A Tool for Automated Reasoning about Traces Based on Configurable Formal Semantics

Ferhat Erata
Wageningen University, the Netherlands
ferhat@computer.org

Bedir Tekinerdogan
Wageningen University, the Netherlands
bedir.tekinerdogan@wur.nl

Arda Goknil
University of Luxembourg, Luxembourg
arda.goknil@uni.lu

Geylani Kardas
Ege University, Turkey
geylani.kardas@ege.edu.tr

ABSTRACT
We present Tarski, a tool for specifying configurable trace semantics to facilitate automated reasoning about traces. Software development projects require that various types of traces be modeled between and within development artifacts. For any given artifact (e.g., requirements, architecture models and source code), Tarski allows the user to specify new trace types and their configurable semantics, while, using the semantics, it automatically infers new traces based on existing traces provided by the user, and checks the consistency of traces. It has been evaluated on three industrial case studies in the automotive domain (https://modelwriter.github.io/Tarski/).

CCS CONCEPTS
• Software and its engineering → Consistency; Traceability; Specification languages; Formal methods;

KEYWORDS
Traceability; Domain-Specific Modeling; Formal Trace Semantics; Automated Reasoning; Alloy; KodKod

ACM Reference format:
Ferhat Erata, Arda Goknil, Bedir Tekinerdogan, and Geylani Kardas. 2017. A Tool for Automated Reasoning about Traces Based on Configurable Formal Semantics. In Proceedings of 2017 11th Joint Meeting of the European Software Engineering Conference and the ACM SIGSOFT Symposium on the Foundations of Software Engineering, Paderborn, Germany, September 4–8, 2017 (ESEC/FSE’17). 11 pages.
https://doi.org/10.1145/3106237.3122825

1 INTRODUCTION
The complexity of software systems in safety critical domains (e.g. avionics and automotive) has significantly increased over the years. Development of such systems requires various phases which result in several artifacts (e.g., requirements documents, architecture models and test cases). In this context, traceability [29, 32] not only establishes and maintains consistency between these artifacts but also helps guarantee that each requirement is fulfilled by the source code and test cases properly cover all requirements, a very important objective in safety critical systems and the standards they need to comply with [25, 30]. As a result, the engineers have to establish and maintain several types of traces, having different semantics, between and within various development artifacts.

We present a tool, Tarski1, which supports specifying configurable trace semantics to facilitate multiple forms of automated trace reasoning. Tarski is developed for environments, requiring maintenance of various artifacts, within the context of our research [13, 14] in collaboration with Ford-Otosan [15], Airbus [1] and Havelsan [24]. The motivation behind Tarski is to provide a way to interactively specify trace types and semantics, which vary for different artifacts, to be used in automated trace reasoning.

There are approaches and tools [2, 16, 17, 21, 22] that use a predetermined set of possible trace types and their semantics for automated reasoning. However, in the case of dealing with complex software systems, instead of a one-size-fits-all approach, it is required to enable the adoption of several trace types and their semantics, and herewith the various forms of automated reasoning about traces. To do so, Tarski provides the following features: (i) specifying trace semantics which can be configured due to project and artifact types, (ii) deducing new traces based on the given trace semantics and on the traces which the engineer has already specified, and (iii) identifying the traces whose existence causes a contradiction according to the trace semantics. The tool provides a traceability domain model which describes the basic concepts of traceability such as Trace-link and Trace-location. The notion of trace-location refers to traceable elements in an artifact, while the notion of trace-link refers to traces between trace-locations. The user defines new trace types by extending Trace-link and Trace-location. The user specifies the semantics of new trace types in a restricted form of Alloy [26], i.e., First-Order Logic (FOL) augmented with the operators of the relational calculus [33]. We employ Kodkod [35, 36], an efficient SAT-based constraint solver for FOL with relational algebra and partial models, for automated trace reasoning using the trace semantics. Our tool is integrated with Eclipse [8] platform.

In the remaining sections, we outline Tarski’s features and components. We highlight the findings from our evaluation of Tarski over multiple industrial case studies with one of our industrial partners.

