Tool Support of Formal Methods for Privacy by Design

Sibylle Schupp

Abstract

Formal methods are, in principle, suited for supporting the recent paradigm of privacy by design, but no overview is available that summarizes which particular approaches have been investigated, for which application domains they are suited, and whether they are implemented and available as tools. Using the techniques of search-based literature review and snowballing this paper answers those questions for a selected set of research papers.

1 Introduction

Whenever privacy regulations for software applications are formulated, they aim at making privacy an integral part of software development—a well-known slogan is “privacy by design”, coined by Ann Cavoukian [33]. When private data is considered even critical, application developers might have to provide provable guarantees for respecting or implementing particular privacy concerns. Formal methods are, in principle, suited for supporting privacy by design, but no overview is available that summarizes which particular methods are “best practice”, or in use at all. The literature itself is spread and can be found not only in venues for applied formal methods, but also in conferences on software engineering, security, data management, or theory.

In this paper we provide a review of the current state of formal methods that may aid software development for privacy concerns. For each paper in a selected list of papers we answer three questions:

Q1. Which particular formal method is presented?

Q2. In which application areas is this method applied and evaluated?

Q3. Which tool—existing or newly developed—implements the presented approach?

While the research area is certainly in flux, it is important to know for application developers as well as for judges or legal advisers whether obvious candidates of formal methods exist that either suggest some kind of state of the art or, conversely, render the use of particular other methods as negligent. This review can also be helpful for prospective researchers in the field, as there are only few conferences and journals dedicated to privacy, and formal-method papers are not necessarily published there.

For selecting a set of primary studies, we employ the so-called hybrid approach, a method for systematic literature reviews that originates in software engineering. The hybrid approach consists of two stages, where stage 1 conducts a systematic search to obtain an initial list ([56, 57]) and stage 2, called snowballing ([104]), traces the forward and backward references to and from
that initial list. We explain the paper selection process in Section 2; in this section we also detail how we pre-process the primary studies by annotating them with sets of tags. The results themselves are presented in Section 3. Section 4 discusses threats to their validity and Section 5 concludes.

## 2 Selection and Tagging

In this section, we describe how the set of primary studies is constructed and how we pre-process those studies by tagging them.

### 2.1 Selection

Following the hybrid approach for paper selection, we perform first a search, then a snowballing step; for an overview, see Figure 1.

In the search stage, we feed the search term (see Table 1) to a search engine, Google scholar, and apply to the resulting hit list a series of exclusion and inclusion criteria to filter out distractors. Those criteria correspond to common criteria for literature reviews (see Table 9 in the appendix). Applying the criteria reduces the list from originally 131 papers to 17 papers. Those papers form the initial list, which serves as input to stage 2.

Stage 2 commences with backward snowballing, using the exclusion, inclusion, and white-listing criteria from before (see Table 9). For each paper in the initial set, we go through its references and apply all exclusion criteria; on the remaining references we apply the white-list criteria to obtain a temporary list. Each reference on the white list, next, is then manually checked for each inclusion criterion and, in the positive case, added to our list of primary studies. Forward snowballing proceeds similarly. Using Google Scholar again, we determine for each paper in the initial set all papers it is cited by. For each citing paper we repeat the process employed for backward snowballing, i.e., apply the exclusion criteria and the white-list criteria, and check by hand the remaining papers for topicality and availability according to the inclusion criteria.

Table 2 provides the results. Altogether 57 additional papers can be obtained through backward snowballing and another 27 papers by forward snowballing.

### Table 1: Search term.

| Search Term            |
|------------------------|
| “privacy by design”    |
| “formal methods”       |
| “software engineering” |

![Figure 1: Selection process: stage 1 (search), stage 2 (forward and backward snowballing), and resulting numbers of primary studies (17, 57, 27).](image)
ward snowballing. For each paper in the initial set we list the number of its references (“refs”) for backward snowballing and citations (“cited”) for forward snowballing, the number of potentially relevant papers (“inc?”) after white-listing, and the number of actually relevant (“inc!”) papers after the inclusion check. The last number refers to the papers that extend the initial set.

We note that the sum over those papers (row “Sum”) is significantly larger than the number of actually added papers (row “Addit. papers”). This is no mistake but implies that some papers are cited multiple times. Multiple citations are a positive sign for the purpose of a review as they signify that a paper has a certain weight in the research discussion. We also note that the citation numbers (column “cited”) are comparatively low. The reason is that the papers in the initial set are all very recent: 8 (of the 17) papers have been published 2016 or later, and the remaining ones date back to not later than 2011.

Altogether, this review is based on a set of 101 primary studies.

### 2.2 Tagging

With each of the three questions Q1-Q3 we associate a number of tags that are used to answer that question. In each case, we introduce three kinds of tags. The first kind of tags is formed by all related terms that are highlighted by the authors themselves, because they use them in the title, abstract, or keyword list of their paper. Apart from minor grammatical changes, those terms are taken verbatim from the papers and directly serve as tags. As it turns out, however, very little of the information relevant for our review questions is directly exposed in the title, abstract, or keyword list. We therefore read curr-

| Initial set | Backward | | Forward | |
|-------------|----------|---|---------|---|
| | refs | inc? | inc! | cited | inc? | inc! |
| 2 | 30 | 12 | 10 | 4 | 4 | 4 |
| 5 | 186 | 30 | 8 | 0 | - | - |
| 6 | 46 | 2 | 1 | 37 | 10 | 0 |
| 8 | 34 | 18 | 6 | 18 | 10 | 10 |
| 9 | 34 | 21 | 6 | 8 | 4 | 2 |
| 10 | 31 | 5 | 1 | 5 | 2 | 1 |
| 23 | 66 | 16 | 12 | 0 | - | - |
| 28 | 146 | 29 | 12 | 0 | - | - |
| 34 | 23 | 1 | 1 | 4 | 1 | 0 |
| 61 | 22 | 8 | 3 | 25 | 4 | 2 |
| 60 | 28 | 8 | 1 | 19 | 4 | 3 |
| 66 | 53 | 20 | 10 | 22 | 14 | 13 |
| 67 | 17 | 7 | 6 | 0 | 0 | 0 |
| 71 | 83 | 1 | 1 | 31 | 9 | 8 |
| 87 | 10 | 5 | 4 | 28 | 15 | 10 |
| 94 | 303 | 6 | 0 | 0 | - | - |
| 98 | 22 | 9 | 4 | 6 | 5 | 5 |
| **Sum** | **1134** | **198** | **86** | **207** | **82** | **58** |
| **Addit. papers** | | | | | | |

| | 57 | | 27 |
| Addit. papers | | | |
| **Total** | | | |
| (initial set) 17 | | |
| (backward) 57 | | 27 |
| (forward) 27 | | 101 |
sory through each paper and extend the list of tags by the terms found thereby. Those terms also form tags directly. The third kind of tags are meta-tags, which we introduce to make the absence of information explicit, to further classify papers, and to group tags; those latter tags are prefixed with “meta-”. Table 3 contains the complete set of tags, ordered by associated question; all meta-tags are listed in the last row.

