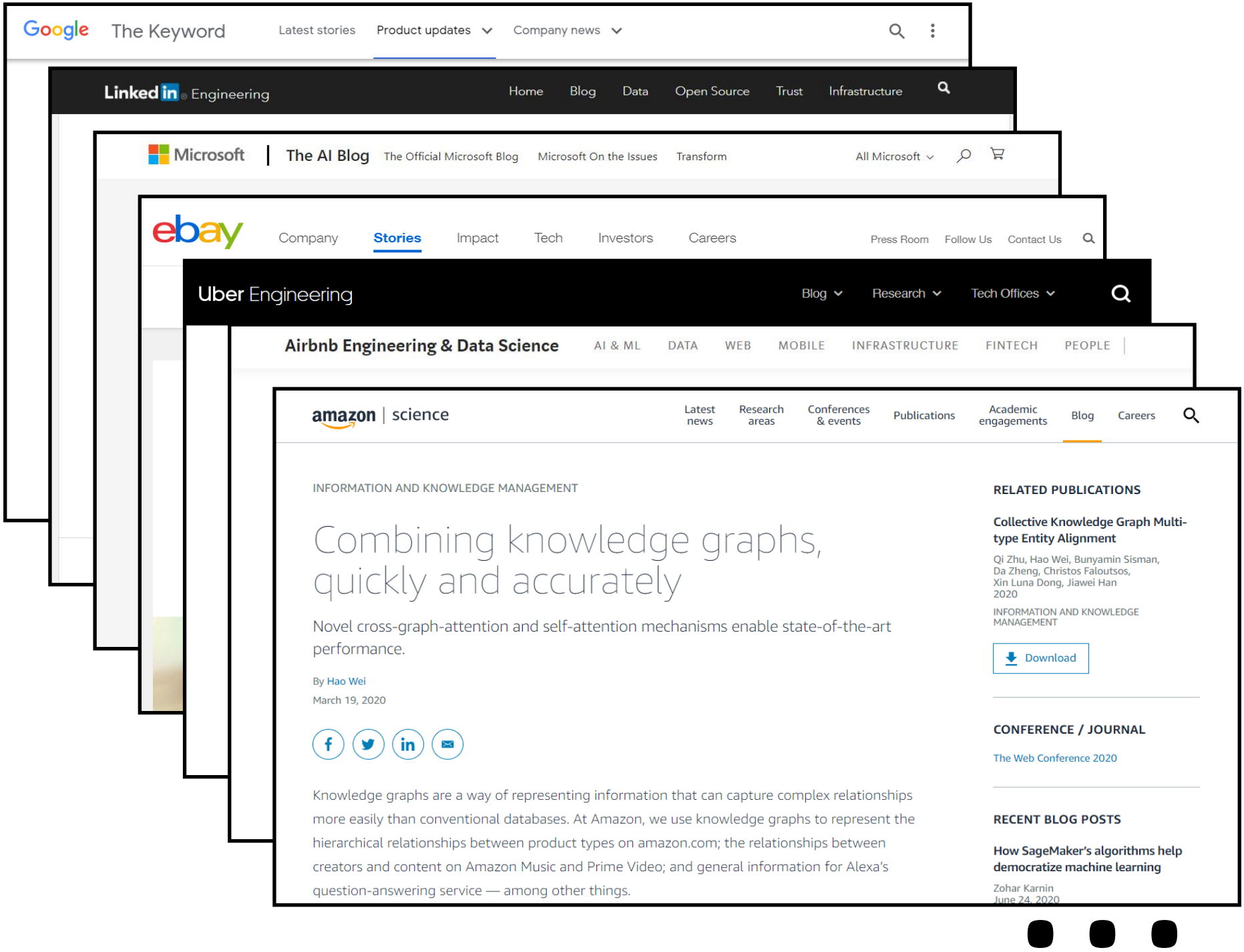
Introduction to Knowledge Graphs

AIB 2022

Aidan Hogan

Universidad de Chile

Instituto Milenio Fundamentos de los datos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Combining knowledge graphs, quickly and accurately
Novel cross-graph-attention and self-attention mechanisms enable state-of-the-art performance.
By Hao Wei
March 19, 2020
Knowledge graphs are a way of representing information that can capture complex relationships more easily than conventional databases. At Amazon, we use knowledge graphs to represent the hierarchical relationships between product types on amazon.com; the relationships between creators and content on Amazon Music and Prime Video; and general information for Alexa's question-answering service — among other things.
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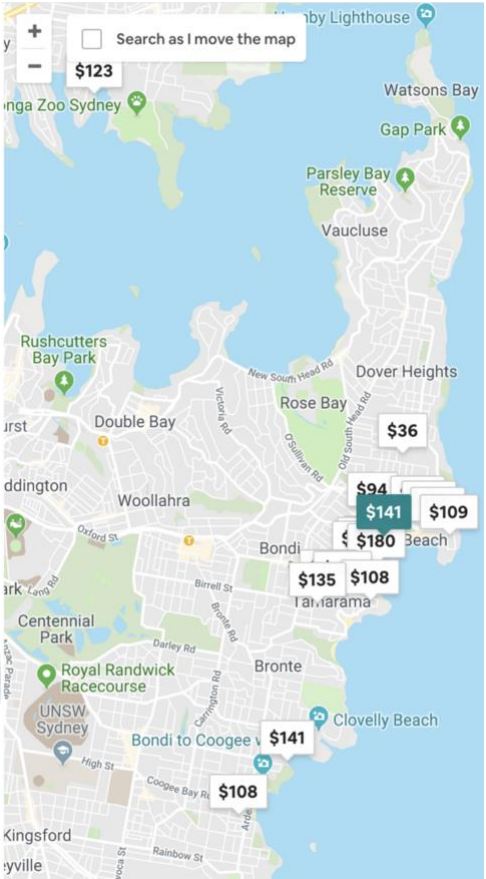
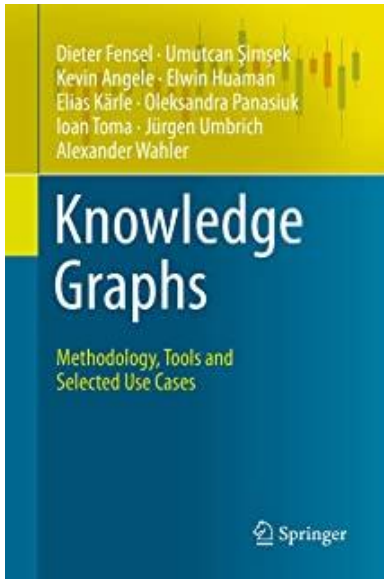
Knowledge Graph

The Knowledge Graph is a knowledge base used by Google and its services to enhance its search engine's results with information gathered from a variety of sources. The information is presented to users in an infobox next to the search results.

Wikipedia

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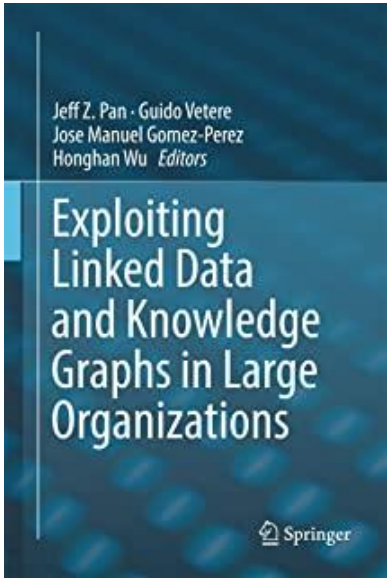
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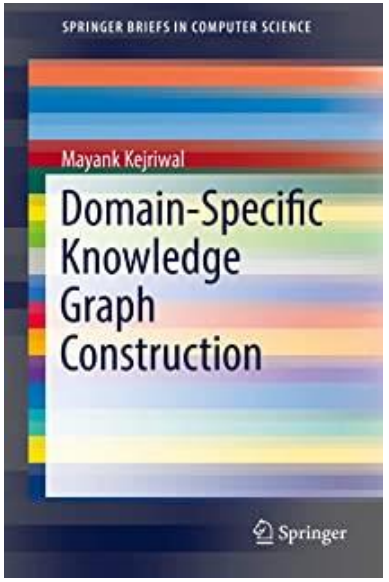
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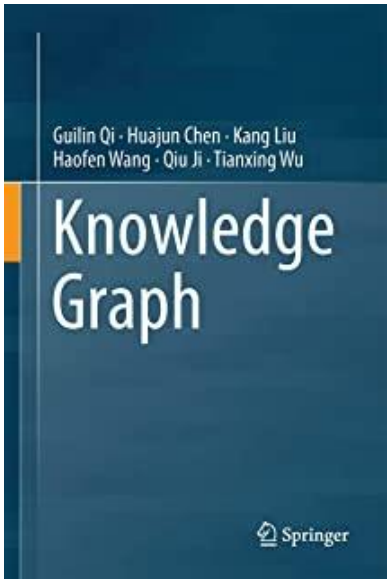
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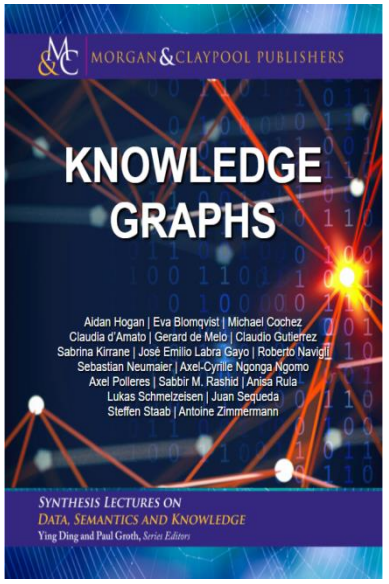
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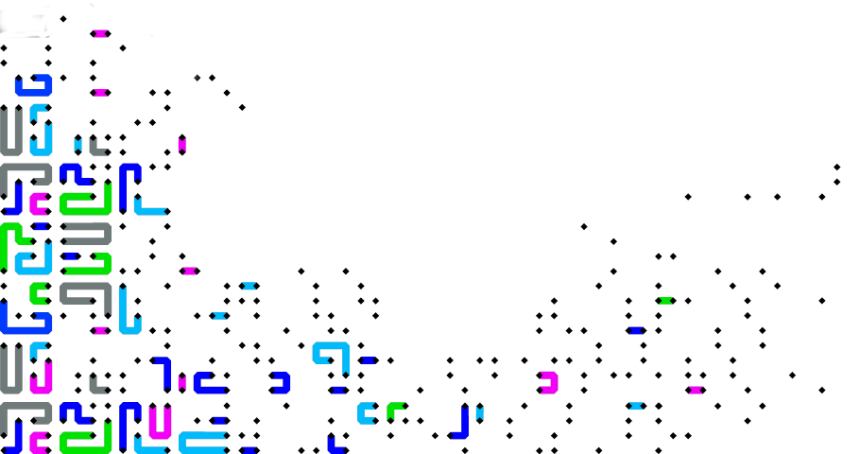
What is a “knowledge graph”?



A knowledge graph …

"is a multi-relational graph composed of entities as nodes and relations as different types of edges"

[Wang et al. 2014]

A knowledge graph …

"is a graph-structured knowledge base"
[Nickel et al. 2016]

A knowledge graph …

“acquires and integrates information into an ontology and applies a reasoner”
[Ehrlinger & Wöß. 2016]

A knowledge graph …

““mainly describes real world entities and their interrelations, organized in a graph”
[Paulheim 2017]

A knowledge graph …

"is a semi-structured data model characterized by three components;

(i) a ground extensional component […]

(ii) an intensional component […];

(iii) a derived extensional component"

[Bellomarini et al. 2019]

A knowledge graph …

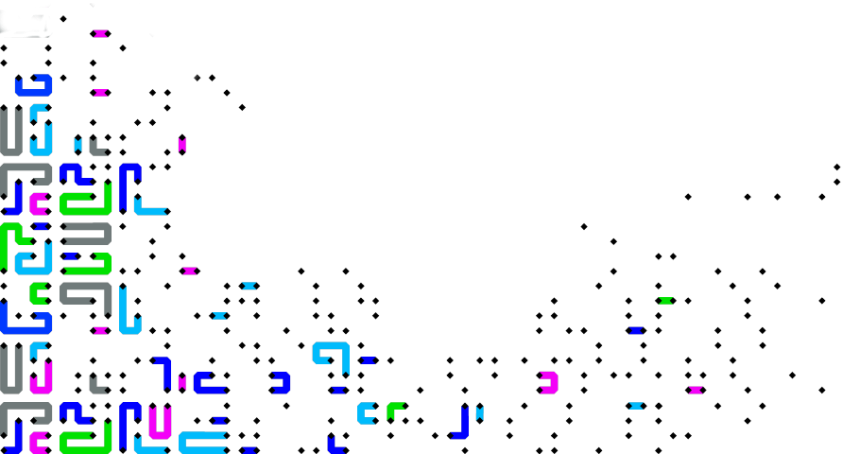
"describes objects of interest and connections between them" and "provides a shared substrate of knowledge within an organization"

[Noy et al. 2019]

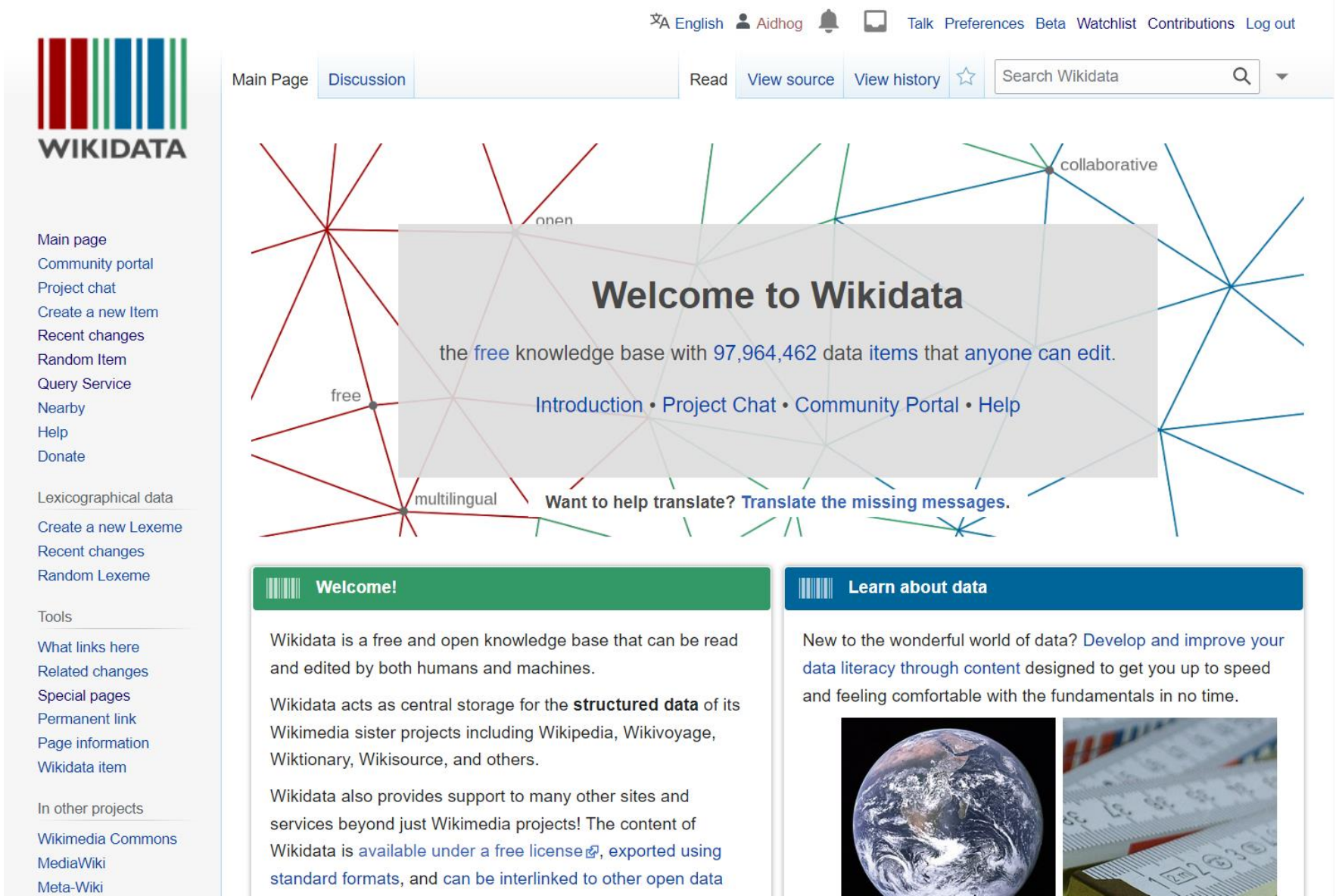
A knowledge graph …

“is a graph of knowledge”
[Hogan 2022]

An example of a “knowledge graph”?



Wikidata: Wikipedia but with graph data



What kinds of entities?

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University of Bergen (Q204457)

university in Norway

Universitetet i Bergen | Universitas Bergensis | UiB | Bergen University

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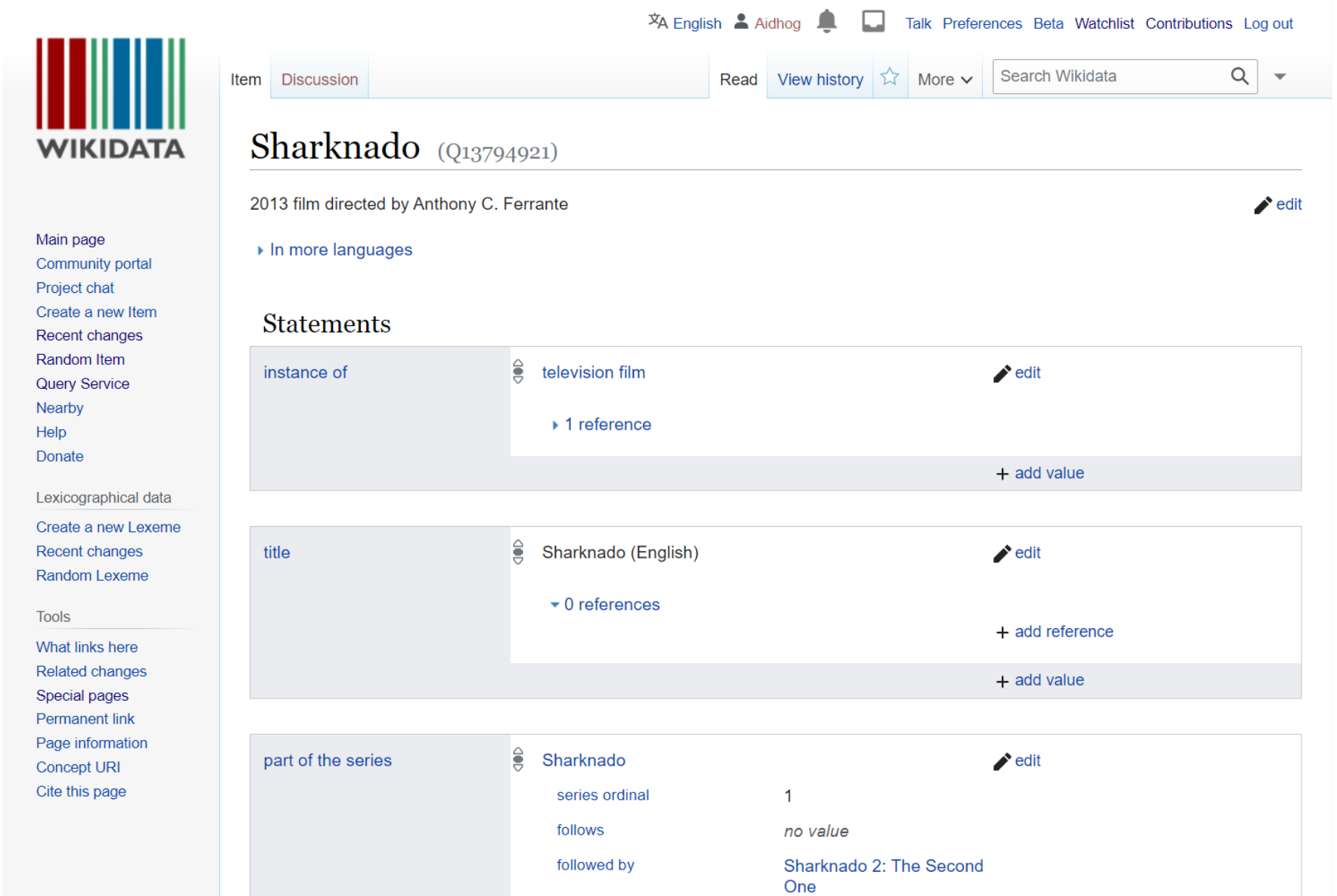
What kinds of entities?



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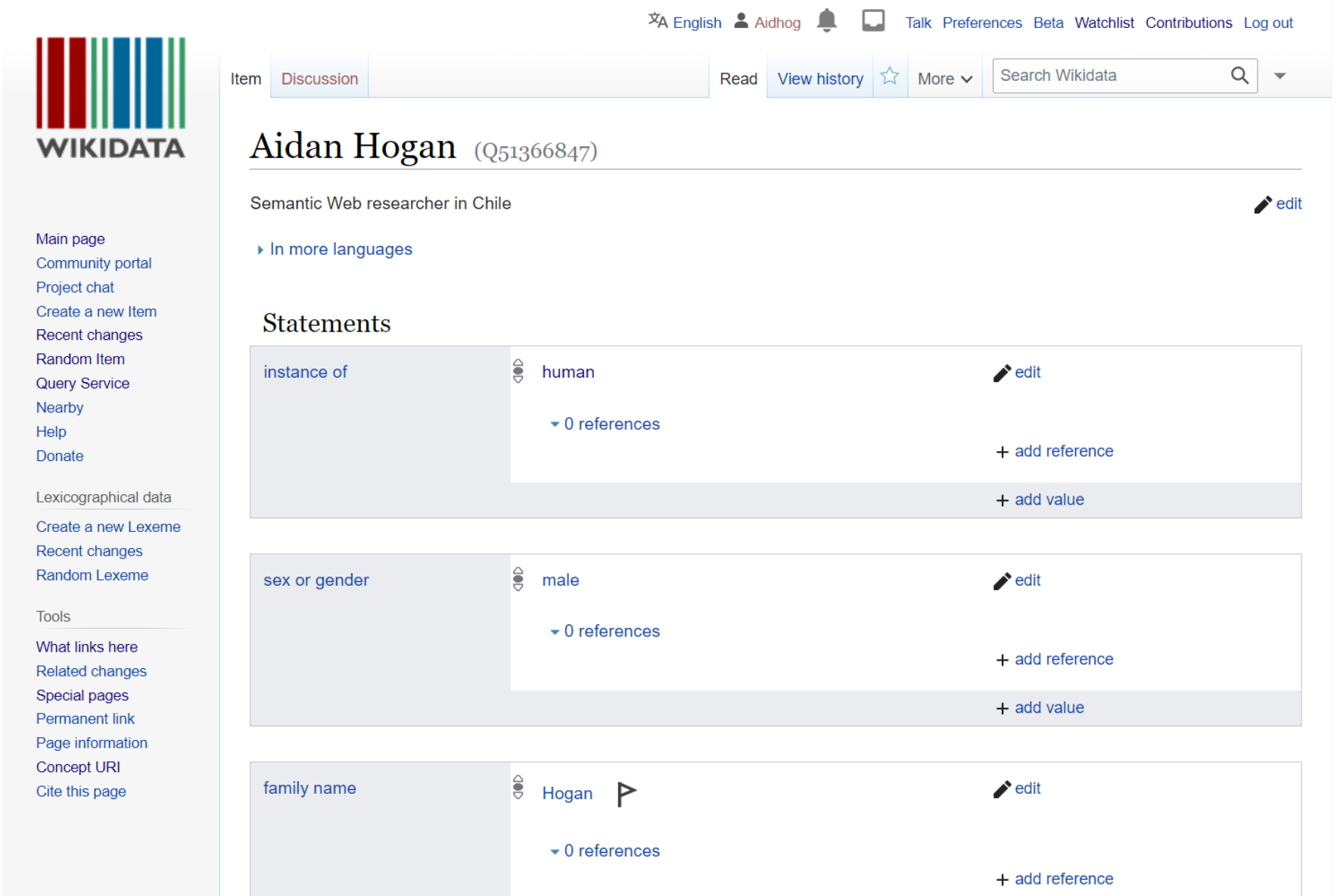

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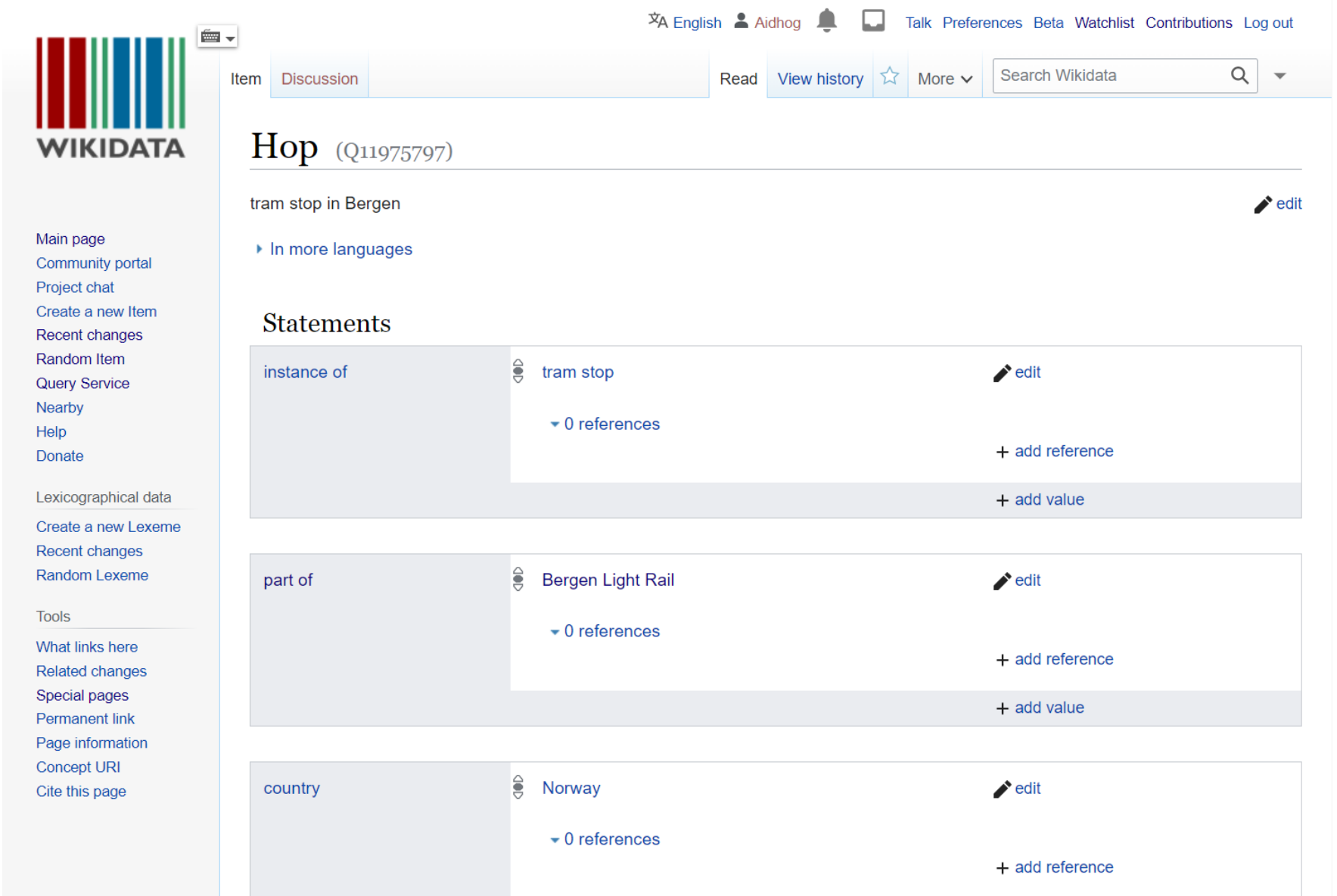

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Råstølen (Q20553552)

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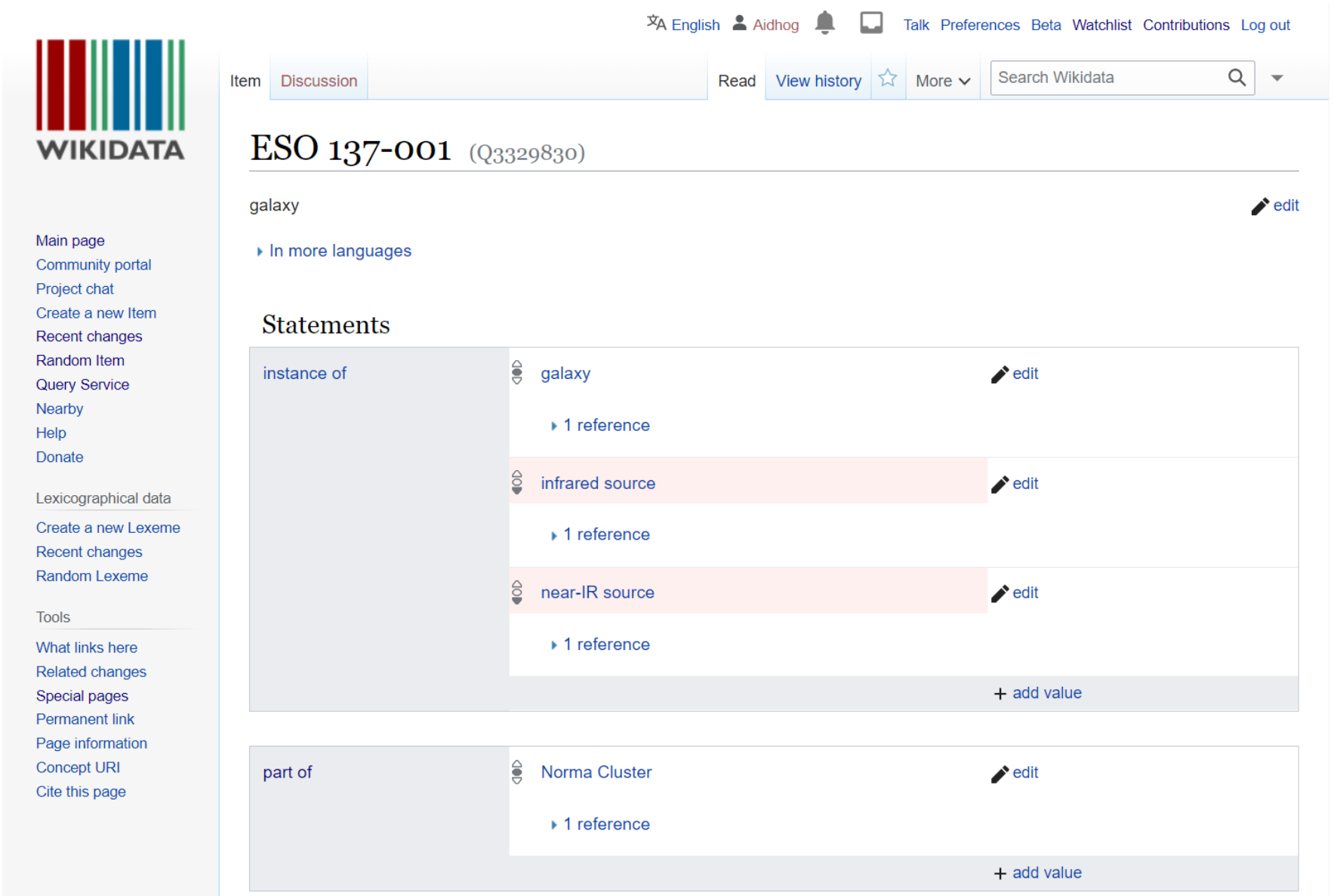
part of	Bergen Light Rail 0 references + add reference + add value	edit
image		edit

What kinds of entities?



What kinds of entities?

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toast sandwich (Q7811415)

sandwich made with two slices of bread in which the filling is a thin slice of heavily buttered toast edit

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Statements

subclass of — sandwich — edit

0 references

+ add reference

+ add value

image — edit

An image of a toast sandwich, shot from the side.jpg
1,024 × 768; 69 KB

1 reference

Why is this a knowledge graph?

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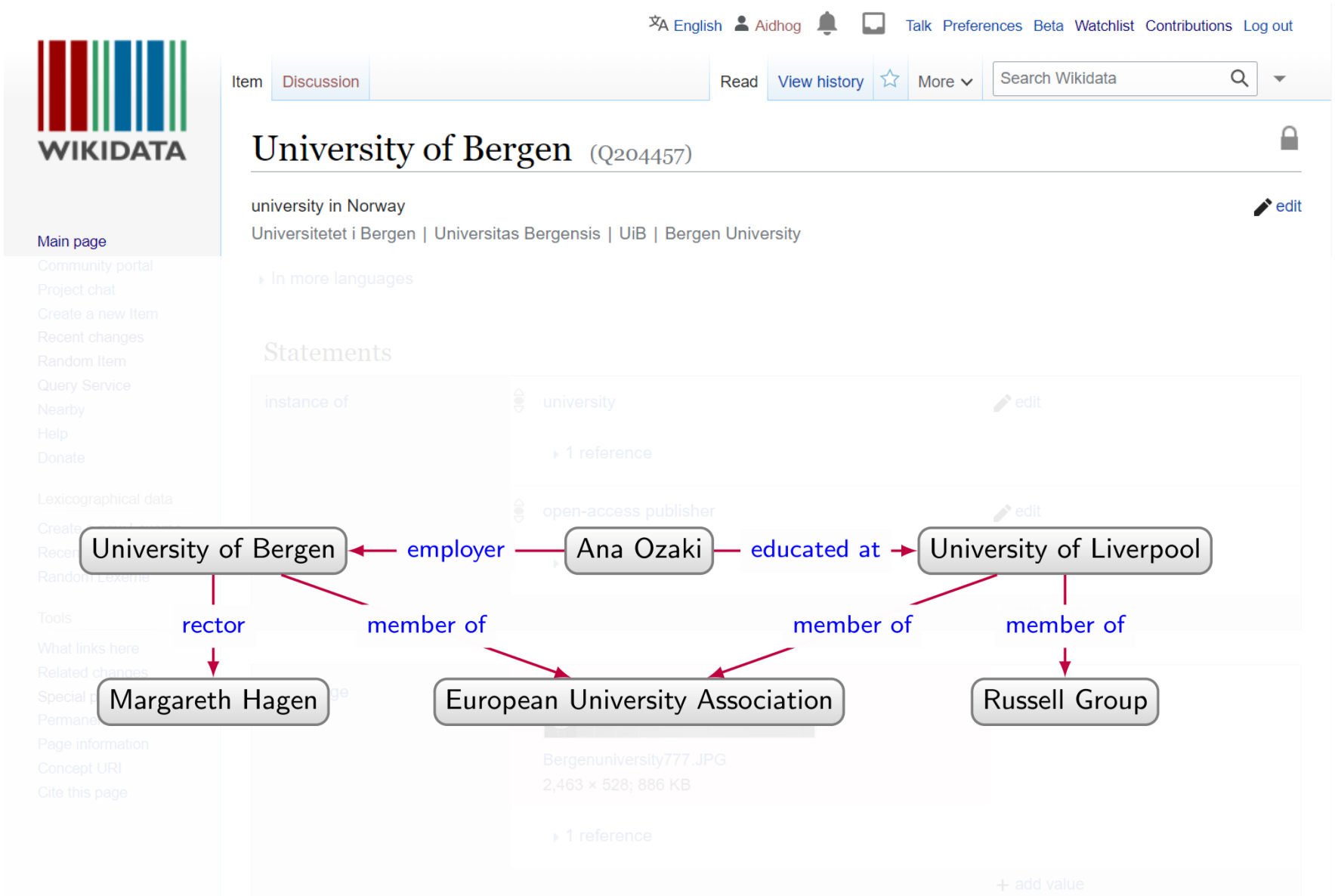
Why is this a knowledge graph?

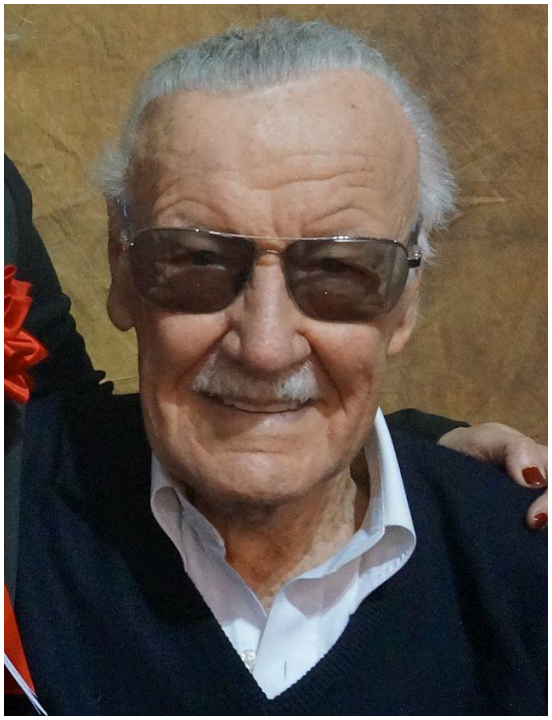


Where is Wikidata used?

GIZMODO

Siri Erroneously Told People Stan Lee Was Dead

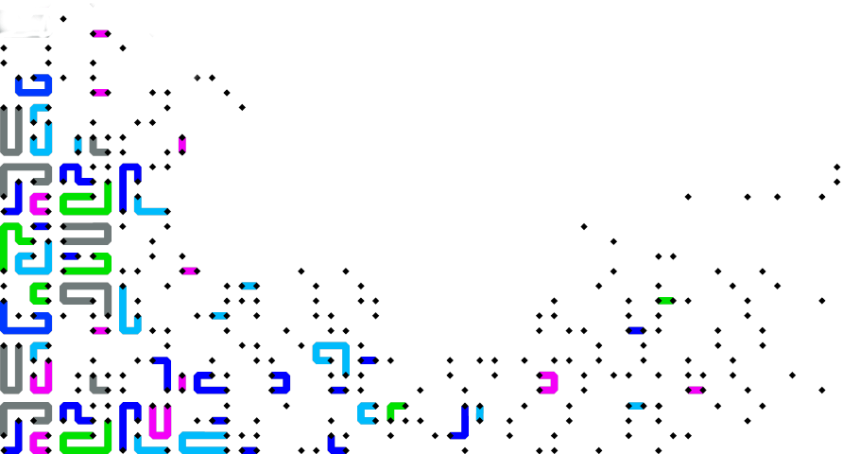
By Beth Elderkin | 7/03/18 2:45PM | Comments (45)



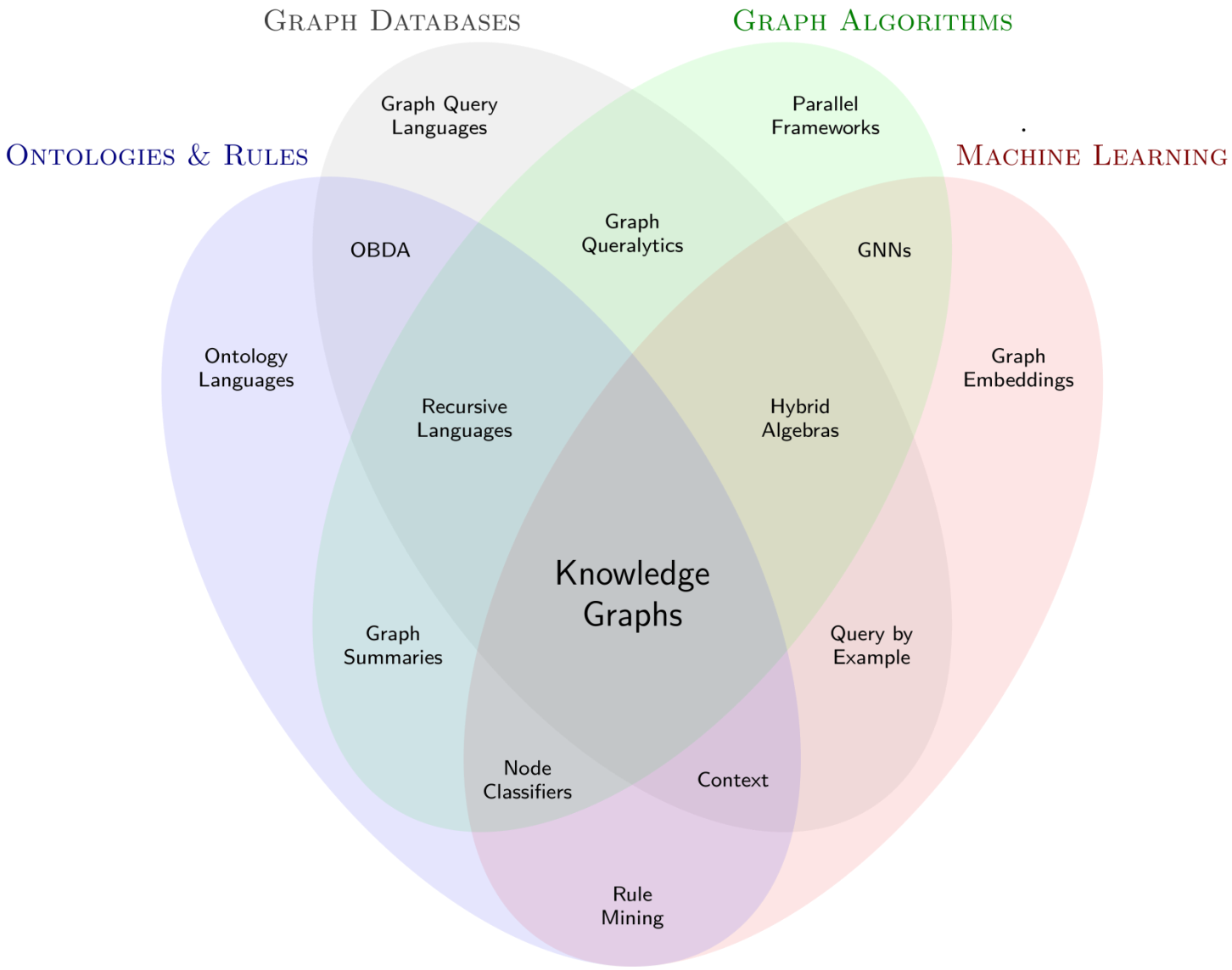
For a few brief moments, comic book fans around the world were shocked to hear some tragic news. But luckily, the panic didn't last long. As first reported by CinemaBlend, Siri spent a little time this week telling people that Stan Lee had died on July 2. Why would a computer program falsely report a famous figure's death? You can blame a Wiki user for that.

Sources tell us the problem can be traced back to revisions in Lee's Wikidata. If you look at the profile's recent history, Wiki user "&beer&love" changed Lee's Wiki data to include a "date of death." Since Siri pulls data automatically from Wiki pages, without edit or modification, the program temporarily included the false death claim. The timing of the inquiry just happened to coincide with the false information being present at that point.

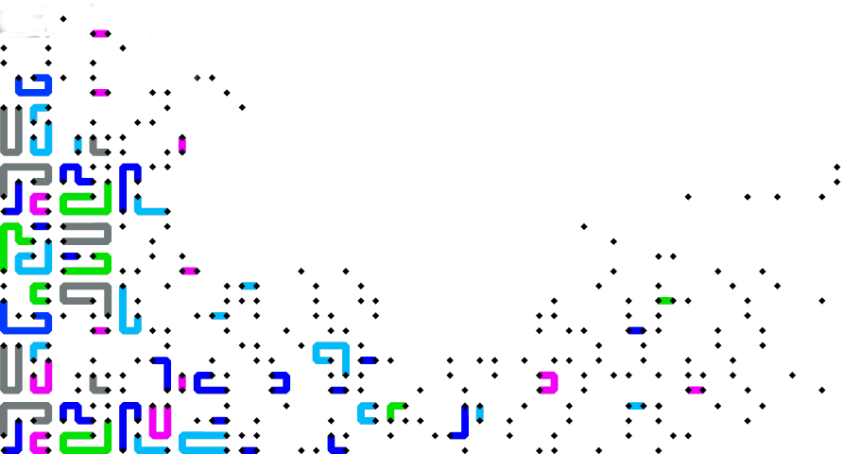
What is new about “knowledge graphs”?



How are knowledge graphs new?



Why graphs?



Relational Databases …

Relational Databases ...

Debit

account	comment	date	time	amount	total	id
7873698669	Initial deposit	2020-21-01	20:02:02	300000	300000	TRCXGU8JSHD
7873698669	C0°0°L Designs	2020-02-06	09:15:33	50000	325000	TRCCIA2J8A0

Credit

account	comment	date	time	amount	total	id
7873698669	Electricity	2020-02-02	20:00:01	8200	291800	TRCJASJDA9A
7873698669	Heat	2020-02-02	20:00:02	600	291200	TRC81KAQWAS
7873698669	Moviestar	2020-02-02	20:00:03	16200	275000	TRCK8J7JA8D
7873698669	ATM	2020-02-08	16:05:02	100000	225000	TRCPM8A45AD

Account

number	rut	type	total_clp	total_usd
7873698669	32.000.273-K	Current	225000	344,94

Client

rut	name	phone	address
32.000.273-K	Kelvin	+56976698463	Campo de Hielo Sur, Depto 273

Exchange

c1	c2	value
CLP	USD	0,0001533
USD	CLP	652,2750000

Planets / Relational Database

Planets / Relational Database

Planet
name
Mercury
Venus
Earth
Mars
Jupiter
Saturn
Uranus
Neptune
Pluto

Planets / Relational Database

Planet	
name	**dist**
Mercury	
Venus	
Earth	1.00
Mars	
Jupiter	
Saturn	
Uranus	
Neptune	
Pluto	

Planets / Relational Database

Planet

name	dist
Mercury	0.39
Venus	0.72
Earth	1.00
Mars	1.52
Jupiter	
Saturn	
Uranus	
Neptune	
Pluto	49.31

Planets / Relational Database

Planet

name	dist	radius
Mercury	0.39	0.38
Venus	0.72	
Earth	1.00	1.00
Mars	1.52	0.53
Jupiter		10.97
Saturn	9.54	
Uranus	19.19	3.98
Neptune		
Pluto	49.31	

Planets / Relational Database

Planet

name	dist	radius	grav	days	years	temp	ring
Mercury	0.39	0.38	2.8	58.646	0.241	440	false
Venus	0.72	0.95	8.9	-243.019	0.615	730	false
Earth	1.00	1.00	9.8	0.997	1.000	288	false
Mars	1.52	0.53	3.7	1.026	1.880	186	false
Jupiter	5.20	10.97	22.9	0.414	11.862	152	true
Saturn	9.54	9.14	9.1	0.444	29.447	134	true
Uranus	19.19	3.98	7.8	-0.719	84.017	76	true
Neptune	30.07	3.86	11.0	0.671	164.791	53	true
Pluto	49.31	0.19	0.063	6.39	248.000	44	false

Planets / Relational Database

Planet

name	dist	radius	grav	days	years	temp	ring
Mercury	0.39	0.38	2.8	58.646	0.241	440	false
Venus	0.72	0.95	8.9	-243.019	0.615	730	false
Earth	1.00	1.00	9.8	0.997	1.000	288	false
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Saturn	9.54	9.14	9.1	0.444	29.447	134	true
Uranus	19.19	3.98	7.8	-0.719	84.017	76	true
Neptune	30.07	3.86	11.0	0.671	164.791	53	true
Pluto	49.31	0.19	0.063	6.39	248.000	44	false

Planets / Relational Database

Planet

name	dist	radius	grav	days	years	temp	ring	moon
Mercury	0.39	0.38	2.8	58.646	0.241	440	false	⊥
Venus	0.72	0.95	8.9	-243.019	0.615	730	false	⊥
Earth	1.00	1.00	9.8	0.997	1.000	288	false	Luna
Mars	1.52	0.53	3.7	1.026	1.880	186	false	Phobos, Deimos
Jupiter	5.20	10.97	22.9	0.414	11.862	152	true	Callisto, Ganymede, ...
Saturn	9.54	9.14	9.1	0.444	29.447	134	true	Titan, Rhea, ...
Uranus	19.19	3.98	7.8	-0.719	84.017	76	true	Oberon, Titania, ...
Neptune	30.07	3.86	11.0	0.671	164.791	53	true	Triton, ...
Pluto	49.31	0.19	0.063	6.39	248.000	44	false	Charon

Planets / Relational Database

Planet

name	dist	radius	grav	days	years	temp	ring
Mercury	0.39	0.38	2.8	58.646	0.241	440	false
Venus	0.72	0.95	8.9	-243.019	0.615	730	false
Earth	1.00	1.00	9.8	0.997	1.000	288	false
Mars	1.52	0.53	3.7	1.026	1.880	186	false
Jupiter	5.20	10.97	22.9	0.414	11.862	152	true
Saturn	9.54	9.14	9.1	0.444	29.447	134	true
Uranus	19.19	3.98	7.8	-0.719	84.017	76	true
Neptune	30.07	3.86	11.0	0.671	164.791	53	true
Pluto	49.31	0.19	0.063	6.39	248.000	44	false

Moon

name	planet
Ganimedes	Jupiter
Calisto	Jupiter
Europa	Jupiter
Io	Jupiter
Titan	Saturn
Triton	Neptune
Luna	Terra
Oberon	Uranus
Charon	Pluto
...	...

