

Data Mining:

Concepts and Techniques


(3rd ed.)

— Chapter 4 —

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Chapter 4: Data Warehousing and On-line Analytical Processing

- Data Warehouse: Basic Concepts 
- Data Warehouse Modeling: Data Cube and OLAP
- Data Warehouse Design and Usage
- Data Warehouse Implementation
- Data Generalization by Attribute-Oriented Induction
- Summary

What is a Data Warehouse?

- Defined in many different ways, but not rigorously.
 - A decision support database that is maintained **separately** from the organization's operational database
 - Support **information processing** by providing a solid platform of consolidated, historical data for analysis.
- "A data warehouse is a subject-oriented, integrated, time-variant, and nonvolatile collection of data in support of management's decision-making process."—W. H. Inmon
- Data warehousing:
 - The process of constructing and using data warehouses

Data Warehouse—Subject-Oriented

- Organized around major subjects, such as **customer, product, sales**
- Focusing on the modeling and analysis of data for decision makers, not on daily operations or transaction processing
- Provide **a simple and concise** view around particular subject issues by **excluding data that are not useful in the decision support process**

Data Warehouse—Integrated

- Constructed by integrating multiple, heterogeneous data sources
 - relational databases, flat files, on-line transaction records
- Data cleaning and data integration techniques are applied.
 - Ensure consistency in naming conventions, encoding structures, attribute measures, etc. among different data sources
 - E.g., Hotel price: currency, tax, breakfast covered, etc.
 - When data is moved to the warehouse, it is converted.

Data Warehouse—Time Variant

- The time horizon for the data warehouse is significantly longer than that of operational systems
 - Operational database: current value data
 - Data warehouse data: provide information from a historical perspective (e.g., past 5-10 years)
- Every key structure in the data warehouse
 - Contains an element of time, explicitly or implicitly
 - But the key of operational data may or may not contain “time element”

Data Warehouse—Nonvolatile

- A **physically separate store** of data transformed from the operational environment
- Operational **update of data does not occur** in the data warehouse environment
 - Does not require transaction processing, recovery, and concurrency control mechanisms
 - Requires only two operations in data accessing:
 - *initial loading of data* and *access of data*

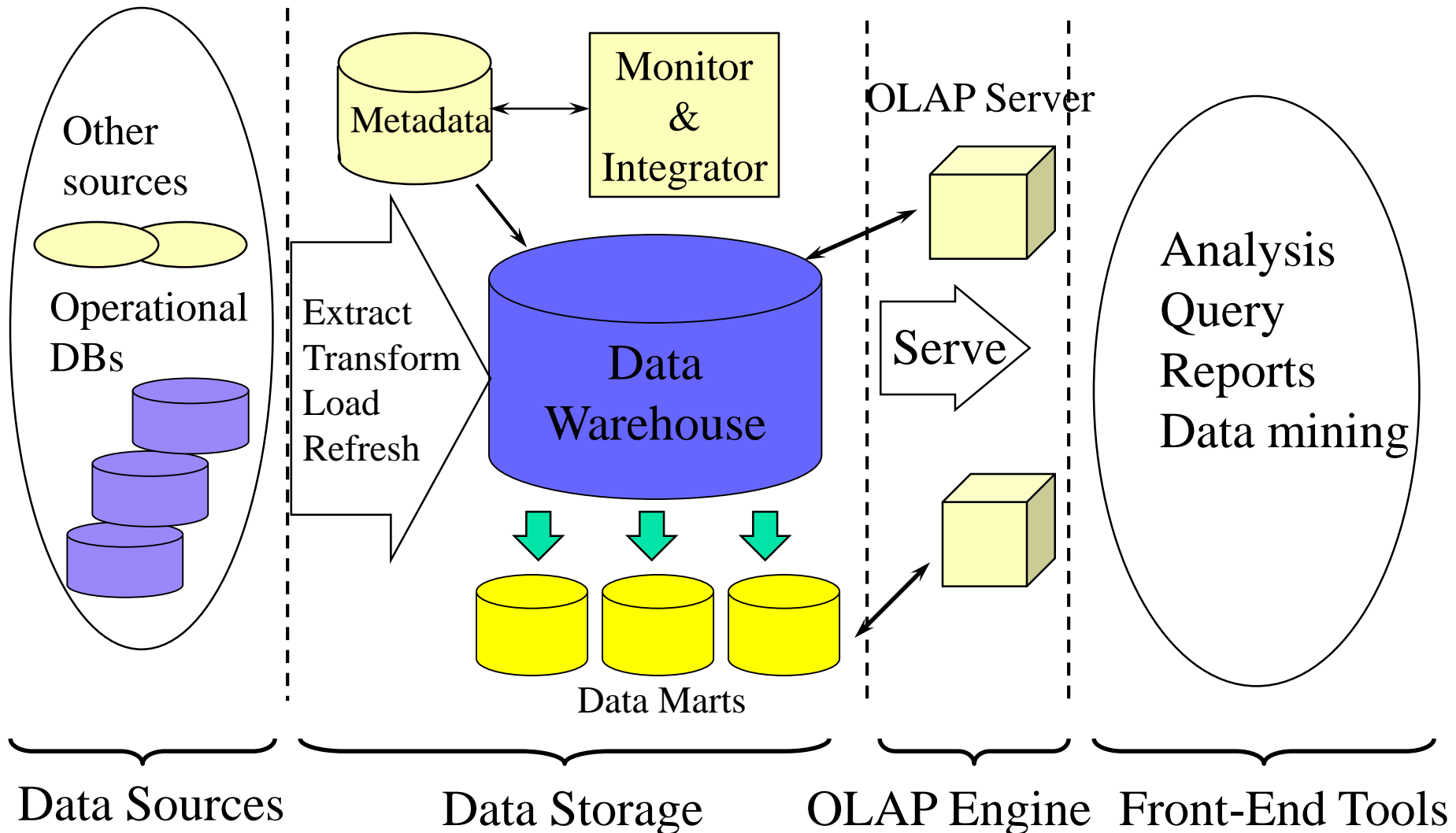
OLTP vs. OLAP

| | OLTP | OLAP |
|---------------------------|--|---|
| users | clerk, IT professional | knowledge worker |
| function | day to day operations | decision support |
| DB design | application-oriented | subject-oriented |
| data | current, up-to-date detailed, flat relational isolated | historical, summarized, multidimensional integrated, consolidated |
| usage | repetitive | ad-hoc |
| access | read/write index/hash on prim. key | lots of scans |
| unit of work | short, simple transaction | complex query |
| # records accessed | tens | millions |
| #users | thousands | hundreds |
| DB size | 100MB-GB | 100GB-TB |
| metric | transaction throughput | query throughput, response |

Why a Separate Data Warehouse?

- High performance for both systems
 - DBMS—tuned for OLTP: access methods, indexing, concurrency control, recovery
 - Warehouse—tuned for OLAP: complex OLAP queries, multidimensional view, consolidation
- Different functions and different data:
 - missing data: Decision support requires historical data which operational DBs do not typically maintain
 - data consolidation: DS requires consolidation (aggregation, summarization) of data from heterogeneous sources
 - data quality: different sources typically use inconsistent data representations, codes and formats which have to be reconciled
- Note: There are more and more systems which perform OLAP analysis directly on relational databases

Data Warehouse: A Multi-Tiered Architecture



Three Data Warehouse Models

- Enterprise warehouse

- collects all of the information about subjects spanning the entire organization

- Data Mart

- a subset of corporate-wide data that is of value to a specific groups of users. Its scope is confined to specific, selected groups, such as marketing data mart
 - Independent vs. dependent (directly from warehouse) data mart

- Virtual warehouse

- A set of views over operational databases
- Only some of the possible summary views may be materialized

Extraction, Transformation, and Loading (ETL)

- **Data extraction**

- get data from multiple, heterogeneous, and external sources

- **Data cleaning**

- detect errors in the data and rectify them when possible

- **Data transformation**

- convert data from legacy or host format to warehouse format

- **Load**

- sort, summarize, consolidate, compute views, check integrity, and build indices and partitions


- **Refresh**

- propagate the updates from the data sources to the warehouse

Metadata Repository

- **Meta data** is the data defining warehouse objects. It stores:
- Description of the **structure** of the data warehouse
 - schema, view, dimensions, hierarchies, derived data defn, data mart locations and contents
- **Operational** meta-data
 - data lineage (history of migrated data and transformation path), currency of data (active, archived, or purged), monitoring information (warehouse usage statistics, error reports, audit trails)
- The **algorithms** used for summarization
- The **mapping** from operational environment to the data warehouse
- Data related to **system performance**
 - warehouse schema, view and derived data definitions
- **Business data**
 - business terms and definitions, ownership of data, charging policies

