Modelling Program Verification Tools for Software Engineers

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ABSTRACT

In software engineering, models are used for many different things. In this paper, we focus on program verification, where we use models to reason about the correctness of systems. There are many different types of program verification techniques which provide different correctness guarantees. We investigate the domain of program verification tools, and present a concise megamodel to distinguish these tools. We also present a data set of almost 400 program verification tools. This data set includes the category of verification tool according to our megamodel, practical information such as input/output format, repository links, and more. The categorisation enables software engineers to find suitable tools, investigate similar alternatives and compare them. We also identify trends for each level in our megamodel based on the categorisation. Our data set, publicly available at https://doi.org/10.4121/20347950, can be used by software engineers to enter the world of program verification and find a verification tool based on their requirements.

CCS CONCEPTS

• **General and reference** → **Surveys and overviews**; • **Software and its engineering** → **Formal software verification**; • **Theory of computation** → *Logic and verification.*

KEYWORDS

Formal Methods; Program Verification; Megamodelling.

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1 INTRODUCTION

Program verification (PV) is a field that has always enjoyed very high expectations, and suffered from them as well. Its objectives are mostly to provide ways to prove that a system satisfies certain requirements. The underlying *techniques* are typically based on rigorous mathematical reasoning or an exhaustive analysis of the state space, thereby giving software engineers stronger guarantees than testing. It is often accepted that to use program verification (or formal methods in general), one needs to specify their system in a formal notation and thus have considerable formal background to do it in a correct and useful way [18].

To simplify, for the rest of the paper we use the established team "program verification" to mean verification (conformance evaluation) of programs (executable models). Hence, it covers generative techniques, testing, model checking, theorem proving, etc, of source code, automata, Petri nets, transition systems, etc.

Adopting verification *tools* has shown to present not only technical challenges, but also organisational, social and managerial ones [22], similar to challenges faced by advanced model-driven engineering tools [40]. PV tools are particularly difficult, because even demonstrating potential benefits of their use is highly non-trivial and relies on users having very specific knowledge of the underlying techniques. For the tool developers, the tools themselves often serve as a means to an end, as an opportunity to demonstrate the extent of applicability of their techniques, to exemplify the problems that could possibly be tackled, and to enter an existing subdomain. (Some subdomains are accompanied by sets of mature benchmarks [6, 12, 36] which make comparing techniques by comparing tools a very attractive and attainable goal). Thus, many tools stay in a prototype phase, and being actively developed only till a certain point: until the tool can handle the minimal set of benchmarks, or until the deadline for submitting the paper explaining the underlying techniques, or until graduating from a PhD project.

Besides techniques and tools, there are multiple *sources* of information to consider. Papers themselves are an obvious source, well-archived on publishers' websites, but requiring high qualifications to be considered readable and understandable. They are also hard-dated, meaning that an average good paper contains detailed comparison of the proposed tool with its existing counterparts, but no comparison or relation to counterparts that were created after the publication. The papers often refer to product or project pages, which are prone not only to being outdated for reasons mentioned above, but also to being removed due to the jobhopping nature of the academic world: when the principal investigator finishes the project and moves to another institution, it is not guaranteed that the project page will be preserved by their original employer. If available, such websites are also wildly varying in the nature of their content: some literally repeat the contents of the papers, while others complement it with valuable information, illustrations, and links.

Another extremely valuable source of information — primarily about the tools and not always about the techniques — is the code repositories. It has become fairly commonplace in recent years to either release the tools for (limited) public use to enable empirical replicability, or expose the entire development history in a form of versioned codebase (typically through `git`, occasionally `hg` or `svn`). There are at least three benefits of repositories: (1) the artefacts become much more tangible, and only require several natural steps (like cloning the repository) to set themselves up on the user's computer instead of extracting them from the paper text; (2) the version history is a technically substantiated claim to the amount of work and to its authorship; and (3) linking tools to one another by shared contributors plays the same social role as linking papers by shared coauthors.

To summarise the problems:

- existing *techniques* are hard to understand and assess their applicability without very deep specific knowledge;
- *tools* are hard to classify conceptually and appropriately relate to *techniques*;
- information *sources* are dispersed, partly unavailable and partly unreliable.

With the vision to open up the arsenal of PV tools and techniques to a broader public of software modellers and, even broader, software engineers, we have developed a megamodel of program verification. The megamodel can help answering questions like "what am I expected to provide as input to use tool X?" or "what other tools exist for the same problem domain as tool X?", or even "when was the last time the code of tool X was updated?". We will elaborate on the megamodel and its **PV0**–**PV6** levels in § 2.

With this megamodel, we show that there are many different types of PV tools, and those types can be grouped in categories that form a hierarchy. Thus, if a tool from one category comes fundamentally short to solve the end user's problems, it can be considered to seek alternatives in a broader category. To concretise the megamodel, we complete it with a data set into which we have collected information about 420+ PV tools, frameworks and languages, published recently at two top conferences in the PV domain known for their tool paper hospitality: CAV and TACAS. The data set is available publicly on GitHub, with a reader-friendly interconnected hypertextual frontend at

https://slebok.github.io/proverb.

We strongly believe that making the data set freely accessible for exploration, makes it an attractive starting point for software engineers to traverse the domain of program verification. § 3 contains more information about the data set, as well as our methods of gathering the data, categorising and enhancing it.

In § 4, we report some preliminary lessons we have learned ourselves by looking at the collected information, level by level, and analysing some of its trends. Further work on enhancing the data set by cross-referencing it with other collections of linked data such as GitHub and DBLP, is ongoing, but the fact that our megamodel splits the PV domain into distinct groups recognisable from prior research, is considered here as a form of evaluation and evidence that the megamodel is viable and useful.

When it comes to related work, we refer to in-depth overviews of problems in adoption of program verification, formal methods, model-driven engineering and domain-specific languages [15, 18, 19, 22, 32, 42, 53, 54, 67, 70, 74]. For the sake of this project, we consider these problems relatively well-known and embrace the fact that most of them are related to tools, their unavailability, low prototypical quality and other concrete problems described above.

Over the years, many ontologies, taxonomies and surveys have been published about program verification. However, these works tend to target either a specific subset of program verification (e.g. run-time verification [29], high-level synthesis [48]) or a specific domain (e.g. vehicular domain [63], smart contracts [37], railway system design [30]). Unlike these works, we do not focus on a specific domain, but aim to deliver both a megamodel to explain tools, as well as an easily accessible (and extensible!) repository with a large data set of classified tools.

The work that is closest to ours is a report [58] that presents several verification techniques in detail. It covers a broad variety of techniques (model checking, verification condition generation and correct-by-construction design). However, they only mention a few tools per technique, whereas we consider all kinds of published tools. Nonetheless, this can also be a nice starting point for engineers.

When it comes to repositories, we also do not claim outright novelty. Over the years, several projects have tried to achieve more or less similar goals. For instance, the Verified Software Repository [14] was intended to become a collection of tools, verified programs, benchmarks and results. Unfortunately, it was last updated in 2009. Schlick et al. [62] have also proposed to set up a repository to make information about formal methods more accessible. They propose a model for a possible repository which includes information such as problem definitions, experiment data as well as tools. However, to the best of our knowledge this repository has not yet been instantiated, and remained a dream. Our work could be used as part of such a repository, if anyone feels inclined to combine their model with our data that matches specifically the "Tool" part in their repository structure. Other directions for future work and consequences of this project, are considered in § 5.

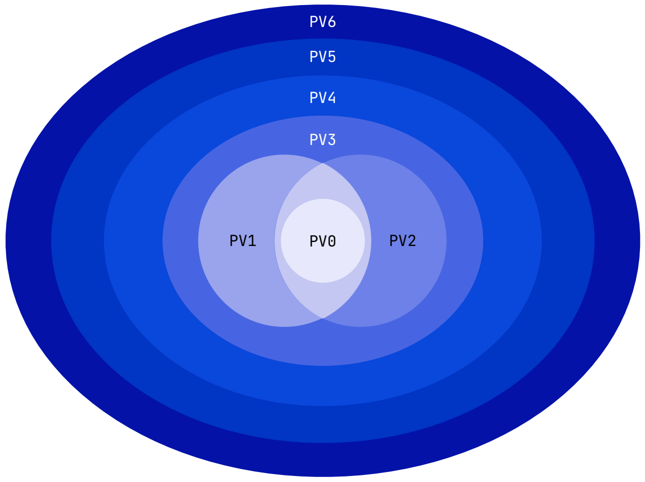
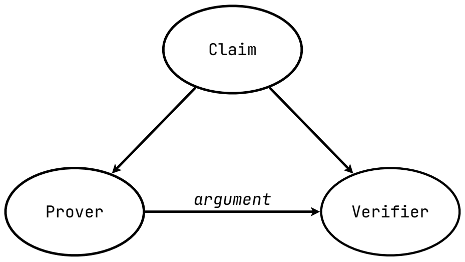


Figure 1: Each ellipse indicates the potential correctness guarantees that can be acquired by using a tool of that level. PV0 tools give the least guarantees of correctness, whereas PV6 tools allow the user to work towards maximum correctness guarantees. Note that these indicate the potential of each level; a tool may only support a little piece of a level.

