Static Information Flow Control Made Simpler

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Static information flow control (IFC) systems provide the ability to restrict data flows within a program, enabling vulnerable functionality or confidential data to be statically isolated from unsecured data or program logic. Despite the wide applicability of IFC as a mechanism for guaranteeing confidentiality and integrity—the fundamental properties on which computer security relies—existing IFC systems have seen little use, requiring users to reason about complicated mechanisms such as lattices of security labels and dual notions of confidentiality and integrity within these lattices. We propose a system that diverges significantly from previous work on information flow control, opting to reason directly about the data that programmers already work with. In doing so, we naturally and seamlessly combine the classically separate notions of confidentiality and integrity into one unified framework, further simplifying reasoning. We motivate and showcase our work through two case studies on TLS private key management: one for Rocket, a popular Rust web framework, and another for Conduit, a server implementation for the Matrix messaging service written in Rust.

CCS Concepts: • Software and its engineering → Formal software verification; Specification languages.

Additional Key Words and Phrases: Information Flow Control, Security Type Systems, Accessible Correctness

1 INTRODUCTION

Security is a paramount concern in a pervasively digital world. The vast increase in digitization of the past decade has come with a proportional increase in the severity of data breaches [Warren et al. 2016], warranting renewed research into accessible, yet powerful, methods of declaring and enforcing security specifications. Information flow control is a program analysis technique that aims to prevent undesirable data flows. For example, in a program implementing a simple web application for performing authentication, there may be modules for (1) performing network I/O, (2) validating user input, (3) checking passwords, and (4) interacting with a database. A reasonable information flow specification, shown in Fig. 1, might be that (1) should never flow to (3) or (4), and that data from (4) should never flow to (1). Green (solid) arrows in the diagram denote the flows required for the program to function, and red (dashed) arrows denote the flows which must be prevented to ensure the program’s security. A flow from, for instance, (1) to (4), occurs when data from (1), or which is transitively dependent on (1), flows to (4). Note that certain flows in the diagram, such as from (1) to (4), are denied directly but permitted transitively—specifically, after data from (1) passes through (2). This is addressed during the case study in Section 2.

Fig. 1. Permitted flows in our example program

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A classical information flow control system [Myers 1999; Simonet 2003] might support the specification of the flow architecture in Fig. 1 by providing two lattices: one for reasoning about confidentiality, or the property that confidential data does not leak to inappropriately visible places, and one for integrity, or the property that untrusted data does not propagate to inappropriately integral places. All data in the program must have a label relevant to each lattice, denoting its levels of confidentiality and integrity. Two separate lattices are required for each property owing to the duality between them: two distinct and opposing invariants must be enforced when data is labeled as both highly confidential and highly integral, such as with \texttt{db\_handle} in Fig. 1. First, it must never flow to data labeled as being of low confidentiality, such as \texttt{network\_io}. Second, data labeled as being of low integrity, again like \texttt{network\_io}, must never flow to \texttt{db\_handle}. This separate treatment complicates reasoning— for example, Jif [Pullicino 2014], a state of the art IFC system for Java, provides entirely new (dual) semantics for lattice operations when reasoning about integrity versus confidentiality.

Our system resolves this issue by presenting a single, straightforward abstraction for declaring information flow policies, simplifying specifications while retaining expressivity. Instead of organizing data inside a lattice and reasoning about flows in the context of it, we opt to allow programmers to directly specify which flows between places in a program are not permitted, as presented in the architecture in Fig. 1. A declaration \texttt{flow b ->! c} states that data affected by variable \texttt{b} cannot flow to variable \texttt{c}, and a declaration \texttt{flow mod network\_io ->! mod db\_handle} states that data affected by the \texttt{network\_io} module cannot flow to the \texttt{db\_handle} module. We will refer to the part before the arrow as the source, and the part after as the destination. This streamlined annotation language contributes to a system which is:

1. **Uniform**: a flow annotation \texttt{flow b ->! c} may be an integrity specification, a confidentiality specification, or potentially both— the programmer need not shift their reasoning
2. **Incremental**: our approach to flow annotations encourages partial and local specifications on the way to proving higher level program properties, and
3. **Simple**: we provide a small number of straightforward constructs which are highly general and composable, minimizing changes needed to the semantics of the language and easing adoption of the system by new users.

