Immutability and Encapsulation for Sound OO Information Flow Control

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Security-critical software applications contain confidential information which has to be protected from leaking to unauthorized systems. With language-based techniques, the confidentiality of applications can be enforced. Such techniques are for example type systems that enforce an information flow policy through typing rules. The precision of such type systems, especially in object-oriented languages, is an area of active research: an appropriate system should not reject too many secure programs while soundly preserving noninterference. In this work, we introduce the language SIFO which supports information flow control for an object-oriented language with type modifiers. Type modifiers increase the precision of the type system by utilizing immutability and uniqueness properties of objects for the detection of information leaks. We present SIFO informally by using examples to demonstrate the applicability of the language, formalize the type system, prove noninterference, implement SIFO as a pluggable type system in the programming language L42, and evaluate it with a feasibility study and a benchmark.

CCS Concepts: • **Security and privacy → Information flow control**.

Additional Key Words and Phrases: security, information flow, type system, mutation control, confidentiality, integrity

1 INTRODUCTION

In security-critical software development, it is important to guarantee the confidentiality and integrity of the data. For example, in a client-server application, the client has a lower privilege than the server. If the client reads information from the server in an uncontrolled manner, we may have a violation of confidentiality; this causes the client to release too much information to the user. On the other hand, if the server reads information from the client in an uncontrolled manner, we may have a violation of integrity; this causes the server to accept input that has not been validated.

Language-based techniques such as type systems are used to ensure specific information flow policies for confidentiality or integrity [Sabelfeld and Myers 2003]. A type system assigns an explicit security type to every variable and expression, and typing rules prescribe the allowed information flow in the program and reject programs violating the security policy. For example, we can define a

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security policy as a lattice of security levels with the highest level `high` and the lowest level `low`, and an information flow from `high` to `low` is prohibited.

For simple while-languages, type systems to control the information flow are widely studied [Hunt and Sands 2006; Li and Zhang 2017; Volpano et al. 1996]. We focus on the less researched area of information flow control for object-oriented languages. Analysis techniques such as fine-grained taint analysis [Arzt et al. 2014; Enck et al. 2014; Graf et al. 2013; Hedin et al. 2014; Huang et al. 2014, 2012; Milanova and Huang 2013] detect insecure flows from sources to secure sinks by analyzing the flow of data in the program. Coarse-grained dynamic information flow approaches [Jia et al. 2013; Nadkarni et al. 2016; Roy et al. 2009; Xiang and Chong 2021] reduce the writing effort of annotations by tracking information at the granularity of lexically or dynamically scoped section of code instead of program variables. By writing annotation, users can increase precision of the information flow results [Xiang and Chong 2021]. Moreover, there are approaches using program logic [Amtoft et al. 2006, 2008; Beckert et al. 2013] to analyze and reason about information flow.

In this work, we focus on security type systems for object-oriented languages [Banerjee and Naumann 2002; Barthe et al. 2007; Myers 1999; Strecker 2003]. Sun, Banerjee, and Naumann [Banerjee and Naumann 2002; Sun et al. 2004] created a Java-like language annotated with security levels for the standard information flow policy with only two security levels. Myers et al. [Myers 1999] created the Jif language which extends Java with a type system that supports information flow control. The precision of the type systems for object-oriented languages is a major challenge. Both related approaches do not have an alias analysis or an immutability concept, so they conservatively reject secure programs where confidential and non-confidential references could alias the same object. This important drawback is addressed in our work. Additionally, as done for other type systems, we give a correctness guarantee through a proof of noninterference: `high` data never influences `low` data. This means that an attacker who can observe `low` data cannot obtain information about `high` data. If an untrusted library is in the code base, the developer can leverage the type system to ensure that only `low` data is served to such library.

We introduce SIFO[1] which supports information flow control for an object-oriented language with type modifiers for mutability and alias control [Giannini et al. 2019]. With respect to former work on security type systems for object-oriented languages, SIFO provides a more precise type system, allowing to type more correct programs. In this work, we show that reasoning about immutability and encapsulation is beneficial to reason about information flow. In addition to adding expressivity, SIFO allows a natural and compact programming style, where only a small part of the code needs to actually be annotated with security levels. This result is achieved by building over the concept of promotion/recovery [Giannini et al. 2019; Gordon et al. 2012], and extending it to allow methods and data structures to be implicitly parametric on the security level. For example, with promotion, a data structure can be used with any security level, but security is still enforced by not allowing data structures of different security levels to interfere with each other. This reduces the programming effort of developers and supports reuse of programs and libraries [Giannini et al. 2019].

The contents of this paper are as follows. First, we introduce the language SIFO for information flow control. Second, we formalize the type system by introducing typing and reduction rules. Third, we show that our language is sound by proving the noninterference property that secret data is never observable by a public state. Fourth, we implement SIFO and evaluate it with a feasibility study and a benchmark to compare SIFO with state-of-the-art information flow analysis tools.

[1] SIFO is an acronym for Secure Information Flow in an Object-oriented language

2 INFORMAL PRESENTATION OF SIFO

In this section, we explain the challenges of securely checking the information flow in object-oriented languages. We then give an informal introduction to SIFO. Last, we discuss well and ill typed SIFO expressions for a more detailed explanation.

2.1 Motivating example

Consider the following partially annotated code using two security levels `low` and `high`:

```
1 class Person { low id;  Person(low id){ this.id=id; }  }
2 ...
3 low local_id =  GiveMe.anId();
4 high p = new Person(local_id);
5 high inside = p.id;
```

In SIFO, security is an instance based property: the person `p` is `high`, but other persons could have a different security level. Security is also a deep property: the content of all the fields of `p` encodes `high` information. In our example, every person has an `id`. Even if the `id` field is declared `low`, it will encode `high` information inside of the `high` instance `p`. The value of `local_id` is `low`. We can use it to initialize `id` since information can flow from `low` to `high`, but not from `high` to `low`.

When extracting the value of the field `id`, the information is now part of the `high` Person, and thus, needs to be seen as `high`: `p.id` produces a `high` value.

Is this code conceptually correct with respect to information flow? Can we complete the type annotations on this code to make it correct? If the `id` is just a primitive integer, this is possible and easy in both SIFO[2] and other languages for information flow, such as Jif [Myers 1999]:

```
1 class Person { //SIFO CODE
2   Int id; //low is the default security level
3   Person(Int id){ this.id = id; }  }
4 ...
5 local_id = GiveMe.anId(); //a low Int
6 high p = new high Person(local_id);
7 high inside = p.id;
```

The corresponding Jif code is also quite easy, but a little more involved and with a different syntax; we report it in Listing 1. Both in SIFO in Line 6, and in Jif in Line 9, the value of `local_id` gets *promoted* from `low` to `high`.

```
1  class Person[label L] {
2    final int{L;this} id;
3    Person(int{L;this} id){ this.id = id; }
4  }
5  ...
6  //label {high->low} allows low and high to read the variable
7  int{high->low} id = GiveMe.anId();
8  //label {high->} allows only high to read the variable
9  Person[{high->}]{high->} p = new Person[{high->}](id);
10 int{high->} inside = p.id;
```

Listing 1. Example in Jif syntax

What happens if the `id` is a more complex custom object type? The following code is accepted in SIFO:

[2]In the examples, we use a rich language including local variables and literals with the usual semantics. Those are supported by our artifact, but in the formal model we present a minimal language where we keep only the most crucial OO features.

```
class Account { Int id; String name; Date firstTransaction;...  }
class Person {
  Account id;
  Person(Account id){ this.id = id; }  }
...
local_id = GiveMe.anId();//a low Account
high p = new high Person(local_id);
high inside = p.id;
high name = inside.name;
```

As you can see, not much has changed. Of course, we need to define the `Account` class, but then we can use it in the same way we use `Int` before.

On the other hand, Jif [Myers 1999] (the most closely related work) cannot accept this kind of code. In a pure object-oriented setting, everything is an object, and pre-defined types, as integers, should be treated as any other object. However, Jif treats primitive types in a privileged way. In Jif, it is possible to write more flexible code relying on primitive types than on objects. The difficulty revolves around aliasing and mutation: the local variable `local_id` is still available, and now it is aliased inside of the **high** `Person` object `p`. Thus, if `p` is used to update any field of the `Account`, then the **low** part of the program could see this **high** information through `local_id`. This can happen because with the base type system of Java all objects can be both mutated and aliased. Jif builds on top of Java and only adds type properties directly related to information flow, so it cannot make immutability and aliasing assumptions. On the other side, SIFO builds on top of L42 [Giannini et al. 2019], a language with built-in support for immutability and aliasing control using type modifiers (also called reference capabilities).

In L42, the default modifier for references is **imm** (immutable), and the default security level of SIFO is **low**. Thus, a fully annotated version of the code above would look as follows:[3]

```
class Account {
  low imm Int id; low imm String name; low imm Date firstTransaction;
  ... }
class Person {
  low imm Account id;
  Person(low imm Account id){ this.id = id; }
  }
...
low imm Account local_id = GiveMe.anId();
high mut Person p = new high Person(local_id);
high imm Account inside = p.id;
high imm String name=inside.name;
```

Since the `Account` is immutable, in SIFO the value of `local_id` is promoted from **low** to **high** for the constructor call, exactly as it happens for `Int` before. Indeed, deeply immutable objects allow for the same kind of reasoning that primitive types allow in Java. In this way, SIFO code can scale and use objects as easily as primitive types in contrast to Jif and other approaches.

To make the same kind of behavior accepted in Jif, the code would have to be modified in the following way:

```
low mut Account local_id = GiveMe.anId(); //in Jif, there is no immutability
low mut Date a = local_id.firstTransaction;
```

[3]To help readability, in the rest of the paper we will write type modifiers and security levels explicitly, but a syntactically much lighter style, as shown above, is accepted by our artifact and it is the preferred way to code, once the programmer gets used to those defaults.

```
high mut Person p = new high Person(
  new high Account(local_id.id,local_id.name,
    new high Date(a.day,a.month,a.year)));
```

This code is accepted by both SIFO and Jif. This is a technique called *defensive cloning* [Bloch 2016]; it is very popular in settings where aliasing and mutability cannot be controlled.

In SIFO, we have *mutable* and *immutable* objects; where the reachable object graph (ROG) of an immutable object is composed only of other immutable objects (deep immutability), while the ROG of a mutable object can contain both mutable and immutable objects [Giannini et al. 2019]. The set of mutable objects in a ROG is called MROG.

In addition to `imm`, L42 also offers the `capsule` concept: a capsule reference refers to a mutable object whose MROG is reachable only through such reference. Both `imm` and `capsule` references can be safely promoted from `low` to `high`; this avoids the need of defensive cloning also when encapsulated mutable state is involved.

```
low capsule Account local_id = GiveMe.anId();
high mut Person p = new high Person(local_id);
```

Capsule variables are affine, that is, they can only be used zero or one time, thus if `p` is used to update the state of the account, the local capsule variable `local_id` cannot be used to examine these updates.

As you can see from those examples, aliasing and mutability control is a fundamental tool needed to support information flow in the context of an object-oriented language. A typical misunderstanding of type modifiers is that a mutable field would always refer to a mutable object. This is not the case, indeed all the fields of immutable objects will transitively contain only immutable objects. This of course includes all fields originally declared as mutable. The same applies to security labels: a `low` field in a `high` object would transitively contain only `high` objects. This is different with respect to many other object-oriented languages, where the declarations determine what to expect. If there is information from the context, that is normally explicit in the usage site. In SIFO instead, the declared type is only a first approximation: the security level (and type modifier) of an expression is a combination of what is declared in the class table and what is implied from the usage site.

Note how in our example the class `Person` is declared with a `low` field, but the `high Person` object actually stores a `high` value for such field. In SIFO, a `low` field is not like a `low` field in Jif, but it is more like a field with generic/parametric security: the value of a `low` field of a `low` object will be `low` but the value of a `low` field of a `high` object will be `high`. In general, the ROG of an object is always at least as secure as the security of the object itself. This aligns nicely with mutability control in L42, where immutable instances of classes declaring a `mut` field will hold immutable values in such fields. Deep properties (like L42 immutability and SIFO security) allow for a much simpler and more predictable reasoning with respect to (optionally) shallow properties, like Rust immutability (that supports internal mutability) and Jif security (where `low` values can be stored in the ROG of `high` values).

2.2 SIFO Concepts

Objects and references. As we anticipated above, in SIFO, we have *mutable* and (deeply) *immutable* objects. We also have four kinds of references: `imm`, `mut`, `capsule`, and `read` [Giannini et al. 2019]. An `imm` reference must point to an immutable object, and can be freely aliased, but as the name suggests, the fields of an immutable object cannot be updated. A `mut` reference must point to a mutable object; such an object can be aliased and mutated. A `capsule` reference points to a mutable object that is kept under strict aliasing control: the mutable ROG reachable from the `capsule` reference cannot be

$$
\begin{array}{lcl}
T & ::= & s\ mdf\ C \\
s & ::= & \texttt{high} \mid \texttt{low} \mid \ldots \text{(user defined)} \\
mdf & ::= & \texttt{mut} \mid \texttt{imm} \mid \texttt{capsule} \mid \texttt{read} \\
CD & ::= & \texttt{class}\ C\ \texttt{implements}\ \overline{C}\ \{\overline{F}\ \overline{MD}\ \} \mid \texttt{interface}\ C\ \texttt{extends}\ \overline{C}\ \{\overline{MH}\} \\
F & ::= & s\ \texttt{mut}\ C\ f; \mid s\ \texttt{imm}\ C\ f; \\
MD & ::= & MH\ \{\texttt{return}\ e;\} \\
MH & ::= & s\ mdf\ \texttt{method}\ T\ m(T_1\ x_1, \ldots, T_n\ x_n) \\
e & ::= & x \mid e.f \mid e_0.f = e_1 \mid e_0.m(\overline{e}) \mid \texttt{new}\ s\ C(\overline{e})
\end{array}
$$

Fig. 1. Syntax of the core calculus of SIFO

reached from other references. The `capsule` reference can be used only once to assign this isolated portion of the heap to a reference of any kind. In particular, this means that a `capsule` reference can be used to initialize/update an `imm` reference/field; when this happens all the objects in the ROG of such a reference become immutable.

