We have seen that graphs can be encoded in several ways:

- **Adjacency matrix** (and variants)
- **Adjacency list** (and variants)
- **Other derived representations**
Encoding Graphs

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- Adjacency matrix (and variants)
- Adjacency list (and variants)
- Other derived representations

This is enough to store and manipulate graphs in software, but it is not enough to exchange graphs across applications.

Open questions:
- What kind(s) of graph do we want to exchange?
- How are vertices given (numbers? strings? specific ids? . . . )?
- Are edge labels supported and what are they?
- Can the graph include values of data types (integer? float? string? times? . . . )?
- How exactly are these things encoded in bytes in a file?
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The Resource Description Framework

RDF is a W3C\textsuperscript{1} standard for exchanging graphs

- First proposed in 1999
- Updated in 2004 (RDF 1.0) and in 2014 (RDF 1.1)
- Originally built for Web data exchange
- Meanwhile used in many graph database applications
- Supported by many other W3C standards (RDFa, SPARQL, OWL, SHACL, \ldots)

\textsuperscript{1}World Wide Web Consortium
The Resource Description Framework

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In this lecture: focus on graph representation features of RDF 1.1

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In this lecture: focus on graph representation features of RDF 1.1

W3C creates open standards: patent-free & freely accessible

- Gentle RDF 1.1 introduction: https://www.w3.org/TR/rdf11-primer/
- Specification of graph model: https://www.w3.org/TR/rdf11-concepts/
- Specific file formats are defined in other documents, linked from those

\(^1\)World Wide Web Consortium
Graphs in RDF

RDF allows us to specify graphs that are:

- **directed** (edges have a source and a target)
- **edge-labelled** (edges have one label)
- a restricted form of **multi-graphs** (multiple edges can exist between same vertices, but only if they have different labels)
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- **edge-labelled** (edges have one label)
- a restricted form of **multi-graphs** (multiple edges can exist between same vertices, but only if they have different labels)

**Example of such a graph:**

- Dresden
- Melitta Bentz
- Melitta
- coffee filter
- company

Dresden born in Melitta Bentz

Melitta bentz named after Melitta

Melitta produces company

Melitta named after inventor

Melitta bentz invented coffee filter

Melitta produced coffee filter
How should we refer to vertices? What kind of labels are allowed?

**Definition 2.1:**
A Uniform Resource Identifier (URI) is a sequence (string) of a subset of ASCII characters as defined in RFC 3986 (link). Every (absolute) URI consists of a string that defines a scheme, followed by a colon (:) and another sequence of characters specifying an authority, path, query, and fragment, where all parts other than the path are optional.

A International Resource Identifier (IRI) is a generalised form of URI that allows for an expanded range of Unicode glyphs in part of its syntax.

**Example 2.2:**
URLs are a well-known form of URI, for example:

```
https://example.org/some/page?get=something&lang=en#results
```

**Convention:**
We ignore the differences between URIs and IRIs in this course. (The lecturer will often say “URI” when he should say “IRI.” Please ignore.)
Identifiers in RDF

How should we refer to vertices? What kind of labels are allowed?

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https://example.org/some/page?get=something&lang=en #results
```

- **scheme**
- **authority**
- **path**
- **query**
- **fragment**

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Markus Krötzsch, 23th Oct 2018
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**Example 2.2:** URLs are a well-known form of URI, for example:

```
https://example.org/some/page?get=something&lang=en #results
```

**Convention:** We ignore the differences between URIs and IRIs in this course. (The lecturer will often say “URI” when he should say “IRI.” Please ignore.)
URIs vs. URLs

The widely used term Uniform Resource Locator (URL) is an informal way to refer to URIs that specify the location of a digital document. Not all URIs support this.

**Example 2.3:** Many URI schemes have been defined. Examples include

- `http`, `https`, `ftp` for transferring data using various protocols
- `mailto` for emails (=path)
- `irc` for specifying IRC channels
- `file` for referring to locations on some file system
- `urn` for naming resources without defining a protocol or resolution mechanism; used, e.g., for ISBNs
- ...

Registered schemes usually provide some additional syntax requirements, access protocols, and resolution mechanisms, and they often relate to a registration procedure based on some authority.
IRIs in RDF

RDF uses IRIs in two ways:

- IRIs define resources that appear as vertices in the graph
- IRIs are used as property labels
IRIs in RDF

RDF uses IRIs in two ways:

- IRIs define resources that appear as vertices in the graph
- IRIs are used as property labels

Example of such a graph:

```
https://example.org/Melitta-Bentz
https://www.dresden.de/#uri
https://example.org/Melitta
https://example.org/company
https://example.org/coffee-filter
https://example.org/named-after
https://example.org/born-in
https://example.org/invention
http://www.w3.org/1999/02/22-rdf-syntax-ns#type
```

Note: It is not always obvious what an IRI is supposed to refer to, and many IRIs may refer to the same thing – we cannot assume that all RDF data in the world is integrated.
Which IRIs to use?

Where do the IRIs that we use in graphs come from?

- They can be newly created for an application to avoid confusion with resources in other graphs.
- They can be IRIs that are already in common use to support information integration and re-use across graphs.

Guidelines for creating new IRIs:
1. Check if you could re-use an existing IRI to avoid duplication if feasible.
2. Use http(s) IRIs to take advantage of useful protocols, registries, and resolution mechanisms.
3. Create new IRIs based on domains that you own to ensure clear ownership and no danger of clashing with other peoples' IRIs.
4. Don't use URLs of existing web pages, unless you want to store data about pages to avoid confusion between pages and more abstract resources.
5. Make your IRIs return some useful content via http(s) to help others get information about your resources.
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Why IRIs?

**URIs may seem a bit complicated**

- They look a bit technical and complex
- They are hard to display or draw in a graph
- The guidelines just given may seem quite demanding to newcomers
Why IRIs?

**URIs may seem a bit complicated**
- They look a bit technical and complex
- They are hard to display or draw in a graph
- The guidelines just given may seem quite demanding to newcomers

**However, it’s not that hard:**
- RDF can work with any form of IRI (most tools would probably accept any Latin letter string with a colon inside!)
- The guidelines help sharing graphs across applications – a strength of RDF
- Internet domain name registration is a very simple way to define ownership in a global data space
- IRIs should not be shown to users (we will introduce human-readable labels soon)
Excursion: Resolvable IRIs

We asked for IRIs that are different from URLs of Web pages while at the same time returning some useful content via http(s).

How is this possible?

1. Use fragments. IRIs with fragments are different from the IRIs (URLs) without the fragment, but resolving them will return the content of this fragment-less IRI.

2. Use HTTP redirects. Web servers can be configured to transparently redirect one URL to another; for IRIs it is common to use HTTP response codes 302 (temporary redirect) or 303 (see other).

Example 2.4: The Wikidata IRI http://www.wikidata.org/entity/Q5 redirects permanently (301) to https://www.wikidata.org/entity/Q5, which redirects (303) to https://www.wikidata.org/wiki/Special:EntityData/Q5, which by default redirects (303) to a JSON document https://www.wikidata.org/wiki/Special:EntityData/Q5.json.

Real-world server configurations can be complicated.
Excursion: Resolvable IRIs

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How is this possible?

(1) **Use fragments.** IRIs with fragments are different from the IRIs (URLs) without the fragment, but resolving them will return the content of this fragment-less IRI.

**Example 2.4:** RDF uses some own IRIs for special purposes, e.g.,
http://www.w3.org/1999/02/22-rdf-syntax-ns#type for denoting the relation between resources and their type (class). This resolves to http://www.w3.org/1999/02/22-rdf-syntax-ns but is not the identifier of this document.
Excursion: Resolvable IRIs

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1. **Use fragments.** IRIs with fragments are different from the IRIs (URLs) without the fragment, but resolving them will return the content of this fragment-less IRI.

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Real-world server configurations can be complicated.
Excursion: Content negotiation

The redirect mechanism has another useful application:
Web servers (and the software they run) can dynamically decide where to redirect to.

**Content negotiation** is the practice of offering several documents under the same URL by redirecting to the version that is most suitable for the request of a client. The HTTP protocol allows clients and servers to exchange extra information with their request that can be used to state preferences.

**Example 2.5:** The `Accept` header is commonly used by clients to select preferred result formats for a request. For example, the command

