Efficient Runtime Enforcement Techniques for Policy Weaving *

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Abstract

Policy weaving is a program-transformation method that rewrites a program so that it is guaranteed to be safe with respect to a stateful security policy. It utilizes (i) static analysis to identify points in the program at which policy violations might occur, and (ii) runtime checks inserted at such points to monitor policy state and prevent violations from occurring. The power and flexibility of policy weaving arises from its ability to blend the best aspects of the static and runtime components. Therefore, a successful instantiation requires careful balance and coordination between the two.

In this paper, we examine the strategy of using a combination of *transaction-based introspection* and *callsite indirection* to implement runtime enforcement in a policy-weaving system. In particular,

- Transaction-based introspection allows the state resulting from the execution of a statement to be examined and, if the policy would be violated, suppressed.
- Callsite indirection serves as a light-weight runtime analysis that can recognize and instrument dynamically-generated code that is not available to the static analysis.
- These techniques can be implemented via static rewriting so that all possible program executions are protected against policy violations.

We describe our implementation of transaction-based introspection and callsite indirection for policy weaving, and report experimental results that show the viability of the approach in the context of real-world JavaScript programs running in a browser.

1. Introduction

Policy weaving for security-policy enforcement is a program-rewriting approach oriented towards striking a balance between static and runtime analysis techniques [7, 8]. It is

- *Sound*, meaning that all program traces that violate the policy are prevented.
- *Transparent*, meaning that the rewritten program has the same semantics as the original program, modulo policy violations.

The policy-weaving approach is motivated by the acknowledgment that in nontrivial scenarios, static analysis alone cannot prove that a program adheres to a policy [4, 10]. In contrast, runtime analyses such as inlined reference monitoring (IRM) [6, 15, 17] can soundly evaluate concrete states at runtime, but at the cost of degraded performance. To address these limitations, policy weaving is a hybrid approach that (i) attempts to statically identify sections of the program that can be proven safe, and (ii) rewrites the program to include runtime checks at locations where policy state may be affected. This approach, while harnessing the best of both worlds, also gives rise to a new challenge: that of coordinating the interoperability of—and managing the trade-offs between—the static and runtime analyses. Our goal in this paper is to present and evaluate a runtime policy-enforcement mechanism that is well-suited to be the target of a static weaving algorithm.

Specifically, we explore and demonstrate the utility of *transactional introspection* applied to a program through static rewriting of source code, and an additional *callsite-indirection* transformation to enable just-in-time sandboxing of code that is generated at runtime. We describe the resulting end-to-end policy-enforcement system, and present experimental data that shows the viability of this approach when applied to real-world JavaScript applications in a browser context.

We find that transactions provides a straightforward and powerful tool for securing untrusted code in the manner required by policy weaving. Transactions are a form of speculative execution, meaning that the effects of an execution can be computed and examined prior to the application of those effects to the execution environment. This ability to *introspect* on actions without committing their effects is necessary when dealing with programs that perform irrevocable actions, such as the initiation of an HTTP request. Because rollback of communication and other I/O actions is not possible in general, a security-policy-enforcement mechanism that aims to mediate such actions needs the ability to recognize and potentially suppress such events prior to their occurrence, rather than reacting after the actions have occurred. The transactions we describe provide this capability to "peek into the future" and take preventive action to avoid policy violations.

We also extend the methodology of policy weaving to incorporate the use of *callsite indirection* to dynamically apply transactional semantics to code that is dynamically generated. This strategy serves two purposes.

- The static analysis is freed from the generally impossible task of precisely modeling all possible executions of dynamically-generated code.
- Callsite indirection serves as a light-weight but special-purpose alternative to the use of hard-coded transactions.

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Transactional-introspection schemes have been studied in other papers in the security literature [2, 5, 9, 14], and various difficulties have been identified:

- Performance overhead of speculative execution can be prohibitive [3, 11].
- Correct placement of transactional instrumentation is a nontrivial task [9, 14, 16].
- Implementation of introspection logic to recognize and prevent policy violations can be error-prone [14].

We address each of these concerns via the formulation described in this paper. The complexity of both manually placing individual transactions and constructing introspection code is replaced by the requirement to formulate an explicit security policy as an automaton. A security-policy automaton allows a programmer to state his intentions and goals explicitly in a typically small and self-contained artifact. Moreover, we find that the use of a transactional paradigm serves as a natural and intuitive runtime enforcement platform for policy weaving, and produces substantial benefits in terms of performance and flexibility when compared to other enforcement mechanisms.

To summarize, our contributions are:

- We show how a policy-weaving algorithm can be used to automatically and soundly weave transactional instrumentation into a program to enforce security invariants.
- We describe the automatic translation of a security-policy specification into introspection code, which substantially reduces the number of opportunities for implementation errors.
- We describe callsite indirection, a program-transformation technique that, in conjunction with transactions applied directly by policy weaving, ensures that the policy is also applied to all dynamically generated code.
- We present JAMScript, a general-purpose but simple extension of the JavaScript language that implements transactional semantics with properties suited to security-policy enforcement.
- We present experimental results that demonstrate that our approach performs well compared to manual placement of transactions and to other types of enforcement mechanisms that could be targeted by a policy-weaving algorithm.

Organization: §2 presents a specification of the program-rewriting algorithm, the semantics of transactional introspection, the mechanism of callsite indirection, and how these techniques conceptually fit together. §3 discusses implementation challenges encountered when applying our approach to JavaScript, and the solutions we devised. §4 evaluates the performance of JAMScript on a set of real-world applications. §5 examines related work and motivates various design choices that differ from other systems that share the same goals. §6 concludes.

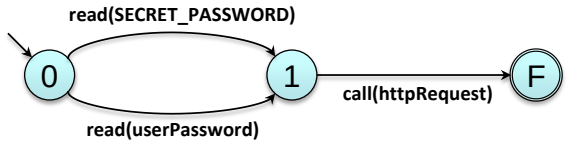
2. Technical Overview

In this section, we examine the properties that a runtime enforcement mechanism must satisfy to meet the requirements of a policy-weaving system. We identify transactional introspection and callsite indirection as two key primitives of an enforcement strategy that meet these conditions. We then incorporate this combined mechanism as the targeted enforcement platform used by a language-independent program-rewriting algorithm.

2.1 Enforcement Primitives

Three principles to be considered when choosing a runtime enforcement mechanism are as follows:

- Runtime overhead induced by the mechanism should be minimal to maintain an acceptable user experience.




```
0,1: read(SECRET_PASSWORD)
0,1: read(userPassword)
1,F: call(httpRequest)
```

Figure 1: Security-policy automaton and textual representation specifying a set of disallowed traces: "read a password value and subsequently make a network request." The identifier `F` is reserved for the final state.

- The mechanism should precisely evaluate the policy at runtime, without spuriously blocking traces.
- The mechanism should be general-purpose, flexible, and straightforward to apply.

