Relational Database Design

Functional Dependencies and Normalization for Relational Databases

October 22, 24, 25, 2019

Normalization of Relations

- **Normalization:**
  - The process of decomposing unsatisfactory "bad" relations by breaking up their attributes into smaller relations.
  - Concept built around the concept of normal form.
- **Normal form:**
  - A relation is said to be in a particular normal form iff it satisfies some condition.

Normalization of Relations

- Normal forms provide DB designers with
  - A formal framework for analyzing relation schemas based on their keys and on the FDs among their attributes.
  - A series of tests that can be carried out on individual relation schemas so that the relational db can be normalized to any degree

    Condition using keys and FDs of a relation

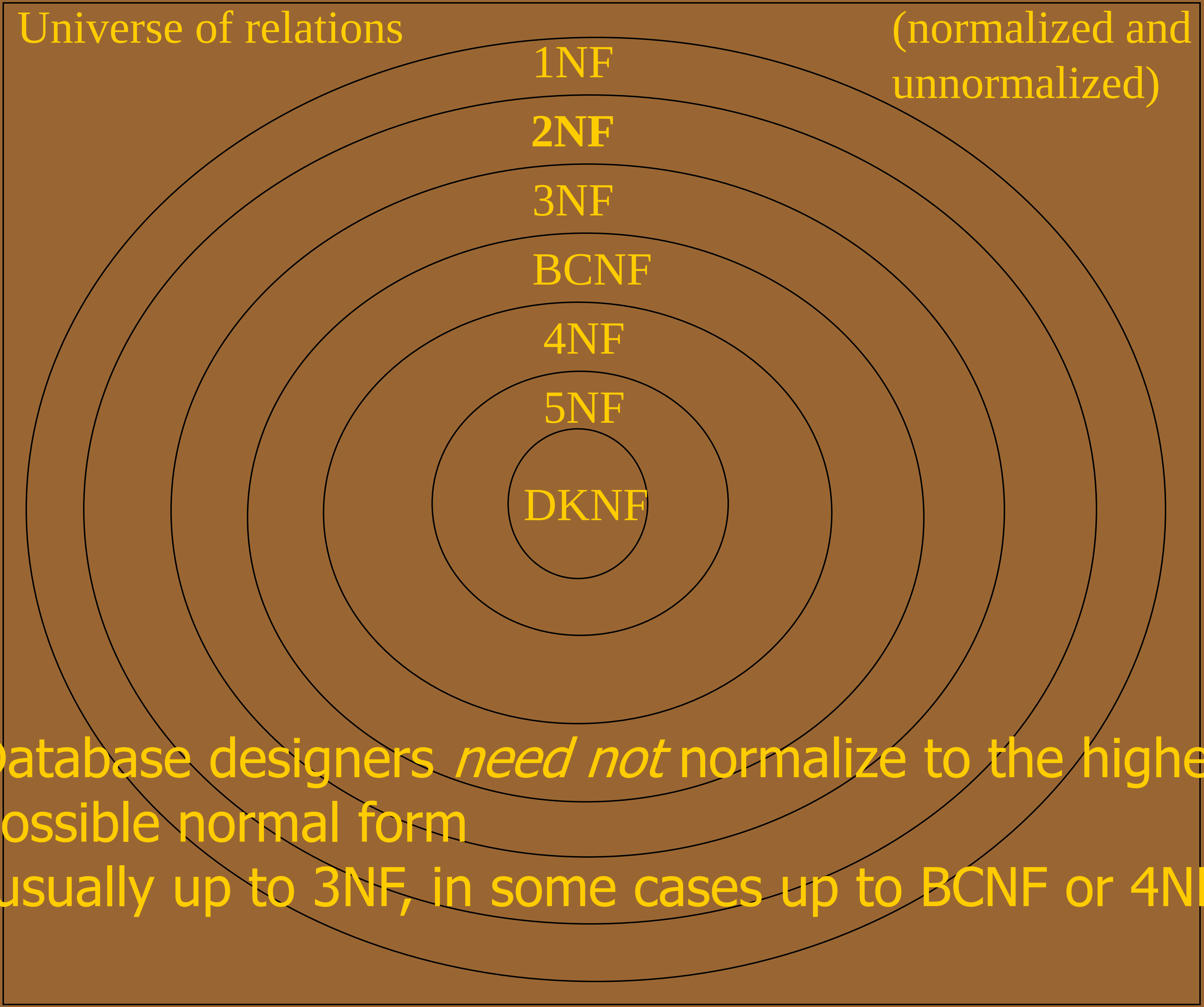
    when a test fails, the relation violating that test must be decomposed into relations that individually meet the normalization tests.

Normalized Design

- Produce a set of relations which:
  - Eliminate redundancy of non-key attributes.
  - Uses foreign keys to express relationships.
  - Has good update properties.
  - Satisfy referential and entity integrity.
- Created through “normalization” process
  - Successive decomposition of relations.
  - Create relations exhibiting certain properties.

Normal Forms

- Normal forms are based on functional dependencies.
- Data normalized to,
  - Minimize redundancies
  - Minimize anomalies
- Relations are decomposed to normalize.
- Concerns with decomposition;
  - Loss-less join or nonadditive join property
  - Dependency preserving property



Database designers *need not* normalize to the highest possible normal form
(usually up to 3NF, in some cases up to BCNF or 4NF)

Normal Forms

- First Normal Form
  - Domain of an attribute must include only **atomic** (simple, indivisible) values
  - Value of any attribute in a tuple must be a single value from domain of that attribute.
  - Now considered part of definition of a relation in relational model.
- 2NF, 3NF, BCNF
  - based on keys and FDs of a relation schema

Normalization of Relations

- 4NF
  - based on keys, multi-valued dependencies : MVDs;
- 5NF
  - based on keys, join dependencies : JDs
- *Additional properties may be needed to ensure a good relational design (lossless join, dependency preservation)*
- **Denormalization:**
  - The process of storing the join of higher normal form relations as a base relation — which is in a lower normal form

Remember: Definitions of Keys

- A **superkey** of a relation schema R = {A1, A2, ..., An} is a set of attributes S *subset-of* R with the property that no two tuples t1 and t2 in any legal relation state r of R will have t1[S] = t2[S]
- A **key** K is a **superkey** with the *additional property* that removal of any attribute from K will cause K not to be a superkey any more.

Remember: Definitions of Keys

- If a relation schema has more than one key, each is called a **candidate** key.
  - One of the candidate keys is *arbitrarily* designated to be the **primary key**, and the others are called **secondary keys**.
- A **Prime attribute** must be a member of *some* candidate key.
- A **Nonprime attribute** is not a prime attribute—that is, it is not a member of any candidate key.

