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Iterative Analysis to Improve the Security of Human-Intensive Processes: An Election Example

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This paper presents an approach for analyzing complex processes, including those involving human agents, hardware devices, and software systems, and illustrates the utility of this approach by analyzing part of a process for holding an election. In the work described here, the Little-JIL process definition language is used to create a precise and detailed model of an election process. Given this process definition, two forms of automated analysis are used to explore the possibility that specified security policies could be undermined. Model checking is first used to identify process execution sequences that violate event-sequence security policies and other properties. After these are addressed, fault-tree analysis is applied to identify when the misperformance of steps might allow security breaches or other undesirable outcomes to occur. The results of these analyses can provide assurance about the process, suggest areas for improvement, and, when applied to a modified process definition, evaluate proposed changes in the process.

Categories and Subject Descriptors: D.2.1 [**Software Engineering**]: Requirements/Specifications—*Languages*; *Methodologies*; *Tools*; K.4.3 [**Computers and Society**]: Reengineering; K.6.m [**Management of Computing and Information Systems**]: Security

General Terms: Languages, Management, Reliability, Security, Verification

Additional Key Words and Phrases: process modeling, iterative analysis, model checking, fault-tree analysis, elections

1. INTRODUCTION

This paper presents an approach for systematically and iteratively evaluating and improving the security of processes. We use the word "process" in the colloquial sense that refers to a real-world system or enterprise. More specifically, we consider a process[1] to be a collaboration among people, hardware devices, and software systems, perhaps using additional resources, to achieve desired goals. Our approach to studying the security of such processes requires that they be specified precisely and in sufficient detail to support automated, rigorous analyses based upon carefully defined security policies. In this paper we present a particular approach for rigorously specifying and then analyzing such processes and illustrate its benefits using part of an election process.

Our approach exploits the rigor of a mathematically precise model of a process that describes its various usage contexts, as well as precise specifications of security policies that may describe either desirable or undesirable behavior. Using these representations we apply two analysis techniques to determine how well the process model satisfies the security policies. We use *model checking* to determine if any executions of a given process would not satisfy specified policies, and if so identify usage scenarios that illustrate such violations. Model checking basically determines if any execution of the process as specified could violate security policies. *Fault-tree analysis* (FTA), on the

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[1] This use of the word "process" is not to be confused with its use in the operating systems literature where it refers more narrowly to the execution of a specific program as part of a larger computer system.

other hand, identifies different ways in which undesirable execution states, referred to as *hazards*, could be reached due to the *incorrect performance* of some parts of the process.

To emphasize the rigorous basis of our models, we refer to them as *process definitions*. In our approach, processes are modeled using a process definition language, called Little-JIL [Cass et al. 2000]. Little-JIL has rigorously defined semantics capable of supporting both the precision and multiple levels of detail needed. Moreover, it provides rich semantics for specifying concurrency, recognizing exceptional situations, and specifying how to handle these situations. Responses to exceptions or the lack of specified responses often reveal flaws in the security defenses of the process that otherwise might be difficult to detect. Thus our work incorporates careful analyses of how processes handle exceptions, even in the presence of concurrency and non-determinism, as such complexities are often critical to understanding how secure processes are.

Our approach can be applied to a broad range of different kinds of processes, including those where computers and automation are not used. But the approach seems particularly useful in specifying and analyzing *human-intensive systems*, namely those in which humans are active participants [Chen et al. 2008; Avrunin et al. 2006; Osterweil et al. 2007; Henneman et al. 2007; Avrunin et al. 2010; Wise et al. 2000]. Process definitions, and consequently the associated analysis of these definitions, are usually more complicated when human activities must be incorporated, since humans often desire a high level of autonomy and often display wider variability and greater fallibility than is typical of non-human components. In this paper we demonstrate our approach using election processes as examples. Election processes are good vehicles for demonstrating our approach as they involve the coordination of the efforts of humans playing various roles, with mechanical devices and software systems playing other roles. Election process definitions must specify the precise roles that each of these entities is expected to play, how they are to be coordinated, and what checks should be put in place to assure that each can be shown to be performing their roles correctly.

In this paper, we present some key details of a precise and rigorous definition of a specific election process, define some specific security policies, and demonstrate how model checking can be used to support reasoning about how well the process definition adheres to these policies. Then, given a particular hazard, we derive a fault tree from that process definition and compute from the fault tree the combinations of incorrectly performed activities that could cause the violations of election policies represented by the hazard. Using this approach, we would expect analysts to work with election officials to identify process modifications, modify the process definition to reflect these changes, and then reapply the analyses to assure that the proposed changes eliminate the detected flaws in the process without adding new ones. Whether proposed process changes are because of flaws detected by our analyses, actual observed security violations, modifications to the laws, or desired proposed efficiency improvements, our approach provides systematic support for *continuous process improvement*.

1.1. Election Processes

An election is the "formal choosing of a person for an office, dignity, or position of any kind; usually by the votes of a constituent body" [Simpson and Weiner 1991]. An election process may be as simple as counting raised hands in a room (e.g., a caucus) or as complex as tallying votes across a multiplicity of jurisdictions, each of which uses its own rules to control the casting, reporting, and tallying of votes.

The process is important because the results of an election can affect the course of history. Imagine how different United States history would have been had George McClellan, rather than Abraham Lincoln, become president in 1864. Thus, it is critical to verify that an election has been carried out consistent with criteria that assure such desirable properties as correctness, fairness, and privacy. Ideally the verification should satisfy all parties that have stakes in the election, especially key stakeholders such as the voters and candidates.

Currently election officials typically use *ad hoc* approaches to address problems as they arise and to anticipate problems before they arise. Some *ad hoc* approaches have resulted in election process improvements. But given the frequent changes to election law over time, current *ad hoc* procedures are often a patchwork of responses to legislation at varying levels of government. Using formal analyses of process definitions to identify problems that might occur systematizes the search for problems before they arise. Once problems have been identified, either through such analyses or through experience in using the processes, the same analyses can then demonstrate that proposed solutions do indeed solve problems without creating new problems.

Verification of a real election process entails performing a rigorous comparison of a definition of the process to a set of characteristics (such as those pertaining to security) that are stated as rigorous criteria. Specifying both the process and the criteria accurately and precisely is difficult because elections are very large and complex processes, and these criteria are numerous and diverse. Some examples of criteria are “all qualified voters must be allowed to vote,” “no voter may vote more than once,” and “no one other than the voter may know how that voter voted.” To support rigorous analysis, these natural language statements of criteria must be refined into precisely specified election process requirements. Thus, “no voter may vote more than once” would be represented by something like “suppose that v is a voter, and C is the set of all voters who have already cast their ballots. If $v \in C$, then voter v must not be issued a ballot”. We express these statements as specifications using formal logic and automata theory.

Issues concerned with the consistency of these requirements with each other and with the entire body of election criteria arise as the number of requirements grows. For example, to prevent voters from voting more than once, jurisdictions in the U.S. state of Ohio kept a list of the names of voters who have voted in the order of their arrival. Expecting to have to verify electronic ballots, they also kept another list of the ballots in the order in which they were cast. Each list satisfied an important requirement. But the simultaneous existence of both lists enabled people to associate a specific voter with a specific ballot, thereby violating the voter’s expectation of privacy, another key requirement [McCullagh 2007].

Other problems arise from the size and complexity of the election processes. These processes may need to define how to handle a single ballot that includes races from multiple jurisdictions, each of which may have its own set of election requirements. In the United States, there are over 3,000 jurisdictions, each with the legal right to carry out its own election process, which may be quite different from the processes in other jurisdictions. A good example is a ballot for an election for federal, state, and local candidates in San Francisco, California. San Francisco uses ranked-choice voting for some local races, and majority voting for state and federal races as required by state law. Another example is an election for officials or ballot initiatives that spans two or more legal jurisdictions, each with its own set of election procedures. Which jurisdiction’s procedures should be used — or should both be used, each in its own jurisdiction? Thus, election requirements may vary even for the elections on a single ballot, and consequently election process specifications must vary accordingly.

Election processes must also specify how to deal with problems arising during the course of balloting. For example, a ballot box might not be submitted for tabulation by a specified deadline, or a set of ballots might not be tabulated, or might be tabulated more than once. If the procedures for handling such contingencies are expected to be developed *ad hoc*, how can it be assured that all affected parties will have the same, correct understanding of the *ad hoc* procedure? And if procedures for handling contingencies are only informally specified and understood, what happens when the only person who understands these procedures is sick on election day? Moreover, humans have widely varying degrees of education, training, age, and cultural backgrounds. In some jurisdictions, the average age of poll workers is over 80. These poll workers may still be required to set up heavy voting equipment, understand the intricacies of the operation of the equipment, and fully grasp all of the details of the voting procedures in the jurisdiction. Because unexpected or unforeseen problems may arise, election processes must make appropriate provisions for detecting and correcting problems in ways that are known to be consistent with election process requirements, and thus election process definitions will need to be constantly improved and analyzed to assure compliance.

2. ITERATIVE PROCESS IMPROVEMENT

To develop a process definition that precisely and rigorously represents the real-world process, several important aspects of the process must be understood, captured, and defined. These include issues that are often overlooked, such as exception handling, different scenarios for different contexts, the precise specification of who is responsible for what activities, and the integration of the efforts of both humans and machines. Developing an appropriately detailed and precise process definition requires substantial effort and consultation with domain experts. But once a suitable process definition has been constructed, it can be leveraged to significantly improve the understanding, security, performance, or automation of the real-world process, as well as to train future cohorts of process performers. It can also be used to evaluate the effect of potential changes on the actual conduct of the process. Because human-intensive processes often require the communication, coordination, and synchronization of many people, machines, and other entities, it is not surprising that such a multi-faceted model may illuminate issues that the domain experts previously overlooked.

