UNIVERSITÄT ZU LÜBECK
INSTITUT FÜR INFORMATIONSSYSTEME

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# Logic, Logic, and Logic

*Lecture 1: Motivation and Overview*
*21 October, 2015*

*Foundations of Ontologies and Databases*
*for Information Systems*
*CS5130 (Winter 2015)*

# Organizational Stuff

# Organization

- Lectures with integrated exercises (sometimes homework)
- Exercise slot may vary: so come to the lectures
- **Start**: Today, Wed, 21 October, 2015, 16.00h
- 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

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> **La loi 101 (Charte de la langue française)**
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Slide example by Bruno Poizat from a conference talk

- Model Theorist
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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)
- Round Up: A Vademecum for Information Systems (0,5 - 1 Lecture)

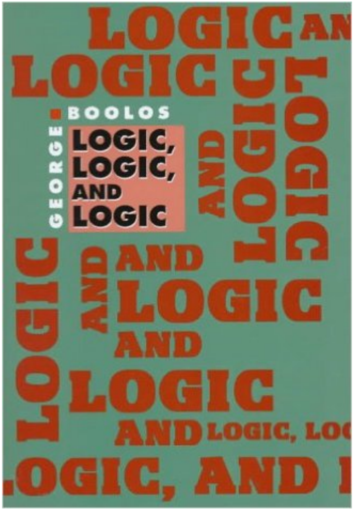
# First-Order Logic

# "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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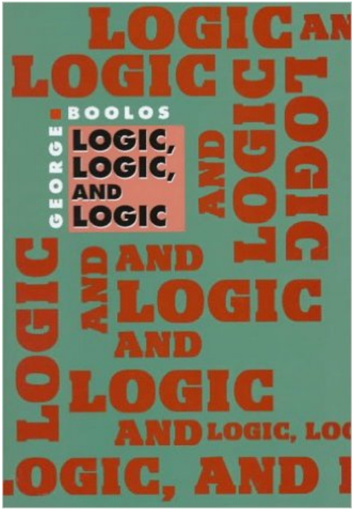


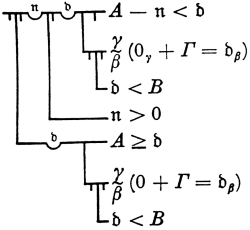
# Logic and Logics

- 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)**
- Investigated languages with syntax and semantics called logics
- In particular there are many 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 "Begriffschrift"
  - 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**

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

- **(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 $\phi$ is a formula, so are
    - $\neg\phi$ ("Not $\phi$")
    - $\forall x\ \phi$ ("For all $x$ it holds that $\phi$")
    - $\exists x\ \phi$ ("There is an $x$ s.t. $\phi$")
  - If $\phi, \psi$ are formula, so are
    - $(\phi \wedge \psi)$ ("$\phi$ and $\psi$")
    - $(\phi \vee \psi)$ ("$\phi$ or $\psi$")
    - $(\phi \rightarrow \psi)$ ("If $\phi$ then $\psi$")
    - $(\phi \leftrightarrow \psi)$ ("$\phi$ iff $\psi$")

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# FOL Semantics

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

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

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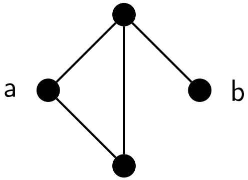
# Examples

- Consider loopless, symmetric graphs $\mathfrak{G} = (G, E^{\mathfrak{G}})$




- $\phi_1 := \exists x \, \exists y \, E(x, y)$ $\qquad \mathfrak{G} \models \phi_1$?
- $\phi_2(x) := \exists y \, \exists z \, E(x, y) \wedge E(x, z) \wedge E(y, z)$ $\qquad \mathfrak{G} \models \phi_2(x/a)$
- $\phi_3(x, y) := E(x, y)$ $\qquad \mathfrak{G} \models \phi_3(x/a, y/b)$

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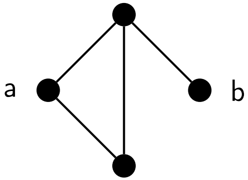