Because the latter two concerns are directly at odds with each other, and both may indirectly hinder the first goal of acceptable runtime performance, it may be difficult or impossible to arrive at an ideal solution that satisfies all three principles simultaneously. Our thesis is that utilizing a policy-weaving strategy can, in effect, bring the enforcement mechanism closer to achieving each of these principles, compared to manually placing instrumentation or relying on an automated modular partitioning strategy as suggested in other work [5, 14].

When used with an enforcement mechanism based on transactional introspection, as advocated in this paper, policy weaving produces the following benefits:

- Fewer program statements are run within transactions, thereby reducing the performance overhead of enforcement (as shown in §4).
- The policy automaton provided as input to the static analysis is automatically translated to introspection code that implements policy monitoring and enforcement at runtime. Examples are described in §3, and the benefits are quantified in §4.
- By placing transactions via static rewriting, policy weaving can ensure certain restrictions on the semantics of introspection, such as sequential execution and a lack of side-effects. (We say more about these benefits later in this section.)

We now introduce an example program and a security policy that we would like to enforce via transactional introspection and callsite indirection. The policy shown in Fig. 1 asserts that network communication should not occur after certain kinds of accesses to local information. The program shown in Fig. 2(a) may have behaviors that violate the policy. The use of a conservative static analysis allows the rewritten program, shown in Fig. 2(b), to have the following properties:

- Any statement that potentially affects the policy state is enclosed in a transaction block, indicated by the keyword `introspect`.
- An *introspector* function is passed as the parameter to each transaction block; these functions are defined in Fig. 3(a).
- Each introspector implements the runtime evaluation of a unique combination of policy predicates, and they each have read and write access to the global `policyStates` array.

This rewriting results in the following runtime behavior.

- During execution of the transaction block, all *actions* (reads, writes, and calls) are recorded sequentially, and the effects of writes are postponed.
- When the closing brace of the transaction block is reached, the introspector is invoked with a *transaction-object* argu-

```
SECRET_PASSWORD = "supersecret";
user_pwd = "";
config = {};

fun getUserInput(prompt) {
  stdout.write(prompt + ": ");
  input = stdin.readLine();
  return input;
}

fun getConfig() {
  param = getUserInput("Enter parameter");
  url = "http://config.example.com?" + param;
  configString = httpRequest(url);
  configValue = eval(configString);
  config[param] = configValue;
}

while (true) {
  opt = getUserInput("Enter option");
  if (opt == "config") {
    getConfig();
  } else if (opt == "run") {
    user_pwd = getUserInput("Enter password");
    match = SECRET_PASSWORD == user_pwd
    if (match) {
      break;
    } else {
      print("Wrong password!");
    }
  } else if (opt == "quit") {
    exit;
  }
}

// The rest of the program...
```

(a) Original code for a program intended to read configuration data from an untrusted server and subsequently perform some computation guarded by a secret password. It is vulnerable to code injection by the untrusted server and accidental password leakage by the user.

```
// ...
fun getConfig() {
  param = getUserInput("Enter parameter");
  url = "http://config.example.com?" + param;
  introspect(policyTransition1_F) {
    configString = httpRequest(url);
  }
  f = indirect(eval, [configString]);
  configValue = f();
  config[param] = configValue;
}
while (true) {
  // ...
  } else if (opt == "run") {
    user_pwd = getUserInput("Enter password");
    introspect(policyTransition0_1) {
      match = SECRET_PASSWORD == user_pwd
    }
    if (match) {
      break;
    } else {
      print("Wrong password!");
    }
  } else if (opt == "quit") {
  // ...
}
```

(b) Secured code. The gray highlighting indicates code that was introduced by the rewriting step. Some unchanged sections are elided to save space. `introspect` is a control-flow keyword parameterized by a function that contains the introspection logic. `indirect` is a function that wraps the `configString` argument within an `introspect` block, and returns a reference to the `eval` function bound to the instrumented argument. Fig. 3(a) shows the implementation of the introspector functions and Fig. 3(b), shows `indirect`.

Figure 2: (a) A program that may violate the policy depicted in Fig. 1, and (b) a secured version.

```
policyStates = [0];

fun policyTransition0_1(tx) {
  rs = tx.getReadSequence();
  for (r in rs) {
    if (policyStates.contains(0)
      && (r.variable == "SECRET_PASSWORD"
      || r.variable == "user_pwd")) {
        policyStates.append(1);
    }
  }
  tx.commit();
}

fun policyTransition1_F(tx) {
  cs = tx.getCallSequence();
  for (c in cs) {
    if (policyStates.contains(1)
      && c.target == httpRequest) {
        throw new ViolationException();
    }
  }
  tx.commit();
}
```

(a) Functions that perform introspection on the actions that occur within an `introspect` block. The parameter `tx` is an object that holds information about the reads, writes, and calls that have been recorded during transaction execution. A collection of policy states reached during the currect global execution is maintained in the `policyState` list, and an exception is thrown when a policy violation is detected.

```
fun policyTransitionAll(tx) {
  as = tx.getActionSequence();
  for (a in as) {
    if (a.type == READ && policyStates.contains(0)
      && (r.variable == "SECRET_PASSWORD"
      || r.variable == "user_pwd")) {
        policyStates.append(1);
    }
    if (a.type == CALL && policyStates.contains(1)
      && c.target == httpRequest) {
        throw new ViolationException();
    }
  }
  tx.commit();
}

fun indirect(f, args) {
  if (f == eval && args.length > 0) {
    args[0] = "introspect(policyTransitionAll) { "
      + args[0] + " }";
  }
  return f.bind(args);
}
```

(b) Implementation of the `indirect` function that (i) wraps dynamically-generated code within an `introspect` block as needed, and (ii) returns the input function bound to its arguments. `indirect` is a general function constructed to handle the interpretive constructs of a language, independent of the specific program being analyzed. The `policyTransitionAll` function is also shown; it combines the logic from the two functions shown in (a), and serves as the introspector for the instrumentation that is constructed by `indirect`.

