An Aside: Matrices and Relations

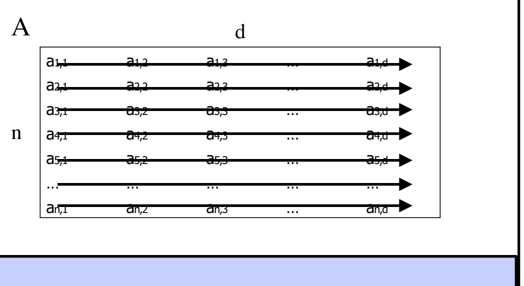
## How do we store a dense matrix?

A

| | | | d | | |
|---|---|---|---|---|---|
| | $a_{1,1}$ | $a_{1,2}$ | $a_{1,3}$ | … | $a_{1,d}$ |
| | $a_{2,1}$ | $a_{2,2}$ | $a_{2,3}$ | … | $a_{2,d}$ |
| | $a_{3,1}$ | $a_{3,2}$ | $a_{3,3}$ | … | $a_{3,d}$ |
| n | $a_{4,1}$ | $a_{4,2}$ | $a_{4,3}$ | … | $a_{4,d}$ |
| | $a_{5,1}$ | $a_{5,2}$ | $a_{5,3}$ | … | $a_{5,d}$ |
| | … | … | … | … | … |
| | $a_{n,1}$ | $a_{n,2}$ | $a_{n,3}$ | … | $a_{n,d}$ |

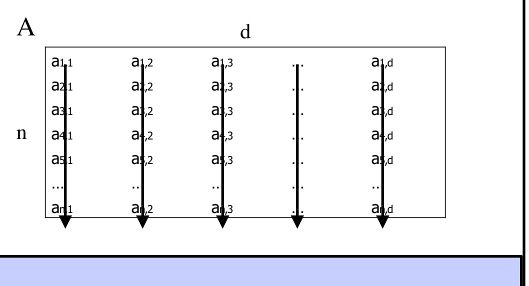
The above is a "logical" model. Storing it (in RAM or disk) is a "physical" model.

## How do we store a dense matrix?



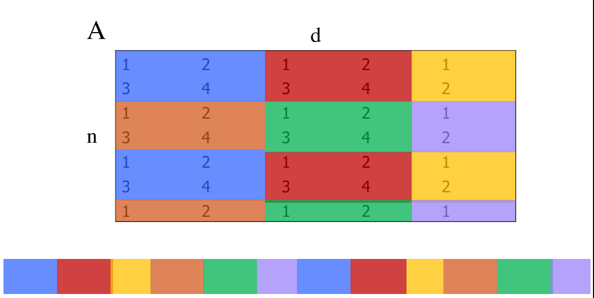

n×d, row-major "linearization" of a matrix

## How do we store a dense matrix?




n×d, column-major "linearization" of a matrix

## How do we store a dense matrix?




block-oriented *linearization* of the matrix (e.g. see ScaLAPACK's block-cyclic linearization)

## But what if it's sparse?

- I.e. mostly 0
  - Common: one-hot and bag-of-words
- Store a set of triples:

  {(row, col, val)}
- I.e. a relation!

## How do we store a sparse matrix?

A

| row | column | val |
|---|---|---|
| 1 | 3 | $a_{1,3}$ |
| 1 | 7 | $a_{1,7}$ |
| 2 | 14 | $a_{2,14}$ |
| 2 | 2741 | $a_{2,2741}$ |
| 3 | 14 | $a_{3,14}$ |
| 3 | 116 | $a_{3,116}$ |
| … | … | … |

store this on disk however you like to store relations… or use special encodings to enhance matrix arithmetic locality (see Wikipedia)

## Tradeoffs

A (n × d)

| | | | | |
|---|---|---|---|---|
| $a_{1,1}$ | $a_{1,2}$ | $a_{1,3}$ | … | $a_{1,d}$ |
| $a_{2,1}$ | $a_{2,2}$ | $a_{2,3}$ | … | $a_{2,d}$ |
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| $a_{5,1}$ | $a_{5,2}$ | $a_{5,3}$ | … | $a_{5,d}$ |
| … | … | … | … | … |
| $a_{n,1}$ | $a_{n,2}$ | $a_{n,3}$ | … | $a_{n,d}$ |

- (row,col) not stored
- Many possible layouts
  - For disk storage
  - For parallel partitioning
- Often tuned for matrix operations, e.g. multiplication