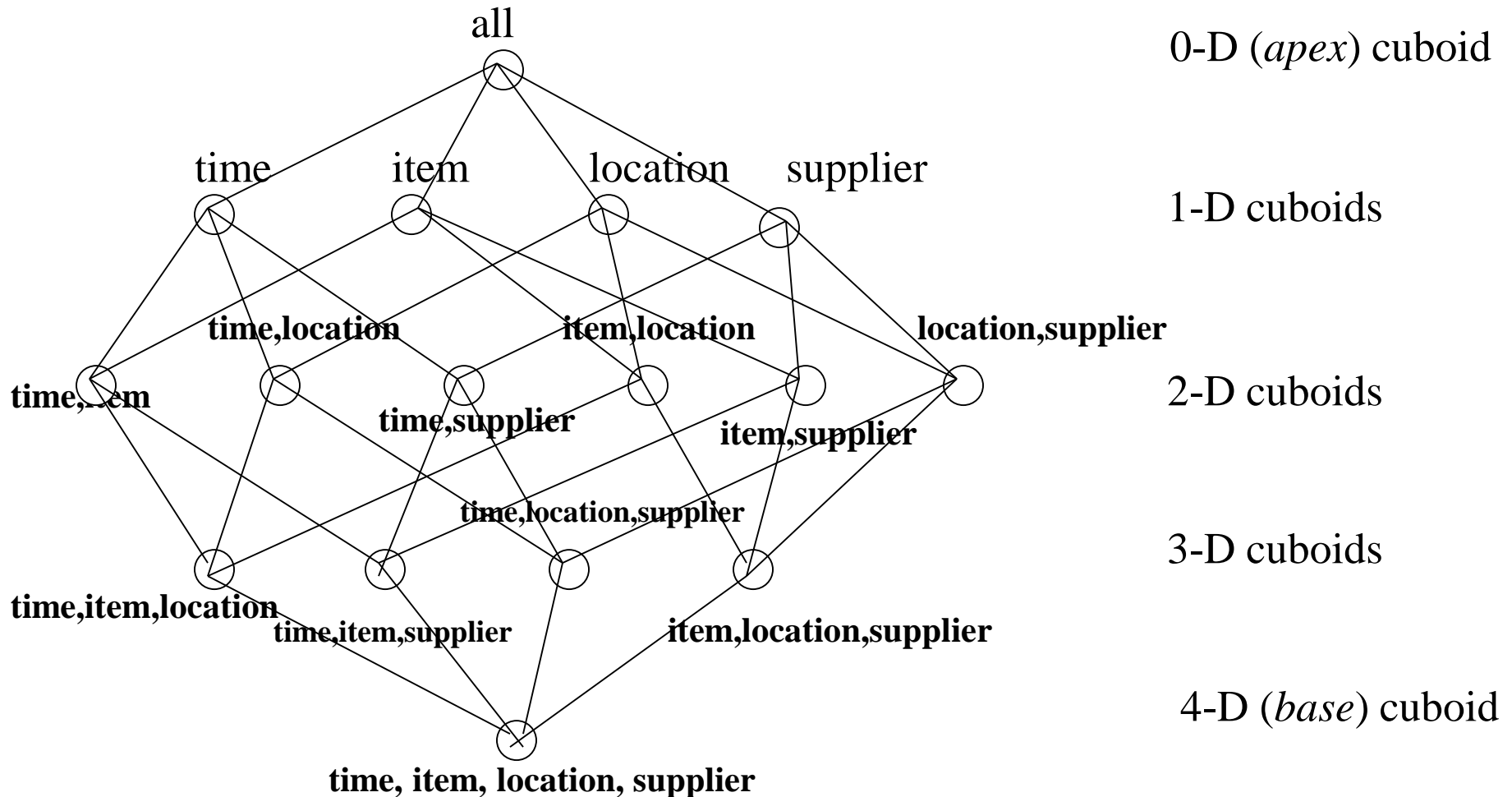
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From Tables and Spreadsheets to Data Cubes

- A **data warehouse** is based on a **multidimensional data model** which views data in the form of a data cube
- A data cube, such as **sales**, allows data to be modeled and viewed in multiple dimensions
 - **Dimension tables**, such as **item** (item_name, brand, type), or **time**(day, week, month, quarter, year)
 - **Fact table** contains **measures** (such as **dollars_sold**) and keys to each of the related dimension tables
- In data warehousing literature, an n-D base cube is called a **base cuboid**. The top most 0-D cuboid, which holds the highest-level of summarization, is called the **apex cuboid**. The lattice of cuboids forms a **data cube**.

