

Knowledge Representation and Reasoning

Sebastian Rudolph

Based on slides of
Bernardo Cuenca Grau, Ian Horrocks, and Przemysław Wałęga
(University of Oxford)

Dresden, October 2026

Lecturer: Sebastian Rudolph
sebastian.rudolph@tu-dresden.de

Tutorials: Sebastian Rudolph
sebastian.rudolph@tu-dresden.de

- Mondays, 9:20 – 10:50, APB E005
- Mondays, 14:50 – 16:20, APB E005

- Dates, slides, and other info on course webpage:
[https://iccl.inf.tu-dresden.de/web/Foundations_of_Knowledge_Representation_\(WS2026\)/en](https://iccl.inf.tu-dresden.de/web/Foundations_of_Knowledge_Representation_(WS2026)/en)

- Oral examination



Applications often need to represent knowledge

- seats on an aeroplane

British Airways Seat Maps

Airbus A319 (319) Domestic V1

Overview

Planes & Seat Maps

Airbus A318 (318)

Airbus A319 (319) Domestic V1

Airbus A319 (319) Domestic V2

Airbus A319 (319) Domestic V3

Airbus A319 (319) European

VIEW MORE PLANES

Check-in

Baggage

Infants

Minors

Pets

There are 4 versions of this aircraft. [Check Version](#)

Seating details

	Pitch	Width	Seating details
UK Domestic	29-30	17.0	143 standard seats

In-flight amenities

Food

British Airways offers a variety of complimentary food and beverages, based on the time of day and departure location. Click [here](#) for more information about food offered onboard.

Overview

This British Airways Airbus A319 is primarily operated on short-haul Domestic routes.

This A319 features a one class configuration with 143 standard UK Domestic seats.

Featured user comments

Read user reviews for British Airways Airbus A319 (319) Domestic V1

Submitted by **Dan R** on 2017/03/19 for Seat 13B
There is no air nozzle above seats in row 13

Submitted by **Rory A** on 2016/08/25 for Seat 1E
Front row seat was good for speedy boarding and disembarking. Extra legroom was welcome too, especially being allocated this seat at check in at no extra cost. Comfortable leather seats, fine for a short flight. On board service is brief but again more than adequate for the duration. Plane was clean and comfortable.

Business Class Flights

Save 50% On Business Class Flights. All Destinations & Airlines Here!

businessclassintern...

Seat map key

- Good seat
- Be Aware - See comments
- Bad seat
- Mixed Review
- Standard seat
- Blocked seat
- Premium seat
- Crew seat
- Power port
- Emergency exit
- Galley
- Lavatory
- Closet
- Bassinet

Applications often need to represent knowledge

- seats on an aeroplane
- account transactions



16 High Street, Anytown, Anyshire YZ99 1XY

Account name: **Mr John Smith**
Sort code: **53-61-33**
Account number: **99988877**

Your current account statement:
1 February to 1 March 2011

Page 1 of 1

Mr John Smith
5 Any Road
Randomford
Anyshire
YZ98 5XY

Your account summary

Balance at 1 February: £312.34
Total money in: £300.00
Total money out: £343.02
Balance at 1 March: £30.68 OD

Date	Description	Money out	Money in	Balance
	Balance brought forward			312.34
1 February	Card payment – High St Petrol Station	24.50		287.84
	Direct debit – Green Mobile Phone Bill	20.00		267.84
3 February	Cash withdrawal – YourDosh, Anytown High Street, timed 17:30 31 Jan	30.00		237.84
8 February	Cheque 00068	22.95		214.89
11 February	BACS – KleanKars, ref JS5-999		300.00	514.89
16 February	Standing order – Rent to J Jones Cash withdrawal – WadBank, Randomford, timed 09.52 14 Feb	300.00		214.89
17 February	Card Payment – High St Petrol Station	40.00		67.14
	Direct debit – Home Insurance	23.00		44.14
19 February	Online transfer to A/C 1116932, Sort 01-92-10 ref: Mum	34.14		10.00
21 February	Card payment - QuidsGifts	15.00		5.00 OD
24 February	Balance carried forward			5.68 OD
28 February	Card payment - QuidsGifts	25.00		30.68 OD
1 March	Interest 29 Jan A/C 99988877	00.68		30.68 OD
	Charges 29 Jan A/C 99988877	25.00		30.68 OD
	Balance carried forward			30.68 OD

Applications often need to represent knowledge

- seats on an aeroplane
- account transactions
- tall buildings

Name	City	State	Height	Feet	Floors	Completed
Federation Tower: East Tower	Moscow	 Russia	373.7	1,226	95	2016
OKO: South Tower	Moscow	 Russia	354.1	1,162	85	2015
Mercury City Tower	Moscow	 Russia	338.8	1,112	75	2013
The Shard ^[1]	London	 United Kingdom	309.7	1,017	87	2012
Eurasia ^[2]	Moscow	 Russia	308.9	1,014	72	2014
CoC: Moscow Tower ^[3]	Moscow	 Russia	301.6	990	76	2010
Skyland İstanbul 1 ^{[4][5]}	Istanbul	 Turkey	293.1	932	65	2017
Skyland İstanbul 2 ^{[4][5]}	Istanbul	 Turkey	293.1	932	65	2017
Metropol İstanbul ^[6]	Istanbul	 Turkey	280	919	66	2017
Emaar Square	Istanbul	 Turkey	280	920	62	2018
Naberezhnaya Tower C	Moscow	 Russia	268.4	881	59	2007
Triumph Palace ^[7]	Moscow	 Russia	264.1	867	57	2005
Commerzbank Tower ^{[8][9]}	Frankfurt	 Germany	258.7	848	56	1997
CoC: Saint Petersburg Tower ^[10]	Moscow	 Russia	256.9	843	65	2010
Messeeturm	Frankfurt	 Germany	256.5	842	55	1990
Nurol Life ^{[11][12]}	Istanbul	 Turkey	252	827	60	2017
Torre de Cristal	Madrid	 Spain	249	817	45	2008
Torre Cepsa	Madrid	 Spain	248.3	815	45	2008
Evolution Tower ^[13]	Moscow	 Russia	245.9	807	53	2014
OKO: North Tower ^[14]	Moscow	 Russia	245	804	49	2014
Federation: West Tower	Moscow	 Russia	243.2	798	62	2007
Main building of Moscow State University	Moscow	 Russia	240	787	36	1953
Imperia Tower	Moscow	 Russia	238.7	783	60	2011
Palace of Culture and Science	Warsaw	 Poland	237	777	43	1955
Torre PwC	Madrid	 Spain	236	774	52	2008
1 Canada Square	London	 United Kingdom	235	771	50	1991
Istanbul Sapphire ^{[15][16]}	Istanbul	 Turkey	234.9	770	54	2010
Tour First	Paris ^B	 France	231	758	56	2011
Unicredit Tower	Milan	 Italy	231	758	35	2011
Heron Tower	London	 United Kingdom	230	755	46	2011

Applications often need to represent knowledge

- seats on an aeroplane
- account transactions
- tall buildings

and to answer questions

- seats available on flight?

 SAS		19:05 LHR	 ARN	12:00 OSL (+1)	15h 55m	£187 Opodo View Deal 	
 SAS		17:20 OSL	 SVG	18:50 LHR (+1)	26h 30m		
Add a hotel with Expedia		Omega £190		tripsta £198	5 more  £187	Share Watch	
 SWISS		12:05 LHR	 ZRH	19:00 OSL	5h 55m	£230 Gotogate View Deal 	
 Lufthansa		06:00 OSL	 FRA	14:40 LHR	9h 40m		
Add a hotel with Expedia		mytrip.com £237		Omega £237	3 more  £243	Share Watch	
 Fly for less to Oslo with Austrian Airlines Enjoy a relaxing flight with delightful Austrian service and hospitality. Book now at austrian.com Austrian.com Sponsored							View Deal
 Lufthansa		06:30 LHR	 FRA	12:00 OSL	4h 30m	£241 Gotogate View Deal 	
 Lufthansa		06:00 OSL	 FRA	14:40 LHR	9h 40m		
Add a hotel with Expedia		BudgetAir £244		mytrip.com £247	4 more  £247	Share Watch	
 Lufthansa		17:30 LHR	 FRA	23:10 OSL	4h 40m	£241 Gotogate View Deal 	
 Lufthansa		06:00 OSL	 FRA	14:40 LHR	9h 40m		
Add a hotel with Expedia		mytrip.com £247		Omega £247	3 more  £254	Share Watch	

Applications often need to represent knowledge

- seats on an aeroplane
- account transactions
- tall buildings

and to answer questions

- seats available on flight?
- can afford to pay rent?



16 High Street, Anytown, Anyshire YZ99 1XY

Account name: **Mr John Smith**
Sort code: **53-61-33**
Account number: **99988877**

Your current account statement:
1 February to 1 March 2011

Page 1 of 1

Mr John Smith
5 Any Road
Randomford
Anyshire
YZ98 5XY

Your account summary

Balance at 1 February: £312.34
Total money in: £300.00
Total money out: £343.02
Balance at 1 March: **£30.68 OD**

Date	Description	Money out	Money in	Balance
	Balance brought forward			312.34
1 February	Card payment – High St Petrol Station	24.50		287.84
	Direct debit – Green Mobile Phone Bill	20.00		267.84
3 February	Cash withdrawal – YourDosh, Anytown High Street, timed 17:30 31 Jan	30.00		237.84
8 February	Cheque 00068	22.95		214.89
11 February	BACS – KleanKars, ref JS5-999		300.00	514.89
16 February	Standing order – Rent to J Jones Cash withdrawal – WadBank, Randomford, timed 09.52 14 Feb	300.00		214.89
17 February	Card Payment – High St Petrol Station	40.00		67.14
	Direct debit – Home Insurance	23.00		44.14
19 February	Online transfer to A/C 1116932, Sort 01-92-10 ref. Mum	34.14		10.00
21 February	Card payment - QuidsGifts	15.00		5.00 OD
24 February	Balance carried forward			5.68 OD
28 February	Card payment - QuidsGifts	25.00		30.68 OD
1 March	Interest 29 Jan A/C 99988877	00.68		30.68 OD
	Charges 29 Jan A/C 99988877	25.00		30.68 OD
	Balance carried forward			30.68 OD

Applications often need
to represent knowledge

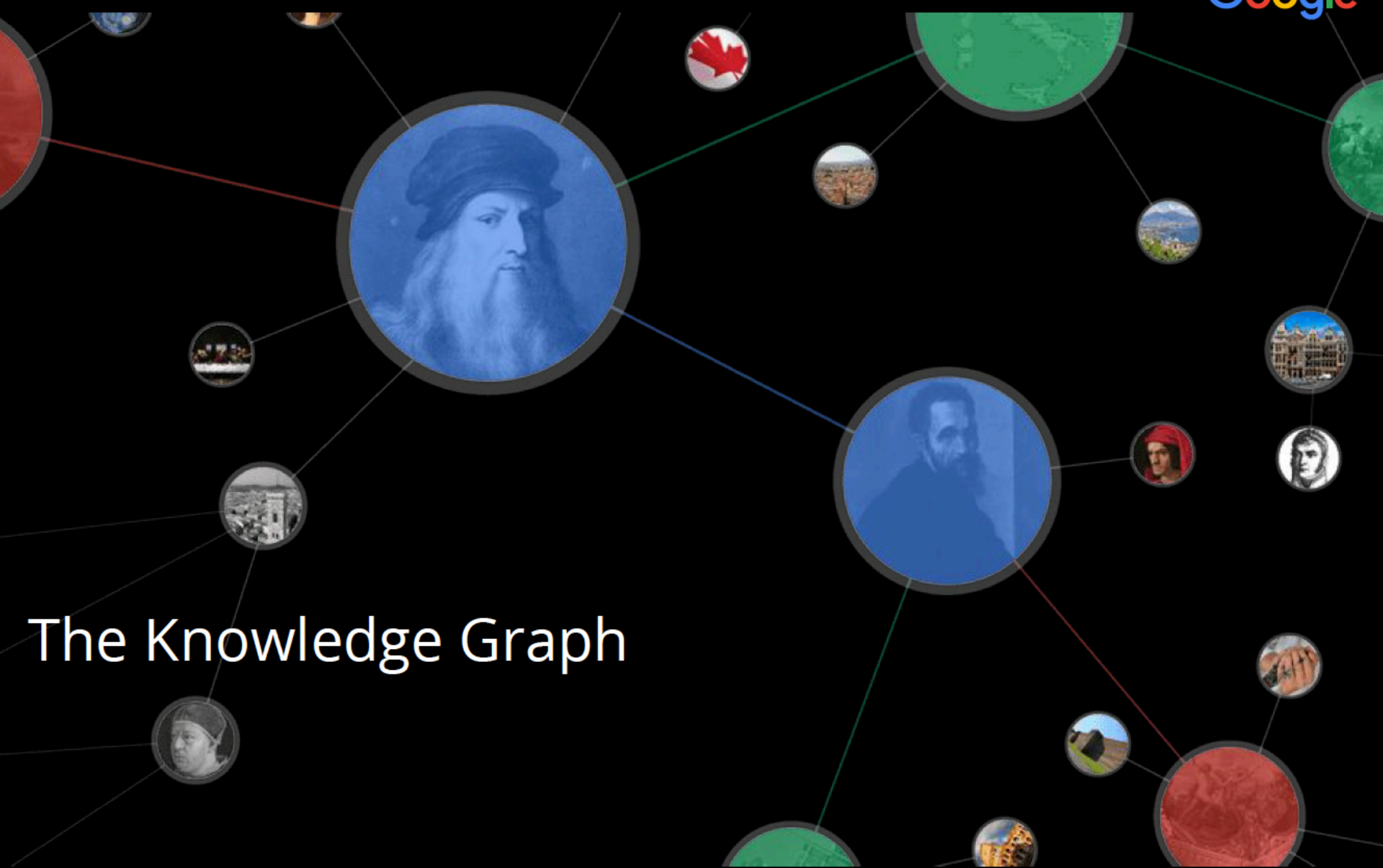
- seats on an aeroplane
- account transactions
- tall buildings

and to answer questions

- seats available on flight?
- can afford to pay rent?
- tallest building in Europe?

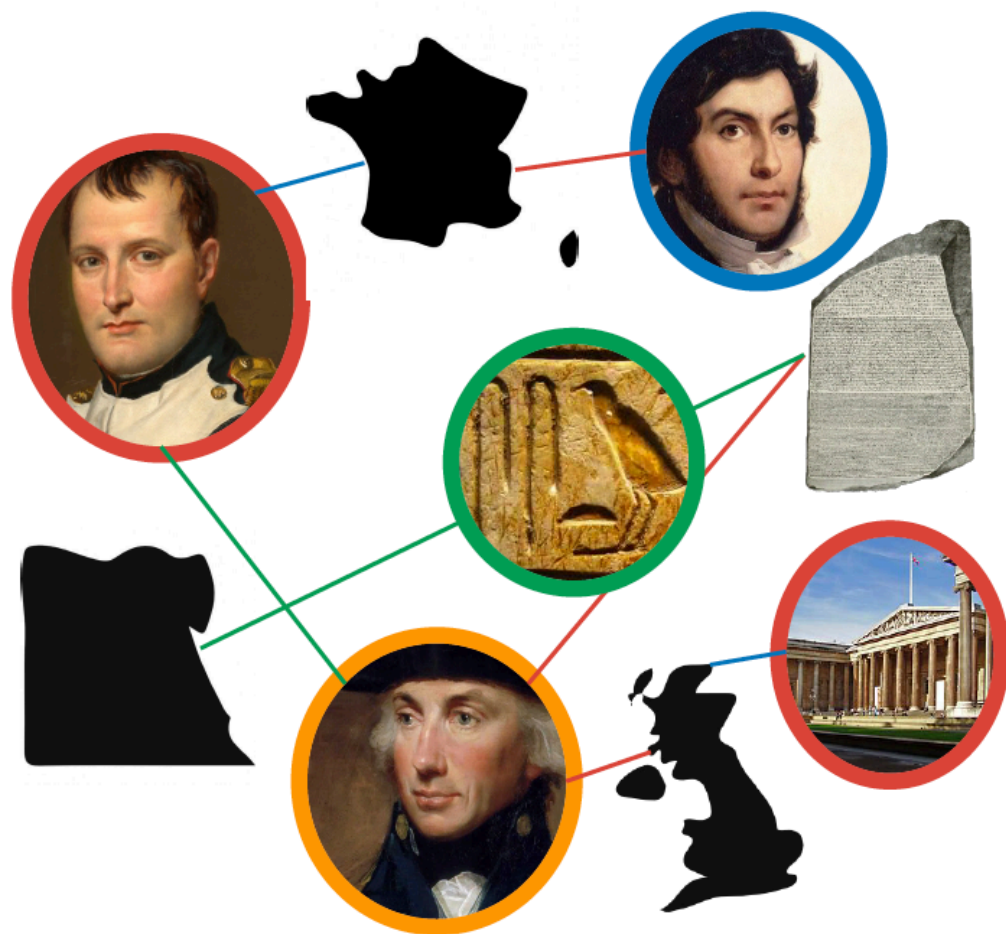


What kind of representation?



