Data exchange

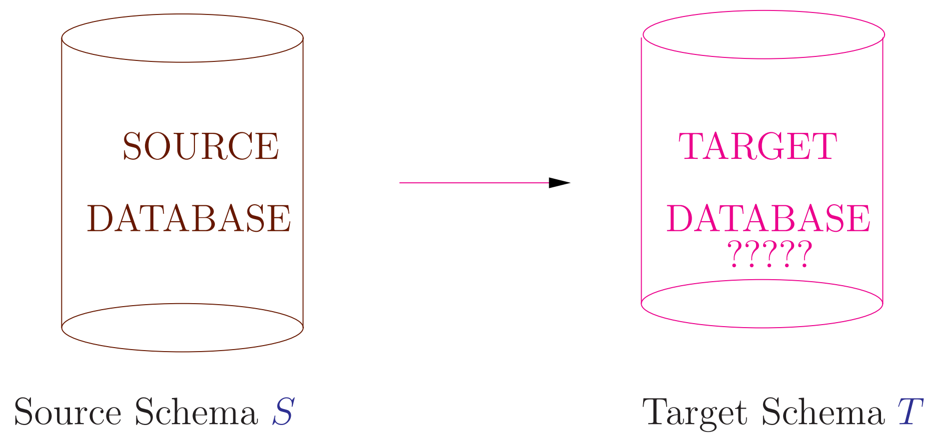
- Source schema, target schema; need to transfer data between them.
- A typical scenario:
  - Two organizations have their legacy databases, schemas cannot be changed.
  - Data from one organization 1 needs to be transfered to data from organization 2.
  - Queries need to be answered against the transferred data.

Data Exchange

Source Schema S

Target Schema T

Data Exchange



Data exchange: an example

- We want to create a target database with the schema

  Flight(city1,city2,aircraft,departure,arrival)
  Served(city,country,population,agency)

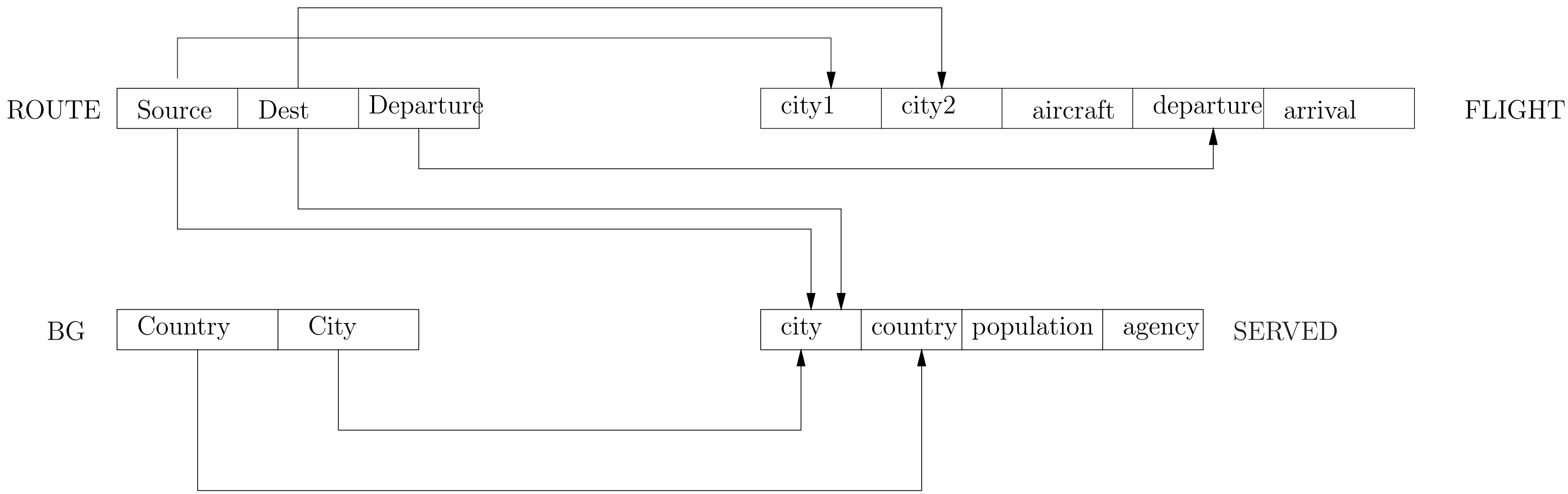
- We don't start from scratch: there is a source database containing relations

  Route(source,destination,,departure)
  BG(country,city)

- We want to transfer data from the source to the target.