First Normal Form

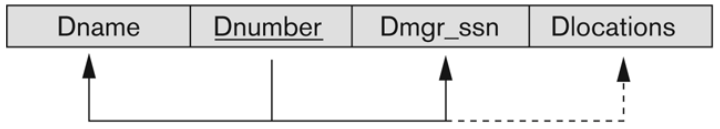
- Disallows
  - composite attributes
  - multivalued attributes
  - **nested relations**; attributes whose values for an *individual tuple* are non-atomic

- Considered to be part of the definition of relation

Normalization into 1NF

(a)

DEPARTMENT



(b)

DEPARTMENT

Dname	<u>Dnumber</u>	Dmgr_ssn	Dlocations
Research	5	333445555	{Bellaire, Sugarland, Houston}
Administration	4	987654321	{Stafford}
Headquarters	1	888665555	{Houston}

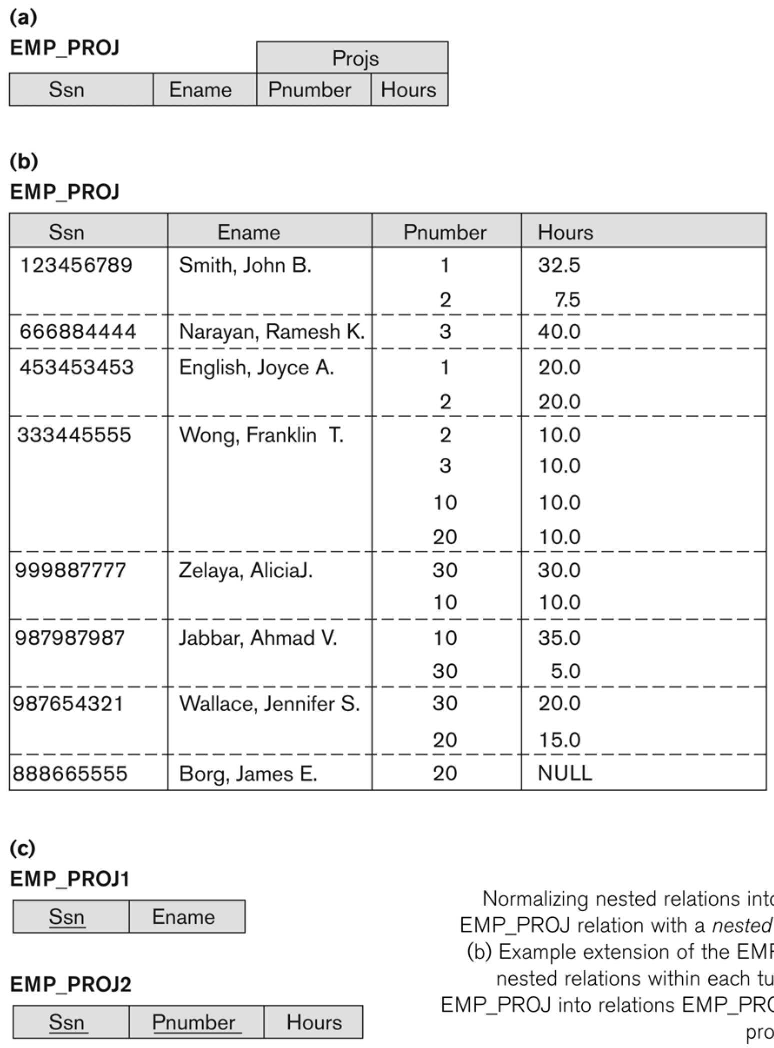
(c)

DEPARTMENT

Dname	<u>Dnumber</u>	Dmgr_ssn	<u>Dlocation</u>
Research	5	333445555	Bellaire
Research	5	333445555	Sugarland
Research	5	333445555	Houston
Administration	4	987654321	Stafford
Headquarters	1	888665555	Houston

Figure 10.8
Normalization into 1NF. (a) A relation schema that is not in 1NF. (b) Example state of relation DEPARTMENT. (c) 1NF version of the same relation with redundancy.

Normalization of nested relations into 1NF



(a)

EMP_PROJ

		Projs	
Ssn	Ename	Pnumber	Hours

(b)

EMP_PROJ

Ssn	Ename	Pnumber	Hours
123456789	Smith, John B.	1	32.5
		2	7.5
666884444	Narayan, Ramesh K.	3	40.0
453453453	English, Joyce A.	1	20.0
		2	20.0
333445555	Wong, Franklin T.	2	10.0
		3	10.0
		10	10.0
		20	10.0
999887777	Zelaya, AliciaJ.	30	30.0
		10	10.0
987987987	Jabbar, Ahmad V.	10	35.0
		30	5.0
987654321	Wallace, Jennifer S.	30	20.0
		20	15.0
888665555	Borg, James E.	20	NULL

(c)

EMP_PROJ1

Ssn	Ename

EMP_PROJ2

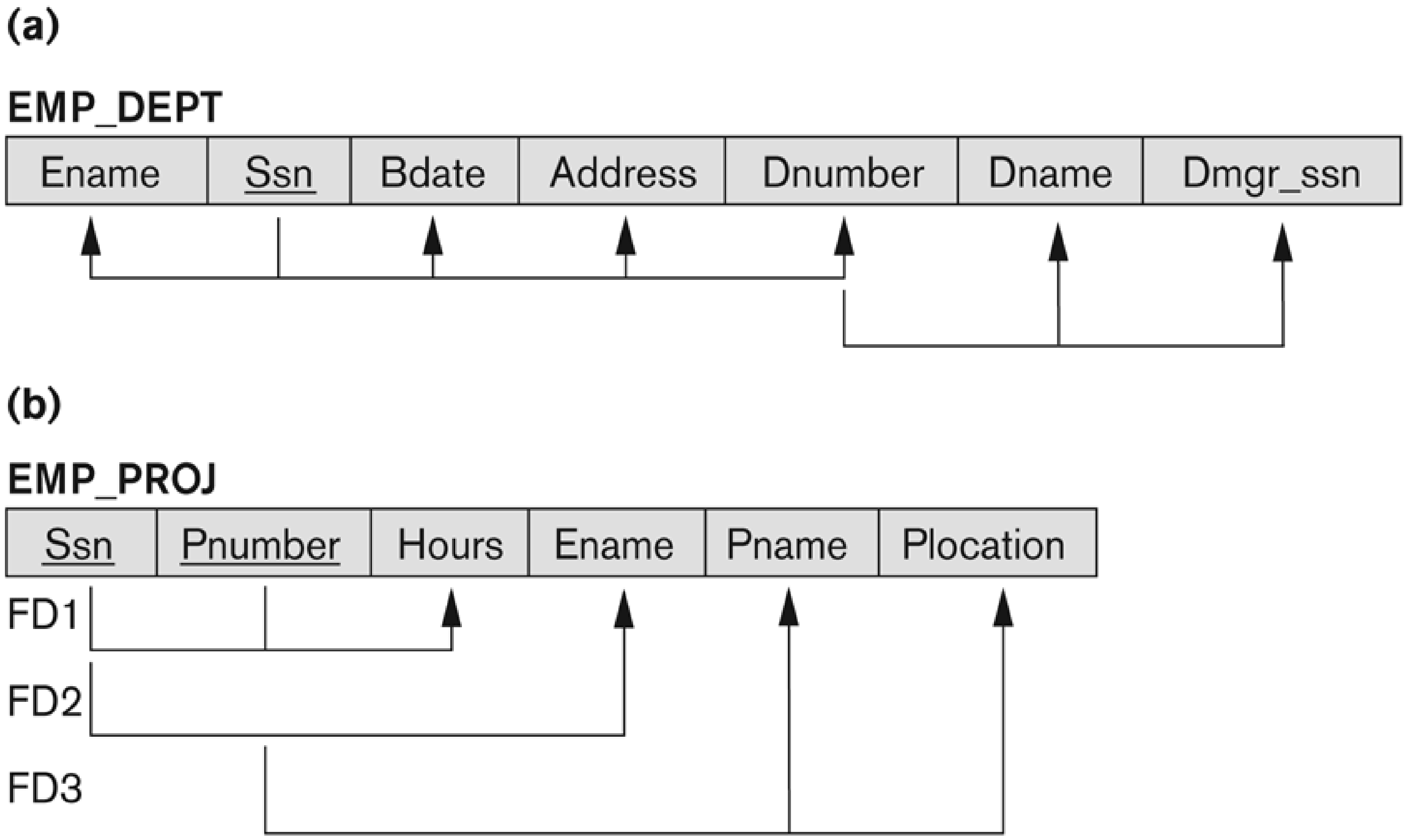
Ssn	Pnumber	Hours

Figure 10.9
Normalizing nested relations into 1NF. (a) Schema of the EMP_PROJ relation with a *nested relation* attribute PROJS. (b) Example extension of the EMP_PROJ relation showing nested relations within each tuple. (c) Decomposition of EMP_PROJ into relations EMP_PROJ1 and EMP_PROJ2 by propagating the primary key.

