Outline

0) Course Info
1) Introduction
2) Data Preparation and Cleaning
3) Schema matching and mapping
4) Virtual Data Integration
5) Data Exchange
6) Data Warehousing
7) Big Data Analytics
8) Data Provenance
6. What is Datawarehousing?

- **Problem: Data Analysis, Prediction, Mining**
  - **Example: Walmart**
  - Transactional databases
    - Run many “cheap” updates concurrently
    - E.g., each store has a database storing its stock and sales
  - Complex Analysis over Transactional Databases?
    - Want to analyze across several transactional databases
      - E.g., compute total Walmart sales per month
      - Distribution and heterogeneity
    - Want to run complex analysis over large datasets
      - Resource consumption of queries affects normal operations on transactional databases
6. What is Datawarehousing?

- **Solution:**
- **Performance**
  - Store data in a different system (the datawarehouse) for analysis
  - Bulk-load data to avoid wasting performance on concurrency control during analysis
- **Heterogeneity and Distribution**
  - Preprocess data coming from transactional databases to clean it and translate it into a unified format before bulk-loading
6. Datawarehousing Process

- 1) Design a schema for the warehouse
- 2) Create a process for preprocessing the data
- 3) Repeat
  - A) Preprocess data from the transactional databases
  - B) Bulk-load it into the warehouse
  - C) Run analytics
6. Overview

• The multidimensional datamodel (cube)
  – Multidimensional data model
  – Relational implementations

• Preprocessing and loading (ETL)

• Query language extensions
  – ROLL UP, CUBE, …

• Query processing in datawarehouses
  – Bitmap indexes
  – Query answering with views
  – Self-tuning
6. Multidimensional Datamodel

- Analysis queries are typically aggregating lower level facts about a business
  - The revenue of Walmart in each state (country, city)
  - The amount of toy products in a warehouse of a company per week
  - The call volume per zip code for the Sprint network
  - …
6. Multidimensional Datamodel

• Commonality among these queries:
  – At the core are **facts**: a sale in a Walmart store, a toy stored in a warehouse, a call made by a certain phone
  – Data is aggregated across one or more **dimensions**
    • These dimensions are typically organized hierarchically: year – month – day – hour, country – state - zip

• Example
  – The **revenue** (sum of sale amounts) of Walmart in each **state**
### 6. Example 2D

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<td>1 2 2 2 2</td>
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</tr>
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<td><strong>King Lear</strong></td>
<td>3 9 6 37 7 92</td>
<td>5 7 3 3</td>
</tr>
</tbody>
</table>
6. Generalization to multiple dimensions

• Given a fixed number of dimensions
  – E.g., product type, location, time

• Given some measure
  – E.g., number of sales, items in stock, …

• In the multidimensional datamodel we store facts: the values of measures for a combination of values for the dimensions
6. Data cubes

• **Given n dimensions**
  – E.g., product type, location, time

• **Given m measures**
  – E.g., number of sales, items in stock, …

• A **datacube** (datahypercube) is an n-dimensional datastructure that maps values in the dimensions to values for the m measures
  – **Schema**: \( D_1, \ldots, D_n, M_1, \ldots, M_m \)
  – **Instance**: a function

\[
\text{dom}(D_1) \times \ldots \times \text{dom}(D_n) \rightarrow \text{dom}(M_1) \times \ldots \times \text{dom}(M_m)
\]
6. Dimensions

• **Purpose**
  – Selection of descriptive data
  – Grouping with desired level of granularity

• A dimension is defined through a **containment hierarchy**

• Hierarchies typically have several **levels**

• The **root level** represents the whole dimensions

• We may associate additional descriptive information with elements in the hierarchy (e.g., number of residents in a city)
6. Dimension Example

• Location
  – Levels: location, state, city

Schema

| location | state | city |

Instance

- Locations
  - Illinois
    - Chicago
    - Schaumburg
  - Wisconsin
    - Madison
    - Whitewater
6. Dimension Schema

• **Schema of a Dimension**
  
  – A set $\mathbf{D}$ of category attributes $D_1, \ldots, D_n, \text{Top}_D$
    
    • These correspond to the levels
  
  – A partial order $\rightarrow$ over $\mathbf{D}$ which represents parent-child relationships in the hierarchy
    
