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Data exposed to the Web via HTML
So what is the problem?

- Web content is only loosely structured
- Difficult for applications to do smart things

Solution:

- Increase the structure of Web content
- Publish data in a machine-friendly way

But wait…
don't we do that already?
Web APIs

- Content providers offer access via Web APIs
- Mashups combine this data
Web APIs

- Content providers offer access via Web APIs
- Mashups combine this data

Shortcomings:

- APIs are proprietary
- Mashups are based on a fixed set of data sources
- You cannot set hyperlinks between data objects
Towards a Web of Linked Data

By using the following, well-established Web technologies the WWW evolves into a Web of Linked Data.

- Access mechanism: Hypertext Transfer Protocol (HTTP)
- Data model: The Resource Description Framework (RDF)
- Globally unique identifiers: Uniform Resource Identifier (URI)
Outline

(1) The Foundation: Linked Data on the Web
   - The RDF Data Model and URIs
   - The SPARQL Query Language
   - The Linked Data Publishing Principles

(2) Querying Linked Data
The Resource Description Framework

- A resource may basically be everything
  - e.g. persons, places, Web documents, abstract concepts

- Descriptions of resources
  - Attributes
  - Relations

- The framework contains:
  - A data model, and
  - Languages and syntaxes
RDF Data Model

- Data comes as a set of *triples* (subject, predicate, object)

- **Subject**: resources
- **Predicate**: properties
- **Object**: literals or resources

- **Examples**:
  - (Mount Baker, last eruption, 1880)
  - (Mount Baker, location, Washington)
RDF Data Model (cont'd)

- **RDF based data may be understood as a graph:**
  - Triples as directed edges
  - Subjects and objects as vertices
  - Edges labeled by predicate

**Example:**
- (Mount Baker, last eruption, 1880)
- (Mount Baker, location, Washington)
Uniform Resource Identifier (URI)

• **URIs extend the concept of URLs**
  • Globally *unique identifier* for resources
  • URL of a Web document usually used as its URI
  • Attention: URIs identify not only Web documents

• **Example:**
  • Me:
    http://olafhartig.de/foaf.rdf#olaf
  • RDF document about me:
    http://olafhartig.de/foaf.rdf
  • HTML document about me:
    http://olafhartig.de/index.html
Example (revisited)

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Querying RDF Data

- **SPARQL**: Declarative query language for RDF data
- **Main idea**: pattern matching
  - Describe subgraphs of the queried RDF graph
  - Subgraphs that match your description yield a result
  - Mean: graph patterns (i.e., RDF graphs with variables)

```
?x http://dbpedia.org/resource/Washington

http://.../location

http://.../lastEruption

?e
```
SPARQL Pattern Matching

Data

http://dbpedia.org/resource/Washington

http://.../location

http://dbpedia.org/resource/Mount_Baker

http://.../lastEruption

1880

Query

http://dbpedia.org/resource/Washington

http://.../location

http://.../lastEruption

Query Result:

?x | ?e
---|---
http://.../Mount_Baker | 1880
Components of a SPARQL Query

```
SELECT ?e ?name
FROM <http://example.org/myGeoData>
WHERE {
    ?x <http://.../location> <http://.../Washington> .
    ?x <http://.../lastEruption> ?e .
    OPTIONAL { ?x <http://.../name> ?name . }
}
ORDER BY ?e
```
Components of a SPARQL Query

```sparql
SELECT ?e ?name
FROM <http://example.org/myGeoData>
WHERE {
  ?x <http://.../location> <http://.../Washington> .
  ?x <http://.../lastEruption> ?e .
  OPTIONAL { ?x <http://.../name> ?name . }
}
ORDER BY ?e
```

- **Result form specification:**
  - SELECT for projection
    (similar to projection in relational algebra)
  - Other forms: DESCRIBE, CONSTRUCT, and ASK
Components of a SPARQL Query

```
SELECT ?e ?name
FROM <http://example.org/myGeoData>
WHERE {
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```

- **Dataset specification:**
  - Specify the RDF dataset to be queried (use URIs that identify particular RDF graphs in your RDF database)
Components of a SPARQL Query

SELECT ?e ?name
FROM <http://example.org/myGeoData>
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- Query Pattern:
  - WHERE clause specifies the graph pattern to be matched
  - Expressive power equivalent to relational algebra
  - SPARQL 1.1 goes beyond (e.g., aggregation, property paths)
Components of a SPARQL Query

```sparql
SELECT ?e ?name
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```

- **Solution modifiers:**
  - Only for SELECT queries
  - Modify the **result set** as a whole (not single solutions)
  - Keywords: DISTINCT, ORDER BY, LIMIT, and OFFSET
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(2) Querying Linked Data
The Linked Data Principles