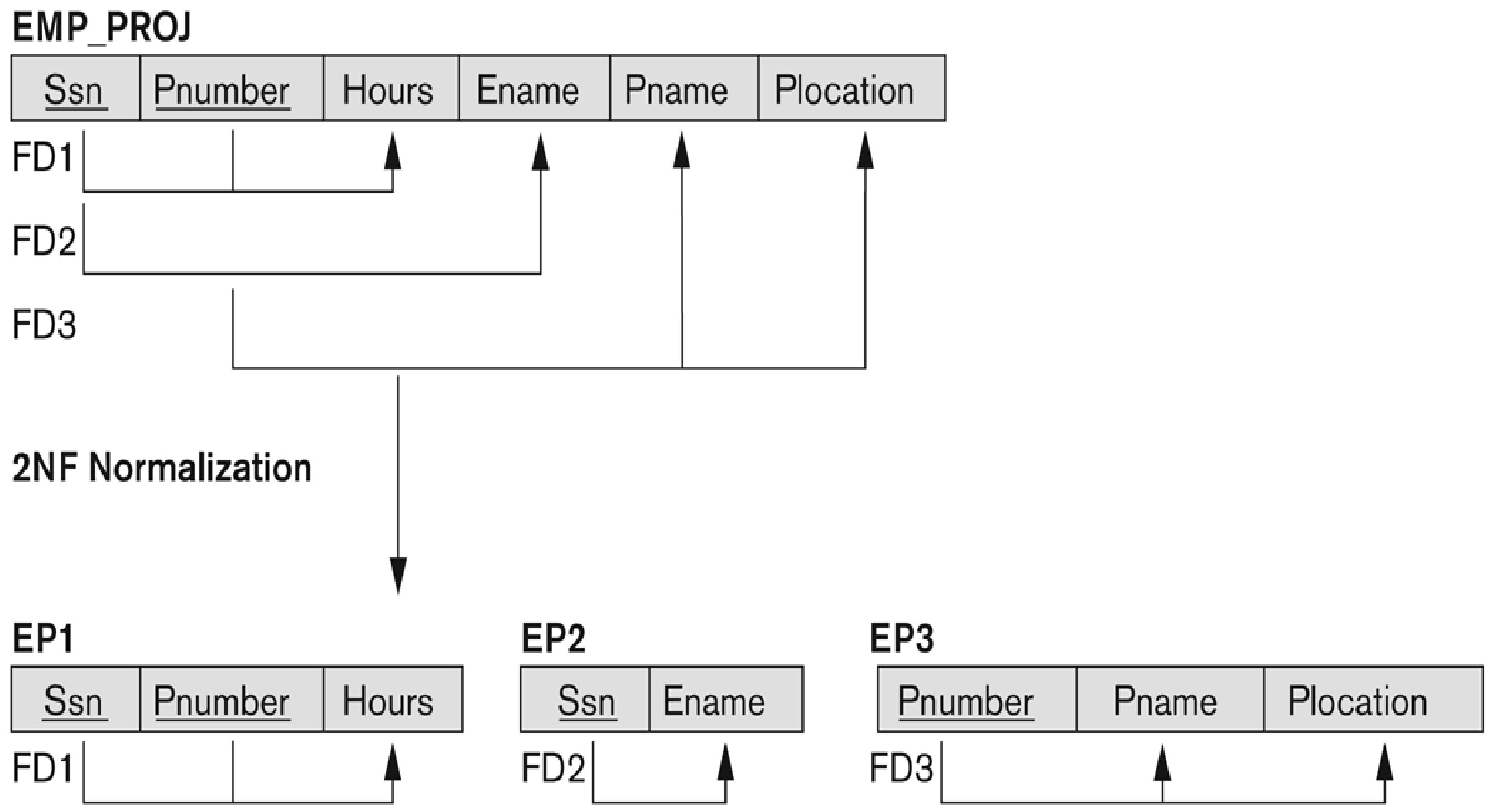
Second Normal Form

- Uses the concepts of **primary key, FDs**.
- A relation schema R is in **second normal form (2NF)** if every non-prime attribute A in R is fully functionally dependent on the primary key.
- R can be decomposed into 2NF relations via the process of 2NF normalization.

Two Relational Schemas Suffering from Update Anomalies

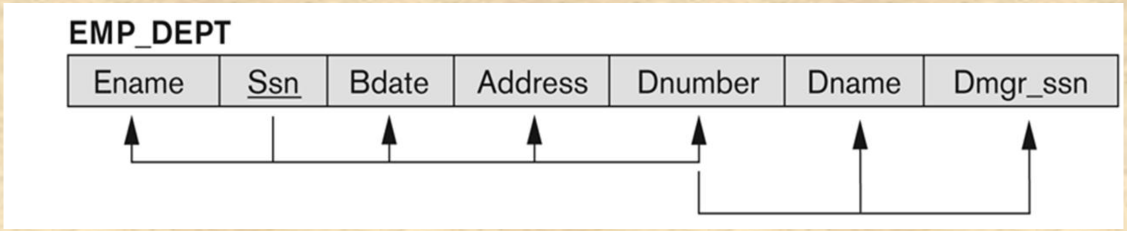


Normalizing into 2NF - Example



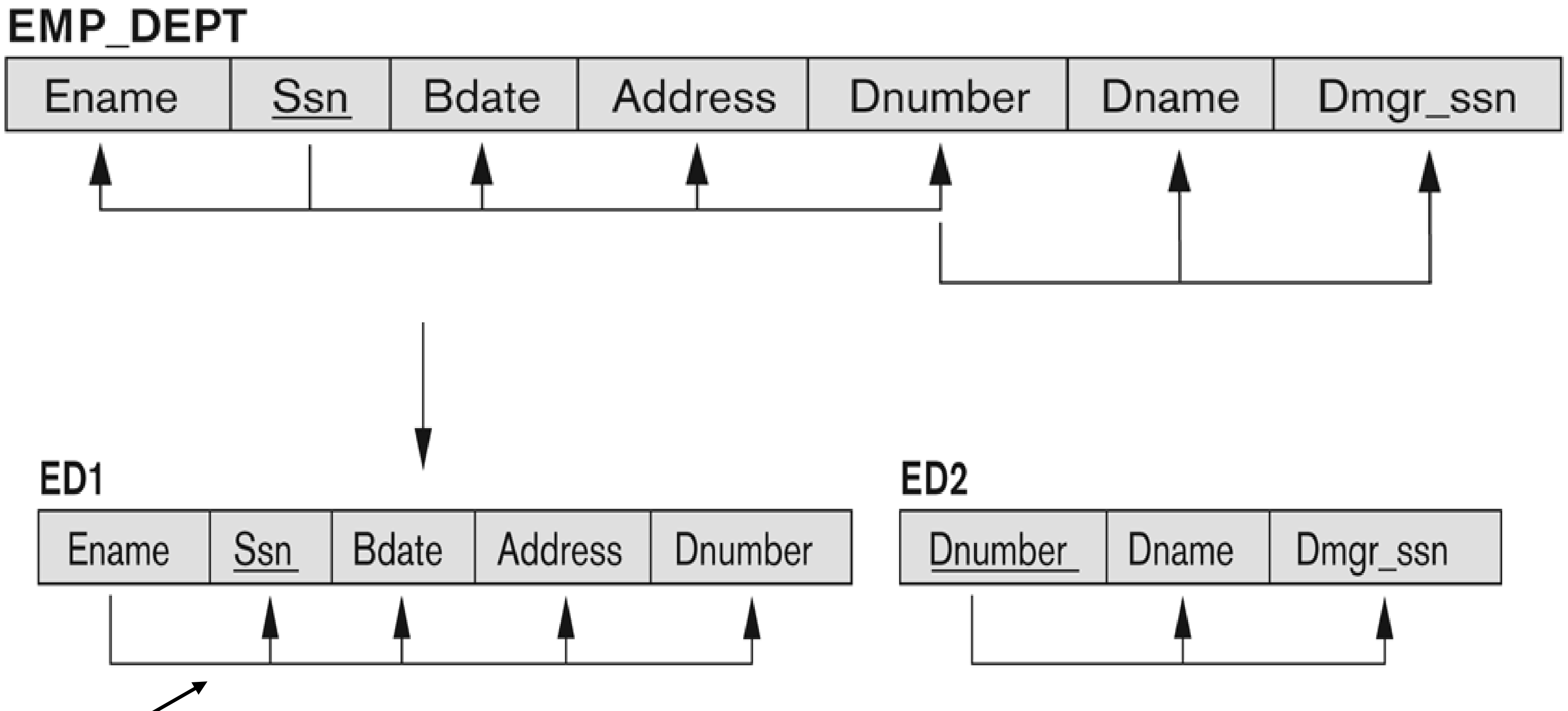
Third Normal Form

- **Transitive functional dependency:**
  - A FD X -> Z that can be derived from two FDs X -> Y and Y -> Z.



