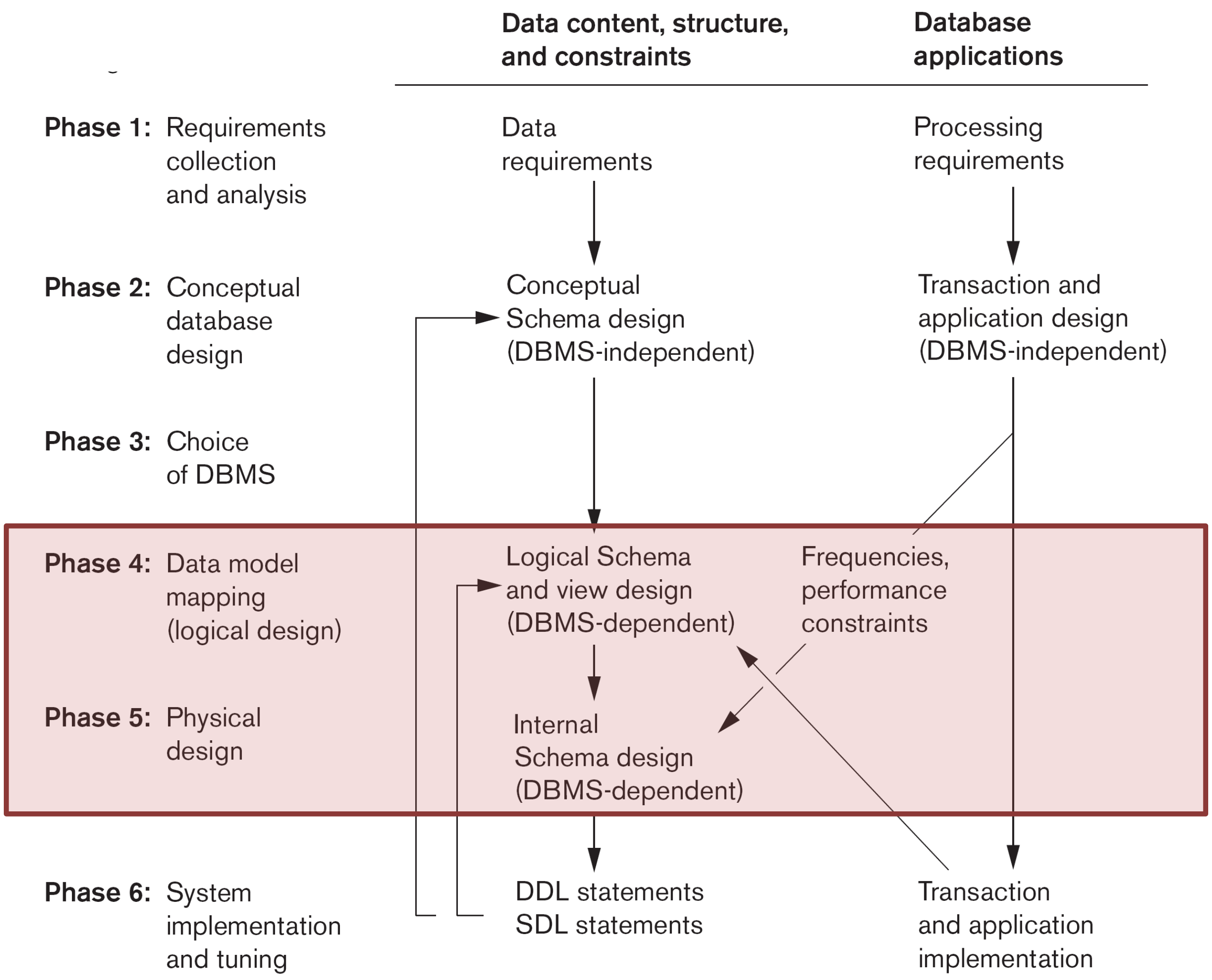
Normalization

Lecture 9

Outline

1. Context
2. Normalization Objectives
3. Functional Dependencies
4. Normal Forms
   - 1NF
   - 2NF
   - 3NF

Database Design and Implementation Process



Data content, structure, and constraints

Database applications

Phase 1: Requirements collection and analysis

Data requirements

Processing requirements

Phase 2: Conceptual database design

Conceptual Schema design (DBMS-independent)

Transaction and application design (DBMS-independent)

Phase 3: Choice of DBMS

Phase 4: Data model mapping (logical design)

Logical Schema and view design (DBMS-dependent)

Frequencies, performance constraints

Phase 5: Physical design

Internal Schema design (DBMS-dependent)

Phase 6: System implementation and tuning

DDL statements SDL statements

Transaction and application implementation

Normalization

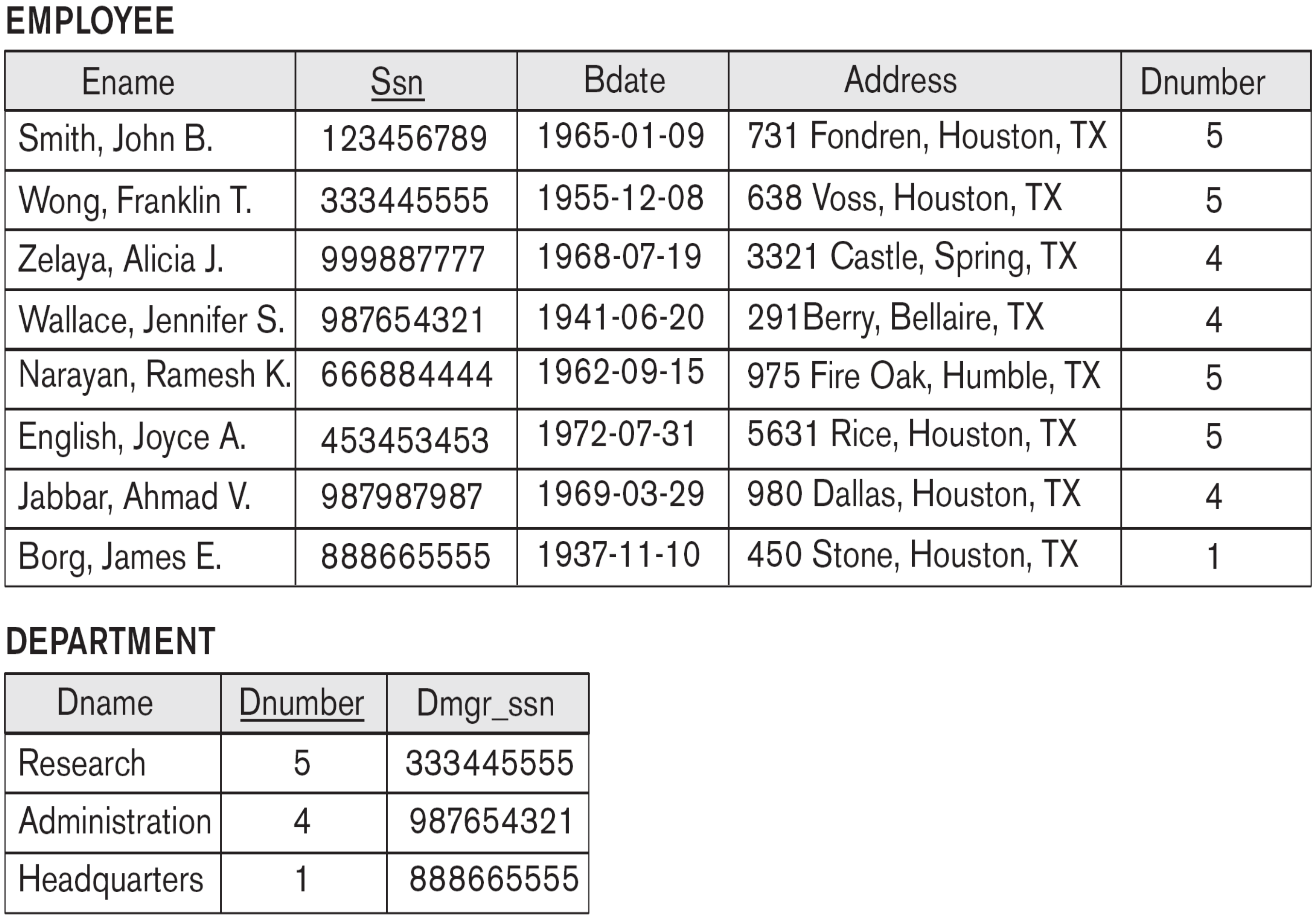
- Theory and process by which to evaluate and improve relational database design
- Typically divide larger tables into smaller, less redundant tables
- Spans both logical and physical database design