The "only used once" restriction is necessary so that no alias for the isolated portion of the heap can be introduced, which would violate the `capsule` property.

Finally, a `read` reference is the common supertype of `imm` and `mut`. With a `read` reference, the ROG cannot be mutated and aliases cannot be created; but there is no immutability guarantee that the object is not accessible by other references, even `mut` ones.

Types. Types in SIFO are composed by a security level s, a type modifier mdf, and a class name C. The security levels s are arranged in a lattice that specifies the allowed data flow direction between them. For example, we have a lattice with a `low` and a `high` security level, where the allowed information flow is from `low` to `high`, but not vice versa. The type modifier mdf can be `mut`, `imm`, `capsule`, and `read` as introduced above. The subtyping relation between modifiers is defined as follows: for all mdf, `capsule` $\leq mdf$, $mdf \leq$ `read`. This means that, for example, a `mut` reference can be used if a `read` is needed, and a `capsule` reference can be used both as a `mut` or as an `imm` one. This is sound, because `capsule` variables can be used only once.

Core Calculus. The syntax of the core calculus of SIFO is shown in Fig. 1. It covers classes C, field names f, method names m, and declarations for classes, interfaces, and methods. A class consists of fields and methods. The class itself has no modifier or security level. The modifiers and security levels are associated with references and expressions. A field has a type T and a name. A method has a return type, a list of input parameters with names and types, and also a security level and a type modifier for the receiver; they are specified in front of the keyword `method`. We have the standard expressions: variable, field access, field assignment, method call, and object construction. When an object is initialized, its security level is initially determined by the constructor invocation. Thus, different references to objects of the same class can have different security levels. C, m, f, and x in Fig. 1 are all disjoint syntactic categories.

Method Calls. A method has to be defined in a class with parameter types, a return type and a receiver type. For example, an `Accumulator` class has a `low Int` field `acc` and a method `add` that adds another `low Int` parameter to the `acc` field and updates the field.

```
1  class Accumulator {
2    low imm Int acc;
3    low mut method low imm Int add(low imm Int x){ return this.acc=this.acc+x; }
4    }
5  ...// below we show examples of user code
```

```
6  low Accumulator a = GiveMe.aLowAcc();//a low Accumulator
7  low imm Int w = 5;
8  low imm Int x = a.add(w); //ok to call as low*low -> low
9
10 high Accumulator b = GiveMe.aHighAcc();//a high Accumulator
11 high imm Int y = 6;
12 high imm Int z = b.add(y); //ok to call as high*high -> high
```

We can call such a method if the receiver and the actual input parameter are `low`. However, SIFO adds flexibility to method calls using *multiple method types*. Formally defined in Section 4, they allow to call a method as if it was declared with a range of different type modifiers and security levels. In this example, the multiple method types rule allows us to call the `add` method also if the receiver and the parameter are all increased to the same security level (for example to `high`) and returning a value with this same security level. Without this feature, the method `add` needs to be declared for each security level. This feature also has benefits in comparison to a parameterized version of the language because legacy code and standard libraries can be used in SIFO without adding security level annotations: `low` is the default security level, and `imm` is the default modifier.

Control Flow and Implicit Information Leaks. Information flow control mechanisms [Sabelfeld and Myers 2003; Volpano et al. 1996] are used to enforce an information flow policy that specifies the allowed data flow in programs. A program can leak information *directly* through a field update. This can be prevented by ensuring that no confidential data is assigned to a less confidential variable. However, information can also flow *implicitly* through conditionals, loops, and (crucial in OO) dynamic dispatch. For example, the chosen branch of a conditional reveals information about the values in the guard. As shown from Smalltalk [Goldberg and Robson 1983], in a pure OO language, dynamic dispatch can be used to emulate conditional statements and various forms of iterations and control flow. Thus, our core language does not contain explicit conditional statements, but they can be added as discussed in Section 4. Loops can be implemented through recursive method calls.

Therefore, SIFO only needs a secure method call rule to prevent implicit information flow leaks. In a method call, information of the method recevier can flow to the return value and mutable parameters. Thus, the security levels of the return value and mutable parameters have to be equal or higher than the security level of the receiver. Consider for example the following code: `res=myValue.aOrB(a,b)` If the method `aOrB` returns the first or the second parameter depending on the dynamic type of `myValue`, we could use the result to identify information about `myValue`. Note how this pattern is very similar to the Church encoding of Booleans. Similarly, if parameter `a` is typed `low mut` and the receiver has a `high` security level, information of the `high` receiver can be leaked by observing the mutations on the parameter `a` after the method call.

2.3 Examples of Well-Typed and Ill-Typed SIFO Expressions

In Listing 2, we show secure and insecure programming statements to explain the reasoning about information flow in SIFO.

A class `Person` contains a `low imm String name` and two `high` fields: a `mut Password` and an `imm AccountId`. The `Password` and `AccountId` class have a `String` field to set the actual password/id. When accessing a field, we consider the security level of both the field and the receiver and determine the least upper bound of both security levels in the lattice. When an object is initialized, it is created as mutable, and the initial security level is determined by the constructor invocation. For example, a `Person` can be initialized with a `low` or with a `high` security level.

Consider the assignments in Listing 2 starting with Line 5 (line numbers are referenced in parentheses in the following): To ensure confidentiality, the type system prevents the password to

```
1  class Person{low imm String name;  high mut Password pwd; high imm AccountId id;}
2  class Password{low imm String pwdS;}
3  class AccountId{low imm String idS;}
4
5  low mut Person p =...//a pre existing low Person reference
6  high mut Password pass = p.pwd;//ok, access of high Password
7  high imm String passS = p.pwd.pwdS;//ok, access is typed high
8  low imm String passS = p.pwd.pwdS;//wrong, high assigned to low
9
10 p.pwd.pwdS = highString;//ok, field update with high String
11 p.pwd.pwdS = p.name;//ok, as an imm String can be promoted
12 p.name = highString;//wrong, high String assigned to low p.name
13 high mut Person pHigh =...//a pre existing high Person
14 pHigh.name = highString;//ok, field update with high String
15
16 low mut Password newPass = new low Password("some");//ok
17 p.pwd = newPass;//wrong, mutable secret shared as low and high
18 newPass.pwdS = "password";//ok? Insecure with previous line
19
20 low capsule Password capsPass=new low Password("secret");//ok
21 p.pwd = capsPass;//ok, no alias introduced
22
23 low imm AccountId aid = new low AccountId("secretId");//ok
24 p.id = aid;//ok, aid is imm and can be aliased
25 aid.idS = "0";//wrong, immutable object cannot be updated
26
27 low read Person pRead = p;//ok, assigned to read reference
28 high imm String passS = pRead.pwd.pwdS;//ok, access is high
29 pRead.pwd.pwdS = highString;//wrong, read cannot be updated
30 someMutObject.fieldName = pRead;//wrong; there are no read fields
31 someMutObject.fieldName = pRead.id;//ok if the field has an imm type
```

Listing 2. SIFO examples

be leaked via a `low` reference (8), but it can be exposed to another `high` reference (6, 7). The password can be updated with another `high` String (10), or with a `low` String (11), as we allow to promote the security level of `imm` references. The opposite of updating a `low` field of a `low` reference with a `high` String is forbidden (12), but the assignment is allowed if the reference and the String are `high` (14).

Until now, we explained assignments of immutable Strings; but the most interesting challenge to guarantee confidentiality is about assigning mutable objects instead. For example, how can we update the mutable `p.pwd` field? When a new `Password` object is created, it can be initialized as a `low` object as the `Password` is not confidential on its own. The confidentiality is the association between the `Person` object and the `Password` object. SIFO prevents that a `low` reference to a `Password` object is assigned to a `Person` object (17). The reason is that the variable `newPass` is still in scope after the field update, thus if (17) was accepted, (18) could be used to sneak a password change without the need of any `high` information.

A secure assignment without aliases is shown in (20, 21). Here, the `capsule` modifier is utilized. A reference to a `Password` object can be assigned to a `Person` object, if the reference to the `Password` object is `high`. The password is initialized by the programmer as `low capsule`. The system of type modifiers is flexible enough to promote the created object from `mut` to `capsule`. Since there is no `mut`

value in the input, we are sure that an isolated portion of memory is created, as the created object cannot be accessed from any other `mut` reference. In (21), the flexible type system can then promote the variable `capsPass` to a `high capsule`, which is assigned to the `p.pwd` field.

As discussed before, aliases over `imm` references (24), are allowed to move from lower security to higher one. The alias does not lead to a security leak because the type system ensures that fields of `AccountId aid` cannot be updated (25). Both `imm` and `capsule` references are referentially transparent, and can be used as a controlled way to communicate between different security levels.

Finally, with `read` references (27), `imm` fields can still be accessed (28), but no fields can be updated (29). Here, we present a simplified L42 type system, where fields can only be `mut` or `imm`; thus there is no field that can be updated using a `read` reference (30). In the full L42, it is possible to have, for example, `read` linked lists of `read` elements, but this has some subtle interaction with promotions, so we omit it here for simplicity. Of course, `imm` references reached from `read` references (31) can be assigned to `imm` fields as usual.

For a more compelling example of our system that can promote expressions, consider the following listing:

```
1  class PassFactory{
2  ...
3    low imm method low mut Password from(low imm String base){
4      low mut Password res = new low Password(base);
5      if (this.tooSimple(base)){res.pwd = this.complete(base);}
6      return res;
7    }
8  }
9  ...
10 p.pwd = passFactory.from("foo")
```

The method `from` is well typed. The method `from` returns a `low mut Password res` which could not be directly assigned in (10) because a `high` security level is needed, but the system of type modifiers is flexible enough to promote `low mut Password res` to a `high` security level by utilizing the `capsule` modifier. Since there is no `mut` value in the input, we are sure that an isolated portion of memory is created (a `capsule`). With controlled aliasing, we can promote the `capsule` reference to a `high` security level (i.e., a `low capsule Password` can be promoted to a `high capsule Password`), and then, it can be assigned to the field in (10). All in all, a `mut` references can be promoted to a `capsule`, transferred to another security level and then reassigned to another `mut` reference.

Any method that takes a single `mut` in input, mutates it, and returns it as `mut` can be called with a `capsule` parameter and the result will also be promoted to `capsule`. This pattern allows great flexibility when encapsulated mutable objects need to be mutated [Giannini et al. 2019].

3 DEFINITIONS FOR THE SIFO TYPE SYSTEM

In this section, we define well-formedness of the type system and useful helper methods to introduce typing rules in the following section.

Well-Formedness. A well-formed program respects the following conditions: All classes and interfaces are uniquely named. All methods in a specific class or interface are uniquely named. All fields in a specific class are uniquely named. All parameters in a method header are uniquely named, and there is no explicit method parameter called `this`. The subtyping graph induced by implemented interfaces is acyclic (in this simplified language, we do not have class extension). `capsule` references can be used at most one time.

- $sec(T) = s$, returns the security level s in type T.
- $mdf(T) = mdf$, returns the modifier in type T.
- $class(T) = C$, returns the class C in the type T.
- $fields(C) = T_1\ f_1 \ldots T_n\ f_n$, returns the field declarations of class C.
- $p(C) = \texttt{class}\ C\ \texttt{implements}\ \overline{C}\ \{\overline{F}\ \ \overline{M}\}$, returns the declaration of class C.
- $lub(s_0, \ldots, s_n) = s$, returns the least upper bound of the parameters $s_0, \ldots s_n$.
- $T[s'] = lub(s, s')\ mdf\ C$, where $T = s\ mdf\ C$, defined only if $s' \leq s$ or $s \leq s'$; returns a new type with security level $lub(s, s')$
- $mdf \triangleright mdf' = mdf''$, returns the modifier of an expression when accessing a field.
  $\texttt{mut} \triangleright mdf = \texttt{capsule} \triangleright mdf = mdf$
  $\texttt{imm} \triangleright mdf = mdf \triangleright \texttt{imm} = \texttt{imm}$
  $\texttt{read} \triangleright \texttt{mut} = \texttt{read}$.