- Examples:
  - SSN -> DMGRSSN is a **transitive** FD
    - Since SSN -> DNUMBER and DNUMBER -> DMGRSSN hold
  - SSN -> ENAME is **non-transitive**
    - Since there is no set of attributes X where SSN -> X and X -> ENAME

Normalizing into 3NF - Example



* correction: arrow will come out from Ssn and not from Ename

Third Normal Form

- A relation schema R is in **third normal form (3NF)** if it is in 2NF *and* no non-prime attribute A in R is transitively dependent on the primary key
- R can be decomposed into 3NF relations via the process of 3NF normalization
- NOTE:
  - In X -> Y and Y -> Z, with X as the primary key, we consider this a problem only if Y is not a candidate key.
  - When Y is a candidate key, there is no problem with the transitive dependency .

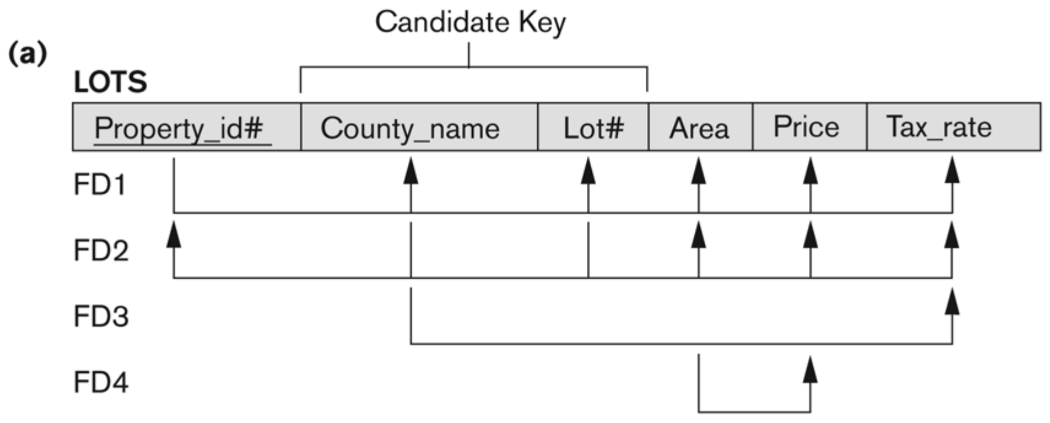
Normal Forms Defined Informally

- 1st normal form
  - All attributes depend on **the key**
- 2nd normal form
  - All attributes depend on **the whole key**
- 3rd normal form
  - All attributes depend on **nothing but the key**

General Normal Form Definitions (For Multiple Keys)

- Previous definitions consider the primary key only
- More general definitions take into account relations with multiple candidate keys
- A relation schema R is in **second normal form (2NF)** if every non-prime attribute A in R is fully functionally dependent on *every* key of R

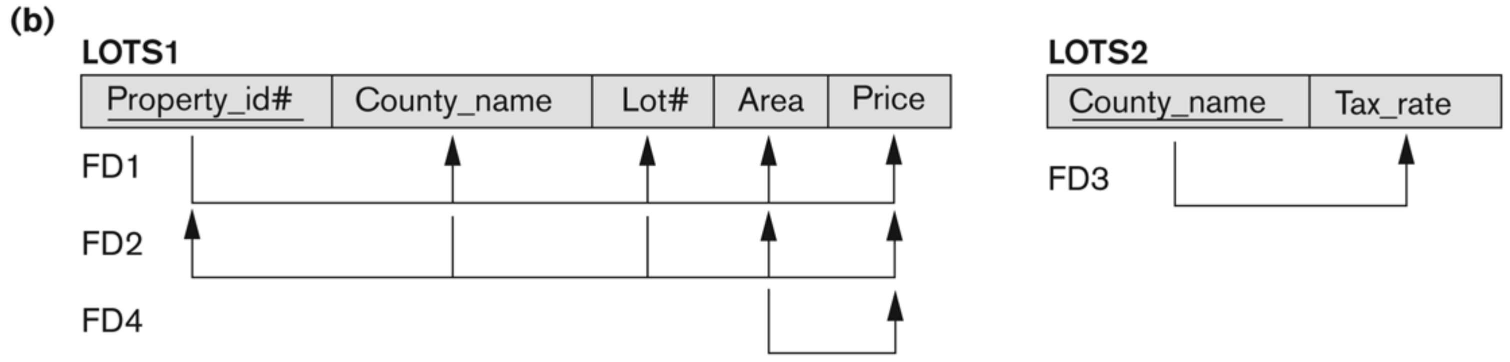
Another Example: 2NF



The LOTS relation with its FDs

FD3 violates the condition of 2NF

Decomposition into the 2NF relations LOTS1 and LOTS2

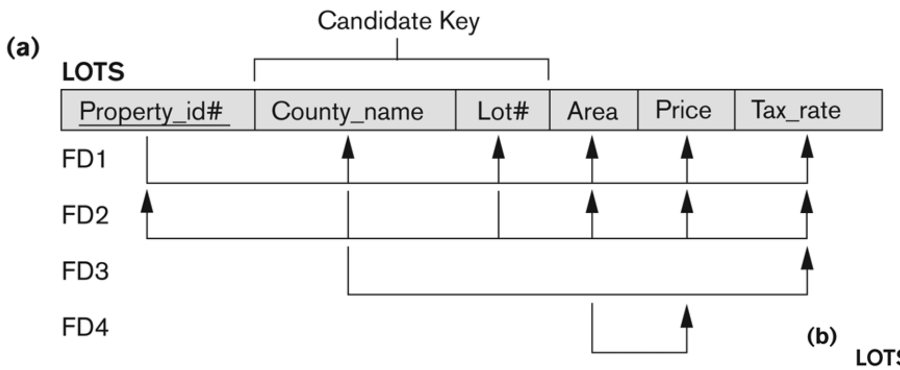


FD4 does not violates the condition of 2NF and is carried over to LOTS1

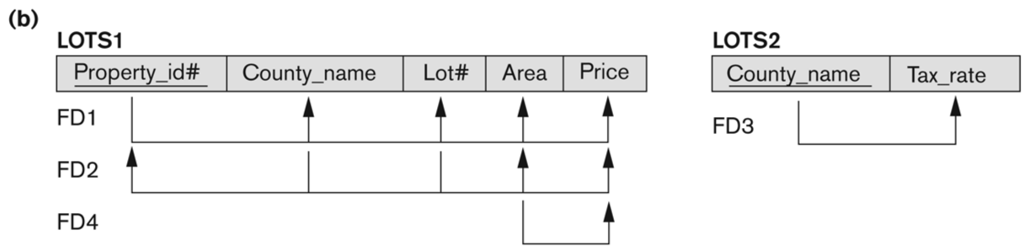
General Normal Form Definitions (For Multiple Keys)

- A relation schema R is in **third normal form (3NF)** if every non-prime attribute of R is
  - Fully functionally dependent on every key of R; and
  - Nontransitively dependent on *every* key of R.