A

| row | column | val |
|---|---|---|
| 1 | 3 | $a_{1,3}$ |
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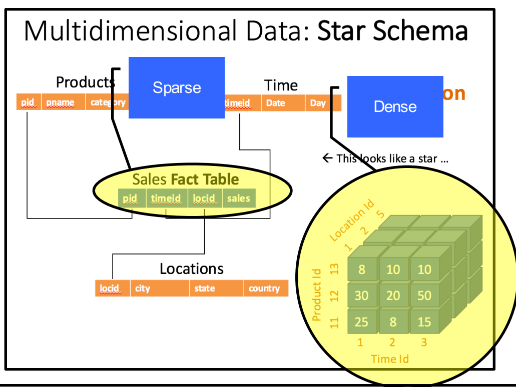
| 2 | 2741 | $a_{2,2741}$ |
| 3 | 14 | $a_{3,14}$ |
| 3 | 116 | $a_{3,116}$ |
| … | … | … |

- Empty vals not stored
- Many possible layouts
  - For disk storage
  - For parallel partitioning
- Harder to tune for matrix operations
  - Irregular structure
- Rows and columns can be arbitrary values
  - Integers, reals, strings, etc.

## Recall this slide




## Imagine Computing AB

- Sparse matrix stored as a relation:
  - (row integer, col integer, value float)
- $(AB)_{ij} = \sum_{k=1}^{m} A_{ik} B_{kj}$

```
SELECT ____________, SUM(A.val*B.val)
  FROM A, B
 WHERE ____________
GROUP BY ___________;
```

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```

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SELECT A.row, B.col, SUM(A.val*B.val)
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GROUP BY A.row, B.col;
```
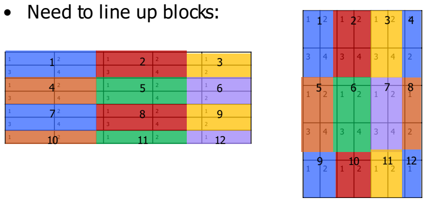

## Imagine Computing AB

- Dense matrix might be stored as a relation of blocks:
  - (blockNum integer, subMatrix blob)
- Need to line up blocks:



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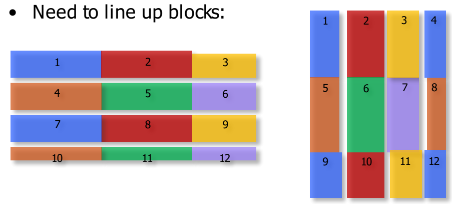


## Imagine Computing AB

- Dense matrix might be stored as a relation of blocks:
  - (blockNum integer, subMatrix blob)
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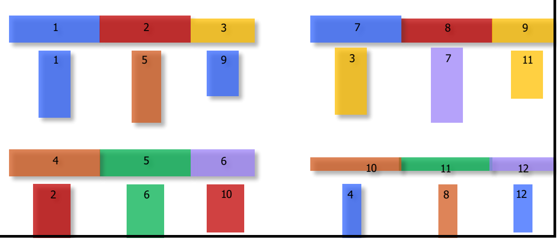



## Imagine Computing AB

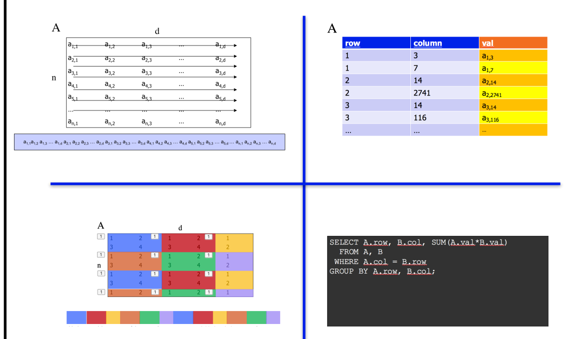
- Dense matrix might be stored as a relation of blocks:
  - (blockNum integer, subMatrix blob)
- Need to line up blocks:

```
SELECT SUM(local-matrix-multiply(A.subMatrix,
                                 B.subMatrix)
  FROM A, B
 WHERE A.blocknum = arithmetic(B.blocknum);
```

## Many other variants

- We looked at:
  - Sparse relations
  - Dense linearizations
  - Dense blocking (relations of dense blocks)
- Also
  - Relations of dense rows (row integer, vals blob)
  - Relations of dense columns (col integer, vals blob)
  - Compression schemes for sparse and dense
    - From the Scientific Computing & DB literature
- And don't forget non-numeric "dimensions"!
- At scale, looks pretty much like DB queries/dataflow!
  - Even for dense matrice, across "blocks"
  - Blocking may be or disk (out-of-core) or for parallelism

## Quick Summary



Data Models

R & G, Chaps. 2&3

## Steps in Traditional Database Design

- Requirements Analysis
  - user needs; what must database do?
- Conceptual Design
  - high level description
- Logical Design
  - translate into DBMS data model
- Schema Refinement
  - consistency, normalization
- Physical Design
  - indexes, disk layout
- Security Design
  - who accesses what, and how

## Describing Data: Data Models

- *Data model*: collection of concepts for describing data.
- *Schema:* description of a particular collection of data, using a given data model.

## Two Data Models

- Linear Algebra
  - Main concept: matrix
  - Matrix schema:
    - dimensions $n \times d$ with indices from the ordinals
    - domain for all "entries"
- Relational Model
  - Main concept: relation (table), rows and columns
  - Every relation has a schema
    - describes the columns
    - column names and simple domains
  - Values in each column all match the domain

## Relational Model

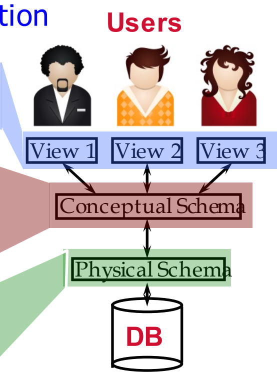
- Very expressive
  - Can represent many data relationships
  - Subsumes matrices, graphs, etc.
- Yet very simple
  - Domains of columns are atomic types
    - No nesting
- Expressive + Simple = Freedom
  - Lots of room for database *design*

## Why Focus on Relational Model?

- Most widely used model
  - And many other models are subsets (e.g. key-value stores)
- Other models exist (and co-exist)
  - "Legacy systems" in older models
    - e.g., IBM's IMS
  - Object-Relational mergers
    - Object-Oriented features provided by DBMS
    - Object-Relational Mapping (ORM) outside the DBMS
      - A la Rails (Ruby), Django (Python), Hibernate (Java)
  - Documents: XML, JSON, etc.
    - Nested or "semi-structured" data
    - Languages like Xquery, XSLT, JSONic
    - Many relational engines now handle these to a degree

## Levels of Abstraction

- Views describe how users see the data.
- Conceptual schema defines logical structure
- Physical schema describes the files and indexes used.

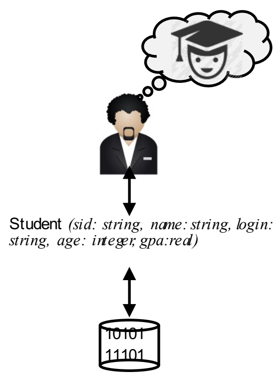



## Example: University Database

- Conceptual schema:
  - Students (sid text, name text, login text, age integer, gpa float)
  - Courses (cid text, cname text, credits integer)
  - Enrolled (sid text, cid text, grade text)
- Physical schema:
  - Relations stored as unordered files.
  - Index on first column of Students.
- External Schema (View):
  - Course_info (cid text, enrollment integer)

## Data Models

- Connect concepts to bits!
- Many models exist
- We will ground ourselves in the *Relational* model
- *Entity-Relationship* model also handy for design
  - Translates down to Relational




## Which came first? Data or Model?

- Traditionally, the model first
  - First, design conceptual schema
  - Then load data.
- Recently, emphasis on data first
  - First load bits
  - Then impose schema lazily upon read
- "Schema-on-Load" vs. "Schema-on-Read"
  - Pros/Cons?
  - Analogies to strong vs. loose typing in PL

## Let's look at both

- Schema-on-Load
  - An "engineered" design for your data
  - Keep things "right": enforce constraints
  - Ensure shared understanding of data
  - Ensure applications work well
- Data Independence
  - Major theme of early relational databases

## DB Design: Data Independence

- Insulate apps from structure of data
  - I.e. model hides details of the bits!
- Logical data independence:
  - Protection from changes in *logical* structure
- Physical data independence:
  - Protection from changes in *physical* structure
- Q: Why particularly important for DBMS?

Because databases and their associated applications persist.

## Hellerstein's Inequality

Data independence matters when…

$$\frac{dapp}{dt} << \frac{denv}{dt}$$

- Not just a database issue!
  - E.g. consider elastic resources in the cloud.
  - E.g. consider Internet-wide performance.
  - …

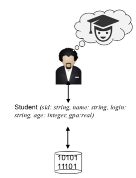
## Agile Analytics & "Schema on Use"

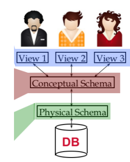
- What about agile, exploratory analytics? $\frac{dapp}{dt} >> \frac{denv}{dt}$
- First, don't let the lack of schema prevent storing data!
  - Just vomit out binary, text, CSV, JSON, xlsx, etc.
  - Shove into DBMS blobs or a filesystem (e.g. HDFS)
- Wrangle the data into shape as needed
  - Essentially defining physio-logical views over the raw bits
  - "Data Dependence"
    - Each Analyst has their own "opinion" about the data
    - "Opinion" embodied in *custom code* that is dependent on the bits!
- Fits well with data that is never (re)organized
  - E.g. Big Data, logs, "data exhaust"
  - Less of a fit with app-centric, update-heavy data

## So Which is Better? It depends.

- On the use case $app$
  - Mission-critical? Exploratory?
  - Stable? Fast-changing?
- On the environment $env$
  - Governance requirements?
  - App developers? IT managers? Analysts?

## Quick Summary




- Logical data independence:
  - Protection from changes in *logical* structure
- Physical data independence:
  - Protection from changes in *physical* structure

$$\frac{dapp}{dt} << \frac{denv}{dt}$$

## Entity-Relationship Diagrams

R & G, Chaps. 2&3

## Entity-Relationship Model

- Relational model is a great formalism
  - and a clean system framework
- But a bit detailed for design time
  - a bit fussy for brainstorming
  - hard to communicate to customers
- Entity-Relationship model is a popular "shim" over relational model
  - graphical, slightly higher level

## Steps in Traditional Database Design

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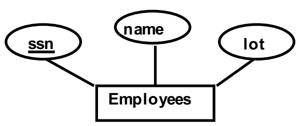
## Conceptual Design

- What are the entities and relationships?
- What info about E's & R's should be in DB?
- What *integrity constraints* (*business rules*) hold?
- *ER diagram* is the "schema"
- Can map an ER diagram into a relational schema.

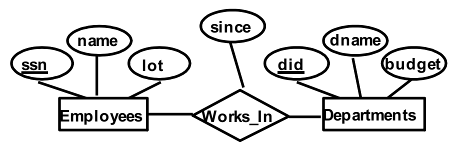
- This is where SW/data engineering *begins*
  - Ruby-on-Rails "models"

## ER Model Basics



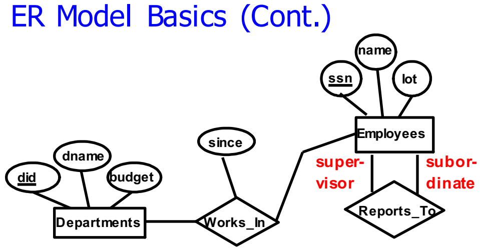

- *Entity:*
  - A real-world object described by a set of *attribute* values.
- *Entity Set*: A collection of similar entities.
  - E.g., all employees.
  - All entities in an entity set have the same attributes.
  - Each entity set has a *key* (underlined)
  - Each attribute has a *domain*

## ER Model Basics (Contd.)




- *Relationship*: Association among two or more entities.
  - E.g., Attishoo works in Pharmacy department.
  - relationships can have their own attributes.
- *Relationship Set*: Collection of similar relationships.
  - An $n$-ary relationship set $R$ relates $n$ entity sets $E_1 \dots E_n$ ; each relationship in $R$ involves entities $e_1 \in E_1, \dots, e_n \in E_n$

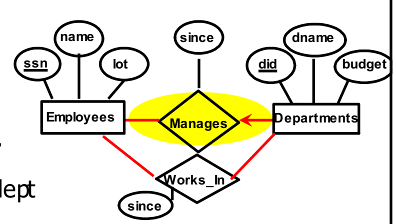
## ER Model Basics (Cont.)




- Same entity set can participate in different relationship sets, or in different "roles" in the same relationship set.

## Key Constraints

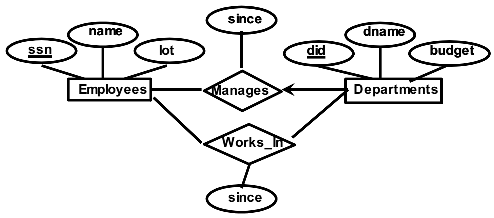
An employee can work in many departments; a dept can have many employees.



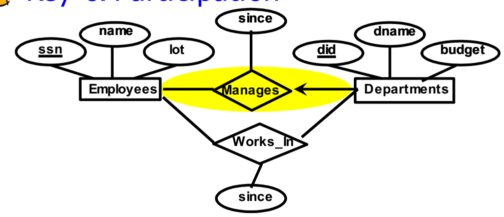

In contrast, each dept has at most one manager, according to the *key constraint* on Manages.

## Participation Constraints

- Does every employee work in a department?
- If so: a *participation constraint*
  - participation of Employees in Works_In is *total* (vs. *partia*
  - What if every department has an employee working in it?
- Participation: "at least one"

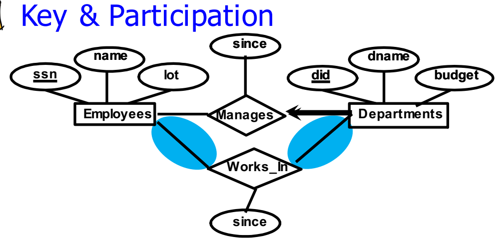



## Key & Participation




- Key: At most one

