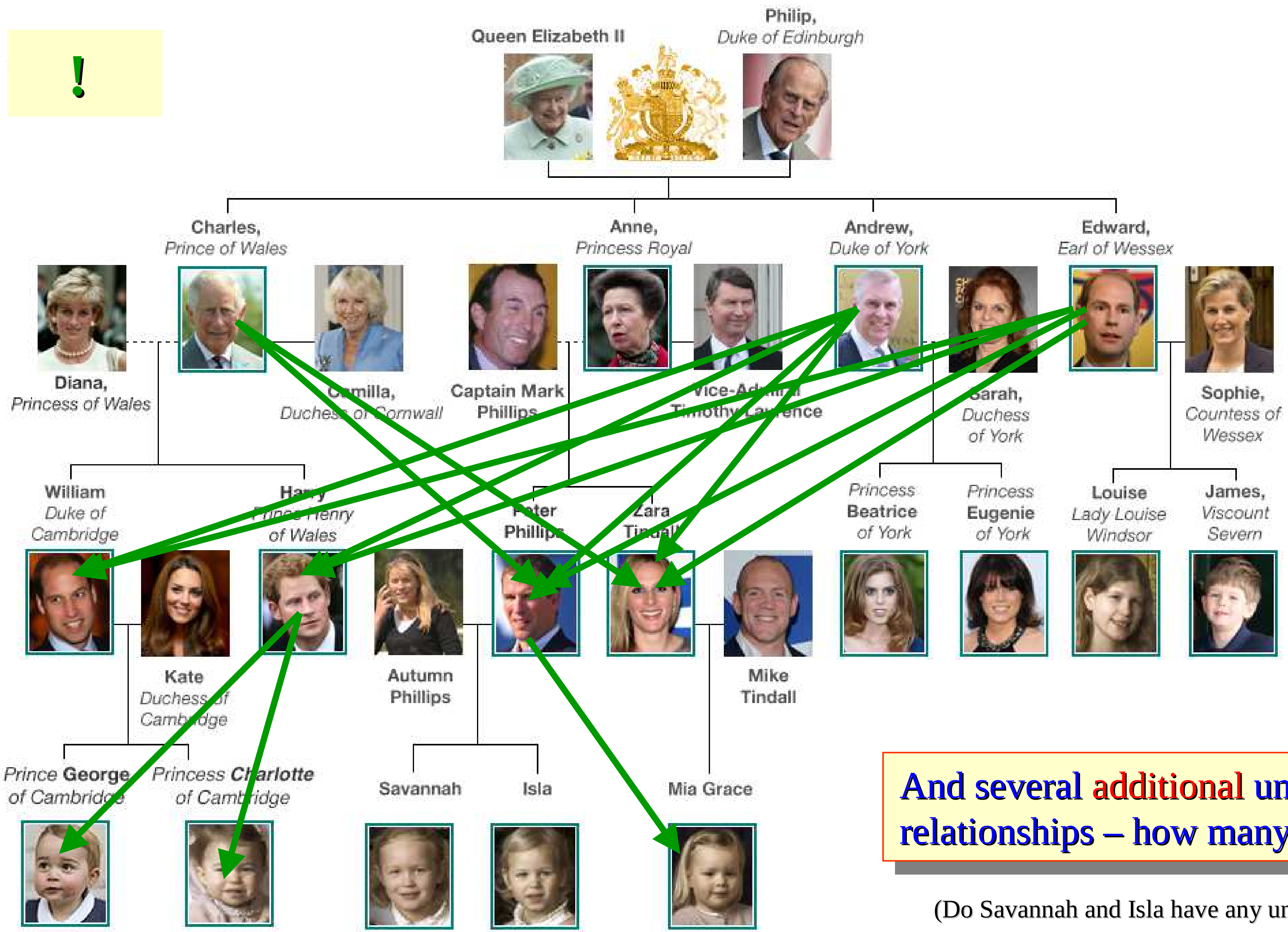


Queen Elizabeth II
Philip, Duke of Edinburgh
Charles, Prince of Wales
Anne, Princess Royal
Andrew, Duke of York
Edward, Earl of Wessex
Diana, Princess of Wales
Camilla, Duchess of Cornwall
Captain Mark Phillips
Vice-Admiral Timothy Laurence
Sarah, Duchess of York
Sophie, Countess of Wessex
William Duke of Cambridge
Harry Prince Henry of Wales
Peter Phillips
Zara Tindall
Princess Beatrice of York
Princess Eugenie of York
Louise Lady Louise Windsor
James, Viscount Severn
Kate Duchess of Cambridge
Autumn Phillips
Mike Tindall
Prince George of Cambridge
Princess Charlotte of Cambridge
Savannah
Isla
Mia Grace

An **uncle** of a person is (one of) his (or her) parent's brothers.

Uncle Relationships in the Royal Family Tree!

!



Queen Elizabeth II

Philip,
Duke of Edinburgh

Charles,
Prince of Wales

Anne,
Princess Royal

Andrew,
Duke of York

Edward,
Earl of Wessex

Diana,
Princess of Wales

Camilla,
Duchess of Cornwall

Captain Mark Phillips

Vice-Admiral Timothy Laurence

Sarah,
Duchess of York

Sophie,
Countess of Wessex

William
Duke of Cambridge

Harry
Prince Henry of Wales

Peter Phillips

Zara Tindall

Princess Beatrice *of York*

Princess Eugenie *of York*

Louise
Lady Louise Windsor

James,
Viscount Severn

Kate
Duchess of Cambridge

Autumn Phillips

Mike Tindall

Prince George *of Cambridge*

Princess Charlotte *of Cambridge*

Savannah

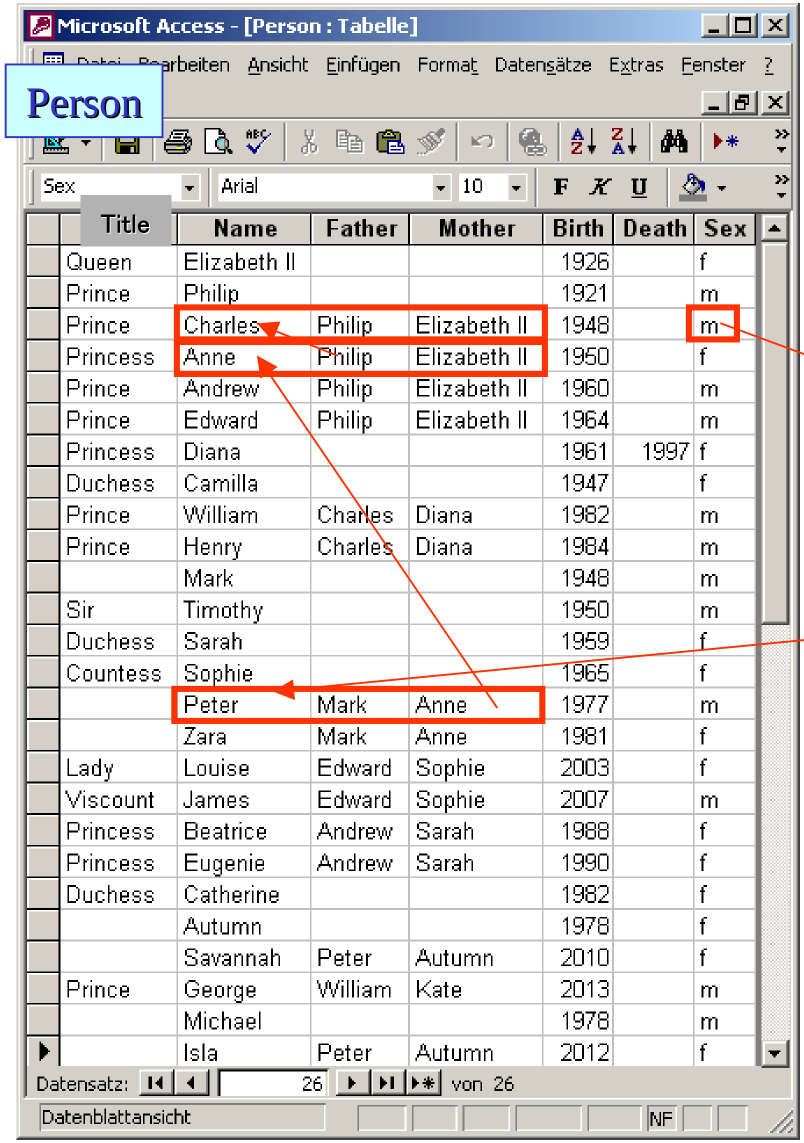
Isla

Mia Grace

And several additional uncle relationships – how many?

(Do Savannah and Isla have any uncles?)

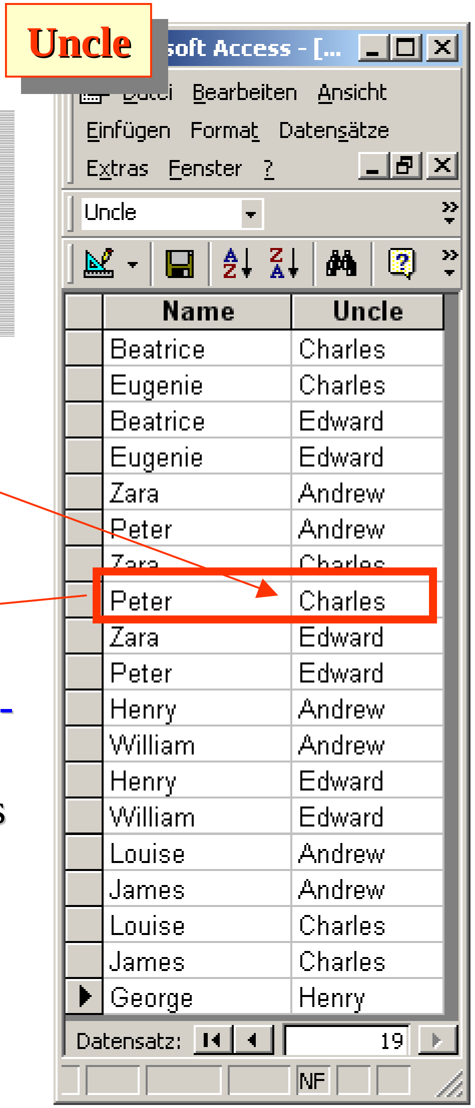
How to Derive a Particular Uncle Row?


Microsoft Access - [Person : Tabelle]
Datei Bearbeiten Ansicht Einfügen Format Datensätze Extras Fenster ?
Sex
Arial
10
F K U
Datensatz: 26 von 26
Datenblattansicht
NF

Person

Title	Name	Father	Mother	Birth	Death	Sex
Queen	Elizabeth II			1926		f
Prince	Philip			1921		m
Prince	Charles	Philip	Elizabeth II	1948		m
Princess	Anne	Philip	Elizabeth II	1950		f
Prince	Andrew	Philip	Elizabeth II	1960		m
Prince	Edward	Philip	Elizabeth II	1964		m
Princess	Diana			1961	1997	f
Duchess	Camilla			1947		f
Prince	William	Charles	Diana	1982		m
Prince	Henry	Charles	Diana	1984		m
	Mark			1948		m
Sir	Timothy			1950		m
Duchess	Sarah			1959		f
Countess	Sophie			1965		f
	Peter	Mark	Anne	1977		m
	Zara	Mark	Anne	1981		f
Lady	Louise	Edward	Sophie	2003		f
Viscount	James	Edward	Sophie	2007		m
Princess	Beatrice	Andrew	Sarah	1988		f
Princess	Eugenie	Andrew	Sarah	1990		f
Duchess	Catherine			1982		f
	Autumn			1978		f
	Savannah	Peter	Autumn	2010		f
Prince	George	William	Kate	2013		m
	Michael			1978		m
	Isla	Peter	Autumn	2012		f

How to **derive** the Uncle table from the Person table?



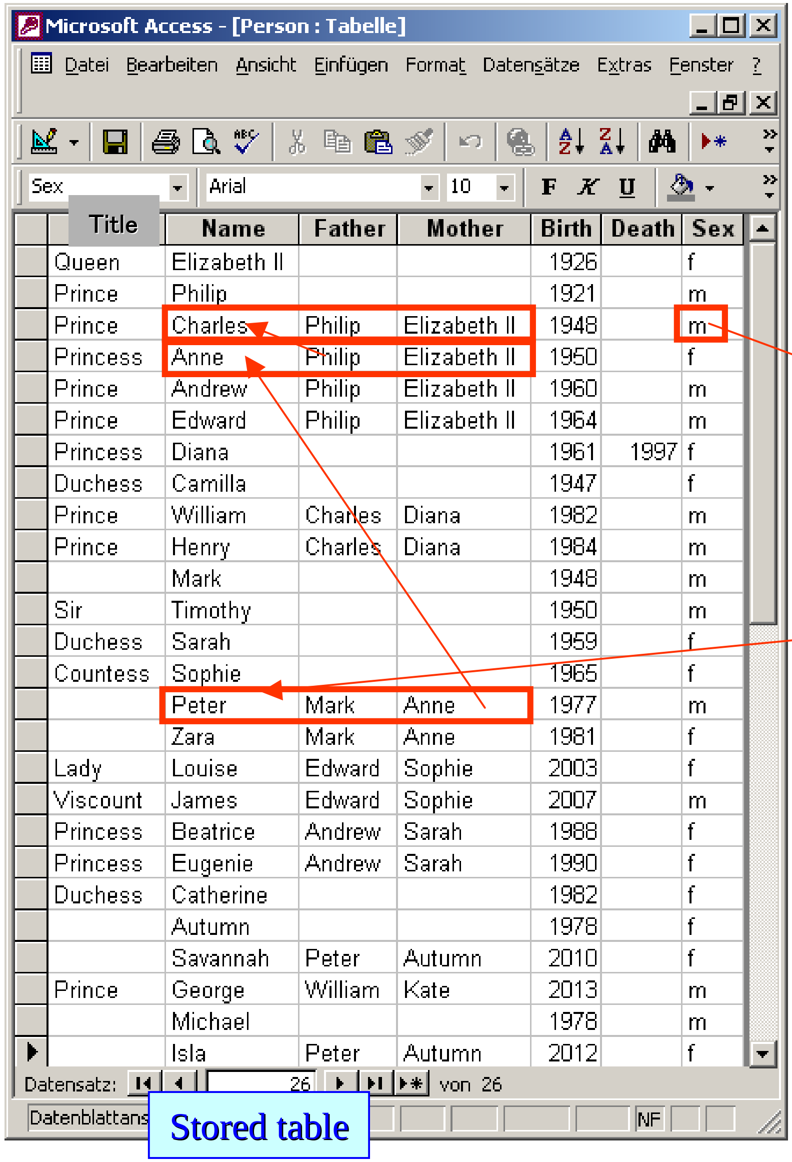
Uncle

Name	Uncle
Beatrice	Charles
Eugenie	Charles
Beatrice	Edward
Eugenie	Edward
Zara	Andrew
Peter	Andrew
Zara	Charles
Peter	Charles
Zara	Edward
Peter	Edward
Henry	Andrew
William	Andrew
Henry	Edward
William	Edward
Louise	Andrew
James	Andrew
Louise	Charles
James	Charles
George	Henry

A derivation strategy a human would use, might serve as a suitable strategy of a deduction „engine“.

(Is this some kind of „artificial intelligence“ ?)

Relational Views as Specifications of a Derivation Strategy


Microsoft Access - [Person : Tabelle]
Datei Bearbeiten Ansicht Einfügen Format Datensätze Extras Fenster ?
Sex
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10
F K U
Datensatz: 26 von 26
Datenblattans
NF

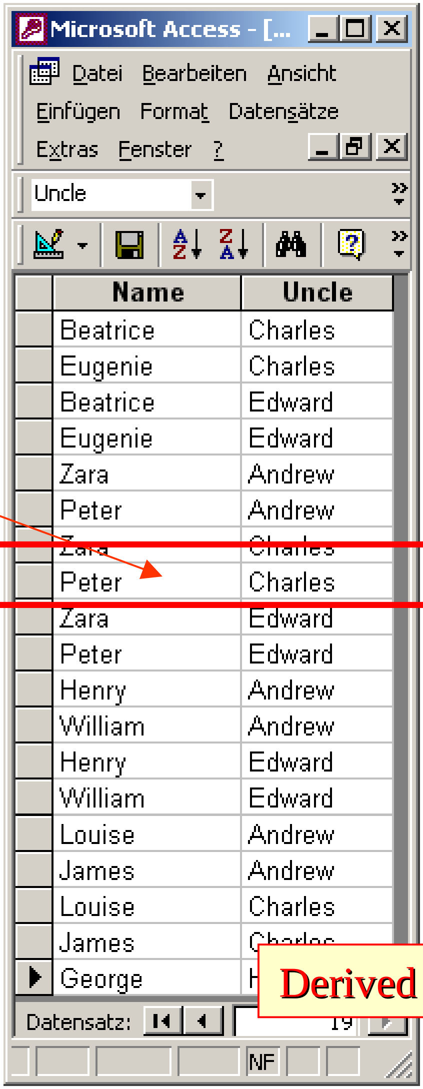
Title	Name	Father	Mother	Birth	Death	Sex
Queen	Elizabeth II			1926		f
Prince	Philip			1921		m
Prince	Charles	Philip	Elizabeth II	1948		m
Princess	Anne	Philip	Elizabeth II	1950		f
Prince	Andrew	Philip	Elizabeth II	1960		m
Prince	Edward	Philip	Elizabeth II	1964		m
Princess	Diana			1961	1997	f
Duchess	Camilla			1947		f
Prince	William	Charles	Diana	1982		m
Prince	Henry	Charles	Diana	1984		m
	Mark			1948		m
Sir	Timothy			1950		m
Duchess	Sarah			1959		f
Countess	Sophie			1965		f
	Peter	Mark	Anne	1977		m
	Zara	Mark	Anne	1981		f
Lady	Louise	Edward	Sophie	2003		f
Viscount	James	Edward	Sophie	2007		m
Princess	Beatrice	Andrew	Sarah	1988		f
Princess	Eugenie	Andrew	Sarah	1990		f
Duchess	Catherine			1982		f
	Autumn			1978		f
	Savannah	Peter	Autumn	2010		f
Prince	George	William	Kate	2013		m
	Michael			1978		m
	Isla	Peter	Autumn	2012		f

Stored table

Derived tables in a relational DB are obtainable as the result of a **query**. Each query thus expresses a deduction „strategy“ of a table.

Named queries can be stored in a relational DB, introducing a named derived table. In SQL, these queries are called **views**.

How does the **SQL view** look like that can „do“ this kind of deduction?



Name	Uncle
Beatrice	Charles
Eugenie	Charles
Beatrice	Edward
Eugenie	Edward
Zara	Andrew
Peter	Andrew
Zara	Charles
Peter	Charles
Zara	Edward
Peter	Edward
Henry	Andrew
William	Andrew
Henry	Edward
William	Edward
Louise	Andrew
James	Andrew
Louise	Charles
James	Charles
George	H

Derived table

„Uncle“ in SQL – 1st Attempt

```
CREATE VIEW Uncle AS
(
            (SELECT     P1.Name,
                        P3.Name  AS Uncle
             FROM       Person AS P1,
                        Person AS P2,
                        Person AS P3
             WHERE      P1.Father = P2.Name
                AND     P2.Mother = P3.Mother
                AND     P2.Father = P3.Father
                AND     P2.Name <> P3.Name
                AND     P3.Sex = 'm')
UNION
            (SELECT     P1.Name,
                        P3.Name  AS Uncle
             FROM       Person AS P1,
                        Person AS P2,
                        Person AS P3
             WHERE      P1.Mother = P2.Name
                AND     P2.Mother = P3.Mother
                AND     P2.Father = P3.Father
                AND     P2.Name <> P3.Name
                AND     P3.Sex = 'm')
)
```

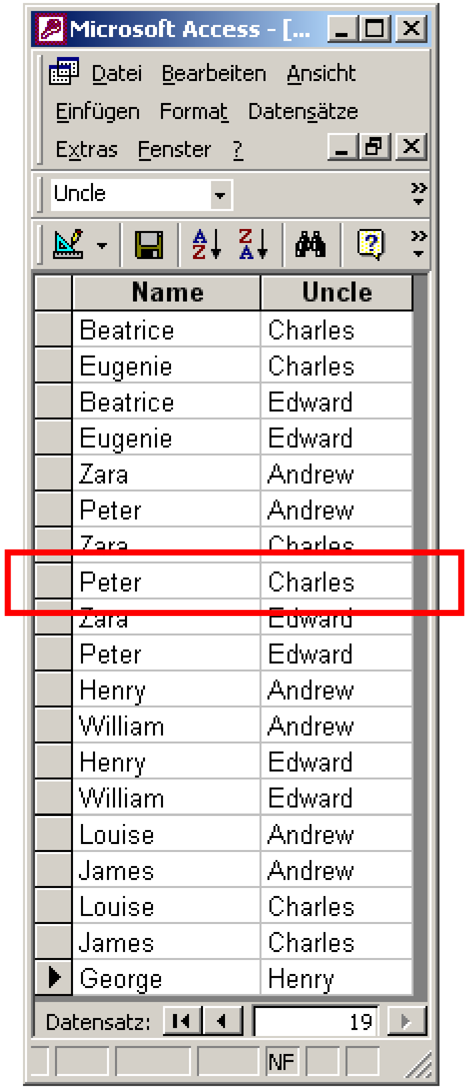
paternal uncle

self father uncle

maternal uncle

self mother uncle

?



Name	Uncle
Beatrice	Charles
Eugenie	Charles
Beatrice	Edward
Eugenie	Edward
Zara	Andrew
Peter	Andrew
Zara	Charles
Peter	Charles
Zara	Edward
Peter	Edward
Henry	Andrew
William	Andrew
Henry	Edward
William	Edward
Louise	Andrew
James	Andrew
Louise	Charles
James	Charles
George	Henry

Apply this code to the Person table on the previous slide!

„Uncle“ in SQL – 2nd Attempt

The direct derivation of *Uncle* from the base table *Person* is very complex – why not try to simulate the Wikipedia definition, which uses auxiliary concepts „parent“ and „brother“?

> **Uncle** ... is a family relationship ... between a person and his or her parent's brother ...

Assume we had views *Parent(Name, Parent)* and *Brother(Name,Brother)* available – then *Uncle* could be specified like this:

```
CREATE VIEW Uncle AS
          (SELECT   P.Name      AS Name,
                    B.Brother   AS Uncle
           FROM     Parent    AS   P,
                    Brother   AS   B
           WHERE    P.Parent = B.Name)
```

Much, much simpler – but we still need specifications of the two other views ...

e.g.: *Parent('Peter', 'Anne')* *Brother('Anne', 'Charles')* } *Uncle('Peter', 'Charles')*

- Both, father and mother of a person are the *parents* of this person.

- In English, the term *parent* exists as a singular noun, too – unlike, e.g., in German.

- So the SQL specification of *Parent* needs two cases, one for paternal and maternal parent each:

```
CREATE VIEW Parent AS
(
          (SELECT   Name,
                    Father  AS  Parent
           FROM     Person)
UNION
          (SELECT   Name,
                    Mother  AS  Parent
           FROM     Person)
)
```

paternal parent

maternal parent

„Brother“ in SQL

- The *brother* of a person is a male with exactly the same pair of parents.
- If just one of mother or father is the same, we speak of a *half-brother*.
- The SQL view *Brother* looks like this:

```
CREATE VIEW Brother AS
        (SELECT    P1.Name,
                   P2.Name  AS Brother
         FROM      Person AS P1,
                   Person AS P2,
         WHERE     P1.Mother = P2.Mother
            AND     P1.Father = P2.Father
            AND     P1.Name <> P2.Name
            AND     P2.Sex = 'm')
```

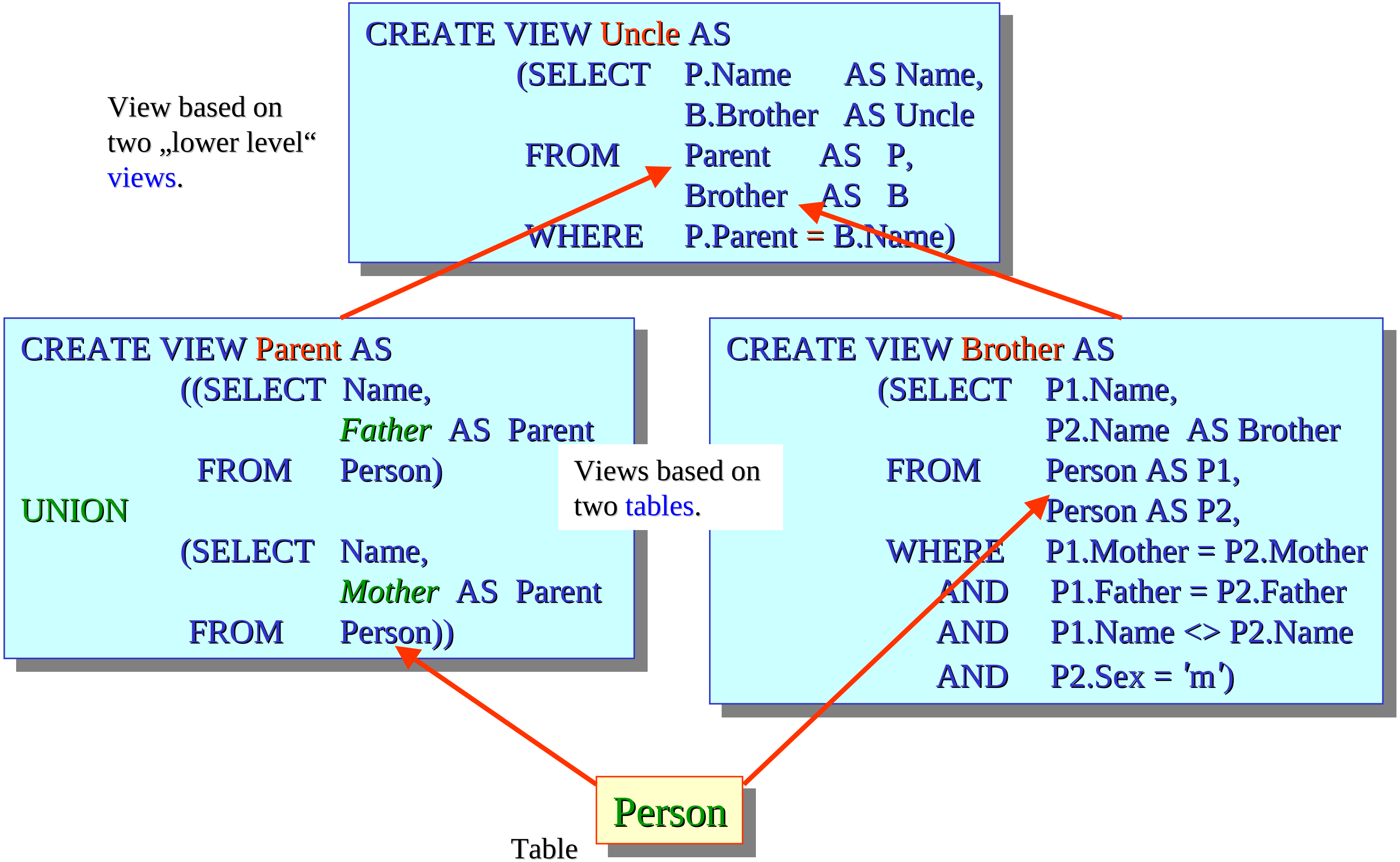
self
brother

} *same parents*

different persons

male

Two-level Specification of „Uncle“



View based on
two „lower level“
views.

```
CREATE VIEW Uncle AS
          (SELECT    P.Name       AS Name,
                     B.Brother    AS Uncle
           FROM      Parent    AS  P,
                     Brother   AS  B
           WHERE     P.Parent = B.Name)
```

```
CREATE VIEW Parent AS
          ((SELECT  Name,
                    Father  AS  Parent
             FROM     Person)
UNION
          (SELECT   Name,
                    Mother  AS  Parent
            FROM      Person))
```

Views based on
two tables.

```
CREATE VIEW Brother AS
          (SELECT    P1.Name,
                     P2.Name  AS Brother
           FROM      Person AS P1,
                     Person AS P2,
           WHERE     P1.Mother = P2.Mother
              AND     P1.Father = P2.Father
              AND     P1.Name <> P2.Name
              AND     P2.Sex = 'm')
```

Table

Person

- Using views enables us to extend a given database of stored tables by means of additional derived tables that are automatically generated by the DBMS on demand.

- We call this generation process deduction (as it follows laws of inference invented in logic). Thus, databases using views are deductive databases.

- View definitions are pieces of code in SQL – i.e., you „program“ SQL, if specifying views. View definitions are the counterpart to procedures (or methods) in imperative programming.

- If using views properly, each view is a declarative specification of a concept (or: a term) of the respective application domain. Each of these specifications has to be constructive, i.e., usable for generating all instances of the concept defined over the given base data.

- It is not (always) easy to correctly and completely specify a concept! You need a precise understanding of the definition of the resp. concept in natural language before coding SQL.

- Quite often there are various alternatives how to formulate a specification. They may differ in elegance of style, ease of understandibility and – most important – in efficiency of organizing deduction processes.

- A multi-level specification, using intermediate concepts, is often preferable.