We will explore these properties further by analyzing cryptographic key management in two popular Rust programs, Rocket and Conduit. A brief formal description of our IFC system, as an extension to the Rust type system, is provided in the appendix for the curious reader.

2 **MOTIVATION: MANAGING KEYS**

2.1 **Case Study: Rocket**

Rocket is a fully fledged and widely used HTTP framework for Rust. Like many web frameworks, it provides optional support for serving traffic over Transport Layer Security, or TLS, connections. TLS is an essential feature for securing data between clients, such as browsers, and servers, encrypting data in transit. A critical component of TLS is a public-private keypair held by the server, in this case Rocket. Each domain which aims to communicate securely with web browsers and clients at large must obtain a certified keypair, which is valid for any traffic served by it. While a typical web service consists of a large number of physical servers, each of them may use the same TLS keypair, assuming they are serving a single domain. This is convenient, but risky— leakage of the private key for a domain from any of its servers risks compromising the security of the entire service. It is essential, then, that this does not occur, and an IFC system may be able to provide that assurance.

Most of our discussion will be directed at the particular Rocket code path that deals with conditionally configuring TLS functionality, shown in Fig. 2. Specifically, we analyze the function
Fig. 2. Verifying non-leakage of TLS key data in Rocket

default_tcp_http_server in file core/lib/src/server.rs, on commit 2fc4b156 of the Rocket
git repository. In order to render this section of code amenable to information flow verification, some
minimal refactoring was required; we will return to this later. We focus our attention here because it
is the primary part of the codebase where key data is accessed directly (through to native_config
and TlsListener::bind on lines 13 and 19), increasing the potential for leaks and need for verifi-
cation. Verification of the latter two functions is not as interesting, because their implementation
is largely straightforward or reliant on primitives provided by Rustls, a TLS library for Rust. A
summary of the displayed Rocket code follows.

Ignoring the information flow constructs, the code in Fig. 2:

• On lines 6 and 7: Binds a variable, listener, which initially holds a TCP socket
• On lines 9 and 10: Checks that TLS is enabled and that a TLS configuration is provided
• In lines 13 through 19: Extracts the provided TLS configuration into a structure understood
  by TlsListener::bind and calls it, setting listener to the returned TLS socket.

We now discuss the IFC specifications for self.config.tls.key, which contains key data, in
Fig. 2. The flow declaration on the first line prohibits the private key from flowing transitively to
any functions which could perform I/O operations, such as those in std::io, std::fs, std::net,
std::ffi, and std::os. The same property could be expressed as a series of individual flow
declarations on each relevant namespace, but the use of a macro here provides a convenient
abstraction. The next declaration employs a special place understood by flow rules: *, which applies
to all variables, along with the return value. This ensures that key data does not leak to any place without being explicitly permitted to do so. We care about flows to places, instead of merely flows to I/O operations, because of abstraction: a module may never perform I/O internally, but it may communicate with another that does, and verifying that it does so safely requires assertions about information flow inside the module. Permission for flows may be granted in two ways: through **overriding** the flow rules we have already declared, or by using the `allow` construct.

Overriding occurs whenever a rule is declared that is more specific than another. Specificity is determined by the length of the prefix being accessed within a variable or namespace. For example, given a rule `flow b ->! c` in some scope, where `b` is a struct with field `f`, a rule `flow b.f -> c` declared in that scope would act as an override, permitting flows from `b.f` to `c` (but not from any other fields of `b`). Additionally, there are two invariants enforced by the system on flow declarations, which ensure that it can always find a _maximally specific_ rule for any given flow. First, it is an error to declare contradictory flow rules. Second, in the case of two opposing flow rules where one flow rule has a more specific destination than another, and the other a more specific source, the one that denies the flow is chosen. This might occur in the case of two flow rules `flow a.b ->! c` and `flow a -> c.d`—a flow from `a.b` to `c.d` would be denied because the first rule is denies the flow. This is done for safety: denied flows are visible, but permitted flows are not. We can now analyze the last three flow rules in Fig. 2.