Another Example: 2NF and 3NF

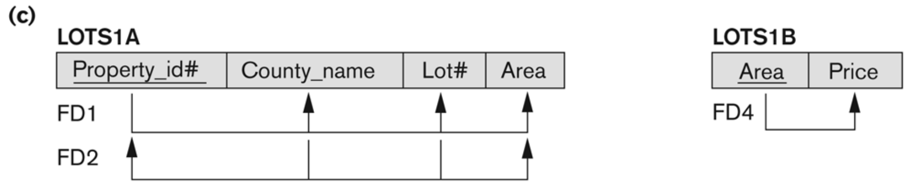


The LOTS relation with its FDs

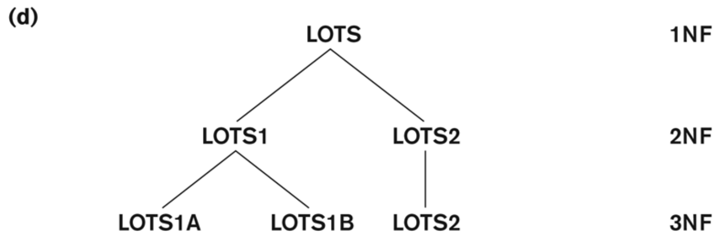


Decomposition into the 2NF relations LOTS1 and LOTS2

FD4 violates 3NF



Decomposing LOTS1 into the 3NF relations and LOTS1A and LOTS1B



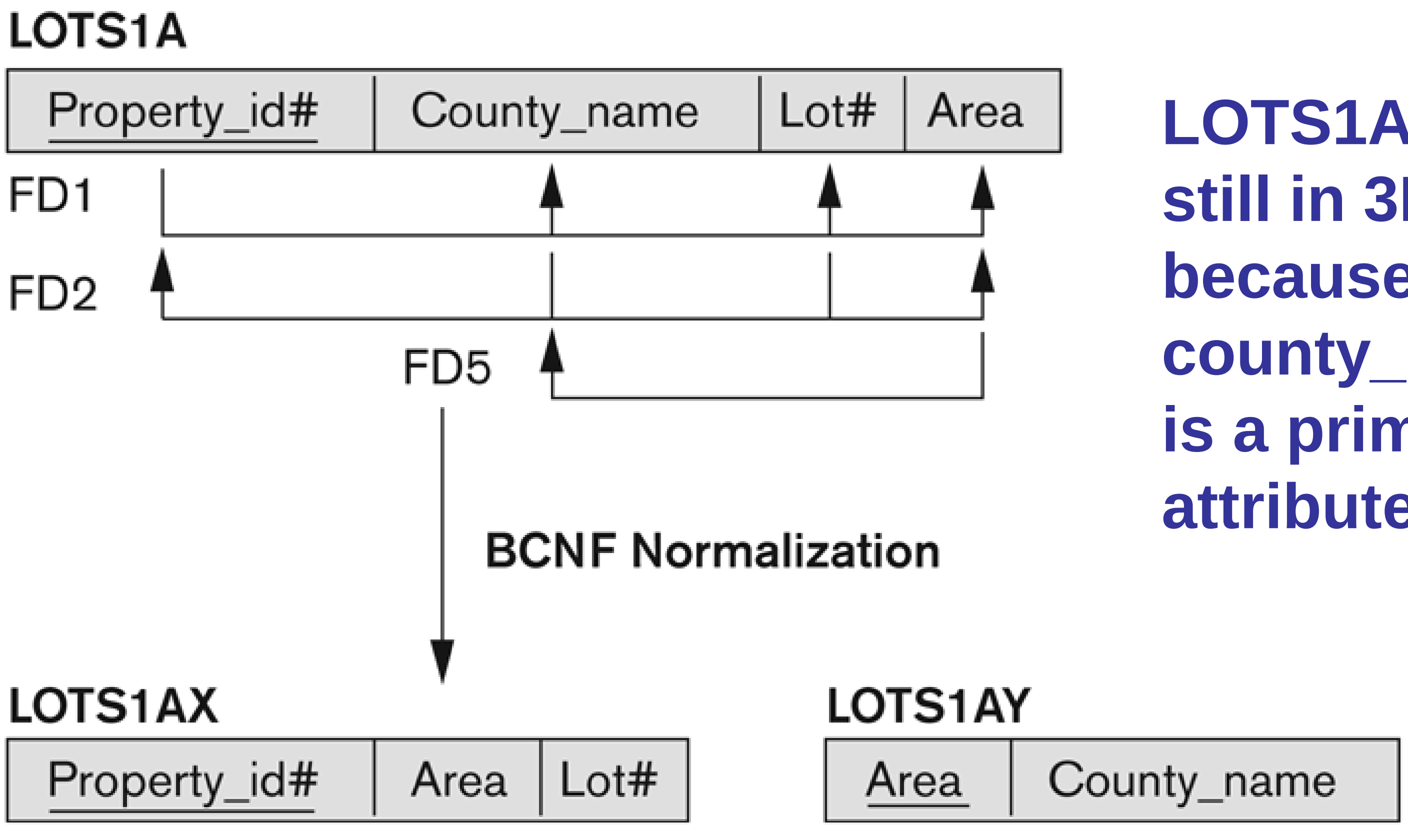
Progressive normalization of lots LOTS1B

Boyce-Codd Normal Form

- An FD is trivial if RHS is subset of LHS.
- A relation schema R is in **Boyce-Codd Normal Form (BCNF)** iff every nontrivial, left-irreducible FD has a candidate key as its determinant.
- Less formal definition
  - A relation is in BCNF iff the only determinants are candidate keys.
- In other words, there will always be arrows out of candidate keys.

BCNF- Example

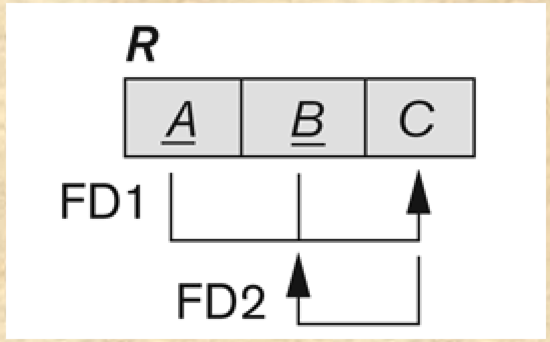
LOTS1A with additional FD (FD5)