Planets / Relational Database

Planet

name	dist	radius	grav	days	years	temp	ring
Mercury	0.39	0.38	2.8	58.646	0.241	440	false
Venus	0.72	0.95	8.9	-243.019	0.615	730	false
Earth	1.00	1.00	9.8	0.997	1.000	288	false
Mars	1.52	0.53	3.7	1.026	1.880	186	false
Jupiter	5.20	10.97	22.9	0.414	11.862	152	true
Saturn	9.54	9.14	9.1	0.444	29.447	134	true
Uranus	19.19	3.98	7.8	-0.719	84.017	76	true
Neptune	30.07	3.86	11.0	0.671	164.791	53	true
Pluto	49.31	0.19	0.063	6.39	248.000	44	false

Moon

name	planet	discoverer	year
Ganimedes	Jupiter	Galileo Galilei	1610
Calisto	Jupiter	Galileo Galilei	1610
Europa	Jupiter	Galileo Galilei	1610
Io	Jupiter	Galileo Galilei	1610
Titan	Saturn	Christiaan Huygens	1655
Triton	Neptune	William Lassell	1846
Luna	Terra	$\perp$	$\perp$
Oberon	Uranus	William Herschel	1787
Charon	Pluto	$\perp$	1978
...	...	...	...

Planets / Relational Database

Planet

name	dist	radius	grav	days	years	temp	ring
Mercury	0.39	0.38	2.8	58.646	0.241	440	false
Venus	0.72	0.95	8.9	-243.019	0.615	730	false
Earth	1.00	1.00	9.8	0.997	1.000	288	false
Mars	1.52	0.53	3.7	1.026	1.880	186	false
Jupiter	5.20	10.97	22.9	0.414	11.862	152	true
Saturn	9.54	9.14	9.1	0.444	29.447	134	true
Uranus	19.19	3.98	7.8	-0.719	84.017	76	true
Neptune	30.07	3.86	11.0	0.671	164.791	53	true
Pluto	49.31	0.19	0.063	6.39	248.000	44	false

Moon

name	planet
Ganimedes	Jupiter
Calisto	Jupiter
Europa	Jupiter
Io	Jupiter
Titan	Saturn
Triton	Neptune
Luna	Terra
Oberon	Uranus
Charon	Pluto
...	...

MoonDiscoverer

name	discoverer
Ganimedes	Galileo Galilei
Calisto	Galileo Galilei
Europa	Galileo Galilei
Io	Galileo Galilei
Titan	Christiaan Huygens
Triton	William Lassell
Oberon	William Herschel
...	...

MoonDiscYear

name	year
Ganimedes	1610
Calisto	1610
Europa	1610
Io	1610
Titan	1655
Triton	1846
Oberon	1787
Charon	1978
...	...

Planets / Relational Database

Planet

name	dist	radius	grav	days	years	temp	ring
Mercury	0.39	0.38	2.8	58.646	0.241	440	false
Venus	0.72	0.95	8.9	-243.019	0.615	730	false
Earth	1.00	1.00	9.8	0.997	1.000	288	false
Mars	1.52	0.53	3.7	1.026	1.880	186	false
Jupiter	5.20	10.97	22.9	0.414	11.862	152	true
Saturn	9.54	9.14	9.1	0.444	29.447	134	true
Uranus	19.19	3.98	7.8	-0.719	84.017	76	true
Neptune	30.07	3.86	11.0	0.671	164.791	53	true
Pluto	49.31	0.19	0.063	6.39	248.000	44	false

Moon

name	planet
Ganimedes	Jupiter
Calisto	Jupiter
Europa	Jupiter
Io	Jupiter
Titan	Saturn
Triton	Neptune
Luna	Terra
Oberon	Uranus
Charon	Pluto
...	...

MoonDiscoverer

name	discoverer
Ganimedes	Galileo Galilei
Calisto	Galileo Galilei
Europa	Galileo Galilei
Io	Galileo Galilei
Titan	Christiaan Huygens
Triton	William Lassell
Oberon	William Herschel
...	...

MoonDiscYear

name	year
Ganimedes	1610
Calisto	1610
Europa	1610
Io	1610
Titan	1655
Triton	1846
Oberon	1787
Charon	1978
...	...

Planets / Relational Database

Planet

name	dist	radius	grav	days	years	temp	ring
Mercury	0.39	0.38	2.8	58.646	0.241	440	false
Venus	0.72	0.95	8.9	-243.019	0.615	730	false
Earth	1.00	1.00	9.8	0.997	1.000	288	false
Mars	1.52	0.53	3.7	1.026	1.880	186	false
Jupiter	5.20	10.97	22.9	0.414	11.862	152	true
Saturn	9.54	9.14	9.1	0.444	29.447	134	true
Uranus	19.19	3.98	7.8	-0.719	84.017	76	true
Neptune	30.07	3.86	11.0	0.671	164.791	53	true
Pluto	49.31	0.19	0.063	6.39	248.000	44	false

Moon

name	P.name
Ganimedes	Jupiter
Calisto	Jupiter
Europa	Jupiter
Io	Jupiter
Titan	Saturn
Triton	Neptune
Luna	Earth
Oberon	Uranus
Charon	Pluto
...	...

MoonDiscoverer

name	discoverer
Ganimedes	Galileo Galilei
Calisto	Galileo Galilei
Europa	Galileo Galilei
Io	Galileo Galilei
Titan	Christiaan Huygens
Triton	William Lassell
Oberon	William Herschel
...	...

MoonDiscYear

name	year
Ganimedes	1610
Calisto	1610
Europa	1610
Io	1610
Titan	1655
Triton	1846
Oberon	1787
Charon	1978
...	...

Planets / Relational Database

Planet

name	dist	radius	grav	days	years	temp	ring
Mercury	0.39	0.38	2.8	58.646	0.241	440	false
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Earth	1.00	1.00	9.8	0.997	1.000	288	false
Mars	1.52	0.53	3.7	1.026	1.880	186	false
Jupiter	5.20	10.97	22.9	0.414	11.862	152	true
Saturn	9.54	9.14	9.1	0.444	29.447	134	true
Uranus	19.19	3.98	7.8	-0.719	84.017	76	true
Neptune	30.07	3.86	11.0	0.671	164.791	53	true
Pluto	49.31	0.19	0.063	6.39	248.000	44	false

Moon

name	P.name
Ganimedes	Jupiter
Calisto	Jupiter
Europa	Jupiter
Io	Jupiter
Titan	Saturn
Triton	Neptune
Luna	Earth
Oberon	Uranus
Charon	Pluto
...	...

MoonDiscoverer

name	discoverer
Ganimedes	Galileo Galilei
Calisto	Galileo Galilei
Europa	Galileo Galilei
Io	Galileo Galilei
Titan	Christiaan Huygens
Triton	William Lassell
Oberon	William Herschel
...	...

MoonDiscYear

name	year
Ganimedes	1610
Calisto	1610
Europa	1610
Io	1610
Titan	1655
Triton	1846
Oberon	1787
Charon	1978
...	...

Planets / Relational Database

Planet

name	dist	radius	grav	days	years	temp	ring
Mercury	0.39	0.38	2.8	58.646	0.241	440	false
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Mars	1.52	0.53	3.7	1.026	1.880	186	false
Jupiter	5.20	10.97	22.9	0.414	11.862	152	true
Saturn	9.54	9.14	9.1	0.444	29.447	134	true
Uranus	19.19	3.98	7.8	-0.719	84.017	76	true
Neptune	30.07	3.86	11.0	0.671	164.791	53	true

DwarfPlanet

name	dist	radius	grav	days	years	temp	ring
Pluto	49.31	0.19	0.063	6.39	248.000	44	false

Moon

name	P.name
Ganimedes	Jupiter
Calisto	Jupiter
Europa	Jupiter
Io	Jupiter
Titan	Saturn
Triton	Neptune
Luna	Earth
Oberon	Uranus
Charon	Pluto
...	...

MoonDiscoverer

name	discoverer
Ganimedes	Galileo Galilei
Calisto	Galileo Galilei
Europa	Galileo Galilei
Io	Galileo Galilei
Titan	Christiaan Huygens
Triton	William Lassell
Oberon	William Herschel
...	...

MoonDiscYear

name	year
Ganimedes	1610
Calisto	1610
Europa	1610
Io	1610
Titan	1655
Triton	1846
Oberon	1787
Charon	1978
...	...

Planets / Relational Database

Planet

name	dist	radius	grav	days	years	temp	ring
Mercury	0.39	0.38	2.8	58.646	0.241	440	false
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Uranus	19.19	3.98	7.8	-0.719	84.017	76	true
Neptune	30.07	3.86	11.0	0.671	164.791	53	true

DwarfPlanet

name	dist	radius	grav	days	years	temp	ring
Pluto	49.31	0.19	0.063	6.39	248.000	44	false

Moon

name	P.name
Ganimedes	Jupiter
Calisto	Jupiter
Europa	Jupiter
Io	Jupiter
Titan	Saturn
Triton	Neptune
Luna	Earth
Oberon	Uranus
Charon	Pluto
...	...

MoonDiscoverer

name	discoverer
Ganimedes	Galileo Galilei
Calisto	Galileo Galilei
Europa	Galileo Galilei
Io	Galileo Galilei
Titan	Christiaan Huygens
Triton	William Lassell
Oberon	William Herschel
...	...

MoonDiscYear

name	year
Ganimedes	1610
Calisto	1610
Europa	1610
Io	1610
Titan	1655
Triton	1846
Oberon	1787
Charon	1978
...	...

Planets / Relational Database

Planet

name	dist	radius	grav	days	years	temp	ring
Mercury	0.39	0.38	2.8	58.646	0.241	440	false
Venus	0.72	0.95	8.9	-243.019	0.615	730	false
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Jupiter	5.20	10.97	22.9	0.414	11.862	152	true
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Uranus	19.19	3.98	7.8	-0.719	84.017	76	true
Neptune	30.07	3.86	11.0	0.671	164.791	53	true

DwarfPlanet

name	dist	radius	grav	days	years	temp	ring
Pluto	49.31	0.19	0.063	6.39	248.000	44	false

Moon

name	planet
Ganimedes	Jupiter
Calisto	Jupiter
Europa	Jupiter
Io	Jupiter
Titan	Saturn
Triton	Neptune
Luna	Earth
Oberon	Uranus
Charon	Pluto
...	...

MoonDiscoverer

name	discoverer
Ganimedes	Galileo Galilei
Calisto	Galileo Galilei
Europa	Galileo Galilei
Io	Galileo Galilei
Titan	Christiaan Huygens
Triton	William Lassell
Oberon	William Herschel
...	...

MoonDiscYear

name	year
Ganimedes	1610
Calisto	1610
Europa	1610
Io	1610
Titan	1655
Triton	1846
Oberon	1787
Charon	1978
...	...

Planets / Relational Database

Planet

name	dist	radius	grav	days	years	temp	ring
Mercury	0.39	0.38	2.8	58.646	0.241	440	false
Venus	0.72	0.95	8.9	-243.019	0.615	730	false
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Jupiter	5.20	10.97	22.9	0.414	11.862	152	true
Saturn	9.54	9.14	9.1	0.444	29.447	134	true
Uranus	19.19	3.98	7.8	-0.719	84.017	76	true
Neptune	30.07	3.86	11.0	0.671	164.791	53	true

DwarfPlanet

name	dist	radius	grav	days	years	temp	ring
Pluto	49.31	0.19	0.063	6.39	248.000	44	false

Moon

name	planet
Ganimedes	Jupiter
Calisto	Jupiter
Europa	Jupiter
Io	Jupiter
Titan	Saturn
Triton	Neptune
Luna	Earth
Oberon	Uranus
Charon	Pluto
...	...

MoonDiscoverer

name	discoverer
Ganimedes	Galileo Galilei
Calisto	Galileo Galilei
Europa	Galileo Galilei
Io	Galileo Galilei
Titan	Christiaan Huygens
Triton	William Lassell
Oberon	William Herschel
...	...

MoonDiscYear

name	year
Ganimedes	1610
Calisto	1610
Europa	1610
Io	1610
Titan	1655
Triton	1846
Oberon	1787
Charon	1978
...	...

Planets / Relational Database

Planet

name	dist	radius	grav	days	years	temp	ring
Mercury	0.39	0.38	2.8	58.646	0.241	440	false
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Uranus	19.19	3.98	7.8	-0.719	84.017	76	true
Neptune	30.07	3.86	11.0	0.671	164.791	53	true

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DwarfPlanet

name	dist	radius	grav	days	years	temp	ring
Pluto	49.31	0.19	0.063	6.39	248.000	44	false

Moon

name	planet
Ganimedes	Jupiter
Calisto	Jupiter
Europa	Jupiter
Io	Jupiter
Titan	Saturn
Triton	Neptune
Luna	Earth
Oberon	Uranus
Charon	Pluto
...	...

MoonDiscoverer

name	discoverer
Ganimedes	Galileo Galilei
Calisto	Galileo Galilei
Europa	Galileo Galilei
Io	Galileo Galilei
Titan	Christiaan Huygens
Triton	William Lassell
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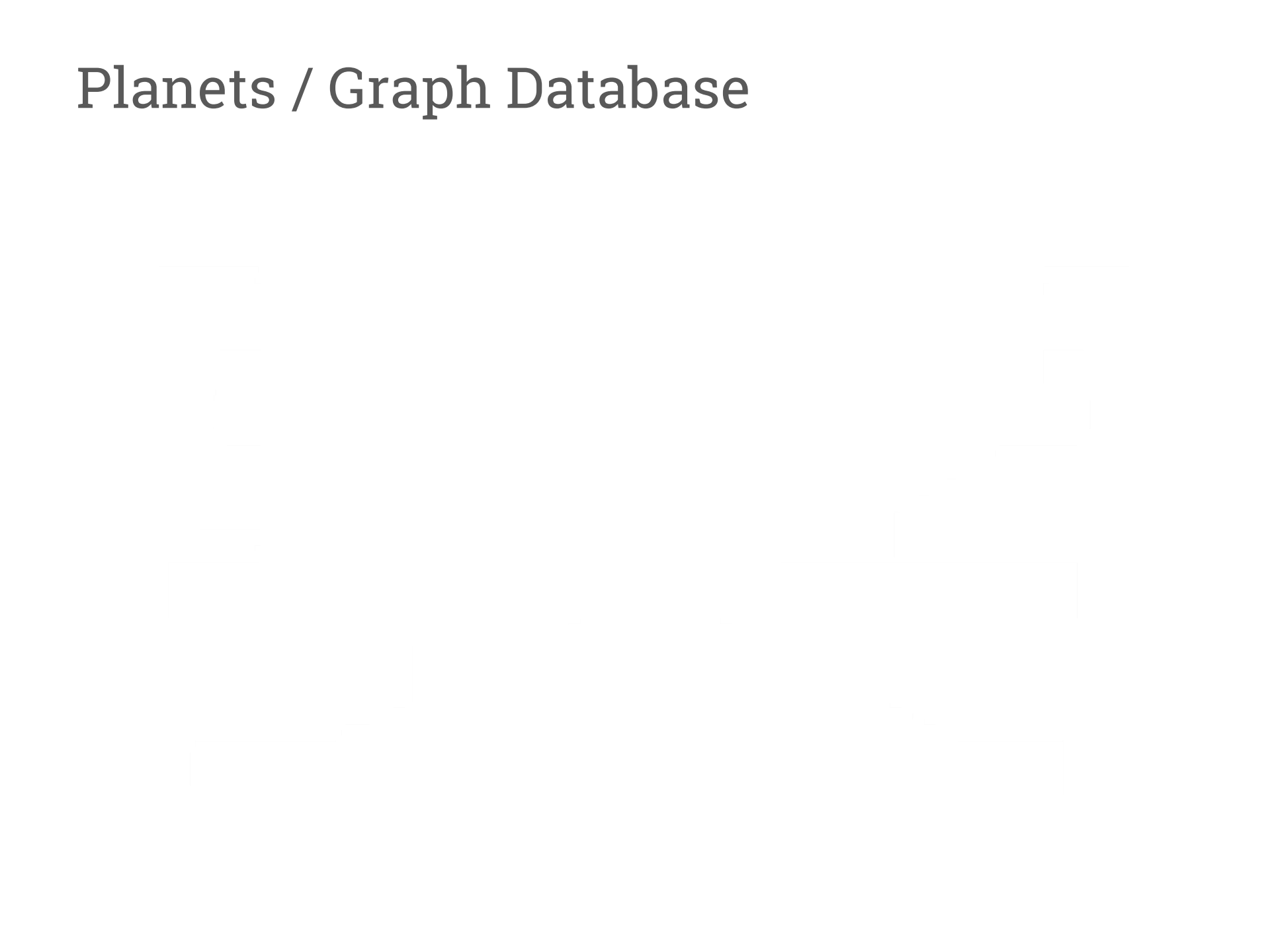
...	...

MoonDiscYear

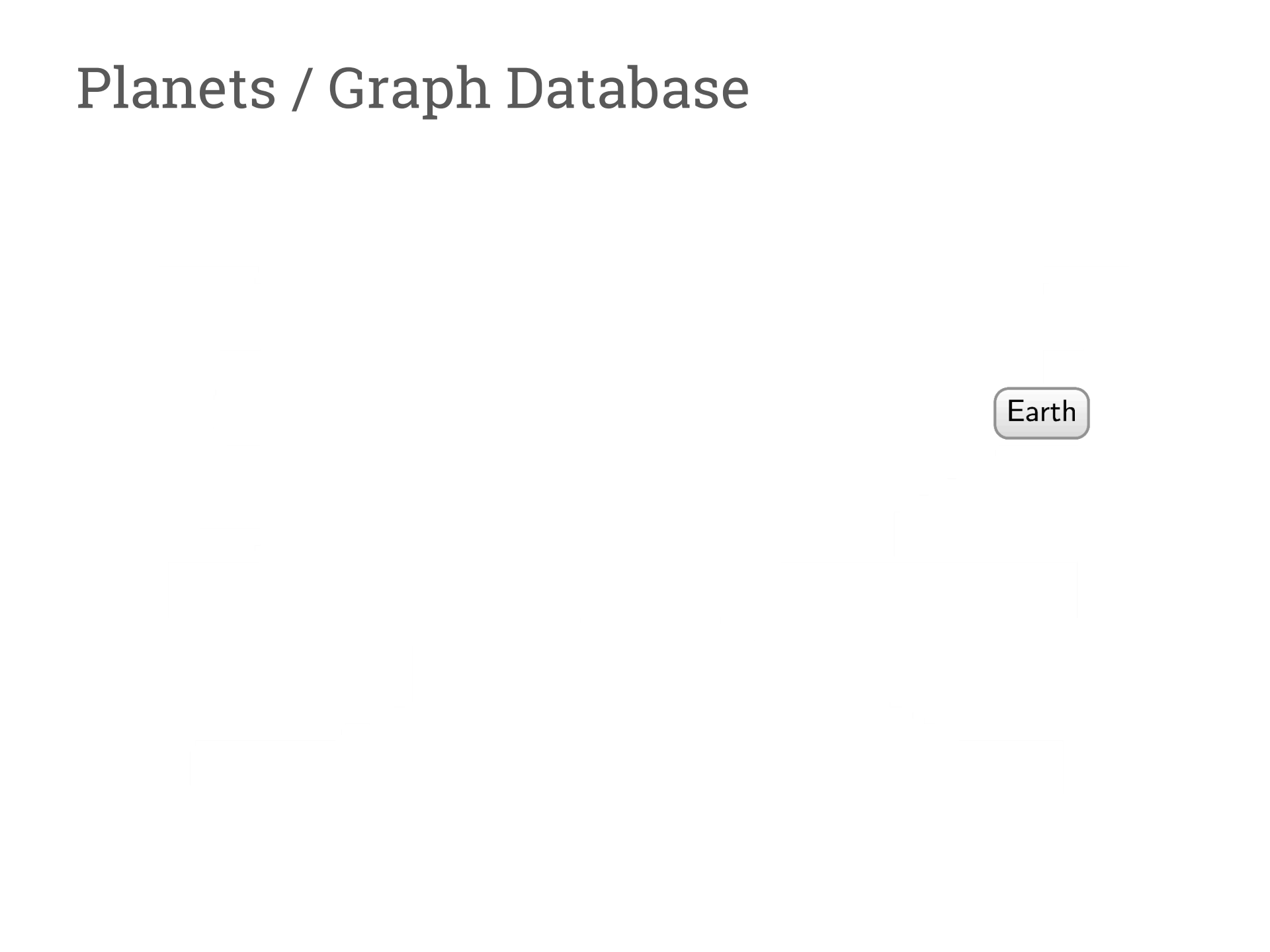
name	year
Ganimedes	1610
Calisto	1610
Europa	1610
Io	1610
Titan	1655
Triton	1846
Oberon	1787
Charon	1978
...	...