Starting with the rule on line 11, we see slightly different syntax, **with flow**, in the declaration. This is done because we cannot declare the flow rule on `config` before it has been bound, and by the time the binding happens, it is already too late, and a violation of the rule on line 2 is inevitable. **with flow** is syntactic sugar provided for the `let` construct which inserts a flow declaration between binding and initialization. We proceed similarly for the flow rules on lines 14 and 16, overriding the flow rule on line 2 as needed, but another element bears discussion: function calls. When a function is called with data affected by rules denying flows, the information flow control system checks that the flow policies declared by the function are compatible with those from the calling context. Only mutually referenced arguments, the return value, and any restrictions on flows to functions are checked here; the precise mechanics are discussed further in Appendix A.1. Importantly, we only look at the publicly visible portion of a function’s signature, preserving abstraction and ensuring modularity. We are able to treat functions in this way because Rust programs generally do not make use of global mutable state— treating it as an error, then, does not result in a materially more conservative system. As a result, for functions which do not perform IO, we must only consider their arguments and return value. In this case, the call to `to_native_config` receives an immutable reference and does not take any other arguments, so the **with flow** declaration suffices to allow the call. The function call on line 19, which takes its two arguments by move, passes similarly. Note that, having explicitly permitted flows from `self.config.tls.key` to `config`, `conf`, and `listener`, flows from these four variables to any other variables will now cause an error.

Lastly, we arrive at the assignment to `listener` on the second-to-last line. **allow** evaluates an expression and returns the result, but without any of the expression’s dependencies. It is comparable to other information flow systems’ `declassify` (for confidentiality) and `endorse` (for integrity) constructs [Hedin and Sabelfeld 2012] in providing an explicit escape hatch, but generalizes over both. In this case, we use **allow** to remove `listener`’s dependency on `self.config.tls.key`, assigning it to itself so that further uses will not produce errors. The usage of **allow** here is safe because, importantly, `TlsListener` no longer provides access to raw key data, only to signing operations with the key. This is still a concern, but a much lesser one— data dependencies on `listener` do not risk revealing information about the cryptographic key. Further, it is reasonable to wonder why we must use **allow** on `listener`, outside the scope of the preceding conditionals, instead of on, say, `conf` in the argument list to `TlsListener::bind`. **Control flow dependencies** are
what make this necessary. These are implicit flows that take place when explicit flows occur inside a conditional branch. In Fig. 2, this crucially happens when listener is assigned to the result of evaluating TlsListener::bind, where it gains a dependency on self.config.tls.key not only because of the function’s return value, but also because the guards for both if statements, on lines 9 and 10, are dependent on self.config.tls.key. As a result, applying allow inside the conditional would remove the dependency from bind’s return value, but not from the conditional branches, which would require two additional usages on the guards themselves. Instead, we do so once outside both conditionals and reassign to listener.

Control flow dependencies also explain why a minor refactor was necessary in order to ease information flow reasoning. default_tcp_http_server, as present in the Rocket repository at the referenced commit, unnecessarily includes several assignments inside the conditionals, in addition to logic afterwards which depends on those assignments. Moving all of this functionality outside of the conditional branches removes unneeded dependencies on the value of self.config.tls.key and additionally results in less overall code duplication. In general, we believe that the introduction of an information flow control type system to programs which did not have it before will encourage shifts in coding style, just as typed programs differ from untyped programs in order to better cooperate with (and take better advantage of) the type system.

To summarize, we show that, under our formal system, we can concisely prove a strong information flow property about TLS key management within Rocket, specifically, that no TLS key data leaks from default_tcp_http_server. Though bugs were not identified while demonstrating our theory of information flow, note that our specifications would suffice to prevent the occurrence of future bugs within relatively complicated and error-prone code. Moreover, this property is only concerning the function itself and two of its callees. Specifications beyond those discussed here could be used to prove higher level properties about the absence of key leakage from the entirety of Rocket. We now apply the mechanisms we have discussed here to a second program.