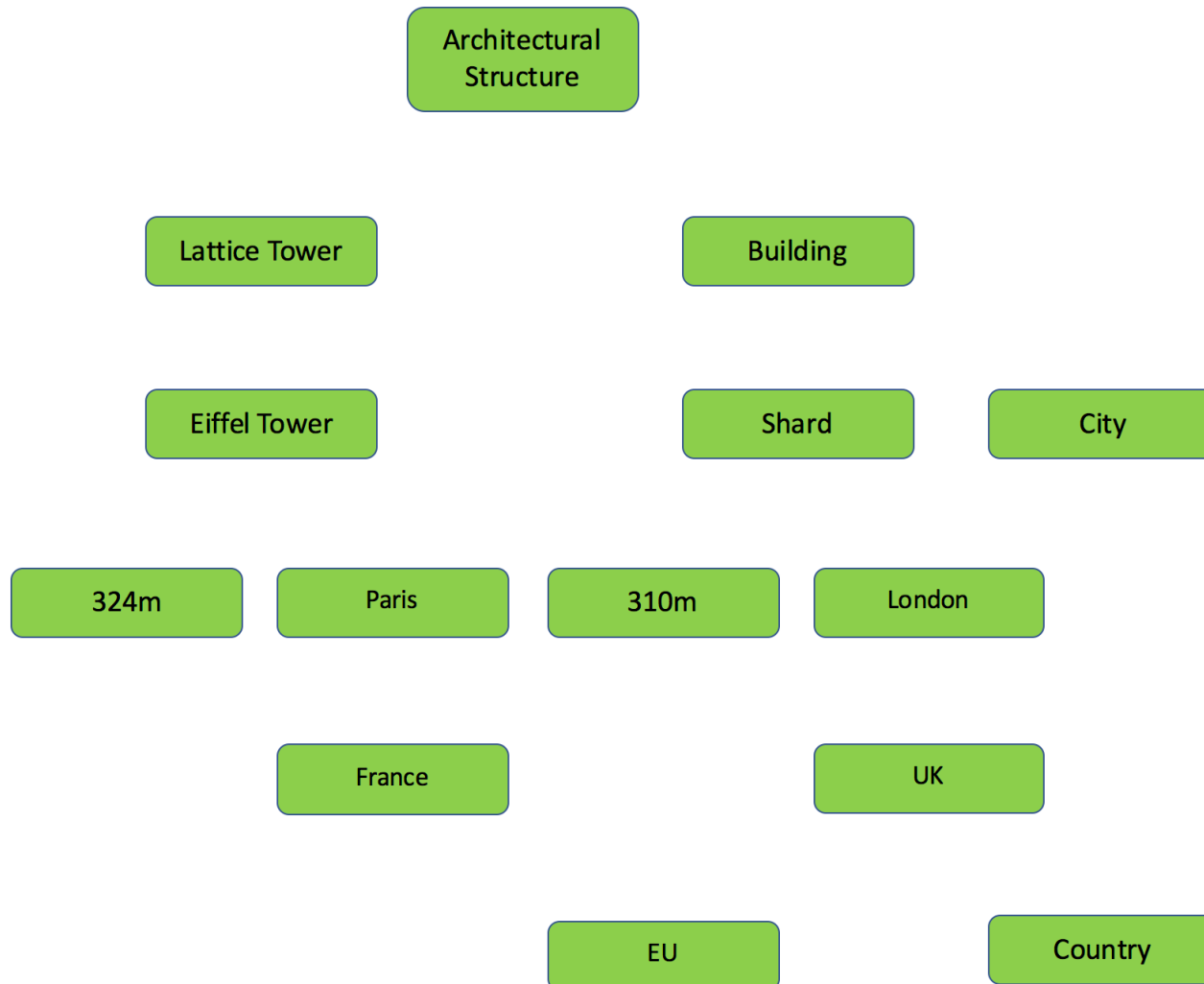
The Knowledge Graph

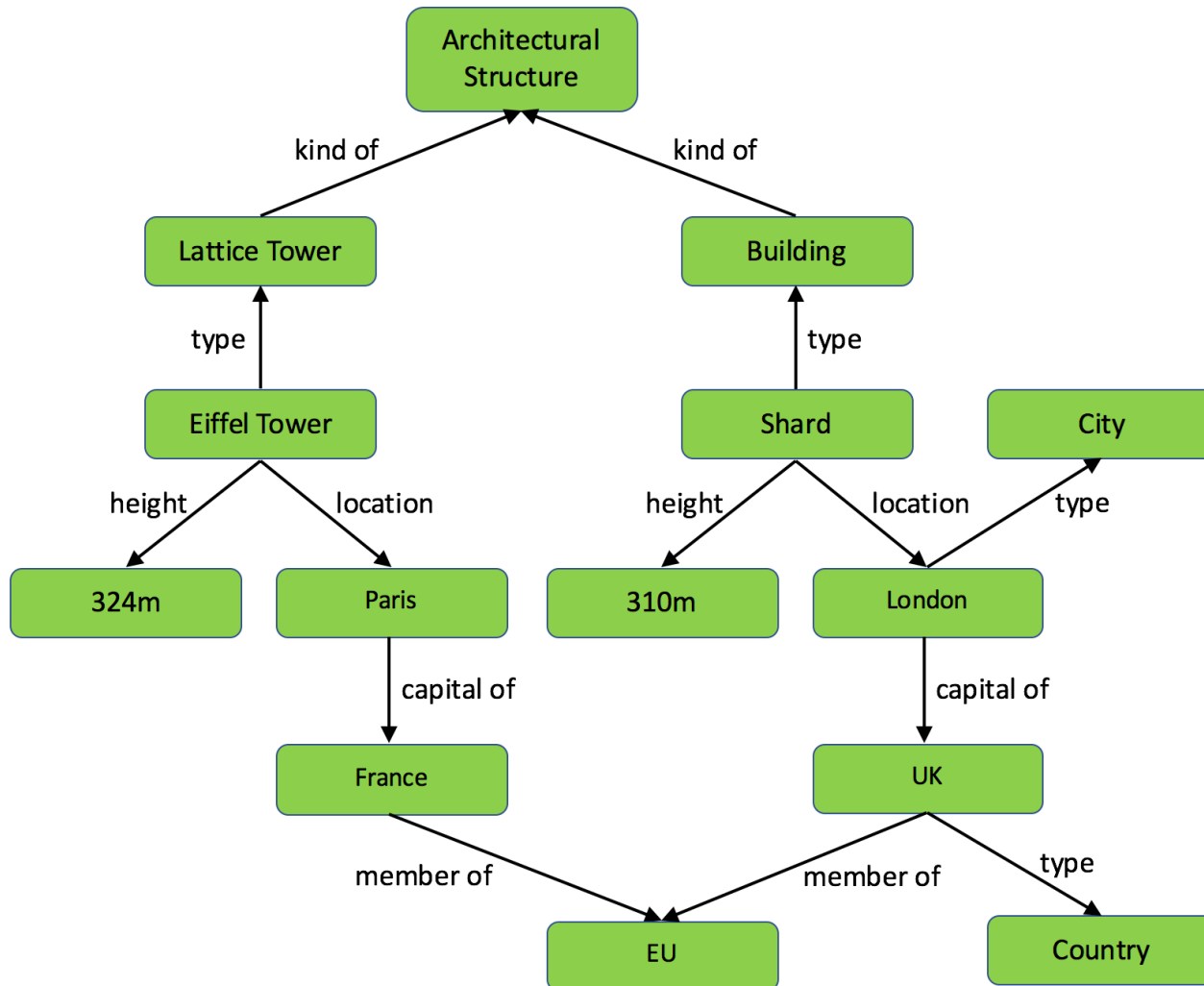
The Knowledge Graph

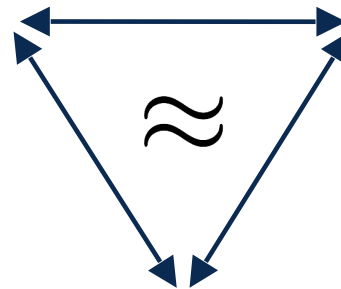
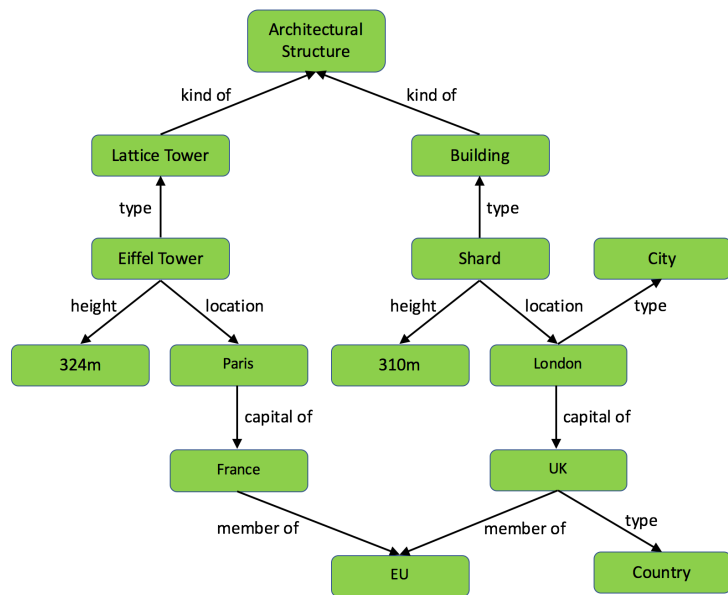


The Knowledge Graph is a comprehensive collection of real-world entities (people, places, things, and concepts) along with relationships and factual attributes that describe them.

Knowledge as Graphs





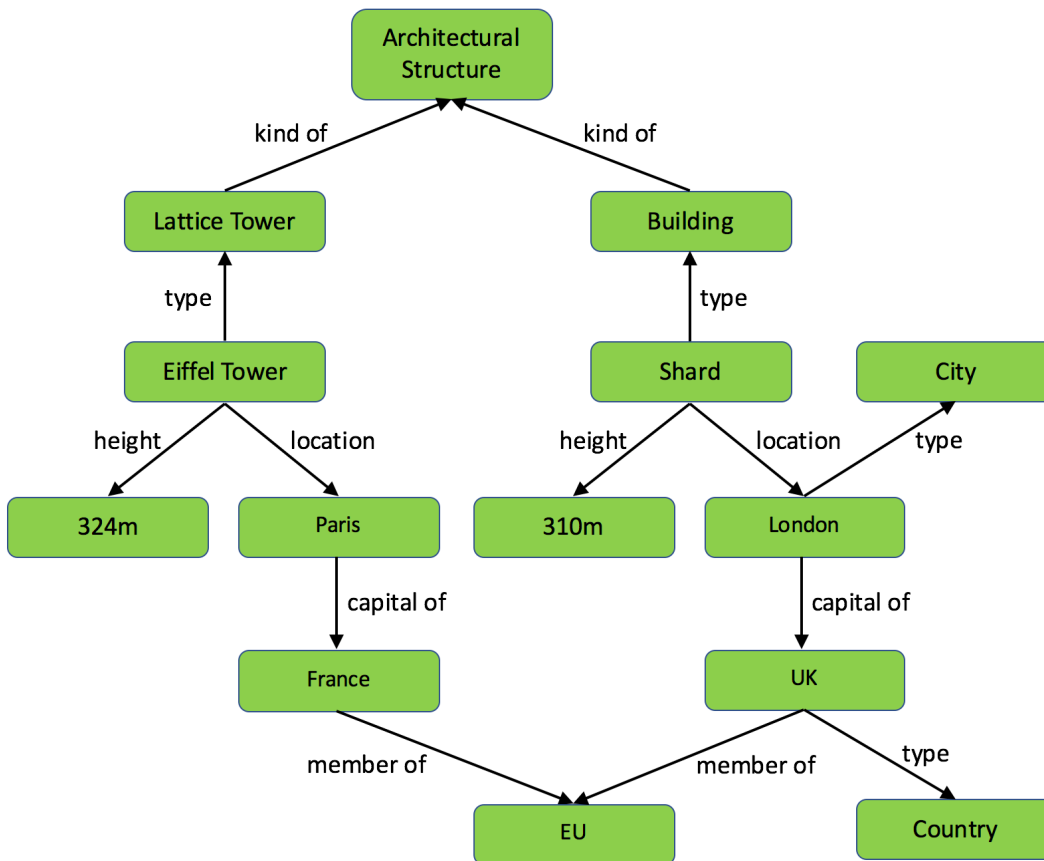


Building(Shard)
City(London)
location(Shard,London)
height(Shard,310m)
capitalOf(London,UK)
...

Architectural Structure			
name	location	height	kind
Shard	London	310m	Building
Eiffel Tower	Paris	324m	Lattice Tower
...	...	...	...

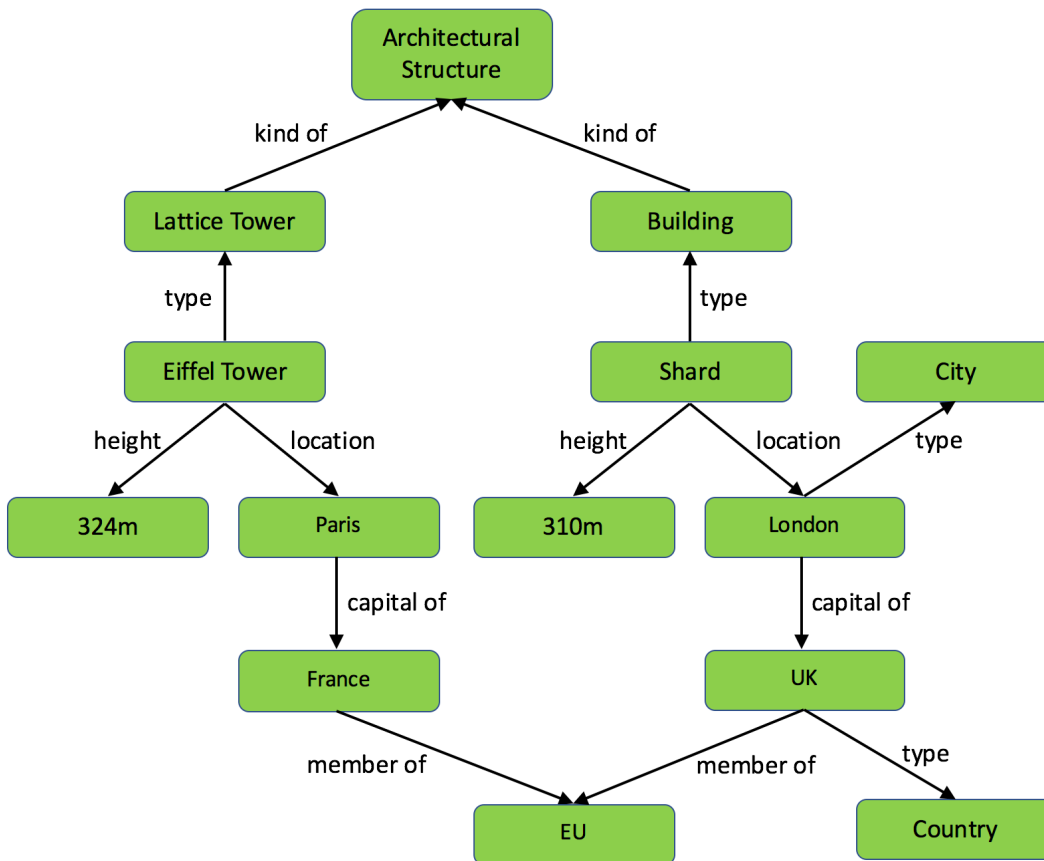
City	
name	capital of
London	UK
Paris	France
...	...

member of	
country	organisation
France	EU
UK	EU
...	...



Reasoning is the process of **answering queries** w.r.t. the represented knowledge

What is the **height** of the **Eiffel Tower**?

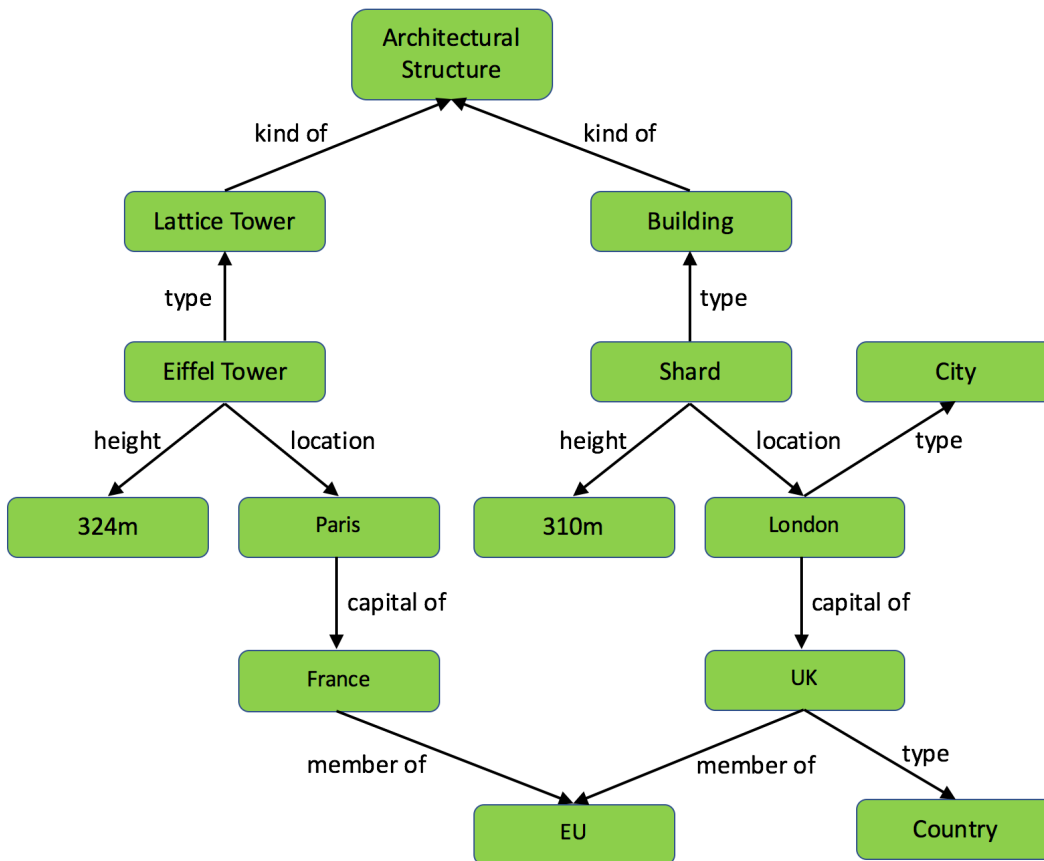


Reasoning is the process of **answering queries** w.r.t. the represented knowledge

What is the **height** of the **Eiffel Tower**?

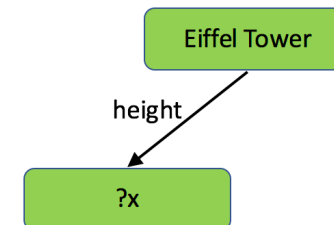
```

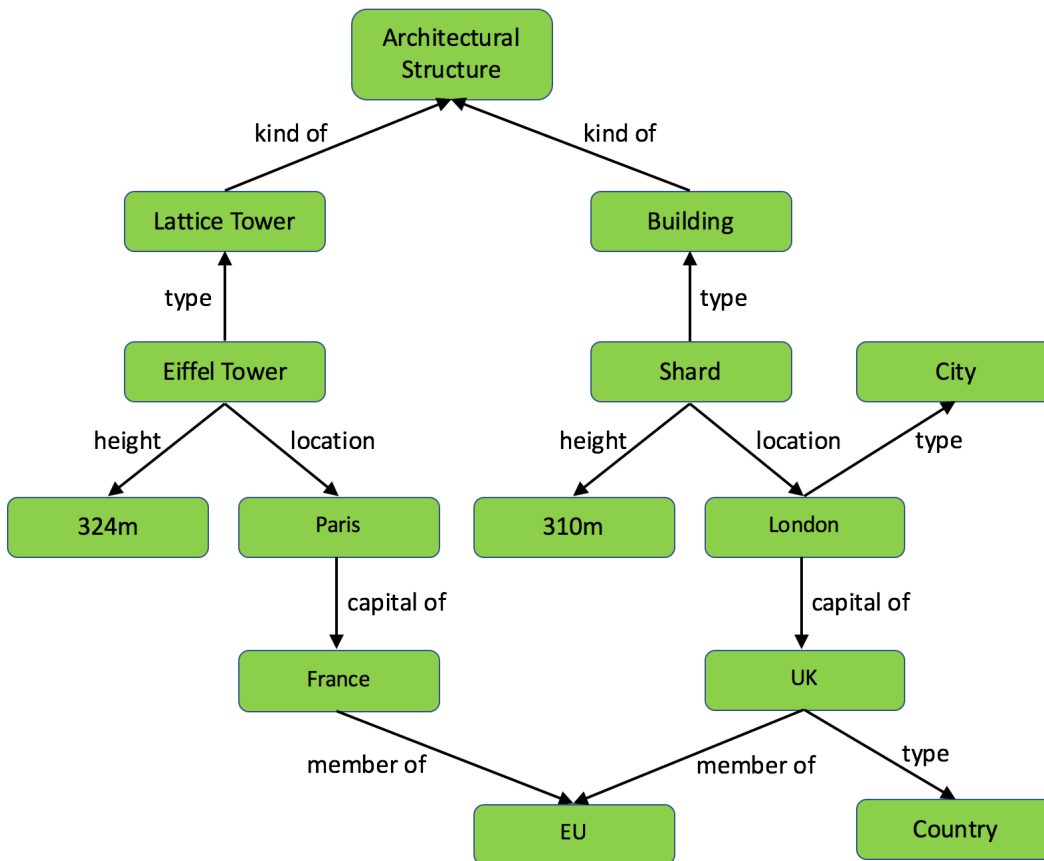
SELECT ?x
WHERE { EiffelTower height ?x. }
  
```



Reasoning is the process of **answering queries** w.r.t. the represented knowledge

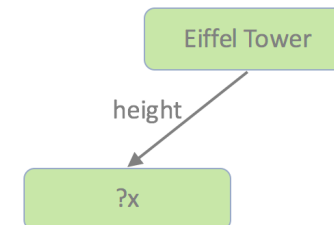
What is the **height** of the **Eiffel Tower**?

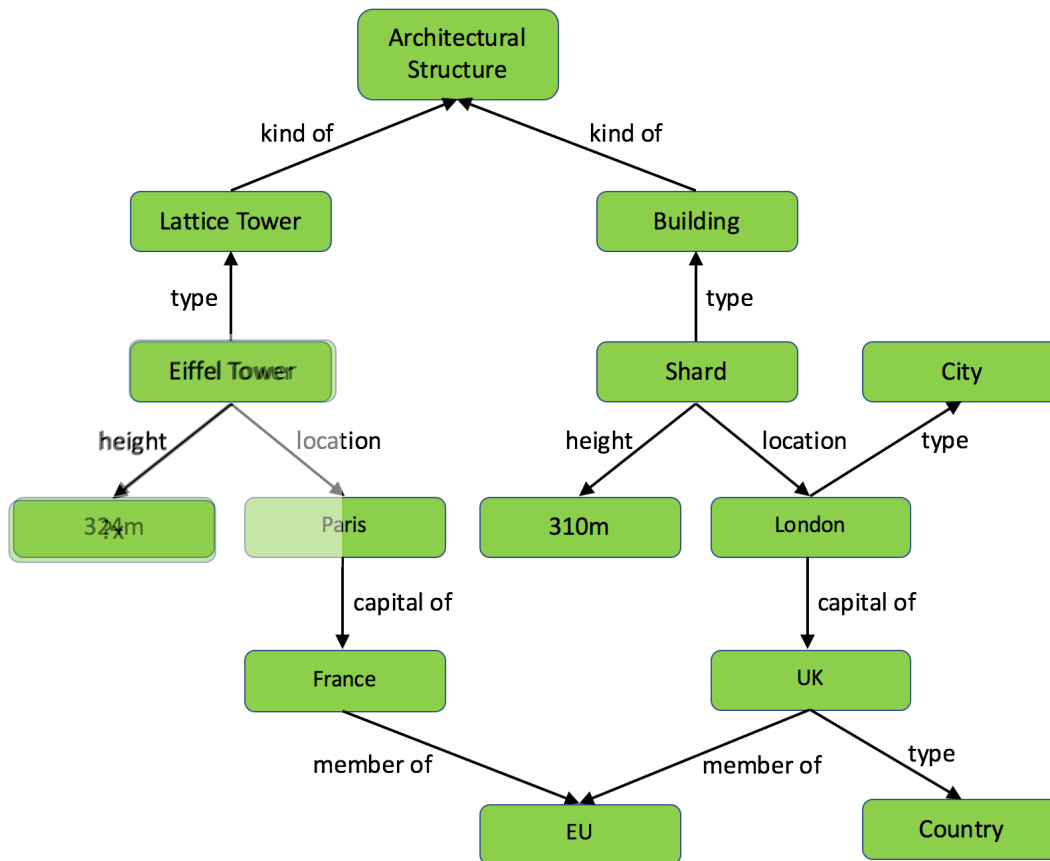




Reasoning is the process of **answering queries** w.r.t. the represented knowledge

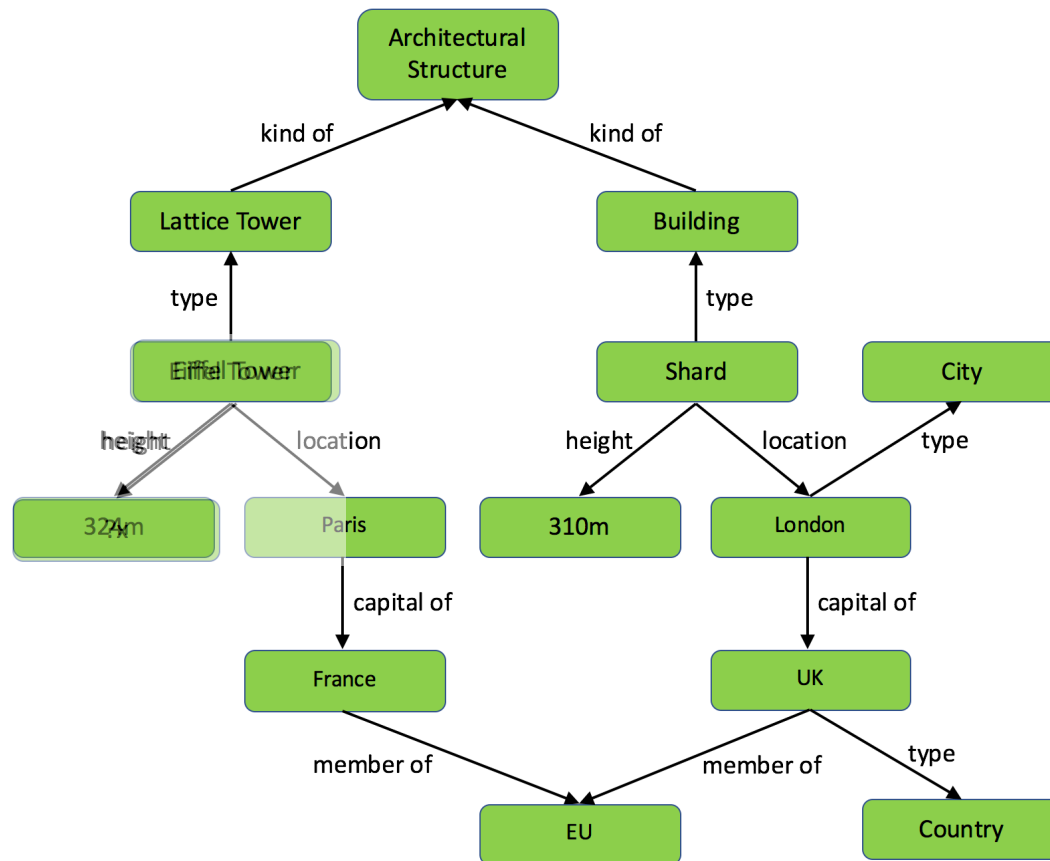
What is the **height** of the **Eiffel Tower**?