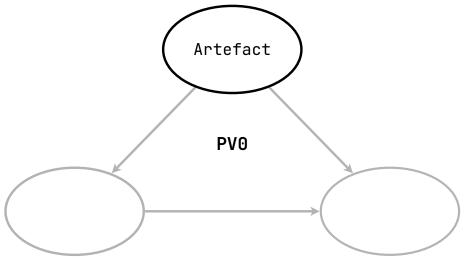
2 THE MEGAMODEL OF PV-LEVELS

In this section, we introduce the seven levels of our megamodel: **PV0**, **PV1**, **PV2**, **PV3**, **PV4**, **PV5** and **PV6** (see Figure 1). Intuitively, higher levels give the user more correctness guarantees, though typically at the cost of more user effort, and lower level tools are usually less strict and thus do not require as much PV expertise to be effectively applicable.

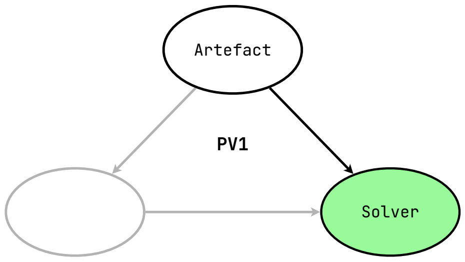
Since the ultimate goal of PV is to prove correctness of the artefact in some form and within some domain, we will use the classic division of roles in a correctness proof. It was originally introduced by Goldwasser, Micali and Rackoff in 1985 [33], we use the more widespread modern terminology here:



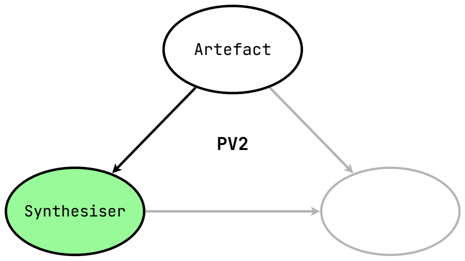
In short, there exists a **claim** of some sort (e.g., "$x \in S$" or "the program has no memory leaks" or "all models are wrong"), which is provided to both the prover and the verifier. The **prover** is very clever and can perform sophisticated manipulations and computations. Its goal is to produce arguments supporting the claim, but the prover can also be biased and prone to producing false positive arguments. The **verifier** has some way of checking the **arguments** and, depending on its verdict, declaring the claim accepted or rejected. We will be illustrating each of the PV tool levels with explanations, examples and also differences on this simple scheme. In the subsequent diagrams we will also use green colour to highlight the main contributing elements that make someone decide to use a tool of this particular level.



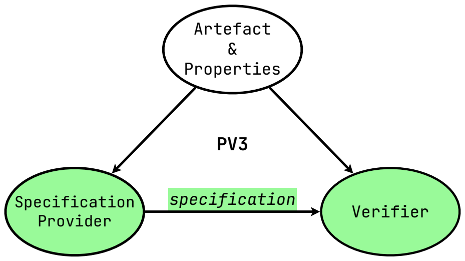
[PV0] Software engineers always work with abstractions and models of reality. Once a software entity satisfies the three properties of the modelling theory [65], it can be be seen as a model. These three are the mapping property (elements of the model represent some elements of the real entity being modelled), the reduction property (only the most important aspects of the real entity are being modelled and others are being abstracted from), and the pragmatic property (the model has a purpose). **Formal models** are a subset of such models, which are clean and well-formed, and often built with the use of some existing mathematical theories. For example, formal models often cover domain-specific variations of automata. In **PV0**, such a formal model may exist but it is often implicit and is used neither to obtain nor to verify any correctness guarantees.



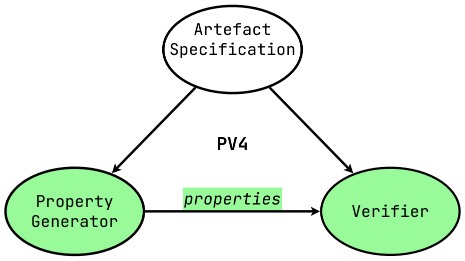
[PV1] Once a formal model can be operated on by a software system, it can also be automatically checked for internal consistency and well-formedness, by a **model solver**. For instance, if the underlying theory states that a model of a process is some specific automaton with one starting state and one or more final states, and all transitions labelled with unique names, then a solver can check that all these properties indeed hold. The more complex the model, the more difficult it could be to make such a solver for it: for example, uniqueness is relatively easy to check on strings (which we assume for transition labels in our previous example), but it is noticeably harder to define and enforce even on database records, where single columns (such as "first name") often contain non-unique values, and combinations are often unreliable due to incompleteness and subtle tolerable inconsistencies (such as a phone number mismatch). From the correctness perspective, a **PV1** tool plays a role of a verifier, and a prover does not exist since the verifier does not need any arguments on top of the ability to observe the given model.



[PV2] The opposite situation is also commonplace: if a user makes a model of their wishes, often taking a form of an almost-consistent artefact with holes to be filled, then one can build a tool to fill in those gaps and infer them from the context. Sources of information can be different, ranging from domain common sense (for example, we obviously want our parallel programs to not get stuck waiting for one another's resources) to constraints and instructions explicitly specified by the user. In a sense, if we want to consider the Eclipse Modelling Framework as a proof system, it would fall into this category because it can produce the textual code of classes that conform to the inheritance structure and the interfaces specified in the class model. In PV, such programs are often said to solve problems of **synthesis** and **repair**, and use generative techniques to create test data, repair known categories of defects, implement queries, generate neural networks fitting for a particular grid, or just to configure a universal algorithm with automatically obtained balanced values. **PV2** tools help users to create software artefacts — either by generating them from scratch or by providing significant assistance in the incremental process of creating them semi-automatically. If the output of a **PV2** tool is expected to be processed by another automated component, then the tool belongs on a higher PV level.

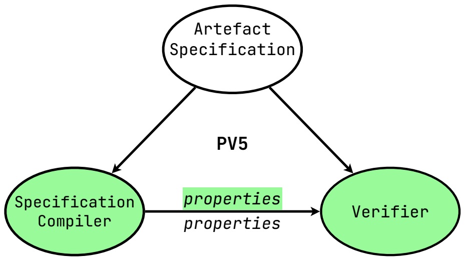


[PV3] Combining the two components into a symmetric setup (cf. Figure 1), in the simplest case we get a situation when a user explicitly states what properties of a formal model they wish to have (beyond well-formedness), and there is an automated **property checker**, conceptually decomposable into two parts: a prover that turns each property into a convincing argument and a verifier which validates the convincing power of such arguments. A typical example of a property checker allows the developers to add assertions to their code, specifying preconditions, postconditions and invariants around a code fragment, thus allowing additional formal ways to validate its correctness. These assertions do not have to be deployed to the end-user, but serve as a powerful tool for the developer to verify the product beforehand. Some checkers have a very extensive formal language to write properties in, usually a variant of some special kind of logic (e.g., temporal logic [45, 57]).

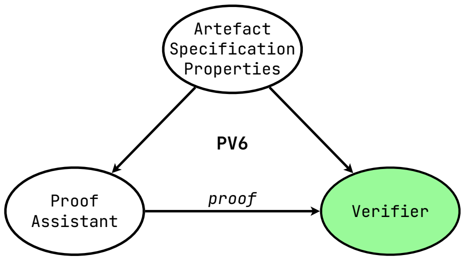


[PV4] On the previous level, the burden to create verifiable properties, was on the end-user of a tool: assertions had to be explicitly written, and invariants had to be provided. However, in some cases it is possible to automate the creation of desired properties as well as their verification — since such techniques require an extensive specification of the desired behaviour, and often focus on only one paradigm, we call them **monoverifiers**. They are very useful tools in debugging, because if used correctly, they can significantly lower the chances of having a particular category of defects, sometimes up to eliminating the very possibility of such a defect ever occurring. For instance, think of a parallel system being checked for deadlocks or a garbage collector checked for the lack of memory leaks. Essentially, monoverifiers verify that the supplied formal model corresponds to the expectations of their own built-in specification.