### 2.2 Case Study: Conduit

Conduit is a Rust implementation of the server portion of the Matrix chat protocol. As a federated messaging service (meaning there does not exist a single canonical server, but a cooperating network of them, much like email), Matrix relies heavily on cryptography to secure and authenticate message contents. This includes communication between Matrix servers themselves. We analyze a similar situation to the one identified with Rocket, in which complicated application initialization logic executes within a context that contains raw key data, and so might benefit from the use of IFC to explicitly enforce security policies. We specifically analyze the load function in file src/database/globals.rs, on commit 566dc0a of the Conduit git repository. The relevant snippet of code is shown in Fig. 3. As before, we begin with a brief summary of its functionality.

- Lines 6 and 7: Process the raw bytes representing the key into a version indicator and a key
- Line 9: Perform several steps of validation on the version string and key data
- Lines 10 through 15: Pass the validated data to a library function that handles cryptography for Matrix applications

Addressing the information flow constructs in Fig. 3, we start with the same two declarations as for Rocket. The first, on line 3, prohibits flows to I/O functions, which might allow sensitive information to escape, and the second prohibits flows to any variables, along with the return value of the current function. We allow the flow on line 7 using the with flow construct and our notion of overriding flow policies. Overriding occurs here because parts is more specific than *. Note, again, that flows from parts will still cause errors.
... 

```rust
def keypair_bytes ->! fn io!();
def keypair_bytes ->! *;

let mut parts = keypair_bytes.splitn(2, |&b| b == 0xff)
  with flow keypair_bytes -> parts;

let keypair = utils::string_from_bytes(...).map_err(...).and_then(...)
  .and_then(|(version, key)| {
    ruma::signatures::Ed25519KeyPair::from_der(key, version)
      .map_err(|_|
        Error::bad_database("Private or public keys are invalid."))
  })
  with flow keypair_bytes -> keypair;

let keypair = allow keypair;

...
```

Fig. 3. Verifying that Conduit does not leak Matrix server keys

A similar `flow` declaration is made on line 15, again using overriding. However, lines 10 through 12, immediately prior to it, warrant further discussion due to their use of closures. The treatment of closures— and higher order functions in general— is straightforward in our system. Besides the checks done for function calls, discussed in Section 2.1, we must perform two additional checks involving any data captured by the closure. First, the captured data is added to the set of dependencies which will flow through the closure’s return value, or to any mutable references passed as arguments to it. Second, we ensure that the closure is never passed any information that might inappropriately flow to variables captured by it. The flow policy for the current scope remains active for the body of the closure itself, so any potential flows between captured variables will be caught when the closure is declared. Luckily, however, the usages on line 10 and 12 do not need these considerations. The closure declaration on line 10 does not close over anything, only taking two arguments, neither of which is a mutable reference, and returning key data, wrapped in a `Result` type. The closure on line 12 is similar, taking one argument (which contains an error value, if applicable) and returning another `Result` to `keypair`. Accordingly, the `with flow` declaration on line 15 suffices to allow `keypair_bytes` to flow to `keypair`.

The function call on line 11 securely abstracts away raw key data, rendering it inaccessible, just as was the case with Rocket. It is again safe, then, to use `allow` on `keypair`, assigning it to itself to prevent further information flow violations from uses of it. Having analyzed this snippet from the Conduit codebase, we note that it is highly similar to the Rocket code before it, both in terms of the information flow control issues raised and the simple, declarative solutions offered by our system. We expect this general pattern of information flow control to arise consistently when managing sensitive data within application configuration and setup logic.

We introduce one final information flow pattern that arises in the Conduit codebase as a consequence of the pervasive use of cryptographic operations in the Matrix protocol, and discuss a natural
method of addressing it offered by our system. This time, the data in question does not grant direct access to the private key, only to cryptographic operations with it. It does, however, exist alongside application logic that interacts with user input over the network, so IFC is once again warranted.

Fig. 4 shows part of the implementation of create_invite_route in file src/server_server.rs on the same commit. We start, as usual, with a short summary of the code.