## Key & Participation




- Key: At most one
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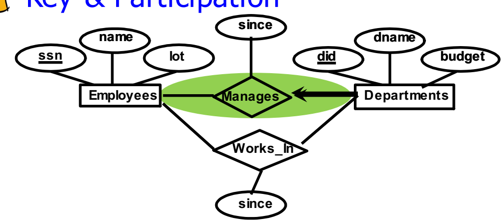
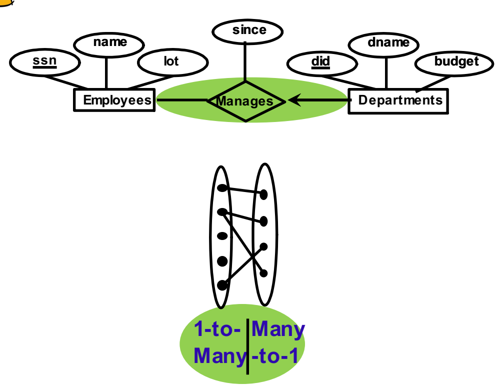
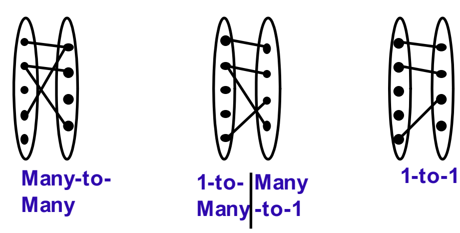
## Key & Participation




- Key: At most one
- Participation: At least one
- Both: ?



## Alternative: Crow's Foot Notation

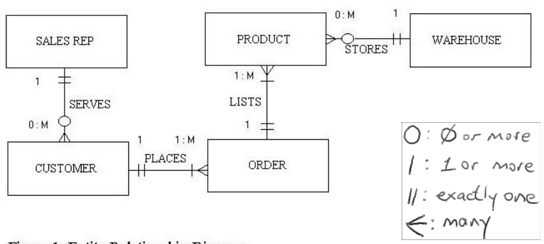
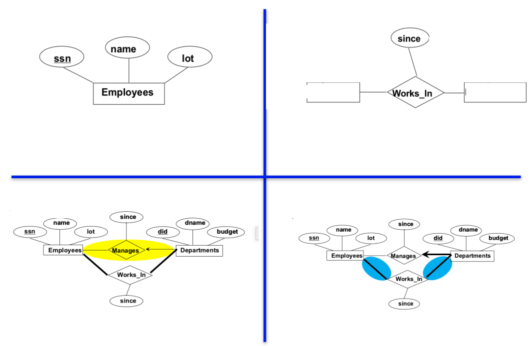



Figure 1. Entity-Relationship Diagram

* 1 INSTANCE OF A SALES REP SERVES 1 TO MANY CUSTOMERS
* 1 INSTANCE OF A CUSTOMER PLACES 1 TO MANY ORDERS
* 1 INSTANCE OF AN ORDER LISTS 1 TO MANY PRODUCTS
* 1 INSTANCE OF A WAREHOUSE STORES 0 TO MANY PRODUCTS

## Quick Summary




## ER so far

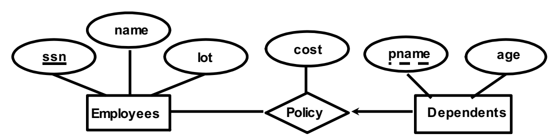
- Entities and Entity Set (boxes)
- Relationships and Relationship sets (diamonds)
- Key constraints (arrows)
- Participation constraints (bold for Total)

These are enough to get started, but we'll need more…

## Weak Entities

A *weak entity* can be identified uniquely only by considering the primary key of another (*owner*) entity.

- Owner entity set and weak entity set must participate in a one-to-many relationship set (one owner, many weak entities).
- Weak entity set must have total participation in this *identifying* relationship set.



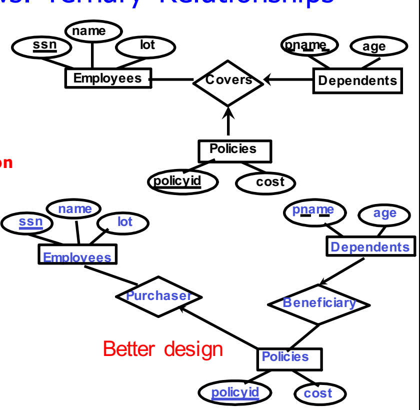

Weak entities have only a "partial key" (dashed underline)

## Binary vs. Ternary Relationships

If each policy is owned by just 1 employee:

**Key constraint on Policies would mean policy can only cover 1 dependent!**

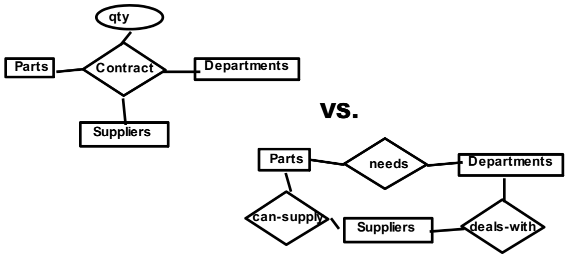
**Think through *all* the constraints in the 2nd diagram!**




## Binary vs. Ternary Relationships (Contd.)

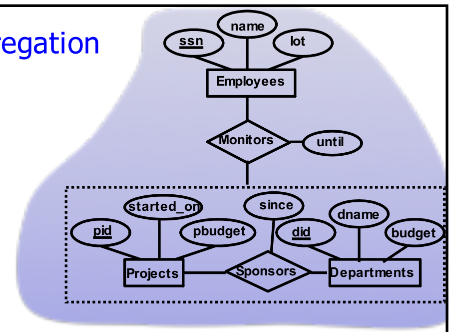
- Previous example:
  - 2 binary relationships better than 1 ternary relationship.
- An example in the other direction:
  - ternary relationship set Contracts relates entity sets Parts, Departments and Suppliers
  - relationship set has descriptive attribute *qty*.
  - no combo of binary relationships is a substitute!
    - See next slide…

## Binary vs. Ternary Relationships (Contd.)



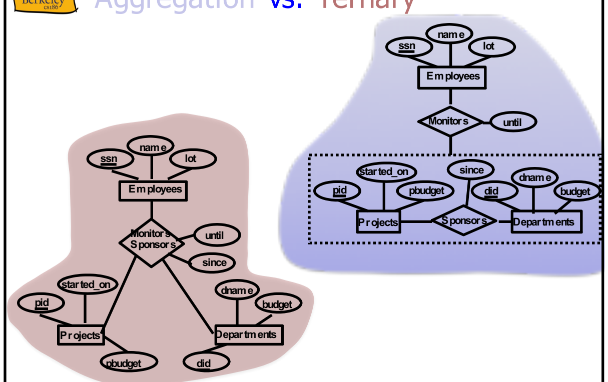

– S "can-supply" P, D "needs" P, and D "deals-with" S does not imply that D has agreed to buy P from S.
– How do we record *qty*?

## Aggregation




Allows relationships with *relationship sets*.

## Aggregation vs. Ternary




## Conceptual Design Using the ER Model

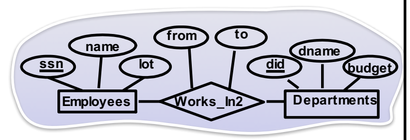
- ER modeling *can* get tricky!
- Design choices:
  – Entity or attribute?
  – Entity or relationship?
  – Relationships: Binary or ternary? Aggregation?
- ER Model goals and limitations:
  – Lots of semantics can (and should) be captured.
  – Some constraints *cannot* be captured in ER.
    - We'll refine things in our logical (relational) design

## Entity vs. Attribute

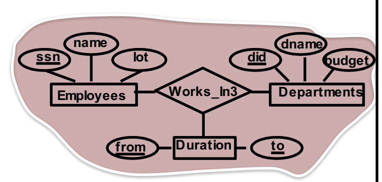
- "Address":
  – attribute of Employees?
  – Entity of its own?
- It depends! Semantics and usage.
  – Several addresses per employee?
    - must be an entity
    - atomic attribute types (no set-valued attributes!)
  – Care about structure? (city, street, etc.)
    - must be an entity!
    - atomic attribute types (no tuple-valued attributes!)

## Entity vs. Attribute (Cont.)

- Works_In2: employee cannot work in a department for >1 period.

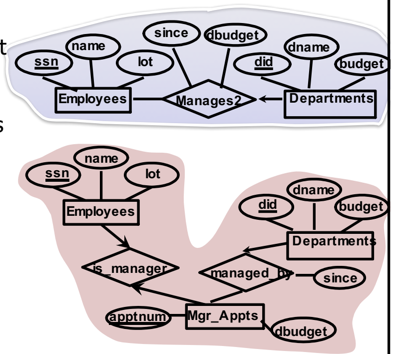



- Like multiple addresses per employee!



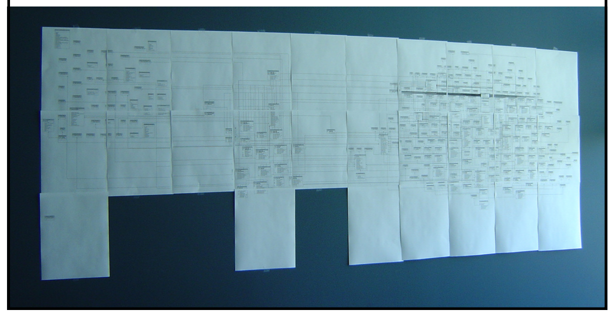
## Entity vs. Relationship

- Separate discretionary budget (dbudget) for each dept.
- What if manager's dbudget covers all managed depts
  - Could repeat value
  - But redundancy = problems
- Better design:




## E-R Diagram as Wallpaper

- Very common for them to be wall-sized

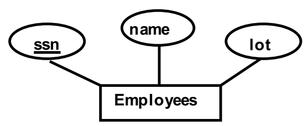


## Converting ER to Relational

- Fairly analogous structure
- But many simple concepts in ER are subtle to specify in relations

## Logical DB Design: ER to Relational

- Entity sets to tables.




| ssn | name | lot |
|---|---|---|
| 123-22-3666 | Attishoo | 48 |
| 231-31-5368 | Smiley | 22 |
| 131-24-3650 | Smethurst | 35 |

