On a Generalized Framework for Time-Aware Knowledge Graphs

SEMANTICS

Towards a Knowledge-Aware AI
A. Dimou et al. (Eds.)

doi:10.3233/SSW220010

On a Generalized Framework for Time-Aware Knowledge Graphs

Franz KRAUSE [a,1], Tobias WELLER [a] and Heiko PAULHEIM [a]
[a] *Data and Web Science Group, University of Mannheim, Germany*

Abstract. Knowledge graphs have emerged as an effective tool for managing and standardizing semistructured domain knowledge in a human- and machine-interpretable way. In terms of graph-based domain applications, such as embeddings and graph neural networks, current research is increasingly taking into account the time-related evolution of the information encoded within a graph. Algorithms and models for stationary and static knowledge graphs are extended to make them accessible for time-aware domains, where time-awareness can be interpreted in different ways. In particular, a distinction needs to be made between the validity period and the traceability of facts as objectives of time-related knowledge graph extensions. In this context, terms and definitions such as *dynamic* and *temporal* are often used inconsistently or interchangeably in the literature. Therefore, with this paper we aim to provide a short but well-defined overview of time-aware knowledge graph extensions and thus faciliate future research in this field as well.

Keywords. Knowledge Graph, Dynamic Knowledge Graph, Temporal Knowledge Graph, Time-Aware Knowledge Graph, Semantic Web

Time-Aware Knowledge Graph Extensions

Why we wrote this paper

- In addition to standard requirements such as **integrability and standardization**, the decision whether to use knowledge graphs increasingly depends on their **added value in downstream tasks** such as

  i. **Knowledge Graph Embeddings**
  ii. **Graph-based learning (GNNs)**
  iii. **Explainability of AI models**

- Until now, these tasks have been dealt with almost exclusively without consideration of time-awareness for ***static* knowledge graphs**.

- In the sparse literature related to time-aware downstream applications, terms such as **temporal, dynamic, static, etc.** are used interchangeably and in particular inconsistently.

What is a SEAL?

That's a seal.

No, that's a seal!

You are both wrong. This is a seal.

I believe seals look more like this.

Have you ever seen a seal before?

SEALS

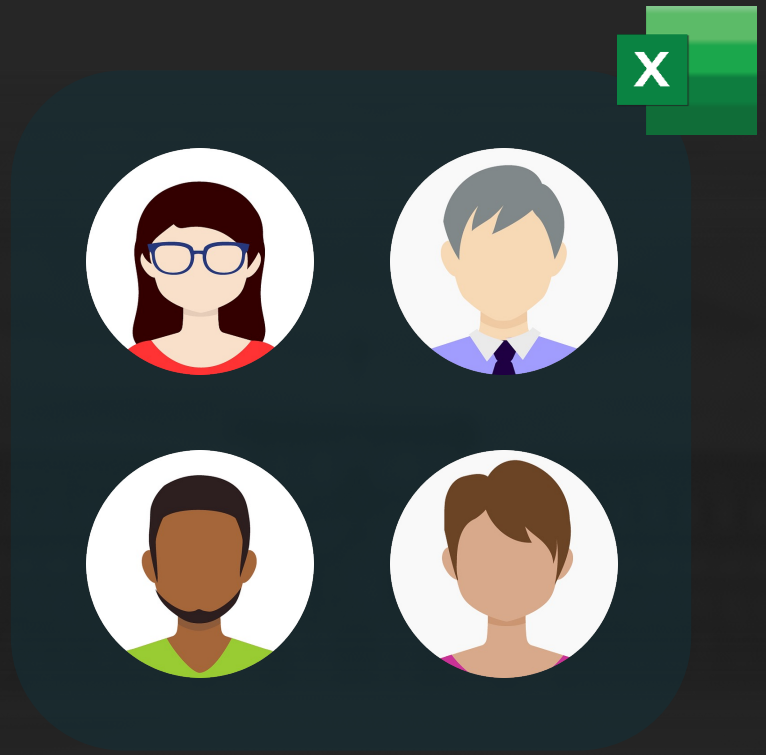
What is a KNOWLEDGE GRAPH?

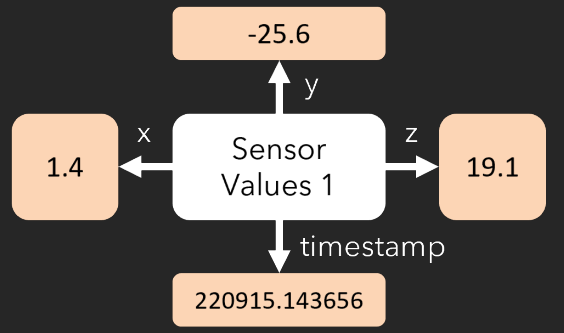
SEALS

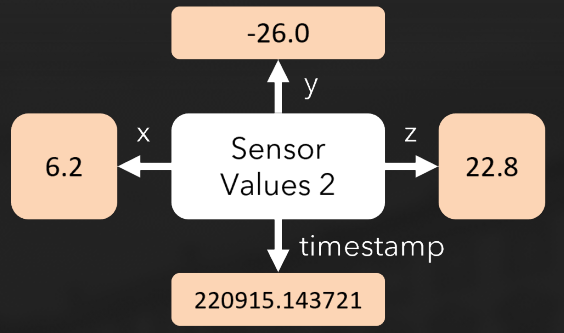
Allegro
Blazegraph
BrightstarDB
Cayley
CM-Well
ClioPatria
Datomic
Dydra
Enterlab SimpleGraph
gStore
Ontotext GraphDB
Halyard
IBM Db2
KiWi (Apache Marmotta)
MarkLogic
Mulgara
Amazon Neptune
NitrosBase
OntoQuad RDF Server
OpenAnzo
OpenLink Virtuoso
Oracle
Oxigraph
Parliament
Pointrel System
Profium Sense
RAP
RDF::Core
RDF::Trine
RDF-3X
Eclipse RDF4J
RDFBroker
RDFLib
RDFox
Redland
RedStore
Semantics Platform
SemWeb-DotNet

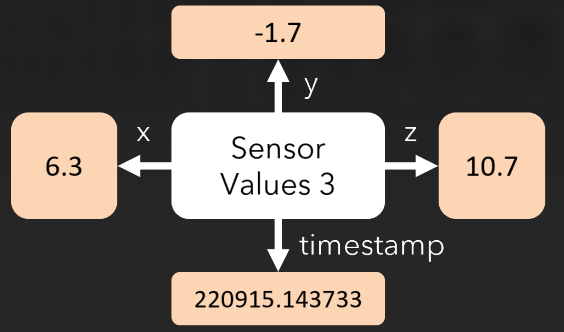
What is a KNOWLEDGE GRAPH?