1The name is inspired by Alfred Tarski’s foundational work on the relational calculus
2 RELATED WORK

Several approaches and tools have been proposed for automated trace reasoning using the trace semantics [2, 6, 7, 9–11, 16, 18–22, 27, 28, 31, 34]. These approaches employ a predefined set of trace types and their corresponding semantics. For instance, Goknil et al. [22] provide a tool for inferencing and consistency checking of traces between requirements using a set of trace types (e.g., refines, requires, and contains) and their formal semantics. Similarly, Egyed and Grünbacher [11] propose a trace generation approach. They do not allow the user to introduce new trace types and their semantics for automated reasoning. In the development of complex systems, it is required to enable the adoption of various trace types, and herewith automated reasoning using their semantics.

Tarski does not encode any predefined trace type or semantics. It allows the user to interactively define new trace types with their semantics to be used in automated reasoning about traces. Using the semantics specified by the user, Tarski deduces new traces and checks the consistency of traces.

3 TOOL OVERVIEW

Tarski is the tool supporting our approach for automated reasoning about traces based on configurable trace semantics, recently described in [12]. Fig. 1 presents an overview of our tool. In Step 1, the user specifies new trace types and their semantics in First-Order Logic (FOL) augmented with the operators of the relational calculus [33]. To do so, Tarski employs a restricted form of Alloy [26] with a custom text editor. New trace types are defined by extending Trace-link and Trace-location in Traceability Domain Model.

Once the user specifies the trace types and their semantics, Tarski allows the user to assign traces between and within the input project artifacts (e.g., requirements specifications, architecture models, and test cases) using the trace types (Step 2). After the traces are manually assigned, the tool proceeds to Step 3 with automated trace reasoning. In the rest of the section, we elaborate each step in Fig. 1 using the Electronically Controlled Air Suspension (ECAS) System of Ford-Otosan [15], a safety-critical system in automotive domain, as a case study.

3.1 Specification of Trace Types and Semantics

As the first step, for the artifacts, the user specifies trace types and their semantics in FOL using a restricted form of Alloy. First, the user extends the traceability domain model with new trace and artifact types. Fig. 2 shows part of the extended traceability domain model for the ECAS case study.

We extend Trace-link in Fig. 2 with new trace types (e.g., contains, refines, and satisfies), while Text-location is extended with new types of elements of the artifacts to be traced in the case study (e.g., Requirement, HighLevelReq, and Code). Fig. 3 shows some of the extensions of Trace-link and Trace-location in Fig. 2.

In the following, we briefly explain the restricted Alloy notation Tarski employs for declaring trace types and their semantics. Signatures define the vocabulary of a model in Alloy (see keyword sig in Fig. 3). We use them to extend Trace-location for declaring artifact element types (see Lines 4, 9, 12, 15, 17, 21, and 24 in Fig. 3). Tarski employs some special annotations to specify artifacts’ location types (Lines 8, 11, 14, 20 and 23). The location type information is later used by Tarski to create the Eclipse workspace fields to save traces assigned in Step 2 in Fig. 1 (see Section 3.2). For instance, Requirement is given as a text location in Line 11 (see Requirement and Text-location in Fig. 2), while Code is given as a source code location in Line 20. For a trace between a textual requirement and a code fragment, using the location information in Fig. 3, Tarski creates a resource field as a path referring to the location of the requirement, while the resource, offset, and length fields are created to refer to the code fragment where resource gives the path of the source code file, offset gives the start index of the code fragment in the code file, and length gives the length of the code fragment.

Figure 1: Tool Overview

Figure 2: Traceability Model with User-defined Trace Types

Figure 3: Some Example Trace Types in Tarski
New trace types are defined as binary relations in the signature fields (see Lines 5, 6, 12, and 18 in Fig. 3). Tarski automatically extends Trace-link for those binary relations (see Fig. 2). For instance, in Line 18, Satisfies is declared as a new trace type between Implementation and Requirement. Trace semantics is given as facts in Alloy (see Fig. 4). Facts are constraints that are assumed to always hold. They are used as axioms in constructing examples and counterexamples [26]. The Refines, Requires and Contains trace types are defined irreflexive and antisymmetric (see Lines 26 and 27 in Fig. 4).