    • These correspond to upward edges in the hierarchy
    
    • $\text{Top}_D$ is larger than anything else
    
    ─ For every $D_i$: $D_i \rightarrow \text{Top}_D$
    
    • There exists $D_{\text{min}}$ which is smaller than anything else
    
    ─ For every $D_i$: $D_{\text{min}} \rightarrow D_i$
6. Dimension Schema Example

- **Schema of Location Dimension**
  - Set of categories $D = \{\text{location, state, city}\}$
  - Partial order
    \[
    \{ \text{city} \rightarrow \text{state}, \text{city} \rightarrow \text{location}, \text{state} \rightarrow \text{location} \}
    \]
  - $\top_D = \text{location}$
  - $D_{\text{min}} = \text{city}$

```
Schema:
location
   state
     city
Instance:
Locations
  Illinois
    Chicago
    Schaumburg
  Wisconsin
    Madison
    Whitewater
```
6. Remarks

- In principle there does not have to exist an order among the elements at one level of the hierarchy
  - E.g., cities
- Hierarchies do not have to be linear
6. Cells, Facts, and Measures

• Each **cell** in the cube corresponds to a combination of elements from each dimension
  – **Facts** are non-empty cells
  – Cells store **measures**

• Cube for a combination of levels of the dimension

```
          Time
          May
          Apr
          Mar
          Feb
          Jan

Product
  Book
  Tool
  Electronic
  Audio
  Gardening

Location
  New York
  Madison
  Chicago
  Seattle
  Aspen

Fact: Items in stock in Jan at Chicago that belong to category Tool
```
Facts

- **Targets of analytics**
  - E.g., revenue, #sales, #stock

- **A fact is uniquely defined by the combination of values from the dimensions**
  - E.g., for dimensions time and location

  Revenue in **Illinois** during **Jan 2015**

- **Granularity**: Levels in the dimension hierarchy corresponding to the fact
  - E.g., state, month
Facts (Event vs. Snapshot)

• **Event Facts**
  – Model real-world events
  – E.g., Sale of an item

• **Snapshot Facts**
  – Temporal state
  – A single object (e.g., a book) may contribute to several facts
  – E.g., number of items in stock
Measures

• A **measure** describes a fact
  – May be derived from other measures

• **Two components**
  – **Numerical value**
  – **Formula** (optional): how to derive it
    • E.g., $\text{avg(revenue)} = \text{sum(revenue)} / \text{count(revenue)}$

• We may associate multiple measures to each cell
  – E.g., **number of sales and total revenue**
Measures - Granularity

• Similar to facts, measures also have a granularity
• How to change granularity of a measure?
• Need algorithm to combine measures
  – Additive measures
    • Can be aggregated along any dimension
  – Semi-additive/non-additive
    • Cannot be aggregated along some/all dimensions
    • E.g., snapshot facts along time dimension
      – Number of items in stock at Jan + Feb + … ≠ items in stock during year
      – Median of a measure
Design Process (after Kimball)

- **Comparison to classical relational modeling**
  - **Analysis driven**
    - No need to model all existing data and relationships relevant to a domain
    - Limit modeling to information that is relevant for predicted analytics
  - **Redundancy**
    - Tolerate redundancy for performance if reasonable
      - E.g., in dimension tables to reduce number of joins
Design Process – Steps

• 1) Select relevant business processes
  – E.g., order shipping, sales, support, stock management

• 2) Select granularity
  – E.g., track stock at level of branches or regions

• 3) Design dimensions
  – E.g., time, location, product, …

• 4) Select measures
  – E.g., revenue, cost, #sales, items in stock, #support requests
Design Process Example

- Coffee shop chain
  - Processes
    - Sell coffee to customers
    - Buy ingredients from suppliers
    - Ship supplies to branches
    - Pay employees
    - HR (hire, advertise positions, …)
  - Which process is relevant to be analysed to increase profits?
Design Process Example

1) Selecting process(es)
   - sell coffee to customers

2) Select granularity
   - Single sale?
   - Sale per branch/day?
   - Sale per city/year?
Design Process Example

• 1) Selecting process(es)
  – sell coffee to customers

• 2) Select granularity
  – Sale of type of coffee per branch per day
  – Sufficient for analysis
    • Save storage

• 3) Determine relevant dimensions
  – Location
  – Time
  – Product, …
Design Process Example