Objectives of Normalization

- Make the schema informative
- Minimize information duplication
- Avoid **modification anomalies**
- Disallow **spurious tuples**

Note: during physical tuning we may prioritize query execution speed and thus *denormalize* (e.g. OLTP vs. OLAP)

Example Schema



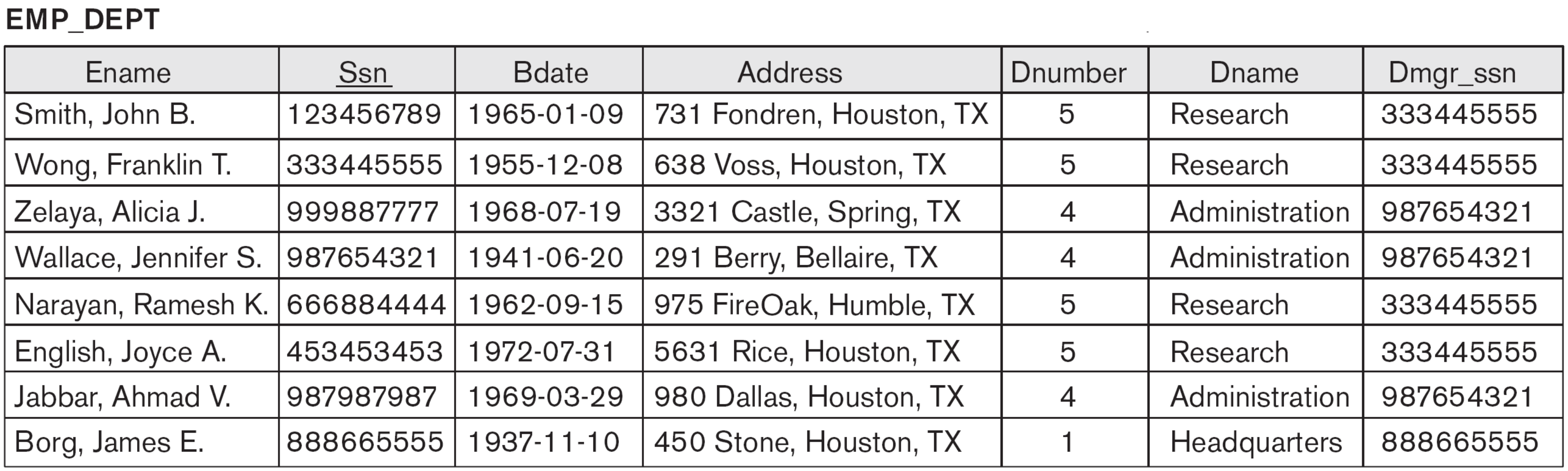
EMPLOYEE

Ename	Ssn	Bdate	Address	Dnumber
Smith, John B.	123456789	1965-01-09	731 Fondren, Houston, TX	5
Wong, Franklin T.	333445555	1955-12-08	638 Voss, Houston, TX	5
Zelaya, Alicia J.	999887777	1968-07-19	3321 Castle, Spring, TX	4
Wallace, Jennifer S.	987654321	1941-06-20	291Berry, Bellaire, TX	4
Narayan, Ramesh K.	666884444	1962-09-15	975 Fire Oak, Humble, TX	5
English, Joyce A.	453453453	1972-07-31	5631 Rice, Houston, TX	5
Jabbar, Ahmad V.	987987987	1969-03-29	980 Dallas, Houston, TX	4
Borg, James E.	888665555	1937-11-10	450 Stone, Houston, TX	1

DEPARTMENT

Dname	Dnumber	Dmgr_ssn
Research	5	333445555
Administration	4	987654321
Headquarters	1	888665555

Straw Man Schema



EMP_DEPT

Ename	Ssn	Bdate	Address	Dnumber	Dname	Dmgr_ssn
Smith, John B.	123456789	1965-01-09	731 Fondren, Houston, TX	5	Research	333445555
Wong, Franklin T.	333445555	1955-12-08	638 Voss, Houston, TX	5	Research	333445555
Zelaya, Alicia J.	999887777	1968-07-19	3321 Castle, Spring, TX	4	Administration	987654321
Wallace, Jennifer S.	987654321	1941-06-20	291 Berry, Bellaire, TX	4	Administration	987654321
Narayan, Ramesh K.	666884444	1962-09-15	975 FireOak, Humble, TX	5	Research	333445555
English, Joyce A.	453453453	1972-07-31	5631 Rice, Houston, TX	5	Research	333445555
Jabbar, Ahmad V.	987987987	1969-03-29	980 Dallas, Houston, TX	4	Administration	987654321
Borg, James E.	888665555	1937-11-10	450 Stone, Houston, TX	1	Headquarters	888665555

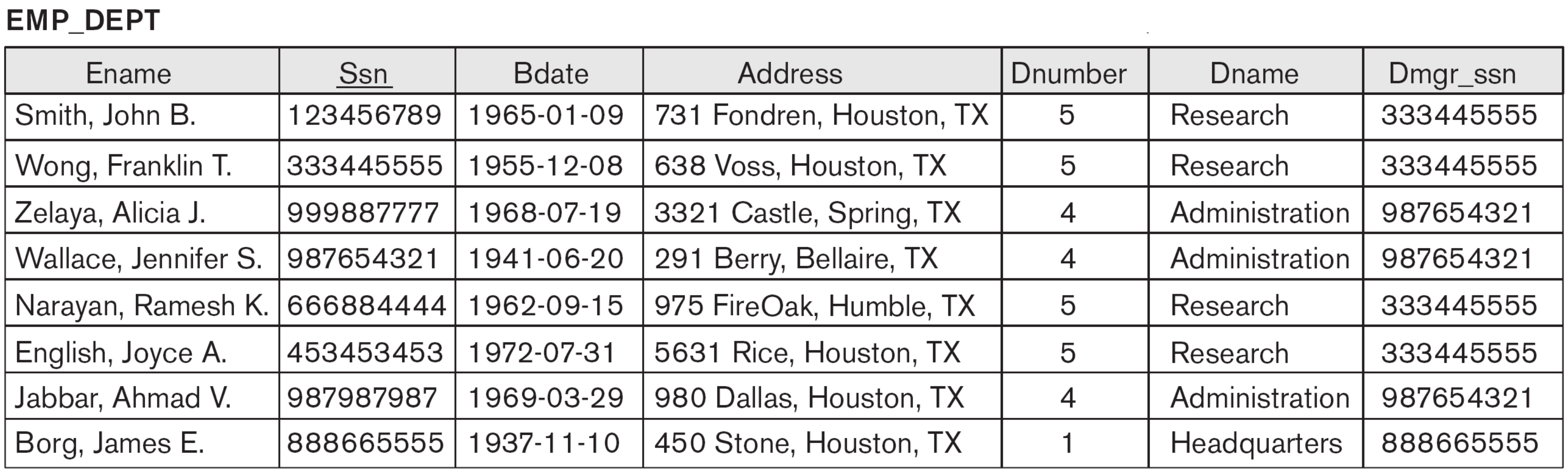
Make the Schema Informative

- Design a relational schema so that it is easy to explain its meaning
- Do **not** combine attributes from multiple entity types and relationship types into a single relation; semantic ambiguities will result and the relation cannot be easily explained
- Normalized tables, and the relationship between one normalized table and another, mirror real-world concepts and their interrelationships

Example Schema

What is this table about?