### 3.2 Trace Assignment in Project Artifacts

Tarski guides the user in assigning traces between and within the input artifacts (see Step 2 in Fig. 1). The user manually assigns traces for the input artifacts using the trace types. The main challenge is that the traceable parts of textual artifacts (e.g., requirements in a requirements specification) need to be determined before assigning traces. To address this challenge, Tarski employs a semantic parsing approach [23] that automatically maps natural language to Description Logic (DL) axioms. The mappings between the natural text and the DL axioms are used by Tarski to automatically identify the traceable parts of textual artifacts. Fig. 5 shows part of the ECAS requirements specification after semantic parsing in Tarski.

The blue colour indicates the traceable parts of the ECAS requirements specification which do not yet have any trace. When the user wants to assign a trace from/to these blue coloured parts, Tarski automatically suggests the possible trace types using the type hierarchy encoded in Step 1 (see Fig. 3). After the trace is assigned, the blue colour automatically becomes red, which indicates having at least one trace.

### 3.3 Automated Reasoning about Traces

Inference and consistency checking aim at deriving new traces based on given traces and determining contradictions among traces. These two activities enrich the set of traces in the artifacts. They are processed in parallel because the consistency checking uses the machinery for inferencing and also checks the inconsistencies among inferred traces as well as among given traces.

#### 3.3.1 Inferring New Traces

Tarski takes the artifacts and their manually assigned traces as input, and automatically deduces, using the user-defined trace types and their semantics, new traces as output. Fig. 6 gives the assigned and inferred traces for some simplified ECAS requirements and source code fragments in Table 1.

![Figure 4: Example Trace Semantics in Tarski](image)

As part of the semantics, we define how trace types are related to each other (Lines 30–49). For instance, according to the fact in Lines 30–33 where \( a, b \) and \( c \) are artifact elements, if \( a \text{ refines } b \) or \( a \text{ requires } c \), then \( a \) also \( \text{conflicts with } c \).

![Figure 5: Part of the ECAS Requirements Specification](image)

The solid arrows represent the manually assigned traces, while the dashed arrows are the traces automatically inferred by Tarski. For instance, the user assigns the \( r_{21} \) and \( i_{34} \), and between \( r_{60} \) and \( r_{11} \). Using the trace semantics in Fig. 4, Tarski automatically infers two \( \text{satisfies} \) trace, two \( \text{requires} \) traces and one \( \text{conflicts} \) trace in Fig. 6. For instance, \( i_{34} \text{ satisfies } r_{11} \) (i.e., inferred) because it \( \text{satisfies} \) \( r_{60} \) which \( \text{refines} r_{11} \) (see the fact in Lines 36–40 in Fig. 4). The \( \text{conflicts} \) trace between \( r_{60} \) and \( r_{98} \) is inferred because \( r_{60} \text{ requires } r_{98} \) which \( \text{conflicts} \) with \( r_{59} \) (see the fact in Lines 30–33 in Fig. 4). Please note that the \( \text{requires} \) trace between \( r_{60} \) and \( r_{98} \) is inferred.
3.3.2 Checking Consistency of Traces. Tarski takes the artifacts and their given and inferred traces as input, and automatically determines, using the user-defined trace types and their semantics, the inconsistent traces as output. Tarski provides an explanation of inconsistent traces by giving all the manually assigned traces causing the inconsistency. In Fig. 6, the requires and conflicts traces between $r_{60}$ and $r_{59}$ are inconsistent (or contradict each other) because a requirement cannot require another requirement which it conflicts with (see the fact in Lines 48-49 in Fig. 4). The inconsistent conflicts trace is inferred using two other inferred traces. First, $r_{60}$ requires $r_{97}$ (i.e., inferred) because $r_{60}$ refines $r_{11}$ which requires $r_{97}$. Second, $r_{60}$ requires $r_{98}$ (i.e., inferred) because $r_{60}$ requires $r_{97}$ which contains $r_{98}$. And lastly, $r_{60}$ conflicts with $r_{59}$ (i.e., inferred and inconsistent with the requires trace) because $r_{60}$ requires $r_{98}$ which conflicts with $r_{59}$. Therefore, the manually assigned refines trace between $r_{60}$ and $r_{11}$, requires trace between $r_{71}$ and $r_{97}$, contains trace between $r_{97}$ and $r_{98}$, conflicts trace between $r_{98}$ and $r_{59}$, and requires trace between $r_{60}$ and $r_{59}$ actually cause the inconsistency in Fig. 6. When we, together with the Ford-Otosan engineers, analyzed all these assigned traces, we identified that the manually assigned requires trace between $r_{60}$ and $r_{59}$ is invalid. We removed it to resolve the inconsistency.