- Research in deductive databases has a nearly 40-years history (as old as SQL), but has been using a different declarative language (not SQL!) most of the time, strongly influenced by the logic programming language PROLOG:

Datalog

- Nearly all publications in this area have been using Datalog – that‘s why we will use Datalog during this lecture, too (and you will have to learn it!).

- Many results of DDB research have been transferred to the SQL world recently! That‘s why SQL will also be appearing throughout the lecture in various places.

SQL:

- used in industry and commerce
- supported by many DBMS products
- standardized
- user-friendly („controlled English“)
- rich set of syntactic features

Datalog:

- used in academia only
- just few academic protoypes
- no standards
- mathematical style
- minimalistic syntax

About this Section

- In 2.1: Informal introduction to Datalog by means of an extended example.

- Simultaneously: Example-based introduction to . . .
  - . . . specifying concepts in a declarative DB language
  - . . . answering queries over deductive rules
  - . . . deduction using SQL views

- At first:
  - No rigorous treatment of concepts and ideas – „wetting“ your appetite is the goal.
  - Just core concepts presented and used in examples, more to come.

- In 2.2: More in-depth systematic treatment of Datalog (in full).

- Aim: Enable students to start „speaking“ the language straightaway.

- So, do make use of this chance: Exercise yourselves – don‘t wait to be „forced“!

- There is no use reflecting about theory if you do not have any first-hand experience in practice – try doing things in SQL, too, using your favorite DBMS.

- "Datalog" : "Database + Prolog", a notion coined around 1984 in the USA.
- Syntactically: Strong influence by logic programming language Prolog
  (but: Only simple form of "pure" Prolog adapted)
- Semantically: Strongly different! Set-oriented like other languages, e.g., SQL
  (instead of instance-oriented like Prolog)

- „Lingua franca" in research on deductive databases („de facto“ standard)
- But: Up till now not used commercially, no standardisation, no DBMS product!

- Rather uniform syntax and semantics of facts and rules
- Various different proposals for queries, updates, constraints, and schemas

- Datalog is based on the domain relational calculus (DRC), while SQL is based on tuple relational calculus (TRC) and relational algebra (RA). Datalog uses just a minimal set of logical operators:

  Conjunction and Negation

- Later in this chapter: Some more background about the three formal relational DB languages just mentioned – RA, DRC, and TRC! A bit more about Prolog will follow.

Datalog vs. SQL: Comparison in a Nutshell

SQL

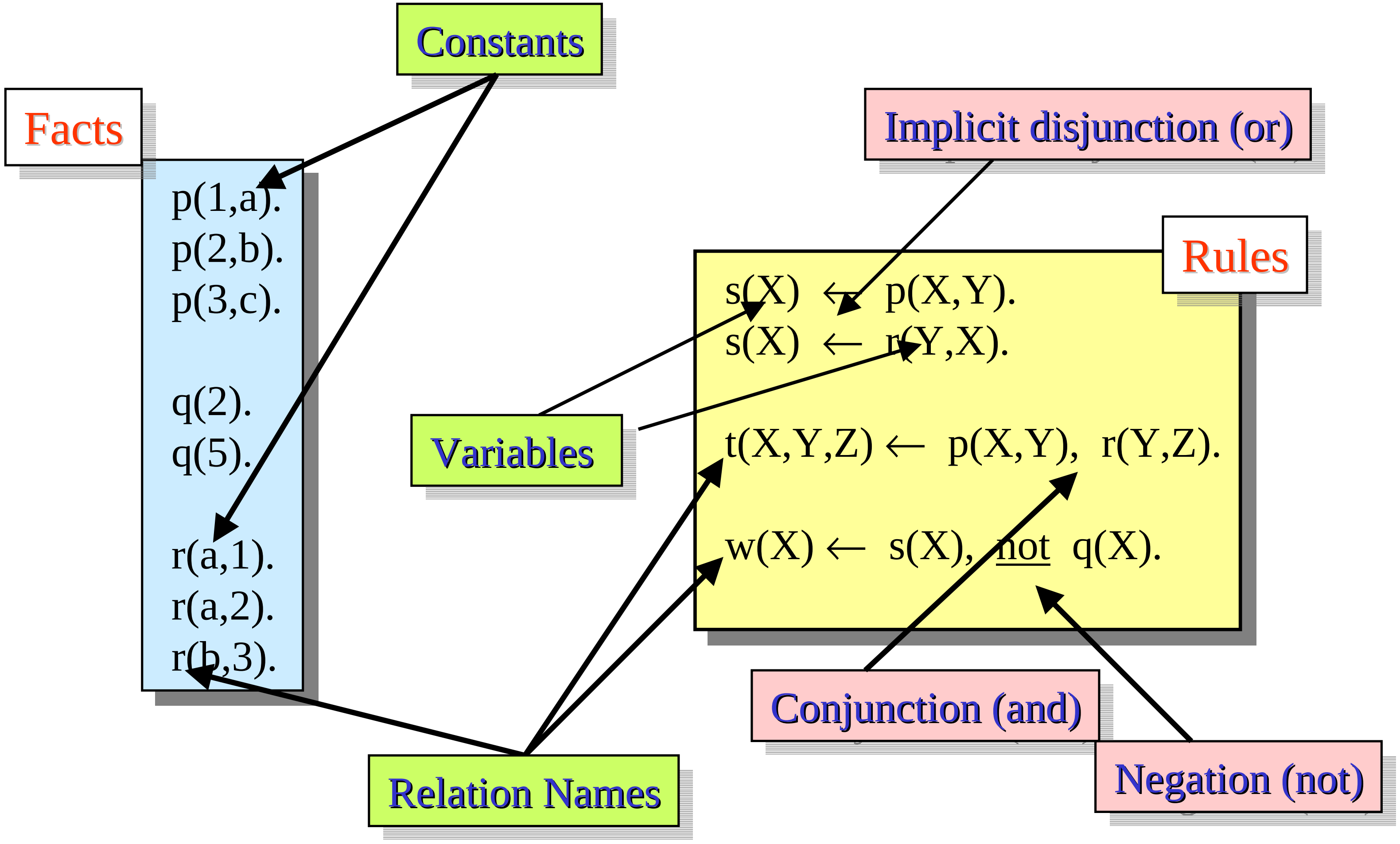
Datalog

```
s(X)  ←  p(X,Y).
s(X)  ←  r(Y,X).

t(X,Y,Z) ←  p(X,Y),  r(Y,Z).

w(X) ←  s(X),  not  q(X).
```

```
CREATE VIEW s  AS
          (SELECT  a  FROM p)
                    UNION
          (SELECT  b  FROM r);

CREATE VIEW t  AS
          SELECT  a, b, c
          FROM p, r
          WHERE p.b = r.a,

CREATE VIEW w  AS
          (TABLE s)
                    MINUS
          (TABLE q);
```

Views in SQL (as named, stored queries) have rules in Datalog as analogous counterparts. Three derived relations are defined in both cases: s, t, w. In both cases, three tables are used: p, q, r. View w depends on view s, too.

Basic Datalog Syntax on a Single Slide



Constants

Facts

```
p(1,a).
p(2,b).
p(3,c).

q(2).
q(5).

r(a,1).
r(a,2).
r(b,3).
```

Implicit disjunction (or)

Rules

```
s(X)  ←  p(X,Y).
s(X)  ←  r(Y,X).

t(X,Y,Z) ←  p(X,Y),  r(Y,Z).

w(X) ←  s(X),  not  q(X).
```

Variables

Relation Names

Conjunction (and)

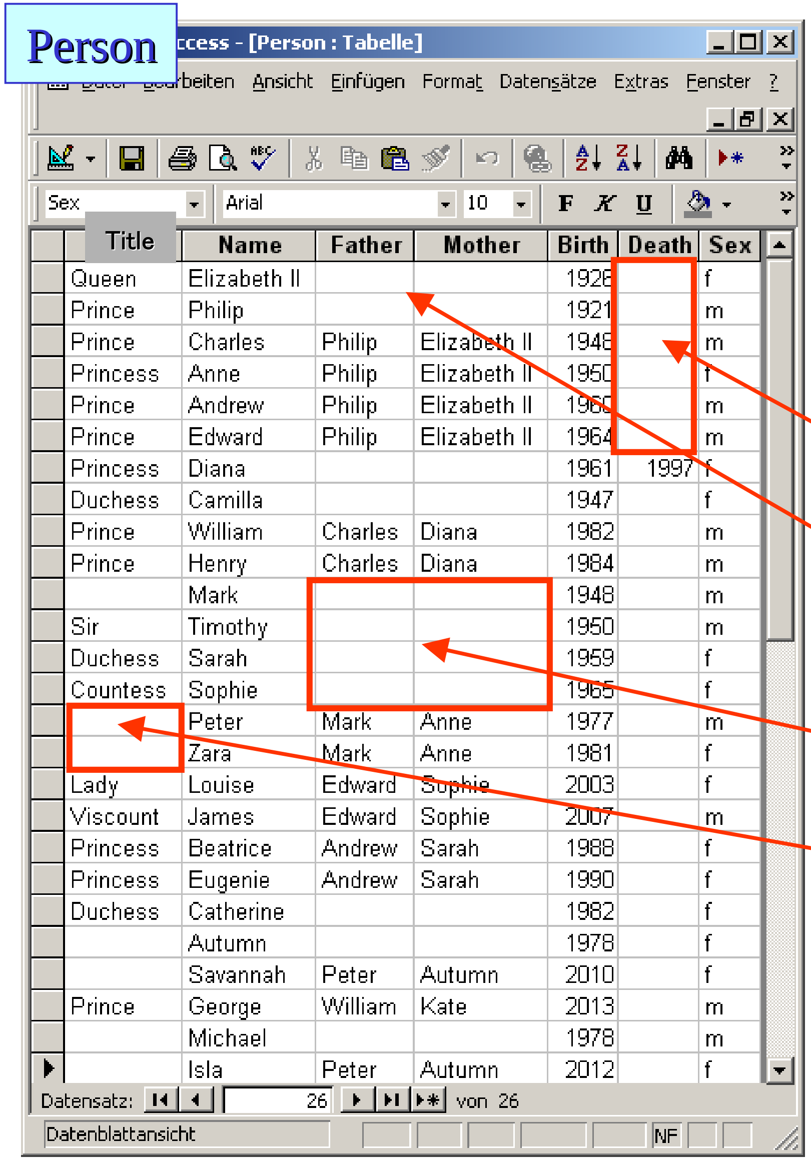
Negation (not)

p, q, r: Base relations

s, t, w: Derived relations

No Nulls in Datalog (1)

Person


ccess - [Person : Tabelle]
Datei Bearbeiten Ansicht Einfügen Format Datensätze Extras Fenster ?
Sex
Arial
10
F K U
Datensatz: 26 von 26
Datenblattansicht
NF

Title	Name	Father	Mother	Birth	Death	Sex
Queen	Elizabeth II			1926		f
Prince	Philip			1921		m
Prince	Charles	Philip	Elizabeth II	1948		m
Princess	Anne	Philip	Elizabeth II	1950		f
Prince	Andrew	Philip	Elizabeth II	1960		m
Prince	Edward	Philip	Elizabeth II	1964		m
Princess	Diana			1961	1997	f
Duchess	Camilla			1947		f
Prince	William	Charles	Diana	1982		m
Prince	Henry	Charles	Diana	1984		m
	Mark			1948		m
Sir	Timothy			1950		m
Duchess	Sarah			1959		f
Countess	Sophie			1965		f
	Peter	Mark	Anne	1977		m
	Zara	Mark	Anne	1981		f
Lady	Louise	Edward	Sophie	2003		f
Viscount	James	Edward	Sophie	2007		m
Princess	Beatrice	Andrew	Sarah	1988		f
Princess	Eugenie	Andrew	Sarah	1990		f
Duchess	Catherine			1982		f
	Autumn			1978		f
	Savannah	Peter	Autumn	2010		f
Prince	George	William	Kate	2013		m
	Michael			1978		m
	Isla	Peter	Autumn	2012		f

First problem (?):

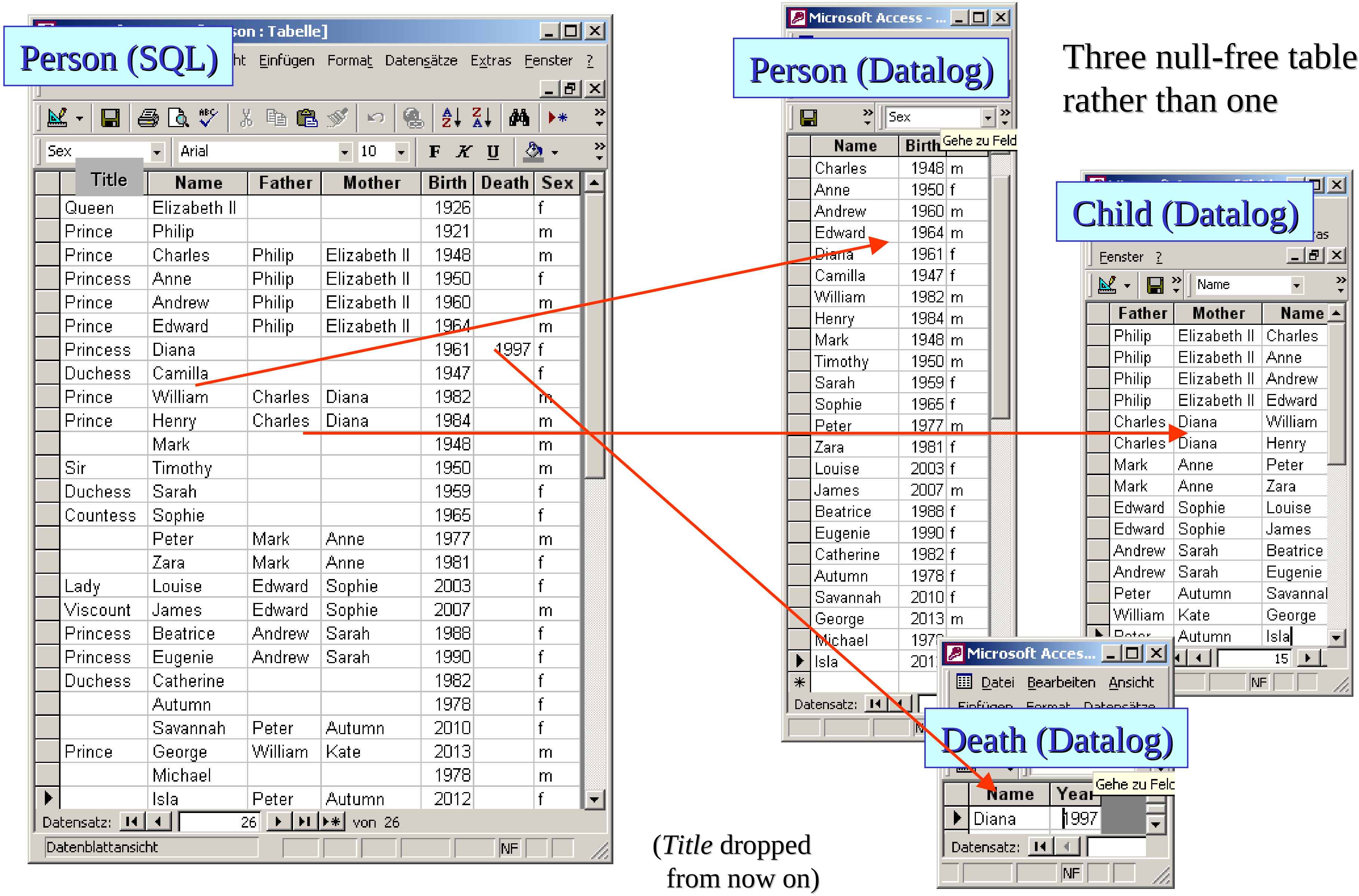
Datalog
cannot accomodate null values,
i.e., no empty cells in a table!

Reasons for nulls in the „SQL database“:

- Everyone except Diana is still alive.
- No ancestors for the royal couple.
- No ancestor data for spouses of royals.
- Some spouses don‘t have any title.

Therefore: „Datalog DB“ needs more than two (normalized) tables

Three null-free tables rather than one



Person (SQL)

Title	Name	Father	Mother	Birth	Death	Sex
Queen	Elizabeth II			1926		f
Prince	Philip			1921		m
Prince	Charles	Philip	Elizabeth II	1948		m
Princess	Anne	Philip	Elizabeth II	1950		f
Prince	Andrew	Philip	Elizabeth II	1960		m
Prince	Edward	Philip	Elizabeth II	1964		m
Princess	Diana			1961	1997	f
Duchess	Camilla			1947		f
Prince	William	Charles	Diana	1982		m
Prince	Henry	Charles	Diana	1984		m
	Mark			1948		m
Sir	Timothy			1950		m
Duchess	Sarah			1959		f
Countess	Sophie			1965		f
	Peter	Mark	Anne	1977		m
	Zara	Mark	Anne	1981		f
Lady	Louise	Edward	Sophie	2003		f
Viscount	James	Edward	Sophie	2007		m
Princess	Beatrice	Andrew	Sarah	1988		f
Princess	Eugenie	Andrew	Sarah	1990		f
Duchess	Catherine			1982		f
	Autumn			1978		f
	Savannah	Peter	Autumn	2010		f
Prince	George	William	Kate	2013		m
	Michael			1978		m
	Isla	Peter	Autumn	2012		f

Person (Datalog)

Name	Birth	
Charles	1948	m
Anne	1950	f
Andrew	1960	m
Edward	1964	m
Diana	1961	f
Camilla	1947	f
William	1982	m
Henry	1984	m
Mark	1948	m
Timothy	1950	m
Sarah	1959	f
Sophie	1965	f
Peter	1977	m
Zara	1981	f
Louise	2003	f
James	2007	m
Beatrice	1988	f
Eugenie	1990	f
Catherine	1982	f
Autumn	1978	f
Savannah	2010	f
George	2013	m
Michael	197	
Isla	201	

Child (Datalog)

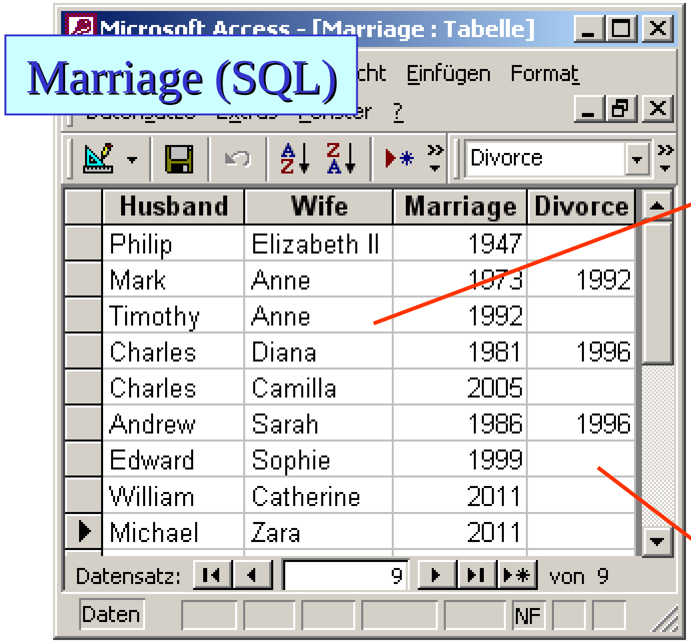
Father	Mother	Name
Philip	Elizabeth II	Charles
Philip	Elizabeth II	Anne
Philip	Elizabeth II	Andrew
Philip	Elizabeth II	Edward
Charles	Diana	William
Charles	Diana	Henry
Mark	Anne	Peter
Mark	Anne	Zara
Edward	Sophie	Louise
Edward	Sophie	James
Andrew	Sarah	Beatrice
Andrew	Sarah	Eugenie
Peter	Autumn	Savannal
William	Kate	George
Peter	Autumn	Isla

Death (Datalog)

Name	Year
Diana	1997

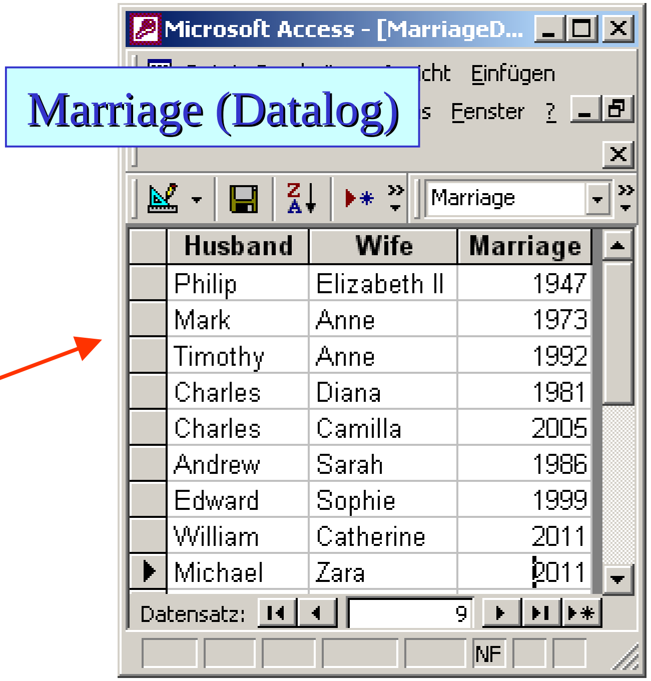
(*Title* dropped from now on)

No Nulls in Datalog (3)



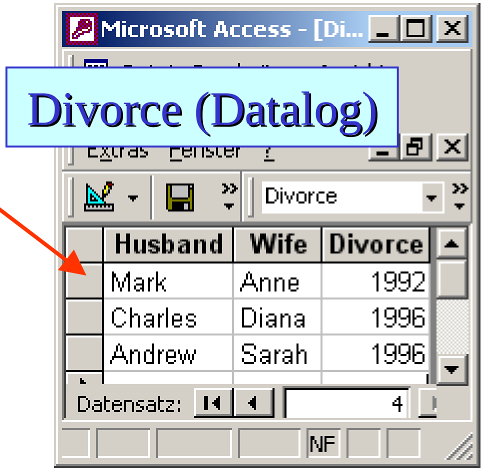
Marriage (SQL)

Husband	Wife	Marriage	Divorce
Philip	Elizabeth II	1947	
Mark	Anne	1973	1992
Timothy	Anne	1992	
Charles	Diana	1981	1996
Charles	Camilla	2005	
Andrew	Sarah	1986	1996
Edward	Sophie	1999	
William	Catherine	2011	
Michael	Zara	2011	



Marriage (Datalog)

Husband	Wife	Marriage
Philip	Elizabeth II	1947
Mark	Anne	1973
Timothy	Anne	1992
Charles	Diana	1981
Charles	Camilla	2005
Andrew	Sarah	1986
Edward	Sophie	1999
William	Catherine	2011
Michael	Zara	2011



Divorce (Datalog)

Husband	Wife	Divorce
Mark	Anne	1992
Charles	Diana	1996
Andrew	Sarah	1996

Similar normalization required for *Marriage* (as most royal couples are not – yet – divorced).

„Brother“ in SQL Using the „Datalog“ Schema

old version

```
CREATE VIEW Brother AS
          (SELECT    P1.Name,
                     P2.Name  AS Brother
           FROM      Person AS P1,
                     Person AS P2,
           WHERE     P1.Mother = P2.Mother
              AND    P1.Father = P2.Father
              AND    P1.Name <> P2.Name
              AND    P2.Sex = 'm')
```

In order to compare the SQL views with the corresponding Datalog rules, we first have to „translate“ view definitions to the new 5-table schema.

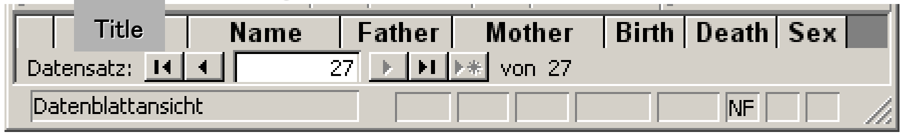
new version

```
CREATE VIEW Brother AS
          (SELECT    C1.Child   AS Name,
                     C2.Name  AS Brother
           FROM      Child    AS C1,
                     Child    AS C2,
                     Person  AS  P2
           WHERE     C1.Mother = C2.Mother
              AND    C1.Father = C2.Father
              AND    C1.Child <> C2.Child
              AND    C1.Child = P2.Name
              AND    P2.Sex = 'm')
```

Person information in Datalog:

person(Name, Birth, Sex)
child(Father, Mother, Child)
death(Name, Year)

Person table in SQL:



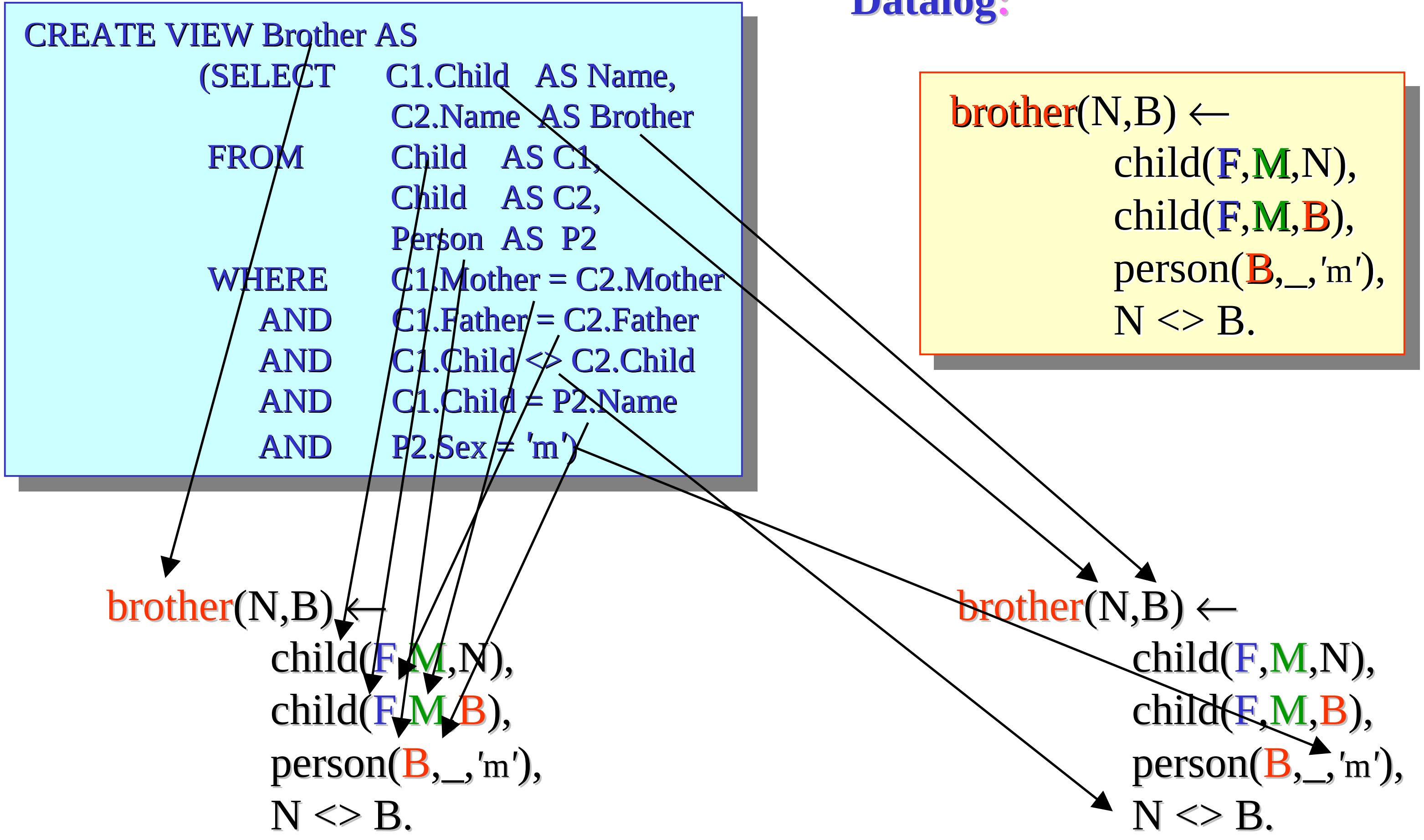
Title	Name	Father	Mother	Birth	Death	Sex

Datensatz: 27 von 27

Datenblattansicht

NF

SQL:



```
CREATE VIEW Brother AS
        (SELECT    C1.Child   AS Name,
                   C2.Name  AS Brother
         FROM      Child    AS C1,
                   Child    AS C2,
                   Person  AS  P2
         WHERE     C1.Mother = C2.Mother
           AND     C1.Father = C2.Father
           AND     C1.Child <> C2.Child
           AND     C1.Child = P2.Name
           AND     P2.Sex = 'm')
```

Datalog:

```
brother(N,B) ←
        child(F,M,N),
        child(F,M,B),
        person(B,_,'m'),
        N <> B.
```

```
brother(N,B) ←
        child(F,M,N),
        child(F,M,B),
        person(B,_,'m'),
        N <> B.
```

```
brother(N,B) ←
        child(F,M,N),
        child(F,M,B),
        person(B,_,'m'),
        N <> B.
```

In SQL: Variables for rows of tables.
In Datalog: Variables for attribute values of rows.