Reasoning is the process of **answering queries** w.r.t. the represented knowledge

What is the **height** of the **Eiffel Tower**?



Reasoning is the process of **answering queries** w.r.t. the represented knowledge

What is the **height** of the **Eiffel Tower**?

324m



how tall is the eiffel tower



All

Images

Maps

Shopping

News

More

Settings

Tools

About 41,100,000 results (0.68 seconds)

Eiffel Tower / Height

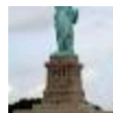
300 m, 324 m to tip



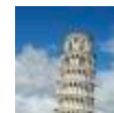
People also search for



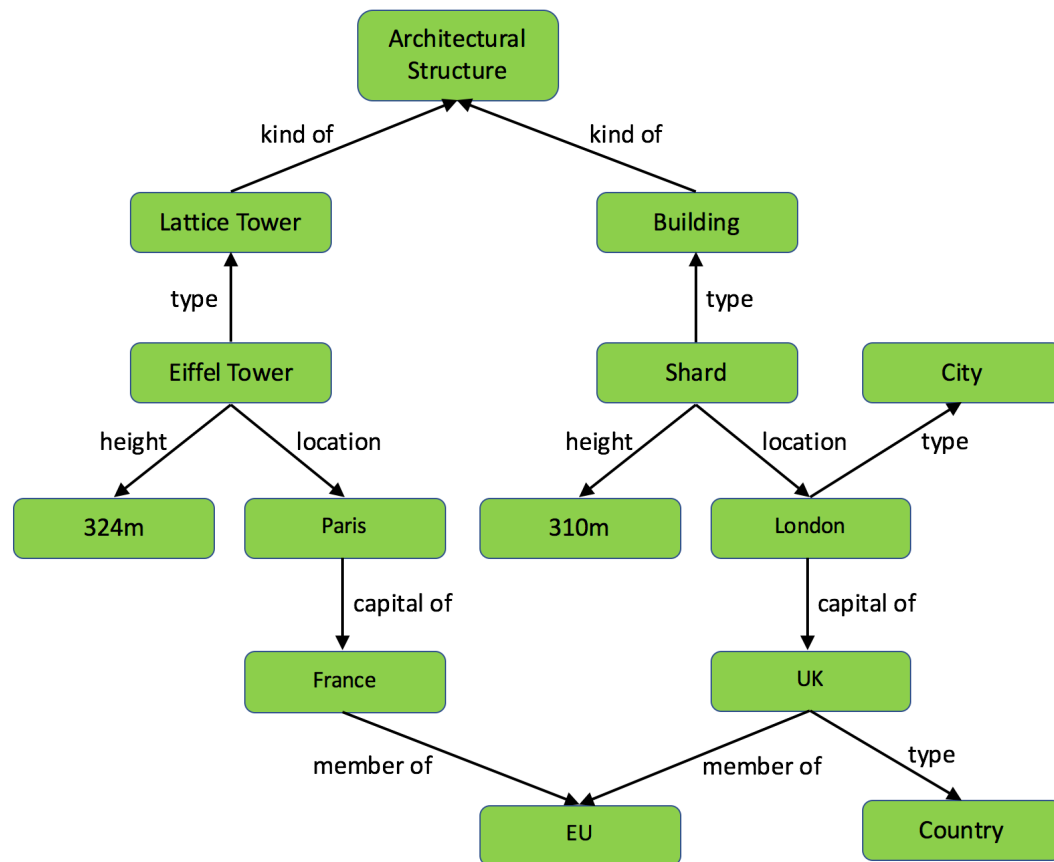
Burj Khalifa
828 m

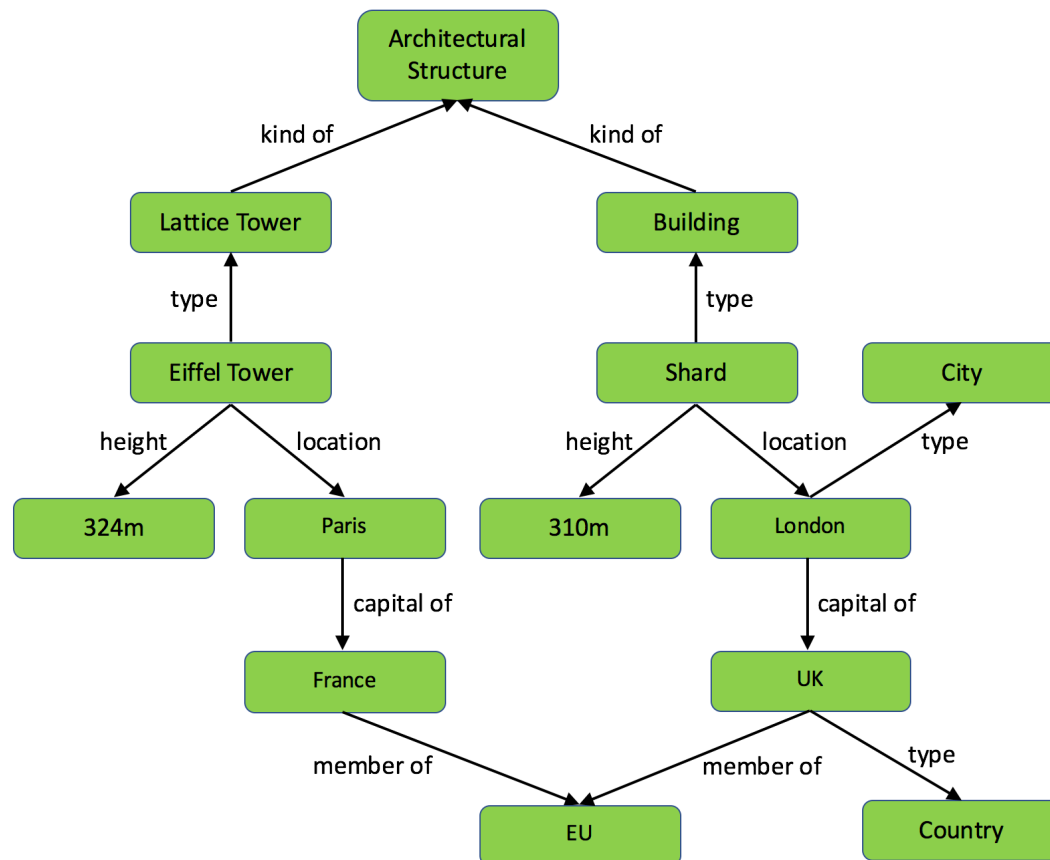


Statue of
Liberty
93 m

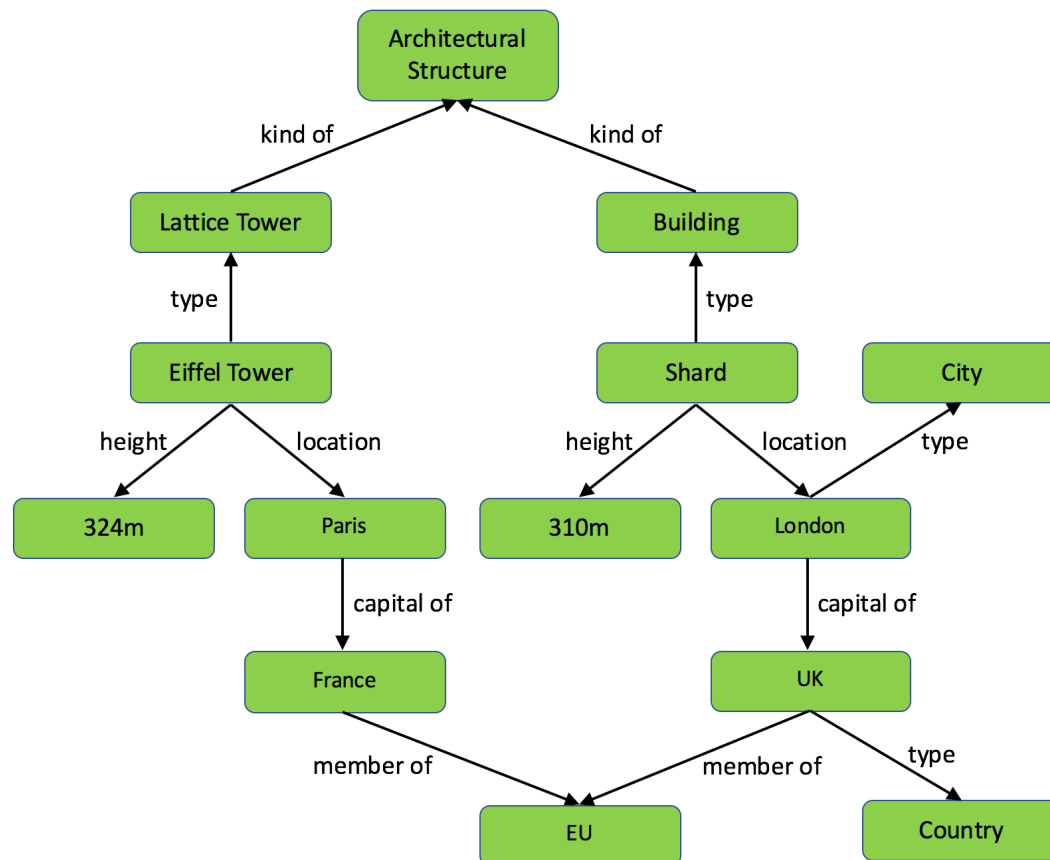


Leaning Tower
of Pisa
58 m

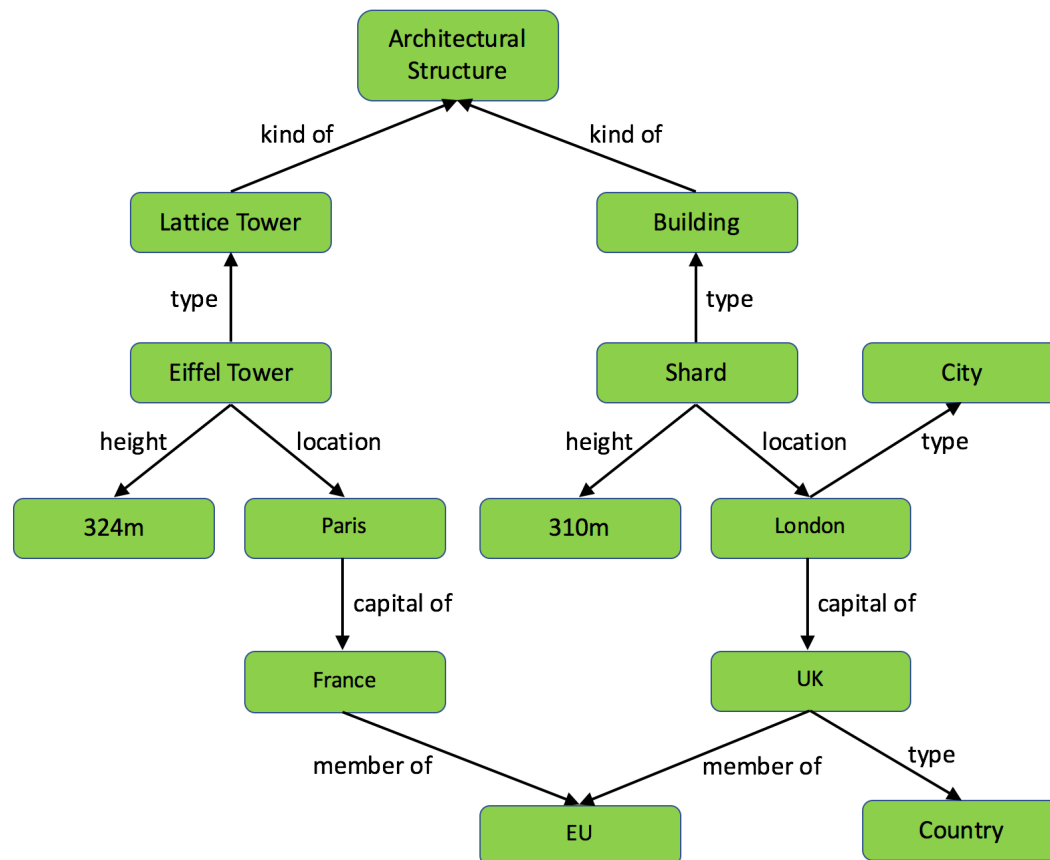




- What is the difference between a **Building**, a **Lattice Tower** and an **Architectural Structure**?



- What is the difference between a **Building**, a **Lattice Tower** and an **Architectural Structure**?
- Is the **Eiffel Tower** a **Building**; is it an **Architectural Structure**?

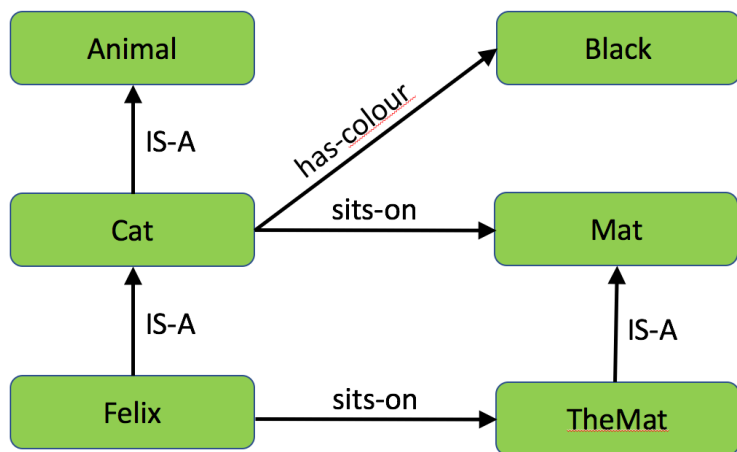


- What is the difference between a **Building**, a **Lattice Tower** and an **Architectural Structure**?
- Is the **Eiffel Tower** a **Building**; is it an **Architectural Structure**?
- Special meaning of, e.g., **type** and **kind of** edges?

- **Semantics**: the study of meaning

(Precise) semantics needed in order to define what (correct) query answers should be

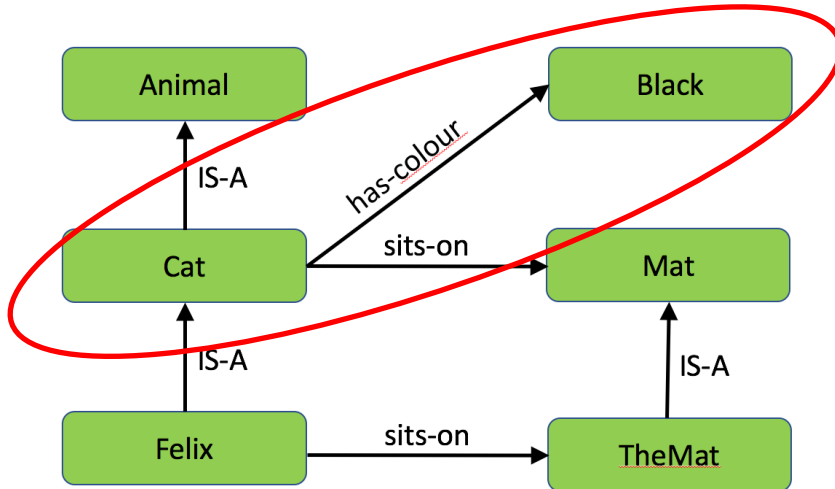
- **Semantics**: the study of meaning



[Quillian, 1967]

(Precise) semantics needed in order to define what (correct) query answers should be

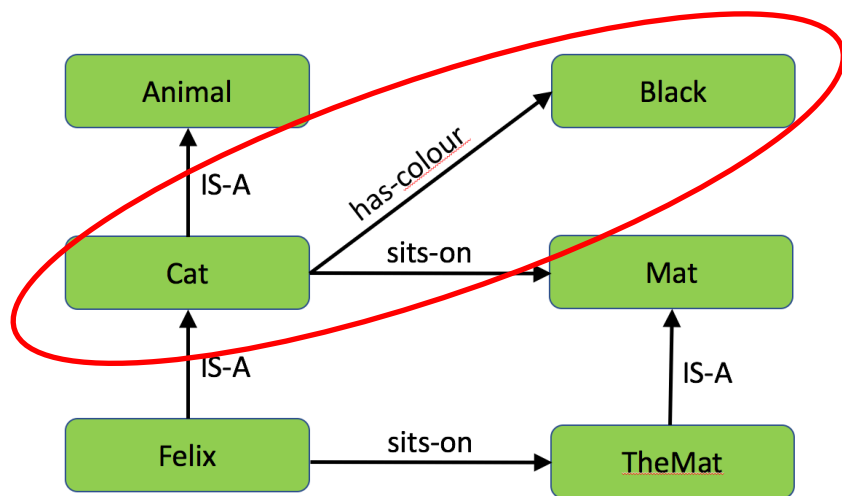
- **Semantics:** the study of meaning



[Quillian, 1967]

(Precise) semantics needed in order to define what (correct) query answers should be

- **Semantics:** the study of meaning

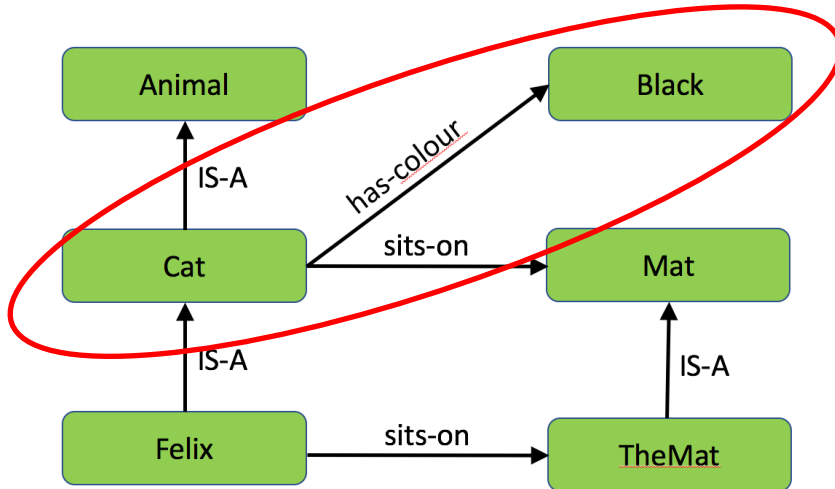


[Quillian, 1967]



(Precise) semantics needed in order to define what (correct) query answers should be

- **Semantics:** the study of meaning

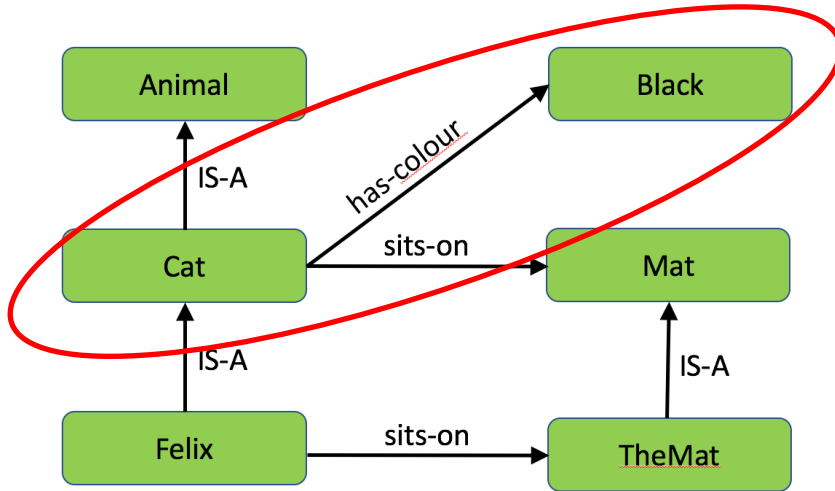


[Quillian, 1967]



(Precise) semantics needed in order to define what (correct) query answers should be

