

Existential Label Flow Inference via CFL Reachability

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Abstract. In programming languages, existential quantification is useful for describing relationships among members of a structured type. For example, we may have a list in which there *exists* some mutual exclusion lock l in each list element such that l protects the data stored in that element. With this information, a static analysis can reason about the relationship between locks and locations in the list even when the precise identity of the lock and/or location is unknown. To facilitate the construction of such static analyses, this paper presents a context-sensitive *label flow analysis* algorithm with support for existential quantification. Label flow analysis is a core part of many static analysis systems. Following Rehof et al, we use context-free language (CFL) reachability to develop an efficient $O(n^3)$ label flow inference algorithm. We prove the algorithm sound by reducing its derivations to those in a system based on polymorphically-constrained types, in the style of Mossin. We have implemented a variant our analysis as part of a data race detection tool for C programs.

1 Introduction

Many modern static program analyses are *context-sensitive*, meaning they can analyze different calls to the same function without conservatively attributing results from one call site to another. While very useful, this form of context-sensitivity aids little in the analysis of data structures. For example, a typical alias analysis conflates all elements of the same data structure, resulting in a “blob” of indistinguishable pointers [1]. In this case context-sensitivity for data-structure manipulation functions does not help much because the data structure elements themselves cannot be distinguished.

One way to solve this problem is to use *existential quantification* [2] to express relations among members of each individual data structure element. For example, an element might contain a buffer and the length of that buffer [3]; a pointer to data and the lock that must be held when accessing it [4, 5]; or a closure, consisting of a function and a pointer to its environment [6]. The important idea is that such relations are sound even when the identity of individual data structure elements cannot be discerned.

This paper presents a context-sensitive *label flow analysis* algorithm that supports existential quantification. Label flow analysis attempts to answer queries of the form “During program execution, can a value v flow to some expression e ?” Answering such queries is at the core of a variety of static analyses, including points-to analysis [7, 8], information flow [9], type qualifier inference [10, 11], and race detection [4]. Our goal is to provide a formal foundation for augmenting such analyses with support for existential quantification.

Our label flow algorithm is implemented as a *type-based program analysis* [12], in which static analysis is defined in terms of type inference. The core result of this paper

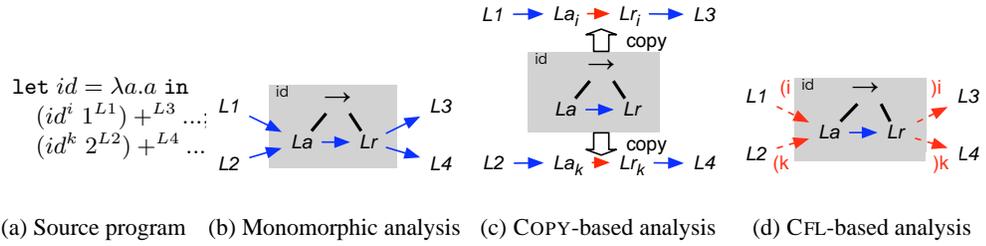


Fig. 1. Universal Types Example

is a provably sound and efficient type inference system for label flow that supports existential quantification. This paper makes the following contributions:

- We present COPY, a subtyping-based label-flow system in the style of Mossin [13]. In COPY, context sensitivity for functions corresponds to universal types (parametric polymorphism). Our contribution is to show how to support existential quantification using existential types [2], applying the duality of \forall and \exists . We prove that the resulting system is sound. (Section 3)
- We present CFL, an alternative to COPY that supports efficient inference. Following Rehof et al [14, 15], determining flow in CFL is reduced to a context-free language (CFL) reachability problem, and the resulting inference system runs in time $O(n^3)$ in the worst case. Our contribution is to show that existentially-quantified flow can also be expressed as a CFL problem, and to prove that CFL is sound by reducing it to COPY. These results are interesting because existential types are *first-class* (as opposed to universal types, which in the style of Hindley-Milner only appear in type environments). To make inference tractable, we require the programmer to indicate where existential types are used, and we restrict the interaction between existentially bound labels and free labels in the program. (Section 4)
- We briefly discuss how a variation of CFL is used as part of LOCKSMITH, a race detection tool [4] for C programs that correlates memory locations to mutual exclusion locks protecting them. LOCKSMITH uses existential quantification to precisely relate locks and locations that reside within dynamic data structures, thereby eliminating a source of false alarms. (Section 2.3)

2 Polymorphism via Context-Free Language Reachability

This section briefly introduces type-based label flow analysis, presents the encoding of context sensitivity as universal types, and sketches our new technique for supporting first-class existential types. We also describe our application of these ideas to LOCKSMITH, a race detection tool for C [4].

2.1 Universal Types and Label Flow

The goal of label flow analysis is to determine which values could flow to which operations. In the program in Fig. 1(a), values 1 and 2 are annotated with *flow labels* $L1$ and $L2$, respectively, and the two $+$ operations are labeled with $L3$ and $L4$. Therefore label flow analysis should show that $L1$ flows to $L3$ and $L2$ flows to $L4$. In this program we annotate calls to id with indices i and k , which we will use shortly.

To compute the flow of labels, we perform a type- and constraint-based analysis in which base types are annotated with labels. For our example, the function id is given the type $int^{La} \rightarrow int^{Lr}$, where La and Lr label the argument and return types, respectively. The body of id returns its argument, which is modeled by the *constraint* $La \leq Lr$. The call id^i yields constraints $L1 \leq La$ and $Lr \leq L3$, and the call id^k yields constraints $L2 \leq La$ and $Lr \leq L4$. Pictorially, constraints form the directed edges in a *flow graph*, as shown in Fig. 1(b), and flow is determined by reachability. Thus the graph accurately shows that $L1$ flows to $L3$ and $L2$ flows to $L4$. However, the graph conflates the two calls to id —its type is monomorphic—and therefore suggests possible flows from $L1$ to $L4$ and from $L2$ to $L3$, which is sound but imprecise.

The precision of the analysis can be improved by adding *context sensitivity* using Hindley-Milner style universal types. The standard approach [13], shown in Fig. 1(c), is to give id a *polymorphically constrained* universal type $\forall La, Lr [La \leq Lr]. int^{La} \rightarrow int^{Lr}$, where we have annotated id 's type with the flow constraints needed to type its body. Each time id is used, we *instantiate* its type and constraints, effectively “inlining” a fresh copy of id 's body. At the call id^i , we instantiate the constraint with the substitution $[La \mapsto La_i, Lr \mapsto Lr_i]$, and then apply the constraints from the call site, yielding $L1 \leq La_i \leq Lr_i \leq L3$, as shown. Similarly, at the call id^k we instantiate again, this time yielding the constraints $L2 \leq La_k \leq Lr_k \leq L4$. Thus we see that $L1$ could flow to $L3$, and $L2$ could flow to $L4$, but we avoid the spurious flows mentioned above.

While this technique is effective, explicit constraint copying can be difficult to implement, because it requires juggling various sets of constraints as they are duplicated and instantiated, and may require complicated constraint simplification techniques [16–18] for efficiency. An alternative approach is to encode the problem in terms of a slightly different graph and use CFL reachability to compute flow, as suggested by Rehof et al [14]. This solution adds call and return edges to the graph and labels them with parentheses indexed by the call site, as shown in Fig. 1(d) with dashed lines. Edges from id^i are labeled with $(_i$ for inputs and $)_i$ for outputs, and similarly for id^k . To compute flow in this graph, we find paths with no mismatched parentheses. In this case the paths from $L1$ to $L3$ and from $L2$ to $L4$ are matched, while the other paths are mismatched and hence not considered. Rehof et al [14] have shown that using CFL reachability with matched paths can be reduced to a type system with polymorphically constrained types.