3 Results

We are now ready to present the findings. For each question Q1-Q3 we first explain how we aggregate the extracted tags, and then report the results in a bar chart, which tallies related papers and provides a numerical overview, and a table, which lists all related references explicitly.

3.1 Q1: Formal methods

Since the number of tags associated with question Q1 totals 101 (Table 3), we need to group those tags as otherwise the presentation would become too fragmented. Table 4 lists our partitioning into 13 groups where the group “Other” contains those tags that do not fit in any other cluster. With the partitioning we intend to capture the view of the formal methods community, but our choice cannot be free from subjectivity. Nor is the annotation process itself, which associates a paper with particular tags in the first place. We therefore decided to make our tagging transparent by publishing the bibliographic source file. Possible additional validity problems we discuss later, in Section 4.

Figure 2 reports the numbers for each group of formal methods, sorted alphabetically, while Table 5 lists for each group, or approach, of formal methods the papers that follow that approach. Interpreting the results from a practitioner’s point of view, no obviously preferred formal method exists. Even the high numbers in the group “Logic” do not change the picture, as, upon closer look, the particular logics in this group vary greatly in their syntax, semantics, and pragmatics. Our second observation concerns the group “Formal Model.” Papers on formal methods often present their method directly since they can assume appropriate underlying formal representations (“models”). For the domain of privacy, however, it is apparently a research effort of its own to provide a formal model, and more than 40% of the papers is engaged in the some part of formalization.

3.2 Q2. Application domains

For presenting the targeted application domains we, again, we partition the corresponding tags. In this case, we partition 38 tags (see Table 3) in 9 groups, using the corresponding application domain as grouping criterion (see Table 6). Most
### Table 3: Data tags and meta-tags.

**Formal methods (101):** analysis, AND/OR tree, API, automata, automata-based, Bayesian networks, BDD, boolean logic, causal analysis, CTL-FO, code generator, colored Petri Net, compiler, conceptual model, data-dependence graph, data-flow diagram, data-flow graph, decision diagram, decision system, deducability, deontic logic, description logic, dynamic logic, epistemic logic, first-order logic, first-order relational logic, first-order temporal logic, formal definition, formal description, formal framework, formal method, formal model, formal notation, formal representation, formal step, formal verification, formalization, games, Gentzen calculus, Hoare, inference, inference system, information flow types, knowledge-based logic, language, logic, logic-based, logic of privacy, logic of privacy and utility, LTL, mapping, Markov-DP, modal logic, model checking, model, model-based, model-driven, modeling, model-theoretic semantics, ontology, pi-calculus, policy analysis, policy automaton, P-RBAD privacy calculus, probabilistic automata, probabilistic logic, process algebra, program analysis, proof, proof technique, quantitative approach, reasoning, relationship-based access control, representation, role-based access model, run-time verification, satisfiability, semantics, spatial context, specification, specification-declarative, specification language, specifying, state-space analysis, static analysis, static verification, symbolic execution, temporal constraints, temporal context, temporal logic, temporal operators, theorem prover, timed traces, transformation, translation, translator, types, type systems, weakest precondition, verification

**Application domains (38):** bank-information-system, biometrics, cloud app, course-eval, delivery service, e-commerce, electric vehicle charging, electronic health-record, e-learning, electronic service, ETP (electronic toll payment), employee data, financial services, health-care, health-information-system, healthcare-appraisal-system, ITS (intelligent transportation system), loan application, location data, loyalty systems, mobile app, passenger-name-record, pay-as-you-go, public-transportation-ticketing, regeneration system, review system, slippery road alert, smart grid, smart meter, social data, social network, spyware, tax preparation, transportation, university, voting, website-app, web shop

**Tool support (37):** Alloy, Caprice, CAPRIV, CAPVerDE, COMPASS, Couenne, CUDD, eHealth Framework, event-B, Grok, IDP, Isabelle, Java, JIF, KeY, Legalese, Margrave, Maude, mCRL2, MetaMORPH(h)SY, MSVL, MyHealth@Vanderbilt, Netlogo, PINQ, PrivCIAAS, ProVerif, ProZ, PV, SAIL, SemPref, S4P, Spin/Promela, TSPASS, unnamed tool, Uppaal, Z, Z3, ZQL

**Meta-tags (27):** no-app, no-tool, example, extended-example, experimental, meta-biometrics, meta-e-commerce, meta-formal-model, meta-formal-other, meta-formal-verification, meta-health, meta-infsys, meta-language, meta-logic meta-model-checking, meta-ontology, meta-process-algebra, meta-semantics, meta-smart-grid, meta-social-network, meta-spec, meta-static-analysis, meta-transform, meta-transportation, meta-trust, meta-types, meta-web
group memberships are easy to decide syntactically and the application domains are largely as expected (see, e.g., the groups “E-Commerce”, “Health”, “Smart Grid”).

The majority of the papers include examples mostly for the purpose of illustrating a theoretical point. Two important tags are therefore the meta-tags “example-extended” and “experimental”, which flag extended, (and ideally) realistic examples and empirical measurements, thus mark those papers that are of particular interest to application developers.

Again, we answer the question by providing a bar chart and a table: Figure 3 shows the distribution of papers across application domains as well as the distribution of papers containing extended examples or experimental data. Conversely, Table 7 lists for each application domain the papers that relate to it.

Comparing the numbers in Figure 3, one can see two application domains with higher numbers: “Health” and “Social Networks.” Looking closer at the numbers of “extended examples” or “extended + empirical”, the domain “Health” clearly exhibits the largest number of papers of practical relevance. Overall, however, the ratio of papers with extended examples is very low, amounting to less than a fifth. At the same time, the dominating number in the figure is the number of papers without examples beyond illustrative snippets (“No-app”), just a bit more than a fifth. Altogether, it is fair to say that—with the possible exception of the health domain—current formal approaches cannot yet refer to many showcases. Accordingly, experimental evaluations—as they matter for practical software development—are scarce: only 9 papers contain experimental data and only two papers contain both an extended example and its empirical evaluation. The bar “No-app” includes additional two papers with experimental data: those papers measure performance parameters of the presented tool rather than an application.

For a legal advisor those numbers imply that there are no “best” formal methods one can application developers expect to follow; the only domain where it is sensible at all to ask for best practices is the health-care domain. For application developers those numbers mean that, at present, there is little software to reuse.