( http://...imdb.../WarChild , release date , 12 July 1999 )
( http://...imdb.../WarChild , filming location , http://cia.../Albania )
( http://...imdb.../MichaelDavie , directed , http://...imdb.../WarChild )

( http://cia.../Albania , unemployment rate , 13.2% )

Data model: RDF
Global identifier: URI
Access mechanism: HTTP
Connection: data links
W3C Linking Open Data Project

- Grassroots community effort
- Publish existing, open license datasets as Linked Data
- Interlink things between different data sources

**Prominent Linked Data publishers today:**
- Governments (UK, US, I, etc.)
- The Library of Congress
- The New York Times
- Thomson Reuters
- Freebase (owned by Google)
- Best Buy
- Sears
- CNET
- BBC
- etc.
W3C Linking Open Data Project

[Diagram showing various nodes and connections related to the W3C Linking Open Data Project]
Outline

(1) The Foundation: Linked Data on the Web ✓

(2) Querying Linked Data
   - Data Warehousing
   - SPARQL Federation
   - Linked Data Query Processing
Outline

(1) The Foundation: Linked Data on the Web ✓

(2) Querying Linked Data
   - Data Warehousing
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   - Linked Data Query Processing
Remember ...

- (http://...imdb.../WarChild, release date, 12 July 1999)
- (http://...imdb.../WarChild, filming location, http://cia.../Albania)
- (http://...imdb.../MichaelDavie, directed, http://...imdb.../WarChild):

- (http://cia.../Albania, unemployment rate, 13.2%)

Data model: RDF
Global identifier: URI
Access mechanism: HTTP
Connection: data links
A Globally Distributed Network of Data

...which we understand as a huge distributed database
Data access capabilities of any system that aims to access this DB are inherently limited

- HTTP requests only
- No queries (i.e., we cannot assume that data sources provide a query service)

Number of potential data sources is infinite

It is impossible to have a DB catalog that is complete or up-to-date (or even both)
... is a new research field that focuses on querying this distributed DB

- **Criteria:**
  - On-line execution
  - Rely only on the Linked Data principles

- **Use cases:** live querying where freshness and discovery of results is more important than an almost instant answer
Languages for Linked Data Queries

- **Navigational query languages**
  - Regular expressions to specify paths of data links
  - Query result: end nodes of matching paths
  - NautiLOD, LDPath

- **SPARQL**
  - Seems to be a natural choice
  - However, standard definition captures queries over a predefined dataset (e.g., stored in an RDF DBMS)
Semantics for SPARQL LD Queries

- **Full-Web query semantics**
  - Scope of evaluating a SPARQL expression is all Linked Data
  - Query result completeness cannot be guaranteed by any (terminating) execution
Semantics for SPARQL LD Queries

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- **Reachability-based query semantics**
  - Query consists of a SPARQL expression, a set of seed URIs $S$, and a reachability condition $c$
  - Scope: all data along paths of data links that satisfy the condition
  - Computationally feasible
Query Execution

- Two processes that may be intertwined:
  - Fetching Linked Data by looking up URIs
  - Constructing the query result

- Classes of approaches:
  - Index-based approaches
  - Traversal-based approaches
  - Hybrids
Index-Based Source Selection

**Idea:** Use pre-populated index to determine relevant URIs and to avoid as many irrelevant ones as possible.

**Index keys:**
- Different approaches possible
- e.g., triple patterns

**Index entries:**
- Usually, a set of URIs
- Indexed URIs may appear multiple times (i.e., associated with multiple index keys)
- Each URI in such an entry may be paired with a cardinality (utilized for source ranking)
Traversal-Based Query Execution

- **Idea:** Discover relevant URIs recursively by traversing (specific) data links at query execution runtime
  - Natural support of reachability-based query semantics

- **Retrieved data serves two purposes:**
  1. Discover further URIs
  2. Construct query result
Traversal-Based – vs. – Index-Based

- Possibilities for parallelized data retrieval are limited
  - Data retrieval adds to query execution time significantly
- Usable immediately
  - Most suitable for “on-demand” querying scenario
- Depends on the structure of the network of data links

- Data retrieval can be fully parallelized
  - Reduces the impact of data retrieval on query exec. time
- Usable only after initialization phase
  - Depends on what has been selected for the index
- May miss new data sources

None of both strategies is superior over the other w.r.t. result completeness (under full-Web query semantics).
  - Both strategies may miss (different) solutions for a query
Summary

- **RDF**
  - Triple-based data model

- **SPARQL**
  - Declarative query language for RDF data
  - Main idea: pattern matching

- **Linked Data**
  - Structured, *interlinked* data on the Web

- **Querying Linked Data**
  - Data warehousing
  - SPARQL federation
  - Linked Data query processing (index-based, traversal-based)