2.2 Existential Types and Label Flow

The goal of this paper is to show how to use existential quantification during static analysis to efficiently model properties of data structures more precisely. Consider the example shown in Fig. 2(a). In this program, functions f and g add an unspecified value to their argument. As before, we wish to determine which integers flow to which $+$ operations. In the third line of this program we create existentially-quantified pairs using pack operations in which f is paired with 1 and g with 2. Using an `if`, we then conflate these two pairs, binding one of them to p . In the last line we use p by applying its first component to its second component.¹

In this example, no matter which pair p is assigned, f is only ever applied to 1, and g is only ever applied to 2. However, an analysis like the one described above would

¹ We use pattern matching for simplicity, while the language in Section 3 would use projection.

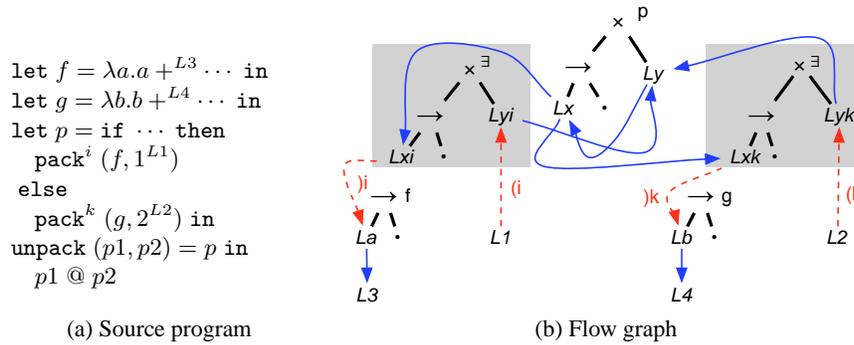


Fig. 2. Existential Types Example

conservatively conflate the types at the two pack sites, generating spurious constraints $L1 \leq L4$ and $L2 \leq L3$. To solve this problem, Section 3 presents COPY, a system that can model p precisely by giving it a polymorphically constrained existential type $\exists Lx, Ly [Ly \leq Lx]. (int^{Lx} \rightarrow int) \times int^{Ly}$, indicating that p contains a pair whose second element flows to the argument position of its first element. (The uninteresting labels are omitted for clarity.) At pack^i , this type is instantiated to yield $L1 \leq La$, and since $La \leq L3$ we have $L1 \leq L3$ transitively. Instantiating at pack^k yields $L2 \leq Lb \leq L4$. Thus we precisely model that 1^{L1} only flows to $+^{L3}$ and 2^{L2} only flows to $+^{L4}$.

Universal and existential quantification are dual notions, which allows us to look to universal types to understand how to support existential types. Intuitively, we give a universal type to id because id is polymorphic in the label it is called with—whatever it is called with, it returns. Conversely, we give an existential type of p because the *rest of the program* is polymorphic in the pairs—no matter which pair is used, the first element is always applied to the second.

Section 4 shows how to perform inference efficiently for existential label flow using CFL reachability. Fig. 2(b) shows the flow graph generated for this example program. When packing the pair $(f, 1^{L1})$, instead of normal flow edges we generate edges labeled by i -parentheses, and we generate edges labeled by k -parentheses when packing $(g, 2^{L2})$. Flow for this graph again corresponds to paths with no mismatched parentheses. For example, in this graph there is a matched path from $L2$ to $L4$, indicating that the value 2^{L2} may flow to $+^{L4}$, and there is similarly a path from $L1$ to $L3$. Notice that restricting flow to matched paths again suppresses spurious flows from $L2$ to $L3$ and from $L1$ to $L4$. Thus, the two existential packages can be conflated without losing the flow relationships of their members.

2.3 Existential Quantification and Race Detection

Our interest in studying existential label flow arose from the development of LOCKSMITH, a C race detection tool [4]. During our experiments we found several examples of code similar to Fig. 3, which is taken from the *knot* multithreaded web server [19]. Here `cache_entry` is a linked list with a per-node lock `refs_mutex` that guards accesses to the `refs` field. Without existential quantification, LOCKSMITH conflates all the locks and locations in the data structure. As a result, it does not know exactly which

```

struct cache_entry { int refs; pthread_mutex_t refs_mutex; ... };

void cache_entry_addrf(cache_entry *entry) { ...
    pthread_mutex_lock(&entry->refs_mutex);
    entry->refs++;
    pthread_mutex_unlock(&entry->refs_mutex);
... }

```

Fig. 3. Example code with a per-element lock

lock is held at the write to `entry->refs`, and reports that `entry->refs` may not always be accessed with the same lock held, falsely indicating a potential data race.

With existential quantification, however, LOCKSMITH is able to model this idiom precisely. We add annotations to specify that in type `cache_entry`, the fields `refs` and `refs_mutex` should be given existentially quantified labels. Then we add `pack` annotations when `cache_entry` is created and `unpack` annotations wherever it is used, i.e., within `cache_entry_addrf`. Using an adaptation of the analysis presented in this paper, LOCKSMITH then can determine that the `refs_mutex` lock in a node always guards the `refs` field in that node. While this prior work sketches the use of existential types, it gives neither type rules nor proofs for them, which are the main contributions of this paper. The remainder of this paper focuses exclusively on existential types for label flow, and we refer the reader to our other paper for details on LOCKSMITH [4].

3 Label Flow with Polymorphically Constrained Types

This section studies label flow in the context of a polymorphically-constrained type system COPY, which is essentially Mossin’s label flow system [13] extended to include existential types. Note that COPY supports label polymorphism but not polymorphism in the type structure. We use the following source language throughout the paper:

$$\begin{aligned}
e ::= n^L \mid x \mid \lambda^L x.e \mid e_1 @^L e_2 \mid \text{if}^L e_0 \text{ then } e_1 \text{ else } e_2 \mid (e_1, e_2)^L \mid e.^L j \\
\mid \text{let } f = e_1 \text{ in } e_2 \mid \text{fix } f.e_1 \mid f^i \mid \text{pack}^{L,i} e \mid \text{unpack}^L x = e_1 \text{ in } e_2
\end{aligned}$$

In this language, constructors and destructors are annotated with constant labels L . The goal of our type system is to determine which constructor labels flow to which destructor labels. For example, in the expression $(\lambda^L x.e) @^{L'} e'$, the label L flows to the label L' . Our language includes integers, variables, functions, function application (written with $@$ to provide a position on which to write a label), conditional branches and pairs. Our language also includes binding constructs `let` and `fix`, which introduce universal types. Each use of a universally quantified function f^i is indexed by an *instantiation site* i . Expressions also include existential packages, which are created with $\text{pack}^{L,i}$ and consumed with `unpack`. Since existential packages are passed around the program, we label them with concrete labels L as with other values. Instantiation sites are ignored in this section, but are used in Section 4.