### 3.3 Q3. Tool support

The last question concerns the tool a paper either uses to implement its approach or newly develops for that purpose. Figure 4 summarizes the current tool support by breaking the set of tools down in three categories: unnamed tools, coming from papers that devise a prototypical implementation; (named) tools that are used either in one paper only or, if cited multiple times, by the same research group; and, lastly, tools that are used by different research groups. As forth cat-
category, we include those papers that mention no tool. In Table 8 we list which tool implements which approach.

The results are perhaps unexpected. For one, one might expect the overall number of tools to be higher—after all the primary studies are authored by software engineers or computer scientists. Yet, almost half of the studies is purely theoretical in that sense (“No tool” in Figure 4).

The spreading of tools, second, is very large: only four tools are used in more than one paper (see Table 8). Generally, such spreading of tools is quite common for formal methods and can be seen elsewhere as well. For the case at hand, high numbers follow already from the variety of formal methods used and the variety within those groups: the group “Logic”, for example comprises a wide range of logics, for which no single tool exists. Still, it is remarkable that there is only one tool in our primary studies, Alloy, that is used by more than one research group.

4 Threats to Validity

The results of this review depend critically on the tags each paper is characterized by, but the process of tagging is done manually, and this presents a threat to the validity of the results. In this subsection we first explain how we address this threat, then discuss additional potential validity problems.

Unfortunately, tagging by hand is inevitable—the majority of relevant information is not directly exposed to the readers but “hidden” in the text. We double-checked so that we can ensure that the set of tags for terms that the authors themselves consider relevant (by including them in the title, abstract, or keyword list of their paper) is complete. Given the number of papers processed, however, we cannot dismiss the risk of having overlooked tags that emerge from cursory reading. Nor can we give a formal argument for our specific partitioning of tags. The best we can do for mitigating validity problems is to make our groupings transparent. We do so through the introduction of appropriate meta-tags, and store with each paper its associated meta-tags.

The second source of threats to the overall validity concerns the selection process. A different search term as well as a different search engine would lead to a different initial list, while an additional iteration of the snowballing step would lead to an extended list of primary studies. On the other hand, research for formal methods on privacy has started only and we look at the references in this review as a starting point only, for a list that needs to be extended as research moves on. We do not dispute that relevant papers might be missing in the current review but we are confident that, using the technique of snowballing, one ultimately reaches all relevant
papers.

While it will not be possible to exclude all mistakes and subjective assessments, we can at least ensure the full reproducibility of the results and therefore make the complete data set available: the bibtex information for the primary studies can be downloaded as three separate files\(^1\), all tags and meta-tags can be found in the field “keywords.” The files were generated using the open-source software Zotero for reference management \([1]\), which allows for various filters and conversions to spreadsheet and bibtex formats, and which was of great help in automating the evaluation.

5 Summary and Conclusion

Since personal data can be considered critical information, application developers may want to employ formal methods so that they can argue in a rigorous manner that private data is protected properly. At present, however, no dedicated venues exist where formal methods are discussed that target specifically privacy concerns. Instead, the literature is scattered over conferences for formal methods, software engineering, security, data management, or theoretical computer science. In this paper we provide a systematic review of the use of formal methods for privacy protection in practice.

A wide variety of methods is available already today, and there is no evidence for more, or less, suitable methods. Notably, a large portion of papers falls in the categories “Formal Model” and “Language”: since privacy regulations are provided in natural language, extra modeling efforts are needed. On the other hand, comparatively few examples are available that application developers could take as a blueprint. Also, about half of the papers do not present an implementation of their approach and, generally, dedicated tool support is in its infancy.

Concluding, privacy protection is an important topic where formal methods can contribute in significant ways. As the publication years of the primary studies show, research in this field has gained momentum. As the review also shows, tooling support is a worthwhile subject for further research.

Acknowledgment My sincere thanks are to Wolfgang Schulz, Max von Grafenstein, Jörg Pohle, and the Humboldt Institute for Internet and Society (HIIG) for feedback and discussions on the legal issues of privacy. I also owe to the participants of the Dagstuhl seminar 18471, "Next Generation Domain Specific Conceptual Modeling: Principles and Methods", and to the Dagstuhl library for granting access to all literature needed for this review.

The paper is part of the project “Information Governance Technologies: Ethics, Policies, Architectures, Engineering” funded by the “Landesforschungsförderung Hamburg.”

References

[1] Zotero reference management software.\(^2\)

[2] Alan Abe and Andrew Simpson. Formal Models for Privacy. In *EDBT/ICDT Workshops*, volume 1558 of *ceur-ws.org*, 2016.
[3] Robin Adams and Sibylle Schupp. Constructing Independently Verifiable Privacy-Compliant Type Systems for Message Passing between Black-Box Components. In 10th Working Conference on Verified Software: Theories, Tools, and Experiments, Springer, pages 196–214, 2018.

[4] Ioannis Agrafiotis, Sadie Creese, Michael Goldsmith, and Nick Papanikolaou. Applying Formal Methods to Detect and Resolve Ambiguities in Privacy Requirements. In IFIP PrimeLife International Summer School on Privacy and Identity Management for Life, pages 271–282, 2011.

[5] Fatmah Y Akeel. Secure Data Integration Systems. PhD thesis, University of Southampton, 2017.

[6] Flora Amato and Francesco Mosato. A Model Driven Approach to Data Privacy Verification in E-Health Systems. Transactions on Data Privacy, 8:273–296, 2015.

[7] Nicolas Anciaux, Benjamin Nguyen, and Michalis Vazirgiannis. Limiting Data Collection in Application Forms: A Real-Case Application of a Founding Privacy Principle. In 2012 Tenth Annual International Conference on Privacy, Security and Trust (PST), pages 59–66, 2012.

[8] Thibaud Antignac and Daniel Le Metayer. Privacy Architectures: Reasoning about Data Minimisation and Integrity. In International Workshop on Security and Trust Management, volume 8743 of Springer, pages 17–32, 2014.

[9] Thibaud Antignac and Daniel Le Metayer. Trust Driven Strategies for Privacy by Design. In IFIP International Conference on Trust Management, volume 454 of Springer, pages 60–75, 2015.

[10] Thibaud Antignac, David Sands, and Gerardo Schneider. Data Minimisation: a Language-Based Approach. In IFIP International Conference on ICT Systems Security and Privacy Protection, pages 442–456. Springer, 2016.

[11] Thibaud Antignac, Riccardo Scandariato, and Gerardo Schneider. A Privacy-Aware Conceptual Model for Handling Personal Data. In 7th International Symposium on Leveraging Applications of Formal Methods (iSoLA), pages 942–957, 2016.