Some monoverifiers offer a choice of checking one or more of a larger set of correctness specifications, in which case we still classify them to belong to **PV4**, even though the *mono-* prefix no longer fits — as long as the end-user has no direct control over the specifications themselves. Also most monoverifiers embrace the fact that their generated properties cannot always cover the end-user's needs, and allow for direct manual specification of additional properties — which allows us to claim that **PV4** functionalities are a strict superset of **PV3** functionalities.



[PV5] When the tool users have an opportunity or obligation not only to specify which properties of the system to check for or how to infer them, but also to build their own specifications, we get to **specification compilers**. Such compilers usually have a language used to write specifications in, sometimes based on a domain-specific notation, and support this entire language by compiling its instances in some automated way to verify their correctness and compatibility. With those, you can build your own specifications of memory management strategies, your own communication protocols, and so forth. To continue with examples from the previous paragraph: when a **PV4** tool could check for deadlock freedom, a **PV5** tool would require a formal specification of the concurrency model, accompanied with a definition of what constitutes a deadlock state. Obviously, some **PV4** tools are built on top of **PV5** frameworks by essentially supplying a useful singular model.



[PV6] If your program verification tool can not only handle different specifications, but also infer correctness of the proof of the needed property, then it belongs among the **proof assistants**. This category is the most powerful one that we have encountered, which means both that it is the hardest and most demanding to use, as well as capable of producing the strongest guarantees. However, as one can see from the diagram we provided, it bears some similarities with the **PV1** level, since there is very limited automation and tool support in composing the arguments for correctness. The proof needs to be written by the end-user, and the tool can only offer some assistance in verifying that the proof is indeed correct. Some of **PV6** tools can *feel* to their users as if they also help them to compose the steps of the proof, but under closer inspection this help comes from the tool knowing which proof step would succeed in

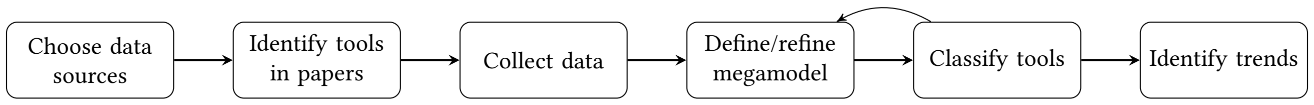


Figure 2: An overview of the different steps that have been undertaken to set up the data set of program verification tools.

reaching a user-stated goal, and not from the tool relying on some generative algorithms. Within the claim/prover/verifier paradigm, proof assistants offer powerful techniques on behalf of the verifier and not the other two components.

3 DATA SET OF VERIFICATION TOOLS

To help users find a suitable PV tool, we have prepared a data set of tools categorised according to the megamodel we have just explained in § 2. The data set, called **ProVerB**, is available at[1]:

https://slebok.github.io/proverb/.

This section explains how the data set has been created (§ 3.1) and presents some statistics about the data that was gathered (§ 3.2).

3.1 Methodology

A methodological overview can be seen in Figure 2. Below we will describe each step of our research method in detail.

3.1.1 Choose data sources. To find PV tools to include in the data set, we looked into two popular conferences about verification of systems. Namely, the International Conference on Computer Aided Verification (CAV) and the International Conference on Tools and Algorithms for the Construction and Analysis of Systems (TACAS). In the CORE conference ranking they are classified as having respective ranks of A* and A. We have decided to use papers from these conferences since both accept and welcome papers about tools. Therefore, we could expect a relatively high percentage of tool papers. Moreover, CAV and TACAS started with artefact evaluations in 2015 and 2018 respectively, therefore we expect that many of the tools presented here will also be available. We have looked at tool papers from TACAS 2016–2021 and all papers from CAV 2017–2021. We chose to use these recent years as this makes it more probable that tools are still findable and possibly maintained, yet still limited ourselves to the last 5 years of each conference in order to gather a substantial amount of data.

This step resulted in 460 papers: 347 from CAV and 113 from TACAS.

3.1.2 Identify tools in papers. Next, we read all the papers from the selected conferences with the intent of identifying tools that are presented in each paper. For each paper we checked whether it contained a reference to a tool. If so, then we would tag this as one of the following claims:

- **Presents**: the paper introduces a new tool;
- **Extends**: an existing tool gains new functionality in the paper;
- **Expands**: the paper uses an existing tool as a basis for building another tool;
- **Uses**: the paper uses an existing tool for a case study or to check the correctness of an approach.

[1]The data set has also been archived at https://doi.org/10.4121/20347950

We only included tools that provided some form of correctness guarantees, to avoid including too many entries in ProVerB. This still left us with some entries that were later reclassified as not belonging to the PV domain (usually from misinterpretations of claims "we use library X").

3.1.3 Collect data. As a format for storing entries in the data set, we have chosen Markdown. This provided the lowest entrance barrier and maintenance cost, still combined with the opportunity to add structure to the data (in our case, in the form of ####-level sections). By choosing this format, we also hope to make it easy for other people to contribute to the data set in the future, since GitHub, our hosting platform for the data, even provides inline editing functionality for Markdown pages.

After some pilot classifications we set up a generic template for tool pages, which has proven to be quite resilient, and after the first couple of sprints it stayed stable and unchanged till the current moment. This template included a section for all the information that we were interested in for a tool, namely:

- Name
- Domain or application field
- Self-identified type of the tool
- Input that is required from the user
- Input format
- Output that is produced
- Internal working of the tools, such as which tools it uses as a backend
- External relations to other tools, such as those that were compared to this tool in the paper
- Links to project pages, repositories and related papers
- Dates when the tool and its documentation were last updated

Next, we created a page based on this template for each tool that was identified in the previous step, by reading a corresponding paper and extracting the information. We also collected information from the code base and project website if these were available. Some sections were left empty if the data was not available (e.g., the last modification data for tools without a repository). If at least two tools referred to another tool, e.g. because it was used as a back end or as a framework, then this tool was added as well and received its own entry.

Some tools that we encountered were developed as prototypes, up to the point that these did not have a name at all, nor a link to an implementation. We decided to exclude such tools since it is difficult to find information about a tool without a name. However, some tools included an artefact, which was mostly still reliably available, so we included this link in the entry whenever it existed.

Aside from the information mentioned above, we have also started adding tags as textual annotations. Tags are used to indicate whether a tool targets a specific language, domain, technique, etc. This should make it easier for users to find suitable tools. For example, there is a tag for tools that target C programs, a tag for neural networks, a tag for hardware verification, and so forth.

The data set also includes pages about several specification formats. A page for a format was created if the format was not tool-specific, if it was used by more tools than one, or if it was for some other reason conceptually separate from the tool.

3.1.4 Define megamodel. When the tool pages had been written, we contemplated the initial setup of the megamodel based on similarities between tools. The first version was already based on the input that the user has to provide, ranging from the no input at all (besides the already existing software artefact), to assertions, properties, specifications, theories and proofs. Several refinement iterations later, based also on consulting the already available domain knowledge [33, 72], we have arrived at the version presented previously in § 2.

3.1.5 Classify tools. Having designed the initial megamodel, we started the process of classifying all the tools. Based on the tools' semi-structured description (cf. § 3.1.3), we have assigned each to a PV level. While doing that, we have also consistently provided a short description motivating this classification by explaining what the tool does. In that way, a tool with a description "verifies properties of a user-specified memory model" was clearly placeable at **PV5**, and the one with "checks user-specified properties and memory-safety of C programs" was easily marked as deserving **PV4**. To prevent misclassifications, the authors actively double checked each other's verdicts and had extensive discussions about arguable conclusions.