Planets / Graph Database

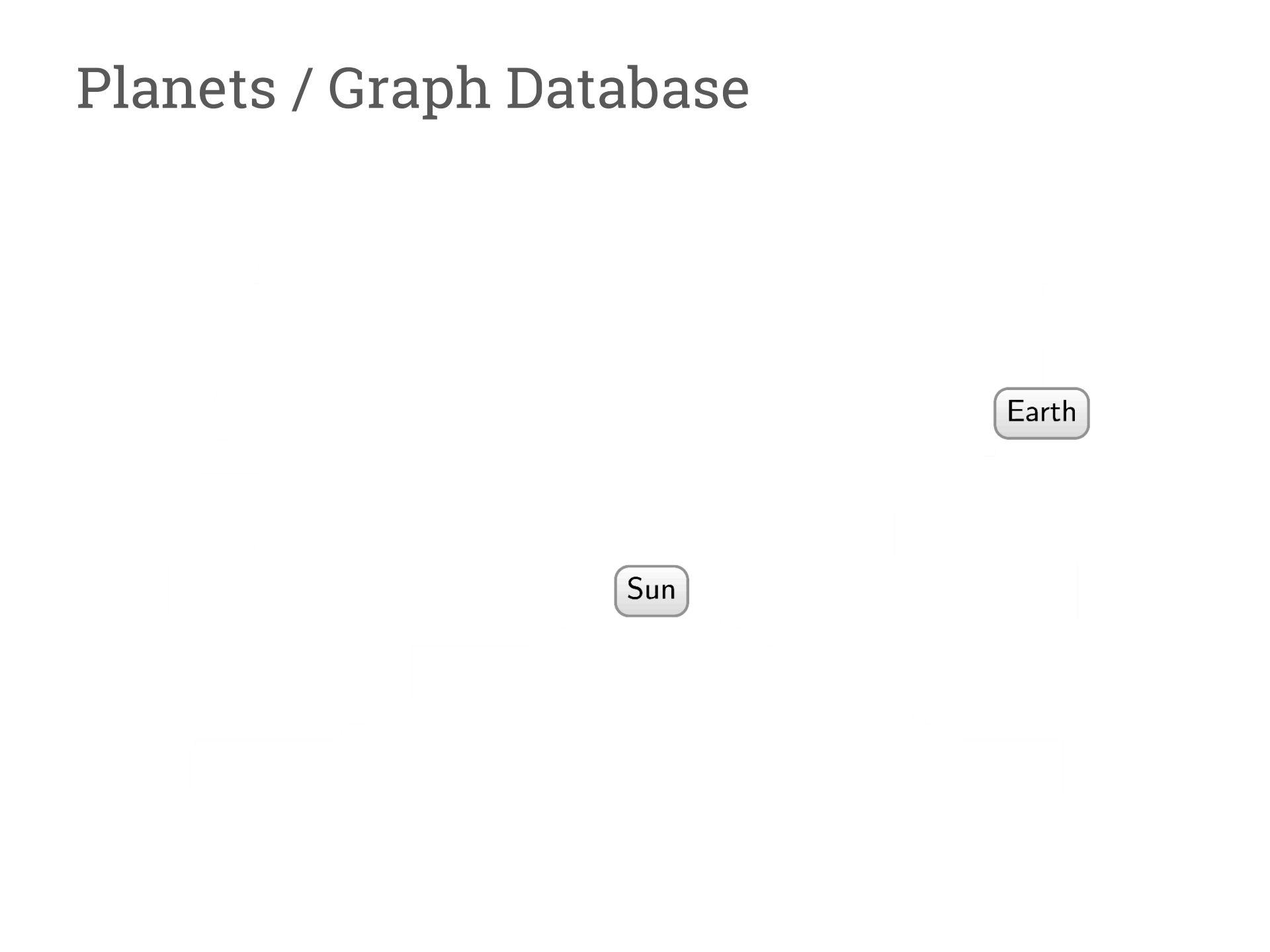
Planets / Graph Database



Planets / Graph Database

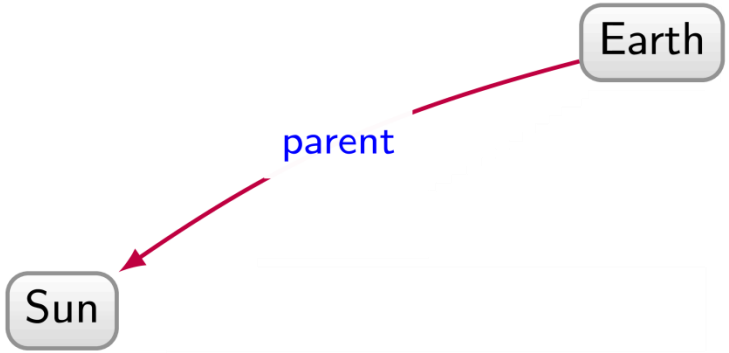


Planets / Graph Database

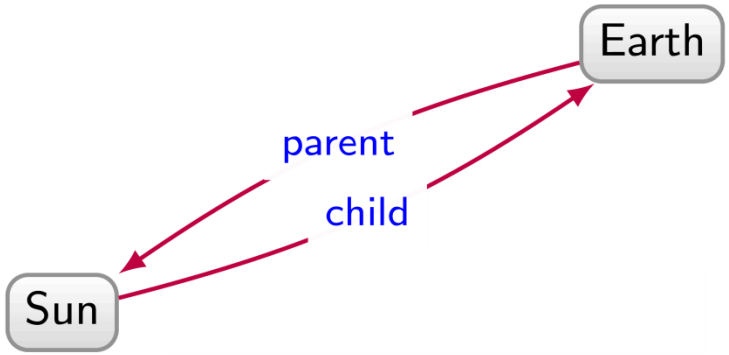


Planets / Graph Database

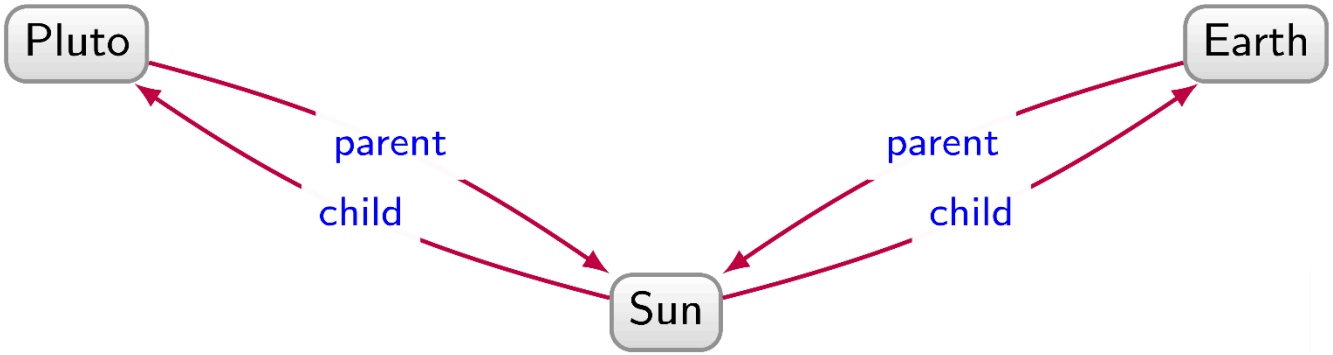
Planets / Graph Database



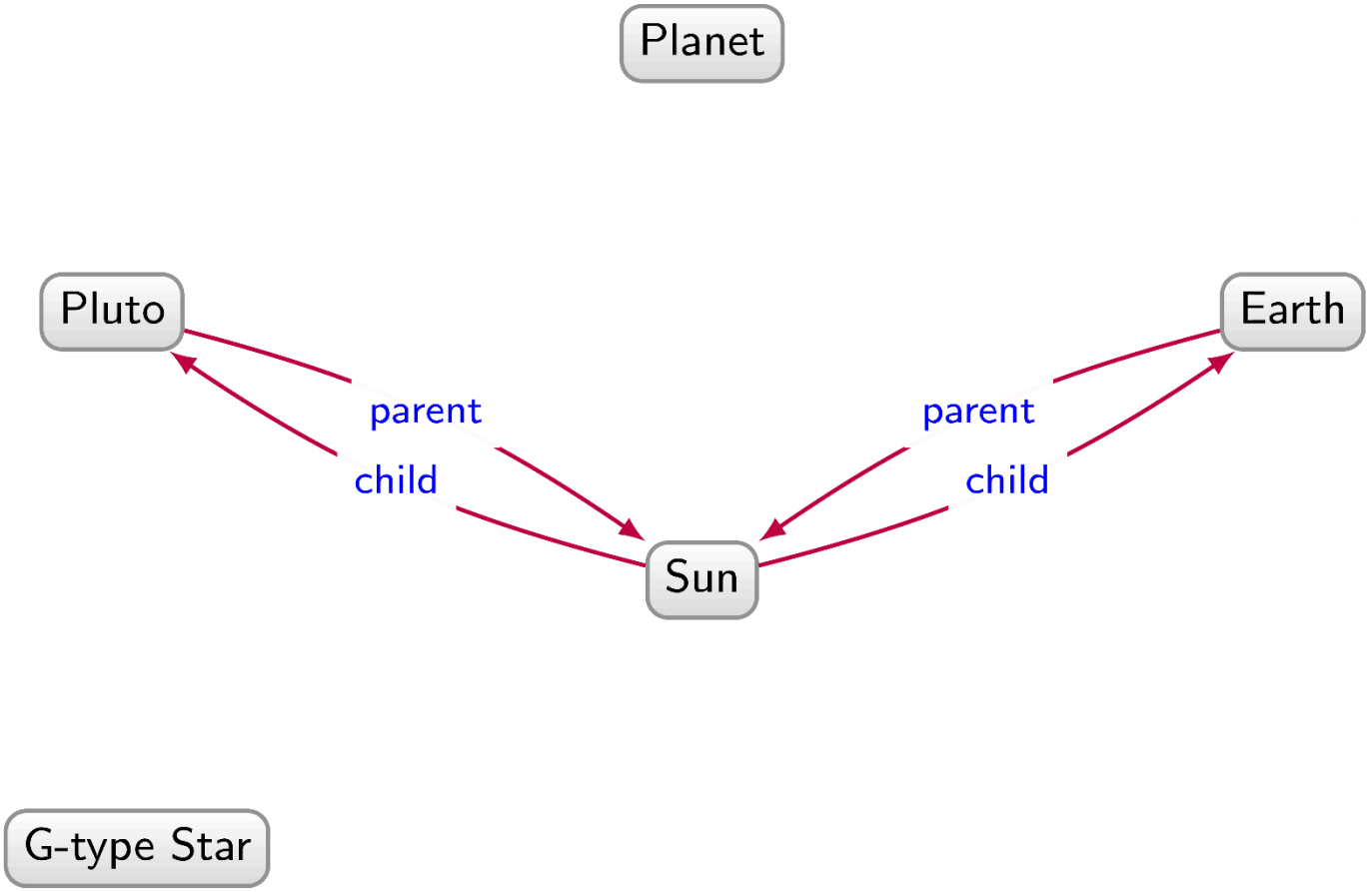
Planets / Graph Database



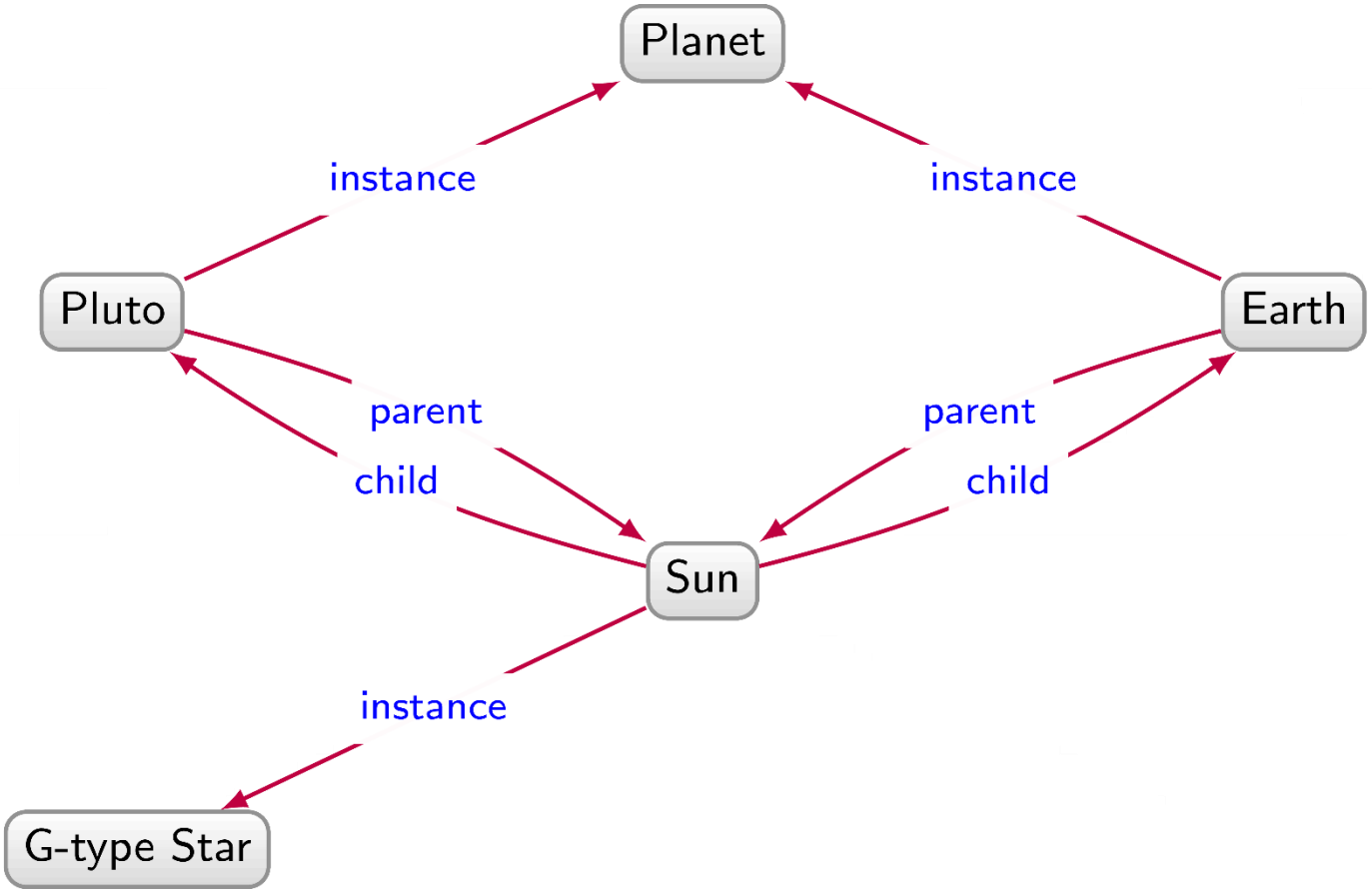
Planets / Graph Database



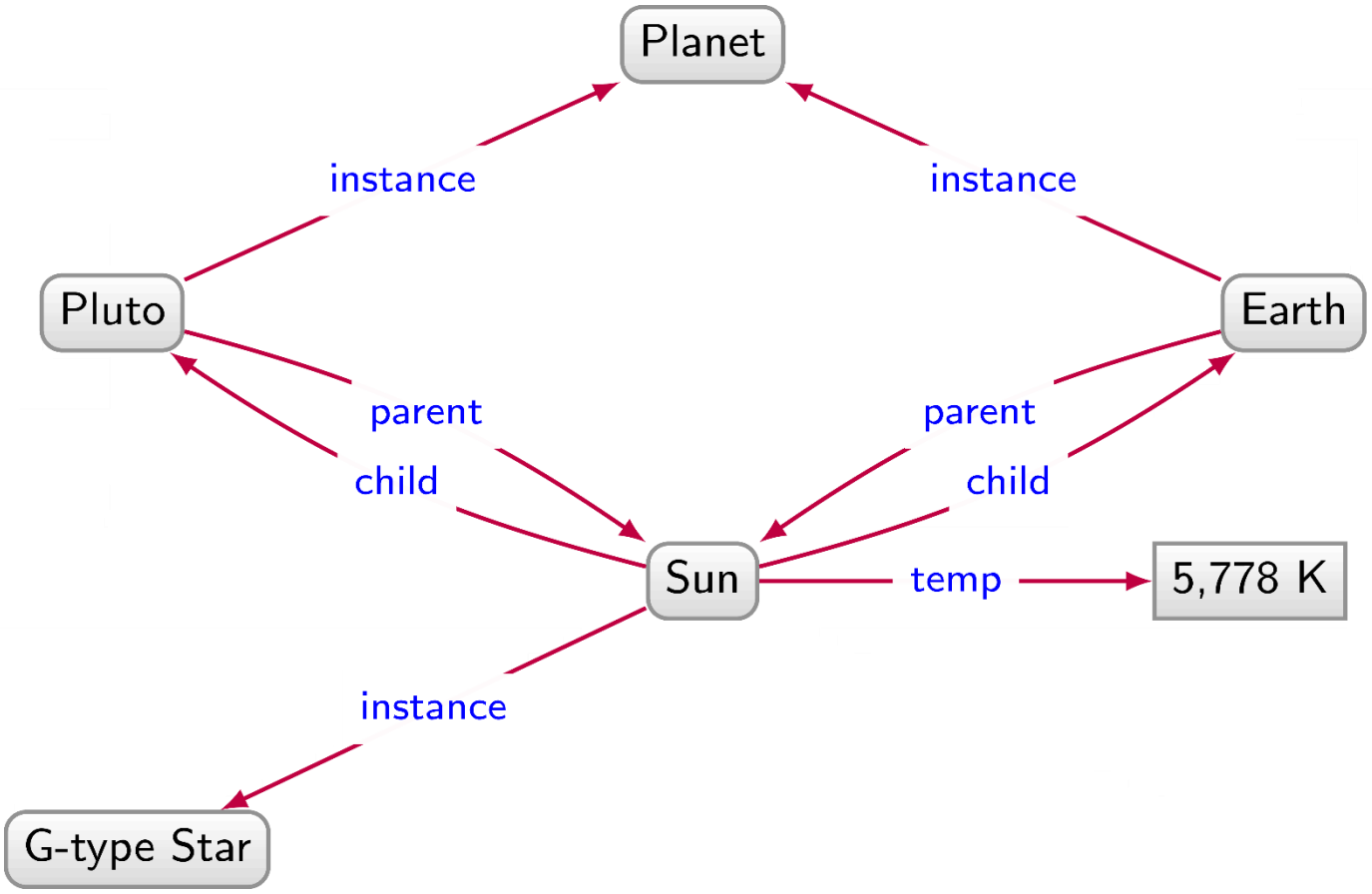
Planets / Graph Database



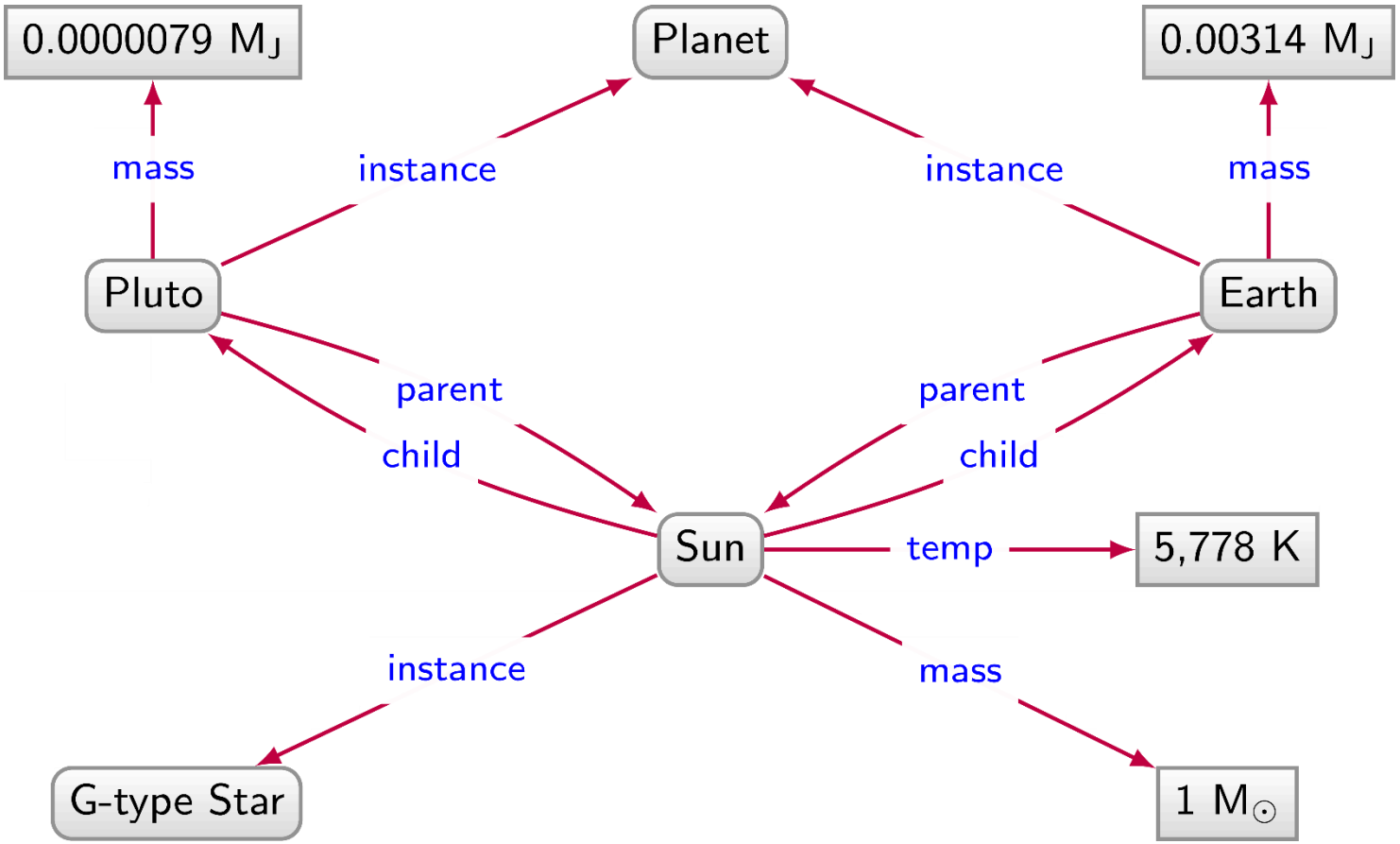
Planets / Graph Database



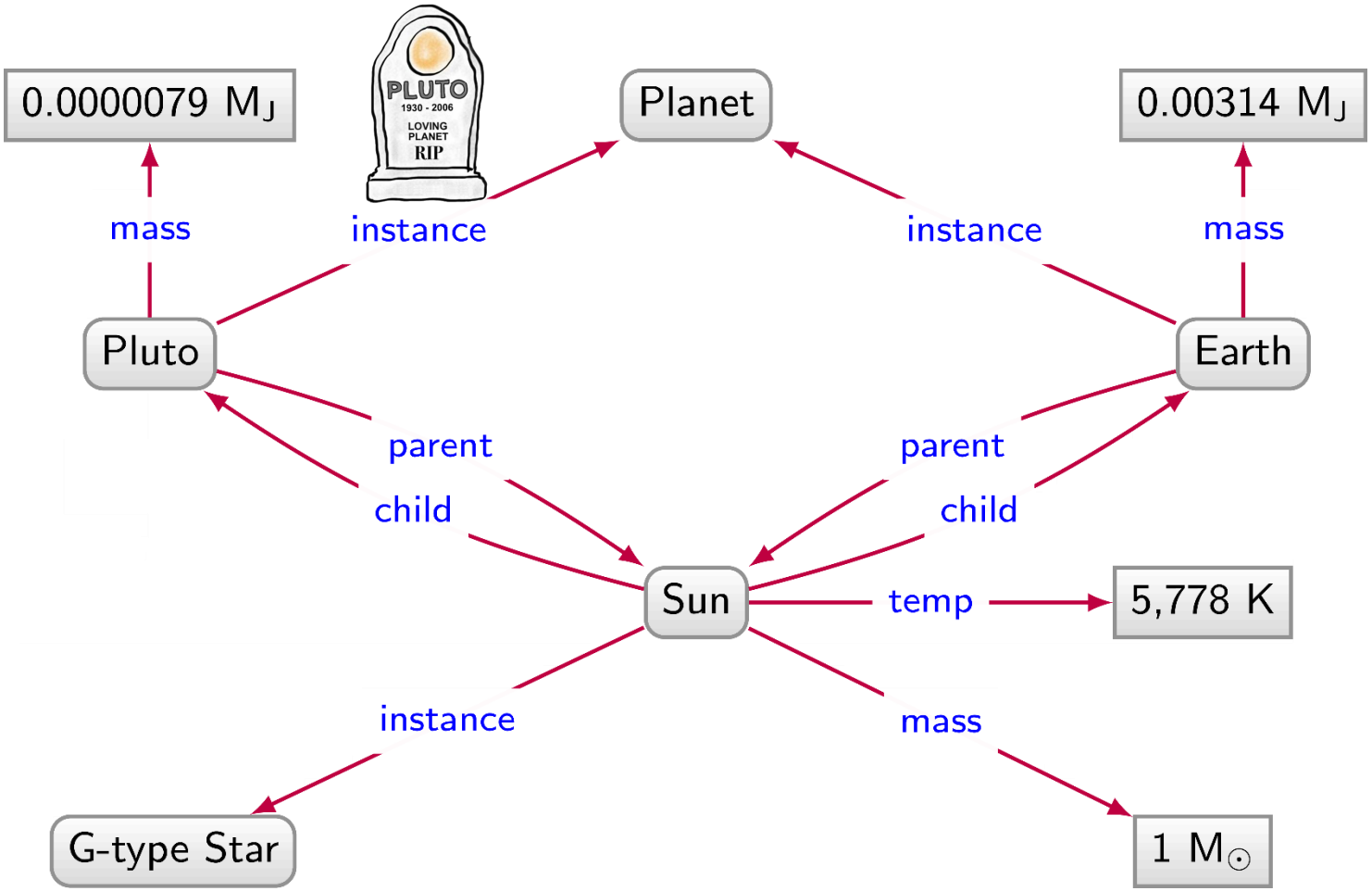
Planets / Graph Database



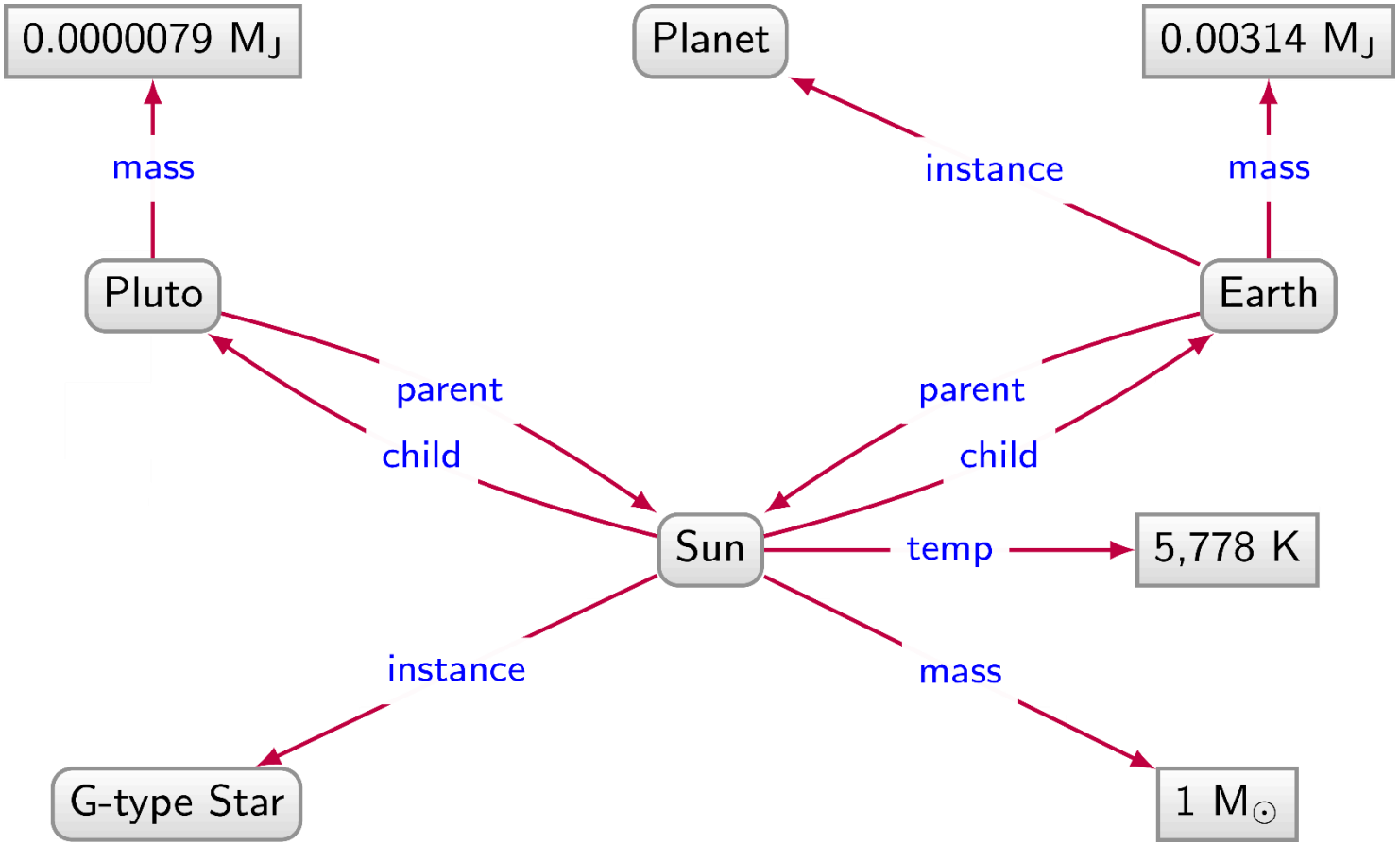
Planets / Graph Database



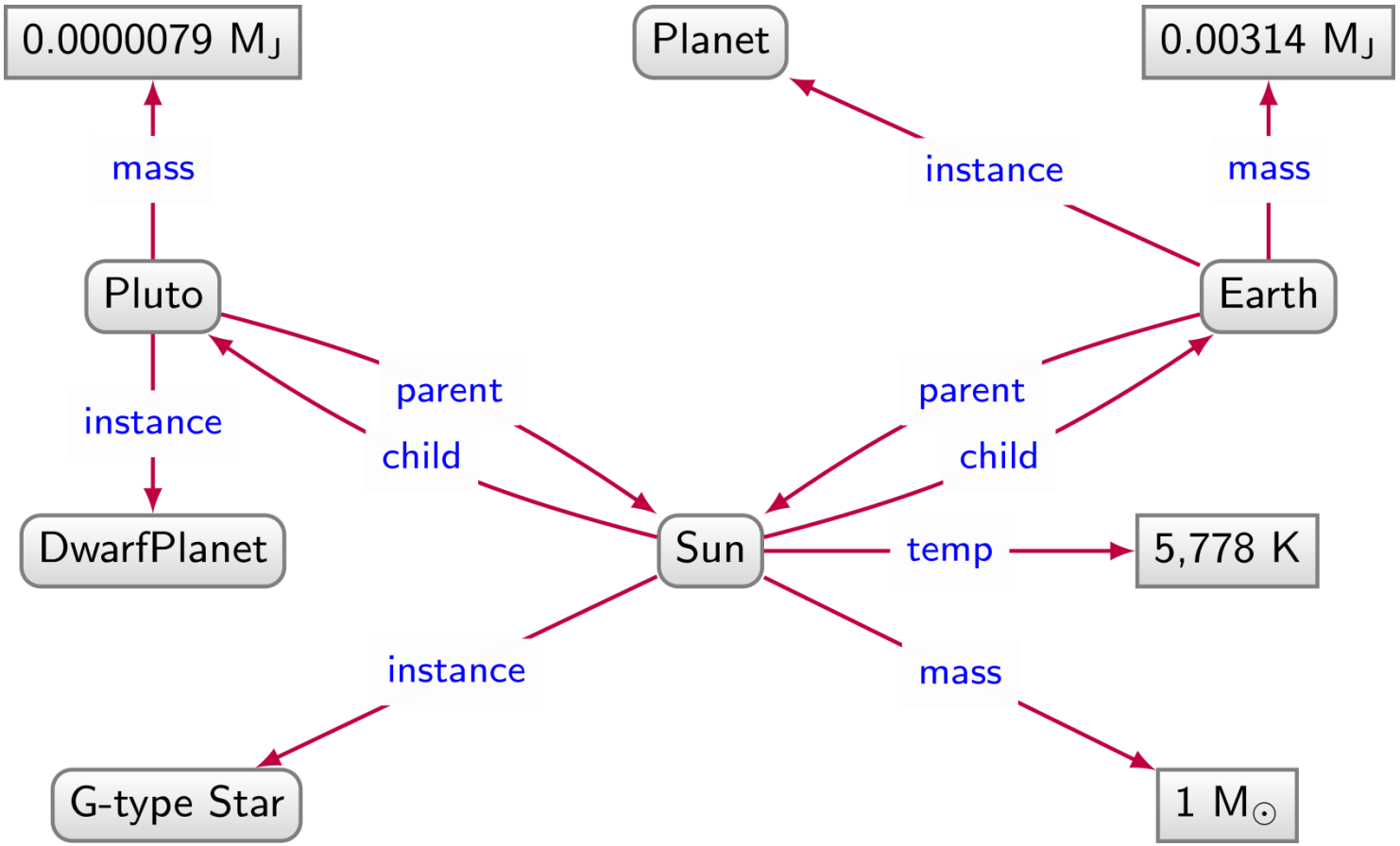
Planets / Graph Database



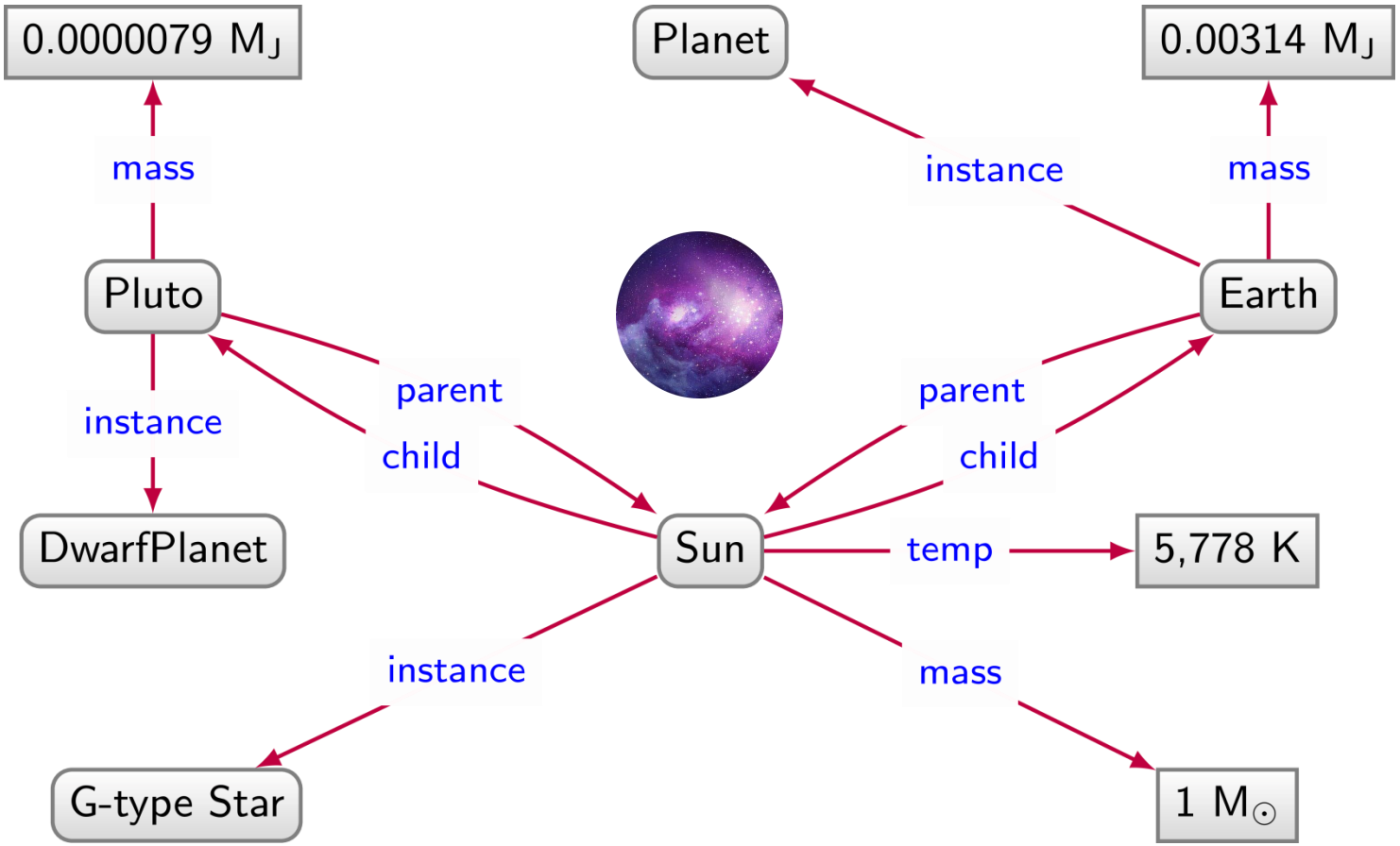
Planets / Graph Database



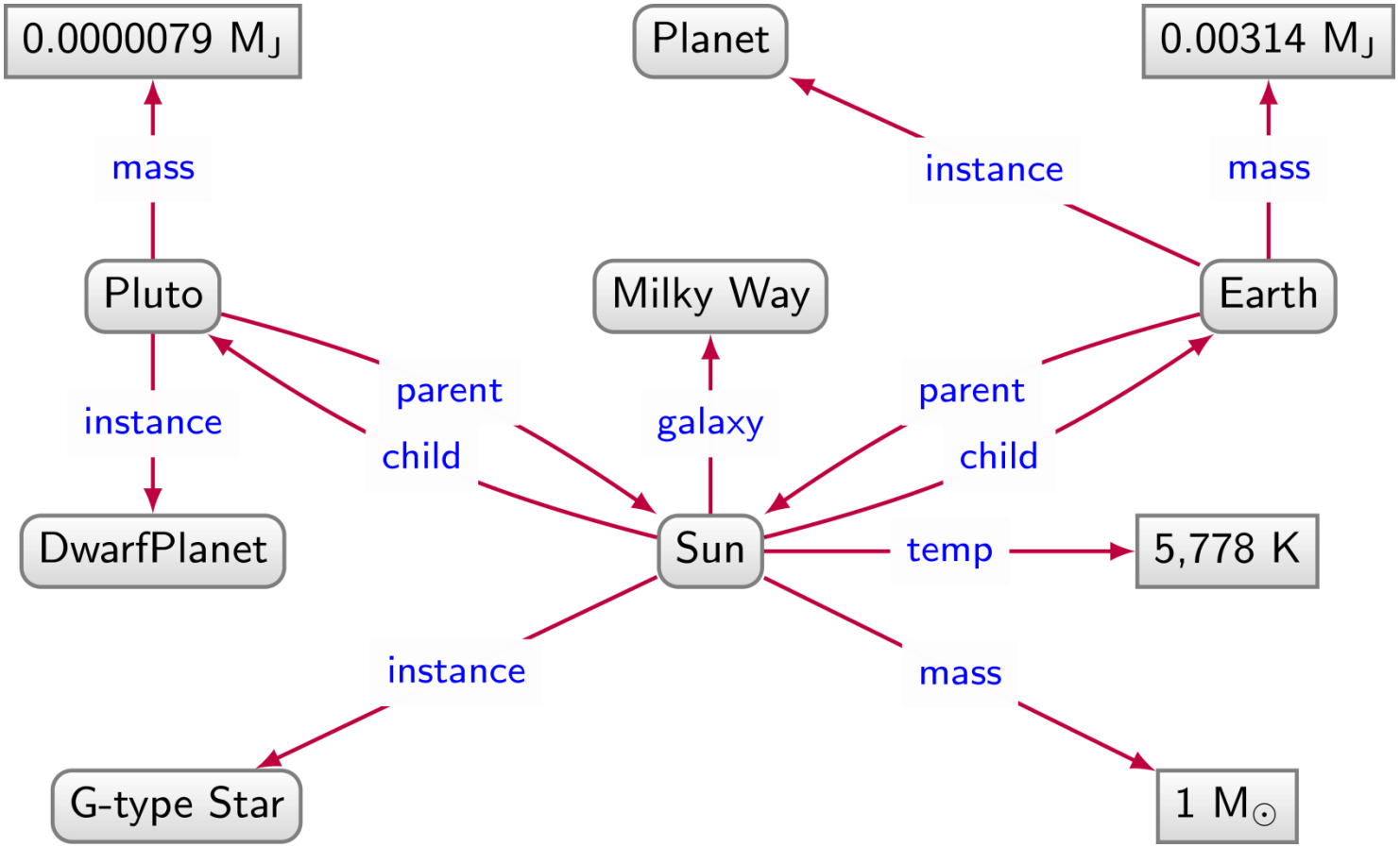
Planets / Graph Database



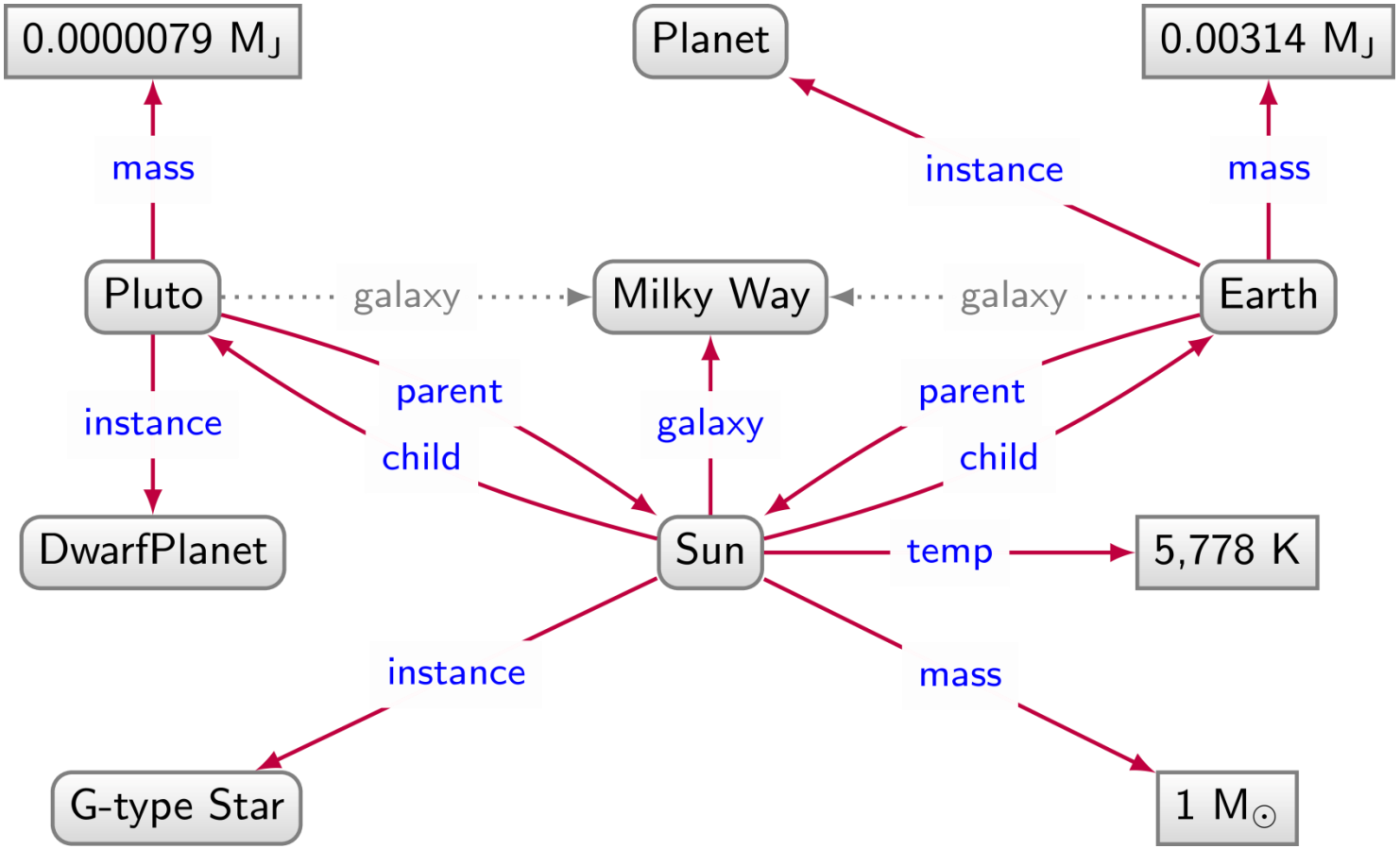
Planets / Graph Database



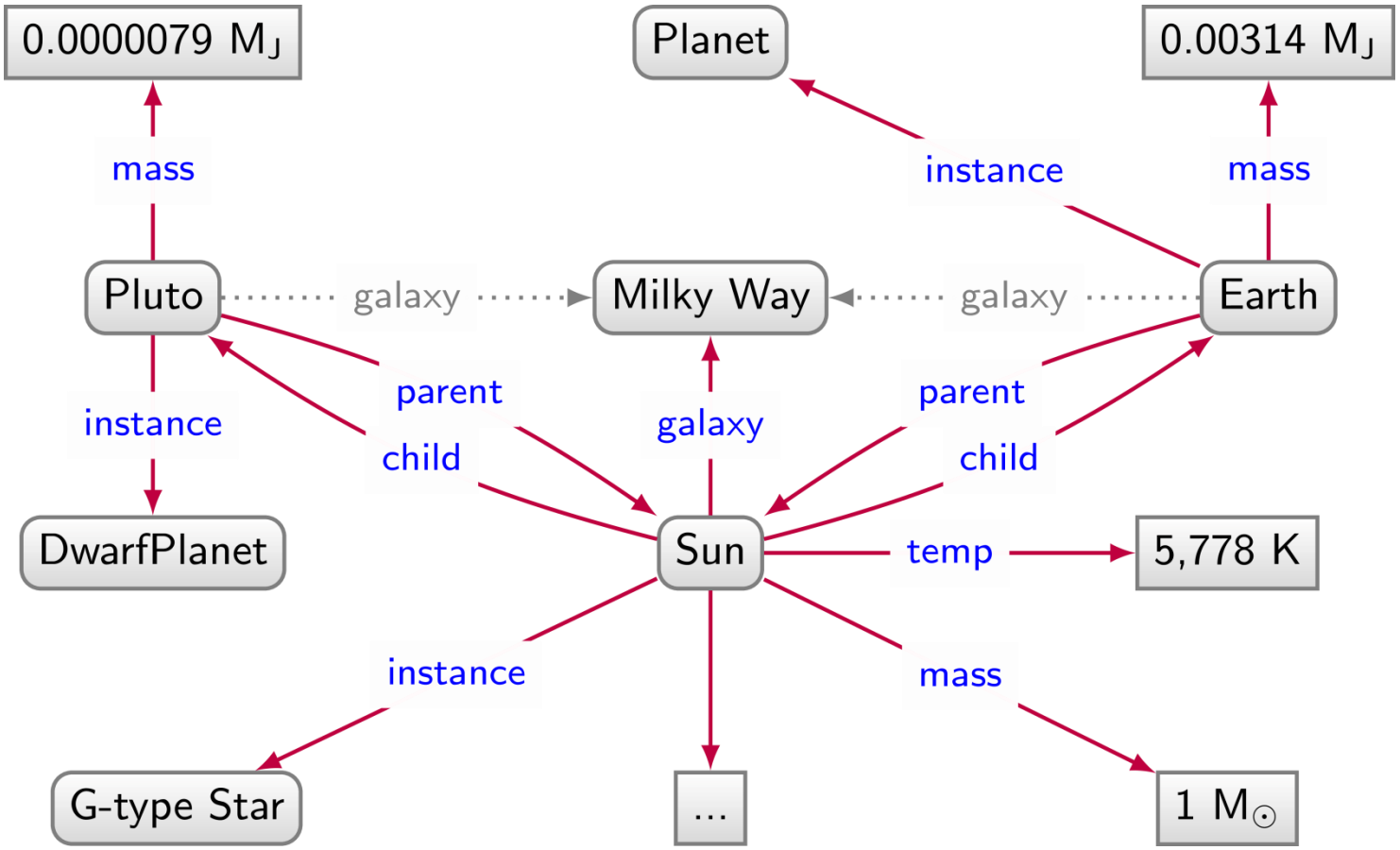
Planets / Graph Database



Planets / Graph Database



Planets / Graph Database

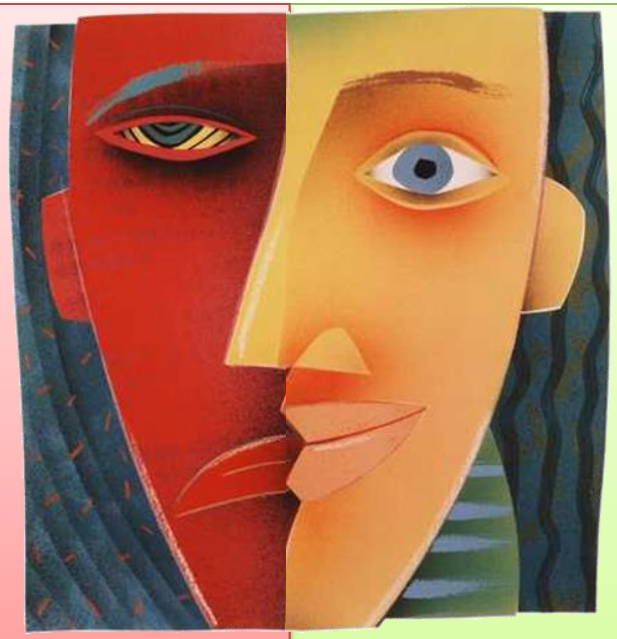


Relational databases: pros and cons

Planet

name	dist	radius	grav	days	years	temp	ring
Mercury	0.39	0.38	2.8	58.646	0.241	440	false
Venus	0.72	0.95	8.9	-243.019	0.615	730	false

We have to impose a
structure (schema)
from the start



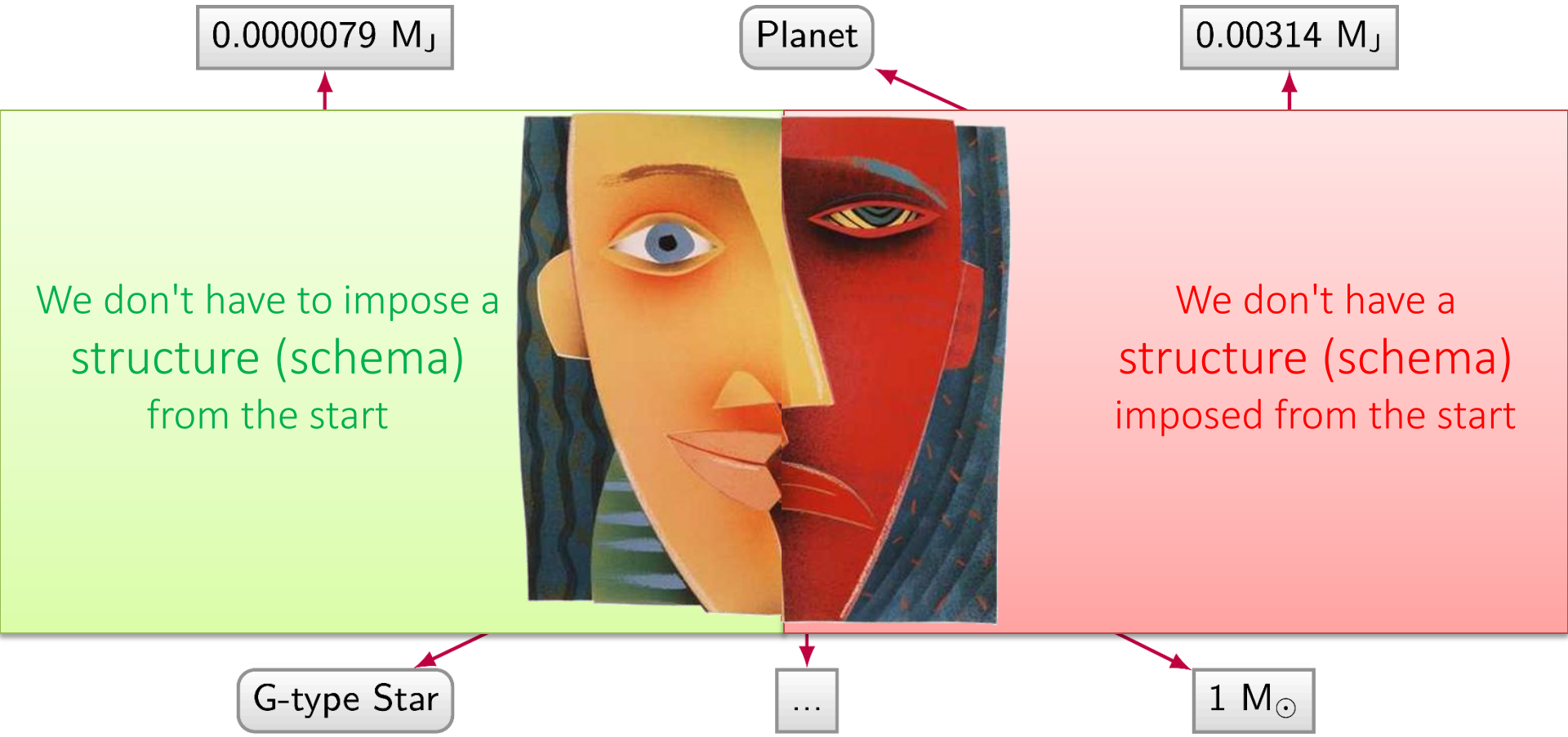
We have a
structure (schema)
imposed from the start

Europa	Jupiter
Io	Jupiter
Titan	Saturn
Triton	Neptune
Luna	Earth
Oberon	Uranus
Charon	Pluto
...	...

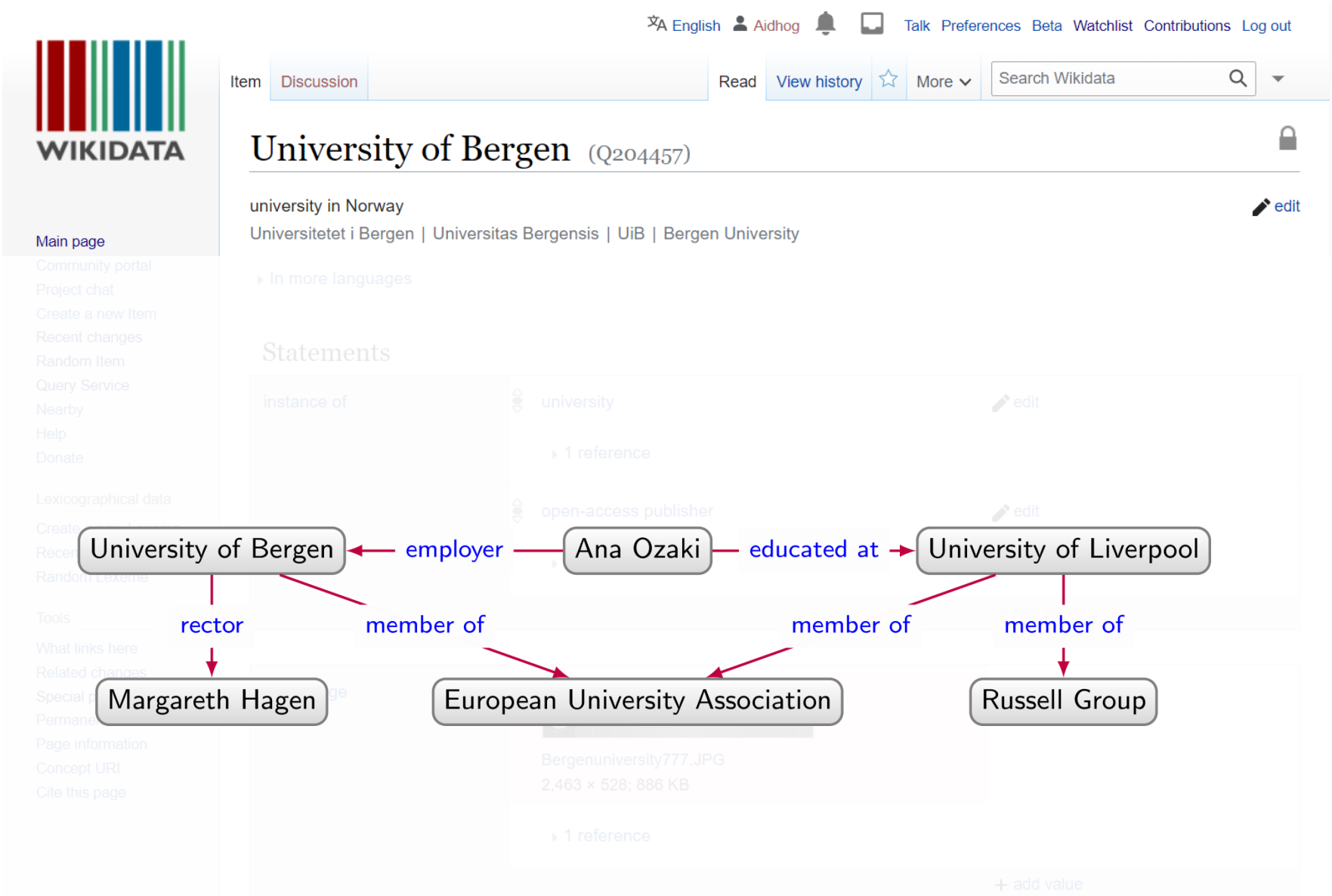
Europa	Galileo Galilei
Io	Galileo Galilei
Titan	Christiaan Huygens
Triton	William Lassell
Oberon	William Herschel
...	...

Europa	1610
Io	1610
Titan	1655
Triton	1846
Oberon	1787
Charon	1978
...	...

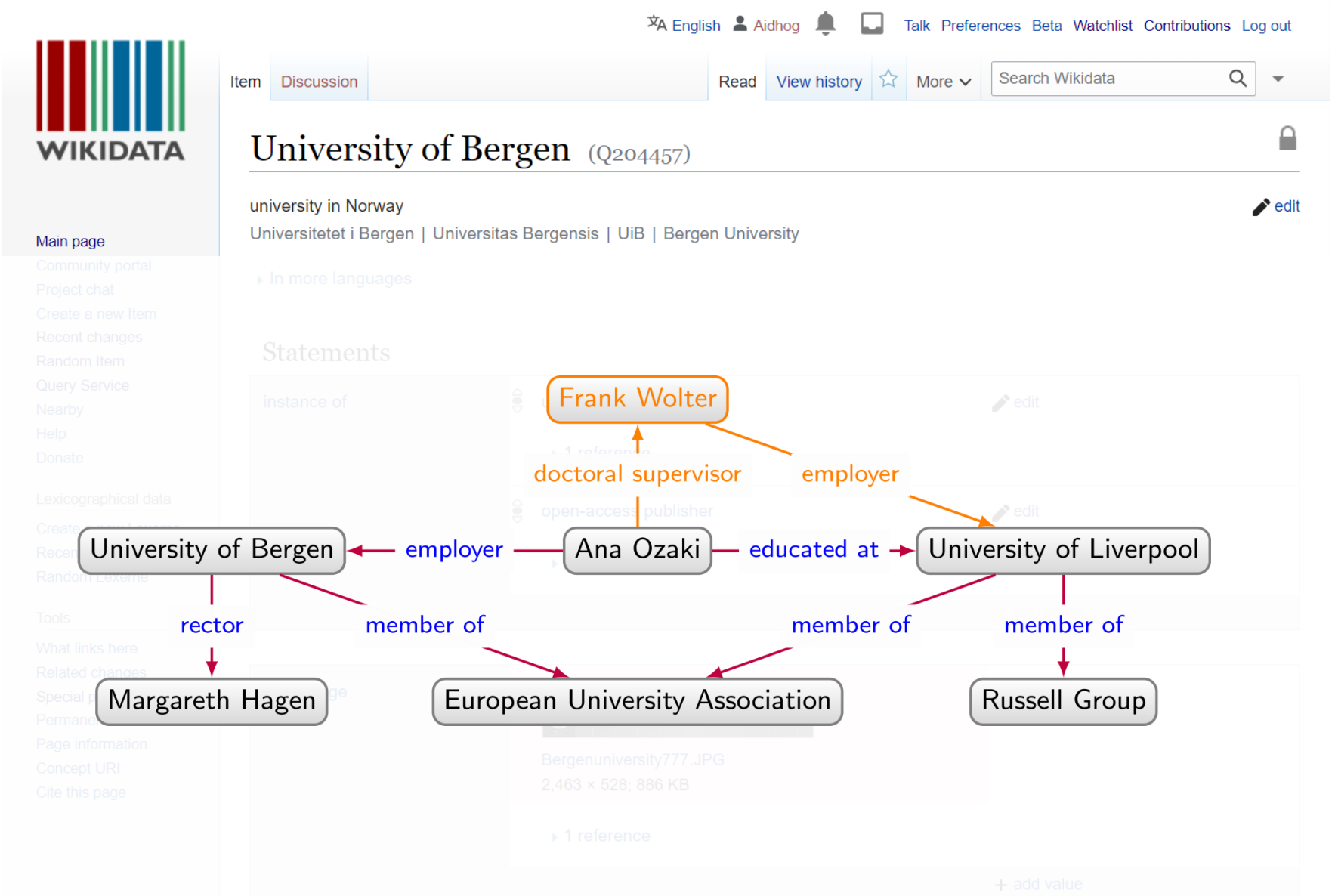
Graph databases: pros and cons



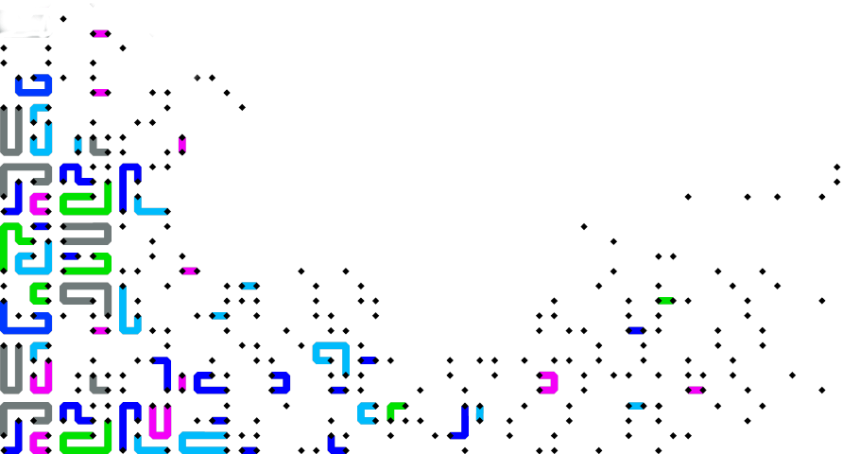
Let's see this on Wikidata …



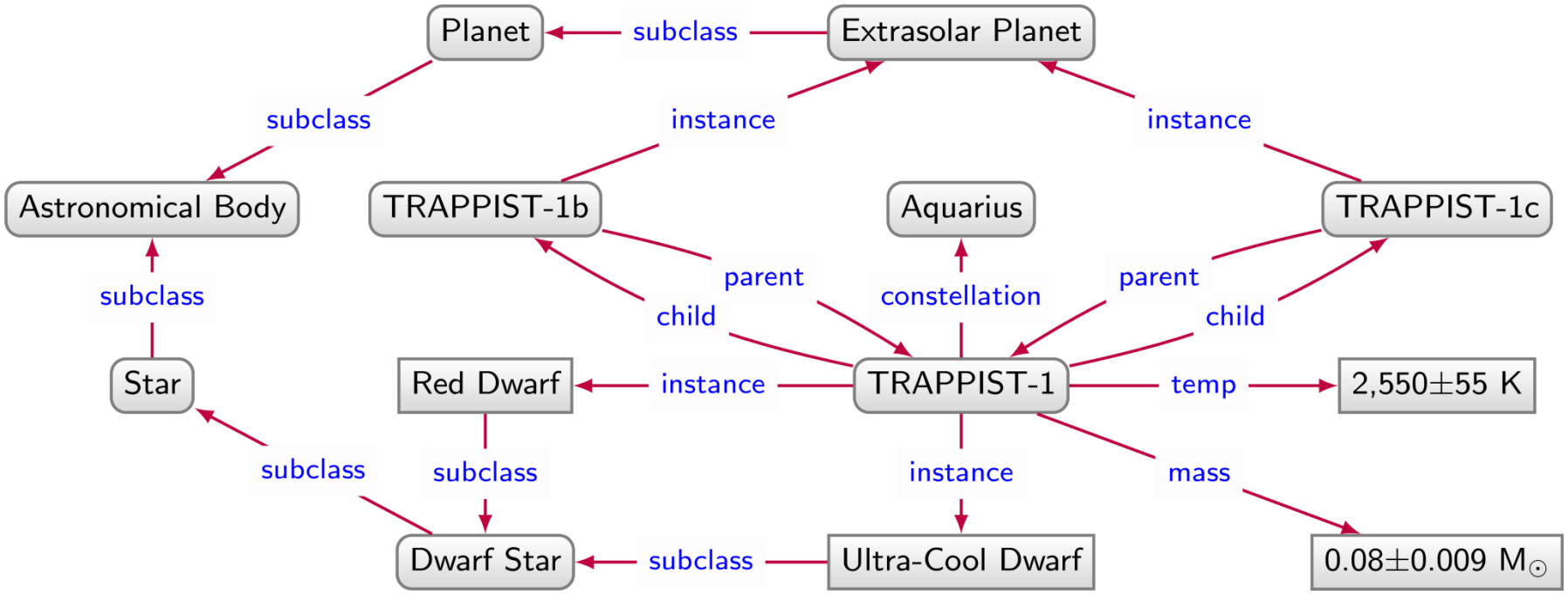
Let's see this on Wikidata …



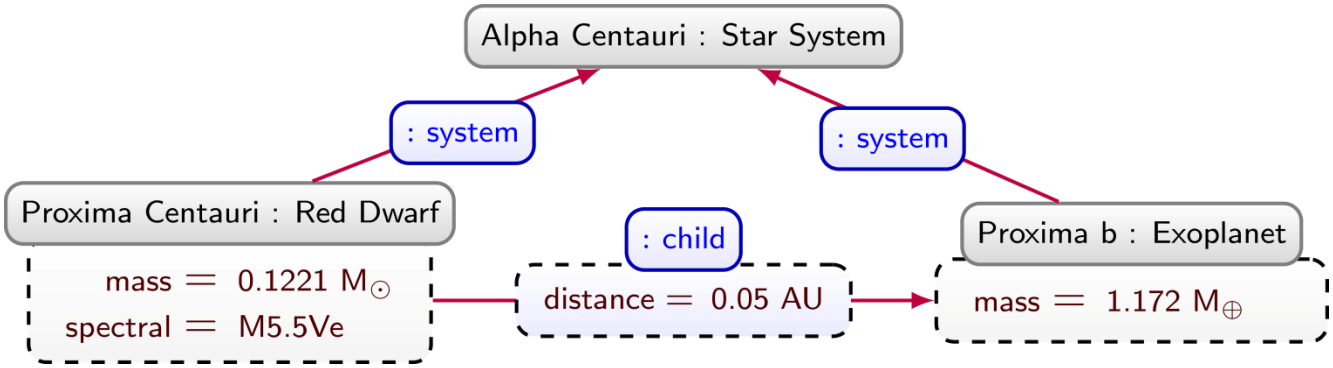
Graph models



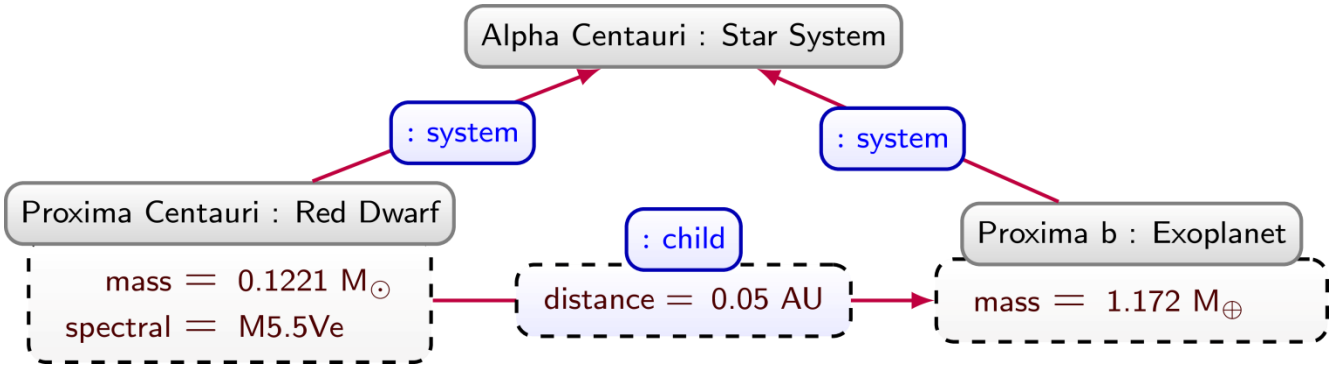
Directed edge-labelled graph (del graph)

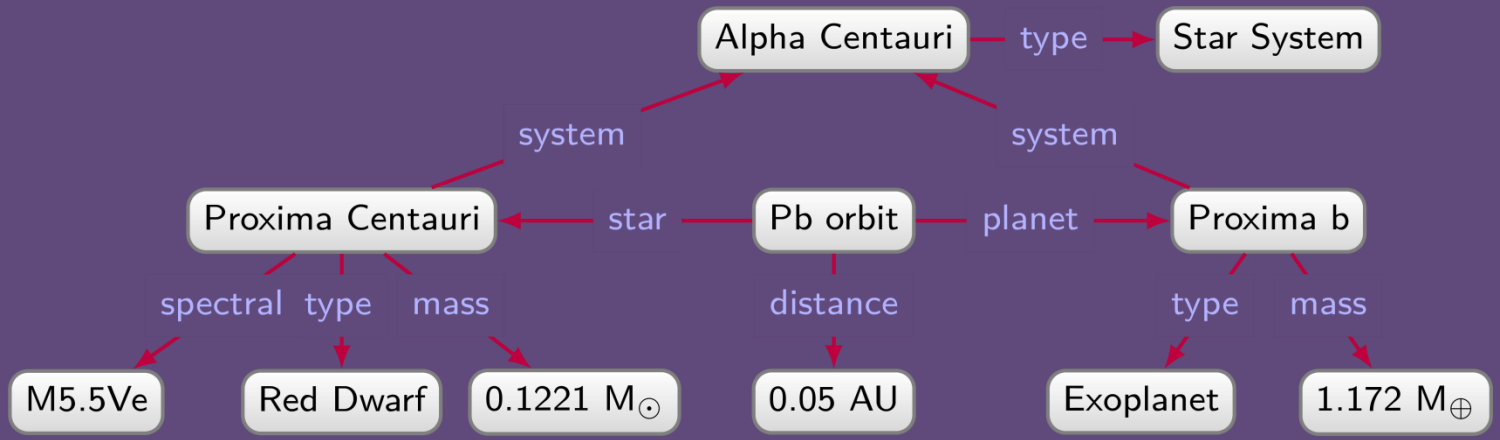


Property graph

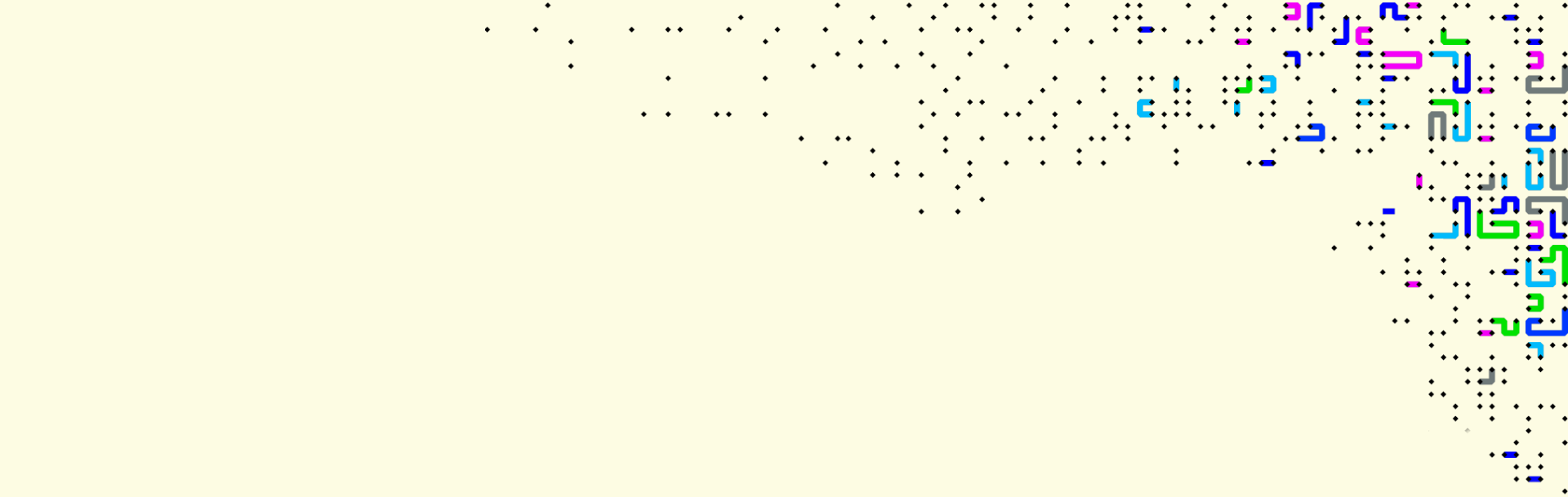


Property graph

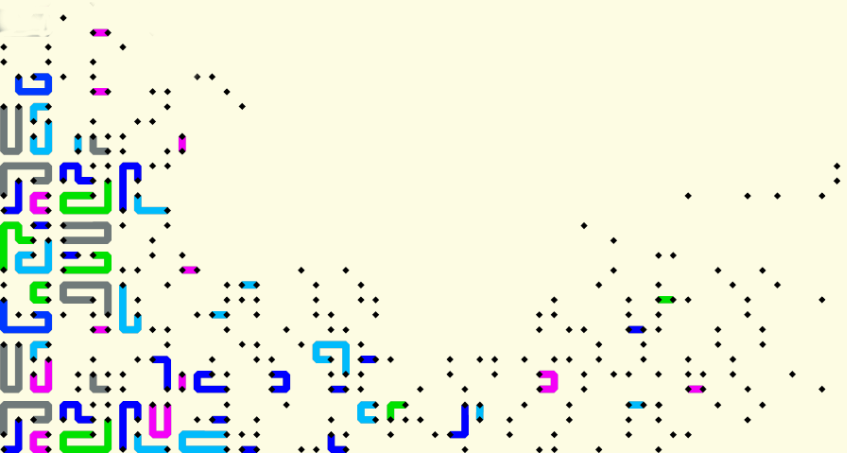




Del graph

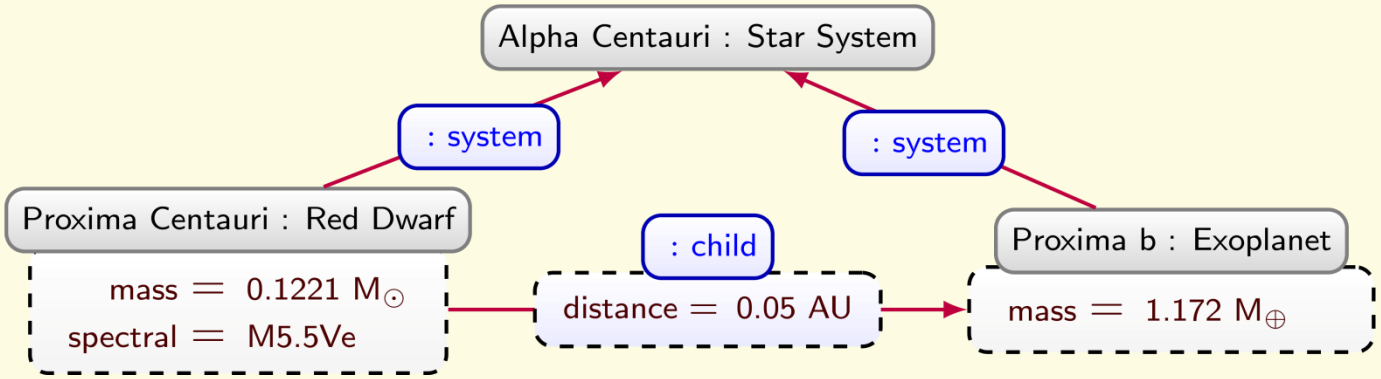


Topic 1:
Property Graph Semantics



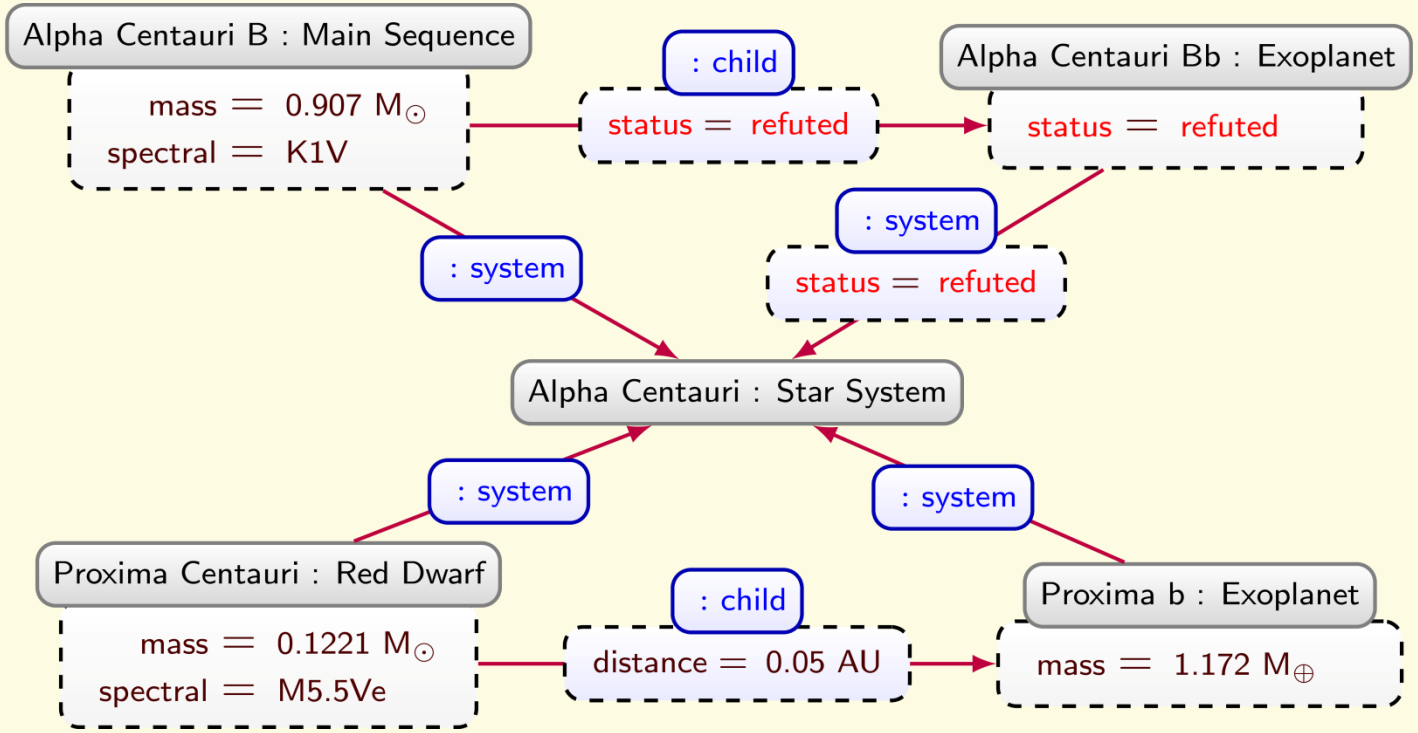
Property graph semantics

How should we define the semantics of property graphs?

