UNIVERSITÄT ZU LÜBECK
INSTITUT FÜR INFORMATIONSSYSTEME

Özgür L. Özçep

Logic, Logic, and Logic

Lecture 1: Motivation and Overview

19 October, 2016

Foundations of Ontologies and Databases for Information Systems

CS5130 (Winter 16/17)

Organizational Stuff

Organization

- Lectures with integrated exercises (sometimes homework)
- Exercise slot may vary: so come to the lectures
- **Start**: Today, Wed, 19 October, 2016, 16.05h
- Lecture and exercise related material in Moodle "Grundlagen von Ontologien und Datenbanken für Informationssysteme - CS5130"
- **Oral exam** at the end of the semester
  - **Register** for the course in Moodle
  - Prerequisite for exam: At least 50 percent of exercises solved successfully
- The lectures and the exercises are in English

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Sometimes English Becomes Less Important

Prologue

La loi 101 (Charte de la langue française)

Principe du deux pour un□le texte français doit être écrit en caractères deux fois plus gros que ceux de la version en langue étrangère.

Two for one principle□an english (for clarity) text should be written in characters twice smaller than its french counterpart.

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Slide example by Bruno Poizat from a conference talk

- Model Theorist
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  - Was not well received (for some years)
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Plan

- Logic, Logic, Logic (2 lectures)
- Logical Foundations of Database Systems: Finite Model Theory (2 lectures)
- Semantic Integration with OBDA: Bridging the DB and Ontology World (2-3 lectures)
- Semantic Integration on Ontology Level: Ontology Integration (2-3 lectures)
- Stream Processing (2-3 lectures)
- Process Analysis and Design (2-3 lectures)

First-Order Logic

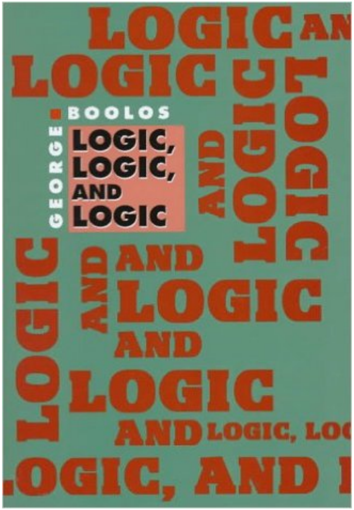
"Logic, Logic, and Logic"

- Interesting collection of essays
- Rather "philosophical logic"

- But we adopt the motto:

  Logic everywhere !

- We are interested not only in logics per se but
- (Knowledge on) logics useful for computer science



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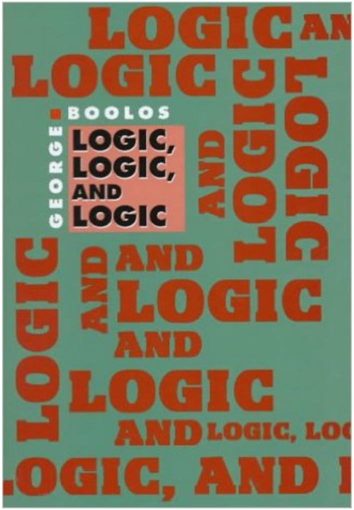