Aside from the **PV0**–**PV6** levels, there are two other categories: "no PV" for false positives and "frameworks" for a possible level mixture. We used "no PV" to explicitly exclude entries that ended up, after close consideration, not performing any PV-related tasks. Such entries were mostly about specification formats, but also about IDE plugins, unrelated programming languages, libraries not performing any PV tasks, etc. We felt that something like an alternative user front end or a linear programming library do not belong to **PV0** either. "Frameworks" were used to classify collections of tools: in many cases it was possible to determine the primary objective of the collection and assign a framework to a proper level as well, but in other cases such an assignment has not been deemed sensible. For example, "Alloy" is used to refer to the Alloy Analyzer (which has its own entry on **PV3**), or to the input level of the Alloy Analyzer, or to the entire ecosystem of Alloy models and their verifiers, — and is not consistently PV-classifiable without disambiguation.

3.1.6 Identify trends. Finally, after we classified all the tools, we could start to identify trends in each level of the megamodel. These trends could be identified based on the short descriptions that were written in the previous step, and require only occasional lightweight double checking with the full data entry or the text of the underlying paper. We will discuss these trends in more detail in § 4.

3.2 Data set statistics

The data set contains 384 tools, 25 specification formats and 66 tags. The tools are split over the PV levels as follows:

- **PV0**: 16 — cf. § 4.1
- **PV1**: 88 — cf. § 4.2
- **PV2**: 82 — cf. § 4.3
- **PV3**: 68 — cf. § 4.4
- **PV4**: 99 — cf. § 4.5
- **PV5**: 14 — cf. § 4.6
- **PV6**: 13 — cf. § 4.7
- No PV: 44

	Tools	Prototypes	No tool
CAV	228 (49%)	36 (8%)	89 (19%)
TACAS	94 (20%)	0 (0%)	19 (4%)
Overall	322 (69%)	36 (8%)	108 (23%)

Table 1: An overview of how many tools were identified in the CAV and TACAS proceedings.

Table 1 gives an overview of how many tools were identified in the CAV and TACAS proceedings respectively. The papers that presented unnamed prototypes were counted separately and excluded from the data set. Papers that did not discuss any implementation, such as theoretical papers or case studies, counted towards the "No tool" column. Overall, 77% of the papers that we looked at included some implementation, 69% of which were identifiable tools and 8% were prototypes. We suspect the percentages to be considerably lower, had we chosen other conferences without a strong tool focus.

The light snowballing principle that we have mentioned above (another tool page is added if at least two existing entries refer to the same tool which is not yet in the data set) led to adding another 62 tools to the data set.

We consider limitations of our data set and the process of creating it, at the very end of the paper, in § 5.1.

4 TRENDS IN PV LEVELS

In this section we identify different subgroups within each PV level of the megamodel.

4.1 PV0: Potential tools

At the time of writing of this paper, ProVerB had 16 tools on **PV0**. 13 of them provide facilities to work with various kinds of seemingly formal artefacts: grammars, regular expressions, automata, decision diagrams, session types, and floating point numbers. However, there is simply not enough formal rigour in the way these tools operate these artefacts, for us to consider them truly a part of the program verifier's arsenal. As an example, consider ANTLR [55]: given a grammar, it generates a parser for it. However, it does so without the grammar being perceived, modelled and transformed as a mathematical object. If the user provides ANTLR with a grammar which is unconnected or ambiguous, then the generated parser will be faulty.

Two remaining **PV0** tools are, in fact, repositories: Ceramist [34] and Prosa [35] are libraries that store formal artefacts (definitions and proofs) but by themselves neither provide arguments about their correctness, nor verify those (both rely on Coq). The last **PV0** tool is Smt-Switch [47], a collection of abstract classes that, if inherited from and implemented, can help integrate SMT solvers—again, this library by itself definitely is related to the PV domain, but does not help bring any correctness guarantees.

What all **PV0** tools have in common is their position on the verification diagram we have shown in § 2: they are claims without arguments, without a prover and without a verifier. The claims can be formal, but the surrounding context does not qualify as PV tool support.

4.2 PV1: Essential tools

Out of 88 tools on the **PV1** level, 18 can be seen as frameworks enabling their end users to work with certain models/abstractions in a formal way. For instance, Frama-C [20] contains functionality to treat C programs as formal artefacts and thus can be used to build different program analyses on top of it; BINSEC [24] provides similar functionality and opportunities to implement binary level code analysis; there are comparable tools that deal with Büchi automata, symbolic automata, decision diagrams, temporal logic formulae, etc. 7 more tools could be seen as limited frameworks that are developed specifically to compare two models in a formal way. For example, SPAN [9] computes whether two protocols are indistinguishable, and RABIT [1] checks inclusion of languages generated by two Büchi automata. Another 6 tools can be seen as normalisers that bring a given model to some well-defined canonical state: Mealy machines and Büchi automata can be automatically minimised, quantified Boolean formulae can be simplified and turned into dependency quantified Boolean formulae, etc.

21 different **PV1** tools are linters, type checkers and checkers of other kinds of properties that are fixed and hardcoded into the tool (we will see checkers of user-specified properties on **PV3**). Such properties can include conformance, semantic preservation, type safety, automata emptiness, safety of Markov decision processes, thread safety, etc. Reachability and termination analyses, due to their internal workings, we count towards another category, which includes metric calculators and tools that compute a set of possible states of a model or infer ranking functions, or compute upper and lower bounds of something — there are 30 of them in total.

Finally, the remaining 6 tools can execute models, simulate their behaviour, (partly) visualise them and resolve them otherwise: CabPy [7] solves a two-player reachability game, Oink [69] solves a parity game, jcstress [64] and PROVER [61] execute test cases in a specific order, CLEAR [8] and dtControl [5] visualise the problematic part of a labelled transition system and previously externally synthesised controller code, respectively.

4.3 PV2: Creational tools

There are 82 tools in **PV2**. The largest identifiable group, with 37 members, consists of tools providing correct-by-construction artefacts given a specification: some synthesise a controller from an LTL formula, others generate a dynamic neural network for a given grid, some generate tests for a given circuit, while others specifically generate classes that attempt to violate given properties. This group of tools can produce fairly formal artefacts that are automatically verifiable, but they do not provide any verifier means themselves. 8 more tools perform limited versions of the same process, generating only enough content to fill in holes in an already partially existing model or program. For instance, τ-DIGITS [26] fills holes in a given loop-free program from a probabilistic specification of its desired behaviour, and MOVEC [21] performs aspect weaving. Two more tools (DIGITS [2] and TarTar [43]) specifically propose repairs as code fragments meant to substitute existing code fragments assumed to be faulty.

The second popular group contains 19 tools that encode or transform the artefact from one format or formalism to another. This group covers tools for sequentialising parallel C code (MU-CSeq [66]), or transforming irreversible programs into reversible circuits (ReVerC [3]). There are several tools on this level that operate on temporal logic formulae, making a timed automaton (MightyL [17]) or an Electrum model (Cervino [56]) or another temporal logic formula in a different dialect (MLTLconverter [46]) from them.

7 tools can be used to refine specifications: for instance, by inferring type annotations from an untyped program such as Typpete [38], or generating permission pre- and postconditions for Viper programs like Sample [25] does.

Finally, 9 tools generate configurations or settings for other tools, such as PeSCo [59] which generates the best fitting configuration for CPAchecker [13] that fits previous experiences; or SATzilla [75] that decides which solver to call per instance based on predictors.

4.4 PV3: Property checking tools

PV3 currently has 68 tools. Within **PV3** we can clearly identify three main subgroups: property checkers, assertion checkers and program repair tools.

The first group consists of 36 tools that check properties for some form of model such as automata or network models. For instance, STAMINA [51] can be used to check properties of infinite-state continuous-time Markov chains.

The second group consists of 27 tools that check assertions for concrete artefacts. For example, SecC [27] can check information flow properties, expressed as assertions, for C programs.

Three tools: Forester [39], SymDIVINE [50] and VeryMax [16] — fall in between these two groups. The first two of these work on LTL formulae as properties, but apply them on real C/C++ code (SymDIVINE allows both "normal" assertions and LTL formulae). VeryMax works both on programs (C/C++) and models (transition systems).

Finally, there is also a small group of tools that focuses on program repair: AllRepair [60] and NNRepair [68]. These tools both identify faults in the program, like other tools in **PV3**, and they also propose a way to fix it.

