COUNTEREXAMPLE-GUIDED VERIFICATION OF IMPERATIVE PROGRAMS AGAINST FUNCTIONAL SPECIFICATION

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Certificate

This is to certify that the thesis titled **Counterexample-Guided Verification of Imperative Programs Against Functional Specification** being submitted by **Mr. Indrajit Banerjee** for the award of **Master of Science (Research)** in **Computer Science and Engineering** is a record of bona fide work carried out by him under my guidance and supervision at the Department of Computer Science and Engineering, Indian Institute of Technology Delhi. The work presented in this thesis has not been submitted elsewhere, either in part or full, for the award of any other degree or diploma.

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Indrajit Banerjee

Abstract

We describe an algorithm capable of checking equivalence of two programs that manipulate recursive data structures such as linked lists, strings, trees and matrices. The first program, called specification, is written in a succinct and safe functional language with algebraic data types (ADT). The second program, called implementation, is written in C using arrays and pointers. Our algorithm, based on prior work on counterexample guided equivalence checking, automatically searches for a sound equivalence proof between the two programs.

We formulate an algorithm for discharging proof obligations containing relations between recursive data structure values across the two diverse syntaxes, which forms our first contribution. Our proof discharge algorithm is capable of generating falsifying counterexamples in case of a proof failure. These counterexamples help guide the search for a sound equivalence proof and aid in inference of invariants. As part of our proof discharge algorithm, we formulate a program representation of values. This allows us to reformulate proof obligations due to the top-level equivalence check into smaller nested equivalence checks. Based on this algorithm, we implement an automatic (push-button) equivalence checker tool named S2C, which forms our second contribution.

S2C is evaluated on implementations of common string library functions taken from popular C library implementations, as well as implementations of common list, tree and matrix programs. These implementations differ in data layout of recursive data structures as well as algorithmic strategies. We demonstrate that S2C is able to establish equivalence between a single specification and its diverse C implementations.

Keywords: *Equivalence checking; Bisimulation; Recursive Data Structures; Algebraic Data Types;*

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Chapter 1

Introduction

The problem of equivalence checking between a functional specification and an implementation written in a low level imperative language such as C has been of major research interest. On one side, the functional programming model closely resembles mathematical functions, which allows for comparatively easier verification of algorithmic correctness. On the other hand, a low level imperative language such as C trades the safer abstractions of a functional language for proximity to the machine language resulting in (usually) significantly faster executables, albeit at the cost of a substantially higher possibility of algorithmic errors. Being able to establish equivalence between the two abstractions would allow the user to take advantage of both worlds – (a) easier proof of functional correctness and (b) more efficient executables. The applications of such an equivalence checker would include (a) program verification, where the equivalence checker is used to verify that the C implementation behaves according to the specification and (b) translation validation, where the equivalence checker attempts to generate a proof of equivalence across the transformations (and translations) performed by an optimizing compiler.

The verification of a C implementation against its manually written functional specification through manually-coded refinement proofs has been performed extensively in the seL4 microkernel [31]. Frameworks for program equivalence proofs have been developed in interactive theorem provers like Coq [20] where correlations and invariants are manually identified during proof codification. On the other hand, programming languages like Dafny [33] offer automated program reasoning for imperative languages with abstract data types such as sets and arrays. Such languages perform automatic compile-time checks for manually-specified correctness predicates through SMT solvers. Additionally, there exists significant prior work on translation validation [39, 52, 49, 51, 32, 54, 55, 44, 53, 34, 30, 35, 12, 47, 18, 27, 46, 38] across multiple programming languages with similar models of computation. In most of these applications, soundness is critial, i.e., if the equivalence checker determines the programs to be equivalent, then the programs are indeed equivalent and evidently have equivalent runtime observable behaviour. On the other hand, a sound equivalence checker may be incomplete and fail to prove equivalence of a program pair, even if they were equivalent.

In this work, we present S2C, a *sound* algorithm to automatically search for a proof of equivalence between a functional specification and its optimized C implementations. We will demonstrate how S2C is capable of proving equivalence of multiple equivalent C implementations with vastly different (a) data layouts (e.g. array, linked list representations for a *list*) and (b) algorithmic strategies (e.g. alternate algorithms, optimizations) against a *single* functional specification. This opens the possibility of regression verification [50, 24], where S2C can be used to automate verification across software updates that change memory layouts of data structures.