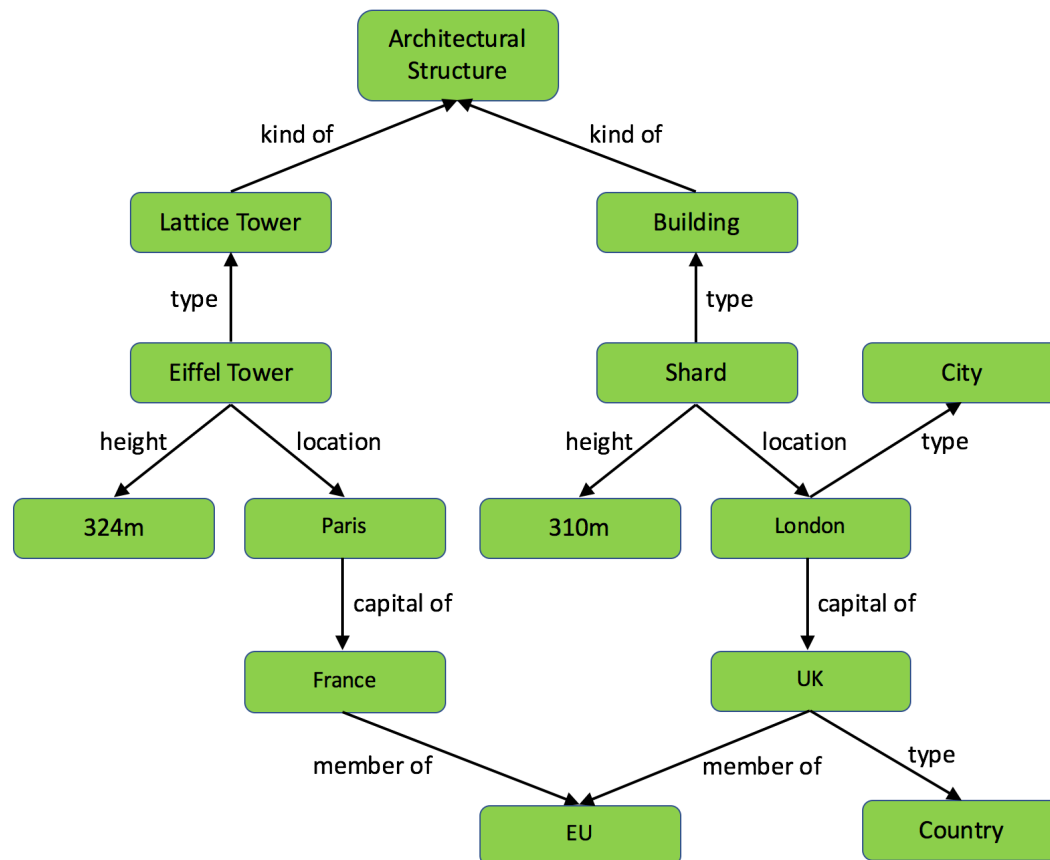
- **Semantics:** the study of meaning



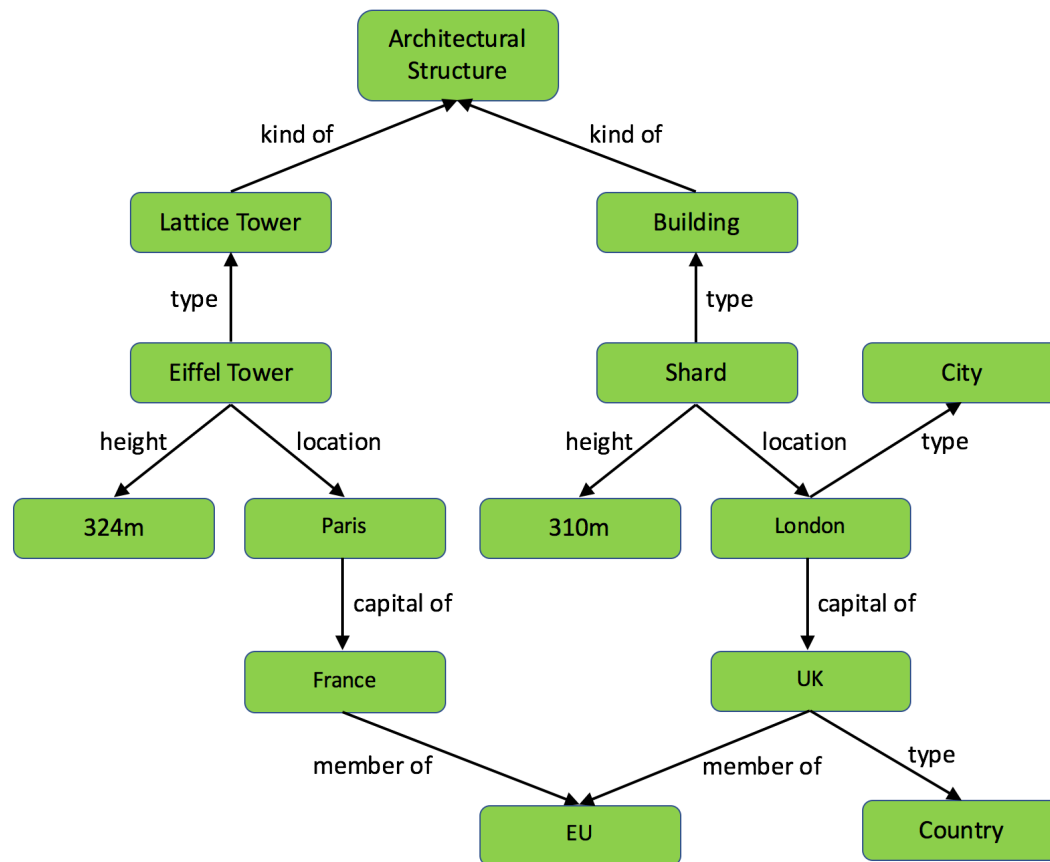
[Quillian, 1967]



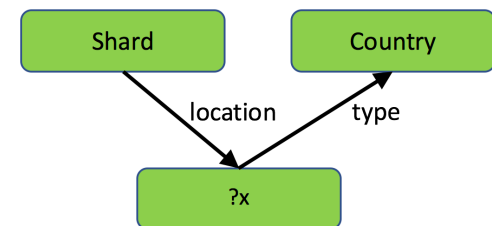
(Precise) semantics needed in order to define what (correct) query answers should be

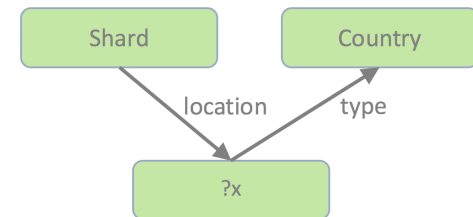
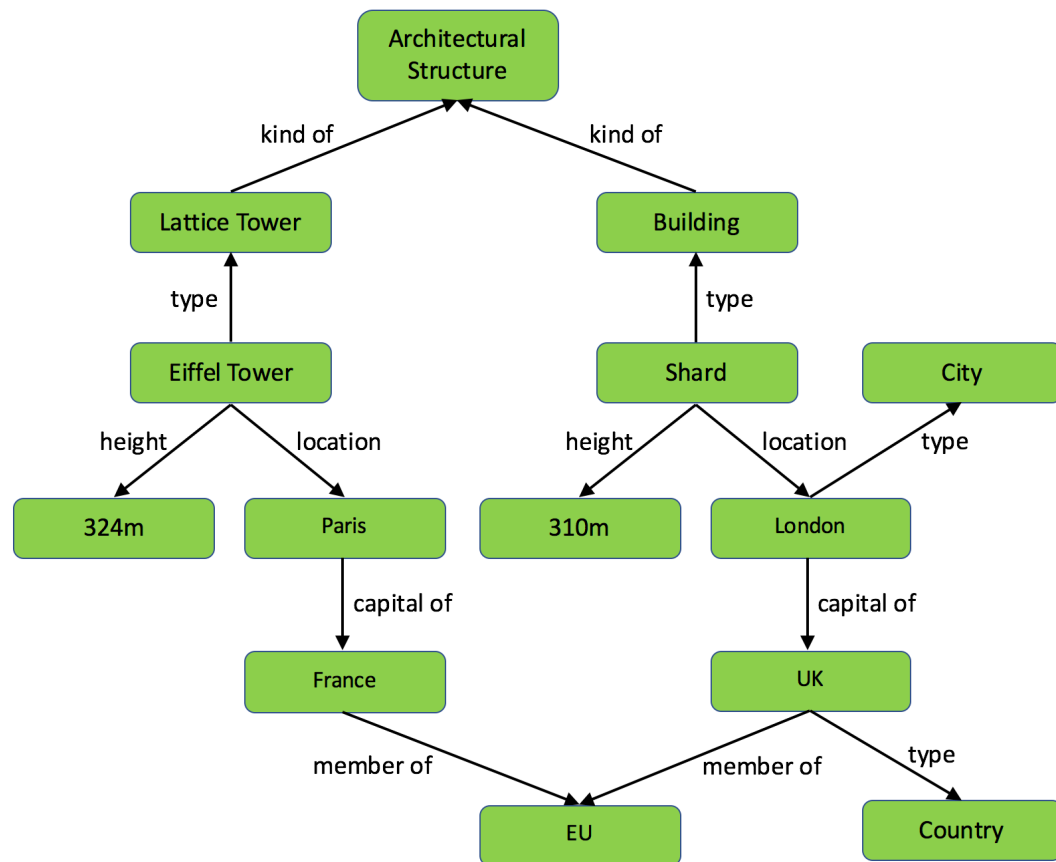


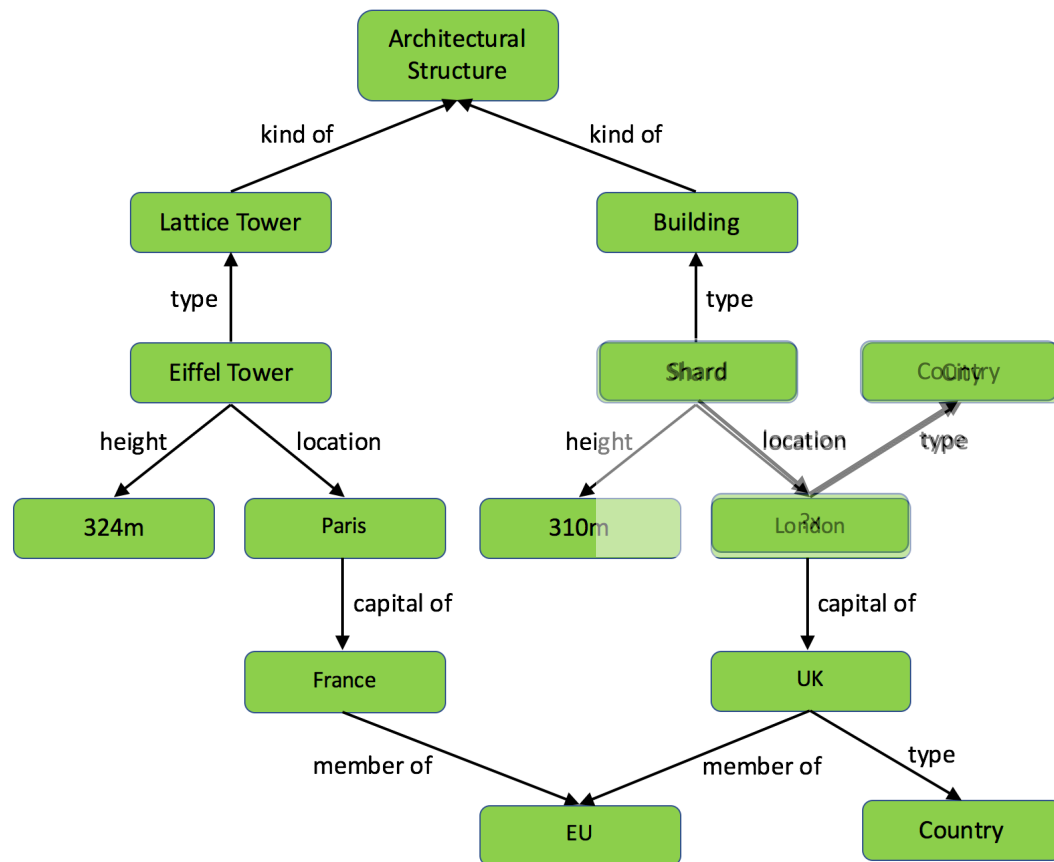
- What **country** is the **Shard** located in?

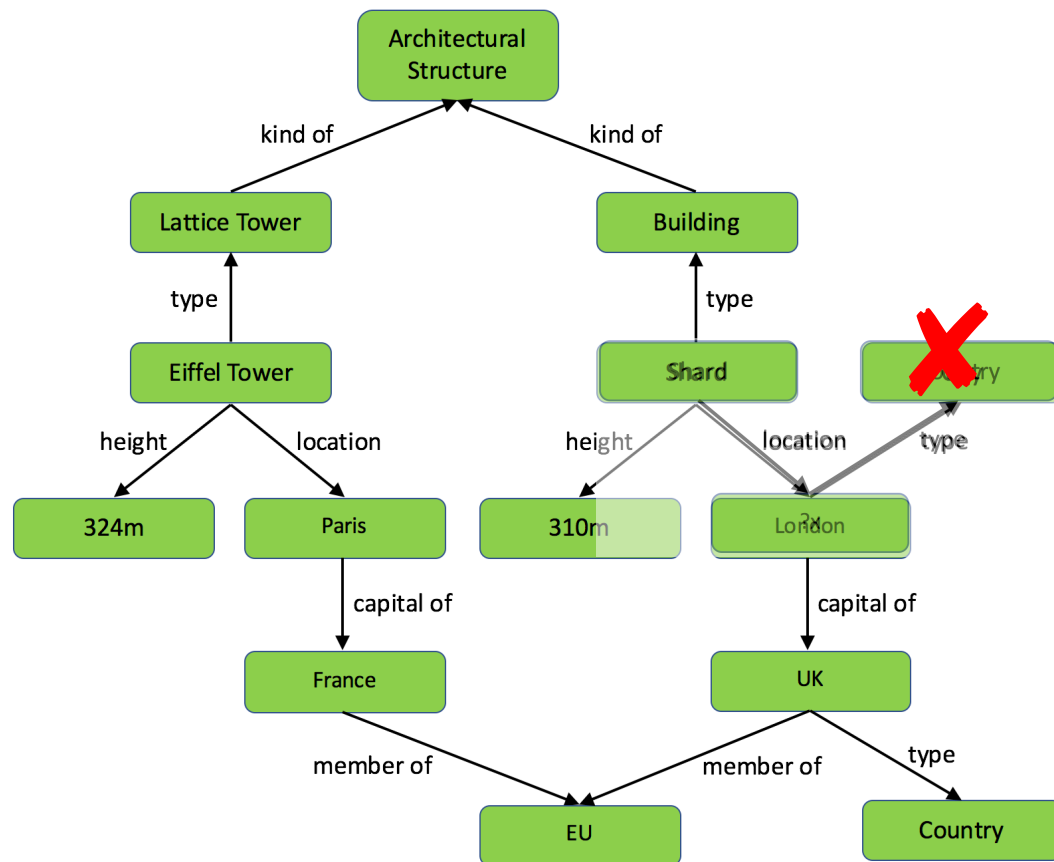


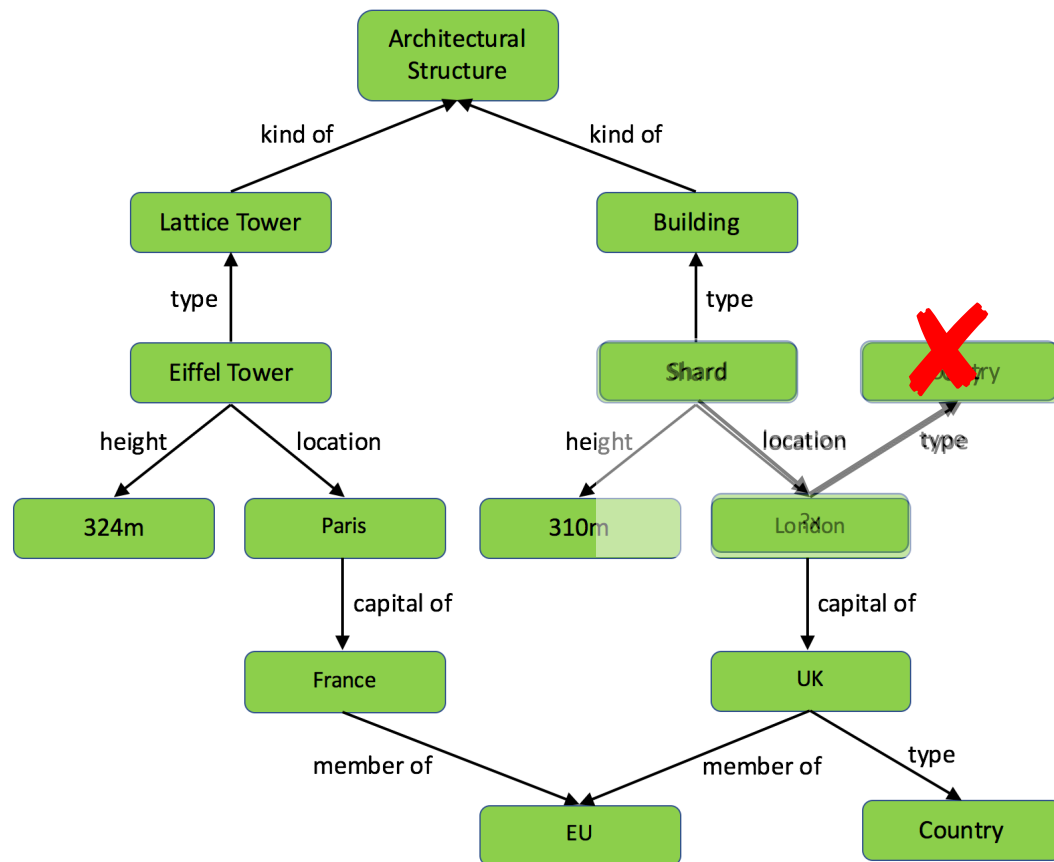
- What **country** is the **Shard** located in?





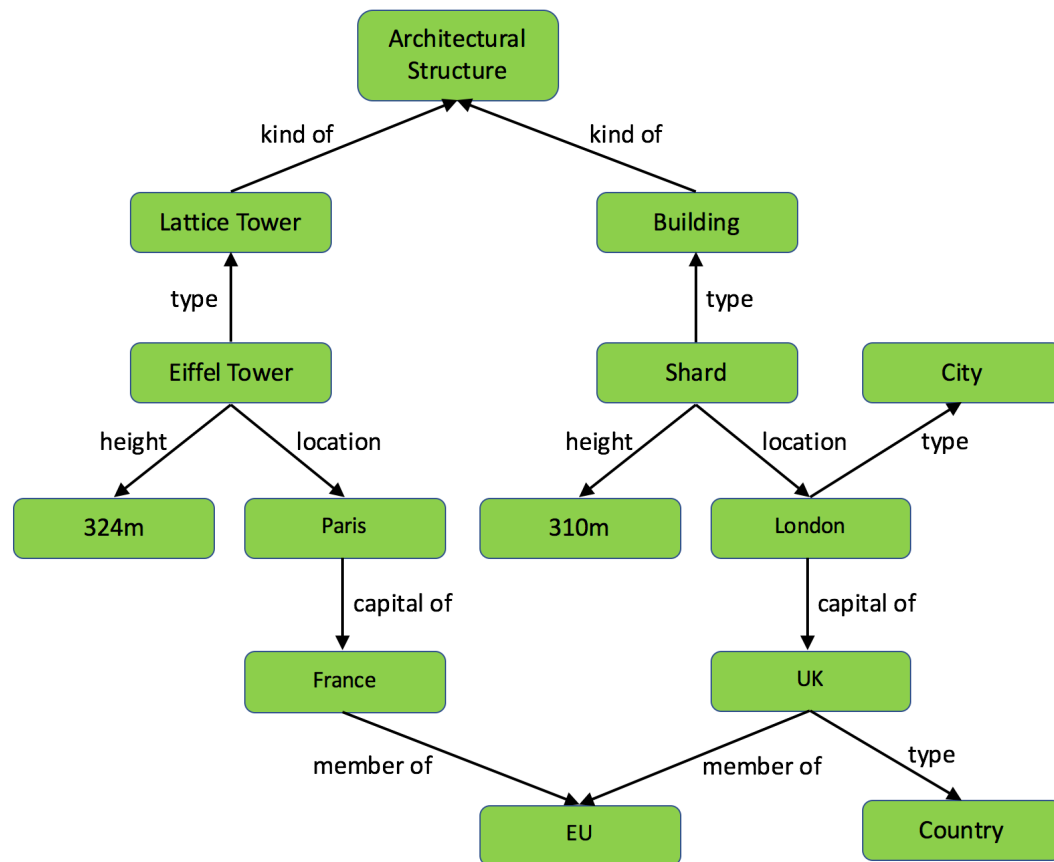




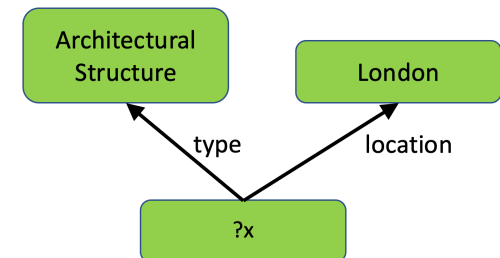


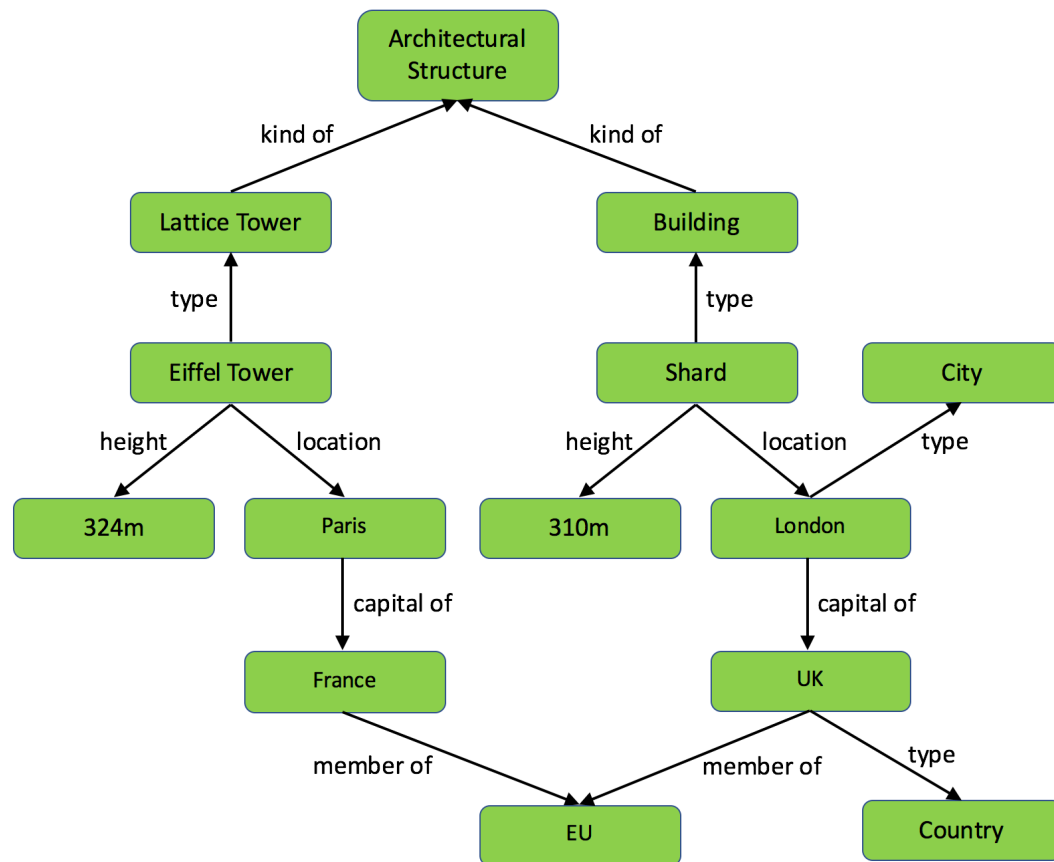
- What **country** is the **Shard** located in?