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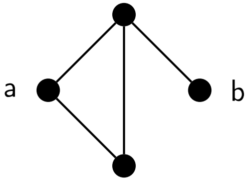


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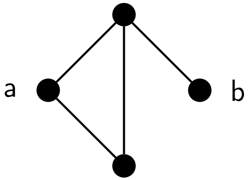


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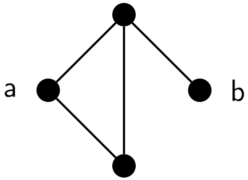


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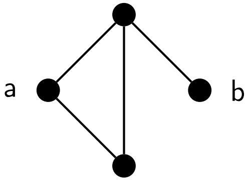


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- $\phi_3(x, y) := E(x, y)$ — $\mathfrak{G} \models \phi_3(x/a, y/b)$ NO!

# 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?

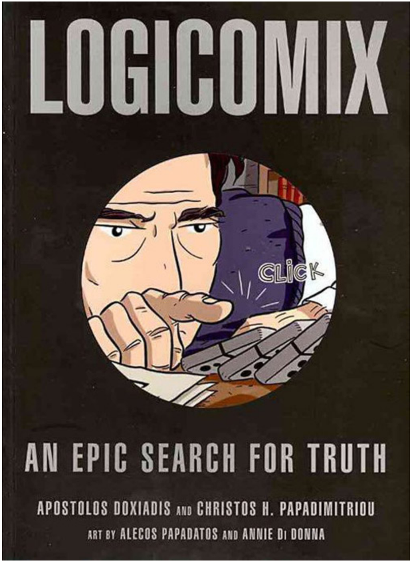
- **Satisfiability Problem**
  - Input: sentence $\phi$
  - Output: Does there exist a structure $\mathfrak{G}$ s.t. $\mathfrak{G} \models \phi$?

- **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 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)

# 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
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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:

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

# Example: Logic In DB Research

- **Finite Model Theory (FMT)** gives a proof for the impossibility to use FOL for recursive of 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)
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# Example: Data Exchange

## Example

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

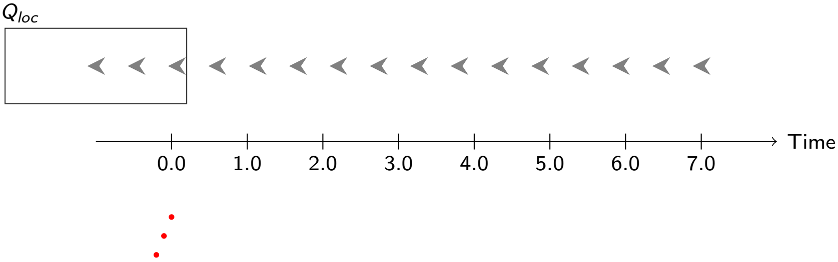
- "It's a streaming world" (Ubiquity)
  - Many data are temporal (sensor, event data)
  - Big data is mostly temporal data
- "Streams are forever" (Potential Infinity)
  - Streams are potentially infinite
  - One has to tame the infinite
  - Streams call for continuous **querying** (as in real-time monitoring)
- "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.

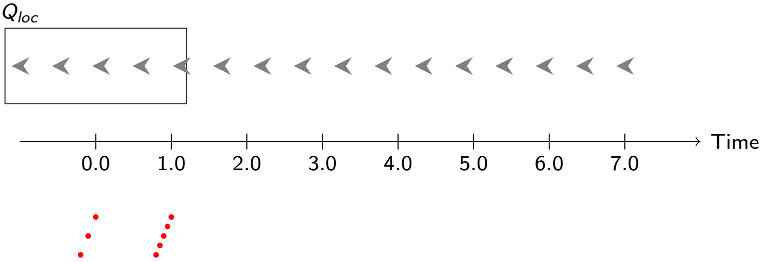
**Lit:** E. D. Valle et al. Order matters! Harnessing a world of orderings for reasoning over massive data. Semantic Web, 4(2):219–231, 2013.