- Employees? Departments?

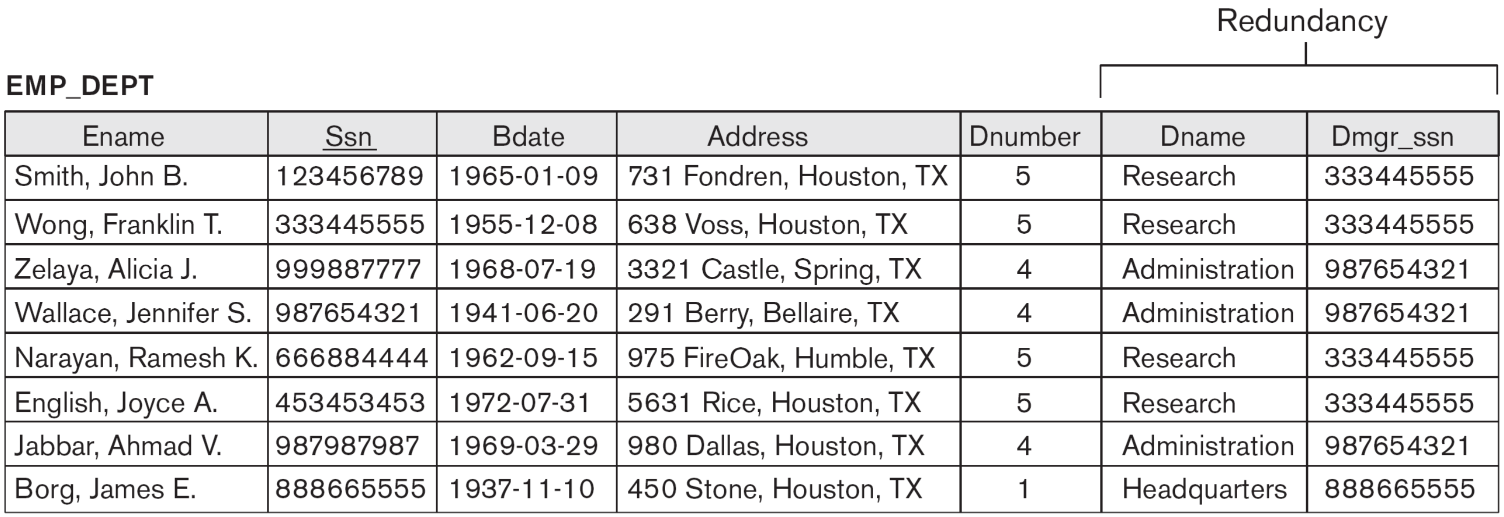


EMP_DEPT

Ename	Ssn	Bdate	Address	Dnumber	Dname	Dmgr_ssn
Smith, John B.	123456789	1965-01-09	731 Fondren, Houston, TX	5	Research	333445555
Wong, Franklin T.	333445555	1955-12-08	638 Voss, Houston, TX	5	Research	333445555
Zelaya, Alicia J.	999887777	1968-07-19	3321 Castle, Spring, TX	4	Administration	987654321
Wallace, Jennifer S.	987654321	1941-06-20	291 Berry, Bellaire, TX	4	Administration	987654321
Narayan, Ramesh K.	666884444	1962-09-15	975 FireOak, Humble, TX	5	Research	333445555
English, Joyce A.	453453453	1972-07-31	5631 Rice, Houston, TX	5	Research	333445555
Jabbar, Ahmad V.	987987987	1969-03-29	980 Dallas, Houston, TX	4	Administration	987654321
Borg, James E.	888665555	1937-11-10	450 Stone, Houston, TX	1	Headquarters	888665555

Minimize Information Duplication

- Avoid data redundancies



Redundancy

EMP_DEPT

Ename	Ssn	Bdate	Address	Dnumber	Dname	Dmgr_ssn
Smith, John B.	123456789	1965-01-09	731 Fondren, Houston, TX	5	Research	333445555
Wong, Franklin T.	333445555	1955-12-08	638 Voss, Houston, TX	5	Research	333445555
Zelaya, Alicia J.	999887777	1968-07-19	3321 Castle, Spring, TX	4	Administration	987654321
Wallace, Jennifer S.	987654321	1941-06-20	291 Berry, Bellaire, TX	4	Administration	987654321
Narayan, Ramesh K.	666884444	1962-09-15	975 FireOak, Humble, TX	5	Research	333445555
English, Joyce A.	453453453	1972-07-31	5631 Rice, Houston, TX	5	Research	333445555
Jabbar, Ahmad V.	987987987	1969-03-29	980 Dallas, Houston, TX	4	Administration	987654321
Borg, James E.	888665555	1937-11-10	450 Stone, Houston, TX	1	Headquarters	888665555

- Avoid excessive use of NULLs (e.g. fat tables)
  - Wastes space
  - Can make information querying/understanding complicated and error-prone

Avoid **Modification Anomalies**

An undesired side-effect resulting from an attempt to modify a table [that has not been sufficiently normalized]

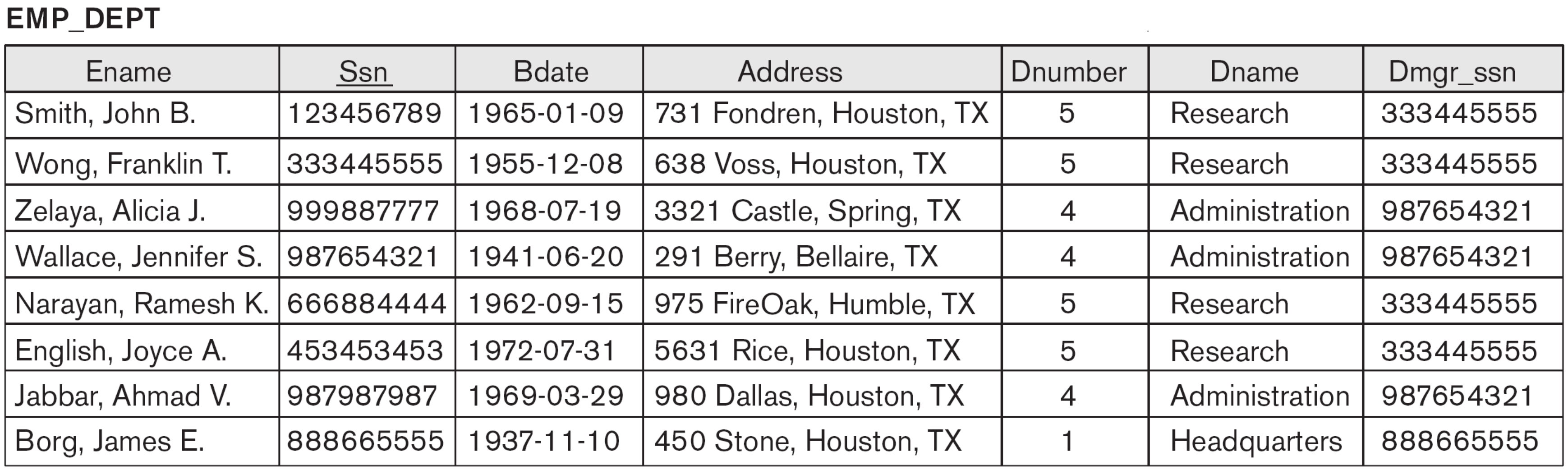
Types of updates:

- Insertion
- Update
- Deletion

Insertion Anomaly

Difficult or impossible to insert a new row

- Add a new employee
  - Unknown manager
  - Typo in department/manager info
- Add a new department
  - Requires at least one employee



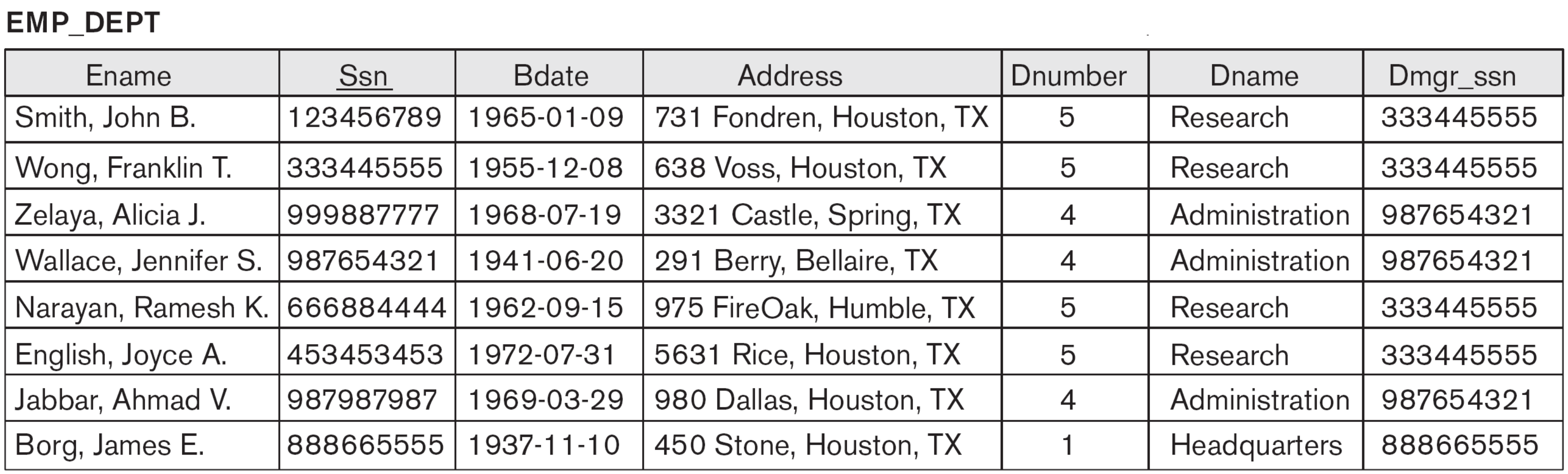
EMP_DEPT

Ename	Ssn	Bdate	Address	Dnumber	Dname	Dmgr_ssn
Smith, John B.	123456789	1965-01-09	731 Fondren, Houston, TX	5	Research	333445555
Wong, Franklin T.	333445555	1955-12-08	638 Voss, Houston, TX	5	Research	333445555
Zelaya, Alicia J.	999887777	1968-07-19	3321 Castle, Spring, TX	4	Administration	987654321
Wallace, Jennifer S.	987654321	1941-06-20	291 Berry, Bellaire, TX	4	Administration	987654321
Narayan, Ramesh K.	666884444	1962-09-15	975 FireOak, Humble, TX	5	Research	333445555
English, Joyce A.	453453453	1972-07-31	5631 Rice, Houston, TX	5	Research	333445555
Jabbar, Ahmad V.	987987987	1969-03-29	980 Dallas, Houston, TX	4	Administration	987654321
Borg, James E.	888665555	1937-11-10	450 Stone, Houston, TX	1	Headquarters	888665555

Update Anomaly

Updates may result in logical inconsistencies

- Change the department name/manager



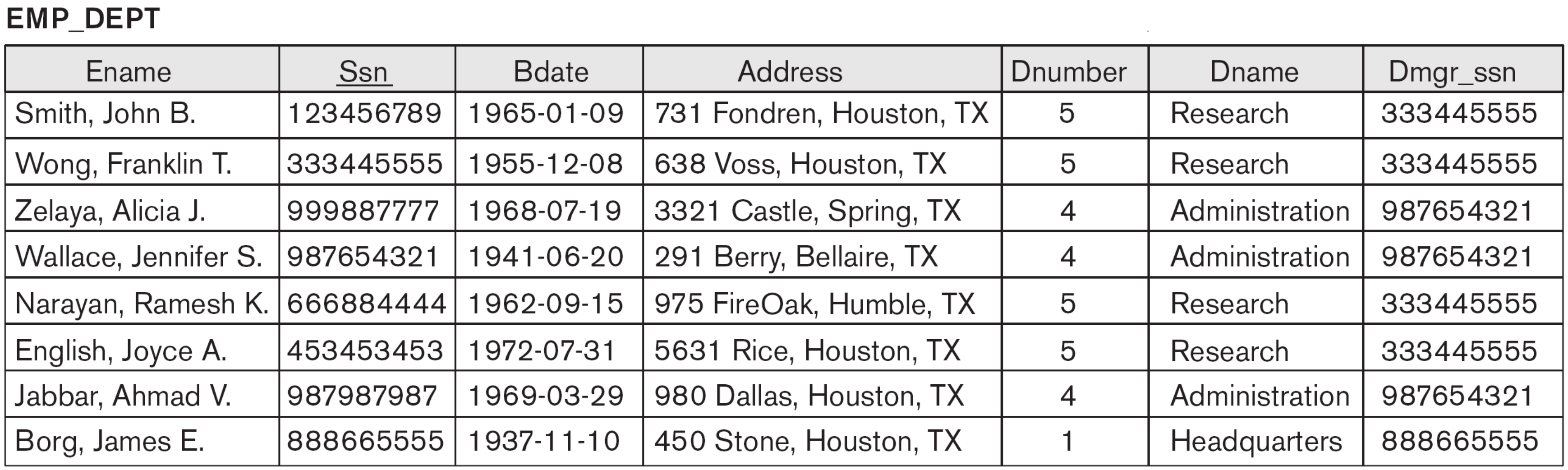
EMP_DEPT

Ename	Ssn	Bdate	Address	Dnumber	Dname	Dmgr_ssn
Smith, John B.	123456789	1965-01-09	731 Fondren, Houston, TX	5	Research	333445555
Wong, Franklin T.	333445555	1955-12-08	638 Voss, Houston, TX	5	Research	333445555
Zelaya, Alicia J.	999887777	1968-07-19	3321 Castle, Spring, TX	4	Administration	987654321
Wallace, Jennifer S.	987654321	1941-06-20	291 Berry, Bellaire, TX	4	Administration	987654321
Narayan, Ramesh K.	666884444	1962-09-15	975 FireOak, Humble, TX	5	Research	333445555
English, Joyce A.	453453453	1972-07-31	5631 Rice, Houston, TX	5	Research	333445555
Jabbar, Ahmad V.	987987987	1969-03-29	980 Dallas, Houston, TX	4	Administration	987654321
Borg, James E.	888665555	1937-11-10	450 Stone, Houston, TX	1	Headquarters	888665555