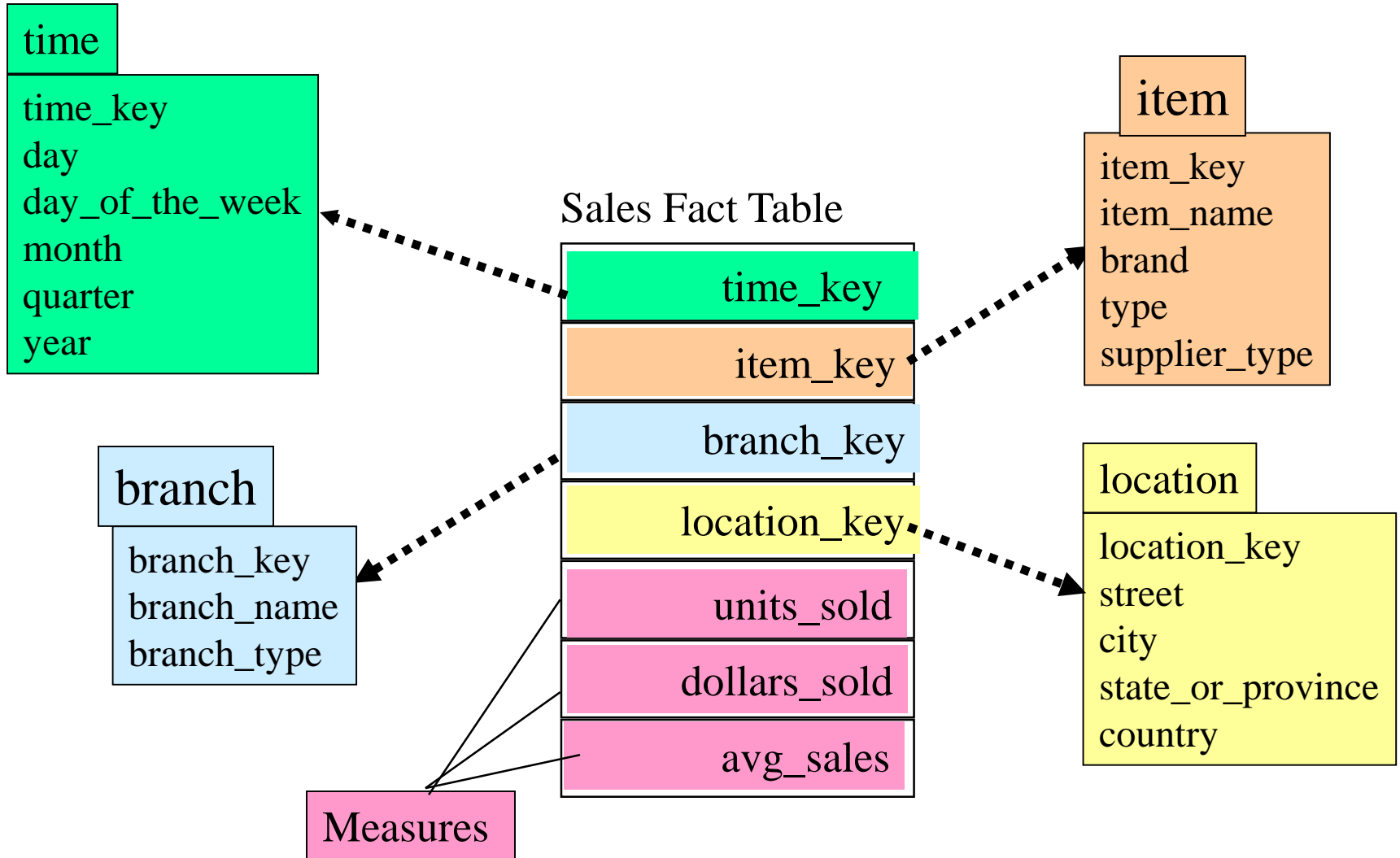
Cube: A Lattice of Cuboids



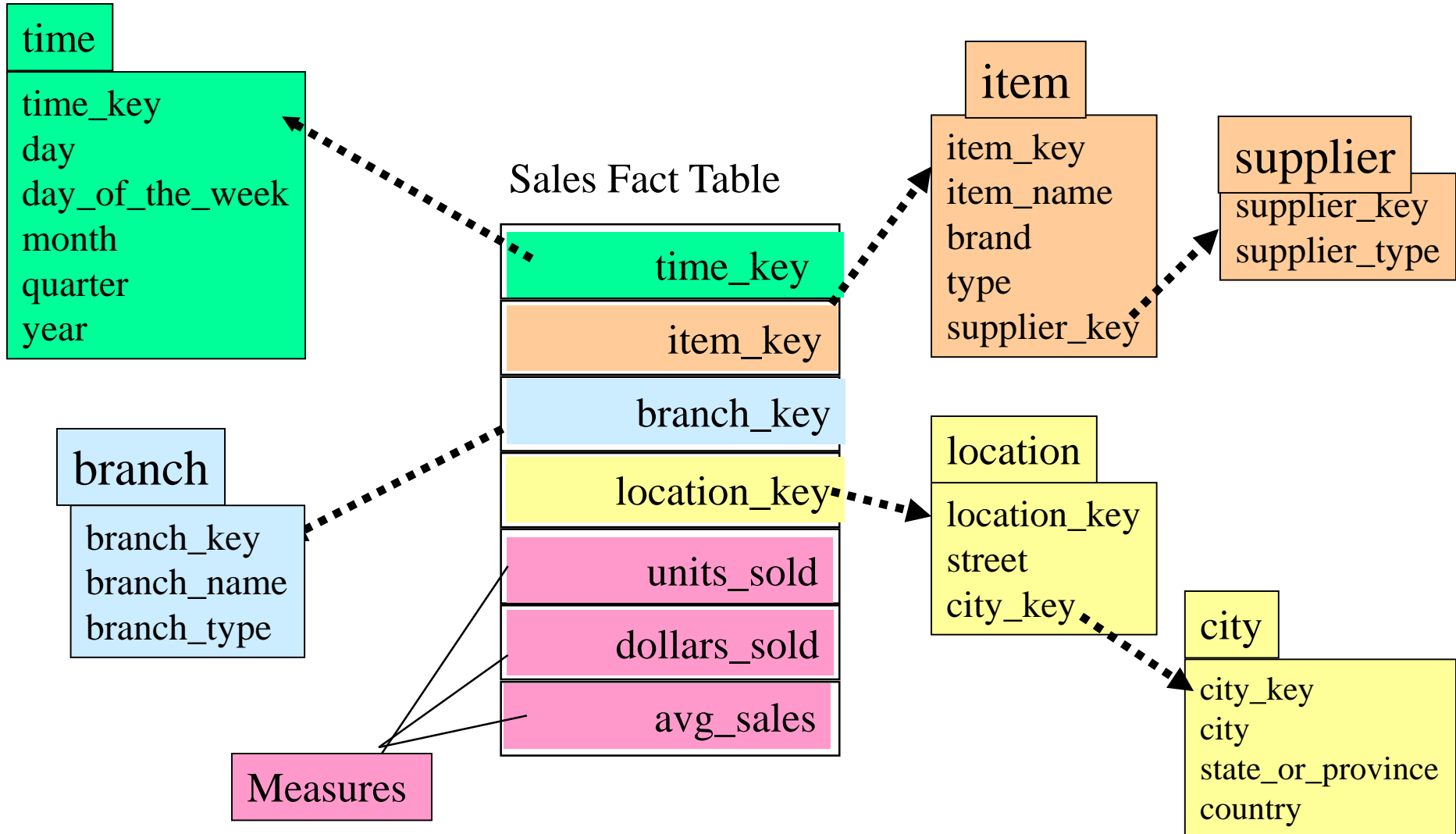
Conceptual Modeling of Data Warehouses

- Modeling data warehouses: dimensions & measures
 - Star schema: A fact table in the middle connected to a set of dimension tables
 - Snowflake schema: A refinement of star schema where some dimensional hierarchy is **normalized** into a set of smaller dimension tables, forming a shape similar to snowflake
 - Fact constellations: Multiple fact tables share dimension tables, viewed as a collection of stars, therefore called **galaxy schema** or fact constellation