Fig. 2. Helper functions

If $s\ mdf\ \texttt{method}\ T\ m(T_1\ x_1 \ldots T_n\ x_n)$ is declared in C, with $T_0 = s\ mdf\ C$ then
1: $T_0[s'] \ldots T_n[s'] \rightarrow T[s'] \in methTypes(C, m)$
2: $(T_0[s'] \ldots T_n[s'] \rightarrow T[s'])[\texttt{mut}\backslash\texttt{capsule}] \in methTypes(C, m)$
3: $(T_0[s'] \ldots T_n[s'] \rightarrow T[s'])[\texttt{read}\backslash\texttt{imm}, \texttt{mut}\backslash\texttt{capsule}] \in methTypes(C, m)$

Fig. 3. Definition of multiple method types

Helper Functions. In Figure 2, we show some helper functions for our type system. The first three notations extract the security level, the type modifier, and the class name from a type. The next two return fields and class declarations. The *lub* operator is defined to return the least upper bound of a set of input security levels arranged in a lattice. For example, since $\texttt{low} \leq \texttt{high}$, we have $lub(\texttt{low}, \texttt{high}) = \texttt{high}$. A lattice of security levels was first introduced by Bell and LaPadula [Bell and La Padula 1976], and Denning [Denning 1976]. A lattice is a structure $\langle L, \leq, lub, \top, \bot \rangle$ where L is a set of security levels and $\leq$ is a partial order (e.g., $\texttt{low} \leq \texttt{high}$). The lattice defines an upper bound of security levels. A set of elements $X \subseteq L$ has an upper bound y if $\forall x \in X : x \leq y$. An upper bound u of X is the least upper bound (*lub*) if $u \leq y$ for each upper bound y of X. To form an upper semi-lattice, a unique least upper bound (*lub*) for every subset of L must exist. Additionally, we restrict the lattice to be bounded with the greatest element $\top$ and the least element $\bot$.

In Figure 2, the function $s\ mdf\ C[s']$ returns a new type whose security level is the least upper bound of the two. The security level is set to $lub(s, s')$ and the modifier and class remain the same. The last function $mdf \triangleright mdf'$ computes a resulting modifier if a field with type modifier mdf' is accessed from some reference with type modifier mdf. For example, if we access a `mut` field from a `mut` reference we get a `mut` value, but if we access a `mut` field from a `read` reference, we get a `read` value. If either the reference or the field are `imm`, then `imm` is returned; thanks to deep immutability, the whole reachable object graph is immutable.

Multiple Method Types. Instead of a single method type as in Featherweight Java [Igarashi et al. 2001], we return a set of method types using $methTypes(C, m) = \{\overline{T_0} \rightarrow T_0,\ \ldots,\ \overline{T_n} \rightarrow T_n\}$. The programmer just declares a method with a single type, and the others are deduced by applying all the transformations shown in Fig. 3. Multiple method types reduce the need of implementing the same functionality several times, where the same parameter has only different type modifiers or security levels. The base case, as declared by the programmer, can be transformed in various ways: (1) A method working on lower security data can be transparently lifted to work on higher

security data (some security level s'). This means that methods that are not concerned with security are usually declared as working on a `low` receiver and `low` parameters, returning a `low` result. Note that the security level remains unchanged when s' is chosen as `low`. Thus, we can use $T[s']$ with s' different from `low` when we are in a context where we need to manipulate secure data. The multiple method types lift the method as if it was declared with higher receiver, parameters, and return type. For example, a mathematical method should return the same security level as the security level of the parameters. In our language, we can just implement this method once with the lowest security level and reuse it with any other security level of the lattice. As a comparison, the Jif tutorial[4] suggests that a mathematical method should be implemented with a generic security level.

(2) The second case swaps all `mut` types for `capsule` ones. If we provide `capsule` instead of `mut` in the input, we can use the method to produce a `capsule` return value. This corresponds to `capsule` recovery/promotion in [Giannini et al. 2019]. By providing all `mut` parameters as `capsule`, the method would not take any `mut` as input. Any `mut` object that is returned, is created inside of the method execution (as we do not have any form of global state/variables) and thus can be seen as a `capsule` from outside the scope of the method body. For example, a method declared as

```
low mut method low mut Person father(low imm String name)
```

can be also used as if it was declared as

```
low capsule method low capsule Person father(low imm String name),
```

where all `mut` parameters (just the receiver in this example) and the return type are turned into `capsule`. (3) The third case swaps all `mut` types for `capsule` ones and all `read` types for `imm` ones. This is useful if the method was returning a `read` value; in this case we can obtain an `imm`. This corresponds to immutable recovery/promotion in [Giannini et al. 2019] and can be intuitively understood by considering that a `read` reference can point to either an immutable or a mutable object. If it was an immutable object, it is fine to return it as `imm`; if it was a mutable object, then for the same reasons as case (2), we can promote it to `capsule`, which is a subtype of `imm`. Note that in all the three cases, a method working on lower security data can be transparently lifted to work on higher security data.

4 TYPING RULES

The typing rules are presented in Fig. 4. We assume a reduction similar to Featherweight Java [Igarashi et al. 2001; Pierce 2002]. We have a typing context $\Gamma ::= x_1 : T_1 \ldots x_n : T_n$ which assigns types T_i to variables x_i.

Sub and Subsumption. We allow traditional subsumption for modifiers and class names. However, we are invariant on the security level. We assume our interfaces to induce the standard subtyping between class names.

T-Var. A variable x is typed using the context Γ.

Field Access. The result of the field access has the class of the field f. The security level is the least upper bound of the security levels of e_0 and f. The resulting modifier is the sum of the modifiers of e_0 and f as defined in Fig. 2. In this way, if we read a `low mut Person` field from a `high read` receiver, we obtain a `high read Person` result.

Field Assign. The reference resulting from e_0 has to be `mut` to allow the assignment. The security level of the assigned expression e_1 is the least upper bound of the security levels of expression e_0 and the field f as declared in C. For example, if we assign a `high` expression e_1, either the field f or the reference resulting from e_0 need to be `high`.

Call. We allow a method call if there is a method type where all parameters and the return value are typable. The security levels of the return type and all `mut` or `capsule` parameters have to be greater than or equal to the security level of the receiver. This requirement is

[4]https://www.cs.cornell.edu/jif/doc/jif-3.3.0/manual.html

$$\frac{C \le C' \qquad mdf \le mdf'}{s\ mdf\ C \le s\ mdf'\ C'}\ (\textsc{Sub}) \qquad \frac{\Gamma \vdash e : T' \qquad T' \le T}{\Gamma \vdash e : T}\ (\textsc{Subsumption}) \qquad \frac{}{\Gamma \vdash x : \Gamma(x)}\ (\textsc{T-Var})$$

$$\frac{\Gamma \vdash e_0 : s_0\ mdf_0\ C_0 \qquad s_1\ mdf_1\ C_1\ f \in fields(C_0)}{\Gamma \vdash e_0.f : lub(s_0, s_1)\ mdf_0 \triangleright mdf_1\ C_1}\ (\textsc{Field Access})$$

$$\frac{\begin{array}{c}\Gamma \vdash e_0 : s_0\ \texttt{mut}\ C_0 \\ \Gamma \vdash e_1 : lub(s_0, s)\ mdf\ C \qquad s\ mdf\ C\ f \in fields(C_0)\end{array}}{\Gamma \vdash e_0.f = e_1 : lub(s_0, s)\ mdf\ C}\ (\textsc{Field Assign})$$

$$\frac{\begin{array}{c}\Gamma \vdash e_0 : T_0 \ldots \Gamma \vdash e_n : T_n \qquad sec(T) \ge sec(T_0) \\ if\ mdf(T_i) \in \{\texttt{mut}, \texttt{capsule}\}\ then\ \mathrm{sec}(T_i) \ge \mathrm{sec}(T_0) \qquad T_0 \ldots T_n \to T \in methTypes(class(T_0),\ m)\end{array}}{\Gamma \vdash e_0.m(e_1 \ldots e_n) : T}\ (\textsc{Call})$$

$$\frac{\Gamma \vdash e_1 : T_1[s] \ldots \Gamma \vdash e_n : T_n[s] \qquad fields(C) = T_1\ f_1 \ldots T_n\ f_n}{\Gamma \vdash \texttt{new}\ s\ C(e_1 \ldots e_n) : s\ \texttt{mut}\ C}\ (\textsc{New}) \qquad \frac{\Gamma[\texttt{mut}\backslash\texttt{read}] \vdash e : s\ \texttt{mut}\ C}{\Gamma \vdash e : s\ \texttt{capsule}\ C}\ (\textsc{Prom})$$

$$\frac{s' \le s \qquad \Gamma \vdash e : s'\ mdf\ C \qquad mdf \in \{\texttt{imm}, \texttt{capsule}\}}{\Gamma \vdash e : s\ mdf\ C}\ (\textsc{Sec-Prom})$$

$$\frac{\texttt{this} : s\ mdf\ C,\ x_1 : T_1 \ldots x_n : T_n \qquad \vdash e : T}{C \vdash s\ mdf\ \texttt{method}\ T\ m(T_1\ x_1 \ldots T_n\ x_n)\{\texttt{return}\ e;\}}\ (\textsc{M-Ok})$$

$$\frac{C \vdash M_1 \ldots C \vdash M_n \qquad mhs(\overline{C}) \subseteq mhs(M_1 \ldots M_n)}{\texttt{class}\ C\ \texttt{implements}\ \overline{C}\ \{\overline{F}\ M_1 \ldots M_n\}}\ (\textsc{C-Ok}) \qquad \frac{mhs(\overline{C}) \subseteq \overline{MH}}{\texttt{interface}\ C\ \texttt{extends}\ \overline{C}\ \{\overline{MH}\}}\ (\textsc{I-Ok})$$

Fig. 4. Expression typing rules

needed because through dynamic dispatch the receiver may leak information. This is one of the crucial points of our formalism, as explained in Section 2.2.

New. The newly allocated object is created as a mutable object, and with a specified security level s. This rule checks that the parameter list $e_1 \ldots e_n$ has the same length as the declared fields. The object of class C has a list of fields $f_1 \ldots f_n$. Each parameter e_i is assigned to a field f_i. This assignment is allowed if the type of parameter e_i is (a subtype of) $T_i[s]$. The programmer can choose s to raise the expected security level over the level originally declared for the fields. In order to use an actual parameter with a higher security level (s) to initialize a field defined with a lower security level, the newly created object needs to have this chosen security level s. By using rule Sec-prom, we can do the opposite, initializing higher security fields with lower security `imm`/`capsule` values. For example if we have a class `Ex {low Object a; high Object b; topSecret Object c;}`, we can create correct objects with

```
1 new low Ex(lowValue, highValue, topSecretValue)
2 new high Ex(highValue, highValue, topSecretValue)
3 new topSecret Ex(topSecretValue, topSecretValue, topSecretValue)
```

An object `new high Ex(highValue, topSecretValue, topSecretValue)` is incorrect because the second parameter is `topSecret`. Accessing a `high` reference and a `high` field would return a `high` value. This leaks the `topSecretValue` object.

The object `new topSecret Ex(highValue, topSecretValue, topSecretValue)` is only correct if the

$$\frac{\Gamma \vdash e : s\ \texttt{imm}\ \texttt{Bool} \qquad \Gamma[mut(s), final(s)] \vdash e_1 : T \qquad \Gamma[mut(s), final(s)] \vdash e_2 : T}{\Gamma \vdash \texttt{if}\ e\ \texttt{then}\ e_1\ \texttt{else}\ e_2 : T} \quad (\textsc{If})$$

$$\frac{\Gamma \vdash e : s\ mdf\ C \qquad mdf \in \{\texttt{imm}, \texttt{capsule}\}}{\Gamma \vdash \texttt{declassify}(e) : \bot\ mdf\ C} \quad (\textsc{Decl})$$

Fig. 5. Extension: expression typing rules for if and declassify

`highValue` object can be promoted to `topSecret`. This is only possible for immutable or encapsulated objects.

Prom. *Promotion* from `mut` to `capsule` is possible if all `mut` references are only seen as `read` in the typing context. Since a `read` cannot be saved into a field of a `mut` object, we know that the reachable object graph from those `read` variables will not be part of the reachable object graph of the result.

Sec-Prom. *Security promotion* raises the security level of a `capsule` or `imm` expression. This captures the intuitive idea that a higher security level is allowed to see all data with lower security levels. However, this is sound only for `capsule` or `imm` expression. An immutable object cannot be modified, so the promotion is secure because no new confidential information can be injected into its ROG. Also a `capsule` object can be passed to a new reference with a higher security level. A leak through the lower `capsule` reference cannot happen, because a `capsule` reference can be used at most one time. Instead, in the case of a mutable object, this assignment would cause a possible leak: it would allow a `high` and `low` alias reference to the same object; and if the `high` reference was updated with `high` data, the `low` reference would see such data as well. Also `read` cannot be promoted: a promoted `read` object can have a `low mut` alias reference to the same object that could now sneakely update the data seen as `high`.

M-Ok. This rule checks that the definition of a method is well typed. Using the receiver type and the parameter types, e must have the same type as the declared return type.

C-Ok. This rule checks that the definition of a class is well typed. The rule uses a helper function *mhs* which returns the method headers declared in a set of classes or interfaces, or it directly returns the headers of a set of methods. A well typed class C implements all methods that are declared in the interfaces $\overline{C}$.

I-Ok. A correct interface must contain all method headers of the implemented interfaces $\overline{C}$.

Implicit Information Flows. The language as presented is minimal but using well-known encodings it can support imperative update of local variables (use box objects with a single field and field updates) and conditionals (use any variation of the Smalltalk [Goldberg and Robson 1983] way to support control structures). However, in Fig. 5, for the sake of a more compelling explanation, we show how the `if` construct could be typed if we expand our language with `if`, Booleans and updatable local variables.

If. For a conditional statement with a `Bool` expression in the guard, we define that both branches e_1 and e_2 must have the same type T. With $\Gamma[mut(s), final(s)]$, we introduce two restrictions: with $mut(s)$, we prevent mutation of `mut` objects with a security level lower than s by seeing them as `read`, and with $final(s)$, we prevent updating all local variables with a security level lower than s. If s is the lowest security level, both functions do not restrict Γ.