The types and environments used by COPY are given by the following grammar:

$$\begin{array}{ll}
\text{types } \tau ::= \text{int}^l \mid \tau \rightarrow^l \tau \mid \tau \times^l \tau \mid \exists^l \bar{\alpha}[C].\tau & \text{schemes } \sigma ::= \forall \bar{\alpha}[C].\tau \mid \tau \\
\text{labels } l ::= L \mid \alpha & \text{constraints } C ::= \emptyset \mid \{l \leq l\} \mid C \cup C \\
\text{env. } \Gamma ::= \cdot \mid \Gamma, x : \sigma &
\end{array}$$

$$\begin{array}{c}
\text{Id} \frac{}{C; \Gamma, x : \tau \vdash_{cp} x : \tau} \\
\\
\text{Lam} \frac{C; \Gamma, x : \tau \vdash_{cp} e : \tau' \quad C \vdash L \leq l}{C; \Gamma \vdash_{cp} \lambda^L x. e : \tau \rightarrow^l \tau'} \\
\\
\text{Pair} \frac{C; \Gamma \vdash_{cp} e_1 : \tau_1 \quad C; \Gamma \vdash_{cp} e_2 : \tau_2 \quad C \vdash L \leq l}{C; \Gamma \vdash_{cp} (e_1, e_2)^L : \tau_1 \times^l \tau_2} \\
\\
\text{Cond} \frac{C; \Gamma \vdash_{cp} e_0 : int^l \quad C \vdash l \leq L \quad C; \Gamma \vdash_{cp} e_1 : \tau \quad C; \Gamma \vdash_{cp} e_2 : \tau}{C; \Gamma \vdash_{cp} \text{if } 0^L e_0 \text{ then } e_1 \text{ else } e_2 : \tau} \\
\\
\text{Int} \frac{C \vdash L \leq l}{C; \Gamma \vdash_{cp} n^L : int^l} \\
\\
\text{App} \frac{C; \Gamma \vdash_{cp} e_1 : \tau \rightarrow^l \tau' \quad C; \Gamma \vdash_{cp} e_2 : \tau \quad C \vdash l \leq L}{C; \Gamma \vdash_{cp} e_1 @^L e_2 : \tau'} \\
\\
\text{Proj} \frac{C; \Gamma \vdash_{cp} e : \tau_1 \times^l \tau_2 \quad C \vdash l \leq L \quad j \in \{1, 2\}}{C; \Gamma \vdash_{cp} e.^L j : \tau_j} \\
\\
\text{Sub} \frac{C; \Gamma \vdash_{cp} e : \tau_1 \quad C; \emptyset \vdash \tau_1 \leq \tau_2}{C; \Gamma \vdash_{cp} e : \tau_2}
\end{array}$$

Fig. 4. COPY Monomorphic Rules

Types include integers, functions, pairs and existential types. All types are annotated with flow labels l , which may be either constant labels L from the program text or label variables α . Type schemes include normal types and polymorphically-constrained universal types of the form $\forall \bar{\alpha}[C].\tau$. Here C is a set of *flow constraints* each of the form $l \leq l'$. In our type rules, *substitutions* ϕ map label variables to labels. The universal type $\forall \bar{\alpha}[C].\tau$ stands for any type $\phi(\tau)$ where $\phi(C)$ is satisfied, for any substitution ϕ . When $l \leq l'$, we say that label l flows to label l' . The type $\exists^l \bar{\alpha}[C].\tau$ stands for the type $\phi(\tau)$ where constraints $\phi(C)$ are satisfied for *some* substitution ϕ . Universal types may only appear in type environments while existential types may appear arbitrarily. The free labels of types ($fl(\tau)$) and environments ($fl(\Gamma)$) are defined as usual.

The expression typing rules are presented in Figs. 4 and 5. Judgments have the form $C; \Gamma \vdash_{cp} e : \tau$, meaning in type environment Γ with flow constraints C , expression e has type τ . In these type rules $C \vdash l \leq l'$ means that the constraint $l \leq l'$ is in the transitive closure of the constraints in C , and $C \vdash C'$ means that all constraints in C' are in the transitive closure of C .

Fig. 4 contains the monomorphic typing rules, which are as in the standard λ calculus except for the addition of labels and subtyping. The constructor rules ([Int], [Lam] and [Pair]) require $C \vdash L \leq l$, i.e., the constructor label L must flow to the corresponding label of the constructed type. The destructor rules ([Cond], [App] and [Proj]) require the converse. The subtyping rule [Sub] is discussed below.

Fig. 5 contains the polymorphic typing rules. Universal types are introduced by [Let] and [Fix]. As is standard, we allow generalization only of label variables that are not free in the type environment Γ . In both these rules, the constraints C' used to type e_1 become the bound constraints in the polymorphic type. Whenever a variable f with a universal type is used in the program text, its type is instantiated. Such instantiations appear in the program text, written f^i , and are checked by [Inst]. The premise $C \vdash \phi(C')$ effectively inlines the constraints of the instantiated function into the caller's context.

$$\begin{array}{c}
\text{[Let]} \frac{C'; \Gamma \vdash_{cp} e_1 : \tau_1 \quad C; \Gamma, f : \forall \vec{\alpha}[C'] . \tau_1 \vdash_{cp} e_2 : \tau_2}{C; \Gamma \vdash_{cp} \text{let } f = e_1 \text{ in } e_2 : \tau_2} \\
\text{[Fix]} \frac{C'; \Gamma, f : \forall \vec{\alpha}[C'] . \tau \vdash_{cp} e : \tau \quad C \vdash \phi(C')}{C; \Gamma \vdash_{cp} \text{fix } f . e : \phi(\tau)} \\
\text{[Inst]} \frac{C \vdash \phi(C')}{C; \Gamma, f : \forall \vec{\alpha}[C'] . \tau \vdash_{cp} f^i : \phi(\tau)} \\
\text{[Pack]} \frac{C; \Gamma \vdash_{cp} e : \phi(\tau) \quad C \vdash \phi(C') \quad C \vdash L \leq l}{C; \Gamma \vdash_{cp} \text{pack}^{L,i} e : \exists^l \vec{\alpha}[C'] . \tau} \\
\text{[Unpack]} \frac{C; \Gamma \vdash_{cp} e_1 : \exists^l \vec{\alpha}[C'] . \tau \quad C \cup C'; \Gamma, x : \tau \vdash_{cp} e_2 : \tau' \quad C \vdash l \leq L}{C; \Gamma \vdash_{cp} \text{unpack}^L x = e_1 \text{ in } e_2 : \tau'}
\end{array}$$

Fig. 5. COPY Polymorphic Rules

Existential types are manipulated using `pack` and `unpack`. To understand `[Pack]` and `[Unpack]`, recall that \forall and \exists are dual notions. Notice that \forall introduction (`[Let]`) restricts what can be universally quantified, and instantiation occurs at \forall elimination (`[Inst]`). Thus \exists introduction (`[Pack]`) should perform instantiation, and \exists elimination (`[Unpack]`) should restrict what can be existentially quantified.

In `[Pack]`, an expression e with a concrete type $\phi(\tau)$ is abstracted to a type $\exists^l \vec{\alpha}[C'] . \tau$. Notice that the substitution goes from abstract to concrete—creating an existential corresponds to passing an argument to “the rest of the program,” as if that were universally quantified in $\vec{\alpha}$. Indeed, the constraint system C' bound in the existential type is expressed over the quantified variables $\vec{\alpha}$, and these constraints C' are determined by how the existential package is used after it is unpacked. Similarly to `[Inst]`, the `[Pack]` premise $C \vdash \phi(C')$ inlines the abstract constraints $\phi(C')$ into the current constraints.

Rule `[Unpack]` binds the contents of the type to x in the scope of e_2 . This rule places two restrictions on the existential package. First, e_2 must type check with the constraints $C \cup C'$. Thus, any constraints among the existentially bound labels $\vec{\alpha}$ needed to check e_2 must be in C' .² Second, the labels $\vec{\alpha}$ must not escape the scope of the `unpack` (as is standard), which is ensured by the subset constraint.

The `[Sub]` rule in Fig. 4 uses the subtyping relation shown in Fig. 6. These rules are standard structural subtyping rules extended to labeled types. We use a simple approach to decide whether one existential is a subtype of another. Rule `[Sub- \exists]` requires $C_1 \vdash C_2$, since an existential type can be used in any position inducing the same or fewer flows between labels. We allow subtyping among existentials of a “similar shape.”