Figure 3: Instrumentation functions that monitor program actions at runtime. See Fig. 2 for their corresponding uses within the analyzed program. We show later in §3 an example of how the references to these function—and the global references used within the functions—can be protected from manipulation by the program being analyzed.

```
1  Introspect(T_s, Actions, Reached):
   Data: T_s: sequence of policy transitions potentially induced by the
         introspected statement(s)
         Actions: sequence of recorded actions
         Reached: set of policy states reached during the current execution
   Result: Terminate execution if a policy violation is detected, or update
           Reached and commit each a ∈ Actions otherwise.
   /* Examine each action in the order it was recorded        */
2  foreach a ∈ Actions do
       /* Evaluate each policy transition                     */
3      foreach (φ_i, φ, φ_j) ∈ T_s do
           /* If the policy-transition prestate has been
              reached and the poststate has not               */
4          if φ_i ∈ Reached ∧ φ_j ∉ Reached then
               /* If the policy-transition predicate holds   */
5              if a ⊨ φ then
                   /* If the poststate is final              */
6                  if φ_j is final then
7                      Throw an exception and quit.
8                  else
9                      Reached ← Reached ∪ {φ_j}
10     if a can affect the program state then
11         Commit a.
```

Algorithm 1: Introspect specifies the logic that evaluates an action sequence, and either commits or suppresses the effects. The condition $a \models \varphi$ is satisfied if action a makes predicate φ true.

```
1  RewriteIntrospect(P, Ψ_Φ):
   Data: P: source code of the program being analyzed
         Ψ_Φ = {(s_0, τ_0), ..., (s_m, τ_n)}: a policy-violating witness
   Result: P′: a rewritten program that prevents Ψ_Φ
2  Let interp be a policy-transition symbol indicating an interpretive construct
3  foreach (s_i, τ_j) ∈ Ψ_Φ do
4      if τ_j = interp then
5          Add s_i to a set of callsite statements to be processed later by Alg. 3
6      else
7          Let T_i be the set of policy transitions for which s_i is already
             instrumented
8          T_prev ← T_i
9          T_i ← T_prev ∪ {τ_j}
10         Generate or retrieve insp_i, the introspector function that
             implements Alg. 1 for all τ ∈ T_i
11         if T_prev = ∅ then
12             Enclose s_i in a transaction with introspector insp_i:
                 s′_i : introspect(insp_i){s_i}
13         else
14             Retrieve insp_prev, the introspector function that implements
                 Alg. 1 for all τ ∈ T_prev
15             Rewrite s_i : introspect(insp_prev){s_sub}:
                 s′_i : introspect(insp_i){s_sub}
```

Algorithm 2: RewriteIntrospect specifies the static-rewriting step of a policy-weaving algorithm for applying direct transactional introspection.

ment, through which all security-relevant information about the recorded actions can be accessed.
- Alg. 1 is used to examine the action sequence and decide whether to commit or suppress the recorded actions.

In addition to the direct weaving of transaction blocks described above, we define a second type of rewriting, called callsite indirection, by which any callsites that potentially invoke *interpretive constructs* are transformed in a way that allows transactional introspection to be performed selectively at runtime. Interpretive constructs are those language facilities that convert a string value into a *dynamically generated* code fragment, which is either immediately executed or can be executed at a later time. Examples of interpretive constructs abound in modern scripting languages, such as JavaScript (`eval`, `Function`), Python (`eval`, `exec`, `compile`), and Perl (`eval`).

Delaying the decision to perform full introspection on these callsites serves as an important optimization in languages (including each of those previously mentioned) in which functions can be invoked by indirect reference. In moderately large systems written in these languages, callgraph construction becomes quite imprecise when performed conservatively. I.e., the targeted function may be statically unconstrained for many callsites. The strategy of callsite indirection serves to avoid enclosing the preponderance of all callsites in transaction blocks in favor of a runtime check to determine whether a given call needs to be evaluated with transactional introspection.

2.2 A Formalization of Rewriting

The rewriting that occurs between Fig. 2(a) and Fig. 2(b) is accomplished via a modified and extended version of the rewriting step of the SafetyWeave algorithm formalized by Fredrikson et al. [7]. While that paper focuses primarily on the static policy-weaving algorithm, it assumes that the enforcement mechanism is an inlined reference monitor that evaluates the pre-image $pre(s, \varphi_{violation})$ of the subsequent statement s and policy predicate $\varphi_{violation}$ with respect to the current program state σ_{pre}, and terminates the program if $[\![pre(s, \varphi_{violation})]\!](\sigma_{pre}) = true$ (i.e., the execution of the statement could cause a policy violation).

A key insight that led us to integrate SafetyWeave with a transactional enforcement mechanism is that the semantics of introspection allows predicates constituting the policy to be directly evaluated in the context of the (speculative) program state. Viewed another way, a code fragment that consists of a transaction block containing a statement s implements the strongest-postcondition operator $post(\sigma_{pre}, s) = \sigma_{post}$ that maps the program state σ_{pre} encountered at transaction entry and the enclosed statement s to the poststate σ_{post} that results from the execution of s. A policy predicate $\varphi_{violation}$ can then be directly evaluated in this poststate. Formally, the condition for policy violation is $(post(\sigma_{pre}, s)) \cap [\![\varphi_{violation}]\!] \neq \emptyset$.

The observations above allow the rewriting step of SafetyWeave to be transparently integrated with a transactional enforcement mechanism. However, despite their similar utility, the implementations of the two approaches are quite different. Computation of the pre-image involves the static construction of a potentially complicated symbolic predicate to characterize the set of dangerous program states. In contrast, the strongest-postcondition operator that we describe in this paper is developed as a built-in feature of the interpreter, and it produces a single program state in which $\varphi_{violation}$ is evaluated.

A policy-weaving algorithm may utilize arbitrary (conservative) static-analysis techniques to investigate a program's behavior with respect to a security policy Φ. However, in a departure from traditional static verification methodology, policy weaving uses a rewriting step, which serves as the interface between the static and runtime analyses. Rewriting is invoked in two situations.

- A valid execution trace that violates the policy is identified.
- An invalid execution trace is identified, and a configurable resource bound on how much effort is to be expended on refining the program abstraction has been met.

Here, a "valid" execution trace is one that is realizable in the concrete program, as determined via symbolic execution, and an "invalid" trace is one that cannot occur in the concrete program, but is extracted from the abstract model of the program due to imprecision. In the first case, rewriting the program allows the policy-weaving algorithm to convert a program that can generate policy violations into a safe, instrumented program. In the second case, rewriting allows the algorithm to terminate in bounded time and to use as much information as can be acquired by static analysis while staying within the resource bound. (The worst-case complexity of

```
1  RewriteIndirect(P, s):
   Data: P: source code of the program being analyzed
         s: program statement containing a callsite
   Result: P′: rewritten program that monitors code that is
           dynamically generated by s over all policy transitions
3  Let T be the set of policy transitions for which s is
     instrumented with an introspect block
4  if T = ∅ then
5      Rewrite s : ret = c(args...):
         s′1 : f = indirect(c, [args...]);
         s′2 : ret = f();
6  else
7      Retrieve insp, the introspector function that implements
         Alg. 1 for all τ ∈ T
8      Rewrite s : introspect(insp){ret = c(args...); }:
         s′1 : introspect(insp){v0 = c; v1 = [args...]; }
         s′2 : f = indirect(v0, v1);
         s′3 : introspect(insp){ret = f(); }
```

Algorithm 3: RewriteIndirect specifies the rewriting step done as a postprocessing step of a policy-weaving algorithm. It applies the callsite-indirection transformation to a statement that may target interpretive constructs.

the static analysis would normally preclude its use if the results of a "full" static analysis were required.)