```
CREATE TABLE Employees
  (ssn  CHAR(11),
   name  CHAR(20),
   lot   INTEGER,
   PRIMARY  KEY   (ssn))
```

## Relationship Sets to Tables

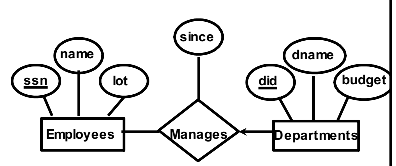
- In translating a many-to-many relationship set to a relation, attributes of the relation must include:
  1) Keys for each participating entity set (as foreign keys). This set of attributes forms a *superkey* for the relation.
  2) All descriptive attributes.

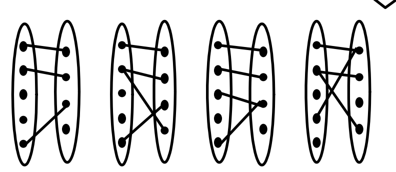
```
CREATE TABLE Works_In(
  ssn  CHAR(1),
  did  INTEGER,
  since  DATE,
  PRIMARY KEY (ssn, did),
  FOREIGN KEY (ssn)
     REFERENCES Employees,
  FOREIGN KEY (did)
   REFERENCES Departments)
```

| ssn | did | since |
|---|---|---|
| 123-22-3666 | 51 | 1/1/91 |
| 123-22-3666 | 56 | 3/3/93 |
| 231-31-5368 | 51 | 2/2/92 |

## Review: Key Constraints

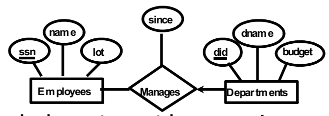
- Each dept has at most one manager, according to the *key constraint* on Manages.




*Translation to relational model?*

## Translating ER with Key Constraints




- Since each department has a unique manager, we could instead combine Manages and Departments.

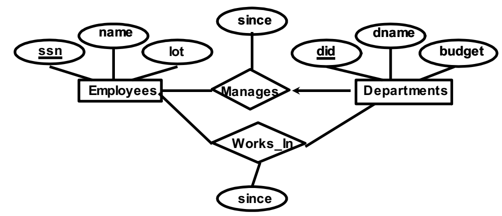
```
CREATE TABLE  Manages(
 ssn  CHAR(11),
 did  INTEGER,
 since  DATE,
 PRIMARY KEY  (did),
 FOREIGN KEY (ssn)
REFERENCES Employees,
   FOREIGN KEY (did)
REFERENCES Departments)
```

Vs.