Deletion Anomaly

Deletion of data representing certain facts necessitates deletion of data representing completely different facts

- Delete James E. Borg



EMP_DEPT

Ename	Ssn	Bdate	Address	Dnumber	Dname	Dmgr_ssn
Smith, John B.	123456789	1965-01-09	731 Fondren, Houston, TX	5	Research	333445555
Wong, Franklin T.	333445555	1955-12-08	638 Voss, Houston, TX	5	Research	333445555
Zelaya, Alicia J.	999887777	1968-07-19	3321 Castle, Spring, TX	4	Administration	987654321
Wallace, Jennifer S.	987654321	1941-06-20	291 Berry, Bellaire, TX	4	Administration	987654321
Narayan, Ramesh K.	666884444	1962-09-15	975 FireOak, Humble, TX	5	Research	333445555
English, Joyce A.	453453453	1972-07-31	5631 Rice, Houston, TX	5	Research	333445555
Jabbar, Ahmad V.	987987987	1969-03-29	980 Dallas, Houston, TX	4	Administration	987654321
Borg, James E.	888665555	1937-11-10	450 Stone, Houston, TX	1	Headquarters	888665555

Disallow **Spurious Tuples**

Avoid relational design that matches attributes across relations that are not (foreign key, primary key) combinations because joining on such attributes may produce invalid tuples

Example Decomposition

CAR

ID	Make	Color
1	Toyota	Blue
2	Audi	Blue
3	Toyota	Red

CAR1

ID	Color
1	Blue
2	Blue
3	Red

CAR2

Make	Color
Toyota	Blue
Audi	Blue
Toyota	Red

Natural Join

ID	Make	Color
1	Toyota	Blue
1	Audi	Blue
2	Toyota	Blue
2	Audi	Blue
3	Toyota	Red

CAR1

ID	Color
1	Blue
2	Blue
3	Red

CAR2

Make	Color
Toyota	Blue
Audi	Blue
Toyota	Red

Additive Decomposition

CAR

ID	Make	Color
1	Toyota	Blue
2	Audi	Blue
3	Toyota	Red

JOIN

ID	Make	Color
1	Toyota	Blue
1	**Audi**	**Blue**
2	**Toyota**	**Blue**
2	Audi	Blue
3	Toyota	Red

Functional Dependency (FD)

In a relation *r*, a set of attributes **Y** is *functionally dependent* upon another set of attributes **X** ($X \to Y$) iff for all two tuples t_1 and t_2 in *r* that have t_1[**X**]=t_2[**X**], they also have t_1[**Y**]=t_2[**Y**]

One cannot determine which FDs hold unless the meaning of and the relationships among the attributes are known; one can state an FD does *not* hold given violating tuples

- FYI: these are the "data dependencies" foreshadowed in Lecture 2 (Relational Model)

FD Example (1)

	StudentID	Year	Class	Instructor
t_1	1	Sophomore	COMP355	Derbinsky
t_2	2	Sophomore	COMP285	Derbinsky
t_3	3	Junior	COMP355	Derbinsky
t_4	3	Junior	COMP285	Derbinsky
t_5	2	Sophomore	COMP355	Russo
t_6	4	Sophomore	COMP355	Russo

$$\{StudentID\} \rightarrow \{Year\}$$

$$\{StudentID, Class\} \rightarrow \{Instructor\}$$

- *Every student is classified as either a Freshman, Sophomore, Junior, or Senior.*
- *Students can take only a single section of a class, taught by a single instructor.*

Key(s): $\{StudentID, Class\}$

FD Example (2)

	StudentID	Year	Class	Instructor
t_1	1	Sophomore	COMP355	Derbinsky
t_2	2	Sophomore	COMP285	Derbinsky
t_3	3	Junior	COMP355	Derbinsky
t_4	3	Junior	COMP285	Derbinsky
t_5	2	Sophomore	COMP355	Russo
t_6	4	Sophomore	COMP355	Russo

$$\{StudentID\} \nrightarrow \{Instructor\}$$

$$\{StudentID\} \nrightarrow \{Class\}$$

$$\{Year\} \nrightarrow \{StudentID\}$$

$$\{Year\} \nrightarrow \{Instructor\}$$

$$\{Year\} \nrightarrow \{Class\}$$

$$\{Class\} \nrightarrow \{Year\}$$

$$\{Class\} \nrightarrow \{StudentID\}$$

$$\{Class\} \nrightarrow \{Instructor\}$$

$$\{Instructor\} \nrightarrow \{Class\}$$

$$\{Instructor\} \nrightarrow \{Year\}$$

$$\{Instructor\} \nrightarrow \{StudentID\}$$

FD Example (3)

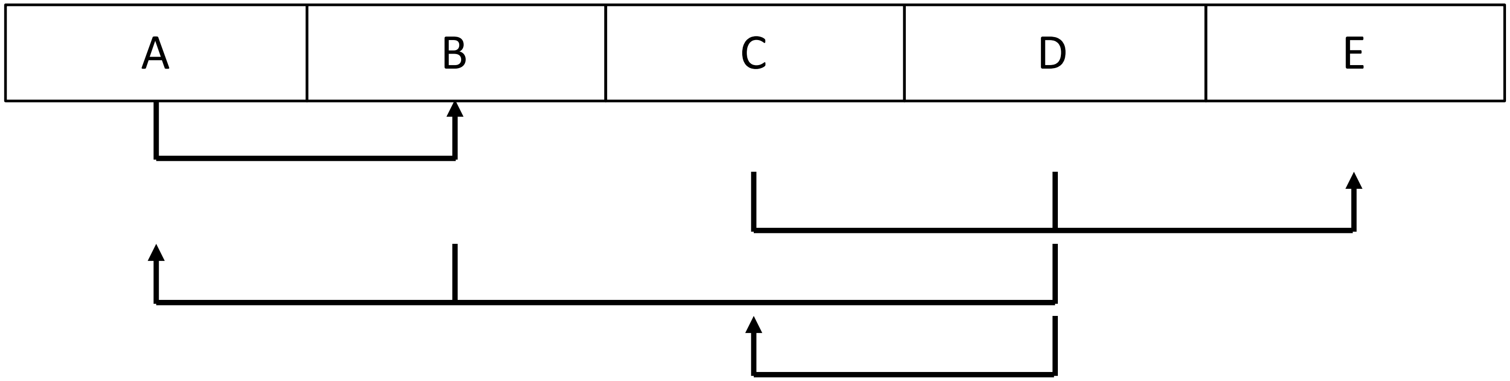
	StudentID	Year	Class	Instructor
t_1	1	Sophomore	COMP355	Derbinsky
t_2	2	Sophomore	COMP285	Derbinsky
t_3	3	Junior	COMP355	Derbinsky
t_4	3	Junior	COMP285	Derbinsky
t_5	2	Sophomore	COMP355	Russo
t_6	4	Sophomore	COMP355	Russo

$$\{StudentID, Instructor\} \nrightarrow \{Class\}$$
$$\{Year, Class\} \nrightarrow \{Instructor\}$$
$$\{Year, Class\} \nrightarrow \{StudentID\}$$
$$\{Class, Instructor\} \nrightarrow \{StudentID\}$$
$$\{Class, Instructor\} \nrightarrow \{Year\}$$
$$\{Year, Class, Instructor\} \nrightarrow \{StudentID\}$$

Exercise

Consider the following visual depiction of the functional dependencies of a relational schema.