The nature of the runtime enforcement mechanism (the primitive inserted into the program by the SafetyWeave rewriting step) is discussed in formal but generic terms in [7]. We now develop a precise specification of the rewriting step that facilitates policy enforcement via transactional introspection (see Alg. 2). We also specify a final rewriting step, which occurs after all invocations of Alg. 2) and applies callsite indirection to all statements that can target interpretive constructs (see Alg. 3).

In Alg. 2, the "policy-violating witness" Ψ_Φ represents an execution trace along which the policy is violated.[1] Each element (s_i, τ_j) of Ψ_Φ consists of a program statement s_i and a policy transition τ_j. A policy transition may be a special symbol $interp$, which indicates that s_i contains a callsite that potentially targets an interpretive construct; these statements are merely collected to be processed later by Alg. 3. Otherwise, τ_j is a triple $(\varphi_{pre}, \varphi, \varphi_{post})$ consisting of a policy state φ_{pre}, a policy state φ_{post}, and a predicate φ that induces the transition. Together, Alg. 2 and Alg. 3 rewrite program $\mathcal{P}$ so that every witness Ψ_Φ is prevented in the resulting program $\mathcal{P}'$.

Informally, given a policy-violating execution trace that is realizable in the conservative, abstract model of the program, the program is rewritten to include transactional introspection of each statement s in the trace that can induce a policy transition τ. As an alternative to hard-coding `introspect` blocks to monitor callsites that can target interpretive constructs, callsite indirection is used to apply transactional introspection only when needed.

In contrast to the rewriting step specified in past work on policy weaving [7], which requires an implementation of the pre-image operator to determine when s will cause a policy transition, Alg. 2 and Alg. 3 rely on the inherent properties of transactional introspection to effectively apply the dynamic implementation of the strongest postcondition operator as specified in Alg. 1.

2.3 Transaction Suspension

While the term "transaction" often implies atomic execution of a block of code, our goal of security-policy enforcement does not impose this requirement. In fact, we find that maintaining both atomicity and security in the presence of actions that have externally visible or unpredictable results is impractical at best. In an imperative language with a built-in I/O interface, for example, it may be impossible to execute I/O actions speculatively while allowing for the possibility of suppression of such actions. Therefore, we introduce the concept of *transaction suspension* as a means of escaping execution of the transaction block into the introspection code where the speculative state can be evaluated and committed prior to resumption. Due to this process, a transaction may end up being committed partially rather than as an atomic unit.

The introduction of transaction suspension does not require alteration of Alg. 1. Upon suspension, the action sequence available through the transaction object will be a consistent prefix of the full action sequence for the entire transaction that would be available in the absence of suspension. Therefore, these actions can be examined, and the policy state updated, just as before.

We restrict the application of transaction suspension to predictable circumstances; in particular, it is useful for suspension to occur at all invocations of native or externally-linked functions. A whitelist of functions that are free of side-effects—and therefore do not need to trigger a suspension—can be maintained to reduce overhead. We discuss specific scenarios in which transaction suspension has utility in §3, but we maintain that some form of suspension will be necessary to support transactions in any imperative language that incorporates external interfaces.

2.4 Semantic Guarantees

The precise specification of the semantics of an introspector function given above is important for maintaining predictable semantics of the rewritten program, and therefore not invalidating the results previously given by the static analysis. The transactional introspection implemented by Alg. 1 and woven by Alg. 2 is guaranteed, up to policy violation by the enclosed code, to (i) have no visible side-effects, and (ii) maintain sequential execution. "Sequential execution" means that the execution of a transaction block will always produce the same results as a prefix of the original unprotected code.

3. Implementation

This section discusses the implementation of the JAMScript extension to the JavaScript language, and the integration of its primitives as the target of a policy weaver.

3.1 A Strawman Approach

An initial attempt at implementing speculative execution, which we refer to as ForkIsolate, failed to have acceptable performance to serve as a policy-weaving enforcement mechanism. As the name indicates, each time speculative mode was entered, the browser process was duplicated via a POSIX fork. The protected code was then executed in the new branch, and the resulting state was reported back to the original process. Despite copy-on-write semantics for a forked process, the overhead incurred by this mechanism caused some applications to run 3–4 orders of magnitude slower than standard (unprotected) execution.

Our experience with ForkIsolate motivated the requirement that an enforcement framework be general with regards to the code that it can evaluate. The core JavaScript language provides methods for executing dynamically-generated code, most notoriously through the use of the `eval` function. This fact necessitates that the speculative-execution framework be able to maintain faithfully the semantics of all possible executions (in the absence of policy violations). We found that due to the underlying mechanism of isolation used by ForkIsolate, several classes of statements, for example those involving calls to DOM methods that expected access to a GUI, resulted in unexpected behavior, including freezes and

[1] More precisely, Ψ_Φ represents a *collection* of traces. It is a sequence of (statement, policy-transition) pairs and thus does not include the statements in the concrete trace that do not affect the policy state. In general, there will be many ways in which the "gaps" between policy-transitions could be filled in to create a specific concrete trace. The rewriting steps serve to prevent all of these traces.

crashes. Because of the architecture of ForkIsolate, these dangerous cases had to be recognized and handled within the introspection mechanism itself. Consequently, converting ForkIsolate from a proof-of-concept experiment into a general-purpose tool would have required special logic for a practically unbounded number of scenarios induced by (i) JavaScript's tendency to be embedded in other systems, and (ii) the degree to which code is dynamically generated.

Moreover, the embedded character of a typical JavaScript environment motivated the requirement that introspection capabilities be extensible. Even if the ForkIsolate mechanism were able to maintain correct semantics of arbitrary code, additional logic would still be needed to achieve sound introspection for all executions. For example, if the speculative execution of an expression results in a call to the `document.write` DOM method, the goal of comprehensive policy enforcement dictates that the contents of any script elements within the generated HTML should be speculatively executed as well; to perform these speculative executions, it is necessary to have a way of identifying and extracting such code during introspection.

In contrast, a framework like JAMScript, which allows specialized enforcement capabilities to be loaded as necessary for each embedding system (such as the DOM), is more general and maintainable than a system with built-in domain-specific logic.

3.2 Description of JAMScript

With JAMScript, we adopt the paradigm of transactional introspection as the key enforcement component for static policy weaving. We have implemented the mechanism as an extension to the JavaScript language in accordance with the formalization described in §2. The extension consists of one new keyword, `introspect`, to indicate the opening of a transaction block that protects a given fragment of code (delimited by enclosing curly braces). A function value is passed as a parameter to the block to provide introspection logic.