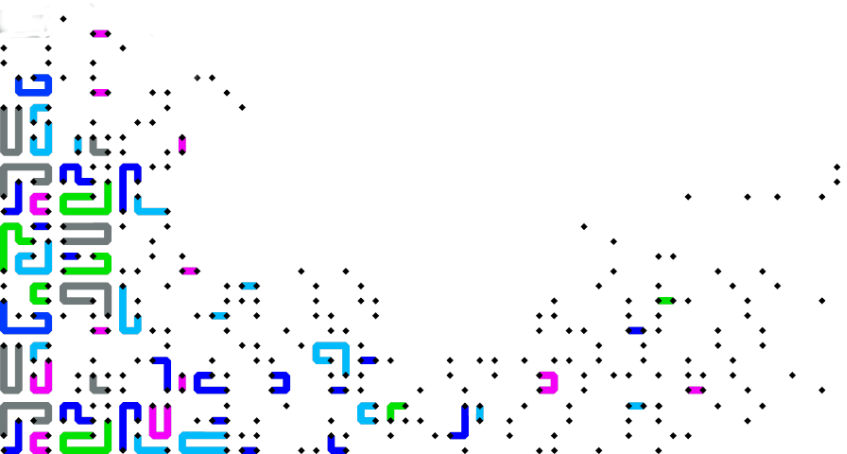


Property graph semantics

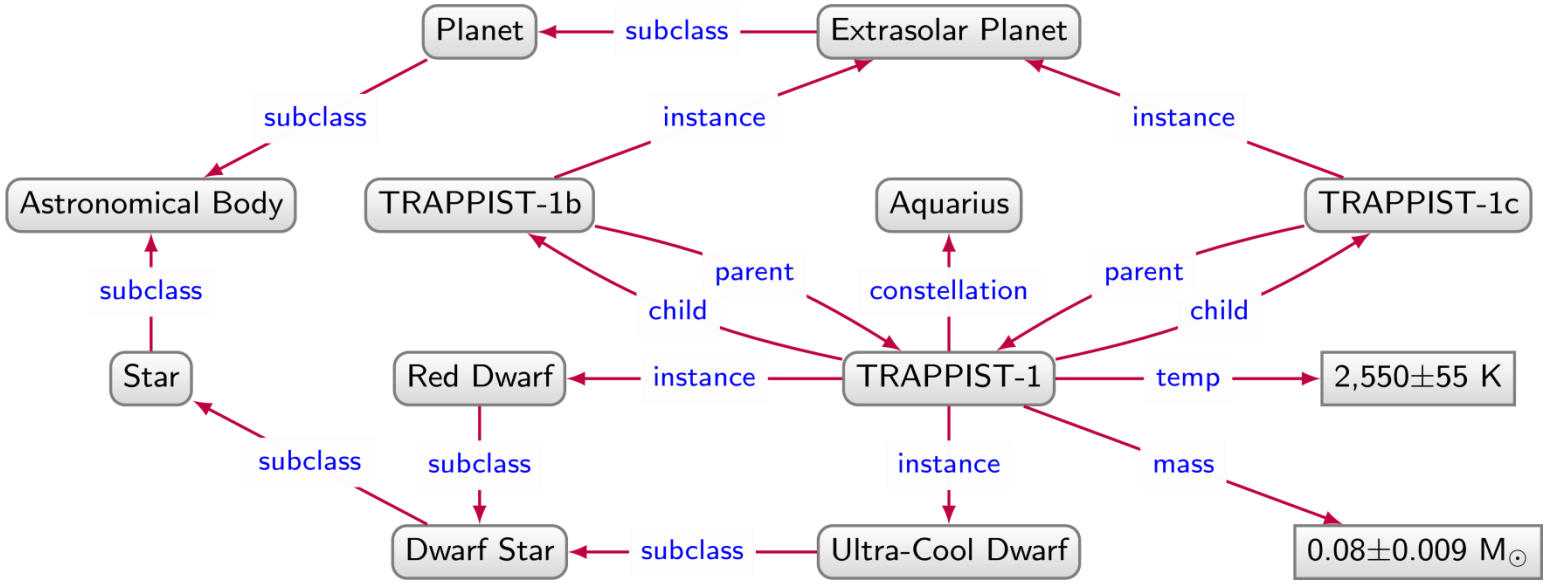
How should we define the semantics of property graphs?



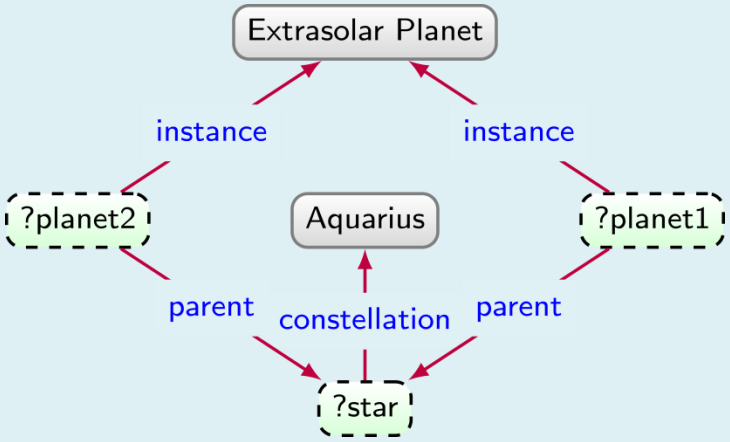
Graph Queries



Graph patterns



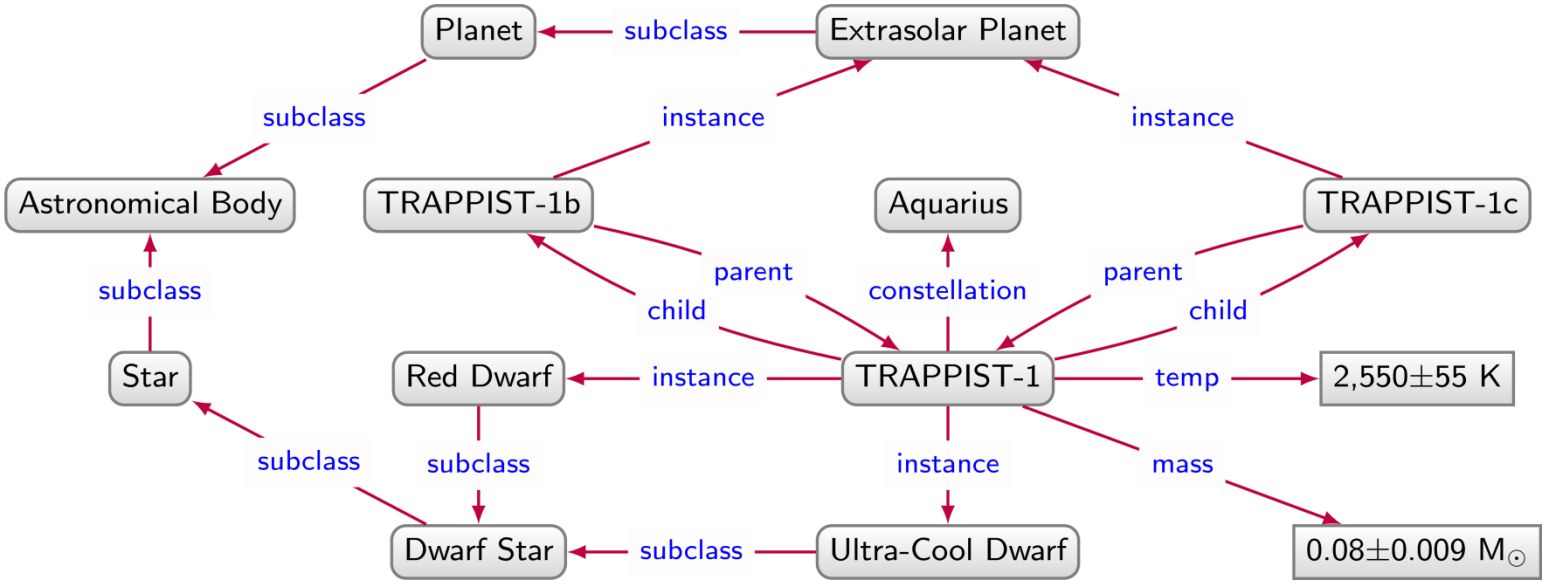
Find pairs of exoplanets orbiting the same star in Aquarius?



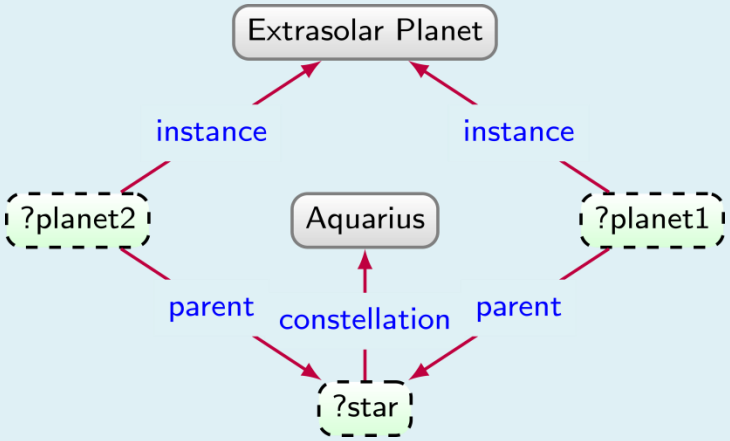
Semantics: Homomorphism

?star	?planet1	?planet2
TRAPPIST-1	TRAPPIST-1b	TRAPPIST-1c
TRAPPIST-1	TRAPPIST-1b	TRAPPIST-1b
TRAPPIST-1	TRAPPIST-1c	TRAPPIST-1b
TRAPPIST-1	TRAPPIST-1c	TRAPPIST-1c

Graph patterns



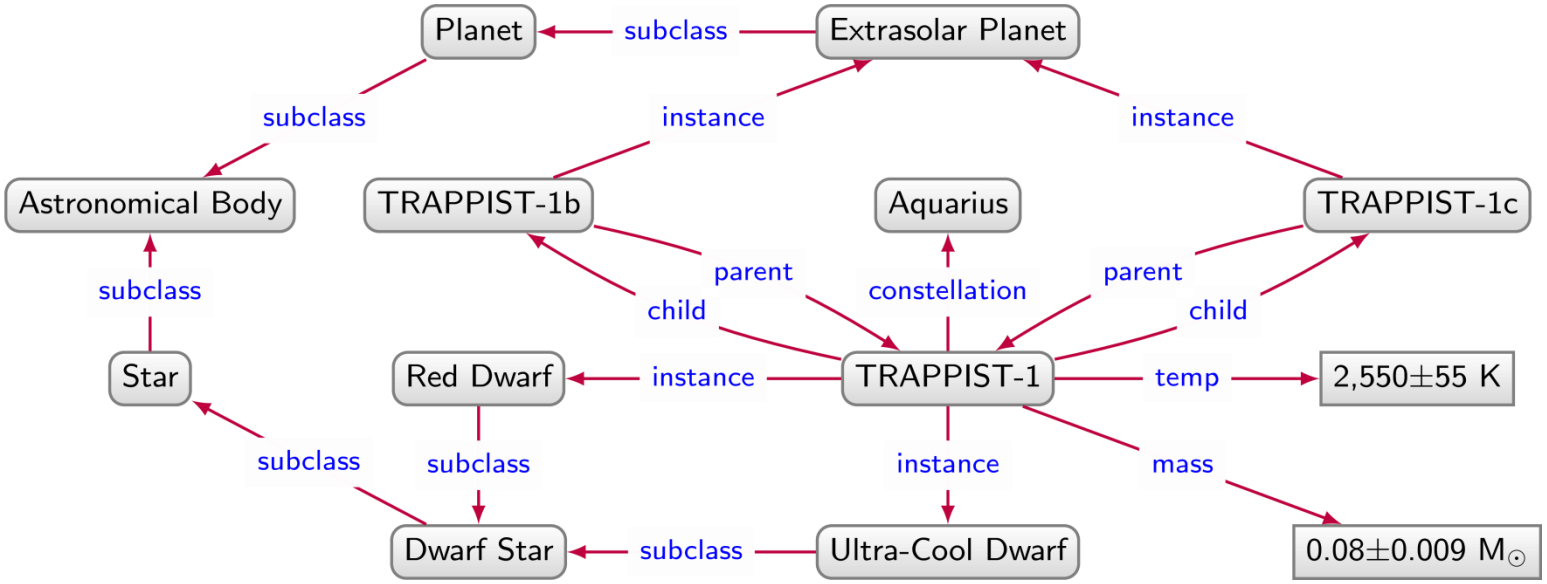
Find pairs of exoplanets orbiting the same star in Aquarius?



Semantics: Isomorphism

?star	?planet1	?planet2
TRAPPIST-1	TRAPPIST-1b	TRAPPIST-1c
TRAPPIST-1	TRAPPIST-1b	TRAPPIST-1b
TRAPPIST-1	TRAPPIST-1c	TRAPPIST-1b
TRAPPIST-1	TRAPPIST-1c	TRAPPIST-1c

Complex graph patterns



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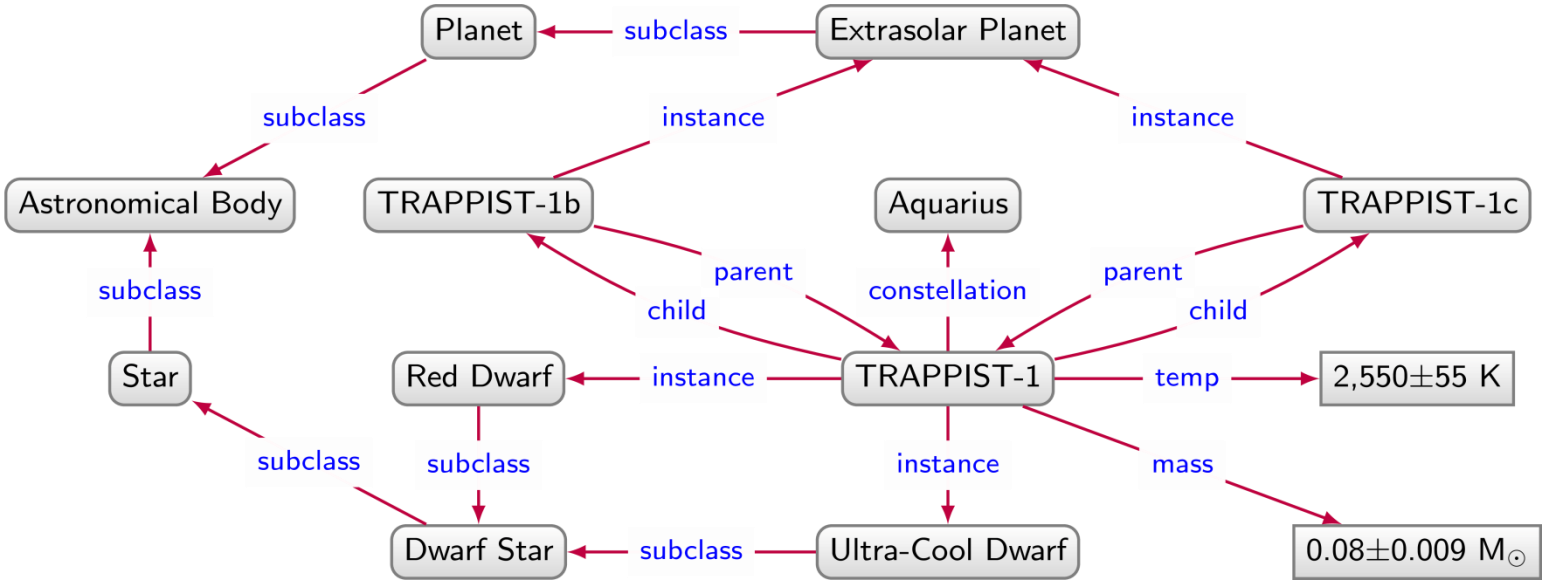
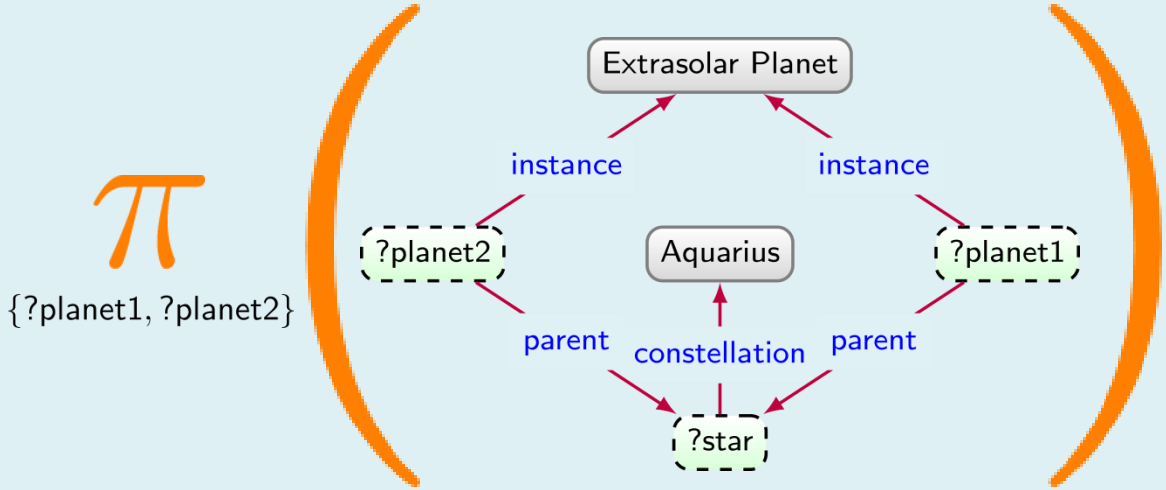
Graph Patterns + Relational Algebra

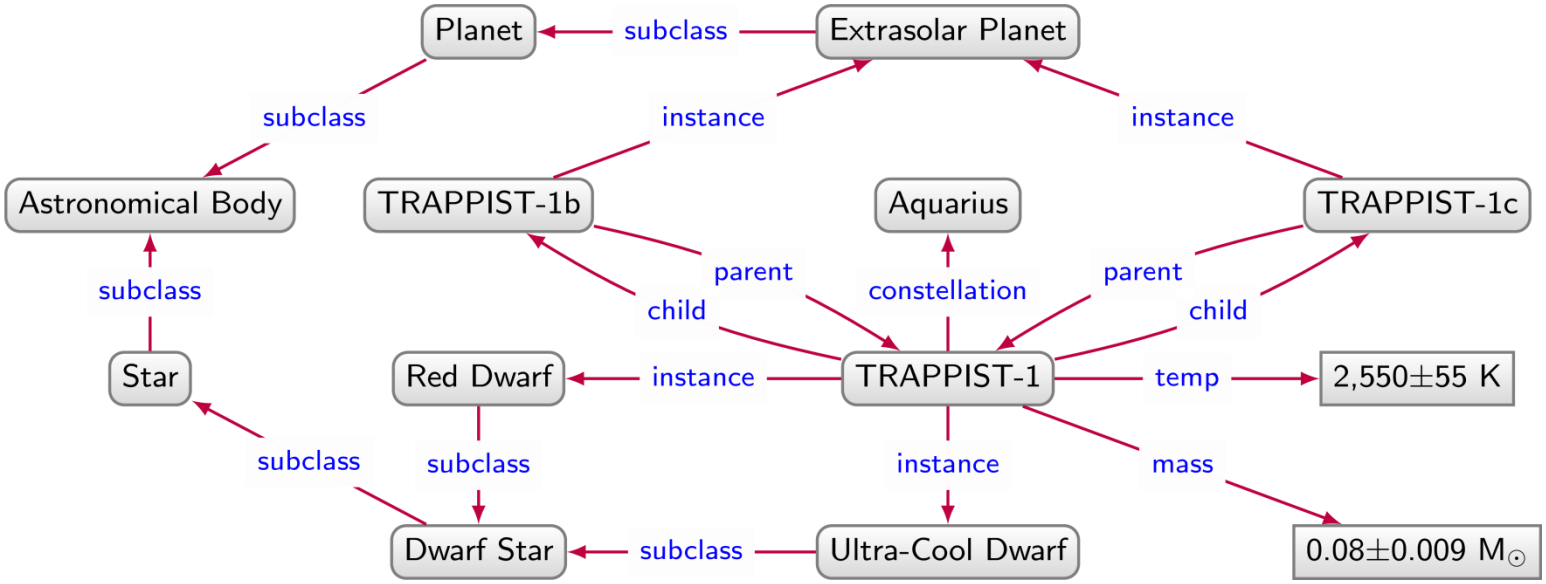
Complex graph patterns



Find pairs of exoplanets orbiting the same star in Aquarius?



Complex graph patterns



Find pairs of exoplanets orbiting the same star in Aquarius?

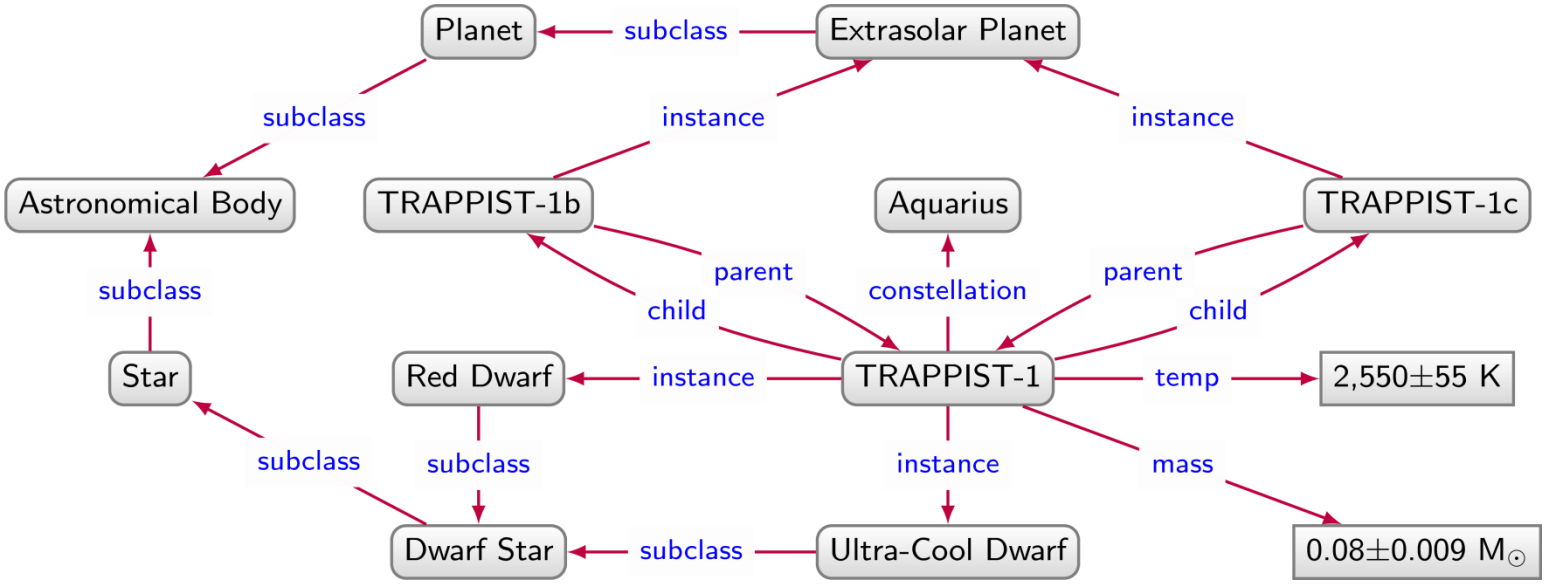
$$\pi_{\{?planet1,\ ?planet2\}}$$

?star	?planet1	?planet2
TRAPPIST-1	TRAPPIST-1b	TRAPPIST-1c
TRAPPIST-1	TRAPPIST-1b	TRAPPIST-1b
TRAPPIST-1	TRAPPIST-1c	TRAPPIST-1b
TRAPPIST-1	TRAPPIST-1c	TRAPPIST-1c

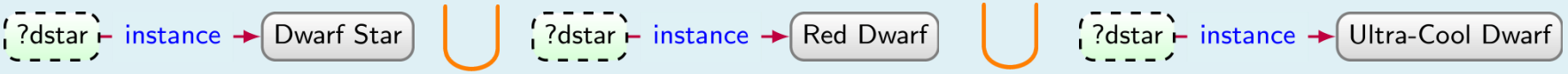
=

?planet1	?planet2
TRAPPIST-1b	TRAPPIST-1c
TRAPPIST-1b	TRAPPIST-1b
TRAPPIST-1c	TRAPPIST-1b
TRAPPIST-1c	TRAPPIST-1c

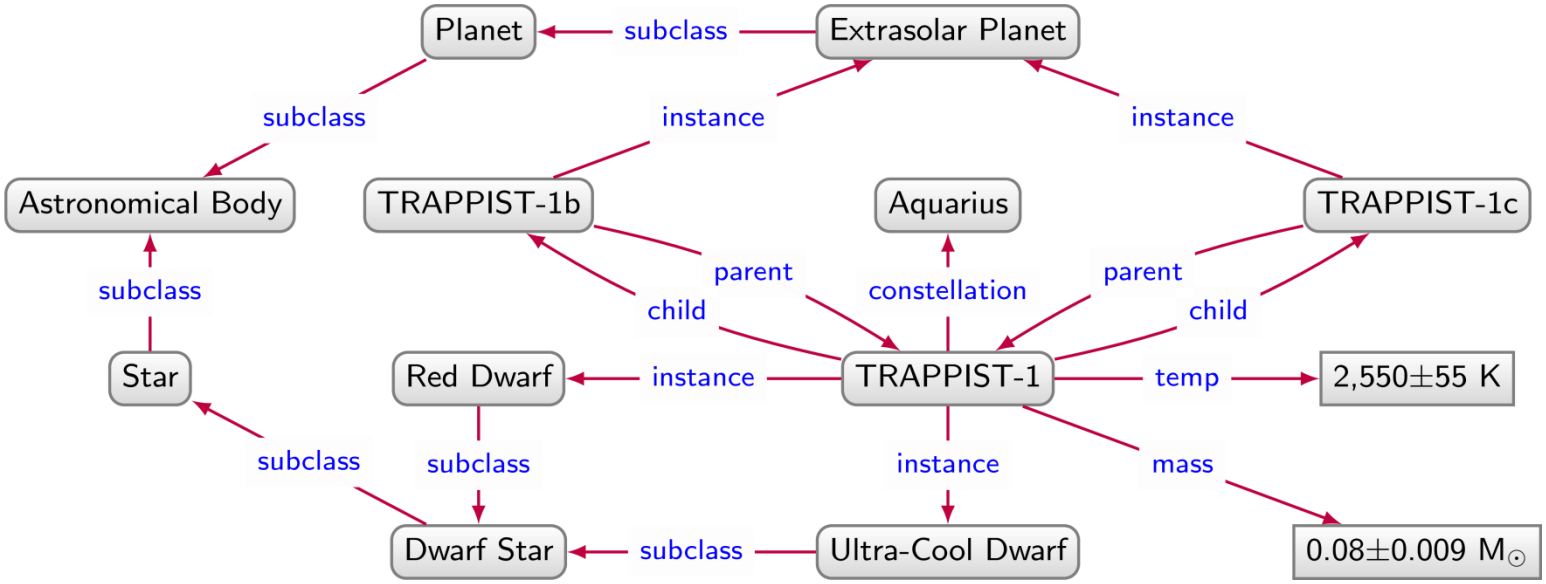
Complex graph patterns



Find instances of Dwarf Star?



Complex graph patterns



Find instances of Dwarf Star?

?dtar

∪

?dtar
TRAPPIST-1

∪

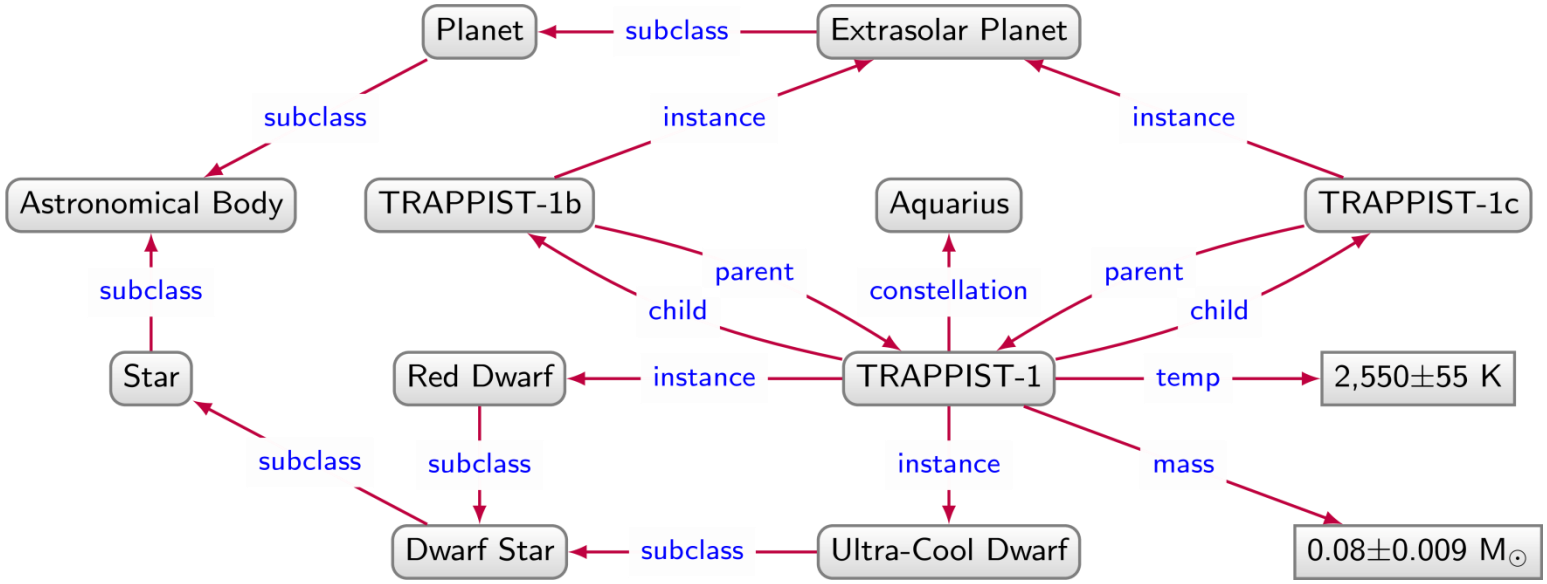
?dtar
TRAPPIST-1

=

?dtar
TRAPPIST-1
TRAPPIST-1

Semantics: Bag

Complex graph patterns



Find instances of Dwarf Star?

?dtar

∪

?dtar
TRAPPIST-1

∪

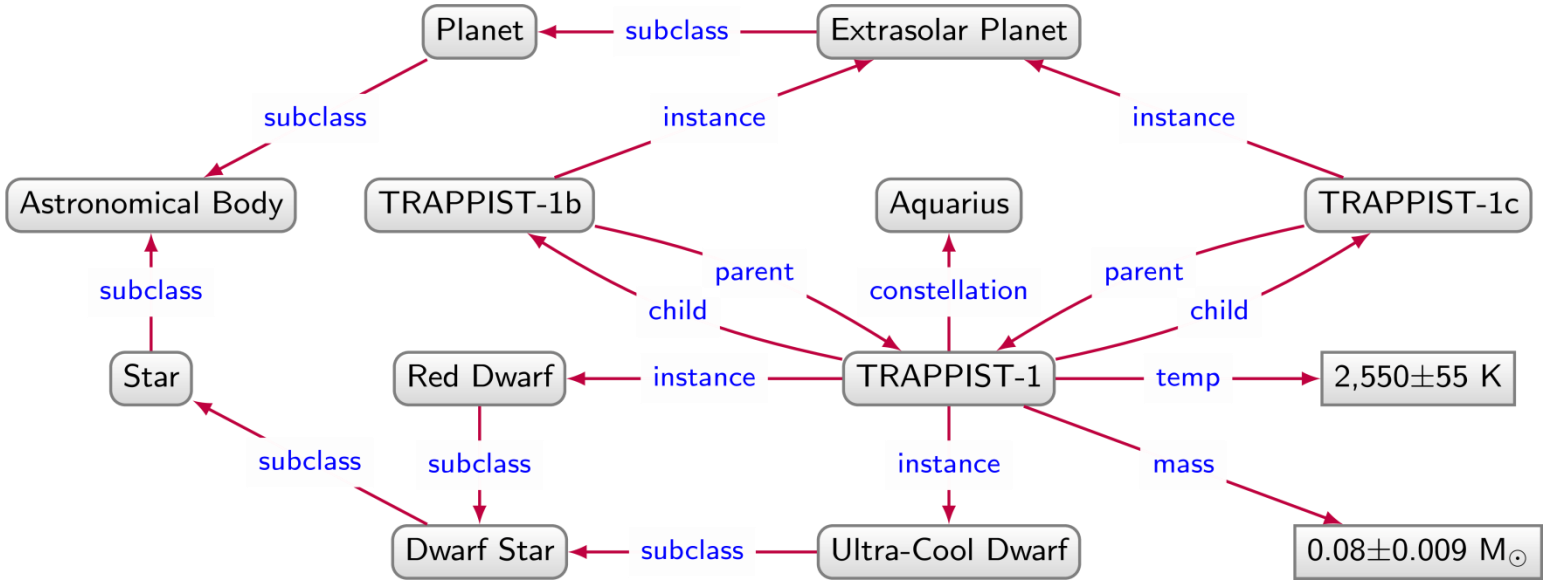
?dtar
TRAPPIST-1

=

?dtar
TRAPPIST-1
TRAPPIST-1

Semantics: Set

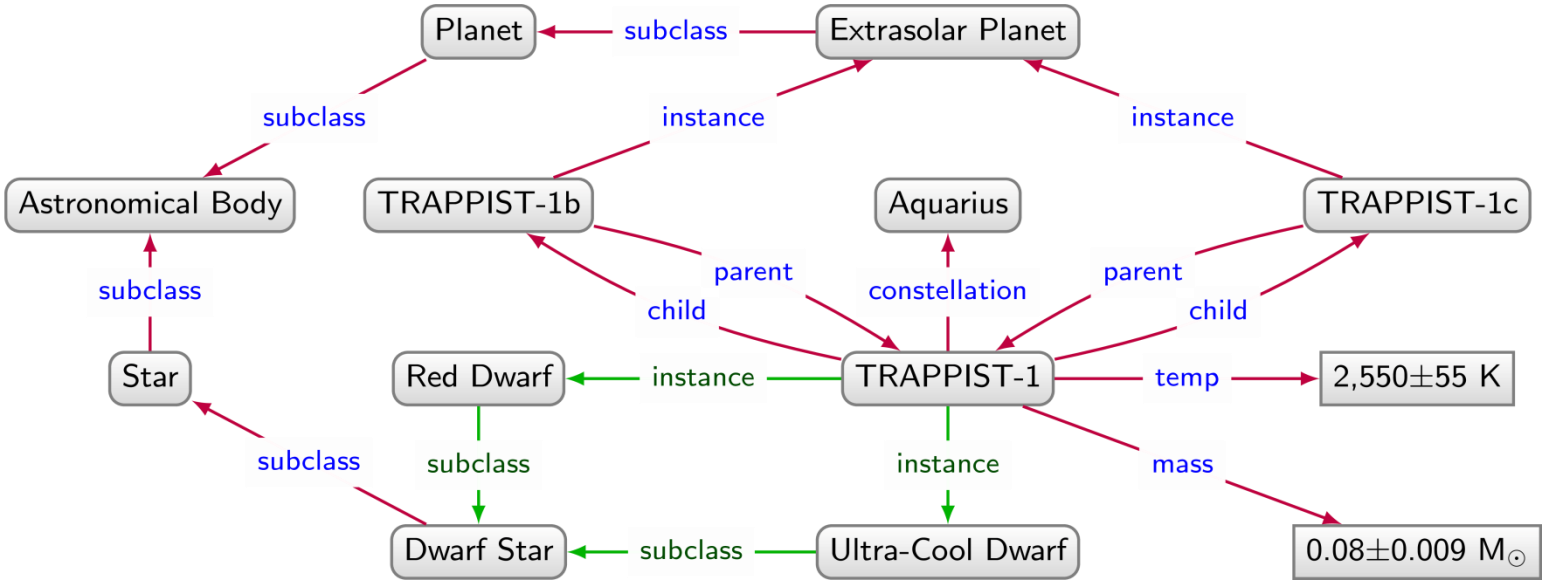
Navigational graph patterns



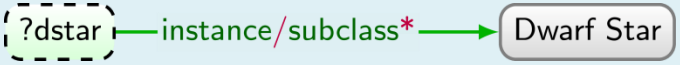
* | / —

Graph Patterns + Regular Path Queries

Regular path queries

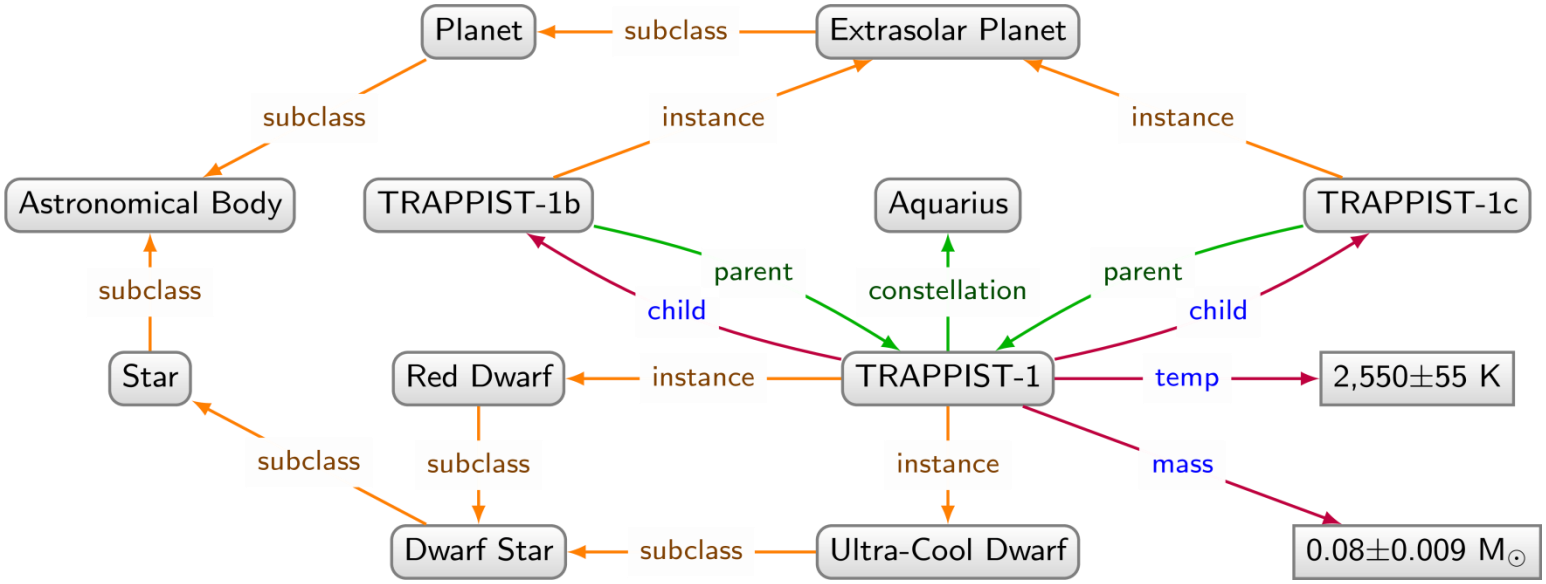


Find instances of Dwarf Star?



?dtar
TRAPPIST-1

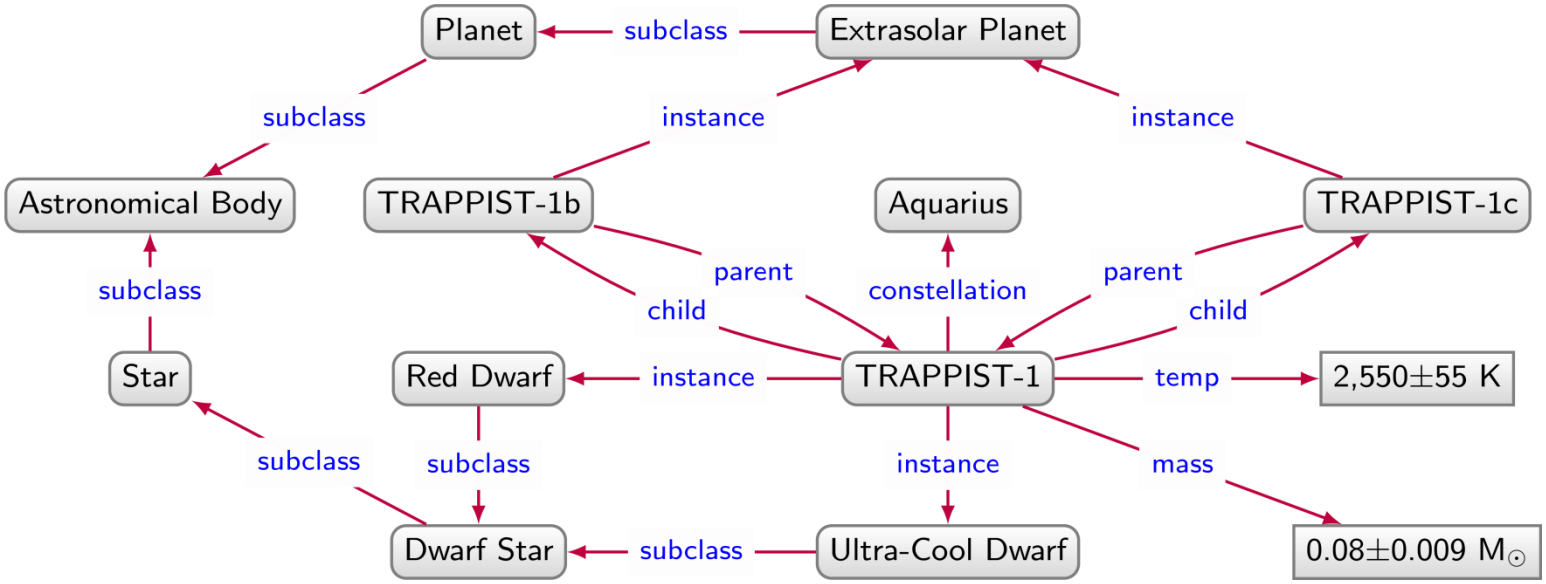
Navigational graph patterns



Find Astronomic Bodies and their constellation?

?body	?con
TRAPPIST-1	Aquarius
TRAPPIST-1b	Aquarius
TRAPPIST-1c	Aquarius

Complex navigational graph patterns



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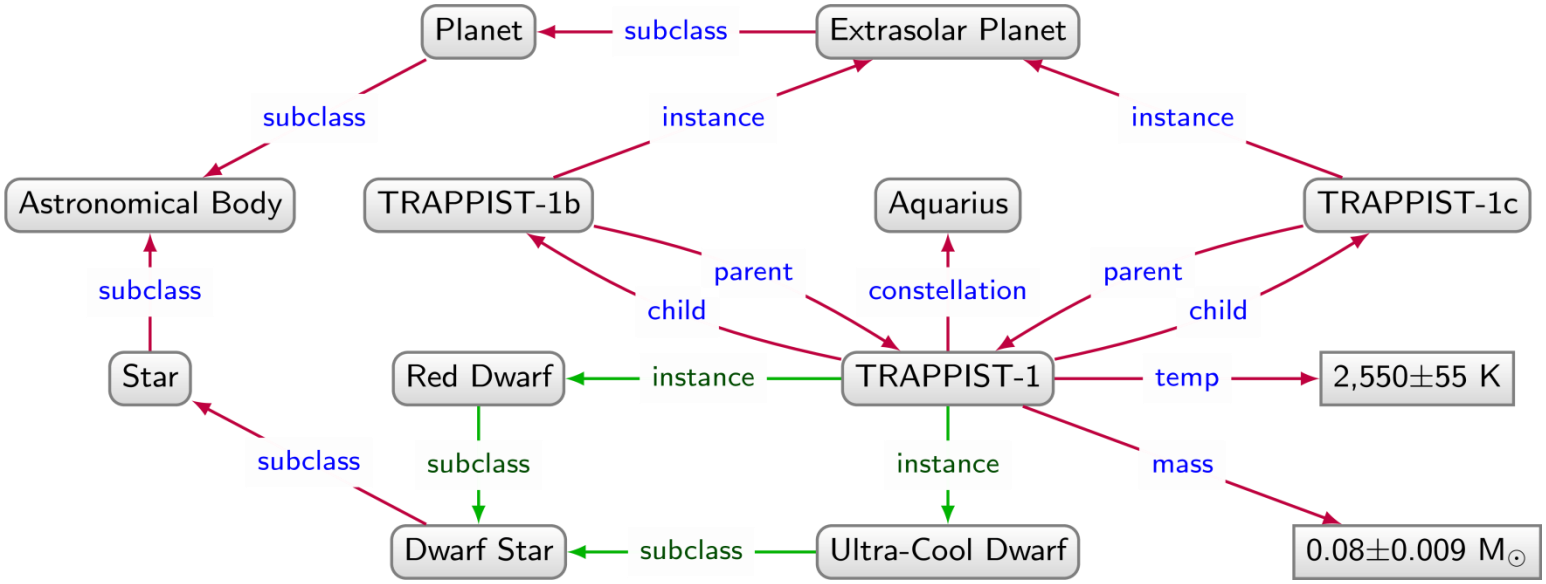
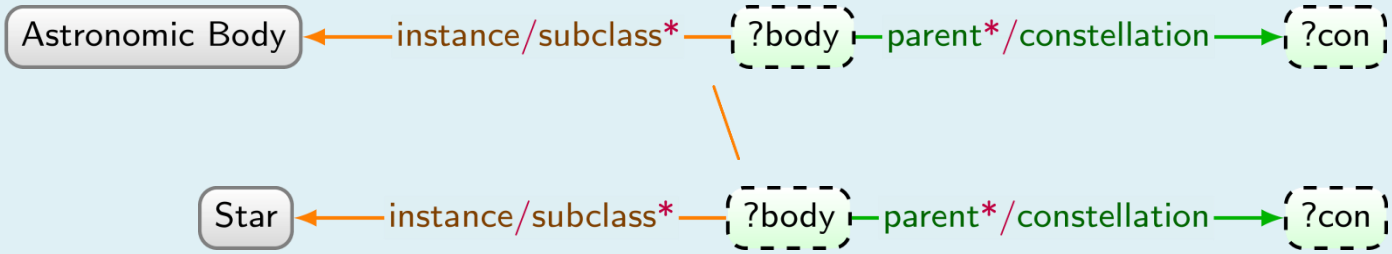
Graph Patterns + Relational Algebra
+ Regular Path Queries

Complex navigational graph patterns

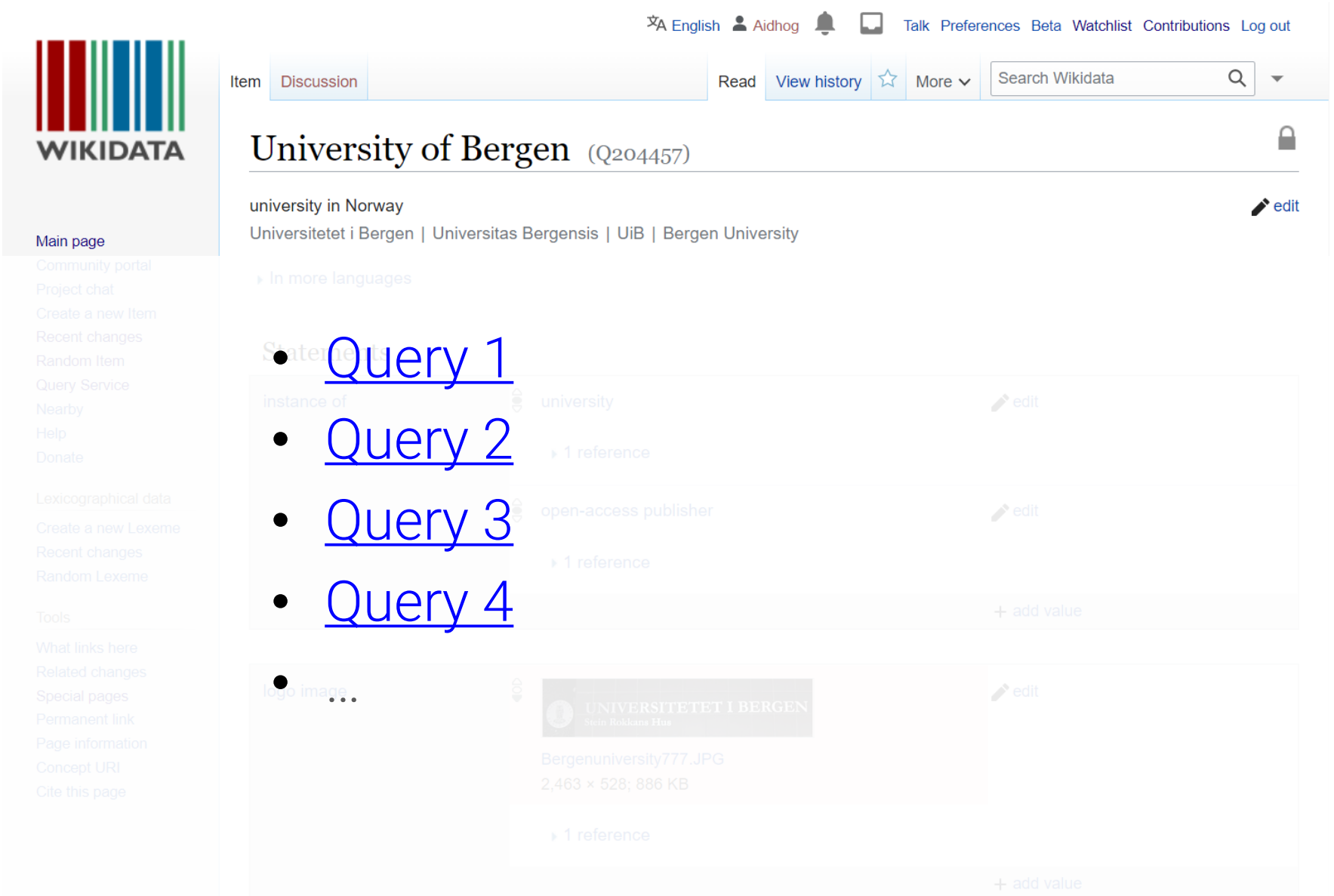


Find non-star astronomic bodies and their constellation?