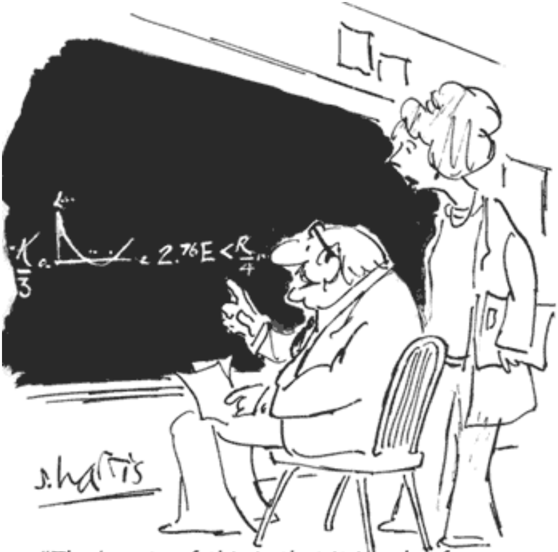

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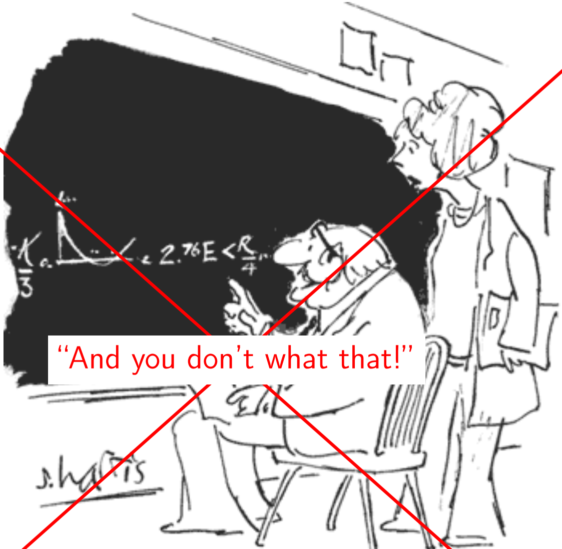

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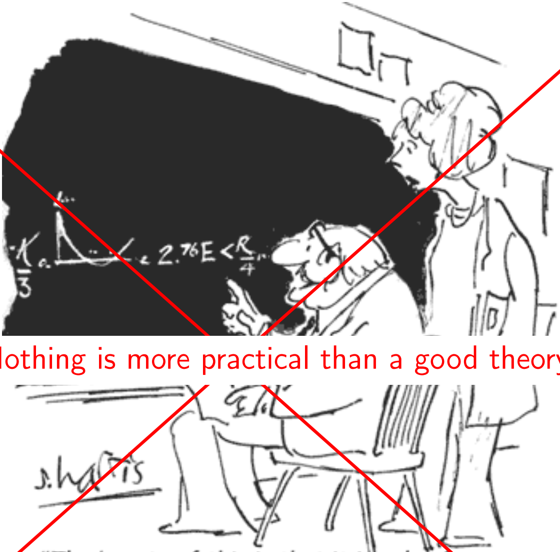
“And you don’t what that!”



But: "Nothing is more practical than a good theory"

"The beauty of this is that it is only of theoretical importance, and there is no way it can be of any practical use whatsoever."

Logic and Logics

- Science of logic
  - investigates mathematical **structures** (static and dynamic)
  - and formal **languages** to describe them
  - distinguishing between **syntax**
  - and **semantics** (truth conditions for sentences)
  - providing notions of **satisfaction, entailment** (from semantics)
  - and of **provability, inference (calculus)**

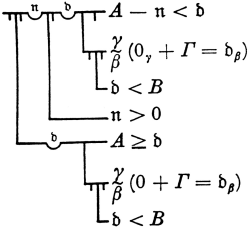
- A logic: A language with syntax, semantics (and possibly calculus)

- There are many different logics (within computer science)
- But in any case somehow related to first-order logic

First-Order Logic (FOL)

- Also called predicate logic (or quantification logic)
- Aristotelian syllogisms already incorporate restricted FOL
  - All Philosophers are wise men. All wise men are nice. Hence all Philosophers are nice men.
  - Restricted to unary predicates

- Modern FOL started with Frege's "Begriffsschrift"
  - language constructs based on constants, variables, predicates, functions, boolean connectives, quantifiers
  - Formal axioms and inference rules
  - His 2-dimensional representation format aesthetic but not practical



FOL Structures

- A formalism to investigate (mathematical) **structures**

$$\mathfrak{A} = (A, R_1^{\mathfrak{A}}, \ldots R_n^{\mathfrak{A}}, f_1^{\mathfrak{A}}, \ldots, f_m^{\mathfrak{A}}, c_1^{\mathfrak{A}}, \ldots, c_l^{\mathfrak{A}})$$