² This differs from `[Let]`, which includes *all* constraints in C' (not just those on quantified labels). While we could write `[Unpack]` and `[Let]` to be more parallel, this separation of constraints simplifies the reduction from CFL to COPY discussed in Sec. 4.

$$\begin{array}{c}
\text{[Sub-Label-1]} \frac{l, l' \notin D \quad C \vdash l \leq l'}{C; D \vdash l \leq l'} \qquad \text{[Sub-Label-2]} \frac{l \in D}{C; D \vdash l \leq l} \\
\\
\text{[Sub-Pair]} \frac{\begin{array}{c} C; D \vdash l \leq l' \\ C; D \vdash \tau_1 \leq \tau'_1 \\ C; D \vdash \tau_2 \leq \tau'_2 \end{array}}{C; D \vdash \tau_1 \times^l \tau_2 \leq \tau'_1 \times^{l'} \tau'_2} \qquad \text{[Sub-Fun]} \frac{\begin{array}{c} C; D \vdash l \leq l' \\ C; D \vdash \tau'_1 \leq \tau_1 \\ C; D \vdash \tau_2 \leq \tau'_2 \end{array}}{C; D \vdash \tau_1 \rightarrow^l \tau_2 \leq \tau'_1 \rightarrow^{l'} \tau'_2} \\
\\
\text{[Sub-Int]} \frac{C; D \vdash l \leq l'}{C; D \vdash \text{int}^l \leq \text{int}^{l'}} \qquad \text{[Sub-}\exists\text{]} \frac{\begin{array}{c} C_1 \vdash C_2 \quad D' = D \cup \vec{\alpha} \\ C; D' \vdash \tau_1 \leq \tau_2 \quad C; D \vdash l_1 \leq l_2 \end{array}}{C; D \vdash \exists^{l_1} \vec{\alpha}[C_1]. \tau_1 \leq \exists^{l_2} \vec{\alpha}[C_2]. \tau_2}
\end{array}$$

Fig. 6. COPY Subtyping

That is, they must have exactly the same (alpha-convertible) bound variables, and constraints must not be between bound and free variables. We use a set D to track the set of bound variables, updated in [Sub- \exists].³ Rule [Sub-Label-2] permits subtyping between identical bound labels ($l \in D$), whereas rule [Sub-Label-1] allows subtyping among non-identical labels only if neither is bound.

These restrictions on existentials forbid some clearly erroneous judgments such as $C \vdash \exists\{\alpha\}[\emptyset]. \text{int}^\alpha \leq \exists\{\alpha\}[\emptyset]. \text{int}^\beta$. The two existential types in this example quantify over the same label; however, the subtyping is invalid because it would create a constraint between a bound label and an unbound label. However, these restrictions also forbid some valid existential subtyping, such as $C \vdash (\exists\{\alpha, \beta\}[\alpha \leq \beta]. \text{int}^\alpha \rightarrow \text{int}^\beta) \leq (\exists\{\alpha\}[\emptyset]. \text{int}^\alpha \rightarrow \text{int}^\alpha)$, which is permissible because β is a bound variable with no other lower bounds except α , hence it can be set to α without losing information. In our experience with LOCKSMITH we have not found this restriction to be an issue, and we leave it as an open question whether it can be relaxed while still maintaining efficient CFL reachability-based inference.

We prove soundness for COPY using subject reduction. Using a standard small-step operational semantics $e \longrightarrow e'$, we define a *flow-preserving evaluation step* as one whose flow is allowed by some constraint set C . Then we prove that if a program is well-typed according to C then it always preserves flow.

Definition 1 (Flow-preserving Evaluation Step). *Suppose $e \longrightarrow e'$ and in this reduction a destructor (if0, @, .j, unpack) labeled L' consumes a constructor ($n, \lambda, (\cdot, \cdot)$, pack, respectively) labeled L . Then we write $C \vdash e \longrightarrow e'$ if $C \vdash L \leq L'$. We also write $C \vdash e \longrightarrow e'$ if no value is consumed during reduction (for let or fix).*

Theorem 1 (Soundness). *If $C; \Gamma \vdash_{cp} e : \tau$ and $e \longrightarrow^* e'$, then $C \vdash e \longrightarrow^* e'$.*

Here, \longrightarrow^* denotes the reflexive and transitive closure of the \longrightarrow relation. The proof is by induction on $C; \Gamma \vdash_{cp} e : \tau$ and is presented in a companion technical report [20].

³ Our technical report [20] uses an equivalent version of D that makes the reduction proof easier.

4 CFL-Based Label Flow Inference

The COPY type system is relatively easy to understand and convenient for proving soundness, but experience suggests it is awkward to implement directly as an inference system. This section presents a label flow inference system CFL based on CFL reachability, in the style of Rehof et al [14, 15]. This system uses a single, global set of constraints that characterize flow graphs, as shown in Figs. 1 and 2. Using the flow graph, we can answer queries “Does any value labeled l_1 flow to a destructor labeled l_2 ?”, written $l_1 \rightsquigarrow l_2$, by using CFL reachability. We first present type checking rules for CFL and then explain how they are used to interpret the flow graph in Fig. 2. Then we explain how the rules can be interpreted to yield an efficient algorithm for inferring flow graphs automatically, and we prove that CFL reduces to COPY and thus is sound.

Types in CFL differ from COPY as follows:

$$\text{types } \tau ::= \text{int}^l \mid \tau \rightarrow^l \tau \mid \tau \times^l \tau \mid \exists^l \vec{\alpha}. \tau \quad \text{schemes } \sigma ::= (\forall \vec{\alpha}. \tau, \vec{l}) \mid \tau$$

In contrast to COPY, universal types $(\forall \vec{\alpha}. \tau, \vec{l})$ do not include a constraint set (since we generate a single, global flow graph) and instead contain a set \vec{l} of labels that are *not* quantified [14, 21]. For clarity universal types also include $\vec{\alpha}$, the set of labels that are quantified, but it is always the case that $\vec{\alpha} = fl(\tau) \setminus \vec{l}$. Existential types do not include a set \vec{l} , because we assume that the programmer has specified which labels are existentially quantified. We check that the specification is correct when existentials are unpacked (more on this below).

Typing judgments in CFL have the form $I; C; \Gamma \vdash e : \tau$, where I and C describe the edges in the flow graph. C has the same form as in COPY, consisting of subtyping constraints $l \leq l'$ (shown as unlabeled directed edges in Figs. 1 and 2). I contains *instantiation constraints* [14] of the form $l \preceq_p^i l'$. Such a constraint indicates that l is renamed to l' at instantiation site i . (Recall that each instantiation site corresponds to a pack or a use of a universally quantified type.) The p indicates a *polarity*, which describes the flow of data. When p is $+$ then l flows to l' , and so in our examples we draw the constraint $l \preceq_+^i l'$ as an edge $l \xrightarrow{i} l'$. When p is $-$ the reverse holds, and so we draw the constraint $l \preceq_-^i l'$ as an edge $l' \xrightarrow{i} l$. Instantiation constraints correspond to substitutions in COPY, and they enable context-sensitivity without need to copy constraint sets. A full discussion of instantiation constraints is beyond the scope of this paper; see Rehof et al [14] for a thorough description.