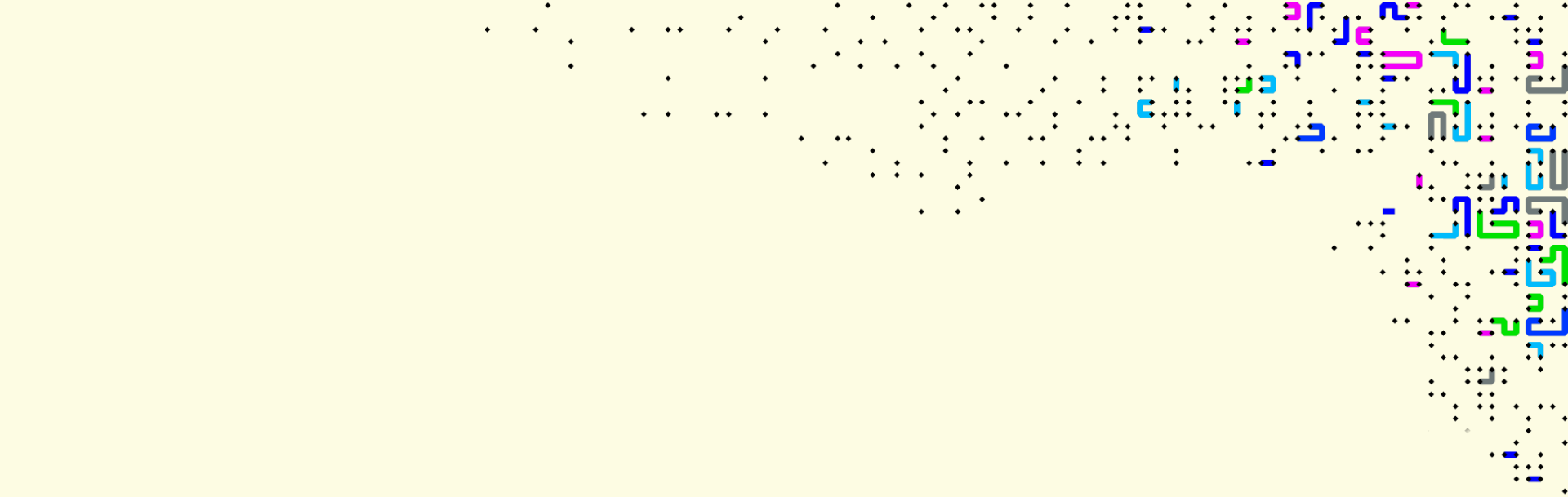


?body	?con
TRAPPIST-1b	Aquarius
TRAPPIST-1c	Aquarius

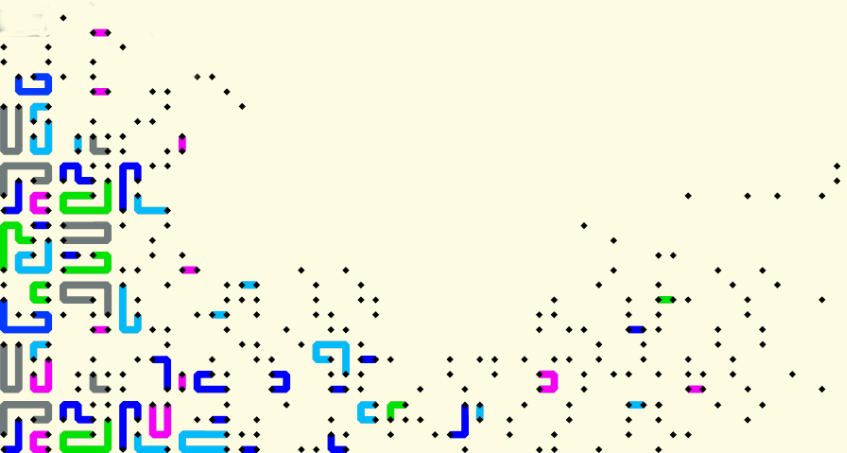
Let’s see this on Wikidata …



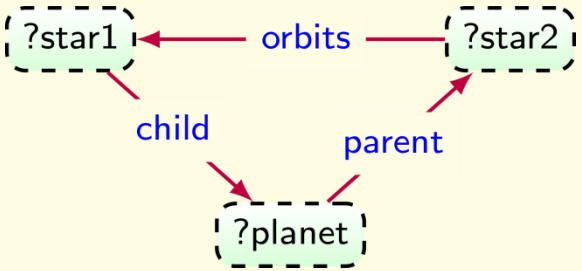
- Query 1
- Query 2
- Query 3
- Query 4
- …



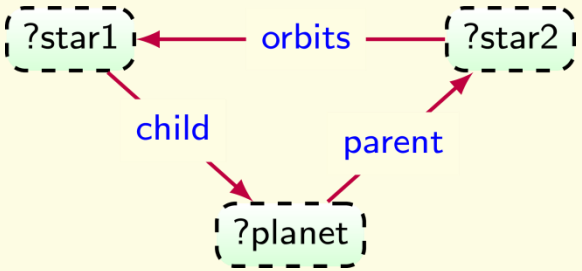
Topic 2:
*-Case Optimality



How many results will the query on the top right return in the worst case given a graph with 4 of each type of edge?



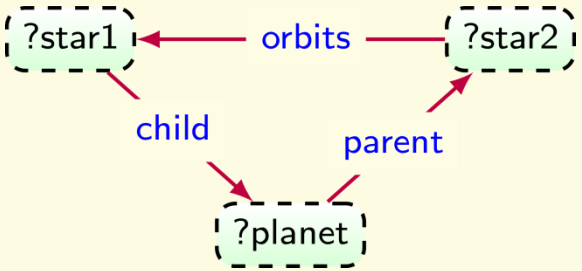
Edge cover



	?planet	?star1	?star2
?planet — parent → ?star2	1	0	1
?star1 — child → ?planet	1	1	0
?star2 — orbits → ?star1	0	0	0
Σ	2	1	1

	?planet	?star1	?star2
?planet — parent → ?star2	1	0	1
?star1 — child → ?planet	0	0	0
?star2 — orbits → ?star1	0	1	1
Σ	1	2	1

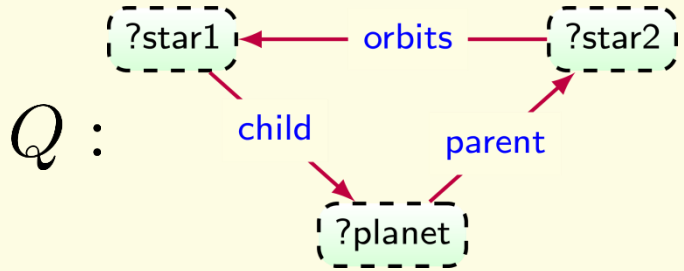
Fractional edge cover



	?planet	?star1	?star2
?planet — parent → ?star2	1	0	1
?star1 — child → ?planet	1	1	0
?star2 — orbits → ?star1	0	0	0
Σ	2	1	1

	?planet	?star1	?star2
?planet — parent → ?star2	$\frac{1}{2}$	0	$\frac{1}{2}$
?star1 — child → ?planet	$\frac{1}{2}$	$\frac{1}{2}$	0
?star2 — orbits → ?star1	0	$\frac{1}{2}$	$\frac{1}{2}$
Σ	1	1	1

AGM bound



Q :

G : a graph

$n_{\mathsf{o}}, n_{\mathsf{c}}, n_{\mathsf{p}}$: cardinality of relations in G

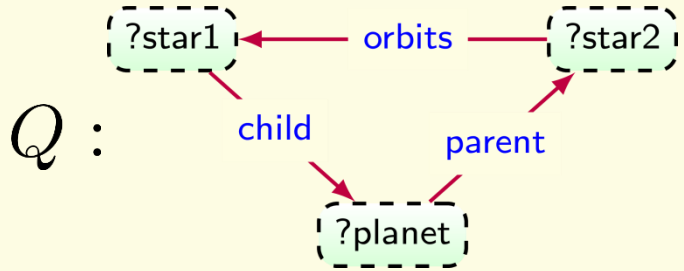
$w_{\mathsf{o}}, w_{\mathsf{c}}, w_{\mathsf{p}}$: fractional edge cover in Q

$$|Q(G)| \leq n_{\mathsf{o}}^{w_{\mathsf{o}}} \cdot n_{\mathsf{c}}^{w_{\mathsf{c}}} \cdot n_{\mathsf{p}}^{w_{\mathsf{p}}}$$

	?planet	?star1	?star2
?planet — parent → ?star2	$\frac{1}{2}$	0	$\frac{1}{2}$
?star1 — child → ?planet	$\frac{1}{2}$	$\frac{1}{2}$	0
?star2 — orbits → ?star1	0	$\frac{1}{2}$	$\frac{1}{2}$
Σ	1	1	1

[Atserias et al. 2008]

AGM bound



Q :

G : a graph

$n_{\mathsf{o}}, n_{\mathsf{c}}, n_{\mathsf{p}}$: cardinality of relations in G

$w_{\mathsf{o}}, w_{\mathsf{c}}, w_{\mathsf{p}}$: fractional edge cover in Q

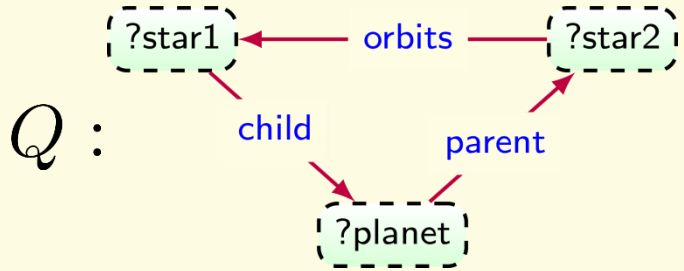
$$|Q(G)| \leq n_{\mathsf{o}}^{w_{\mathsf{o}}} \cdot n_{\mathsf{c}}^{w_{\mathsf{c}}} \cdot n_{\mathsf{p}}^{w_{\mathsf{p}}}$$

$$|Q(G)| \leq n_{\mathsf{o}}^{\frac{1}{2}} \cdot n_{\mathsf{c}}^{\frac{1}{2}} \cdot n_{\mathsf{p}}^{\frac{1}{2}}$$

	?planet	?star1	?star2
?planet — parent → ?star2	$\frac{1}{2}$	0	$\frac{1}{2}$
?star1 — child → ?planet	$\frac{1}{2}$	$\frac{1}{2}$	0
?star2 — orbits → ?star1	0	$\frac{1}{2}$	$\frac{1}{2}$
Σ	1	1	1

[Atserias et al. 2008]

AGM bound



G : a graph

$n_{\mathsf{o}}, n_{\mathsf{c}}, n_{\mathsf{p}}$: cardinality of relations in G

$w_{\mathsf{o}}, w_{\mathsf{c}}, w_{\mathsf{p}}$: fractional edge cover in Q

$$|Q(G)| \leq n_{\mathsf{o}}^{w_{\mathsf{o}}} \cdot n_{\mathsf{c}}^{w_{\mathsf{c}}} \cdot n_{\mathsf{p}}^{w_{\mathsf{p}}}$$

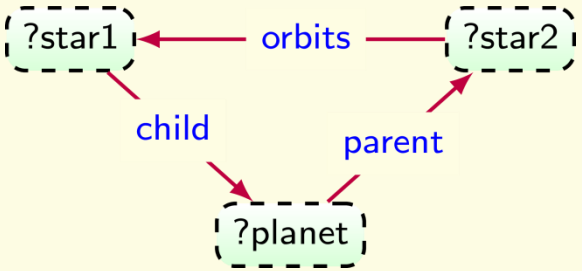
$$|Q(G)| \leq n_{\mathsf{o}}^{\frac{1}{2}} \cdot n_{\mathsf{c}}^{\frac{1}{2}} \cdot n_{\mathsf{p}}^{\frac{1}{2}}$$

$$|Q(G)| \leq n^{\frac{3}{2}} \text{ assuming } n_{\mathsf{o}} = n_{\mathsf{c}} = n_{\mathsf{p}}$$

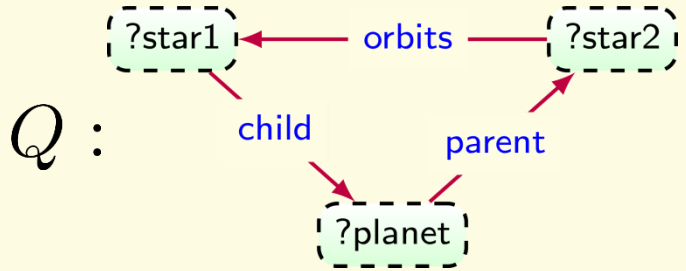
	?planet	?star1	?star2
?planet — parent → ?star2	$\frac{1}{2}$	0	$\frac{1}{2}$
?star1 — child → ?planet	$\frac{1}{2}$	$\frac{1}{2}$	0
?star2 — orbits → ?star1	0	$\frac{1}{2}$	$\frac{1}{2}$
Σ	1	1	1

[Atserias et al. 2008]

How many results will the query on the top right return in the worst case given a graph with 4 of each type of edge?



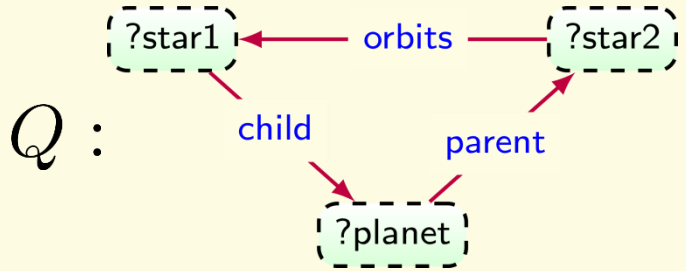
Worst-case optimality



$\beta(Q, G)$ AGM bound of Q wrt G

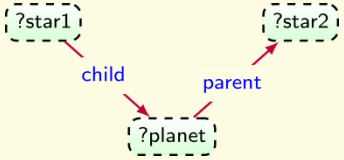
Worst case optimality: enumerate $Q(G)$ in $O(\beta(Q, G))$

Worst-case optimality



$\beta(Q, G)$ AGM bound of Q wrt G

Worst case optimality: enumerate $Q(G)$ in $O(\beta(Q, G))$

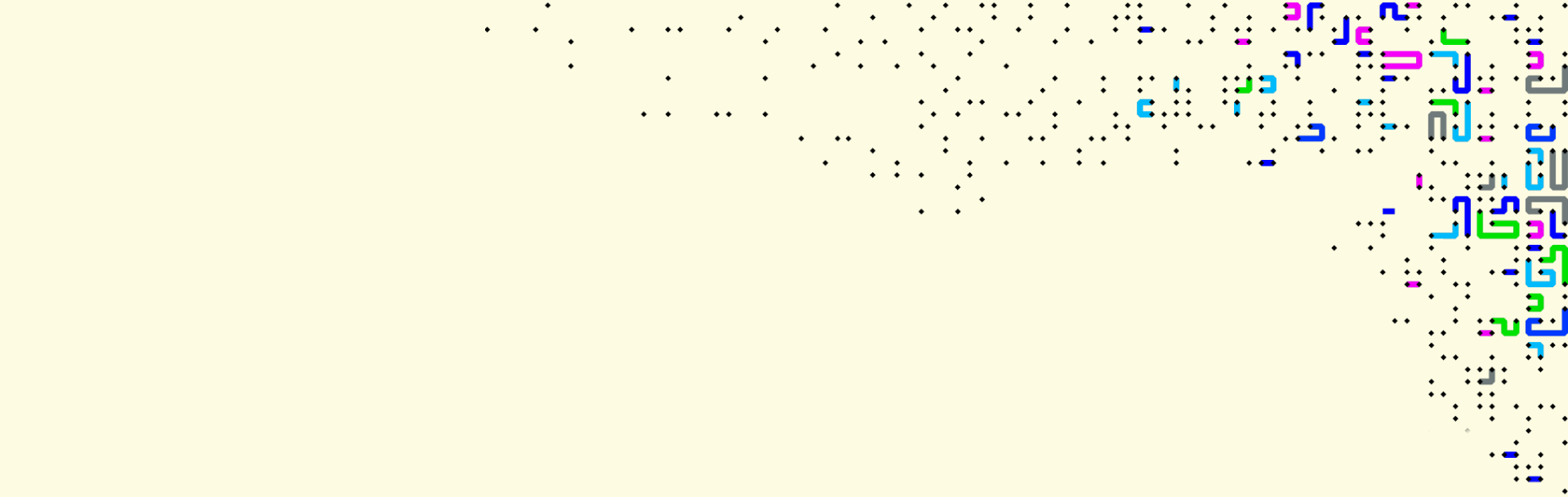
Note: We cannot evaluate 

first as its bound is n^2

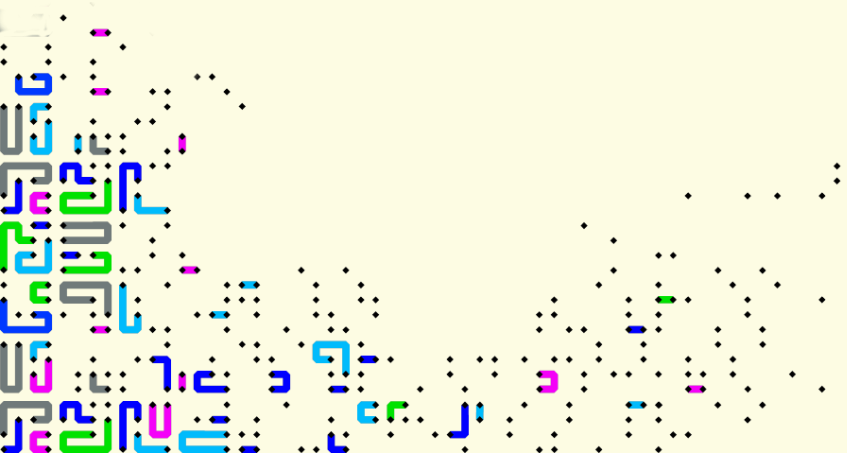
Approach: Evaluate variable-at-a-time rather than tuple-at-a-time

What about worst-case optimality for navigational graph patterns?

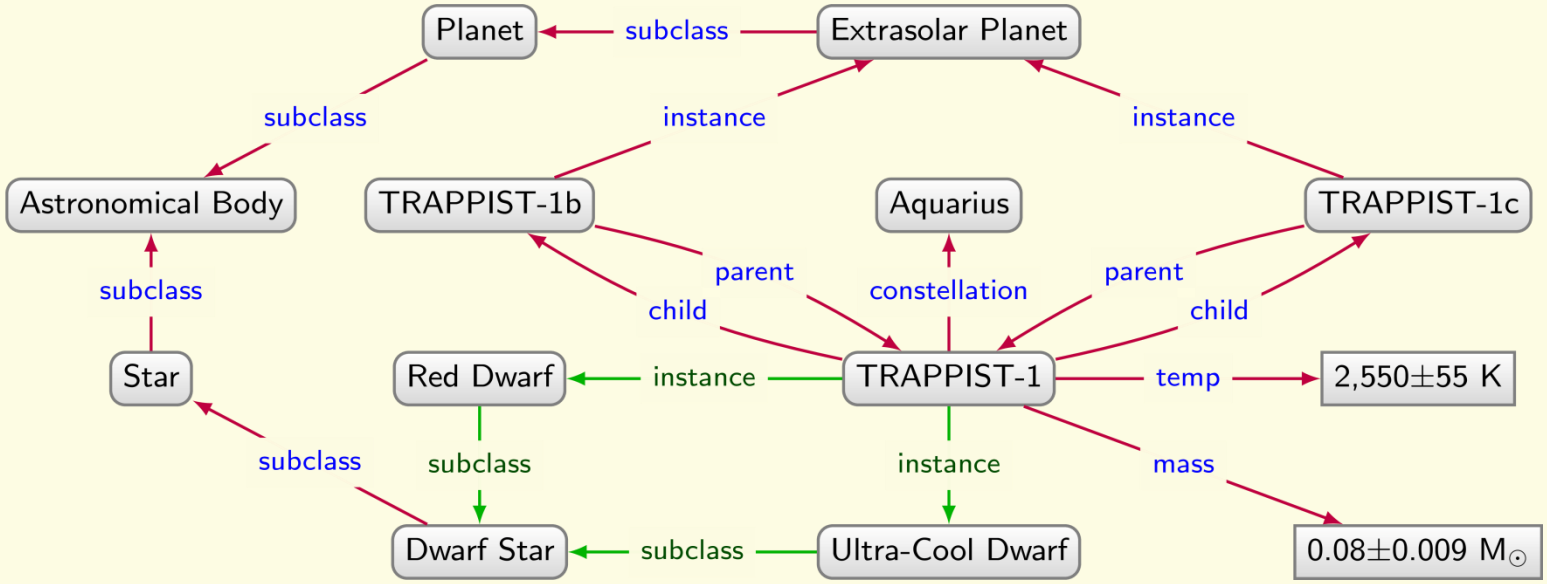
What about average-case or instance optimality?

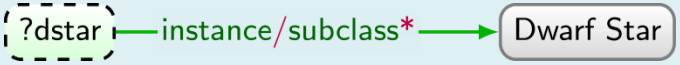


Topic 3:
Native Graph Querying



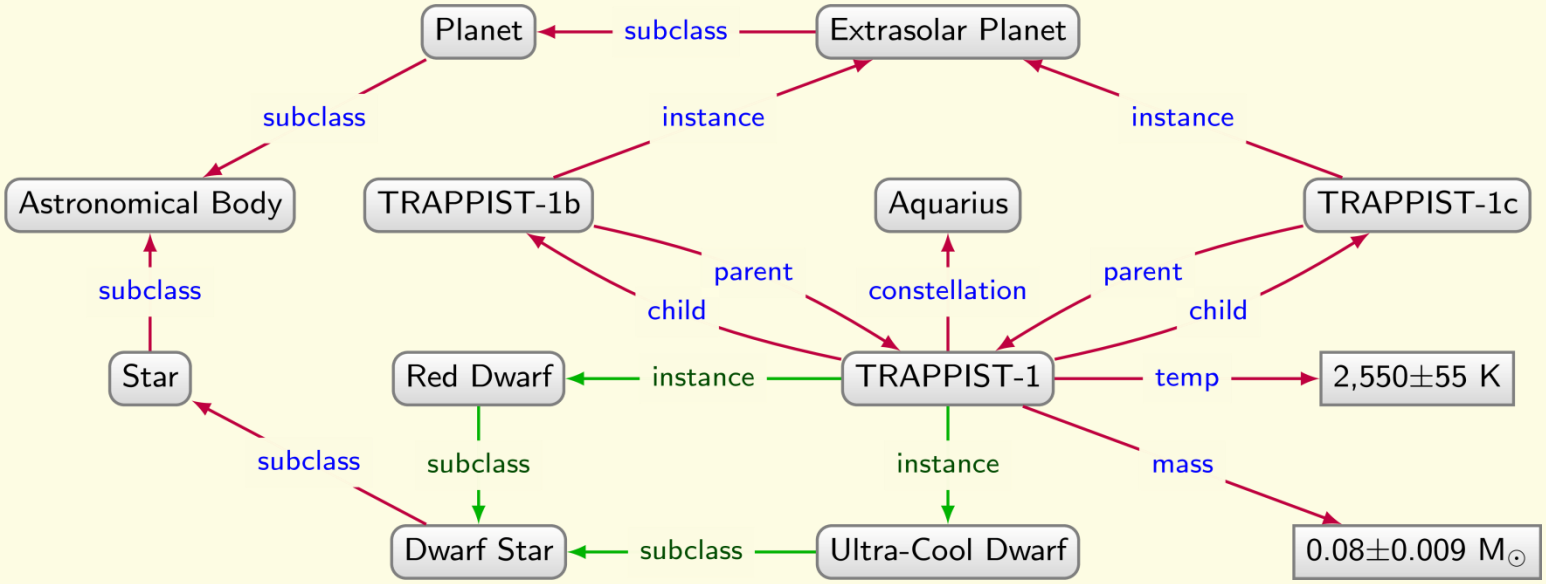
Returning paths



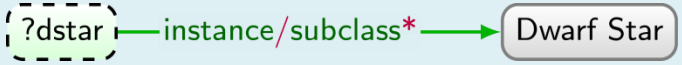


?dtar
TRAPPIST-1

Returning paths

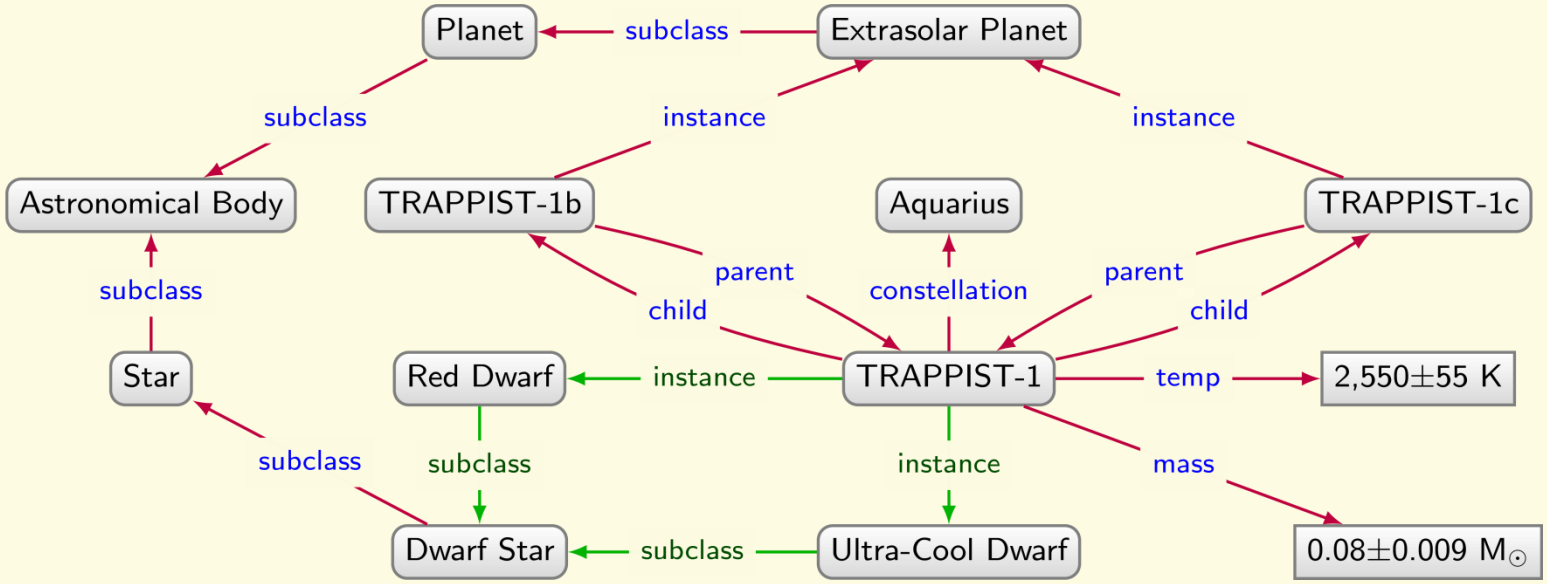


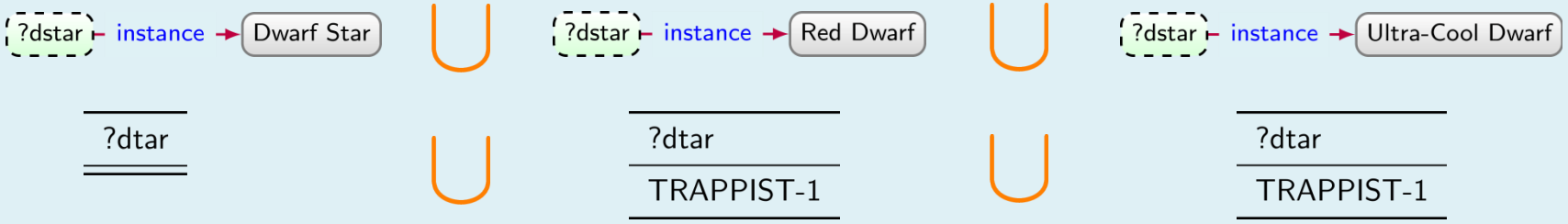
How should we return and handle paths in results?



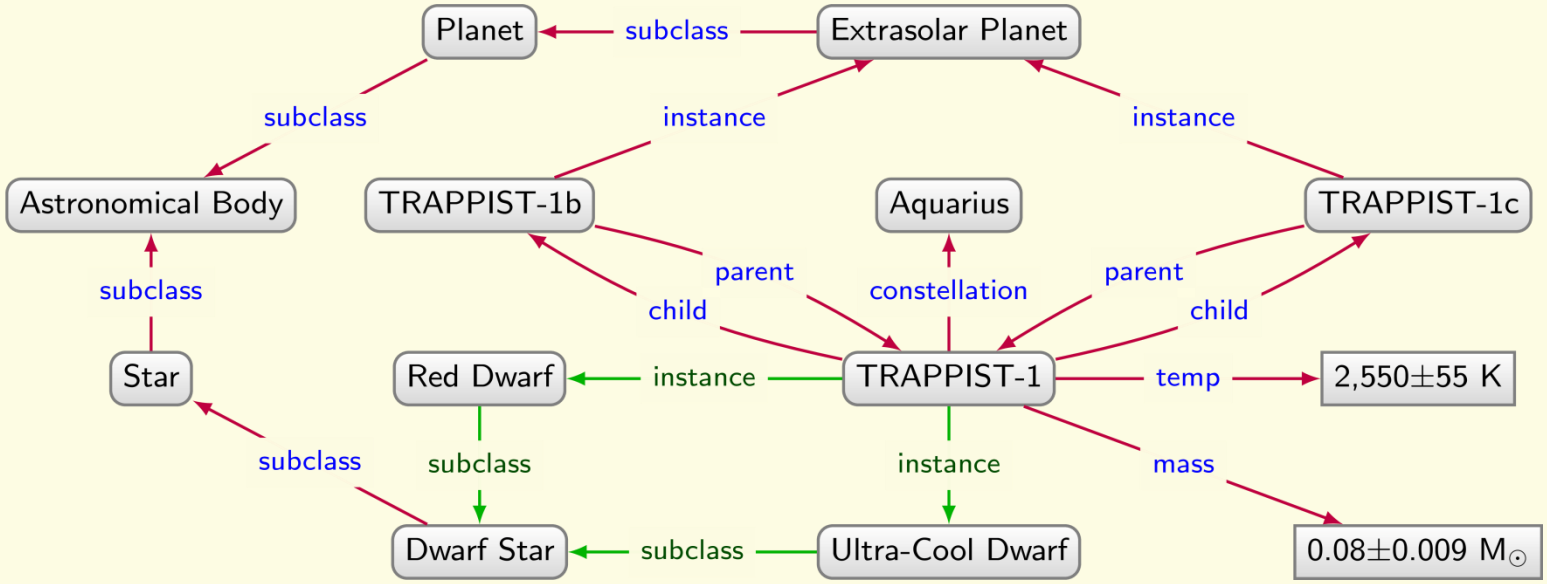
$path
TRAPPIST-1 — instance → Red Dwarf — instance → Dwarf Star
TRAPPIST-1 — instance → Ultra-Cool Dwarf — instance → Dwarf Star

Returning graphs

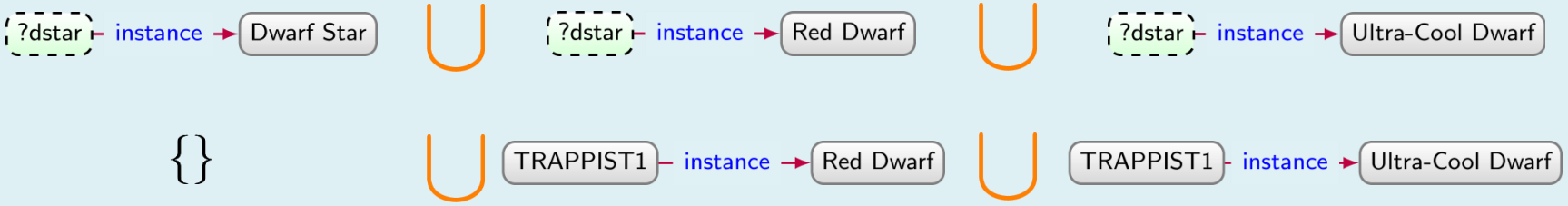




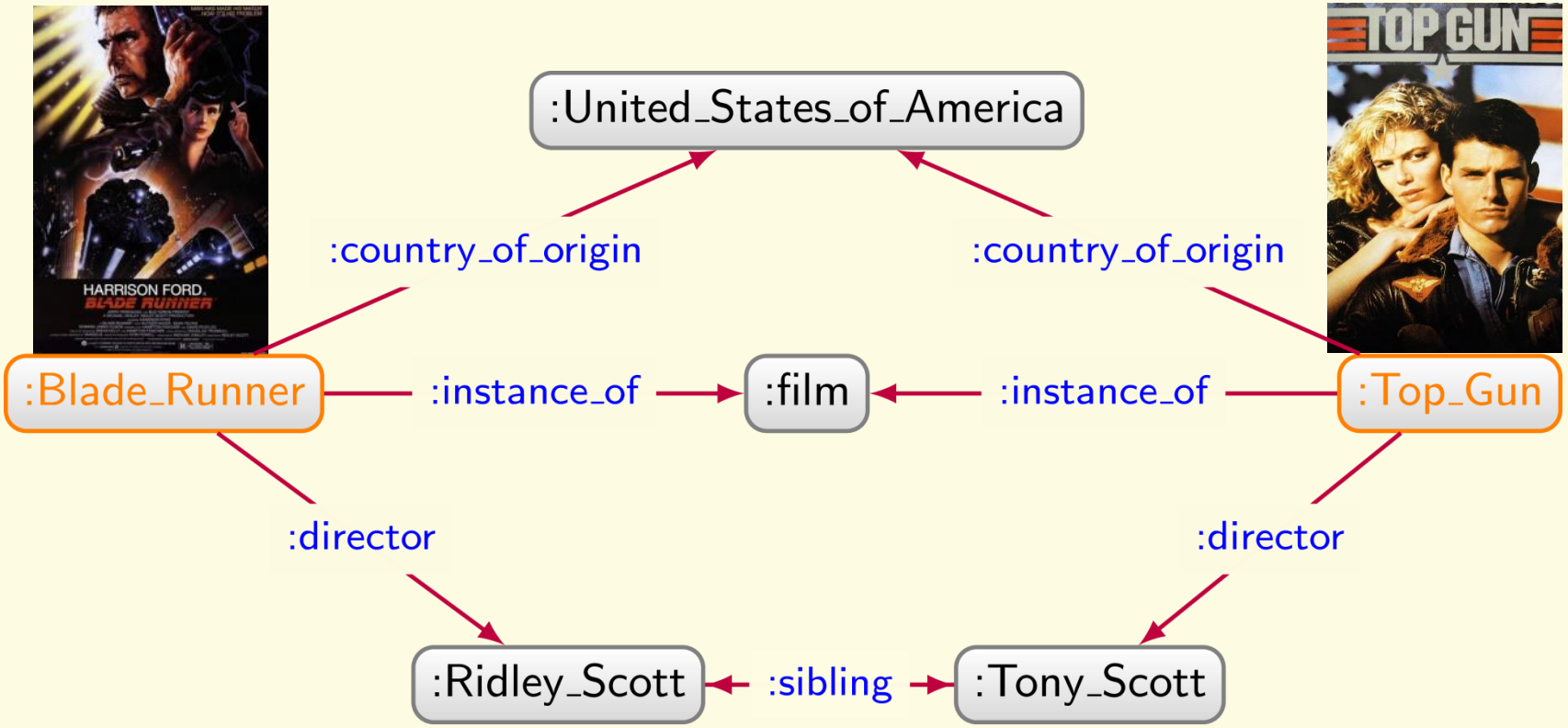
Returning graphs



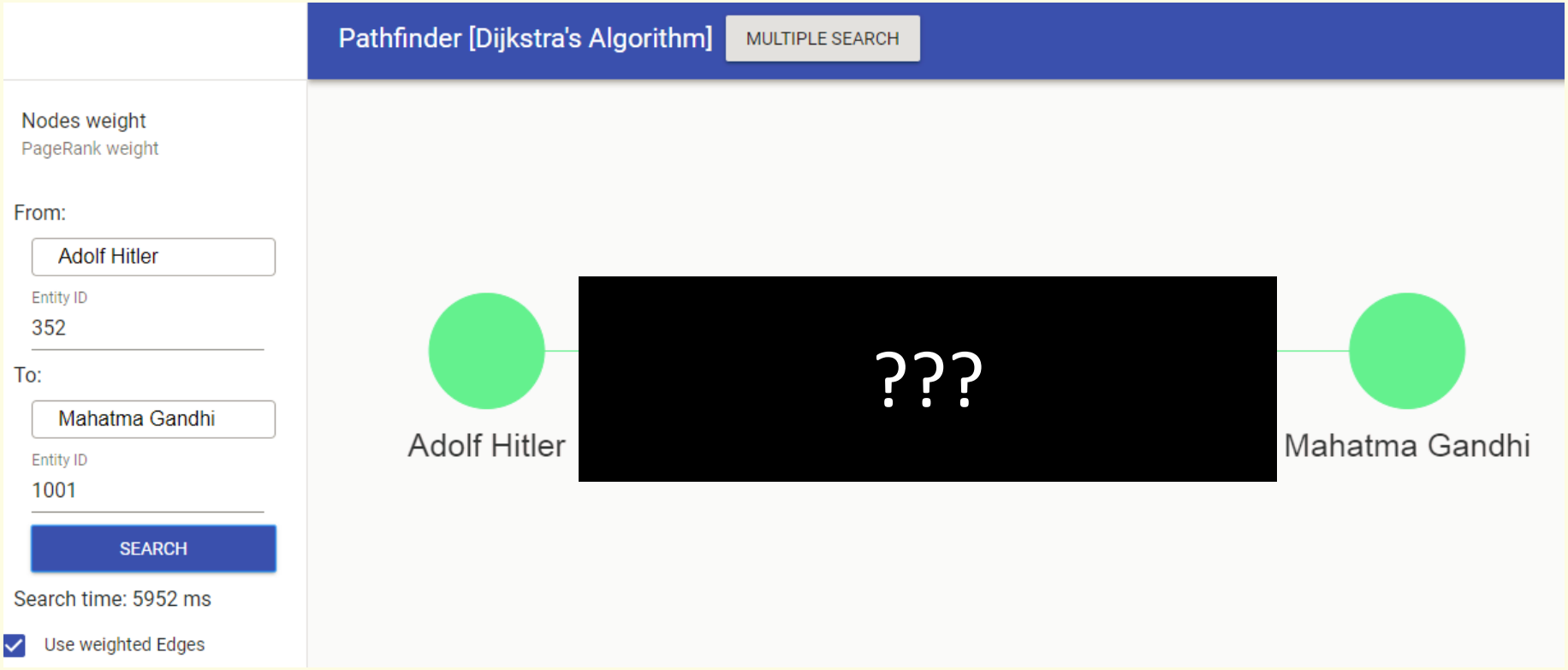
Can we define a native algebra ($\bowtie$, $\setminus$, σ, π, $\cup$) for graphs?



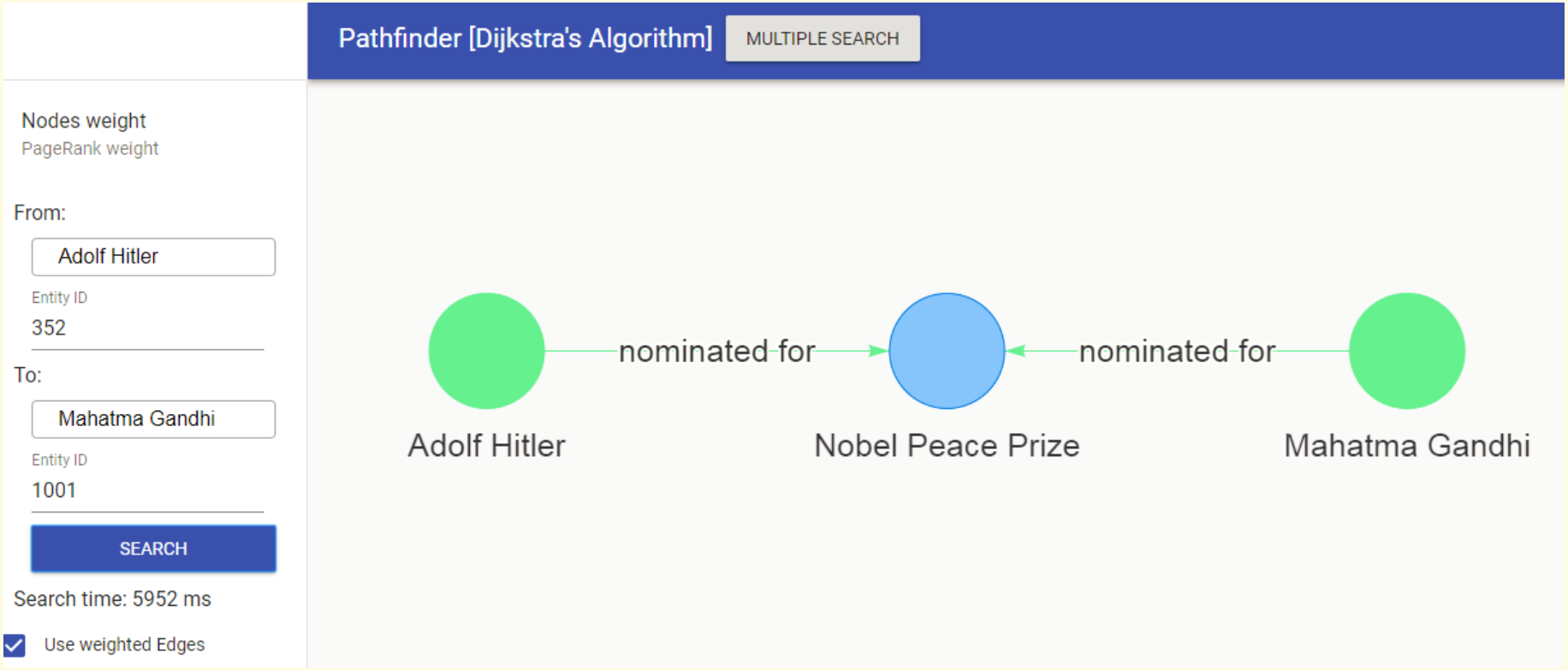
Finding “interesting” paths



Finding “interesting” paths

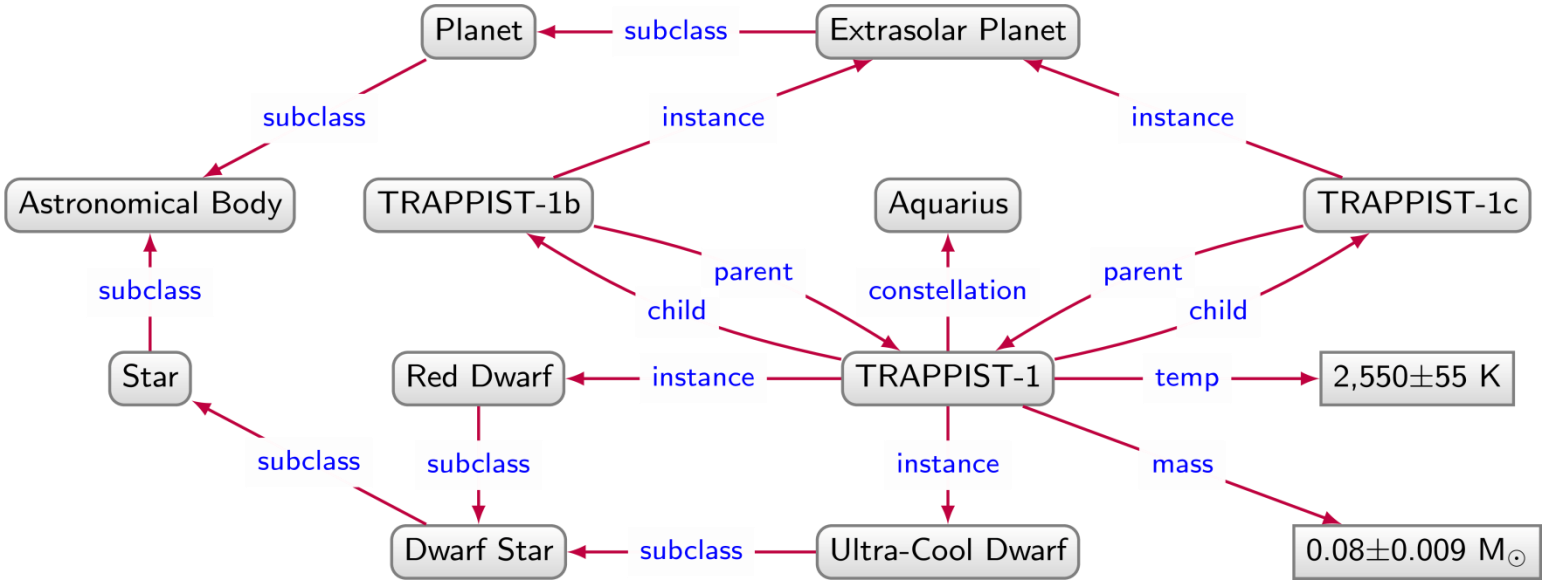


Finding “interesting” paths



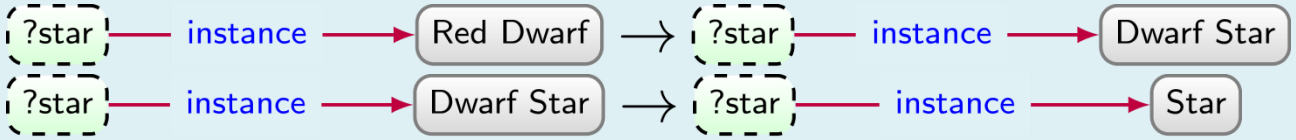
Rules

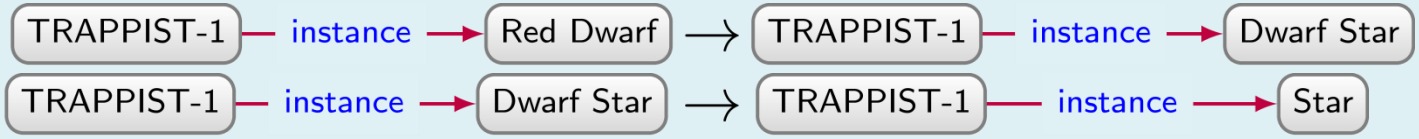
Rules



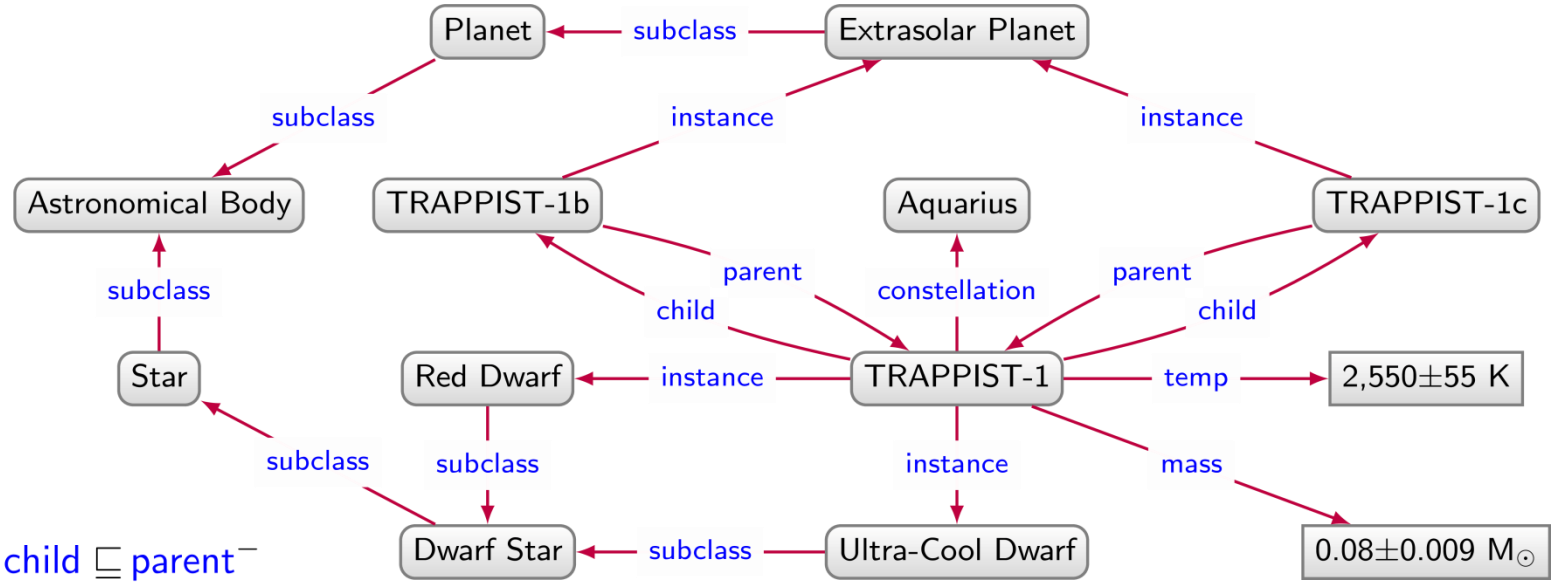
RedDwarf $\sqsubseteq$ DwarfStar

DwarfStar $\sqsubseteq$ Star





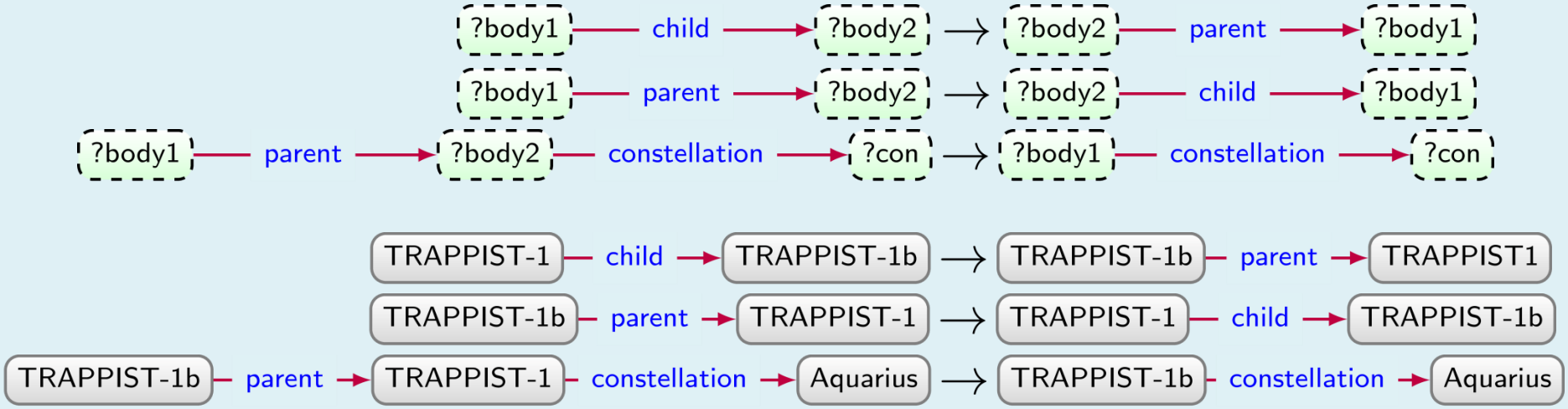
Rules



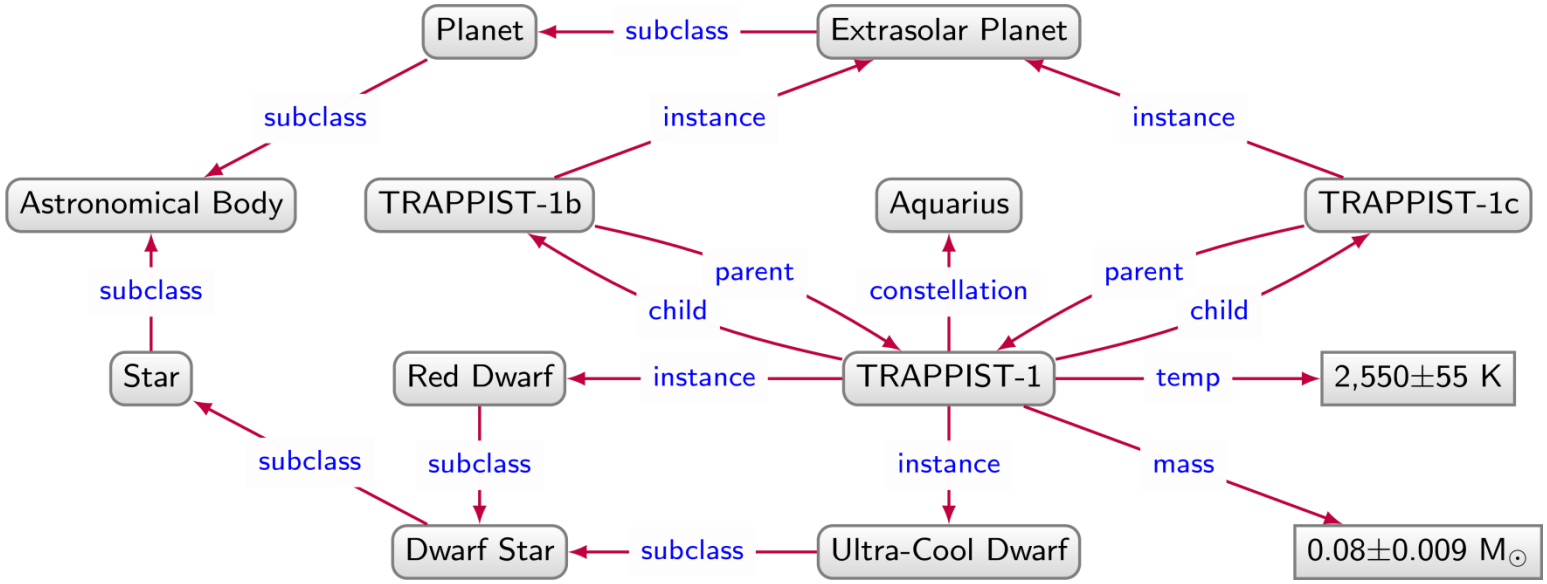
$\text{child} \sqsubseteq \text{parent}^-$