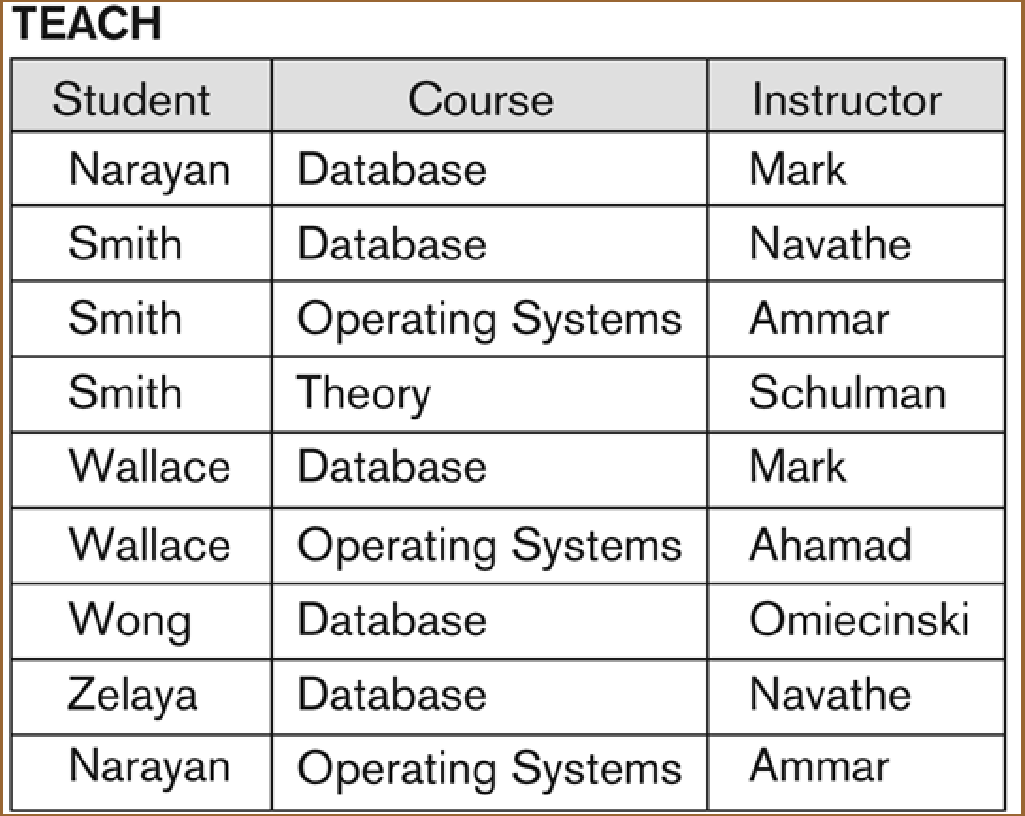
LOTS1A is still in 3NF because county_name is a prime attribute

Boyce-Codd Normal Form

- Each normal form is strictly stronger than the previous one
  - Every 2NF relation is in 1NF
  - Every 3NF relation is in 2NF
  - Every BCNF relation is in 3NF
- There exist relations that are in 3NF but not in BCNF

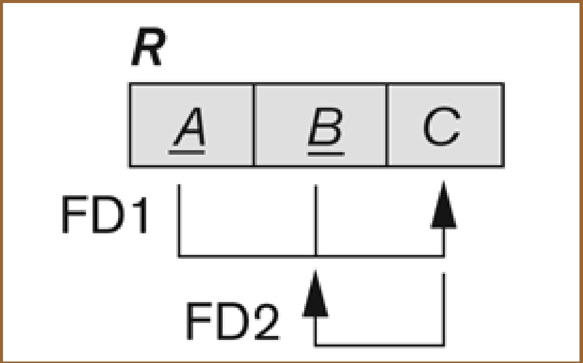


BCNF - Another Example


TEACH

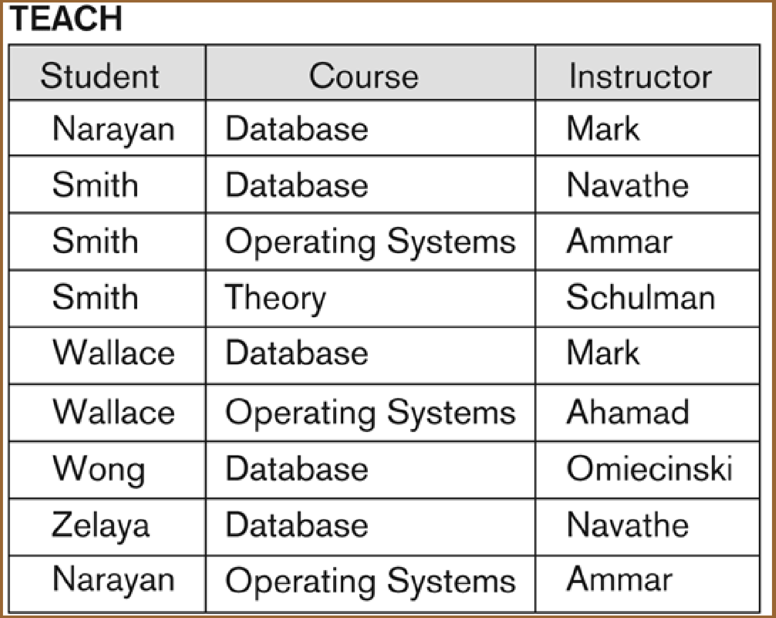
Student	Course	Instructor
Narayan	Database	Mark
Smith	Database	Navathe
Smith	Operating Systems	Ammar
Smith	Theory	Schulman
Wallace	Database	Mark
Wallace	Operating Systems	Ahamad
Wong	Database	Omiecinski
Zelaya	Database	Navathe
Narayan	Operating Systems	Ammar

A relation that is in 3NF but not in BCNF



- Two FDs exist in the relation TEACH:
  - fd1: { student, course} -> instructor
  - fd2: instructor -> course
- {student, course} : candidate key

BCNF - Another Example



TEACH

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Wong	Database	Omiecinski
Zelaya	Database	Navathe
Narayan	Operating Systems	Ammar

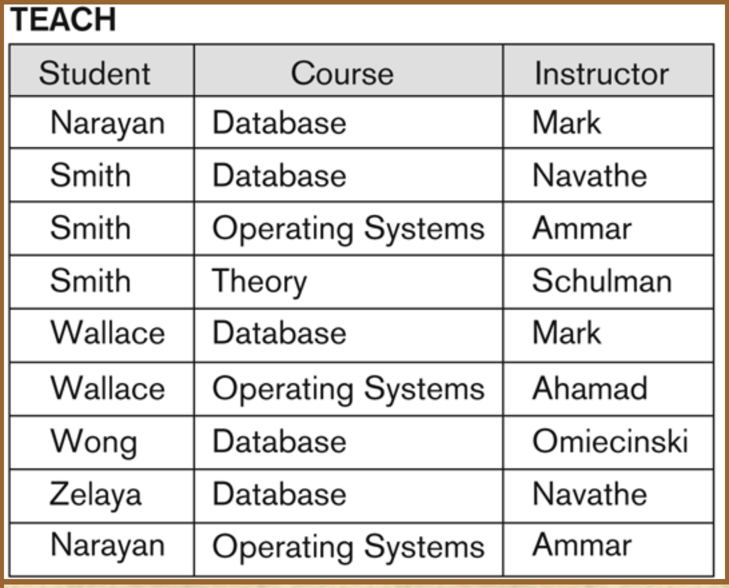
fd1: { student, course} -> instructor

fd2: instructor -> course

Which decomposition should be followed ?

- Three possible decompositions for this relation
  - {student, instructor} and {student, course}
  - {course, instructor } and {course, student}
  - {instructor, course } and {instructor, student}

BCNF - Another Example



TEACH

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Smith	Theory	Schulman
Wallace	Database	Mark
Wallace	Operating Systems	Ahamad
Wong	Database	Omiecinski
Zelaya	Database	Navathe
Narayan	Operating Systems	Ammar

fd1: { student, course} -> instructor
fd2: instructor -> course

See that all three decompositions will lose fd1 and only the 3rd decomposition satisfies lossless join property

- Remember: we have to settle for sacrificing the functional dependency preservation. But we cannot sacrifice lossless join property

- Three possible decompositions for this relation
  - {student, instructor} and {student, course}
  - {course, instructor } and {course, student}
  - **{instructor, course } and {instructor, student}**

What's really going on?

- The original design, consisting of single relation LOTS is clearly bad.
- It is unlikely that any competent db designer would ever seriously propose it, even if he/she had no exposure to the ideas of BCNF and so on.
- Common sense would tell the designer that which design is better.
  - What do we mean by "common sense"?
  - What are the principles inside the designer's brain that the designer is applying when he/she chooses a particular design?
  - **Ans:** principles of FDs and BCNF

What’s really going on?