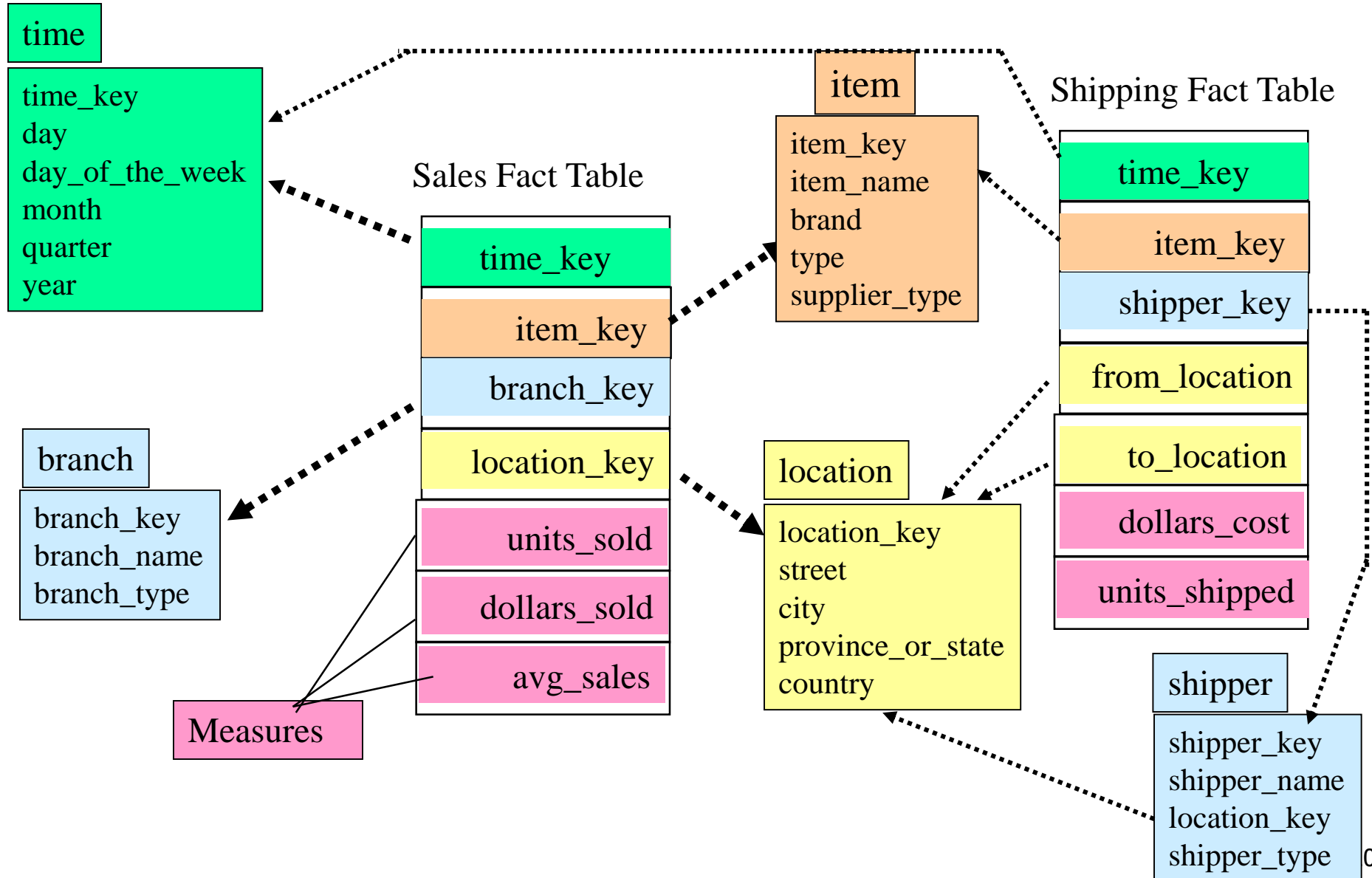
Example of Star Schema



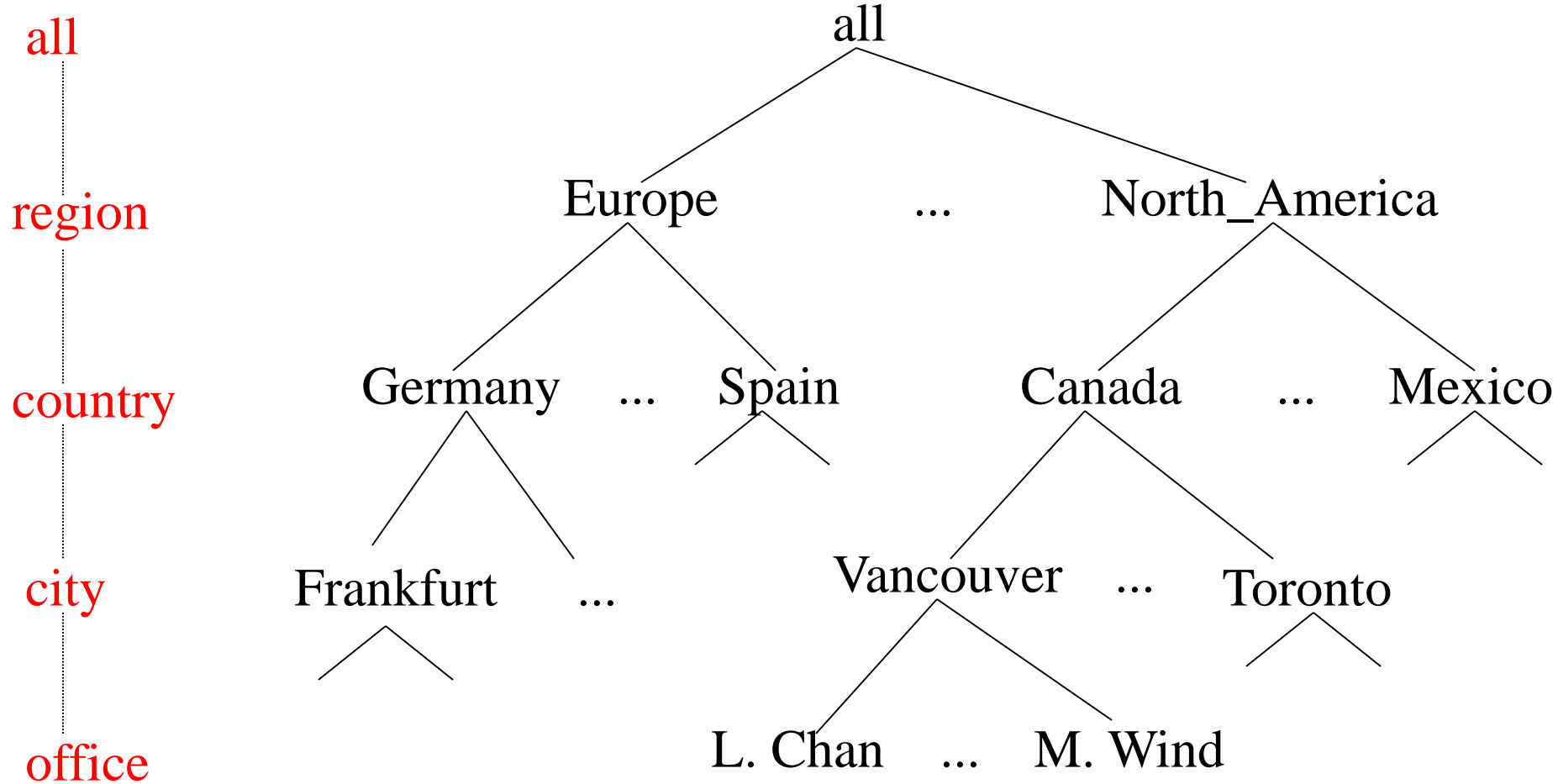
Example of Snowflake Schema



Example of Fact Constellation



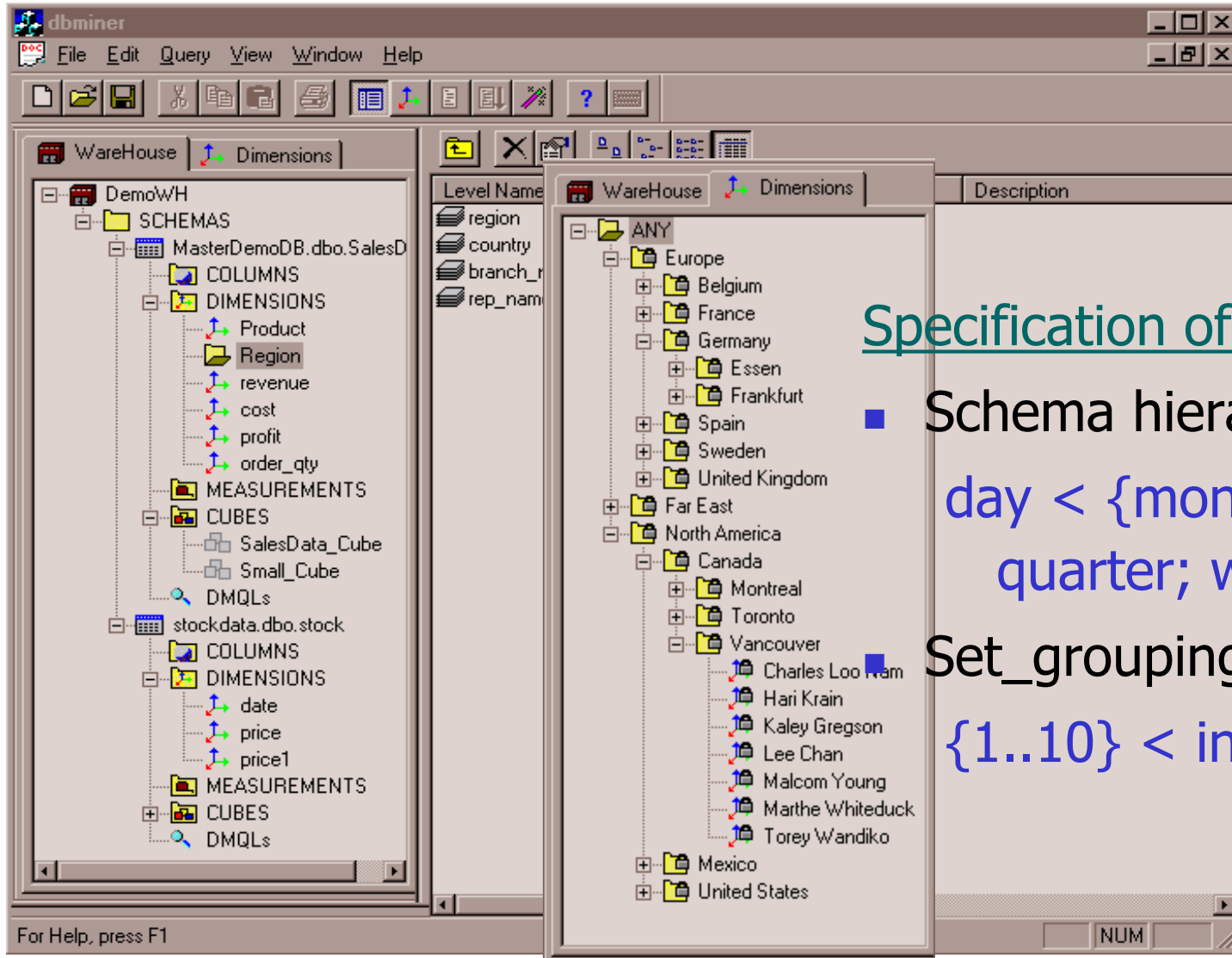
A Concept Hierarchy: Dimension (location)



Data Cube Measures: Three Categories

- **Distributive**: if the result derived by applying the function to n aggregate values is the same as that derived by applying the function on all the data without partitioning
 - E.g., `count()`, `sum()`, `min()`, `max()`
- **Algebraic**: if it can be computed by an algebraic function with M arguments (where M is a bounded integer), each of which is obtained by applying a distributive aggregate function
 - E.g., `avg()`, `min_N()`, `standard_deviation()`
- **Holistic**: if there is no constant bound on the storage size needed to describe a subaggregate.
 - E.g., `median()`, `mode()`, `rank()`