$\text{parent} \sqsubseteq \text{child}^-$

$\text{parent} \circ \text{constellation} \sqsubseteq \text{constellation}$

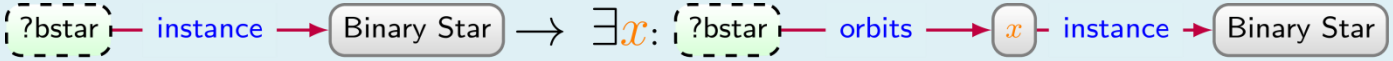


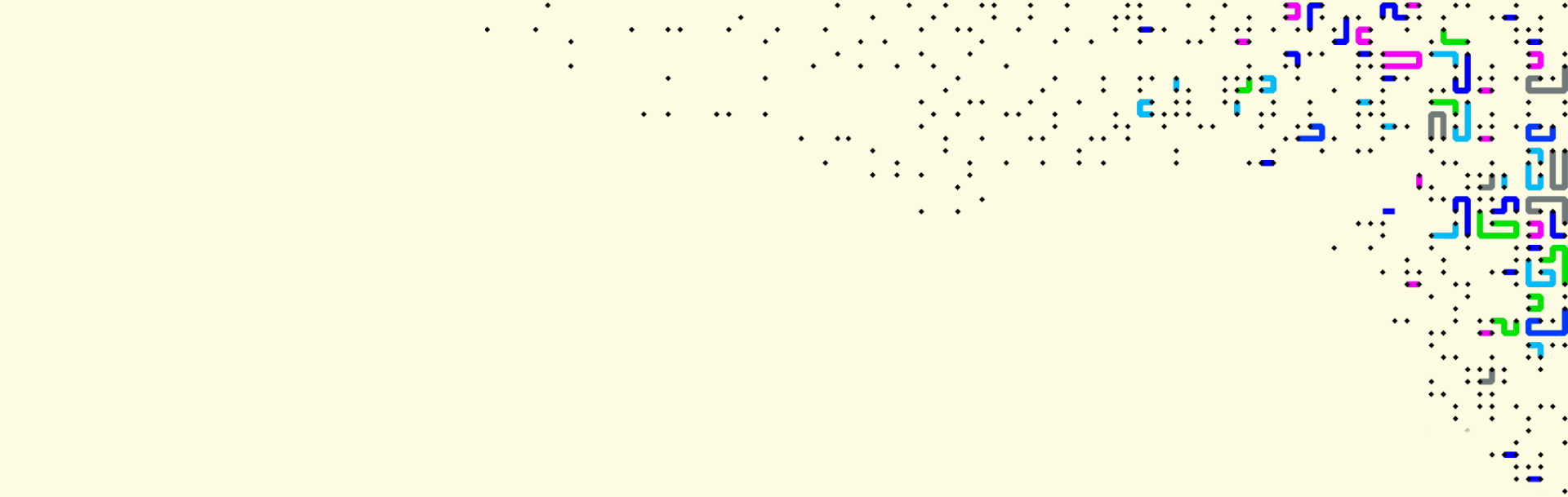
Rules: disjunction & existentials



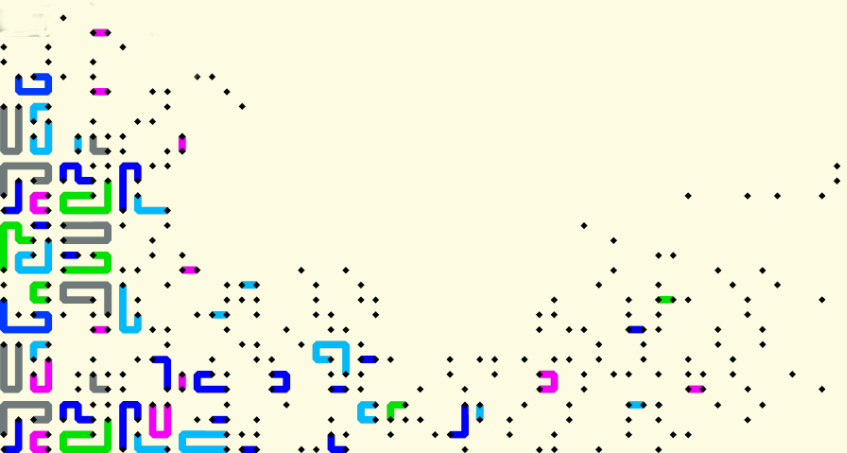
Planet $\sqsubseteq$ ExtrasolarPlanet $\sqcup$ SolarPlanet

BinaryStar $\sqsubseteq \exists$orbits.BinaryStar $\sqcap$ Star

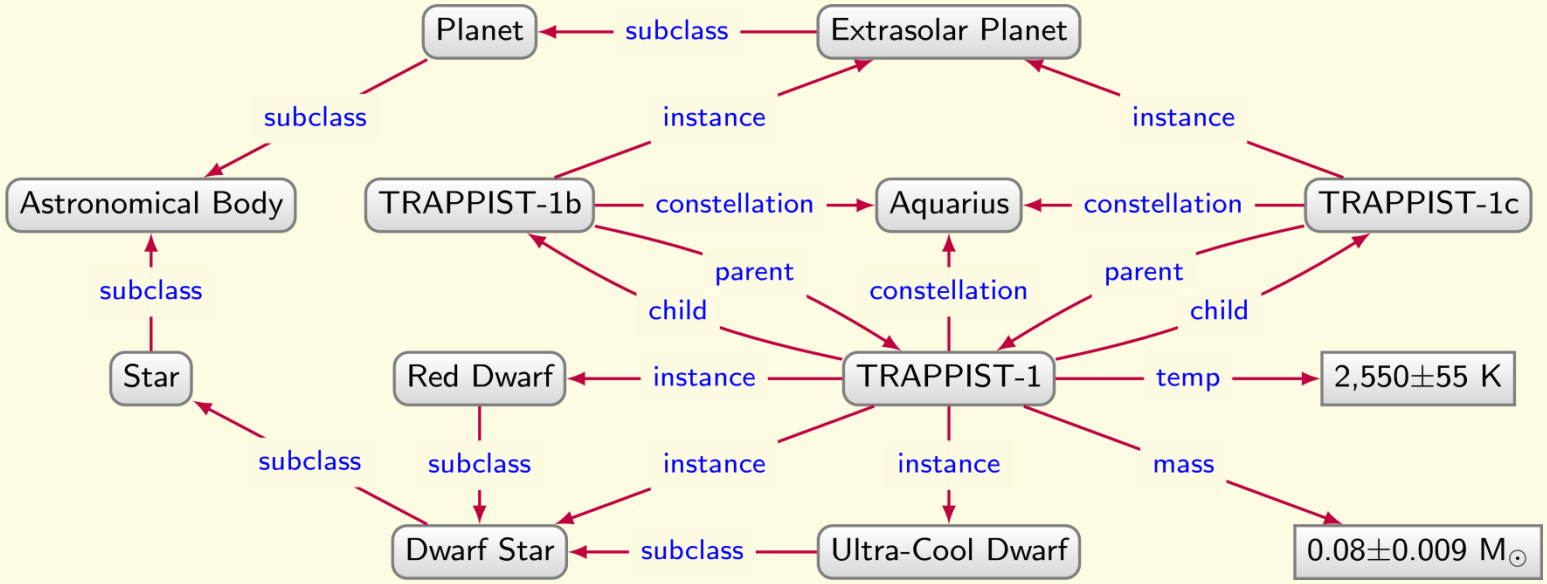


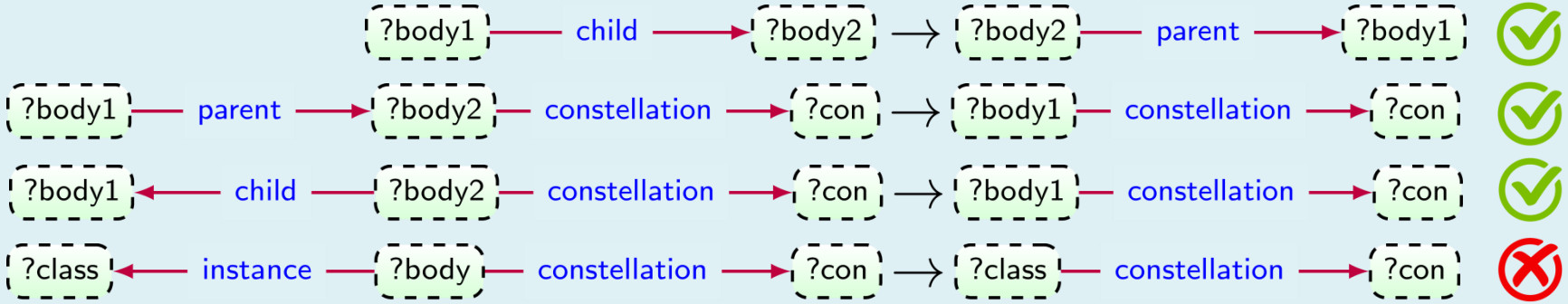


Topic 5:
Rule Mining



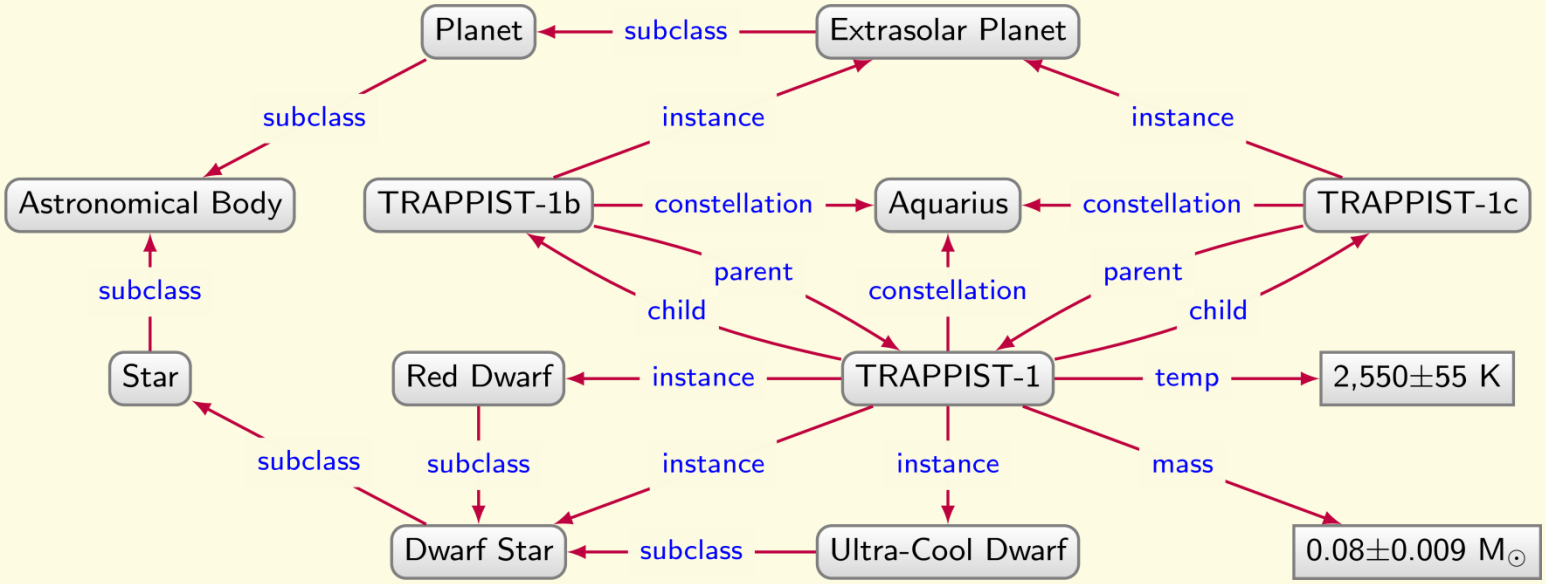
Rule Mining



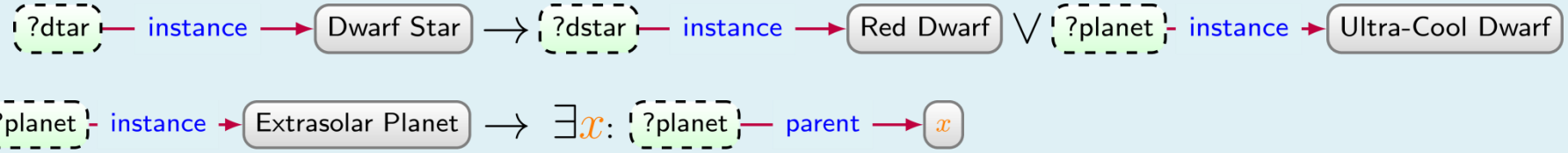


[Galárraga et al. 2015]

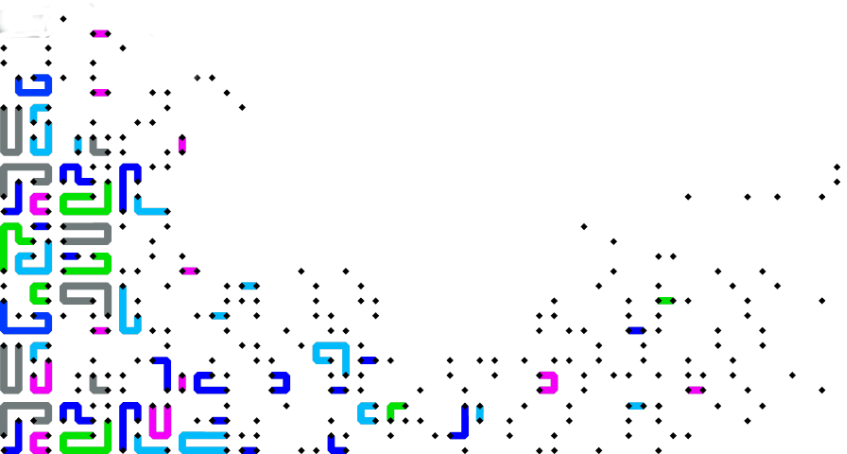
Rule Mining



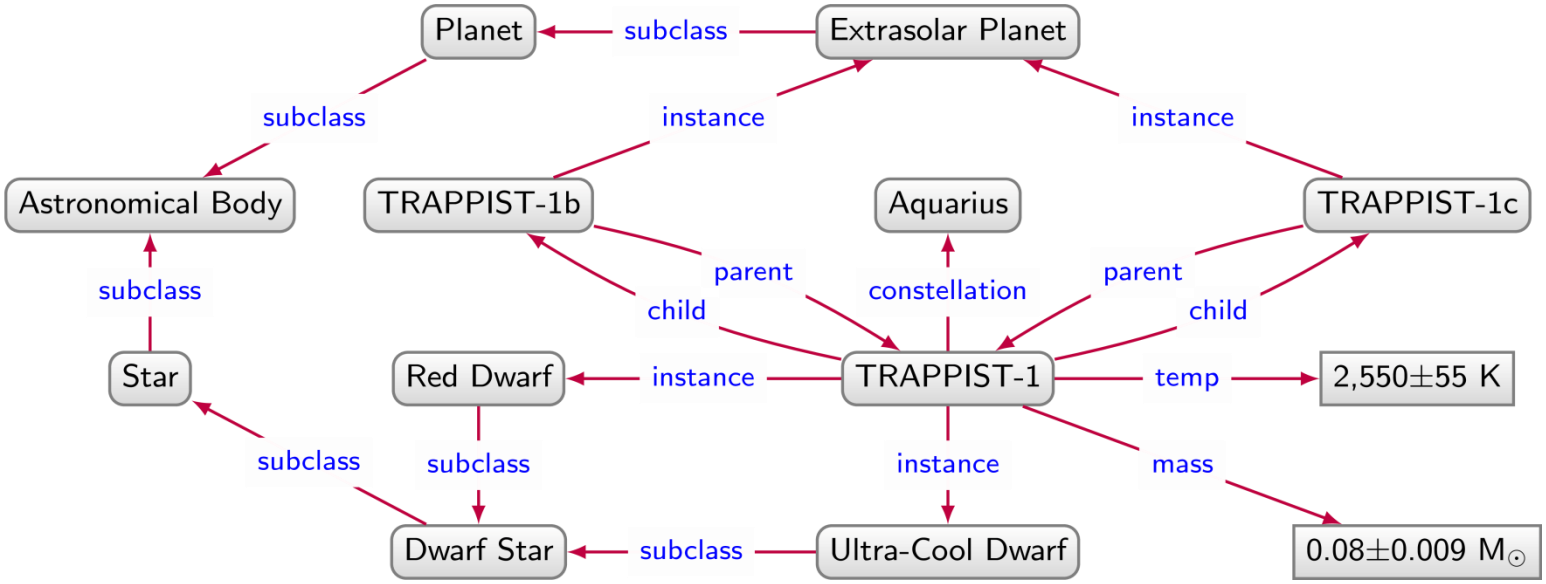
Can we mine disjunctive and/or existential rules?



Ontologies



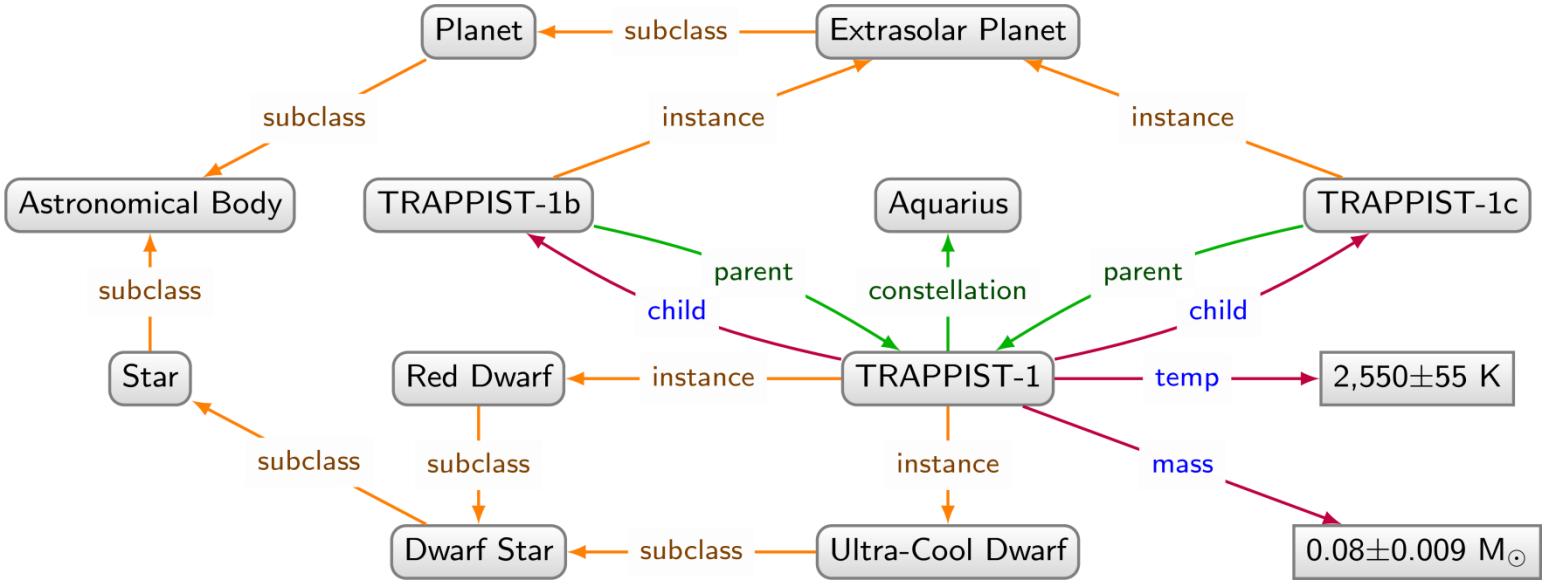
The need for semantics



Find instances of Dwarf Star?

?dstar ⊢ instance → Dwarf Star ∪ ?dstar ⊢ instance → Red Dwarf ∪ ?dstar ⊢ instance → Ultra-Cool Dwarf

The need for semantics



Find Astronomic Bodies and their constellation?

Description Logics: A-Box

A-Box

$\mathsf{child}(\mathsf{TRAPPIST\text{-}1}, \mathsf{TRAPPIST\text{-}1b})$

$\mathsf{constellation}(\mathsf{TRAPPIST\text{-}1}, \mathsf{Aquarius})$

$\mathsf{RedDwarf}(\mathsf{TRAPPIST\text{-}1})$

$\mathsf{BinaryStar}(\mathsf{AlphaCentauriB})$

Ontology

Name	**Syntax**	**Semantics** $(\cdot^I)$
	Assertional Definitions	
Individual	a	a^I (an element of Δ^I)
	Assertional Axioms (A-Box)	
Role Assertion	$\mathsf{R}(\mathsf{a}, \mathsf{b})$	$(\mathsf{a}^I, \mathsf{b}^I) \in \mathsf{R}^I$
Negative Role Assertion	$\neg\mathsf{R}(\mathsf{a}, \mathsf{b})$	$(\mathsf{a}^I, \mathsf{b}^I) \notin \mathsf{R}^I$
Concept Assertion	$\mathsf{C}(\mathsf{a})$	$\mathsf{a}^I \in \mathsf{C}^I$
Equality	$\mathsf{a} = \mathsf{b}$	$\mathsf{a}^I = \mathsf{b}^I$
Inequality	$\mathsf{a} \neq \mathsf{b}$	$\mathsf{a}^I \neq \mathsf{b}^I$

Description Logics: T-Box

A-Box

$\mathsf{child}(\mathsf{TRAPPIST\text{-}1}, \mathsf{TRAPPIST\text{-}1b})$

$\mathsf{constellation}(\mathsf{TRAPPIST\text{-}1}, \mathsf{Aquarius})$

$\mathsf{RedDwarf}(\mathsf{TRAPPIST\text{-}1})$

$\mathsf{BinaryStar}(\mathsf{AlphaCentauriB})$

T-Box

$\mathsf{RedDwarf} \sqsubseteq \mathsf{DwarfStar}$

$\mathsf{DwarfStar} \sqsubseteq \mathsf{Star}$

$\mathsf{Planet} \sqsubseteq \mathsf{ExtrasolarPlanet} \sqcup \mathsf{SolarPlanet}$

$\mathsf{BinaryStar} \sqsubseteq \exists \mathsf{orbits}.\mathsf{BinaryStar} \sqcap \mathsf{Star}$

Ontology

Name	**Syntax**	**Semantics** $(\cdot^I)$
	Concept Definitions	
Atomic Concept	A	A^I (a subset of Δ^I)
Top Concept	$\top$	Δ^I
Bottom Concept	$\bot$	$\emptyset$
Concept Negation	$\neg\mathsf{C}$	$\Delta^I \setminus \mathsf{C}^I$
Concept Intersection	$\mathsf{C} \sqcap \mathsf{D}$	$\mathsf{C}^I \cap \mathsf{D}^I$
Concept Union	$\mathsf{C} \sqcup \mathsf{D}$	$\mathsf{C}^I \cup \mathsf{D}^I$
Nominals	$\{\mathsf{a}\}$	$\{\mathsf{a}^I\}$
Existential Restriction	$\exists \mathsf{R}.\mathsf{C}$	$\{\mathsf{x} \mid \exists \mathsf{y} : (\mathsf{x},\mathsf{y}) \in \mathsf{R}^I \text{ and } \mathsf{y} \in \mathsf{C}^I\}$
Universal Restriction	$\forall \mathsf{R}.\mathsf{C}$	$\{\mathsf{x} \mid \forall \mathsf{y} : (\mathsf{x},\mathsf{y}) \in \mathsf{R}^I \text{ implies } \mathsf{y} \in \mathsf{C}^I\}$
Self Restriction	$\exists \mathsf{R}.\mathsf{Self}$	$\{\mathsf{x} \mid (\mathsf{x},\mathsf{x}) \in \mathsf{R}^I\}$
Number Restriction	$\star n\, \mathsf{R}$ (where $\star \in \{\geq, \leq, =\}$)	$\{\mathsf{x} \mid \#\{\mathsf{y} : (\mathsf{x},\mathsf{y}) \in \mathsf{R}^I\} \star n\}$
Qualified Number Restriction	$\star n\, \mathsf{R}.\mathsf{C}$ (where $\star \in \{\geq, \leq, =\}$)	$\{\mathsf{x} \mid \#\{\mathsf{y} : (\mathsf{x},\mathsf{y}) \in \mathsf{R}^I \text{ and } \mathsf{y} \in \mathsf{C}^I\} \star n\}$
	Concept Axioms (T-Box)	
Concept Inclusion	$\mathsf{C} \sqsubseteq \mathsf{D}$	$\mathsf{C}^I \subseteq \mathsf{D}^I$

Description Logics: R-Box

A-Box	T-Box	R-Box
$\mathsf{child}(\mathsf{TRAPPIST\text{-}1}, \mathsf{TRAPPIST\text{-}1b})$	$\mathsf{RedDwarf} \sqsubseteq \mathsf{DwarfStar}$	$\mathsf{child} \sqsubseteq \mathsf{parent}^-$
$\mathsf{constellation}(\mathsf{TRAPPIST\text{-}1}, \mathsf{Aquarius})$	$\mathsf{DwarfStar} \sqsubseteq \mathsf{Star}$	$\mathsf{parent} \sqsubseteq \mathsf{child}^-$
$\mathsf{RedDwarf}(\mathsf{TRAPPIST\text{-}1})$	$\mathsf{Planet} \sqsubseteq \mathsf{ExtrasolarPlanet} \sqcup \mathsf{SolarPlanet}$	$\mathsf{parent} \circ \mathsf{constellation} \sqsubseteq \mathsf{constellation}$
$\mathsf{BinaryStar}(\mathsf{AlphaCentauriB})$	$\mathsf{BinaryStar} \sqsubseteq \exists \mathsf{orbits}.\mathsf{BinaryStar} \sqcap \mathsf{Star}$	$\mathsf{Asym}(\mathsf{parent})$
		Ontology

Name	**Syntax**	**Semantics** $(\cdot^I)$
	Role Definitions	
Role	R	R^I (a subset of $\Delta^I \times \Delta^I$)
Inverse Role	R^-	$\{(\mathsf{y},\mathsf{x}) \mid (\mathsf{x},\mathsf{y}) \in \mathsf{R}^I\}$
Universal Role	U	$\Delta^I \times \Delta^I$
	Role Axioms (R-Box)	
Role Inclusion	$\mathsf{R} \sqsubseteq \mathsf{S}$	$\mathsf{R}^I \subseteq \mathsf{S}^I$
Complex Role Inclusion	$\mathsf{R}_1 \circ \ldots \circ \mathsf{R}_n \sqsubseteq \mathsf{S}$	$\mathsf{R}_1^I \circ \ldots \circ \mathsf{R}_n^I \subseteq \mathsf{S}^I$
Transitive Roles	$\mathsf{Trans}(\mathsf{R})$	$\mathsf{R}^I \circ \mathsf{R}^I \subseteq \mathsf{R}^I$
Functional Roles	$\mathsf{Func}(\mathsf{R})$	$\{(\mathsf{x},\mathsf{y}),(\mathsf{x},\mathsf{z})\} \subseteq \mathsf{R}^I$ implies $\mathsf{y} = \mathsf{z}$
Reflexive Roles	$\mathsf{Ref}(\mathsf{R})$	for all $\mathsf{x} \in \Delta^I : (\mathsf{x},\mathsf{x}) \in \mathsf{R}^I$
Irreflexive Roles	$\mathsf{Irref}(\mathsf{R})$	for all $\mathsf{x} \in \Delta^I : (\mathsf{x},\mathsf{x}) \notin \mathsf{R}^I$
Symmetric Roles	$\mathsf{Sym}(\mathsf{R})$	$\mathsf{R}^I = (\mathsf{R}^-)^I$
Asymmetric Roles	$\mathsf{Asym}(\mathsf{R})$	$\mathsf{R}^I \cap (\mathsf{R}^-)^I = \emptyset$
Disjoint Roles	$\mathsf{Disj}(\mathsf{R},\mathsf{S})$	$\mathsf{R}^I \cap \mathsf{S}^I = \emptyset$

Description Logics: R-Box

A-Box

$\mathsf{child}(\mathsf{TRAPPIST\text{-}1}, \mathsf{TRAPPIST\text{-}1b})$

$\mathsf{constellation}(\mathsf{TRAPPIST\text{-}1}, \mathsf{Aquarius})$

$\mathsf{RedDwarf}(\mathsf{TRAPPIST\text{-}1})$

$\mathsf{BinaryStar}(\mathsf{AlphaCentauriB})$

T-Box

$\mathsf{RedDwarf} \sqsubseteq \mathsf{DwarfStar}$

$\mathsf{DwarfStar} \sqsubseteq \mathsf{Star}$

$\mathsf{Planet} \sqsubseteq \mathsf{ExtrasolarPlanet} \sqcup \mathsf{SolarPlanet}$

$\mathsf{BinaryStar} \sqsubseteq \exists \mathsf{orbits}.\mathsf{BinaryStar} \sqcap \mathsf{Star}$

R-Box

$\mathsf{child} \sqsubseteq \mathsf{parent}^-$

$\mathsf{parent} \sqsubseteq \mathsf{child}^-$

$\mathsf{parent} \circ \mathsf{constellation} \sqsubseteq \mathsf{constellation}$

$\mathsf{Asym}(\mathsf{parent})$

Ontology

Entailments

A-Box

$\mathsf{parent}(\mathsf{TRAPPIST\text{-}1b}, \mathsf{TRAPPIST\text{-}1})$

$\mathsf{constellation}(\mathsf{TRAPPIST\text{-}1b}, \mathsf{Aquarius})$

$\mathsf{DwarfStar}(\mathsf{TRAPPIST\text{-}1})$

$\mathsf{Star}(\mathsf{AlphaCentauriB})$

$\mathsf{orbits}(\mathsf{AlphaCentauriB}, x)$

$\mathsf{BinaryStar}(x)$

$\mathsf{orbits}(x, y)$

$\ldots$

T-Box

$\mathsf{RedDwarf} \sqsubseteq \mathsf{Star}$

$\mathsf{BinaryStar} \sqsubseteq \exists \mathsf{orbits}.\mathsf{BinaryStar}$

$\mathsf{BinaryStar} \sqsubseteq \exists \mathsf{orbits}.\mathsf{Star}$

$\mathsf{BinaryStar} \sqsubseteq \exists \mathsf{orbits}.\top$

$\mathsf{BinaryStar} \sqsubseteq \mathsf{Star}$

$\mathsf{RedDwarf} \sqsubseteq \top$

$\bot \sqsubseteq \mathsf{RedDwarf}$

$\ldots$

R-Box

$\mathsf{Irref}(\mathsf{parent})$

$\mathsf{Asym}(\mathsf{child})$

$\mathsf{Irref}(\mathsf{child})$

$\mathsf{Disj}(\mathsf{child}, \mathsf{parent})$

$\mathsf{Disj}(\mathsf{parent}, \mathsf{child})$

$\ldots$

Description Logics: graphs

A-Box

child(TRAPPIST-1, TRAPPIST-1b)

constellation(TRAPPIST-1, Aquarius)

RedDwarf(TRAPPIST-1)

...

T-Box

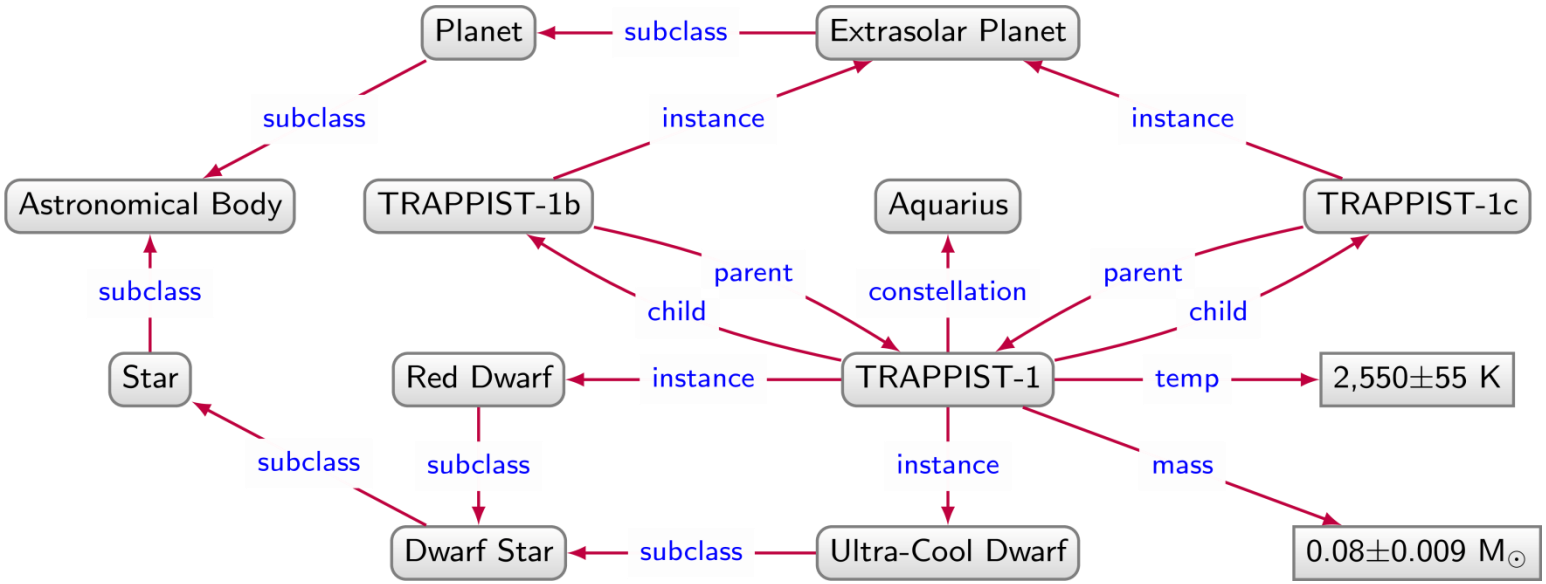
RedDwarf $\sqsubseteq$ DwarfStar

DwarfStar $\sqsubseteq$ Star

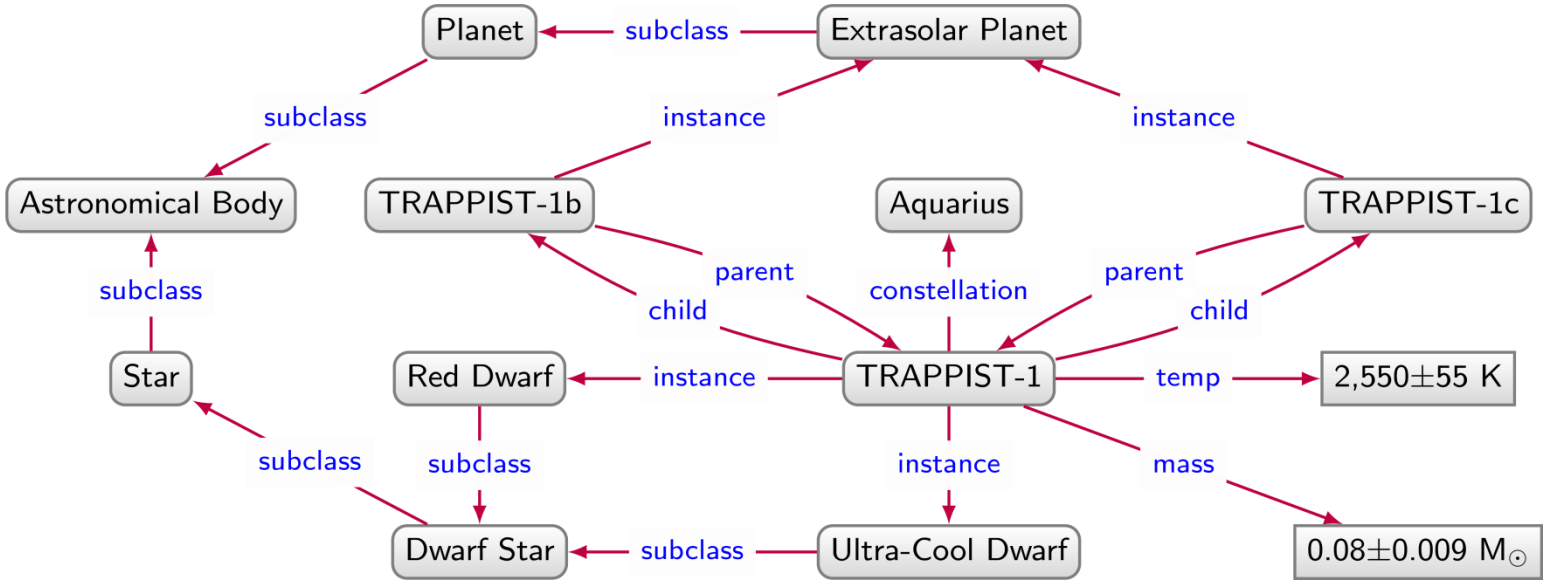
...