The monomorphic rules for CFL are presented in Fig. 7. With the exception of [Sub] and the presence of I , these are identical to the rules in Fig. 4. Fig. 8 presents the polymorphic CFL rules. In these type rules $I \vdash l \preceq_p^i l'$ means that the instantiation constraint $l \preceq_p^i l'$ is in I . We define $fl(\tau)$ to be the free labels of a type as usual, except $fl(\forall \vec{\alpha}. \tau, \vec{l}) = (fl(\tau) \setminus \vec{\alpha}) \cup \vec{l}$. Rules [Let] and [Fix] bind f to a universal type. As is standard we cannot quantify label variables that are free in the environment Γ , which we represent by setting $\vec{l} = fl(\Gamma)$ in type $(\forall \vec{\alpha}. \tau, \vec{l})$. The [Inst] rule instantiates the type τ of f to τ' using an instantiation constraint $I; \emptyset \vdash \tau \preceq_+^i \tau' : \phi$. This constraint represents a renaming ϕ , analogous to that in COPY’s [Inst] rule, such that $\phi(\tau) = \tau'$. All non-quantifiable labels, i.e., all labels in \vec{l} , should not be instantiated, which we model by requiring that any such label instantiate to itself, both positively and negatively.

$$\begin{array}{c}
\text{[Id]} \frac{}{I; C; \Gamma, x : \tau \vdash_{\text{cfl}} x : \tau} \qquad \text{[Int]} \frac{C \vdash L \leq l}{I; C; \Gamma \vdash_{\text{cfl}} n^L : \text{int}^l} \\
\text{[Lam]} \frac{I; C; \Gamma, x : \tau \vdash_{\text{cfl}} e : \tau' \quad C \vdash L \leq l}{I; C; \Gamma \vdash_{\text{cfl}} \lambda^L x. e : \tau \rightarrow^l \tau'} \quad \text{[App]} \frac{I; C; \Gamma \vdash_{\text{cfl}} e_1 : \tau \rightarrow^l \tau' \quad I; C; \Gamma \vdash_{\text{cfl}} e_2 : \tau \quad C \vdash l \leq L}{I; C; \Gamma \vdash_{\text{cfl}} e_1 @^L e_2 : \tau'} \\
\text{[Pair]} \frac{I; C; \Gamma \vdash_{\text{cfl}} e_1 : \tau_1 \quad I; C; \Gamma \vdash_{\text{cfl}} e_2 : \tau_2 \quad C \vdash L \leq l}{I; C; \Gamma \vdash_{\text{cfl}} (e_1, e_2)^L : \tau_1 \times^l \tau_2} \quad \text{[Proj]} \frac{I; C; \Gamma \vdash_{\text{cfl}} e : \tau_1 \times^l \tau_2 \quad C \vdash l \leq L \quad j = 1, 2}{I; C; \Gamma \vdash_{\text{cfl}} e.^L j : \tau_j} \\
\text{[Cond]} \frac{I; C; \Gamma \vdash_{\text{cfl}} e_0 : \text{int}^l \quad C \vdash l \leq L \quad I; C; \Gamma \vdash_{\text{cfl}} e_1 : \tau \quad I; C; \Gamma \vdash_{\text{cfl}} e_2 : \tau}{I; C; \Gamma \vdash_{\text{cfl}} \text{if} 0^L e_0 \text{ then } e_1 \text{ else } e_2 : \tau} \quad \text{[Sub]} \frac{I; C; \Gamma \vdash_{\text{cfl}} e : \tau_1 \quad C; \emptyset; \emptyset \vdash \tau_1 \leq \tau_2}{I; C; \Gamma \vdash_{\text{cfl}} e : \tau_2}
\end{array}$$

Fig. 7. CFL Monomorphic Rules

Rule [Pack] constructs an existential type by abstracting a concrete type τ' to abstract type τ . In COPY's [Pack], there is a substitution such that $\tau' = \phi(\tau)$, and thus CFL's [Pack] has a corresponding instantiation constraint $\tau \preceq_{-}^i \tau'$. The instantiation constraint has negative polarity because although the substitution is from abstract τ to concrete τ' , the direction of flow is the reverse, since the packed expression e flows to the packed value. In [Pack] the choice of what $\vec{\alpha}$ to quantify is non-deterministic. As in other systems for inferring first-class existential and universal types [22–25], we expect the programmer to choose this set. In contrast to [Inst], we do not generate any self-instantiations in [Pack], because we enforce a stronger restriction for escaping variables in [Unpack].

Rule [Unpack] treats the abstract existential type as a concrete type for the scope of the unpack, and thus any uses of the unpacked value place constraints on the existential type. The last premise of [Unpack] ensures that abstract labels not escape, and moreover abstract labels may not constrain any escaping labels in any way. Specifically, we require that there are no flows (see below) between any labels in $\vec{\alpha}$ and any labels in \vec{l} , which is the set of labels that could escape. If this condition is violated, then the existentially quantified labels $\vec{\alpha}$ chosen by the programmer are invalid and the program is rejected. Note that this restriction forbidding interaction between free and bound labels is not present in the [Unpack] rule of COPY, and therefore CFL is strictly weaker than COPY. However, without this restriction we can produce cases where mixing existentials and universals produces flow paths that should be valid but have mismatched parentheses. Appendix A contains one example. In practice we believe the restriction is acceptable, as we have not found it to be an issue with LOCKSMITH. We leave it as an open question whether the restriction can be relaxed while still maintaining efficient CFL reachability-based inference.

Fig. 9 defines the subtyping relation used in [Sub]. The only interesting difference with COPY arises because of alpha-conversion. In COPY alpha-conversion is implicit, and only trivial constraints are allowed between bound labels (by [Sub-Label-

$$\begin{array}{c}
\text{[Let]} \frac{I; C; \Gamma \vdash_{\text{cfl}} e_1 : \tau_1 \quad I; C; \Gamma, f : (\forall \vec{\alpha}. \tau_1, \vec{l}) \vdash_{\text{cfl}} e_2 : \tau_2}{I; C; \Gamma \vdash_{\text{cfl}} \mathbf{let} f = e_1 \mathbf{in} e_2 : \tau_2} \\
\begin{array}{c}
\vec{\alpha} = \text{fl}(\tau_1) \setminus \vec{l} \quad \vec{l} = \text{fl}(\Gamma)
\end{array} \\
\text{[Fix]} \frac{I; C; \Gamma, f : (\forall \vec{\alpha}. \tau, \vec{l}) \vdash_{\text{cfl}} e : \tau \quad \vec{\alpha} = \text{fl}(\tau) \setminus \text{fl}(\Gamma) \quad \vec{l} = \text{fl}(\Gamma)}{I; \emptyset \vdash \tau \preceq_+^i \tau' : \phi \quad I \vdash \vec{l} \preceq_+^i \vec{l} \quad I \vdash \vec{l} \preceq_-^i \vec{l}} \\
\text{[Inst]} \frac{I; \emptyset \vdash \tau \preceq_+^i \tau' : \phi \quad I \vdash \vec{l} \preceq_+^i \vec{l} \quad I \vdash \vec{l} \preceq_-^i \vec{l}}{I; C; \Gamma, f : (\forall \vec{\alpha}. \tau, \vec{l}) \vdash_{\text{cfl}} f^i : \tau'} \\
\text{[Pack]} \frac{I; C; \Gamma \vdash_{\text{cfl}} e : \tau' \quad I; \emptyset \vdash \tau \preceq_-^i \tau' : \phi \quad \text{dom}(\phi) = \vec{\alpha} \quad C \vdash L \leq l}{I; C; \Gamma \vdash_{\text{cfl}} \mathbf{pack}^{L,i} e : \exists^l \vec{\alpha}. \tau} \\
\text{[Unpack]} \frac{I; C; \Gamma \vdash_{\text{cfl}} e_1 : \exists^l \vec{\alpha}. \tau \quad I; C; \Gamma, x : \tau \vdash_{\text{cfl}} e_2 : \tau' \quad \vec{l} = \text{fl}(\Gamma) \cup \text{fl}(\exists^l \vec{\alpha}. \tau) \cup \text{fl}(\tau') \cup L \quad \vec{\alpha} \subseteq \text{fl}(\tau) \setminus \vec{l} \quad C \vdash l \leq L \quad \forall l \in \vec{\alpha}, l' \in \vec{l}. (I; C \not\vdash l \rightsquigarrow l' \text{ and } I; C \not\vdash l' \rightsquigarrow l)}{I; C; \Gamma \vdash_{\text{cfl}} \mathbf{unpack}^L x = e_1 \mathbf{in} e_2 : \tau'}
\end{array}$$

Fig. 8. CFL Polymorphic Rules

2] of Fig. 6). We cannot use implicit alpha-conversions in CFL, however, because we are producing a single, global set of constraints. Thus instead of the single D used in COPY’s[Sub] rule, CFL uses two D_i , which are sequences of ordered vectors of existentially-bound labels, updated in [Sub- \exists]. In the rules, the syntax $D \oplus \{l_1, \dots, l_n\}$ means to append vector $\{l_1, \dots, l_n\}$ to sequence D . Rule [Sub-Ind-2] in Fig. 9, which corresponds to [Sub-Label-2] in Fig. 6, does allow subtyping between bound labels l_j and l'_j —but only if they occur in exactly the same quantification position. Thus these subtyping edges actually correspond to alpha-conversion. We could also allow this in the COPY system, but it adds no expressive power and complicates proving soundness.