4 EVALUATION

Our goal was to assess, in an industrial context, the feasibility of using Tarski to facilitate automated trace reasoning using user-defined trace types and semantics. For this assessment, we selected three industrial case studies which are subsystems of the ECAS system developed by different teams at Ford-Otosan [15]. They are relatively mid-sized systems with multiple artifacts (e.g., requirement specifications, SysML models, Simulink models, test suites and C code) requiring various trace types (see Table 2).

Before conducting the case studies, the Ford-Otosan engineers were given presentations illustrating the Tarski steps and a tool demo. The engineers held various roles (e.g., senior software engineer and system engineer) and all had substantial experience in software development. For each case study, we asked the engineers to identify trace types and assisted them in specifying trace types and their semantics in Tarski (the 1st and 2nd columns in Table 2). The artifacts in each case study had already some typeless traces (i.e., trace to/from) manually assigned by the engineers. We asked them to reassign those traces using the trace types they specified using Tarski (the 3rd and 4th columns).

Table 2: Number of Trace Types, Facts, Assigned & Inferred Traces, and Inconsistent Parts in the Case Studies

| Trace Types | Facts | Traced Elements | Manual Traces | Inferred Traces | Incons. Parts |
|-------------|-------|-----------------|---------------|----------------|--------------|
| #1          | 7     | 11              | 125           | 138            | 502          | 3            |
| #2          | 11    | 20              | 47            | 102            | 145          | 5            |
| #3          | 10    | 14              | 16            | 21             | 53           | 1            |

To evaluate the output of Tarski, we had semi-structured interviews with the engineers. All the inferred traces and the found inconsistencies in the case studies were confirmed by the engineers to be correct (the 5th and 6th columns). The engineers considered the automated generation of new traces and the consistency checking of traces to be highly valuable. The restricted Alloy Tarski employs was sufficient to specify all the trace types and their semantics for the case studies. The engineers agreed about the useful guidance provided by Tarski for specifying trace types and semantics. They stated that it was intuitive to specify trace types and semantics using Tarski although more practice and training were still needed to become familiar with the tool.

5 IMPLEMENTATION & AVAILABILITY

Tarski has been implemented as an Eclipse plug-in. This plug-in activates the user interfaces of Tarski and provides the features specifying trace types and their semantics, assigning traces in the artifacts using user-defined trace types, and reasoning about traces (i.e., deducing new traces and checking consistency of traces). We use Kodkod [35, 36], an efficient SAT-based finite model finder for relational logic, to perform automated trace reasoning using the user-defined semantics. Trace types and their semantics are specified in the restricted form of Alloy, while the artifacts containing manually assigned traces are automatically transformed into Alloy specifications. Using the trace semantics and the artifacts in Alloy, we directly call Kodkod API [5] to reason about traces.

Tarski relies upon (i) a customized Eclipse editor to specify trace types and their semantics in FOL, (ii) another customized Eclipse editor to assign traces between and within the artifacts (including textual artifacts such as requirements specifications) using user-defined trace types, and (iii) alloy4graph [3] and alloy4viz [4], the Alloy API packages for performing graph layout and displaying Alloy instances, to visualize the output of automated trace reasoning.

Tarski is approximately 50K lines of code, excluding comments and third-party libraries. Additional details about Tarski, including executable files and a screencast covering motivations, are available on the tool’s website:

https://modelwriter.github.io/Tarski/

6 CONCLUSION

We presented a tool, Tarski, to allow the user to specify configurable trace semantics for various forms of automated trace reasoning such as inferencing and consistency checking. The key characteristics of our tool are (1) allowing the user to define new trace types and their semantics which can be later configured, (2) deducing new traces based on the traces which the user has already specified, and (3) identifying traces whose existence causes a contradiction. Tarski has been evaluated over three industrial case studies. The evaluation shows that our tool is practical and beneficial in industrial settings to specify trace semantics for automated trace reasoning. We plan to conduct more case studies to better evaluate the practical utility and usability of the tool.

