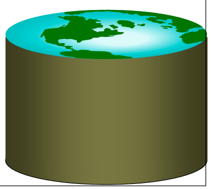
Schema Refinement and Normalization

Nobody realizes that some people expend tremendous energy merely to be normal.
Albert Camus



Functional Dependencies (FDs) (Review)

- **A <u>functional dependency</u> X → Y holds over relation schema R if, for every allowable instance *r* of R:**

  $t1 \in r,\ t2 \in r,\ \pi_X(t1) = \pi_X(t2)$

  implies $\pi_Y(t1) = \pi_Y(t2)$

  (where t1 and t2 are tuples;X and Y are sets of attributes)
- **In other words: X → Y means**

  Given any two tuples in *r*, if the X values are the same, then the Y values must also be the same. (but not vice versa)
- **Read "→" as "determines"**

Reasoning About FDs (Review)

- **Given some FDs, we can usually infer additional FDs:**

  title → studio, star implies *title → studio* and *title → star*

  title → studio and *title → star* implies *title → studio, star*

  title → studio, studio → star implies *title → star*

  But,

  title, star → studio does NOT necessarily imply that *title → studio* or that *star → studio*
- **An FD *f* is *<u>implied by</u>* a set of FDs *F* if *f* holds whenever all FDs in *F* hold.**
- **F^+ = *<u>closure of F</u>* is the set of all FDs that are implied by *F*. (includes "trivial dependencies")**

Rules of Inference (Review)

- **Armstrong's Axioms (X, Y, Z are <u>sets</u> of attributes):**
  - *<u>Reflexivity</u>*: If $X \supseteq Y$, then X → Y
  - *<u>Augmentation</u>*: If X → Y, then XZ → YZ for any Z
  - *<u>Transitivity</u>*: If X → Y and Y → Z, then X → Z
- **These are *sound* and *complete* inference rules for FDs!**
  - i.e., using AA you can compute all the FDs in F+ and only these FDs.
- **Some additional rules (that follow from AA):**
  - *Union*: If X → Y and X → Z, then X → YZ
  - *Decomposition*: If X → YZ, then X → Y and X → Z

Attribute Closure

- **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* → *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*.
    X^+ = Set of all attributes A such that X → A is in F^+
    - X^+ := X
    - Repeat until no change: if there is an fd U → V in *F* such that U is in X^+, then add V to X^+
  - Check if Y is in X^+
  - Approach can also be used to find the keys of a relation.
    - If all attributes of R are in the closure of X then X is a superkey for R.
    - Q: How to check if X is a "candidate key"?

Normal Forms

- **Back to schema refinement…**
- **Q1: is any refinement needed??!**
- **If a relation is in a *normal form* (BCNF, 3NF etc.):**
  - we know that certain problems are avoided/minimized.
  - helps decide whether decomposing a relation is useful.
- **Role of FDs in detecting redundancy:**
  - Consider a relation R with 3 attributes, ABC.
    - No (non-trivial) FDs hold: There is no redundancy here.
    - Given A → B: If A is not a key, then several tuples could have the same A value, and if so, they'll all have the same B value!
- **1st Normal Form – all attributes are atomic**
  - i.e. the relational model
- **1st ⊃2nd (of historical interest) ⊃ 3rd ⊃ Boyce-Codd ⊃ …**

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 is a superkey for R.
- **In other words: *"R is in BCNF if the only non-trivial FDs over R are key constraints."***
- **If R in BCNF, then every field of every tuple records information that cannot be inferred using FDs alone.**
  - Say we know FD X → A holds this example relation:

- Can you guess the value of the missing attribute?
- Yes, so relation is not in BCNF

X	Y	A
x	y1	A
x	y2	?

Decomposition of a Relation Schema

- If a relation is not in a desired normal form, it can be *decomposed* into multiple relations that each are in that normal form.
- Suppose that relation R contains attributes *A1 ... An.* A *decomposition* 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
  - Every attribute of R appears as an attribute of at least one of the new relations.

Example (same as before)

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

Hourly_Emps

- SNLRWH has FDs S → SNLRWH and R → W
- Q: Is this relation in BCNF?

No, The second FD causes a violation;
W values repeatedly associated with R values.

Decomposing a Relation

- Easiest fix is to create a relation RW to store these associations, and to remove W from the main schema:

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

Hourly_Emps2

R	W
8	10
5	7

Wages

- Q: Are both of these relations now in BCNF?
- **Decompositions should be used only when needed.**
  - Q: potential problems of decomposition?

Problems with Decompositions

- There are three potential problems to consider:
  1) May be impossible to reconstruct the original relation! (Lossy Decomposition)
     - Fortunately, not in the SNLRWH example.
  2) Dependency checking may require joins (not Dependency Preserving)
     - Fortunately, not in the SNLRWH example.
  3) Some queries become more expensive.
     - e.g., How much does Guldu earn?

***Tradeoff*: Must consider these issues vs. redundancy.**
(Well, not usually #1)

Lossless Decomposition (example)

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

$\bowtie$

R	W
8	10
5	7

=

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

Lossy Decomposition (example)

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

$A \rightarrow B$; $C \rightarrow B$

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

Lossless Join Decompositions

- **Decomposition of R into X and Y is *lossless* 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! (Avoids Problem #1)***

More on Lossless Decomposition

- The decomposition of R into X and Y is **lossless with respect to F** *if and only if* the closure of F contains:

  $X \cap Y \rightarrow X$, **or**

  $X \cap Y \rightarrow Y$

  i.e. the common attributes form a **superkey** for one side or the other

  in example: decomposing ABC into AB and BC is lossy, because intersection (i.e., "B") is not a key of either resulting relation.
- Useful result: If $W \rightarrow Z$ holds over R and $W \cap Z$ is empty, then decomposition of R into R-Z and WZ is loss-less.