We use an iterative approach to identify potential areas for improvement. Shewhart [Shewhart 1931] introduced the basic tenets of continuous process improvement, and they were applied with perhaps the greatest effect by Deming [Deming 1982]. The essence of this approach is to capture the process to be improved in a model, compare the characteristics of the model to those that are desired, identify weaknesses and shortcomings in the model, propose and evaluate improvements to the model, and, once these improvements have been shown to be effective and efficient without introducing additional problems or defects, deploy the improvements in the real-world process to complete the improvement cycle and form the basis for a subsequent improvement cycle. This cycle has been referred to in various ways (e.g., the Plan-Do-Check-Act, or PDCA, Cycle; Define-Measure-Analyze-Improve-Control, or DMAIC; Observe, Orient, Decide, and Act, or OODA) over the past decades. In all of its names and manifestations, it has relied primarily on the ability to understand the process and its desired criteria and to analyze the ways in which the process does or does not adhere to those criteria.

These understandings and analyses have usually been pursued informally. Processes and requirements are typically described in informal natural language, and analyses of their conformance have typically been done through informal discussion and argumentation. More recently, research has shown that processes and requirements can be defined using precise and rigorous notations that render the evaluation of their consistency amenable to powerful technological support. Our approach moves the approach towards a disciplined engineering practice supported by scientific rigor. This approach to rigorous definition and analysis of processes has also been used in several other domains, including science [Altintas et al. 2004; Ellison et al. 2006],

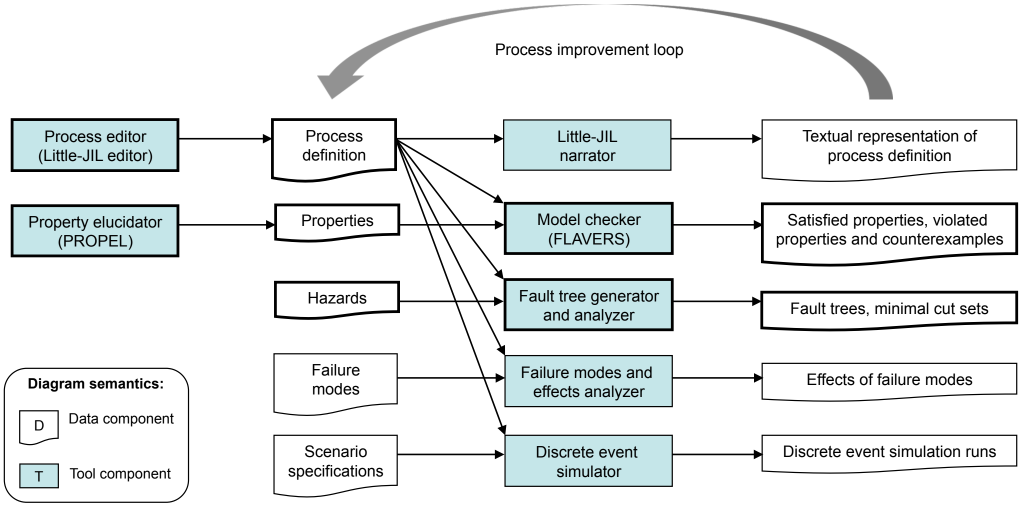

Fig. 1. A framework for iterative process improvement

medicine [Clarke et al. 2008; Henneman et al. 2007], and business [Georgakopoulos et al. 1995; Wiegert 1998].

2.1. A Systematic Process Improvement Loop

To demonstrate our approach, in this paper we define parts of an election process using Little-JIL. Once the process is defined in sufficient detail, it can be analyzed using different approaches grounded in mathematical reasoning that allow for the automatic derivation of important assertions about the process definition. Figure 1 illustrates our framework for continuous process improvement. It shows how a single process definition can be leveraged to attain a multi-faceted understanding of the process. A formal process definition can be created using the Visual-JIL environment[2], which provides a visual representation that helps the domain experts understand the definition. This formal definition then serves as the input for a variety of reasoning approaches, such as automatic derivation of a hyperlinked textual representation of the process, or discrete event simulations to evaluate different scenarios for performance or efficiency. Each reasoning approach creates a specific output (illustrated in the last column of data components in Figure 1), and these outputs are used as inputs for the next iteration in the continuous process improvement loop by informing changes to the process definition, the properties representing precise requirement specifications, or both. Applying this framework iteratively allows us to identify and test improvements to ensure they do not introduce undesirable side effects before deploying them in the real-world process. Here, we focus on a subset of this framework that highlights the tools and components shown in the boxes with thick outlines in Figure 1, showing two analysis approaches, namely model checking and FTA.

Model checking determines if a process definition is consistent with a set of requirements, specified formally as properties, by considering every relevant path through a representation of the process. This approach has been used in previous work, for example to determine if a set of circumstances may allow an impostor pretending to be

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[2] Distributed as a plugin for the Eclipse IDE

an eligible voter to cast a provisional ballot[3] [Simidchieva et al. 2008]. FTA is quite different from model checking. Given a specification of a hazard, an undesirable outcome at a certain point in the process, FTA considers the conditions or events that might allow that undesirable event to occur. The analysis creates a fault tree where each such event is considered in turn. Our automated FTA tool uses the artifact flow through the process definition to automatically construct and analyze a fault tree for a specified undesirable event. In previous work, we demonstrated how FTA could be applied to an election process definition to construct the different scenarios that may lead to an incorrect vote tally [Simidchieva et al. 2010]. This paper shows how model checking and FTA, two very different techniques, can be applied in tandem to provide a more comprehensive analysis and to better inform the process improvement loop. Specifically, before deploying a new release, analysts would use this approach to evaluate known security properties, specified either as event sequence properties verified using model checking or as undesirable events evaluated using FTA.

2.2. Modeling the Process

The election process defined and discussed throughout this paper is used in Yolo County, California, USA. We elicited it from laws, procedure documents, and extensive interviews with Yolo County election officials. The election officials then carefully reviewed the process definition to ensure that it faithfully represented their election process. It models a wide range of exceptional situations along with how they are handled, and also carefully specifies what agents perform what activities using what artifacts. These artifacts form the basis for deriving some of the answers to the questions that the different analysis techniques focus on.

The process of eliciting the information that the process model embodies bears some discussion. Initially, we had a basic understanding of how the generic election process works in that county, as one of the authors lives there and has observed many elections as part of other research. We then constructed a very high level process definition and reviewed it with the election officials of Yolo County. Their feedback enabled the process definition to be refined to match the process they used at a high level. We then focused on specific parts of the process, notably (for our purposes here) the subprocess by which votes were counted. We met with the election officials several times and they gave us detailed descriptions of the tallying of the votes, the California mandatory 1% manual audit, and the canvass, during which the totals are completed and the counts certified.

To elicit information about the process, we had the election officials describe the election process at a high level and identify specific parts of the process that they wished analyzed in more detail. From this description, we developed a graphical model of the process (see the next section). We then went back to the election officials, showed them our model, and walked them through what we had done. Sometimes they realized details had been omitted; indeed, one of the benefits of the elicitation process was that their understanding of the process improved by their having to recall and discuss these details. Other times, they clarified parts of the process we did not understand properly.

We then began to “drill down” into specific areas of interest. One of the areas, which we examine in this paper, is the subprocess for describing the counting of votes. For that subprocess, we repeated the elicitation process, but confined our focus to that area. We interacted regularly with the election officials to ensure our model reflected their practice. Also, one of the authors observed the counting process over the course

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[3] A provisional ballot is used by a voter to cast a vote when there is a question by election officials about the voter’s eligibility to vote. If the voter is deemed to be eligible to vote by election officials after adjudication, then the vote is accepted and, if not, it is rejected.

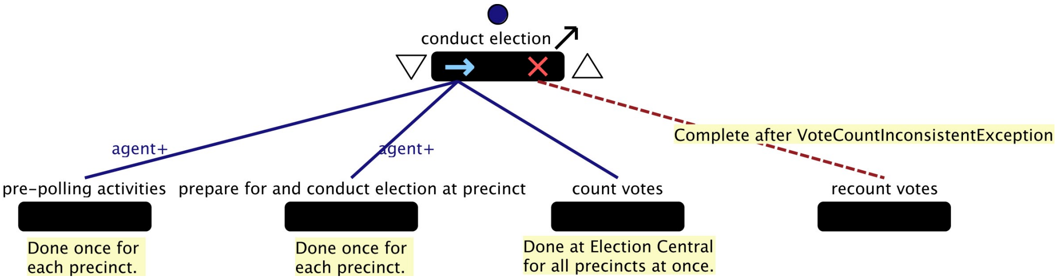

Fig. 2. Little-JIL process model: Top level of the "conduct election" process

of many elections, and participated as a deputy clerk in some. Thus, in addition to the information the election officials provided, we benefitted from actual observations.

2.2.1. Little-JIL: A Process Definition Language. Little-JIL proved to be an effective vehicle for defining election processes. Its rich semantics support the precise definition of many different aspects of processes, such as concurrency, communication, and coordination among human actors as well as software and hardware components; the specification of possible human choice and flexibility; the creation, use, and modification of artifacts; and the specification of complex exceptional situations and their mitigation. The diagrams presented in this paper omit many such important details to avoid visual clutter.

A Little-JIL process coordination diagram, such as the one shown in Figure 2, specifies a hierarchical decomposition of steps. A step in the process is shown as a black rounded rectangle, with the step name above it. Each step is assigned an agent that is responsible for its execution; this agent may be a human actor, such as an election official or a voter, or a hardware or software component, such as a direct-recording electronic voting machine (DRE)[4]. Agents can also be composites, combinations of other component agents, such as polling places that are defined to consist of various devices, space, and people. A step in turn may be decomposed into *substeps* or children (the steps that connect to the lower left side of the parent step rectangle bar via edges), each with its own agent responsible for its execution. Each step that has children also has a *sequence badge*, which appears in the left half of the step bar and specifies the order in which its children will be carried out. For example, in Figure 2, the root step `conduct election` is a sequential step, indicated by a right arrow, specifying that its children will be executed in left to right order, so `pre-polling activities` will be followed by `prepare for and conduct election at precinct`, which in turn will be followed by `count votes`. Each of these activities is further decomposed in the complete definition of the process, but as noted above, here we focus on the `count votes` activity. A step without children is called a *leaf step*. Responsibility for the execution of leaf steps is left entirely to the step's agent. A step in a Little-JIL process definition is akin to a procedure or method specification that, once specified, can be invoked from anywhere in the process definition through an appropriate reference.