- **(Non-logical) Vocabulary**
  - Relation symbols/predicates R_i with arities
  - Function symbols f_i (with arities)
  - Constant symbols c_i

- Components of the structure
  - **Universe/Domain** A
  - **Interpretations/denotations** of nonlogical symbols
    - Relation $R^{\mathfrak{A}} \subseteq A^n$ (for n-ary relation symbol R)
    - Function $f^{\mathfrak{A}} \in A^n \longrightarrow A$ (for n-ary function symbol f)
    - Individuals $c^{\mathfrak{A}} \in A$ (for constants c)

Example FOL Structures

- **Graphs** $\mathfrak{G} = (V, E^{\mathfrak{G}})$
  1. V = nodes of the graph
  2. $E^{\mathfrak{G}} \subseteq V^2$ = edges of the graph

- **Undirected, loopless graphs** $\mathfrak{G} = (V, E^{\mathfrak{G}})$
  1. as above
  2. as above
  3. Additionally: edge relation is symmetric and a-reflexive

- Need an appropriate language to formulate constraints such as in 3.

FOL Syntax

- Allow variables $(x_1, x_2, \ldots)$ and logical constructors

- **Terms**
  - variables and constants are terms
  - if $t_1, \ldots, t_n$ are terms, so is $f(t_1, \ldots, t_n)$ (for n-ary function symbol f

- **Formulae**
  - $t_i = t_j$ and $R(t_1, \ldots, t_n)$ (for terms t_i and n-ary relation) R
  - If ϕ is a formula, so are
    - $\neg\phi$ ("Not ϕ")
    - $\forall x\ \phi$ ("For all x it holds that ϕ")
    - $\exists x\ \phi$ ("There is an x s.t. ϕ")

  - If ϕ, ψ are formula, so are
    - $(\phi \wedge \psi)$ ("ϕ and ψ")
    - $(\phi \vee \psi)$ ("ϕ or ψ")
    - $(\phi \rightarrow \psi)$ ("If ϕ then ψ")
    - $(\phi \leftrightarrow \psi)$ ("ϕ iff ψ")

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FOL Semantics

- **Interpretation** $\mathcal{I} = (\mathfrak{A}, \nu)$
  - ν assigns to all variables elements from domain A
  - Needed to deal with open formulae
    e.g. $\forall y\; R(y, x)$ open/free in variable x

- x-**Variant** $\mathcal{I}_{[x/d]}$
  same as $\mathcal{I}$ but with $d \in A$ assigned to x

- **Interpretation of terms**
  - $\mathcal{I}(c) = c^{\mathfrak{A}}$
  - $\mathcal{I}(x) = \nu(x)$
  - $\mathcal{I}(f(t_1, \ldots, t_n)) = f^{\mathfrak{A}}(\mathcal{I}(t_1), \ldots, \mathcal{I}(t_n))$

Because dealing with variables is non-trivial...

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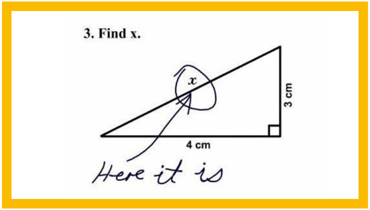

FOL Semantics

- **Satisfaction relation $\models$**
  - $\mathcal{I} \models t_1 = t_2$ iff $\mathcal{I}(t_1) = \mathcal{I}(t_2)$
  - $\mathcal{I} \models R(t_1, \ldots, t_n)$ iff $(\mathcal{I}(t_1), \ldots, \mathcal{I}(t_n)) \in R^{\mathfrak{A}}$