First Observations About Datalog 2

- The basic building blocks of Datalog rules are called literals. They consist of a relation name and a list of parameters (either variables or constants), e.g., *child(F,M,N)*.

- Variables in Datalog stand for individual attribute values, i.e., elements of data types occupying a single cell in the table/view under consideration.

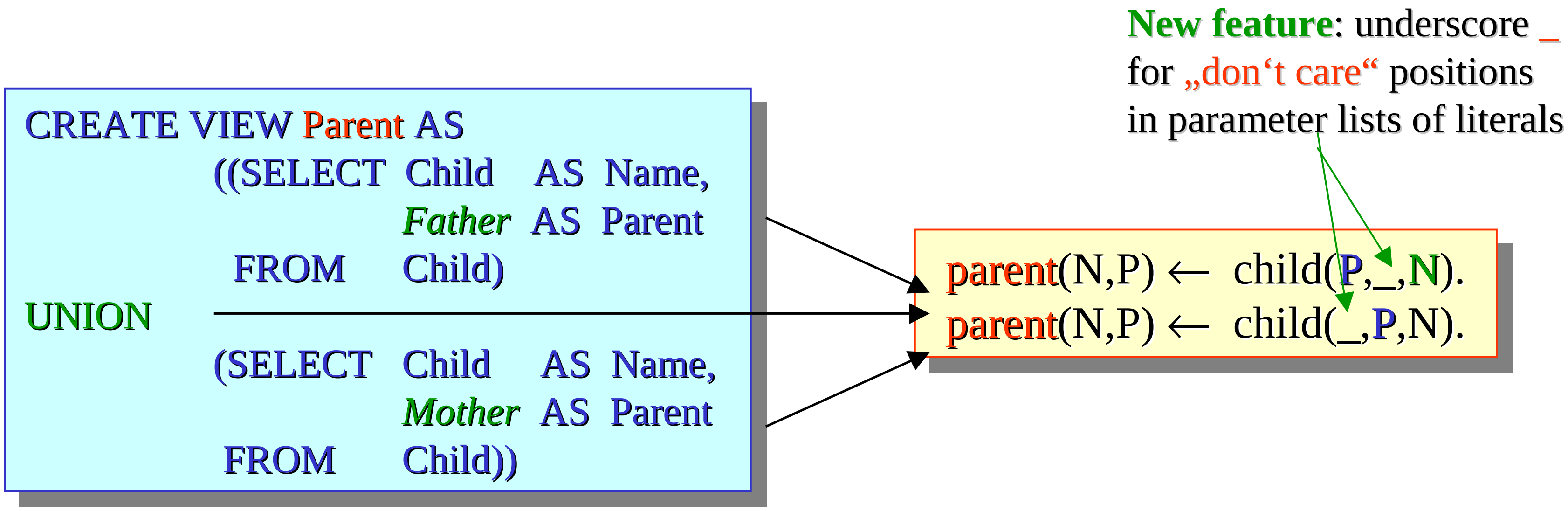
- Datalog doesn‘t make use of any attributes (column names), though. Columns are identified by their position within the parameter list. The order of columns matters and has to be fixed.

- Datalog rules are expressions of the form *Head* ← *Body*. where *Head* is a literal representing name and column structure of the newly defined view (derived relation). The rule body is a conjunction of literals accessing tables or other views on which the new view depends.

- The same variable occurring in different places in a rule always represents the same value (variable binding), whereas different variables may (but don‘t have to) represent different values.

- Underscores represent „unnamed“ variables „filling up“ irrelevant positions in a parameter list.

```
brother(N,B) ←
        child(F,M,N),
        child(F,M,B),
        person(B,_,'m'),
        N <> B.
```



New feature: underscore _ for „don‘t care“ positions in parameter lists of literals

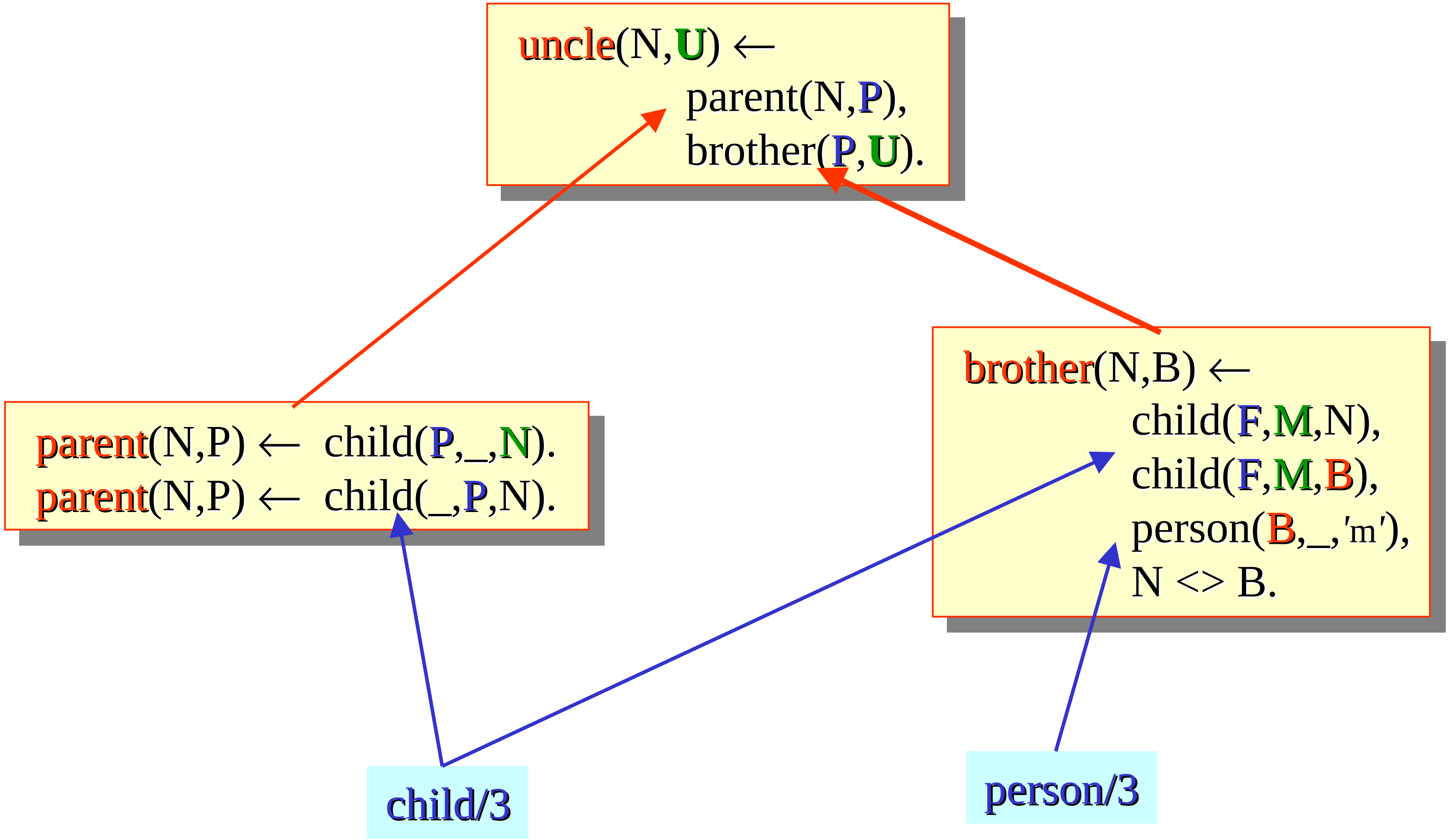
```
CREATE VIEW Parent AS
            ((SELECT  Child    AS  Name,
                      Father   AS  Parent
              FROM    Child)
UNION
             (SELECT  Child    AS  Name,
                      Mother   AS  Parent
              FROM    Child))
```

parent(N,P) ← child(P,_,N).
parent(N,P) ← child(_,P,N).

```
CREATE VIEW Uncle AS
            (SELECT   P.Name      AS Name,
                      B.Brother   AS Uncle
             FROM     Parent      AS  P,
                      Brother     AS  B
             WHERE    P.Name = B.Name)
```

uncle(N,U) ←
parent(N,P),
brother(P,U).

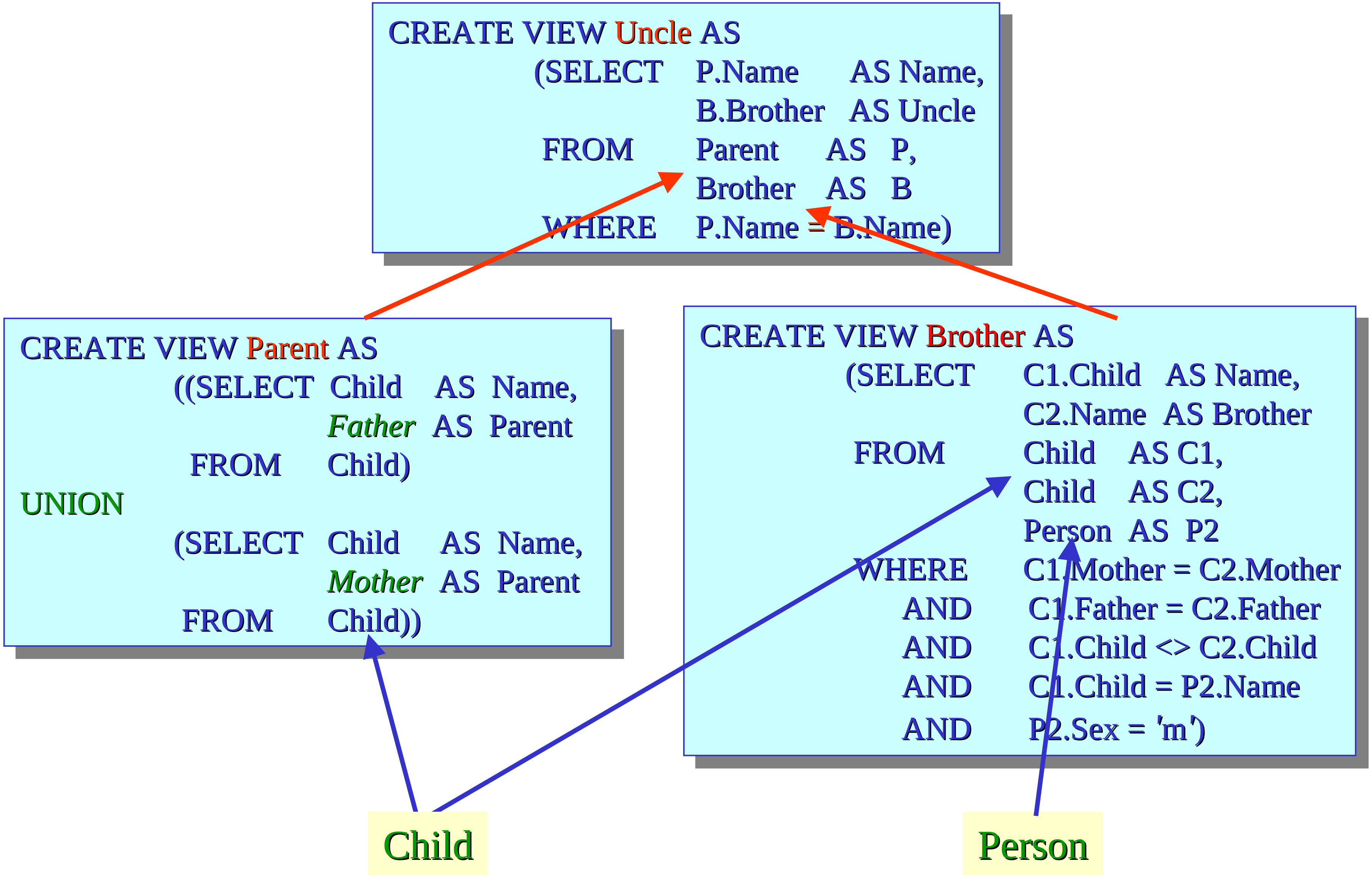
Uncle Definition in Datalog: Full Dependency Graph



uncle(N,U) ←
    parent(N,P),
    brother(P,U).

parent(N,P) ← child(P,_,N).
parent(N,P) ← child(_,P,N).

brother(N,B) ←
    child(F,M,N),
    child(F,M,B),
    person(B,_,'m'),
    N <> B.



```
CREATE VIEW Uncle AS
            (SELECT   P.Name     AS Name,
                      B.Brother  AS Uncle
             FROM     Parent     AS  P,
                      Brother    AS  B
             WHERE    P.Name = B.Name)
```

```
CREATE VIEW Parent AS
            ((SELECT  Child    AS  Name,
                      Father   AS  Parent
              FROM    Child)
UNION
             (SELECT  Child    AS  Name,
                      Mother   AS  Parent
              FROM    Child))
```

```
CREATE VIEW Brother AS
            (SELECT   C1.Child   AS Name,
                      C2.Name  AS Brother
             FROM     Child    AS C1,
                      Child    AS C2,
                      Person   AS  P2
             WHERE    C1.Mother = C2.Mother
                 AND  C1.Father = C2.Father
                 AND  C1.Child <> C2.Child
                 AND  C1.Child = P2.Name
                 AND  P2.Sex = 'm')
```

- In our initial example comparing Datalog and SQL (when declaring the same derived relations/tables) we used one rule/view containing logical negation:

```
. . .

w(X) ← s(X), not q(X).
```

```
. . .

CREATE VIEW w  AS
           (TABLE s)
                    MINUS
           (TABLE q);
```

- In Datalog, the Boolean operator not appears in the rule body next to the operator and written in Datalog-style as a comma symbol. In the SQL view declaration the set-theoretic counterpart MINUS is used instead.

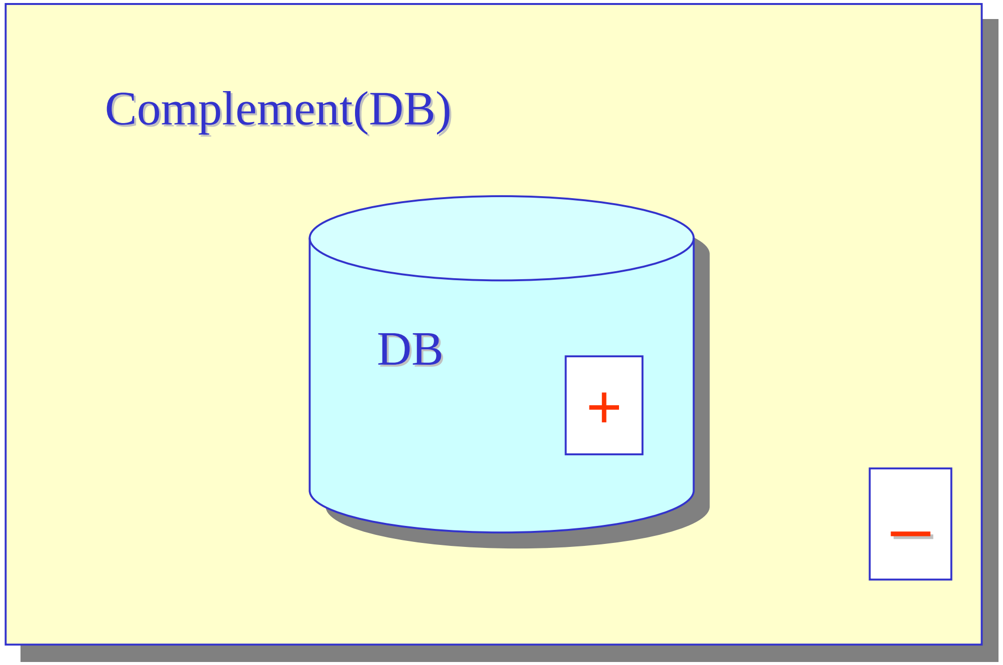
- Negation (regardless in which syntatic variant) potentially causes trouble in a deductive (relational) database – to be explained later. Therefore we will have to treat negation with particular care!

- SQL knows logical NOT, too. How to express this example rule in SQL using NOT?

In (relational) databases:

+

- All stored facts are (supposed to be) true.
- All true facts are (supposed to be) stored (or derivable).



–

- All non-stored or non-derivable facts are (supposed to be) false.
- No false facts are (supposed to be) stored (or derivable).

Datalog: Negation by Example

- We need a bit of preparation before being able to use negation in our genealogy context.

- In the exercises, we will try to formalize the concept of being (currently) married – a rather difficult affair. Now let us define who was ever married, and who has at least one child. For making things easier, we just look at the male case (husband, 1st parameter of *marriage* as well as *child*):

```
ever_married(P) ←
            marriage(P,_,_).
```

```
has_child(P) ←
            child(P,_,_).
```

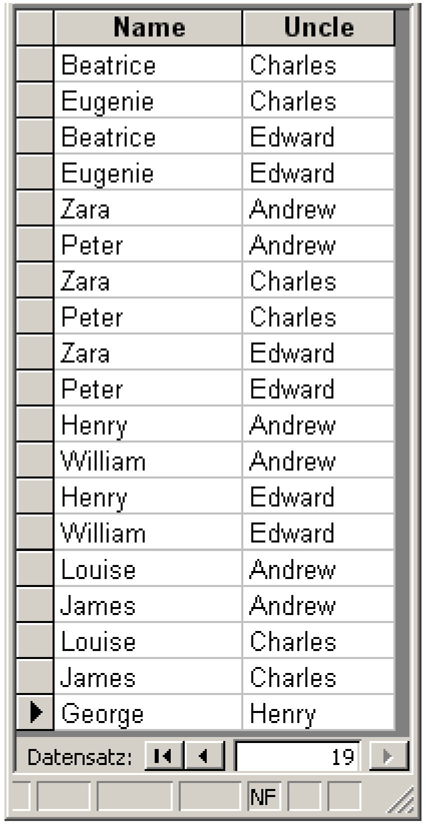
- Now for the rule requiring negation: An uncle who has no children and was never married is interesting (because we might inherit his fortune, when he dies!).

```
interesting_uncle(N,U) ←
            uncle(N,U),
            not ever_married(U),
            not has_child(U).
```

Corresponding Data over Royals DB

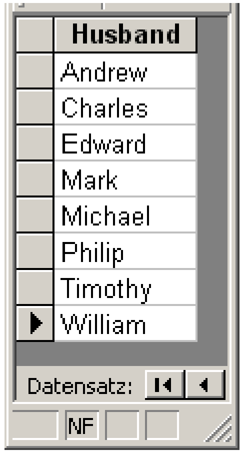
interesting_uncle(N,**U**) ←
uncle(N,**U**),
not ever_married(**U**),
not has_child(**U**).

Uncle



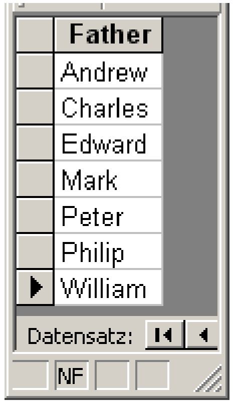
Name	Uncle
Beatrice	Charles
Eugenie	Charles
Beatrice	Edward
Eugenie	Edward
Zara	Andrew
Peter	Andrew
Zara	Charles
Peter	Charles
Zara	Edward
Peter	Edward
Henry	Andrew
William	Andrew
Henry	Edward
William	Edward
Louise	Andrew
James	Andrew
Louise	Charles
James	Charles
George	Henry

Ever_married



Husband
Andrew
Charles
Edward
Mark
Michael
Philip
Timothy
William

Has_child



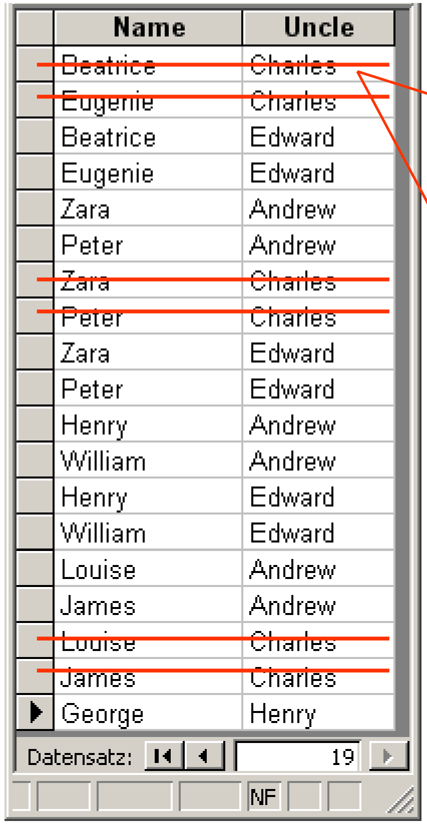
Father
Andrew
Charles
Edward
Mark
Peter
Philip
William

How to compute
interesting uncles
if you only have
positive data
at hand ?

Although we do not have data about persons who never married, or are childless . . .

interesting_uncle(N,U) ←
uncle(N,U),
not ever_married(U),
not has_child(U).

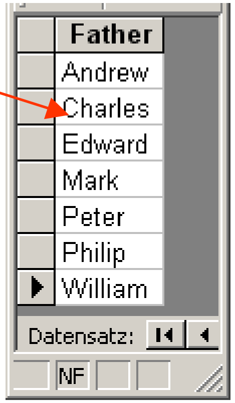
Uncle



Name	Uncle
~~Beatrice~~	~~Charles~~
~~Eugenie~~	~~Charles~~
Beatrice	Edward
Eugenie	Edward
Zara	Andrew
Peter	Andrew
~~Zara~~	~~Charles~~
~~Peter~~	~~Charles~~
Zara	Edward
Peter	Edward
Henry	Andrew
William	Andrew
Henry	Edward
William	Edward
Louise	Andrew
James	Andrew
~~Louise~~	~~Charles~~
~~James~~	~~Charles~~
George	Henry

Datensatz: 19

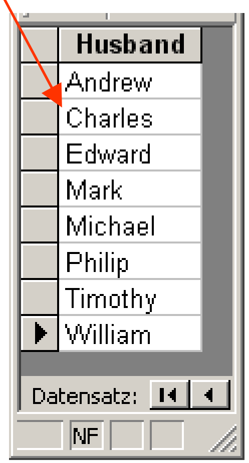
Has_child



Father
Andrew
Charles
Edward
Mark
Peter
Philip
William

Datensatz:

Ever_married



Husband
Andrew
Charles
Edward
Mark
Michael
Philip
Timothy
William

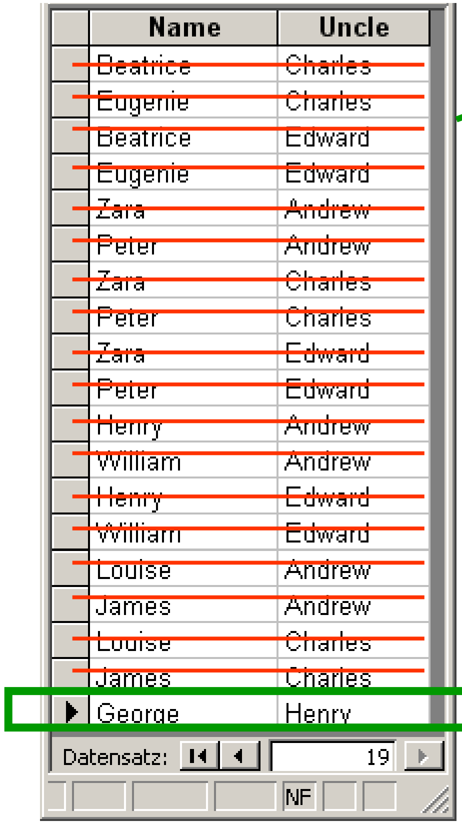
Datensatz:

. . . we can use the positive data about persons who did marry or do have a child for eliminating uncles who definitely are not interesting! No need to „access“ the complement of any table explicitly.

Discovering Negative Data (2)

interesting_uncle(N,**U**) ←
uncle(N,**U**),
not ever_married(**U**),
not has_child(**U**).

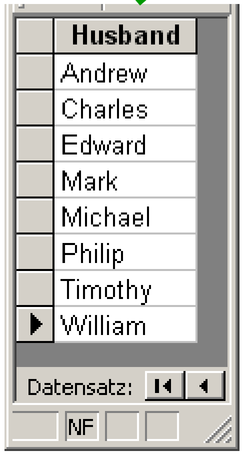
Uncle



Name	Uncle
~~Beatrice~~	~~Charles~~
~~Eugenie~~	~~Charles~~
~~Beatrice~~	~~Edward~~
~~Eugenie~~	~~Edward~~
~~Zara~~	~~Andrew~~
~~Peter~~	~~Andrew~~
~~Zara~~	~~Charles~~
~~Peter~~	~~Charles~~
~~Zara~~	~~Edward~~
~~Peter~~	~~Edward~~
~~Henry~~	~~Andrew~~
~~William~~	~~Andrew~~
~~Henry~~	~~Edward~~
~~William~~	~~Edward~~
~~Louise~~	~~Andrew~~
~~James~~	~~Andrew~~
~~Louise~~	~~Charles~~
~~James~~	~~Charles~~
George	Henry

Datensatz: 19

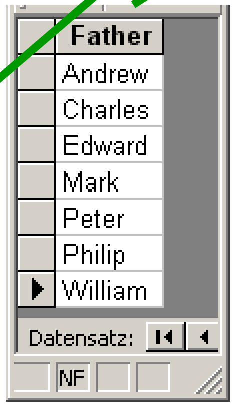
Ever_married



Husband
Andrew
Charles
Edward
Mark
Michael
Philip
Timothy
William

Datensatz:

Has_child

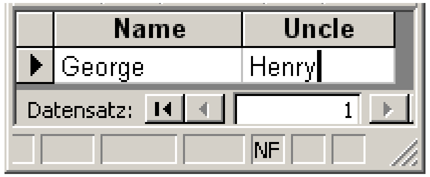


Father
Andrew
Charles
Edward
Mark
Peter
Philip
William

Datensatz:

At the end, only Henry is interesting (for George)!

Interesting_uncle



Name	Uncle
George	Henry

Datensatz: 1

Translation to SQL 2

```
interesting_uncle(N,U) ←
          uncle(N,U),
          not ever_married(U),
          not has_child(U).
```

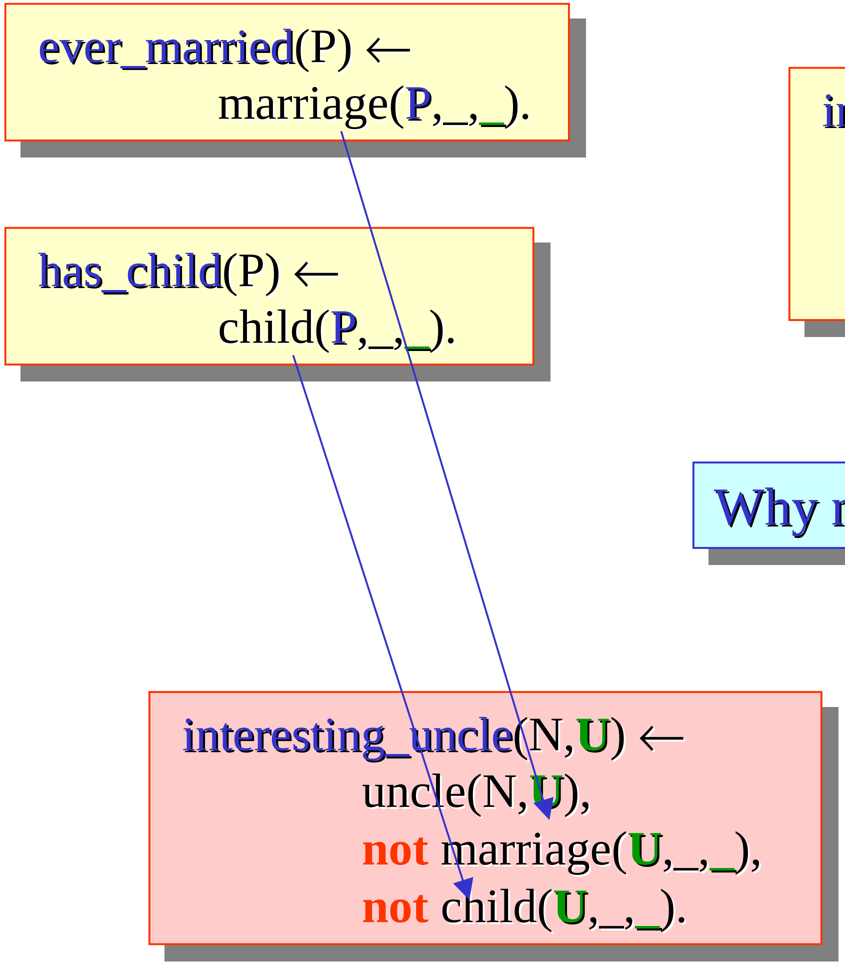
In SQL, the corresponding query defining the view requires two embedded subqueries correlated with the main query by means of NOT IN (or, similarly, NOT EXISTS):

```
CREATE VIEW  Interesting_uncle  AS
           (SELECT   *
            FROM     Uncle
            WHERE  Uncle  NOT IN
                     (SELECT *  FROM  Ever_married)
               AND   Uncle  NOT IN
                     (SELECT *  FROM  Has_child))
```

A formulation using MINUS instead (and no WHERE part) works, too, as previously.