R-Box

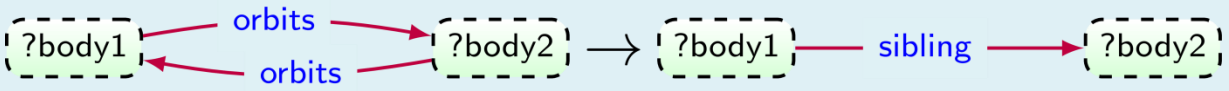
Ontology



Rules: beyond ontologies

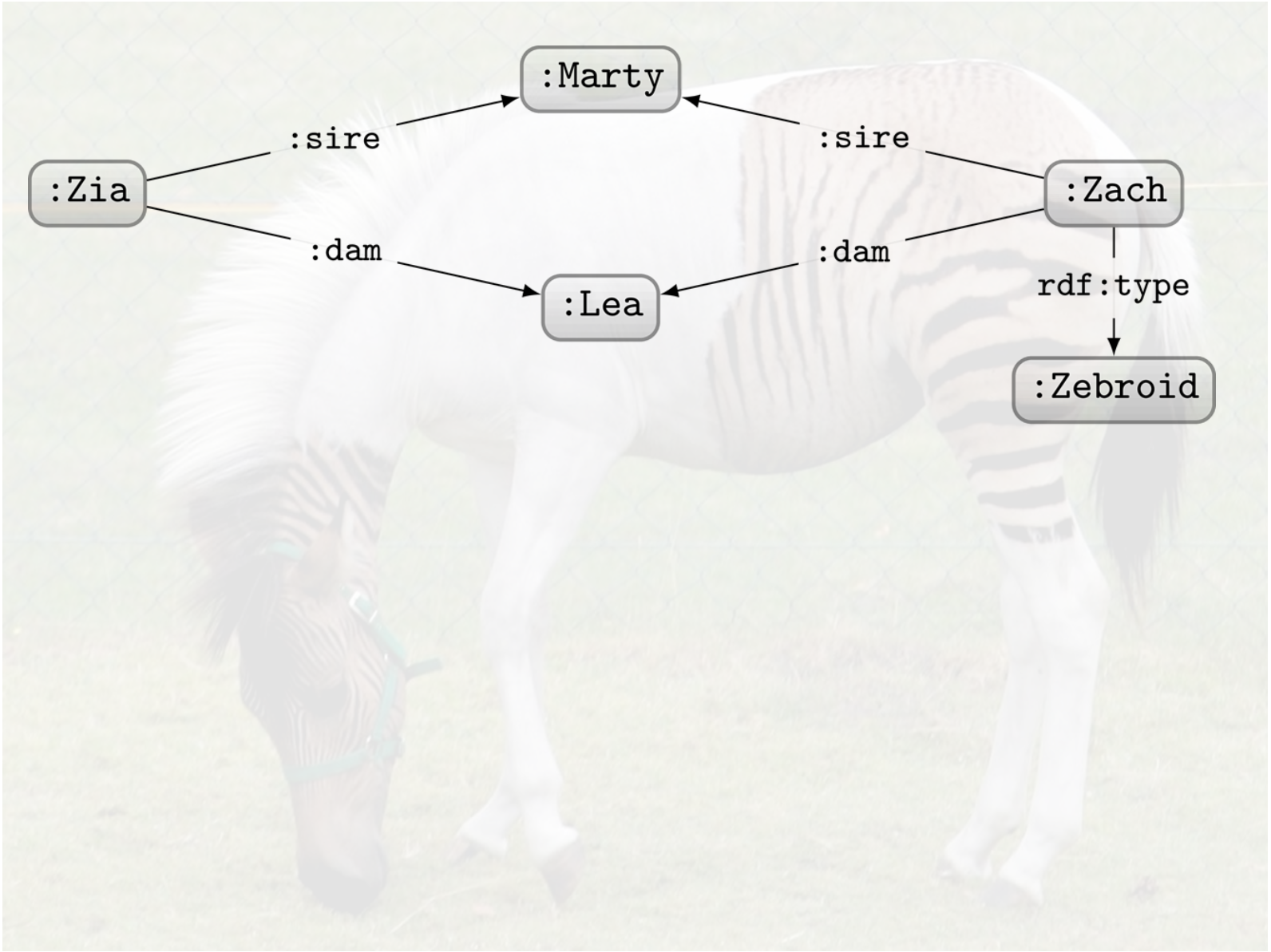


orbits ⊓ orbits$^-$ ⊑ sibling

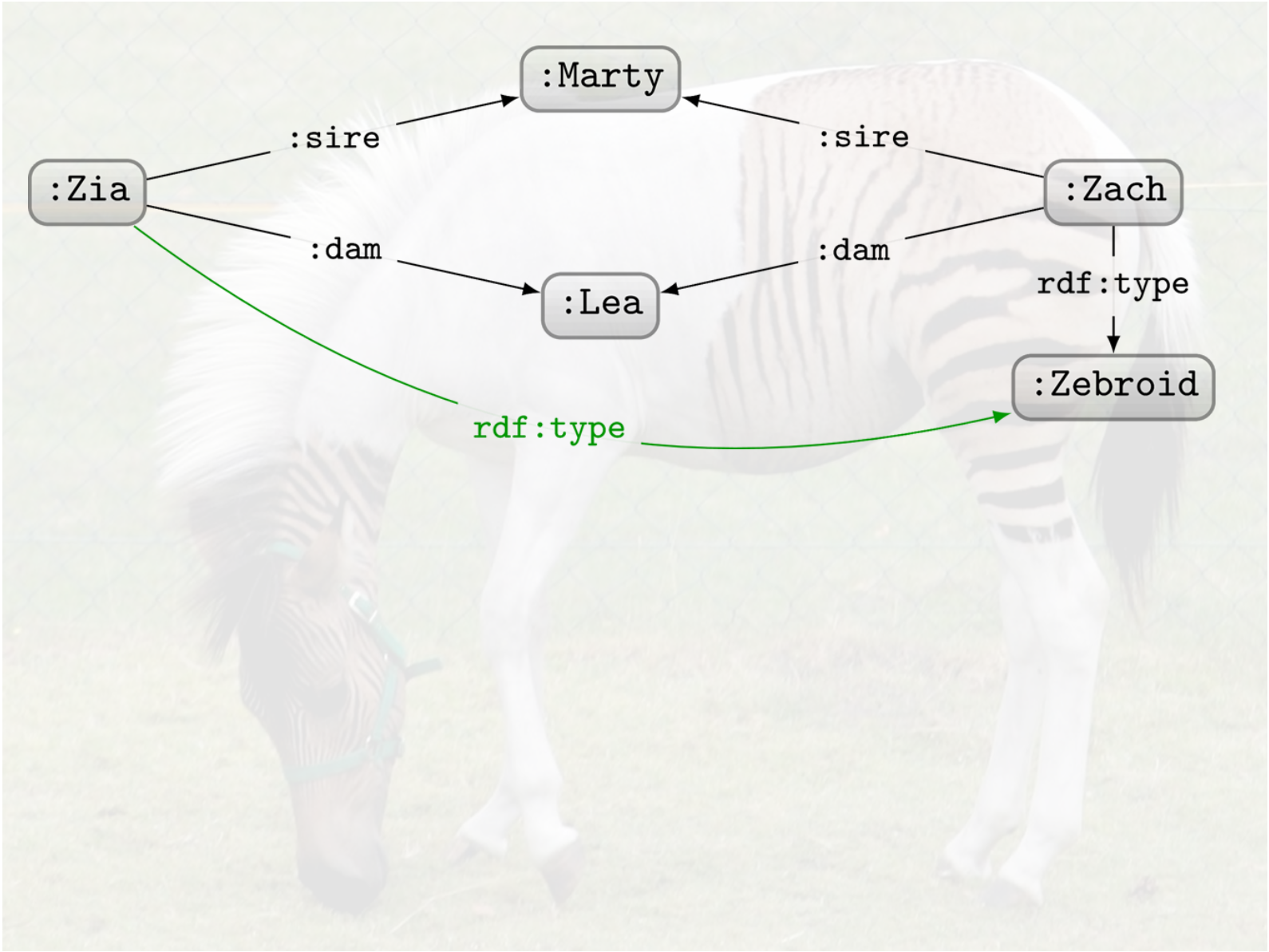


Ontologies: beyond rules

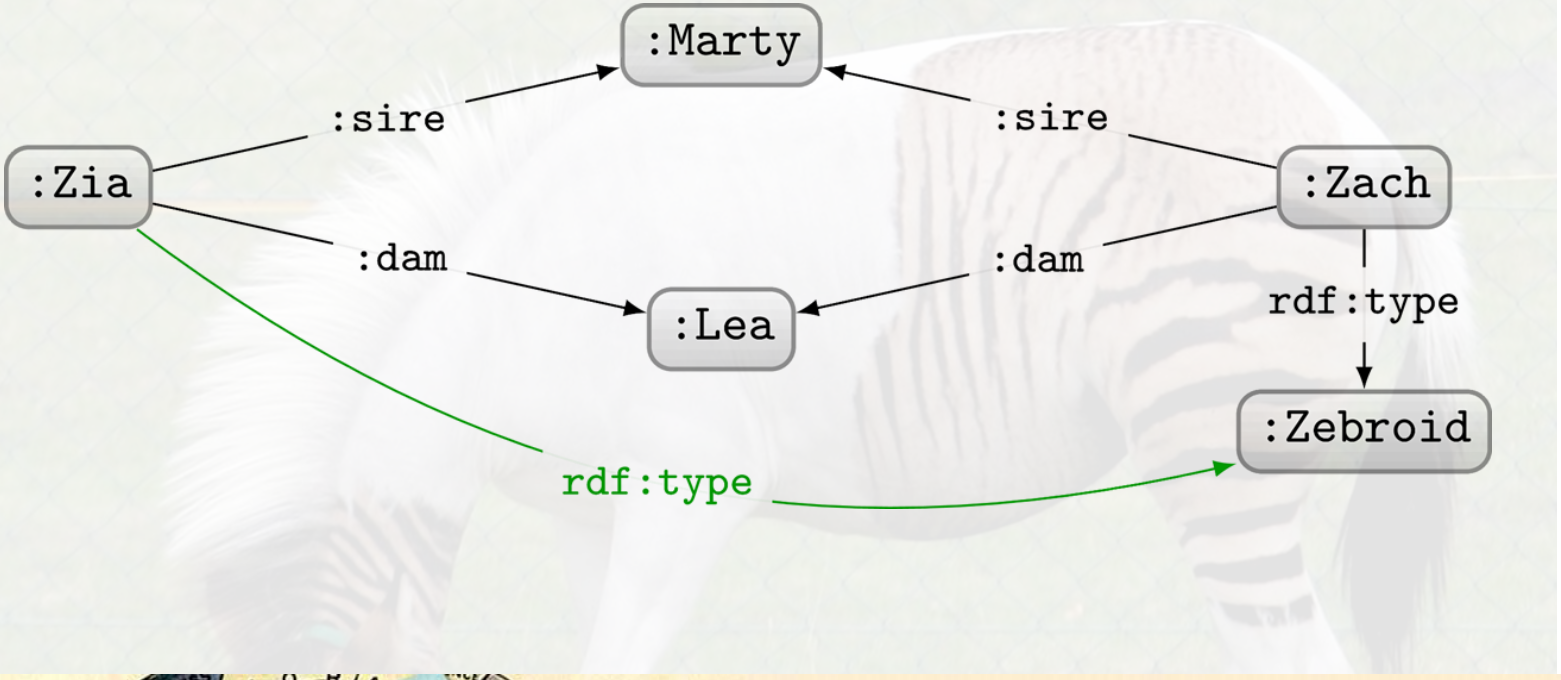
Ontologies: beyond rules

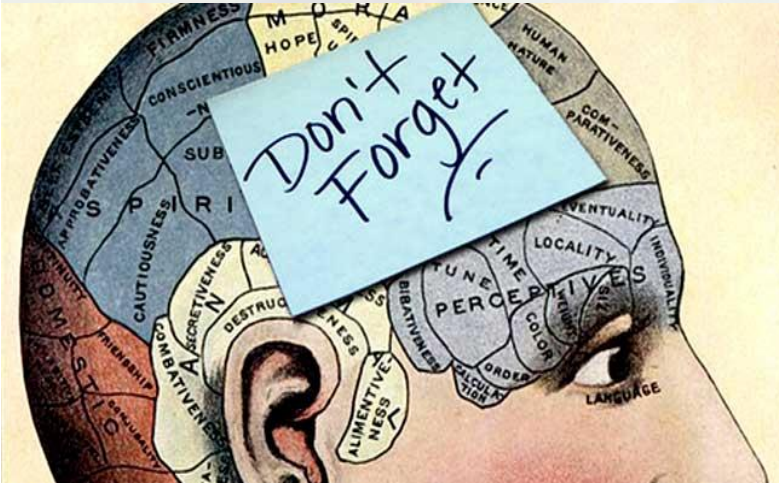


Ontologies: beyond rules

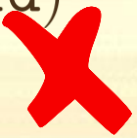


Ontologies: beyond rules

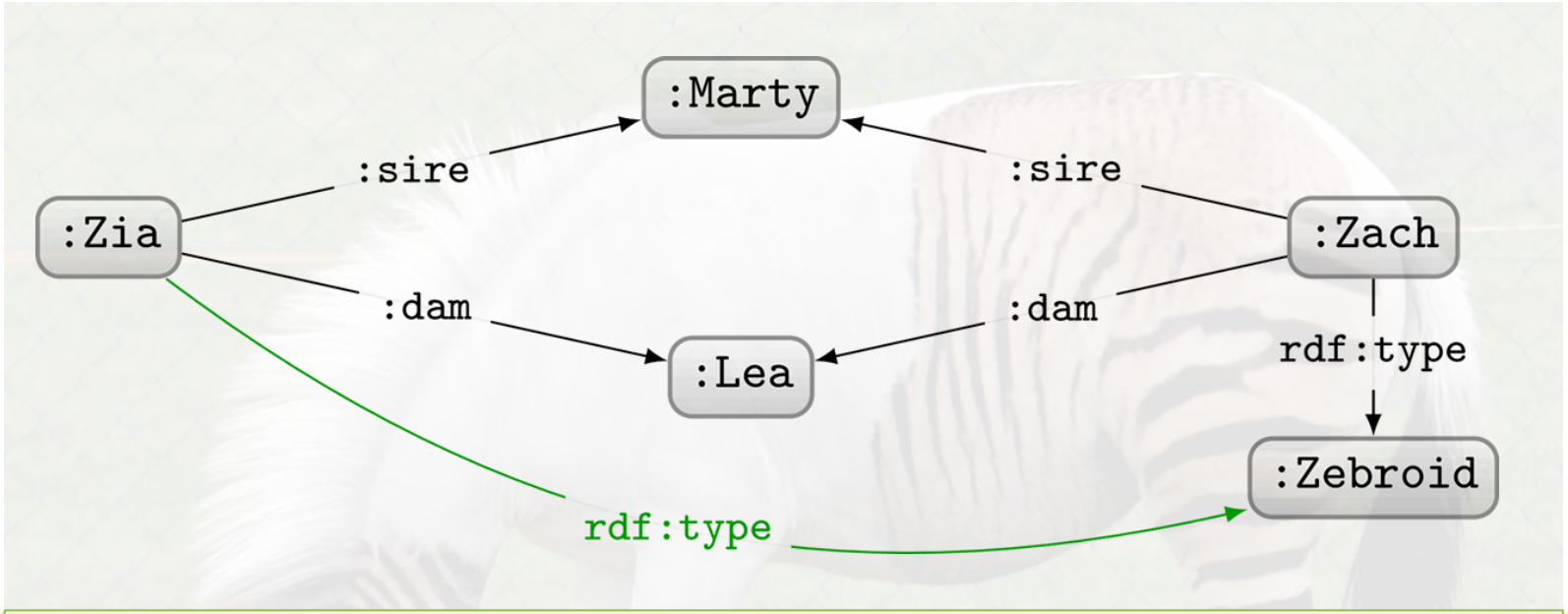




$(x, \texttt{:dam}, z_1)$, $(x, \texttt{:sire}, z_2)$,
$(y, \texttt{:dam}, z_1)$, $(y, \texttt{:sire}, z_2)$,
$(y, \texttt{rdf:type}, \texttt{:Zebroid})$
$\rightarrow (x, \texttt{rdf:type}, \texttt{:Zebroid})$



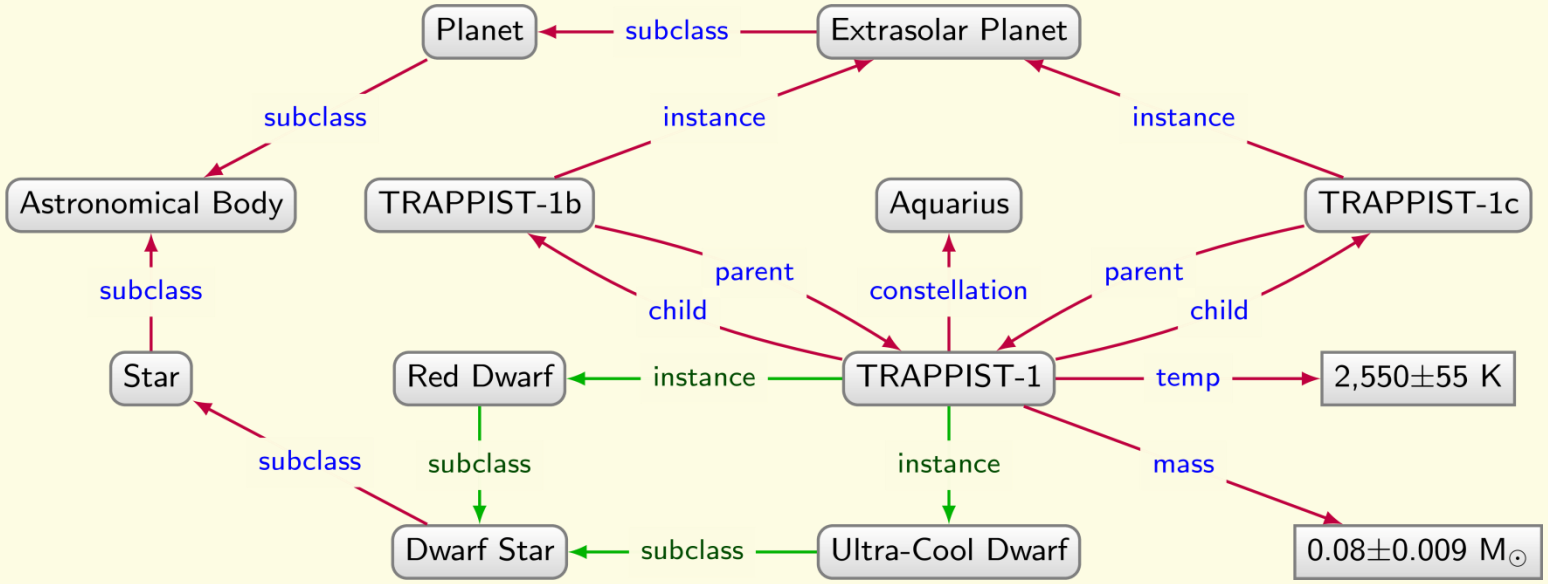
Ontologies: beyond rules



- `sire` is a sub-property of `parent`
- `dam` is a sub-property of `parent`
- A `Zebroid` has exactly one `parent` a `Zebra`
- A `Zebroid` has exactly one `parent` a (¬`Zebra` and a `Equine`)
- A `Zebroid` is a sub-class of `Equine`
- An `Equine` has exactly two `parents`
- Two things cannot be related by `sire` and `dam` at the same time

Topic 4:
OBDA on Graphs

OBDA: complex graph patterns



Graph Pattern

Q : ?dstar — instance → Dwarf Star

O : RedDwarf $\sqsubseteq$ DwarfStar

UltraCoolDwarf $\sqsubseteq$ DwarfStar

DwarfStar $\sqsubseteq$ Star

...

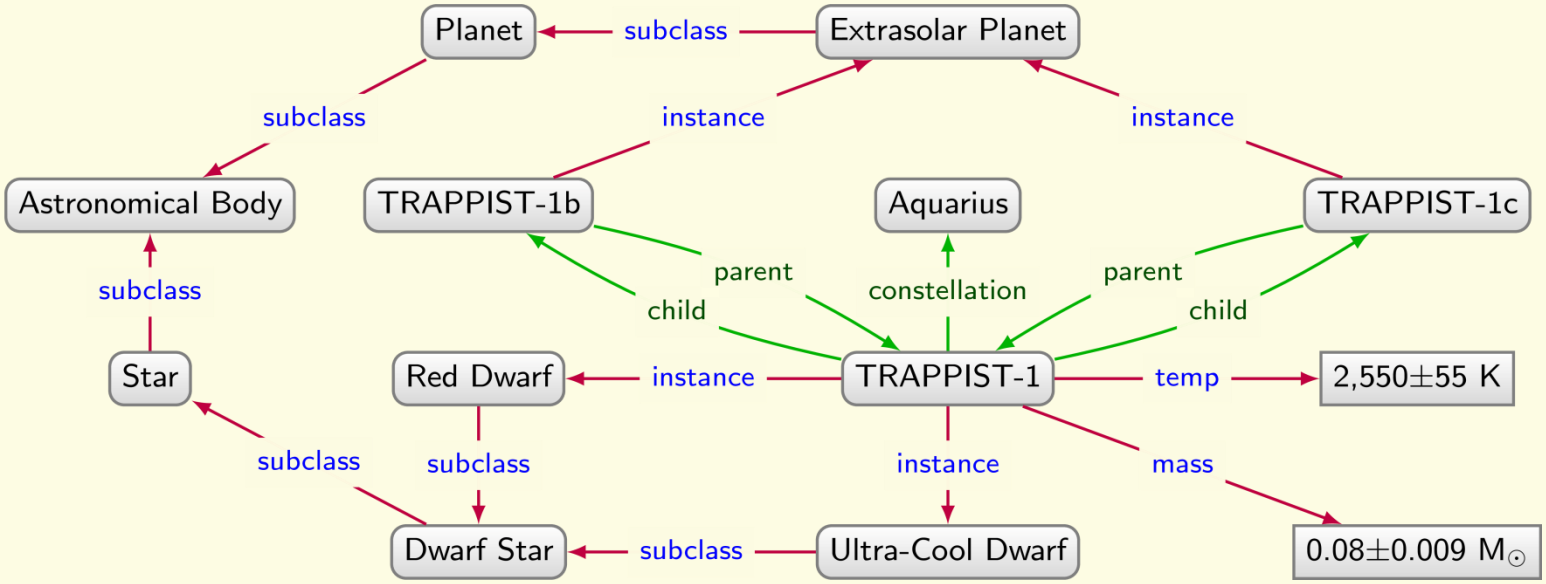
Complex Graph Pattern

$O(Q)$: ?dstar — instance → Dwarf Star ∪

?dstar — instance → Red Dwarf ∪

?dstar — instance → Ultra-Cool Dwarf

OBDA: navigational graph patterns



How can paths be leveraged/supported in OBDA?

Graph Pattern

Q : ?body —constellation→ Aquarius

O :

$\text{child} \sqsubseteq \text{parent}^-$

$\text{parent} \sqsubseteq \text{child}^-$

$\text{parent} \circ \text{constellation} \sqsubseteq \text{constellation}$

...

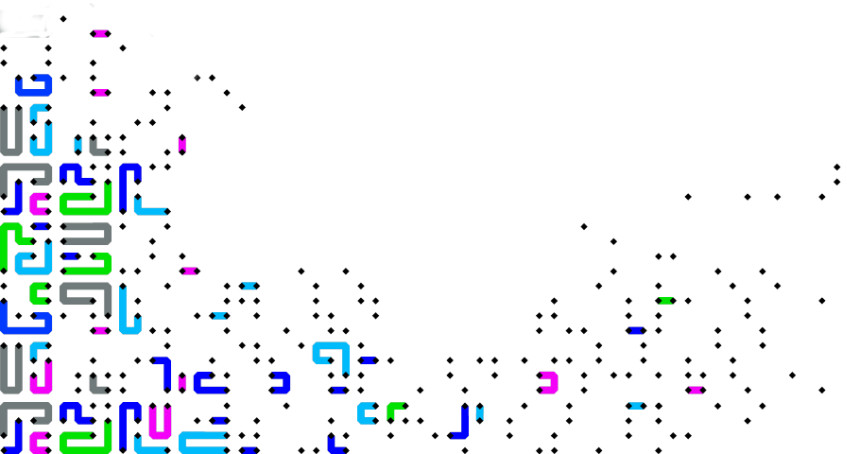
Complex Navigational Graph Pattern

$O(Q)$: ?body —constellation→ Aquarius ∪

?body —parent*/constellation→ Aquarius ∪

?body —(child⁻)*/constellation→ Aquarius

Context



The truth is rarely pure and never simple.

(Oscar Wilde)

Without context

A proposition φ is TRUE.

- `president(Clinton,US)` is TRUE.
- `Illegal(Bitcoin)` is TRUE.
- `bornIn(Obama,Kenya)` is TRUE.

With context

A proposition φ is TRUE *in context* c.

- `president(Clinton,US)` is TRUE.
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With context

A proposition φ is TRUE *in context* c.

- `president(Clinton,US)` is TRUE *in context* `[1993,2001]` (*temporal*).
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With context

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With context

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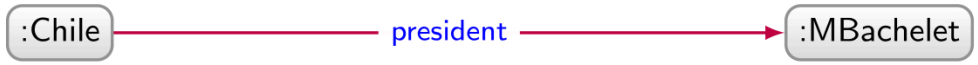
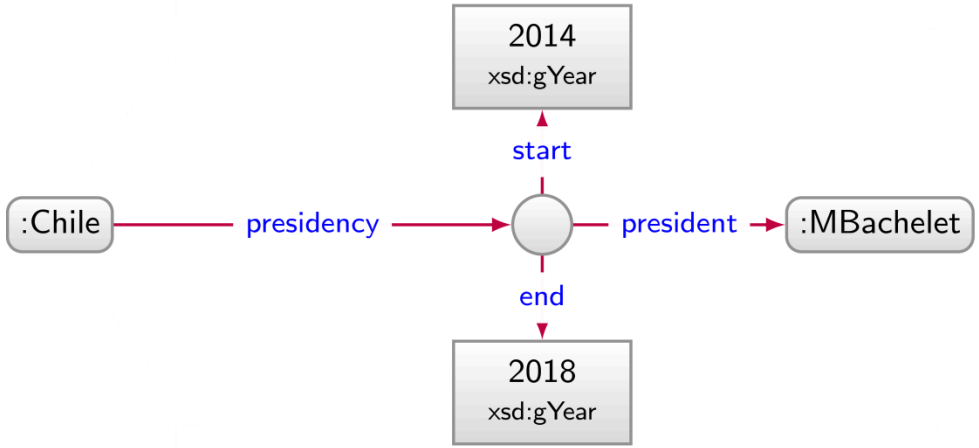
- `Illegal(Bitcoin)` is TRUE *in context* `Bolivia` (*geographical*).
- `bornIn(Obama,Kenya)` is TRUE *in context* `Breitbart` (*provenance*).
- ...

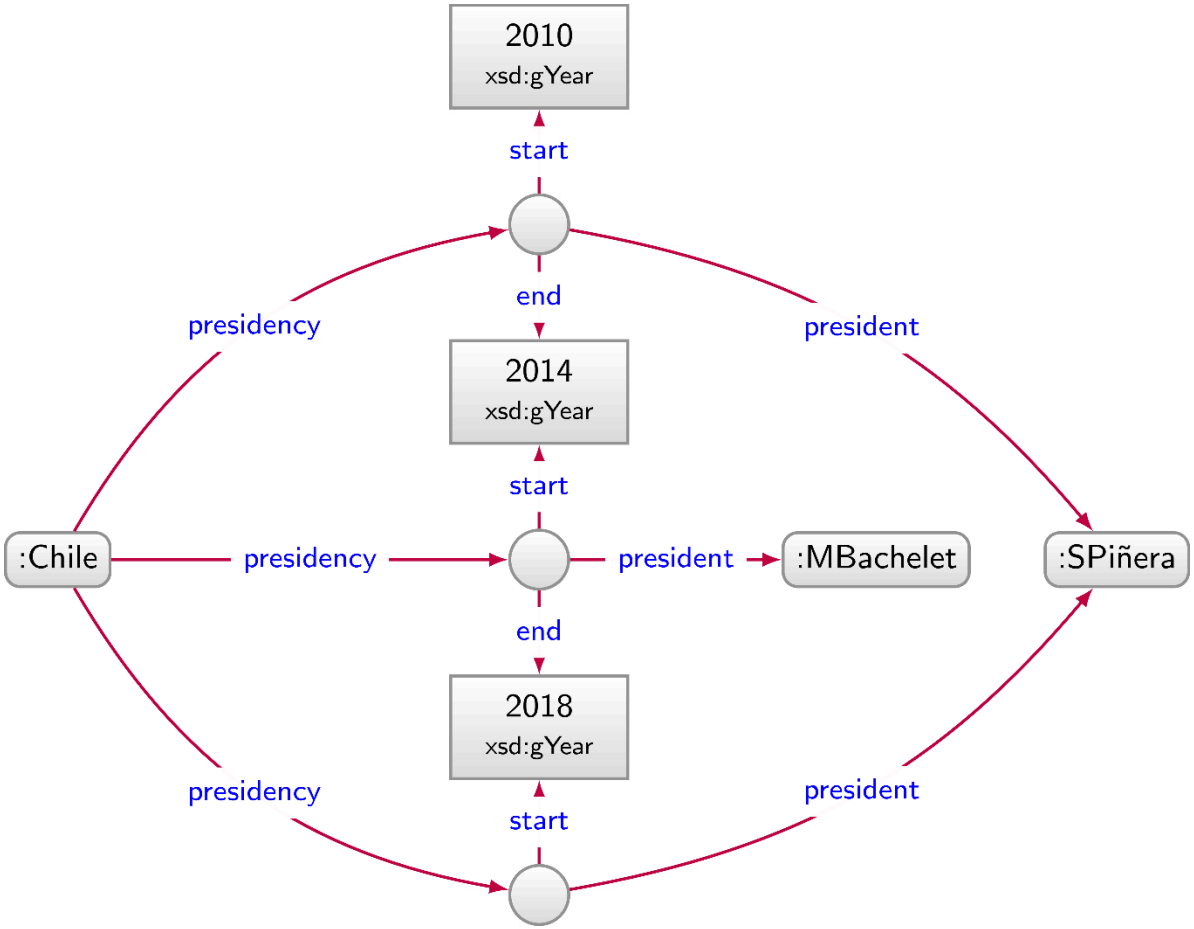
Context in graphs



Context in graphs



Context in graphs



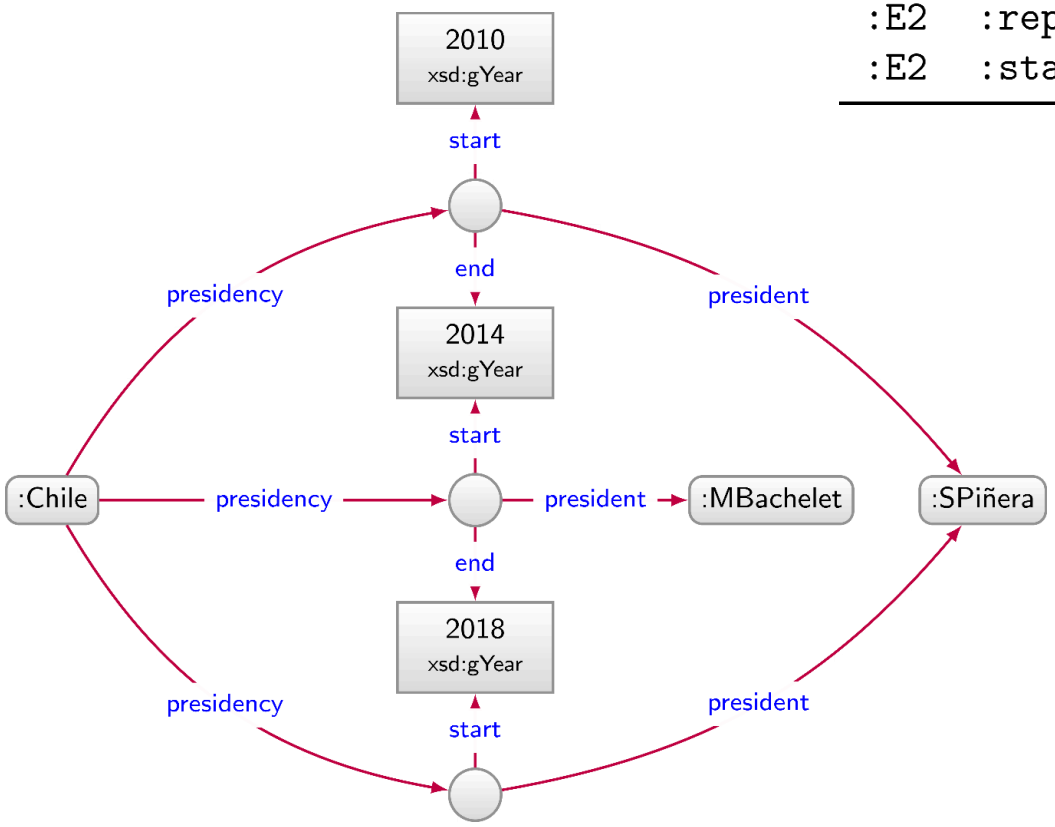
Is this context? Or is this data?

DATACONTEXT

Contextual representation

S	P	O	E
:SPiñera	:president	:Chile	:E1
:SPiñera	:president	:Chile	:E2

E	Q	V
:E1	:start	"2010"^^xsd:gYear
:E1	:end	"2014"^^xsd:gYear
:E1	:replaces	:MBachelet
:E1	:replacedBy	:MBachelet
:E2	:replaces	:MBachelet
:E2	:start	"2018"^^xsd:gYear



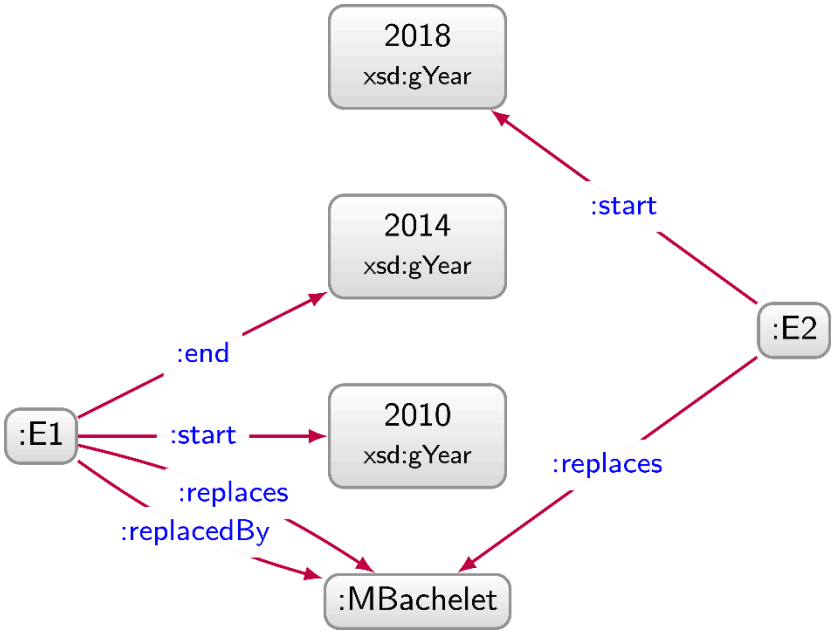
Contextual representation

S	P	O	E
:SPiñera	:president	:Chile	:E1
:SPiñera	:president	:Chile	:E2

How to represent this as a graph?

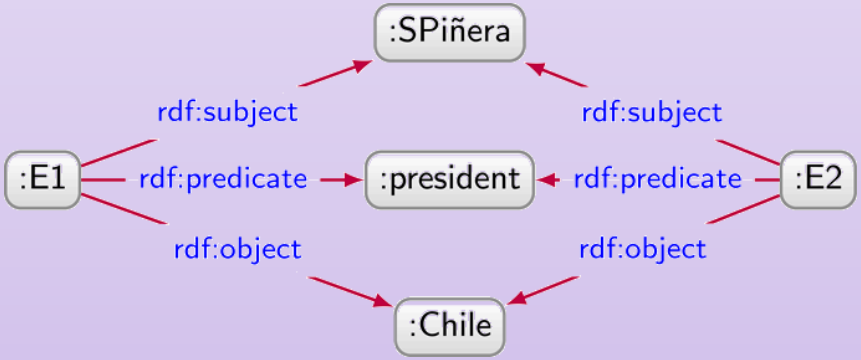
???

E	Q	V
:E1	:start	"2010"^^xsd:gYear
:E1	:end	"2014"^^xsd:gYear
:E1	:replaces	:MBachelet
:E1	:replacedBy	:MBachelet
:E2	:replaces	:MBachelet
:E2	:start	"2018"^^xsd:gYear

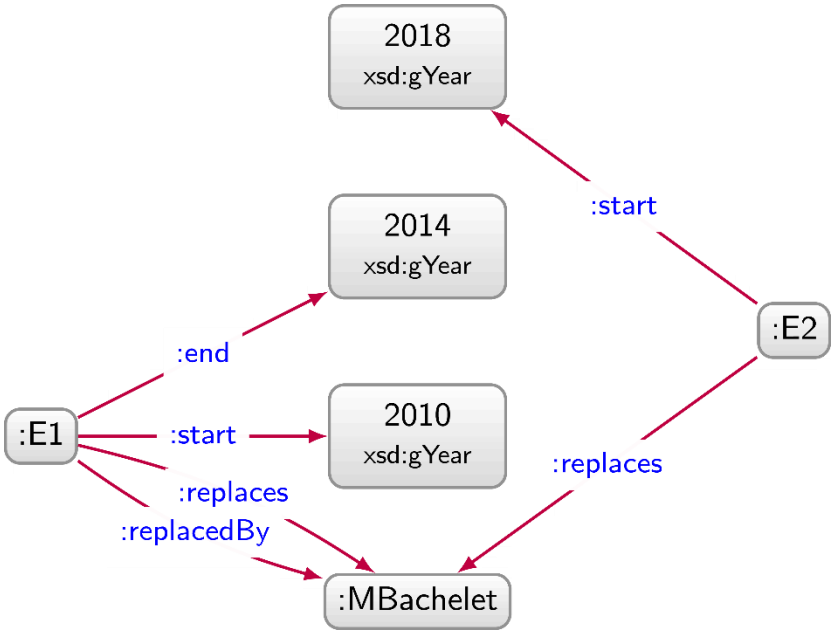


Reification

S	P	O	E
:SPiñera	:president	:Chile	:E1
:SPiñera	:president	:Chile	:E2

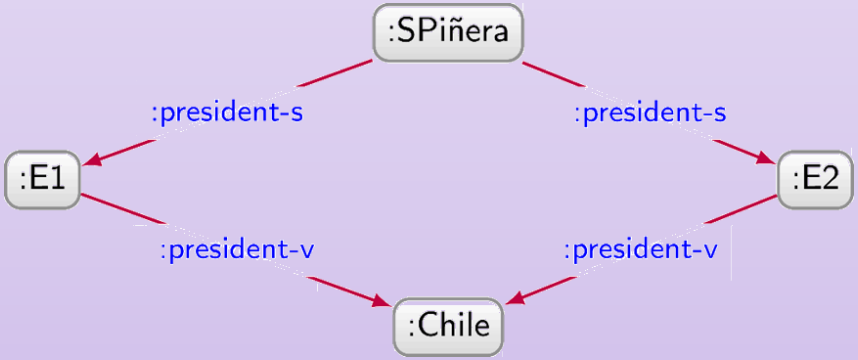


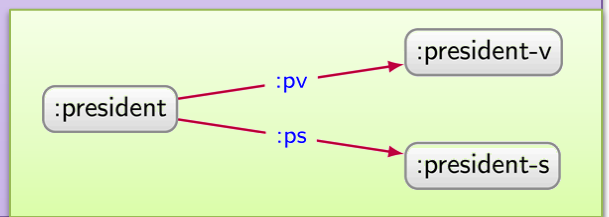
E	Q	V
:E1	:start	"2010"^^xsd:gYear
:E1	:end	"2014"^^xsd:gYear
:E1	:replaces	:MBachelet
:E1	:replacedBy	:MBachelet
:E2	:replaces	:MBachelet
:E2	:start	"2018"^^xsd:gYear



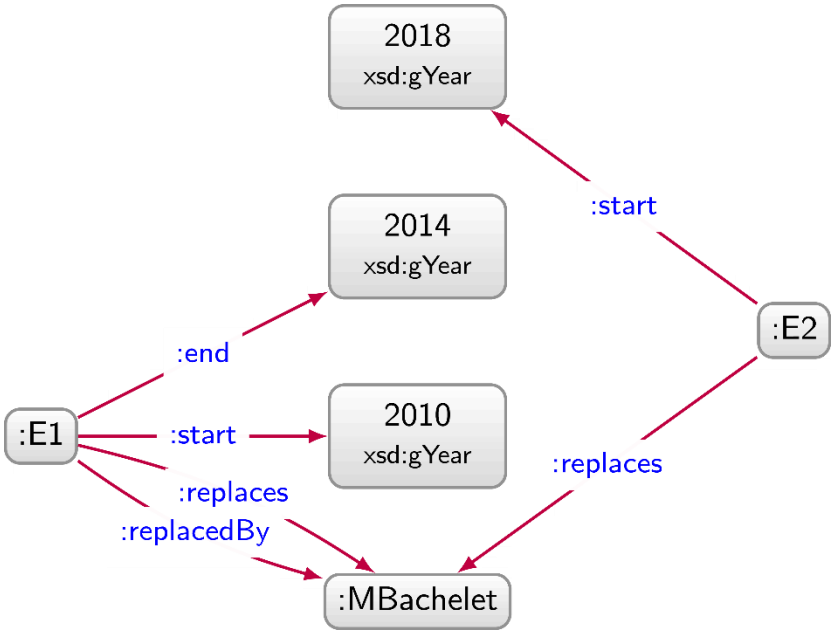
n-ary Relations

S	P	O	E
:SPiñera	:president	:Chile	:E1
:SPiñera	:president	:Chile	:E2



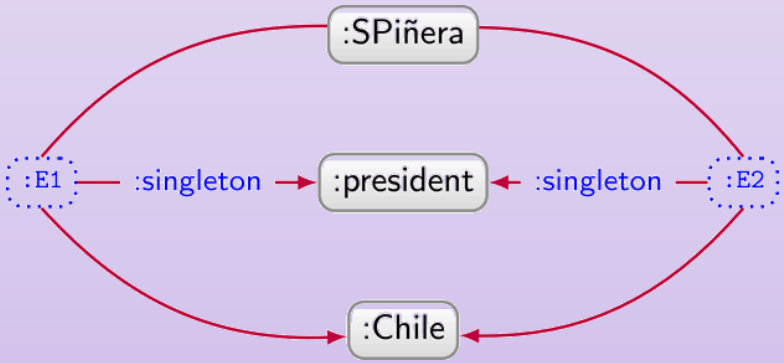


E	Q	V
:E1	:start	"2010"^^xsd:gYear
:E1	:end	"2014"^^xsd:gYear
:E1	:replaces	:MBachelet
:E1	:replacedBy	:MBachelet
:E2	:replaces	:MBachelet
:E2	:start	"2018"^^xsd:gYear



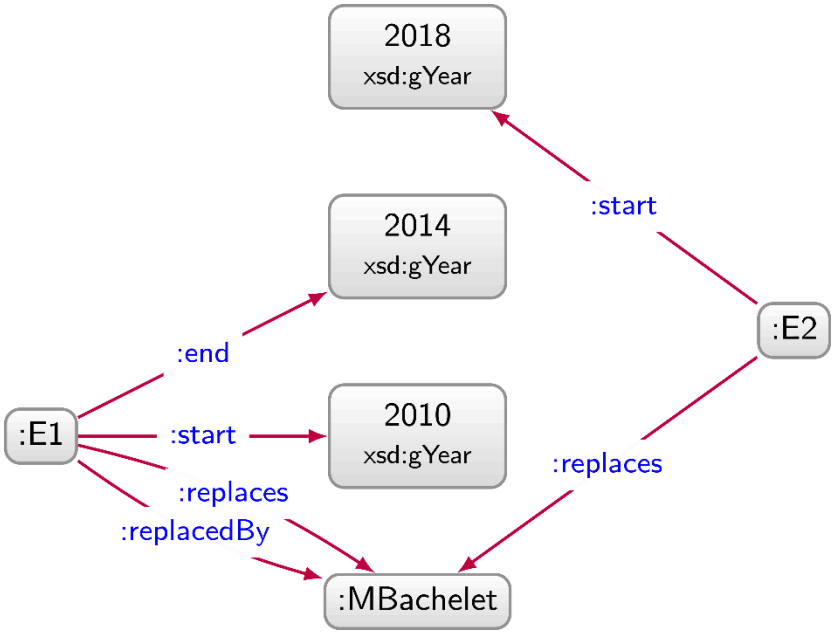
Singleton Properties

S	P	O	E
:SPiñera	:president	:Chile	:E1
:SPiñera	:president	:Chile	:E2



[Nguyen et al. 14]

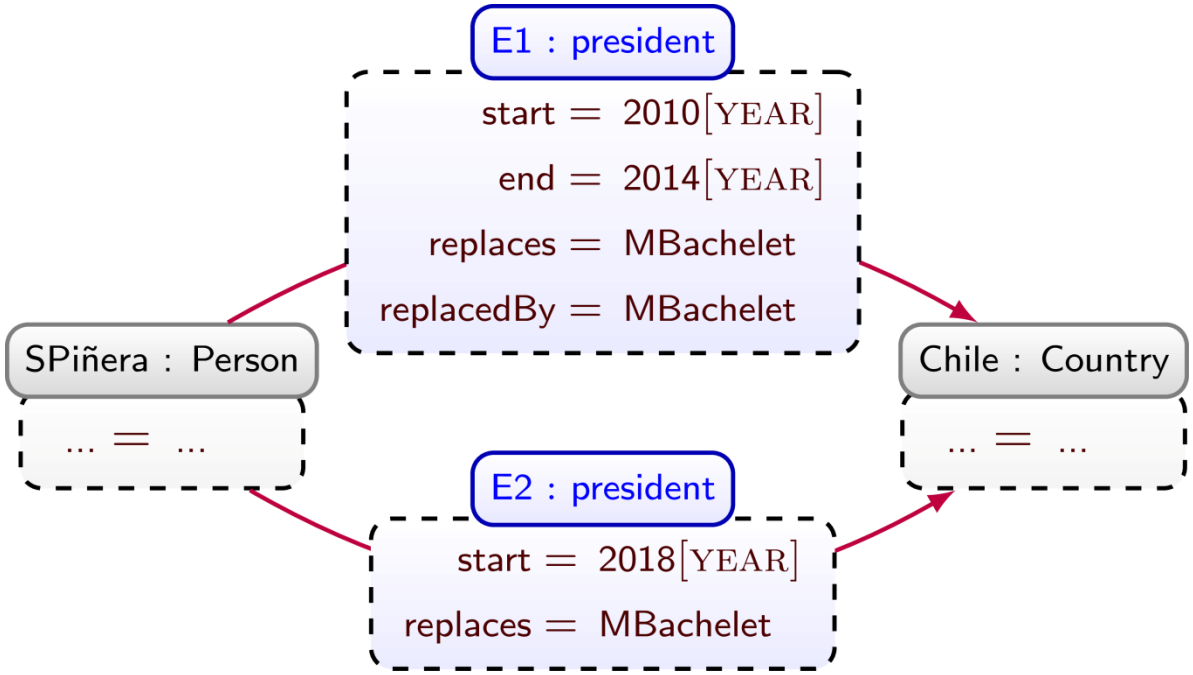
E	Q	V
:E1	:start	"2010"^^xsd:gYear
:E1	:end	"2014"^^xsd:gYear
:E1	:replaces	:MBachelet
:E1	:replacedBy	:MBachelet
:E2	:replaces	:MBachelet
:E2	:start	"2018"^^xsd:gYear



Property Graph

S	P	O	E
:SPiñera	:president	:Chile	:E1
:SPiñera	:president	:Chile	:E2

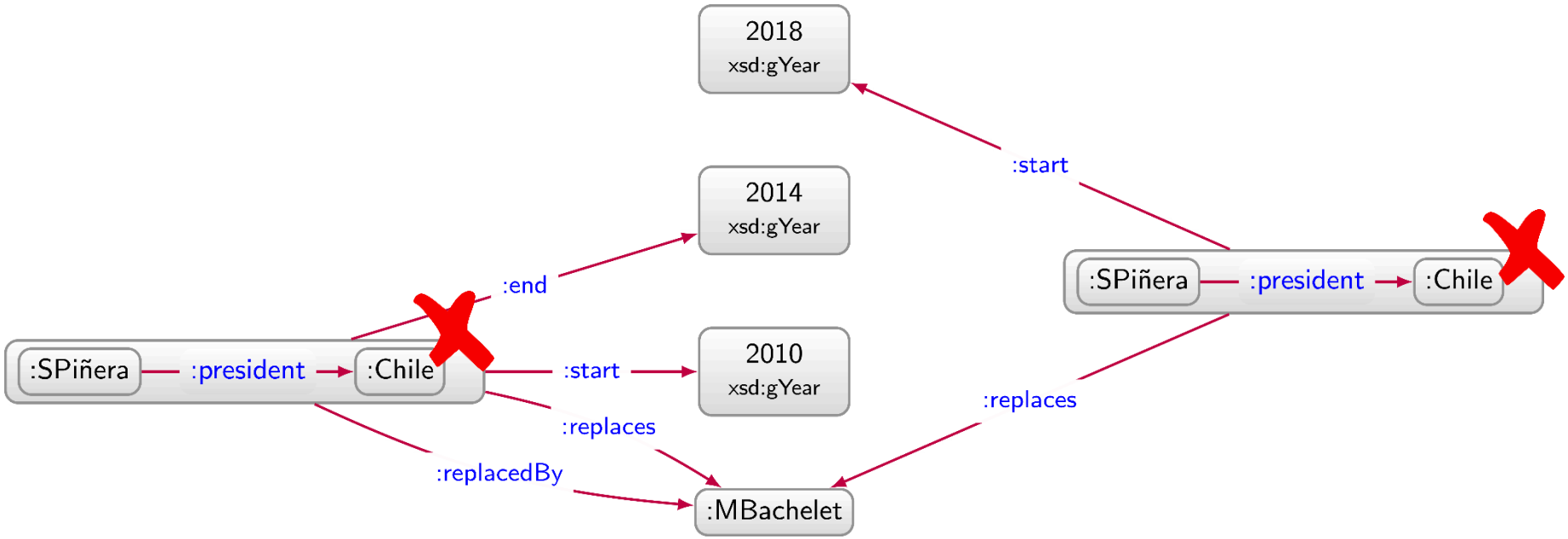
E	Q	V
:E1	:start	"2010"^^xsd:gYear
:E1	:end	"2014"^^xsd:gYear
:E1	:replaces	:MBachelet
:E1	:replacedBy	:MBachelet
:E2	:replaces	:MBachelet
:E2	:start	"2018"^^xsd:gYear



RDF*

S	P	O	E
:SPiñera	:president	:Chile	:E1
:SPiñera	:president	:Chile	:E2

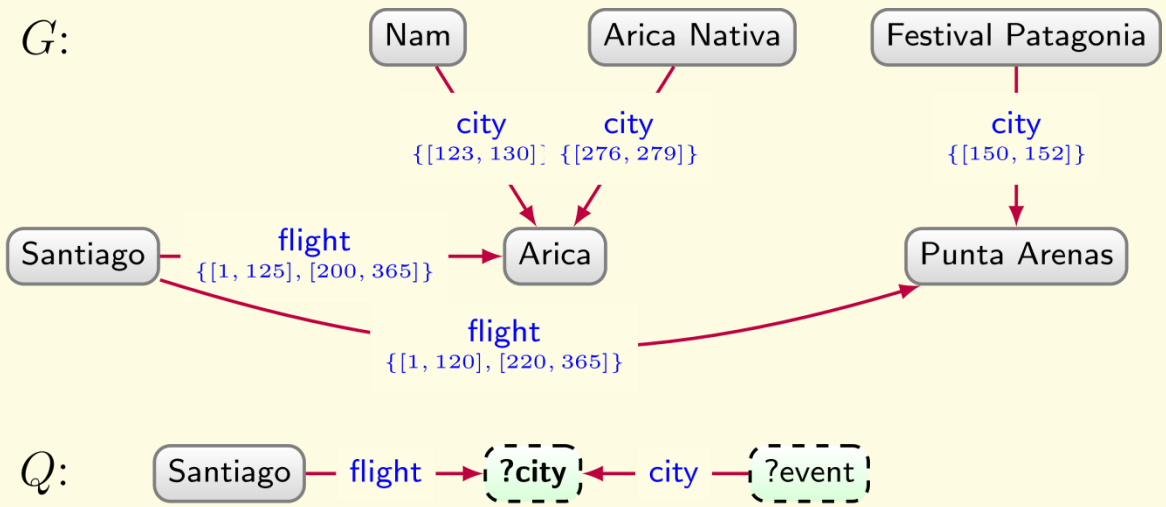
E	Q	V
:E1	:start	"2010"^^xsd:gYear
:E1	:end	"2014"^^xsd:gYear
:E1	:replaces	:MBachelet
:E1	:replacedBy	:MBachelet
:E2	:replaces	:MBachelet
:E2	:start	"2018"^^xsd:gYear



[Hartig 17]

Topic 6:
Complex Contextual Semantics

Contextual semantics

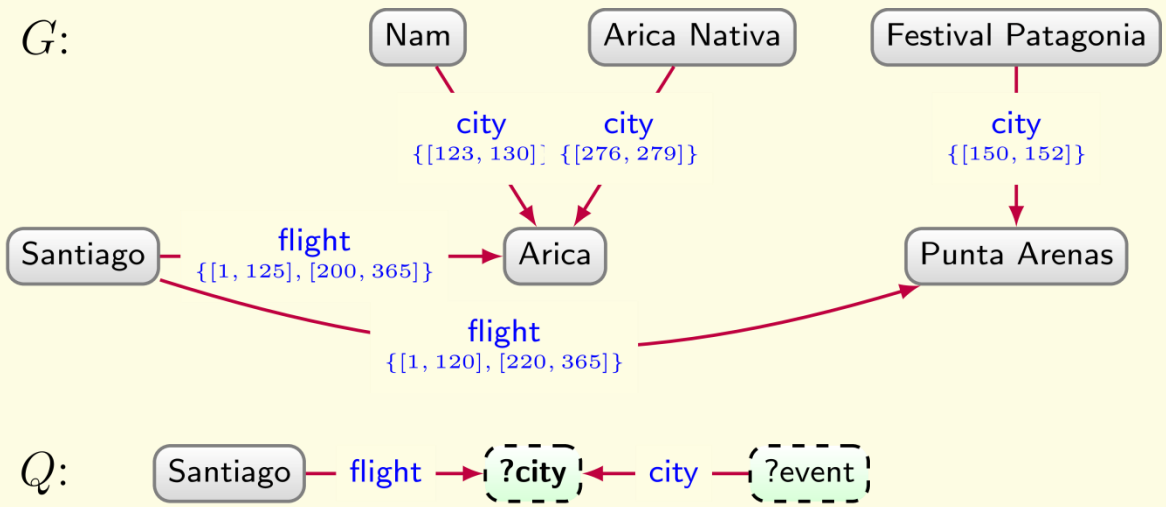


$Q(G)$:

?city	context
Arica	$\{[123, 125], [276, 279]\}$

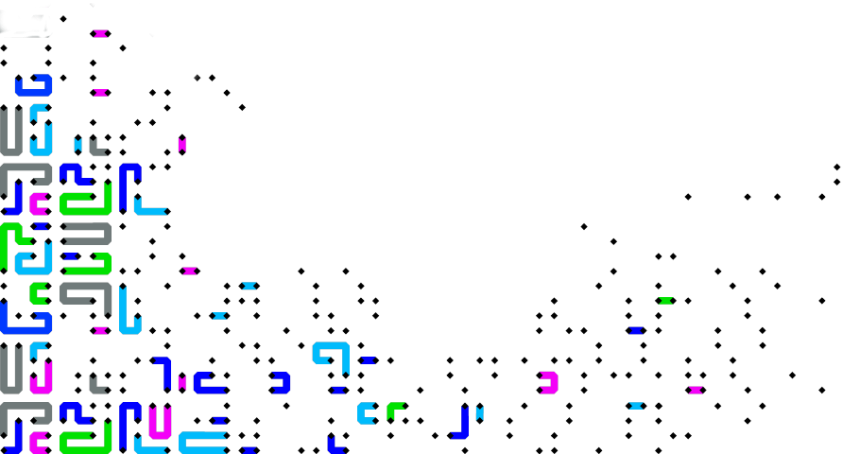
[Zimmermann et al. 2012]

Contextual semantics

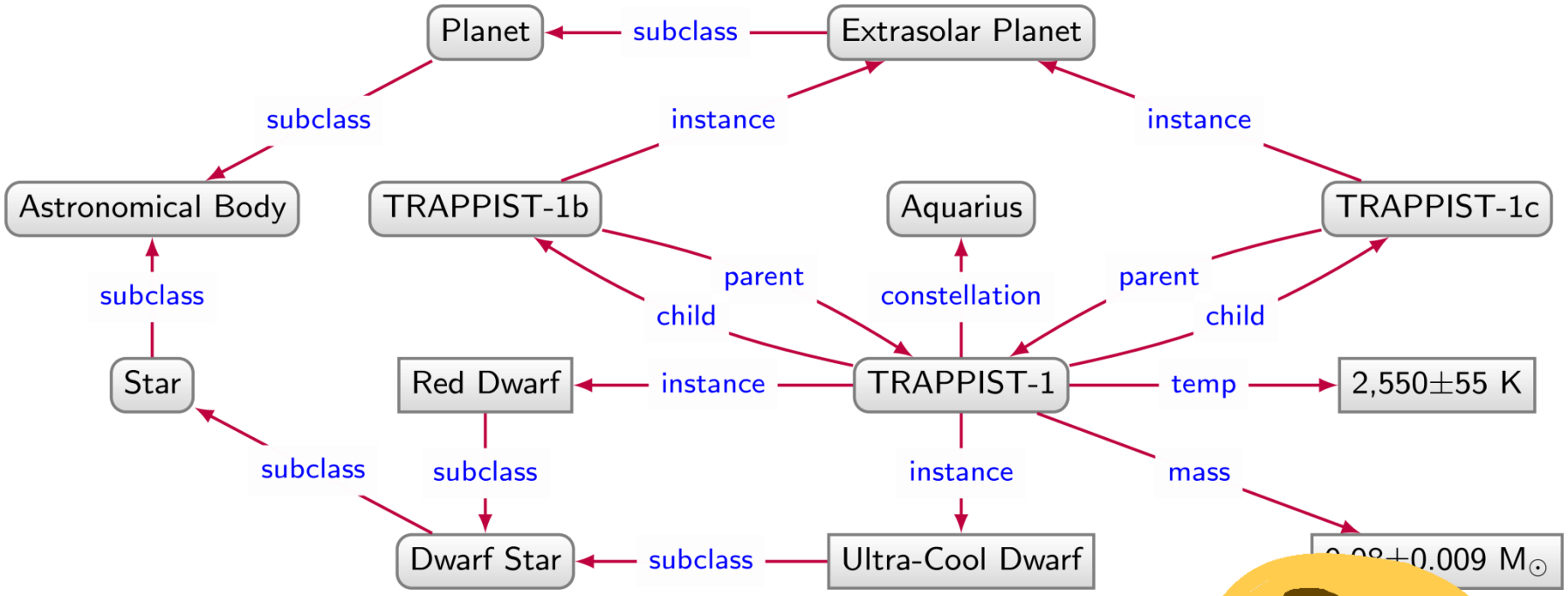


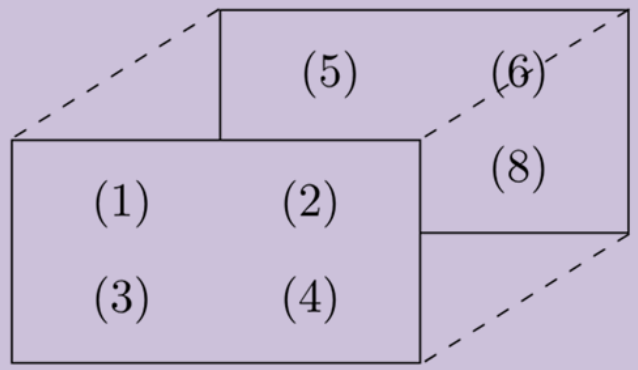
How can we handle more complex contexts?