A Little-JIL process definition also contains complete specifications of the artifact flow and the different agents responsible for the steps. The artifact specification consists of all the artifacts that are created, modified, or consumed in the process, for example a `ballot repository` (a repository containing all the ballots cast) and different `tallies` (a report of the number of ballots used at a precinct or votes cast for each candidate). Each step definition declares what artifacts it will be accessing and pro-

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[4] A DRE records votes directly to electronic media without the additional use of a paper trail.

viding. Artifacts are generally passed within the hierarchical flow of the coordination hierarchy (i.e., from parents to children and vice versa). If steps are thought of as procedures, this artifact passing is essentially a parameter-passing mechanism. Lateral artifact flow is also supported.

The agent specification allows each process step to request that a specific type of agent be responsible for its execution. Little-JIL allows the definition of both human and automated (hardware devices or software systems) agents. For the election process, `Voter`, `Election Official`, `Voting Machine`, and `Polling Place` are some example types of agents. Note that the former two are human agents while the latter two are non-human, and the last, `Polling Place` is a compound agent, consisting of such components as voting booths, election officials, and ballot-marking equipment. Little-JIL definitions only specify the type of agent (e.g., `Voter`) that should execute a specific step, and not a specific agent instance (e.g., Jane Doe). In Figure 2, the `agent+` notation on the edges to the first two substeps of `conduct election` indicates that each agent of the type requested should carry out these activities. Given that both steps request a `Polling Place` agent, this indicates that each Polling Place will provide the specific resources (e.g. tabulating devices) needed in order to support the execution of the specific election activities mandated by the authorities having cognizance over that site. The `count votes` step will occur once afterward, just as in the real-world Yolo County process where the precincts carry out election activities in parallel with each other, but the counting of all votes is carried out at Election Central.

In real-world processes, exceptional conditions may arise frequently and must be resolved before the process continues along its normative path. To accurately model this, Little-JIL provides comprehensive exception-handling semantics. For example, in Figure 2, the `recount votes` step in Figure 2 connects to the × in the right half of the step bar of its parent, `conduct election`, to indicate that `recount votes` is an exception handler. Exceptions in Little-JIL are typed, which means that different exception handlers must be defined for each exception type. This is especially important in complex human-intensive systems such as elections as different exceptions usually necessitate different protocols. Thus, for example, the `recount votes` step is an exception handler for exceptions of the type `Vote Count Inconsistent Exception`. Finally, Little-JIL's exception-handling mechanism also provides flexible continuation semantics after exception handling takes place. In this case, `recount votes` specifies how to resolve inconsistencies in the counting of the votes and the step that threw this exception is considered completed and is not to be repeated or revisited after the exception has been handled. Other exceptions may require the re-execution of the step that threw the exception, and this continuation behavior can be defined in Little-JIL as well.

To demonstrate the analysis approaches described in the previous section, we focus on the part of the process definition responsible for the tabulation of ballots and votes after the voting is completed. Figure 3 shows the decomposition of the `count votes` step from Figure 2. In Yolo County, every precinct brings its ballots, along with a summary cover sheet (indicating how many ballots were issued to the precinct, and how many of them are used, spoiled or blank after election day), to Election Central for tabulation. There, election officials first `count votes from all precincts`, then `perform random audit`, and then, finally, if no exceptions are raised, `report final vote totals to Secretary of State`. The `agent+` notation on the edge from the first substep to its child step indicates that the decomposition of this activity is into separate `count votes from precinct` steps, each of which tallies the votes from a different precinct separately before the precinct tally is added to a total tally. Ballot counts are compared to the summary sheets for each precinct, and after reconciling the actual and reported numbers the ballots are scanned to obtain the actual vote counts. Random auditing

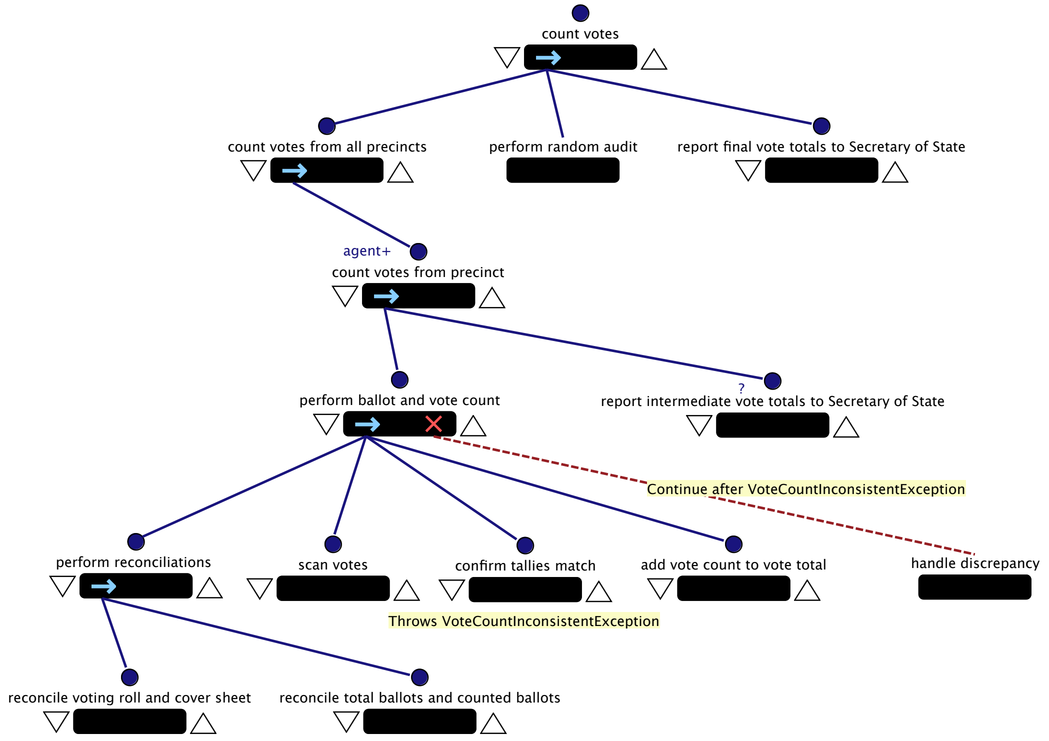

Fig. 3. “count votes” sub-process

(or a mandatory manual recount of 1% of precincts to ensure consistency) is a state requirement in California and many other states [VerifiedVoting 2013; National Association of Secretaries of State (NASS) 2007].

It is important to understand how the regular tabulation of votes is performed as well as how reconciliation works should any discrepancies occur. Yolo County uses primarily paper ballots, which are scanned and counted by automated optical scanners. It also has voting machines designed for disabled voters, but that any voter may use. California election law requires all DRE machines to have an attached printer so that a voter-verified paper audit trail (VVPAT) can be maintained at all times. In Yolo County, these paper trails are in fact the artifact used to count votes cast on these machines. A damaged or missing paper trail can therefore lead to many problems in the election process, as fault tree analysis demonstrates and is discussed in the Results Section.

2.3. Model Checking

In this section, we briefly describe model checking and the tools we use, discuss the translation of legal and other requirements into formal properties that can be checked by model checking, and present the results of model checking the process definition described in the previous section.

2.3.1. Background. Before considering the ways in which the security of a process such as an election might be vulnerable to attack, we would like to be sure that the process works as required when it is not subject to attack. This means that we must check that all possible executions of the process in which each step is executed correctly (i.e., assuming correct inputs and outputs) satisfy the requirements for the process as stated, for example, in election law. But complex real-world processes such as elections are typically concurrent systems that need to coordinate and synchronize their activities and communications. The number of possible executions of a concurrent system is usually exponential in the number of concurrent activities. This makes it hard to understand all the ways that such processes could be executed, and infeasible to list them and examine each one manually.

Model checking techniques [Clarke et al. 2000; Baier and Katoen 2008] work by constructing a representation of all possible relevant executions of the concurrent system with respect to a specification, usually defined as an automaton or by using a modal logic formalism, and then comparing that representation to the formal specification. We refer to such a precise specification as a *property* to distinguish it from the original requirement or policy that may be informal (e.g., natural language) or even unstated. The model checking technique that we use expects a property to be represented as a finite-state automaton (FSA) that specifies intended (or unintended) sequences of *events* drawn from an *alphabet* of all events of interest.

Model checking techniques try to determine whether every execution represented by the model satisfies a given property. When the property is not satisfied by all executions, the analysis identifies *counterexamples*, particular executions that violate the property. For most classes of systems, the complexity of model checking techniques is at least NP-hard (and undecidable for some classes), but numerous optimizations have been developed, so that model checking techniques are now sufficiently practical that they are widely used to analyze real-world hardware and software systems.

Our process analysis and improvement framework translates Little-JIL to the Bandera Intermediate Representation (BIR) [Iosif et al. 2005], a guarded command language. From the BIR, we can construct models suitable for use with various model checking techniques; for the work described in this paper, we have primarily used the FLAVERS [Dwyer et al. 2004] tool. FLAVERS uses qualified data flow analysis [Holley and Rosen 1980] to check whether all executions of a system satisfy a property by propagating tuples of states from the property automaton, as well as various feasibility constraint automata, through a graph describing the possible orderings of events in the process. FLAVERS can make use of symbolic representations of sets of states, such as Zero-suppressed Binary Decision Diagrams [Minato 1996], to handle large processes.