1. List all FDs in algebraic notation
2. Identify all key(s) of of this relation



Answer

Functional Dependencies

$$A \rightarrow B$$

$$CD \rightarrow E$$

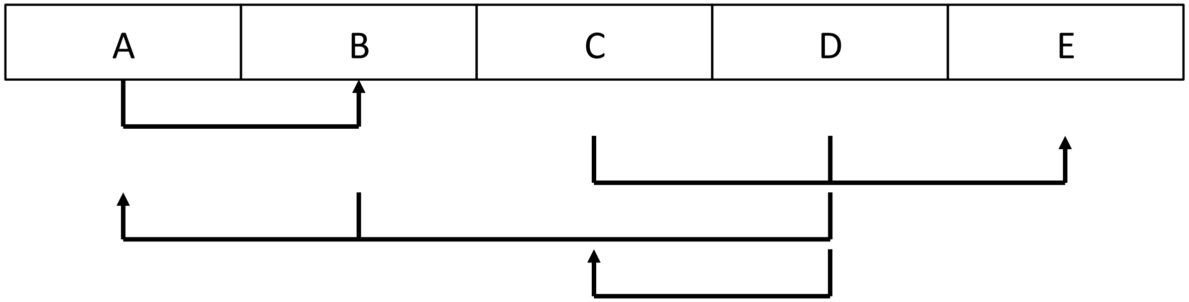
$$BD \rightarrow A$$

$$D \rightarrow C$$

Keys

$$DA$$

$$DB$$



Important FD Definitions

Trivial FD	$X \rightarrow Y,\ Y \subseteq X$
Non-Prime	An attribute that does not occur in any key (opposite: Prime)
Full FD	$X \rightarrow Y,\ \forall A \in X((X - \{A\}) \nrightarrow Y)$
Transitive FD	$X \rightarrow Z \because X \rightarrow Y\ and\ Y \rightarrow Z$

Normalization Process

- Submit a relational schema to a set of tests (related to FDs) to certify whether it satisfies a **normal form**

- If it does not pass, decompose into smaller relations that satisfy the normal form
  - Must be non-additive (i.e. no spurious tuples!)

- The normal form of a relation refers to the highest normal form that it meets
  - As of 2002 the most constraining is 6NF

- The normal form of a database refers to the lowest normal form that any relation meets
  - Practically, a database is normalized if all relations ≥ 3NF

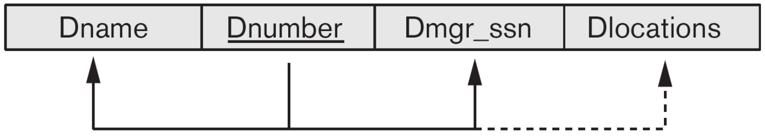
1NF – First Normal Form

- The domain of an attribute must include only atomic values and that the value of any attribute in a tuple must be a single value from the domain of that attribute
- No relations within relations or relations as attribute values within tuples
- Considered part of the formal definition of a relation in the basic (flat) relational model
  - In other words, an *implicit* constraint (Lecture 2)

1NF Violation (1)

(a)

DEPARTMENT



Dname	Dnumber	Dmgr_ssn	Dlocations

(b)

DEPARTMENT

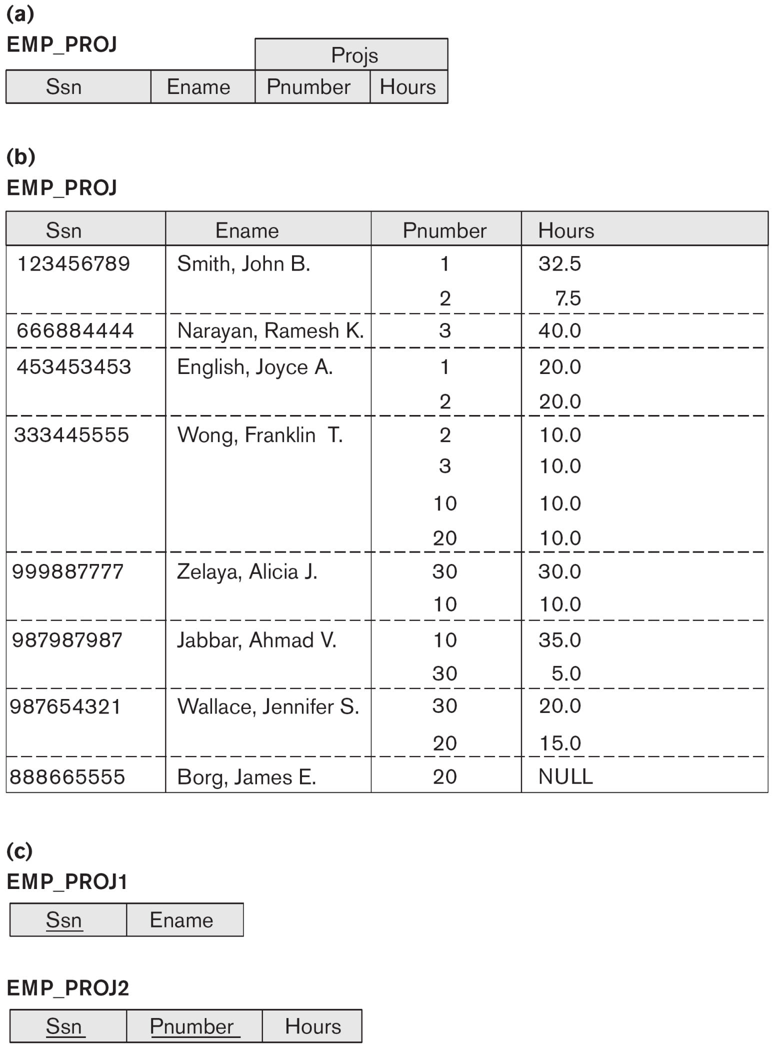
Dname	Dnumber	Dmgr_ssn	Dlocations
Research	5	333445555	{Bellaire, Sugarland, Houston}
Administration	4	987654321	{Stafford}
Headquarters	1	888665555	{Houston}

(c)

DEPARTMENT

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

1NF Violation (2)



(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, Alicia J.	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

2NF – Second Normal Form

- 1NF **AND** every non-prime attribute is fully FD on the primary key
  - Must test all FDs whose LHS is part of the PK

- To fix, decompose into relations in which non-prime attributes are associated only with the part of the primary key on which they are fully functionally dependent

2NF Example

StudentID	Course	StudentAddress
1	COMP570	555 Huntington
1	COMP285	555 Huntington
2	COMP570	610 Huntington
3	COMP355	Louis Prang
3	COMP553	Louis Prang

$$\{StudentID, Course\} \rightarrow \{StudentAddress\}$$

$$\{StudentID\} \rightarrow \{StudentAddress\}$$

StudentID	StudentAddress
1	555 Huntington
2	610 Huntington
3	Louis Prang

StudentID	Course
1	COMP570
1	COMP285
2	COMP570
3	COMP355
3	COMP553

2NF Can Suffer Update Anomalies

Year	Winner	Nationality
1994	Miguel Indurain	Spain
1995	Miguel Indurain	Spain
1996	Bjarne Riis	Denmark
1997	Jan Ullrich	Germany

- Relation is in 2NF?
  - Trivially true (why?)
- List all non-trivial FDs for this relation state
  - $\{Year\} \rightarrow \{Winner, Nationality\}$
  - $\{Winner\} \rightarrow \{Nationality\}$
- What if we insert (1998, Jan Ullrich, USA)?