Additional utilities for runtime enforcement, such as the implementation of the `indirect` function described in §2, are provided as part of the `JAMScript` library. This code is written in JavaScript and is loaded prior to the rewritten program, and after the policy logic that is generated at rewriting time by Alg. 2. Because the `JAMScript` library methods are accessible as source code rather than being built into the interpreter, they can be extended in a straightforward manner to handle constructs provided by embedding systems. We have developed a fully functional version of this library for the core JavaScript language, and a prototype implementation that accounts for DOM and other Web API constructs provided by a browser environment.

As previously mentioned, interaction with all interfaces provided by systems outside of the core JavaScript language, for example the DOM, causes suspension of a running transaction to allow the ambient memory state to "catch up" to the speculative state. The upshot of this approach is that external systems that wish to integrate with our modified JavaScript interpreter do not need to make special accommodations for the potentially transactional nature of what is occurring in the JavaScript heap. A complementary consequence is that the JavaScript interpreter does not need to be aware of the systems into which it is integrated. JAMScript's simple model of suspension enables transactional semantics of the JavaScript interpreter that are not entangled with the semantics of ancillary systems.

3.3 Protecting the Instrumentation

An overarching concern when a new runtime security technique is developed is that the instrumentation itself must be protected from being modified or bypassed. In JAMScript, we leverage JavaScript's implementation of lexical scoping and closures to create

```
1  var policy = (function() {
2    // A record of reached policy states
3    var policyStates = [0];
4
5    // Close over native objects for reliable references
6    var _HTMLElement = HTMLElement;
7
8    // Introspector preventing access to the "appendChild" method
9    // of objects with a prototype chain that includes HTMLElement
10   function introspectReads(tx) {
11     var commit = true;
12     var rs = tx.getReadSequence();
13     for (var i=0; i<rs.length; i++) {
14       var node = rs[i];
15       if (node.id === "appendChild"
16           && node.obj instanceof _HTMLElement)
17         commit = false;
18         break;
19     }
20     if (commit) {
21       JAMScript.commit();
22     } else {
23       JAMScript.prevent();
24     }
25   }
26
27   // Return the policy object itself
28   return {
29     introspectors: {
30       introspectReads: introspectReads
31     }
32   };
33 }());
34 Object.freeze(policy);
```

Figure 4: Generating the `policy` object as a self-enclosed entity. The local `_HTMLElement` variable is used to save a private reference to an object that is needed for policy evaluation. Function `introspectReads` recognizes when the `appendChild` property of an `HTMLElement` object is read, and prevents the read from occurring.

immutable and self-enclosed introspectors. Because all native objects that will be referenced by the enforcement code are statically known, the system automatically generates an introspector package that closes over these references when created. Additionally, JavaScript's `Object.defineProperty` and `Object.freeze` methods are used to enforce immutability for all of the properties of both the `JAMScript` and `JAMScript.introspectors` objects.

See Fig. 4 for an example of how closures are used to maintain private references. The `policy` object is returned by the anonymous function shown in lines 1–33. Private state (lines 2–6: the `policyStates` array and a local reference to the DOM `HTMLElement` constructor) is accessible only to the object's methods as a result of JavaScript's lexical scoping.

One requirement for fully protected execution is that the code that generates these closures must be run prior to any modifications of the required global references (`HTMLElement` in our example). Consequently, our rewriter includes the policy code and JAMScript library code prior to any other JavaScript on the page.

Additionally, we must ensure that the function reference provided as the argument to each `introspect` block cannot be reassigned by the untrusted code as a means of subverting the enforcement. The static rewriting provides that all introspector expressions have the form `JAMScript.introspectors.ispect`. Therefore, we define the `JAMScript` property of the global object through the `Object.defineProperty` method, which sets the `writable` and `configurable` attributes to `false` by default, and use `Object.freeze` to render all subproperties immutable (line 34). JavaScript also supports variable shadowing, which is another potential way of subverting the introspector reference: malicious guest code may declare its own `JAMScript` variable whose value overrides, or "shadows," the instrumentation itself. This attack possibility is addressed by a simple static preprocessing step that re-

```
1 var ret = obj.meth(arg);
```

(a) A statically-indeterminate callsite in the original program.

```
1 var bound = JAMScript.bind(obj, [obj.meth, arg]);
2 var ret = bound();
```

(b) Transformed callsite that enables the call to be examined at runtime, at which point the policy can be applied.

Figure 5: Example of callsite indirection to extend the policy to dynamically-generated code. If `obj.meth` references a function that can generate code dynamically, such as `eval` or `Function`, the use of the `JAMScript.bind` method allows the security policy to be applied dynamically (see Fig. 6).

names declared variables that would shadow the JAMScript instrumentation. Because the global `JAMScript` object is the entry point for all enforcement code, this identifier is the only one of interest for this step, although the technique could easily be applied to multiple global-variable names.

3.4 Indirection in JAMScript

The problem of applying a security-enforcement mechanism to code that is interpreted by the `eval` function or `Function` constructor has led many security researchers to limit their tools to language subsets [1]. However, surveys have shown that interpretive constructs are commonly used in existing JavaScript programs found on the Web [13]. In this section, we explain a program transformation that enables the safe, sound, and efficient analysis of dynamically-generated code at runtime.

The core JavaScript language provides two ways to generate code dynamically. The `eval` function executes a string passed as its first argument, and the `Function` constructor coerces a string argument to code that is used as the body of a function that can be executed later. External systems such as the DOM expose other routes to inject code into the execution stream. The method that we describe below applies to many of these cases as well, but we will focus on the application to `eval` and `Function`.

The key observation in developing the statement transformation described below is that any code that is to be generated dynamically will be passed as a string-valued argument to some function call. In both cases examined here, the string to be executed is the first argument passed to either `eval` or `Function`. We therefore implement a transformation on all callsites for which the target of invocation cannot be determined statically (or at least for which `eval` and `Function` cannot be ruled out as targets). Consider the callsite in Fig. 5(a). If it cannot be excluded via static analysis that the reference `obj.meth` points to an interpretive construct, we must consider the possibility that the value of `arg` may be executed as code.

The transformation passes the function, receiver, and arguments for each affected callsite to the `JAMScript.bind` method, which (i) examines the function reference to determine if it is an interpretive construct, (ii) wraps any string argument that will be interpreted as code in a transaction block, and (iii) returns a new function that is bound (using JavaScript's `bind` method) to its receiver and new arguments. This function is then invoked to produce the same effects as the original method-invocation expression, except that it is instrumented to monitor the policy state and prevent violations.