Data exchange – relationships between the source and the target

How to specify the relationship?



Relationships between the source and the target

- Formal specification: we have a *relational calculus query* over both the source and the target schema.
- The query is of a restricted form, and can be thought of as a sequence of rules:

Flight(c1, c2, __, dept, __) :– Route(c1, c2, dept)

Served(city, country, __, __) :– Route(city, __, __), BG(city, country)

Served(city, country, __, __) :– Route(__, city, __), BG(city, country)

Data exchange – targets

- Target instances should satisfy the rules.
- What does it mean to satisfy a rule?
- Formally, if we take:

  Flight(c1, c2, __, dept, __) :– Route(c1, c2, dept)

  then it is satisfied by a source S and a target T if the constraint

$$\forall c_1, c_2, d \Big(\textit{Route}(c_1, c_2, d) \rightarrow \exists a_1, a_2 \ \big(\textit{Flight}(c_1, c_2, a_1, d, a_2) \big) \Big)$$

- This constraint is a relational calculus query that evaluates to *true* or *false*

Data exchange – targets

- What happens if there no values for some attributes, e.g. *aircraft*, *arrival*?
- We put in null values or some real values.
- But then we may have multiple solutions!

Data exchange – targets

Source Database:

ROUTE:

Source	Destination	Departure
Edinburgh	Amsterdam	0600
Edinburgh	London	0615
Edinburgh	Frankfurt	0700

BG:

Country	City
UK	London
UK	Edinburgh
NL	Amsterdam
GER	Frankfurt

Look at the rule

Flight(c1, c2, __, dept, __) :– *Route(c1, c2, dept)*

The right hand side is satisfied by

Route(Edinburgh, Amsterdam, 0600)

But what can we put in the target?

Data exchange – targets

Rule: *Flight(c1, c2, _, dept, _) :– Route(c1, c2, dept)*

Satisfied by: Route(Edinburgh, Amsterdam, 0600)

Possible targets:

- Flight(Edinburgh, Amsterdam, $\bot_1$, 0600, $\bot_2$)
- Flight(Edinburgh, Amsterdam, B737, 0600, $\bot$)
- Flight(Edinburgh, Amsterdam, $\bot$, 0600, 0845)
- Flight(Edinburgh, Amsterdam, $\bot$, 0600, $\bot$)
- Flight(Edinburgh, Amsterdam, B737, 0600, 0845)

They all satisfy the constraints!

Which target to choose

- One of them happens to be right:
  - Flight(Edinburgh, Amsterdam, B737, 0600, 0845)
- But in general we do not know this; it looks just as good as
  - Flight(Edinburgh, Amsterdam, 'The Spirit of St Louis', 0600, 1300),

  or
  - Flight(Edinburgh, Amsterdam, F16, 0600, 0620).
- Goal: look for the "most general" solution.
- How to define "most general": can be mapped into any other solution.
- It is not unique either, but the space of solution is greatly reduced.
- In our case Flight(Edinburgh, Amsterdam, $\bot_1$, 0600, $\bot_2$) is most general as it makes no additional assumptions about the nulls.

Universal solutions

- A homomorphism is a mapping h : Nulls $\longrightarrow$ Nulls $\cup$ Constants.
- For example, $h(\bot_1) = B737,\ \ h(\bot_2) = 0845$.
- If we have two solutions T_1 and T_2, then h is a homomorphism from T_1 into T_2 if for each tuple t in T_1, the tuple $h(t)$ is in T_2.
- For example, if we have a tuple

  $$t = \text{Flight(Edinburgh, Amsterdam}, \bot_1, \text{0600}, \bot_2)$$

  then

  $$h(t) = \text{Flight(Edinburgh, Amsterdam, B737, 0600, 0845).}$$

- A solution is universal if there is a homomorphism from it into every other solution.
- (We shall revisit this definition later, to deal with nulls properly.)