Therefore, assignments to less confidential variables or fields in the branches are prohibited to prevent leaks. This means that if the expression in the guard of a conditional statement has

```
1  interface I {
2    low mut method low imm I doIt(low imm I l1, low imm I l2);
3  }
4  class C1 implements I {
5    low mut method low imm I doIt(low imm I l1, low imm I l2) {
6      return l1; }
7  }
8  class C2 implements I {
9    low mut method low imm I doIt(low imm I l1, low imm I l2) {
10     return l2; }
11 }
12 ...
13 high mut C1 c1 = new high C1();
14 high mut C2 c2 = new high C2();
15 low imm C1 l1 = new low C1();
16 low imm C2 l2 = new low C2();
17 high mut I i = c1;//c1 assigned to reference of type I
18 low imm I x = i.doIt(l1,l2);//ILL TYPED in our system
19 //if it was accepted, by observing low variable x = l1
20 //we could deduce the content of the high variable i = c1
21
22 //equivalent behaviour using an if
23 if (i instanceof C1){ x = l1; } else { x = l2; }
```

Listing 3. Ill-typed example of a method call

a security level that is higher than the lowest security level, only assignments to variables of at least the security level of the guard are allowed. Additionally, only mutable objects of at least the security level of the guard can be mutated. In this way, only data whose security level is at least the one of the guard can be mutated.

Using the Smalltalk-style as discussed above, our pre-existing rules would handle the encoded code exactly as with the explicit If-rule, Booleans, and local variables. Thus, our system is minimal, but does not lack expressiveness. The If-rule has a similar constraint as the Call-rule where return type and `mut` and `capsule` parameters have to be greater than or equal to the security level of the receiver.

The following example, in both OO style and with an explicit `if` shows the mechanism to prevent implicit information flow leaks: In Listing 3, we have an interface `I` that declares a method `doIt` that gets two `low imm I` parameters as input. The classes `C1` and `C2` implement the interface and the method. The implemented method of `C1` returns the first parameter and the implemented method of `C2` returns the second parameter. We initialize two `high` variables `C1 c1` and `C2 c2` and two `low` variables `C1 l1` and `C2 l2`. By assigning `c1` to `i` in Line 17, we hide the information of the explicit class behind the interface. However, if we are allowed to execute Line 18, calling the method `doIt`, the class `c1` is revealed because `l1` is returned. The attacker gets the information about the explicit class by observing the return value. This example is an object-oriented implementation of a conditional statement. If we use an `if` instead of dynamic dispatch, the leak is clearly visible (see Line 23), as we assign `low` variables in branches of a `high` guard. To prevent such leaks, we define that the security level of the return type is never lower than the security level of the receiver. Information does not only flow through the method result: also `mut` or `capsule` parameters can be used to push information out of the method; thus also the security level of `mut` and `capsule` parameters must never

be lower than the security level of the receiver. Thus, in both cases with the Call-rule and with the If-rule the implicit leak is prevented.

Declassification. A `mut` or `read` reference can only be assigned to references of the same security level. However, since `imm` and `capsule` references are referentially transparent, it is safe to assign an `imm` or `capsule` object from a lower security level to a higher one. On the other hand, we are not allowed to assign an object with a higher security level to a reference with a lower security level. Similar to the `if`, we consider adding a `declassify` operator that can be used to manipulate the security level *s* of expressions to allow a reverse information flow in appropriate cases. In some cases, this reverse information flow is needed to develop meaningful programs. For example, if a confidential password is hashed, the value should be assignable to a public output. With the `declassify` expression, the security level of a `capsule` or `imm` reference is set to the lowest security level. In Fig. 5, the Decl rule is shown.

Decl. The `declassify` rule is used to change the security level of `capsule` or `imm` expressions to the bottom level of the lattice.

`declassify` should be used with caution because secure information is leaked in the case of inappropriate use. In this rule, we cannot declassify an expression to a specific security level, but this is not a limitation, since we can encapsulate declassification statements inside of methods which directly promote the declassified expression to the desired security level. `mut` and `read` references cannot be declassified because potentially existing aliases are a security hazard. For example, if you declassify a `high mut` reference and a `high read` alias still exists, an attacker could use that now `low mut` reference to mutate information visible as `high`. Declassification is not part of our system to type check secure programs, and we do not need it to make secure programs, rather it is a mechanism to break security in a controlled way. That is, when comparing with examples of other papers [Myers 1999], we do not use `declassify` to encode behavior. We can still use it to print out results to show that the code is working. In the Decl rule that we present, `declassify` is just a special expression. In the full SIFO language embedded in L42, declassification can be flexibly tuned to the user needs preventing accidental declassification.

5 PROOF OF NONINTERFERENCE

In this section, we aim to ensure *noninterference* [Goguen and Meseguer 1982] according to our information flow policy. Noninterference is a central criterion for secure information flow, as we want to ensure that an attacker cannot deduce confidential data by observing data with lower security levels. It is based on the indistinguishability of program states. Two program states are indistinguishable (also referred to as *observably similar*) up to a certain security level if they agree on their memory reachable from references with a security level lower than that specific security level. Using this property, a program satisfies the noninterference Theorem 5.0 if and only if the following holds: if a program is executed in two observably similar memories up to a certain security level, then the resulting memories are also observably similar up to the same security level, but may differ in higher security levels.

Theorem 5.0 (General Noninterference).
If we have expressions e_1 and e_2 without declassification that are well typed and have the same low values, but possible different high values (e_1 lowEqual e_2 see Definition 5.6), M_1 and M_2 are well typed memories, M_1 and M_2 are low observably similar, $M_1|e_1 \rightarrow^* M_1'|v_1$, $M_2|e_2 \rightarrow^* M_2'|v_2$, then M_1' and M_2' are low observably similar, and memories M_1', M_2', values v_1, and v_2 are well typed and v_1 lowEqual v_2.

In this section, we prove noninterference for a lattice with a `low` and a `high` security level (`low` $\leq$ `high`) for terminating programs. Nonterminating programs and programs with an arbitrary lattice

$$
\begin{array}{lcl}
e & ::= & x \mid e.f \mid e.f = e \mid e.m(\overline{e}) \mid \texttt{new}\ s\ C(\overline{e}) \mid v \\
\mathcal{E}_v & ::= & [] \mid \mathcal{E}_v.f \mid \mathcal{E}_v.f = e \mid v.f = \mathcal{E}_v \mid \mathcal{E}_v.m(\overline{e}) \mid v.m(\overline{v}\ \mathcal{E}_v\ \overline{e}) \mid \texttt{new}\ s\ C(\overline{v}\ \mathcal{E}_v\ \overline{e}) \\
\mathcal{E} & ::= & [] \mid \mathcal{E}.f \mid \mathcal{E}.f = e \mid e.f = \mathcal{E} \mid \mathcal{E}.m(\overline{e}) \mid e.m(\overline{e}\ \mathcal{E}\ \overline{e'}) \mid \texttt{new}\ s\ C(\overline{e}\ \mathcal{E}\ \overline{e'}) \\
v & ::= & s\ mdf\ o \\
M & ::= & o_1 \mapsto C_1(\overline{o_1}) \ldots o_n \mapsto C_n(\overline{o_n})
\end{array}
$$

Fig. 6. Runtime syntax and values

$$
\frac{M|e \rightarrow M'|e'}{M|\mathcal{E}_v[e] \rightarrow M'|\mathcal{E}_v[e']}\ (\textsc{Ctx}) \qquad \frac{v = s\ mdf\ o \qquad o \mapsto C(o_1 \ldots o_n) \in M \qquad fields(C) = T_1\ f_1 \ldots T_n\ f_n}{M|v.f_i \rightarrow M|lub(s, \sec(T_i))\ \ mdf \triangleright mdf(T_i)\ o_i}\ (\textsc{Field Access})
$$

$$
\frac{fields(C) = \_\ T_0\ f_0 \ldots T_n\ f_n \qquad v_1 = s\ mdf\ o \qquad v_2 = \_\ \_\ o' \qquad v_2' = lub(s, \sec(T_0))\ \ mdf(T_0)\ o'}{M, o \mapsto C(\overline{o}\ o_0 \ldots o_n)|v_1.f_0 = v_2 \rightarrow M, o \mapsto C(\overline{o}\ o'\ o_1 \ldots o_n)|v_2'}\ (\textsc{Field Update})
$$

$$
\frac{\begin{array}{c} T_i' = s_i'\ mdf_i'\ C_i \qquad v_i = s_i\ mdf_i\ o_i \qquad v_i' = s_i'\ mdf_i'\ o_i \qquad o_0 \mapsto C_0(\overline{o}) \in M \\ p(C_0) = \texttt{class}\ C_0\_\{\_\ s\ mdf\ \{\texttt{method}\ T\ m(T_1\ x_1\ \ldots T_n\ x_n)\{\texttt{return}\ e\}\_\} \\ T_0' \ldots T_n' \rightarrow T' = mostSpecMethType(C_0, m, s_0 \ldots s_n, mdf_0 \ldots mdf_n) \end{array}}{M|v_0.m(v_1 \ldots v_n) \rightarrow M|e[this \backslash v_0', x_1 \backslash v_1', \ldots, x_n \backslash v_n']}\ (\textsc{call})
$$

$$
\frac{v_1 = s_1\ mdf_1\ o_1 \ldots v_n = s_n\ mdf_n\ o_n}{M|\texttt{new}\ s\ C(v_1 \ldots v_n) \rightarrow M, o \mapsto C(o_1 \ldots o_n)|s\ \texttt{mut}\ o}\ (\textsc{New})
$$

Fig. 7. Reduction rules

do typecheck, and we expect noninterference to work for those too, but our proof technique does not address those cases. We also do not include the `declassify` operation because this rule explicitly allows `high` data to interfere with data of lower security levels. This means, `declassify` is only an explicit mechanism to break security in a controlled way, as we explained in Section 4. In the section, we use the notation of memory and expression. The meaning of these terms are overloaded. A memory is often a stack in a while languages, in object-oriented languages, the memory is often a heap. In our expression-based language, we model a heap (a map from memory locations to the values stored for each field as defined by the location's class), and we use the expressions themselves to track the values that are accessible within each expression (similar to how the stack achieves this during the execution). This means, memory M captures the heap and expression e captures the stack and any inputs. We cannot model the whole memory without the expression.

5.1 Reduction Rules

SIFO is an additional type system layer and does not influence the language semantics. However, for the sake of the noninterference proof, we need to instrument the small-step reduction to keep track of security and modifiers during program execution. To this aim, we define in Fig. 6 values v as a location o in a store with security level and type modifier. The store is some memory M. In M, a location points to some class C where each field is again a location o_i in the memory M. With the evaluation context $\mathcal{E}_v$, we define the order of evaluation. We assume two well-formedness properties. The memory is well-formed if M is a map from o to $C(\overline{o})$, thus the locations $\overline{o}$ in domain of M are unique. The reduction arrow ($M|e \rightarrow M'|e'$) is well-formed if M and M' have no dangling pointers with respect to e and e' (i.e., every pointer points to a valid object in the memory). In Figure 7, the following reduction rules are shown.

Definition 5.1 (mostSpecMethType).

- $mostSpecMethType(C, m, ss, mdfs) = openCapsules(Ts' \to T, mdfs)$
  $s\ mdf$ **method** $T_0\ m(T_1\ x_1 \dots T_n\ x_n)$ *in* C
  $raiseFormalSecurity(s\ mdf\ C\ T_1 \dots T_n \to T_0, ss) = Ts \to T$
  $raiseActualSecurity(Ts, ss, mdfs) = Ts'$

- $raiseFormalSecurity(T_1 \dots T_n \to T_0, s'_1 \dots s'_n) = T'_1 \dots T'_n \to T'_0$
  $T_i = s_i\ mdf_i\ C_i$
  $T'_i = lub(s, s_i)\ mdf_i\ C_i$
  $s = lub(\{s'_i | s'_i > s_i\})$

- $raiseActualSecurity(T_0 \dots T_n, s_0 \dots s_n, mdf_0 \dots mdf_n) = T'_0 \dots T'_n$
  $T_i = s''_i\ mdf_i\ C_i$
  $T'_i = sec(T_i)\ mdf_i\ C_i$
  $if\ s_i < sec(T_i)\ then\ mdf_i \in \{$**capsule**, **imm**$\}$

- $openCapsules(T_1 \dots T_n \to T, mdf'_1 \dots mdf'_n) = T'_1 \dots T'_n \to T$
  $T_i = s_i\ mdf_i\ C_i$
  $T'_i = s_i\ mdf'_i \triangleright mdf\ C_i$

$$\frac{M|(\textbf{high}\ mdf\ o).m(\overline{v}) \to^{+} M'|(s\ mdf\ o')}{M|\mathcal{E}_v[(\textbf{high}\ mdf\ o).m(\overline{v})] \to_{call} M'|\mathcal{E}_v[(\textbf{high}\ mdf\ o')]} \quad (\textsc{Hrec})$$

$$\frac{e \text{ not of form } \mathcal{E}_v[(\textbf{high}\ mdf\ o).m(\overline{v})] \qquad M|e \to M'|e'}{M|e \to_{call} M'|e'} \quad (\textsc{Hother})$$

Fig. 8. Additional reduction rules for the noninterference proof

Ctx. This is the conventional contextual rule, allowing the execution of subexpressions.