The core JavaScript language defines a few other constructs that must be detected and handled within the body of `JAMScript.bind` to interpose on all cases of dynamically generated code; these cases involve the ways in which interpretive constructs may be invoked indirectly. One such avenue for invoking a function indirectly in JavaScript is to use the `call`, `apply`, or `bind` methods of function objects. When an invocation of any of these methods is detected at runtime within `JAMScript.bind`, we make use of the

```
1  Object.defineProperty(this, "JAMScript", {
2    "value": (function(pol) {
3      var _eval = eval;
4      var _Function = Function;
5      var _bind = Function.prototype.bind;
6      var _apply = Function.prototype.apply;
7      var _call = Function.prototype.call;
8      var _bind_apply = _apply.bind(_bind);
9      var _Array_slice = Array.prototype.slice;
10     var _Array_slice_call = _call.bind(_Array_slice);
11
12     return {
13       introspectors: pol.introspectors;
14
15       /* ... other JAMScript library methods */
16
17       bind: function(f, args) {
18         if (f === _bind) {
19           f = args[0];
20           args = _Array_slice_call(args, 1);
21           var bound = JAMScript.bind(f, args);
22           return function() { return bound; }
23         }
24         if (f === _call) {
25           f = args[0];
26           args = _Array_slice_call(args, 1);
27           return JAMScript.bind(f, args);
28         }
29
30         if (f === _eval || f === _Function) {
31           args[1] =
32             "introspect(JAMScript.introspectors.all) {"
33               + args[1] + "};";
34         }
35
36         return _bind_apply(f, args);
37       },          /* end bind method */
38     }             /* end JAMScript object literal */
39   }(policy))      /* end anonymous function call */
40 });               /* end call to Object.defineProperty */
41 Object.freeze(JAMScript);
42 Object.freeze(JAMScript.introspectors);
```

Figure 6: Initialization of the `JAMScript` library and definition of its `bind` method for dynamically-generated code indirection. (Logic to handle the `call` method and getter/setter definitions, and to check the length of the `args` array is elided to conserve space.) This example also illustrates closing over native objects to maintain private references (lines 3–10), incorporating the `introspectors` object produced by the `policy` (line 13, see also Fig. 4), and freezing the `JAMScript` library and its properties so that they are immutable (lines 41–42).

same logic described above for sanitizing interpretive constructs that may be the receiver of the original invocation—i.e., by rearranging the arguments and recursively calling `JAMScript.bind` (see Fig. 6). This recursive approach also protects against (presumably malicious) attempts to obfuscate a call to an interpretive construct within multiple nested invocations of `call` and `apply`. Additionally, the `defineProperty`, `__defineGetter__`, and `__defineSetter__` methods of the `Object` class are of interest if the getter/setter being assigned is an interpretive construct. In a typical, well-intentioned JavaScript program, this is likely a very rare practice, but such a technique could be used by malicious code to attempt to subvert a policy.

3.5 Extending the Callsite Indirection Transformation

It is useful for the JAMScript enforcement mechanism to support a policy-specification language that includes "call" predicates, which induce a policy transition when particular native functions are invoked. Due to the inherent imprecision when static analysis is applied to a language with first-class functions, it is common for several callsites that target user-defined functions at runtime to be instrumented with transaction blocks. During testing, we found that this situation can cause substantial performance degradation due to an oftentimes deep nesting of transactions. Concretely, if a call to a user-defined function is enclosed in a transaction block,

```
1 introspect(JAMScript.introspectors.introspectCalls) {
2   obj.meth(param);
3 }
```

(a) The initial instrumentation of a callsite. `obj.meth` may reference a user-defined function that contains other transaction blocks, leading to arbitrary nesting.

```
1 function introspectCalls(tx) {
2   var commit = true;
3   var cs = tx.getCallSequence();
4   for (var i=0; i<cs.length; i++) {
5     var node = cs[i];
6     if (node.value === _createElement
7         && node.args[0] === "script") {
8       commit = false;
9       break;
10    }
11  }
12  // ... commit or prevent.
13 }
```

(b) Introspector code to evaluate the original call predicate.

```
1 introspect(JAMScript.introspectors.introspectCallValues) {
2   var v1 = obj.meth;
3   var v2 = [obj, param];
4 }
5 var bound = JAMScript.bind(v1, v2);
6 bound();
```

(c) Transformation that applies the policy based on the values constituting the call. The callsite itself is uninstrumented.

```
1 function introspectCallValues(tx) {
2   var commit = true;
3   var ws = tx.getWriteSequence();
4   var node = { args: ws[0].value, value: ws[1].value };
5   if (node.value === _createElement
6       && node.args[1] === "script") {
7     commit = false;
8   }
9   // ... commit or prevent.
10 }
```

(d) Refactored introspector code that evaluates the call parameters. The creation of the object on line 4 is coordinated with the transformation in (c). The condition for detecting a policy transition is the same in figure (b) lines 6–7 and (d) lines 5–6.

Figure 7: Example of the callsite transformation that serves to avoid transaction nesting at runtime and to extend the policy to dynamically generated code. If `obj.meth` points to a user-defined function that also contains transactions, this transformation extracts the call invocation from within the transaction to avoid nesting. At the same time, if `obj.meth` invokes a dynamic function such as `eval` or `Function`, passing the values through `JAMScript.bind` allows the policy to be dynamically applied to generated code.

and that function contains other callsites enclosed in transaction blocks, arbitrary nesting of transactions can occur. To address this problem, we rely on an extension of the callsite transformation described above, along with an associated automated refactoring of the policy-introspection code (see Fig. 7 for an example). The conversion is structured so that the assignments to the identifiers `v1` and `v2` correspond to (i) the invoked function value, and (ii) an array containing the receiver and arguments, and the introspector is restructured accordingly. In effect, this converts a "call" policy predicate into an equivalent "write" predicate. Consequently, no callsites are directly enclosed within `introspect` blocks and nesting is prevented, while, simultaneously, the policy can be applied to dynamically generated code.

4. Experimental Results

In this section, we present an evaluation of the performance of JAMScript on a set of real-world applications. Our experiments were designed to answer the following questions:

- How well does transaction-based introspection perform when applied to real-world applications? Is the overhead acceptable?
- Does the policy-weaving approach to transaction placement provide performance benefits over a naive use of transactional instrumentation?
- What are the savings to the user in terms of conceptual complexity? In particular, how does the size of a security-policy automaton compare to the generated introspection code?

For this paper, we have not addressed experimentally the question of the soundness of our implementation. Rather, we are working with an independent "red team," which has probed the system from an attacker's point of view and has provided invaluable feedback. We also intend to release JAMScript as an open-source project to be subjected to scrutiny by the community.

4.1 Setup and Methodology

To answer the questions posed above, we collected a set of 20 distinct JavaScript applications and an additional 51 sub-applications of the SMS2 DNA analysis suite from the World Wide Web. With the goal of increasing the signal-to-noise ratio of our performance measurements, we intentionally sought applications that perform computationally intensive tasks, such as decoding a QR code or processing a DNA sequence. We developed policies ranging from simple properties, like preventing calls to `window.open`, to compound policies that reflect higher-level goals, such as preventing all external network communication.