Universal solutions: still too many of them

- Take any $n > 0$ and consider the solution with n tuples:

$$\begin{array}{lllll} \text{Flight(Edinburgh,} & \text{Amsterdam,} & \bot_1, & 0600, & \bot_2) \\ \text{Flight(Edinburgh,} & \text{Amsterdam,} & \bot_3, & 0600, & \bot_4) \\ \ldots & & & & \\ \text{Flight(Edinburgh,} & \text{Amsterdam,} & \bot_{2n-1}, & 0600, & \bot_{2n}) \end{array}$$

- It is universal too: take a homomorphism

$$h'(\bot_i) = \begin{cases} \bot_1 & \text{if } i \text{ is odd} \\ \bot_2 & \text{if } i \text{ is even} \end{cases}$$

- It sends this solution into

$$\text{Flight(Edinburgh, Amsterdam, } \bot_1, \text{ 0600, } \bot_2)$$

Universal solutions: cannot be distinguished by conjunctive queries

- There are queries that distinguish large and small universal solutions (e.g., does a relation have at least 2 tuples?)
- But these cannot be distinguished by conjunctive queries
- Because: if $\bot_{i_1}, \ldots, \bot_{i_k}$ witness a conjunctive query, so do $h(\bot_{i_1}), \ldots, h(\bot_{i_k})$ — hence, one tuple suffices
- In general, if we have
  - ○ a homomorphism $h : T \to T'$,
  - ○ a conjunctive query Q
  - ○ a tuple t without nulls such that $t \in Q(T)$
- then $t \in Q(T')$

Universal solutions and conjunctive queries

- If
  - T and T' are two universal solutions
  - Q is a conjunctive query, and
  - t is a tuple without nulls,

  then

  $$t \in Q(T) \quad \Leftrightarrow \quad t \in Q(T')$$

  because we have homomorphisms $T \to T'$ and $T' \to T$.

- Furthermore, if
  - T is a universal solution, and T'' is an arbitrary solution,

  then

  $$t \in Q(T) \quad \Rightarrow \quad t \in Q(T'')$$

Universal solutions and conjunctive queries cont'd

- Now recall what we learned about answering conjunctive queries over databases with nulls:
  - T is a naive table
  - the set of tuples without nulls in $Q(T)$ is precisely certain(Q, T) – certain answers over T
- Hence if T is an arbitrary universal solution

$$\text{certain}(Q, T) \quad = \quad \bigcap\{Q(T') \mid T' \text{ is a solution}\}$$

- $\bigcap\{Q(T') \quad | \quad T' \text{ is a solution}\}$ is the set of certain answers in data exchange under mapping M: certain$_M(Q, S)$. Thus

$$\text{certain}_M(Q, S) \quad = \quad \text{certain}(Q, T)$$

  for every universal solution T for S under M.

Universal solutions cont'd

- To answer conjunctive queries, one needs an arbitrary universal solution.
- We saw some; intuitively, it is better to have:

  Flight(Edinburgh, Amsterdam, $\perp_1$, 0600, $\perp_2$)

  than

  Flight(Edinburgh, Amsterdam, $\perp_1$, 0600, $\perp_2$)
  Flight(Edinburgh, Amsterdam, $\perp_3$, 0600, $\perp_4$)
  ...
  Flight(Edinburgh, Amsterdam, $\perp_{2n-1}$, 0600, $\perp_{2n}$)

- We now define a canonical universal solution.