4.5 PV4: Specification checking tools

Currently, **PV4** is the largest category with 98 tools. The largest group (50) of tools within **PV4** are the solvers. These tools produce a satisfiability result for SAT (satisfiability), SMT (satisfiability modulo theories), QBF (quantified Boolean formulae) or CHC (constrained Horn clauses) problems. Because these tools verify a specific property (namely, satisfiability), one may have expected to find them in **PV1**. However, these tools typically generate interpretations for the given problem to show that it is (un)satisfiable. So, internally each of these tools consists of two essential parts: the **property generator** which generates the interpretation and the **verifier** which checks whether this interpretation makes the formula satisfiable. This group also contains the tool that is referred to the most often in our data set — namely, Z3 [23]. It belongs to SMT solvers together with 17 other tools; there are also 22 SAT solvers; 3 CHC solvers; and 6 solvers of other kinds.

Many PV tools from other levels encode their problems into satisfiability problems and then use one of the tools in this group as a back end.

PV4 also includes 23 tools that generate properties or check built-in specifications typically depending on the domain that the tool targets. Some examples of built-in specifications that are checked, include memory safety, data-race freedom, termination and absence of runtime errors. Many of these tools also provide support to check user-written properties. For instance, Gobra [73] can check user-written assertions for Go programs as well as memory safety, data-race freedom and crash safety.

Finally, there is a small group of what we can call language workbenches [31], and we strongly suspect that there are more of this kind that escaped our selection only because nobody published about them directly at CAV and TACAS recently. A language workbench was envisioned in 2005 as a set of tools aiding the language engineer to design, implement and integrate a collection of domain-specific languages into one unified solution. Some of the popular language workbenches in model-driven software engineering include Xtext, MPS, MetaEdit+, Rascal and Spoofax. The two language workbenches that we have found mentioned for the domain of program verification, were DLC [28], which can automatically generate distributed implementation of concurrent systems modelled in the LNT language, which can be verified using the CADP toolbox; and PrDK [41], a development kit for programming communication protocols.

4.6 PV5: Fully controlled verification tools

Continuing the same trend, on **PV5** we see a uniform group of 14 verification workbenches. These are tools that allow users to write their own specifications and combine these together with desired properties into a formal mathematical representation. These formal representations can then be compared with representations of programs or their properties for the verification. Users can have very fine-grained influence on the results of these tools because they are allowed to write their own specification. For example, Attestor [4] allows the user to specify the initial heap configuration and the behaviour of the garbage collector that should be taken into account when verifying a property for a Java program. Similarly, UPPAAL [10] is a workbench for automatic verification of safety and bounded liveness properties of real-time systems modelled as networks of timed automata.

4.7 PV6: Proving tools

All 13 tools in **PV6** are proof workbenches. Many of the tools in previous categories give a yes/no answer to indicate whether a property holds, and in any case allowing at most some influence on the property generating and handling process, but not on the final proof. **PV6** tools, however, will help the user to construct and infer the correctness of a proof that shows **why** a property is true or false. Some well known tools in **PV6** are Coq [11], Isabelle/HOL [52], Lean [49] and Vampire [44]. Their comparison is a highly nontrivial task even for professional mathematicians [71].

5 CONCLUSION & FUTURE WORK

Our contribution of this paper is two-sided. On one side, we have analysed a fairly complex domain and turned one of the commonly used visualisation of its core processes into a full fledged megamodel that helped us to split the domain into much more intelligible smaller categories. On the other side, we have processed hundreds of academic papers published across several recent years, classified them according to the proposed megamodel and generated a user-friendly website allowing software engineers to compare and assess papers in a bit more secure, complete and safe way than before.

The megamodel that we have presented, identifies the different type of program verification tools that we found existing or that can possibly be made to exist. This megamodel is based on the classic division of roles in a correctness proof as introduced by Goldwasser et al. [33] that is currently accepted by the computational community. Our megamodel divides the different types of tools into seven categories: **PV0**, **PV1**, **PV2**, **PV3**, **PV4**, **PV5** and **PV6**. These categories are increasingly more demanding and increasingly more powerful: it is possible to gain some benefit from a **PV0** or **PV1** tool within the first day of being introduced to it, but much further refinement and improvement might not be possible; on the other side of the spectrum, **PV6** tools can do almost everything, and require a relevant PhD degree to operate. Thus, there is no discussion on "what is the best PV level", just a classification that helps to match a tool to customer needs.

To bring the megamodel to life, we have designed a metamodel to hold semi-structured information about a PV tool, including its PV-level, name, input/output, etc, and instantiated it for all tools that we have found being mentioned and used in the last five years of two top conferences in the field: CAV and TACAS. Our data set at the time of writing consists of 420+ tools, formats and libraries. By setting up a megamodel as well as a dataset, we hope to provide both a theoretical as well as a practical starting point to get into the world of PV tools and methods. A good starting point for browsing and exploring ProVerB would be its hypertext frontend: http://slebok.github.io/proverb/ which also contains links to other sites (GitHub, DOIs, etc) for each tool.

One of the most important things to consider for the future is how to keep the data set up to date. To achieve this, we think that it is essential that other users can easily contribute to the project, e.g. through pull requests. It would also be nice to further extend the data set, e.g. by including other conferences. We are actively looking into APIs of related linked data repositories to extend the data set and automatically update information such as the timestamp of the last commit.

5.1 Threats to validity

Conclusion validity. All the PV-classifications that we have performed, come from our personal interpretations of the contents of a fairly large body of fairly complex academic papers. Thus, it is possible that some tools have been misclassified as belonging to one level while they actually belong to another level. To prevent misclassifications, the authors were actively double checking each other's verdicts and had extensive discussions about arguable conclusions. Eventually we plan to reach out to authors of all tools included in ProVerB individually, with a detailed explanation of the seven PV levels and a request to review our summaries and refine them, possibly leading to reclassifications. If such a community effort causes a noticeable resonance, it would be possible to eliminate this threat entirely.

Internal validity. Since our project is more of an observational and classificational nature, and we do not attempt to establish any causal relationships, internal validity is not among our major concerns. Once we start enhancing the data set with other sources of linked data (such as GitHub and SpringerLink API), it might become more relevant to correctly establish contributor identity equivalence across multiple platforms with varying usernames and non-strictly matching names.

Construct validity. As we have explained in § 2, our megamodel was designed based on the classic division of roles in a correctness establishing setup as described by Goldwasser, Micali and Rackoff [33], in the modern reinterpretation by Wigderson [72]. By reusing a model that originates from the right domain, we hope to have found a mature foundation that will allow us to classify any possible tool in the future by matching its components and concepts to the claim, the prover, the arguments and the verifier. Only if we encounter future tools that do not fit into this model, will we have to redesign the megamodel again. However, in the works of Wigderson [72], generalising the notion of a proof from being a unidirectional communication from the prover towards the verifier, to a bidirectional series of communications, handling interactivity, errors, randomness and other natural aspects of computation, has opened a lot of doors and led to the discovery of a number of complexity classes with a distinctly higher expressive power. For instance, relying on more than two verifiers at the same time is not uncommon in PV, but this is mostly done for practical considerations such as trying all available ones to watch only the fastest complete its proof. It is neither considered nor suspected that multi-prover or multi-oracle PV tools can lead us to a broader computational class. Since this has not been researched or established before, we also do not consider such multi-tier setups as one of the PV-levels explicitly.

External validity. We have gathered data from publications at CAV and TACAS, which seemed like a good choice of information since both favour papers about program verification tools to non-tool papers and non-PV content. However, there are more venues that target the program verification field (POPL, PLDI, FASE, LICS, etc). It is unknown at the moment what biases we have created in the data set by limiting ourselves to only CAV and TACAS and related papers, techniques and tools. While limited, the number of tools (380+) included is significant, and they seem reasonably spread out among the different PV levels. We see that the most popular tools are included, partly because we also include tools if they are referred to by at least two other tools. So, while perhaps limited, we think that this is a good starting point for the data set.