ACKNOWLEDGMENTS

This work is conducted within ModelWriter[13] and ASSUME[14] projects and partially supported by the Scientific and Technological Research Council of Turkey (TUBITAK) under project #9140014, #9150181, and by the Luxembourg National Research Fund (FNR) (FNR/P10/03). We acknowledge networking support by European Cooperation in Science and Technology Action IC1404 "Multi-Paradigm Modelling for Cyber-Physical Systems".
REFERENCES

[1] Airbus. 2017. http://www.airbus.com/. (2017).
[2] Netta Aizenbud-Reshef, Richard F. Paige, Julia Rubin, Yael Shaham-Gafni, and Dimitrios S. Kolovos. 2005. Operational Semantics for Traceability. In ECMDA Traceability Workshop (ECMDA-TW’05). 8–14.
[3] Alloy4graph. 2017. http://alloy.mit.edu/alloy/documentation/alloy-api/. (2017).
[4] Arduino. 2017. http://www.fordotosan.com.tr. (2017).
[5] Kodkod API. 2017. https://github.com/kodkod/release/current/doc/. (2017).
[6] ITEA (Information Technology for European Advancement). 2015. ASSUME: Text & Model Synchronized Document Engineering Platform. https://itea3.org/asssume. (2015).
[7] Arda Göknil, Ivan Kurtev, and Wietze Spijkerman. 2016. Change Impact Analysis for Requirements: A Metamodeling Approach. Information and Software Technology 58, 8 (2014), 950 – 972.
[8] Arda Göknil, Ivan Kurtev, Klaas van den Berg, and Jan-Willem Veldhuis. 2011. Semantics of Trace Relations in Requirements Models for Consistency Checking and Inference. Software and System Modeling 10, 1 (2011), 31–54.
[9] Bikash Gyawali, Anastasia Shimorina, Claire Gardent, Samuel Cruz-Lara, and Mariem Mahfoudh. 2017. Mapping Natural Language to Description Logic. In 14th European Semantic Web Conference (ESWC’17). 273–288.
[10] Balasubramaniam Ramesh and Matthias Jarke. 2001. Toward Reference Models for Requirements Specification. In 1st International Conference on Software Language Engineering (SLE’98). 151–167.
[11] Alexander Egyed. 2003. A Scenario-Driven Approach to Trace Dependency Analysis. IEEE Transactions on Software Engineering 29, 2 (2003), 116–132.
[12] Edsger W. Dijkstra. 1965. Goedel: A Constraint Solver for Software Engineering: Finding Models of Dynamically Configurable Traceability Semantics. In Proceedings of the Symposium on Applied Computing (SAC ’17). ACM, New York, NY, USA, 1607–1614. https://doi.org/10.1145/3019612.3019747
[13] ISS (Information Systems Society). 2017. ASSUME: Text & Model Synchronized Document Engineering Platform. https://itea3.org/asssume. (2017).
[14] ITEA (Information Technology for European Advancement). 2015. ASSUME: Text & Model Synchronized Document Engineering Platform. https://itea3.org/asssume. (2015).
[15] ITEA (Information Technology for European Advancement). 2014. ModelWriter: Text & Model Synchronized Document Engineering Platform. https://itea3.org/project/modelwriter.html. (Sep 2014).
[16] ITEA (Information Technology for European Advancement). 2015. ASSUME: Text & Model Synchronized Document Engineering Platform. https://itea3.org/project/assume.html. (Sep 2015).
[17] Arda Göknil, Ivan Kurtev, and Klaas van den Berg. 2014. Generation and Validation of Traces between Requirements and Architecture based on Formal Trace Semantics. Journal of Systems and Software 88 (2014), 112–127.
[18] Arda Göknil, Ivan Kurtev, and Jean-Vivien Mull. 2013. A Metamodeling Approach for Reasoning on Multiple Requirements Models. In 17th IEEE International Enterprise Distributed Object Computing Conference (EDOC’13). 159–166.
[19] Arda Göknil, Ivan Kurtev, and Klaas van den Berg. 2008. A Metamodeling Approach for Reasoning about Requirements. In European Conference on Model Driven Architecture-Foundations and Applications (ECMDA-FA’08). 310–325.
[20] Arda Göknil, Ivan Kurtev, and Klaas van den Berg. 2010. Tool Support for Generation and Validation of Traces between Requirements and Architecture. In the 6th ECMDA Traceability Workshop (ECMDA-TW’10). 39–46.
[21] Arda Göknil, Ivan Kurtev, Klaas van den Berg, and Wietze Spijkerman. 2014. Change Impact Analysis for Requirements: A Metamodeling Approach. Information and Software Technology 56, 8 (2014), 950 – 972.
[22] Arda Göknil, Ivan Kurtev, Klaas van den Berg, and Jan-Willem Veldhuis. 2011. Semantics of Trace Relations in Requirements Models for Consistency Checking and Inference. Software and System Modeling 10, 1 (2011), 31–54.
APPENDICES