  - $\mathcal{I} \models \neg\phi$ iff not $\mathcal{I} \models \phi$

  - $\mathcal{I} \models (\phi \wedge \psi)$ iff $\mathcal{I} \models \phi$ and $\mathcal{I} \models \psi$
  - $\mathcal{I} \models (\phi \vee \psi)$ iff $\mathcal{I} \models \phi$ or $\mathcal{I} \models \psi$
  - $\mathcal{I} \models (\phi \rightarrow \psi)$ iff: If $\mathcal{I} \models \phi$ then $\mathcal{I} \models \psi$
  - $\mathcal{I} \models (\phi \leftrightarrow \psi)$ iff: $\mathcal{I} \models \phi$ iff $\mathcal{I} \models \psi$

  - $\mathcal{I} \models \forall x\ \phi$ iff: For all $d \in A$: $\mathcal{I}_{[x/d]} \models \phi$
  - $\mathcal{I} \models \exists x\ \phi$ iff: There is $d \in A$ s.t. $\mathcal{I}_{[x/d]} \models \phi$

- Known result: ν can be assumed to be defined only for the free variables in the formula.
- Terminology $\mathcal{I}$ satisfies ϕ, $\mathcal{I}$ makes ϕ true, $\mathcal{I}$ is a model for ϕ
- We also write $\mathfrak{A} \models \phi(\vec{x}/\nu)$

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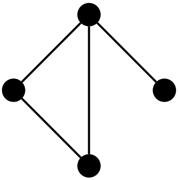

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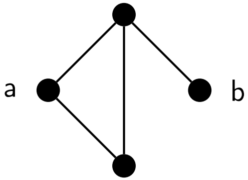

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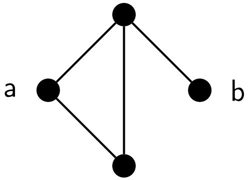

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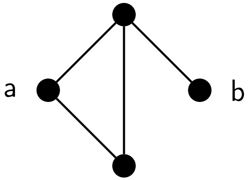

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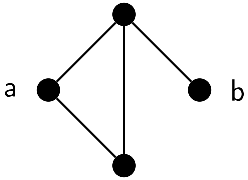

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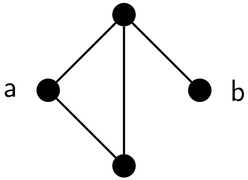

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Entailment

- $X \models \phi$ iff all models of X are models of ϕ
  - We say: X **entails** ϕ or ϕ follows from X
  - X: set of sentences
  - ϕ: sentence

- Note: entailment definition (per se) not easy implementable $\Longrightarrow$: Notion of derivibility/inference in a calculus (see later lectures)

Algorithmic Problems in First-Order Logic

- **Model Checking**:
  - Input: graph (or generally structure) $\mathfrak{G}$, formula $\phi(x_1, \ldots, x_n)$ and assignment $[x_1/a_1, \ldots, x_n/a_n]$
  - Output: Is $\mathfrak{G} \models \phi(x_1/a_1, \ldots, x_n/a_n)$ the case?

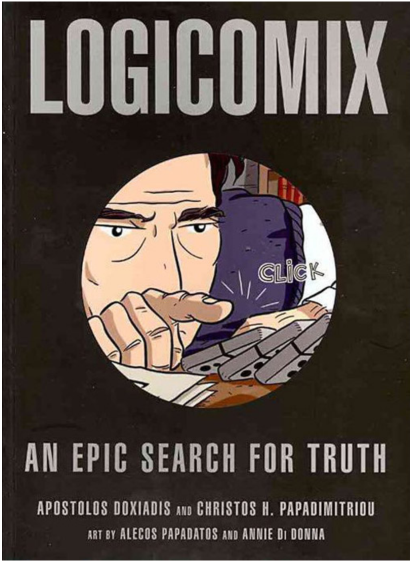
- **Satisfiability Problem**
  - Input: sentence ϕ
  - Output: Does there exist a structure $\mathfrak{G}$ s.t. $\mathfrak{G} \models \phi$?