REFERENCES

[1] Parosh Aziz Abdulla, Yu-Fang Chen, Lorenzo Clemente, Lukáš Holík, Chih-Duo Hong, Richard Mayr, and Tomáš Vojnar. 2010. Simulation Subsumption in Ramsey-Based Büchi Automata Universality and Inclusion Testing. In *Proceedings of the 22nd International Conference on Computer Aided Verification (CAV)*, Tayssir Touili, Byron Cook, and Paul Jackson (Eds.). Springer, 132–147. https://doi.org/10.1007/978-3-642-14295-6_14

[2] Aws Albarghouthi, Loris D'Antoni, and Samuel Drews. 2017. Repairing Decision-Making Programs Under Uncertainty. In *Proceedings of the 29th International Conference on Computer Aided Verification (CAV)*, Rupak Majumdar and Viktor Kunčak (Eds.). Springer, 181–200. https://doi.org/10.1007/978-3-319-63387-9_9

[3] Matthew Amy, Martin Roetteler, and Krysta M. Svore. 2017. Verified Compilation of Space-Efficient Reversible Circuits. In *Proceedings of the 28th International Conference on Computer Aided Verification (CAV)*, Rupak Majumdar and Viktor Kunčak (Eds.). Springer, 3–21. https://doi.org/10.1007/978-3-319-63390-9_1

[4] Hannah Arndt, Christina Jansen, Joost-Pieter Katoen, Christoph Matheja, and Thomas Noll. 2018. Let this Graph Be Your Witness!. In *Proceedings of the 30th International Conference on Computer Aided Verification (CAV)*, Hana Chockler and Georg Weissenbacher (Eds.). Springer, 3–11. https://doi.org/10.1007/978-3-319-96142-2_1

[5] Pranav Ashok, Mathias Jackermeier, Jan Křetínský, Christoph Weinhuber, Maximilian Weininger, and Mayank Yadav. 2021. dtControl 2.0: Explainable Strategy Representation via Decision Tree Learning Steered by Experts. In *Tools and Algorithms for the Construction and Analysis of Systems*, Jan Friso Groote and Kim Guldstrand Larsen (Eds.). Springer, Cham, 326–345. https://doi.org/10.1007/978-3-030-72013-1_17

[6] Brian E. Aydemir, Aaron Bohannon, Matthew Fairbairn, J. Nathan Foster, Benjamin C. Pierce, Peter Sewell, Dimitrios Vytiniotis, Geoffrey Washburn, Stephanie Weirich, and Steve Zdancewic. 2005. Mechanized Metatheory for the Masses: The PoplMark Challenge. In *Proceedings of the 18th International Conference on Theorem Proving in Higher Order Logics (TPHOLs) (LNCS, Vol. 3603)*, Joe Hurd and Thomas F. Melham (Eds.). Springer, 50–65. https://doi.org/10.1007/11541868_4

[7] Christel Baier, Norine Coenen, Bernd Finkbeiner, Florian Funke, Simon Jantsch, and Julian Siber. 2021. Causality-Based Game Solving. In *Computer Aided Verification*, Alexandra Silva and K. Rustan M. Leino (Eds.). Springer, Cham, 894–917. https://doi.org/10.1007/978-3-030-81685-8_42

[8] Gianluca Barbon, Vincent Leroy, and Gwen Salaün. 2019. Debugging of Behavioural Models with CLEAR. In *Tools and Algorithms for the Construction and Analysis of Systems*, Tomáš Vojnar and Lijun Zhang (Eds.). Springer, 386–392. https://doi.org/10.1007/978-3-030-17462-0_26

[9] Matthew S. Bauer, Rohit Chadha, A. Prasad Sistla, and Mahesh Viswanathan. 2018. Model Checking Indistinguishability of Randomized Security Protocols. In *Computer Aided Verification (CAV)*, Hana Chockler and Georg Weissenbacher (Eds.). Springer, 117–135. https://doi.org/10.1007/978-3-319-96142-2_10

[10] Johan Bengtsson, Kim Larsen, Fredrik Larsson, Paul Pettersson, and Wang Yi. 1996. UPPAAL: A Tool Suite for Automatic Verification of Real-Time Systems. In *Hybrid Systems III*, Rajeev Alur, Thomas A. Henzinger, and Eduardo D. Sontag (Eds.). Springer, 232–243. https://doi.org/10.1007/BFb0020949

[11] Yves Bertot and Pierre Castéran. 2004. *Interactive Theorem Proving and Program Development. Coq'Art: The Calculus of Inductive Constructions.* Springer Berlin, Heidelberg, London.

[12] Dirk Beyer. 2022. Progress on Software Verification: SV-COMP 2022. In *Tools and Algorithms for the Construction and Analysis of Systems*, Dana Fisman and Grigore Rosu (Eds.). Springer, Cham, 375–402.

[13] Dirk Beyer and M. Erkan Keremoglu. 2011. CPAchecker: A Tool for Configurable Software Verification. In *Computer Aided Verification*, Ganesh Gopalakrishnan and Shaz Qadeer (Eds.). Springer, 184–190.

[14] Juan Bicarregui, C. A. R. Hoare, and J. C. P. Woodcock. 2006. The Verified Software Repository: A Step Towards the Verifying Compiler. *Formal Aspects of Computing* 18, 2 (2006), 143–151. https://doi.org/10.1007/s00165-005-0079-4

[15] Jean-Paul Bodeveix, Mamoun Filali, Julia Lawall, and Gilles Muller. 2005. Formal Methods Meet Domain Specific Languages. In *Proceedings of the Fifth International Conference on Integrated Formal Methods (iFM) (LNCS, Vol. 3771)*, Judi Romijn, Graeme Smith, and Jaco van de Pol (Eds.). Springer, 187–206. https://doi.org/10.1007/11589976_12

[16] Cristina Borralleras, Marc Brockschmidt, Daniel Larraz, Albert Oliveras, Enric Rodríguez-Carbonell, and Albert Rubio. 2017. Proving Termination Through Conditional Termination. In *Tools and Algorithms for the Construction and Analysis of Systems*, Axel Legay and Tiziana Margaria (Eds.). Springer, 99–117.

[17] Thomas Brihaye, Gilles Geeraerts, Hsi-Ming Ho, and Benjamin Monmege. 2017. MightyL: A Compositional Translation from MITL to Timed Automata. In *Computer Aided Verification*, Rupak Majumdar and Viktor Kunčak (Eds.). Springer, 421–440.

[18] Guy H. Broadfoot and Philippa J. Broadfoot. 2003. Academia and Industry Meet: Some Experiences of Formal Methods in Practice. In *Proceedings of the 10th Asia-Pacific Software Engineering Conference (APSEC)*. IEEE Computer Society, 49. https://doi.org/10.1109/APSEC.2003.1254357

[19] Antonio Bucchiarone, Federico Ciccozzi, Leen Lambers, Alfonso Pierantonio, Matthias Tichy, Massimo Tisi, Andreas Wortmann, and Vadim Zaytsev. 2021. What is the Future of Modelling? *IEEE Software Insights (IEEE Software)* 38 (2021), 119–127. Issue 2. https://doi.org/10.1109/MS.2020.3041522

[20] Géraud Canet, Pascal Cuoq, and Benjamin Monate. 2009. A Value Analysis for C Programs. In *Ninth IEEE International Working Conference on Source Code Analysis and Manipulation, SCAM 2009, Edmonton, Alberta, Canada, September 20-21, 2009*. IEEE Computer Society, 123–124. https://doi.org/10.1109/SCAM.2009.22

[21] Zhe Chen, Zhemin Wang, Yunlong Zhu, Hongwei Xi, and Zhibin Yang. 2016. Parametric Runtime Verification of C Programs. In *Tools and Algorithms for the Construction and Analysis of Systems*, Marsha Chechik and Jean-François Raskin (Eds.). Springer, 299–315.

[22] Jennifer A. Davis, Matthew A. Clark, Darren D. Cofer, Aaron Fifarek, Jacob Hinchman, Jonathan A. Hoffman, Brian W. Hulbert, Steven P. Miller, and Lucas G. Wagner. 2013. Study on the Barriers to the Industrial Adoption of Formal Methods. In *Proceedings of the 18th International Workshop on Formal Methods for Industrial Critical Systems (FMICS) (LNCS, Vol. 8187)*, Charles Pecheur and Michael Dierkes (Eds.). Springer, 63–77. https://doi.org/10.1007/978-3-642-41010-9_5

[23] Leonardo Mendonça de Moura and Nikolaj S. Bjørner. 2008. Z3: An Efficient SMT Solver. In *Proceedings of the 14th International Conference on Tools and Algorithms for the Construction and Analysis of Systems (TACAS) (LNCS, Vol. 4963)*, C. R. Ramakrishnan and Jakob Rehof (Eds.). Springer, 337–340. https://doi.org/10.1007/978-3-540-78800-3_24

[24] Adel Djoudi and Sébastien Bardin. 2015. BINSEC: Binary Code Analysis with Low-Level Regions. In *Proceedings of the 21st International Conference on Tools and Algorithms for the Construction and Analysis of Systems (TACAS) (LNCS, Vol. 9035)*, Christel Baier and Cesare Tinelli (Eds.). Springer, 212–217. https://doi.org/10.1007/978-3-662-46681-0_17

[25] Jérôme Dohrau, Alexander J. Summers, Caterina Urban, Severin Münger, and Peter Müller. 2018. Permission Inference for Array Programs. In *Computer Aided Verification*, Hana Chockler and Georg Weissenbacher (Eds.). Springer, 55–74.