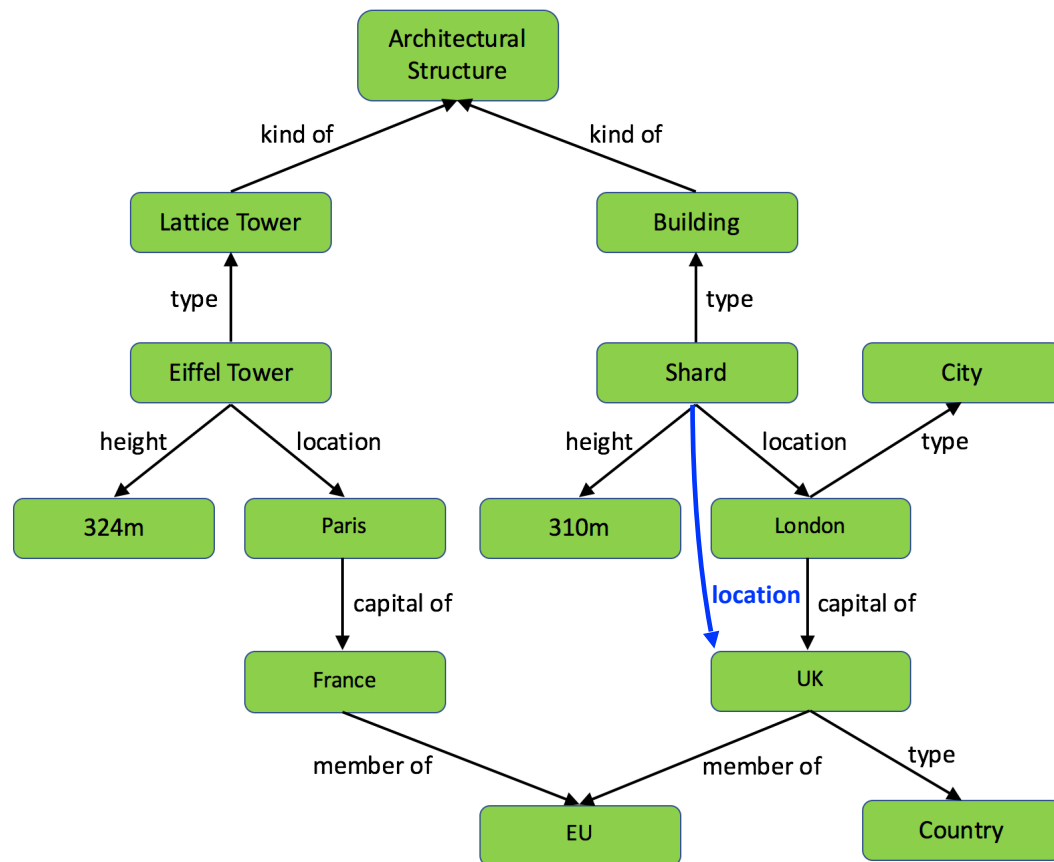
- **???**

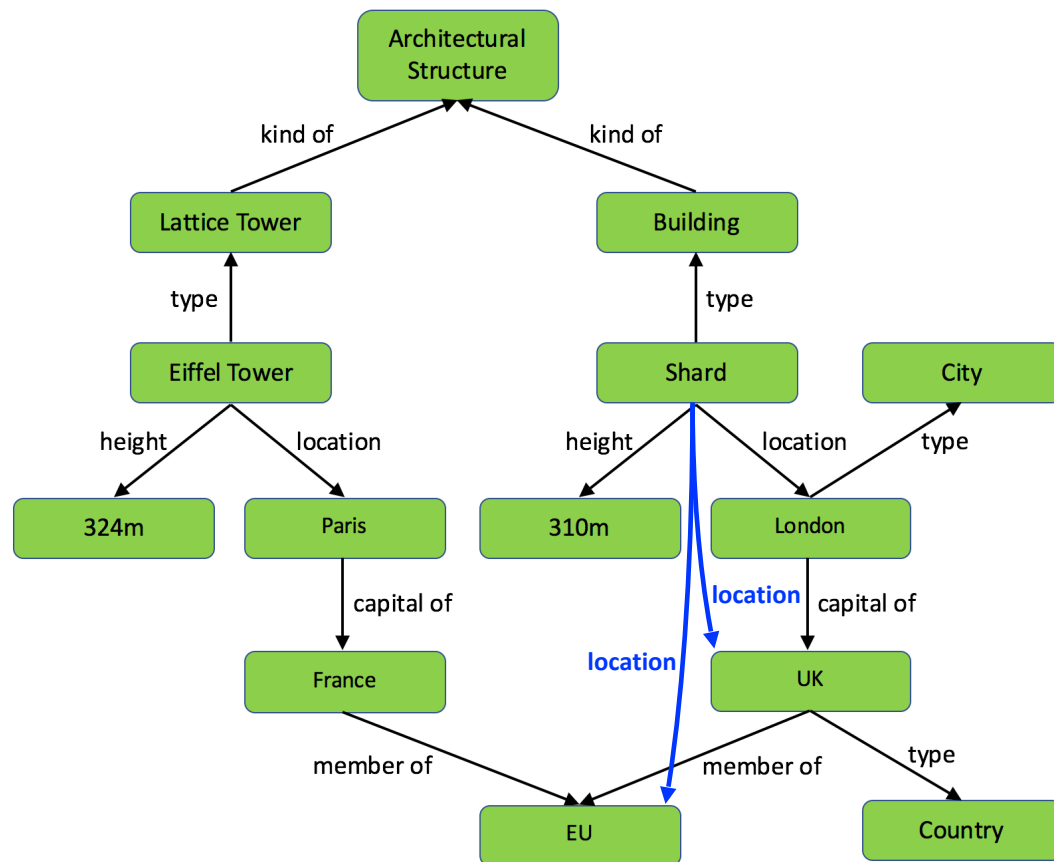


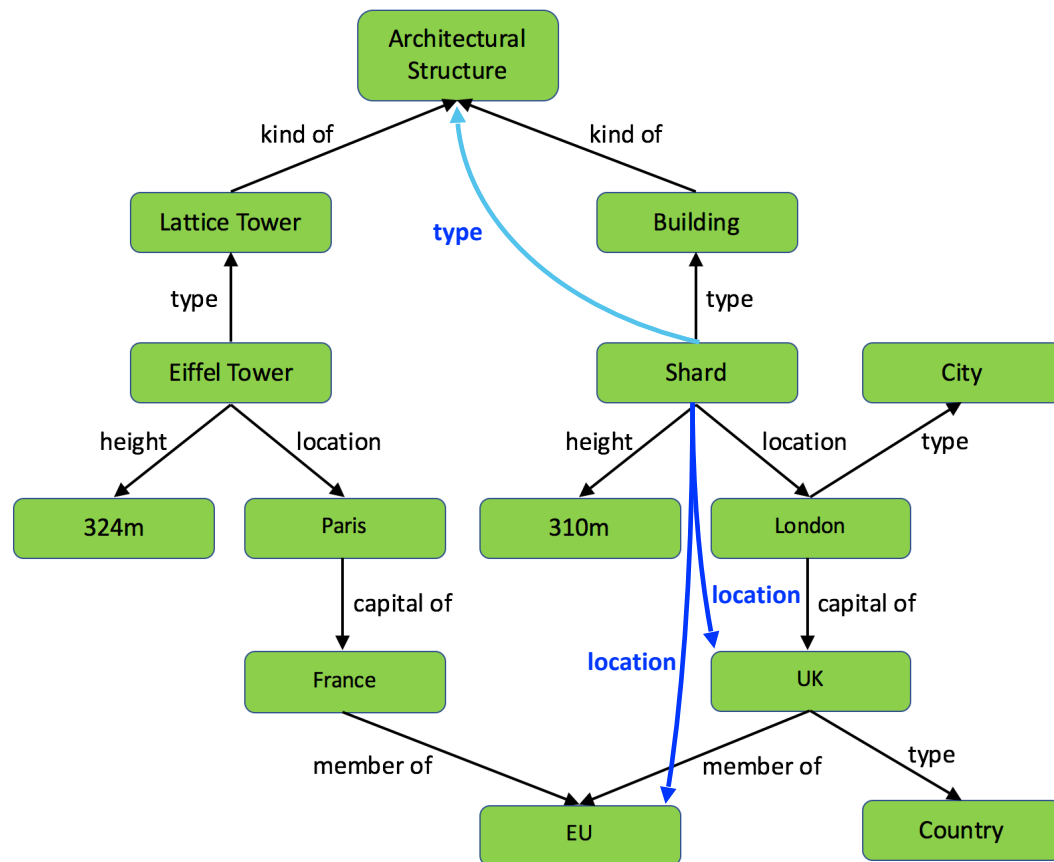
- What **Architectural Structures** are located in **London**?

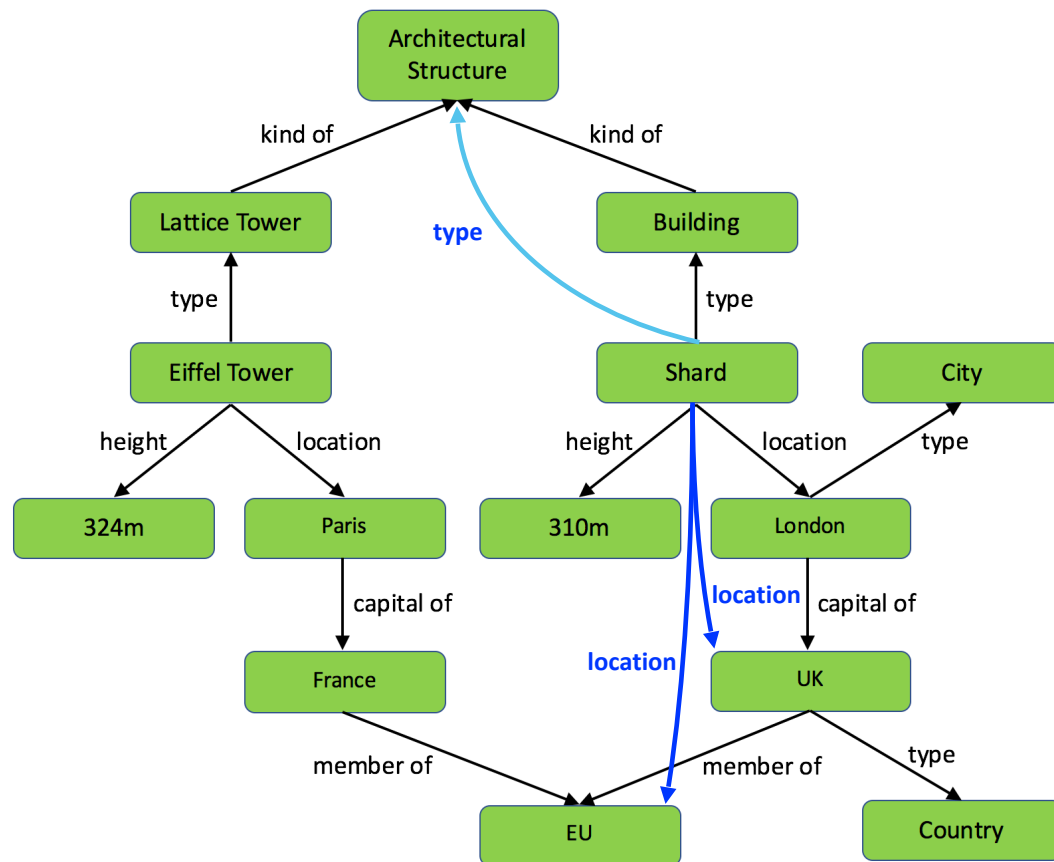


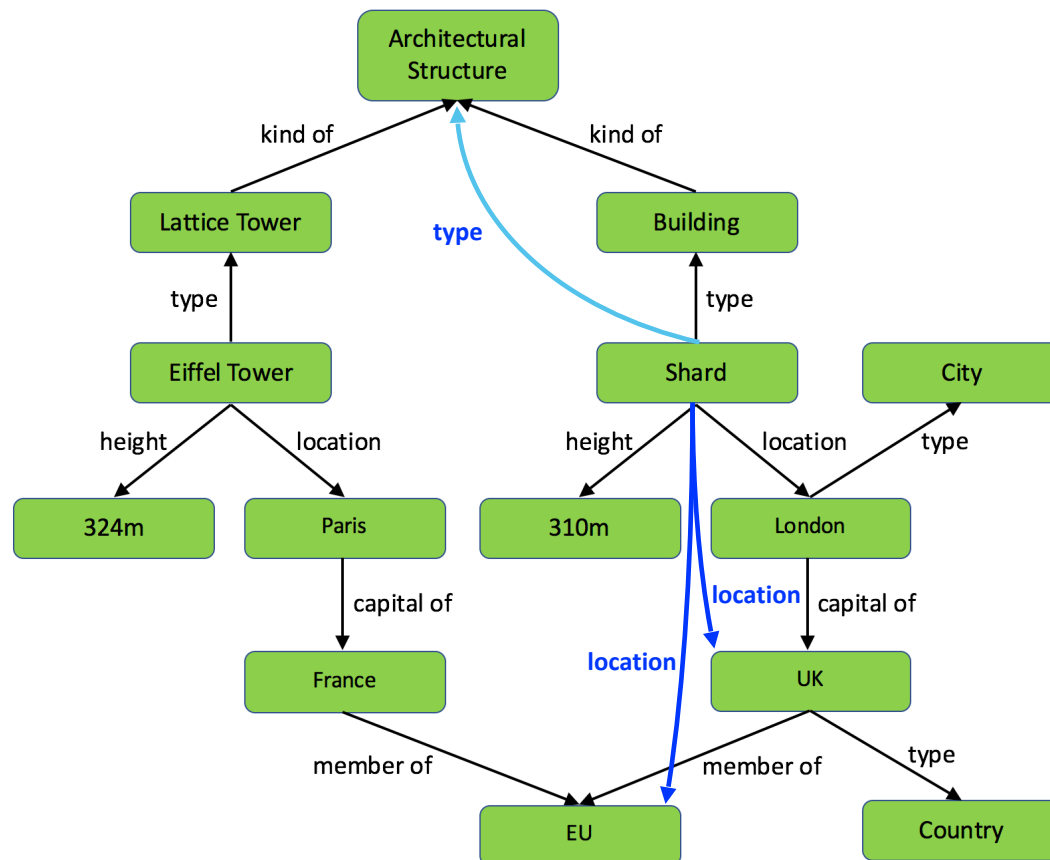




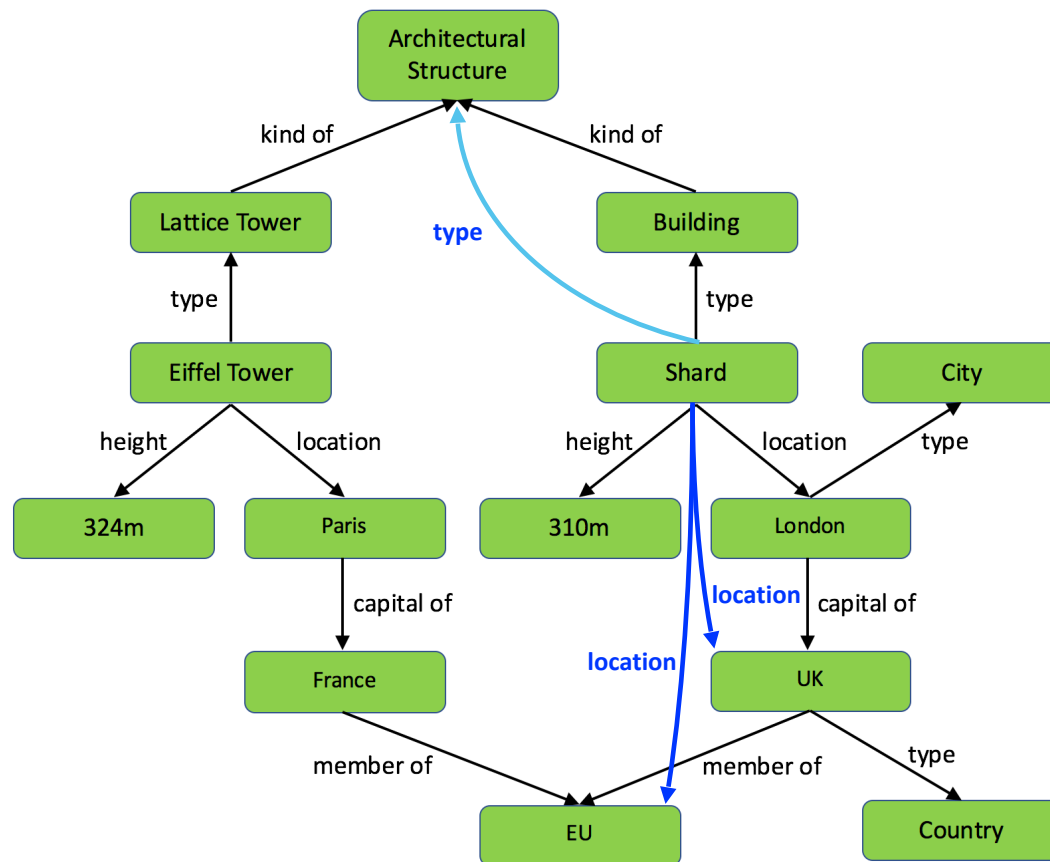








- Every **Building located in London** is also located in
 - UK
 - EU
 - England
 - Northern Hemisphere
 - ...



- Every **Building** located in **London** is also located in
 - UK
 - EU
 - England
 - Northern Hemisphere
 - ...
- Need to add a **very** large number of edges

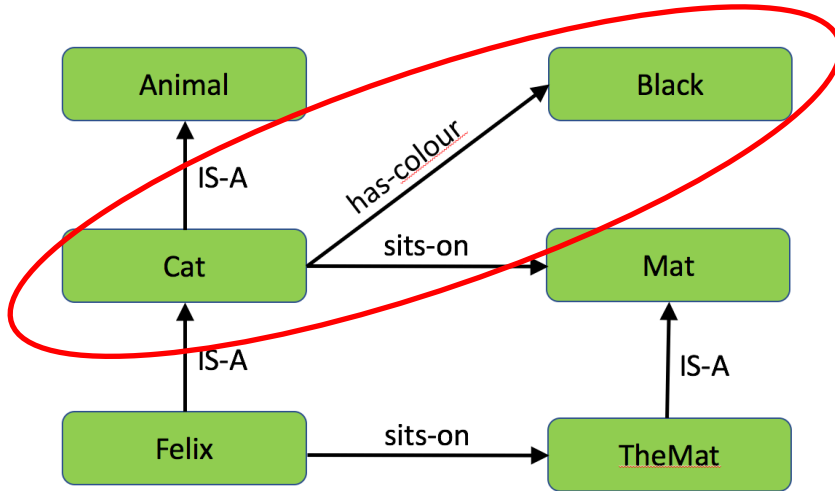
A city that is the capital of a country is a (geographical) part of that country[†]

A thing that is located in a city that is a (geographical) part of a country is also located in that country

A thing that is located in a country that is a member of a supranational union is also located in that supranational union

[†] Part-whole relationships are complicated! They are the subject of a whole field of study in logic and philosophy: mereology

- **Semantics:** the study of meaning



[Quillian, 1967]



(Precise) semantics needed in order to define what (correct) query answers should be





Supreme genus:

Differentiae:

Subordinate genera:

Differentiae:

Subordinate genera:

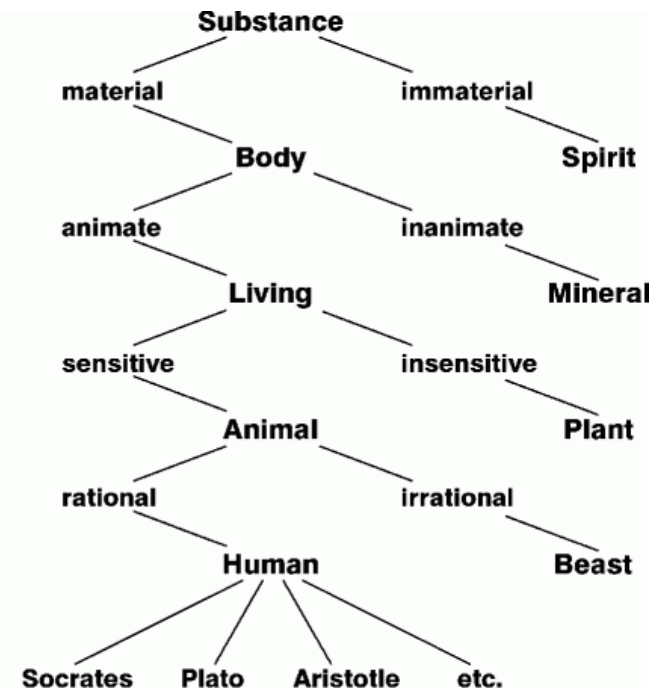
Differentiae:

Proximate genera:

Differentiae:

Species:

Individuals:





Supreme genus:

Differentiae:

Subordinate genera:

Differentiae:

Subordinate genera:

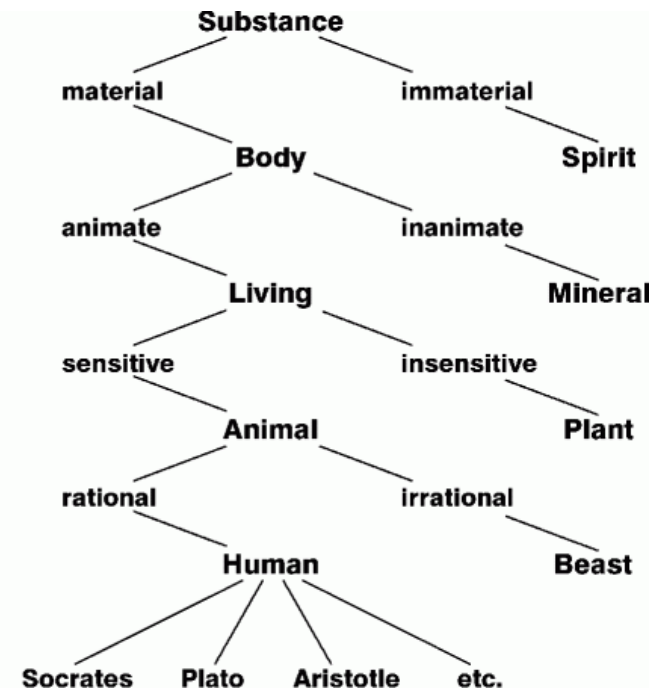
Differentiae:

Proximate genera:

Differentiae:

Species:

Individuals:



“All men are mortal, all Greeks are men,
therefore all Greeks are mortal” (syllogism)

Modern KR languages are often based on logic
Typically (subsets of) First Order Predicate
Calculus

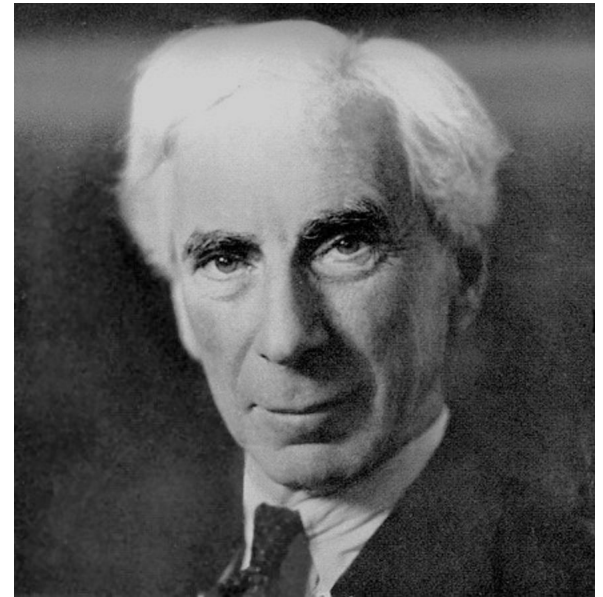
Modern KR languages are often based on logic
Typically (subsets of) First Order Predicate
Calculus



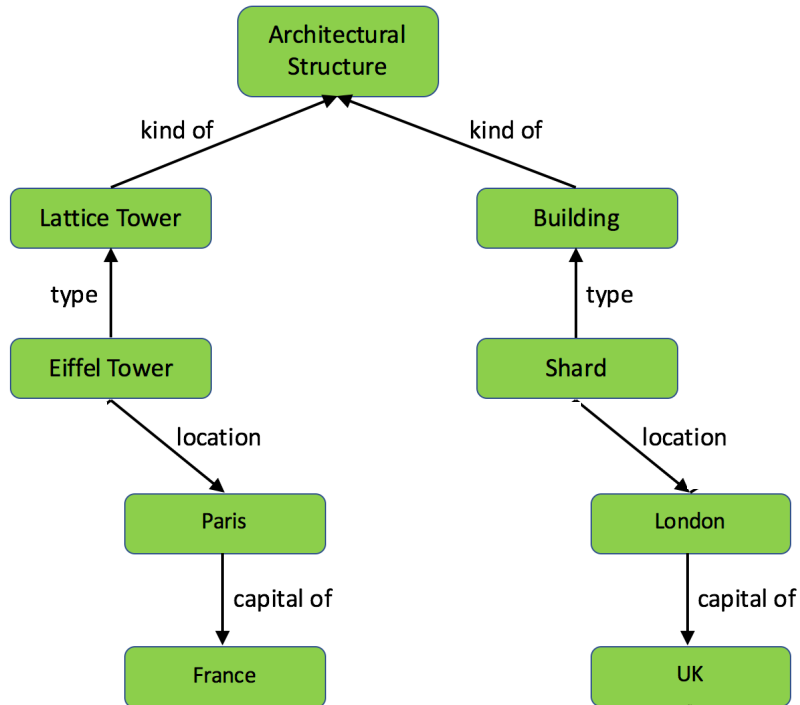
Gottlob Frege

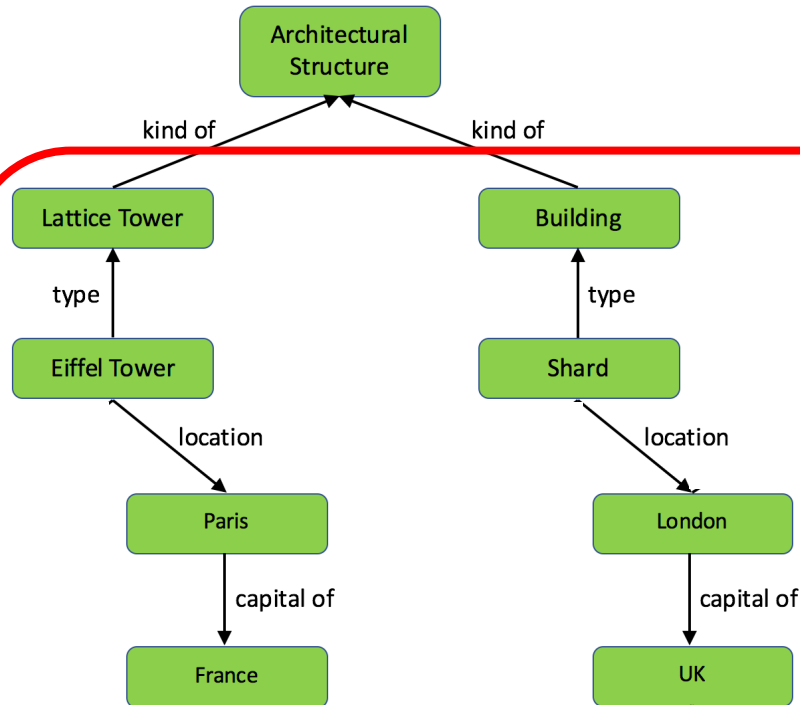


Charles Sanders Peirce



Bertrand Russell

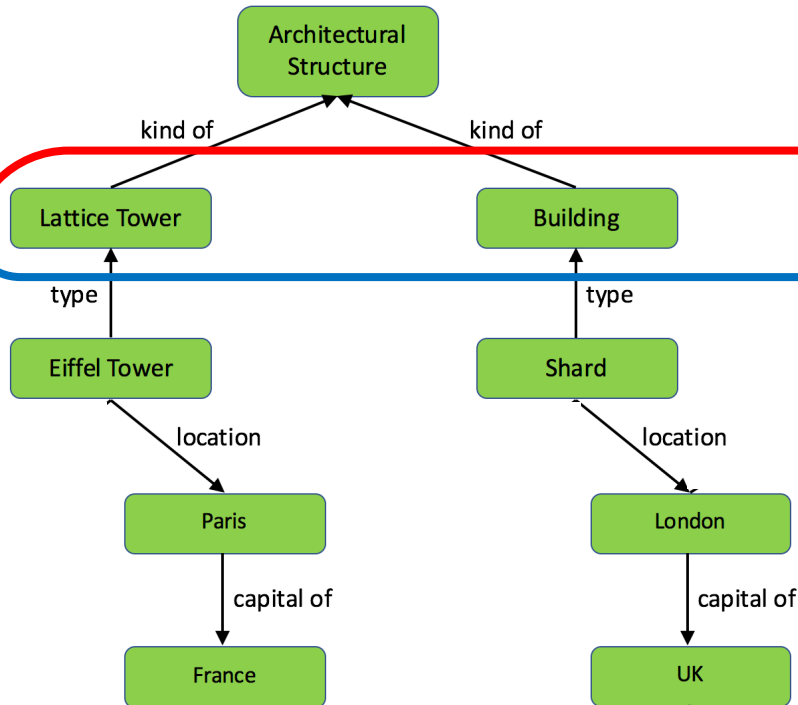




LatticeTower(EiffelTower)
Location(EiffelTower, Paris)
Location(Shard, London)

Building(Shard)
CapitalOf(Paris, France)
CapitalOf(London, UK)

facts / data / (RDF) graph



$\forall x \text{ LatticeTower}(x) \rightarrow \text{ArchStruct}(x)$

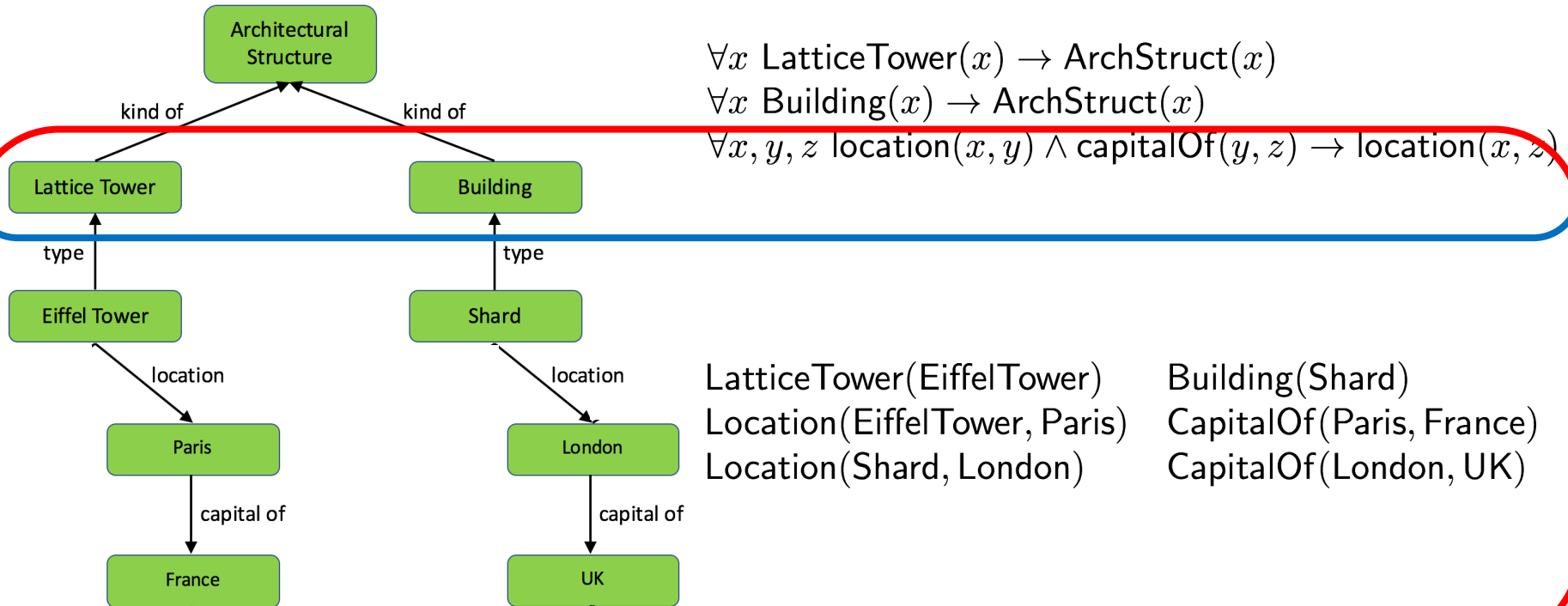
$\forall x \text{ Building}(x) \rightarrow \text{ArchStruct}(x)$

LatticeTower(EiffelTower)
Location(EiffelTower, Paris)
Location(Shard, London)

Building(Shard)
CapitalOf(Paris, France)
CapitalOf(London, UK)

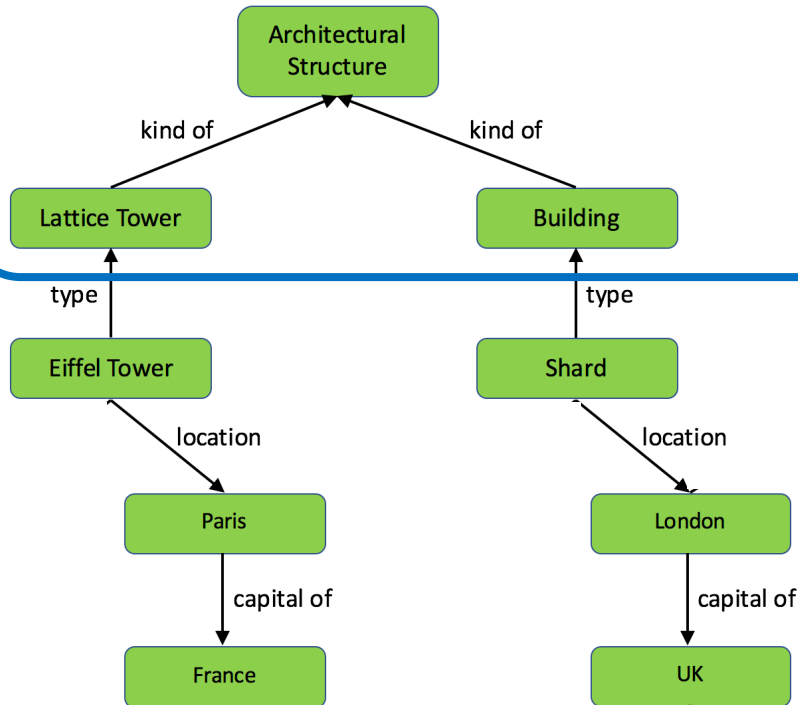
facts / data / (RDF) graph

ontology / conceptual schema



facts / data / (RDF) graph

ontology / conceptual schema



$\text{LatticeTower}(x) \rightarrow \text{ArchStruct}(x)$

$\text{Building}(x) \rightarrow \text{ArchStruct}(x)$

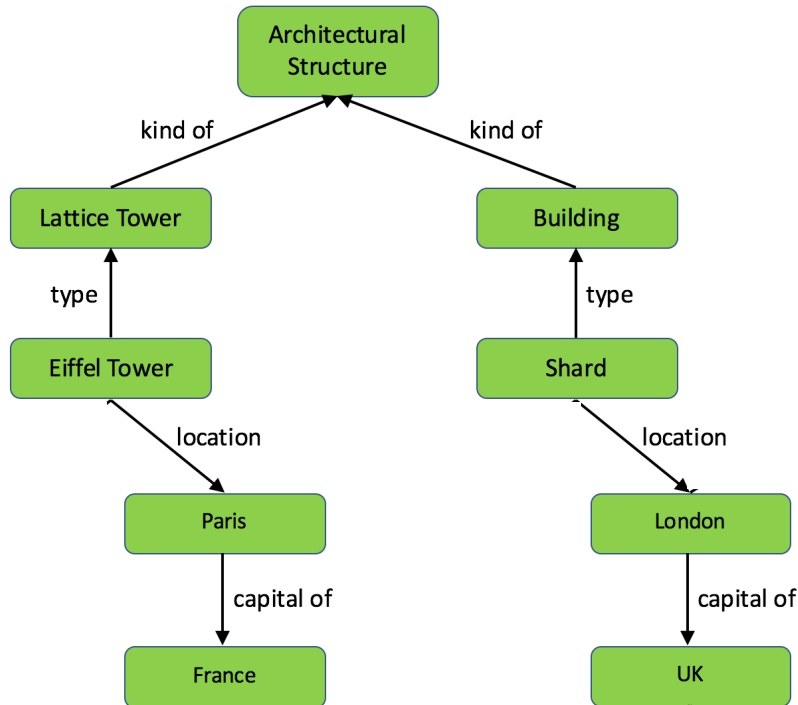
$\text{location}(x, y) \wedge \text{capitalOf}(y, z) \rightarrow \text{location}(x, z)$

$\text{LatticeTower}(\text{EiffelTower})$
 $\text{Location}(\text{EiffelTower}, \text{Paris})$
 $\text{Location}(\text{Shard}, \text{London})$

$\text{Building}(\text{Shard})$
 $\text{CapitalOf}(\text{Paris}, \text{France})$
 $\text{CapitalOf}(\text{London}, \text{UK})$

facts / data / (RDF) graph

ontology / conceptual schema



$\text{LatticeTower}(x) \rightarrow \text{ArchStruct}(x)$

$\text{Building}(x) \rightarrow \text{ArchStruct}(x)$

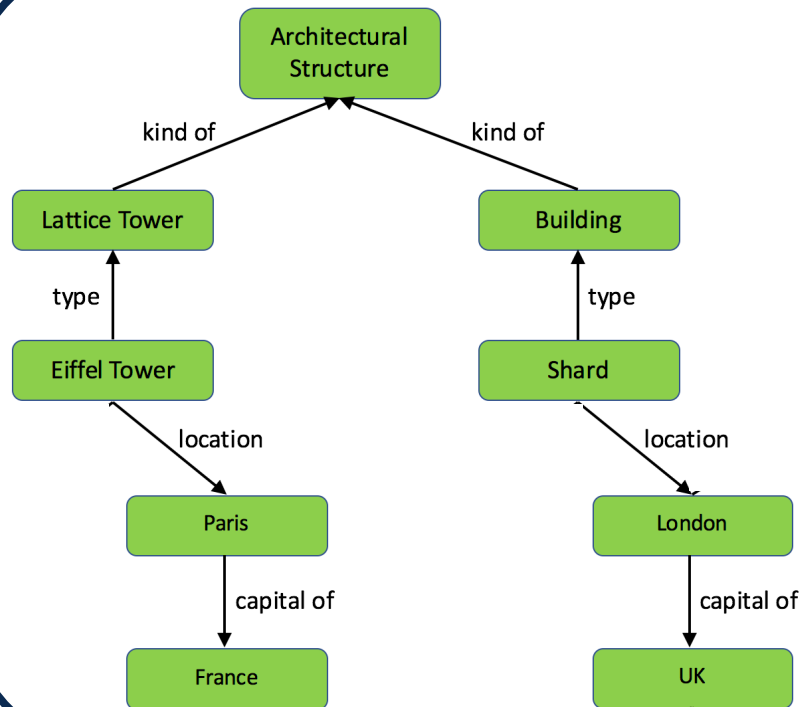
$\text{location}(x, y) \wedge \text{capitalOf}(y, z) \rightarrow \text{location}(x, z)$

$\text{LatticeTower}(\text{EiffelTower})$
 $\text{Location}(\text{EiffelTower}, \text{Paris})$
 $\text{Location}(\text{Shard}, \text{London})$

$\text{Building}(\text{Shard})$
 $\text{CapitalOf}(\text{Paris}, \text{France})$
 $\text{CapitalOf}(\text{London}, \text{UK})$

facts / data / (RDF) graph

ontology / conceptual schema



$\text{LatticeTower}(x) \rightarrow \text{ArchStruct}(x)$

$\text{Building}(x) \rightarrow \text{ArchStruct}(x)$

$\text{location}(x, y) \wedge \text{capitalOf}(y, z) \rightarrow \text{location}(x, z)$

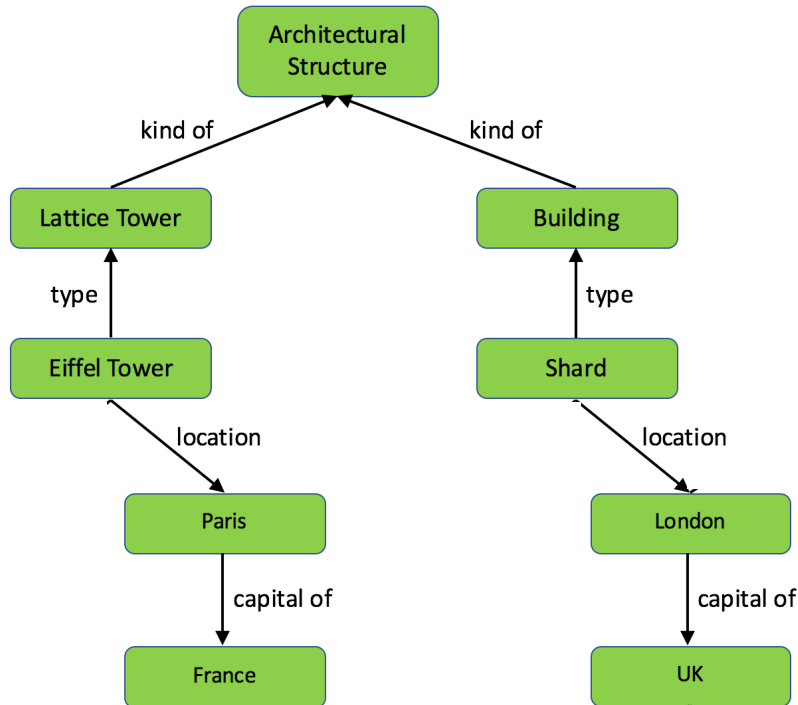
$\text{LatticeTower}(\text{EiffelTower})$
 $\text{Location}(\text{EiffelTower}, \text{Paris})$
 $\text{Location}(\text{Shard}, \text{London})$

$\text{Building}(\text{Shard})$
 $\text{CapitalOf}(\text{Paris}, \text{France})$
 $\text{CapitalOf}(\text{London}, \text{UK})$

facts / data / (RDF) graph

ontology / conceptual schema

} knowledge base



$\text{LatticeTower}(x) \rightarrow \text{ArchStruct}(x)$

$\text{Building}(x) \rightarrow \text{ArchStruct}(x)$

$\text{location}(x, y) \wedge \text{capitalOf}(y, z) \rightarrow \text{location}(x, z)$