2.3.2. Specifying properties by refining requirements. Requirements for elections are typically given in natural language documents such as laws and regulations. To determine whether a particular election process satisfies such requirements using model checking techniques requires that each requirement be refined to one or more precisely specified properties. This is tricky and error-prone, especially since natural language is inherently ambiguous and incomplete. We use the PROPEL (PROPerty ELucidator) tool [Smith et al. 2002; Cobleigh et al. 2006] to help address these difficulties.

PROPEL provides templates for commonly occurring property specification patterns [Dwyer et al. 1999], and each template has a set of options that must be considered in order to specify the property precisely and completely. For instance, the template for properties that require one event to have already occurred before a second event can occur includes options such as whether the first event is required to occur at all, whether it can occur more than once, and whether each occurrence of the second event must be preceded by a different occurrence of the first event. PROPEL provides three different views of a property: a hierarchical series of questions (referred to as the question tree view), the answers to which determine the template and the detailed options; a graphical FSA view in which the user selects transitions, transition labels, and accepting states to choose the options; and a Disciplined Natural Language (DNL) view in which the user selects phrases from drop-down boxes. Although the question tree and DNL views assist domain experts, who may not be comfortable with automata, all three views result in an FSA representation of the property that is then used in model checking.

To illustrate our approach, we focus on the *canvass*, that portion of the election process that validates the results of the election by verifying that the counting is accurate and all applicable laws and regulations have been followed. Figure 4 lists the six high-level legislative requirements for the canvass that we verified, where each requirement (the Ri in the figure) has been refined to one or more properties (the $Pi.j$ in the figure). The California election code[5] requires local election officials to conduct a canvass after the close of the polls (R1) and before reporting the election results to the Secretary of State (R2). Most of the tasks to be carried out in the canvass are laid out in Section 15302 (R3, R4) and Section 15360 (R5) of the California election code. In cases where electronic voting equipment is used, a manual audit of 1% of the precincts is required as part of the canvass (R5). Since Yolo County allows voters to use DREs to mark their ballots and the election officials use scanners to count ballots and votes, the county must always perform this audit. Our formulations of the properties therefore always require the audit. If any audit shows a discrepancy, then a recount must be conducted (R6).

The refinement from requirements to properties must take into account that one requirement might impact other requirements. For instance, requirements R1 and R2 impact requirements R3, R4, and R5. Additionally, PROPEL supports alternative ways to represent a requirement and a particular choice could affect the number of properties and their complexity. To illustrate, we describe here the refinement of requirement R3 that there be a reconciliation of the number of signatures on the roster with the number of ballots recorded on the ballot statement.

To capture this requirement in PROPEL, we describe the canvass in terms of three events: **begin canvass**, **reconcile number of voter signatures and number of recorded ballots**, and **report final results to the Secretary of State**. We take the initial reporting of the final results to signify the end of the canvass (in the case of recounts, for example, there may be more than one report to the Secretary of State). PROPEL provides a template for properties that are intended to hold between two events, and so we could represent this requirement as a single property requiring that the reconciliation occur between the beginning of the canvass and the initial report of the final results to the Secretary of State. We chose, however, to express this requirement using two properties, one saying that the reconciliation occurs after the canvass begins and the other saying that the reconciliation occurs before the final results are reported. We felt that this separation made the choice of options simpler, thereby making it easier for election officials to validate our formalization of this part of the election code.

To illustrate, Figure 5 shows the question tree (some of the lower-level questions have been omitted for brevity), and Figure 6 shows the FSA and DNL produced by PROPEL for property 3.1. The patterns on which PROPEL is based describe each property using a *scope* that specifies the parts of an execution to which the property applies, and a *behavior*, which specifies the restriction on sequences of events in those parts. PROPEL's question tree and DNL views give the scope and behavior separately. The "secondary events" mentioned in the DNL refer to other events whose occurrence between the events of primary interest might need to be restricted; in this case, there are no such events. The FSA views can give the scope and behavior together, or only the

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[5] http://www.leginfo.ca.gov/.html/elec_table_of_contents.html

R1. The canvass begins after the polls close.
  P1. After the event **close polls** occurs, the event **begin canvass** must occur.
R2. The canvass needs to report the final results to the Secretary of State.
  P2. The event **report final results to Secretary of State** must occur.
R3. The canvass must include a reconciliation of the number of voter signatures and the number of recorded ballots.
  P3.1. After the event **begin canvass** occurs, the event **reconcile number of voter signatures and number of recorded ballots** must occur.
  P3.2. The event **report final results to Secretary of State** is not allowed to occur until after the event **reconcile number of voter signatures and number of recorded ballots** has occurred.
R4. The canvass must include a reconciliation of the number of recorded ballots and the number of tallied ballots.
  P4.1. After the event **begin canvass** occurs, the event **reconcile number of recorded ballots and number of tallied ballots** must occur.
  P4.2. The event **report final results to Secretary of State** is not allowed to occur until after the event **reconcile number of recorded ballots and number of tallied ballots** has occurred.
R5. The canvass must include a 1% manual audit.
  P5.1. After the event **begin canvass** occurs, the event **conduct one percent manual audit** must occur.
  P5.2. The event **report final results to Secretary of State** is not allowed to occur until after the event **conduct one percent manual audit** has occurred.
R6. If the 1% manual audit shows a discrepancy, then a recount must be conducted.
  P6. After the event **one percent manual audit shows discrepancy** occurs, the event **recount votes** must occur.

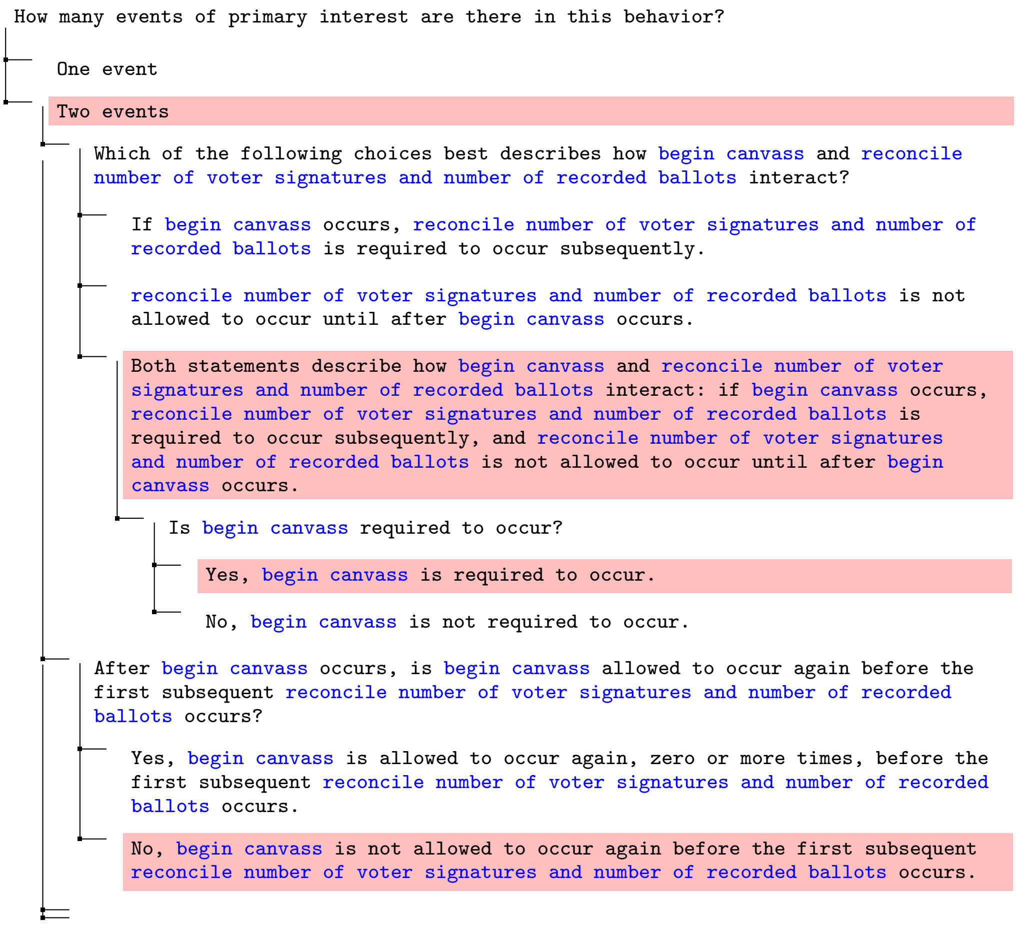
Fig. 4. Refinement of canvass-related requirements to low-level properties

behavior. More formally, the FSAs produced by PROPEL are deterministic and total, so there is exactly one transition from each state labeled by each event in the alphabet of the property. If a particular event should not be allowed to occur in some state, the transition labeled by that event goes to a *violation* state. The violation state is a sink—every transition from the violation state is a loop that goes back to the violation state—and is a non-accepting state. For simplicity, the FSAs in the figures do not show the violation state or any transitions to it, so if there is no transition shown with a particular label from a given state, there is an implicit transition with that label to the violation state.

A key part of the requirement partially encoded in Property 3.1 is that, once the event **begin canvass** has occurred, the event **reconcile number of voter signatures and number of recorded ballots** must subsequently occur. But the specification must resolve a number of ambiguities that could lead to events occurring that should be forbidden. Are there any allowed executions of the process in which the **begin canvass** event does not occur? Can **begin canvass** occur multiple times? Can the reconciliation occur before the beginning of the canvass? Based on discussions with the domain experts, we interpret the legal requirement as meaning that no executions of the election process should be allowed in which the canvass is not begun and the reconciliation of the numbers of signatures and ballots should not occur before the canvass has begun. The canvass may not begin more than once and the reconciliation may not occur more than once.

2.3.3. Binding property events to the process definition.

The properties discussed in the preceding subsection are formalizations of the requirements for the real-world process. Therefore, any process defined to achieve the same goal should satisfy those proper-



How many events of primary interest are there in this behavior?

One event

Two events

Which of the following choices best describes how begin canvass and reconcile number of voter signatures and number of recorded ballots interact?