```
```

makes Wikidata return RDF data in Turtle format rather than JSON.
IRIs can represent anything, but **data values** (numbers, strings, times, ...) should not be represented by IRIs!
Data values

IRIs can represent anything, but data values (numbers, strings, times, ...) should not be represented by IRIs!

Why not use IRIs here too?
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Data values

IRIs can represent anything, but data values (numbers, strings, times, ...) should not be represented by IRIs!

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1. Data values are the same everywhere \(\sim\) no use in application-specific IRIs
2. Many RDF-based applications need a built-in understanding of data values (e.g., for sorting content)
Data values

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Why not use IRIs here too?

1. Data values are the same everywhere $\sim$ no use in application-specific IRIs
2. Many RDF-based applications need a built-in understanding of data values (e.g., for sorting content)
3. Data values are usually more “interpreted” than IRIs.

Example 2.6: Using a hypothetical scheme “integer,” the IRIs integer:42 and integer:+42 would be different, but intuitively they should represent the same number.
Encoding data values

- Data values in RDF are written in the format "lexical value"^^datatype-IRI
- They are drawn as rectangular nodes in graphs
Encoding data values

- Data values in RDF are written in the format "lexical value"^^datatype-IRI
- They are drawn as rectangular nodes in graphs

Example graph with data values:

- "Melitta Bentz"^^xsd:string
- "547172"^^xsd:int
- "1873-01-31"^^xsd:date

RDF supports many different datatypes, most of which are based on XML Schema ("xsd")
Definition 2.7: A datatype in RDF is specified by the following components:

- The value space is the set of possible values of this type.
- The lexical space is a set of strings\(^a\) that can be used to denote values of this type.
- the lexical-to-value mapping is a function that maps each string from the lexical space to an element of the value space.

\(^a\)RDF is based on Unicode strings, but this is inessential here.

Datatypes for RDF must be identified by IRIs (known to software that supports them).
Definition 2.7: A datatype in RDF is specified by the following components:

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- The lexical-to-value mapping is a function that maps each string from the lexical space to an element of the value space.

\(^a\)RDF is based on Unicode strings, but this is inessential here.

Datatypes for RDF must be identified by IRIs (known to software that supports them).

Example 2.8: The W3C standard XML Schema defines the datatype \texttt{integer}, identified by the IRI http://www.w3.org/2001/XMLSchema\#integer, has the value space of all integer numbers (of arbitrarily large absolute value), the lexical space of finite-length strings of decimal digits (0–9) with an optional leading sign (− or +), and the expected lexical-to-value mapping.
Many standard datatypes are defined by XML Schema (currently in version 1.1 of 2012):

<table>
<thead>
<tr>
<th>Name</th>
<th>Value space</th>
<th>Lexical space</th>
</tr>
</thead>
<tbody>
<tr>
<td>string</td>
<td>XML-defined subset of Unicode strings</td>
<td>Value space (mapping is identity)</td>
</tr>
<tr>
<td>boolean</td>
<td>The set {true, false}</td>