- Lines 8 through 10: Create a JSON object with a reproducible serialized representation to prepare it to be hashed, assigning it to signed_event
- Lines 12 through 15: Hash and sign the JSON object by passing it, db.globals.keypair(), and a mutable reference to signed_event to a library function responsible for handling cryptography; signed_event is assigned the result through the reference

Preceding and following the code in Fig. 4 is a large amount of logic for inviting a user to a room through the Matrix protocol—create_invite_route implements the relevant API endpoint for doing so. This pattern arises not just in this function, but throughout Conduit, for every API endpoint which must use key data. In other words, large portions of Conduit both have access to db.globals.keypair(), which is passed to every function that needs it, and process networked user input. Our IFC system adapts naturally to this challenge because of its focus on local reasoning.

We begin with the usual flow declarations on lines 3 and 4, restricting db.globals.keypair() from flowing to any functions which perform I/O, any variables, or the return value. It should be noted that while db.globals.keypair() cannot reveal raw key data, it may still produce sensitive information (such as signed events), so data dependent on it should be prevented from flowing to I/O. We use a single allow in the call to ruma::signatures::hash_and_sign_event on line 12, because signed_event does not pose any risk of compromising access to the key.

Though this is an exceptionally simple flow specification, note that we have also verified an exceptionally strong information flow property. Besides signed_event, no other data in the program is permitted to invoke, or use data from invoking, db.globals.keypair(). Program logic not pictured in Figs. 3 and 4 for brevity requires further specifications in order to pass information...
flow checking (in particular, functions to which db is passed, whose flow policies would need to be updated in order for the call to succeed), but the added complexity is negligible.

2.3 What about lattices?
We now briefly compare our system to one implementing a generic lattice-based theory of information flow. We avoid complicated constructs such as principals [Myers and Liskov 2000] and robust declassification [Myers et al. 2004] for which we currently lack meaningful comparisons.

The most apparent advantage of our system, relative to any that employs lattices, is that our specifications act as a declarative description of the desired information flow policies in effect for any program scope. At a glance, it is trivially easy to determine the desired flow architecture, what data is critical, and how to work within programs annotated with IFC specifications. Should the user desire to enforce, taking Fig. 2 for example, that self.config.tls.key does not leak to unsecured areas in the program, it’s necessary only to declare precisely that property, explicitly permitting flows where needed and explicitly disengaging the IFC system once the language’s normal abstraction mechanisms have guaranteed the property at hand. A lattice-based system would need to talk about the property that the key does not leak indirectly, giving it a label that indicates high confidentiality and providing other data with labels of lower confidentiality. Adding additional flow restrictions, especially integrity policies, would make the desired information flow architecture much less clear in this setting.

Finally, a last point should be noted about label-based reasoning versus the direct usage of program places: locality. Generally, our system’s ability to reason about programs locally is not due to any increase in formal reasoning power over prior work, but can instead be owed to its removal of labels as a mechanism for abstracting over places in a program— labels naturally encourage the creation of specifications that attempt to talk about multiple, potentially disparate, places at once, instead of incrementally declaring flow policies on critical data and proving them. For instance, when using a system such as Flow Caml [Simonet 2003], a lattice of security levels is declared globally and enforced for the whole program at once.

3 CONCLUSION AND RELATED WORK
Much related work on information flow control, particularly usable information flow control, includes support for dynamic verification when static reasoning presents too high a barrier— [Myers 1999] does just this. The formal system described here, however, carries enough novelty in the fully static realm to warrant an exclusive focus; future work may introduce dynamic elements. [Simonet 2003] increases the usability of its IFC system by precisely inferring security labels, which may similarly be an interesting direction for future work. [Crichton et al. 2022] provides a modular information flow analysis for Rust programs on which we build our formalism, but it does not provide a way to specify intended restrictions on information flow.

We have reviewed classical systems of information flow, introducing a simplified specification language and system constructed around it which we hope will aid in advancing the accessibility of information flow. We conducted two case studies in which we demonstrated the natural applicability of our system to local reasoning. After proving the soundness of our system, we hope to pursue a practical implementation for use on real-world Rust programs.