If begin canvass occurs, reconcile number of voter signatures and number of recorded ballots is required to occur subsequently.

reconcile number of voter signatures and number of recorded ballots is not allowed to occur until after begin canvass occurs.

Both statements describe how begin canvass and reconcile number of voter signatures and number of recorded ballots interact: if begin canvass occurs, reconcile number of voter signatures and number of recorded ballots is required to occur subsequently, and reconcile number of voter signatures and number of recorded ballots is not allowed to occur until after begin canvass occurs.

Is begin canvass required to occur?

Yes, begin canvass is required to occur.

No, begin canvass is not required to occur.

After begin canvass occurs, is begin canvass allowed to occur again before the first subsequent reconcile number of voter signatures and number of recorded ballots occurs?

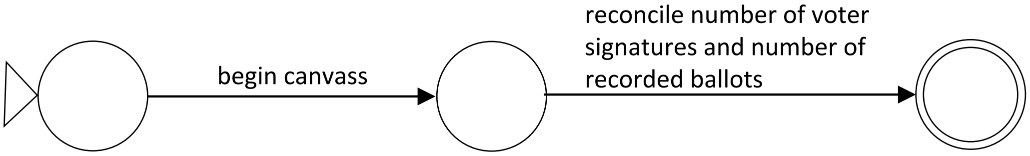
Yes, begin canvass is allowed to occur again, zero or more times, before the first subsequent reconcile number of voter signatures and number of recorded ballots occurs.

No, begin canvass is not allowed to occur again before the first subsequent reconcile number of voter signatures and number of recorded ballots occurs.

Fig. 5. PROPEL question tree for Property 3.1. Red highlighting indicates the selected answer.

ties. But different process definitions may satisfy those properties in different ways and may represent the events in the properties in different ways. So, to check whether our particular Little-JIL process definition satisfies these properties, we must first *bind* each of the events in the properties to all of the Little-JIL process definition activities whose execution causes the event to occur. In most cases, we bind a property event, such as **begin canvass**, to the start or completion of a Little-JIL step. For example, we bound the event **begin canvass** to the start of the Little-JIL step `count votes` (shown in Figure 3), and the event **reconcile number of voter signatures and number of recorded ballots** to the completion of the Little-JIL step `reconcile voting roll and cover sheet` (shown in the same figure). Our process analysis and improvement framework provides support for indicating which process steps should be bound to each event in a property.

2.3.4. Benefits from model checking. Execution of the FLAVERS model checker succeeded in verifying that our election process definition satisfies the Propel representation of property 3.1 as well as all of the other properties enumerated in Figure 4. Verifying that the process definition satisfies each of the properties increases our assurance that the election process definition adheres to federal and state laws and regulations.



Scope:

(1) From the start of any event sequence through to the end of that event sequence, the behavior must hold.

Behavior:

(1) The events of primary interest in this behavior are **begin canvass** and **reconcile number of voter signatures and number of recorded ballots**.
(2) There are no events of secondary interest in this behavior.
(3) If **begin canvass** occurs, **reconcile number of voter signatures and number of recorded ballots** is required to occur subsequently.
(4) Before the first **begin canvass** occurs, **reconcile number of voter signatures and number of recorded ballots** is not allowed to occur.
(5) **begin canvass** is required to occur.
(6) After **begin canvass** occurs, but before the first subsequent **reconcile number of voter signatures and number of recorded ballots** occurs, **begin canvass** is not allowed to occur again.
(7) After **begin canvass** and the first subsequent **reconcile number of voter signatures and number of recorded ballots** occur:
    — Neither **begin canvass** nor **reconcile number of voter signatures and number of recorded ballots** are allowed to occur again.

Fig. 6. PROPEL finite state automaton and disciplined natural language views for Property 3.1.

In general, it usually takes many iterations of analysis and refinement of the model (and properties) to convince ourselves and the domain experts that the process model is an accurate representation of the real process. Model checking is an important tool in reaching this consensus. When there is significant concurrency and exceptional behavior, human analysts are increasingly challenged to be sure that they have adequately considered all possible executions. Model checking provides this assurance, at least with respect to the properties that are considered important for the process. Thus, it is not surprising that numerous errors are usually found in the process definition and in the property specifications. But without such rigorous analysis, domain experts would be relying on inaccurate models. After errors in the process definition and property specifications are removed, we begin to find errors that are actual problems in the real process.

Although the initial process modeling and model checking are time consuming, the resulting process models and properties are valuable assets that can continue to be modified and improved as the process itself evolves. For election processes that are continually being updated, these are valuable resources that allow important accuracy and security checks to be applied before changes are made to the actual process; this is especially important since elections cannot easily be redone. In our framework, these models become the fundamental basis for subsequent vulnerability analysis, described in the next subsection, and thus their accuracy is vitally important.

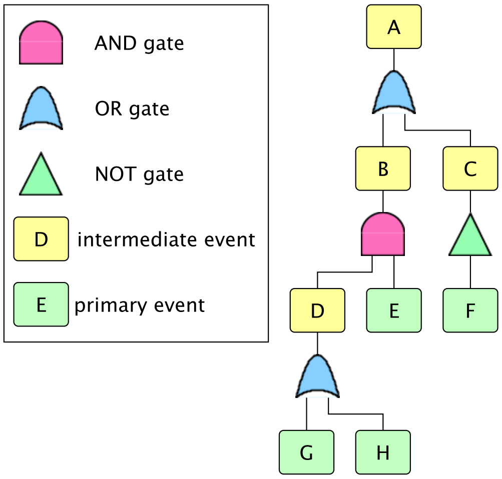


Fig. 7. Simple fault tree

2.4. Fault-Tree Analysis

Model checking evaluates whether the process model adheres to stated properties, assuming that the steps in the model are carried out correctly. As noted earlier, however, process steps may not be done accurately, especially when humans, who may become fatigued or confused or maliciously desire to undermine a process, are involved. Thus we use FTA to evaluate how vulnerable the process, as represented by the process definition, is to incorrectly executed process steps.

FTA is a deductive, top-down analytical technique that is used in a variety of industries [Ericson II 1999; Ward et al. 2007; Hyman and Johnson 2008; Chen 2010] to study conditions under which an accident or hazard that can cause substantial damage or loss might occur. In the case of our election process, a very serious hazard would be for an incorrect count of votes to be delivered to the Secretary of State, creating the condition that the wrong candidate would be declared to have been elected. This hazard might result, for example, if a batch of ballots was not counted because it was mistakenly or maliciously assumed to have been counted previously.

With FTA, one first specifies a hazard and then attempts to determine which process execution events could combine to cause the actual occurrence of that hazard. Given the hazard, FTA produces a *fault tree*, a visualization of all the various combinations of these events that could lead to the hazard. A fault tree consists of *events* and *gates*. At the top (root) of the fault tree lies the hazard. In the fault tree, *intermediate events* are the consequences of previous events, and this dependence is shown by hierarchical elaboration down to *primary events*, which are not further elaborated. Events are connected to each other by Boolean-logic gates. A gate connects one or more lower-level input events to a single higher-level output event. There are three types of gates:

— AND gates: the output event occurs only if all the input events occur, implying that the occurrence of all the input events causes the output event;
— OR gates: the output event occurs only if at least one of the input events occurs, implying that the occurrence of any input event causes the output event; and
— NOT gates: the output event occurs only if the (only) input event does not occur.

Figure 7 shows a fault tree with the top event, or hazard, A. An OR gate connects this event with two lower-level events, B and C, so A occurs if B or C occurs or they both occur. The event B in turn occurs if and only if both of the two lower-level events connected to it through an AND gate occur. The event E is a primary event so it is not elaborated further in the fault tree. A *cut set* is a set of *event literals* such that the occurrence of all the events associated with the event literals in the set could allow the hazard to occur. An *event literal* is either a primary event or the negation of a primary event. A cut set is considered *minimal* if, when any of its event literals is removed, the resulting set is no longer a cut set. For example, $\{H, E\}$ is a minimal cut set (MCS) of the fault tree in Figure 7. An MCS indicates a potential process vulnerability, which might be a flaw or weakness in the process design, implementation, or operation and management that could be exploited to allow a hazard to occur. An MCS with one element represents a *single point of failure*. An example of a single point of failure in Figure 7 is the event literal $\{\neg F\}$. The probability of a hazard occurring can be calculated if sufficient information about the probabilities of the events associated with the event literals in the MCSs is available.

Many software tools facilitate the manual construction of fault trees. When fault trees become large, as is typical, manual construction, even with such tool support, becomes error-prone and time-consuming. We developed a process-driven FTA tool to automate fault-tree construction and MCS calculation from process definitions written in precisely-defined languages [Chen 2010]. Thus, for example, given a process definition written in the Little-JIL language and a hazard specification, our tool constructs a fault tree and then calculates its MCSs.

2.4.1. Identifying a hazard. Once domain experts have validated the process definition as a correct representation of an actual real-world process, the resulting fault trees can lead to the discovery of unforeseen process vulnerabilities and can suggest modifications to improve the robustness and safety of the real-world process. Typically, domain experts can suggest multiple hazards from their own experiences. Furthermore, they can often evaluate the importance of a hazard, depending on its anticipated impact and the perceived probability of its occurrence. One hazard of particular interest, which we discuss in this paper, is “the final vote totals reported to the Secretary of State is wrong”. As noted above, if realized, this hazard could change the election result.

2.4.2. Tying the events and hazard to the process definition. To automatically generate a fault tree from a Little-JIL process definition and a given hazard, the FTA tool requires the process definition (including the coordination diagram and artifact and agent specifications), a pointer to the root step in the process, and the hazard definition. The only events in the generated Fault Tree are incorrect execution of steps in the process definition. The FTA tool requires a hazard to be defined as an artifact being wrong when input to or output from a step. Thus, the hazard “the final vote totals reported to the Secretary of State is wrong” is defined in the tool as:

Artifact “finalTallies” to “report vote totals to Secretary of State” is wrong., and it is shown as the root of a tree of incorrectly executed process steps.

