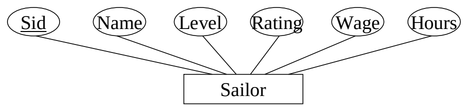
Schema Design and Normal Forms

Entity-Relationship Diagram



Data Redundancy

S	N	L	R	W	H
123-22-3666	Attishoo	48	8	10	40
231-31-5368	Smiley	22	8	10	30
131-24-3650	Smethurst	35	5	7	30
434-26-3751	Guldu	35	5	7	32
612-67-4134	Madayan	35	8	10	40

- Application constraint: all sailors with the same rating have the same wage ($R \rightarrow W$)
- Problems due to data redundancy?

Problems due to Data Redundancy

- Problems due to $R \rightarrow W$:
  - *Update anomaly*: Can we change W in just the first tuple of SNLRWH?
  - *Insertion anomaly*: What if we want to insert an employee and don't know the hourly wage for his rating?
  - *Deletion anomaly*: If we delete all employees with rating 5, we lose the information about the wage for rating 5!
- Solution?

Relation Decomposition

S	N	L	R	W	H
123-22-3666	Attishoo	48	8	10	40
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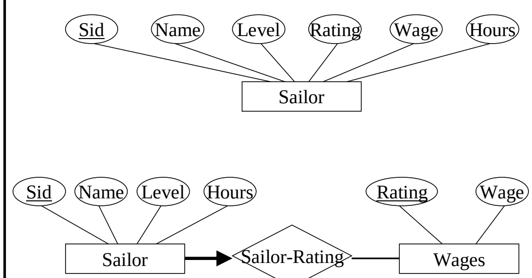
Wages

R	W
8	10
5	7

Problem?

Modifying ER Diagram



Normal Forms

- First question is to ask whether any schema refinement is needed
- If a relation is in a *normal form* (BCNF, 3NF etc.), certain anomalies are avoided/minimized
- If not, decompose relation to normal form
- Role of FDs in detecting redundancy:
  - Consider a relation R with 3 attributes, ABC.
    - No FDs hold: There is no redundancy here.
    - Given A $\rightarrow$B: Several tuples could have the same A value, and if so, they'll all have the same B value!

Outline

- Functional Dependencies
- Decompositions
- Normal Forms

Functional Dependencies (FDs)

- A <u>functional dependency</u> X$\rightarrow$ Y holds over relation R if, for every allowable instance *r* of R:
  - $t1 \in r,\ t2 \in r,\ \pi_X(t1) = \pi_X(t2)$ implies $\pi_Y(t1) = \pi_Y(t2)$
  - i.e., given two tuples in *r*, if the X values agree, then the Y values must also agree. (X and Y are *sets* of attributes.)
- An FD is a statement about *all* allowable relations.
  - Must be identified based on semantics of application.
  - Given some allowable instance *r1* of R, we can check if it violates some FD *f*, but we cannot tell if *f* holds over R!
- K is a candidate key for R means that K$\rightarrow$ R
  - However, K$\rightarrow$R does not require K to be *minimal*!

Reasoning About FDs

- Given some FDs, we can usually infer additional FDs:
  - *ssn* $\rightarrow$ *did*, *did* $\rightarrow$ *lot* implies *ssn* $\rightarrow$ *lot*
- An FD *f* is <u>*implied by*</u> a set of FDs *F* if *f* holds whenever all FDs in *F* hold.
  - F^+ = *closure of F* is the set of all FDs that are implied by *F*.
- Armstrong's Axioms (X, Y, Z are sets of attributes):
  - <u>*Reflexivity*</u>: If X $\subseteq$ Y, then X $\rightarrow$ Y
  - <u>*Augmentation*</u>: If X $\rightarrow$ Y, then XZ $\rightarrow$ YZ for any Z
  - <u>*Transitivity*</u>: If X $\rightarrow$ Y and Y $\rightarrow$ Z, then X $\rightarrow$ Z
- These are *sound* and *complete* inference rules for FDs!

Reasoning About FDs (Contd.)

- Couple of additional rules (that follow from AA):
  - *Union*: If X $\rightarrow$ Y and X $\rightarrow$ Z, then X $\rightarrow$ YZ
  - *Decomposition*: If X $\rightarrow$ YZ, then X $\rightarrow$ Y and X $\rightarrow$ Z
- Example: Contracts(*cid,sid,jid,did,pid,qty,value*), and:
  - C is the key: C $\rightarrow$ CSJDPQV
  - Project purchases each part using single contract: JP $\rightarrow$ C
  - Dept purchases at most one part from a supplier: SD $\rightarrow$ P
- Can you infer SDJ $\rightarrow$ CSJDPQV ?