$\text{LatticeTower}(\text{EiffelTower})$

$\text{Location}(\text{EiffelTower}, \text{Paris})$

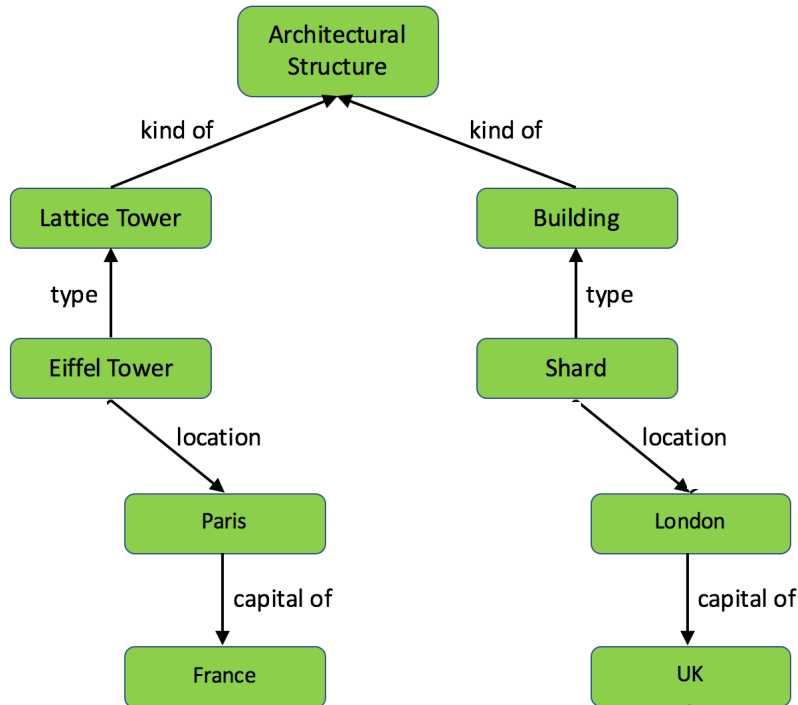
$\text{Location}(\text{Shard}, \text{London})$

$\text{Building}(\text{Shard})$

$\text{CapitalOf}(\text{Paris}, \text{France})$

$\text{CapitalOf}(\text{London}, \text{UK})$

$\mathcal{K} \models \text{ArchStruct}(\text{EiffelTower}) ?$



$\text{LatticeTower}(x) \rightarrow \text{ArchStruct}(x)$

$\text{Building}(x) \rightarrow \text{ArchStruct}(x)$

$\text{location}(x, y) \wedge \text{capitalOf}(y, z) \rightarrow \text{location}(x, z)$

$\text{LatticeTower}(\text{EiffelTower})$

$\text{Location}(\text{EiffelTower}, \text{Paris})$

$\text{Location}(\text{Shard}, \text{London})$

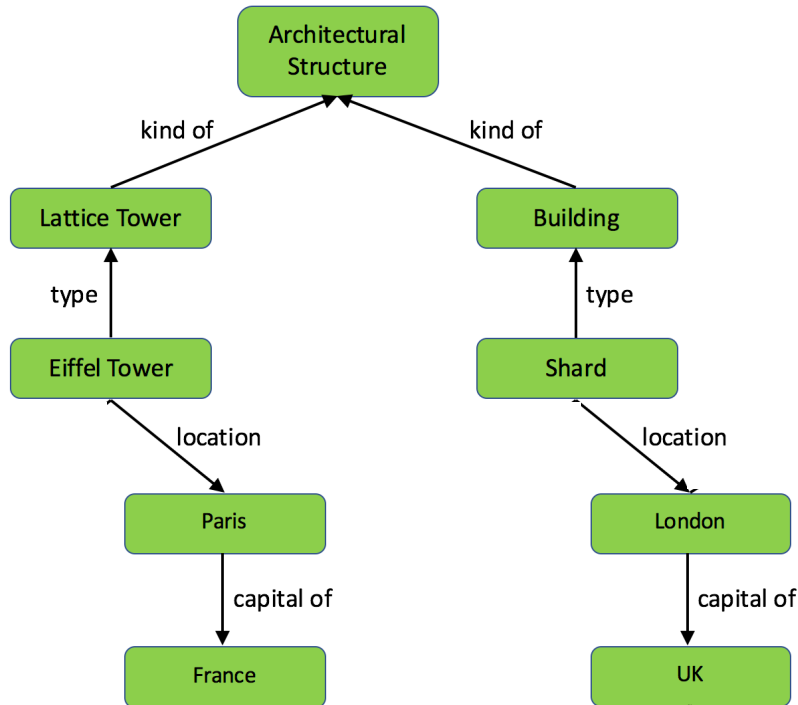
$\text{Building}(\text{Shard})$

$\text{CapitalOf}(\text{Paris}, \text{France})$

$\text{CapitalOf}(\text{London}, \text{UK})$

$\mathcal{K} \models \text{ArchStruct}(\text{EiffelTower}) ?$

True



$\text{LatticeTower}(x) \rightarrow \text{ArchStruct}(x)$

$\text{Building}(x) \rightarrow \text{ArchStruct}(x)$

$\text{location}(x, y) \wedge \text{capitalOf}(y, z) \rightarrow \text{location}(x, z)$

$\text{LatticeTower}(\text{EiffelTower})$

$\text{Location}(\text{EiffelTower}, \text{Paris})$

$\text{Location}(\text{Shard}, \text{London})$

$\text{Building}(\text{Shard})$

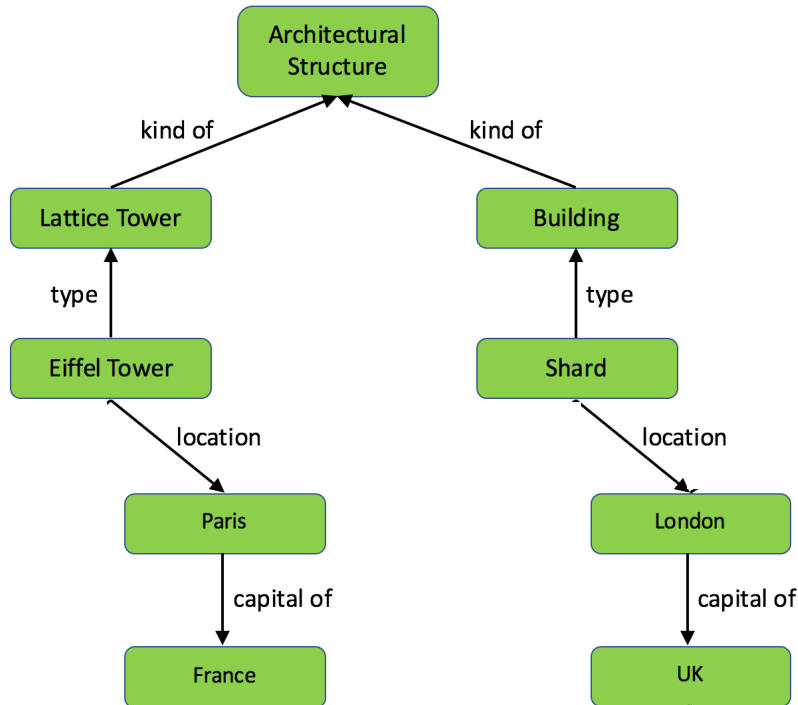
$\text{CapitalOf}(\text{Paris}, \text{France})$

$\text{CapitalOf}(\text{London}, \text{UK})$

$\mathcal{K} \models \text{ArchStruct}(\text{EiffelTower}) ?$

$\mathcal{K} \models \text{ArchStruct}(\text{Shard}) ?$

True



$\text{LatticeTower}(x) \rightarrow \text{ArchStruct}(x)$

$\text{Building}(x) \rightarrow \text{ArchStruct}(x)$

$\text{location}(x, y) \wedge \text{capitalOf}(y, z) \rightarrow \text{location}(x, z)$

$\text{LatticeTower}(\text{EiffelTower})$

$\text{Location}(\text{EiffelTower}, \text{Paris})$

$\text{Location}(\text{Shard}, \text{London})$

$\text{Building}(\text{Shard})$

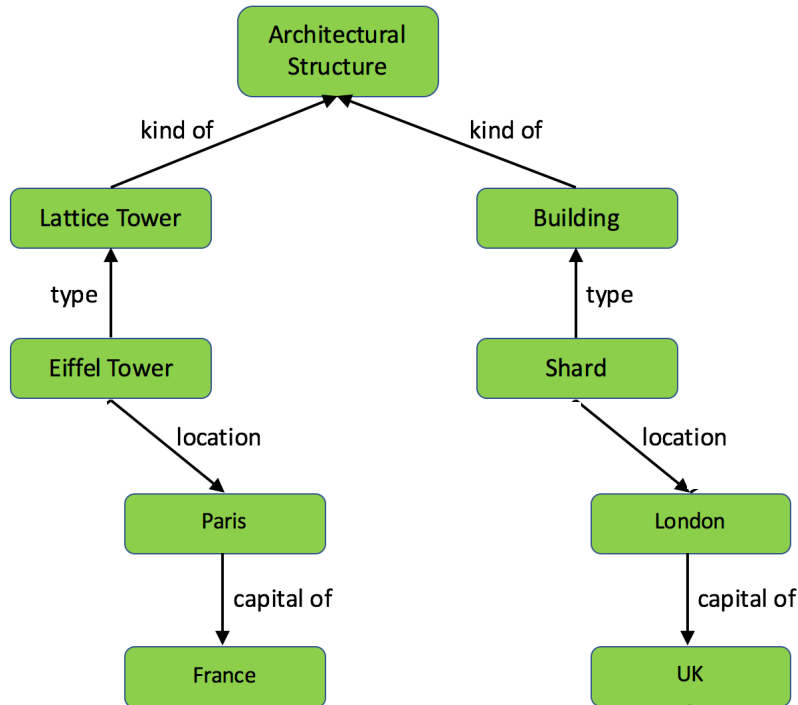
$\text{CapitalOf}(\text{Paris}, \text{France})$

$\text{CapitalOf}(\text{London}, \text{UK})$

$\mathcal{K} \models \text{ArchStruct}(\text{EiffelTower}) ?$

$\mathcal{K} \models \text{ArchStruct}(\text{Shard}) ?$

True
True



$\text{LatticeTower}(x) \rightarrow \text{ArchStruct}(x)$

$\text{Building}(x) \rightarrow \text{ArchStruct}(x)$

$\text{location}(x, y) \wedge \text{capitalOf}(y, z) \rightarrow \text{location}(x, z)$

$\text{LatticeTower}(\text{EiffelTower})$

$\text{Location}(\text{EiffelTower}, \text{Paris})$

$\text{Location}(\text{Shard}, \text{London})$

$\text{Building}(\text{Shard})$

$\text{CapitalOf}(\text{Paris}, \text{France})$

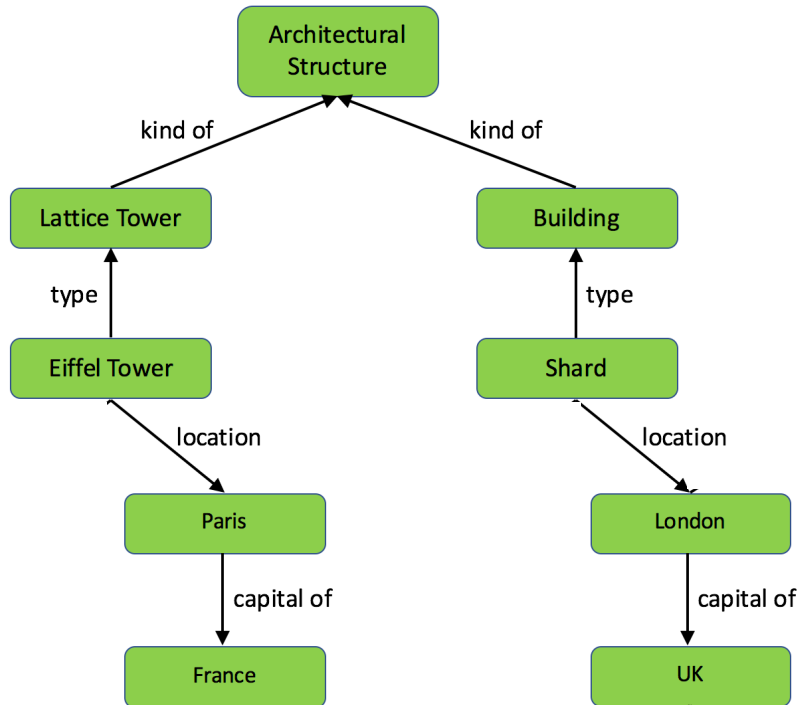
$\text{CapitalOf}(\text{London}, \text{UK})$

$\mathcal{K} \models \text{ArchStruct}(\text{EiffelTower}) ?$

$\mathcal{K} \models \text{ArchStruct}(\text{Shard}) ?$

$\mathcal{K} \models \text{location}(\text{EiffelTower}, \text{France}) ?$

True
True



$\text{LatticeTower}(x) \rightarrow \text{ArchStruct}(x)$

$\text{Building}(x) \rightarrow \text{ArchStruct}(x)$

$\text{location}(x, y) \wedge \text{capitalOf}(y, z) \rightarrow \text{location}(x, z)$

$\text{LatticeTower}(\text{EiffelTower})$

$\text{Location}(\text{EiffelTower}, \text{Paris})$

$\text{Location}(\text{Shard}, \text{London})$

$\text{Building}(\text{Shard})$

$\text{CapitalOf}(\text{Paris}, \text{France})$

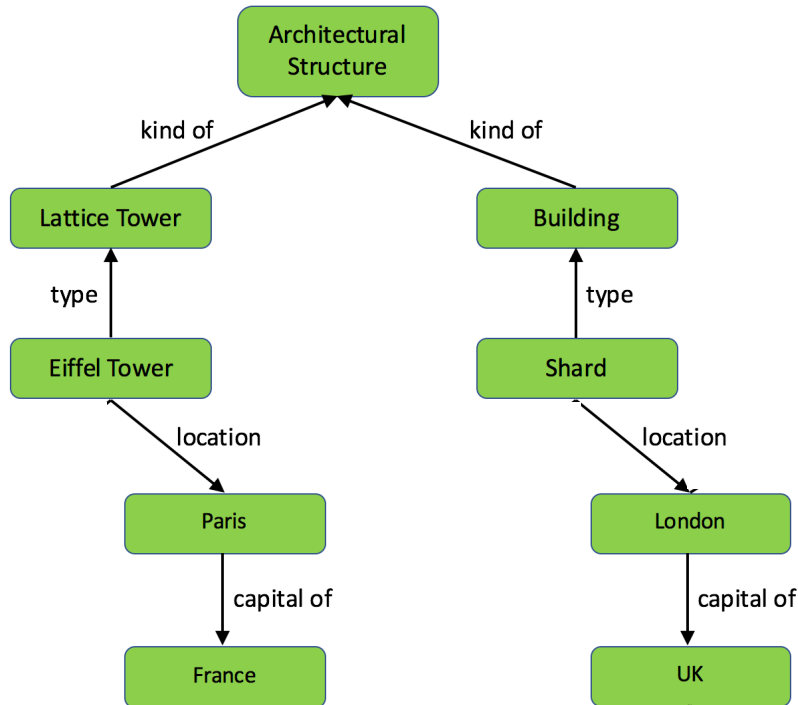
$\text{CapitalOf}(\text{London}, \text{UK})$

$\mathcal{K} \models \text{ArchStruct}(\text{EiffelTower}) ?$

$\mathcal{K} \models \text{ArchStruct}(\text{Shard}) ?$

$\mathcal{K} \models \text{location}(\text{EiffelTower}, \text{France}) ?$

True
True
True



$\text{LatticeTower}(x) \rightarrow \text{ArchStruct}(x)$

$\text{Building}(x) \rightarrow \text{ArchStruct}(x)$

$\text{location}(x, y) \wedge \text{capitalOf}(y, z) \rightarrow \text{location}(x, z)$

$\text{LatticeTower}(\text{EiffelTower})$
 $\text{Location}(\text{EiffelTower}, \text{Paris})$
 $\text{Location}(\text{Shard}, \text{London})$

$\text{Building}(\text{Shard})$
 $\text{CapitalOf}(\text{Paris}, \text{France})$
 $\text{CapitalOf}(\text{London}, \text{UK})$

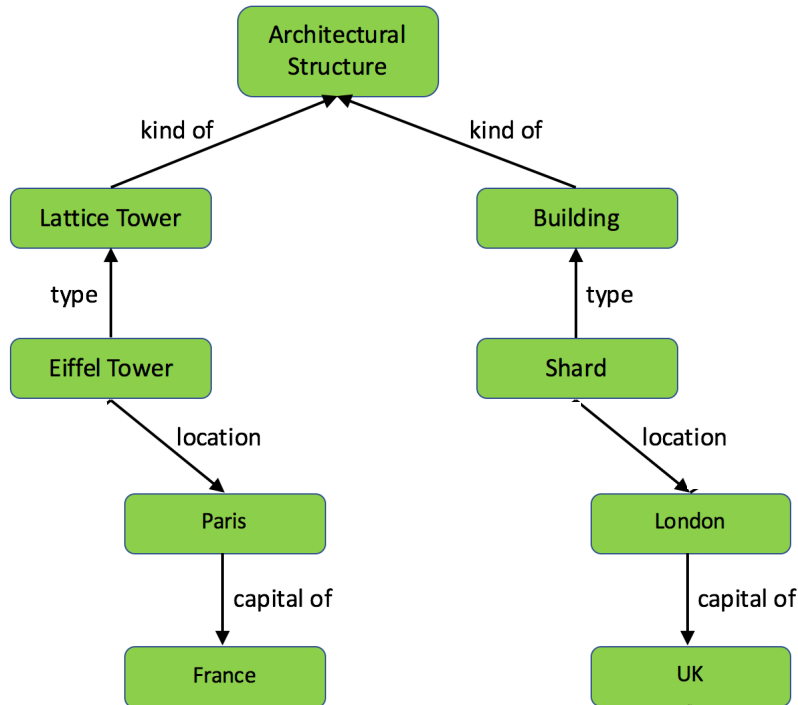
$\mathcal{K} \models \text{ArchStruct}(\text{EiffelTower}) ?$

$\mathcal{K} \models \text{ArchStruct}(\text{Shard}) ?$

$\mathcal{K} \models \text{location}(\text{EiffelTower}, \text{France}) ?$

$\mathcal{K} \models \text{location}(\text{Shard}, \text{UK}) ?$

True
True
True



$\text{LatticeTower}(x) \rightarrow \text{ArchStruct}(x)$

$\text{Building}(x) \rightarrow \text{ArchStruct}(x)$

$\text{location}(x, y) \wedge \text{capitalOf}(y, z) \rightarrow \text{location}(x, z)$

$\text{LatticeTower}(\text{EiffelTower})$

$\text{Location}(\text{EiffelTower}, \text{Paris})$

$\text{Location}(\text{Shard}, \text{London})$

$\text{Building}(\text{Shard})$

$\text{CapitalOf}(\text{Paris}, \text{France})$

$\text{CapitalOf}(\text{London}, \text{UK})$

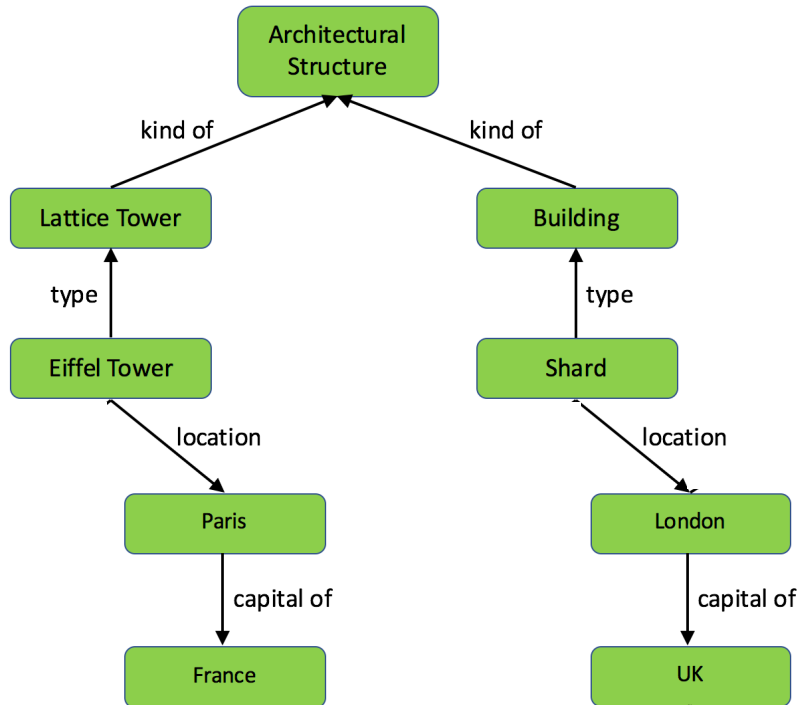
$\mathcal{K} \models \text{ArchStruct}(\text{EiffelTower}) ?$

$\mathcal{K} \models \text{ArchStruct}(\text{Shard}) ?$

$\mathcal{K} \models \text{location}(\text{EiffelTower}, \text{France}) ?$

$\mathcal{K} \models \text{location}(\text{Shard}, \text{UK}) ?$

True
True
True
True



$\text{LatticeTower}(x) \rightarrow \text{ArchStruct}(x)$

$\text{Building}(x) \rightarrow \text{ArchStruct}(x)$

$\text{location}(x, y) \wedge \text{capitalOf}(y, z) \rightarrow \text{location}(x, z)$