[12] Anna P. Antonakopoulou, Fotios I. Gogoulos, Georgios V. Lioudakis, Aziz S. Mousas, Dimitra I. Kaklamani, and Iakovos S. Venieris. An Ontology for Privacy-Aware Access Control in Network Monitoring Environments. Journal of Research and Practice in Information Technology, 46(4):263–285, 2014.

[13] Guillaume Aucher, Guido Boella, and Leendert Van der Torre. A Dynamic Logic for Privacy Compliance. Artificial Intelligence and Law, 19(2-3):187–232, 2011.

[14] Monir Azraoui, Kaoutar Elkhiyaoui, Melek Onen, Karin Bernsmed, Anderson Santana de Oliveira, and Jakub Sendor. A-PPL: An Accountability Policy Language. In Data Privacy Management, Autonomous Spontaneous Security, and Security Assurance., volume 8872, pages 319–326. Springer, 2015.
[15] Michael Backes, Fabian Bendun, Joerg Hoffmann, and Ninja Marnau. PriCL: Creating a Precedent, a Framework for Reasoning about Privacy Case Law. In International Conference on Principles of Security and Trust, volume 9036, pages 344–363. Springer, 2015.

[16] Michael Backes, Markus Duermuth, and Guenter Karjoth. Unification in Privacy Policy Evaluation - Translating EPAL into Prolog. In Fifth IEEE International Workshop on Policies for Distributed Systems and Networks (Policy’03), pages 185–188, 2004.

[17] Michael Backes, Matteo Maffei, and Kim Pecina. Automated Synthesis of Privacy-Preserving Distributed Applications. In Proceedings Network and Distributed System Security Symposium (NDSS’12), 2012.

[18] Mahmoud Barhamgi, Djamal Benslimane, Chirine Ghedira, and Alda Gancarski. Privacy-Preserving Data Mashup. In 2011 IEEE International Conference on Advanced Information Networking and Applications, pages 467–474, 2011.

[19] Aam Barth, Anupam Datta, John C. Mitchell, and Helen Nissenbaum. Privacy and Contextual Integrity: Framework and Applications. In 2006 IEEE Symposium on Security and Privacy, pages 184–198. IEEE, 2006.

[20] Adam Barth, John C. Mitchell, Anupam Datta, and Sharada Sundaram. Privacy and Utility in Business Processes. In 20th IEEE Computer Security Foundations Symposium (CSF’07), pages 279–294, 2007.

[21] Kai Bavendiek, Robin Adams, and Sibylle Schupp. Privacy-Preserving Architectures with Probabilistic Guarantees. In 16th Annual Conference on Privacy, Security and Trust (PST), pages 1–10. IEEE, 2018.

[22] Moritz Y. Becker, Alexander Malkis, and Laurent Bussard. S4p: A Generic Language for Specifying Privacy Preferences and Policies. Technical report, Microsoft Research, MSR-TR-2010-32, 167, 2010.

[23] Moritz Y. Becker, Alexander Malkis, and Laurent Bussard. A Practical Generic Privacy Language. In International Conference on Information Systems Security (ICISS), pages 125–139, 2011.

[24] Walid Benghabrit, Herve Grall, Jean-Claude Royer, and Anderson Santana de Oliveira. The Abstract Accountability Language: its Syntax, Semantics and Tools. [Research Report] IMT Atlantique hal-01856329, 2018.

[25] Walid Benghabrit, Herve Grall, Jean-Claude Royer, and Mohamed Sellami. Accountability for Abstract Component Design. In 40th EUROMICRO Conference on Software Engineering and Advanced Applications (SEAA), pages 213–220. IEEE, 2014.

[26] Walid Benghabrit, Herve Grall, Jean-Claude Royer, and Mohamed Sellami. Abstract Accountability Language: Translation, Compliance and Application. In 2015 Asia-Pacific Software Engineering Conference (APSEC), pages 214–221, 2015.

[27] Walid Benghabrit, Herve Grall, Jean-Claude Royer, and Mohamed Sellami.
Checking Accountability with a Prover. In *2015 IEEE 39th Annual Computer Software and Applications Conference*, volume 2, pages 83–88, 2015.

[28] Sebastian Benthall. *Context, Causality, and Information Flow: Implications for Privacy Engineering, Security, and Data Economics*. PhD thesis, UC Berkeley, 2018.

[29] Julien Bringer, Herve Chabanne, Daniel Le Metayer, and Roch Lescuyer. Privacy by Design in Practice: Reasoning about Privacy Properties of Biometric System Architectures. In *International Symposium on Formal Methods*, volume 9109, pages 90–107, 2015.

[30] Julien Bringer, Herve Chabanne, Daniel Le Metayer, and Roch Lescuyer. Reasoning about Privacy Properties of Biometric Systems Architectures in the Presence of Information Leakage. In *International Conference on Information Security*, volume 9290, pages 493–510, 2015.

[31] Julien Bringer, Herve Chabanne, Daniel Le Metayer, and Roch Lescuyer. Reasoning About Privacy Properties of Architectures Supporting Group Authentication and Application to Biometric Systems. In *IFIP Annual Conference on Data and Applications Security and Privacy 2016*, pages 313–327, 2016.

[32] Julien Bringer, Herve Chabanne, Daniel Le Metayer, and Roch Lescuyer. Biometric Systems Private by Design: Reasoning about Privacy Properties of Biometric System Architectures. arXiv 1702.08301, 2017.

[33] Ann Cavoukian. Privacy by design in law, policy and practice. A white paper for regulators, decision-makers and policy-makers. [www.ontla.on.ca/library/repository/mon/25008/312239.pdf](http://www.ontla.on.ca/library/repository/mon/25008/312239.pdf), 2011.

[34] Mohammed Jabed Morshed Chowdhury, Alan Colman, Jun Han, and Muhammad Asha Kabir. A Policy Framework for Subject-Driven Data Sharing. In *Proceedings of the 51st Hawaii International Conference on System Sciences (HICSS)*, pages 3996–4005, 2018.

[35] Omar Chowdhury, Andreas Gampe, Jianwei Niu, Jeffrey von Ronne, Jared Bennett, Anupam Datta, Limin Jia, William Winsborough, and Mauro Conti. Privacy Promises That Can be Kept. In *Proceedings of the 18th ACM Symposium on Access Control Models and Technologies - SACMAT ’13*, pages 3–14, 2013.

[36] Veronique Cortier, Niklas Grimm, Joseph Lalleman, Matteo Maffei, and Bhavani Thuraisingham. A Type System for Privacy Properties. In *Proceedings of the 2017 ACM SIGSAC Conference on Computer and Communications Security - CCS’17*, pages 409–423, 2017.