We provide three appendices for the paper. In Appendix A, we provide source code, tool and data availability details. In Appendix B, we explain a walk through of the actual presentation in details. Finally in Appendix C, we present a full axiomatization of the industrial use case in predicate calculus style for interested readers.

A AVAILABILITY & OPEN SOURCE LICENSE

Source Codes, Screencast and Datasets. The source codes files and datasets of Tarski are publicly available for download and use at the project website. A screencast and the installation steps for Tarski are also available at the same website and can be found at:

https://modelwriter.github.io/Tarski/

Tarski is being developed under Work Package 3 within Model-Writer project, labeled by the European Union’s EUREKA Cluster programme ITEA (Information Technology for European Advancement). Further details about the project can be found at:

https://itea3.org/project/modelwriter.html

Open Source License. Tarski is distributed with an open source software license, namely Eclipse Public License v1. This commercially friendly copyleft license provides the ability to commercially license binaries; a modern royalty-free patent license grant; and the ability for linked works to use other licenses, including commercial ones.

B TOOL DEMONSTRATION PLAN

There will be four parts to our presentation: (1) motivation and industrial use cases, (2) overview of the solution and tool architecture, (3) demonstration walktrough, and (4) evaluation. Parts 1, 2 and 4 are presented using slides while Part 3 is presented as a demo using the industrial use case scenario described in Section 3 and detailed in Appendix C. To present these parts, we use a combination of slides, animations, and a live demo. In the following subsections, we provide further details about our presentation plan.

A 25-minute slot has been assumed for the presentation. The estimated duration for the different parts of the presentation suggested below will be adjusted proportionally if the allocated time slot at the conference is different from the above.

B.1 Motivation & Challenges

Estimated Duration: 4 - 5 minutes.
Delivery: 3 to 4 slides.

Motivation. We will emphasize the importance of traceability by introducing “DO-178C Software Considerations in Airborne Systems and Equipment Certification” [30] from aviation industry and “ISO-26262 Road vehicles - Functional safety” [25] from automotive Industry.

Industrial Use Cases We will briefly describe the challenges of Traceability Analysis Activities faced in industry by introducing industrial use cases from Airbus [1], Ford-Otosan [15] and Havel-san [24]. We will explain the importance of semantically meaningful traceability and traceability configuration in industry.

B.2 Tool Overview

Estimated Duration: 1 - 2 minutes.
Delivery: 2 to 3 slides.

Overview of the Solution. We will explain the approach and the user workflow of Tarski by following the steps as shown in Fig. 1.

Tarski Features. We will briefly explain tool features such as Inferring New Traces and Checking Consistency of Traces using animated slides by giving concrete examples from the industrial use case ECAS system presented in the paper. Apart from those features, Tarski provides two more analysis functions, which are Type Approximation for Trace-Locations and Reasoning about a Specific Trace-Location.

B.3 Walk-trough of the Tool Demonstration

Estimated Duration: 9 - 11 minutes.
Delivery: 3 to 4 slides together with a live demo.

Tool Demonstration. In this section, first, we will describe the traceability domain model of the industrial use case, namely Electronically Controlled Air Suspension (ECAS) System, which is illustrated in Fig. 2 and formalized in Fig. 3 and Fig. 4 using Tarski. We will perform a live demonstration taking the following steps:

(1) Introduction of the Eclipse workspace. A workspace in Eclipse contains a collection of resources, i.e. projects, folders and files. In Fig. 7, in the user workspace there exist several projects, one of them contains a requirement specification file, a source code file and an architectural model.