3NF – Third Normal Form

- 2NF **AND** every non-prime attribute is non-transitively dependent on every key

  “A non-key field must provide a fact about the key, the whole key, and nothing but the key. So help me Codd.”

- To fix, decompose into multiple relations, whereby the intermediate non-key attribute(s) functionally determine other non-prime attributes

3NF Example

Year	Winner	Nationality
1994	Miguel Indurain	Spain
1995	Miguel Indurain	Spain
1996	Bjarne Riis	Denmark
1997	Jan Ullrich	Germany

$Year \to Nationality \because$

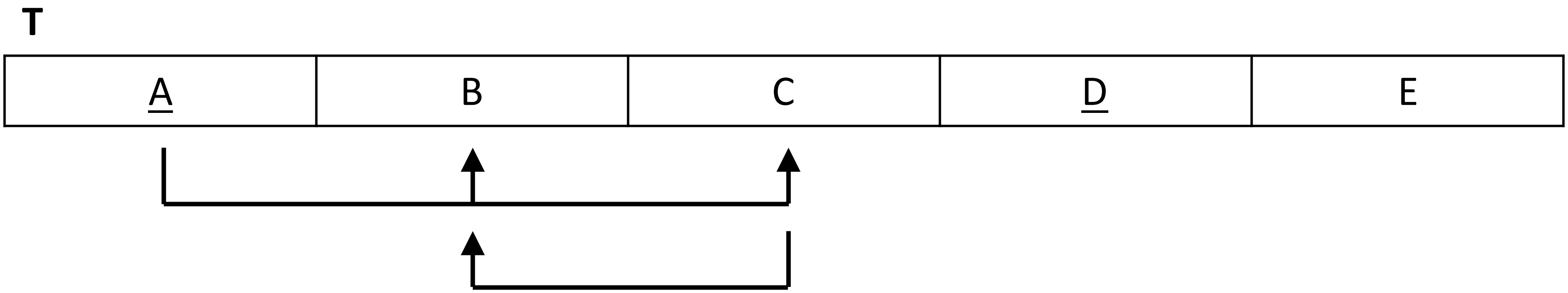
$Year \to Winner$ **and**

$Winner \to Nationality$

Year	Winner
1994	Miguel Indurain
1995	Miguel Indurain
1996	Bjarne Riis
1997	Jan Ullrich

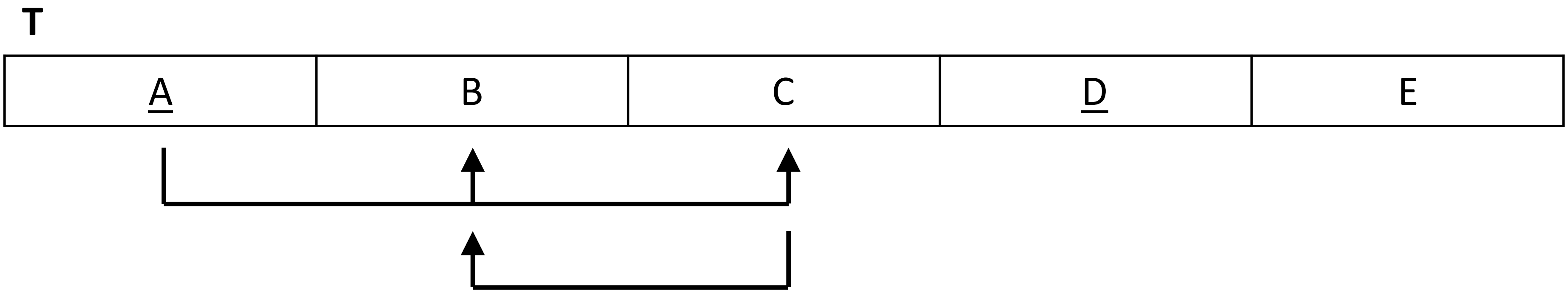
Winner	Nationality
Miguel Indurain	Spain
Bjarne Riis	Denmark
Jan Ullrich	Germany

Exercise



Consider the schema for relation **T**, as well as all FDs. What is the normal form of **T**? If **T** violates 3NF, provide a 3NF decomposition that satisfies the FDs (including the primary key) and does not produce spurious tuples. Show and explain all steps of your analysis and decomposition (if applicable).

Answer (1)



T

$\underline{A}$	B	C	$\underline{D}$	E

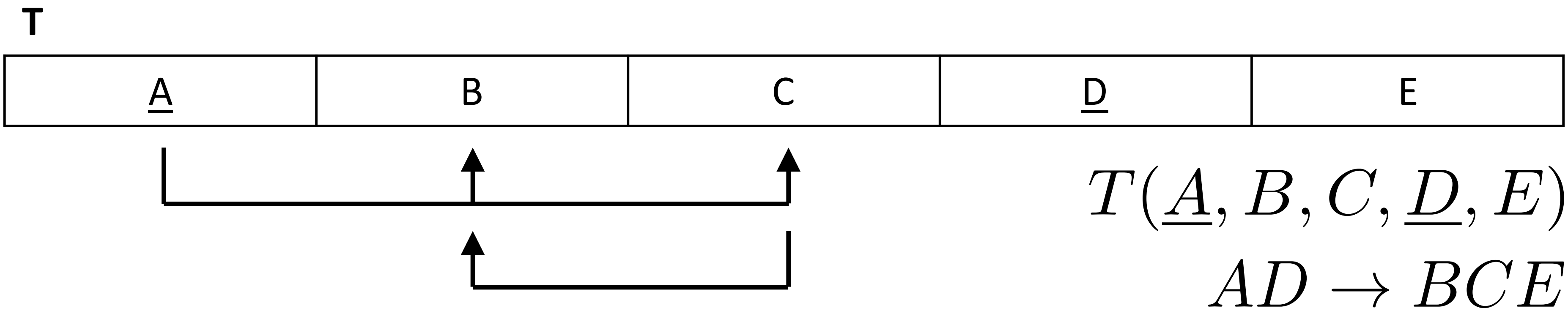
List non-trivial FDs

$$AD \rightarrow BCE$$
$$A \rightarrow BC$$
$$C \rightarrow B$$

Written algebraically

$$T(\underline{A}, B, C, \underline{D}, E)$$

Answer (2)



$$T(\underline{A}, B, C, \underline{D}, E)$$

$$AD \rightarrow BCE$$

$$A \rightarrow BC$$

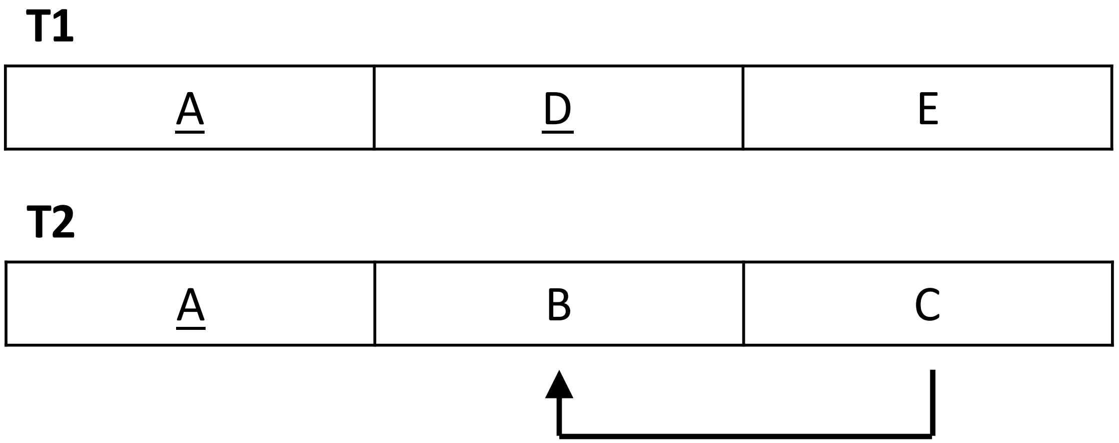
$$C \rightarrow B$$

T is in …

- Both B & C are FD on A
  - Thus not fully FD on PK (AD)

Decompose!