View of Warehouses and Hierarchies



Specification of hierarchies

■ Schema hierarchy

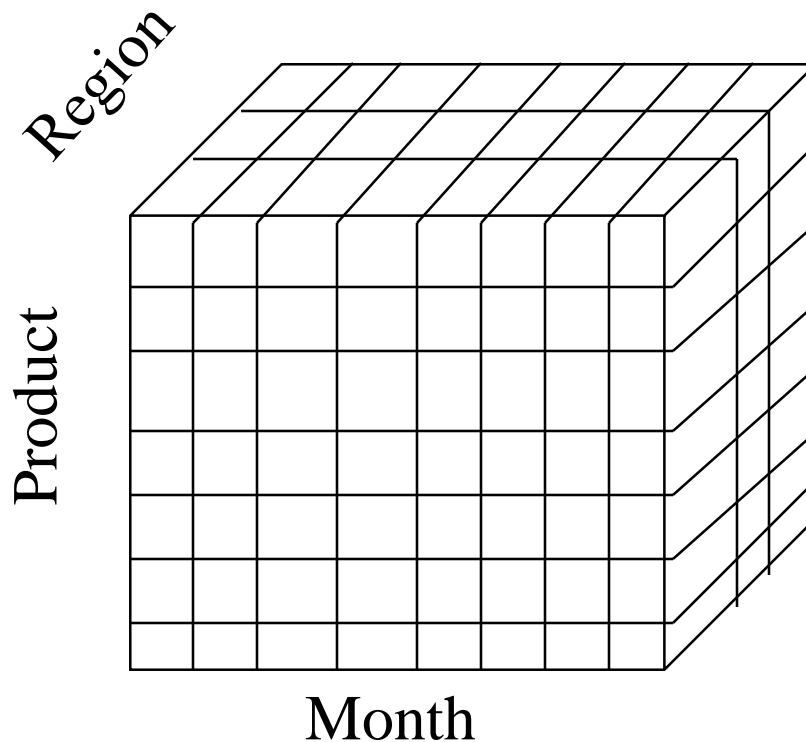
day < {month < quarter; week} < year

■ Set_grouping hierarchy

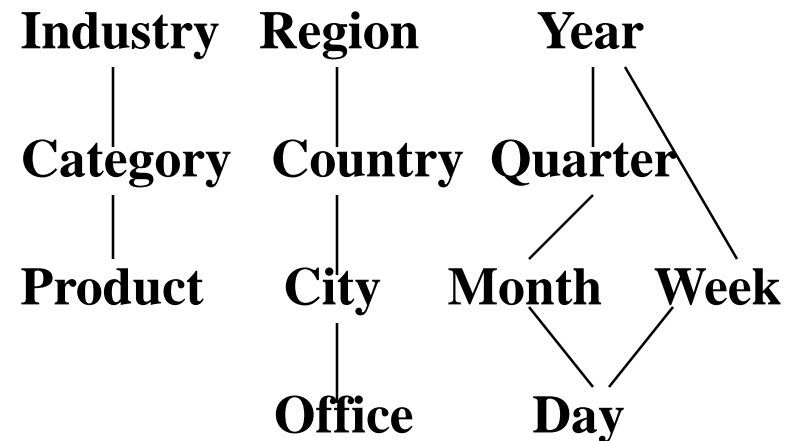
{1..10} < inexpensive

Multidimensional Data

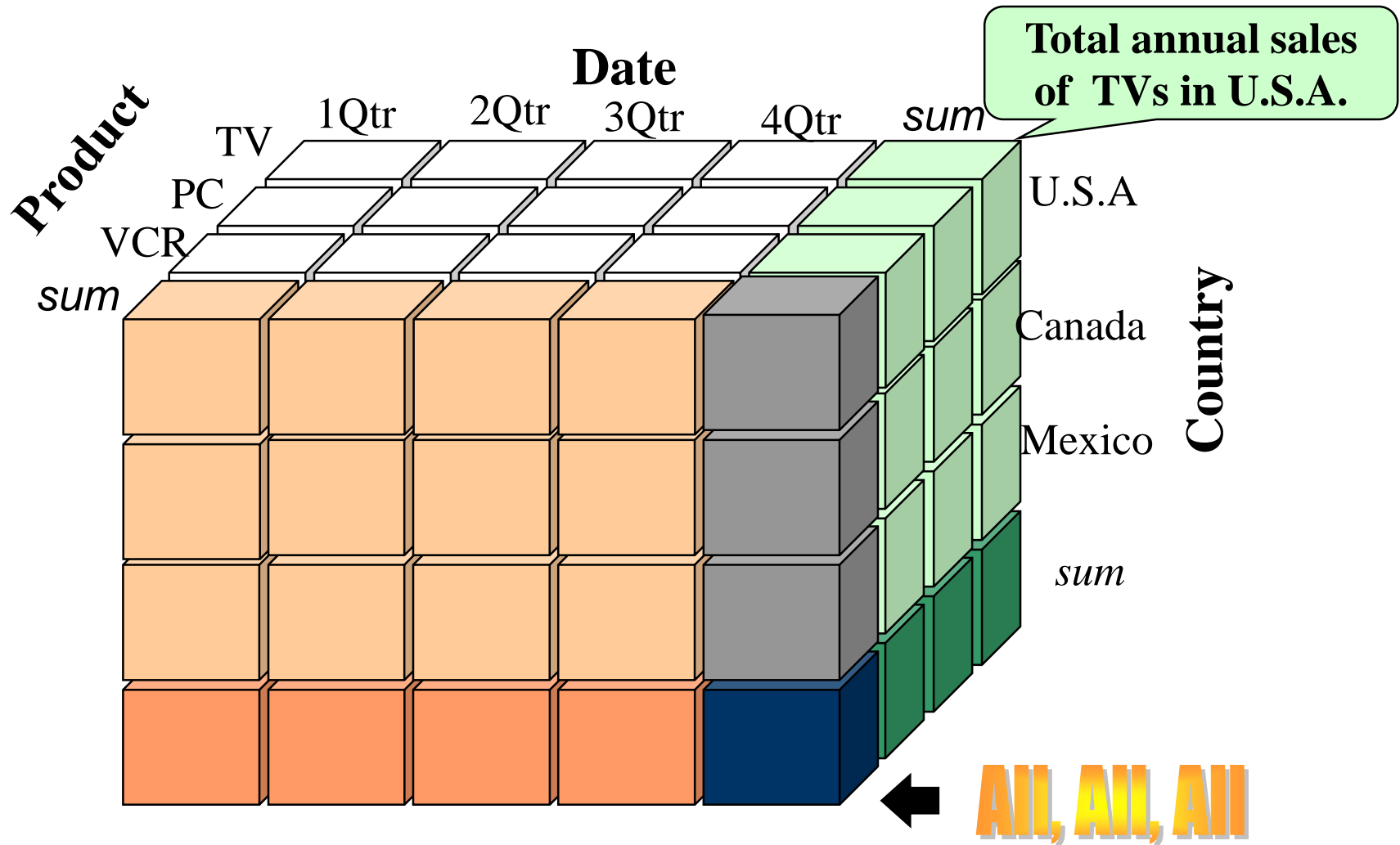
- Sales volume as a function of product, month, and region



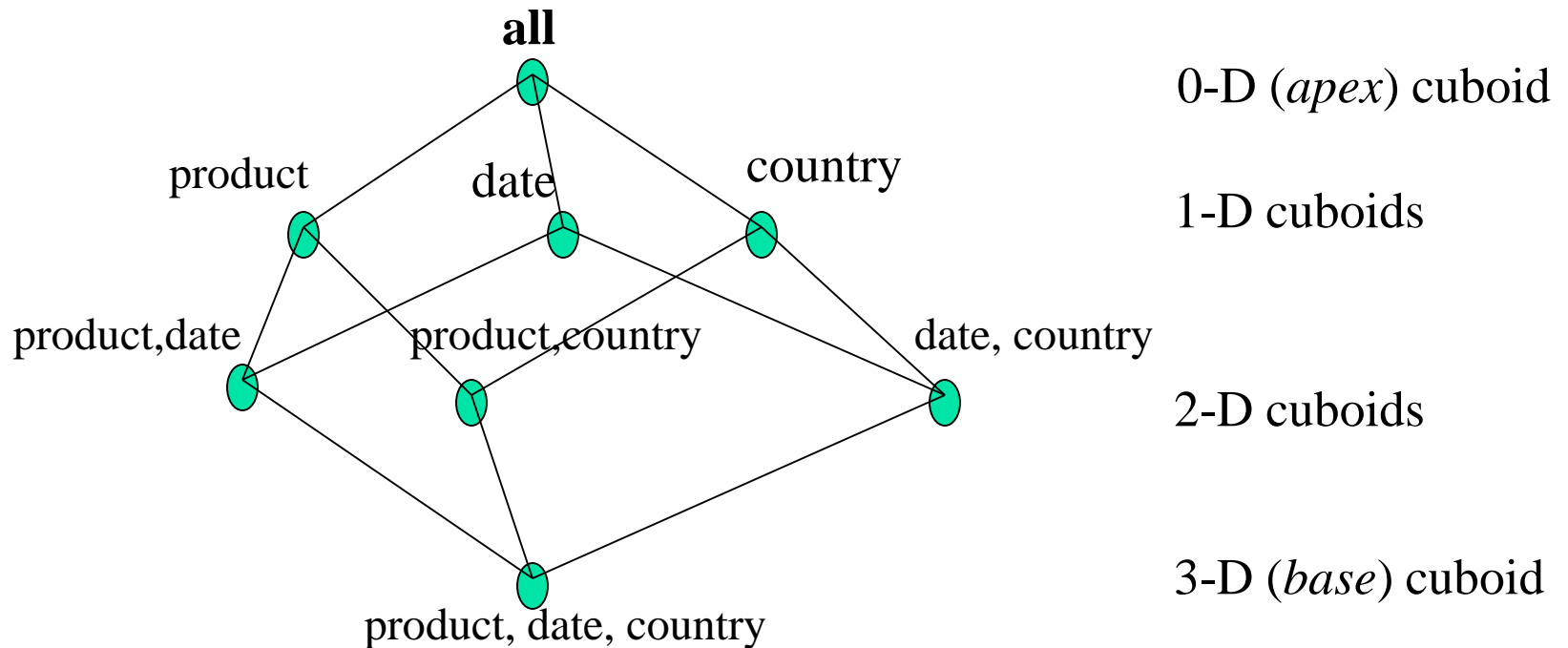
Dimensions: *Product, Location, Time*
Hierarchical summarization paths



A Sample Data Cube



Cuboids Corresponding to the Cube



Typical OLAP Operations

- Roll up (drill-up): summarize data
 - *by climbing up hierarchy or by dimension reduction*
- Drill down (roll down): reverse of roll-up
 - *from higher level summary to lower level summary or detailed data, or introducing new dimensions*
- Slice and dice: *project and select*
- Pivot (rotate):
 - *reorient the cube, visualization, 3D to series of 2D planes*
- Other operations
 - *drill across: involving (across) more than one fact table*
 - *drill through: through the bottom level of the cube to its back-end relational tables (using SQL)*