<td>The set {true, false, 1, 0}</td>
</tr>
<tr>
<td>decimal</td>
<td>Arbitrary-precision decimal numbers</td>
<td>Sequences of decimal digits, optionally signed and with one .</td>
</tr>
<tr>
<td>integer</td>
<td>Arbitrary integer numbers</td>
<td>Like decimal but without .</td>
</tr>
<tr>
<td>int</td>
<td>{-2147483648, ..., 2147483647} (32bit)</td>
<td>Integer strings that map to values within this range</td>
</tr>
<tr>
<td></td>
<td>Similar types exist for long (64bit), short (16bit), byte (8bit), unsigned versions, etc.</td>
<td></td>
</tr>
<tr>
<td>double</td>
<td>IEEE double-precision 64-bit floating point numbers</td>
<td>decimal strings, exp notation numbers, special values (e.g., NaN)</td>
</tr>
<tr>
<td>float</td>
<td>single-precision 32-bit floating point numbers</td>
<td>same as double</td>
</tr>
</tbody>
</table>
Important datatypes in RDF (2)

There are also many types for dates and times:

<table>
<thead>
<tr>
<th>Name</th>
<th>Value space</th>
<th>Lexical space</th>
</tr>
</thead>
<tbody>
<tr>
<td>dateTime</td>
<td>dates with times represented by a seven-tuple consisting of year, month, day, hours, minutes, seconds, timezone offset (constrained to time-like ranges)</td>
<td>ISO-style date-time strings, e.g., 2018-10-23T11:45:30+01:00; one can write Z for offset 00:00</td>
</tr>
</tbody>
</table>

There are also partial time types, such as date, time, gYear (Gregorian year), etc.

Many further types exist: a full list can be found at https://www.w3.org/TR/2014/REC-rdf11-concepts-20140225/#section-Datatypes
**Definition 2.9:** An **RDF literal** is an expression of form "lexical value"^^datatype, where lexical value is a string and datatype is an IRI.

Literals are semantically interpreted to denote a value in the value space as defined by the datatype’s lexical-to-value mapping. If the given string is not a valid lexical value, the literal is ill-typed.

**Note:** RDF 1.1 also allows for string literals "lexical value"; in this case XML Schema string is assumed as datatype.
Furthermore, RDF supports strings that have a specific language:

**Definition 2.10:** A language-tagged string is an expression of the form "string"@language where string is a Unicode string and language is a well-formed language tag (after BCP47). They are interpreted as pairs of strings with a (lowercased) language tag.

The datatype of these literals is defined to be http://www.w3.org/1999/02/22-rdf-syntax-ns#langString (but this is never used in syntax).

**Example 2.11:** The strings "Pommes Frites"@de, "chips"@en-UK, and "French fries"@en-US are language-tagged.

This special case of literal is widely used in practice to encode human-readable labels.
Blank nodes

RDF also supports vertices that are not identified by a IRI, called blank nodes or bnodes.

- Intuitively, bnodes are placeholder for some specific (but unspecified) node
- Their use makes the claim: “there is something at this position”
- Similar to existentially quantified variables in logic
Blank nodes

RDF also supports vertices that are not identified by a IRI, called **blank nodes** or **bnodes**.

- Intuitively, bnodes are placeholder for some specific (but unspecified) node
- Their use makes the claim: “there is something at this position”
- Similar to existentially quantified variables in logic

**Example:** Blank nodes have historically been used for auxiliary vertices