• 1) Selecting process(es)
  – sell coffee to customers

• 2) Select granularity
  – Sale of type of coffee per branch per day

• 3) Determine relevant dimensions
  – Location (country, state, city, zip, shop)
  – Time (year, month, day)
  – Product (type, brand, product)
Design Process Example

• 1) Selecting process(es)
  – sell coffee to customers

• 2) Select granularity
  – Sale of type of coffee per branch per day

• 3) Determine relevant dimensions
  – Location (country, state, city, zip, shop)
  – Time (year, month, day)
  – Product (type, brand, product)

• 4) Select measures
Design Process Example

1) Selecting process(es)
   - sell coffee to customers

2) Select granularity
   - Sale of type of coffee per branch per day

3) Determine relevant dimensions
   - Location (country, state, city, zip, shop)
   - Time (year, month, day)
   - Product (type, brand, product)

4) Select measures
   - cost, revenue, profit?
Relational representation

• How to model a datacube using the relational datamodel

• We start from
  – Dimension schemas
  – Set of measures
Star Schema

• A data cube is represented as a set of dimension tables and a fact table

• Dimension tables
  – For each dimension schema $D = (D_1, \ldots, D_k, \text{Top}_D)$ we create a relation
  – $D (PK, D_1, \ldots, D_k)$
  – Here PK is a primary key, e.g., $D_{\text{min}}$

• Fact table
  – $F (FK_1, \ldots, FK_n, M_1, \ldots, M_m)$
  – Each $FK_i$ is a foreign key to $D_i$
  – Primary key is the combination of all $Fk_i$
Star Schema - Remarks

• Dimension tables have redundancy
  – Values for higher levels are repeated
• Fact table is in 3NF
• $\text{Top}_D$ does not have to be stored explicitly
• Primary keys for dimension tables are typically generated (surrogate keys)
  – Better query performance by using integers
Snowflake Schema

• A data cube is represented as a set of dimension tables and a fact table

• Dimension tables
  – For each dimension schema \( D = (D_1, \ldots, D_k, \text{Top}_D) \) we create a relation multiple relations connected through FKs
  – \( D_i \) (\( PK, A_1, \ldots, A_l, FK_j \))
  – \( A_l \) is a descriptive attribute
  – \( FK_j \) is foreign key to the immediate parent(s) of \( D_i \)

• Fact table
  – \( F(FK_1, \ldots, FK_n, M_1, \ldots, M_m) \)
  – Each \( FK_i \) is a foreign key to \( D_i \)
  – Primary key is the combination of all \( Fk_i \)
Snowflake Schema - Remarks

- Avoids redundancy
- Results in much more joins during query processing
- Possible to find a compromise between snowflake and star schema
  - E.g., use snowflake for very fine-granular dimensions with many levels
Snowflake Schema - Example

– Coffee chain example
6. Extract-Transform-Load (ETL)

- The preprocessing and loading phase is called extract-transform-load (ETL) in data warehousing.
- Many commercial and open-source tools available.
- ETL process is modeled as a workflow of operators:
  - Tools typically have a broad set of build-in operators: e.g., key generation, replacing missing values, relational operators,
  - Also support user-defined operators.
6. Extract-Transform-Load (ETL)

- Some ETL tools
  - Pentaho Data Integration
  - Oracle Warehouse Builder (OWB)
  - IBM Infosphere Information Server
  - Talend Studio for Data Integration
  - CloverETL
  - Cognos Data Manager
  - Pervasive Data Integrator
  - ...

CS520 - 6) Data Warehousing
Operators supported by ETL

- Many of the preprocessing and cleaning operators we already know
  - Surrogate key generation (like creating existentials with skolems)
  - Fixing missing values
    - With default value, using trained model (machine learning)
  - Relational queries
    - E.g., union of two tables or joining two tables
  - Extraction of structured data from semi-structured data and/or unstructured data
  - Entity resolution, data fusion
6. ETL Process

• Operators can be composed to form complex workflows
6. Typical ETL operators

- **Elementizing**
  - Split values into more fine-granular elements
- **Standardization**
- **Verification**
- **Matching with master data**
- **Key generation**
- **Schema matching, Entity resolution/Deduplication, Fusion**
6. Typical ETL operators

- Control flow operators
  - AND/OR
  - Fork
  - Loops
  - Termination
    - Successful
    - With warning/errors
6. Typical ETL operators