2.4.3. Deriving the fault tree. The fault tree is automatically derived from the process definition by tracing process artifact flow back through the steps of the process to determine where artifacts may have been modified or created incorrectly. These incorrect artifacts may have been generated by the erroneous execution of a step or because a step may have failed to identify an artifact as being incorrect (e.g., when a step should have thrown an exception, but did not). A complete fault tree for the hazard “the final vote totals reported to the Secretary of State is wrong” is shown in Figure 8 for the simplified count votes subprocess shown in Figure 3 to give the reader an intuitive sense

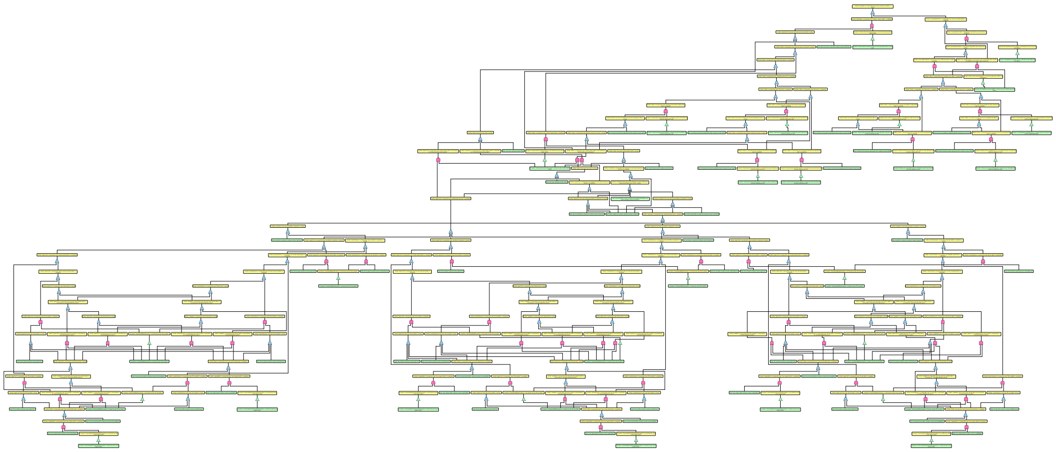


Fig. 8. The fault tree automatically derived for the hazard specification "the final vote totals tally reported to the Secretary of State is wrong."

of the size and structure of a typical fault tree derived from a complex process. The fault tree presented here is actually not a tree, but an optimized directed acyclic graph (DAG), where repeated nodes have been consolidated to reduce the size of the original structure, in this case by a factor of more than three. Before optimization, there were 1194 events and 1106 gates in the fault tree. After optimization, the DAG contains 735 events and 659 gates. From this example, it is clear why attempting to construct such structures by hand quickly becomes intractable.

2.4.4. Calculating Minimal Cut Sets. Once a fault tree has been automatically derived from the Little-JIL process definition, it could be manually inspected to identify different scenarios that could cause the hazard to occur by identifying paths containing combinations of event literals that lead back to the root. Given that the optimized fault tree generated for this hazard contains hundreds of nodes, however, the ability to automate the calculation of the MCSs, and thus give the analyst guidance about where to look for vulnerabilities, becomes particularly valuable.

MCSs can be automatically calculated from the fault tree by using standard Boolean algebra techniques to represent and simplify flow equations, where the root node, the hazard, is equal to a disjunction of conjunctive clauses of event literals. Given this equation, the hazard could occur only if one or more of the conjunctive clauses evaluates to $true$, which can only happen if all the terms in a conjunctive clause evaluate to $true$, indicating all participating event literals in that clause occur. Therefore each conjunctive clause forms a cut set. The substitution for the simple fault tree in Figure 7 therefore proceeds as follows:

$$\begin{aligned} A &= B + C \\ &= D * E + \neg F \\ &= (G + H) * E + \neg F \\ &= G * E + H * E + \neg F \end{aligned}$$

Thus the fault tree has 3 cut sets: $\{G, E\}$, $\{H, E\}$, and $\{\neg F\}$.

MCSs are then obtained by removing events until non-minimal cut sets become minimal. Applying this to the fault tree shown in Figure 8 for the Yolo County election process and the hazard "the final vote totals reported to the Secretary of State is wrong" results in 125 MCSs: 2 MCSs of size 2, 23 of size 3, 58 of size 4, 30 of size 5, and 12 of size 6.

2.4.5. Leveraging the results to alleviate process vulnerabilities . The fault tree provides a detailed description of the combinations of events that can lead to the occurrence of the hazard. Certain traces through the fault tree structure, however, indicate more likely scenarios than others. By examining the MCSs, analysts can focus on those scenarios that seem likely to occur or are likely to have a large impact. In this section, we examine a few of the smaller MCSs.

One example MCS for the fault tree is:

MCS-1 (see Figure 9)

(1) Step "increment and announce appropriate tally" produces wrong "tallies",
(2) Exception "VoteCountInconsistentException" is NOT thrown by step "increment and announce appropriate tally",
(3) Exception "VoteCountInconsistentException" is NOT thrown by step "perform random audit"

In this case, the tallies produced by "count votes" are incorrect because the steps "increment and announce appropriate tally" and "perform random audit" are not carried out correctly since neither step recognized a VoteCountInconsistentException. Figure 9 shows only a portion of the fault tree that contains the nodes and edges that are relevant to this MCS. Such a targeted fault tree, which we call a *mini fault tree*, can be automatically generated for any selected MCS by analyzing the original high-level fault tree and extracting partial paths or scenarios corresponding to the MCS of interest.

MCS-1 demonstrates the impact that election officials could have on the election results by performing all three of these three steps incorrectly. Moreover, this suggests that a single election official could successfully attack this election process if that official were assigned to perform all three steps. This suggests that the security and robustness of the process might be improved by putting in place checks to assure that different election officials are always assigned to these steps.

Another example MCS for the fault tree is:

MCS-2 (see Figure 10)

(1) Step "scan votes" produces wrong "tallies",
(2) Exception "VoteCountInconsistentException" is NOT thrown by step "perform random audit"

The tallies produced by "count votes" are incorrect as a result of the step "perform random audit" not being carried out correctly. After receiving incorrect tallies from the "scan votes" step, the "perform random audit" step does not recognize a VoteCountInconsistentException. So the audit fails to catch the incorrect result. This MCS suggests another way in which a single election official might attack the process unless the process is modified to assure that no single official could ever be assigned to both of these steps.

The third example MCS demonstrates the impact an optical scanner could have on the election results. Since the scanner is dealing with entire batches of ballots, incorrect performance of the scanner could have a very large impact. The MCS for this fault tree is:

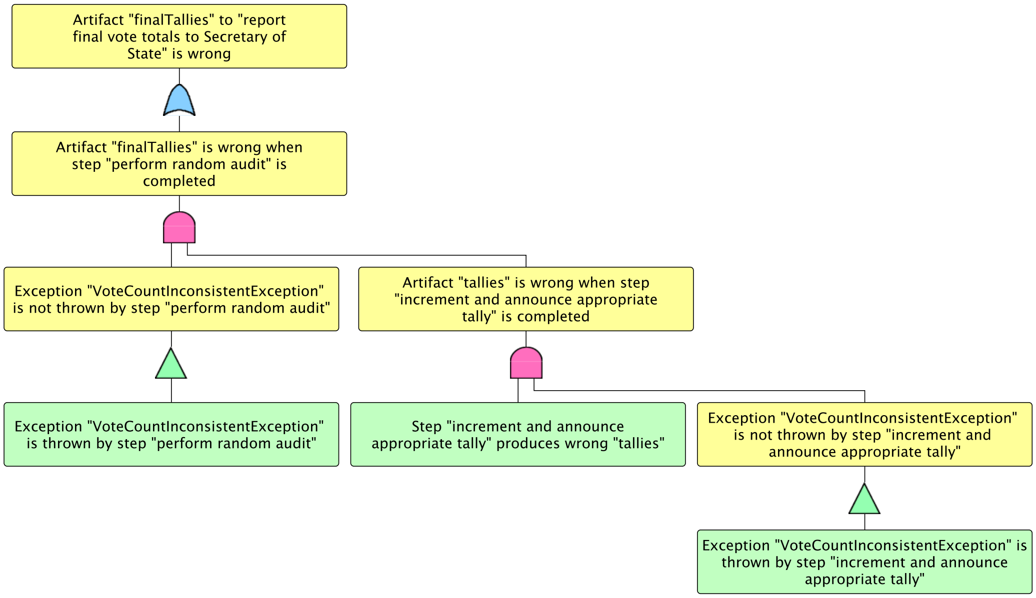


Fig. 9. MCS-1's mini fault tree

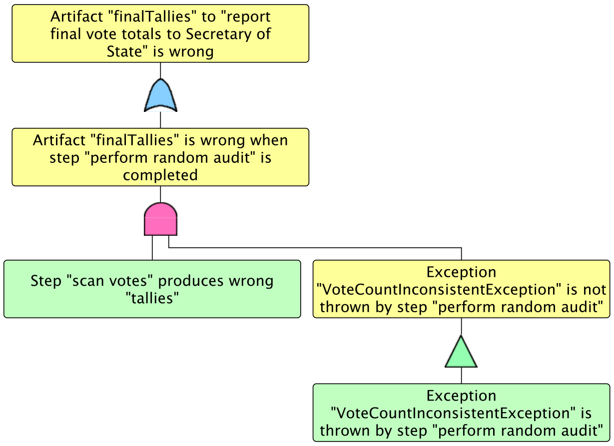


Fig. 10. MCS-2's mini fault tree

MCS-3 (See Figure 11)

(1) Step "fill out ballot" produces wrong "paperTrail",
(2) Exception "VoterSpoiledBallotException" is NOT thrown by step "fill out ballot",
(3) Exception "VoteCountInconsistentException" is NOT thrown by step "confirm tallies match",
(4) Exception "VoteCountInconsistentException" is NOT throw by step "perform random audit"