```
https://www.dresden.de/#uri

https://example.org/coordinates

https://example.org/latitude

https://example.org/longitude

"51.049259"^^xsd:decimal

"13.73836"^^xsd:decimal
```

**Note:** Today, bnodes are largely avoided. They still occur in the RDF-encoding of the OWL Web Ontology Language, but specialised tools are used in this application anyway.
We now have defined all necessary kinds of RDF terms: IRIs, blank nodes, and literals.
RDF Graphs

We now have defined all necessary kinds of RDF terms: IRIs, blank nodes, and literals. The formal definition of RDF graph is maybe slightly different from expectations:

**Definition 2.12:** An RDF graph is a set of triples consisting of the following parts:

- a **subject** that is an IRI or blank node
- a **predicate** that is an IRI
- a **object** that is an IRI, blank node, or literal
RDF Graphs

We now have defined all necessary kinds of RDF terms: IRIs, blank nodes, and literals. The formal definition of RDF graph is maybe slightly different from expectations:

**Definition 2.12:** An RDF graph is a set of triples consisting of the following parts:

- a subject that is an IRI or blank node
- a predicate that is an IRI
- a object that is an IRI, blank node, or literal

**Notes:**

- This view resembles a (labelled) adjacency list encoding
- The restrictions on the use of blank nodes and literals in triples is a bit arbitrary
- RDF graphs are mostly syntactic (rather what we write than what we mean)
- In particular, literals are not interpreted when defining graphs
  - $\Rightarrow$ multiple ways of writing the same value lead to multiple graphs
  - $\Rightarrow$ ill-formed literals are allowed in graphs
What we outlined so far is the abstract syntax of RDF. To exchange graphs, we need concrete syntactic forms to encode RDF graphs.
RDF Serialisations

What we outlined so far is the abstract syntax of RDF. To exchange graphs, we need concrete syntactic forms to encode RDF graphs.

There are numerous syntactic formats available:

- N-Triples as a simple line-based format
- Turtle adds convenient abbreviations to N-Triples
- JSON-LD for encoding RDF graphs in JSON
- RDF/XML for encoding RDF graphs in XML
- RDFa for embedding RDF graphs into HTML

Further historic/unofficial formats exist but are hardly relevant today.
N-Triples

N-Triples is almost the simplest format conceivable:

- Each line encodes one triple:
  - IRIs are written in pointy brackets, e.g., <https://www.dresdenrespekt.de/>
  - Literals are written as usual with a given type IRI, e.g., "2018-10-21"^^<http://www.w3.org/2001/XMLSchema#date> or with a language-tag, e.g., "Wir sind mehr"@de
  - Blank nodes are written as _ : stringId, where stringId is a string that identifies the blank node within the document (it has no global meaning)
  - Parts are separated by whitespace, and lines end with .

- Unicode is supported, but various escape sequences also work
- Comments are allowed after triples (nowhere else); they start with #

Full specification at https://www.w3.org/TR/n-triples/
could be encoded as (line-breaks within triples for presentation only):

```turtle
<https://example.org/Melitta-Bentz> <https://example.org/invention> _:1 .
_:1 <https://example.org/inventor> <https://example.org/Melitta-Bentz> .
```
N-Triples: Summary

**Advantages:**

- Very simple
- Fast and easy to parse
- Processable even with basic text-processing tools, e.g., grep

**Disadvantages:**

- Somewhat inefficient in terms of storage space
- Not particularly human-friendly (reading and writing)
The Turtle format extends N-Triples with several convenient abbreviations:

- Prefix declarations and base namespaces allow us to shorten IRIs
- If we terminate triples with ; (respectively with ,) then the next triple is assumed to start with the same subject (respectively with the same subject and predicate)
- Blank nodes can be encoded using square brackets; they might contain predicate-object pairs that refer to the blank node as subject
- More liberal support for comments (possibly on own line)
- Simpler forms for some kinds of data values

There are several other shortcuts and simplifications. Full specification at https://www.w3.org/TR/turtle/.
PREFIX and BASE by example

- BASE is used to declare a base IRI, so that we can use relative IRIs
- PREFIX is used to declare abbreviations for IRI prefixes

**Example 2.13:** We can write the previous example as follows:

```xml
BASE <https://example.org/>
PREFIX xsd: <http://www.w3.org/2001/XMLSchema#>
PREFIX rdfs: <http://www.w3.org/2000/01/rdf-schema#>

<Melitta-Bentz> rdfs:label "Melitta Bentz"@en .
<Melitta-Bentz> <birthdate> "1873-01-31"^^xsd:date .
<Melitta-Bentz> <invention> _:1 .
<https://www.dresden.de/#uri> <population> "547172"^^xsd:int .
_:1 <inventor> <Melitta-Bentz> .
```

**Note:** Relative IRIs are still written in `<` and `>` (e.g., `<birthdate>`); prefixed names are written without brackets (e.g., `rdfs:label`).
Use of semicolon by example

- If we terminate triples with ; then the next triple is assumed to start with the same subject
- If we terminate triples with , then the next triple is assumed to start with the same subject and predicate

Example 2.14: We can write the previous example as follows:

```xml
BASE <https://example.org/>
PREFIX xsd: <http://www.w3.org/2001/XMLSchema#>
PREFIX rdfs: <http://www.w3.org/2000/01/rdf-schema#>