- **Elementizing**
  - Split non 1NF data into individual elements

- **Examples**
  - name: “Peter Gertsen” -> firstname: “Peter”, lastname: “Gertsen”
  - Address: “10 W 31st, Chicago, IL 60616” -> street = “10 W 31st”, city = “Chicago”, state = “IL”, zip = “60616”
6. Typical ETL operators

• **Standardization**
  – Expand abbreviation
  – Resolve synonyms
  – Unified representation of, e.g., dates

• **Examples**
  – “IL” -> “Illinois”
  – “m/w”, “M/F” -> “male/female”
  – “Jan”, “01”, “January”, “january” -> “January”
  – “St” -> “Street”, “Dr” -> “Drive”, …
6. Typical ETL operators

- **Verification**
  - Same purpose as constraint based data cleaning but typically does not rely on constraints, but, e.g., regular expression matching

- **Examples**
  - Phone matches “\[0-9\]\{3\}-\[0-9\]\{3\}-\[0-9\]\{4\}”
  - For all t in Tokens(product description), t exists in English language dictionary
6. Typical ETL operators

• Matching master data (lookup)
  – Check and potentially repair data based on available master data

• Examples
  – E.g., using a clean lookup table with (city,zip) replace the city in each tuple if the pair (city,zip) does not occur in the lookup table
6. Metadata management

• As part of analysis in DW data is subjected to a complex pipeline of operations
  – Sources
  – ETL
  – Analysis queries

• -> important, but hard, to keep track of what operations have been applied to data and from which sources it has been derived
  – Need metadata management
    • Including provenance (later in this course)
6. Querying DW

- Targeted model (cube vs. relational)
  - Design specific language for datacubes
  - Add suitable extensions to SQL

- Support typical analytical query patterns
  - Multiple parallel grouping criteria
    - Show total sales, subtotal per state, and subtotal per city
    - Three subqueries with different group-by in SQL
  - Windowed aggregates and ranking
    - Show 10 most successful stores
    - Show cumulative sales for months of 2016
      - E.g., the result for Feb would be the sum of the sales for Jan + Feb
6. Querying DW

• Targeted model (cube vs. relational)
  – Design specific language for datacubes
    • MDX
  – Add suitable extensions to SQL
    • GROUPING SETS, CUBE, …
    • Windowed aggregation using OVER(), PARTITION BY, ORDER BY, window specification
    • Window functions
      – RANK, DENSE_RANK()
6. Cube operations

• Roll-up
  – Move from fine-granular to more coarse-granular in one or more dimensions of a datacube
    • E.g., sales per (city, month, product category) to Sales per (state, year, product category)

• Drill-down
  – Move from coarse-granular to more fine-granular in one of more dimensions
    • E.g., phonecalls per (city, month) to phonecalls per (zip, month)
6. Cube operations

• Drill-out
  – Add additional dimensions
    • special case of drill-down starting from $\text{Top}_D$ in dimension(s)
    • E.g., sales per (city, product category) to Sales per (city, year, product category)

• Drill-in
  – Remove dimension
    • special case for roll-up move to $\text{Top}_D$ for dimension(s)
    • E.g., phonecalls per (city, month) to phonecalls per (month)
6. Cube operations

• Slice
  – Select data based on restriction of the values of one dimension
    • E.g., sales per (city,month) -> sales per (city) in Jan

• Dice
  – Select data based on restrictions of the values of multiple dimensions
    • E.g., sales per (city,month) -> sales in Jan for Chicago and Washington DC
6. SQL Extensions

• Recall that grouping on multiple sets of attributes is hard to express in SQL
  – E.g., give me the total sales, the sales per year, and the sales per month
  • Practice
6. SQL Extensions

• Syntactic Sugar for multiple grouping
  – GROUPING SETS
  – CUBE
  – ROLLUP

• These constructs are allowed as expressions in the GROUP BY clause
6. GROUPING SETS

- GROUP BY GROUPING SETS ((set_1), ..., (set_n))
- Explicitly list sets of group by attributes
- Semantics:
  - Equivalent to UNION over duplicates of the query each with a group by clause GROUP BY set_i
  - Schema contains all attributes listed in any set
  - For a particular set, the attribute not in this set are filled with NULL values
6. GROUPING SETS

SELECT quarter, 
    city, 
    product_typ, 
    SUM(profit) AS profit 
FROM facttable F, time T, location L, product P 
WHERE 
    F.TID = T.TID AND F.LID = L.LID AND F.PID = P.PID 
GROUP BY GROUPING SETS 
    ( (quarter, city), (quarter, product_typ))
6. GROUPING SETS