$\text{LatticeTower}(\text{EiffelTower})$

$\text{Location}(\text{EiffelTower}, \text{Paris})$

$\text{Location}(\text{Shard}, \text{London})$

$\text{Building}(\text{Shard})$

$\text{CapitalOf}(\text{Paris}, \text{France})$

$\text{CapitalOf}(\text{London}, \text{UK})$

$\mathcal{K} \models \text{ArchStruct}(\text{EiffelTower}) ?$

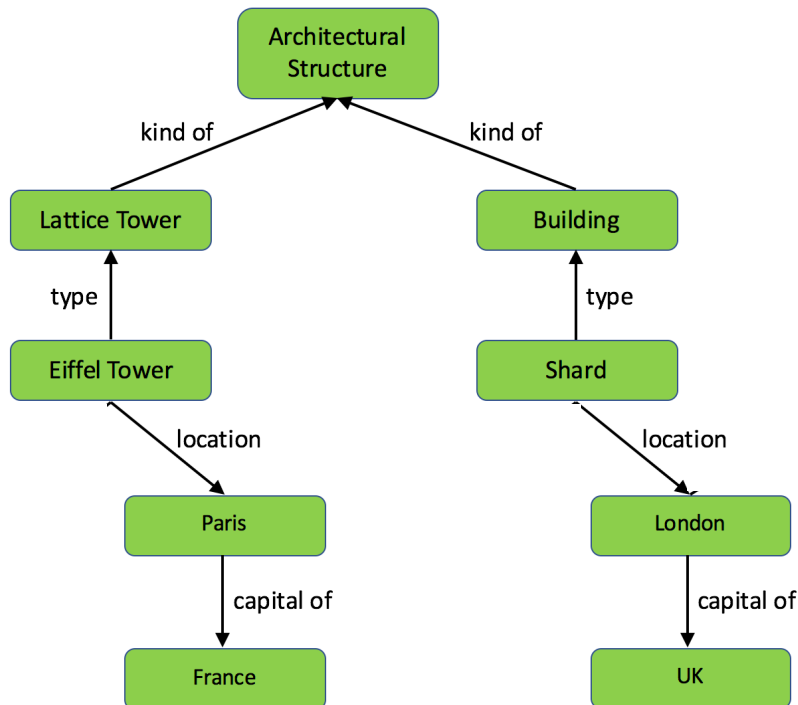
$\mathcal{K} \models \text{ArchStruct}(\text{Shard}) ?$

$\mathcal{K} \models \text{location}(\text{EiffelTower}, \text{France}) ?$

$\mathcal{K} \models \text{location}(\text{Shard}, \text{UK}) ?$

$\mathcal{K} \models \text{location}(\text{Shard}, \text{France}) ?$

True
True
True
True



$\text{LatticeTower}(x) \rightarrow \text{ArchStruct}(x)$

$\text{Building}(x) \rightarrow \text{ArchStruct}(x)$

$\text{location}(x, y) \wedge \text{capitalOf}(y, z) \rightarrow \text{location}(x, z)$

$\text{LatticeTower}(\text{EiffelTower})$
 $\text{Location}(\text{EiffelTower}, \text{Paris})$
 $\text{Location}(\text{Shard}, \text{London})$

$\text{Building}(\text{Shard})$
 $\text{CapitalOf}(\text{Paris}, \text{France})$
 $\text{CapitalOf}(\text{London}, \text{UK})$

$\mathcal{K} \models \text{ArchStruct}(\text{EiffelTower}) ?$

$\mathcal{K} \models \text{ArchStruct}(\text{Shard}) ?$

$\mathcal{K} \models \text{location}(\text{EiffelTower}, \text{France}) ?$

$\mathcal{K} \models \text{location}(\text{Shard}, \text{UK}) ?$

$\mathcal{K} \models \text{location}(\text{Shard}, \text{France}) ?$

True
True
True
True
False

Devise **algorithms** that compute query answers
E.g., using **natural deduction** rules:

$$\frac{\forall x. P(x) \rightarrow Q(x) \quad \forall x. Q(x) \rightarrow R(x)}{\forall x. P(x) \rightarrow R(x)}$$

$$\frac{\forall x. \text{Greek}(x) \rightarrow \text{Man}(x) \quad \forall x. \text{Man}(x) \rightarrow \text{Mortal}(x)}{\forall x. \text{Greek}(x) \rightarrow \text{Mortal}(x)}$$

$$\frac{\forall x. P(x) \rightarrow Q(x) \quad P(a)}{Q(a)}$$

$$\frac{\forall x. \text{Building}(x) \rightarrow \text{ArchStruc}(x) \quad \text{Building}(\text{EiffelTower})}{\text{ArchStruc}(\text{EiffelTower})}$$

Can check/prove algorithms are **sound** and **complete**
w.r.t. semantics

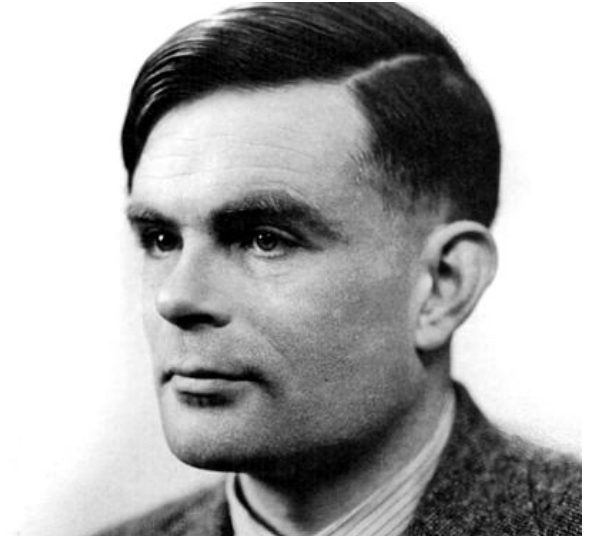
Turing showed that some problems cannot be completely solved using standard computational model

- halting problem
- **FOL entailment problem**

Even if decidable, reasoning might be of inherently **high complexity** and so take an **infeasibly long time**

Turing showed that some problems cannot be completely solved using standard computational model

- halting problem
- **FOL entailment problem**



Even if decidable, reasoning might be of inherently **high complexity** and so take an **infeasibly long time**

“Scruffy” approach:

Ad-hoc representation

Efficient but (at least) incomplete algorithms

- ✓ Can use arbitrarily powerful representation
- ✓ Favourable scalability properties
- ✗ Incomplete answers
 - ✗ Degree of incompleteness unknown
 - ✗ Incompleteness can easily become unsoundness

“Neat” approach:

Study KR languages to find appropriate balance of expressive power and computability

Design algorithms that work well in **typical** cases

Develop highly optimised implementations

- ✓ Precisely defined semantics
- ✓ Formal properties well understood
- ✓ Sound and complete reasoning
- ✗ Limited representation power
- ✗ Optimisations may not offer robust scalability

Family of **logic-based KR languages**

Most are decidable **subsets of FO logic**

Provide a range of **different constructors**

- Booleans (and, or, not)
- Restricted forms of quantification (exists, forall)
- Counting (atmost, atleast)
- ...

Decidability/complexity and (efficient) **algorithms**
known for many combinations of constructors

Highly **optimised implementations** for various
“sweet spot” languages



Complexity of reasoning in Description Logics

Note: the information here is (always) incomplete and [updated](#) often

Base description logic: *A*tributive *L*anguage with *C*omplements

$\mathcal{ALC} ::= \perp \mid A \mid \neg C \mid C \wedge D \mid C \vee D \mid \exists R.C \mid \forall R.C$



Concept constructors:

- ☐ $\mathcal{F}$ – functionality²: $(\leq 1 R)$
- ☒ $\mathcal{N}$ – (unqualified) number restrictions: $(\geq n R), (\leq n R)$
- ☐ $\mathcal{Q}$ – qualified number restrictions: $(\geq n R.C), (\leq n R.C)$
- ☒ $\mathcal{O}$ – nominals: $\{a\}$ or $\{a_1, \dots, a_n\}$ ("one-of" constructor)
- ☐ μ – least fixpoint operator: $\mu X.C$
- ☐ $R \subseteq S$ – role-value-maps
- ☐ $f = g$ – agreement of functional role chains ("same-as")

TBox is *internalized* in extensions of $\mathcal{ALCIO}$, see [76, Lemma 4.12], [54, p.3]

- ☒ Empty TBox
- ☐ Acyclic TBox ($A \sqsubseteq C$, A is a concept name; no cycles)
- ☐ General TBox ($C \sqsubseteq D$ for arbitrary concepts C and D)

Role constructors:

- ☒ $\mathcal{I}$ – role inverses: R^{-}
- ☐ $\cap$ – role intersection³: $R \cap S$
- ☐ $\cup$ – role union: $R \cup S$
- ☐ $\neg$ – role complement: $\text{full} \downarrow$
- ☐ $\circ$ – role chain (composition): $R \circ S$
- ☐ $*$ – reflexive-transitive closure⁴: R^*
- ☐ id – concept identity: $id(C)$
- ☐ $\text{Forbid} \downarrow$ complex roles⁵ in number restrictions⁶

Role axioms (RBox):

- ☒ $\mathcal{S}$ – Role transitivity: $\text{Trans}(R)$
- ☒ $\mathcal{H}$ – Role hierarchy: $R \subseteq S$
- ☐ $\mathcal{R}$ – Complex role inclusions: $R \circ S \subseteq R, R \circ S \subseteq S$
- ☐ $\mathcal{J}$ – some additional features

[Reset](#)

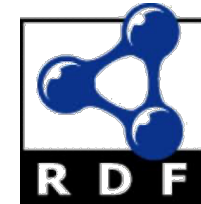
You have selected the Description Logic: *SHOIN*

Complexity of reasoning problems⁷

Reasoning problem	Complexity ⁸	Comments and references
Concept satisfiability	NExpTime-complete	• <u>Hardness</u> of even $\mathcal{ALCFIO}$ is proved in [76, Corollary 4.13]. In that paper, the result is formulated for $\mathcal{ALCQIO}$, but only number restrictions of the form $(\leq 1 R)$ are used in the proof. • A different proof of the NExpTime-hardness for $\mathcal{ALCFIO}$ is given in [54] (even with 1 nominal, and role inverses not used in number restrictions). • <u>Upper bound</u> for $\mathcal{SHOIQ}$ is proved in [77, Corollary 6.31] with numbers coded in unary (for binary coding, the upper bound remains an open problem for all logics in between $\mathcal{ALCQIO}$ and $\mathcal{SHOIQ}$). • Important: in number restrictions, only <i>simple</i> roles (i.e. which are neither transitive nor have a transitive subroles) are allowed; otherwise we gain undecidability even in $\mathcal{SHN}$; see [46]. • Remark: recently [47] it was observed that, in many cases, one can use transitive roles in number restrictions – and still have a decidable logic! So the above notion of a <i>simple</i> role could be substantially extended.
ABox consistency	NExpTime-complete	By reduction to concept satisfiability problem in presence of nominals shown in [69, Theorem 3.7].

Standardised KR language

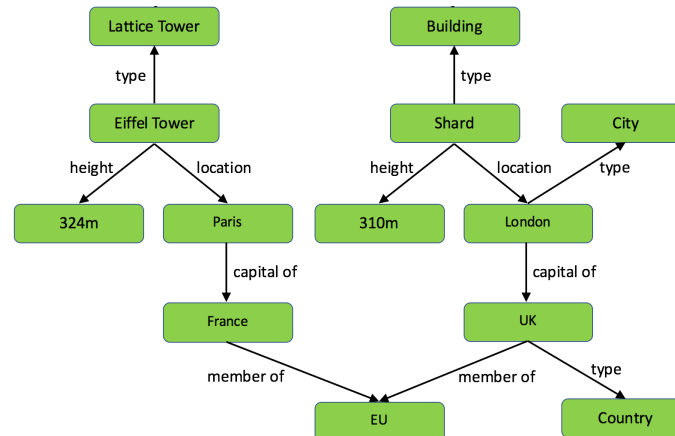
- RDF provides a graphical data model
- OWL provides a DL-based ontology language



$\text{LatticeTower}(x) \rightarrow \text{ArchStruct}(x)$

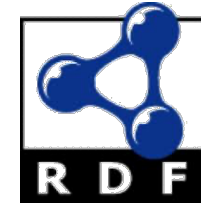
$\text{Building}(x) \rightarrow \text{ArchStruct}(x)$

$\text{location}(x, y) \wedge \text{capitalOf}(y, z) \rightarrow \text{location}(x, z)$



Standardised KR language

- RDF provides a graphical data model
- OWL provides a DL-based ontology language



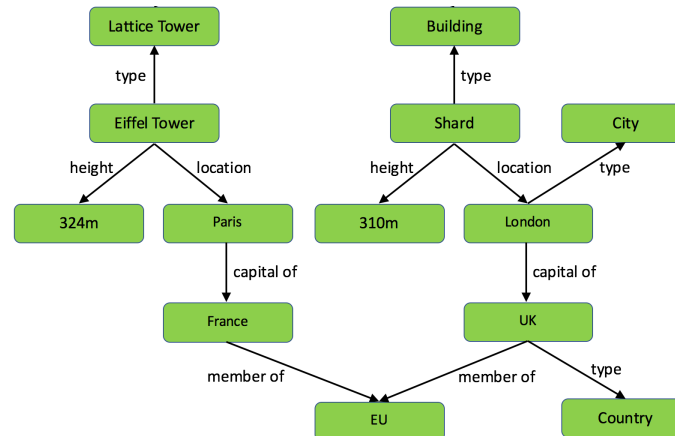
OWL ontology:

$\text{LatticeTower}(x) \rightarrow \text{ArchStruct}(x)$

$\text{Building}(x) \rightarrow \text{ArchStruct}(x)$

$\text{location}(x, y) \wedge \text{capitalOf}(y, z) \rightarrow \text{location}(x, z)$

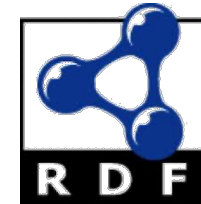
RDF data:



Standardised KR language

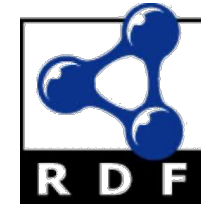
- RDF provides a graphical data model
- OWL provides a DL-based ontology language

Developed as part of **W3C's Semantic Web** project



“A new form of Web content that is meaningful to computers will unleash a revolution of new possibilities” (!)





Standardised KR language

- RDF provides a graphical data model
- OWL provides a DL-based ontology language

Developed as part of **W3C's Semantic Web** project

Now **widely used** in science,
healthcare and Industry

Often referred to as
“**semantic technology**”



Applications: Question Answering



what country is the shard located in?



Google

what country is the shard located in?

All Maps News Images Shopping More Settings Tools

About 6,400,000 results (0.81 seconds)

The Shard / Country



United Kingdom

People also search for

View 10+ more

						
England	London	Great Britain	Scotland	United States of America	Wales	Ireland



KR Success Story:

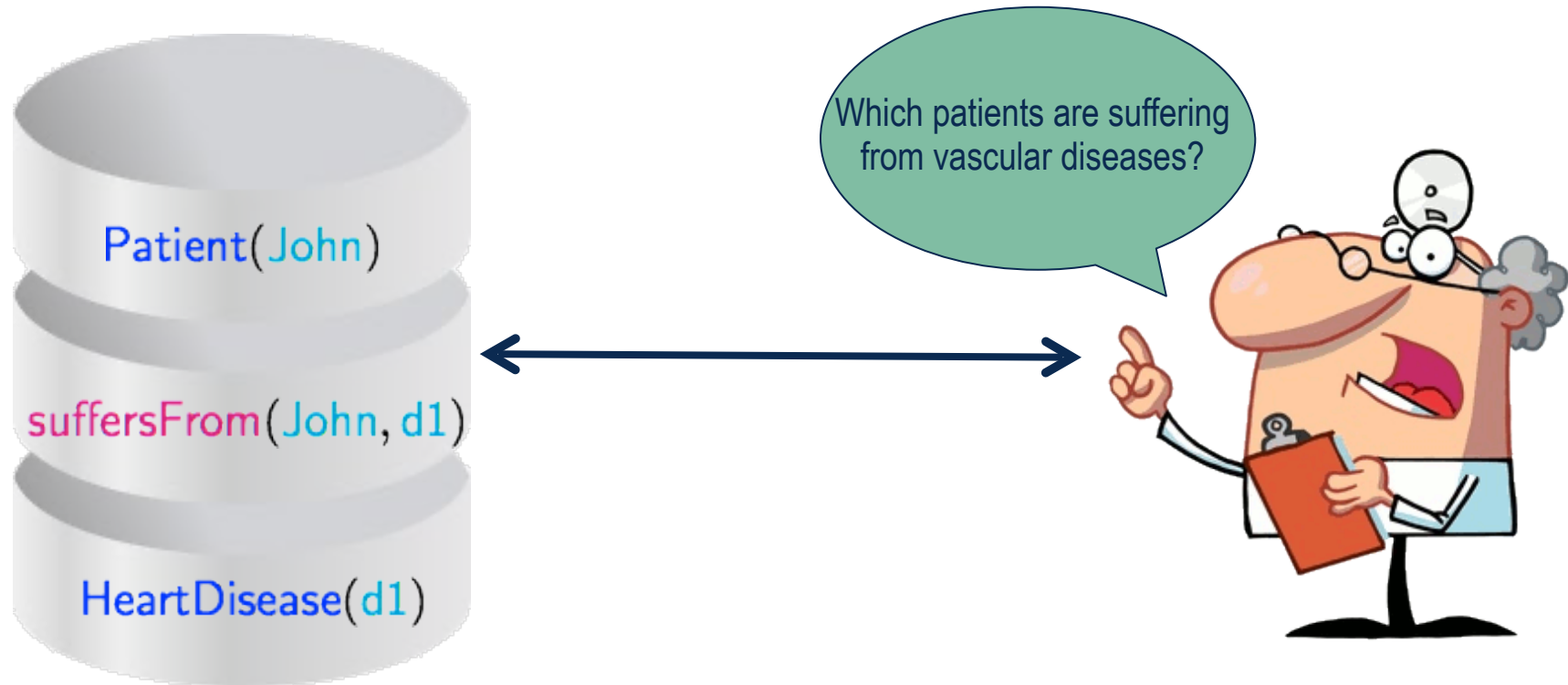
SNOMED is a **huge** medical ontology

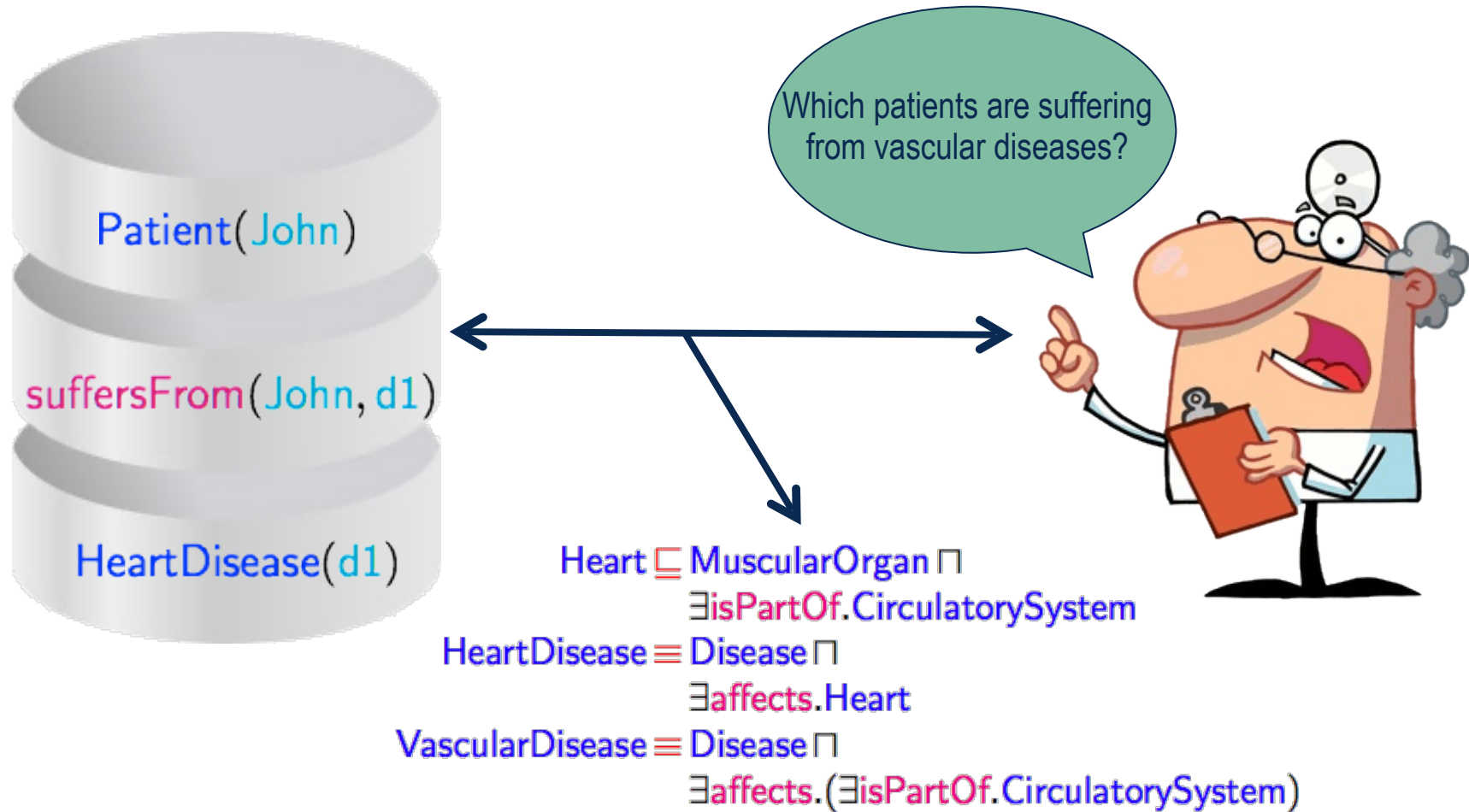
- More than 500,000 terms!

Why SNOMED? Let's ask Healthcare experts!

- "We need a clinical ontology that is **universal**, so any term I use is the same as every other colleague around the country"
- "SNOMED is the **glue** that binds the clinical community together and is the platform for all clinically relevant information"

Used to annotate patient records in **more than 20 countries**, including UK, USA, New Zealand, ...





The end?

Extensions

- Arithmetic functions and aggregation
- Reasoning about time
- Data streams

Algorithms

- Consequence-based reasoning
- Hybrid rewriting/materialisation

Optimisation and implementation

- Incremental reasoning
- Query planning
- HPC, including large-scale and distributed architectures

Tools and applications

Logics for Knowledge Representation

Horn Logics and Datalog

Description Logics – Syntax and Semantics

Description Logics – Reasoning with Data

Nonmonotonic Reasoning

Inconsistency Handling

Argumentation

Uncertainty