Field Access. A field access f_i of a value v is reduced to a location o_i if the location o of v points to the suitable class $C(o_1 \dots o_n)$. The security level is the least upper bound of the security levels of v and f_i and the modifier is the sum of modifiers of v and f_i.

Field Update. The store $o \mapsto C(\overline{o}\ o_0 \dots o_n)$ is updated with an assignment of v_2 to the field f_0. The location o_0 is replaced with o'. The security level of the resulting value v'_2 is the least upper bound of the security levels of expression v_0 and the field f_0 as declared in C. The type modifier of v'_2 is equal to the type modifier of the field f_0 as declared in C.

Call. We reduce a method call to an expression e, where each value v_i is assigned to a parameter x_i. As we use multiple method types, the actual assigned values v'_i can have an updated security level or type modifier. Additionally, the called method has to be declared in the class C_0 pointed to by the location in v_0. The concrete calculation of the updated types T'_i with *mostSpecMethType* is shown in Definition 5.1. The definition calculates the exact

method types to support the proof of noninterference. To calculate the types T_i', the functions needs as parameters, the class name C, the method name m, and the used security levels ss and type modifiers $mdfs$ to call this method. First with *raiseFormalSecurity*, for each formal parameter type T_i, the security level can be raised. We collect all security levels s_i' where a security level higher than declared in the formal parameter is passed. The least upper bound of the collected security levels is the minimum security level for all actual parameters. It is allowed that formal parameter have higher security levels than s if a current parameter is passed with the same security level higher than s. With *raiseActualSecurity*, it is checked that the actual parameters have the same security level as the now raised formal parameters. Only actual parameters with type modifier `imm` or `capsule` can be raised to the needed level. In the last step, the combined type modifier of the actual and formal parameter is calculated with the function of Fig. 2.

New. The newly created object is reduced to a location o in the memory that points to the class C where each field is again a location o_i. The reduced value has the same security level s as in the expression before the reduction and a `mut` type modifier. Note that we do not need to say that a new reference is not in the domain of the old memory. This is implicit by the well-formedness of the memory.

Hrec, Hother. The two rules in Fig. 8 are added to condense the reduction of methods calls on high receivers ($\rightarrow_{call}$). These rules only consider a `low` $\leq$ `high` lattice of security levels and are needed for our noninterference proof for technical reasons. We will prove noninterference only for a `low` $\leq$ `high` lattice, but the typing rules work with any security lattice. As you can see, we condense all execution steps that happen under the control of a `high` receiver into a single more abstract step. Here, $\rightarrow^+$ is the transitive closure. Of course, rule (Hrec) is not applicable when the reduction of such a method does not terminate; this is why our proof technique only works on terminating programs: it does not make sense to talk about noninterference for a program stuck into a non-terminating loop inside of a `high` method. This program would never reach again a state where a `low` attacker may attempt to observe data.

5.2 Definition of Similarity w.r.t. Security Levels

In this subsection, we define the (observable) similarity of two memories for the proof of noninterference. Therefore, we need further definitions of reachable object graphs (ROG). We define mutable, `low`, and `high` memories using a notation of reachable object graph. Definition 5.2 defines the mutable ROG of a memory and the current state of the main expression e. Note how this is similar to ownership work where the stack is used to track the current top level state. In an expression-based language, the stack is represented as the set of values inside of the main expression. The MROG contains every location inside of the expression e that has a `mut` or a `capsule` type modifier. Additionally, `mut` fields of locations in the MROG are included. In Definition 5.3, the `low` ROG contains every location inside of the expression e that has a `low` security level. Additionally, `low` fields of locations in the `low` ROG are included.

Definition 5.2. $MRog(M, e) = \overline{o}$
- $o \in MRog(M, e)$ if:
  $e = \mathcal{E}[s \texttt{ mut } o]$
- $o \in MRog(M, e)$ if:
  $e = \mathcal{E}[s \texttt{ capsule } o]$
- $o_i \in MRog(M, e)$ if:
  $o \in MRog(M, e)$
  $o \mapsto C(o_1 \dots o_n)$ *in* M
  $\{\texttt{class } C \_ \{T_1 f_1 \dots T_n f_n \_\}$
  $mdf(T_i) = \texttt{mut}$

Definition 5.3. $lowRog(M, e) = \overline{o}$
- $o \in lowRog(M, e)$ if:
  $e = \mathcal{E}[\texttt{low } \_ \; o]$
- $o_i \in lowRog(M, e)$ if:
  $o \in lowRog(M, e)$
  $o \mapsto C(o_1 \dots o_n)$ *in* M
  $\texttt{class } C \_ \{T_1 f_1 \dots T_n f_n \_\}$
  $sec(T_i) = \texttt{low}$

In Definition 5.4, the high ROG includes locations of high mut values. The high ROG also includes every mut value that is pointed to by a location in the high ROG. Furthermore, the high mut fields of a location in the low ROG are included. We exclude high imm values, as imm values can be referenced by both low and high references.

Definition 5.4. $highRog(M, e) = \overline{o}$

- $o \in highRog(M, e)$ *if* :
  $e = \mathcal{E}[\texttt{high mut } o]$
- $o_i \in highRog(M, e)$ *if* :
  $o' \in highRog(M, e)$
  $o' \mapsto C(o_1 \dots o_n)$ *in* M
  $\texttt{class } C \_ \{T_1 f_1 \dots T_n f_n \_\}$
  $mdf(T_i) = \texttt{mut}$

- $o_i \in highRog(M, e)$ *if* :
  $o' \in lowRog(M, e)$
  $o' \mapsto C(o_1 \dots o_n)$ *in* M
  $\texttt{class } C \_ \{T_1 f_1 \dots T_n f_n \_\}$
  $sec(T_i) = \texttt{high}$
  $mdf(T_i) = \texttt{mut}$
  $o_i \in dom(M)$

In Definition 5.5, we define the observable similarity of two memories. Two memories M_1 and M_2 are similar given an expression e, if and only if the low locations of both memories are equal. As explained before, the expression e is needed to track the top level state. We need a transformation on the memories to filter high locations and high fields of classes pointed by low locations. As we are only interested in similarity of low locations for the noninterference proof, these high locations have to be filtered. The filtering is defined by $M[only\ \overline{o}]$. In the given memory M, each location o is removed that is not in the input set $\overline{o}$. Additionally, for the o in the input set $\overline{o}$, each o_i in $o \mapsto C(o_1 \dots o_n)$, where the corresponding field in class C is defined with a high security level, is replaced with the location o to filter the explicit high location o_i. Thus, with this transformation two memories are equal, if they differ only in the high ROG.

Removing the high locations in this way may produce an ill type memory; this is not a problem since those memories are only used as a device to define $\_similar(e)\_$ and not in the reduction.

Definition 5.5.
$M_1\ similar(e)\ M_2 \leftrightarrow M_1[only\ lowRog(M_1, e)] = M_2[only\ lowRog(M_2, e)]$
where $M[only\ \overline{o}] = M'$ is defined as:
- $(o_1 \mapsto C_1(\overline{o_1}) \dots o_n \mapsto C_n(\overline{o_n}))[only\ \overline{o}] =$
  $o_1 \mapsto C_1(\overline{o_1})[only\ \overline{o}] \dots o_n \mapsto C_n(\overline{o_n})[only\ \overline{o}]$
- $(o \mapsto C(\_))[only\ \overline{o}] = empty$ *if* o *is not in* $\overline{o}$
- $(o \mapsto C(o_1 \dots o_n))[only\ \overline{o}] = o \mapsto C(o'_1 \dots o'_n)$ *if* o *in* $\overline{o}$ with:
  $fields(C) = T_1\ f1 \dots T_n\ fn$
  $o'_i = o_i$ *if* $sec(T_i) = \texttt{low}$
  $o'_i = o$ *if* $sec(T_i) = \texttt{high}$

The Definition 5.6 compares that two expressions are equal if we only consider the `low` values. It is defined as rule induction, where the only interesting case is that `high` values are ignored. This means, two expressions are *lowEqual* if either they are the same `low` expression, or possibly-different `high` locations.

Definition 5.6. e *lowEqual* e'
- x *lowEqual* x
- $e.f$ *lowEqual* $e'.f$ *iff* e *lowEqual* e'
- $e_0.f = e_0'$ *lowEqual* $e_1.f = e_1'$ *iff* e_0 *lowEqual* e_1 *and* e_0' *lowEqual* e_1'
- $e_0.m(e_1 \dots e_n)$ *lowEqual* $e_0'.m(e_1' \dots e_n')$ *iff* e_i *lowEqual* e_i' *for* i *in* $0 \dots n$
- `new` $s\ C(e_1 \dots e_n)$ *lowEqual* `new` $s\ C(e_1' \dots e_n')$ *iff* e_i *lowEqual* e_i' *for* i *in* $1 \dots n$
- (`low` $mdf\ o$) *lowEqual* (`low` $mdf\ o$)
- (`high` $mdf\ o$) *lowEqual* (`high` $mdf'\ o'$)

The Definition 5.7 is essential to constrain reduction: an alternative to our reduction that is undesirable could trivially preserve security by adding everything to the `high` memory so that no `low` objects remain. The definition of *preserves* constraints the reduction to only change the `high` memory in the few appropriate and necessary cases as follows: In the first trivial case, nothing is added. In the second case, a new `high` object is created and added to the `high` ROG. In the third case, a `low capsule` object is promoted to `high` and added to the `high` ROG. Here, all options of a promotion of a `capsule` object are shown (field assign, method call as receiver and as parameter, and object construction as a parameter).

Definition 5.7. M *preserves*(e/e') M' if one of the three holds:
1) $highRog(M, e) = highRog(M', e')$
2) $highRog(M, e), o = highRog(M', e')$ *then*
   $e = ctx_0[new\ high\ C(\overline{v})],\ e' = ctx_0[\texttt{high}\ mdf\ o]$
3) $highRog(M, e), MROG(M, \texttt{high}\ mdf'\ o) = highRog(M', e')$ *then*
   $e = ctx_0[low\ capsule\ o],\ e' = ctx_1[\texttt{high}\ mdf'\ o]$
   and e is equal to one of the following:
   $ctx[v.f = low\ capsule\ o]$
   $ctx[(low\ capsule\ o).m(\overline{v})]$,
   $ctx[v.m(\overline{v}(low\ capsule\ o)\overline{v'})]$,
   $ctx[new\ C(\overline{v}(low\ capsule\ o)\overline{v'})]$

5.3 Noninterference Theorem and Proof

We prove noninterference according to our information flow policy. In literature, there are many proposed languages (with proofs) that are very similar to the type system proposed in this work [Giannini et al. 2019]. Here, to avoid repeating those same proofs that are already presented in those other works, we accept two assumptions. (1) Soundness: the reduction does not get stuck. (2) Immutability and encapsulation: In addition to not getting stuck, the reduction also never mutates the ROG of an immutable object, and the ROG of capsules is always encapsulated (i.e., all mutable objects can be reached only through the `capsule` reference). Both assumptions are established and proved before [Giannini et al. 2019].

To prove noninterference, we first introduce two lemmas that facilitate the proof. We show that the reduction terminates using $\rightarrow_{call}$ and we show that, given two similar memories, each reduction step results in similar memories.

Call-Reduction Termination. We prove in Lemma 5.8 that the reduction $\rightarrow_{call}$ does not interfere with termination: if we have a well typed memory M and an expression e and the program terminates

with the normal reduction, then it also terminates with $\rightarrow_{call}$. The result for both reductions is also the same.

Lemma 5.8 ($\rightarrow_{call}$ Termination). *If memory M and expression e are well typed and if the reduction terminates with $\rightarrow$, then it terminates also with the reduction $\rightarrow_{call}$ with the same result.*

Proof. This can be verified by cases: $\rightarrow_{call}$ behaves exactly like $\rightarrow$, but has a different granularity of the steps. Therefore, $\rightarrow_{call}$ terminates in every case where $\rightarrow$ terminates. □

Bisimulation. To establish noninterference, Lemma 5.9, the bisimulation core, states that two well typed and similar memories M_1 and M_2 and expressions e_1 and e_2, where e_1 *lowEqual* e_2 holds, reduce to $M_1'|e_1'$ and $M_2'|e_2'$ that are also similar, and the reduced expressions e_1' and e_2' are *lowEqual*. We need property (2) to state that both memories are observably similar, and property (3) that also the expressions are similar regarding the observable values. Both properties together represent observably similar memories as in Theorem 5.0. Furthermore, the preservation property of each memory ensures that the reduction only changes the `high` memory in necessary cases. With this lemma, we know that each reduction step from similar memories results in similar memories: each $\rightarrow_{call}$ reduction step ensures noninterference.

Lemma 5.9 (Bisimulation Core).
Given well typed memories and expressions without declassification M_1, M_2, e_1, and e_2
where $M_1|e_1 \rightarrow^* \_|v_1$ and $M_2|e_2 \rightarrow^* \_|v_2$.
If the following holds
1) $M_1|e_1 \rightarrow_{call} M_1'|e_1'$,
2) M_1 similar(e_1) M_2,
3) and e_1 lowEqual e_2,
then:
A) $M_2|e_2 \rightarrow_{call} M_2'|e_2'$ and e_1' lowEqual e_2',
B) M_1' similar(e_1') M_2',
C) M_1 preserves(e_1/e_1') M_1',
D) M_2 preserves(e_2/e_2') M_2',
E) M_1', M_2', e_1', e_2' are well typed

Proof. We prove that all five conditions *A–E* are satisfied. For *A* and *B*, we prove this theorem by cases on $\rightarrow_{call}$. We only prove the cases including a context, because the proofs with an empty context imply the correctness of the rules without a context.