<Melitta-Bentz> rdfs:label "Melitta Bentz"@en ;
    <birthdate> "1873-01-31"^^xsd:date ;
    <invention> _:1 ;
</https://www.dresden.de/#uri> <population> "547172"^^xsd:int .
_:1 <inventor> <Melitta-Bentz> .
```
Brackets for bnodes by example

- The expression [] represents a bnode (without id)
- predicate-object pairs within [...] are allowed to give further triples with the bnode as subject

Example 2.15: We can write the previous example as follows:

```xml
BASE <https://example.org/>
PREFIX xsd: <http://www.w3.org/2001/XMLSchema#>
PREFIX rdfs: <http://www.w3.org/2000/01/rdf-schema#>

<Melitta-Bentz> rdfs:label "Melitta Bentz"@en ;
    <birthdate> "1873-01-31"^^xsd:date ;
    <invention> [ <inventor> <Melitta-Bentz> ] ;
<https://www.dresden.de/#uri> <population> "547172"^^xsd:int .
```
Abbreviating numbers and booleans

• Numbers can just be written without quotes and type to denote literals in default types (integer, decimal, or double)
• Booleans can also be written as true or false directly

Example 2.16: We can write the previous example as follows:

BASE <https://example.org/>
PREFIX xsd: <http://www.w3.org/2001/XMLSchema#>
PREFIX rdfs: <http://www.w3.org/2000/01/rdf-schema#>

<Melitta-Bentz> rdfs:label "Melitta Bentz"@en ;
    <birthdate> "1873-01-31"^^xsd:date ;
    <invention> [ <inventor> <Melitta-Bentz> ] ;
<https://www.dresden.de/#uri> <population> 547172 .
Turtle: Summary

**Advantages:**
- Still quite simple
- Not hard to parse
- Human-readable (if formatted carefully)

**Disadvantages:**
- Not safely processable with grep and similar tools
Other syntactic forms

There are various further syntactic forms:

- **RDF/XML**: An XML-based encoding; historically important in RDF 1.0; hard-to-parse but unable to encode all RDF graphs; not human-readable either
- **JSON-LD**: A JSON-based encoding and away of specifying how existing JSON maps to RDF; can re-use fast JSON parsers (esp. those in browsers)
- **RDFa**: An HTML embedding of RDF triples; used for HTML document annotations (e.g., with schema.org); mostly for consumption by Web crawlers

Details are found online; we will not cover them here.
Common namespaces/prefixes

Many syntactic encodings of RDF support some abbreviation mechanism for IRIs by declaring some form of namespaces or prefixes.

While prefixes can usually be declared freely, there are some standard prefixes that are conventionally used and virtually always declared in the same way. They include:

<table>
<thead>
<tr>
<th>Abbr.</th>
<th>Abbreviated IRI prefix</th>
<th>Usage</th>
</tr>
</thead>
<tbody>
<tr>
<td>xsd:</td>
<td><a href="http://www.w3.org/2001/XMLSchema#">http://www.w3.org/2001/XMLSchema#</a></td>
<td>XML Schema datatypes</td>
</tr>
<tr>
<td>rdf:</td>
<td><a href="http://www.w3.org/1999/02/22-rdf-syntax-ns#">http://www.w3.org/1999/02/22-rdf-syntax-ns#</a></td>
<td>RDF vocabulary</td>
</tr>
<tr>
<td>rdfs:</td>
<td><a href="http://www.w3.org/2000/01/rdf-schema#">http://www.w3.org/2000/01/rdf-schema#</a></td>
<td>“RDF Schema,” more RDF vocabulary</td>
</tr>
</tbody>
</table>

Convention 2.17: We will henceforth assume that these abbreviations are used with the above meaning throughout this course.

Abbreviations such as xsd:dateTime are sometimes called qualified names (qnames)
Summary

RDF is a W3C standard for describing directed, edge-labelled graphs in an interoperable way.

It identifies vertices and edge-types using IRIs, and it can use many datatypes.

Several syntactic formats exist for exchanging RDF data.

What’s next?

• How can we encode data in RDF?
• Where can we get RDF data? Application examples?
• How can we query and analyse such graphs?