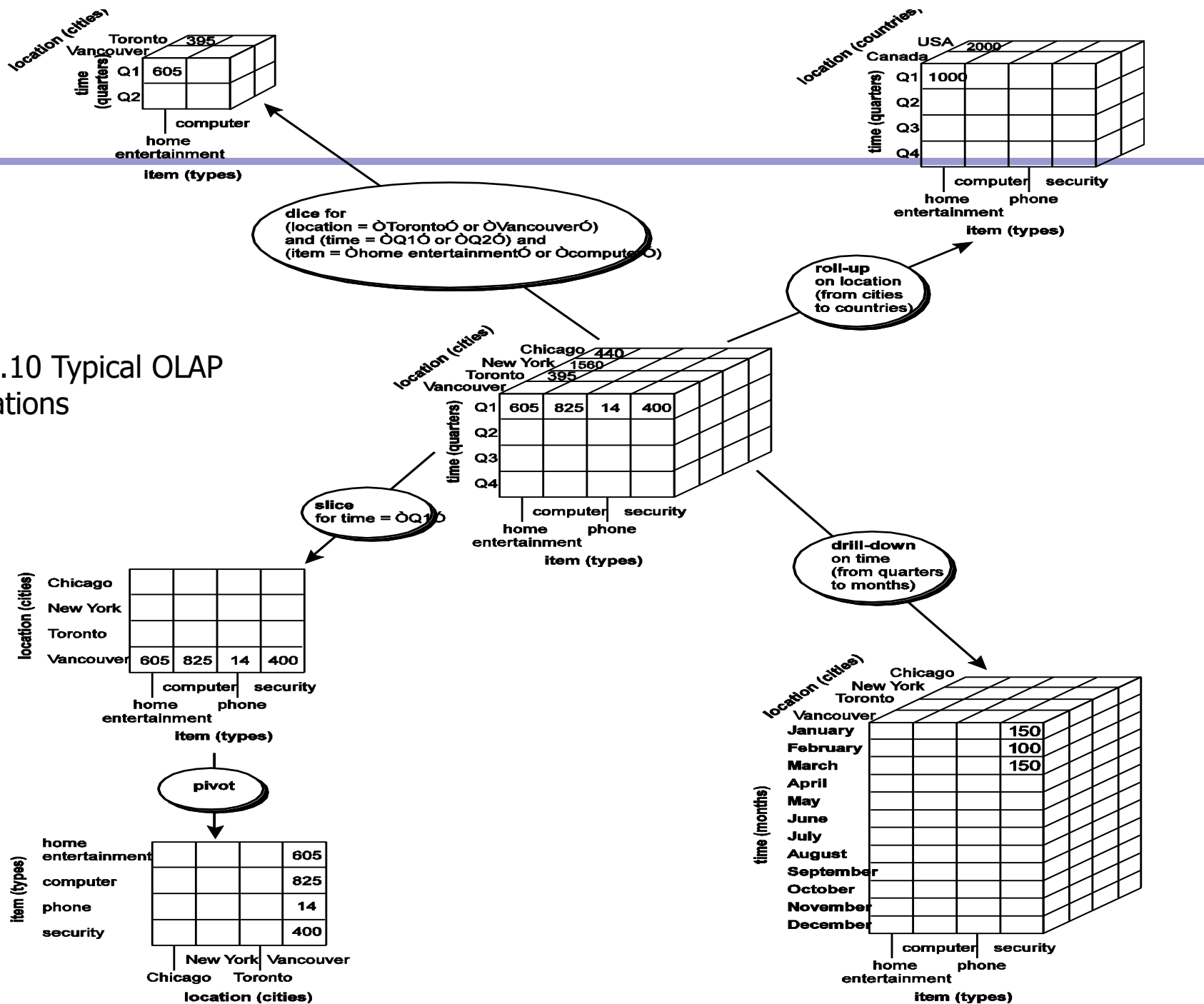
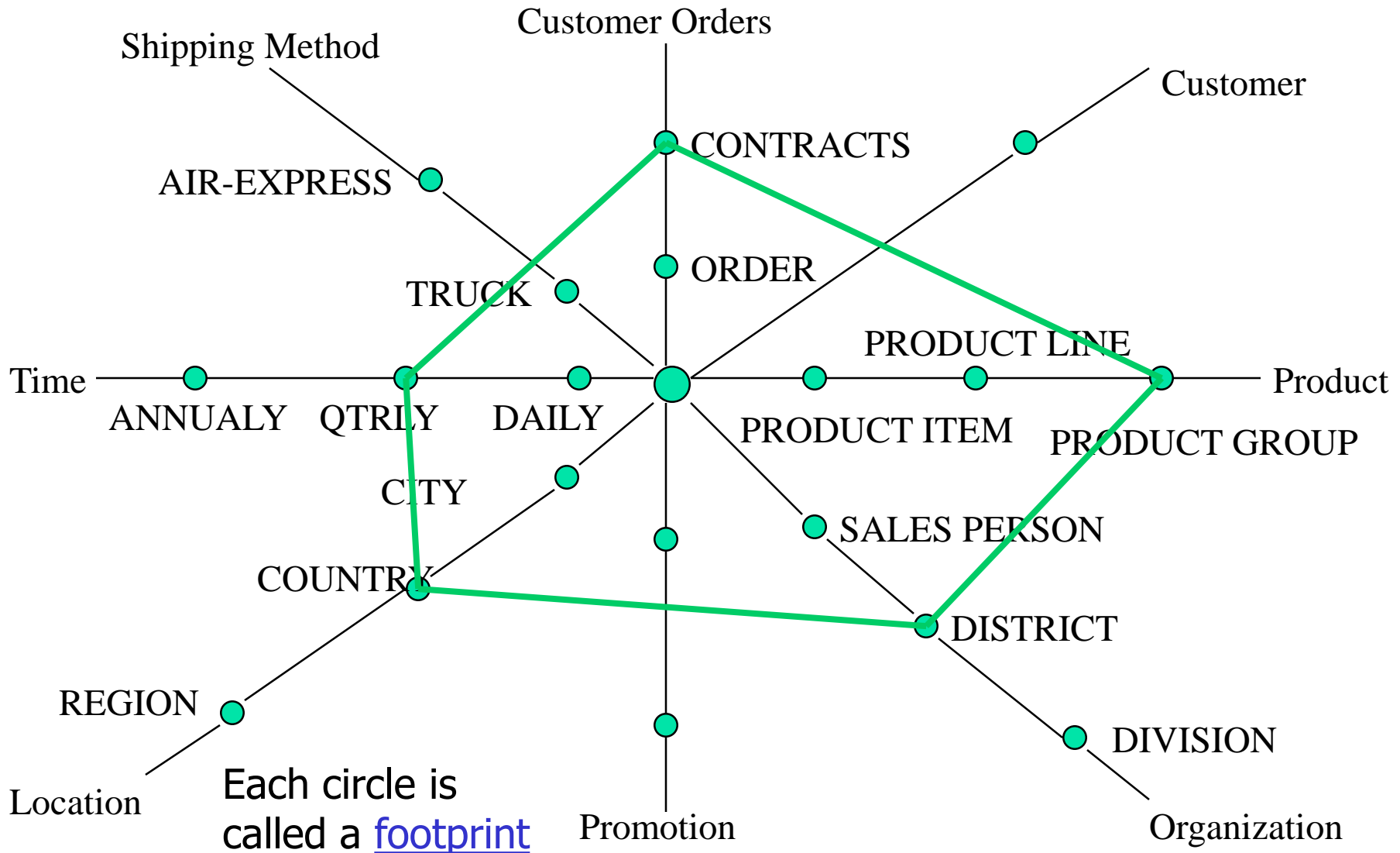
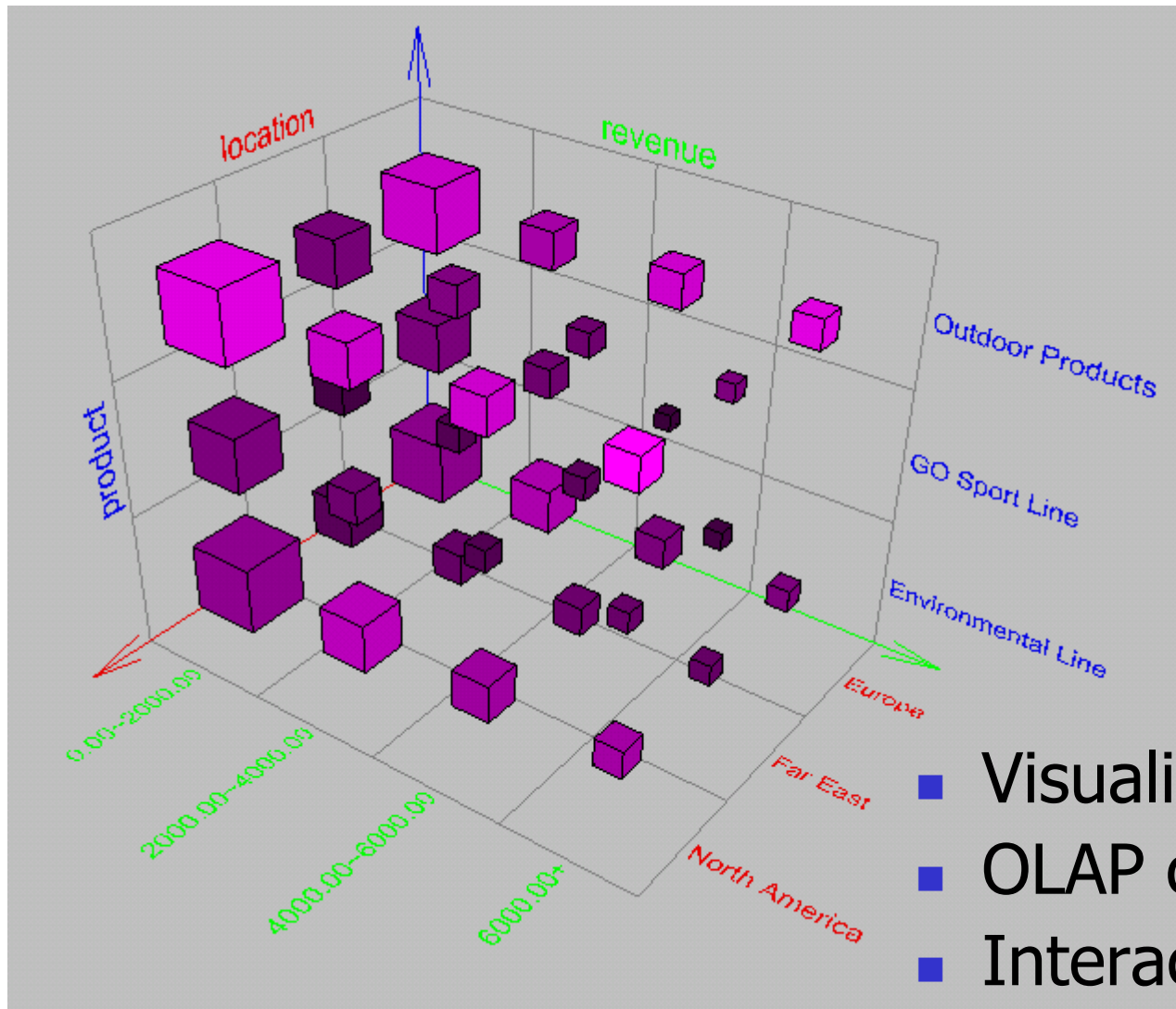