Proof of A and B by cases:

Case Ctx + Call:

If e_1 and e_2 are of form $\mathcal{E}_v[(\texttt{high}\ mdf\ o).m(\overline{v})]$, the proof is by rule (Hrec).

Proof of A: The only point of non-determinism in this language is the way new object identities are chosen, and the only way to introduce a new o is with the New rule. From assumption (*1*) and Lemma 5.8, we know that there is an execution of $\rightarrow_{call}$, containing an arbitrary number of reduction steps ($\rightarrow$). The reduction is of form $M|\mathcal{E}_v[(\texttt{high}\ mdf\ o).m(\overline{v})] \rightarrow_{call} M'|\mathcal{E}_v[(\texttt{high}\ mdf\ o'')]$, where the result is a `high` value, thus by the definition of *lowEqual*, $\mathcal{E}_v[(\texttt{high}\ \_\ \_)]$ *lowEqual* $\mathcal{E}_v[\texttt{high}\ \_\ \_)]$ holds.

Proof of B: We execute a number of steps on the `high` receiver. By assumption (*1*) and Lemma 5.8, this process terminates and produces a result. By typing rule Call, we know the result is `high` and the parameters *vs* must only contain `low` `read`/`imm`/`capsule` values. By the assumption that the language satisfies the modifier properties (e.g. immutability), we do not modify the ROG of the `low` `read`/`imm` parameters. The `low` capsules are promoted to `high` in both memories, and thus, will not be

part of the low ROG anymore.
All the other parameters and the receivers are high, so they will not influence the low values: the whole ROG of a high object is high, and computation can only influence reachable objects since we do not have any static variables. So B holds since the (shrunken) low ROG on both memories cannot be mutated.
If e_1 and e_2 are not of form $\mathcal{E}_v[(\texttt{high}\ mdf\ o).m(\overline{o})]$, the proof is by rule (Hother).

Proof of A: In this case we are doing a single reduction step $\rightarrow$. The only way to introduce non-determinism is by creating a new object, but this step is a method call. Thus, $M_1 = M_1'$, $M_2 = M_2'$ and e_1' *lowEqual* e_2'.

Proof of B: The expressions e_1 and e_2 must be of form $\mathcal{E}_v[(\texttt{low}\ mdf\ o).m(\overline{o})]$ and the low receiver is the same on both sides. Moreover, since the original memories are similar, the low o is an instance of the same class, thus the method call will resolve to the same body, and the application of reduction rule (Call) is deterministic and is identically in both cases, so the memories are not influenced (except for the usual shrinkage on promoted low capsule and low imm objects). Thus, B holds.

Case Ctx + Field Update:

Proof of A: By assumption (*1*), we know the expression reduces. The only way to introduce a new o is with the (new) rule; thus A holds since we use the same process to get v_2' (the rule applies a deterministic procedure).

Proof of B: In this case, if v_2 is low, we know: $M_1|\mathcal{E}_v[v_1.f_0 = v_2]$, $M_2|\mathcal{E}_v[v_1.f_0 = v_2]$, and M_1 *similar*$(\mathcal{E}_v[v_1.f_0 = v_2])$ M_2. Thus, $M_1'|v_2'$, $M_2'|v_2'$, and M_1' *similar* $(\mathcal{E}_v[v_2'])$ M_2'.

If v_2 is high, then we could have a different value in the second reduction, but this value will also be high, and thus, not influence similarity. By well typing, this high value will be stored in a high field. Intuitively, if v_1 is low, we can assign a high only if f_0 is high. In this case, the low ROG did not contain v_2 and now does not contain v_2', so B holds. If v_1 is high, then it was not part of the low ROG to begin with, so B holds.

However, we need to inspect all possible field update cases to check that all assignments do not violate our similarity property:
To shorten the writing for all cases, we assume a low reference `low1`, a high reference `high1` with a low field `lowF` and a high field `highF`. The assigned objects can be low `low2` or high `high2`.

- `low1.lowF=low2` This is equal in both reduction, so B holds.
- `low1.highF=low2` This is ok if low is imm or capsule. If we have removed the last low reference to 'low', then the result of _[only _] will shrink in the same way in both computations.
- `high1.highF=low2` This is ok if low is imm or capsule, and thus, it is absent in the low ROG.
- `high1.lowF=low2` This is ok if low is imm or capsule, and thus, it is absent in the low ROG.

Note for the capsule cases: The value v_2 was low capsule in $\mathcal{E}_v[v_1.f_0 = v_2]$, thus it was kept as part of the low memory by _[only _]. In the next step v_2' is now high, thus it is not kept as part of the low memory by _[only _]. Since the only change between the result of the _[only _] memory is the absence of the low capsule, B holds.

- `low1.lowF=high2` This is forbidden by the type system.
- `low1.highF=high2` This is ok and irrelevant, since it does not change the low ROG.
- `high1.highF=high2` This is ok and irrelevant, since it does not change the low ROG.
- `high1.lowF=high2` This is ok and irrelevant, since it does not change the low ROG.

Case Ctx + Field Access:

Proof of A: The only way to introduce non-determinism is the way new objects are created. We are accessing a location o that is equal in both cases or it is a high location. As we are not modifying the memories, $M_1 = M_1'$ and $M_2 = M_2'$ and e_1' *lowEqual* e_2' holds.

Proof of B: The memory is not changed by accessing a field. M_1 *similar*(e) M_2 holds before and $M_1 = M_1'$ and $M_2 = M_2'$, thus B holds.

Case Ctx + New:
In this case, assumption (1) is of form $M_1|\mathcal{E}_v[\texttt{new}\ s\ C(\overline{v})] \rightarrow_{call} M_1, o \mapsto C(\_)|\ \mathcal{E}_v[(s\ \texttt{mut}\ o)]$, and (A) is similar with M_2.

Proof of A: This can be obtained by simply choosing a suitable reference 'o' for the New rule.

Proof of B: It holds because the new memories grow by adding the same exact object on both sides.

Proof of C and D:
To prove the conditions C and D, we have to show that if M and e are well typed and $M|e \rightarrow_{call} M'|e'$ then M *preserves*(e/e') M'. That means, each reduction step ensures the preserve property that the `high` memory is only changed in necessary cases. This statement holds by the construction of our reduction rules. We only promote expressions to `high` if it is necessary. No unnecessary promotions are done. The only changes from `low` to `high` are explicitly stated in Definition 5.7: creation of a new `high` object and the promotion of a `low capsule` expression. Thus, C and D holds.

Proof of E:
Proving condition E is more complex. From our assumptions we conclude that the well typedness of the base language is not violated, since the SIFO type system is just stricter than the regular L42 system. However, we need to prove that the $\rightarrow_{call}$ reduction preserves the added security typing. This is quite subtle thanks to multiple method types (Fig. 3): The type system as presented does not respect preservation; that is, when calling a method that has been typed using multiple method types, the inlined body of the method may not respect our provided type system. However, we are using the $\rightarrow_{call}$ reduction, and the call reduction skips in a single step to the full method evaluation. The method body will evaluate to a value; we have not formally specified typing rules for values and memory; the intuition we present here in our proof sketch is that security is not relevant in the memory; as you can see from the grammar in Fig. 6, we keep the security level on the value (outside of the memory), so the result of a high method call with $\rightarrow_{call}$ is well typed because it is only concerned with the non-security aspects of the type system, and the security level is tracked during reduction. See how, for example, in rule Call of Fig. 4, the security level and modifier of the parameters can be promoted before inlining the method body. □

To prove the noninterference Theorem 5.10, we use the property that the reduction terminates (Lemma 5.8) and the bisimulation core that each reduction step meets the requirements of noninterference (Lemma 5.9). We prove, if two memories that are similar and both expressions reduce, the new memories still have to be similar and the reduced values are equal w.r.t. `low` values. This Theorem 5.10 has the same shape as Theorem 5.0, but uses the definitions for similarity of memories (Def. 5.5) and expressions (Def. 5.6). As we said before, we exclude declassification in the proof. Therefore, we cannot guarantee security for programs with `declassify` expressions. Related works generalize the noninterference property to provide stronger guarantees for programs including declassification [Sabelfeld and Sands 2009].

Theorem 5.10 (Noninterference).
If we have expressions e_1 and e_2 without declassification that are well typed and e_1 lowEqual e_2, M_1 and M_2 are well typed memories, M_1 similar(e_1) M_2, $M_1|e_1 \rightarrow^* M_1'|v_1$, and $M_2|e_2 \rightarrow^* M_2'|v_2$ then M_1' similar(v_1) M_2', v_1 lowEqual v_2, and M_1', M_2', v_1, and v_2 are well typed.

Proof. From Lemma 5.8 and $M_1|e_1 \rightarrow^* M_1'|v_1$ and $M_2|e_2 \rightarrow^* M_2'|v_2$, we know that $M_1|e_1 \rightarrow_{call} M_1'|v_1$ and $M_2|e_2 \rightarrow_{call} M_2'|v_2$. Then, by induction on the number of steps of $\rightarrow_{call}$:

Base: e_1 *lowEqual* e_2 *lowEqual* v_1 *lowEqual* v_2, $M_1 = M_1'$, $M_2 = M_2'$. Thus, M_1' *similar*(v_1) M_2' holds because M_1 *similar*(e_1) M_2.

Inductive step: By Lemma 5.9 (bisimulation core) and the inductive hypothesis, each reduction step establishes similar memories M_1' and M_2', computes *lowEqual* expressions, and preserves that only necessary values are in the `high` ROG. □

6 TOOL SUPPORT AND EVALUATION

In this section we present tool support for SIFO and evaluate feasibility of SIFO by implementing five case studies. Additionally, we benchmark precision and recall of the information flow analysis by adapting the IFSpec benchmark suite [Hamann et al. 2018] to SIFO.

6.1 Tool Support

We implement SIFO as a pluggable type system for L42 [Giannini et al. 2019]. L42 is a pure object-oriented language with a rich type system supporting the type modifiers used by SIFO.

Conveniently, L42 allows pluggable type systems [Andreae et al. 2006; Papi et al. 2008] to add an additional layer of typing. We add rules to support the typing of expressions with security levels. Both Java and L42 supports pluggable type systems using annotations: type names preceded by the symbol @. In our SIFO library, these annotations are used to introduce the security levels.[5]

Some changes of SIFO are necessary to comply with L42: L42 supports the uniform access principle [Meyer 1988]; thus there is no dedicated syntax for field assign and field access, but they are modeled by getters and setters. Additionally, the constructor does not have dedicated syntax, but it is a static method with return type `This`. In this way, we only need to type check method calls. Moreover, this allows more flexibility since multiple method types are now transparently and consistently applied in all those cases. We also had to extend our type system to support the features of L42. While adding loops and other conventional constructs was trivial, we had to be careful while extending our type system to support exceptions, since exceptions constitute yet another way for a method execution to propagate secret information to an observer. Thus, we consider exceptions similar to a return type.

Additionally, an exception prevents the execution of the code after it was thrown. Thus, after the exception is caught, the program may collect information about when the execution was interrupted in order to discover what expression raised the exception. This is another option to propagate secret information to an observer. Our current extension supporting exceptions is quite conservative, requiring the use of a single security level for all free variables, exceptions, and results of a try-catch block. In future work, we plan to formalize the extension with exceptions more precisely.

6.2 Feasibility Evaluation

To evaluate the feasibility of SIFO, we implemented four case studies from the literature in SIFO: Battleship [Stoughton et al. 2014; Zheng et al. 2003], Email [Hall 2005], Banking [Thüm et al. 2012], and Paycard (`http://spl2go.cs.ovgu.de/projects/57`). Additionally, we implemented a novel case study of our own, the *Database*. The metrics of the case studies are shown in Table 1.

6.2.1 Battleship. Our evaluation is focused on the *Battleship* case study because this program is carefully described by Stoughton et al. [Stoughton et al. 2014] as a general benchmark to evaluate

[5]You can find a version of L42 with our SIFO library and the case studies at https://l42.is/SifoArtifactLinux.zip and https://l42.is/SifoArtifactWin.zip. This also contains more information about the detailed syntax in the readme.

Name	#Security Levels	#Security Annotations	#Lines of Code
Battleship	4 (+2 generic)	21 (208 in Jif)	431 (611 in Jif)
Database	4	6	73
Email	2	20	260
Banking	2	20	127
Paycard	2	15	95

Table 1. Metrics of the case studies

information flow control. Moreover, this case study is also implemented in Jif[6], thus allowing us to directly compare their results with our work.

Battleship is the implementation of a two player board game. At the start, each player places a fixed number of ships of varying length on their private board. The board has a two-dimensional grid. The players only know the placement on their board and have to guess where the other player placed the ships. During the game, the players take turns and *shoot* cells on the board of the opponent to sink ships. The first player wins the game who sinks all opponent's ships.

Thanks to our flexible SIFO type system, we implemented most of the code without any security annotations. We wrote a generic `PlayerTrait` trait that is parameterized over the security levels *SelfL* and *OtherL* to distinguish both players. Our implementation of *Battleship* uses many features from full L42, not just the minimal core presented in this paper. In particular, we rely on L42 traits and their encoding for generics. We will expand on this in Section 7.