1.1 A Motivating Example

We start by restricting our attention to programs that construct, read, and write to recursive data structures. In languages like C, pointer and array based implementations of these data-structures are prone to safety and liveness bugs. Similar recursive data structures are also available in safer functional languages like Haskell [36], where algebraic data types (ADTs) [15] ensure several safety properties. We define a minimal functional language, called Spec, that enables the safe and succinct specification of programs manipulating and traversing recursive data structures. Spec is equipped with ADTs as well as boolean (`bool`) and fixed-width bitvector (`i<N>`) types.

We motivate our work by considering example Spec and C programs. The major hurdles of our approach are listed alongside an informal discussion of our proposed solutions. We state our

```
A0: type List = LNil | LCons (val:i32, tail:List).
A1:
A2: fn mk_list_impl (n:i32) (i:i32) (l:List) : List =
A3:    if i ≥_u n then l
A4:             else make_list_impl(n, i+1_i32, LCons(i, l)).
A5:
A6: fn mk_list (n:i32) : List = mk_list_impl(n, 0_i32, LNil).
```

(a) Spec program

```
B0:  typedef struct lnode {
B1:    unsigned val; struct lnode* next;
B2:  } lnode;
B3:
B4:  lnode* mk_list(unsigned n) {
B5:    lnode* l = NULL;
B6:    for (unsigned i = 0; i < n; ++i) {
B7:      lnode* p = malloc(sizeof lnode);
B8:      p→val = i; p→next = l; l = p;
B9:    }
B10:   return l;
B11: }
```

(b) C program with `malloc()`

Figure 1.1: Spec and C programs each constructing a Linked List.

primary contributions in section 1.2 and finish with the organization of the rest of the thesis in section 1.3.

Figures 1.1a and 1.1b show the construction of lists in Spec and C respectively. The `List` ADT in the Spec program is defined at line `A0` in fig. 1.1a. An empty `List` is represented by the *data constructor* `LNil`, whereas a non-empty list uses the `LCons` constructor to combine its first value (`val:i32`) and the remaining list (`tail:List`). The inputs to a Spec procedure (aka function) are its well-typed arguments, which may include recursive data structure (i.e. ADT) values. The inputs to a C procedure are its explicit arguments and the implicit state of program memory at procedure entry. Similarly, the output of a C procedure consists of its explicit return value and

```
S0: List mk_list (i32 n) {
S1:   List l := LNil;
S2:   i32  i := 0_i32;
S3:   while ¬(i ≥_u n):
S4:     l := LCons(i, l);
S5:     i := i + 1_i32;
S6:   return l;
SE: }
```

(a) (Abstracted) Spec IR

```
C0: i32 mk_list (i32 n) {
C1:   i32 l := 0_i32;
C2:   i32 i := 0_i32;
C3:   while i <_u n:
C4:     i32 p := malloc_C4(sizeof(lnode));
C5:     𝕞 := 𝕞[addrof(p →^𝕞_lnode val)←i]_i32;
C6:     𝕞 := 𝕞[addrof(p →^𝕞_lnode next)←l]_i32;
C7:     l := p;
C8:     i := i + 1_i32;
C9:   return l;
CE: }
```

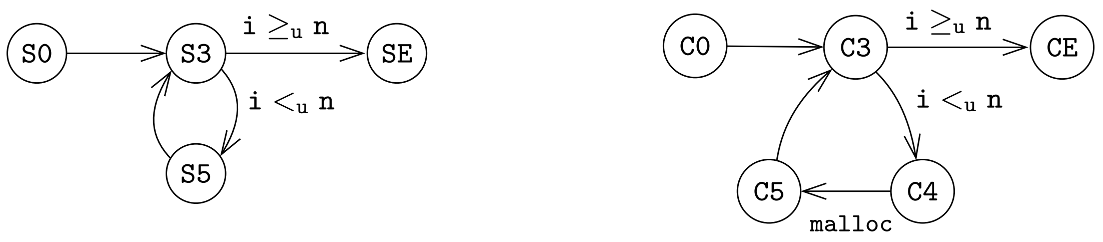
(b) (Abstracted) C IR

Figure 1.2: IRs for the Spec and C `mk_list` procedures in figs. 1.1a and 1.1b respectively.

the state of program memory at procedure exit.