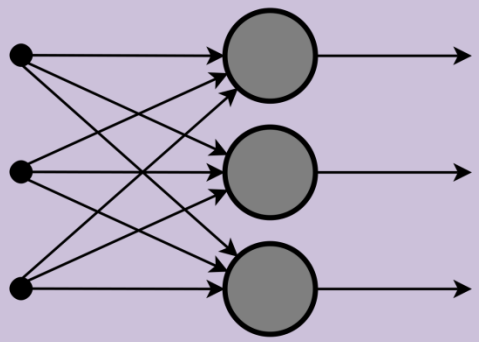
Knowledge Graph Embeddings

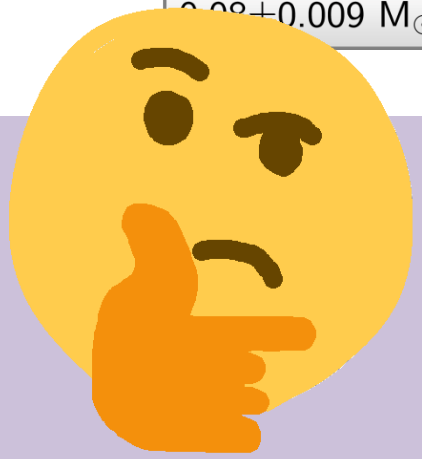


Machine learning over graphs



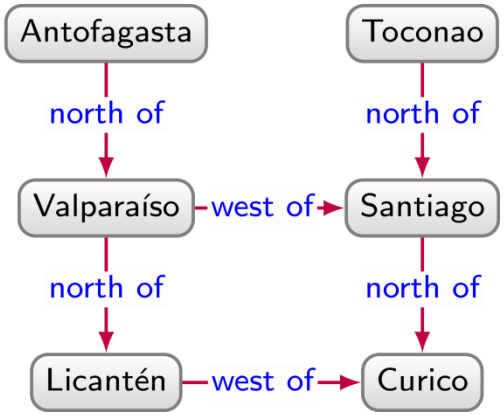




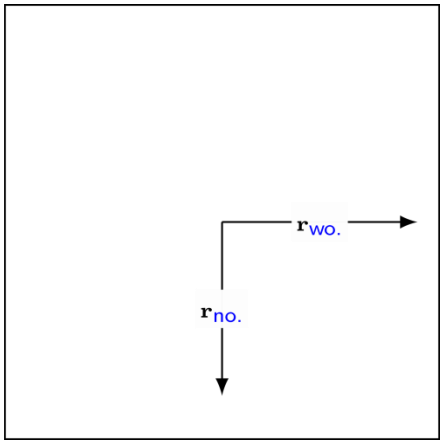


Knowledge Graph Embeddings: Translational Embeddings

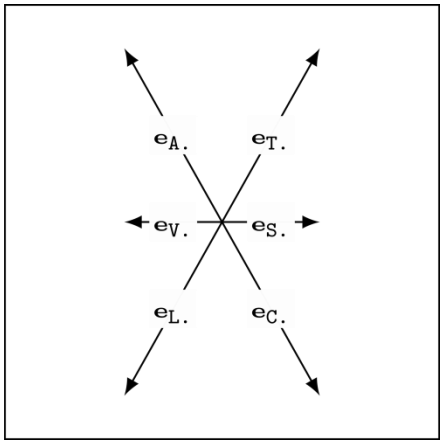
Input Graph



Relation Embedding

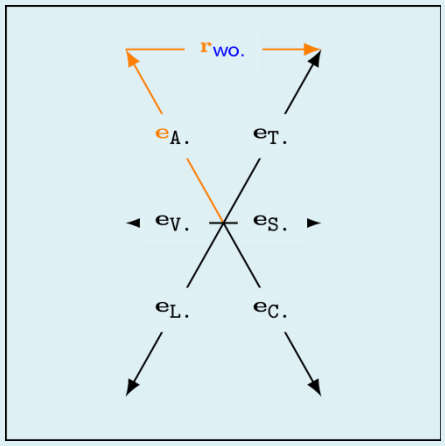


Entity Embedding



What is west of Antofagasta?

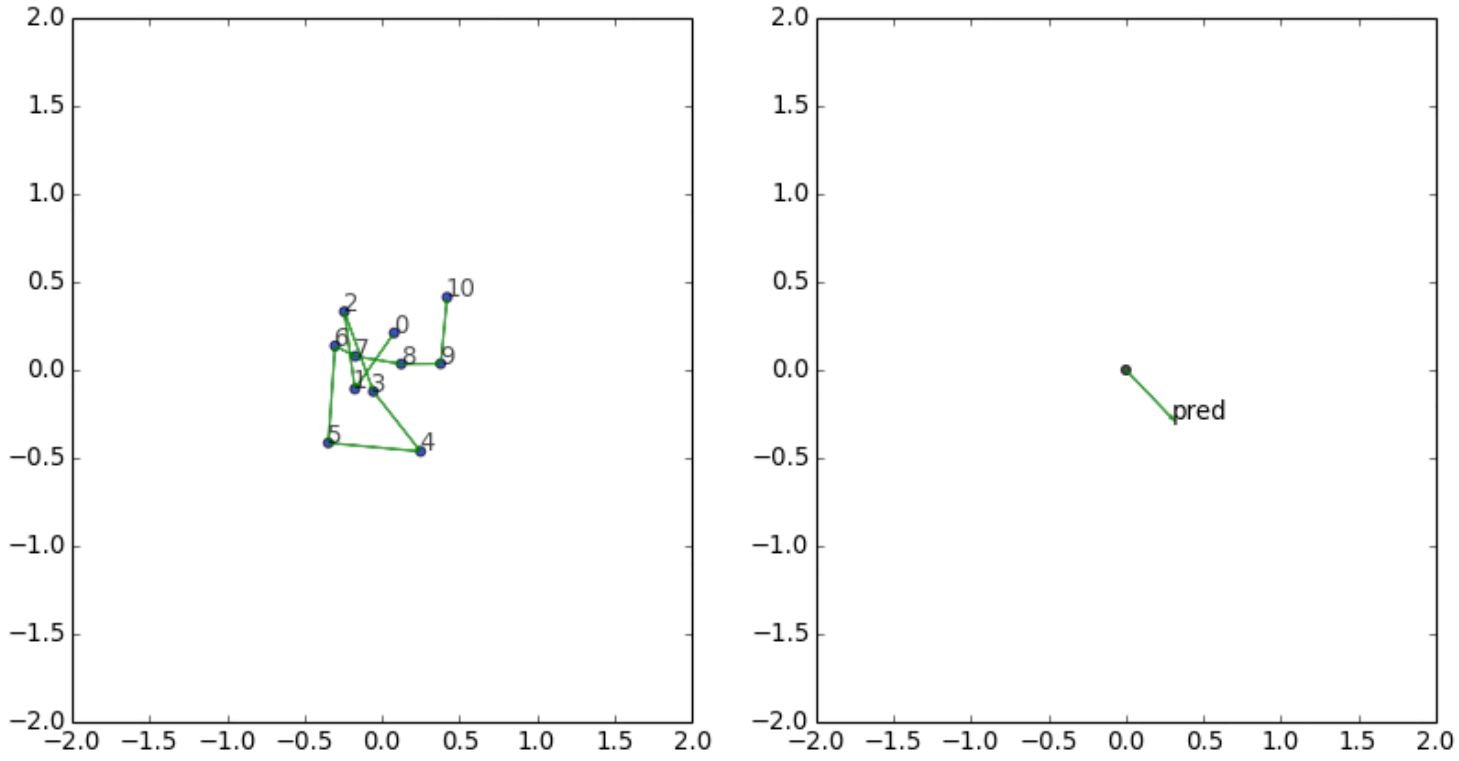
Link Prediction:



Highest Plausibility:

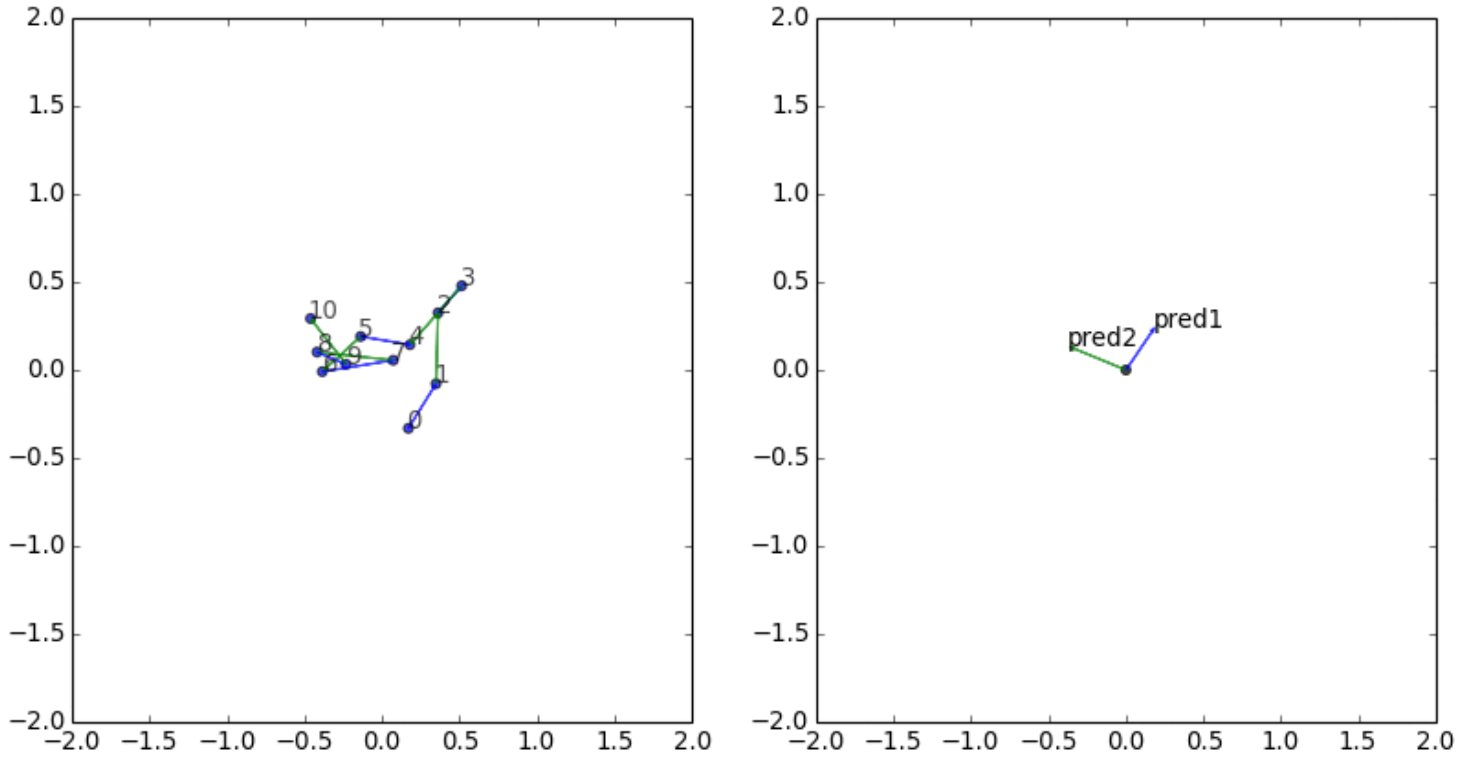
Antofagasta —west of→ Toconao

Knowledge Graph Embeddings: Translational Embeddings



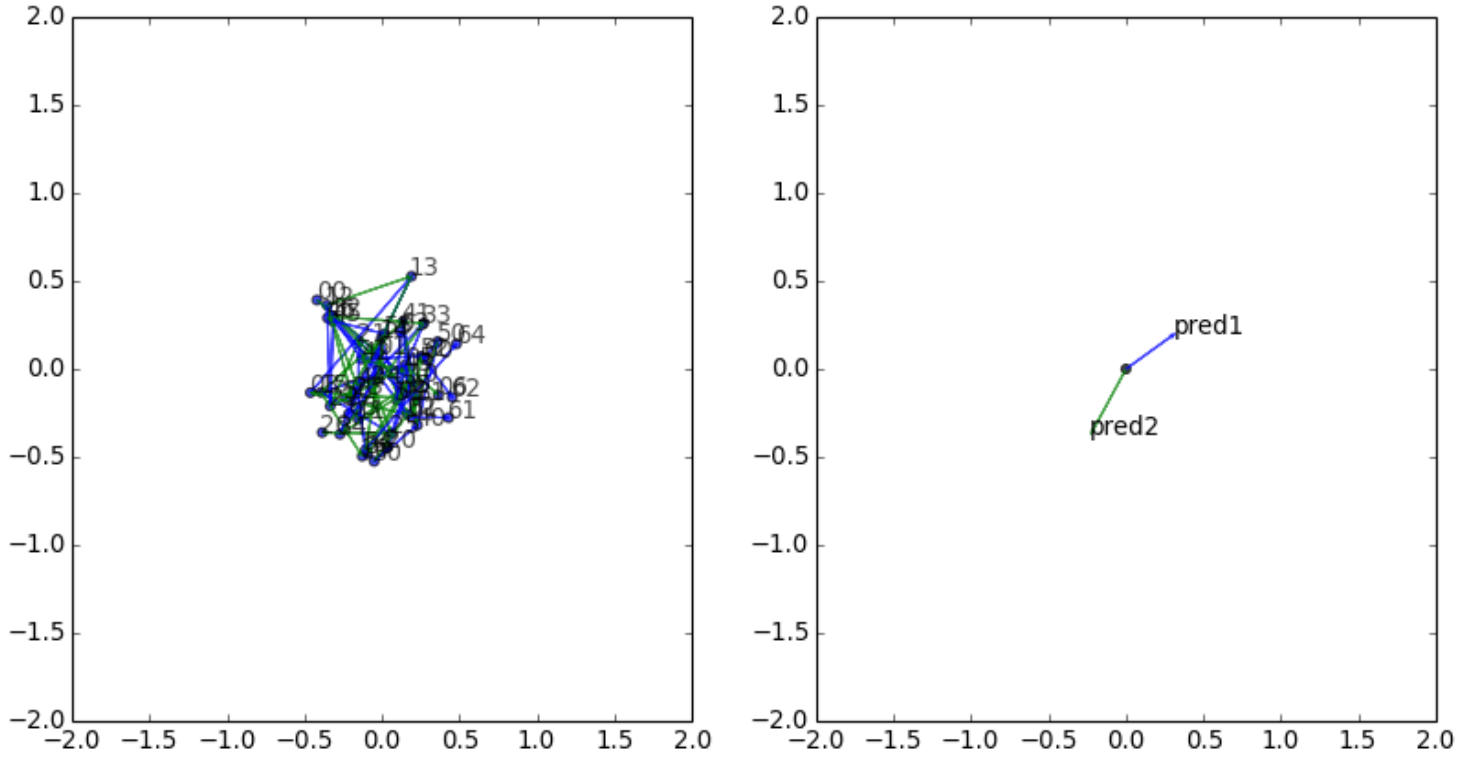
Dhand; http://www.ccri.com/2018/06/27/use-transe-effectively/

Knowledge Graph Embeddings: Translational Embeddings



Dhand; http://www.ccri.com/2018/06/27/use-transe-effectively/

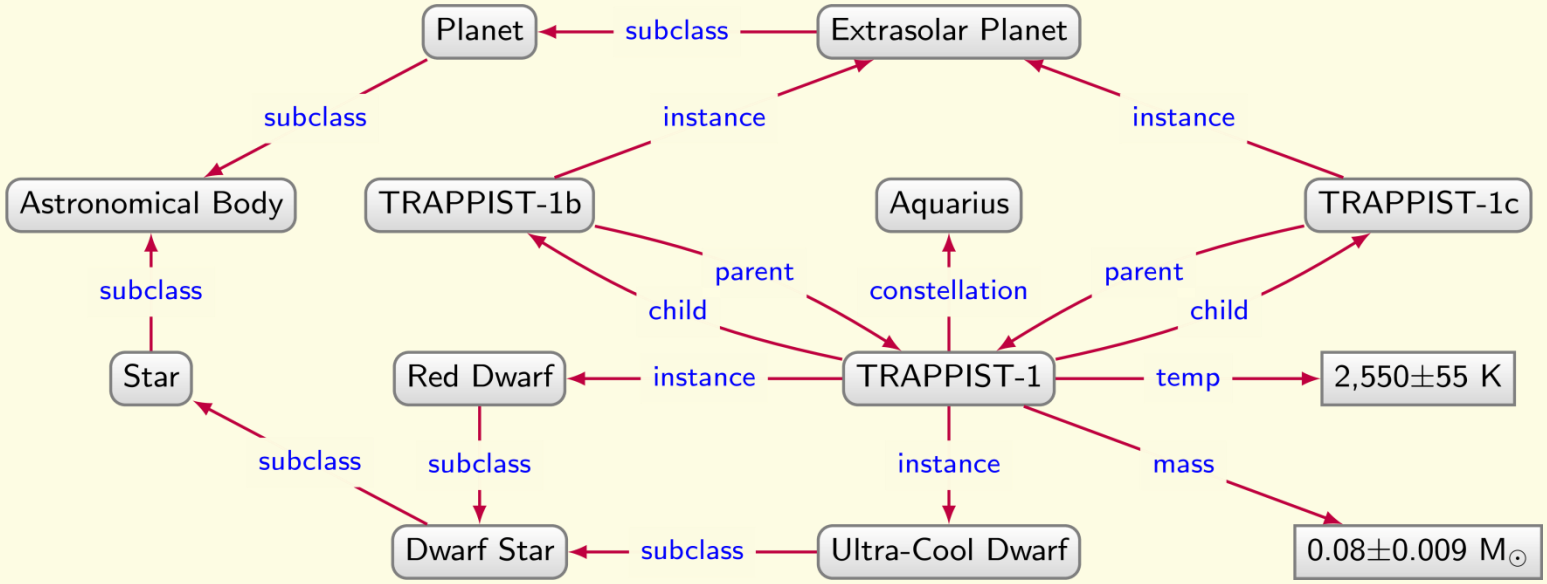
Knowledge Graph Embeddings: Translational Embeddings



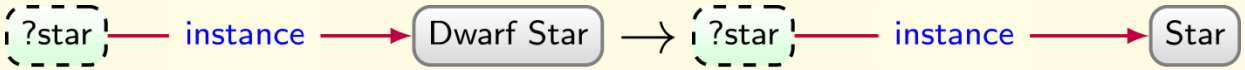
Dhand; http://www.ccri.com/2018/06/27/use-transe-effectively/

Topic 7:
Semantic Embeddings

Plausibility of entailed triples



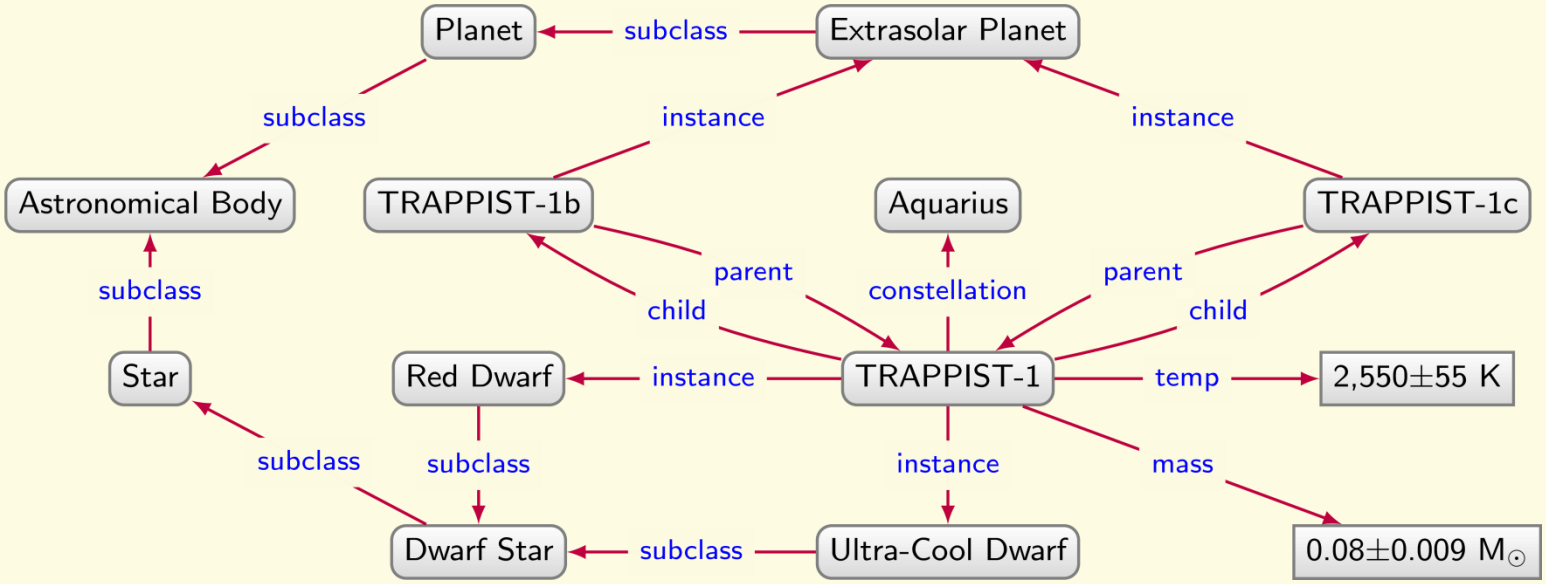
DwarfStar $\sqsubseteq$ Star



Should always be more plausible than:

[Demeester et al. 2016]

Plausibility of entailed triples



What about more complex rules?

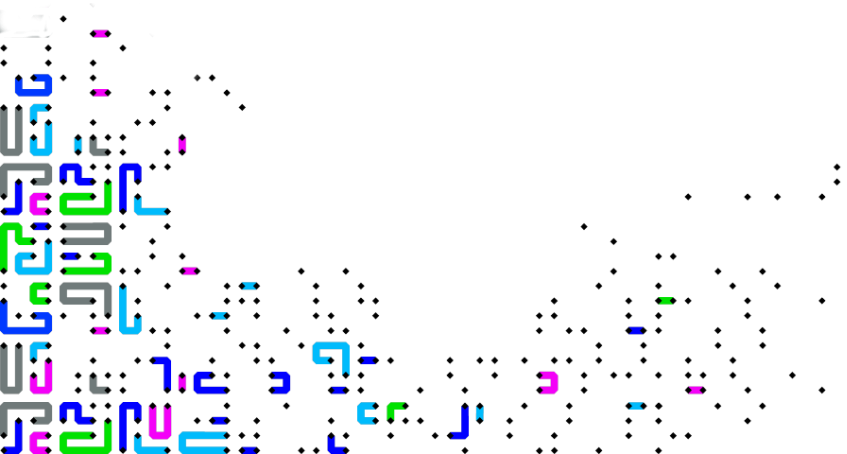
TRAPPIST-1b — parent → TRAPPIST-1 — constellation → Aquarius ⟶ TRAPPIST-1b — constellation → Aquarius

What about existential/disjunctive rules?

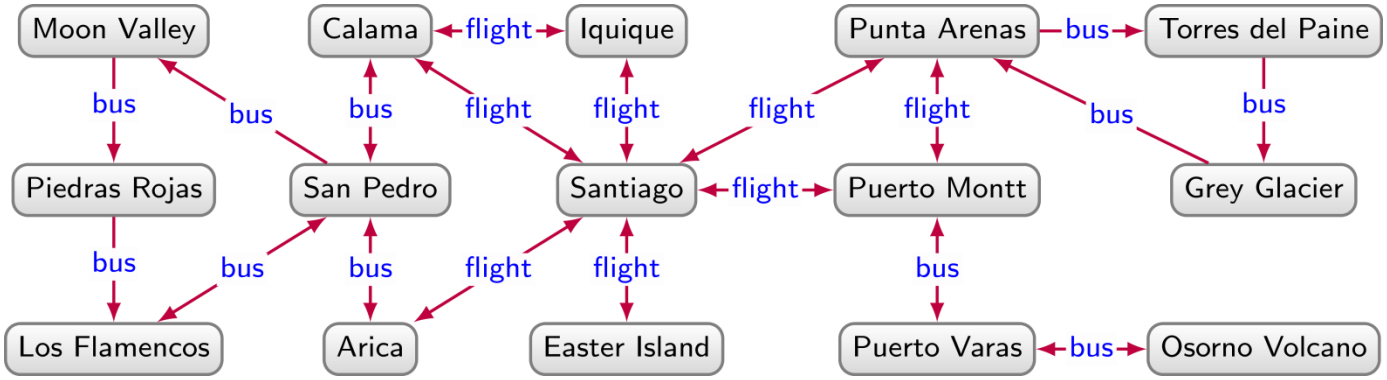
?planet — instance → Planet ⟶ ?planet — instance → Extrasolar Planet ⋁ ?planet — instance → Solar Planet

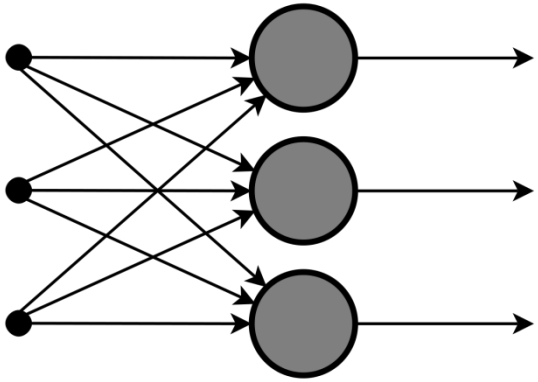
?bstar — instance → Binary Star ⟶ $\exists x$: ?bstar — orbits → x — instance → Binary Star

Graph Neural Networks

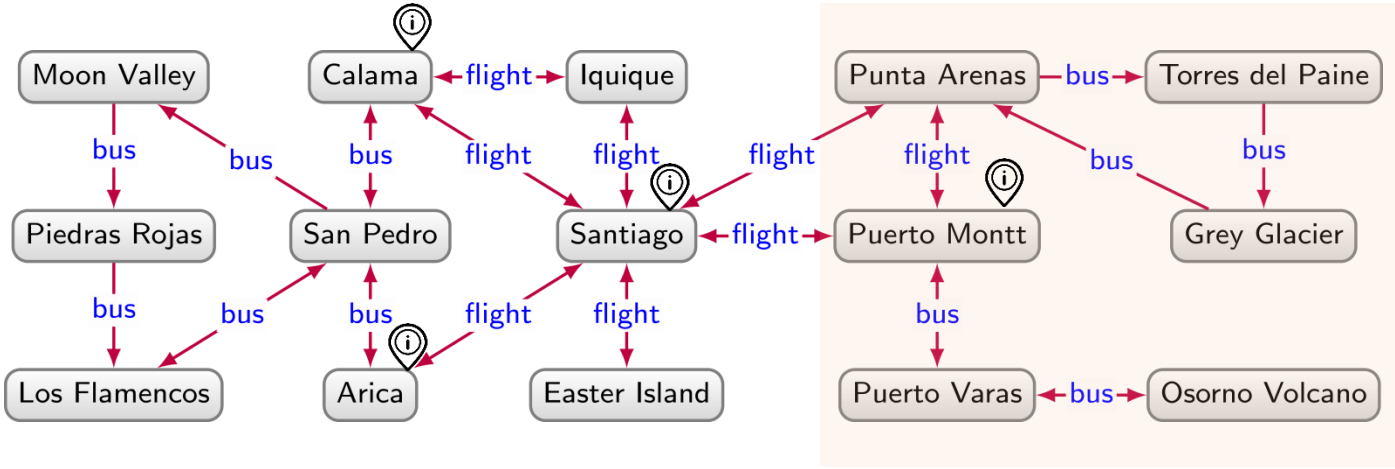


Neural networks are graphs too!

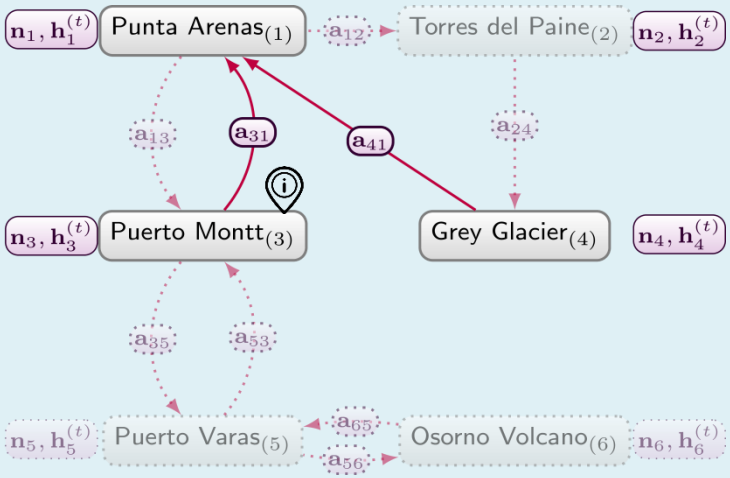




Recursive Graph Neural Networks



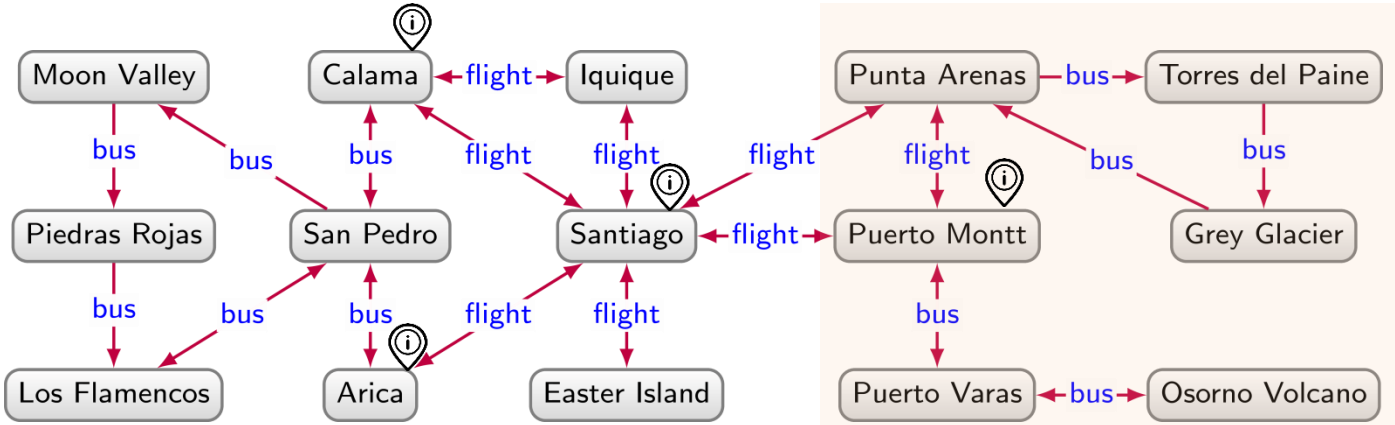
Where should we open the next tourist office?



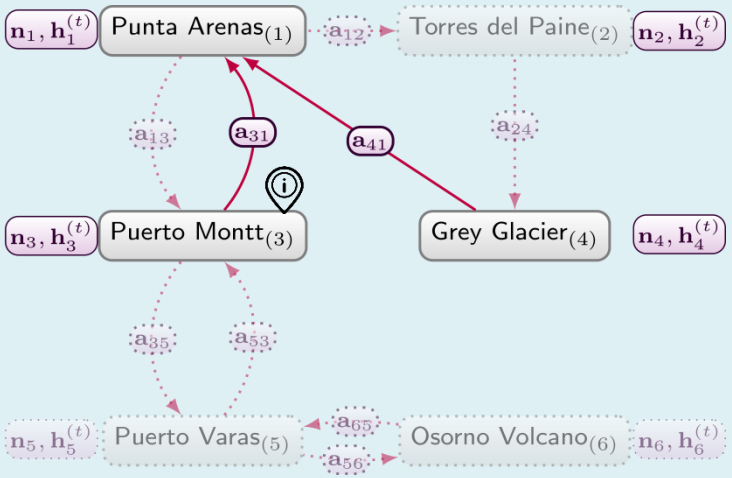
$$\mathbf{h}_x^{(t)} = \sum_{y \in \mathrm{N}(x)} f_{\mathbf{w}}(\mathbf{n}_x, \mathbf{n}_y, \mathbf{a}_{yx}, \mathbf{h}_y^{(t-1)})$$
$$\mathbf{o}_x^{(t)} = g_{\mathbf{w}'}(\mathbf{h}_x^{(t)}, \mathbf{n}_x)$$

[Scarselli et al. 2009]

Recursive Graph Neural Networks



Where should we open the next tourist office?



$$\mathbf{h}_x^{(t)} = \sum_{y \in \mathrm{N}(x)} f_{\mathbf{w}}(\mathbf{n}_x, \mathbf{n}_y, \mathbf{a}_{yx}, \mathbf{h}_y^{(t-1)})$$
$$\mathbf{o}_x^{(t)} = g_{\mathbf{w}'}(\mathbf{h}_x^{(t)}, \mathbf{n}_x)$$

$$\mathbf{h}_1^{(t)} = f_{\mathbf{w}}(\mathbf{n}_1, \mathbf{n}_3, \mathbf{a}_{31}, \mathbf{h}_3^{(t-1)}) + f_{\mathbf{w}}(\mathbf{n}_1, \mathbf{n}_4, \mathbf{a}_{41}, \mathbf{h}_4^{(t-1)})$$
$$\mathbf{o}_1^{(t)} = g_{\mathbf{w}'}(\mathbf{h}_1^{(t)}, \mathbf{n}_1)$$

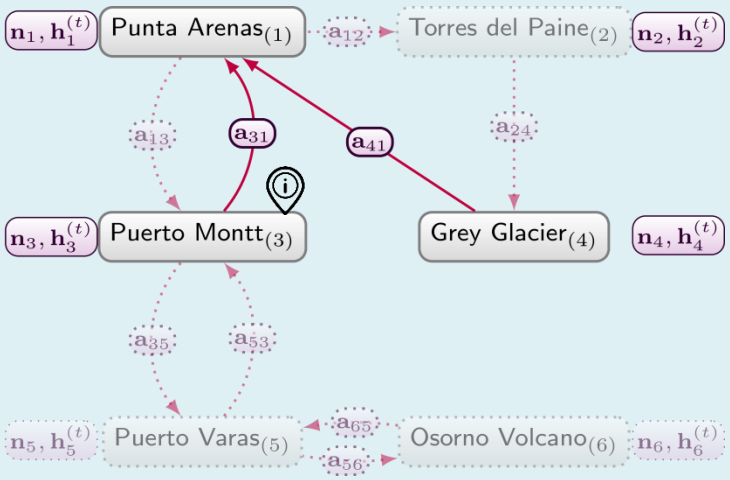
$\dots$

[Scarselli et al. 2009]

Topic 8:
Node Classifiers

Non-Recursive GNNs related to $\mathcal{ALCQ}$

$$\mathcal{ALCQ} :: \mathsf{C} := \top \mid \bot \mid \mathsf{A} \mid \mathsf{C} \sqcap \mathsf{C} \mid \mathsf{C} \sqcup \mathsf{C} \mid \neg \mathsf{C} \mid \exists \mathsf{R}.\mathsf{C} \mid \forall \mathsf{R}.\mathsf{C} \mid \geq n \mathsf{R}.\mathsf{C}$$



$\longleftrightarrow$

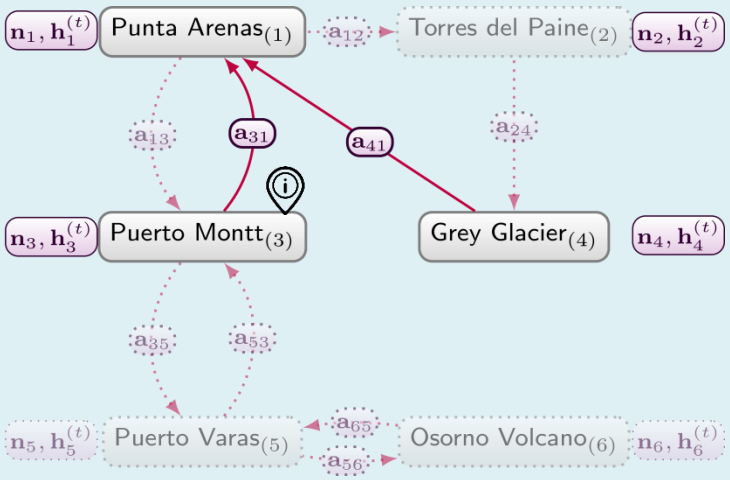
$$\mathsf{City} \sqsubseteq \mathsf{TouristOffice}$$
$$\exists \mathsf{flight}.\top \sqsubseteq \mathsf{TouristOffice}$$
$$\geq 3 \mathsf{bus}.\mathsf{City} \sqsubseteq \mathsf{TouristOffice}$$
$$\ldots$$

[Barceló et al. 2020]

What about more expressive DLs?

Name	Syntax	Semantics $(\cdot^I)$
	Concept Definitions	
Atomic Concept	A	A^I (a subset of Δ^I)
Top Concept	$\top$	Δ^I
Bottom Concept	$\bot$	$\emptyset$
Concept Negation	$\neg C$	$\Delta^I \setminus C^I$
Concept Intersection	$C \sqcap D$	$C^I \cap D^I$
Concept Union	$C \sqcup D$	$C^I \cup D^I$
Nominals	$\{a\}$	$\{a^I\}$
Existential Restriction	$\exists R.C$	$\{x \mid \exists y : (x,y) \in R^I \text{ and } y \in C^I\}$
Universal Restriction	$\forall R.C$	$\{x \mid \forall y : (x,y) \in R^I \text{ implies } y \in C^I\}$
Self Restriction	$\exists R.\text{Self}$	$\{x \mid (x,x) \in R^I\}$
Number Restriction	$\star n\, R$ (where $\star \in \{\geq, \leq, =\}$)	$\{x \mid \#\{y : (x,y) \in R^I\} \star n\}$
Qualified Number Restriction	$\star n\, R.C$ (where $\star \in \{\geq, \leq, =\}$)	$\{x \mid \#\{y : (x,y) \in R^I \text{ and } y \in C^I\} \star n\}$
	Concept Axioms (T-Box)	
Concept Inclusion	$C \sqsubseteq D$	$C^I \subseteq D^I$

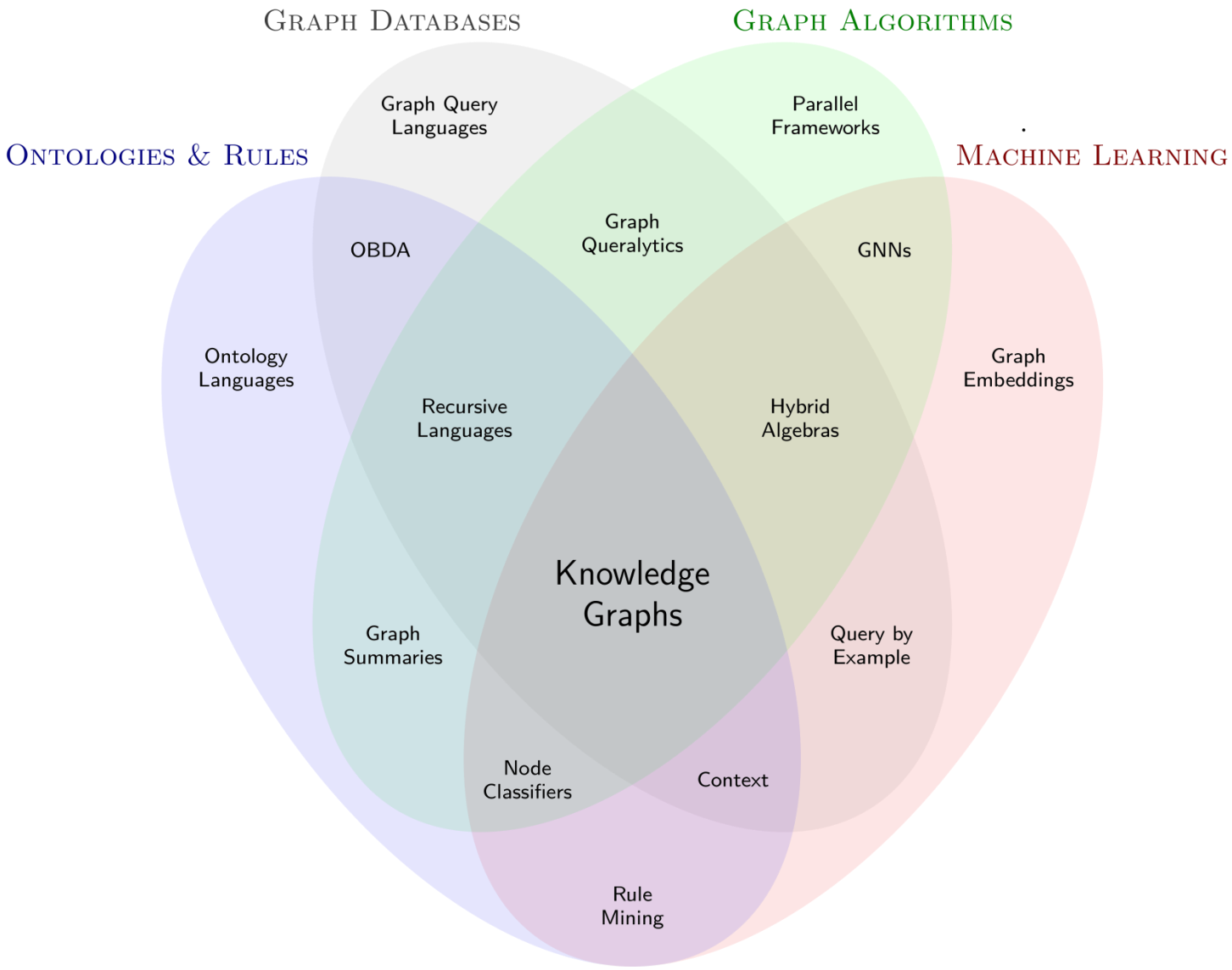
Are there GNNs that can learn more expressive DL classifiers?



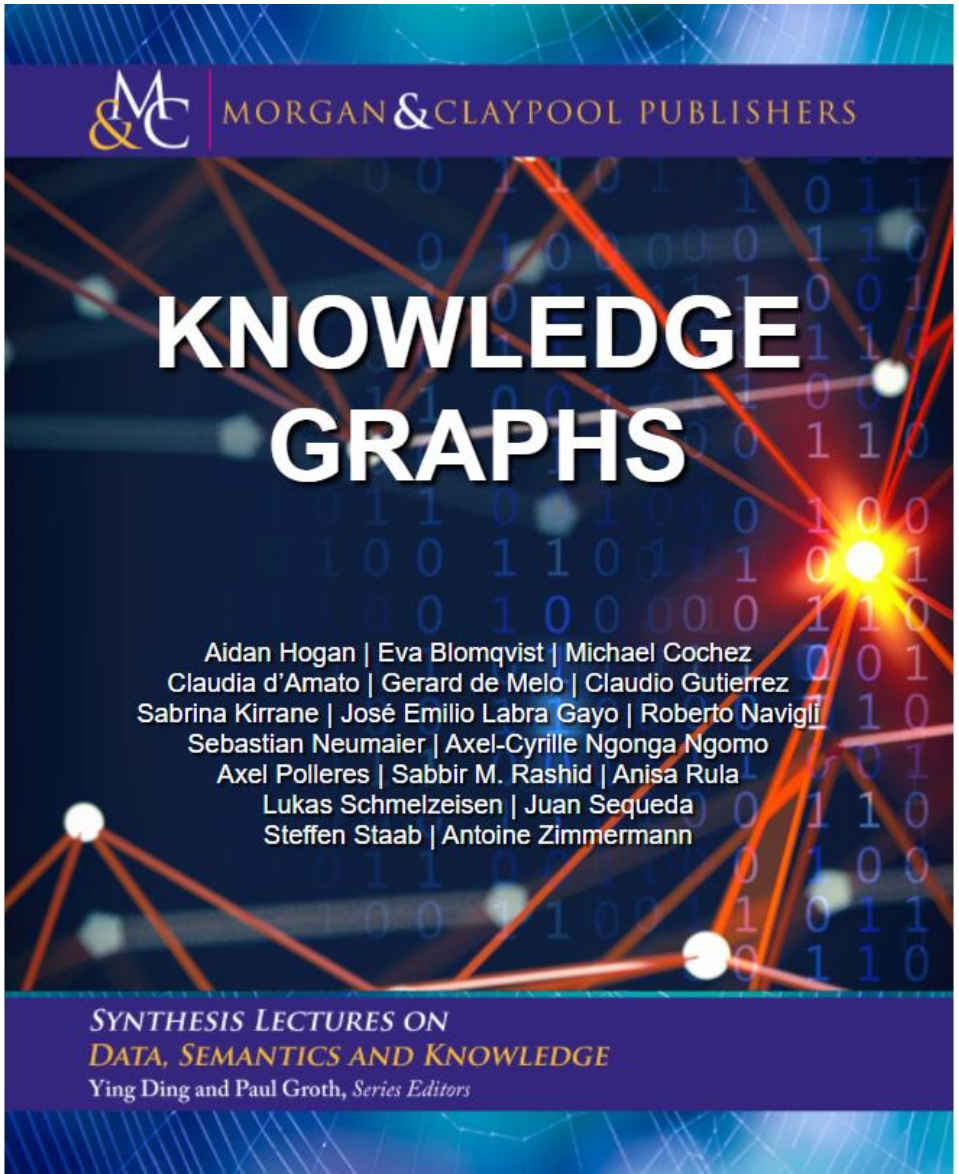
$\leftrightarrow$???

Conclusion

How are knowledge graphs new?



For further discussion …



http://kgbook.org/

For further discussion ...

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