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A APPENDIX

A.1 Formal System: Extending Rust

We now formally describe our IFC system as an extension to Rust’s type system. The formal model of Rust is provided by Oxide [Weiss et al. 2019]. We take inspiration from the work on tracking information flow in Rust presented by Flowistry [Crichton et al. 2022], though we diverge significantly from it in order to capture the full expressivity of our system. Rust was chosen as the foundation for our system because, as noted in [Crichton et al. 2022], the language already performs a highly precise pointer analysis as part of borrow checking, which is essential for any information flow system. Users need not contend with an overly conservative pointer analysis, or with any additional restrictions imposed by a precise one. Additionally, there is very little existing work on IFC in Rust, and given the language’s history of embracing lightweight correctness techniques, we feel that our approach is likelier to succeed within it. Our extensions to Oxide are colored in brown. We only consider flows between variables here, because more complicated flow declarations such as those between functions and modules do not present additional challenges to the formal system, behaving similarly to the constructs already handled by it.

Variables $x$  Naturals $m, n, k$  Concrete Regions $r$  Type Vars. $\alpha$

Path $q$ ::= $e | n.q$
Places $\pi$ ::= $x.q$
Place Exprs. $p$ ::= $x | *p | p.n$
Dependency Exprs. $d$ ::= $\delta | p$
Access Exprs. $a$ ::= $* | p$
Place Expr. Contexts $p^\Box ::= \Box | *p^\Box | p^\Box.n$

Loans $l ::= \alpha p$
Ownership Qualifiers $\omega ::= \text{shrd} | \text{uniq}$
Constants $c ::= () | n | \text{true} | \ldots$
Expressions $e ::= c | p | &\omega p | \ldots$
Base Types $r^B ::= \text{u32} | \text{bool} | \ldots$
Sized Types $r^{SI} ::= r^B | \alpha | \ldots$

Fig. 5. Oxide’s syntax, extended
Beginning with the syntax, we present the parts of Oxide’s syntax most relevant to our discussion. We make two additions, the first of which introduces dependency expressions, which tracks dependencies, and place expressions p, which are used by Oxide to represent values which can be assigned to. The other addition is similar, creating access expressions a, combining *, which appears in Fig. 2, with place expressions.

Our typing judgement is \( \Sigma; \Delta; \Gamma; \Theta; \Pi; \Psi; \Xi \vdash e : \tau \), which reads “given the global environment \( \Sigma \), the type environment \( \Delta \), the stack typing environment \( \Gamma \), the continuation typing environment \( \Theta \), the dependency environment \( \Pi \), the flow policy environment \( \Psi \), and the branch dependency environment \( \Xi \), the expression \( e \) with type \( \tau \) and dependencies \( \delta \) produces an updated stack typing environment \( \Gamma’ \) and dependency environment \( \Pi’ \).” This is similar to the one used by Flowistry, with additional environments for tracking flow policies and control flow dependencies—the latter with increased precision.

### A.1.1 Tracking flows

Our first rule, for the value \( \text{true} \), appears in Fig. 6. Bare values are effectively ignored by the information flow system, producing an empty dependency expression \( \delta \), because flow rules cannot be declared on them. The next two rules, T-Move and T-Copy, are more interesting, but require the introduction of a few metafunctions. Much of the theory presented here is founded on the treatment of places, \( p \), as nothing more than the composition of their leaves. That is, given a place which represents a struct with fields \( f \) and \( g \), where \( g \) is itself a struct with field \( h \), the leaves of \( p \) are \( f \) and \( h \). Dependencies are always leaves—dependency sets contain the leaves of a place that is depended on, rather than the ‘top level’ place. The \( \delta \)-place and \( \delta_1 \cup_\tau \delta_2 \) operations used by T-Move and T-Copy depend on this notion of analyzing a place expression for the set of atomic places it contains; doing so allows the analysis to be maximally precise without sacrificing simplicity. We exclude type constructors, supported through the special inclusion of the \( \text{Either} \) type by Oxide, because their treatment is similar to that for fields. Oxide also does not support the declaration of recursive types, but these can soundly be treated as leaves themselves in a practical implementation. The definition of these two metafunctions is shown on the first two lines of Fig. 7.