What is a KNOWLEDGE GRAPH?



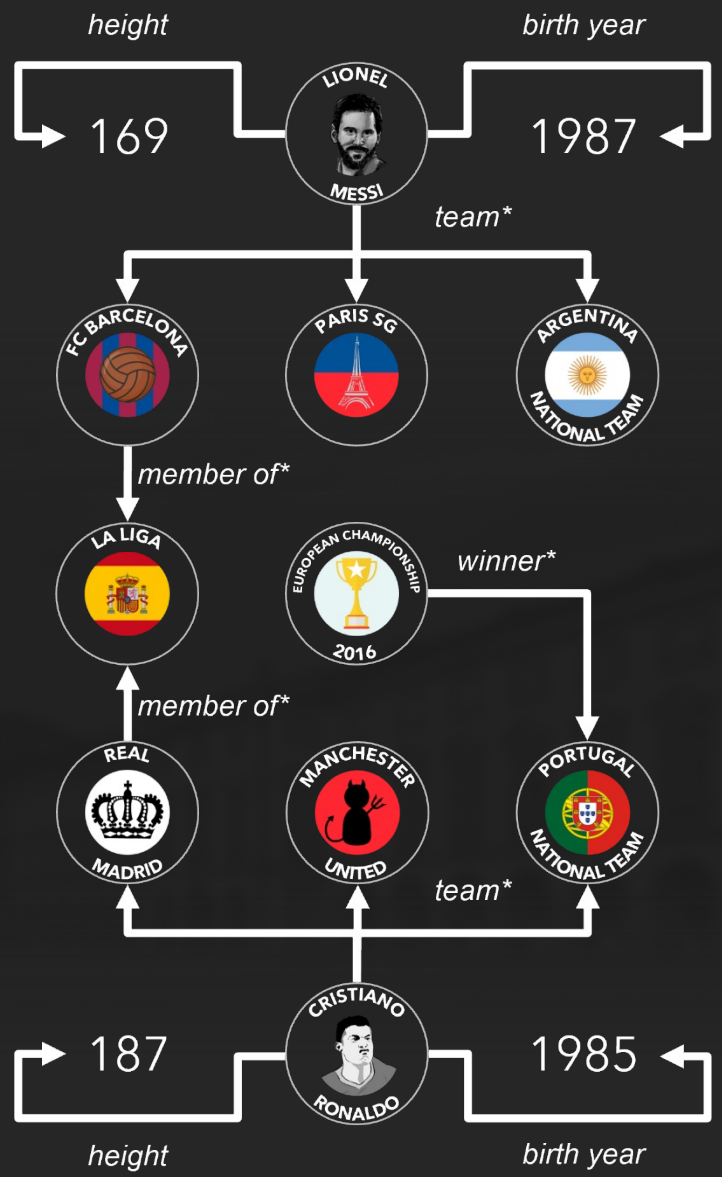




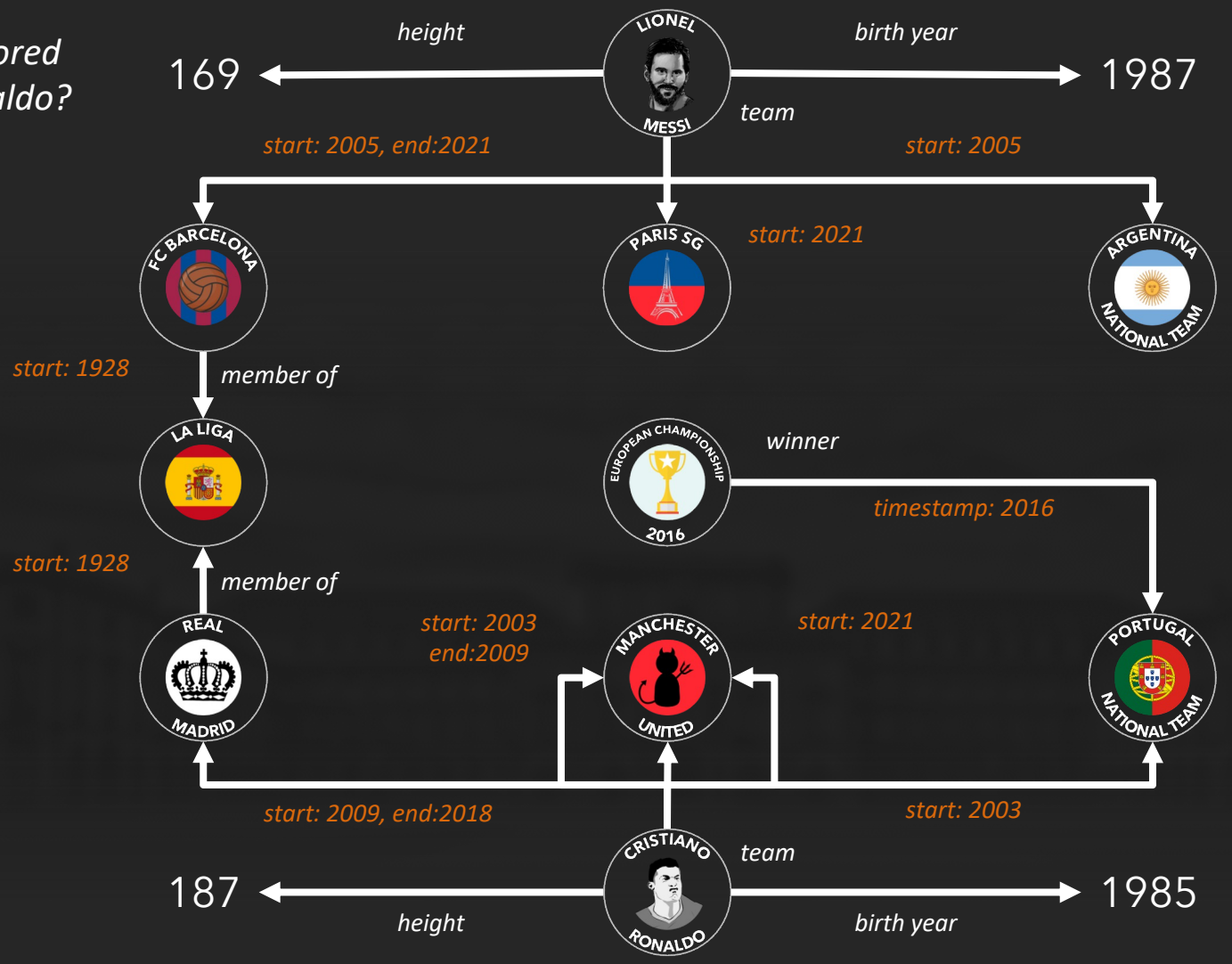


What is a KNOWLEDGE GRAPH?