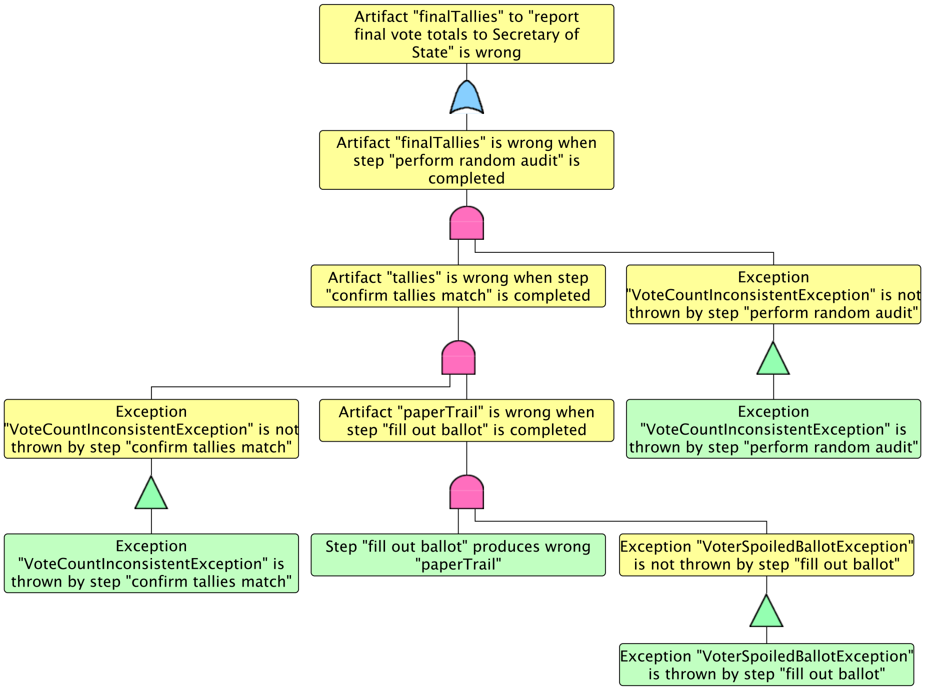


Fig. 11. MCS-3's mini fault tree

In this case, the voter chooses the electronic voting option, and the step “fill out ballot” fails to produce the correct paper trail. In addition, no exception is thrown at this step nor at the later steps, “confirm tallies match” and “perform random audit”. Such a scenario results in the wrong totalTallies being output from the step “count votes,” and then input to “report final vote totals to Secretary of State”.

This MCS example demonstrates a vulnerability introduced by electronic voting, and suggests the desirability of introducing some kind of redundant checking to improve the robustness of this process. Indeed, the event *Step “fill out ballot” produces wrong “paperTrail”* appears in 18 out of 125 MCSs of the fault tree. Thus, it seems important to bring the significance of the possible failure of this step to the attention of election officials so that they can try either to minimize the probability of the event's occurrence, or put in place redundant checking.

These examples have shown how MCSs can help a process developer identify areas of the process definition that may be problematic. These areas can then be further explored with additional hazard specifications. The MCSs presented here particularly highlight the need for election processes to be more robust with respect to possible incorrect performance, either intentional or unintentional, by the process performers. For example, if an election official unintentionally announces the tally incorrectly once or twice, that might not make a big difference to the final outcome of the election. But if an official maliciously misperforms this step continually, and in collusion with the person doing the random audit, the election results might well be compromised. Similarly, if a defective scanner continually produces results that are not checked redundantly, the final election results could be changed significantly.

3. RESULTS

For the election process described here, the process definition was first elicited by interviewing California election officials, studying the California election code, and by first-hand observations. The resulting process definitions were then validated with manual reviews performed by the election officials along with both model checking and fault tree analysis.

These efforts produced a full process definition has 98 steps: 71 step declarations and 27 references to previously defined steps. The agents include election officials, voters, optical scanners, voting machines, and precincts. The control flow often involves iteration, concurrency and exceptional situations. There are eight exceptions defined for this process and twelve of the leaf steps (one third of the leaf steps) may throw an exception that then must be handled appropriately. For the full process definition, we ran the model checking and fault tree analysis tools that are implemented in Java on a laptop with two 2.5 GHz processors and 8 GB of memory. The laptop was using a UNIX-based operating system (OS X Yosemite Version 10.10.5) and Java 7 (Version 1.7.0_80-b15).

For the model checking, we elicited high-level requirements from the California election code. We applied the FLAVERS model checker to the full process definition to verify six high-level requirements, represented by the nine lower-level properties shown in Figure 4. Each property had one or two events and three or four states (counting the violation state). As is often the case with model checking, the verification of each property typically required several attempts where refinement of the process definition or property was needed before the process definition was shown to be consistent with the property for all possible executions. The simpler properties typically required two attempts while the paired properties required about half a dozen. Initially we often needed to add detail to the process definition to capture important aspects of the process. Later attempts typically required refinements to the properties to capture scope and repeatability aspects accurately. Often we needed to confer with the election officials to determine precisely what the actual requirements should be. In these cases, the property or process definition was often too restrictive, not fully representing all allowed behaviors when unusual special cases are taken into account. After making these improvements to the process definition and to the properties, FLAVERS reported that the process definition satisfies each property. For each property, the space needed was less than 64 MB and the time needed was at most six seconds. Although, we did not discover any problems in the actual process, this exercise had several benefits. The discussion with the election officials about the details of the process and the properties led to a better understanding of the process both by the analysts, and also by the election officials themselves. Importantly, it led to a more complete and accurate process definition, which was especially important because this definition was then used as the basis for further security and vulnerability analyses.

After the model checking was successfully completed, we then applied our fault tree generator to the full process definition. For the hazard “the final vote totals reported to the Secretary of State is wrong,” the unoptimized fault tree we generated has 1194 events and 1106 gates, while the optimized fault tree has 735 events and 659 gates. The generator needed less than 64 MB and took a little under a minute. We then applied the fault tree analyzer to the generated fault tree to compute its minimal cut sets. The analyzer found 125 minimal cut sets with sizes ranging from two to six events for this hazard. The fault tree analyzer needed less than 64 MB and took less than one second. Observe that this hazard demonstrates some of the process vulnerabilities that electronic voting introduces. The event *step “fill out ballot” produces wrong “paperTrail”* appears in 18 out of 125 MCSs of the fault tree. Bringing this failure to the attention of election officials will enable them to try to mitigate the risks created by over-reliance on the correctness of the execution of this step.

When used together, model checking and FTA are complementary approaches. Given an MCS with a small number of events having reasonably high probabilities, model checking could be used to identify process execution paths on which all those events occur, providing domain experts with insight into how to modify the process to increase its robustness. Applying model checking to the modified process definition using the original properties could then be used to check whether the modifications had introduced property violations, and FTA would determine whether these modifications had removed the MCS or additional paths need to be considered.

Choosing how to change the process definition requires the input of domain experts. They determine how to respond to errors discovered using model checking. For the election process this involved how to change the process definition or the properties to reflect the real process and actual properties. The domain experts also identified the MCSs that they deem to be of highest priority. This usually begins with the identification of several small candidate MCSs with steps that are often performed incorrectly in the real-world process and would therefore benefit the most from risk mitigation, such as extra redundancy. Domain experts can also provide insight into steps that, in their experience, have a lower chance of being carried out erroneously, or are performed so infrequently that added redundancy would have much less impact than would added redundancy at steps that are performed more frequently.

Once these analyses identify problems, process modifications are introduced to try to address these problems. These modifications are usually proposed by the domain experts through discussions of the process definition to ensure that the proposed modifications are reasonable, would not interfere unacceptably with performance of the real-world process, and would be relatively easy to make. Reanalyzing the modified process definition ensures that it successfully corrects the problems without introducing more problematic vulnerabilities in other parts of the process.

4. RELATED WORK

In our work, we have applied process definition, model checking, and fault-tree analysis to election processes in order to test, understand, and improve the process with respect to security and other problems.

4.1. Elections and Security

The widespread introduction of electronic voting machines in the early-to-mid 2000s was originally intended to make the process of casting and counting votes faster and less costly while also eliminating ambiguous markings of ballots. But it introduced a new set of concerns about the accuracy, privacy, and security of elections.

Electronic voting systems are computers, and computers have security vulnerabilities. Realizing this, the Federal Election Commission (FEC) and the Election Assistance Commission (EAC) developed a series of standards that electronic devices should meet, the latest of which is the 2005 Voluntary Voting System Guidelines (VVSG) set of standards[6] [Election Assistance Commission 2005; Federal Election Commission 1990; 2002]. Many states require that any voting systems used in their elections meet these standards, so validation and testing of such machines is critical. Mercuri and Neumann [Mercuri and Neumann 2003] give an overview of how electronic voting systems can be verified and emphasize the importance of a verifiable paper trail, and Saltman [Saltman 2003] outlines different techniques for performing auditing to improve public confidence for both ballot and non-artifactual systems. The EAC is developing

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[6] A new standard [TGDC 2007] has been developed but not yet adopted.

a set of Election Management Guidelines (EMG) to complement the technical standards for voting equipment [Election Assistance Commission 2010]. These standards and guidelines, however, focus only on the electronic voting system itself.

The election security community has focused on the electronic voting system vulnerabilities. Examination of vendor source code [Kohno et al. 2004; Yasinsac et al. 2007; Office of the California Secretary of State 2007; Brunner 2007] considered ways an attacker could compromise such systems, or make them produce inaccurate results. Red-team testing, in which testers played the role of attackers, has found ways to compromise these systems [RABA Innovative Solution Cell (RiSC) 2004; Proebstel et al. 2007; Office of the California Secretary of State 2007; Brunner 2007; Springall et al. 2014; Wolchok et al. 2012]. Indeed, studies have found that these systems "failed to adopt, implement and follow industry standard best practices" [Brunner 2007] and that their security mechanisms were "inadequate to ensure the accuracy and integrity of the election results" [Bishop 2007; Office of the California Secretary of State 2007]. This has caused many states to re-evaluate electronic voting systems and *how* those systems are to be handled and used before, during, and after an election.