We elide the simple definition of the leaves metafunction, which has a case for each of the syntactic forms an Oxide type might take. \( \delta \)-place generates a \( \delta \) which contains all the dependencies of a place, retrieved from \( \Pi \). Note that \( \delta \) mirrors the structure of the type of the place whose dependencies it models, containing the same fields (specifically, leaves) as the type it corresponds to.
$$\delta\text{-place}(p : r^S_1, \Pi) = \forall p^\Box_{\text{leaf}}[\delta] \in \text{leaves}(p : r^S_1) . \ p^\Box_{\text{leaf}}[\delta] = \{ p^\Box_{\text{leaf}}[\delta] \} \cup \Pi(p^\Box_{\text{leaf}}[\delta]); \delta$$

$$\delta_1 \{ \overline{p} \} \cup \delta_2 = \forall p^\Box_{\text{leaf}}[\delta_1] \in \text{leaves}(\delta_1 : r^S_1) . \ p^\Box_{\text{leaf}}[\delta_1] = p^\Box_{\text{leaf}}[\delta_1] \cup p^\Box_{\text{leaf}}[\delta_2] \cup \{ \overline{p} \}; \delta_r$$

assign-deps$$(p : r^S_1, \delta, \{ \overline{p} \}) = \forall p^\Box_{\text{leaf}}[\delta] \in \text{leaves}(p : r^S_1) . \ p^\Box_{\text{leaf}}[\delta] \mapsto p^\Box_{\text{leaf}}[\delta] \cup \{ \overline{p} \}$$

$$\delta\text{-leaves}(\delta : r^S_1) = \bigcup \text{leaves}(\delta : r^S_1)$$

Fig. 7. Selected metatransformations for manipulating dependencies

$$\Sigma; \Delta; \Gamma; \Theta; \Pi; \Psi; \Xi \vdash e_1 : r^S_1 \bullet \delta \Rightarrow \Gamma_1; \Pi_1 \quad \Delta; \Gamma_1; \Theta \vdash^r r^S_1 \leadsto r^S_1 + \Gamma_1'$$

$$\forall r \in \text{free-regions}(r^S_1) . \Gamma'_r \vdash \text{r nrrb} \quad \text{is-allowed}((\delta\text{-leaves}(\delta : r^S_1) \cup \Xi, \{ x : r^S_1 \}), \Psi)$$

$$\Pi'_1 = \Pi_1[\text{assign-deps}((x : r^S_1), \delta, \Xi)]$$

$$\Sigma; \Delta; \text{gc-loans}_\Theta(\Gamma'_1, x : r^S_a); \Theta; \Pi'_1; \Psi; \Xi \vdash e_2 : r^S_2 \bullet \delta' \Rightarrow \Gamma_2, x : r^S_D; \Pi_2$$

$$\Sigma; \Delta; \Gamma; \Theta; \Pi; \Psi; \Xi + \text{let } x : r^S_a = e_1; e_2 : r^S_2 \bullet \delta' \Rightarrow \Gamma_2; \Pi_2$$

T-LET

$$\forall p^\Box[x] : r^S_\text{leaf} \in \text{leaves}(p : r^S_1). \text{is-allowed}(p^\Box[\delta] \cup \Xi, \{ p^\Box[x] : r^S_\text{leaf} \}), \Psi)$$

$$\Sigma; \Delta; \Gamma; \Theta; \Pi; \Psi; \Xi + \text{unif } \pi = e : \text{unit } \bullet \emptyset \Rightarrow \Gamma'[\pi \mapsto r^S_1], \Pi_2$$

T-ASSIGN

Fig. 8. Selected rules responsible for checking flows

with. Each of these leaves of $\delta$ contains a set of dependencies. It is treated as a place itself as a syntactic simplification; it should be thought of as a map which is compatible with place expression contexts $p^\Box$. The next metatransformation, $\delta_1 \{ \overline{p} \} \cup \delta_2$, acts as a union on a $\delta_1$ and a $\delta_2$ which correspond to the same type, merging dependency sets between like leaves. An additional parameter, $\{ \overline{p} \}$, can be used to unconditionally add dependencies to all leaves of the resulting $\delta$.