[37] Elisa Costante, Frederica Paci, and Nicola Zannone. Privacy-Aware Web Service Composition and Ranking. In *2013 IEEE 20th International Conference on Web Services*, pages 131–138, 2013.

[38] Anupam Datta. Privacy through Accountability: A Computer Science Perspective. In *International Conference on Distributed Systems and E-Government Technologies*, pages 170–179, 2009.
[39] Anupam Datta, Jeremiah Blocki, Nicolas Christin, Henry DeYoung, Deepak Garg, Limin Jia, Dilsun Keynar, and Arunesh Sinha. Understanding and Protecting Privacy: Formal semantics and Principled Audit Mechanisms. In International Conference on Information Systems Security (ICISS), volume 7093 of Lecture Notes in Computer Science, pages 1–27, 2011.

[40] Anupam Datta, Matthew Frederikson, Gilhyuk Ko, Piotr Mardziel, Shayak Sen, and Bhavani Thuraisingham. Use Privacy in Data-Driven Systems. In Proceedings of the 2017 ACM SIGSAC Conference on Computer and Communications Security - CCS ’17, pages 1193–1210, 2017.

[41] Koen Decroix. Model-Based Analysis of Privacy in Electronic Services. PhD thesis, KU Leuven, 2015.

[42] Koen Decroix, Jorn Lapon, Bart De Decker, and Vincent Naessens. A Framework for Formal Reasoning about Privacy Properties Based on Trust Relationships in Complex Electronic Services. In International Conference on Information Systems Security (ICISS), volume 8303, pages 106–120. Springer, 2013.

[43] Koen Decroix, Jorn Lapon, Laurens Lemaire, Bart De Decker, and Vincent Naessens. Formal Reasoning About Privacy and Trust in Loyalty Systems. In International Conference on Business Information Systems (BIS), volume 228, pages 211–223. Springer, 2015.

[44] Henry DeYoung, Deepak Garg, Limin Jia, Dilsun Kaynar, and Anupam Datta. Experiences in the Logical Specification of the HIPAA and GLBA Privacy Laws. In Proceedings of the 9th Annual ACM Workshop on Privacy in the Electronic Society - WPES ’10, pages 73–82, 2010.

[45] Yun Ding and Karsten Klein. Model-Driven Application-Level Encryption for the Privacy of E-health Data. In 2010 International Conference on Availability, Reliability and Security, pages 341–346, 2010.

[46] Marouane Fazouane, Henning Kopp, Rens W. van der Heijden, Daniel Le Metayer, and Frank Kargl. Formal Verification of Privacy Properties in Electric Vehicle Charging. In International Symposium on Engineering Secure Software and Systems, volume 8978, pages 17–33. Springer, 2015.

[47] Kathi Fisler, Shriram Krishnamurthi, Leo Meyerovich, and Michael Carl Tschantz. Verification and Change-Impact Analysis of Access-Control Policies. In Proceedings of the 27th International Conference on Software Engineering (ICSE ’05), pages 196–205, 2005.

[48] Philip W Fong. Relationship-Based Access Control: Protection Model and Policy Language. In Proceedings of the First ACM Conference on Data and Application Security and Privacy, pages 191–202, 2011.

[49] Philip W.L Fong, Mohd Anwar, and Zhen Zhao. A Privacy Preservation Model for Facebook-Style Social Network Systems. In European Symposium on Research in
Computer Security (ESORICS), volume 5789, pages 303–320. Springer, 2009.

[50] Cedric Fournet, Markulf Kohlweiss, George Danezis, and Zhengqin Luo. ZQL: A Compiler for Privacy-Preserving Data Processing. In USENIX Security Symposium, pages 163–178, 2013.

[51] Xiang Fu. Conformance Verification of Privacy Policies. In International Workshop on Web Services and Formal Methods., pages 86–100. Springer, 2010.

[52] Michael Hecker, Tharam S. Dillon, and Elizabeth Chang. Privacy Ontology Support for E-Commerce. IEEE Internet Computing, 12(2):54–61, 2008.

[53] Yuh-Jong Hu, Jiun-Jan Yang, and Rajendra Akerkar. A Semantic Privacy-Preserving Model for Data Sharing and Integration. In Proceedings of the International Conference on Web Intelligence, Mining and Semantics (WIMS ’11), page Article No. 9 (12 pages), 2011.

[54] Mohammed Jafari, Philip W.L Fong, Rei Safavi-Naini, Ken Barker, and Nicholas P. Sheppart. Towards Defining Semantic Foundations for Purpose-Based Privacy Policies. In Proceedings of the First ACM Conference on Data and Application Security and Privacy (CODASPY’11), pages 213–224, 2011.

[55] Guenter Karjoth, Matthias Schunter, and Els Van Herreweghen. Translating Privacy Practices into Privacy Promises - How to Promise What You Can Keep. In IEEE 4th International Workshop on Policies for Distributed Systems and Networks (Policy ’03), pages 135–146, 2003.

[56] Barbara Kitchenham. Procedures for performing systematic reviews. Keele, UK, Keele University, 33(2004):1–26, 2004.

[57] Barbara Kitchenham, O Pearl Brereton, David Budgen, Mark Turner, John Bailey, and Stephen Linkman. Systematic literature reviews in software engineering—a systematic literature review. Information and Software Technology, 51(1):7–15, 2009.

[58] Fabian Knirsch, Engel Dominik, Christian Neureiter, Mark Frincu, and Viktor Prasanna. Model-Driven Privacy Assessment in the Smart Grid. In 2015 International Conference on Information Systems Security and Privacy (ICISSP), pages 1–9, 2015.

[59] Fabian Knirsch, Dominik Engel, Christian Neureiter, Mark Frincu, and Viktor Prasanna. Privacy Assessment of Data Flow Graphs for an Advanced Recommender System in the Smart Grid. In 2015 International Conference on Information Systems Security and Privacy (ICISSP), volume 576, pages 89–106, 2015.

[60] Martin Kost and Johann-Christoph Freytag. Privacy Analysis using Ontologies. In Proceedings of the Second ACM Conference on Data and Application Security and Privacy - CODASPY’12, ACM, pages 205–217, 2012.

[61] Martin Kost, Johann-Christoph Freytag, Frank Kargl, and Antonio Kung. Privacy Verification using Ontologies. In 2011
Sixth International Conference on Availability, Reliability and Security (ARES), IEEE, pages 627–632, 2011.

[62] Dimitrios Kouzapas and Anna Philippou. A Typing System for Privacy. In Proceedings of Software Engineering and Formal Methods (SEFM) 2013 Collocated Workshops, volume 8368, pages 56–68. Springer, 2014.