The evaluation strategy is the same in SQL: Reduce *Uncle* by eliminating those rows for which the NOT IN condition does not hold!

Open Question Remaining about Negation



```
ever_married(P) ←
        marriage(P,_,_).
```

```
has_child(P) ←
        child(P,_,_).
```

```
interesting_uncle(N,U) ←
        uncle(N,U),
        not marriage(U,_,_),
        not child(U,_,_).
```

Don‘t use this in Datalog!

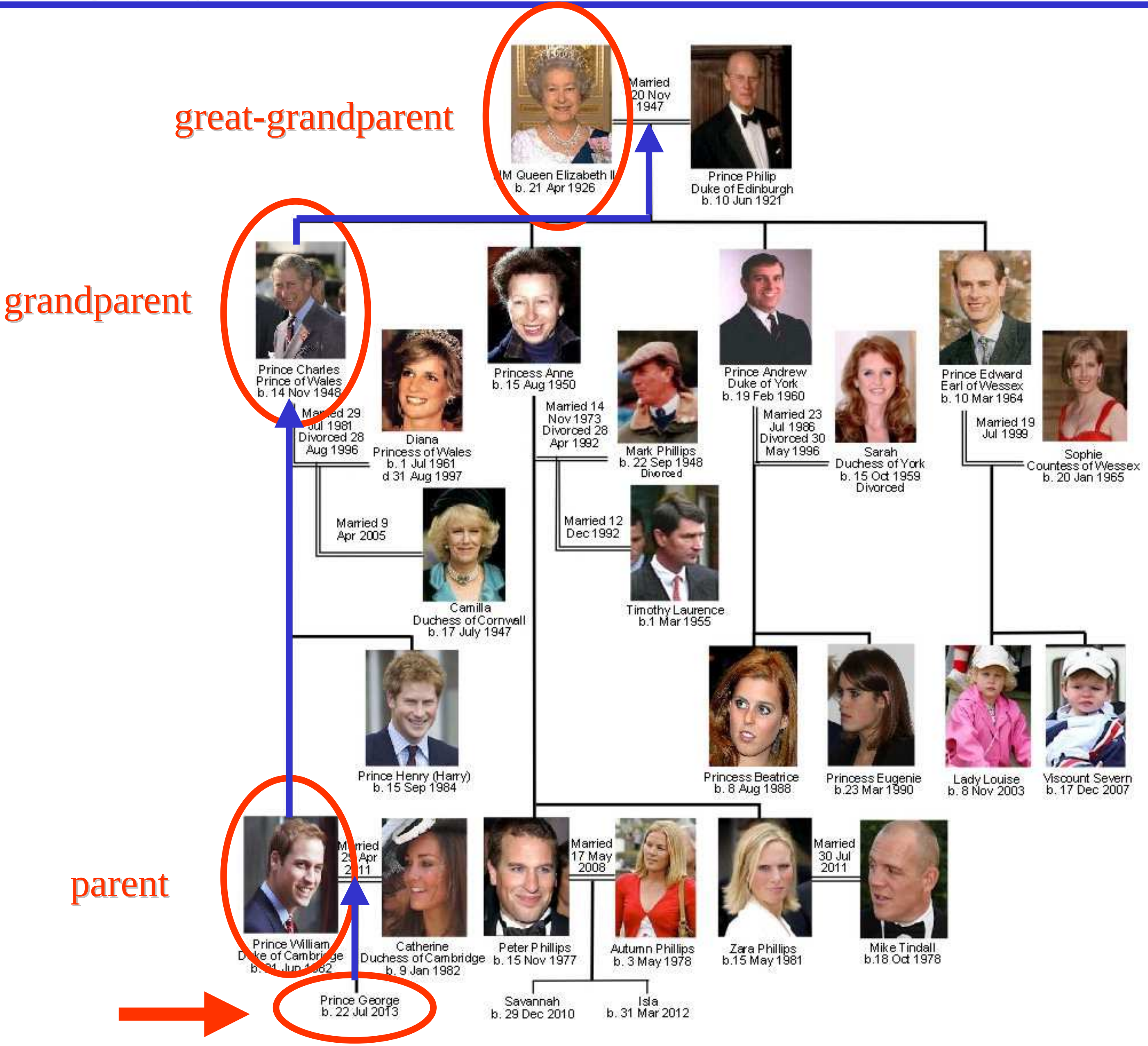
```
interesting_uncle(N,U) ←
        uncle(N,U),
        not ever_married(U),
        not has_child(U).
```

Why not simply use one rule rather than three?

There is a good – even though debatable – reason for using the three rules rather than one.

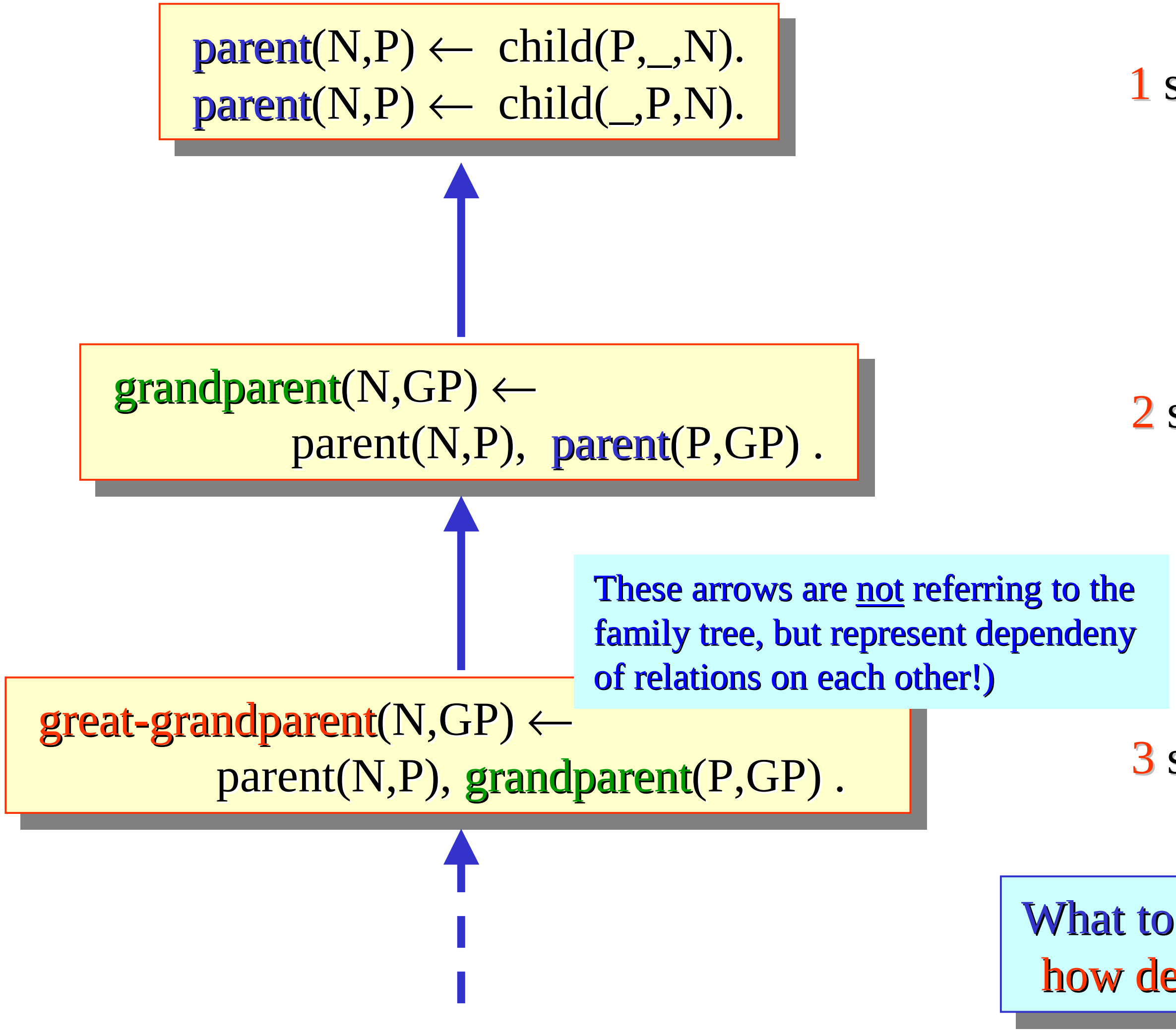
This will be discussed in the next section, please wait!

Traversing Family Trees: Fixed Number of Steps (1)



Don‘t be surprised, this is the Royals family tree image from last year

Traversing Family Trees: Fixed Number of Steps (2)



parent(N,P) ← child(P,_,N).
parent(N,P) ← child(_,P,N).

grandparent(N,GP) ←
parent(N,P), parent(P,GP) .

great-grandparent(N,GP) ←
parent(N,P), grandparent(P,GP) .

These arrows are not referring to the family tree, but represent dependeny of relations on each other!)

1 step down the tree
(in direction of ancestors,
i.e. towards the root of
the family tree)

2 steps down the tree

3 steps down the tree

What to do if we don't even know **how deep** we can go in the tree?

Recursive Views: Generalizing Tree Traversal 2

Traversal of a family tree down to arbitrary depth can be expressed very elegantly using the most powerful syntactic feature of declarative query languages: **Recursion**

Datalog:

```
ancestor(X,Y) ← parent(X,Y).
ancestor(X,Y) ← parent(X,Z), ancestor(Z,Y).
```

SQL:

```
CREATE RECURSIVE VIEW Ancestor AS
(          (SELECT  Name,
                    Parent    AS Ancestor
            FROM    Parent)
 UNION
           (SELECT  P.Name,
                    A.Ancestor
            FROM    Parent    AS P,
                    Ancestor  AS A
            WHERE   A.Name = P.Parent))
```

Recursive views are allowed in SQL since the standard of 1999!

All the children of a person X are ancestors of X, as well as all ancestors of the children of X (and so on):

Ancestor is a recursively defined concept!

```
ancestor(X,Y)  ←  parent(X,Y).
ancestor(X,Y)  ←  parent(X,Z), ancestor(Z,Y).
```

Descendant is the inverse concept of ancestor:

```
descendant(X,Y)  ←  ancestor(Y,X).
```

The generation (or level) of an ancestor can be expressed by means of an additional parameter, which is recursively incremented:

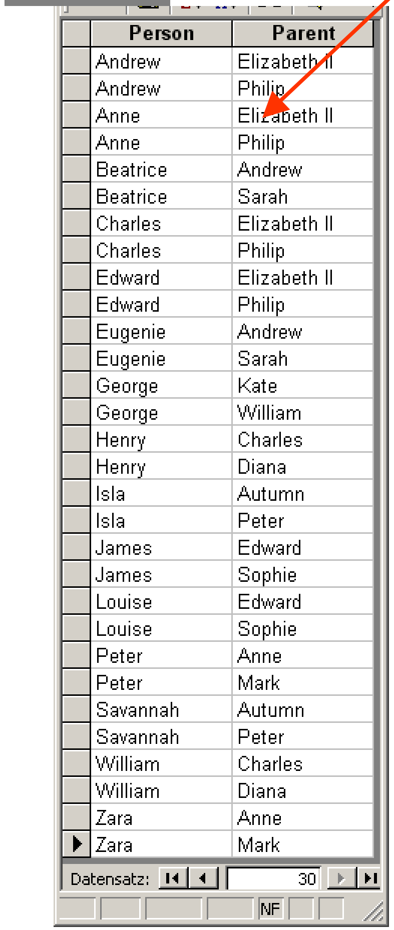
```
ancestor(X,Y, 1)  ←  parent(X,Y).
ancestor(X,Y, J)  ←  parent(X,Z), ancestor(Z,Y, I), J = I+1.

descendant(X,Y, I)  ← ancestor(Y,X, I).
```

Computing Royal Ancestors Recursively (1)

2

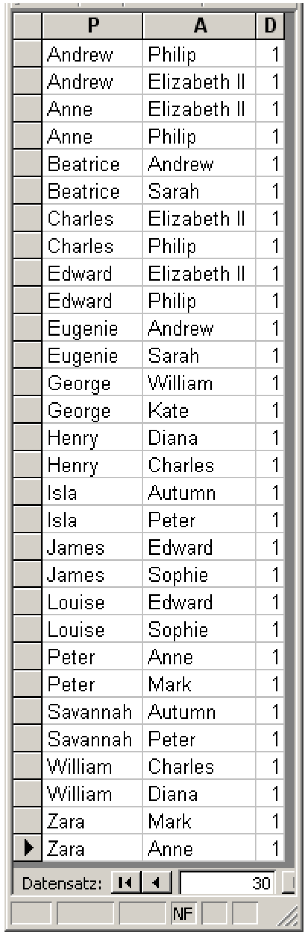
ancestor(X,Y,1) ← parent(X,Y).
ancestor(X,Y,J) ← parent(X,Z), ancestor(Z,Y,I), J = I+1.

Parent



Person	Parent
Andrew	Elizabeth II
Andrew	Philip
Anne	Elizabeth II
Anne	Philip
Beatrice	Andrew
Beatrice	Sarah
Charles	Elizabeth II
Charles	Philip
Edward	Elizabeth II
Edward	Philip
Eugenie	Andrew
Eugenie	Sarah
George	Kate
George	William
Henry	Charles
Henry	Diana
Isla	Autumn
Isla	Peter
James	Edward
James	Sophie
Louise	Edward
Louise	Sophie
Peter	Anne
Peter	Mark
Savannah	Autumn
Savannah	Peter
William	Charles
William	Diana
Zara	Anne
Zara	Mark

1



P	A	D
Andrew	Philip	1
Andrew	Elizabeth II	1
Anne	Elizabeth II	1
Anne	Philip	1
Beatrice	Andrew	1
Beatrice	Sarah	1
Charles	Elizabeth II	1
Charles	Philip	1
Edward	Elizabeth II	1
Edward	Philip	1
Eugenie	Andrew	1
Eugenie	Sarah	1
George	William	1
George	Kate	1
Henry	Diana	1
Henry	Charles	1
Isla	Autumn	1
Isla	Peter	1
James	Edward	1
James	Sophie	1
Louise	Edward	1
Louise	Sophie	1
Peter	Anne	1
Peter	Mark	1
Savannah	Autumn	1
Savannah	Peter	1
William	Charles	1
William	Diana	1
Zara	Mark	1
Zara	Anne	1

Computation of the ancestor table is done iteratively.

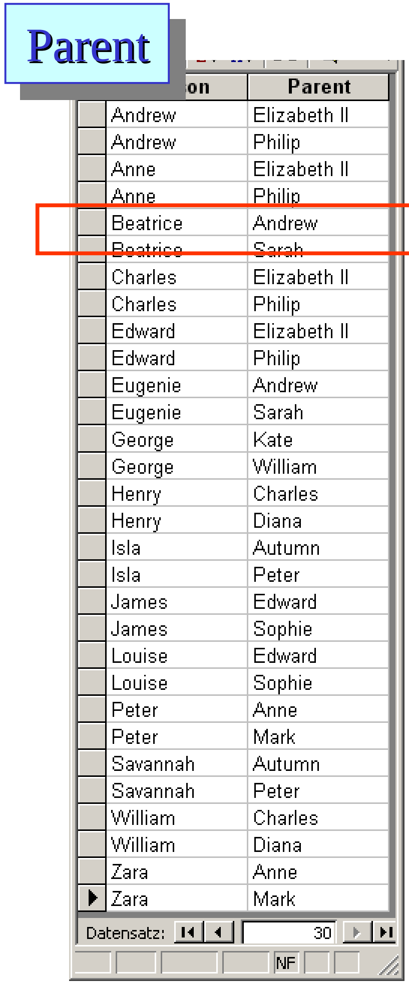
At the beginning, there are no ancestor facts yet, so that the recursive rule cannot „produce“ anything.

Just the non-recursive rule is able to provide an initial bunch of ancestor facts „copied“ from parent.

Computing Royal Ancestors Recursively (2)

ancestor(X,Y,1) ← parent(X,Y).

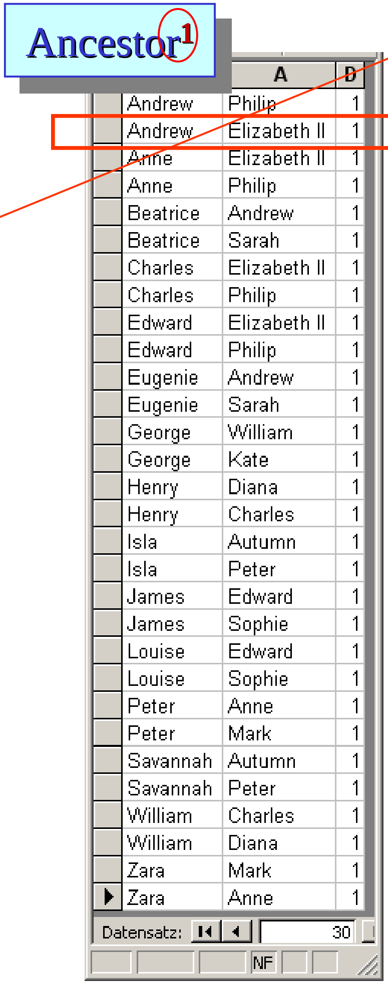
ancestor(X,Y,J) ← parent(X,Z), ancestor(Z,Y,I), J = I+1.



Parent

on	Parent
Andrew	Elizabeth II
Andrew	Philip
Anne	Elizabeth II
Anne	Philip
Beatrice	Andrew
Beatrice	Sarah
Charles	Elizabeth II
Charles	Philip
Edward	Elizabeth II
Edward	Philip
Eugenie	Andrew
Eugenie	Sarah
George	Kate
George	William
Henry	Charles
Henry	Diana
Isla	Autumn
Isla	Peter
James	Edward
James	Sophie
Louise	Edward
Louise	Sophie
Peter	Anne
Peter	Mark
Savannah	Autumn
Savannah	Peter
William	Charles
William	Diana
Zara	Anne
Zara	Mark

Datensatz: 30 NF

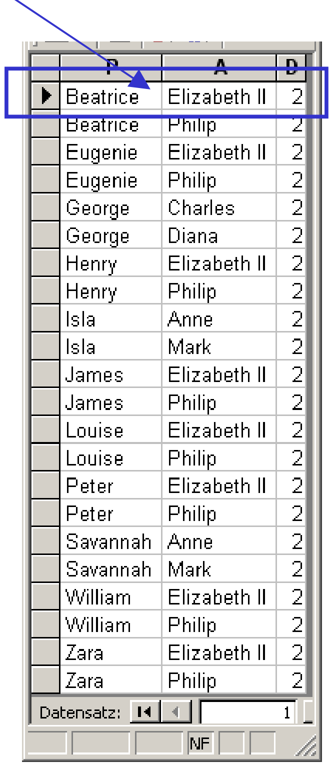


Ancestor1

	A	D
Andrew	Philip	1
Andrew	Elizabeth II	1
Anne	Elizabeth II	1
Anne	Philip	1
Beatrice	Andrew	1
Beatrice	Sarah	1
Charles	Elizabeth II	1
Charles	Philip	1
Edward	Elizabeth II	1
Edward	Philip	1
Eugenie	Andrew	1
Eugenie	Sarah	1
George	William	1
George	Kate	1
Henry	Diana	1
Henry	Charles	1
Isla	Autumn	1
Isla	Peter	1
James	Edward	1
James	Sophie	1
Louise	Edward	1
Louise	Sophie	1
Peter	Anne	1
Peter	Mark	1
Savannah	Autumn	1
Savannah	Peter	1
William	Charles	1
William	Diana	1
Zara	Mark	1
Zara	Anne	1

Datensatz: 30 NF

2



P	A	D
Beatrice	Elizabeth II	2
Beatrice	Philip	2
Eugenie	Elizabeth II	2
Eugenie	Philip	2
George	Charles	2
George	Diana	2
Henry	Elizabeth II	2
Henry	Philip	2
Isla	Anne	2
Isla	Mark	2
James	Elizabeth II	2
James	Philip	2
Louise	Elizabeth II	2
Louise	Philip	2
Peter	Elizabeth II	2
Peter	Philip	2
Savannah	Anne	2
Savannah	Mark	2
William	Elizabeth II	2
William	Philip	2
Zara	Elizabeth II	2
Zara	Philip	2

Datensatz: 1 NF

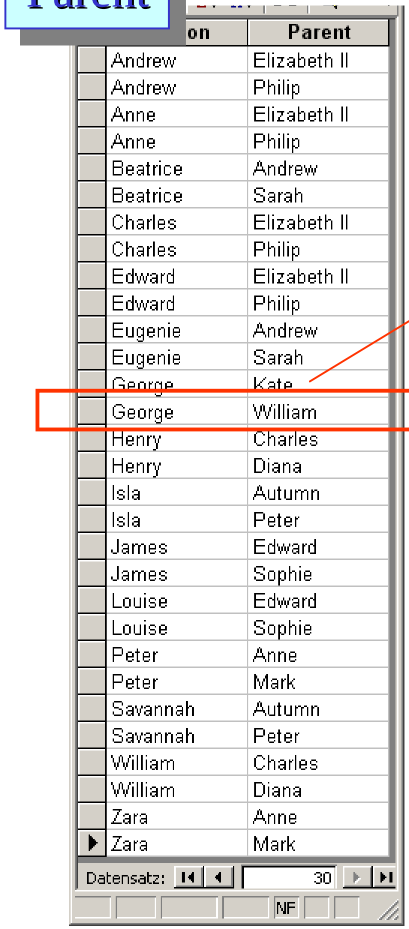
First application of the recursive rule produces further ancestor facts.

Computing Royal Ancestors Recursively (3)

ancestor(X,Y,1) ← parent(X,Y).

ancestor(X,Y,J) ← parent(X,Z), ancestor(Z,Y,I), J = I+1.

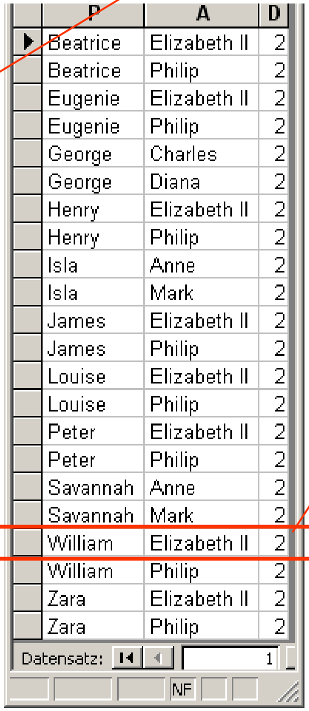
Parent



on	Parent
Andrew	Elizabeth II
Andrew	Philip
Anne	Elizabeth II
Anne	Philip
Beatrice	Andrew
Beatrice	Sarah
Charles	Elizabeth II
Charles	Philip
Edward	Elizabeth II
Edward	Philip
Eugenie	Andrew
Eugenie	Sarah
George	Kate
George	William
Henry	Charles
Henry	Diana
Isla	Autumn
Isla	Peter
James	Edward
James	Sophie
Louise	Edward
Louise	Sophie
Peter	Anne
Peter	Mark
Savannah	Autumn
Savannah	Peter
William	Charles
William	Diana
Zara	Anne
Zara	Mark

Datensatz: 30

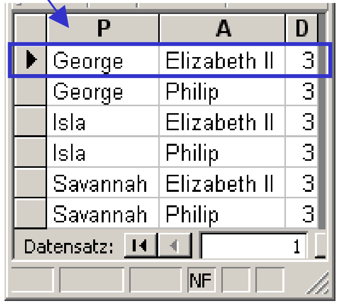
Ancestor^2



P	A	D
Beatrice	Elizabeth II	2
Beatrice	Philip	2
Eugenie	Elizabeth II	2
Eugenie	Philip	2
George	Charles	2
George	Diana	2
Henry	Elizabeth II	2
Henry	Philip	2
Isla	Anne	2
Isla	Mark	2
James	Elizabeth II	2
James	Philip	2
Louise	Elizabeth II	2
Louise	Philip	2
Peter	Elizabeth II	2
Peter	Philip	2
Savannah	Anne	2
Savannah	Mark	2
William	Elizabeth II	2
William	Philip	2
Zara	Elizabeth II	2
Zara	Philip	2

Datensatz: 1

3



P	A	D
George	Elizabeth II	3
George	Philip	3
Isla	Elizabeth II	3
Isla	Philip	3
Savannah	Elizabeth II	3
Savannah	Philip	3

Datensatz: 1

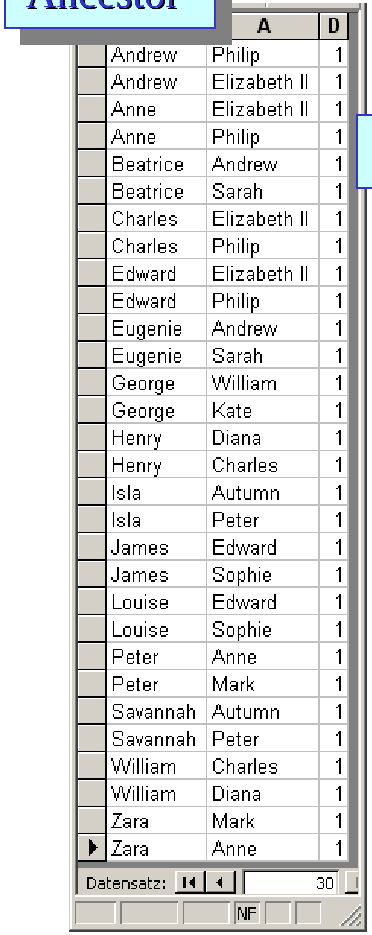
Similarly in iteration 3: Combining generation 2 facts with parent facts.

Nothing new in iteration 4: stop!.

Computing Royal Ancestors Recursively (4)

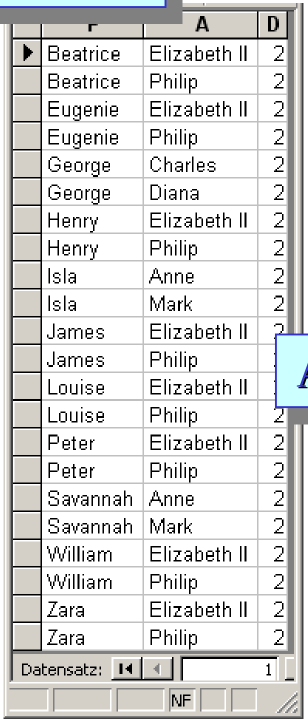
ancestor(X,Y) ← parent(X,Y).
ancestor(X,Y) ← parent(X,Z), ancestor(Z,Y).