What is a KNOWLEDGE GRAPH?



How often has Messi scored in matches against Ronaldo?



Does Cristiano Ronaldo like British food?

What is a Knowledge Graph?

We refer to triples (h, r, t) based on an ontology $O = (C, L, R, \rho)$ as **static edges** and to a set of such triples accordingly as a **static knowledge graph**.

An ontology that is only designed for logical inference of static edges is called a **static ontology**.

We propose the notion that a **data model D induces a (static) knowledge graph G** if G can be derived directly from D.

$(head, relation, tail)$

$Ontology = (Concepts, Literals, Relations, rules)$

```
:c_ronaldo   :team   :real_madrid.
:c_ronaldo   :team   :man_united.
:leo_messi   :team   :fcbarcelona.
...
```

```
:team   rdfs:domain   :football_player.
:team   rdfs:range    :football_team.
...
```

Constrain the data model D to suit your needs!

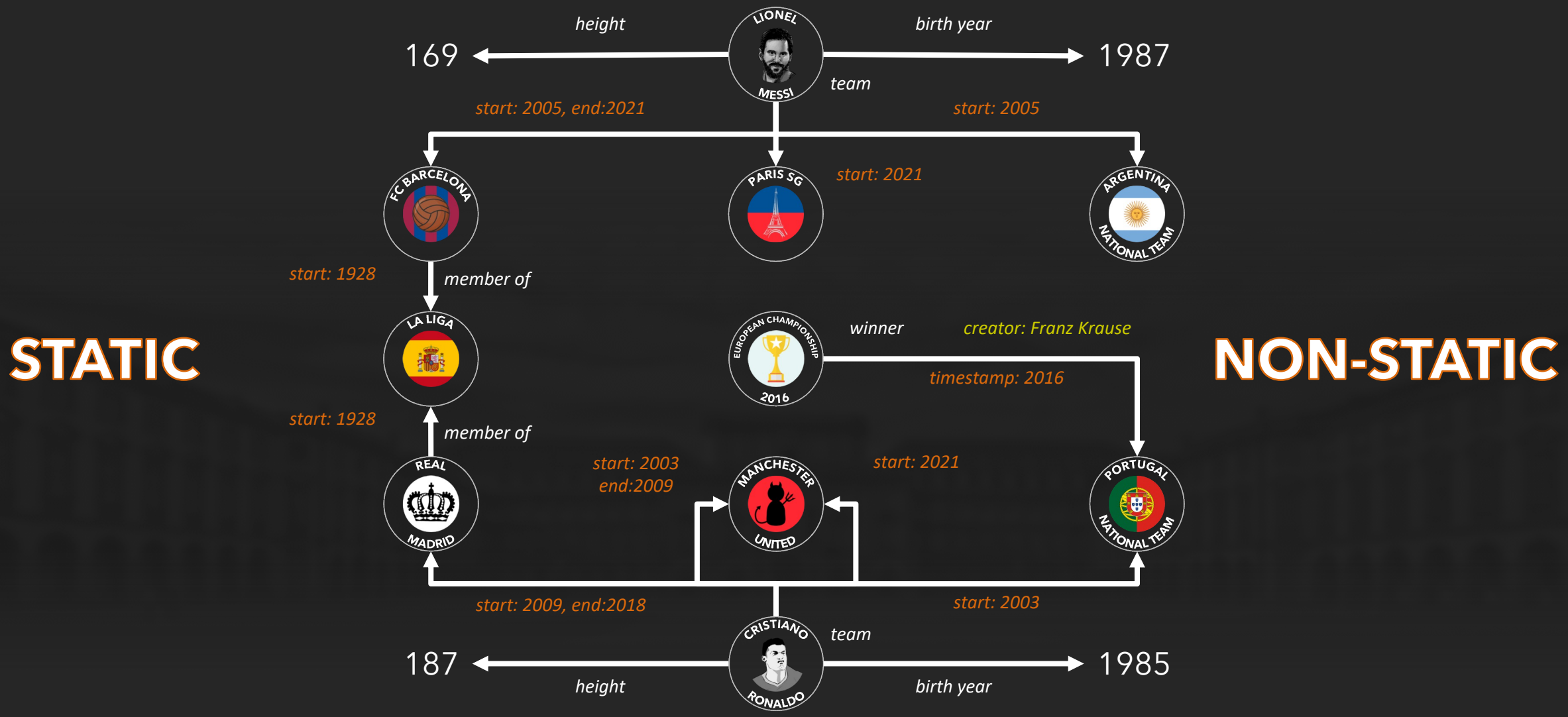
What is a Knowledge Graph?

We refer to triples (h, r, t) based on an ontology $O = (C, L, R, \rho)$ as **static edges** and to a set of such triples accordingly as a **static knowledge graph**.

An ontology that is only designed for logical inference of static edges is called a **static ontology**.

We propose the notion that a **data model D induces a (static) knowledge graph G** if G can be derived directly from D.

Constrain the data model D to suit your needs!