Canonical universal solution

- Convert each rule into a rule of the form:

$$\psi(x_1, \ldots, x_n,\ z_1, \ldots, z_k) \quad \text{:–}\ \ \varphi(x_1, \ldots, x_n,\ y_1, \ldots, y_m)$$

  (for example,
  Flight(c1, c2, __, dept, __) :– Route(c1, c2, dept)

  becomes

  Flight(x_1, x_2, z_1, x_3, z_2) :– *Route*(x_1, x_2, x_3))

- Evaluate $\varphi(x_1, \ldots, x_n,\ y_1, \ldots, y_m)$ in S.
- For each tuple $(a_1, \ldots, a_n,\ b_1, \ldots, b_m)$ that belongs to the result (i.e.

$$\varphi(a_1, \ldots, a_n,\ b_1, \ldots, b_m) \text{ holds in } S,$$

  do the following:

Canonical universal solution cont'd

- ... do the following:
  - Create new (not previously used) null values $\bot_1, \ldots, \bot_k$
  - Put tuples in target relations so that

$$\psi(a_1, \ldots, a_n,\ \bot_1, \ldots, \bot_k)$$

    holds.

- What is ψ?
- It is normally assumed that ψ is a conjunction of atomic formulae, i.e.

$$R_1(\bar{x}_1, \bar{z}_1) \wedge \ldots \wedge R_l(\bar{x}_l, \bar{z}_l)$$

- Tuples are put in the target to satisfy these formulae

Canonical universal solution cont'd

- Example: no-direct-route airline:

$$\text{Newroute}(x_1, z) \wedge \text{Newroute}(z, x_2) \ \text{:-}\ \text{Oldroute}(x_1, x_2)$$

- If $(a_1, a_2) \in \text{Oldroute}(a_1, a_2)$, then create a new null $\perp$ and put:

  $\text{Newroute}(a_1, \perp)$
  $\text{Newroute}(\perp, a_2)$

  into the target.

- Complexity of finding this solution: polynomial in the size of the source S:

$$O\Big(\sum_{\text{rules } \psi \text{ :- } \varphi} \text{Evaluation of } \varphi \text{ on } S\Big)$$

Canonical universal solution and conjunctive queries

- Canonical solution: $\textsc{CanSol}_M(S)$.
- We know that if Q is a conjunctive query, then $\text{certain}_M(Q, S) = \text{certain}(Q, T)$ for every universal solution T for S under M.
- Hence

$$\text{certain}_M(Q, S) \quad = \quad \text{certain}(Q, \textsc{CanSol}_M(S))$$

- Algorithm for answering Q:
  - Construct $\textsc{CanSol}_M(S)$
  - Apply naive evaluation to Q over $\textsc{CanSol}_M(S)$

Beyond conjunctive queries

- Everything still works the same way for $\sigma, \pi, \bowtie, \cup$ queries of relational algebra. Adding union is harmless.
- Adding difference (i.e. going to the full relational algebra) is not.
- Reason: same as before, can encode validity problem in logic.
- Single rule, saying "copy the source into the target"

$$T(x, y) \ \text{:-} \ S(x, y)$$

- If the source is empty, what can a target be? Anything!
- The meaning of $T(x, y)$:- $S(x, y)$ is

$$\forall x \forall y \ \big(S(x, y) \rightarrow T(x, y)\big)$$

Beyond conjunctive queries cont'd

- Look at $\varphi = \forall x \forall y \, \big(S(x,y) \rightarrow T(x,y)\big)$
- $S(x,y)$ is always false (S is empty), hence $S(x,y) \rightarrow T(x,y)$ is true ($p \rightarrow q$ is $\neg p \vee q$)
- Hence φ is true.
- Even if T is empty, φ is true: universal quantification over the empty set evaluates to true:
  - Remember SQL's `ALL`:

    ```
    SELECT * FROM R
    WHERE R.A > ALL (SELECT S.B FROM S)
    ```

  - The condition is true if `SELECT S.B FROM S` is empty.

Beyond conjunctive queries cont'd

- Thus if S is empty and we have a rule $T(x, y)$:– $S(x, y)$, then all T's are solutions.
- Let Q be a Boolean (yes/no) query. Then

$$\text{certain}_M(Q, S) = \text{true} \quad \Leftrightarrow \quad Q \text{ is valid}$$

- Valid = always true.
- Validity problem in logic: given a logical statement, is it:
  - valid, or
  - valid over finite databases
- Both are undecidable.