Reasoning About FDs (Contd.)

- Computing the closure of a set of FDs can be expensive. (Size of closure is exponential in # attrs!)
- Typically, we just want to check if a given FD $X \rightarrow Y$ is in the closure of a set of FDs *F*. An efficient check:
  - Compute <u>*attribute closure*</u> of X (denoted X^+) wrt *F:*
    - Set of all attributes A such that X $\rightarrow$A is in F^+
    - There is a linear time algorithm to compute this.
  - Check if Y is in X^+
- Does F = {A $\rightarrow$ B, B $\rightarrow$ C, C D $\rightarrow$ E } imply A $\rightarrow$ E?
  - i.e, is A $\rightarrow$ E in the closure F^+? Equivalently, is E in A^+ ?
  - Can be used to find keys!!!

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Decomposition of a Relation Scheme

- Suppose that relation R contains attributes *A1 ... An.* A <u>*decomposition*</u> of R consists of replacing R by two or more relations such that:
  - Each new relation scheme contains a subset of the attributes of R (and no attributes that do not appear in R), and
  - Every attribute of R appears as an attribute of one of the new relations.
- Intuitively, decomposing R means we will store instances of the relation schemes produced by the decomposition, instead of instances of R.
- E.g., Can decompose SNLRWH into SNLRH and RW.

Example Decomposition

- Decompositions should be used only when needed.
  - SNLRWH has FDs S $\rightarrow$ SNLRWH and R $\rightarrow$ W
  - Data duplication due to second FD
  - Will make this more precise during the definition of normal forms
- Decompose to SNLRH and RW
  - What should we be careful about?

Problems with Decompositions

- There are three potential problems to consider:
  - Some queries become more expensive.
    - e.g., How much did sailor Joe earn? (salary = W*H)
  - Given instances of the decomposed relations, we may not be able to reconstruct the corresponding instance of the original relation!
    - Fortunately, not in the SNLRWH example.
  - Checking some dependencies may require joining the instances of the decomposed relations.
    - Fortunately, not in the SNLRWH example.
- <u>*Tradeoff*</u>: Must consider these issues vs. redundancy.

Lossless Join Decompositions

- Decomposition of R into X and Y is <u>*lossless-join*</u> w.r.t. a set of FDs F if, for every instance *r* that satisfies F:
  - $\pi_X(r) \bowtie \pi_Y(r) = r$
- It is always true that $r \subseteq \pi_X(r) \bowtie \pi_Y(r)$
  - In general, the other direction does not hold! If it does, the decomposition is lossless-join.
- Definition extended to decomposition into 3 or more relations in a straightforward way.
- *It is essential that all decompositions used to deal with redundancy be lossless! <u>(Avoids Problem (2).)</u>*

More on Lossless Join

- The decomposition of R into X and Y is lossless-join wrt F if and only if the closure of F contains:
  - X $\cap$ Y $\rightarrow$ X, or
  - X $\cap$ Y $\rightarrow$ Y
- In particular, the decomposition of R into UV and R - V is lossless-join if U $\rightarrow$ V holds over R.

A	B	C
1	2	3
4	5	6
7	2	8

A	B
1	2
4	5
7	2

B	C
2	3
5	6
2	8

A	B	C
1	2	3
4	5	6
7	2	8
1	2	8
7	2	3

Dependency Preserving Decomposition

- Consider CSJDPQV, C is key, JP → C and SD → P.
  - Decomposition: CSJDQV and SDP
  - (Is it lossless join?)
  - Problem: Checking JP → C requires a join!
- Dependency preserving decomposition (Intuitive):
  - If R is decomposed into X, Y and Z, and we enforce the FDs that hold on X, on Y and on Z, then all FDs that were given to hold on R must also hold. *(Avoids Problem (3).)*
- *Projection of set of FDs F*: If R is decomposed into X, ... projection of F onto X (denoted F_X) is the set of FDs U → V in F^+ (*closure of F*) such that U, V are in X.

Dependency Preserving Decompositions (Contd.)