STATIC
NON-STATIC
LIONEL MESSI
height
169
birth year
1987
team
start: 2005, end:2021
start: 2005
start: 2021
FC BARCELONA
PARIS SG
ARGENTINA NATIONAL TEAM
start: 1928
member of
LA LIGA
EUROPEAN CHAMPIONSHIP 2016
winner
creator: Franz Krause
timestamp: 2016
start: 1928
member of
REAL MADRID
start: 2003
end:2009
MANCHESTER UNITED
start: 2021
PORTUGAL NATIONAL TEAM
start: 2009, end:2018
start: 2003
CRISTIANO RONALDO
team
187
height
birth year
1985

Time-Aware Knowledge Graph Extensions

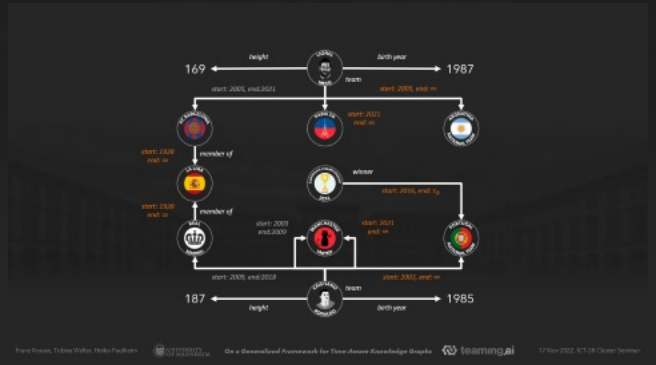
Time-aware knowledge graph extensions are considered with respect to an **ordered set of timestamps T**, such as $T = \mathbb{N}$ or $T = \mathbb{R}$.

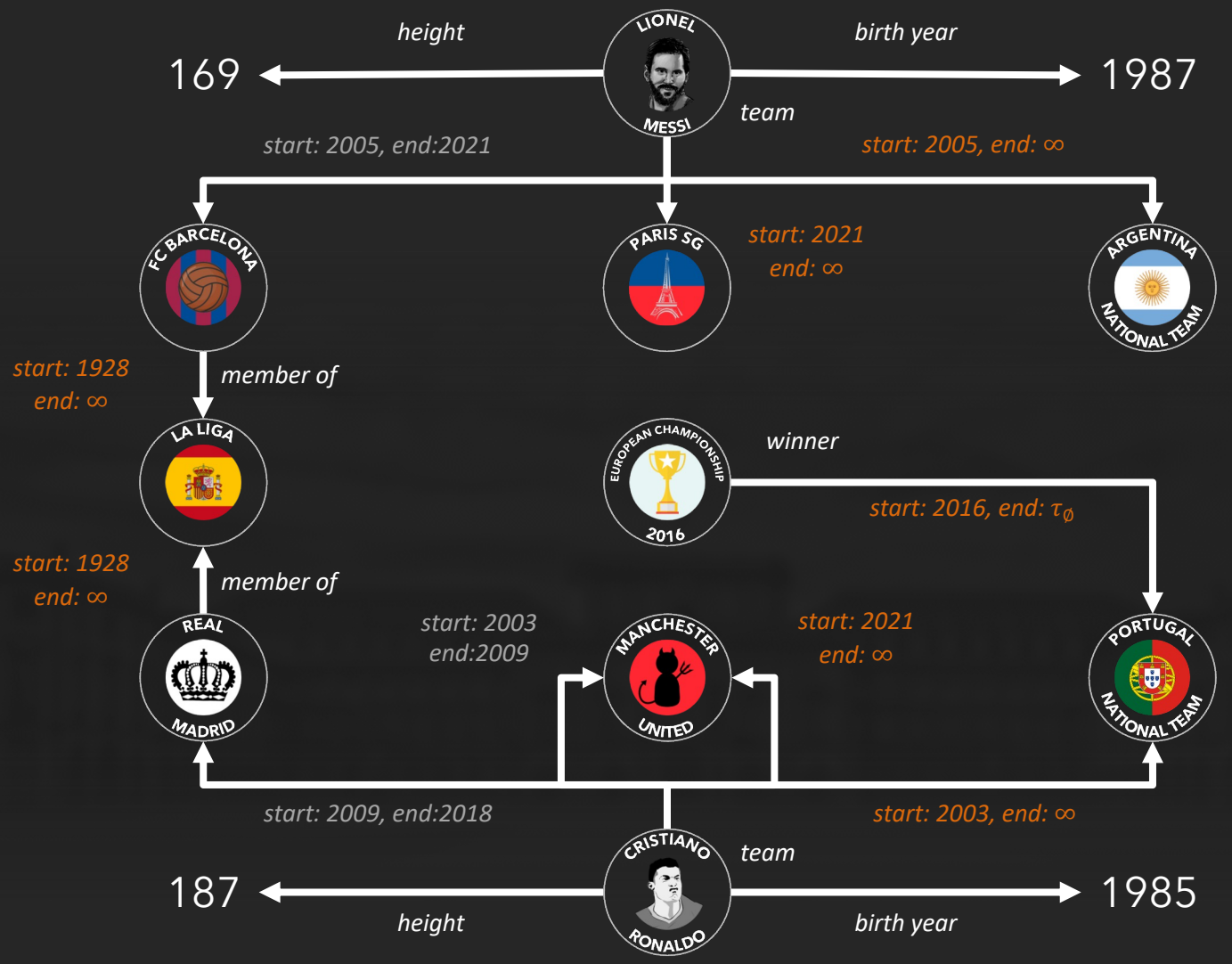
Given such a set of timestamps T, we define **the closure $\overline{T} := T \cup \{-\infty, \infty, \tau_\emptyset\}$**, where $-\infty$ and ∞ define unknown start and end timestamps and $\tau_\emptyset$ identifies nonexistent timestamps.

Time-Aware Knowledge Graph Extensions

Time-aware knowledge graph extensions are considered with respect to an **ordered set of timestamps T**, such as $T = \mathbb{N}$ or $T = \mathbb{R}$.

Given such a set of timestamps T, we define **the closure $\overline{T} := T \cup \{-\infty, \infty, \tau_\emptyset\}$**, where $-\infty$ and ∞ define unknown start and end timestamps and $\tau_\emptyset$ identifies nonexistent timestamps.




LIONEL MESSI
height
169
birth year
1987
team
start: 2005, end:2021
start: 2005, end: ∞
FC BARCELONA
PARIS SG
start: 2021
end: ∞
ARGENTINA NATIONAL TEAM
start: 1928
end: ∞
member of
LA LIGA
EUROPEAN CHAMPIONSHIP 2016
winner
start: 2016, end: $\tau_\emptyset$
start: 1928
end: ∞
member of
REAL MADRID
start: 2003
end:2009
MANCHESTER UNITED
start: 2021
end: ∞
PORTUGAL NATIONAL TEAM
start: 2009, end:2018
start: 2003, end: ∞
CRISTIANO RONALDO
team
187
height
birth year
1985

Temporal Knowledge Graph Extensions

Given T and a static ontology $O = (C, L, R, \rho)$, a **temporal ontology** $O^T = (C, L, R, \rho^T)$ with $\rho \subseteq \rho^T$ is an extension of O which allows for logical inference of **quintuples** $(h, r, t, \tau^s, \tau^e)$ as extensions of static triples (h, r, t) with **additional start and end timestamps** $\tau^s, \tau^e \epsilon \bar{T}$.