Ancestor^1



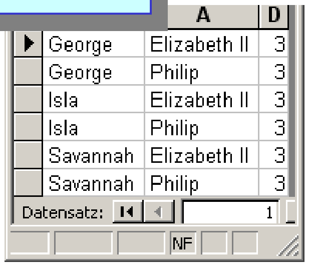
	A	D
Andrew	Philip	1
Andrew	Elizabeth II	1
Anne	Elizabeth II	1
Anne	Philip	1
Beatrice	Andrew	1
Beatrice	Sarah	1
Charles	Elizabeth II	1
Charles	Philip	1
Edward	Elizabeth II	1
Edward	Philip	1
Eugenie	Andrew	1
Eugenie	Sarah	1
George	William	1
George	Kate	1
Henry	Diana	1
Henry	Charles	1
Isla	Autumn	1
Isla	Peter	1
James	Edward	1
James	Sophie	1
Louise	Edward	1
Louise	Sophie	1
Peter	Anne	1
Peter	Mark	1
Savannah	Autumn	1
Savannah	Peter	1
William	Charles	1
William	Diana	1
Zara	Mark	1
▶ Zara	Anne	1

Ancestor^2



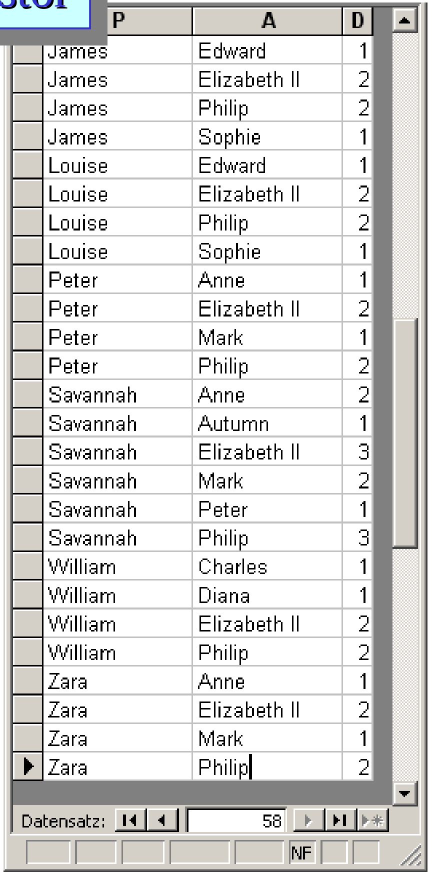
	A	D
▶ Beatrice	Elizabeth II	2
Beatrice	Philip	2
Eugenie	Elizabeth II	2
Eugenie	Philip	2
George	Charles	2
George	Diana	2
Henry	Elizabeth II	2
Henry	Philip	2
Isla	Anne	2
Isla	Mark	2
James	Elizabeth II	2
James	Philip	2
Louise	Elizabeth II	2
Louise	Philip	2
Peter	Elizabeth II	2
Peter	Philip	2
Savannah	Anne	2
Savannah	Mark	2
William	Elizabeth II	2
William	Philip	2
Zara	Elizabeth II	2
Zara	Philip	2

Ancestor^3



	A	D
▶ George	Elizabeth II	3
George	Philip	3
Isla	Elizabeth II	3
Isla	Philip	3
Savannah	Elizabeth II	3
Savannah	Philip	3

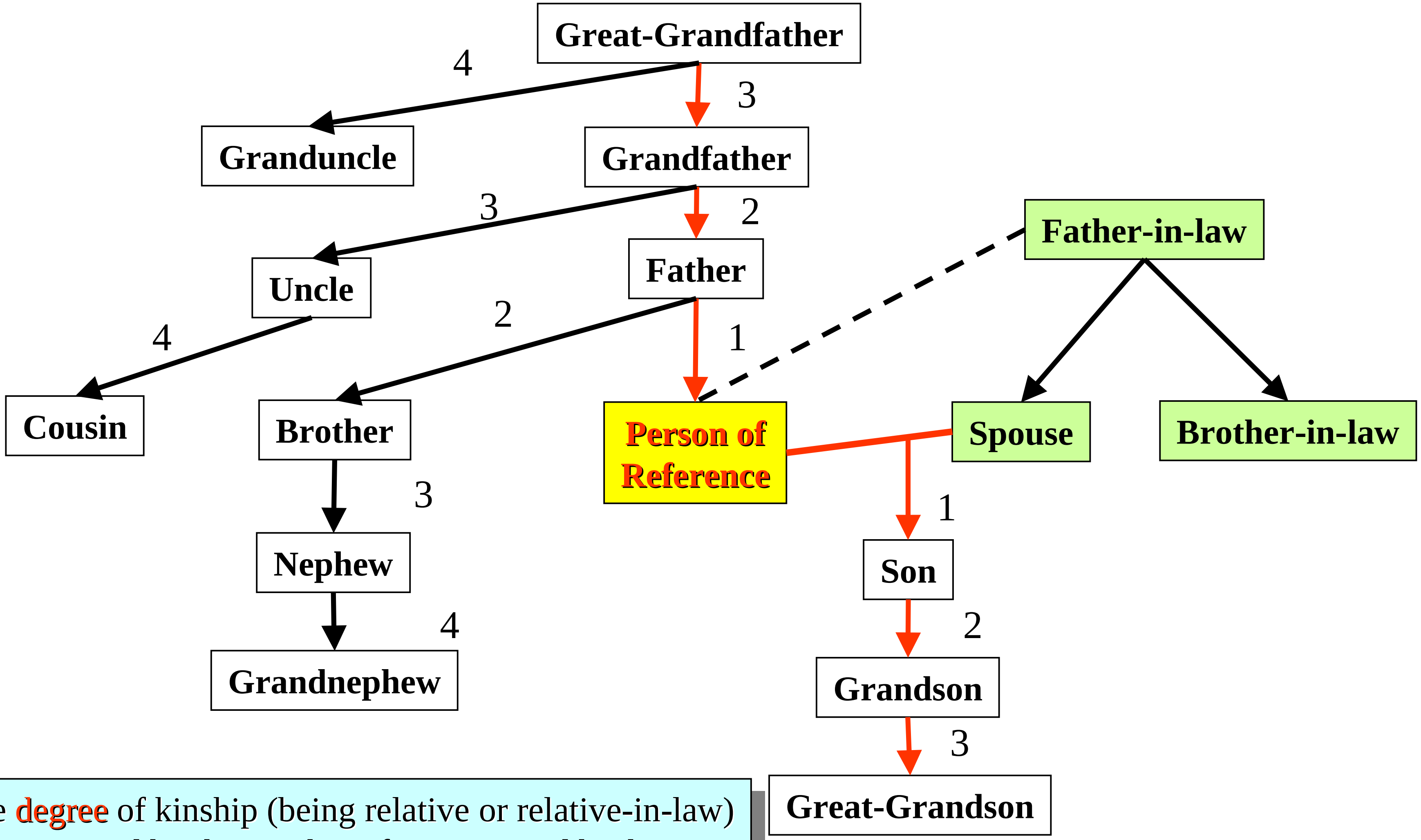
Ancestor



P	A	D
James	Edward	1
James	Elizabeth II	2
James	Philip	2
James	Sophie	1
Louise	Edward	1
Louise	Elizabeth II	2
Louise	Philip	2
Louise	Sophie	1
Peter	Anne	1
Peter	Elizabeth II	2
Peter	Mark	1
Peter	Philip	2
Savannah	Anne	2
Savannah	Autumn	1
Savannah	Elizabeth II	3
Savannah	Mark	2
Savannah	Peter	1
Savannah	Philip	3
William	Charles	1
William	Diana	1
William	Elizabeth II	2
William	Philip	2
Zara	Anne	1
Zara	Elizabeth II	2
Zara	Mark	1
▶ Zara	Philip	2

30 facts + 22 facts + 6 facts = 58 facts

(Male form only, due to space limitations)



The degree of kinship (being relative or relative-in-law) is determined by the number of intermittend births.

The concept "relative of" can be defined via several Datalog rules, too, using the concepts *ancestor* and *descendant* introduced before (*to be discussed in the exercises*):

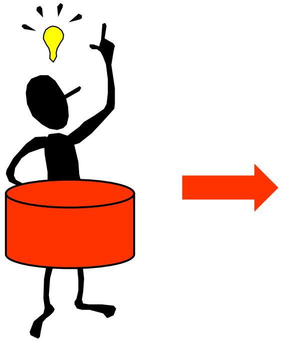
in the main line

```
relative(X, Y, Degree) ←
            ancestor(X, Y, Degree).
relative(X, Y, Degree) ←
            descendant(X, Y, Degree).
```

in the sideline

```
relative(X, Y, Degree) ←
            ancestor(Z, X, Degree1),
            ancestor(Z, Y, Degree2),
            not ancestor(X, Y),
            not ancestor(Y, X),
            not has_younger_common_anc(X,Y,Z),
            X \= Y,
            Degree = Degree1 + Degree2.
```

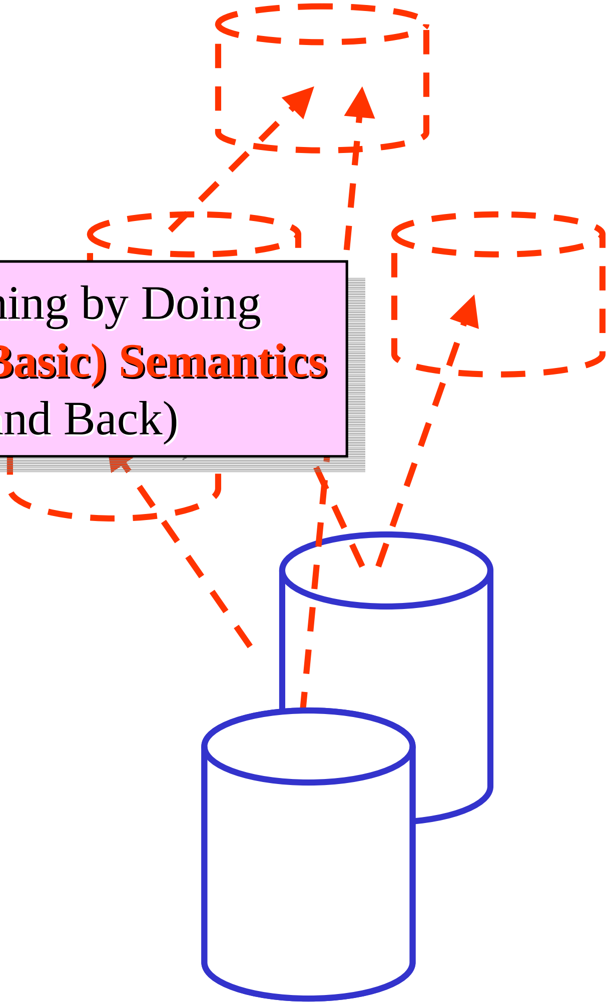
```
has_younger_common_anc(X,Y,Z) ←
            ancestor(Z1, X, _),
            ancestor(Z1, X, _),
            ancestor(Z, Z1, _).
```



2.1 Datalog and SQL: Learning by Doing

2.2 Datalog: Syntax and (Basic) Semantics

2.3 From SQL to Datalog (and Back)



About this Section

- After an intuitive, example-based introduction to the most important principles of Datalog in 2.1, 2.2 will look at the features and conventions of this language from a more abstract, systematic point of view.

- The introduction will not be a formal one, however, even though it is no problem to come along with a formal grammar for the syntax of each construct.

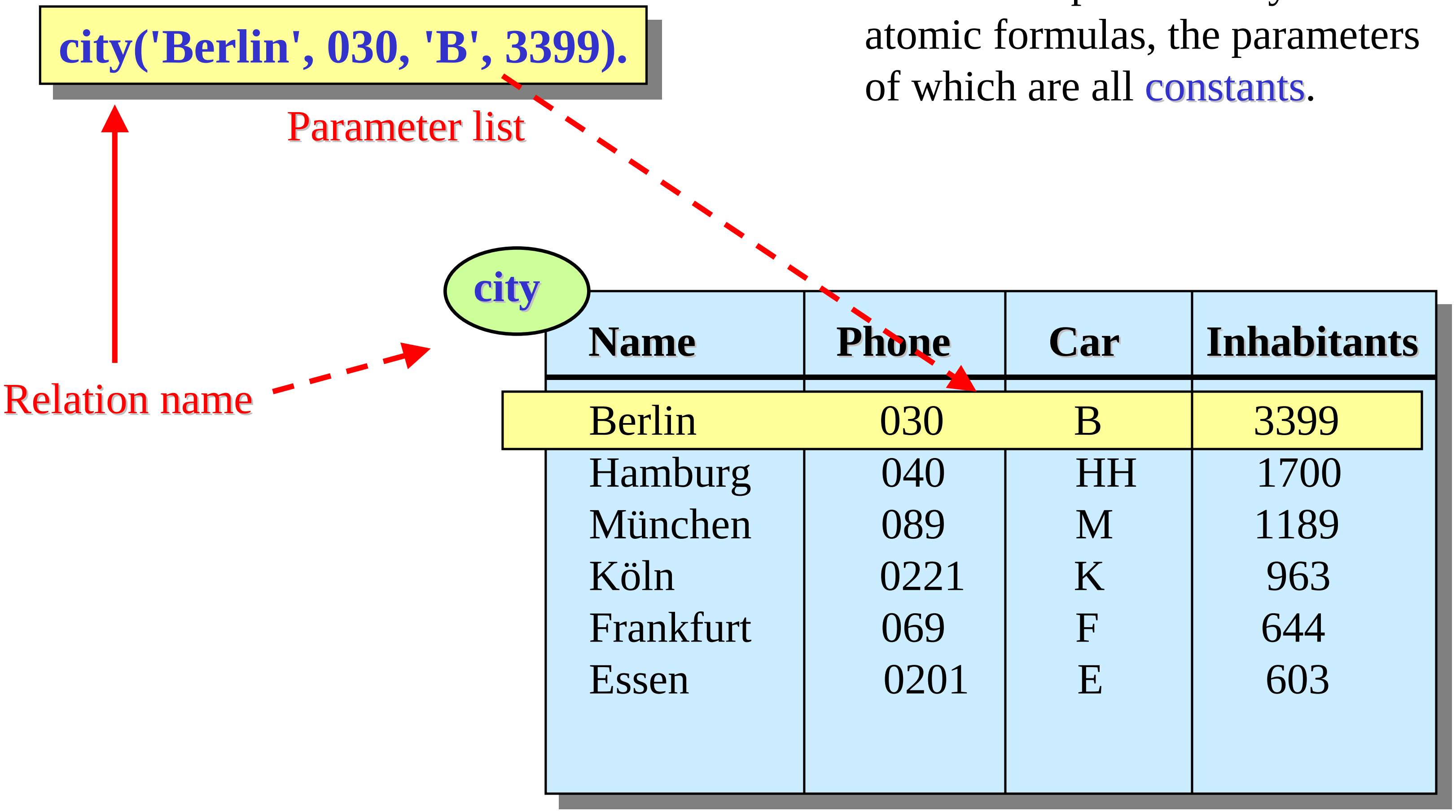
- Semantics is more problematic and will be dealt with in chapter 3 (formally, at least in part).

- Many of the introductory slides will just repeat „officially“ what was already mentioned before – but there will be key features (such as safety, CWA, or negation-as-failure) which will be discussed more in-depth as they are a bit intricate.

- Altogether, this is a section for your own reading more than for lengthy oral presentation within the lecture.

- Take this serious nevertheless – the details of the language will be relevant for the rest of the semester (including the exam).

Facts are represented by atomic formulas, the parameters of which are all constants.



city('Berlin', 030, 'B', 3399).

Parameter list

Relation name

city

Name	**Phone**	**Car**	**Inhabitants**
Berlin	030	B	3399
Hamburg	040	HH	1700
München	089	M	1189
Köln	0221	K	963
Frankfurt	069	F	644
Essen	0201	E	603

Constants, Variables and Relation Names

- Variables: Capital letters or strings beginning with a capital:

e.g.: **X** **X_1** **City** **X1a2b%**

- Constants: Digits, lower case letters, or strings beginning with a lower case letter or a digit, . . .

e.g.: **x** **1** **city** **1a2b%**

(„Inherited“ from conventions in most Prolog systems)

. . . or arbitrary strings in apostrophes:

e.g.: **'City'** **'X'** **'?-abc-!'**

- Relation names: Strings beginning with a lower case letter

e.g.: **city** **p** **q_1**

Tables

```
city( 'Berlin', 030, 'B', 3399 ).
city( 'Hamburg', 040, 'HH', 1700 ).
city( 'München', 089, 'M', 1189 ).
city( 'Köln', 0221, 'K', 963 ).
city( 'Frankfurt', 069, 'F', 644 ).
city( 'Essen', 0201, 'E', 603 ).
```

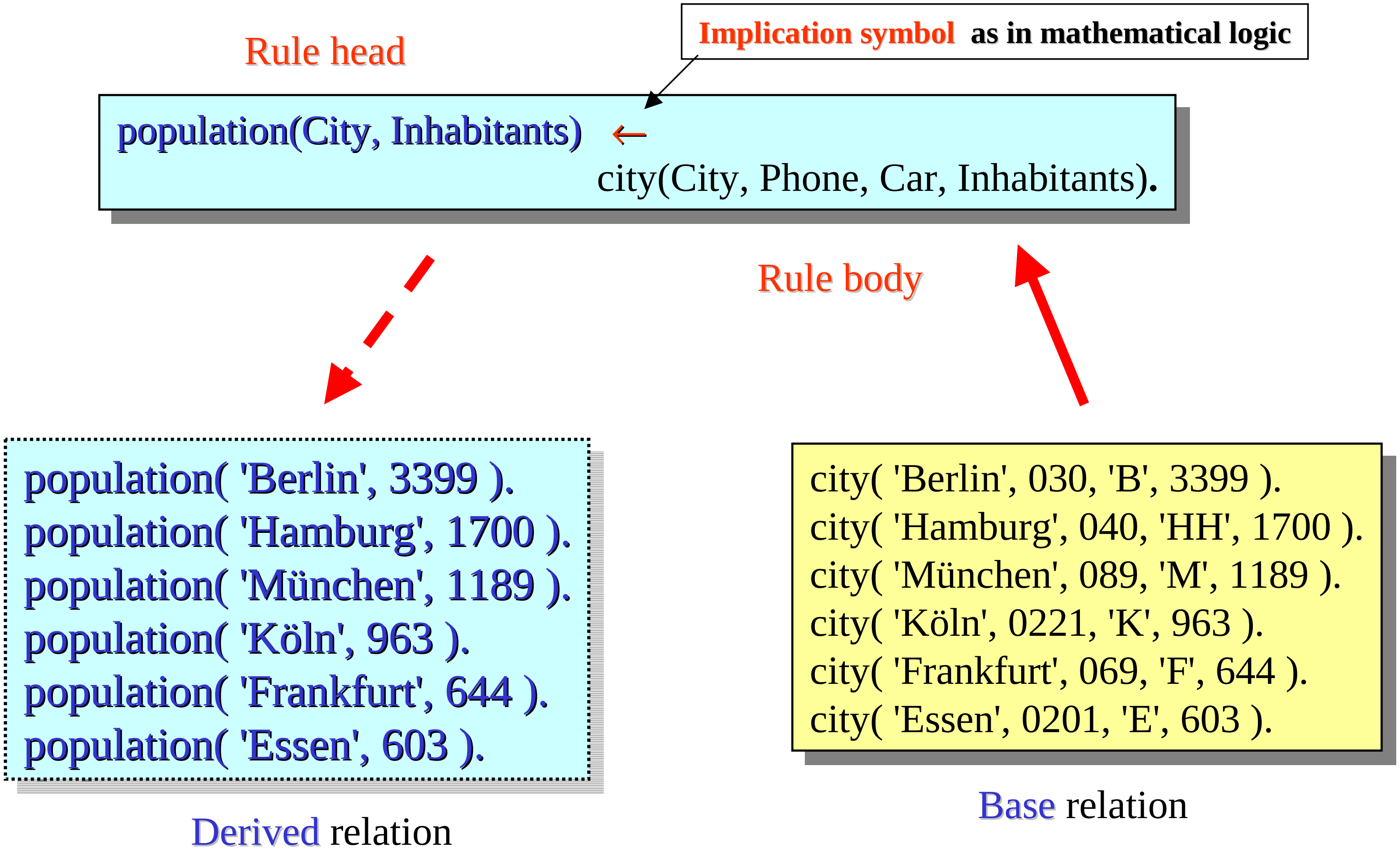
Table (relation) as a set of facts in **Datalog**

conventional table
(à la SQL)

City

Name	**Phone**	**Car**	**Inhabitants**
Berlin	030	B	3399
Hamburg	040	HH	1700
München	089	M	1189
Köln	0221	K	963
Frankfurt	069	F	644
Essen	0201	E	603

Deductive Rules in Datalog: Structure



Implication symbol as in mathematical logic

Rule head

population(City, Inhabitants) ←
city(City, Phone, Car, Inhabitants).

Rule body

```
population( 'Berlin', 3399 ).
population( 'Hamburg', 1700 ).
population( 'München', 1189 ).
population( 'Köln', 963 ).
population( 'Frankfurt', 644 ).
population( 'Essen', 603 ).
```

Derived relation

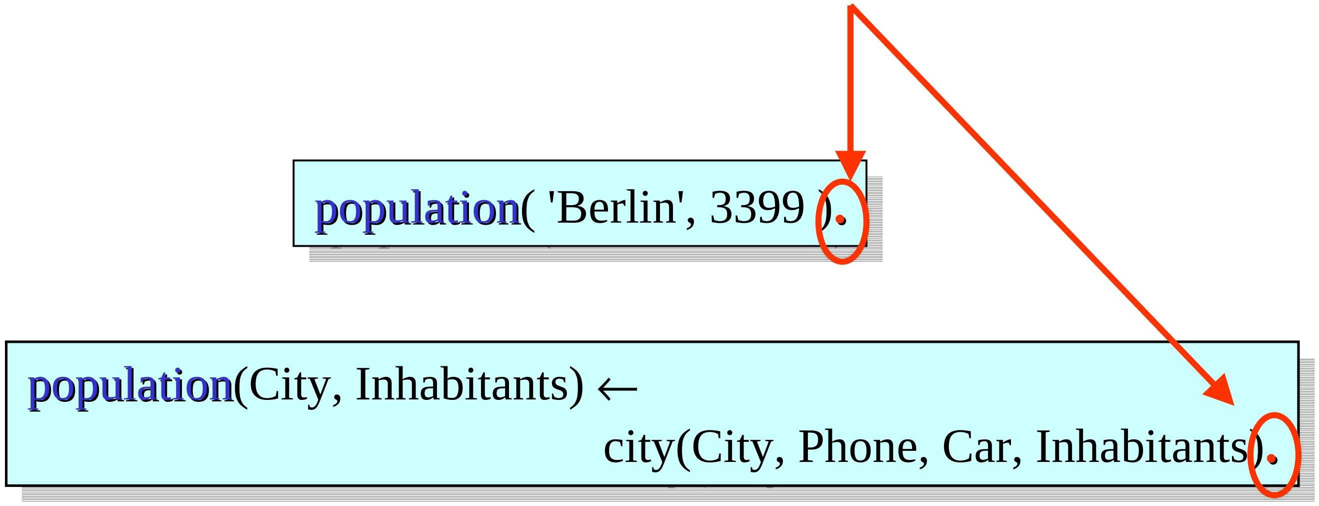
```
city( 'Berlin', 030, 'B', 3399 ).
city( 'Hamburg', 040, 'HH', 1700 ).
city( 'München', 089, 'M', 1189 ).
city( 'Köln', 0221, 'K', 963 ).
city( 'Frankfurt', 069, 'F', 644 ).
city( 'Essen', 0201, 'E', 603 ).
```

Base relation

Just a Convention, but . . . : The Dot at the End!

Another "syntactical tradition" from the Prolog world:

Facts and rules are always terminated with a dot !



```
population( 'Berlin', 3399 ).
```

```
population(City, Inhabitants) ←
                         city(City, Phone, Car, Inhabitants).
```

(As Datalog is <u>not standardized</u> – like, e.g., SQL – such syntactic rules are quite often neglected by authors following a tradition of their own. Take care!)

Literals

- The basic constituents of all Datalog-expressions are positive or negative atomic formulas, from which facts and rules are built.

- Such formulas are called literals.

positive literals	negative literals

p(X,Y)
q(a, Y, 1)
r(a,b)
	not p(X,Y)
	not q(a,Y,1)
	not r(a,b)

- Rule heads and facts are positive literals; rule bodies may contain both, positive and (possibly) negative literals.

- Literals without any variables are called ground literals. Therefore, all facts are ground literals in Datalog.

Literals (2)

- Literals play a double role in Datalog :
    - In facts and rule heads:

      For asserting confirmed or assumed data.
    - In rule bodies (and later on in queries):

      For finding confirmed or assumed data.

- A fact in a deductive database asserts, that something is the case:

  ! child_of('William', 'Diana', 'Charles').

- This is true for derived facts as well, thus rule heads play an asserting role, too:

  ! father_of(Y, Z) ← child_of(Z, X, Y).

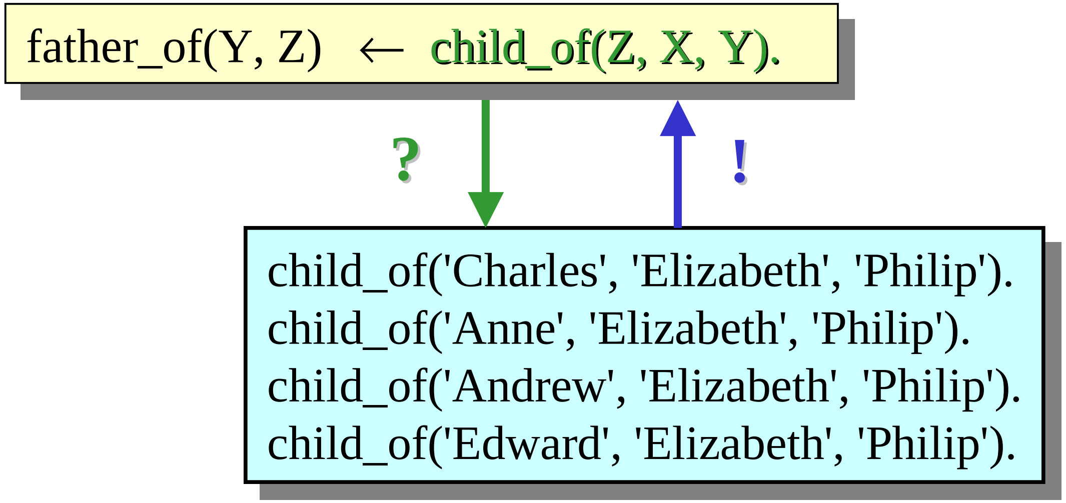
- Literals in role bodies, however, serve as questions if something is the case resp. for which variable substitutions something is the case:

  father_of(Y, Z) ← child_of(Z, X, Y). ?

- In order to derive father_of-facts with this rule, it is necessary to find child_of-facts and to transfer variable bindings found to the head literal, in order to assert new facts .

- Literals on „asserting“ positions – i.e., in facts and rule heads – „mean themselves“.

- Literals in „querying“ positions – i.e., in particular in rule bodies – get their meaning via an evaluation over a certain set of facts only, e.g.:



father_of(Y, Z) ← child_of(Z, X, Y).

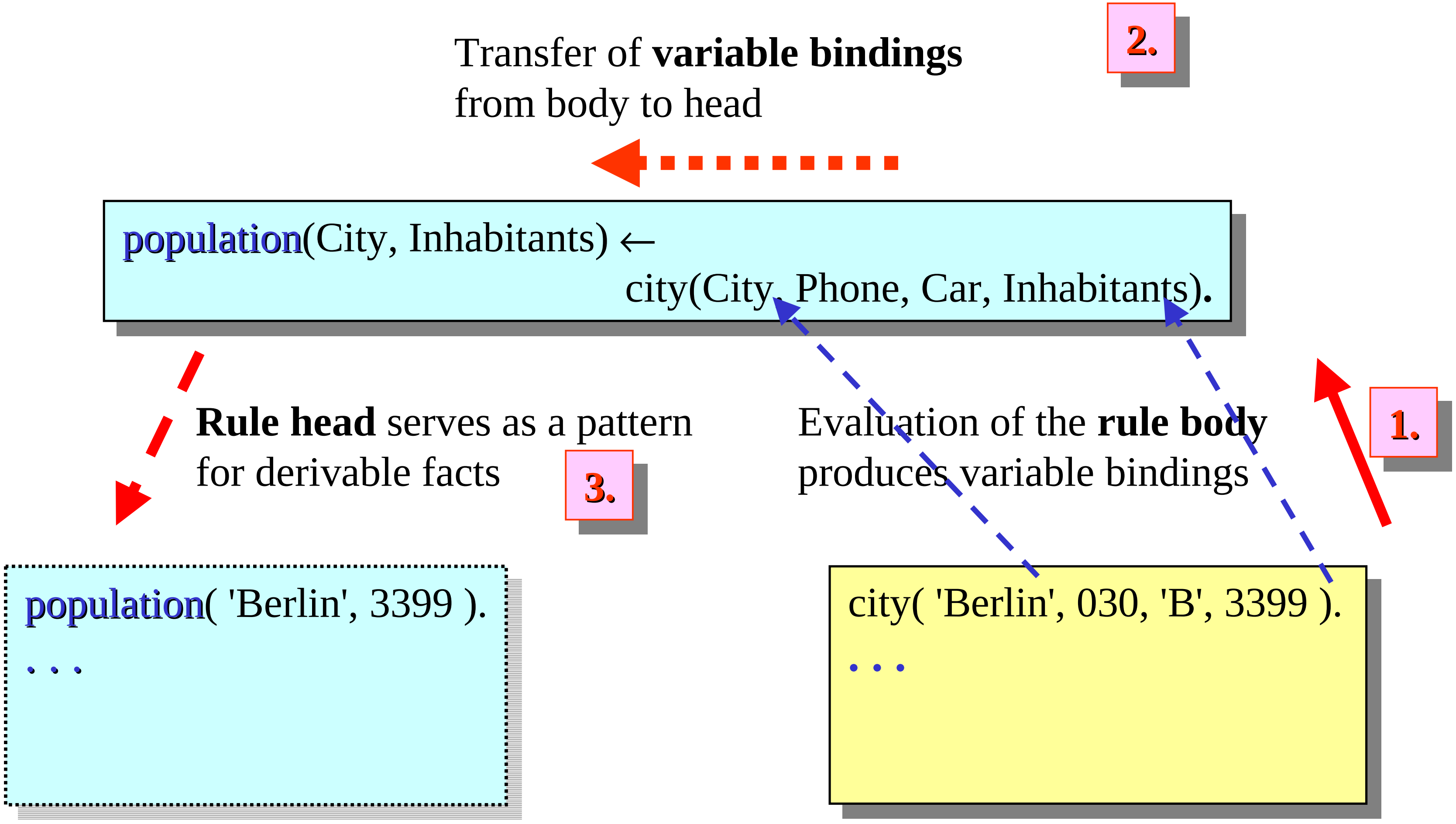
child_of('Charles', 'Elizabeth', 'Philip').
child_of('Anne', 'Elizabeth', 'Philip').
child_of('Andrew', 'Elizabeth', 'Philip').
child_of('Edward', 'Elizabeth', 'Philip').

This is like simple pattern matching!

- The body literal represents an (atomic) query:
  For which (X,Y,Z)-combination is the resulting fact true?

- The expected answer is the set of all variable substitutions that can be obtained by evaluating the literal over the given set of facts.

Application of Deductive Rules: Principle



Transfer of **variable bindings** from body to head

2.

population(City, Inhabitants) ← city(City, Phone, Car, Inhabitants).

Rule head serves as a pattern for derivable facts

3.

Evaluation of the **rule body** produces variable bindings

1.

population('Berlin', 3399).
. . .