Beyond conjunctive queries cont'd

- If we want to answer queries by rewritings, i.e. find a query Q' so that

$$\text{certain}_M(Q, S) \quad = \quad Q'(\textsc{CanSol}_M(S))$$

  then there is no algorithm that can construct Q' from Q!

- Hence a different approach is needed.

Key problem

- Our main problem:

  Solutions are open to adding new facts

- How to close them?
- By applying the CWA (Closed World Assumption) instead of the OWA (Open World Assumption)

More flexible query answering: dealing with incomplete information

- Key issue in dealing with incomplete information:
  - Closed vs Open World Assumption (CWA vs OWA)
- CWA: database is closed to adding new facts except those consistent with one of the incomplete tuples in it.
- OWA opens databases to such facts.
- In data exchange:
  - we move data from source to target;
  - query answering should be based on that data and not on tuples that might be added later.
- Hence in data exchange CWA seems more reasonable.

Solutions under CWA – informally

- Each null introduced in the target must be justified:
  - there must be a constraint $\ldots T(\ldots, z, \ldots) \ldots$:– $\varphi(\ldots)$ with φ satisfied in the source.
- The same justification shouldn't generate multiple nulls:
  - for $T(\ldots, z, \ldots)$:– $\varphi(\bar{a})$ only one new null $\perp$ is generated in the target.
- No unjustified facts about targets should be invented:
  - assume we have $T(x, z)$:– $\varphi(x)$, $T(z', x)$:–$\psi(x)$ and $\varphi(a)$, $\psi(b)$ are true in the source.
  - Then we put $T(a, \perp)$ and $T(\perp', b)$ in the target but not $T(a, \perp), T(\perp, b)$ which would invent a new "fact": a and b are connected by a path of length 2.

How to formalize this – idea

Source-to-target dependencies of the form:

$$\psi_i(\bar{a}, z_1, \ldots, z_j, \ldots, z_k) \ \text{:-}\ \varphi_i(\bar{a}, \bar{b})$$

Justification for a null consists of:

- a dependency (i)
- a witness ($\bar{a}, \bar{b}$) for $\varphi_i(\bar{a}, \bar{b})$
- a position (j) of a null in the head of the rule.

Example

- Rule: *Flight(c1, c2, z1, dept, z2)* :– *Route(c1, c2, dept)*
- Witness: Route(Edinburgh, Amsterdam, 0600)
- This justifies up to two nulls:

$$\text{Flight(Edinburgh, Amsterdam, } \bot_1, \text{ 0600, } \bot_2)$$

or

$$\text{Flight(Edinburgh, Amsterdam, } \bot, \text{ 0600, } \bot)$$

- but not

$$\begin{array}{llll} \text{Flight(Edinburgh, Amsterdam,} & \bot_1, & 0600, & \bot_2) \\ \text{Flight(Edinburgh, Amsterdam,} & \bot_3, & 0600, & \bot_4) \\ \ldots & & & \\ \text{Flight(Edinburgh, Amsterdam,} & \bot_{2n-1}, & 0600, & \bot_{2n}) \end{array}$$

Solutions under the CWA

- Each justification generates a null in $\textsc{CanSol}(S)$
- Hence for each solution T under CWA there is a homomorphism

$$h : \textsc{CanSol}(S) \to T$$

  so that $T = h(\textsc{CanSol}(S))$

- The third requirement rules out tuples like

$$\text{Flight(Edinburgh, Amsterdam, } \perp\text{, 0600, } \perp\text{)}$$

- It invents a new fact: the same null is used twice in a tuple.
  - Not justified by the source and the rules

Solutions under the CWA

- The third requirement implies two facts:
  - There is a homomorphism $h' : T \to \textsc{CanSol}(S)$
  - T contains the core of T
- What is the core?
- Suppose the Route relation has an extra attribute, in addition to source, destination, and departure time: it is flight#
- The same actual flight can have many flight numbers due to "code-sharing" so we might have