Fig. 3.10 Typical OLAP Operations

A Star-Net Query Model




Browsing a Data Cube



- Visualization
- OLAP capabilities
- Interactive manipulation

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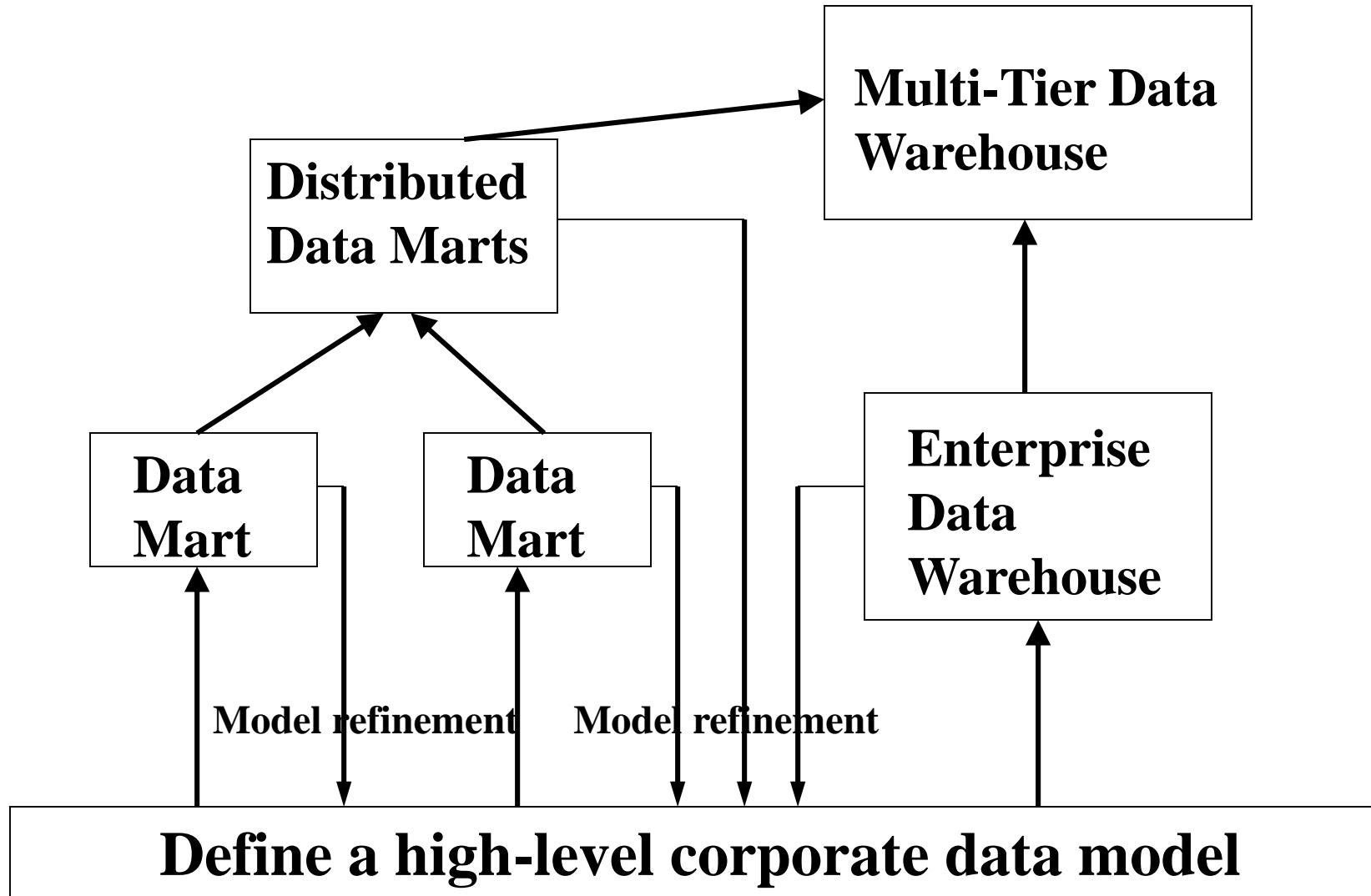
Design of Data Warehouse: A Business Analysis Framework

- Four views regarding the design of a data warehouse
 - **Top-down view**
 - allows selection of the relevant information necessary for the data warehouse
 - **Data source view**
 - exposes the information being captured, stored, and managed by operational systems
 - **Data warehouse view**
 - consists of fact tables and dimension tables
 - **Business query view**
 - sees the perspectives of data in the warehouse from the view of end-user

Data Warehouse Design Process

- **Top-down, bottom-up approaches or a combination** of both
 - Top-down: Starts with overall design and planning (mature)
 - Bottom-up: Starts with experiments and prototypes (rapid)
- **From software engineering point of view**
 - Waterfall: structured and systematic analysis at each step before proceeding to the next
 - Spiral: rapid generation of increasingly functional systems, short turn around time, quick turn around
- **Typical data warehouse design process**
 - Choose a **business process** to model, e.g., orders, invoices, etc.
 - Choose the ***grain (atomic level of data)*** of the business process
 - Choose the **dimensions** that will apply to each fact table record
 - Choose the **measure** that will populate each fact table record

Data Warehouse Development: A Recommended Approach




Data Warehouse Usage

- Three kinds of data warehouse applications
 - Information processing
 - supports querying, basic statistical analysis, and reporting using crosstabs, tables, charts and graphs
 - Analytical processing
 - multidimensional analysis of data warehouse data
 - supports basic OLAP operations, slice-dice, drilling, pivoting
 - Data mining
 - knowledge discovery from hidden patterns
 - supports associations, constructing analytical models, performing classification and prediction, and presenting the mining results using visualization tools

From On-Line Analytical Processing (OLAP) to On Line Analytical Mining (OLAM)

- Why **online analytical mining**?
 - High quality of data in data warehouses
 - DW contains integrated, consistent, cleaned data
 - Available information processing structure surrounding data warehouses
 - ODBC, OLEDB, Web accessing, service facilities, reporting and OLAP tools
 - OLAP-based exploratory data analysis
 - Mining with drilling, dicing, pivoting, etc.
 - On-line selection of data mining functions
 - Integration and swapping of multiple mining functions, algorithms, and tasks

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Efficient Data Cube Computation

- Data cube can be viewed as a lattice of cuboids
 - The bottom-most cuboid is the base cuboid
 - The top-most cuboid (apex) contains only one cell
 - How many cuboids in an n-dimensional cube with L levels?

$$T = \prod_{i=1}^n (L_i + 1)$$

- Materialization of data cube
 - Materialize every (cuboid) (**full materialization**), none (**no materialization**), or some (**partial materialization**)
 - Selection of which cuboids to materialize
 - Based on size, sharing, access frequency, etc.

The “Compute Cube” Operator

- Cube definition and computation in DMQL

define cube sales [item, city, year]: sum (sales_in_dollars)

compute cube sales

- Transform it into a SQL-like language (with a new operator **cube by**, introduced by Gray et al.'96)

SELECT item, city, year, SUM (amount)

FROM SALES

CUBE BY item, city, year

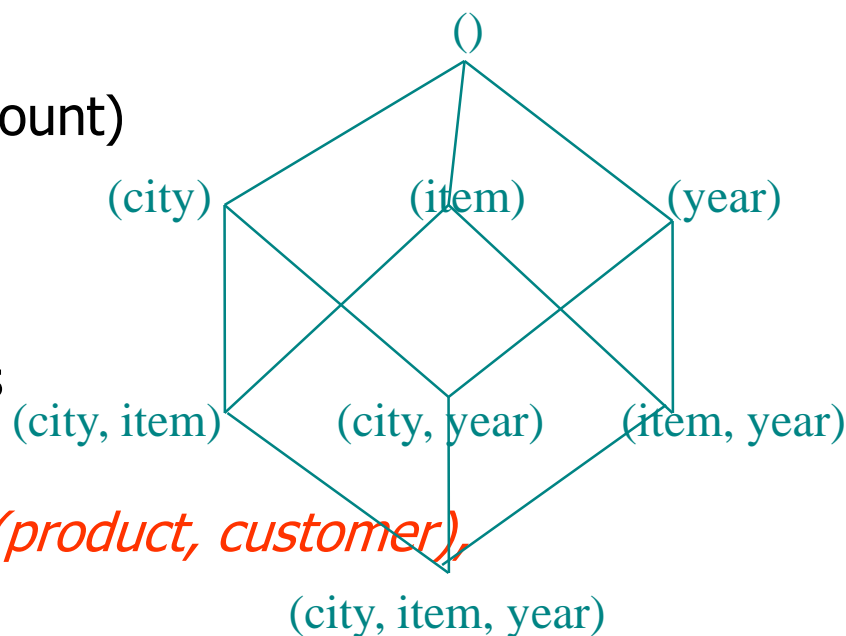
- Need compute the following Group-Bys

(date, product, customer),

(date, product), (date, customer), (product, customer),

(date), (product), (customer)

()



Indexing OLAP Data: Bitmap Index

- Index on a particular column
- Each value in the column has a bit vector: bit-op is fast
- The length of the bit vector: # of records in the base table
- The i -th bit is set if the i -th row of the base table has the value for the indexed column
- not suitable for high cardinality domains
- A recent bit compression technique, Word-Aligned Hybrid (WAH), makes it work for high cardinality domain as well [Wu, et al. TODS'06]

Base table

| Cust | Region | Type |
|------|---------|--------|
| C1 | Asia | Retail |
| C2 | Europe | Dealer |
| C3 | Asia | Dealer |
| C4 | America | Retail |
| C5 | Europe | Dealer |