Lossless Decomposition (example)

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

→

A	C
1	3
4	6
7	8

B	C
2	3
5	6
2	8

$A \rightarrow B$; $C \rightarrow B$

A	C
1	3
4	6
7	8

⋈

B	C
2	3
5	6
2	8

=

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

But, now we can't check $A \rightarrow B$ without doing a join!

Dependency Preserving Decomposition

- **Dependency preserving decomposition (Intuitive):**
  - If R is decomposed into X, Y and Z, and we enforce the FDs that hold individually on X, on Y and on Z, then all FDs that were given to hold on R must also hold. *(Avoids Problem #2 on our list.)*
    - Why do we care??
- ***Projection of set of FDs F*: If R is decomposed into X and Y the projection of F on X (denoted F_X) is the set of FDs $U \rightarrow V$ in F^+ (*closure of F, not just F*) such that all of the attributes U, V are in X. *(same holds for Y of course)***

Dependency Preserving Decompositions (Contd.)

- **Decomposition of R into X and Y is *dependency preserving* if $(F_X \cup F_Y)^+ = F^+$**
  - 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^+ in this definition:**
  - ABC, $A \rightarrow B$, $B \rightarrow C$, $C \rightarrow A$, decomposed into AB and BC.
  - Is this dependency preserving? Is $C \rightarrow A$ preserved?????
    - note: F^+ contains $F \cup \{A \rightarrow C, B \rightarrow A, C \rightarrow B\}$, so…
- F_{AB} contains $A \rightarrow B$ and $B \rightarrow A$; F_{BC} contains $B \rightarrow C$ and $C \rightarrow B$
- So, $(F_{AB} \cup F_{BC})^+$ contains $C \rightarrow A$

Decomposition into BCNF

- **Consider relation R with FDs F. If X → Y violates BCNF, decompose R into R - Y and XY (guaranteed to be loss-less).**
  - 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
  - *{contractid, supplierid, projectid,deptid,partid, qty, value}*
  - To deal with SD → P, decompose into SDP, CSJDQV.
  - To deal with J → S, decompose CSJDQV into JS and CJDQV
  - So we end up with: SDP, JS, and CJDQV
- **Note: 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

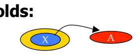
- **In general, there may not be a dependency preserving decomposition into BCNF.**
  - e.g., CSZ, CS → Z, Z → C
  - Can't decompose while preserving 1st FD; not in BCNF.
- **Similarly, decomposition of CSJDQV into SDP, JS and CJDQV is not dependency preserving (w.r.t. the FDs JP → C, SD → P and J → S).**
- ***{contractid, supplierid, projectid,deptid,partid, qty, value}***
  - However, it is a lossless join decomposition.
  - In this case, adding JPC to the collection of relations gives us a dependency preserving decomposition.
    - but JPC tuples are stored only for checking the f.d. (*Redundancy!*)

Third Normal Form (3NF)

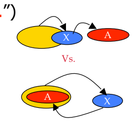
- **Reln R with FDs *F* is in 3NF if, for all X → A in F^+**
  - $A \in X$ (called a *trivial* FD), or
  - X is a superkey of R, or
  - A is part of some candidate key (not superkey!) for R. (sometimes stated as "A is *prime*")
- ***Minimality* of a key is crucial in third condition above!**
- **If R 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 ("partial dependency")



    - We store (X, A) pairs redundantly.
    - e.g. Reserves SBDC (C is for credit card) with key SBD and S → C
  - X is not a proper subset of any key. ("transitive dep.")



    - There is a chain of FDs K → X → A
    - So we can't associate an X value with a K value unless we also associate an A value with an X value (different K's, same X implies same A!)
      - problem with initial SNLRWH example.
- **But: even if R is in 3NF, these problems could arise.**
  - e.g., Reserves SBDC (note: "C" is for credit card here), S → C, C → S is in 3NF (why?)
  - Even so, for each reservation of sailor S, same (S, C) pair is stored.
- **Thus, 3NF is indeed a compromise relative to BCNF.**
  - You have to deal with the partial and transitive dependency issues in your application code!

An Aside: Second Normal Form

- **Like 3NF, but allows transitive dependencies:**
  - Reln R with FDs *F* is in 2NF if, for all X → A in F^+
    - $A \in X$ (called a *trivial* FD), or
    - X is a superkey of R, or
    - X is not part of any candidate key for R. (i.e. "X is *not prime*")
- **There's no reason to use this in practice**
  - And we won't expect you to remember it

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) but does not ensure dependency preservation.**
- **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. implies Lossless-Join, Dep. Pres. Decomp!!!**
  - (in book, p. 627)

Summary of Schema Refinement

- **BCNF: each field contains information that cannot be inferred using only FDs.**
  - ensuring BCNF is a good heuristic.
- **Not in BCNF? Try decomposing into BCNF relations.**
  - Must consider whether all FDs are preserved!
- **Lossless-join, dependency preserving decomposition into BCNF impossible? Consider 3NF.**
  - Same if BCNF decomp is unsuitable for typical queries
  - Decompositions should be carried out and/or re-examined while keeping *performance requirements* in mind.
- **Note: even more restrictive Normal Forms exist (we don't cover them in this course, but some are in the book.)**