- In fact, the concepts presented here are nothing more nor less than formalized common sense.
- The whole point of normalization theory is to try to identify such commonsense principles and formalize them. (not an easy thing to do…)
- Which is But if it can be done, then we can mechanize those principles (through writing a program).
- Critics of normalization usually miss this point. They claim, quite rightly, that the ideas are all basically common sense,
- But they typically do not realize that it is a significant achievement to state what “common sense” means in a precise and formal way.

Designing a Set of Relations

- **Goals:**
  - Lossless join/nonadditive property (a must)
  - Dependency preservation property

- Algorithms are available
  - To tests for general losslessness.
  - To decompose a relation into BCNF components by sacrificing the dependency preservation.

Designing a Set of Relations

- **The Approach of Relational Synthesis (Bottom-up Design):**
  - Assumes that all possible functional dependencies are known.
  - First constructs a minimal set of FDs.
  - Then applies algorithms that construct a target set of 3NF or BCNF relations.
  - Additional criteria may be needed to ensure the *set of relations* in a relational database are satisfactory.

Multivalued Dependencies

- In many cases relations have constraints that can not be specified as FDs.
- Multivalued dependencies (MVDs) are a consequence of 1NF, which disallows an attribute in a tuple to have a set of values.
- A multivalued dependency occurs when a determinant determines a particular set of values
- Consider the problem when we have two/more multivalued independent attributes in the same relation schema ….

Multivalued Dependencies

EMP

ENAME	PNAME	DNAME
Smith	X	John
Smith	Y	Anna
Smith	X	Anna
Smith	Y	John

The EMP relation with two MVDs:

ENAME —>> PNAME and

ENAME —>> DNAME.

This constraint is specified as a multivalued dependency on the EMP

- An employee may work on several projects and may have several dependents.
- The employee's projects and dependents are independent of one another.
- Constraint: a separate tuple to represent every combination of an employee's dependent and an employee's project.
- Need to repeat every value of one of the attributes with every value of the other attribute

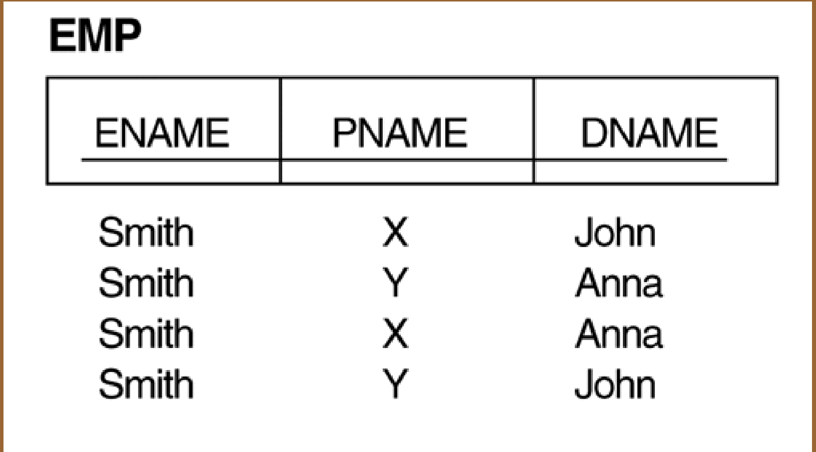
Multivalued Dependencies

- An MVD A —>> B in R is a trivial MVD if
  - B is a subset of A, or AuB = R.
- A trivial MVD will hold in any relation state r of R
  - It is called trivial because it does not specify any significant or meaningful constraint on R.
- If we have nontrivial MVD in a relation, we may have to repeat values redundantly in the tuples
  - This redundancy is clearly undesirable.

EMP schema is in BCNF because no functional dependencies hold in EMP

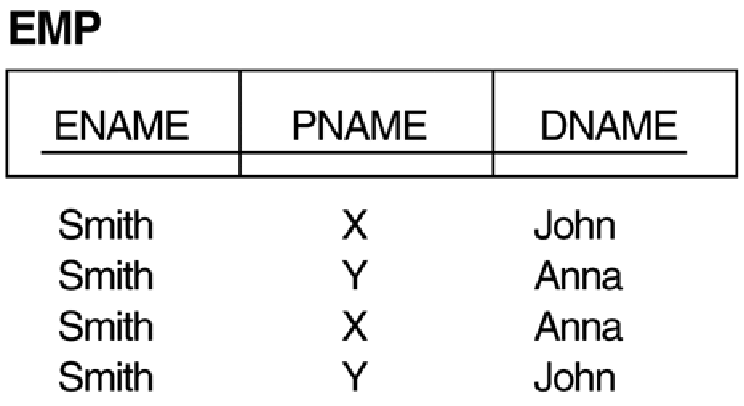
Need to define a fourth normal form

Relations containing nontrivial MVDs tend to be all - key relations


EMP

ENAME	PNAME	DNAME
Smith	X	John
Smith	Y	Anna
Smith	X	Anna
Smith	Y	John

Multivalued Dependencies



EMP

ENAME	PNAME	DNAME
Smith	X	John
Smith	Y	Anna
Smith	X	Anna
Smith	Y	John

The EMP relation with two MVDs:

ENAME —>> PNAME and

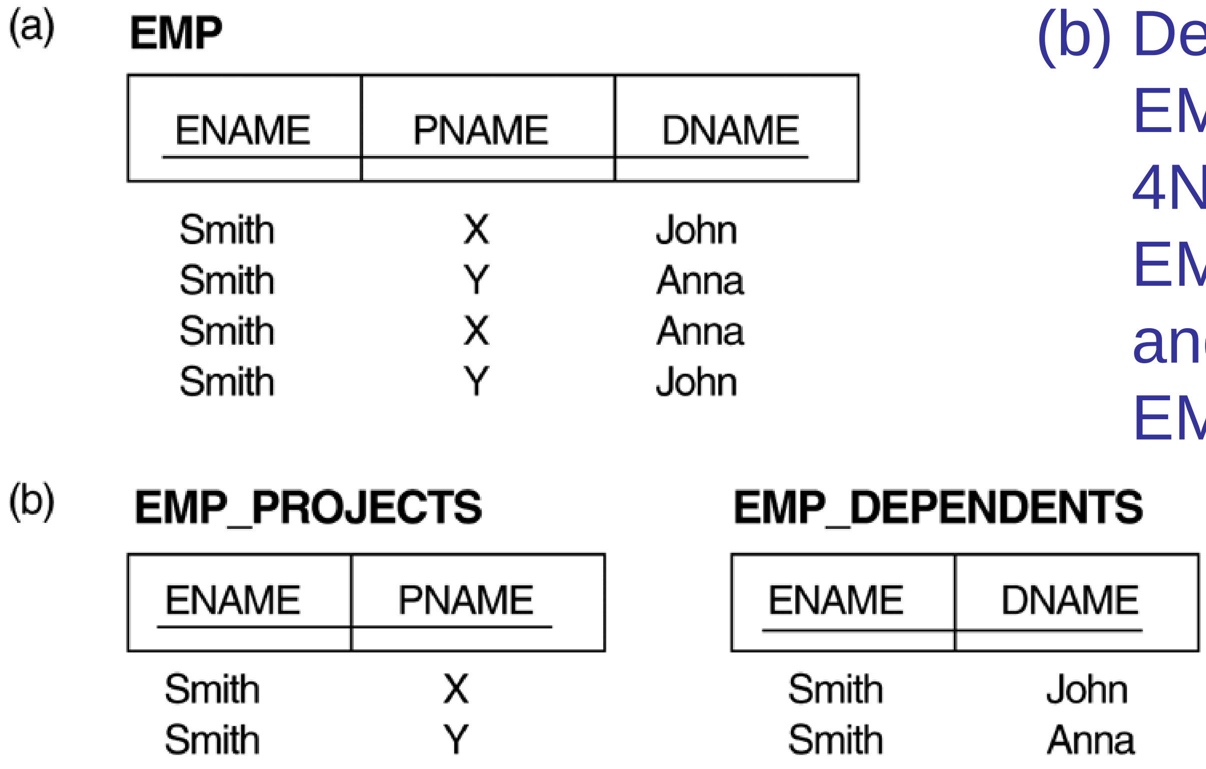
ENAME —>> DNAME.