Fig. 10 defines instantiation constraints on types in terms of instantiation constraints on labels. Judgments have the form $I; D \vdash \tau \preceq_p^i \tau'$, where D is the same as in Fig. 6—we do not need to allow alpha-conversion here, because we can always apply [Sub] if we wish to alpha-rewrite. Thus [Inst-Ind-1] permits instantiation of unbound labels, and rule [Inst-Ind-2] forbids renaming bound labels. For example, if we have an \exists type nested inside a \forall type, instantiating the \forall type should not rename any of the bound variables of the \exists type. Aside from this the rules in Fig. 10 are standard, and details can be found in Rehof et al [14].

Given a flow graph induced by constraints I and C , Fig. 11 gives inference rules to compute the relation $l_1 \rightsquigarrow l_2$, which means label l_1 flows to label l_2 .⁴ Rule [Level] states that constraints in C correspond to flow (these are represented as unlabeled edges in the

⁴ Our relation \rightsquigarrow corresponds to the \rightsquigarrow_m relation from Rehof et al [14], where m stands for “matched paths,” which are distinguished from the so-called “PN” flow paths they also support. In our system we concern ourselves only with constants, which always produce matched paths, and hence we have no need for more than one relation.

$$\begin{array}{c}
\text{[Sub-Ind-1]} \frac{C \vdash l \leq l'}{C; \emptyset; \emptyset \vdash l \leq l'} \quad \text{[Sub-Int]} \frac{C; D_1; D_2 \vdash l \leq l'}{C; D_1; D_2 \vdash \text{int}^l \leq \text{int}^{l'}} \\
\\
\text{[Sub-Ind-2]} \frac{C \vdash l_j \leq l'_j}{C; D_1 \oplus \{l_1, \dots, l_n\}; D_2 \oplus \{l'_1, \dots, l'_n\} \vdash l_j \leq l'_j} \\
\\
\text{[Sub-Ind-3]} \frac{C; D_1; D_2 \vdash l \leq l' \quad l \neq l_i \quad l' \neq l'_j \quad \forall i, j \in [1..n]}{C; D_1 \oplus \{l_1, \dots, l_n\}; D_2 \oplus \{l'_1, \dots, l'_n\} \vdash l \leq l'} \\
\\
\text{[Sub-Pair]} \frac{C; D_1; D_2 \vdash l \leq l' \quad C; D_1; D_2 \vdash \tau_1 \leq \tau'_1 \quad C; D_1; D_2 \vdash \tau_2 \leq \tau'_2}{C; D_1; D_2 \vdash \tau_1 \times^l \tau_2 \leq \tau'_1 \times^{l'} \tau'_2} \\
\\
\text{[Sub-Fun]} \frac{C; D_1; D_2 \vdash l \leq l' \quad C; D_1; D_2 \vdash \tau'_1 \leq \tau_1 \quad C; D_1; D_2 \vdash \tau_2 \leq \tau'_2}{C; D_1; D_2 \vdash \tau_1 \rightarrow^l \tau_2 \leq \tau'_1 \rightarrow^{l'} \tau'_2} \\
\\
\text{[Sub-}\exists\text{]} \frac{\begin{array}{c} D'_1 = D_1 \oplus \vec{\alpha}_1 \quad D'_2 = D_2 \oplus \vec{\alpha}_2 \quad \phi(\vec{\alpha}_2) = \vec{\alpha}_1 \\ C; D'_1; D'_2 \vdash \tau_1 \leq \tau_2 \quad C; D_1; D_2 \vdash l_1 \leq l_2 \end{array}}{C; D_1; D_2 \vdash \exists^{l_1} \vec{\alpha}_1. \tau_1 \leq \exists^{l_2} \vec{\alpha}_2. \tau_2}
\end{array}$$

Fig. 9. CFL Subtyping

graph). Rule [Trans] adds transitive closure. Rule [Match] allows flow on a matched path $l_0 \xrightarrow{i} l_1 \rightsquigarrow l_2 \xrightarrow{i} l_3$. Intuitively, this rule corresponds to “copying” the constraint $l_1 \rightsquigarrow l_2$ to a constraint $l_0 \rightsquigarrow l_3$ at instantiation site i . Rule [Constant] adds a “self-loop” that permits matching flows to or from any constant label in the program; intuitively, we generate these edges because constants are global names, and thus context-insensitive.

Example Consider again the example in Fig. 2. The expression $\text{pack}^i(f, 1^{L_1})$ is given the type $\exists Lxi, Lyi. (\text{int}^{Lxi} \rightarrow \cdot) \times \text{int}^{Lyi}$ by the [Pack] rule. [Pack] also instantiates the pair’s abstract type to its concrete type using the judgment $I; C \vdash (\text{int}^{Lxi} \rightarrow \text{int}) \times \text{int}^{Lyi} \preceq^i_+ (\text{int}^{Lx} \rightarrow \text{int}) \times \text{int}^{L1}$. Proving this judgment requires appealing in several places to [Inst-Ind-1], whose premise $I \vdash l \preceq^i_p l'$ requires that I contain constraints $Lyi \preceq^i_- L1$ and $Lxi \preceq^i_+ La$, among others. These are shown as dashed, labeled edges in the figure. Notice that the direction of the renaming is opposite the direction of flow: The concrete labels flow to the abstract labels, but the abstract type is instantiated to the concrete type. Hence the instantiation has negative polarity. This instantiated existential type flows via subtyping to the type of p shown at the center of the figure; the directed edges between the components of the types are induced by the subtyping judgment (applying [Sub- \exists] at the top level).