[26] Samuel Drews, Aws Albarghouthi, and Loris D'Antoni. 2019. Efficient Synthesis with Probabilistic Constraints. In *Proceedings of the 30th International Conference on Computer Aided Verification (CAV)*, Isil Dillig and Serdar Tasiran (Eds.). Springer, 278–296. https://doi.org/10.1007/978-3-030-25540-4_15

[27] Gidon Ernst and Toby Murray. 2019. SecCSL: Security Concurrent Separation Logic. In *Computer Aided Verification*, Isil Dillig and Serdar Tasiran (Eds.). Springer, 208–230.

[28] Hugues Evrard. 2016. DLC: Compiling a Concurrent System Formal Specification to a Distributed Implementation. In *Tools and Algorithms for the Construction and Analysis of Systems*, Marsha Chechik and Jean-François Raskin (Eds.). Springer, 553–559. https://doi.org/10.1007/978-3-662-49674-9_34

[29] Yliès Falcone, Srdan Krstic, Giles Reger, and Dmitriy Traytel. 2021. A Taxonomy for Classifying Runtime Verification Tools. *International Journal on Software Tools for Technology Transfer* 23, 2 (2021), 255–284. https://doi.org/10.1007/s10009-021-00609-z

[30] Alessio Ferrari, Franco Mazzanti, Davide Basile, Maurice H. ter Beek, and Alessandro Fantechi. 2020. Comparing Formal Tools for System Design: A Judgment Study. In *Proceedings of the ACM/IEEE 42nd International Conference on Software Engineering (ICSE '20)*. Association for Computing Machinery, 62–74. https://doi.org/10.1145/3377811.3380373

[31] Martin Fowler. 2005. Language Workbenches: The Killer-App for Domain Specific Languages? MartinFowler.com. https://martinfowler.com/articles/languageWorkbench.html

[32] Georg Frey and Lothar Litz. 2000. Formal Methods in PLC Programming. In *Proceedings of the International Conference on Systems, Man & Cybernetics: "Cybernetics Evolving to Systems, Humans, Organizations, and their Complex Interactions"*. IEEE, 2431–2436. https://doi.org/10.1109/ICSMC.2000.884356

[33] Shafi Goldwasser, Silvio Micali, and Charles Rackoff. 1985. The Knowledge Complexity of Interactive Proof-Systems. In *Proceedings of the Seventeenth Annual ACM Symposium on Theory of Computing (SToC) (STOC)*. Association for Computing Machinery, 291–304. https://doi.org/10.1145/22145.22178

[34] Kiran Gopinathan and Ilya Sergey. 2020. Certifying Certainty and Uncertainty in Approximate Membership Query Structures. In *Computer Aided Verification (CAV)*, Shuvendu K. Lahiri and Chao Wang (Eds.). Springer, 279–303. https://doi.org/10.1007/978-3-030-53291-8_16

[35] Xiaojie Guo, Maxime Lesourd, Mengqi Liu, Lionel Rieg, and Zhong Shao. 2019. Integrating Formal Schedulability Analysis into a Verified OS Kernel. In *Computer Aided Verification (CAV)*, Isil Dillig and Serdar Tasiran (Eds.). Springer, 496–514. https://doi.org/10.1007/978-3-030-25543-5_28

[36] Arnd Hartmanns, Michaela Klauck, David Parker, Tim Quatmann, and Enno Ruijters. 2019. The Quantitative Verification Benchmark Set. In *Proceedings of the 25th International Conference on Tools and Algorithms for the Construction and Analysis of Systems (TACAS) (LNCS, Vol. 11427)*, Tomás Vojnar and Lijun Zhang (Eds.). Springer, 344–350. https://doi.org/10.1007/978-3-030-17462-0_20

[37] Dominik Harz and William J. Knottenbelt. 2018. Towards Safer Smart Contracts: A Survey of Languages and Verification Methods. *CoRR* abs/1809.09805 (2018), 20. arXiv:1809.09805 http://arxiv.org/abs/1809.09805

[38] Mostafa Hassan, Caterina Urban, Marco Eilers, and Peter Müller. 2018. MaxSMT-Based Type Inference for Python 3. In *Computer Aided Verification*, Hana Chockler and Georg Weissenbacher (Eds.). Springer, 12–19.

[39] Lukáš Holík, Martin Hruška, Ondřej Lengál, Adam Rogalewicz, Jiří Šimáček, and Tomáš Vojnar. 2017. Forester: From Heap Shapes to Automata Predicates. In *Tools and Algorithms for the Construction and Analysis of Systems*, Axel Legay and Tiziana Margaria (Eds.). Springer, 365–369.

[40] John Edward Hutchinson, Jon Whittle, and Mark Rouncefield. 2014. Model-Driven Engineering Practices in Industry: Social, Organizational and Managerial Factors that Lead to Success or Failure. *Science of Computer Programming* 89 (2014), 144–161. https://doi.org/10.1016/j.scico.2013.03.017

[41] Sung-Shik T. Q. Jongmans and Farhad Arbab. 2016. PrDK: Protocol Programming with Automata. In *Tools and Algorithms for the Construction and Analysis of Systems*, Marsha Chechik and Jean-François Raskin (Eds.). Springer, 547–552. https://doi.org/10.1007/978-3-662-49674-9_33

[42] René Klösch and Wolfgang Eixelsberger. 1999. Challenges and Experiences in Managing Major Software Evolution Endeavours Such as Euro Conversion or Y2000 Compliance. In *Proceedings of the 15th International Conference on Software Maintenance (ICSM)*. IEEE Computer Society, 161–166. https://doi.org/10.1109/ICSM.1999.792600

[43] Martin Kölbl, Stefan Leue, and Thomas Wies. 2020. TarTar: A Timed Automata Repair Tool. In *Computer Aided Verification*, Shuvendu K. Lahiri and Chao Wang (Eds.). Springer, 529–540.

[44] Laura Kovács and Andrei Voronkov. 2013. First-Order Theorem Proving and Vampire. In *Computer Aided Verification*, Natasha Sharygina and Helmut Veith (Eds.). Springer, 1–35.

[45] Leslie Lamport. 1994. The Temporal Logic of Actions. *ACM Transactions on Programming Languages and Systems (ToPLaS)* 16, 3 (1994), 872–923. https://doi.org/10.1145/177492.177726

[46] Jianwen Li, Moshe Y. Vardi, and Kristin Y. Rozier. 2019. Satisfiability Checking for Mission-Time LTL. In *Computer Aided Verification*, Isil Dillig and Serdar Tasiran (Eds.). Springer, 3–22.

[47] Makai Mann, Amalee Wilson, Yoni Zohar, Lindsey Stuntz, Ahmed Irfan, Kristopher Brown, Caleb Donovick, Allison Guman, Cesare Tinelli, and Clark W. Barrett. 2021. Smt-Switch: A Solver-Agnostic C++ API for SMT Solving. In *SAT 2021 (LNCS, Vol. 12831)*, Chu-Min Li and Felip Manyà (Eds.). Springer, 377–386. https://doi.org/10.1007/978-3-030-80223-3_26

[48] Wim Meeus, Kristof Van Beeck, Toon Goedemé, Jan Meel, and Dirk Stroobandt. 2012. An overview of today's high-level synthesis tools. *Des. Autom. Embed. Syst.* 16, 3 (2012), 31–51. https://doi.org/10.1007/s10617-012-9096-8

[49] Leonardo de Moura and Sebastian Ullrich. 2021. The Lean 4 Theorem Prover and Programming Language. In *Proceddings of the 28th International Conference on Automated Deduction (CADE)*, André Platzer and Geoff Sutcliffe (Eds.). Springer, 625–635. https://doi.org/10.1007/978-3-030-79876-5_37

[50] Jan Mrázek, Petr Bauch, Henrich Lauko, and Jiří Barnat. 2016. SymDIVINE: Tool for Control-Explicit Data-Symbolic State Space Exploration. In *Model Checking Software*, Dragan Bošnački and Anton Wijs (Eds.). Springer, 208–213.