Our `ExampleGame` class implements a mutually distrustful player scenario [Stoughton et al. 2014]. In this setting, even if one of the two players is replaced with an adversarial player, we ensure that only a correctly executed game will terminate without exception. This scenario highlights nicely the properties of our system: we ensure noninterference that an adversarial player is unable to read the opponent's board state. In `ExampleGame`, the two players *Player1* and *Player2* create the boards and shoot consecutively. We have to ensure that each player creates a confidential board that the other player cannot read. In the concrete implementation, we annotate the board with the security level of one of the players to restrict readability. Deep immutability enforces that the board is not manipulated during the game. Then, each player gets a reference to the confidential board of the opponent. Contrast this with the Jif implementation of the same game: Jif uses the concept of label expressions that specify the allowed readers and writers of objects. In Jif, boards can be read by only one player, but they are trusted by both players. The first player creates a board, the second player endorses this board, and the first player then saves this board that is trusted by both players. Endorsement is the name of downgrading integrity, similar to declassification for confidential data. The endorsement of the board is implemented in Jif with defensive cloning. A new trusted board is created, and all ships on the input board are cloned to add them to the trusted board. In SIFO, the endorsement and defensive cloning is not necessary because we can rely on deep immutability of the type system that prevents manipulation of the boards.

When a player shoots, it has to be correctly revealed if it was a miss, a hit, or a hit that sunk a specific ship. The process of one shooting round is shown in Listing 4. The method `round` has as parameter which is the opposing player. In Line 2, there is a dynamic check for validity of the game.

[6]See [Zheng et al. 2003] found on the Jif website https://www.cs.cornell.edu/jif/

```
1  mut method Bool round(mut OtherPlayer other) = (
2    X[this.myRound(); !this.win(this.myShots()); !this.win(this.otherShots())]
3    coord = this.fire()
4    @OtherL FireResult res = this.board().fire(coord=coord,shots=this.myShots())
5    ResultSigner s = this.signer()
6    @OtherL ResultSigner.Signed signed = s(label=coord.toS(),data=res)
7    ResultSigner.Signed freeSigned=other.declassify(signed)
8    X[this.signer().mine(freeSigned,label=coord.toS())]
9    r = freeSigned.data().answer().repr()
10   this.myShots(\myShots.with(row=coord.row(),col=coord.col(),val=r))
11   this.myRound(Bool.false())
12   this.win(this.myShots())
13 )
```

Listing 4. Implementation of one shooting in SIFO

`X` works like `assert` in Java. It must be the round of the player, and the game must not be yet won by any player. The method `fire` in Line 3 asks for the next coordinates to shoot. These coordinates are used to check for the result of the shot on the board. As this is the board of the opponent, the result is labeled with the opponent's security level (Line 4). We now have to declassify the result to be able to read it, but only the opponent has the right to declassify the result of such shot. An adversarial opponent could manipulate the declassified result, we therefore use a signing mechanism to exclude manipulation. Thus, the confidential result is signed by the shooting player and send to the opponent (Line 6), so that the opponent declassifies the result (miss, hit, ship sunk) in Line 7. In Line 8, it is checked that the correct signed result is returned. In our implementation, we can rule out manipulation as the correct result is immutable and a newly created result by the opponent cannot have the signature of the shooting player. The shot and the result are then added to a list for validating subsequent rounds (e.g., in Line 12 to check whether the game is won). Then, the opponent player takes turn. If a game rule violation is detected during the game (e.g., a manipulated result of a shot), the game can be aborted by either player.

In Jif, a player must trust that the result of a shot is correctly revealed by the opponent. In Jif, it would be easy to implement a `BadPlayer` that returns an incorrect result of a shot, as there is no check for a manipulation [Stoughton et al. 2014]. Additionally, the Jif implementation uses defensive cloning when passing the coordinates of a shot to the opposing player.

We now compare both implementation on a more general level. Most classes are written parameterized with a security level L in Jif. In SIFO, we write classes like `Ship` without any security annotation, but we are able to use them in secure contexts with our promotion rules. With this technique, we are able to write only 21 security annotations in the whole implementation. In Jif, we count 208 annotations.

For the creation of players, we have a similar concept as Jif. While Jif used a generic `Player` class, we created a generic `PlayerTrait` trait with two security levels *SelfL* and *OtherL*. This generic trait is instantiated as `PlayerTrait['SelfL=>Player1;'OtherL=>Player2]` which can then be used to create object instances. In Jif, `[Player1,Player2] player1 = new Player[Player1,Player2]();` is written to create a new player.

In summary, we implemented *Battleship* in SIFO by relying on our promotion rules and the immutability of trustworthy objects. Thanks to preexisting L42 features, we have not needed the complex expressiveness of Jifs label expression, which is also discussed in Section 7.

6.2.2 Database. The *Database* is a system where two databases are not allowed to interfere. Through the different security levels, we ensure that a value read from one database cannot be inserted into the other one. This can be obtained just by annotating the `Gui` class with six security annotations, as shown in Listing 5.

```
1  Gui={
2    mut @Left Database dbLeft
3    mut @Right Database dbRight
4    class method mut This (mut @Left Database dbLeft, mut @Right Database dbRight)
5    class method mut This ()=(
6      capsule @Left Database dbl=Database(name=S"left",rows=Rows())
7      capsule @Right Database dbr=Database(name=S"right",rows=Rows())
8      This(dbLeft=dbl, dbRight=dbr)
9      )
10   }
```

Listing 5. Gui implementation in SIFO

The other classes are implemented without any security level. This is possible because the class `Gui` is the only class that uses databases with different security levels. This means that the actual database code is all free from security annotations; as you can see above different instances of **`low capsule`** `Database` can be transparently promoted to different security levels `Left` and `Right`.

6.2.3 Further case studies. The *Email* system ensures that encrypted emails are only decrypted if the public and private key pair used is valid. It also guarantees that private keys are not leaked. The `Email` system needed only 20 security annotations in 260 lines of code.

Banking and *Paycard* are two systems that represent payment systems where it is crucial that the calculations of new balances are correct and information is not leaked. By setting the balance to **`high`** and checking that the system is typable, we are certain that the balance is not leaked to attackers. For *BankAccount* and *Paycard* 20 and 15 security annotations were needed with 127 and 95 lines of code.

6.2.4 Discussion. Code following a pure object-oriented style is often directly supported by SIFO without any special adaptation. However, when updates to local variables and statements/conditionals are used, the programmer may have to rely on some simple programming patterns: for example, in a conditional, we cannot directly update a **`high`** field of a **`low`** object, as **`low`** objects cannot be manipulated in **`high`** conditional statements. This limitation can be circumvented by wrapping the updatable field into a mutable proxy object (e.g., `o.proxy.field` instead of `o.field`). Such a proxy object can then be saved in a **`high`** temporary variable; and such a variable can be used to manipulate the state. We have to use the **`high`** proxy object because our IF-rule is slightly conservative. It does not check if only **`high`** fields of a **`low`** object are manipulated. This is still easier in comparison to Jif because in Jif, the object instance has to be cloned so that the user keeps a reference to the **`low`** object and can manipulate the **`high`** field data with the cloned instance.

Another insight is that major parts of the case studies could be written without any use of security levels because the multiple method types promote the parameters of a called method to the required security levels in necessary cases. This allowed us to write secure programs relying on libraries and data structures without any security annotation. In our case study, we could reuse a list implementation and securely promote it to any security level if needed. The type system then checks that instantiated lists of different security levels did not interfere. For example, a **`high`** list can only contain objects of at least a **`high`** security level. Moreover, we were also able to encode domain-specific data structures and functionality without any security annotation. In Jif,

this requires generic classes written with security annotations in all cases. Information flow can be enforced by annotating just the few method bodies that put separate systems into communication.

Major parts of the case studies were implemented without the use of declassify. We only needed it in *Battleship* to declassify shot results as intended by the game. Additionally, we declassified console output at the end of program execution in the other case studies to print results for the user.

By explicitly typing references as `imm` or `capsule`, the code quality increases, because programmers can rely on properties which are enforced by the type system. Furthermore, the security levels serve as active documentation for the programmer. In the *Database* example, we know which database a value comes from by reading the security level. To reduce the writing effort for programmers, sensible defaults are useful: if a security level is not specified, `low` is used.

6.3 Benchmarking with IFSpec

To evaluate precision and recall of SIFO, we applied SIFO to the IFSpec benchmark suite [Hamann et al. 2018]. IFSpec contains 80 samples to test information flow analysis tools. In addition to the core samples, 152 samples from the benchmark suite SecuriBench Micro[7] are adapted and integrated into IFSpec. The samples are all available in Java and Dalvik. To benchmark SIFO, we translated the 80 core sample when it was possible. Samples that used Java specific features were not translated. In total 40 samples are implemented in SIFO. For these samples, we compare SIFO with Cassandra [Lortz et al. 2014], JOANA [Graf et al. 2013], JoDroid [Mohr et al. 2015], KeY [Ahrendt et al. 2016], and Co-Inflow [Xiang and Chong 2021] (with and without additional security annotations) which were all evaluated before with IFSpec.

Each sample is labeled as secure or insecure. When a sample contains a leak and a tool reports a leak, we categorize it as true positive (TP). When a sample contains no leak and a tool reports no leak, we categorize it as true negative (TN). When a sample contains no leak but a tool reports a leak, we categorize it as false positive (FP). When a sample contains a leak but a tool reports no leak, we categorize it as false negative (FN). From these four categories, we can calculate precision and recall of the tools. The recall is computed as: $\#TP/(\#TP+\#FN)$. Recall determines the percentage of samples correctly classified as insecure considering all samples containing a leak. The precision is computed as: $\#TP/(\#TP+\#FP)$. Precision determines the percentage of samples correctly classified as insecure considering all samples classified as insecure by the tool.

In Table 2, we show the results of the benchmarking. All six tools found the 18 samples containing a leak. This results in a recall of 100% for all tools. No tool classified a sample false negative. Regarding precision, the tools have slight differences. Cassandra and Co-Inflow without additional annotations have the lowest precision of 54.5%. JOANA has the highest precision of 62.1%, but Co-Inflow has a higher precision of 81.8% if additional security annotation is given by the programmer. SIFO has a precision of 58.1%.

Discussion of the False Positive Samples. With SIFO, 13 samples are typed as insecure, which are labeled as secure by the authors of the benchmark. We will classify these samples into categories to discuss the result of SIFO. For six samples, the type system of SIFO is not precises enough to recognize that the sample is secure. For example, if in a conditional expression both branches assign the same value to a `low` reference, we pessimistically dismiss this program.

Three samples are constructed to introduce a leak which is overwritten in the end. A simple example is that a secret value is assigned to a public variable and in the next line, the public variable is overwritten. We clearly prohibit the first assignment of the secret value. These examples are constructed for taint analysis tools and are not suitable for type systems.

[7] https://github.com/too4words/securibench-micro

Tool	#Samples	TP	TN	FP	FN	Recall	Precision
Cassandra	40	18	7	15	0	100%	54.5%
JOANA	40	18	11	11	0	100%	62.1%
JoDroid	40	18	9	13	0	100%	58.1%
KeY	40	18	8	14	0	100%	56.3%
Co-Inflow	40	18	7	15	0	100%	54.5%
Co-Inflow-Annotations	40	18	18	4	0	100%	81.8%
SIFO	40	18	9	13	0	100%	58.1%

Table 2. Overview of the benchmark results

One sample is labeled as secure because in the provided code there is no way to access the secret values. In sample `Webstore`, a secret and a public value are assigned to a public list and only the public value is accessed in the code. When a simple getter-method for the secret value is added, the sample would be insecure. As our type system is modular, we directly prohibit the assignment of secret values to the public list. We do not check that there is currently no available method to access the stored value.

For three samples, again the modular reasoning of the type system pessimistically rejects secure programs. In `DeepCall`, a chain of method calls is insecure because the first secret value is propagated through all calls and returned as a public value. In the similar sample `DeepCall2`, the last call always returns the same value independent of the secret input value. This sample is considered secure. Our types system does not check all method calls globally, it just reasons that a secret value is passed to the next method and that a secret return value is expected. That the secret return value is actually a public constant in the sample `DeepCall2` is outside of the modular reasoning.

Most examples that SIFO rejects are constructed by developers to contain a security problem which is erased or not accessible in the remaining code of the sample. As our type system prohibits any introduction of security violations, we reject these samples. To support this statement, we rewrote eight of the 13 false positive samples to be semantically similar and accepted by SIFO.

7 RELATED WORK

Static and dynamic program analysis [Austin and Flanagan 2009; Nielson et al. 1999; Russo and Sabelfeld 2010; Zhang et al. 2015], as well as security type systems [Banerjee and Naumann 2002; Ferraiuolo et al. 2017; Hunt and Sands 2006; Li and Zhang 2017; Simonet 2003; Volpano et al. 1996] are used to enforce information flow policies. We refer to Sabelfeld and Myers [2003] for a detailed overview.

Taint Analysis. Taint analysis [Arzt et al. 2014; Enck et al. 2014; Hedin et al. 2014; Huang et al. 2014, 2012; Milanova and Huang 2013; Roy et al. 2009] is a related analysis technique that detects direct information flows from tainted sources to secure sinks by analyzing the assignments of variables and fields. Those taint analysis works do not provide a soundness property, while the SIFO noninterference proof guarantees the security of type checked code. Except for JSFlow [Hedin et al. 2014], Cassandra [Lortz et al. 2014], JOANA [Graf et al. 2013], and JoDroid [Mohr et al. 2015], these related works do not cover implicit information flows through conditionals, loop statements,

or dynamic dispatch. SIFO also detects implicit information flows through dynamic dispatch (conditional and loop statements are not in the core language, but included in our implementation). Crucially, the noninterference proof of SIFO relies on detecting implicit information flow.