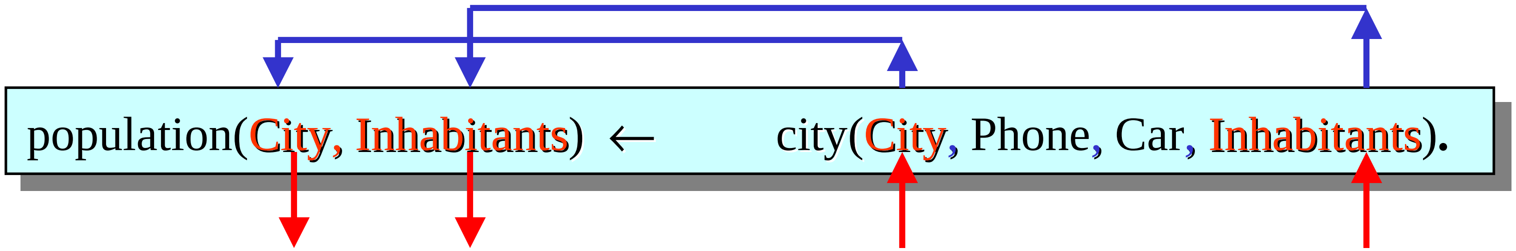
city('Berlin', 030, 'B', 3399).
. . .

Derived facts

Base facts or previously derived facts

- Rules are able to serve as "fact producers" only if the evaluation of the rule body generates variable bindings for all variables in the rule head.
- Thus: All variables in the head have to appear in the body of a rule, too!
- Rules satisfying this requirement are called safe.

All variables in the rule head . . .

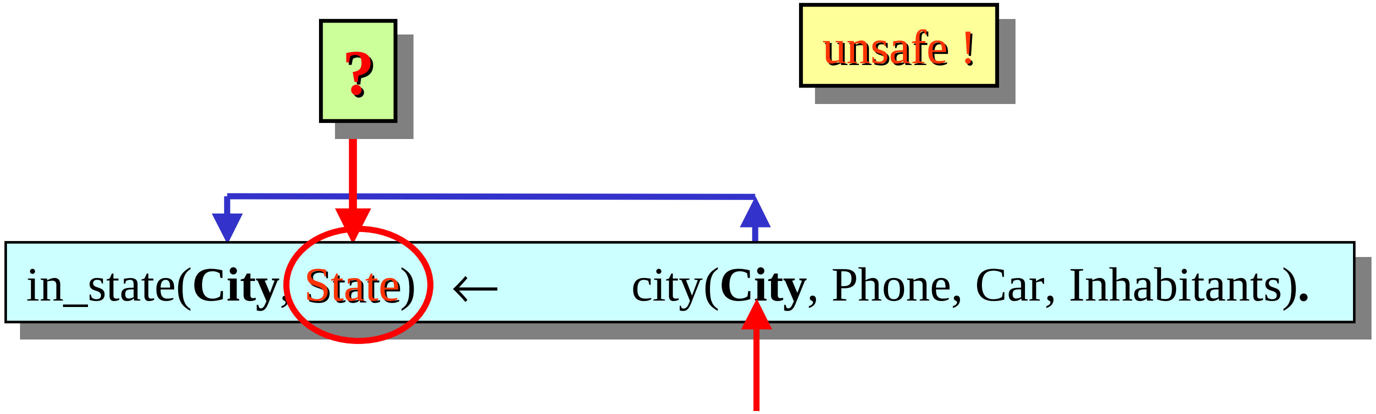


population(City, Inhabitants) ← city(City, Phone, Car, Inhabitants).

. . . have to appear in the rule body , too!

(But not necessarily vice versa!)

Unsafe Rules 2


?
unsafe !
in_state(**City**, State) ← city(**City**, Phone, Car, Inhabitants).

- An unsafe rule (like this one) is not able to produce complete facts for the defined relation ,in_state':

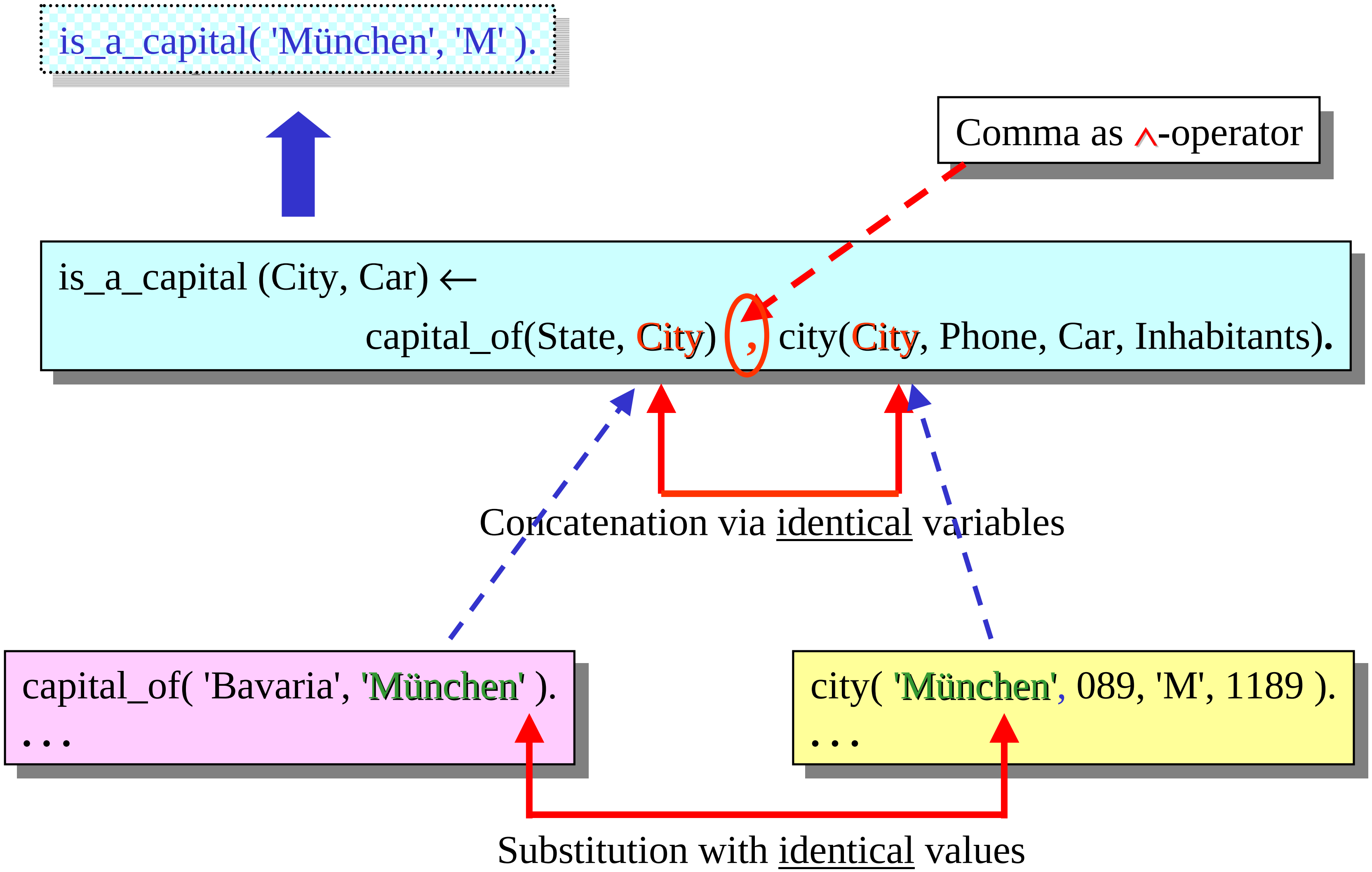
  Where to take values for binding variable 'State' from?

- Im principle: For 'State' any constant value could be substituted, so that the resulting relation ,in_state' ought to be infinitely large!

- Later in this lecture: Unsafe rules will be admitted though under certain contraints!

- But for now: All rules are assumed to be safe – no unsafe rules!

Conjunctive Rules



is_a_capital('München', 'M').

Comma as ∧-operator

is_a_capital (City, Car) ←
capital_of(State, City) , city(City, Phone, Car, Inhabitants).

Concatenation via identical variables

capital_of('Bavaria', 'München').
. . .

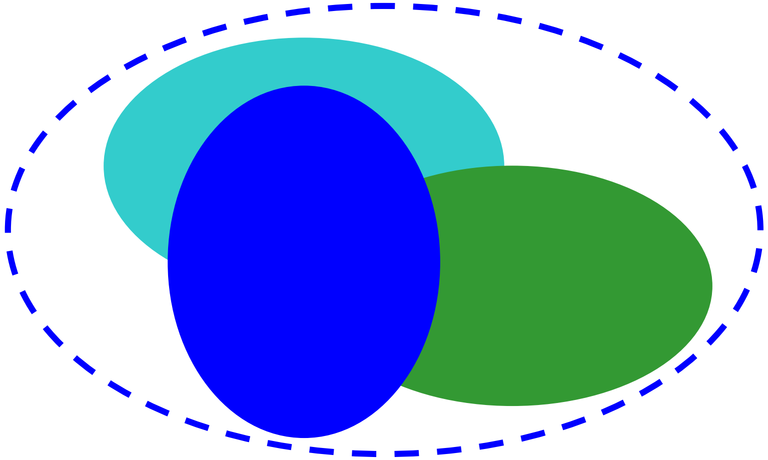
city('München', 089, 'M', 1189).
. . .

Substitution with identical values

Derived Relations may be defined by more than one rule:

Implicit disjunction (logical ∨)

```
european_city(X) ←   situated_in(X, 'Denmark' ) .
european_city(X) ←   situated_in(X, 'Germany' ) .
european_city(X) ←   situated_in(X, 'Russia' ) .
. . .
```



„Union semantics“

Each rule is able to derive a partial relation.

Some derived facts may be simultaneously derivable by several rules. As relations are sets, just one „copy survives“!

The entire relation thus is the union of all these partial relations (i.e., subsets of the full relation).

Order Independence in Datalog

- Datalog has been conceived as a purely declarative language, for which any aspect of execution – in particular of efficient evaluation – is irrelevant for the definition of syntax and semantics.

- Thus: The order of notation is irrelevant . . .
  - . . . if several rules define the same relation.
  - . . . if several literals occur in a rule body.

- The following rule sets are considered equivalent in Datalog, even though they are syntactically different:

p(X) ← q(X,Y), not s(Y).
p(X) ← r(X), t(X), w(X).

p(X) ← t(X), w(X), r(X).
p(X) ← not s(Y), q(X,Y).

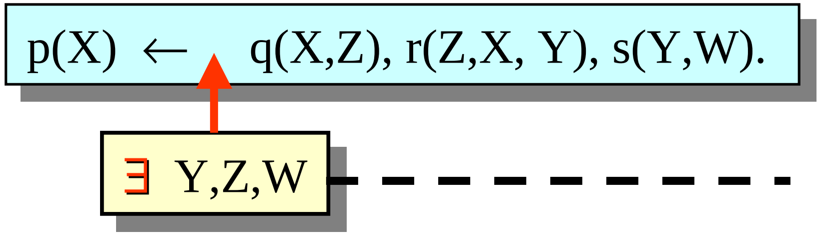
- For any concrete evaluation strategy, however, an evaluation order for literals and rules has to be fixed, though, and to be planned well for efficiency‘s sake.

∃-Position for Local Variables: Motivation

- The convention

  „Implicit ∃-quantifiers are always assumed to stand in front of all literals!“

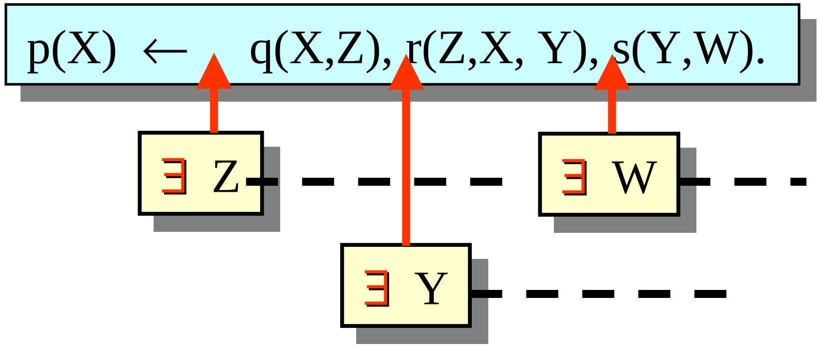
  seems to be unnecessary on first glance. For this reason, it it worthwhile to discuss alternatives by means of a more complex example:



p(X) ← q(X,Z), r(Z,X, Y), s(Y,W).

∃ Y,Z,W

- The only true alternative would be to keep the „scope“ (range of validity) of quantifiers as small as possible and thus to make them individually different:



p(X) ← q(X,Z), r(Z,X, Y), s(Y,W).

∃ Z

∃ W

∃ Y

Disadvantage:

- Considerably more complex
- Different quantifier structure for each reordering of the rule body

Anonymous Variables (1)

- <u>Frequent situation in Datalog-rules:</u>

  Various local variables are not used for connecting literals or for representing output values, but just for „filling“ parameter positions.

```
is_a_capital(City, Car) ←
          capital_of(State, City) ,  city(City, Phone, Car, Inhabitants).
```

- Adopted from Logic Programming:

  Abbreviating notation for this kind of "fill-up parameters" by underscore

```
is_a_capital(City, Car) ←
          capital_of ( _ , City) ,  city(City, _ , Car, _ ).
```

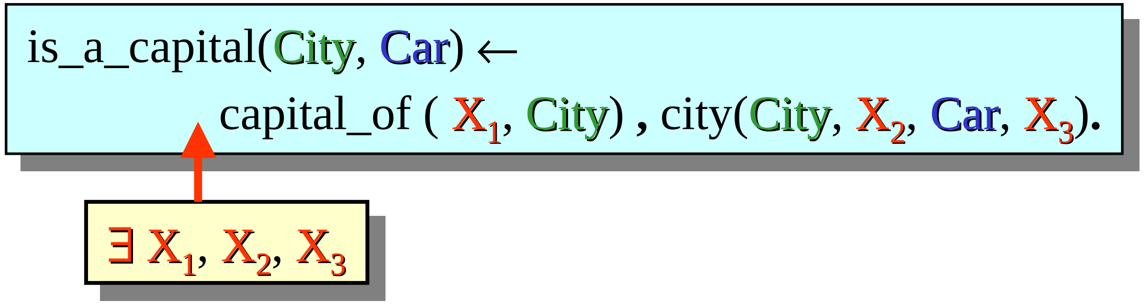
"anonymous variables"   (<u>aka</u>: "don't care"-variables)

Anonymous Variables (2)

- Although the same symbol (underscore) is used for representing anonymous variables, each occurrence of such a variable stands for a different, completely new variable occurring in this position only (the „true name“ of which we do not know):

is_a_capital(City, Car) ←

capital_of (_ , City) , city(City, _ , Car, _).



is_a_capital(City, Car) ←

capital_of (X_1, City) , city(City, X_2, Car, X_3).

$\exists X_1, X_2, X_3$

- Each of these variables has its own implicit quantifier. All these quantifiers is placed (as usual) at the beginning of the rule body (see above).

Hierarchical Dependencies 2

Important in particular for constructing terminological hierarchies:

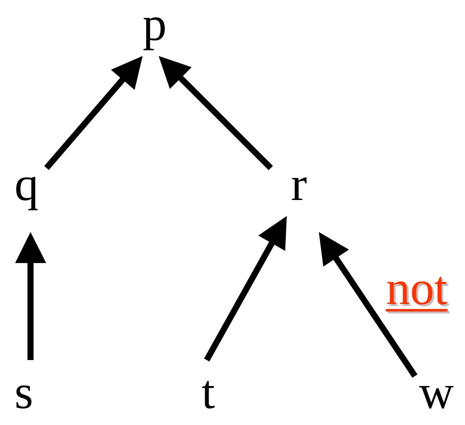
> **Derived** relations may **depend on** other **derived** relations (not only on base relations), i.e.:
>
> In the body of a rule, arbitrary relations may be referenced by literals.

e.g.:

p(X,Y) ← q(X,Y), r(Y, X).

q(X,Y) ← s(X, Y, Z).
r(Y, X) ← t(X,Y), not w(Y).

Corresponding dependency graph:



- Moreover: Rule-defined relations may depend on themselves, i.e., rules may be recursive.

- But: Recursive rules ought to come with at least one non-recursive rule defining the same relation („well-founded recursion")

Restriction to be lifted later on!

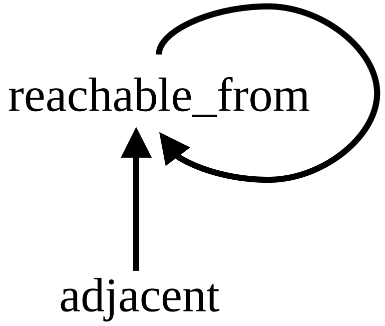
e.g.:

Non-recursive

```
reachable_from(A, B) ←
            adjacent(A, B).
```

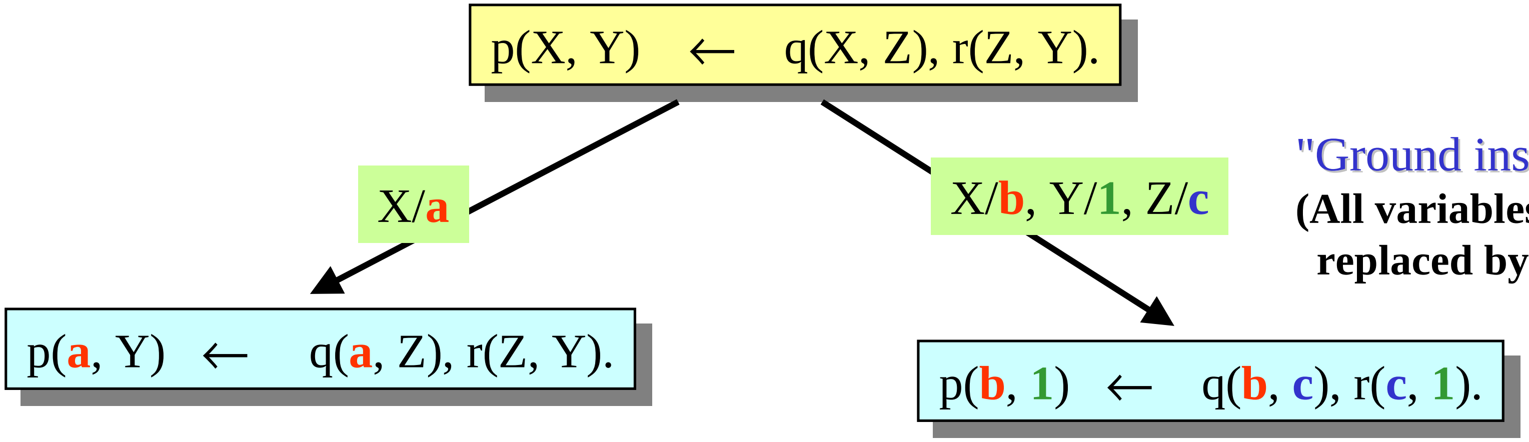
Recursive

```
reachable_from(A, B) ←
            adjacent(A, C),
            reachable_from(C, B).
```



Instances of Datalog Rules

- By stepwise replacement of variables by constants in a rule, various instances of this rule can be obtained:



p(X, Y) ← q(X, Z), r(Z, Y).

X/**a**

X/**b**, Y/**1**, Z/**c**

p(**a**, Y) ← q(**a**, Z), r(Z, Y).

p(**b**, **1**) ← q(**b**, **c**), r(**c**, **1**).

"Ground instance"

(All variables have been replaced by constants.)

- In each step, consistent replacements are admissible only, i.e., different occurrences of the same variable are always replaced by the same constant.

p(**a**, Y) ← q(**b**, Z), r(Z, Y).

Not an instance!

- In SQL, „empty fields“ in a table are permitted, in case information about the particular attribute is missing for the particular object represented in the resp. row.

- Theoretically, empty fields are considered to contain a special value – called NULL, or: a null value – representing an „existing, but unknown“ value in the resp. domain.

- Thus, NULL cannot (or better: ought not) be used for representing cases where, e.g., the resp. attribute does not apply, or where we do not know whether a value exists at all for the resp. field.

- Null values introduce quite sophisticated problems for query evaluation to SQL – ultimately, a 3-valued logic (with an extra value „unknown“) has to be introduced in order to properly deal with the implications of using NULL in the particular interpretation fixed in the SQL standard.

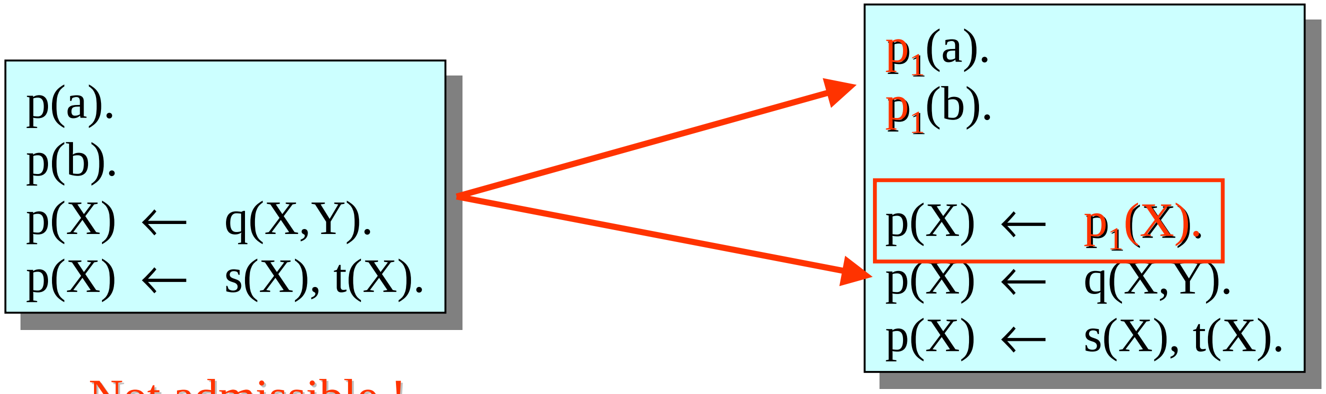
- Even though nulls are rather helpful in many practical cases, we do not allow NULL in Datalog, due to the problems resulting. Researchers in deductive DBs have been agreeing on this till now.

No NULL in Datalog !

- A deductive database in Datalog is a set of facts and rules (later on in this lecture, we will reconsider this "definition" a bit).

- By now people are used to assume that each relation in a Datalog-DB is either defined by stored facts only (base relation) or defined by rules only (derived relation): "Standardization Assumption"

- If you want to extend a rule-defined relation with some facts (for expressing special cases), however, an auxiliary relation summarizing the special cases is necessary again:



p(a).
p(b).
p(X) ← q(X,Y).
p(X) ← s(X), t(X).

p_1(a).
p_1(b).

p(X) ← p_1(X).
p(X) ← q(X,Y).
p(X) ← s(X), t(X).

Not admissible !

Standardized

"Closed World Assumption" (CWA)

- In databases up till now, one does not store negative information, but positive data only (or data derivable from stored data).

- Nevertheless, many (not all!) queries containing negation can be answered, e.g.:

Which cities are no major cities?

- This is possible, because we (tacitly) assume that all facts in DB-relations which are not stored are wrong in reality – and, of course, that all stored facts are true!

- This assumption is called the "Closed World Assumption" (CWA) in DDB-literature:
  - Each piece of knowledge about "the world" (i.e., the resp. application area) is represented in the DB in form of positive facts (stored or derivable).
  - There is no doubt about true and false information (2-valued logic).
  - In an "open world" it would be necessary to distinguish between negative and unknown information (e.g. by storing false facts explicitly in addition to true ones).

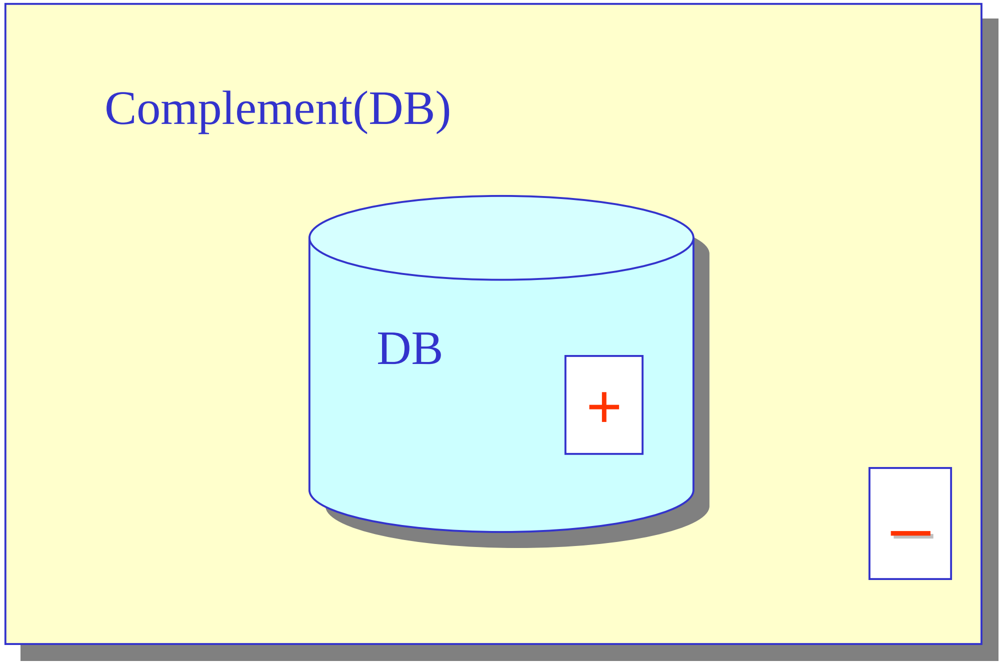
Obviously, CWA is hopelessly idealistic – but there is hardly any alternative!

CWA (2)

CWA: 1) All true facts are represented in the DB.
2) All facts in the DB are true.
3) All false facts form the complement (in set-theoretic terms) of the DB and, thus, exist implicitly only.

Reference set
for constructing
the complement:

Set of all
syntactically
constructable
facts



Constructable from
- all relation names in the schema
- all constant in all value domains

The complement of the DB is <u>never</u> explicitly computed or even stored (for efficiency reasons)!

- Consequence of CWA: Negation in Datalog is admissible in rule bodies only, not in facts and not in the head of a rule (i.e., not for derivable facts).

- There is no directly expressible negative information in a Datalog-DB:

~~not capital_of('Germany', 'Bonn') .~~

No stored "negative facts" !!

- Derivation of negative information is excluded, too:

~~not is_a_capital(X) ← situated_in(X, 'Bavaria') .~~

No derivable "negative facts" !!

- Deriving positive information exclusively from negative information is not possible in Datalog, too, because the complement of the DB would have to be made explicit for this purpose (which is unrealistic, see above):

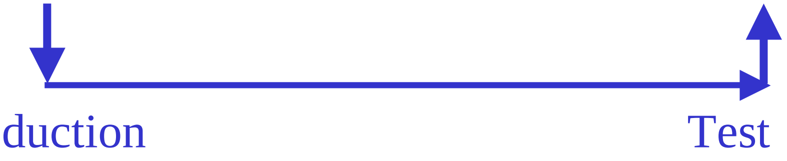
~~north_german_city(X) ← not is_situated_in(X, 'Bavaria') .~~

Negation is "unproductive" !!