Other work has focused on the requirements that an election must meet, such as privacy, anonymity, accessibility, and ballot design [Brennan Center Task Force on Voting System Security 2006; Lambrinoudakis et al. 2003; Mitrou et al. 2003]. Some, such as Chaum, et al, have studied the Scantegrity voting system [Chaum et al. 2008], to enable voters to verify that their votes have been counted correctly without being able to prove to others how they voted, thereby preventing vote selling. The Scantegrity work focuses on the cryptographic protocols and system requirements that provide these properties.

Perhaps surprisingly, little published work has focused on how elections themselves are conducted, even though proper implementation of policies and procedures designed to conduct elections are critical to their success [Barr et al. 2007; Simidchieva et al. 2008]. This aspect of elections raises critical security and privacy concerns. For example, consider an election worker misplacing marked but uncounted ballots. The results of the election might be different were those ballots counted. Worse, suppose a malicious election official alters ballots to favor a particular candidate. Such an attack, called an *insider attack*, may well alter the results of the election. Insider attacks are of great concern in other realms as well, and are a topic of active research in the security community [Bishop et al. 2008; Pfleeger et al. 2010; Hunker and Probst 2011; Probst et al. 2010; Bishop et al. 2014; Sarkar et al. 2014]. Other issues, such as seemingly benign disruptions in the proper running of a polling place or a failure to follow proper procedures could also compromise the results of an election by preventing voters from casting their votes in a timely manner. Even maintaining both security and privacy simultaneously may sometimes create conflicts [Peisert et al. 2009].

Attacks against a *process*, such as those identified above, are often more effective than attacks against the electronic voting systems because they focus on people. Humans make mistakes, have different competency levels, and often have widely varying notions of security and privacy of elections [Hall et al. 2012]. Similarly, the processes that election officials design to carry out election tasks also have vulnerabilities that may cause the tasks not to be completed, or be completed incorrectly. There has been little formal study of election *processes* as opposed to protocols or electronic voting systems. Analyzing the process of how elections are conducted may uncover weaknesses, or potential weaknesses, that could result in compromising the election without compromising any of the electronic systems involved in the election. Further, it may be unclear how system errors or failures impact the results of an election. Thus, studying such processes should help build an understanding of their security, integrity, and accuracy. Our work undertakes such a study.

4.2. Process definition and improvement

The security assurance of an electronic voting system does not provide assurance of the security or accuracy of an election [Barr et al. 2007] in which it is used, because the system is not intended to enforce all of the election process requirements. For example, the requirement that eligible voters can vote at most once is typically enforced by a process external to the electronic voting system. Studying the effectiveness of a process in satisfying such a requirement falls within the area of process modeling and analysis, which “focuses [on] interacting behaviors among agents, regardless of whether a computer is involved in the transactions” [Curtis et al. 1992]. Process analysis is most effective when applied to process models that are rigorously defined, and relatively complete and detailed.

Raunak et al. apply process definition and analysis to election processes to determine whether fraudulent behavior can result in incorrect election results [Raunak et al. 2006]. Simidchieva et al. extend this approach to determine whether an election process definition meets selected requirements [Simidchieva et al. 2008], and then extend the approach further to improve the robustness of election processes using fault-tree analysis [Simidchieva et al. 2010].

Audit procedures have been a fertile field for the application of process-oriented techniques. Antonyan et al. use AccuVote Optical Scan systems and a generic election process model to study how additional auditing processes may improve the integrity of elections [Antonyan et al. 2009]. The authors focus on how different election processes can affect the ability to prevent or detect attacks on the underlying election systems. Our work focuses on how the election processes themselves may fail. Hall et. al. examine audit processes, specifically focusing on post-election audits [Hall 2008; Hall et al. 2009]. Like our work, the authors examine the processes for a specific county and use iterative process improvement before generalizing their approach. Our work, however, is not focused on audit processes, but on automatically finding errors and vulnerabilities in specific election processes.

4.3. Model Checking

The history of using model checking techniques in security goes back at least to Lowe’s application of the FDR model checker to find a subtle attack on the Needham-Schroeder authentication protocol [Lowe 1996]. While much of this work has focused on the analysis of protocols, other work has used model checking to analyze information flow (e.g., [Dimitrova et al. 2012]) or verify access control policies (e.g., [Wolter et al. 2009]). A number of researchers have used model checking techniques to generate possible attacks. For instance, Sheyner et al. [Sheyner et al. 2002a] constructed atomic attacks, such as buffer overflows, and modeled a computer network as a finite state machine with transitions corresponding to the atomic attacks. They then used model checking to generate an attack graph in which any path from the initial system state to a leaf node represents a sequence of atomic attacks that allow an intruder to violate a specified security property (such as “no intruder can achieve root access on host A”).

Other researchers have used model checking techniques to analyze the aspects of the security of business processes (e.g., [Armando and Ponta 2009]. A few papers have applied model checking approaches to election processes, including [Raunak et al. 2006]. Closest to our approach is the work of Weldemariam et al. [Weldemariam and Villafiorita 2008; Villafiorita et al. 2009]. In this work, the authors modeled processes that incorporated best practice, defining how critical assets are to be managed, elaborated, and transformed, and then inject threats—actions that alter some features of an asset or allow some actors additional privileges. The extended model is then encoded for the NuSMV model checker and a property (such as “poll officers will never receive an altered version of the election software that can be run on the machines”) is checked. Any generated counterexample provides an example attack. Our approach differs from theirs in our use of FTAs to devise more structured and detailed attack plans given a hazard.

Recently, Phan et al. has built on the work described here to use fault-tree analysis to find process vulnerabilities and then build attack processes exploiting them. This work uses model checking to evaluate the robustness of the process definition to the derived attack processes [Phan et al. 2012].

4.4. Fault-Tree Analysis

Numerous safety-critical industries, including the aerospace, nuclear power, and automotive industries, use FTA. Brooke et al. demonstrate that fault trees may also be used to analyze security-critical systems [Brooke and Paige 2003]. Helmer et al. used augmented Software Fault Trees (SFTs), attack trees with temporal order, to model intrusions [Helmer et al. 2002]. In their models, the root node represents the intrusion and an MCS contains events to be monitored to detect intrusions. Zhang et al. use fault trees for vulnerability evaluation [Zhang et al. 2005]. Rushdi and Ba-Rukab apply fault trees to measure a system’s exposure to a vulnerability [Rushdi and Ba-rukab 2005]. Yee discusses how safety cases, a construct similar to fault trees, may be used to increase confidence in voting systems [Yee 2007].

Leveson et al. [Leveson et al. 1991] proposed using fault trees to guide analysts in identifying errors that cause Ada programs to produce incorrect outputs. The incorrect output is represented as the hazard. Templates, one for each kind of Ada statement, are used to elaborate intermediate events to construct the full fault tree. Friedman developed a template-based tool to construct fault trees from a Pascal program and a software-caused hazard [Friedman 1993]. Pai and Bechta Dugan [Pai and Bechta Dugan 2002] showed an algorithm to automatically derive fault trees from UML models. Our approach also uses language-based templates, but the analysis is based on models that incorporate the more elaborate semantics needed to more completely and faithfully represent the variability encountered in real life processes.

Like fault trees, attack trees are hierarchical logic diagrams in which one event is represented as a logical combination of lower-level events [Schneier 1999]. They are used to model the different paths an attacker may take to reach an objective. Moore et al. used attack trees to model attacks and document them [Moore et al. 2001]. Lazarus created a catalog of election attacks in the form of a single attack tree, attempting to provide a threat model and a quantitative threat evaluation approach intended to be reusable across different jurisdictions [Lazarus 2010]. Attack trees have also been used in penetration testing [McDermott 2001], in identifying insider attacks [Ray and Poolsapassit 2005], and for forensics [Bishop et al. 2009; Peisert 2007; Peisert et al. 2007; Poolsapassit and Ray 2007]. Nai Fovino et al. combine fault trees and attack trees for quantitative security risk assessment [Nai Fovino et al. 2009]. Attack graphs [Phillips and Swiler 1999; Sheyner et al. 2002b] are similar to attack trees, but may be cyclical and do not use logic operators between nodes.

Attack tree analysis generally assumes that faults arise from malicious intent. Since we do not ascribe an intent to how these faults arise, we focus on FTA in this paper. As fault trees and attack trees are structurally equivalent, the analyses described here for fault trees would apply equally well to attack trees.

5. CONCLUSION

This paper presents a systematic approach for evaluating the security and accuracy of processes, especially those involving human performers. We describe and illustrate the application of this approach by defining and analyzing an election process. Using election code policies and considerable guidance from election officials, we developed a definition of how an election is conducted. We expressed our definition in Little-JIL, and then iteratively refined the definition with the help of domain experts. We performed model checking and FTA on this definition and identified errors and vulnerabilities that suggest problems in the election process. The two analysis techniques provided powerfully complementary ways to identify process defects and vulnerabilities. Taking the analysis results back to the domain experts, we worked with them on how to modify the process to remove these errors and reduce vulnerabilities through an iterative improvement cycle of analysis and restructuring.

The approach can also be used to study hypothetical scenarios, such as the effects of changes to requirements. For example, suppose a law requires that all ballots be counted at the precinct, rather than allowing them to be counted at Election Central (as in our definition). What must change in the new process to ensure that it still satisfies the other requirements and does not introduce new vulnerabilities? By generating a definition of the new process and applying our analysis techniques, we are able to identify potential problems and address them in advance, rather than waiting until the problems occur in practice, when it may be too late to remedy them effectively.

Our experience with this approach suggests that it can be used on a wide range of processes to systematically address security concerns, especially for processes that coordinate technologies and human activity.

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