- **Complexity of problems**
  - Model checking problem is decidable and PSPACE complete (in combined complexity)
  - Satisfiability is undecidable

Role of Logic for/in Computer Science

The Burden of Logic in the 19-20th Century

- Role of logic as a foundation for all of mathematics
- Literature hint: Logicomix
  - fantastic graphic novel
  - Narrator: Philosopher and logician B. Russell
  - About the illusions, disillusions, and landmarking results at the end of the 19th century



Foundations of Mathematics with Mathematical Logic

- Attempts to find formal foundation for mathematical logic
- Hilberts Program (1900-1928)
  - Mathematics is consistent
  - Mathematics is (semantically) complete
  - Mathematics is decidable

Awakening

- Young Gödel proves (1931-33)
  - arithmetics not complete
  - consistency of set theory not provable

- Church/Turing (1936/37)
  - First-order logic is not decidable
  - Valid sentences not recursive
  - Sentences true in arithmetic not recursively enumerable (semi-decidable)

- Nonetheless there are the following positive insights
  - Syntactically completeness for FOL (Gödel, 1930)
  - ZFC (Zermelo-Fraenkel Set Theory) can be used to formalize all contemporary mathematics

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The Unusual Effectiveness of Logic

- Logic (Research) and Computer Science had fruitful effects onto each other
- Logic even more w.r.t. CS (than w.r.t. mathematics)
- "Logic is the calculus of CS"

Lit: M. Y. Vardi. From philosophical to industrial logics. In Proceedings of the 3rd Indian Conference on Logic and Its Applications, ICLA'09, pages 89–115, Berlin, Heidelberg, 2009. Springer-Verlag.

Lit: J. Y. Halpern, R. Harper, N. Immerman, P. G. Kolaitis, M. Y. Vardi, and V. Vianu. On the unusual effectiveness of logic in computer science. Bull. Symbolic Logic, 7(2):213–236, 2001.

Why is this the Case?

- Logic is so general that it allows to
  - talk precisely about the objects within a computer/computation model
  - specify and reason about the properties of runs in the model
- Even more: One can characterize complexity classes with logics (Descriptive Complexity)

So ...

As an upcoming computer scientist (in academia or industry) you should train in formal models, in particular **logics**, because:

- you want to **apply successfully** for a job
- But more importantly: you want to **keep** your job

Computer Science Areas Effected by Logic Research

- Database Systems
- Ontology-Based Information Systems
- Semantic Integration
- Computer-Aided Verification (Model Checking)
- Computational Complexity
- High-Level Stream Processing
- Multi-Agent Systems
- Machine Learning (e.g. probabilistic graph models and logics)
- Semantic Web
- Logic Programming
- Knowledge Representation
- Semantics of Programms
- Digital Design ...

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This course
Other courses of module "Web and Data Science" (CS4513)
This semester: "Web-Mining-Agenten"

Effects of Computer Science to Logic Research

- Focus/Intensive research on finite structures
  - Objects of computation are finite (Finite Model Theory)
  - But: potentially infinite structures (such as infinite DBs or streams) are useful as well
- Need for extensions of FOL
  - Higher-order logics (quantification over sets/relations)
  - Recursion (Datalog)
- Feasibility of reasoning services $\Longrightarrow$ restrictions of FOL
  - Modal and temporal logics
  - Description Logics
- Connections of logic and automata models
  - Regular expressions, finite automata, sequential logics
  - Buechi automata
- Logic engineering
- Different forms of inference ...

Overview on Course With Examples

Example: Logic in DB Research (Lectures 3-4)

- Travel DB with direct connection flights
- Reachability query
- SQL allows for recursion (CONNECT key word)
- But is it really necessary?

Table Flight

Start	End
Hamburg	Berlin
Hamburg	New York
New York	Berlin
...	...

Query Q_{reach}: List all cities reachable from Hamburg!