Index on Region

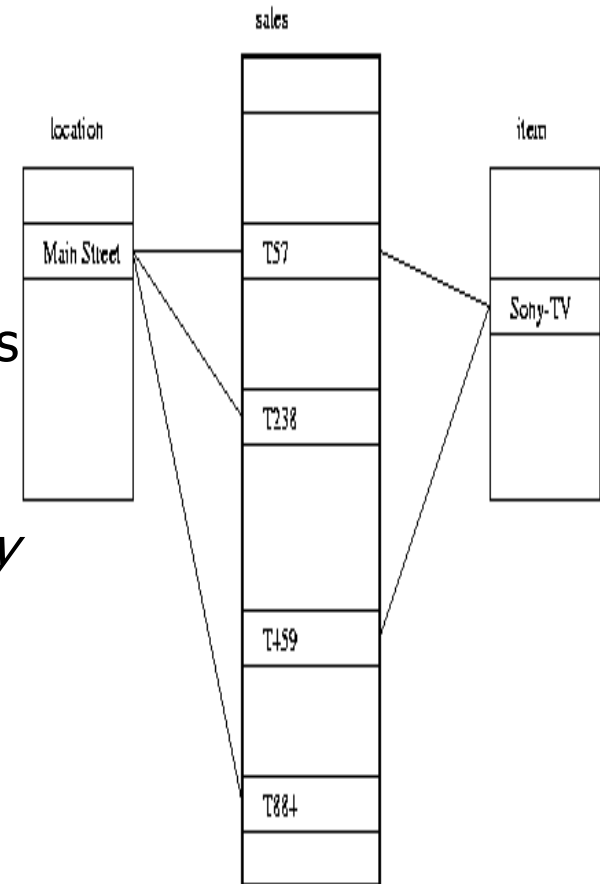
| RecID | Asia | Europe | America |
|-------|------|--------|---------|
| 1 | 1 | 0 | 0 |
| 2 | 0 | 1 | 0 |
| 3 | 1 | 0 | 0 |
| 4 | 0 | 0 | 1 |
| 5 | 0 | 1 | 0 |

Index on Type

| RecID | Retail | Dealer |
|-------|--------|--------|
| 1 | 1 | 0 |
| 2 | 0 | 1 |
| 3 | 0 | 1 |
| 4 | 1 | 0 |
| 5 | 0 | 1 |

Indexing OLAP Data: Join Indices

- Join index: $JI(R\text{-id}, S\text{-id})$ where $R(R\text{-id}, \dots) \triangleright \triangleleft S(S\text{-id}, \dots)$
- Traditional indices map the values to a list of record ids
 - It materializes relational join in JI file and speeds up relational join
- In data warehouses, join index relates the values of the dimensions of a star schema to rows in the fact table.
 - E.g. fact table: *Sales* and two dimensions *city* and *product*
 - A join index on *city* maintains for each distinct city a list of R-IDs of the tuples recording the Sales in the city
 - Join indices can span multiple dimensions




Efficient Processing OLAP Queries

- **Determine which operations** should be performed on the available cuboids
 - Transform *drill*, *roll*, etc. into corresponding SQL and/or OLAP operations, e.g., *dice* = selection + projection
- **Determine which materialized cuboid(s)** should be selected for OLAP op.
 - Let the query to be processed be on $\{brand, province_or_state\}$ with the condition "*year = 2004*", and there are 4 materialized cuboids available:
 - 1) $\{year, item_name, city\}$
 - 2) $\{year, brand, country\}$
 - 3) $\{year, brand, province_or_state\}$
 - 4) $\{item_name, province_or_state\}$ where *year = 2004*Which should be selected to process the query?
- Explore indexing structures and compressed vs. dense array structs in MOLAP

OLAP Server Architectures

- Relational OLAP (ROLAP)
 - Use relational or extended-relational DBMS to store and manage warehouse data and OLAP middle ware
 - Include optimization of DBMS backend, implementation of aggregation navigation logic, and additional tools and services
 - Greater scalability
- Multidimensional OLAP (MOLAP)
 - Sparse array-based multidimensional storage engine
 - Fast indexing to pre-computed summarized data
- Hybrid OLAP (HOLAP) (e.g., Microsoft SQLServer)
 - Flexibility, e.g., low level: relational, high-level: array
- Specialized SQL servers (e.g., Redbricks)
 - Specialized support for SQL queries over star/snowflake schemas

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Attribute-Oriented Induction

- Proposed in 1989 (KDD '89 workshop)
- Not confined to categorical data nor particular measures
- How it is done?
 - Collect the task-relevant data (*initial relation*) using a relational database query
 - Perform generalization by attribute removal or attribute generalization
 - Apply aggregation by merging identical, generalized tuples and accumulating their respective counts
 - Interaction with users for knowledge presentation

Attribute-Oriented Induction: An Example

Example: Describe general characteristics of graduate students in the University database

- Step 1. Fetch relevant set of data using an SQL statement, e.g.,

Select * (i.e., name, gender, major, birth_place,
birth_date, residence, phone#, gpa)

from student

where student_status in {"Msc", "MBA", "PhD" }

- Step 2. Perform attribute-oriented induction
- Step 3. Present results in generalized relation, cross-tab, or rule forms

Class Characterization: An Example

**Initial
Relation**

| Name | Gender | Major | Birth-Place | Birth_date | Residence | Phone # | GPA |
|----------------|-----------------|---------------------|-----------------------|------------------|--------------------------|----------------|---------------------|
| Jim Woodman | M | CS | Vancouver,BC, Canada | 8-12-76 | 3511 Main St., Richmond | 687-4598 | 3.67 |
| Scott Lachance | M | CS | Montreal, Que, Canada | 28-7-75 | 345 1st Ave., Richmond | 253-9106 | 3.70 |
| Laura Lee | F | Physics | Seattle, WA, USA | 25-8-70 | 125 Austin Ave., Burnaby | 420-5232 | 3.83 |
| ... | ... | ... | ... | ... | ... | ... | ... |
| Removed | Retained | Sci,Eng, Bus | Country | Age range | City | Removed | Excl, VG,... |

**Prime
Generalized
Relation**

| Gender | Major | Birth_region | Age_range | Residence | GPA | Count |
|--------|---------|--------------|-----------|-----------|-----------|-------|
| M | Science | Canada | 20-25 | Richmond | Very-good | 16 |
| F | Science | Foreign | 25-30 | Burnaby | Excellent | 22 |
| ... | ... | ... | ... | ... | ... | ... |

| Gender \ Birth_Region | | | |
|-----------------------|--------|---------|-------|
| | Canada | Foreign | Total |
| M | 16 | 14 | 30 |
| F | 10 | 22 | 32 |
| Total | 26 | 36 | 62 |

Basic Principles of Attribute-Oriented Induction

- Data focusing: task-relevant data, including dimensions, and the result is the *initial relation*
- Attribute-removal: remove attribute A if there is a large set of distinct values for A but (1) there is no generalization operator on A , or (2) A 's higher level concepts are expressed in terms of other attributes
- Attribute-generalization: If there is a large set of distinct values for A , and there exists a set of generalization operators on A , then select an operator and generalize A
- Attribute-threshold control: typical 2-8, specified/default
- Generalized relation threshold control: control the final relation/rule size

Attribute-Oriented Induction: Basic Algorithm

- InitialRel: Query processing of task-relevant data, deriving the *initial relation*.
- PreGen: Based on the analysis of the number of distinct values in each attribute, determine generalization plan for each attribute: removal? or how high to generalize?
- PrimeGen: Based on the PreGen plan, perform generalization to the right level to derive a “prime generalized relation”, accumulating the counts.
- Presentation: User interaction: (1) adjust levels by drilling, (2) pivoting, (3) mapping into rules, cross tabs, visualization presentations.

Presentation of Generalized Results

- Generalized relation:
 - Relations where some or all attributes are generalized, with counts or other aggregation values accumulated.
- Cross tabulation:
 - Mapping results into cross tabulation form (similar to contingency tables).
 - Visualization techniques:
 - Pie charts, bar charts, curves, cubes, and other visual forms.
- Quantitative characteristic rules:
 - Mapping generalized result into characteristic rules with quantitative information associated with it, e.g.,
$$grad(x) \wedge male(x) \Rightarrow birth_region(x) = "Canada"[t:53\%] \vee birth_region(x) = "foreign"[t:47\%].$$

Mining Class Comparisons

- Comparison: Comparing two or more classes
- Method:
 - Partition the set of relevant data into the target class and the contrasting class(es)
 - Generalize both classes to the same high level concepts
 - Compare tuples with the same high level descriptions
 - Present for every tuple its description and two measures
 - support - distribution within single class
 - comparison - distribution between classes
 - Highlight the tuples with strong discriminant features
- Relevance Analysis:
 - Find attributes (features) which best distinguish different classes

Concept Description vs. Cube-Based OLAP


■ **Similarity:**

- Data generalization
- Presentation of data summarization at multiple levels of abstraction
- Interactive drilling, pivoting, slicing and dicing

■ **Differences:**

- OLAP has systematic preprocessing, query independent, and can drill down to rather low level
- AOI has automated desired level allocation, and may perform dimension relevance analysis/ranking when there are many relevant dimensions
- AOI works on the data which are not in relational forms

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Summary

- **Data warehousing**: A **multi-dimensional model** of a data warehouse
 - A data cube consists of *dimensions* & *measures*
 - Star schema, snowflake schema, fact constellations
 - **OLAP** operations: drilling, rolling, slicing, dicing and pivoting
- **Data Warehouse Architecture, Design, and Usage**
 - Multi-tiered architecture
 - Business analysis design framework
 - Information processing, analytical processing, data mining, **OLAM** (Online Analytical Mining)
- **Implementation**: Efficient computation of data cubes
 - Partial vs. full vs. no materialization
 - Indexing OLAP data: Bitmap index and join index
 - OLAP query processing
 - OLAP servers: ROLAP, MOLAP, HOLAP
- **Data generalization**: Attribute-oriented induction

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Surplus Slides

Compression of Bitmap Indices

- Bitmap indexes must be compressed to reduce I/O costs and minimize CPU usage—majority of the bits are 0's
- Two compression schemes:
 - Byte-aligned Bitmap Code (BBC)
 - Word-Aligned Hybrid (WAH) code
- Time and space required to operate on compressed bitmap is proportional to the total size of the bitmap
- Optimal on attributes of low cardinality as well as those of high cardinality.
- WAH out performs BBC by about a factor of two