```
CREATE TABLE  Dept_Mgr(
 did  INTEGER,
 dname  CHAR(20),
 budget  REAL,
 ssn  CHAR(11),
 since  DATE,
 PRIMARY KEY  (did),
 FOREIGN KEY (ssn)
  REFERENCES Employees)
```

## Review: Participation Constraints

- Does every department have a manager?
  - If so, this is a *participation constraint*: the participation of Departments in Manages is said to be *total* (vs. *partial*).
    - Every *did* value in Departments table must appear in a row of the Manages table (with a non-null *ssn* value!)



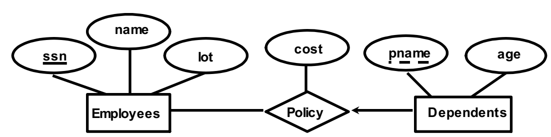

## Participation Constraints in SQL

- We can capture participation constraints involving one entity set in a binary relationship, but little else (without resorting to CHECK constraints).

```
CREATE TABLE  Dept_Mgr(
   did  INTEGER,
   dname  CHAR(20),
   budget  REAL,
   ssn  CHAR(11) NOT NULL,
   since  DATE,
   PRIMARY KEY  (did),
   FOREIGN KEY  (ssn) REFERENCES
Employees
      ON DELETE NO ACTION)
```

## Review: Weak Entities

- A *weak entity* can be identified uniquely only by considering the primary key of another (*owner*) entity.
  - Owner entity set and weak entity set must participate in a one-to-many relationship set (1 owner, many weak entities).
  - Weak entity set must have total participation in this *identifying* relationship set.

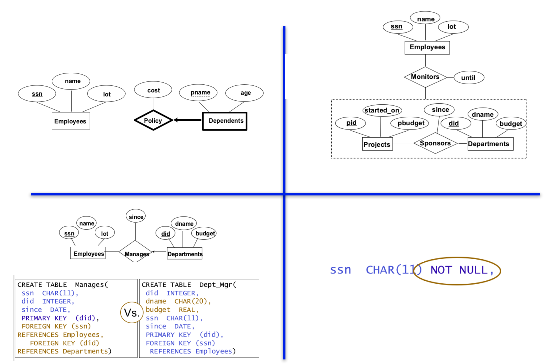



## Translating Weak Entity Sets

- Weak entity set and identifying relationship set are translated into a single table.
  - When the owner entity is deleted, all owned weak entities must also be deleted.