![Figure 7: User’s Eclipse Workspace](image)

(2) Project-based configuration of trace-location types. In Fig. 8, user declares a type hierarchy by creating trace types, which are explained in Section 3.1. The type hierarchy for trace locations in Fig. 8 consists of three sorts, namely REQUIREMENT, IMPLEMENTATION and SPECIFICATION. HighLevelReq and LowLevelReq is sub-types of REQUIREMENT, whereas MODEL and CODE are sub-types of IMPLEMENTATION.
Each Tarski specification configures the Eclipse IDE to trace artifacts in a specific Eclipse workspace. In Fig. 9, the type hierarchy of the configuration file is visualized using the editor. The user can drag and drop selected text and code fragments onto types to create a trace-locations. Since in Alloy formalism, abstract signatures have no elements except those belonging to its extensions, the system does not allow the user to create a trace-location with an abstract type such as Implementation or Artefact.

(3) Project-based configuration of the trace semantics. In Fig. 10, the user defines several consistency rules such as injectivity of contains trace, and reflexivity and anti-symmetry of refines, contains and requires. The user also selects conflicts, satisfies and requires traces for inferring new trace relations.

(4) Uploading configuration file. User upload the configuration file to Tarski plug-in using the menu item as shown in Fig. 11.

(5) Tracing different parts of various artifacts. In Tarski, each trace-location and trace-link subject to formal analysis must be annotated with a type from the hierarchy obtained from the signature and the field declarations on the specification (e.g. Fig. 8). In the user’s workspace, for instance, user traces text fragments of a requirement specification in Fig. 12, several model elements of an architecture document in Fig. 13, and several language constructs of a source code file in Fig. 14.
(6) Creating trace-relation with type. First, the user selects a
trace-location which constitutes the domain of the intended
relation using the context-menu. In Fig. 15, (s)he selects a code
typed trace-location.

A wizard pops up to list legitimate trace types as shown
in Fig. 15. Tarski is able to resolve subtype polymorphism and
suggests suitable trace-types. In this case, the user selects the
type of satisfies.

(7) Traceability management. The traceability information
is adapted to a first-order relational model by the user’s type
annotations to locations (unary relations) and traces (binary,
ternary and n-ary relations). Each user function has a counter-
part API method in order to create automatically those trace-
elements especially in model-based development. Furthermore,
Tarski platform provides functions such as create, delete, update
and change type of the relations with respect to type hierarchy and multiplicity constraints to enable users to elaborate further on the formal instance. The user can manage the locations and traces using Tarski Traceability Visualization View as shown in Fig. 18.

The user is also able to change the type of a location as shown in Fig. 19.

(8) **Consistency checking.** The user can check the consistency on the existing traces and detect an inconsistency as explained in Section 3.3.2. The user is informed if such an inconsistency occurs (Fig. 20).

(9) **Inferring new traces.** The details of inferring new traces are explained in Section 3.3.1. If the user performs reasoning operations about traces, the result is reported back to the user by dashed traces as shown in Fig. 21. If there exists different solutions, the user can traverse them back and forth. He can also accept the inferred traces, and perform another analysis operation including inferred traces.

(10) **Reconfiguring the trace semantics.** Using the current traces the user is able to change the trace semantics and submit the new specification to the system unless (s)he changes trace types. In this way, (s)he can generate new traces adopting different semantics based on his/her project’s changing needs. The user then continues the analysis process with Step 4.
B.4 Evaluation and Lessons Learned

Estimated Duration: 1 - 2 minutes.

Delivery: 2 slides.

We conclude with a summary that presents the evaluation results and the lessons learned.

C AXIOMATIZATION OF THE CASE STUDY

In this section, we axiomatize trace semantics of the case study using First-order Predicate Logic with the signature:

$$\Sigma_T : \{=, \in\} \cup \Sigma_T^1 \cup \Sigma_T^2$$

$$\Sigma_T^1 : \{\text{Artifact, Requirement, Implementation}\}$$

$$\Sigma_T^2 : \{\text{requires, refines, contains, equals, conflicts, satisfies}\}$$

$$\Sigma_T^1$$ is the set of unary predicate symbols and $$\Sigma_T^2$$ is the set of binary predicate symbols. For simplicity, we assume that the universe only consists of the type, Artifact which is partitioned into disjoint subsets of Requirement and Implementation. From now on, $$A$$ represents the set of Artifacts.