[63] Yann Krupa and Laurent Vercouter. Handling Privacy as Contextual Integrity in De-Centralized Virtual Communities: The privaCIAS Framework. Web Intelligence and Agent Systems: An International Journal, 10(1):105–116, 2012.

[64] Teo Kuang, Hamidah Ibrahim, and Gabriele Kotsis. Security Privacy Access Control for Policy Integration and Conflict Reconciliation in Health Care Organizations Collaborations. In Proceedings of the 11th International Conference on Information Integration and Web-based Applications & Services - iiWAS ’09, pages 750–754, 2009.

[65] Daniel Le Metayer. A Formal Privacy Management Framework. In International Workshop on Formal Aspects in Security and Trust., pages 162–176. Springer, 2008.

[66] Daniel Le Metayer. Privacy by Design: A Formal Framework for the Analysis of Architectural Choices. In Proceedings of the Third ACM Conference on Data and Application Security and Privacy, ACM, pages 95–104, 2013.

[67] Daniel Le Metayer and Pablo Rauzy. Capacity: an Abstract Model of Control over Personal Data. In Proceedings of the Eighth ACM Conference on Data and Application Security and Privacy, ACM, pages 64–75, 2018.

[68] Min Li, Hua Wang, and Ashly Plank. Privacy-aware Access Control with Generalization Boundaries. In Proceedings of the Thirty-Second Australasian Conference on Computer Science, volume 91, pages 105–112, 2009.

[69] Yang Liu. Privacy-Preserving Targeted Advertising for Mobile Devices. PhD thesis, University of Oxford, 2017.

[70] Yang Liu and Andrew Simpson. Privacy-Preserving Targeted Mobile Advertising: Formal Models and Analysis. In Data Privacy Management and Security Assurance, pages 94–110, 2016.

[71] Matteo Maffei, Kim Pecina, and Manuel Reinert. Security and Privacy by Declarative Design. In 2013 IEEE 26th Computer Security Foundations Symposium, IEEE, pages 81–96, 2013.

[72] Asmita Manna, Anirban Sengupta, and Chandan Mazumdar. Towards Formal Modeling of Privacy Policies of Enterprises. In 2018 Fifth International Conference on Emerging Applications of Information Technology (EAIT), pages 1–6. IEEE, 2018.

[73] Michael J. May, Carl A. Gunter, and Insup Lee. Privacy APIs: Access Control Techniques to Analyze and Verify Legal Privacy Policies. In Computer Security Foundations Workshop, 2006. 19th IEEE, pages 85–97. IEEE, 2006.
[74] Frank D. McSherry. Privacy Integrated Queries: An Extensible Platform for Privacy-Preserving Data Analysis. *Proceedings of the 2009 ACM SIGMOD International Conference on Management of Data*, pages 19–30, 2009.

[75] Mohammed M Moniruzzaman and Ken Barker. Delegation of Access Rights in a Privacy Preserving Access Control Model. In *Ninth Annual International Conference on Privacy, Security and Trust (PST)*, pages 124–133. IEEE, 2011.

[76] Andrew Myers and Barbara Liskov. Protecting Privacy Using the Decentralized Label Model. *ACM Transactions on Software Engineering and Methodology (TOSEM)*, 9(4):410–422, 2000.

[77] Qun Ni, Elisa Bertino, Jorge Lobo, and Ray Indrakshi. An Obligation Model Bridging Access Control Policies and Privacy Policies. In *Proceedings of the 13th ACM Symposium on Access Control Models and Technologies - SACMAT ’08*, pages 133–142, 2008.

[78] Qun Ni, Dan Lin, Elisa Bertino, and Jorge Lobo. Conditional Privacy-Aware Role Based Access Control. In *Proceedings of the 12th European Symposium On Research In Computer Security (ESORICS 2007)*, pages 72–89, 2007.

[79] Li Ninghui, Ting Yu, and Annie I. Anton. A Semantics-Based Approach to Privacy Languages. *Computer Systems Science and Engineering*, 21(5):339–361, 2006.

[80] Inah Omoronyia, Luca Cavallaro, Mazeiar Salehie, Liliana Pasquale, and Bashar Nuseibeh. Engineering Adaptive Privacy: On the Role of Privacy Awareness Requirements. In *Proceedings of the 2013 International Conference on Software Engineering*, pages 632–641, 2013.

[81] Inah Omoronyia, Liliana Pasquale, Mazeiar Salehie, Luca Cavallaro, Gavin Doherty, and Bashar Nuseibeh. Caprice: A Tool for Engineering Adaptive Privacy. In *Proceedings of the 27th IEEE/ACM International Conference on Automated Software Engineering - ASE 2012*, pages 354–357, 2012.

[82] Gordon J. Pace, Raul Pardo, and Gerardo Schneider. On the Runtime Enforcement of Evolving Privacy Policies in Online Social Networks. In *Leveraging Applications of Formal Methods, Verification and Validation: Discussion, Dissemination, Applications. ISoLA 2016*, volume 9953, pages 407–412. Springer, 2016.

[83] Raul Pardo, Musard Balliu, and Gerardo Schneider. Formalising Privacy Policies in Social Networks. *Journal of Logical and Algebraic Methods in Programming*, 90:125–157, 2017.

[84] Raul Pardo, Christian Colombo, Gordon J. Pace, and Gerardo Schneider. An Automata-based Approach to Evolving Privacy Policies for Social Networks. In *International Conference on Runtime Verification*, pages 285–301. Springer, 2016.

[85] Raul Pardo, Ivana Kellyerova, Cesar Sanchez, and Gerardo Schneider. Specification of Evolving Privacy Policies for Online Social Networks. In *2016 23rd International Symposium on Temporal Rep-*
presentation and Reasoning (TIME), pages 70–79, 2016.

[86] Raul Pardo, Cesar Sanchez, and Gerardo Schneider. Timed Epistemic Knowledge Bases for Social Networks. In *International Symposium on Formal Methods*, volume 10951, pages 185–202. Springer, 2018.

[87] Raul Pardo and Gerardo Schneider. A Formal Privacy Policy Framework for Social Networks. In *International Conference on Software Engineering and Formal Methods*, volume 8702 of *Springer*, pages 378–392, 2014.

[88] Raul Pardo and Gerardo Schneider. Model Checking Social Network Models. In *8th Symposium on Games, Automata, Logics and Formal Verification (GandALF’17)*, pages 238–252, 2017.

[89] Siani Pearson and Azzedine Benameur. A Decision Support System for Design for Privacy. In *Privacy and Identity 2010.*, IFIP AICT 352, pages 283–296, 2011.