Coarse-grained dynamic information flow approaches [Jia et al. 2013; Nadkarni et al. 2016; Xiang and Chong 2021] track information at the granularity of lexically or dynamically scoped section of code. Instead of labeling every value individually, coarse-grained approaches label an entire section with one label. All produced values within this scope implicitly have that same label. Therefore, the writing effort for developers to annotate programs is reduced. To still obtain good results of the information flow analysis, for example, Xiang and Chong [Xiang and Chong 2021] introduce opaque labeled values to permit labeled values where programmers have not provided a label. If no further annotation is given by the programmer, the precision of the information flow analysis can be decreased. As the evaluation shows, Co-Inflow [Xiang and Chong 2021] has better precision when the programmer annotates the program. However, the precision is not a limitation of coarse-grained approaches compared to fine-grained approaches. Type systems for fine- and coarse-grained information flow control are equivalent in terms of precision as shown by Rajani et al. [Rajani et al. 2017; Rajani and Garg 2018]. For dynamic information flow control mechanisms, Vassena et al. [Vassena et al. 2019] have similar results.

The work by Huang, Milanova et al. [Huang et al. 2014, 2012; Milanova and Huang 2013] is closely related to our approach because viewpoint adaption with polymorphic types is similar to our $mdf \triangleright mdf'$ operator for type modifiers. For field accesses, the type of the accessed object depends on the reference and the field type. They use read-only references to improve the precision of their static analysis technique by allowing subtyping if the reference is read-only. In SIFO, we also use deep immutable and capsule references, extending the expressiveness of our language.

Comparison to Jif. In this work, we explored the specific area of secure type systems for object-oriented languages [Banerjee and Naumann 2002; Barthe et al. 2007; Barthe and Serpette 1999; Myers 1999; Sabelfeld and Myers 2003; Strecker 2003; Sun et al. 2004]. The most important work to compare against is Jif [Myers 1999] (see Section 2). In this paper, we presented a minimal core of SIFO for the soundness and noninterference proofs. Nonetheless, we compare SIFO with Jif by discussing their common and different features. A main difference is the handling of aliases: Jif does not use any kinds of regions or alias analysis to reason about bounded side effects. Therefore, Jif pessimistically discards many programs introducing aliases (see the example in Section 2.1 that is not typable in Jif). On the other hand, SIFO restricts the introduction of insecure aliases and is therefore able to safely type more programs. SIFO's expressiveness relies on the safe promotion of `imm` or `capsule` references. As shown in Section 2 and in Section 6.2, programs can be typed securely without defensive cloning [Bloch 2016] because `imm` and `capsule` modifiers allow promoting objects to higher security levels. In Jif, a similar promotion is only allowed for primitive types.

The SIFO type system leverages on a minimalistic syntax of security annotation, where types contain a security level. Jif offers a much more elaborated syntax: in Jif, a security label is an expression consisting of a set of policies [Myers and Liskov 2000]. Each policy has an owner o and a set of readers r. For example, the label $o_1 : r_1; o_2 : r_1, r_2$ states that the policy of o_1 allows r_1 to read the value and o_2 allows r_1 and r_2 to read the value. Hence, r_1 is the only reader to fulfill both policies. These label expressions get more complicated, the more policies are conjoined, but a programmer gets more flexibility to express fine-grained access restrictions.

SIFO has a similar expressiveness to Jif, but does not need to resort to such complex label expressions. To show this, consider the following scenario from Jif [Myers and Liskov 2000]: A person Bob that wants to create his tax form using an online service. In the scenario, Bob wants to prevent his information from being leaked to the online service, and the provider of the

```
class Protected {
  final label{this} lb;
  Object{*lb} content;
  public Protected{LL}(Object{*LL} x, label LL) {
    lb = LL;
    super();
    content = x;}
  public Object{*L} get(label L):{L} throws (IllegalAccess) {
    switch label(content) {
      case (Object{*L} unwrapped) return unwrapped;
      else throw new IllegalAccess();}}
  public label get_label() {
    return lb;}}
```

Listing 6. Class Protected in Jif with security parameterization [Myers 1999]

service does not want its technology and data to be leaked in the process of generating the tax form. This constraint is related to the mutually distrustful players of the *Battleship* case study. To comply with these constraints, Bob labels his data with $bob : bob$ and sends it to the online service provider. The provider, labels its own data with $provider : provider$, so the calculated tax has the label $bob : bob; provider : provider$. This result cannot be read because the labels disagree on their reader sets. To release the information to Bob, the provider declassifies the label by removing the provider policy. As only the final tax form is declassified, the released information from the provider is limited. The final tax form with the label $bob : bob$ is then sent to Bob.

In SIFO, we can handle the same scenario as follows: Bob wants to protect his private information, so he can set the security level to `bob`, but he can also set a type modifier. With `read`, he ensures that his data cannot be manipulated and integrated into the provider's data. With `imm`, only the manipulation is prevented. If Bob trust the provider, he can send a `capsule` object to the provider. The provider can then manipulate and alias the data, but Bob is sure, that the manipulation is restricted to only the data reachable from the given reference. In the case of the provider, they get a reference to the data of Bob with a security level and a type modifier. In the most restricted case of a `read` reference, the provider can still use the information and calculate the final tax form, but a manipulation or aliasing of Bob's data is prevented. The security level of the result is the least upper bound of `bob` and `provider`. To declassify the results for Bob, the final tax form needs to be `imm` or `capsule` to allow safe sharing or transfer of the confidential data.

With this example, we discuss the secure transfer of data. In SIFO, by using a `read`, `imm`, or `capsule` modifiers, Bob specifies how the information is usable. In Jif, the label `bob:bob` does not restrict the use in the same way. There is no language support to ensure that a unique portion of store is transferred to the provider. There is also no guarantee that the data is not manipulated, as with `imm`. In Jif, if the provider has a read permission for Bob's data, they can freely manipulate it. Furthermore, if the provider wants to ensure that they are the current owner of Bob's tax data, they have to clone the data (defensive cloning [Bloch 2016]).

To grasp the difference in the annotation burden, consider the Jif example in Listing 6 of a class that protects data from insecure access. Jif uses a parameterized label system where a class or methods have a generic label L. The label L can be initialized with any specific security level. This places a large conceptual burden on the programmer, as the label L is used in every field and method of the class. Additionally, no legacy code can be used that is not parameterized properly.

SIFO encourages a style where most code is completely clear of any security annotation; in particular, most algorithms and most common data types like collections does not need any kind of security annotations at all. Only code that is explicitly and directly involved in the handling of security-critical data needs to be written with security in mind. Unlabeled classes and methods are implicitly annotated with the lowest security level. Thanks to the flexibility of multiple method types, they can be safely promoted to any higher level.

Jif has additional features that are not presented in the core of SIFO. The SIFO core works with a finite lattice of security levels instead of the complex label expressions in Jif [Myers and Liskov 2000] with an infinite set of possible labels. Thanks to the embedding in L42, we get label polymorphism for free by relying on L42 encodings for generics. Thus, on one side SIFO allows to remove the complexity of having most of the labels generic, on the other side when generic labels are truly needed (for example to write code that have to work on unknown labels) we can rely on the L42 generics encoding, as we do in the BattleShip example.

Jif has dynamic checks of security labels. See Line 9 in Listing 6 where the security level of the object `content` is checked. This feature can be emulated in SIFO with the following programming pattern. `Any` is the equivalent of `Object` in Java.

```
1 BoxLeft=Data:{@Left Any left}
2 BoxRight=Data:{@Right Any right}
3 ...
4 low Any a
5 if a <:BoxRight return a.right()
```

In a more concrete example, a Person Bob creates a `BoxLeft` or `BoxRight` object with the secure data in the field. This object is then sent as `low Any a` to Alice and Alice can discover with `instanceof` (`<:` in L42) if it is a `BoxLeft` or a `BoxRight` object. As you can see, by knowing the explicit type, we know also the security level of the data in the field. Thus, by adding an explicit boxing step, we enable the users to handle any kind of label and to dynamically check on those.

Jif has robust declassification [Chong and Myers 2006] which means that an attacker is not able to declassify information, or to influence what information is declassified by the system that is above the security level that the attacker is allowed to read. In the full embedding in L42, declassification can be sealed behind the object capability model, as we did in the *Battleship* case study. The L42 object capability model is flexible and can provide a range of useful guarantees [Miller 2006]. Indeed, you can see the *Battleship* case study as an exemplar representation of robust declassification. Even if we replace one of the player with adversarial code, such code will not be able to declassify the opposing board; even while holding a reference to such a board.

In future work, we want to extend SIFO to work with any partial order of security levels as discussed in Section 9. With this feature, we are closer to the expressive power of Jifs label expressions.

Other Information Flow Techniques. Hoare-style program logics are also used to reason about information flow. The work of Andrews and Reitman [Andrews and Reitman 1980] encodes information flow in a logical form for parallel programs. Amtoft et al. [Amtoft et al. 2006; Amtoft and Banerjee 2004] use Hoare-style program logic and abstract interpretation to analyze information flow. This approach is the basis in SPARK Ada for specifying and checking information flow [Amtoft et al. 2008]. For Java, Beckert et al. [Beckert et al. 2013] formalized the information flow property in a programming logic using self-composition of programs and an existing program verification tool to check information flow. Similarly, Barthe et al. [Barthe et al. 2004] and Darvas et al. [Darvas et al. 2005] analyze the information flow by using self-composition of programs and standard software verification systems. Terauchi and Aiken [Terauchi and Aiken 2005] combined a self-composition

technique with a type system to profit from both techniques. Küsters et al. [Küsters et al. 2015] propose a hybrid approach by using JOANA [Graf et al. 2013] and verification with KeY [Ahrendt et al. 2016] to check the information flow.

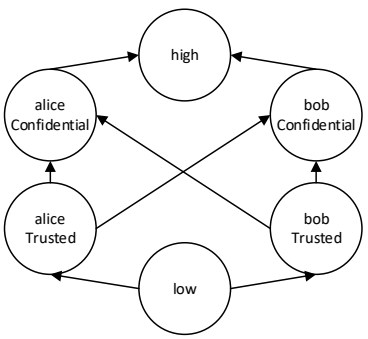
The related IFbC approach by Schaefer et al. [Runge et al. 2020; Schaefer et al. 2018] ensures information flow-by-construction. Here, the information flow policy is ensured by applying a sound set of refinement rules to a starting specification. Instead of checking the security after program creation, the programmer is guided by the rules to never violate the policy. Compared to SIFO, their approach is limited to a while language without objects.

8 CONCLUSION

In this work, we presented a type system of an object-oriented language for secure lattice-based information flow control using type modifiers that detects direct and implicit information flows. This language supports secure software development by enforcing noninterference. We leverage previous work on immutability and encapsulation to greatly increase the expressive power of our language. Additionally, promotion/multiple method types encourage reusability of secure programs without burdening the developer. We formalized the secure type system, proved noninterference, and showed feasibility by implementing SIFO as a pluggable type system for L42, and conducting an evaluation with several case studies. In the future, we want to formalize exceptions in SIFO to extend the expressiveness of the language. We also want to generalize the proof to include declassification.Furthermore, we could reduce the typing effort of programmers by introducing type inference.

9 FUTURE WORK: INTEGRITY AND CONFIDENTIALITY

As noted by Biba [Biba 1977] integrity can be seen as a dual to confidentiality, which means that either of them can be checked with the same information flow analysis techniques. For confidentiality, information must not flow to inappropriate destinations; dually, for integrity, information must not flow from inappropriate sources. In this work, we made all our discussion about confidentiality. If a user of SIFO is instead interested in integrity, they can simply use our type system with any lattice of integrity levels. However, it is also possible to track both properties at the same time: The trick is to not rely too much on data sources with the lowest or highest security level (e.g. `low` and `high`): since `high` can see all the information, `high` offers no integrity. In the same way, `low` can write to all the information, thus `low` data needs to be always intrinsically valid/trusted. Note that we can still declare `low` fields and `low` data structures, it is sufficient for sensitive data to be stored somewere nested inside the `ROG` from a non `low` reference, as we shown with the database case study.



In this work, we assumed a lattice of security levels. However, Logrippo [Logrippo 2018] has proposed that just a partially ordered set would be appropriate to model security. If we allowed just a partial order of security levels, SIFO would allow to encode both integrity and confidentiality at the same time instead of using two lattices for confidentiality levels and integrity levels. Consider the following example, where Bob and Alice have both confidential and trusted data. We can define a partially ordered set as shown on the right.

Integrity: `aliceTrusted`/`bobTrusted` is data that Alice/Bob trust to be valid. For example, only `low` and `bobTrusted` can write on `bobTrusted` data. Confidentiality: `aliceConfidential`/`bobConfidential` is data

that Alice/Bob wants to keep private. For example, `low`, `aliceTrusted`, `bobTrusted`, and `bobConfidential` can write on `bobConfidential`, but `bobConfidential` can only be read by `bobConfidential` and `high`. Those security levels also imply that `bobTrusted` can be read by `bobTrusted`, `aliceConfidential`, `bobConfidential`, and `high`.

Being able to express integrity and confidentiality at the same time with the same lattice is clearly a great advantage; however we are still investigating if supporting partially ordered sets instead of a lattice would have subtle consequences that interfere with our noninterference property.

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