# 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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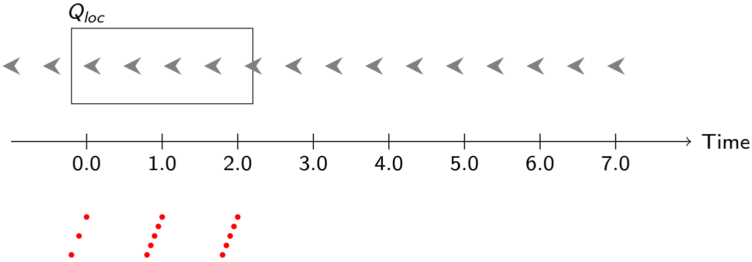


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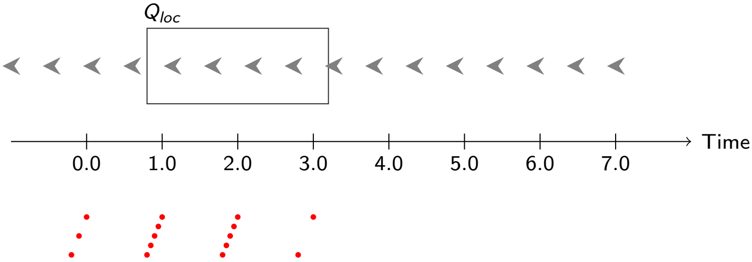


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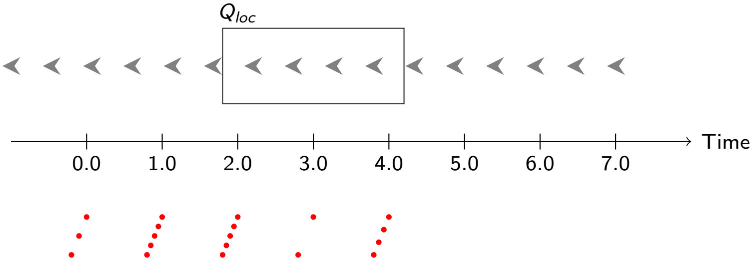


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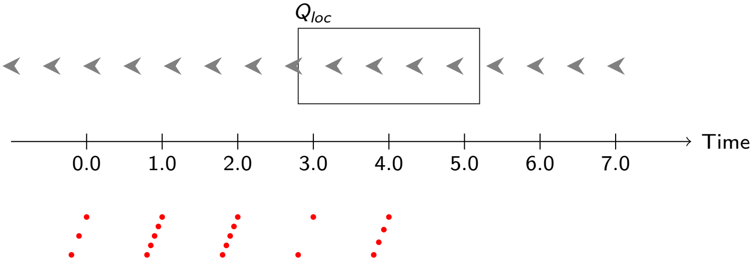


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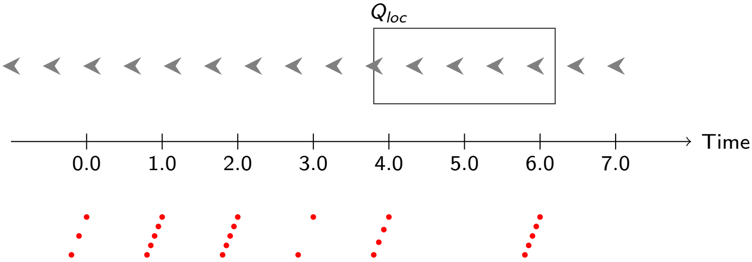


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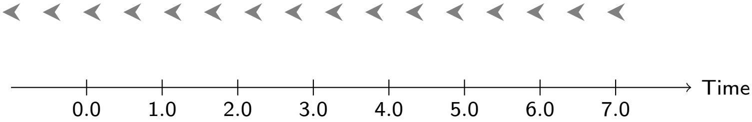


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# Process Verification (Lectures 12-13)

- 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 (all runs of the) model fulfills specification

## 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 Tuesday evening, 27th of October 2015 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