[90] Srinivas Pinisetty, Thibaud Antignac, David Sands, and Gerardo Schneider. Monitoring Data Minimisation. In *arXiv 1801.02484*, 2018.

[91] Guillaume Piolle and Yves Demazeau. Representing Privacy Regulations with Deontico-Temporal Operators. *Web Intelligence and Agent Systems*, 9(3):209–226, 2011.

[92] Georgios Pitsiladis and Petros Stefaneas. Implementation of Privacy Calculus and Its Type Checking in Maude. In *International Symposium on Leveraging Applications of Formal Methods (ISoLA)*, volume 11245, pages 477–493, 2018.

[93] Shayak Sen, Saikat Ghuha, Anupam Datta, Sriram Rajamani, Janice Tsai, and Jeannette M. Wing. Bootstrapping Privacy Compliance in Big Data Systems. In *2014 IEEE Symposium on Security and Privacy*, pages 327–342, 2014.

[94] Ibrahim Shiyam. *Formal Analysis of Confidentiality Conditions Related to Data Leakage*. PhD thesis, University of York, 2017.

[95] Lili Sun, Hua Wang, Xialhui Tao, Yanchun Zhang, and Jing Yang. Privacy Preserving Access Control Policy and Algorithms for Conflicting Problems. In *IEEE 10th International Conference on Trust, Security and Privacy in Computing and Communications*, pages 250–257, 2011.

[96] Suriadi Suriadi, Chun Ouyang, Jason Smith, and Ernest Foo. Modeling and Verification of Privacy Enhancing Protocols. In *Proceedings of the 11th International Conference on Formal Engineering Methods (ICFEM 2009)*, pages 127–146. Springer, 2009.

[97] Vinh-Thong Ta. Privacy by Design: On the Formal Design and Conformance Check of Personal Data Protection Policies and Architectures. In *arXiv 1511.01249v2 [cs.CR]*, 2018.

[98] Vinh-Thong Ta and Thibaud Antignac. Privacy by Design: On the Conformance Between Protocols and Architectures. In *International Symposium on Foundations*
and Practice of Security, volume 8930 of Springer, pages 65–81, 2015.

[99] Matt Tierney and Lakshminarayanan Subramanian. Realizing Privacy by Definition in Social Networks. In Proceedings of 5th Asia-Pacific Workshop on Systems - AP-Sys ’14, pages 1–7, 2014.

[100] Michael Tschantz, Anupam Datta, and Jeannette M. Wing. Formalizing and Enforcing Purpose Restrictions in Privacy Policies. In 2012 IEEE Symposium on Security and Privacy, pages 176–190, 2012.

[101] Michael Tschantz, Anupam Datta, and Jeannette M. Wing. Purpose Restrictions on Information Use. In European Symposium on Research in Computer Security (ESORICS), volume 8134, pages 610–627. Springer, 2013.

[102] Michael Carl Tschantz, Dilsun Kaynar, and Anupam Datta. Formal Verification of Differential Privacy for Interactive Systems. In Electronic Notes in Theoretical Computer Science (ENTCS), volume 276, pages 61–79, 2011.

[103] Xiaobing Wang and Tao Sun. A Method Based on MSVL for Verification of the Social Network Privacy Policy. In Workshop on Structured Object-Oriented Formal Language and Method, pages 118–131. Springer, 2015.

[104] Claes Wohlin. Guidelines for snowballing in systematic literature studies and a replication in software engineering. In Proceedings of the 18th International Conference on Evaluation and Assessment in Software Engineering, EASE’14, pages 38:1–38:10. ACM, 2014.

[105] Matteo Zanioli, Pietro Ferrara, Agostino Cortesi, and Sascha Ossowski. SAILS: Static Analysis of Information Leakage with Sample. In Proceedings of the 27th Annual ACM Symposium on Applied Computing - SAC ’12, pages 1308–1313, 2012.

[106] Da Zhang, Yong Zheng, Lingyu Wang, Hongtao Li, and Yuanfeng Geng. Modeling and Evaluating Information Leakage Caused by Inferences in Supply Chains. Computers in Industry, 62(3):351–363, 2011.
Table 4: Q1. Formal methods: Grouping of tags.

| Id       | Tags (see Table 3)                                                                 |
|----------|-----------------------------------------------------------------------------------|
| Formal Model | formal description, formal framework, formal model, formal notation,              |
|           | formal representation, formal steps, formalization, model, model-based,           |
|           | model-driven, modeling, representation                                             |
| Formal Verification | formal method, formal verification, proof, reasoning, static verification,         |
|           | verification                                                                      |
| Language | language, specification language                                                 |
| Logic    | AND/OR tree, boolean logic, CTL-FO, decision diagram, deducibility,               |
|          | deontic logic, dynamic logic, epistemic logic, first-order logic, first-order      |
|          | relational logic, first-order temporal logic, Gentzen calculus, Hoare, inference,  |
|          | inference system, knowledge-based logic, LTL, logic, logic-based,                 |
|          | logic of privacy and utility, modal logic, privacy calculus, probabilistic logic, |
|          | proof technique, satisfiability, spatial context, symbolic execution, temporal     |
|          | logic, temporal operators, temporal constraints, temporal context, weakest         |
|          | precondition                                                                      |
| Model Checking | model-checking, state-space analysis                                              |
| Ontology | description logic, ontology                                                       |
| Process Algebra | process algebra, pi-calculus, colored Petri Net                                   |
| Semantics | semantics, model-theoretic semantics                                             |
| Specification | declarative specification, formal definition, specification, specifying           |
| Static Analysis | analysis, BDD, data-dependence graph, data-flow diagram, data-flow                |
|            | graph, dependence graph, policy analysis, program analysis, static analysis        |
| Transform | code generator, compiler, mapping, transformation, translator, translation         |
| Types     | information-flow types, types, type system                                        |
| Other     | API, automata, automata-based, causal analysis, conceptual-model,                |
|          | Bayesian networks, decision system, relationship-based access control, role-based |
|          | access models, P-RBAC, theorem-prover, Markov-DP, policy automaton, probabilistic |
|          | automata, quantitative approach, run-time verification, timed-traces              |
| Table 5: Q1. Formal methods: listing by papers. |
|-----------------------------------------------|
| **Formal Model**                             |
| [2], [4], [5], [6], [8], [9], [19], [20], [28], [29], [30], [31], [40], [41], [42], [44], |
| [45], [46], [49], [51], [53], [60], [61], [62], [63], [65], [67], [68], [69], [70], [72], |
| [75], [78], [77], [79], [80], [83], [87], [88], [91], [95], [96], [100], [103], [106] |
| **Formal Verification**                       |
| [3], [4], [6], [11], [12], [15], [27], [24], [29], [31], [30], [32], [43], [42], [46], |
| [47], [51], [61], [70], [81], [83], [86], [91], [97], [98], [103] |
| **Language**                                 |
| [8], [9], [10], [14], [17], [21], [22], [23], [25], [24], [31], [35], [47], [65], [70], |
| [78], [79], [85], [84], [92], [93], [97], [98] |
| **Logic**                                    |
| [4], [6], [7], [8], [10], [12], [13], [16], [17], [19], [35], [20], [21], [23], [25], [27], |
| [24], [29], [30], [31], [32], [35], [37], [39], [41], [42], [43], [44], [47], [48], [51], |
| [54], [55], [65], [66], [64], [71], [72], [75], [77], [79], [81], [80], [83], [86], [87], |
| [88], [85], [91], [92], [97], [98], [102], [103] |
| **Model Checking**                           |
| [2], [6], [13], [25], [48], [51], [73], [88], [85], [96] |
| **Ontology**                                 |
| [12], [18], [28], [52], [53], [58], [60], [61] |
| **Process Algebra**                          |
| [46], [62], [92], [98] |
| **Semantics**                                |
| [8], [9], [10], [22], [23], [26], [24], [38], [39], [54], [60], [79], [83], [93], [97], |
| [100] |
| **Specification**                            |
| [8], [10], [22], [24], [32], [35], [39], [44], [51], [71], [84], [93], [94], [97] |
| **Static Analysis**                          |
| [11], [35], [40], [41], [33], [37], [49], [51], [58], [59], [60], [61], [70], [71], [76], |
| [93], [94], [96], [99], [105], [106] |
| **Transformation**                           |
| [6], [14], [16], [17], [26], [45], [50], [55], [74], [98] |
| **Types**                                    |
| [3], [36], [42], [62], [71], [76], [92], [93] |
| **Other**                                    |
| [11] (conceptual model), [27] (theorem prover), [28] (Bayesian networks), |
| [38] (Markov-DP), [40] (causal analysis), [48] (relation-based), [61] (role-based access model), |
| [71] (API), [75] (P-RBAC), [78] (role-based), [77] (role-based), [82] (automata-based, run-time verification), [86] (timed-traces), |
| [84] (policy automaton, run-time verification), [89] (decision system), [90] (run-time verification), [102] (prob. automata), [100] (Markov-DP), [101] (Markov-DP), [106] (conceptual model, quant. approach) |
Table 6: Q2. Application domains: Grouping of tags.