  Route(Edinburgh, Amsterdam, 0600, KLM 123)
  Route(Edinburgh, Amsterdam, 0600, AF 456)
  Route(Edinburgh, Amsterdam, 0600, CSA 789)

Solutions under the CWA and cores cont'd

- The canonical solution then is:

  Flight(Edinburgh, Amsterdam, $\bot_1$, 0600, $\bot_2$)
  Flight(Edinburgh, Amsterdam, $\bot_3$, 0600, $\bot_4$)
  Flight(Edinburgh, Amsterdam, $\bot_5$, 0600, $\bot_6$)

- The core collapses it by means of a homomorphism

  $$h(\bot_1) = h(\bot_3) = h(\bot_5) = \bot_1 \quad h(\bot_2) = h(\bot_4) = h(\bot_6) = \bot_2$$

  to

  Flight(Edinburgh, Amsterdam, $\bot_1$, 0600, $\bot_2$)

- Core: A minimal subinstance T of $\textsc{CanSol}(S)$ so that there is a homomorphism $h : \textsc{CanSol}(S) \to T$

Cores and CWA

- Cores are universal solutions too.
  - Advantage: space savings
  - Disadvantage: harder to compute
    - but still in polynomial time
- Basic fact: solutions under the CWA contain the core.
- Hence tuples such as

  $$\text{Flight(Edinburgh, Amsterdam, } \perp\text{, 0600, } \perp\text{)}$$

  are disallowed.

Solutions under the CWA: summary

- There are homomorphisms

$$h : \textsc{CanSol}(S) \to T \qquad h' : T \to \textsc{CanSol}(S)$$

  - so that $T = h(\textsc{CanSol}(S))$
- T contains the core of $\textsc{CanSol}(S)$

Query answering under the CWA

- Given
  - a source S,
  - a set of rules M,
  - a target query Q,

  a tuple t is in

  $$\text{certain}_M^{\mathrm{CWA}}(Q, S)$$

  if it is in $Q(R)$ for every
  - solution T under the CWA, and
  - $R \in \text{POSS}(T)$
- (i.e. no matter which solution we choose and how we interpret the nulls)

Query answering under the CWA – characterization

- Given a source S, a set of rules M, and a target query Q:

$$\text{certain}_M^{\text{CWA}}(Q, S) \quad = \quad \text{certain}(Q, \textsc{CanSol}(S))$$

- That is, to compute the answer to query one needs to:
  - Compute the canonical solution $\textsc{CanSol}(S)$ – which has nulls in it
  - Find certain answers to Q over $\textsc{CanSol}(S)$
- If Q is a conjunctive query, this is exactly what we had before
- Under the CWA, the same evaluation strategy applies to all queries!

Query answering under the CWA cont'd

- Finding certain answers is possible for many classes of queries, e.g. for all relational algebra queries.
- $$\text{Complexity of finding } \text{certain}_M^{\text{CWA}}(Q, S)$$
  $$=$$
  complexity of finding certain answers to a query over a table with nulls
- polynomial time for conjunctive queries
- coNP-complete for relational algebra queries

CWA vs OWA: a comparison

- Recall the problematic case we had before:

$$T(x, y) \coloneq S(x, y)$$

- Possible targets are extensions of the source
- Hence finding certain answers to an arbitrary relational algebra query Q was undecidable.
- Under the CWA:
  - The only solution is a copy of S itself (and hence it is the canonical solution)
  - So certain answers to Q are just $Q(S)$ – i.e. we copy S, and evaluate queries over it, as suggested by the rule.