```
CREATE TABLE  Dep_Policy (
   pname  CHAR(20),
   age  INTEGER,
   cost  REAL,
   ssn  CHAR(11) NOT NULL,
   PRIMARY KEY  (pname, ssn),
   FOREIGN KEY  (ssn) REFERENCES Employees
      ON DELETE CASCADE)
```

## Quick Summary



## Summary of Conceptual Design

- *Conceptual design* follows *requirements analysis*,
  - Yields a high-level description of data to be stored
  - You may want to postpone it for read-only "schema on use"
- ER model popular for conceptual design
  - Constructs are expressive, close to the way people think about their applications.
  - Note: There are many variations on ER model
    - Both graphically and conceptually
- Basic constructs: *entities*, *relationships*, and *attributes* (of entities and relationships).
- Some additional constructs: *weak entities*, *ISA hierarchies* (see text if you're curious), and *aggregation*.

## Summary of ER (Cont.)

- Several kinds of integrity constraints:
  - *key constraints*
  - *participation constraints*
- Some *foreign key constraints* are also implicit in the definition of a relationship set.
- Many other constraints (notably, *functional dependencies*) cannot be expressed.
- Constraints play an important role in determining the best database design for an enterprise.

## Summary of ER (Cont.)

- ER design is *subjective*. There are often many ways to model a given scenario!
- Analyzing alternatives can be tricky, especially for a large enterprise. Common choices include:
  - Entity vs. attribute, entity vs. relationship, binary or n-ary relationship, whether or not to use ISA hierarchies, aggregation.
- Ensuring good database design: resulting relational schema should be analyzed and refined further.
  - Functional Dependency information and normalization techniques are especially useful.