| Id | Tags (see Table 3) |
|----|-------------------|
| Biometrics | biometrics |
| E-Commerce | e-commerce, electronic service, delivery service, loyalty systems, passenger-name-record, public-transportation-ticketing, web shop |
| Health | electronic health-record, healthcare-appraisal-system, health-care, health-information-system |
| Information Systems | bank-information-system, course-eval, e-learning, employee data, financial services, loan application, review system, university |
| Transportation | electric vehicle charging, ETP (electronic toll payment), ITS (intelligent transportation system), location service, pay-as-you-go, transportation |
| Smart Grid | smart grid, smart meter |
| Social Network | social data, social network |
| Web | cloud-app, mobile ads, mobile app, website-app |
| Other | GUI-design, regeneration system, slippery-road alert, spyware, tax preparation, voting |

Table 7: Q2. Application domains: listing by papers. “X” marks papers with extended examples, “E” papers with experimental data.

| Biometrics | 28, 29, X, 31, X, 32, X |
| E-Commerce | 10, 28, 37, X, 41, 42, 43, 52, 53, 55, 90 |
| Health | 5, 6, X, 18, EX, 20, X, 26, X, 27, X, 35, X, 35, 48, X, 53, 54, 62, 64, 94, X, 101, 100, E |
| Information Systems | 4, 7, E, 17, 34, 40, E, 42, 47, 49, 71, EX, 72, 91, 94, X |
| Smart Grid | 2, 8, 21, 50, E, 58, 59, 97, X |
| Social Networks | 17, 48, X, 49, 62, 67, 80, E, 82, 83, 86, 87, 88, 85, 54, 103 |
| Transportation | 9, 46, 50, E, 60, 61, 63, 66, 99 |
| Web | 3, 13, 22, 23, 25, 51, 70, X, 69, 77, 81 |
| Other | 111 (slippery-road alert), 13 (spyware), 36 (voting), 76 (tax preparation), 89 (GUI design), 106 (regeneration system) |
| no-app | 12, 14, 16, 15, 19, 24, 38, 39, 41, 55, 65, 68, 73, 74, 75, 78, 79, 92, 93, E, 95, 96, 98, 102, 105, E |
| Tool                | Papers |
|---------------------|--------|
| Alloy               | 34, 51 |
| CAPRIV              | 9      |
| COMPASS             | 99     |
| CUDD                | 47     |
| event-B             | 5      |
| IDP                 | 41     |
| Java                | 37     |
| KeY                 | 10     |
| Margrave            | 47     |
| mCRL2               | 25     |
| MSVL                | 103    |
| Netlogo             | 80     |
| PrivaClAS           | 63     |
| ProZ                | 70     |
| SAIL                | 105    |
| S4P                 | 22, 23 |
| TSPASS              | 26, 27, 24 |
| Uppaal              | 6      |
| Z3                  | 10     |
| no-tool             | 3, 4, 11, 12, 13, 42, 44, 49, 48, 52, 88, 85, 84, 90, 14, 15, 18, 19, 53, 54, 55, 58, 62, 91, 95, 96, 97, 29, 30, 31, 32, 61, 65, 68, 75, 78, 102, 101, 35, 38, 39, 43, 77, 82, 83, 86, 87 |
|                     |        |

**Table 8: Q3. Tool support: listing by papers.**
Table 9: Criteria for inclusion, exclusion, and white-listing.

| Inclusion criteria                  |
|-------------------------------------|
| I1 Papers meeting the search terms “privacy”, “formal method”, “software” and written for a computer science/software engineering audience |
| I2 Papers available in full text    |

| Exclusion criteria                  |
|-------------------------------------|
| E1 Handbooks, collections, surveys, position papers, milestone report, project summaries, master theses |
| E2 Standards, manuals, guidelines   |
| E3 Papers not written in English    |
| E4 Duplicates, including short versions of included papers |
| E5 Papers published in law journals or conferences |
| E6 Artifact links, e.g., to web-pages instead of papers |
| E7 Papers dealing with formal methods in domains other than privacy |
| E8 Papers dealing with mathematical/computer science methods for privacy concerns other than formal methods |

| White-list criteria (snowballing)   |
|-------------------------------------|
| W1 Papers with relevant title       |
| W2 Papers by authors already included |
| W3 Papers in relevant conferences or journals |