[51] Thakur Neupane, Chris J. Myers, Curtis Madsen, Hao Zheng, and Zhen Zhang. 2019. STAMINA: STochastic Approximate Model-Checker for INfinite-State Analysis. In *Computer Aided Verification*, Isil Dillig and Serdar Tasiran (Eds.). Springer, 540–549.

[52] Tobias Nipkow, Markus Wenzel, and Lawrence C. Paulson (Eds.). 2002. *5. The Rules of the Game.* Springer, 67–104. https://doi.org/10.1007/3-540-45949-9_5

[53] Arif Nurwidyantoro, Mojtaba Shahin, Michel Chaudron, Waqar Hussain, Harsha Perera, Rifat Ara Shams, and Jon Whittle. 2021. Towards a Human Values Dashboard for Software Development: An Exploratory Study. In *Proceedings of the 15th International Symposium on Empirical Software Engineering and Measurement (ESEM)*, Filippo Lanubile, Marcos Kalinowski, and Maria Teresa Baldassarre (Eds.). ACM, 23:1–23:12. https://doi.org/10.1145/3475716.3475770

[54] Arif Nurwidyantoro, Mojtaba Shahin, Michel R. V. Chaudron, Waqar Hussain, Rifat Ara Shams, Harsha Perera, Gillian Oliver, and Jon Whittle. 2022. Human Values in Software Development Artefacts: A Case Study on Issue Discussions in Three Android Applications. *Information & Software Technology* 141 (2022), 106731. https://doi.org/10.1016/j.infsof.2021.106731

[55] T. Parr. 2013. *The Definitive ANTLR 4 Reference.* Pragmatic Bookshelf. https://books.google.nl/books?id=gA9QDwAAQBAJ

[56] Quentin Peyras, Jean-Paul Bodeveix, Julien Brunel, and David Chemouil. 2021. Sound Verification Procedures for Temporal Properties of Infinite-State Systems. In *Computer Aided Verification*, Alexandra Silva and K. Rustan M. Leino (Eds.). Springer, 337–360. https://doi.org/10.1007/978-3-030-81688-9_16

[57] Amir Pnueli. 1977. The Temporal Logic of Programs. In *Proceedings of the 18th Annual Symposium on Foundations of Computer Science*. IEEE Computer Society, 46–57. https://doi.org/10.1109/SFCS.1977.32

[58] Ratish J. Punnoose, Robert C. Armstrong, Matthew H. Wong, and Mayo Jackson. 2014. *Survey of Existing Tools for Formal Verification.* Technical Report. USDOE National Nuclear Security Administration (NNSA). https://doi.org/10.2172/1166644

[59] Cedric Richter and Heike Wehrheim. 2019. PeSCo: Predicting Sequential Combinations of Verifiers. In *Tools and Algorithms for the Construction and Analysis of Systems*, Dirk Beyer, Marieke Huisman, Fabrice Kordon, and Bernhard Steffen (Eds.). Springer, 229–233.

[60] Bat-Chen Rothenberg and Orna Grumberg. 2020. Must Fault Localization for Program Repair. In *Computer Aided Verification*, Shuvendu K. Lahiri and Chao Wang (Eds.). Springer, 658–680.

[61] Wonryong Ryou, Jiayu Chen, Mislav Balunovic, Gagandeep Singh, Andrei Dan, and Martin Vechev. 2021. Scalable Polyhedral Verification of Recurrent Neural Networks. In *Computer Aided Verification (CAV*, Alexandra Silva and K. Rustan M. Leino (Eds.). Springer, 225–248. https://doi.org/10.1007/978-3-030-81685-8_10

[62] Rupert Schlick, Michael Felderer, István Majzik, Roberto Nardone, Alexander Raschke, Colin F. Snook, and Valeria Vittorini. 2018. A Proposal of an Example and Experiments Repository to Foster Industrial Adoption of Formal Methods. In *Proceedings of the Eighth International Symposium on Leveraging Applications of Formal Methods, Verification and Validation (ISoLA) (LNCS, Vol. 11247)*, Tiziana Margaria and Bernhard Steffen (Eds.). Springer, 249–272. https://doi.org/10.1007/978-3-030-03427-6_20

[63] Abdelkader Magdy Shaaban, Christoph Schmittner, Thomas Gruber, A. Baith Mohamed, Gerald Quirchmayr, and Erich Schikuta. 2019. Ontology-Based Model for Automotive Security Verification and Validation. In *Proceedings of the 21st International Conference on Information Integration and Web-based Applications & Services (iiWAS)*. ACM, 73–82. https://doi.org/10.1145/3366030.3366070

[64] Aleksey Shipilëv. 2013. Java Concurrency Stress (jcstress). https://github.com/openjdk/jcstress/.

[65] Herbert Stachowiak. 1973. *Allgemeine Modelltheorie*. Springer.

[66] Ermenegildo Tomasco, Truc L. Nguyen, Omar Inverso, Bernd Fischer, Salvatore La Torre, and Gennaro Parlato. 2016. MU-CSeq 0.4: Individual Memory Location Unwindings. In *Tools and Algorithms for the Construction and Analysis of Systems*, Marsha Chechik and Jean-François Raskin (Eds.). Springer, 938–941.

[67] Federico Tomassetti and Vadim Zaytsev. 2020. Reflections on the Lack of Adoption of Domain Specific Languages. In *STAF Workshop Proceedings (STAF) (CEUR Workshop Proceedings, Vol. 2707)*, Loli Burgueño and Lars Michael Kristensen (Eds.). CEUR-WS.org, 85–94. http://ceur-ws.org/Vol-2707/oopslepaper5.pdf

[68] Muhammad Usman, Divya Gopinath, Youcheng Sun, Yannic Noller, and Corina S. Păsăreanu. 2021. NNrepair: Constraint-Based Repair of Neural Network Classifiers. In *Computer Aided Verification*, Alexandra Silva and K. Rustan M. Leino (Eds.). Springer, 3–25.

[69] Tom van Dijk. 2018. Oink: An Implementation and Evaluation of Modern Parity Game Solvers. In *Proceedings of the 24th International Conference on Tools and Algorithms for the Construction and Analysis of Systems (TACAS)*, Dirk Beyer and Marieke Huisman (Eds.), Vol. 10805. Springer, 291–308. https://doi.org/10.1007/978-3-319-89960-2_16

[70] Jon Whittle, Maria Angela Ferrario, Will Simm, and Waqar Hussain. 2021. A Case for Human Values in Software Engineering. *IEEE Software* 38, 1 (2021), 106–113. https://doi.org/10.1109/MS.2019.2956701

[71] Freek Wiedijk. 2003. Comparing Mathematical Provers. In *Proceedings of the Second International Conference on Mathematical Knowledge Management (MKM) (LNCS, Vol. 2594)*, Andrea Asperti, Bruno Buchberger, and James H. Davenport (Eds.). Springer, 188–202. https://doi.org/10.1007/3-540-36469-2_15

[72] Avi Wigderson. 2019. *Mathematics and Computation: Ideas Revolutionizing Technology and Science*. Princeton University Press. https://www.math.ias.edu/avi/book

[73] Felix A. Wolf, Linard Arquint, Martin Clochard, Wytse Oortwijn, João C. Pereira, and Peter Müller. 2021. Gobra: Modular Specification and Verification of Go Programs. In *Proceedings of the 33rd International Conference on Computer Aided Verification (CAV) (LNCS, Vol. 12759)*, Alexandra Silva and K. Rustan M. Leino (Eds.). Springer, 367–379. https://doi.org/10.1007/978-3-030-81685-8_17

[74] Jim Woodcock, Peter Gorm Larsen, Juan Bicarregui, and John S. Fitzgerald. 2009. Formal Methods: Practice and Experience. *Comput. Surveys* 41, 4 (2009), 19:1–19:36. https://doi.org/10.1145/1592434.1592436

[75] Lin Xu, Frank Hutter, Holger H. Hoos, and Kevin Leyton-Brown. 2008. SATzilla: Portfolio-based Algorithm Selection for SAT. *Journal of Artificial Intelligence Research* 32 (2008), 565–606. https://doi.org/10.1613/jair.2490