- Decomposition of R into X and Y is *dependency preserving* if (F_X union F_Y) $^+$ = F^+
  - i.e., if we consider only dependencies in the closure F^+ that can be checked in X without considering Y, and in Y without considering X, these imply all dependencies in F^+.
- Important to consider F^+, not F, in this definition:
  - ABC, A → B, B → C, C → A, decomposed into AB and BC.
  - Is this dependency preserving? Is C → A preserved?????
- Dependency preserving does not imply lossless join:
  - ABC, A → B, decomposed into AB and BC.
- And vice-versa! (Example?)

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Boyce-Codd Normal Form (BCNF)

- Reln R with FDs *F* is in BCNF if, for all X → A in F^+
  - A ∈ X (called a *trivial* FD), or
  - X contains a key for R.
- In other words, R is in BCNF if the only non-trivial FDs that hold over R are key constraints.
  - No dependency in R that can be predicted using FDs alone.
  - If we are shown two tuples that agree upon the X value, we cannot infer the A value in one tuple from the A value in the other.
  - If example relation is in BCNF, the 2 tuples must be identical (since X is a key).

X	Y	A
x	y1	a
x	y2	?

Decomposition into BCNF

- Consider relation R with FDs F. If X → Y violates BCNF, decompose R into R - Y and XY.
  - Repeated application of this idea will give us a collection of relations that are in BCNF; lossless join decomposition, and guaranteed to terminate.
  - e.g., CSJDPQV, key C, JP → C, SD → P, J → S
  - To deal with SD → P, decompose into SDP, CSJDQV.
  - To deal with J → S, decompose CSJDQV into JS and CJDQV
- In general, several dependencies may cause violation of BCNF. The order in which we ``deal with'' them could lead to very different sets of relations!

BCNF and Dependency Preservation

- In general, there may not be a dependency preserving decomposition into BCNF.
  - e.g., CSZ, CS → Z, Z → C
  - Can't decompose while preserving 1st FD; not in BCNF.
- Similarly, decomposition of CSJDQV into SDP, JS and CJDQV is not dependency preserving (w.r.t. the FDs JP → C, SD → P and J → S).
  - However, it is a lossless join decomposition.

Third Normal Form (3NF)

- Reln R with FDs *F* is in 3NF if, for all X→ A in F^+
  - A ∈ X (called a *trivial* FD), or
  - X contains a key for R, or
  - A is part of some key for R.
- *Minimality* of a key is crucial in third condition above!
- If R is in BCNF, obviously in 3NF.
- If R is in 3NF, some redundancy is possible. It is a compromise, used when BCNF not achievable (e.g., no ``good'' decomp, or performance considerations).
  - *Lossless-join, dependency-preserving decomposition of R into a collection of 3NF relations always possible.*

What Does 3NF Achieve?

- If 3NF violated by X→A, one of the following holds:
  - X is a subset of some key K
    - We store (X, A) pairs redundantly.
  - X is not a proper subset of any key.
    - There is a chain of FDs K→ X →A, which means that we cannot associate an X value with a K value unless we also associate an A value with an X value.
- But: even if reln is in 3NF, these problems could arise.
  - e.g., Reserves SBDC, S → C, C → S is in 3NF, but for each reservation of sailor S, same (S, C) pair is stored.
- Thus, 3NF is indeed a compromise relative to BCNF.

Decomposition into 3NF

- Obviously, the algorithm for lossless join decomp into BCNF can be used to obtain a lossless join decomp into 3NF (typically, can stop earlier).
- To ensure dependency preservation, one idea:
  - If X →Y is not preserved, add relation XY.
  - Problem is that XY may violate 3NF! e.g., consider the addition of CJP to `preserve' JP → C. What if we also have J → C ?
- Refinement: Instead of the given set of FDs F, use a *minimal cover for F*.

Minimal Cover for a Set of FDs

- *Minimal cover* G for a set of FDs F:
  - Closure of F = closure of G.
  - Right hand side of each FD in G is a single attribute.
  - If we modify G by deleting an FD or by deleting attributes from an FD in G, the closure changes.
- Intuitively, every FD in G is needed, and ``*as small as possible*'' in order to get the same closure as F.
- e.g., A → B, ABCD → E, EF → GH, ACDF→ EG has the following minimal cover:
  - A→ B, ACD→ E, EF→ G and EF → H
- M.C. → Lossless-Join, Dep. Pres. Decomp!!! (in book)

Summary of Schema Refinement

- BCNF implies free of redundancies due to FDs
- If a relation is not in BCNF, we can try to decompose it into a collection of BCNF relations.
- If a lossless-join, dependency preserving decomposition into BCNF is not possible, consider 3NF
- Decompositions should be carried out and/or re-examined keeping *performance issues* in mind