SELECT quarter, city, NULL AS product_typ,
    SUM(profit) AS profit
FROM facttable F, time T, location L, product P
WHERE F.TID = T.TID AND F.LID = L.LID AND F.PID = P.PID
GROUP BY quarter, city

UNION

SELECT quarter, NULL AS city, product_typ,
    SUM(profit) AS profit
FROM facttable F, time T, location L, product P
WHERE F.TID = T.TID AND F.LID = L.LID AND F.PID = P.PID
GROUP BY quarter, product_type
6. GROUPING SETS

- Problem:
  - How to distinguish between NULLs based on grouping sets and NULL values in a group by column?

GROUP BY GROUPING SETS
   ( (quarter, city), (quarter, product_typ), (quarter, product_typ, city) )

<table>
<thead>
<tr>
<th>quarter</th>
<th>city</th>
<th>product_typ</th>
<th>profit</th>
</tr>
</thead>
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<td>2010 Q1</td>
<td></td>
<td></td>
<td>8347</td>
</tr>
<tr>
<td>2012 Q2</td>
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<td></td>
<td>7836</td>
</tr>
<tr>
<td>2012 Q2</td>
<td></td>
<td></td>
<td>12300</td>
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<tr>
<td>2012 Q2</td>
<td>Chicago</td>
<td></td>
<td>12344</td>
</tr>
<tr>
<td>2012 Q2</td>
<td>Seattle</td>
<td></td>
<td>124345</td>
</tr>
<tr>
<td>2012 Q2</td>
<td>Seattle</td>
<td>Gardening</td>
<td>12343</td>
</tr>
</tbody>
</table>

Did not group on product_typ or this is the group for all NULL values in product_typ?
6. GROUPING SETS

- Solution:
  - GROUPING predicate
  - GROUPING(A) = 1 if grouped on attribute A, 0 else

SELECT ... GROUPING(product_typ) AS grp_prd
...
GROUP BY GROUPING SETS
  ( (quarter, city), (quarter, product_typ), (quarter, product_typ, city)

<table>
<thead>
<tr>
<th>quarter</th>
<th>city</th>
<th>product_typ</th>
<th>profit</th>
<th>grp_prd</th>
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<td>Seattle</td>
<td>Gardening</td>
<td>12343</td>
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</tr>
</tbody>
</table>

Now it’s clear!
6. GROUPING SETS

• Combining GROUPING SETS

GROUP BY A, B
= GROUP BY GROUPING SETS ((A,B))

GROUP BY GROUPING SETS ((A,B), (A,C), (A))
= GROUP BY A, GROUPING SETS ((B), (C), ( ))

GROUP BY GROUPING SETS ((A,B), (B,C),
GROUPING SETS ((D,E), (D))
= GROUP BY GROUPING SETS ( (A,B,D,E), (A,B,D), (B,C,D,E), (B,C,D) )
6. CUBE

- GROUP BY CUBE (set)
- Group by all $2^n$ subsets of set

GROUP BY CUBE (A,B,C)

= GROUP BY GROUPING SETS ( 
  (),
  (A), (B), (C),
  (A,B), (A,C), (B,C),
  (A,B,C)
)
6. CUBE

- GROUP BY **ROLLUP**\( (A_1, \ldots, A_n) \)
- Group by all prefixes
- Typically different granularity levels from single dimension hierarchy, e.g., year-month-day
  - Database can often find better evaluation strategy

\[
\text{GROUP BY ROLLUP} (A,B,C) = \text{GROUP BY GROUPING SETS} ( \\
(A,B,C), \\
(A,B), \\
(A), \\
(()) \\
) \\
\]
6. OVER clause

• Agg OVER (partition-clause, order-by, window-specification)

• New type of aggregation and grouping where
  – Each input tuple is paired with the aggregation result for the group it belongs to
  – More flexible grouping based on order and windowing
  – New aggregation functions for ranking queries
    • E.g., RANK(), DENSE_RANK()
6. OVER clause

- Agg OVER (partition-clause, order-by, window-specification)

- New type of aggregation and grouping where

  \[ \text{SELECT shop, sum(profit) OVER()} \]
  
  - aggregation over full table

  \[ \text{SELECT shop, sum(profit) OVER(PARTITION BY state)} \]
  