- Negation in Datalog is admissible in combination with positive facts only, i.e., only in connection with logical conjunction: and not

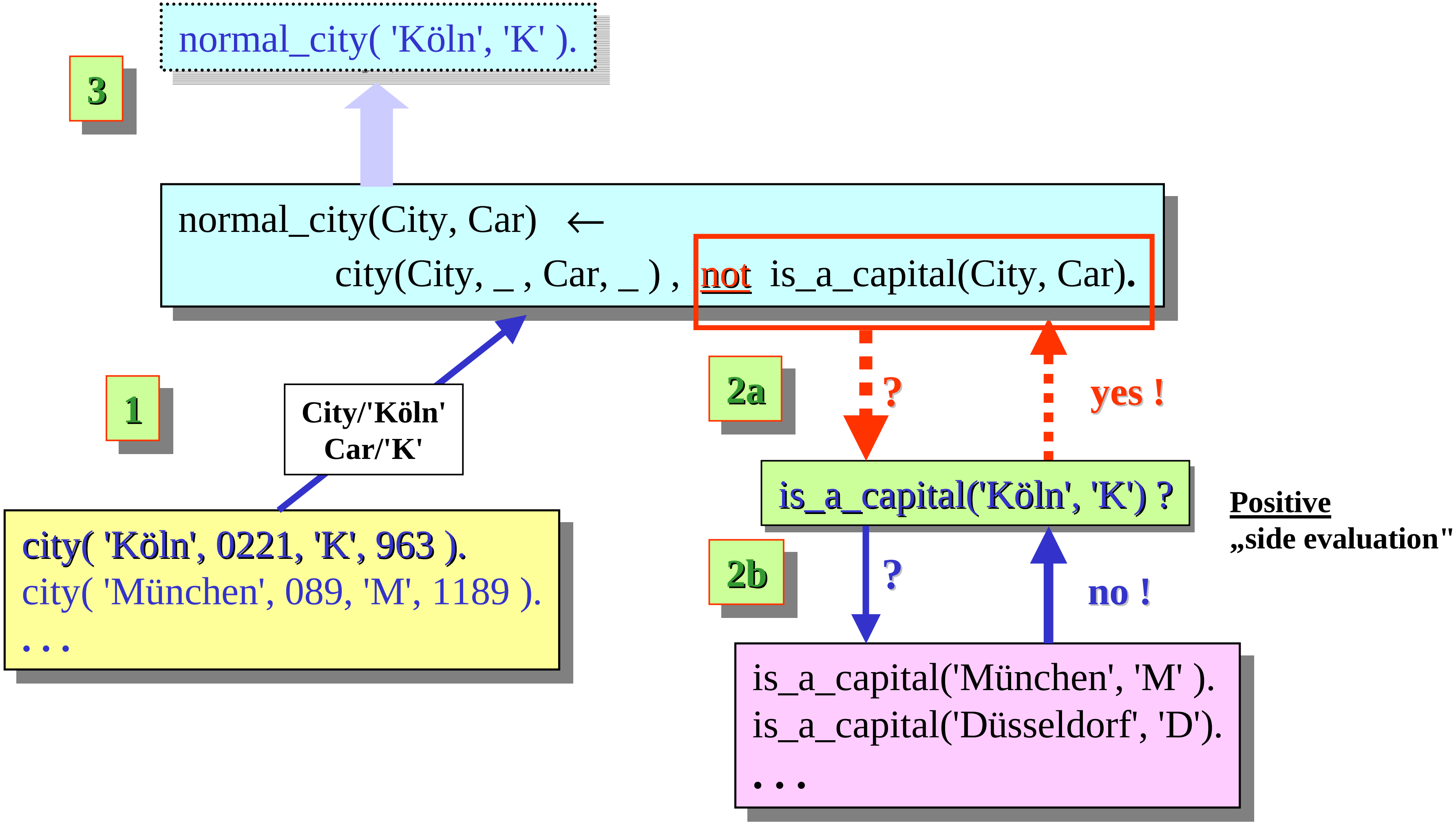
- Negation can be used for "testing" variable bindings only, which have been "produced" in the positive parts of the rule before:

north_german_city(X) ←
city(X, Y1, Y2, Y3) , not is_situated_in(X, 'Bavaria') .


Production

Test

Evaluating Negative Literals



3

normal_city('Köln', 'K').

normal_city(City, Car) ←
city(City, _ , Car, _) , not is_a_capital(City, Car).

1

City/'Köln'
Car/'K'

city('Köln', 0221, 'K', 963).
city('München', 089, 'M', 1189).
. . .

2a

?

yes !

is_a_capital('Köln', 'K') ?

Positive
„side evaluation"

2b

?

no !

is_a_capital('München', 'M').
is_a_capital('Düsseldorf', 'D').
. . .

"Negation as Failure"

- The corresponding evaluation principle for negative literals is called

  "Negation as failure"

  (If we fail to find the positive literal to be tested in the DB, we assume it to be false.)
- Prerequisite:
  - Before evaluating any negative literals, all variables contained in this literal have to be bound by evaluating "suitable" positive literals.
  - Only negative ground literals are evaluable via "negation as failure".

- In order to evaluate a literal not F, . . .
  - . . . try to answer its positive part F.
  - If F is true, then not F is false.
  - If F is false, then not F is true:

    "(Proof of the) negation (of 'F') by failure (to prove 'F')"

- Negative literals with variables are not evaluable by accessing DB-facts:
  - 'not p(X)': Find X-bindings, so that 'p(X)' is not true (in the DB)!
  - Inspecting the p-Relation produces only such X-bindings, for which 'p(X)' is true!
  - Where to find "all the other possible" X-bindings?

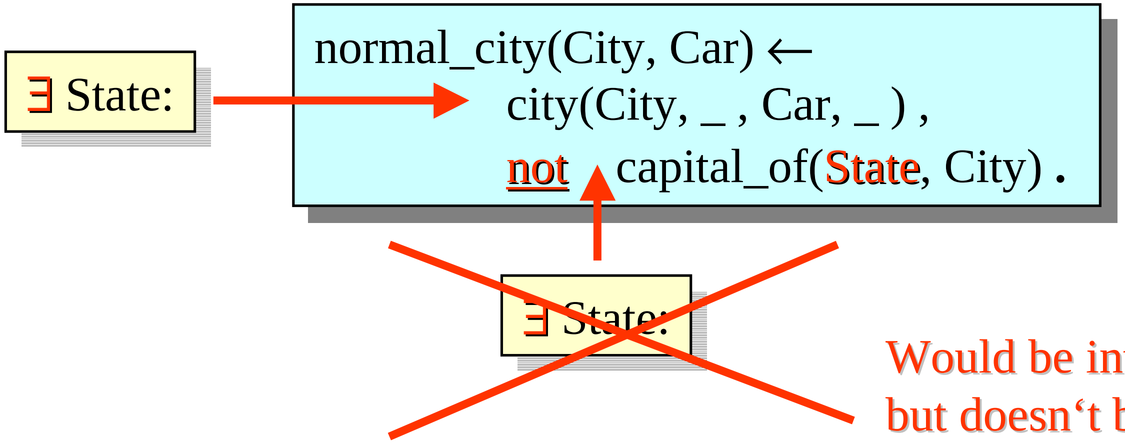
    (Complement remains implicit due to CWA!)

Safe Negation (1)

- Thus, we need an additional safety condition for negated literals:

Each variable occurring in a negative literal has to occur in at least one positive literal, too.

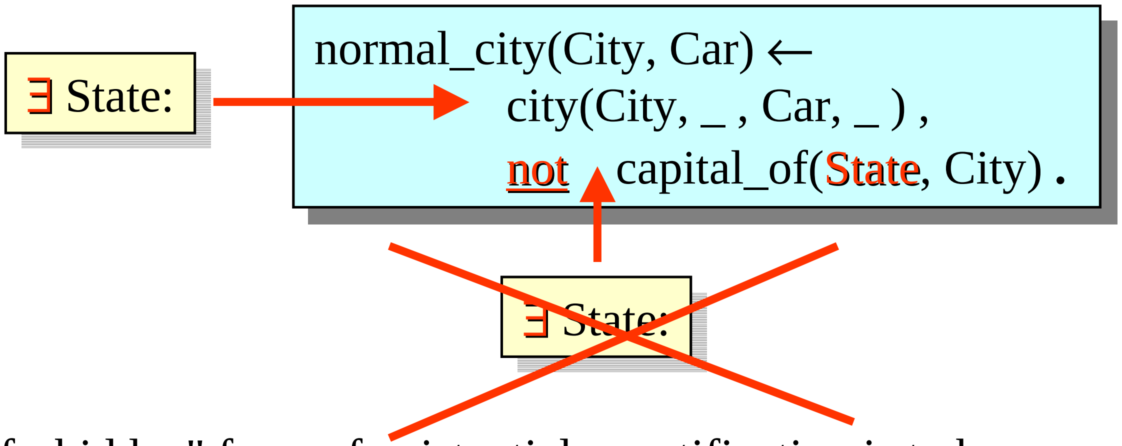
- Dangerous: Erroneous application of unsafe variables may easily happen, if misinterpreting the assuption about implicit existential quantification



```
normal_city(City, Car) ←
        city(City, _ , Car, _ ) ,
        not  capital_of(State, City) .
```

Would be intuitively meaningful, but doesn‘t belong here according to the „quantifier rule“!

Safe Negation (2)

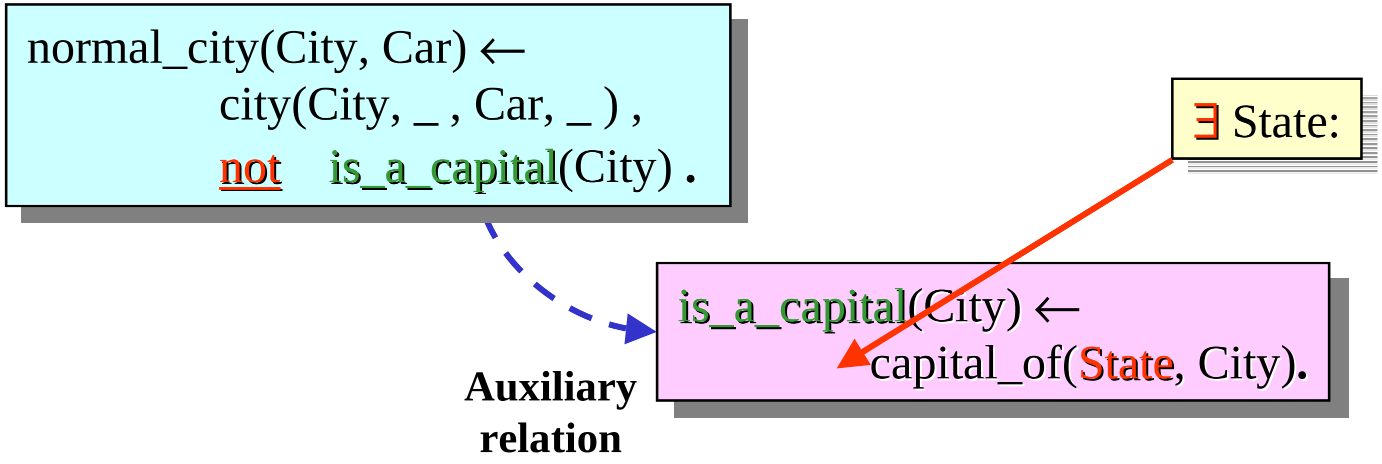


∃ State:

normal_city(City, Car) ←
city(City, _ , Car, _) ,
not capital_of(State, City) .

~~∃ State:~~

If the "forbidden" form of existential quantification is to be expressed in a different way, it is necessary to "swap" the existential quantifier into a separate rule:



normal_city(City, Car) ←
city(City, _ , Car, _) ,
not is_a_capital(City) .

∃ State:

is_a_capital(City) ←
capital_of(State, City).

Auxiliary relation

No Nesting in Datalog!

- Negation is admitted only if occurring directly in front of individual literals, not for negating entire conjunctive expressions. Thus, rule bodies may not contain nesting of logical operators!

north_or_west_german_city(X) ←
city(**X**, _, _, _) ,
not (~~south_of (**X**, 'Hannover'), east_of(X, 'Lübeck')~~).

- If such a rule is to be expressed differently in Datalog, it is necessary to introduce another auxiliary relation definied by a separate rule (without nesting):

north_or_west_german_city(X) ←
city(**X**, _, _, _) , not south_east_of(X) .
south_east_of(X) ←
south_of (**X**, 'Hannover'), east_of(X, 'Lübeck').

- We learnt previously, that all local variables in a rule body are implicitly existentially quantified. What about universal quantifiers („forall“ in logic – symbolically: ∀)?

- As a motivating example, consider the following natural language sentence (to be turned into a Datalog rule):

A student is successful if (s)he has passed exams of all mandatory modules.

- For the corresponding Datalog formalization, consider relations *students(MatrNr)*, *exams(MatrNr,ModNr,Result)*, and *modules(ModNr,Status).* Further assume that exam results are either *pass* or *fail*, and that module status is either *m(andatory)* or *o(ptional).*

- There is no forall in Datalog, not even implicity (as for SQL, also lacking forall)!

- Instead, a law of equivalence from predicate logic has to be exploited for „simulating“ *forall* by means of *not* and *exists*:

$$\forall\ x: F(x) \equiv \neg \exists\ x: \neg\ F(x)$$

- In natural language, applying the same reasoning principle leads to the reformulation of the example as follows:

A student is successful if there is no mandatory module (s)he did not pass.

Simulating Universal Quantifiers (2)

A student is successful if there is no mandatory module (s)he did not pass.

- If Datalog would permit explicit quantifiers (and nesting), the following rule could be written, formalizing the above sentence:

successful(S) ← students(S) and not (∃ M: modules(M,'m') and not exams(S,M,'pass')).

- Beware! This is not Datalog, but hypothetical „extended Datalog“, we just use didactically!

- Applying techniques introduced before (unnesting, implicit existential quantification), we obtain the following (equivalent) version – using an auxiliary rule – which is proper Datalog:

```
successful(S) ←
            students(S), not has_failed_module(S).
has_failed_module(S) ←
            students(S), modules(M,'m'), not exams(S,M,'pass')).
```

∃ M

- Doesn‘t belong to the „core“ of Datalog, by unavoidable in practice:

Comparison operators

<
=<
=
\=
>=
>

- In logic: Relation names, too
  (like names of DB-relations)

- But: These „relations“ are obviously not definable by facts oder rules in extensional form, but have to be realized in external programming languages by means of suitable "test procedures" (i.e., from the perspective of Datalog as "built-ins")

- For better distinction between (DB-)relations and this kind of test relations we use another notion from logic (more or less synonym with „relation“): "Predicate"

- In Datalog, we use test predicates in test literals, e.g.

X > Y X =< 1 not a = b

Safe Comparisons 2

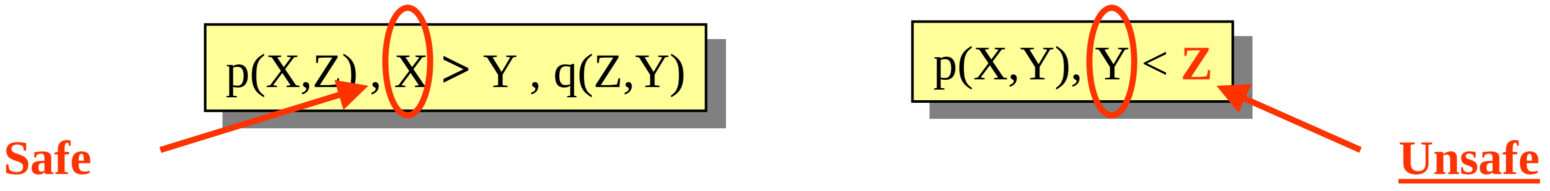
- Comparison predicates are used exclusively for testing whether two elements of a certain data type denoted by two terms satisfy the resp. test.

- Comparisons are possible only if none of the two parameters of a test literal are still variable when performing the test.

- A test literal thus is subject to similar safety requirements as negative literals:

> Each variable in a test literal has to occur in at least one, positive DB-literal within the same conjunction which contains the resp. test literal.

- Examples for safe resp. unsafe usage of comparisons:



p(X,Z) , X > Y , q(Z,Y)

p(X,Y), Y < Z

Safe

Unsafe

Built in-Functions

- Unavoidable, too: Arithmetic operations
  (and possibly other elementary operations on data types)

- Such "built in"-functions are to be realized in an external programming language, too.

- Evaluable (functional) terms in DB-literals are "disturbing" as they have to be treated different from the "matching"-based evaluation of DB-literals over facts and rules:

+
-
/
*

⇒ Functional terms are (for now) admissible in test literals only!

- Reason: Test literals are to be evaluated externally anyway;
  moreover, functions rely on "safety" of all parameters, too.

~~$p(X, X+1) \leftarrow q(X, X-1)$.~~

$p(X,Y) \leftarrow Y = X+1, q(X,Z), Z = X-1.$

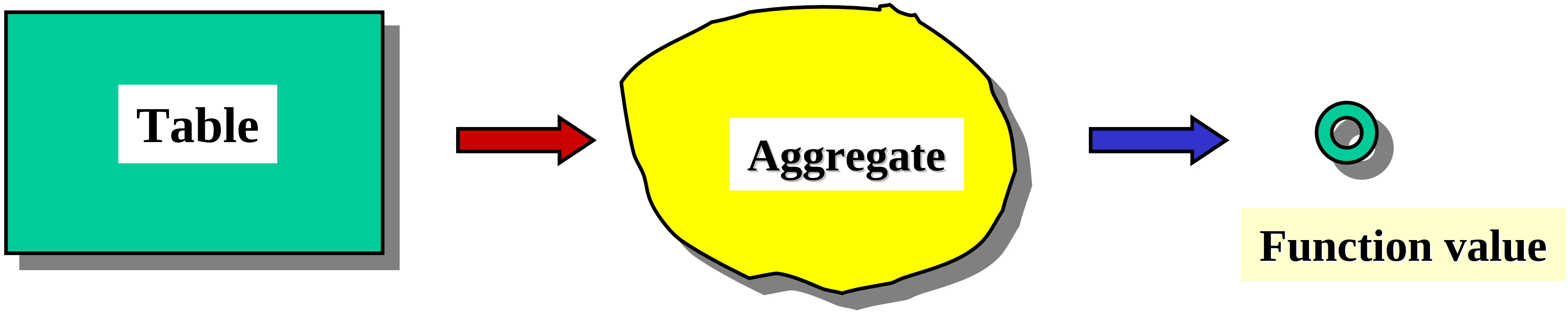
Not really tests anymore!

Aggregate functions

- important class of „built-in“ functions in SQL:

COUNT	Number of
SUM	Sum
AVG	Average
MAX	Maximum
MIN	Minimum

- Aggregate functions compute <u>one</u> scalar value out of a <u>set</u> of scalar values (the „aggregate“) originating from <u>one</u> column of <u>one</u> table:



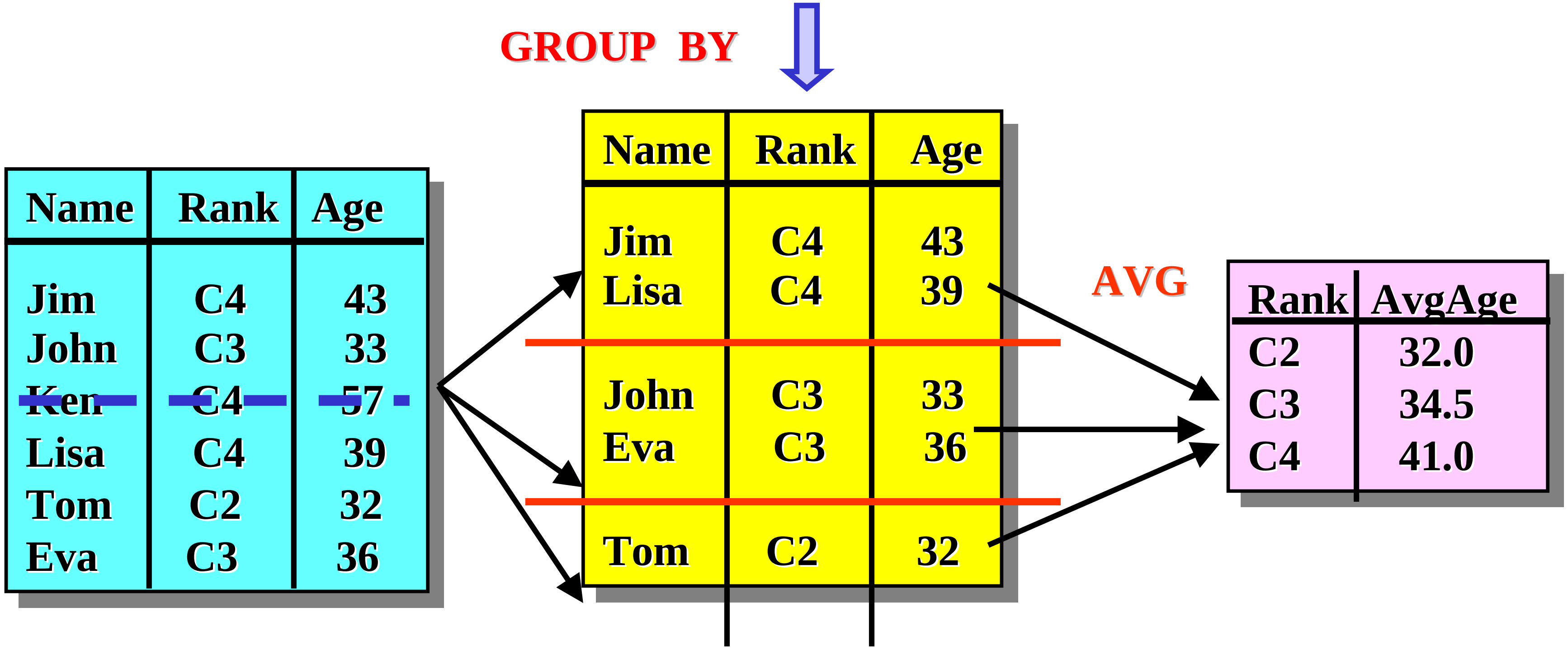
Table

Aggregate

Function value

This is how aggregates work in SQL:

```
SELECT      P. Rank,   AVG( P.Age )  AS   AvgAge
FROM        professors  AS  P
WHERE       P.Name <> ‚Ken‘
GROUP BY    P. Rank
```



Name	Rank	Age
Jim	C4	43
John	C3	33
~~Ken~~	~~C4~~	~~57~~
Lisa	C4	39
Tom	C2	32
Eva	C3	36

Name	Rank	Age
Jim Lisa	C4 C4	43 39
John Eva	C3 C3	33 36
Tom	C2	32

Rank	AvgAge
C2	32.0
C3	34.5
C4	41.0

Aggregate Functions (2)

- We need aggregate functions in Datalog as well – they ought to be treated similarly with other functions (at least as far as they exhibit comparable properties), e.g., terms containing aggregate functions should appear in test literals only.

- But aggregates are considerably different from, e.g., arithmetic functions as they require the prior computation of „the aggregate“, i.e., the collection of objects to which they are to be applied.

- Therefore, we need a special construct expressing an aggregate inside the body of the rule, which means a kind of nesting „hidden“ by a special syntax, e.g.:

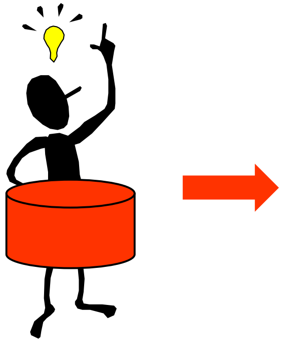
```
avg_salary(Dept, AvgS) ← AvgS = avg(Salary, Dept, employee(E, Dept, Salary))
```

  - There are special ternary aggregate functions: avg, sum, max, min, card.
    (We prefer *card(inality)* rather than *count*.)
  - The 1st parameter of each aggregate term is the variable to be aggregated about.
  - The 2nd parameter is the grouping variable.
  - The 3rd parameter is a literal defining the grouping condition.
  - Thus, the example reads: AvgS is the average salary per department computed from the *employee* relation.

Summary of Notations and Concepts

- fact
- rule
  - rule head
  - rule body
- literal
  - ground literal
  - retrieval literal
  - test literal
- safety
- conjunction, disjunction
- negation
- quantifier
- variable
  - anonymous variable
  - local variable
- order independence
- instance
  - ground instance

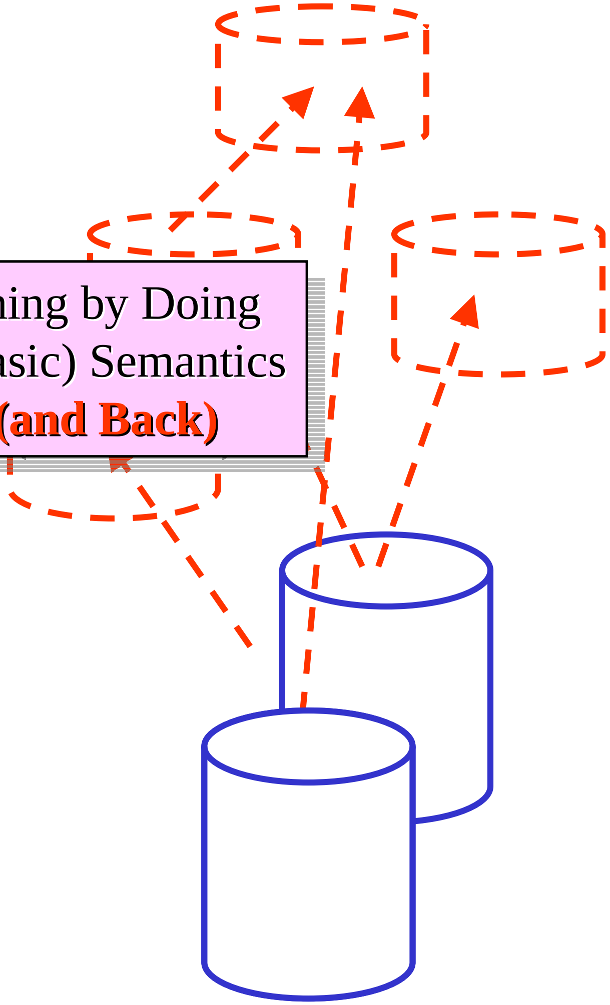
- CWA
- negation as failure
- dependency graph
- recursion
- standardization
- built-ins
- aggregates



2.1 Datalog and SQL: Learning by Doing

2.2 Datalog: Syntax and (Basic) Semantics

2.3 From SQL to Datalog (and Back)



About this Section (1)

- Section 2.3 plays an important role in various respects:
  - It tries to link the („academic“) key language of this lecture, Datalog, to the key language in the „professional“ DB world, SQL, in order to make sure that you know about the relevance of our topics for the „real world“.
  - It tries to provide you with a solid background on the theoretical basis of the languages covered, a background that is relevant for more recent approaches to IS/DB models and formalisms, too (such as XML and RDF, e.g.).
- At the same time, this section – extending just to the next lecture this week – is not able to provide you with a more detailed introduction to the languages addressed, in particular SQL. Effort of your own is needed, at least for making sure you leave the university with skills you can directly use in practice.
- For our exam expectations, however, we try to treat everything you need explicitly and deep enough.

About this Section (2)

- The order in which topics will be presented this week is not the one which will be chosen finally, due to „context reasons“. In particular, the foundations ought to be discussed first, not last (as we will have to do in the lecture).

- SQL basics would be necessary as second topic in 2.3, as Datalog has been well introduced enough. This topic will also appear in a bit more detail and in a different position within the slide order later.

- Even though the „Datalog to SQL“ transformation is the more important one (wrt „exporting“ results from this lecture to the SQL „world“) we will start the other way round and address “SQL to Datalog” first, again for “context reasons”.

- We will „call“ this part SQL2Datalog in the headings. Slides are from last year (and thus directly „re-usable“).

SQL2Datalog: General Remarks Ahead

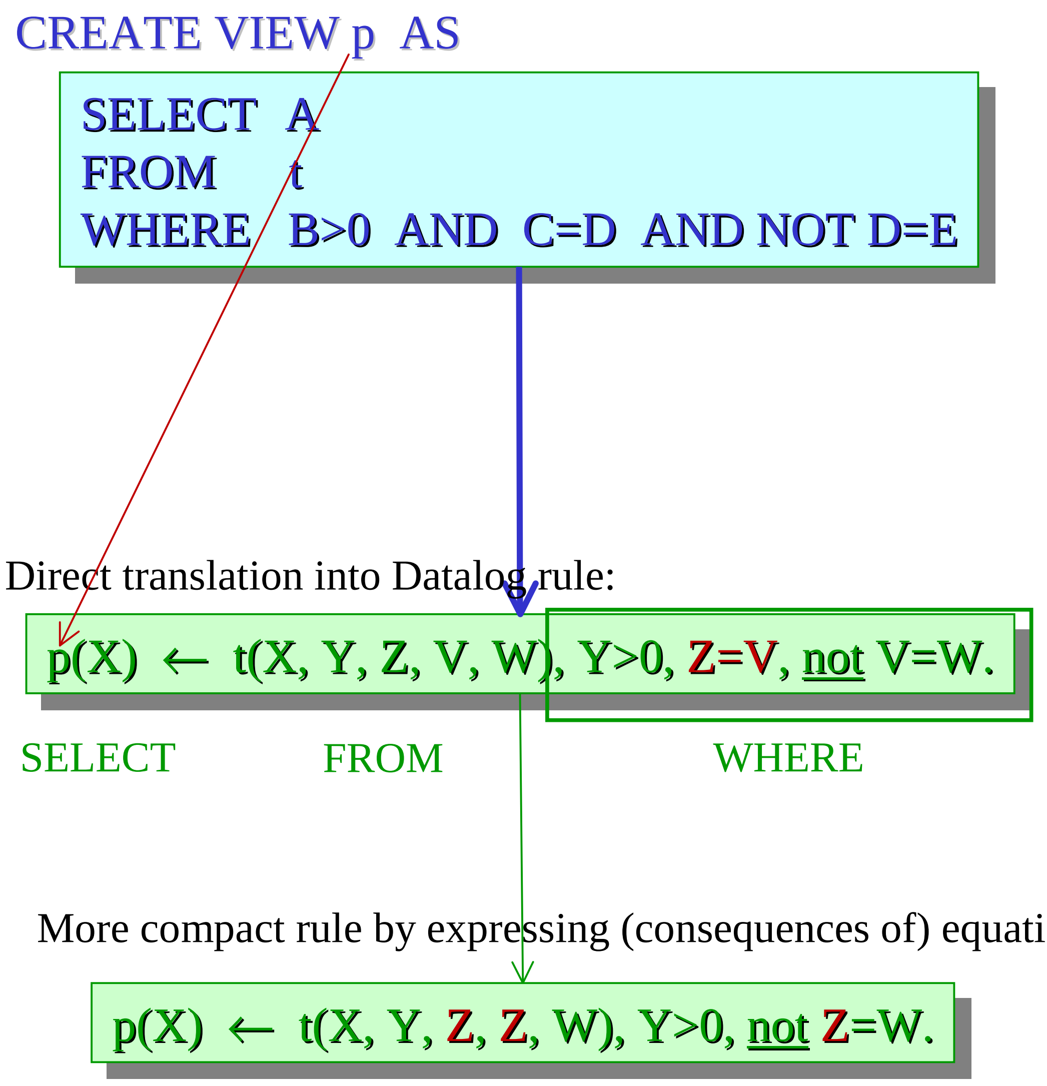
- Every result (to be) presented during this lecture in the context of Datalog can be transferred to SQL – the only exception concerning unstratifiable rules to be discussed in 3.3.