Application	AST Nodes	Description of Applied Policy	Transactions Inserted by JAM Analysis
squirrelmail	110	disallow access to src property	0
doubleclick-loader	271	prevent navigation	0
userprefs	375	disallow appendChild and eval	12
sunspider	407	disallow XMLHttpRequest.open	2
kraken	414	disallow XMLHttpRequest.open	3
beacon	787	isolate document from cookie	36
plusone	1195	prevent script creation, document edits	34
imageloader	3957	disallow document.write	40
sms2-*	6656.7	prevent all network communication	162.3
snote	6852	certain elements write-once/read-only	59
piwik	7132	isolate document from cookie	230
mwwidgets	7504	certain elements write-once/read-only	59
midori	9018	prevent modification of cookie	17
greybox	9914	prevent creation of script elements	343
googiespell	11603	disallow document.write	40
ga	13236	prevent script creation, document edits	388
hulurespawn	30269	disallow local storage access	1496
colorpicker	32653	prevent navigation, src/cookie access	309
adsense	37709	isolate document from cookie	227
puzzle	104486	prevent creation of script elements	319

Figure 8: Program size and number of woven transactions for analyzed applications. The "sms2-*" item represents the average over a set of 51 applications taken from the Sequence Manipulation Suite for DNA analysis.

We do not present data related to the strawman implementation described in §3.1, because it performed much too poorly to serve as a reasonable point of comparison. (Instrumented code ran 3–4 orders of magnitude slower than the original, uninstrumented code.) Instead, we compare the performance of the applications secured by policy weaving (referred to as the "fine-grained" approach, because individual statements are speculatively executed) to that of applications secured in a whole-program fashion (referred to as the "coarse-grained" approach) in which transaction blocks are used to secure entire scripts at a time. The latter approach has been used in prior work [5, 14] in which scripts are delimited by individual `script` tags or by the browser's same-origin policy. Additionally, to test the absolute performance of transactions as an enforcement

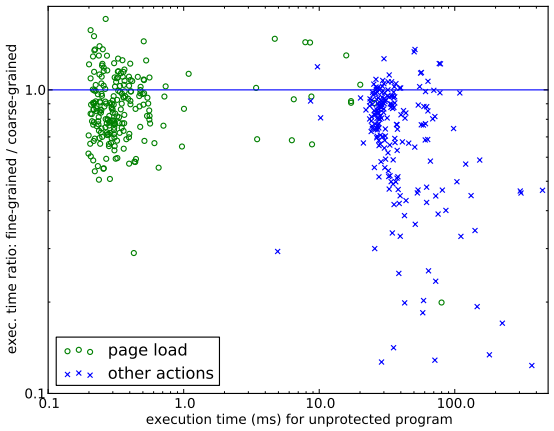


Figure 9: Log-log plot of the execution time of programs with fine-grained transactional enforcement applied through weaving compared to coarse-grained whole-program transactions. The ratio of the two approaches is plotted against the execution time of the original unprotected program. The preponderance of points below the line $y = 1$, when the original execution time is non-trivial, indicates an overall performance benefit from policy weaving, compared to the coarse-grained approach.

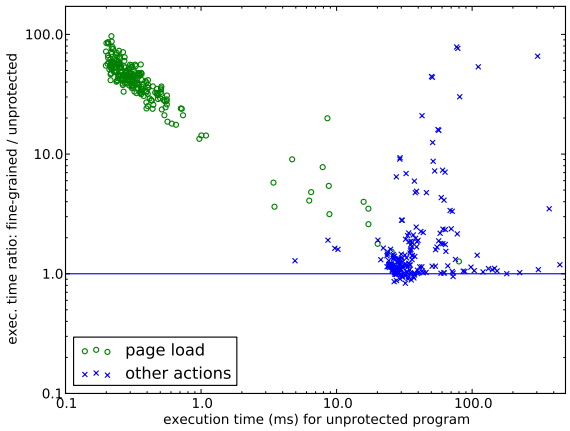


Figure 10: Log-log plot of the ratio of execution time of programs with fine-grained transactional enforcement applied through weaving compared to the unprotected execution, plotted as a function of the execution time of the original unprotected program. Page-load actions include the time to initialize the policy object and JAMScript library; this overhead becomes less of a factor as the overall page-load time increases. The overall trend decreasing to the right indicates that the percentage overhead of security-policy enforcement becomes less dramatic for more computationally-intensive applications.

mechanism for policy weaving, we compare the running time of the secured applications to that of the original program.

The static analysis was performed by the JAM policy weaver [7], modified to use the rewriting technique described in Alg. 2. JAMScript is implemented in the SpiderMonkey JavaScript interpreter, version 1.8.5, which is embedded in the Firefox browser, version 17.0.5esr. Experiments were run on a Dell Inspiron E6520 laptop computer with an 8-core Intel Core i5-2540M 2.60GHz CPU with 8GB RAM, running the 64-bit Ubuntu 12.04 LTS operating system.

4.2 Runtime Performance

The plot shown in Fig. 9 shows that in most cases, and particularly for test cases that involve computationally-heavy processes, a program woven with fine-grained transactions outperforms the corresponding program protected by a coarse-grained strategy. This result was not a foregone conclusion, because the two approaches represent opposing sides of a performance trade-off between transaction start-up time and in-transaction processing time. A weaving strategy that uses many fine-grained transactions for policy enforcement relies on the assumption that most of the overhead of speculative execution is incurred during the course of the transaction, rather than in the initialization of the transaction. Our experiments bear out this assumption, as we measured an overall 25% speed-up for program actions instrumented with fine-grained transactions versus coarse-grained transactions when summarized by the geometric mean. This breaks into a 12% speed-up for page-load actions, which includes the time taken to load the JavaScript policy object and the JAMScript library, and a 37% speed-up for other program actions. Moreover, there are no prospects for reducing the observed overhead with the coarse-grained approach, whereas policy weaving provides the opportunity to exert additional effort during static analysis to rule out spurious transactional instrumentation to further reduce the runtime overhead.

Similarly, Fig. 10 shows the ratio of the execution time for programs protected by woven transactions versus the original unprotected program, plotted as a function of the original execution time. When summarized by the geometric mean, the measured execution time for actions other than the initial page load protected by fine-grained transactions is 166% of the time for the unprotected program. (This number can be compared to 265% for coarse-grained transactions.) Loading the page took 35.6 times longer for the instrumented programs (both fine-grained and coarse-grained), which must load the policy object and JAMScript library prior to the program itself. However, the absolute time represented by this slowdown ranges from 6.7ms to 33.5ms, which is negligible to human perception.