Intuitively without recursion:

$$
\begin{aligned}
Q_{reach}(x) \quad = \quad & Flight(Hamburg, x) \vee \\
& \exists x_1 Flight(Hamburg, x_1) \wedge Flight(x_1, x) \vee \\
& \exists x_1, x_2 Flight(Hamburg, x_2) \wedge Flight(x_2, x_1) \wedge Flight(x_1, x) \vee \\
\ldots &
\end{aligned}
$$

Example: Logic In DB Research

- **Finite Model Theory (FMT)** gives a proof for the impossibility to use FOL for recursive queries
- FMT models DBs as finite relational FOL structures

Example

- Flight table becomes structure $\mathfrak{A} = (D, \mathit{Flight}^{\mathfrak{A}}, \mathit{Hamburg}^{\mathfrak{A}}, \mathit{Berlin}^{\mathfrak{A}}, \dots)$
- Domain D: all constants in DB
- Constants named by themselves, e.g., $\mathit{Hamburg}^{\mathfrak{A}} = \mathit{Hamburg}$
- $\mathit{Flight}^{\mathfrak{A}} = \{(\mathit{Hamburg}, \mathit{Berlin}), (\mathit{Hamburg}, \mathit{NewYork}), \dots\}$

Example: Logic In DB Research

- Investigate all relevant reasoning problems w.r.t. finite models
  - Many properties for classical FOL do not hold
  - Also w.r.t. complexity
    $\Longrightarrow$ Calls for new techniques
- In particular: Investigate properties that all FOL queries have.

Theorem

*All FOL formulas are **local**.*
(Holds even for FOL extended with aggregation)

- Recursive queries are not local!

Example: Data Exchange (Lectures 5-6)

- Deals in a specific way with the integration of DBs

- Scenario
  - You have two DBs (source and target) on the same domain but different schemata S and T
  - You have some relationship specifications $\Sigma(T, S)$ for T and S
  - Aim: Answer queries over T to get answers with DBs over S
  - Subaims: Find (good) instances for T corresponding to given instances over S and answer over found solution set.

- And here comes logic
  - Language for specifying $\Sigma_{ST} \Longrightarrow$ Specific FOL formulas called tuple generating dependencies (tgds)
  - Criteria for goodness of solutions $\Longrightarrow$ universal model notion
  - How specify answers? $\Longrightarrow$ Certain answer semantics

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Example: Data Exchange

Example

- S: student(name)
- T: univ(sname, uname)
- Σ_{ST} : $student(x) \rightarrow \exists y\ univ(x, y)$

  "If something is a student in a S-DB, then there is an associated university in the T-DB"

- Example T-query: $Q(x) = \exists y.univ(x, y)$
- What should be the answers for given S-DB $I = \{\text{student(Frege)}\}$?
  cert(Q(x),I) = {Frege}

Example: Querying via Ontologies (Lectures 7-8)

- Ontologies as formal means to represent and reason over data
- Ontologies specify constraints and completeness rules
- Ontologies may have many models (open world assumption)
- May be used for access of heterogeneous data sources

- Appropriate ontology languages: Description Logics (OWL and variants)
  - Constants, concepts (unary predicates), roles (binary predicates)
  - Terminological axioms, e.g., $\mathit{Students} \sqsubseteq \mathit{Humans}$
  - Assertions axioms, e.g., $\mathit{Student}(\mathit{Frege})$
  - Description logics are **feasible fragments** of FOL

Example

- No university known for *Goedel*
- Completeness:
  $Student \sqsubseteq \exists hasUniv.University$
- Functionality constraint:
  $(func\ hasUniv)$

Table university

Student	Univ
Frege	U-Jena
Russell	U-London
Goedel	NULL
...	...

Example: Ontology Integration (Lectures 9-10)

- There exist many ontologies out there
- For some applications need to integrate ontologies
- Problem: Joining ontologies may lead to incoherences/inconsistencies

Example

Ontology A

- $Article \equiv \exists publ.Journal$
- $Journal \sqsubseteq \neg Proceedings$
- $(func\ publ)$

Ontology B

- $Article \equiv \exists publ.Journal \sqcup Proceedings$
- $publish(ab, procXY)$

- $O_A \cup O_B$ is inconsistent
- How to repair this?