A set of such quintuples is refered to as a **temporal knowledge graph** with respect to the induced static knowledge graph of triples (h, r, t).

$\bar{T}$-Domains of *winner*:

$\tau^s \in \bar{T} \setminus \{\tau_\emptyset\}$ and $\tau^e = \tau_\emptyset$

$(x, team, y, \tau_y^s, \tau_y^e) \wedge (x, team, z, \tau_z^s, \tau_z^e) \Rightarrow \tau_y^{se} \cap \tau_z^{se} = \emptyset$

with $\tau^{se} := \{\tau \epsilon T : \tau^s \leq \tau \leq \tau^e\}$.

:c_ronaldo	:team	:real_madrid	2009	2018
:c_ronaldo	:team	:man_united	2021	∞
:leo_messi	:team	:fcbarcelona	2005	2021
…				

Temporal extensions of static knowledge graphs already occur in several knowledge bases and **downstream tasks** (KG Embeddings, Relational Machine learning, …)

Temporal Knowledge Graph Extensions

Given T and a static ontology $O = (C, L, R, \rho)$, a **temporal ontology** $O^T = (C, L, R, \rho^T)$ with $\rho \subseteq \rho^T$ is an extension of O which allows for logical inference of **quintuples** $(h, r, t, \tau^s, \tau^e)$ as extensions of static triples (h, r, t) with **additional start and end timestamps** $\tau^s, \tau^e \epsilon \bar{T}$.

A set of such quintuples is refered to as a **temporal knowledge graph** with respect to the induced static knowledge graph of triples (h, r, t).

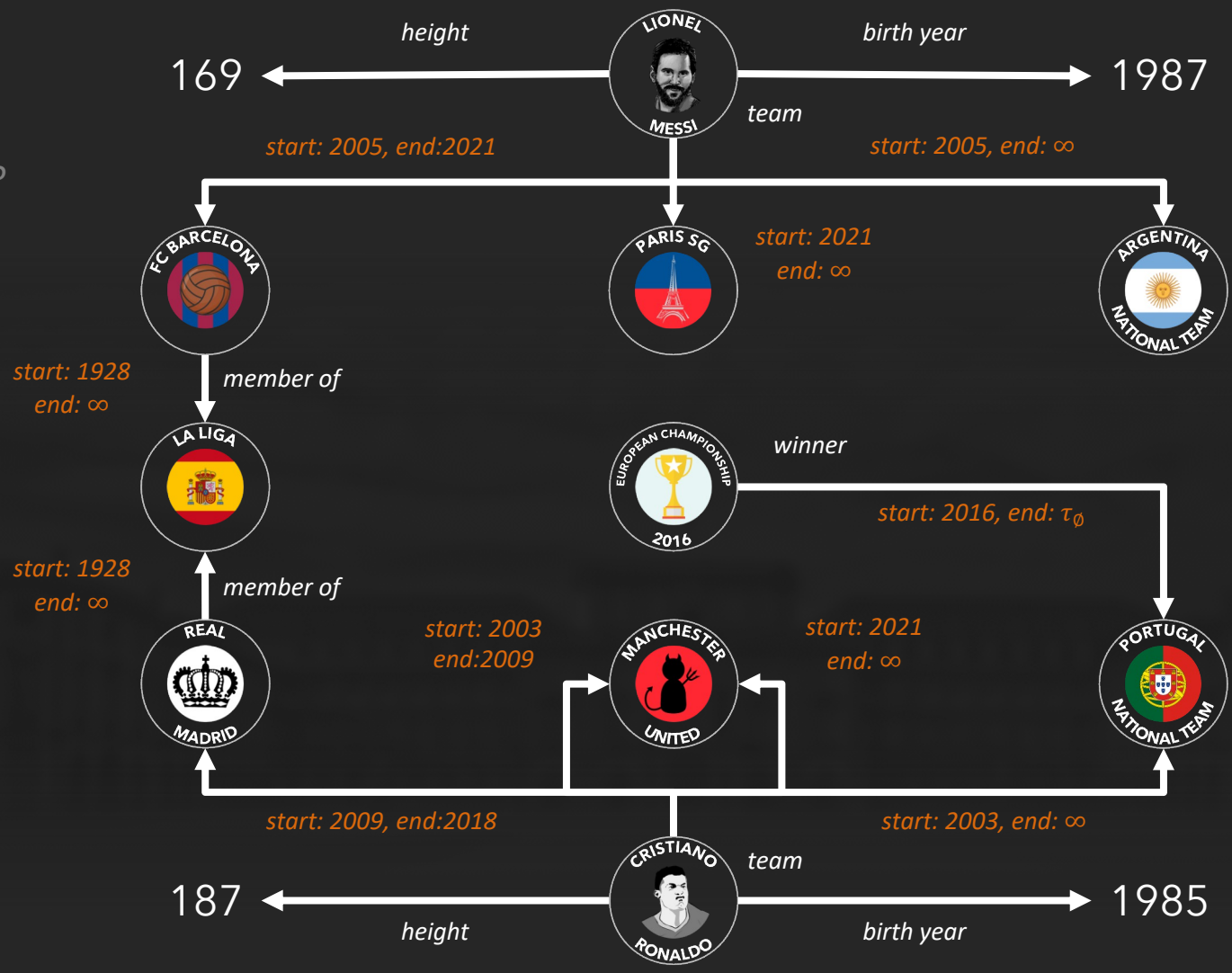
Temporal extensions of static knowledge graphs already occur in several knowledge bases and **downstream tasks** (KG Embeddings, Relational Machine learning, …)

How often has Messi scored in matches against Ronaldo?

Is Lionel Messi happy with his national career?

Does Cristiano Ronaldo speak italian?

How much does Cristiano Ronaldo like British food?