The unpack of p is typed by the [Unpack] rule. Within the body of the unpack, we apply the second part of the pair ($p2$) to the first ($p1$). Here, $p2$ has type int^{Ly} while $p1$ has type $\text{int}^{Lx} \rightarrow \text{int}$, and thus to apply the [App] rule, we must first prove (among other things) that $C; \emptyset; \emptyset \vdash \text{int}^{Ly} \leq \text{int}^{Lx}$. This requires that $Ly \leq Lx$ be in C according to [Sub-Ind-1], and is shown as an unlabeled edge in the figure. With this edge we have $I; C \vdash L1 \rightsquigarrow L3$ and $I; C \vdash L2 \rightsquigarrow L4$ (but $I; C \not\vdash L1 \rightsquigarrow L4$). The

$$\begin{array}{c}
\text{[Inst-Ind-1]} \frac{l, l' \notin D \quad I \vdash l \preceq_p^i l'}{I; D \vdash l \preceq_p^i l' : \emptyset} \qquad \text{[Inst-Ind-2]} \frac{l \in D}{I; D \vdash l \preceq_p^i l : \phi} \\
\text{[Inst-Pair]} \frac{I; D \vdash l \preceq_p^i l' : \phi \quad I; D \vdash \tau_1 \preceq_p^i \tau'_1 : \phi \quad I; D \vdash \tau_2 \preceq_p^i \tau'_2 : \phi}{I; D \vdash \tau_1 \times^l \tau_2 \preceq_p^i \tau'_1 \times^{l'} \tau'_2 : \phi} \qquad \text{[Inst-Fun]} \frac{I; D \vdash l \preceq_p^i l' : \phi \quad I; D \vdash \tau_1 \preceq_p^i \tau'_1 : \phi \quad I; D \vdash \tau_2 \preceq_p^i \tau'_2 : \phi}{I; D \vdash \tau_1 \rightarrow^l \tau_2 \preceq_p^i \tau'_1 \rightarrow^{l'} \tau'_2 : \phi} \\
\text{[Inst-Int]} \frac{I; D \vdash l \preceq_p^i l' : \phi}{I; D \vdash \text{int}^l \preceq_p^i \text{int}^{l'} : \phi} \qquad \text{[Inst-}\exists\text{]} \frac{D' = D \cup \vec{\alpha} \quad I; D' \vdash \tau_1 \preceq_p^i \tau_2 : \phi \quad I; D \vdash l_1 \preceq_p^i l_2 : \phi}{I; D \vdash \exists^{l_1} \vec{\alpha}. \tau_1 \preceq_p^i \exists^{l_2} \vec{\alpha}. \tau_2 : \phi}
\end{array}$$

Fig. 10. CFL Instantiation

$$\begin{array}{c}
\text{[Level]} \frac{C \vdash l_1 \leq l_2}{I; C \vdash l_1 \rightsquigarrow l_2} \qquad \text{[Trans]} \frac{I; C \vdash l_0 \rightsquigarrow l_1 \quad I; C \vdash l_1 \rightsquigarrow l_2}{I; C \vdash l_0 \rightsquigarrow l_2} \\
\text{[Constant]} \frac{}{I; C \vdash L \preceq_p^i L} \qquad \text{[Match]} \frac{I \vdash l_1 \preceq_p^i l_0 \quad I; C \vdash l_1 \rightsquigarrow l_2 \quad I \vdash l_2 \preceq_p^i l_3}{I; C \vdash l_0 \rightsquigarrow l_3}
\end{array}$$

Fig. 11. Flow

final premises of [Unpack] are satisfied because the bound labels Ly and Lx only flow among themselves or to bound variables in existential types (which are not part of the free labels).

An inference algorithm CFL has been presented thus far as a checking system in which the flow graph C and I is assumed to be known. To infer this flow graph automatically requires a simple reinterpretation of the rules. The algorithm has three stages and runs in time $O(n^3)$, where n is the size of the type-annotated program.

First, we type the program according to the rules in Figs. 7-10. As usual the non-syntactic rule [Sub] can be incorporated into the remaining rules to produce a syntax-directed system. During typing, we interpret a premise $C \vdash l \leq l'$ or $I \vdash \vec{l} \preceq_p^i \vec{l}'$ as *generating* a constraint; i.e., we add $l \leq l'$ (or $\vec{l} \preceq_p^i \vec{l}'$) to the set of global constraints C (or I). Free occurrences of l in the rules are interpreted as fresh label variables. Thus, in [Int], we interpret l as a fresh variable α and add $L \leq l$ to C . When choosing types (e.g., τ in [Lam] or τ' in [Inst]) we pick a type τ with fresh label variables in every position. After typing we have a flow graph defined by constraint sets C and I .

Next, we compute all flows according to the rules in Figure 11. Excluding the final premise of [Unpack] and the D 's in [Sub] and [Inst], performing typing and computing all flows takes time $O(n^3)$ [14]. To implement [Sub-Ind- i] efficiently, rather than maintaining D sets explicitly and repeatedly traversing them, we temporarily mark each variable with a pair (i, j) indicating its position in D and its position in $\vec{\alpha}$ as we traverse an existential type. We can assume without loss of generality that $|\vec{\alpha}| \leq |fl(\tau)|$ in an existential type, so traversing $\vec{\alpha}$ does not increase the complexity. Then we can select among

[Sub-Ind-1] and [Sub-Ind-2] in constant time for each constraint $C; D_1; D_2 \vdash l \leq l'$, so this does not affect the running time, and similarly for [Inst-Ind- i].

Finally, we check the last reachability condition of [Unpack] to ensure the programmer chose a valid specification of existential quantification. Given that we have computed all flows, we can easily traverse the labels in $\vec{\alpha}$ and check for paths to \vec{l} and vice-versa. Since each set is of size $O(n)$, this takes $O(n^2)$ time, and since there are $O(n)$ uses of [Unpack], in total this takes $O(n^3)$ time. Thus the algorithm as a whole is $O(n^3) + O(n^3) = O(n^3)$.

Soundness We have proven that programs that check under CFL are reducible to COPY. The first step is to define a translation function $\Psi_{C,I}$ that takes CFL types and transforms them to COPY types. For monomorphic types $\Psi_{C,I}$ is simply the identity. To translate a polymorphic CFL type $(\forall \vec{\alpha}. \tau, \vec{l})$ or $\exists^l \vec{\alpha}. \tau$ into a COPY type $\forall \vec{\alpha}[C']. \tau$ or $\exists^l \vec{\alpha}[C']. \tau$, respectively, we need to produce a bound constraint set C' . Rehof et al [14, 15] were able to choose $C' = C^I = \{l_1 \leq l_2 \mid I; C \vdash l_1 \rightsquigarrow l_2\}$, i.e., the closure of C and I . However, the addition of first class existentials causes this approach to fail, because, for example, instantiating a \forall type containing a type $\exists^l \vec{\alpha}[C']. \tau$ could rename some variables in C' and thereby violate the inductive hypothesis. Thus we introduce a projection function ψ_S , where ψ_S is the identity on labels in S , and ψ_S replaces any other variable α by the least-upper bound of the labels in S and constants that flow to α . Then for a universal type we choose $C' = \psi_{(\vec{\alpha} \cup \vec{l})}(C^I)$, and for an existential type we choose $C' = \psi_{\vec{\alpha}}(C^I)$. By projecting the full constraint system C^I onto the label variables necessary for each type, we are able to prove reduction [20].

Theorem 2 (Reduction from CFL to COPY). *Let \mathcal{D} be a normal CFL derivation of $I; C; \Gamma \vdash_{cfl} e : \tau$. Then $C^I; \Psi_{C,I}(\Gamma) \vdash_{cp} e : \Psi_{C,I}(\tau)$.*

By combining Theorems 1 and 2, we then have soundness for the flow relation \rightsquigarrow computed by CFL. Notice that we have shown reduction in one direction but not equivalence. Rehof et al [14, 15] also only show one direction of reduction, but conjecture equivalence of their systems. In our case, equivalence clearly does not hold, because of the extra non-escaping condition on [Unpack] in CFL. We leave it as an open question whether this condition can be relaxed to yield provably equivalent systems.

5 Related Work

Our work builds directly on the CFL reachability-based label flow system of Rehof et al [14]. Their cubic-time algorithm for polymorphic recursive label flow inference improves on the previously best-known $O(n^8)$ algorithm [13]. The idea of using CFL reachability in static analysis is due to Reps et al [26], who applied it to first-order data flow analysis problems. Our contribution is to extend the use of CFL reachability further to include existential types for modeling data structures more precisely.