  - like group-by

  \[ \text{SELECT shop, sum(profit) OVER(ORDER BY month)} \]
  
  - rolling sum including everything with smaller month

  \[ \text{SELECT shop, sum(profit) OVER(ORDER BY month 6 PRECEDING 3 FOLLOWING)} \]
6. OVER clause

- `Agg OVER (partition-clause order-by,window-specification)`

- New type of aggregation and grouping where

  `<window frame preceding> ::= {`  
  
  `UNBOUNDED PRECEDING`  
  | `n PRECEDING`  
  | `CURRENT ROW`  
  }`

  `<window frame following> ::= {`  
  
  `UNBOUNDED FOLLOWING`  
  | `n FOLLOWING`  
  | `CURRENT ROW`  
  }`
6. OVER clause

SELECT year, month, city, profit
  SUM(profit) OVER () AS ttl
FROM sales

• For each tuple build a set of tuples belonging to the same window
  – Compute aggregation function over window
  – Return each input tuple paired with the aggregation result for its window

• OVER() = one window containing all tuples
6. OVER clause

SELECT year, month, city
    SUM(profit) OVER (PARTITION BY year) AS ttl
FROM sales

• PARITION BY
  – only tuples with same partition-by attributes belong to the same window

• Like GROUP BY

<table>
<thead>
<tr>
<th>year</th>
<th>month</th>
<th>city</th>
<th>profit</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010</td>
<td>1</td>
<td>Chicago</td>
<td>10</td>
</tr>
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<td>2010</td>
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</table>
6. OVER clause

SELECT year, month, city
    SUM(profit) OVER (ORDER BY year, month) AS ttl
FROM sales

• ORDER BY
  – Order tuples on these expressions
  – Only tuples which are <= to the order as the current tuple belong to the same window

• E.g., can be used to compute an accumulate total

<table>
<thead>
<tr>
<th>year</th>
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• E.g., can be used to compute an accumulate total

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</tr>
</tbody>
</table>
SELECT year, month, city 
    SUM(profit) OVER (ORDER BY year, month) AS ttl
FROM sales

• ORDER BY
  – Order tuples on these expressions
  – Only tuples which are <= to the order as the current tuple belong to the same window

• E.g., can be used to compute an accumulate total

<table>
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<tr>
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<td>12</td>
<td>22</td>
</tr>
</tbody>
</table>
6. OVER clause

SELECT year, month, city
    SUM(profit) OVER (ORDER BY year, month) AS ttl
FROM sales

- **ORDER BY**
  - Order tuples on these expressions
  - Only tuples which are \( \leq \) to the order as the current tuple belong to the same window

- E.g., can be used to compute an accumulate total

<table>
<thead>
<tr>
<th>year</th>
<th>month</th>
<th>city</th>
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<tbody>
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<td>10</td>
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</tr>
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<tr>
<td>2010</td>
<td>1</td>
<td>New York</td>
<td>12</td>
<td>22</td>
</tr>
</tbody>
</table>
6. OVER clause

```sql
SELECT year, month, city 
    SUM(profit) OVER (PARTITION BY year ORDER BY month) 
AS ttl 
FROM sales
```

- **Combining PARTITION BY and ORDER BY**
  - First partition, then order tuples within each partition

<table>
<thead>
<tr>
<th>year</th>
<th>month</th>
<th>city</th>
<th>profit</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010</td>
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<td>1</td>
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<td>45</td>
<td>45</td>
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<tr>
<td>2010</td>
<td>1</td>
<td>New York</td>
<td>12</td>
<td>22</td>
</tr>
</tbody>
</table>
6. OVER clause

SELECT year, month, city
    SUM(profit) OVER (PARTITION BY year ORDER BY month
    RANGE BETWEEN 1 PRECEDING
    AND 1 FOLLOWING) AS ttl
FROM sales

- Explicit window specification
  - Requires ORDER BY
  - Determines which tuples “surrounding” the tuple according to the sort order to include in the window

<table>
<thead>
<tr>
<th>year</th>
<th>month</th>
<th>city</th>
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<th>ttl</th>
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<td>27</td>
</tr>
</tbody>
</table>
6. OVER clause

SELECT year, month, city
    SUM(profit) OVER (ORDER BY year, month
        ROWS BETWEEN 1 PRECEDING
            AND 1 FOLLOWING) AS ttl
FROM sales

• Explicit window specification
  – Requires ORDER BY
  – Determines which tuples “surrounding” the tuple according to the sort order to include in the window
• **Multidimensional expressions (MDX)**
  – Introduced by Microsoft
  – Query language for the cube data model
  – SQL-like syntax
    • Keywords have different meaning
  – MDX queries return a multi-dimensional report
    • 2D = spreadsheet
    • 3D or higher, e.g., multiple spreadsheets
6. MDX Query

• Basic Query Structure

SELECT <axis-spec₁>, ...
FROM <cube-spec₁>, ...
WHERE ( <select-spec> )

• Note!