T-MOVE, then, generates a $\delta$ which represents the dependencies of a place $\pi$, using it to represent the dependencies of the moved variable. T-COPY functions analogously, taking into account that place expressions (which may hold dereferences, see Fig. 5), not just places, may be copied. As a result, it must use the ownership judgement (in the first premise) to retrieve the dependencies of all the loans for the place expression $p$ to be copied. A loan is any place expression which represents the same abstract memory location as the place expression $p$, such as a dereference of a shared reference to $p$. We use the $\sqcup$ operator to merge each loan’s generated $\delta$ with the rest. Finally, T-TUPLE demonstrates how $\delta$ is used with place expression contexts $p^\Box$ in tracking dependencies.

A.1.2 Preventing flows. A second selection of rules, presented in Fig. 8, is responsible not only for tracking flows, but for preventing them when needed. The first is T-LET, which provides the base case for information flow— all dependencies tracked throughout the system originate here. In order to explain T-LET, we introduce our final set of metatransformations. assign-deps takes a place $p$, its $\delta$, and a set of dependencies as arguments, and adds those dependencies to each leaf of $p$; it is used to update a place’s entry in $\Pi$. $\delta$-leaves gathers all the dependencies from a $\delta$, unifying the dependency sets from its leaves. Finally, is-allowed (shown in Fig. 9) takes a set of sources, a set of destinations, and a flow policy set $\Psi$ as arguments, and checks that each of the sources is allowed to flow to each of the destinations, succeeding if all of the flows are allowed. It relies on
get-min-perms (shown in Fig. 10) to search $\Psi$ for the correct flow policy to apply, which it does according to the overriding policy discussed in Fig. 2. To do this, it relies on $\rightarrow$, a reflexive and transitive binary relation on access expressions $a$ which will succeed if the first access expression syntactically represents access to the second one. $p \rightarrow p.f$ and $* \rightarrow *$ define success.

Given these definitions, T-Let checks if the dependencies of the expression $e$ to be bound, as well as any branch dependencies, are permitted to flow to the variable to be bound, according to the current flow policy. Additionally, it gives the bound variable the expression’s dependencies by updating $\Pi$. Similarly, T-Assign updates the assignee’s dependencies in the dependency environment with those of the expression being assigned, along with any dependencies from control flow. It then checks whether flows are allowed from each leaf of the assignee from the relevant dependencies of the expression being assigned.

We now briefly discuss our handling of function application, eliding typing rules for brevity. Note that we change Oxide’s function call form, removing the return value— any program which uses function return values may be transformed to a program which returns information through a mutable reference passed to the function. This simplifies information flow checking for function calls. Like [Crichton et al. 2022], our system is modular, opting to preserve abstraction at the cost of precision. When a function call is encountered, we first retrieve the flow policies declared by the function which are valid for its entire scope, in addition to any policies permitting flows, adding them all to a new $\Psi$ representing the function’s flow policy set. We then substitute the function call’s actual parameters for its formal parameters within this $\Psi$, and compare it to the $\Psi$ for the calling context. If the calling context’s $\Psi$ implies the one generated for the function call, then no error is raised. Specifically we check that, for all the mutable references passed to the function, any flow permitted by the function to that unique reference is also permitted by the calling context. We exclusively consider uniq refs because they are the only means by which information may escape our function call form, and violate the calling context’s information flow policies.

The typing rules for the flow and allow constructs are straightforward, so we also elide their definitions for brevity. When a flow policy is declared, it is added to the current flow policy environment $\Psi$. Flow policies may be declared between access expressions; for any access expression which is not $*$, the ownership judgement is used to ensure that the-place expression is accessible. When allow is used on an expression $e$ of type $\tau$, it returns a $\delta$ with all of its leaves (according to $\tau$) set to $\emptyset$. 

\[
\text{get-min-perms}(p_1, p_2, \Psi) = \\
\text{foldr}((a_2, a_3, \beta_1), (a_4, a_5, \beta_2)) \rightarrow \\
\text{if } a_2 \rightarrow p_1 \land a_3 \rightarrow p_2 \land \\
((a_4 \rightarrow a_2 \land a_5 \rightarrow a_3) \lor \\
((a_4 \rightarrow a_2 \lor a_5 \rightarrow a_3) \land \beta_1 = \text{false})) \\
\text{then } (a_2, a_3, \beta_1) \\
\text{else } (a_4, a_5, \beta_2), \\
(*, *, \text{true}), \Psi \\
\]

Fig. 9. Checks if flows are allowed