Existential types can be encoded in System F [27] (p. 377), in which polymorphism is first class and type inference is undecidable [28]. There have been several proposals to support first-class polymorphic type inference using type annotations to avoid the undecidability problem. In ML^F [23], programmers annotate function arguments that have universal types. Laufer and Odersky [22] propose an extension to ML with first-class existential types, and Remy [24] similarly proposes an extension with first-class

universal types. In both systems, the programmer explicitly lists which type variables are quantified. Packs and unpacks correspond to data structure construction and pattern matching, and hence are determined by the program text. Our system also requires the programmer to specify packs and unpacks as well as which variables are quantified, but in contrast to these three systems we support subtyping (and therefore we need polymorphically constrained types), rather than unification. Note that our solution is restricted to label flow, and only existential types are first-class (but we believe adding first-class universals with programmer-specified quantification would be straightforward). We conjecture that full first-class polymorphic type inference for label flow is decidable, and plan to explore such a system in future work.

Simonet [25] extends HM(X) [29], a generic constraint-based type inference framework, to include first-class existential and universal types with subtyping. Simonet requires the programmer to specify the polymorphically constrained type, including the subtyping constraints C , whereas we infer these (we assume we have the whole program). Another key difference is that we use CFL reachability for inference. Once again, however, our system is concerned only with label flow.

In ours and the above systems, both existential quantification as well as pack and unpack must be specified manually. An ideal inference algorithm requires no work from the programmer. For example, we envision a system in which all pairs and their uses are considered as candidate existential types, and the algorithm chooses to quantify only those labels that lead to a minimal flow in the graph. It is an open problem whether such an algorithm exists.

6 Conclusion

Existential quantification can be used precisely characterize relationships within elements of a dynamic data structure, even when the precise identity of those elements is unknown. This paper aims to set a firm theoretical foundation on which to build efficient program analyses that benefit from existential quantification. Our main contribution is a context-sensitive inference algorithm for label flow analysis that supports existential quantification. Programmers specify where existentials are introduced and eliminated, and our inference algorithm automatically infers the bounds on their flow. Our algorithm is efficient, employing context free language (CFL) reachability in the style of Rehof et al [14], and we prove it sound by reducing it to a system based on polymorphically-constrained types in the style of Mossin [13]. We have adapted our algorithm to improve the precision of LOCKSMITH, a tool that aims to prove the absence of race conditions in C programs [4] by correlating locks with the locations they protect. We plan to explore other applications of existential label flow in future work.

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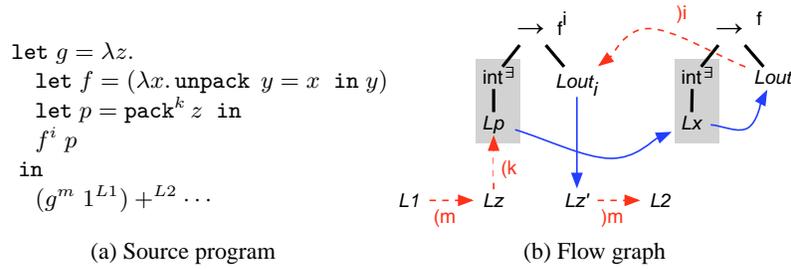


Fig. 12. Example with Mismatched Flow

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A Differences between COPY and CFL

As mentioned in Section 4, if we weaken the [Unpack] rule in CFL to not prevent existentially bound labels from interacting with free labels, then we can construct examples with mismatched flow. One such example program is shown in Figure 12(a). In this program, the function g takes an argument z , packs it into an existential, and then returns the result of calling function f with it. Function f simply unpacks the existential and returns the contents. Thus g is the identity function, but with complicated control flow. The function g is then applied to the value 1, labeled $L1$, and the result of g is added at $+^{L2}$. Thus clearly we should have that $L1$ flows to $L2$. Let us assume that at pack^k , the programmer wishes to quantify the type of the packed integer, and then compare COPY and CFL as applied to the program.

The COPY types rules assign f the following type scheme:

$$\forall Lout[\emptyset]. (\exists Lx[Lx \leq Lout]. int^{Lx}) \rightarrow int^{Lout}$$

Notice that there is a constraint between the existentially-bound variable Lx and the universally quantified variable $Lout$ (which itself is free in the existential type). This

constraint arises because at the unpack site the abstracted integer escapes by flowing out of the unpack and is then returned by the function. Notice that this is allowed because by using [Sub] with a constraint $Lx \leq Lout$ just before y escapes the scope of the unpack, we prevent the label Lx itself from escaping. Then at the call site, we instantiate the type of f to $(\exists Lx[Lx \leq Lout_i].int^{Lx}) \rightarrow int^{Lout_i}$ where $Lout_i$ is returned by g , and thus $Lout_i \leq Lz'$, where Lz' is the label on the return type of g . Notice that this instantiation (i) renamed $Lout$ but left Lx alone, since the latter was not free. Moreover, p has the same type as the domain of f^i , and at $pack^k$ we instantiate the abstract Lx to concrete Lz , yielding the constraint $Lz \leq Lout_i$. Here Lz is the label on the parameter type of g . Notice that this instantiation (k) renamed Lx but not $Lout_i$. Finally, g has type $\forall Lz, Lz', Lout_i[Lz \leq Lout_i, Lout_i \leq Lz'].int^{Lz} \rightarrow int^{Lz'}$ and thus when we instantiate this type at g^m , apply it to $L1$, and apply $+^{L2}$ to the result, we get $L1 \leq Lz_m \leq Lout_{im} \leq Lz'_m \leq L2$, and thus we have flow from $L1$ to $L2$.

Now consider what happens if we apply CFL to the same program. Fig. 12(b) shows the resulting flow graph. The type of f , shown at the right of the figure, is $(\forall Lout.(\exists Lx.int^{Lx}) \rightarrow int^{Lout}, \emptyset)$ where in the global flow graph there is a constraint $Lx \leq Lout$. As before, this is a constraint between an existentially bound and free variable, which is forbidden by the strong non-escaping condition in [Unpack] from Fig. 8. However, assume for the moment that we ignore this condition. Then the type of f^i , shown in the left of the figure, is $(\exists Lp.int^{Lp}) \rightarrow int^{Lout_i}$ where we have an instantiation constraint $Lout \preceq_+^i Lout_i$, drawn as a dashed, labeled edge in the figure. Note that we have also applied an extra step of subtyping to make the figure easier to read and drawn an edge $Lp \leq Lx$, although we could also set $Lp = Lx$. Since the result of the function is returned, we have $Lout_i \leq Lz'$, where again Lz' is the label on the return type of g . Moreover, at $pack^k$, we instantiate the abstract type of p to its concrete type, resulting in the instantiation constraint $Lp \preceq^k Lz$, as shown in the figure, where Lz is the label on the parameter type of g . Finally, at the instantiation of g we generate constraints $Lz \preceq^m L1$ and $Lz' \preceq_+^m L2$ as shown in the figure. (We omit the structure of g in the figure for clarity.)

Notice that there is no path from $L1$ to $L2$, because (k does not match i). The problem is that instantiation i must not rename Lp , and instantiation k must not rename $Lout_i$. In CFL, we prevent instantiations from renaming labels by adding “self-loops,” as in [Inst] in Fig. 8. In this case, we should have $Lp \preceq_{\pm}^i Lp$ and $Lout_i \preceq_{\pm}^k Lout_i$. We expended significant effort in trying to discover a system that would add exactly these self-loops, but we were unable to discover a solution that would work consistently in all cases. For example, adding a self-loop on $Lout_i$ seems particularly problematic, since the label $Lout_i$ is created only after f^i is instantiated, and not at the pack nor the unpack points. Moreover, because we have an (m and $)m$ to the left and right of the mismatched path, the self-loops on $L1$ and $L2$ do not help.

Thus in [Unpack] in Fig. 8, we require existentially-quantified labels to not have any flow with escaping labels, which forbids this example.