Application	Input Policy (AST Nodes)	Baseline Policy (AST Nodes)	Specialized Policy (AST Nodes)
googiespell	7	94	170
imageloader	7	94	170
kraken	11	94	170
squirrelmail	11	94	94
sunspider	11	94	170
hulurespawn	13	138	367
puzzle	13	134	290
greybox	13	134	290
midori	13	137	310
doubleclick-loader	18	125	125
beacon	19	151	386
piwik	19	151	386
userprefs	22	109	197
ga	24	121	411
plusone	24	121	411
adsense	29	152	634
colorpicker	33	136	376
mwwidgets	92	273	1209
snote	92	273	1279
sms2-*	116.7	251.7	507.2
jsqrcode	156	277	655

Figure 11: Size of the input policy versus the automatically generated enforcement code, given by abstract-syntax-tree nodes. "Input policy" refers to the automaton provided to the static analysis (see Fig. 1). The "baseline policy" is a single introspector that checks all policy transitions to protect the full program in lieu of analysis. The "specialized policy" represents introspection code produced for the woven program (as in Fig. 3(a)), and is generally larger because multiple introspector functions are produced to evaluate different combinations of policy predicates, as deemed necessary by the static analysis.

4.3 Policy Complexity

A substantial benefit of the automated policy-weaving approach to program security is that it permits policies to be specified declar-

atively. The rewriting framework converts the declarative policy into imperative code that makes use of the introspection capabilities of JAMScript to enforce the policy at runtime. An example of this translation appears in the relationship between Fig. 1 (the input policy) and Fig. 3(a) (the specialized policy). The baseline policy, which is a single introspector function that monitors all transitions of the input policy for a transaction object, is not shown. The policy weaver that we have integrated with JAMScript provides a policy-specification language, which is a dialect of JavaScript that supports predicates over calls (and corresponding arguments) to native functions, reads and writes to properties of native objects, reference (in)equality, and various string relations. To quantify the benefits provided by the automated production of introspection code, we compare the size of the input policy to the size of the generated code in Fig. 11. Summarized by the geometric mean, the implementation of the baseline policy is 6.3x larger than the input policy for our benchmarks, and the specialized policy is 14.5x larger. The size of the representation is admittedly an indirect measure of implementation complexity, but we also propose that the input policy automaton provides an intuitive interface for specifying a set of disallowed execution traces. These factors together provide strong support for the usability of the policy-weaving approach to security-policy enforcement.

5. Related Work

Transaction-Based Policy Enforcement. The use of transactional introspection for security-policy enforcement can be viewed as an evolution of inlined reference monitoring, which was developed around 2000 by Schneider and Erlingsson [6, 15, 17]. The primary difference is that the semantics of introspection enables a more direct examination of the effects of the monitored program statements, rather than relying on a calculation of the effects.

Transcript [5] is an extension to the JavaScript language that implements speculative execution with introspection for security-policy enforcement. As presented, transactions are applied in a modular fashion to untrusted "guest" code, delineated as different source-code files included in a web page via HTML `script` tags. In contrast, JAMScript was developed to be the target of a static weaving process that results in fine-grained transactions applied to the full program, including the host code. Also, while Transcript relies on a complex conflict-resolution system to maintain the consistency of the DOM during a transaction, JAMScript uses a relatively simple suspend mechanism that is oblivious to the context in which the core JavaScript interpreter is running.

The Transactional Memory Introspection (TMI) system [2] applied transactional instrumentation to multithreaded server software and demonstrated the benefits of the approach in that context. The JavaScript language does not exhibit true multithreaded behavior (the proposed standardization of the Worker API allows for parallel execution, but with each thread in a natively isolated environment, and communication limited to the exchange of strings [18]). Thus, TMI addresses issues that are orthogonal to the ones addressed in this paper.

Richards et al. [14] apply speculative-execution semantics (referred to as "delimited histories") to untrusted code in an automatic but coarse-grained fashion based on the browser's same-origin policy. In their approach, the entirety of the third-party code is speculatively executed and the host code is trusted to execute without protection. In contrast, we argue for an approach in which *all* code is subjected to the security policy, and the scope of instrumentation is reduced by using the results of a conservative static analysis. The assumption that the host code can be trusted may be reasonable in some contexts, but leaves open the possibility of indirect subversion of the policy by clever attackers that can manipulate the environment to coerce the host code into violating the intended policy. It also precludes the practice of hosting copies of untrusted third-party code or integrating untrusted code snippets into the host program. Another difference between their work and ours is that the introspection code in [14] is written manually on a case-by-case (albeit reusable) basis in C++ modules, with the intent of shielding the instrumentation from manipulation. In contrast, our system automatically produces introspection code as a translation of the policy automaton, and we make use of a relatively simple scheme for protecting the integrity of the instrumentation.

The TxBox system [9] provides transactional introspection as an operating-system security feature. Their approach uses system-level policies to limit the access of applications to system resources, in contrast to JAMScript's application-specific policies that can restrict internal program behavior. Our approach is also distiguished by the use of static analysis for runtime performance benefits, as well as the techniques for securing dynamically generated code.

Aspect Weaving for JavaScript. A number of prior works investigate an aspect-oriented approach to enforcing security policies for JavaScript in a browser. In general, the solution for runtime enforcement that we describe in this paper is distinguished from prior work by the choice of transactional introspection as the mechanism, and the resulting ability to safely handle the full JavaScript language, rather than a restricted subset.

Fredrikson et al. [7] describe the JAM policy weaver for JavaScript as an implementation of their general technique. (Policy weaving is differentiated from aspect weaving by an emphasis on semantics-based—as opposed to syntax-based—rewriting.) That paper focuses primarily on the static rewriting methodology, and leaves the nature of the runtime enforcement mechanism largely unspecified. In a complementary manner, we investigate the desirable properties of the runtime component, while allowing for the possibility of integrating with a wide range of static-analysis techniques.

Yu et al. [19] present a rewriting scheme that introduces the concept of callsite indirection for applying security policies to dynamically generated code. That work emphasizes a comprehensive and sound placement of instrumentation and the formal specification of policies. In contrast, we discuss the concrete requirements of an effective enforcement mechanism and the translation of policies into operational code.

ConScript is a browser-based aspect system for security [12]. The primary security mechanism utilized by ConScript is a built-in form of indirection (implemented as a modification to the JavaScript interpreter in Internet Explorer 8). This mechanism allows a function object to be wrapped within a user-defined function that vets arguments and potentially suppress calls at runtime. ConScript policies are constructed either manually or by an automatic dynamic-observation process, and a static analysis is used to gain confidence (but not prove) that the implementations are correct. In contrast, in our system the policy implementation is generated automatically from a declarative specification.

6. Conclusions

We have developed and evaluated an approach for using transactional introspection and callsite indirection as integrated runtime enforcement mechanisms for policy weaving. Introspection enables the examination and potential suppression of the effects of program statements identified by a static analysis, and indirection serves as a light-weight runtime analysis that can apply introspection to dynamically generated code that is not available to the static analysis. We have shown how programs can be rewritten to apply these techniques; the resulting programs are protected against policy violations for all possible program executions.

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