– Semantics of SELECT, FROM, WHERE not what you would expect knowing SQL
SELECT { Chicago, Schaumburg } ON ROWS
   { [2010], [2011].CHILDREN } ON COLUMNS
FROM PhoneCallsCube
WHERE ( Measures.numCalls, Carrier.Spring )

• Meaning of
  – [] interpret number as name
  – {} set notation
  – () tuple in where clause

<table>
<thead>
<tr>
<th></th>
<th>2010</th>
<th>2011 Jan</th>
<th>2011 Feb</th>
<th>2011 Mar</th>
<th>...</th>
<th>2011 Dec</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chicago</td>
<td>23423</td>
<td>5425234523</td>
<td>432</td>
<td>43243434</td>
<td>...</td>
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<td>12315</td>
<td>213333</td>
<td>123213</td>
<td>...</td>
<td>123153425</td>
</tr>
</tbody>
</table>
6. MXD

```sql
SELECT { Chicago, Schaumburg } ON ROWS
{ [2010], [2011].CHILDREN } ON COLUMNS
FROM PhoneCallsCube
WHERE (Measures.numCalls, Carrier.Spring)
```

**Datacube(s) to use**

**Select measures to aggregate over**

**Slice (e.g., here only aggregation over Spring calls)**

Determine result layout rows and columns of spreadsheet

Specify sets of dimensional concepts

<table>
<thead>
<tr>
<th></th>
<th>2010</th>
<th>2011 Jan</th>
<th>2011 Feb</th>
<th>2011 Mar</th>
<th>...</th>
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SELECT { Chicago, Schaumburg } ON ROWS
   { [2010], [2011].CHILDREN } ON COLUMNS
FROM PhoneCallsCube
WHERE ( Measures.numCalls, Carrier.Spring )

• Select specifies dimensions in result and how to visualize
  – ON COLUMNS, ON ROWS, ON PAGES, ON SECTIONS, ON CHAPTERS
• Every dimension in result corresponds to one dimension in the cube
  – Set of concepts from this dimensions which may be from different levels of granularity
6. MXD - SELECT

• Specify concepts from dimensions
  – List all values as set, e.g., \{ [2010], [2011] \}
  – Not necessarily from same level of hierarchy (e.g., mix years and months)

• Language constructs for accessing parents and children or members of a level in the hierarchy
  – **CHILDREN**: all direct children
    • E.g., \[2010\].\text{CHILDREN} = \{ [2010 \ Jan], \ldots, [2010 \ Dec] \}
  – **PARENT**: the direct parent
    • E.g., \[2010 \ Jan\].\text{PARENT} = [2010]
  – **MEMBERS**: all direct children
    • E.g., \text{Time.Years.MEMBERS} = \{ [1990], [1991], \ldots, [2016] \}
  – **LASTCHILD**: last child (according to order of children)
    • E.g., \[2010\].\text{LASTCHILD} = [2010 \ Dec]
  – **NEXTMEMBER**: right sibling on same level
    • E.g., \[2010\].\text{NEXTMEMBER} = [2011]
  – \[a]\,:[b]\,: all members in interval between a and b
6. MXD - SELECT

- Specify concepts from dimensions
  - List all values as set, e.g., \{ [2010], [2011] \}
  - Not necessarily from same level of hierarchy (e.g., mix years and months)