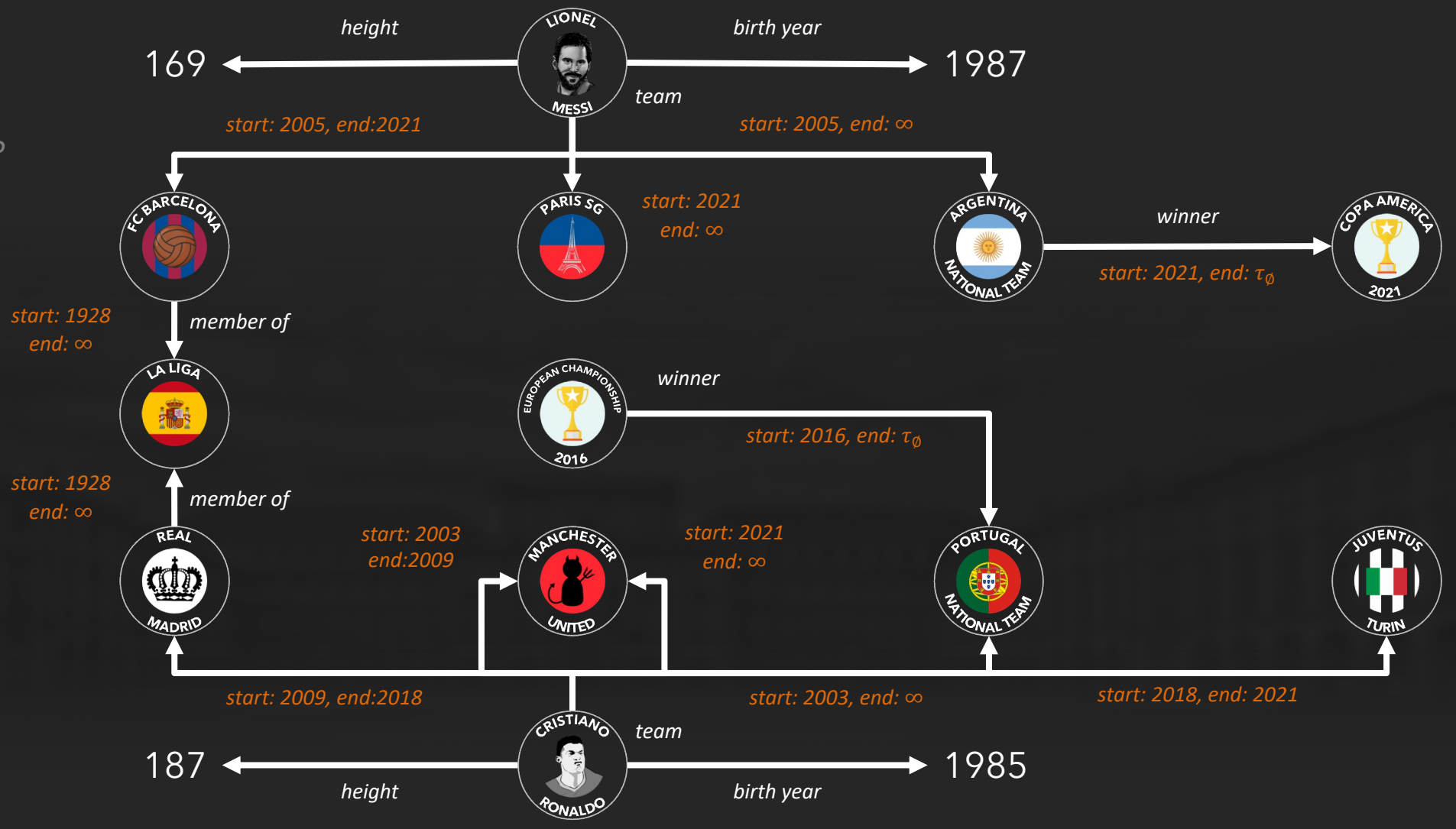


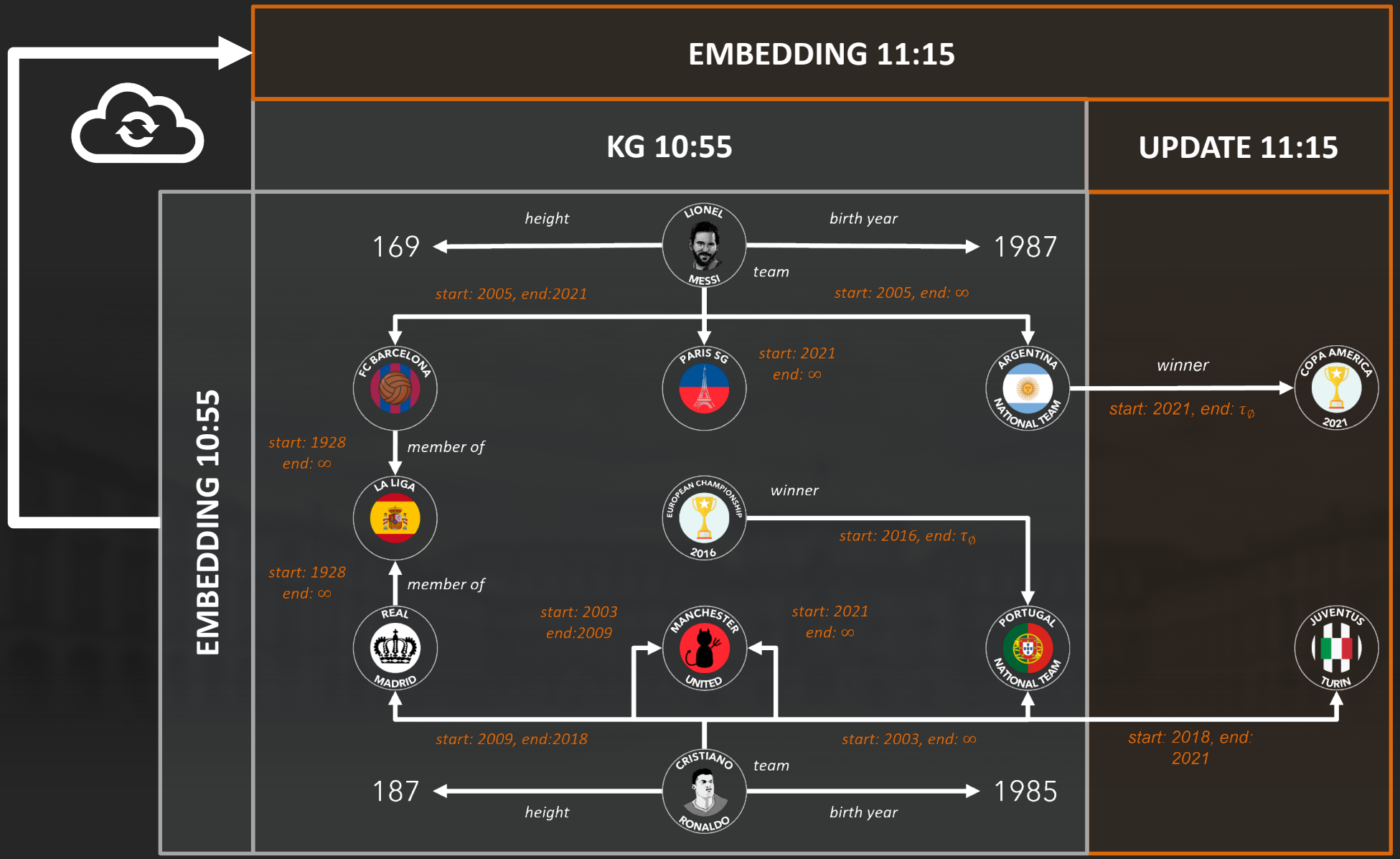
How often has Messi scored in matches against Ronaldo?