Belief Revision

- Belief Revision deals with operators for revising theories under possible inconsistencies
- Investigates concrete revision operators
- Principles that these must fulfill (minimality etc.)
- Representation theorems

- Recent research how to adapt these for non-classical logics/ontologies

Streams (Lectures 11-12)

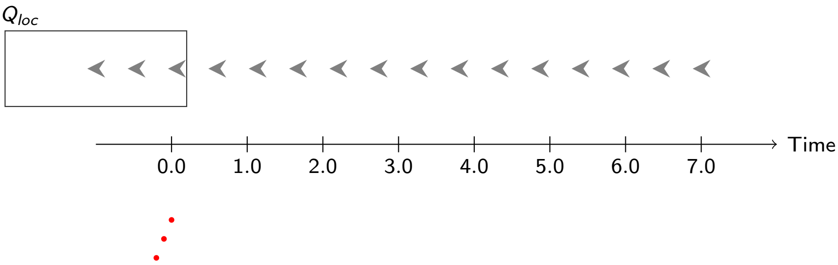
- "It's a streaming world" **(Ubiquity)**
  - Many data are temporal (sensor, event data)
  - Big data is mostly temporal data
- "Streams are forever" **(Potential Infinity)**
  - Streams are potentially infinite
  - One has to tame the infinite
  - Streams call for continuous **querying** (monitoring)
- "Order Matters" **(Sequentiality)**
  - Stream elements have an arriving order next to temporal order
  - Re-ordering or special sequencing may be needed

Lit: E. Della Valle. et al. It's a streaming world! Reasoning upon rapidly changing information. Intelligent Systems, IEEE, 24(6):83–89, nov.-dec. 2009.

Lit: J. Endrullis, D. Hendriks, and J. W. Klop. Streams are forever. Bulletin of the EATCS, 109:70–106, 2013.

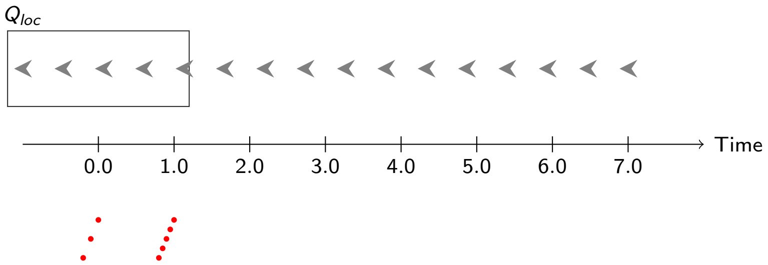
Lit: E. D. Valle et al. Order matters! Harnessing a world of orderings for reasoning over massive data. Semantic Web, 4(2):219–231, 2013.

Query With Sliding Window



- Sliding window for taming the infinite
- **Query** window contents with local query Q_{loc}
- Example: Q_{loc} = Show all failure events in the window
- For High-Level Stream Processing: Incorporate background knowledge

Query With Sliding Window



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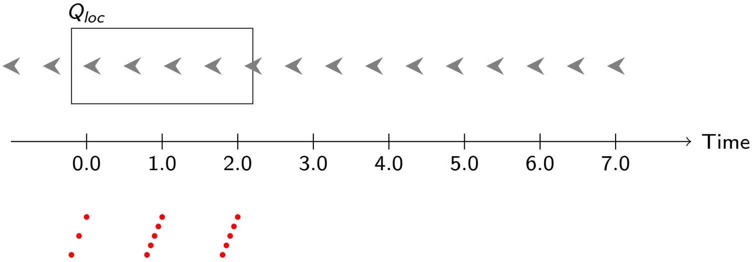

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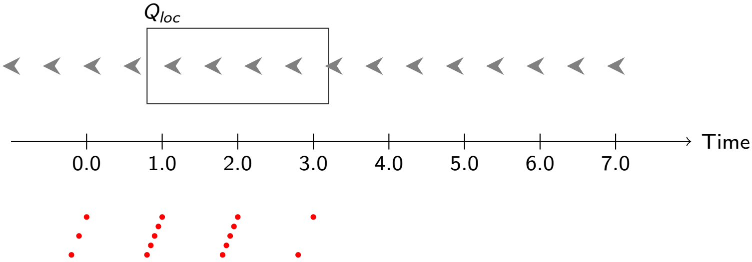