C.1 Informal Definitions of Trace-types

In the following list, we informally give the meaning of the trace-types:

1. **requires** Artifact $$A_1$$ requires Artifact $$A_2$$ if $$A_1$$ is fulfilled only when $$A_2$$ is fulfilled. The required artifact can be seen as a pre-condition for the requiring artifact.

2. **contains**. Artifact $$A_1$$ contains Artifacts $$A_2 \ldots A_n$$ if $$A_2 \ldots A_n$$ are parts of the whole $$A_1$$ (part-whole hierarchy).

3. **refines**. Artifact $$A_1$$ refines another Artifact $$A_2$$ if $$A_1$$ is derived from $$A_2$$ by adding more details to its properties. The refined artifact can be seen as an abstraction of the detailed artifacts.

4. **conflicts**. Artifact $$A_1$$ conflicts with Artifact $$A_2$$ if the fulfillment of $$A_1$$ excludes the fulfillment of $$A_2$$ and vice versa.

5. **equals**. Artifact $$A_1$$ equals to Artifact $$A_2$$ if $$A_1$$ states exactly the same properties with their constraints with $$A_2$$ and vice versa.

6. **satisfies**. Implementation $$A_1$$ satisfies Requirement $$A_2$$ if $$A_1$$ implements all the properties stated by $$A_2$$.

C.2 Formal Semantics of Trace-types

In the following several axiom schemas are listed to formalize Traceability Theory, that is used in the ECAS case study.

1. Reasoning about **equals** relation, the pattern in Fig. 22 is used.

2. Reasoning about **requires** relation (1): 

   $$\forall a, b, c \in A | (a, b) \in \text{equals} \land (b, c) \in \square \rightarrow (a, c) \in \square$$

3. Reasoning about **satisfies** relation:

   $$\forall a, b, c \in A | (a, b) \in \square \land (b, c) \in \square \rightarrow (a, c) \in \square$$

   where $$\square \in \{\text{contains, requires, refines, satisfies, conflicts}\}$$
\[ \forall a, b, c \in A \mid (a, b) \in \square \land (b, c) \in \text{conflicts} \rightarrow (a, c) \in \text{conflicts} \quad (8) \]

\[ \forall a \in A \mid (a, a) \in \text{conflicts} \quad (9) \]

where \( \square \in \{ \text{requires}, \text{refines}, \text{contains} \} \) and \( \triangle = \text{conflicts} \)

(5) In the following axiom schema, (10) is used for reasoning new traces, whereas (11) and (12) are used to check consistency.

\[ \forall a, b, c \in A \mid (a, b) \in \square \land (b, c) \in \square \rightarrow (a, c) \in \square, \quad (10) \]

\[ \forall a, b \in A \mid (a, b) \in \square \land (b, a) \in \square \rightarrow a = b, \quad (11) \]

\[ \forall a \in A \mid (a, a) \notin \square, \quad (12) \]

where \( \square \in \{ \text{contains}, \text{requires}, \text{refines} \} \)

(6) Consistency of \text{contains} Relation, which is left-unique (injective relation)

\[ \forall a, a', b \in A \mid (a, b) \in \square \land (a', b) \in \square \rightarrow a = a' \quad (13) \]

where \( \square = \text{contains} \)

(7) For instance, in addition to the previously defined axioms using the following axiom schema (14), the system detects an inconsistency between two requirements, \( r_{60} \) and \( r_{59} \) as shown in

\[ \forall a, b \in A \mid (a, b) \in \square \rightarrow (a, b) \notin \triangle \land (b, a) \notin \triangle, \quad \text{where} \quad (14) \]

for each \( \square \in \{ \text{requires}, \text{refines}, \text{satisfies}, \text{contains}, \text{conflicts} \} \) 

\( \text{requires} \cup \text{refines} \cup \text{satisfies} \cup \text{contains} \cup \text{conflicts} \) \( \setminus \square \mapsto \triangle \)

Figure 26: Example Inferred and Inconsistent Traces