Is Lionel Messi happy with his national career?

Does Cristiano Ronaldo speak italian?

How much does Cristiano Ronaldo like British food?





How to incorporate KG Dynamics in downstream tasks?

Dynamic Knowledge Graph Extensions

A (static or non-static) knowledge graph is called a **stationary knowledge graph** if the inherent information encodes a domain image for a **fixed timestamp** and must be considered as **final**.

:c_ronaldo	:team	:real_madrid.
:c_ronaldo	:team	:man_united.
:leo_messi	:team	:fcbarcelona.
…		

10:55

:c_ronaldo	:team	:real_madrid	**2009**	**2018**.
:c_ronaldo	:team	:man_united	**2021**	∞.
:leo_messi	:team	:fcbarcelona	**2005**	**2021**.
:c_ronaldo	:team	:juve_turin	**2018**	**2021**.
…				

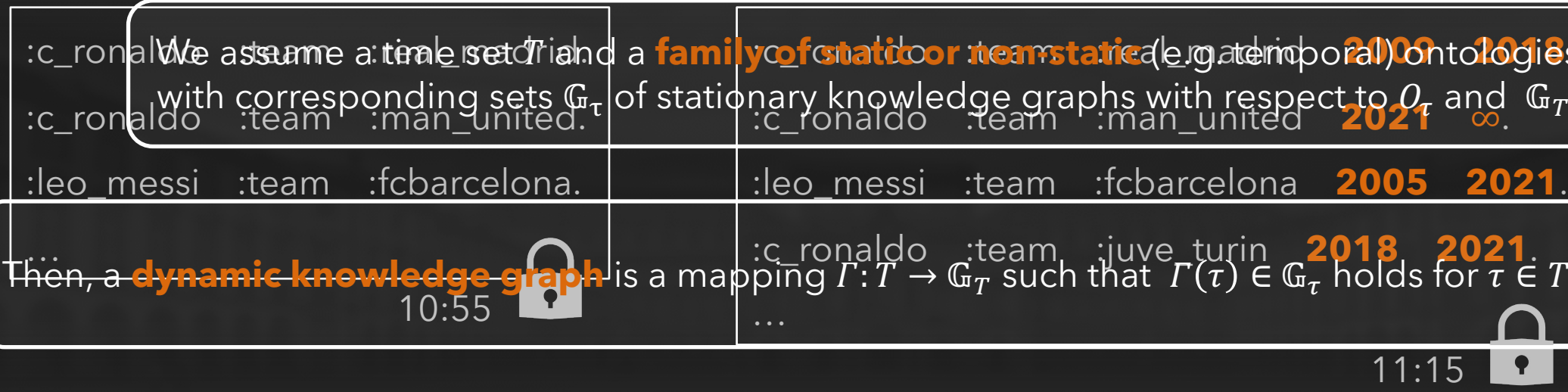
11:15

Dynamic Knowledge Graph Extensions

A (static or non-static) knowledge graph is called a **stationary knowledge graph** if the inherent information encodes a domain image for a **fixed timestamp** and must be considered as **final**.

We assume a time set $\mathcal{T}$ and a **family of static or non-static** (e.g. temporal) ontologies $\{\mathcal{O}_\tau : \tau \in T\}$ with corresponding sets $\mathbb{G}_\tau$ of stationary knowledge graphs with respect to $\mathcal{O}_\tau$ and $\mathbb{G}_T := \bigcup_{\tau \in T} \mathbb{G}_\tau$.

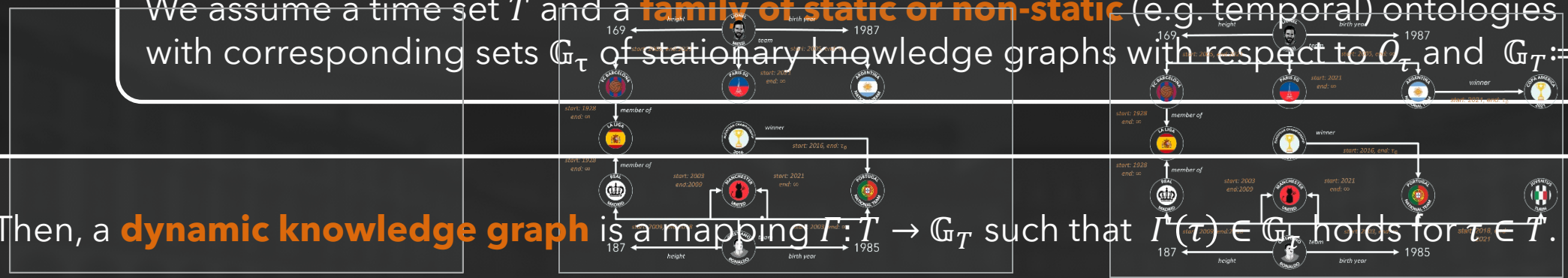
Then, a **dynamic knowledge graph** is a mapping $\Gamma : T \to \mathbb{G}_T$ such that $\Gamma(\tau) \in \mathbb{G}_\tau$ holds for $\tau \in T$.



Dynamic Knowledge Graph Extensions

A (static or non-static) knowledge graph is called a **stationary knowledge graph** if the inherent information encodes a domain image for a **fixed timestamp** and must be considered as **final**.