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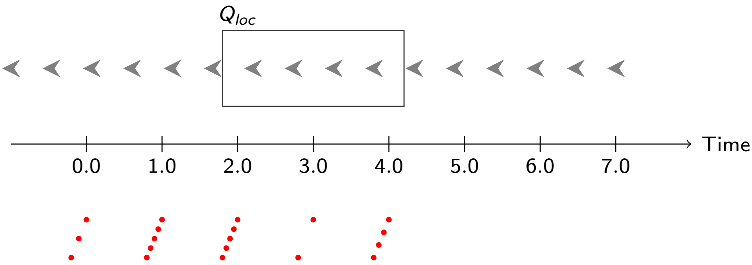

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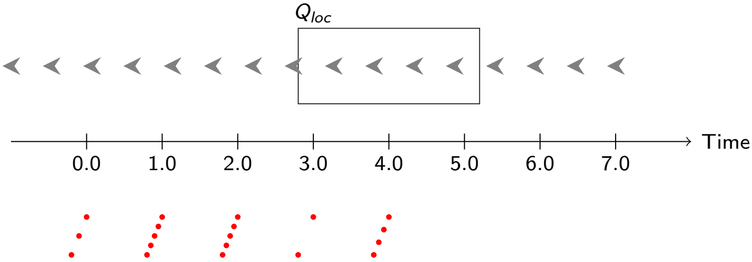

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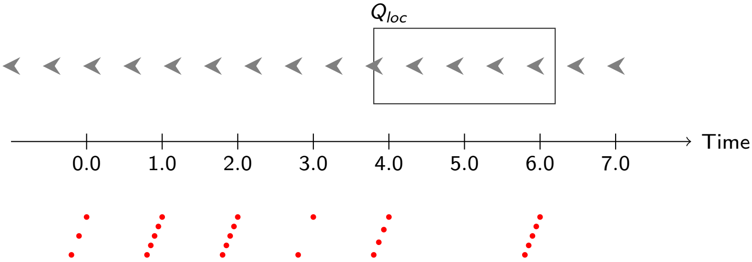

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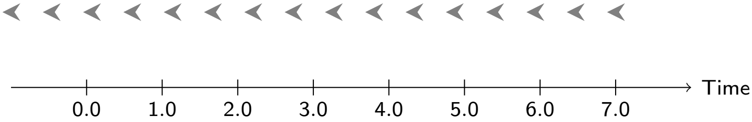

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Process Verification (Lectures 12-13)

- Verification of system behavior very important for industrial applications
- Model Checking mature theory with well-proven software implementations used in industry
  - given a system description (model) and (desired) specifications (axioms in (**temporal logics**))
  - Check whether specification is fulfilled by (all runs of) model

Example (Linear Temporal Logic)

- Excluding unwanted conditions for every time point

$$\Box \neg(\mathit{turbineTemp} > 90^\circ)$$

- Ensuring wanted conditions

$$\Box(\mathit{startTurbine} \rightarrow \diamond \mathit{TurbineIsRunning})$$

Process Verification

- Lift verification ideas/tools to verify business processes
- Challenges
  - Have to incorporate (large amounts of) data
    $\Longrightarrow$ artifact-centric approach (early 2000)
  - Finite state models not sufficient
    $\Longrightarrow$ finite state transducers

Exercise 1 (6 points)

Describe an example application or a computer science sub-area from your CS studies or from your job which exemplifies the "use" of some form of logic. In particular answer the following questions (on 2-3 slides in pdf):

1. What kind of logic is used?
2. What is its relation to FOL?
3. How/why is it used in the area/application?

- Send your solutions in one pdf file as presentation until Monday night, 24th of October 2016 to oezcep@ifis.uni-luebeck.de.
- You may work in pairs
- State your name, your study course (Studiengang) and your identity number (Matrikelnummer) at the title page