- We will discuss translation of SQL views (vice versa) into Datalog rules first in this section. The examples chosen can be easily generalized.

- A core sublanguage of SQL is sufficient for mapping into Datalog (and back). Core SQL offers the following operators:
  - SELECT-FROM-WHERE queries (without nesting in SELECT and FROM)
  - JOIN and its variants are omitted: They can be expressed using „normal“ FROM and join conditions in the WHERE-part.
  - UNION is the only operator needed for forming complex queries. OR is not needed, just AND occurs in the WHERE-part.
  - Nested subqueries (after EXISTS with and without NOT) are sufficient for expressing MINUS and INTERSECT).

- Transformation in the other direction (Datalog into SQL) uses the same techniques in principle – two slides on this issue will be discussed at the end of this chapter.

SQL2Datalog (1): Simple 1-Table Query



CREATE VIEW p AS

```
SELECT  A
FROM    t
WHERE   B>0  AND  C=D  AND NOT D=E
```

Direct translation into Datalog rule:

p(X) ← t(X, Y, Z, V, W), Y>0, Z=V, not V=W.

SELECT FROM WHERE

More compact rule by expressing (consequences of) equation using the same variable:

p(X) ← t(X, Y, Z, Z, W), Y>0, not Z=W.

Table t:

SQL-Style: attributes, no positions

A, B, C, D, E

Datalog-Style: positions, no attributes

Correspondence:

1. A, 2. B, 3. C, 4. D, 5. E

X, Y, Z, V, W are variables, not attributes!

SQL2Datalog (1a): Some Background on TRC vs. DRC

CREATE VIEW p AS

```
SELECT  A
FROM    t
WHERE   B>0  AND  C=D  AND NOT D=E
```

TRC: Tuple Relational Calculus

Implicit tuple variable in query:

```
SELECT  x.A
FROM    t  AS  x
WHERE   x.B>0  AND  x.C=x.D  AND NOT x.D=x.E
```

- x bound to t-tuples one after the other
- Attributes are functions „extracting“ components from current value of x.
- Function application expressed in postfix notation

```
p(X)  ←  t(X, Y, Z, V, W), Y>0, Z=V, not V=W.
```

DRC: Domain Relational Calculus

- Variables represent components of the same tuple in t
- „same tuple in t“: expressed by common t-literal

SQL2Datalog (2): Simple Multi-Table Query

New tables:
r(A,B,C)
s(A,B)

```
CREATE VIEW p  AS
    SELECT  A
    FROM    r, s
    WHERE   r.B=s.A
```

Same translation idea:

```
p(X) ← r(X, Y, Z), s(V,W), Y=V.
```

SELECT FROM WHERE

Compactification by multiple variable occurrence and anonymous variables:

```
p(X) ← r(X, Y, _), s(Y,_).
```

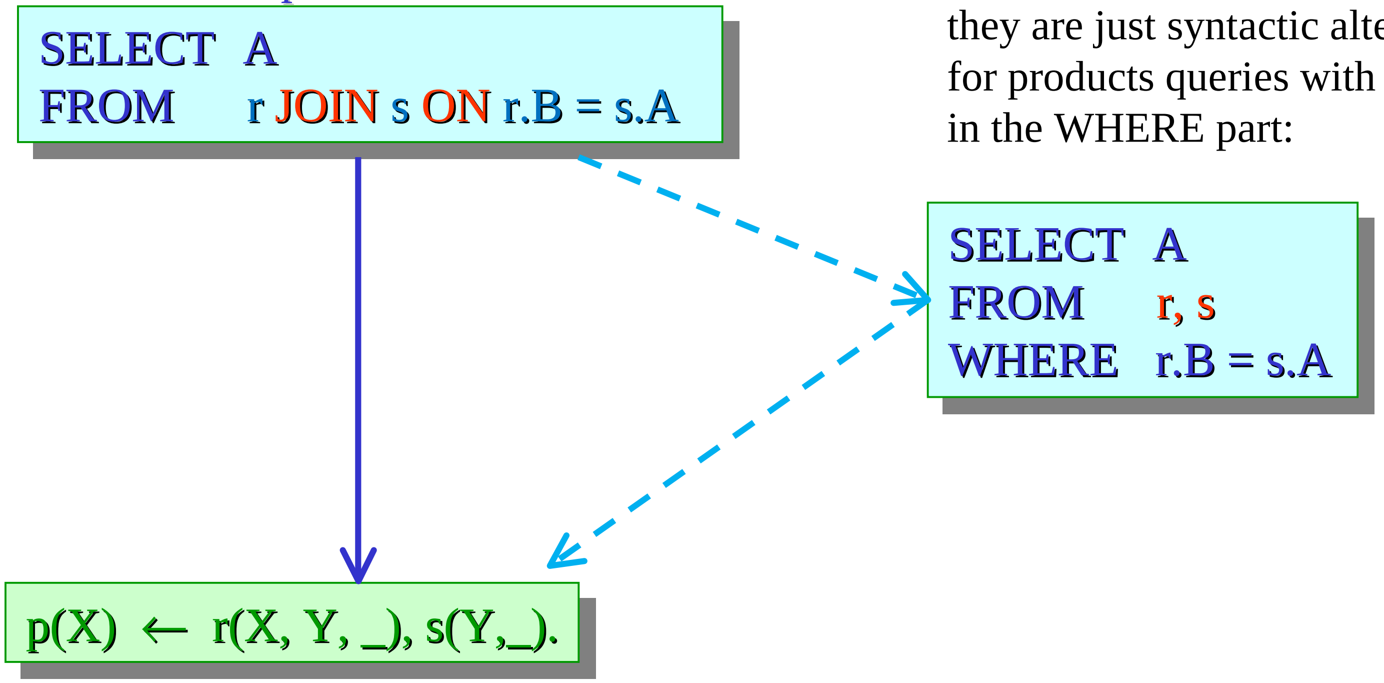
Variant with double occurrence of s and aliasing:

```
CREATE VIEW p  AS
    SELECT  A
    FROM    s AS s1, s  AS s2
    WHERE   s1.B=s.2A
```

```
p(X) ← s(X, Y), s(Y,_).
```

SQL2Datalog (2a): JOIN as „Syntactic Sugar“

JOIN queries are dispensable in SQL, they are just syntactic alternatives for products queries with conditions in the WHERE part:



```
CREATE VIEW p  AS
SELECT  A
FROM      r JOIN s ON r.B = s.A
```

```
SELECT  A
FROM      r, s
WHERE   r.B = s.A
```

$p(X) \leftarrow r(X, Y, \_), s(Y,\_).$

Datalog doesn‘t offer any such special „luxury“ notations: Same translation!

SQL2Datalog (3): Complex UNION-Query

CREATE VIEW p AS

```
SELECT   A
FROM     r
WHERE    B=C
```

UNION

```
SELECT   A
FROM     s
WHERE    B>0
```

Each subquery in a UNION query is turned into a rule of its own, defining the same relation:

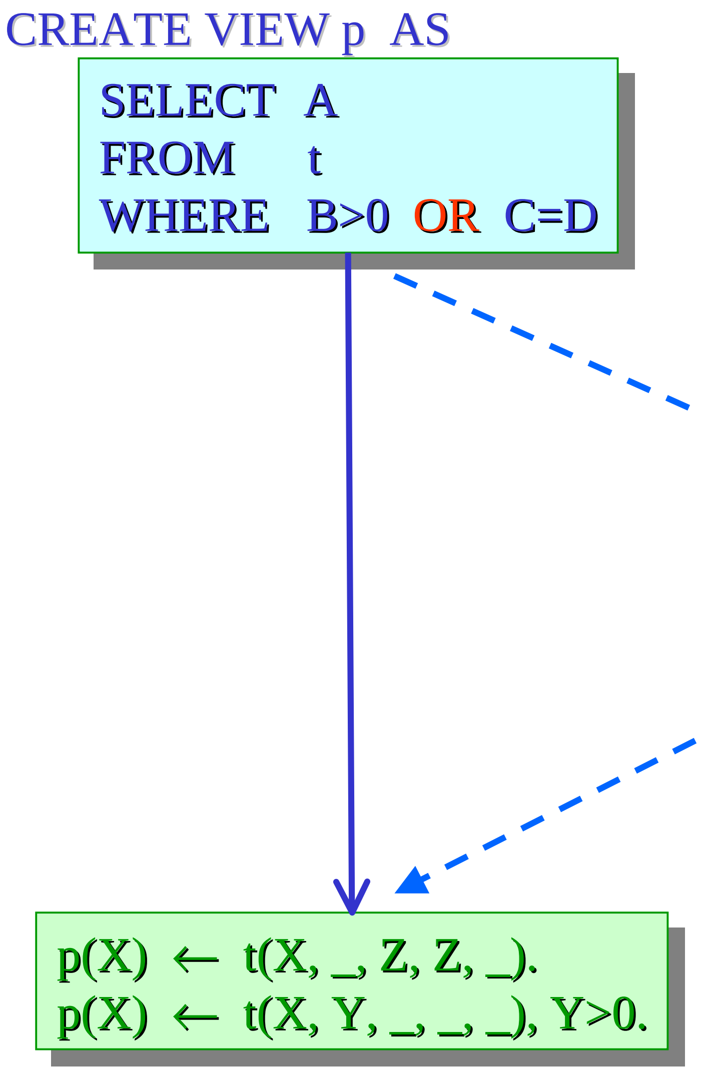
```
p(X)  ←  r(X, Y, Y).
p(X)  ←  s(X, Z), Z>0.
```

Variant: Y instead of Z in 2nd rule
(Ys are different in different rules!)

```
p(X)  ←  r(X, Y, Y).
p(X)  ←  s(X, Y), Y>0.
```

SQL2Datalog (3a): OR in WHERE-part Turned into UNION

OR in WHERE parts is dispensable,
UNION serves the same purpose!

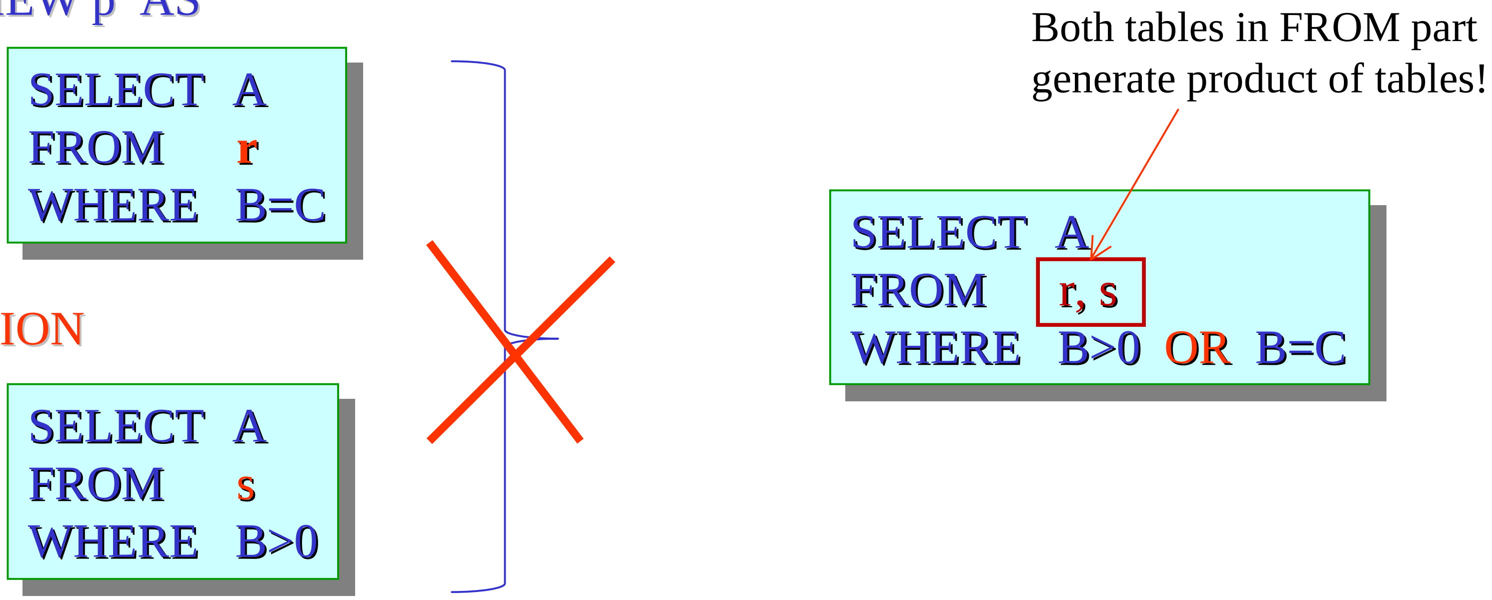


```
CREATE VIEW p  AS
    SELECT  A
    FROM    t
    WHERE   B>0  OR  C=D
```

```
CREATE VIEW p  AS
    SELECT  A
    FROM    t
    WHERE   C=D
UNION
    SELECT  A
    FROM    t
    WHERE   B>0
```

p(X) ← t(X, _, Z, Z, _).
p(X) ← t(X, Y, _, _, _), Y>0.

SQL2Datalog (3b): UNION Cannot Always be Turned into OR in WHERE-part



```
CREATE VIEW p  AS
        SELECT   A
        FROM     r
        WHERE    B=C

   UNION

        SELECT   A
        FROM     s
        WHERE    B>0
```

```
SELECT   A
FROM     r, s
WHERE    B>0  OR  B=C
```

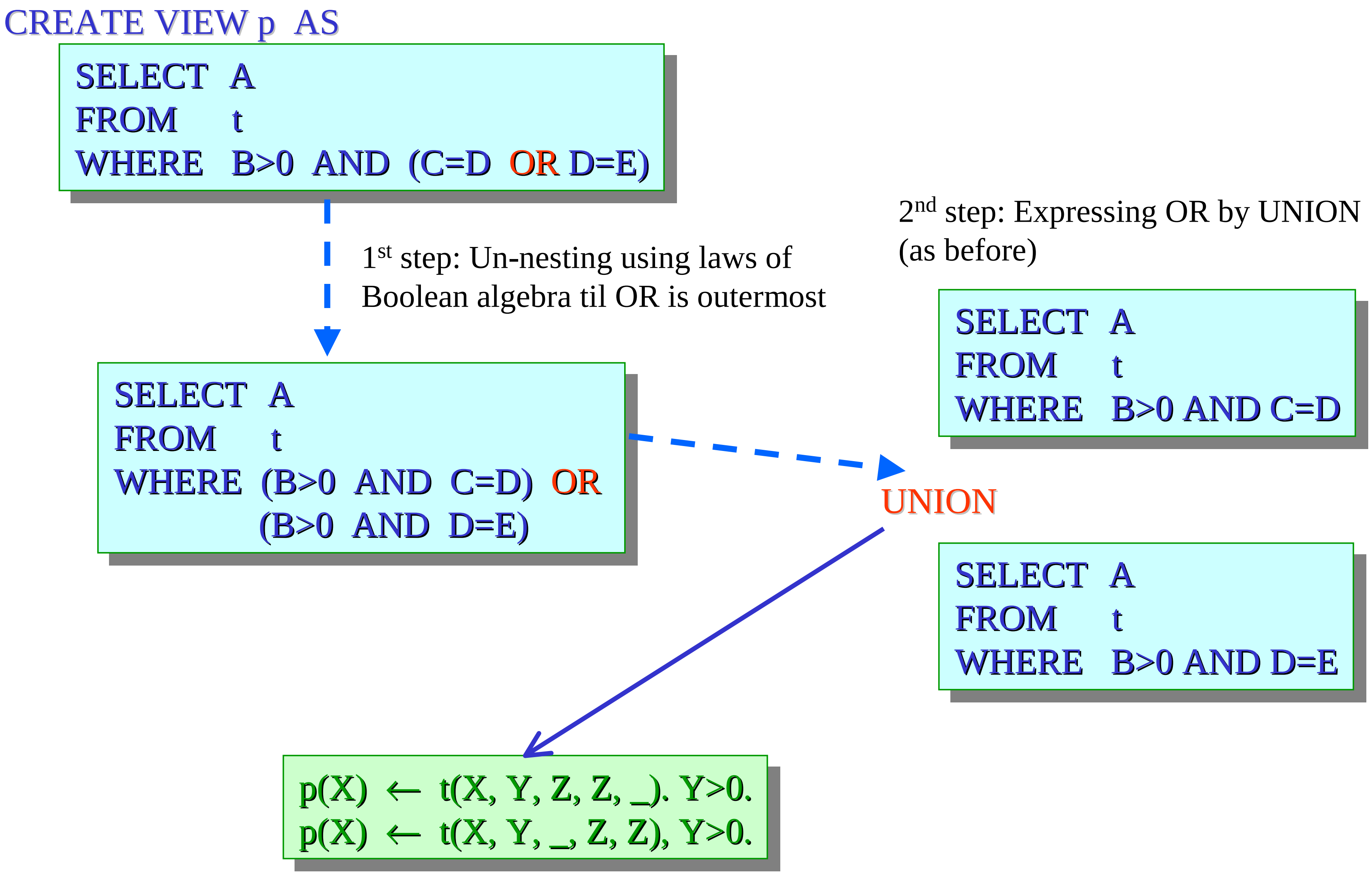
Both tables in FROM part generate product of tables!

UNION is more general than OR as it applies to inhomogeneous input as well (two different tables in sub-queries):

In such a case: No transformation using OR in a single query is possible!

```
p(X)  ←  t(X, _, Z, Z, _).
p(X)  ←  t(X, Y, _, _, _), Y>0.
```

SQL2Datalog (4): Complex Query With Nesting in WHERE-part



CREATE VIEW p AS

```
SELECT  A
FROM      t
WHERE   B>0  AND  (C=D  OR D=E)
```

1st step: Un-nesting using laws of Boolean algebra til OR is outermost

```
SELECT  A
FROM      t
WHERE  (B>0  AND  C=D)  OR
             (B>0  AND  D=E)
```

2nd step: Expressing OR by UNION (as before)

```
SELECT  A
FROM      t
WHERE   B>0 AND C=D
```

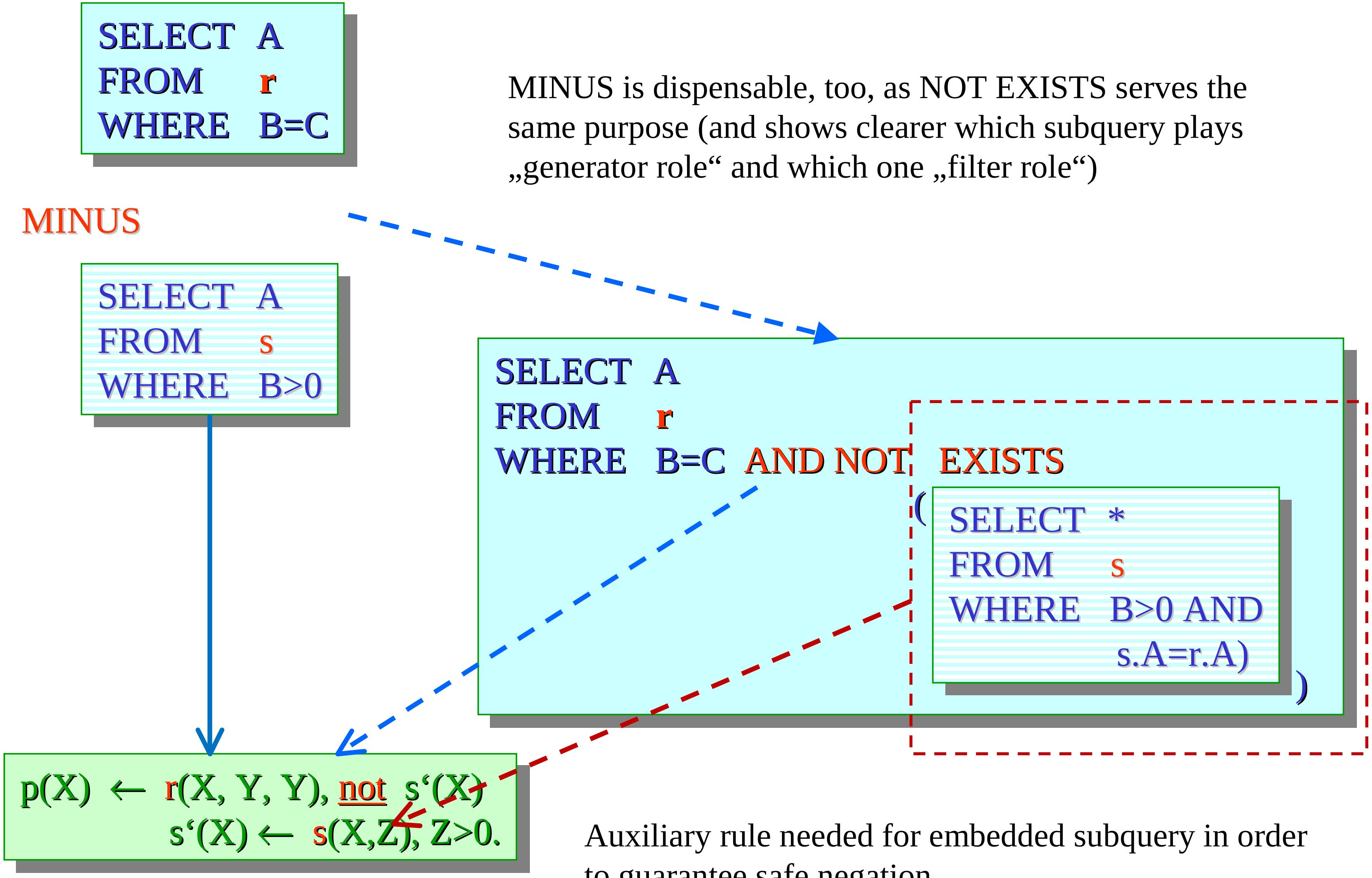
UNION

```
SELECT  A
FROM      t
WHERE   B>0 AND D=E
```

p(X) ← t(X, Y, Z, Z, _). Y>0.
p(X) ← t(X, Y, _, Z, Z), Y>0.

SQL2Datalog (5): MINUS Queries Translated Via NOT EXISTS

CREATE VIEW p AS



```
SELECT  A
FROM    r
WHERE   B=C
```

MINUS

```
SELECT  A
FROM    s
WHERE   B>0
```

MINUS is dispensable, too, as NOT EXISTS serves the same purpose (and shows clearer which subquery plays „generator role“ and which one „filter role“)

```
SELECT  A
FROM    r
WHERE   B=C  AND NOT  EXISTS
                     ( SELECT  *
                       FROM    s
                       WHERE   B>0 AND
                               s.A=r.A)
                                          )
```

```
p(X)  ←  r(X, Y, Y), not  s‘(X)
              s‘(X) ←  s(X,Z), Z>0.
```

Auxiliary rule needed for embedded subquery in order to guarantee safe negation.

SQL2Datalog (6): INTERSECT Queries Translated Via EXISTS

CREATE VIEW p AS

```
SELECT  A
FROM    r
WHERE   B=C
```

INTERSECT

```
SELECT  A
FROM    s
WHERE   B>0
```

```
SELECT  A
FROM    r
WHERE   B=C  AND EXISTS
                        ( SELECT  *
                          FROM    s
                          WHERE   B>0 AND
                                   s.A=r.A)
                                            )
```

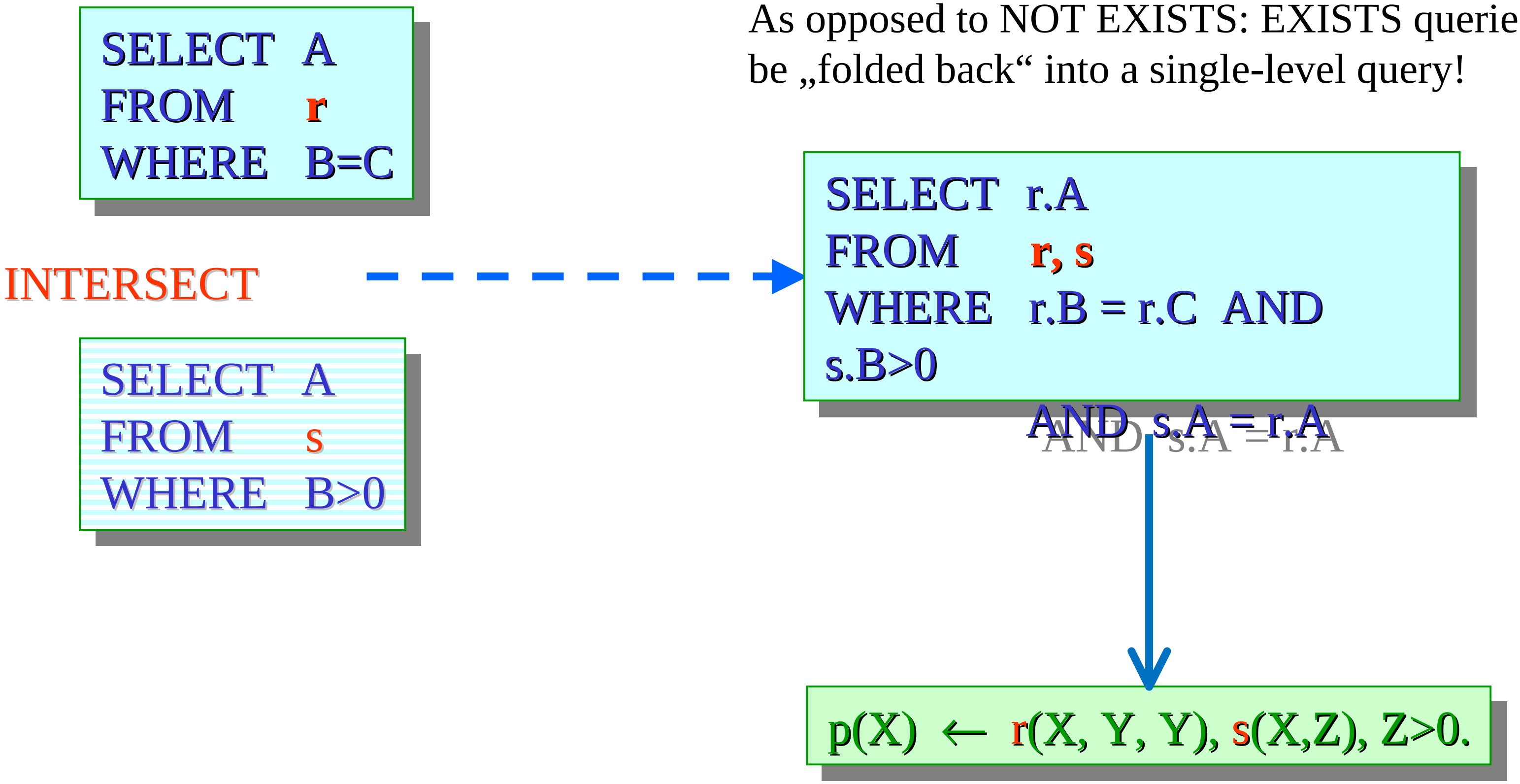
```
p(X) ← r(X, Y, Y), s‘(X).
          s‘(X) ← s(X,Z), Z>0.
```

Auxiliary relation s‘ instead of nesting in Datalog.

SQL2Datalog (6a): INTERSECT Queries Translated Without EXISTS 2

CREATE VIEW p AS

As opposed to NOT EXISTS: EXISTS queries can be „folded back“ into a single-level query!



```
SELECT  A
FROM    r
WHERE   B=C
```

INTERSECT

```
SELECT  A
FROM    s
WHERE   B>0
```

```
SELECT  r.A
FROM    r, s
WHERE   r.B = r.C  AND
s.B>0
AND s.A = r.A
```

$p(X) \leftarrow r(X, Y, Y), s(X,Z), Z>0.$

Corresponding effect in Datalog: No auxiliary rule necessary as not is missing!

SQL2Datalog (7): Recursion

```
CREATE RECURSIVE VIEW  p  AS
    (   (SELECT  *
         FROM     s )
     UNION
        (SELECT  s.A, p.B
         FROM     s, p
         WHERE  s.B=p.A ) )
```

```
p(X,Y)  ← s(X,Y).

p(X,Y)  ← s(X,Z), p(Z,Y).
```

SQL has recursive views, like Datalog having recursive rules.

There are certain restrictions remaining in SQL, though, most notable:

- linear recursion
- stratifiable rule sets (see chapter 3)

Therefore, every recursive view in SQL can be equivalently translated into a set of recursive Datalog rules (but not always vice versa).