We assume a time set T and a **family of static or non-static** (e.g. temporal) ontologies $\{O_\tau : \tau \in T\}$ with corresponding sets $\mathbb{G}_\tau$ of stationary knowledge graphs with respect to O_τ, and $\mathbb{G}_T := \bigcup_{\tau \in T} \mathbb{G}_\tau$.



Then, a **dynamic knowledge graph** is a mapping $\Gamma : T \to \mathbb{G}_T$ such that $\Gamma(\tau) \in \mathbb{G}_\tau$ holds for $\tau \in T$.

10:30 10:55 11:15

Time-Aware Knowledge Graph Extensions

Summary: Why we wrote this paper

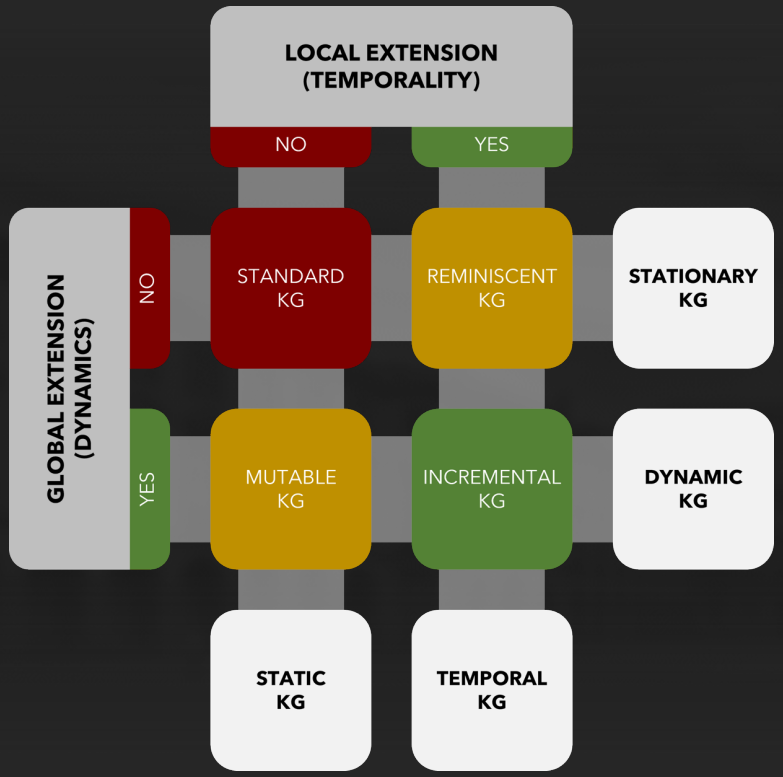
- In addition to standard requirements such as integrability and standardization, the decision whether to use knowledge graphs increasingly depends on their added value in downstream tasks such as

  i. **latent numerical feature representations (embeddings),**
  ii. **graph-based machine learning methods,**
  iii. **(improved) explainability of black box models by semantic enrichment.**

- Until now, these tasks have been dealt with almost exclusively without consideration of **time-awareness** for ***static*** knowledge graphs.

- In the sparse literature related to time-aware downstream applications, terms such as **temporal, dynamic, static, etc.** are used interchangeably and in particular inconsistently.

Time-Aware Knowledge Graph Extensions



- **Local extensions are globally valid:**

  Temporal edge metadata should be factual

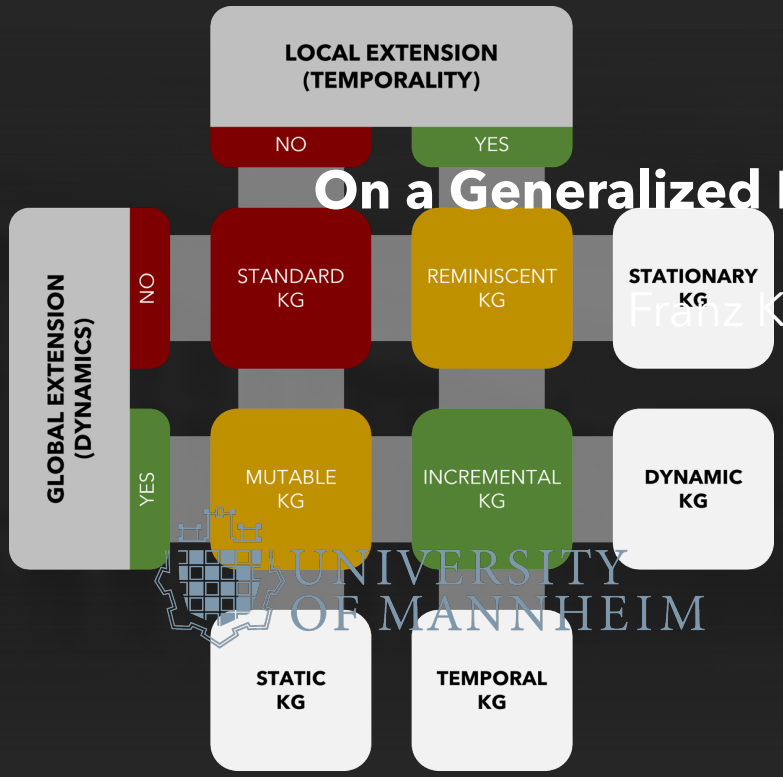
- **Global extensions are locally valid:**

  Different agents learn in different ways

- Time-awareness is a crucial requirement for knowledge graphs and successive applications to be implemented in highly flexible and dynamic domains such as manufacturing.

- The definitions introduced in this work provide a common framework which aims at improving the interoperability of graph-based conceptualizations and AI applications.

Time-Aware Knowledge Graph Extensions



- **Local extensions are globally valid:**

  Temporal edge metadata should be factual

- **Global extensions are locally valid:**

  Different agents learn in different ways

- Time-awareness is a crucial requirement for knowledge graphs and successive applications to be implemented in highly flexible and dynamic domains such as manufacturing.

- The definitions introduced in this work provide a common framework which aims at improving the interoperability of graph-based conceptualizations and AI applications.

On a Generalized Framework for Time-Aware Knowledge Graphs

Franz Krause, Tobias Weller, and Heiko Paulheim

{first.last}@uni-mannheim.de

"Raise Awareness for Time-Awareness."

Sealvester Stallone

On a Generalized Framework for Time-Aware Knowledge Graphs

Franz Krause, Tobias Weller, and Heiko Paulheim

{first.last}@uni-mannheim.de

UNIVERSITY OF MANNHEIM

teaming.ai