- Language constructs for accessing parents and children or members of a level in the hierarchy
  - **CHILDREN**: all direct children
    - E.g., \[2010\].CHILDREN = \{[2010 Jan], ..., [2010 Dec]\}
  - **PARENT**: the direct parent
    - E.g., \[2010 Jan\].PARENT = \[2010\]
  - **MEMBERS**: all direct children
    - E.g., Time.Years.MEMBERS = \{[1990], [1991], ..., [2016]\}
  - **LASTCHILD**: last child (according to order of children)
    - E.g., \[2010\].LASTCHILD = \[2010 Dec\]
  - **NEXTMEMBER**: right sibling on same level
    - E.g., \[2010\].NEXTMEMBER = \[2011\]
  - **[a] : [b]**: all members in interval between a and b
    - E.g., \[1990\] : \[1993\] = \{[1990], [1991], [1992], [1993]\}
6. MXD - SELECT

- Nesting of sets: **CROSSJOIN**
  - Project two dimensions into one
  - Forming all possible combinations

```sql
SELECT CROSSJOIN (
    { Chicago, Schaumburg },
    { [2010], [2011] }
) ON ROWS
{ [2010], [2011].CHILDREN } ON COLUMNS
FROM PhoneCallsCube
WHERE ( Measures.numCalls )
```

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
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</thead>
<tbody>
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<td>32321132</td>
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<tr>
<td></td>
<td>2011</td>
<td>12355</td>
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</tbody>
</table>
6. MXD - SELECT

• Conditional selection of members: FILTER
  – One use members that fulfill condition
  – E.g., condition over aggregation result

• Show results for all month of 2010 where there are more Sprint calls than ATT calls

```
SELECT FILTER([2010].CHILDREN,
               (Sprint, numCalls) > (ATT, numCalls))
ON ROWS { Chicago } ON COLUMNS
FROM PhoneCallsCube
WHERE ( Measures.numCalls )
```
6. Query Processing in DW

- Large topic, here we focus on two aspects
  - Partitioning
  - Query answering with materialized views
6. Partitioning

- **Partitioning** splits a table into multiple fragments that are stored independently
  - E.g., split across X disks, across Y servers

- **Vertical partitioning**
  - Split columns across fragments
    - E.g., \( R = \{A, B, C, D\} \), fragment \( F_1 = \{A, B\} \), \( F_2 = \{C, D\} \)
    - Either add a row id to each fragment or the primary key to be able to reconstruct

- **Horizontal partitioning**
  - Split rows
  - Hash vs. range partitioning
6. Partitioning

• Why partitioning?
  – Parallel/distributed query processing
    • read/write fragments in parallel
    • Distribute storage load across disks/servers
  – Avoid reading data that is not needed to answer a query
    • Vertical
      – Only read columns that are accessed by query
    • Horizontal
      – only read tuples that may match queries selection conditions
### 6. Partitioning

**Vertical Partitioning**

- Fragments $F_1$ to $F_n$ of relation $R$ such that
  - $\text{Sch}(F_1) \cup \text{Sch}(F_2) \cup \ldots \cup \text{Sch}(F_n) = \text{Sch}(R)$
  - Store row id or PK of $R$ with every fragment
  - Restore relation $R$ through natural joins

<table>
<thead>
<tr>
<th>Name</th>
<th>Salary</th>
<th>Age</th>
<th>Gender</th>
<th>Rowid</th>
<th>Name</th>
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</tbody>
</table>
6. Partitioning

- **Horizontal Partitioning**
  - **Range** partitioning on attribute A
    - Split domain of A into intervals representing fragments
    - E.g., tuples with A = 15 belong to fragment [0,20]
  - Fragments F₁ to Fₙ of relation R such that
    - Sch(F₁) = Sch(F₂) = … = Sch(Fₙ) = Sch(R)
    - R = F₁ u … u Fₙ

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Salary [0,15000]

Salary [15001,10000]
6. Partitioning

- **Horizontal Partitioning**
  - **Hash** partitioning on attribute A
    - Split domain of A into x buckets using hash function
    - E.g., tuples with \( h(A) = 3 \) belong to fragment \( F_3 \)
    - \( \text{Sch}(F_1) = \text{Sch}(F_2) = \ldots = \text{Sch}(F_n) = \text{Sch}(R) \)
    - \( R = F_1 \cup \ldots \cup F_n \)

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Salary
- \( h(24,000) = 0 \)
- \( H(14,000) = 0 \)
- \( h(12,000) = 1 \)
- \( H(20,000) = 1 \)
- \( H(50,000) = 1 \)
Outline

0) Course Info
1) Introduction
2) Data Preparation and Cleaning
3) Schema matching and mapping
4) Virtual Data Integration
5) Data Exchange
6) Data Warehousing
7) Big Data Analytics
8) Data Provenance