- Whenever two independent 1:N relationships A:B and A:C are mixed in the same relation, R(A, B, C) an MVD may arise
- MVDs are a generalization of FDs, in the sense that every FD is an MVD but the converse is not true.

Multivalued Dependencies and Fourth Normal Form - Example

(a) The EMP relation with two MVDs:
ENAME —>> PNAME and ENAME —>> DNAME

(b) Decomposing the EMP relation into two 4NF relations EMP_PROJECTS and EMP_DEPENDENTS.



(a) **EMP**

ENAME	PNAME	DNAME
Smith	X	John
Smith	Y	Anna
Smith	X	Anna
Smith	Y	John

(b) **EMP_PROJECTS**

ENAME	PNAME
Smith	X
Smith	Y

EMP_DEPENDENTS

ENAME	DNAME
Smith	John
Smith	Anna

Fourth Normal Form

- Fagin's Theorem
  - A relation R with attributes A, B, and C, can be nonloss-decomposed into its two projections R1(A, B) and R2 (A, C) iff the MVD A —>> B|C holds in R.

- A relation R is in 4NF iff, whenever there exist an MVD in R, say A —>> B, then all attributes of R are also functionally dependent on A (i.e. A->x for all attributes x of R)

Two Projections Always?

- So far every relation was non-loss decomposable into two projections
  - is this always possible?

- **n-decomposable** relations

Example: Relation CTL

- Courses - Tutors - Levels (CTL)

Course	Tutor	Level
Databases	Usha	Level3
Databases	Mahesh	Level2
Programming	Usha	Level2
Databases	Usha	Level2

Two Attribute Projections of CTL

- Courses - Tutors - Levels (CTL)

CT

Course	Tutor
Databases	Usha
Databases	Mahesh
Programming	Usha

TL

Tutor	Level
Usha	Level3
Mahesh	Level2
Usha	Level2

CL

Course	Level
Databases	Level3
Databases	Level2
Programming	Level2

Two Attribute Projections of CTL

CT

Course	Tutor
Databases	Usha
Databases	Mahesh
Programming	Usha

TL

Tutor	Level
Usha	Level3
Mahesh	Level2
Usha	Level2

Join(CT, TL)

Course	Tutor	Level
Databases	Usha	Level3
Databases	Usha	Level2
Databases	Mahesh	Level2
Programming	Usha	Level3
Programming	Usha	Level2

The join of any two projections is not CTL

CTL is a 3-decomposable relation

3-Decomposable Relation

- Constraint: Let R be a degree 3 relation.

IF	(**a**, **b**, x) $\in$ R
AND	(**a**, y, **c**) $\in$ R
AND	(z, **b**, **c**) $\in$ R
THEN	(**a**, **b**, **c**) $\in$ R

- Constraint illustrated on the CTL relation

IF	tutor t1 teaches subject s1
AND	level l1 studies subject s1
AND	tutor t1 teaches level l1
THEN	tutor t1 teaches subject s1 for level l1

- Note: this constraint is **not** expressed in CTL

Join Dependencies and 5NF

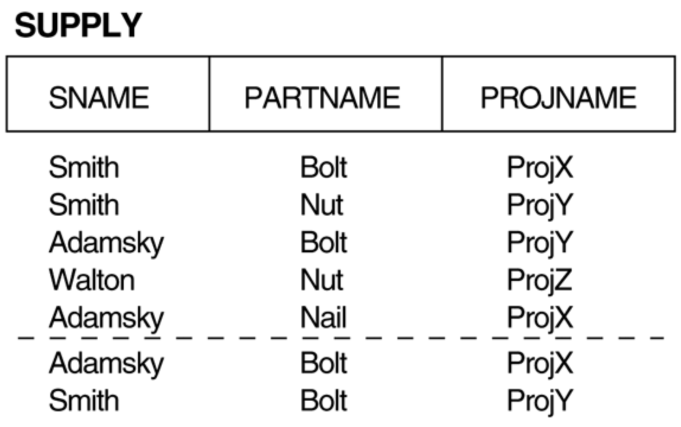
- Very peculiar semantic constraint that is very difficult to detect in practice
  - Normalization into 5NF - rarely done in practice.
- Definition of Join Dependency:
  - A join dependency denoted by JD(R1, R2, .., Rn), specified on relation schema R, specifies a constraint on the states of R.
  - The constraint states that every legal state r of R should have a nonadditive join decomposition into R1, R2, .., Rn
  - i.e., for every such r we have

$$*(\pi_{R1}(r), \pi_{R2}(r), \ldots \pi_{Rn}(r)) = r$$

Join Dependencies and 5NF

- MVD is a special case of a JD where n = 2.
- A relation schema R is in fifth normal form (5NF) iff every join dependency in R is implied by the candidate keys of R.
- Let R be a relation. Let A, B, ..., Z be arbitrary subsets of R's attributes. R satisfies the * (R1, R2, .., Rn) if and only if R is equal to the join of its projections on (R1, R2, .., Rn)
- Also called projection-join form (PJ/NF)

5NF: Another Example



SUPPLY

SNAME	PARTNAME	PROJNAME
Smith	Bolt	ProjX
Smith	Nut	ProjY
Adamsky	Bolt	ProjY
Walton	Nut	ProjZ
Adamsky	Nail	ProjX
Adamsky	Bolt	ProjX
Smith	Bolt	ProjY

Additional constraint:

Whenever a supplier S supplies part P, and a project J uses part P, and the supplier S supplies at least one part to project J,

Then supplier S will also be supplying part P to project J.

If this constraint holds, the tuples below the dotted line must exist in any legal state of the SUPPLY relation that also contains the tuples above the dotted line.

5NF: Another Example

SUPPLY

SNAME	PARTNAME	PROJNAME
Smith	Bolt	ProjX
Smith	Nut	ProjY
Adamsky	Bolt	ProjY
Walton	Nut	ProjZ
Adamsky	Nail	ProjX
Adamsky	Bolt	ProjX
Smith	Bolt	ProjY

The relation SUPPLY with no MVDs is in 4NF but not in 5NF if it has the JD(R1, R2, R3).

Note that applying a natural join to any two of these relations produces spurious tuples, but applying a natural join to all three together does not

R1

SNAME	PARTNAME
Smith	Bolt
Smith	Nut
Adamsky	Bolt
Walton	Nut
Adamsky	Nail

R2

SNAME	PROJNAME
Smith	ProjX
Smith	ProjY
Adamsky	ProjY
Walton	ProjZ
Adamsky	ProjX

R3

PARTNAME	PROJNAME
Bolt	ProjX
Nut	ProjY
Bolt	ProjY
Nut	ProjZ
Nail	ProjX

Decomposing the relation SUPPLY into the 5NF relations R1, R2, and R3.

N - decomposability

Domain-Key Normal Form

- Proposed by Fagin
- DKNF is not defined in terms of FDs, MVDs, or JDs at all
- A relation schema is said to be in DKNF if all constraints and dependencies that should hold on the valid relation states can be enforced simply by enforcing the domain constraints and key constraints on the relation.
- *"if every **constraint** on the relation is a logical consequence of the definition of **keys** and **domains**"*

Domain-Key Normal Form

- For a relation in DKNF, it becomes very straightforward to enforce all db constraints by simply checking that each attribute value in a tuple is of the appropriate domain and that every key constraint is enforced.
- Fagin shows that any DKNF is necessarily in 5NF (and hence in 4NF..etc.)
- However, DKNF is not always achievable, nor has the question "exactly when can it be achieved ?" been answered.

- Let us take some problems….