Data exchange and integrity constraints

- Integrity constraints are often specified over target schemas
- In SQL's data definition language one uses keys and foreign keys most often, but other constraints can be specified too.
- Adding integrity constraints in data exchange is often problematic, as some natural solutions – e.g., the canonical solution – may fail them.
- Plan:
  - review most commonly used database constraints
  - see how they may create problems in data exchange

Functional dependencies and keys

- Functional dependency:

$$X \rightarrow Y$$

where X, Y are sequences of attributes. It holds in a relation R if for every two tuples t_1, t_2 in R:

$$\pi_X(t_1) = \pi_X(t_2) \quad \text{implies} \quad \pi_Y(t_1) = \pi_Y(t_2)$$

- The most important special case: keys
- $K \rightarrow U$, where U is the set of all attributes:

$$\pi_K(t_1) = \pi_K(t_2) \quad \text{implies} \quad t_1 = t_2$$

- That is, a key is a set of attributes that uniquely identify a tuple in a relation.

Inclusion constraints

- Referential integrity constraints: they talk about attributes of one relation but refer to values in another.
- An inclusion dependency

$$R[A_1, \ldots, A_n] \subseteq S[B_1, \ldots, B_n]$$

It holds when

$$\pi_{A_1,\ldots,A_n}(R) \quad \subseteq \quad \pi_{B_1,\ldots,B_n}(S)$$

Foreign keys

- Most often inclusion constraints occur as a part of a foreign key
- Foreign key is a conjunction of a key and an ID:

$$R[A_1, \ldots, A_n] \subseteq S[B_1, \ldots, B_n] \quad \text{and}$$

$$\{B_1, \ldots, B_n\} \rightarrow \text{all attributes of } S$$

- Meaning: we find a key for relation S in relation R.
- Example: Suppose we have relations:
  `Employee(EmplId, Name, Dept, Salary)`
  `ReportsTo(Empl1,Empl2)`.
- We expect both `Empl1` and `Empl2` to be found in `Employee`; hence:
  `ReportsTo[Empl1]` $\subseteq$ `Employee[EmplId]`
  `ReportsTo[Empl2]` $\subseteq$ `Employee[EmplId]`.
- If `EmplId` is a key for `Employee`, then these are foreign keys.

Target constraints cause problems

- The simplest example:
  - Copy source to target
  - Impose a constraint on target not satisfied in the source
- Data exchange setting:
  - $T(x, y)$:– $S(x, y)$ and
  - Constraint: the first attribute is a key
- Instance S:

1	2
1	3

- Every target T must include these tuples and hence violates the key.

Target constraints: more problems

- A common problem: an attempt to repair violations of constraints leads to an sequence of adding tuples.
- Example:
  - Source DeptEmpl(dept_id,manager_name,empl_id)
  - Target
    - Dept(dept_id,manager_id,manager_name),
    - Empl(empl_id,dept_id)
  - Rule Dept(d, z, n), Empl(e, d) :– DeptEmpl(d, n, e)
  - Target constraints:
    - Dept[manager_id] $\subseteq$ Empl[empl_id]
    - Empl[dept_id] $\subseteq$ Dept[dept_id]

Target constraints: more problems cont'd

- Start with (CS, John, 001) in DeptEmpl.
- Put Dept(CS, $\bot_1$, John) and Empl(001, CS) in the target
- Use the first constraint and add a tuple Empl($\bot_1$, $\bot_2$) in the target
- Use the second constraint and put Dept($\bot_2$, $\bot_3$, $\bot_3$') into the target
- Use the first constraint and add a tuple Empl($\bot_3$, $\bot_4$) in the target
- Use the second constraint and put Dept($\bot_4$, $\bot_5$, $\bot_5$') into the target
- this never stops....

Target constraints: avoiding this problem

- Change the target constraints slightly:
  - Target constraints:
    - Dept[dept_id,manager_id] $\subseteq$ Empl[empl_id, dept_id]
    - Empl[dept_id] $\subseteq$ Dept[dept_id]
- Again start with (CS, John, 001) in DeptEmpl.
- Put Dept(CS, $\perp_1$, John) and Empl(001, CS) in the target
- Use the first constraint and add a tuple Empl($\perp_1$, CS)
- Now constraints are satisfied – we have a target instance!
- What's the difference? In our first example constraints are very cyclic causing an infinite loop. There is less cyclicity in the second example. Bottom line: avoid cyclic constraints.