Answer (3)



$$T1(\underline{A}, \underline{D}, E)$$
$$T2(\underline{A}, B, C)$$

$$AD \rightarrow E$$
$$A \rightarrow BC$$
$$C \rightarrow B$$

T1 is in …

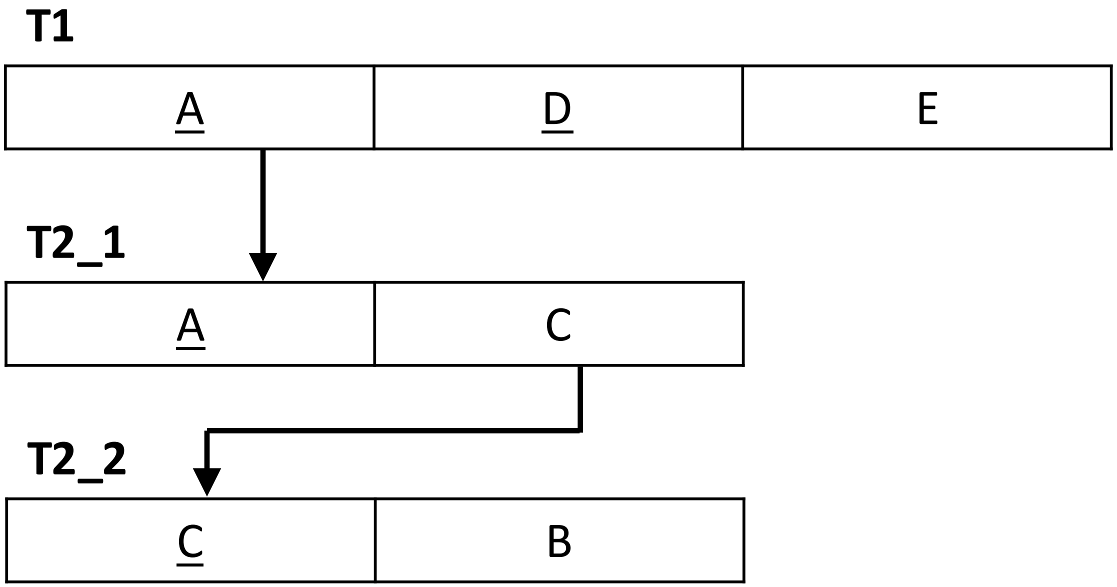
- 2NF: E is fully FD on AD
- 3NF: No transitive FDs (trivially true)

T2 is in …

- 2NF: B and C fully FD on A (trivially true)
- !3NF: B is transitively FD on A [via C]

Decompose!

Answer (4)



T1

A | D | E

T2_1

A | C

T2_2

C | B

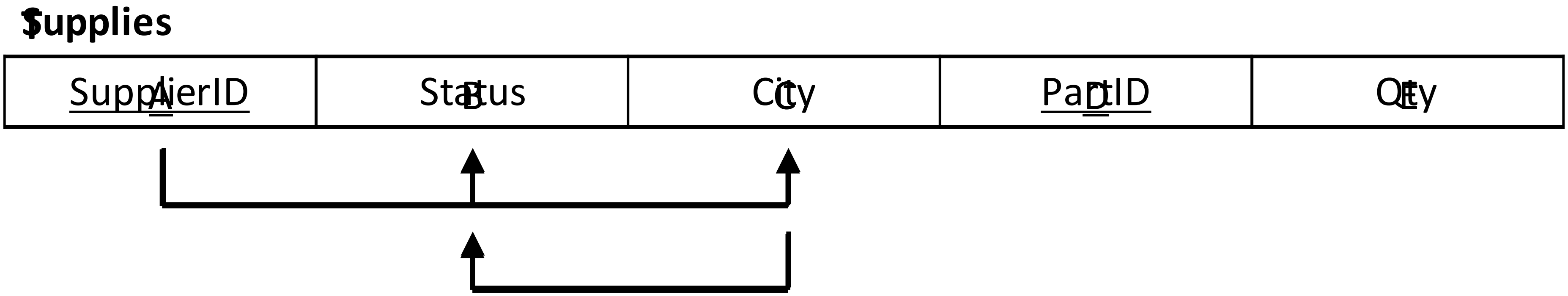
$$T1(\underline{A}, \underline{D}, E)$$
$$T2\_1(\underline{A}, C)$$
$$T2\_2(\underline{C}, B)$$

$$AD \rightarrow E$$
$$A \rightarrow C$$
$$C \rightarrow B$$

Database is in 3NF

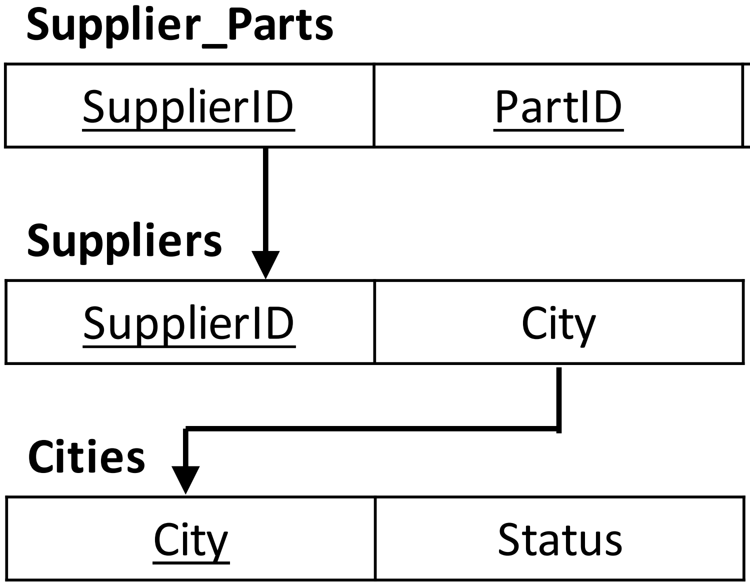
- Why?

Answer (5)



Supplies

SupplierID A	Status B	City C	PartID D	Qty E



Supplier_Parts

SupplierID	PartID	Qty

Suppliers

SupplierID	City

Cities

City	Status

$$\{SupplierID, PartID\} \rightarrow \{Qty\}$$

$$\{SupplierID\} \rightarrow \{City\}$$

$$\{City\} \rightarrow \{Status\}$$

Summary

- Normalization is the theory and process by which to evaluate and improve relational database design
  - Makes the schema informative
  - Minimizes information duplication
  - Avoids modification anomalies
  - Disallows spurious tuples
- Make sure all your relations are *at least* 3NF!
  - Higher normal forms exist
  - We may reduce during physical design