The Spec function `mk_list` (defined at line `A6` in fig. 1.1a), takes a bitvector of size `32` (`n:i32`). It returns a `List` value representing the list $[(\mathtt{n}-1), (\mathtt{n}-2), \ldots, 1, 0]$. On the other hand, the C function `mk_list` (defined at line `B4` in Figure 1.1b) constructs a *pointer based* linked list representing a list identical to the Spec function. Unlike Spec, the construction of the linked list in C requires explicit allocation of memory through calls to `malloc` in addition to stores to the memory. We are interested in showing that the Spec and C `mk_list` procedures are 'equivalent' i.e., given equal `n` inputs, they both construct lists that are 'equal'.

For comparison, we represent both programs in a common abstract framework. This involves converting both `mk_list` functions to a common logical representation (intermediate representation or IR for short). Figures 1.2a and 1.2b show the IRs of the Spec and C `mk_list` procedures in figs. 1.1a and 1.1b respectively. For the Spec program, the tail-recursive function `mk_list_impl` is converted to a loop and inlined in the top-level function `mk_list` in the IR. In case of the C program in fig. 1.1b, the memory state is made explicit (represented by $\mathbb{m}$), and the size and memory layout of each type is concretized in the IR. For example, the `unsigned` and pointer types are encoded as the `i32` bitvector type. A comprehensive description of the logical model is given in section 2.2.



(a) CFG of Spec procedure

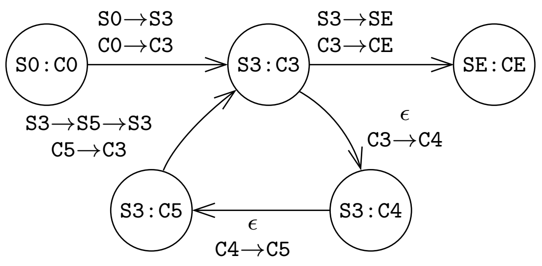
(b) CFG of C procedure

Figure 1.3: CFG representation of Spec and C IRs shown in figs. 1.2a and 1.2b for the `mk_list` procedures in figs. 1.1a and 1.1b respectively.

To reiterate, we are interested in showing equivalence of the Spec and C IRs. Since the argument `n` to both procedures have identical types (i.e. `i32`), their equality is trivially expressible as: $\mathtt{n}_S = \mathtt{n}_C$ [1]. However, Spec uses the `List` ADT to represent a list, whereas the C procedure represents its list using a collection of `lnode` objects linked through their `next` fields in the memory $\mathbb{m}$, and simply returns a value of type `i32` (`lnode*` in the original C program) pointing to the first `lnode` in the list (or the null value in case of an empty list). In order to express equality between these two list values (of types `List` and `i32`), we would like to 'adapt' one of the values so as to match their types. We choose to lift the C linked list (represented by the `i32` value and the C memory state) to a `List` value using an operator called a *lifting constructor*. Let us call this lifting constructor $\mathtt{Clist}^{\mathtt{lnode}}_{\mathbb{m}}$, where the expression $\mathtt{Clist}^{\mathtt{lnode}}_{\mathbb{m}}(p\!:\!\mathtt{i32})$ represents a `List` value constructed from a C pointer p (pointing to an `lnode` object) in memory state $\mathbb{m}$. We will formally define $\mathtt{Clist}^{\mathtt{lnode}}_{\mathbb{m}}$ subsequently in section 2.5. For now, such an operator allows us to express equality between the outputs of the Spec and C procedures as $\mathtt{ret}_S = \mathtt{Clist}^{\mathtt{lnode}}_{\mathbb{m}}(\mathtt{ret}_C)$, where $\mathtt{ret}_S$ and $\mathtt{ret}_C$ represents the values returned by the respective Spec and C procedures in figs. 1.2a and 1.2b. To further emphasize the fact that we are comparing (a) a Spec ADT value with (b) an ADT value lifted from C values using a lifting constructor, we use '$\sim$' instead of '=' and call it a recursive relation: $\mathtt{ret}_S \sim \mathtt{Clist}^{\mathtt{lnode}}_{\mathbb{m}}(\mathtt{ret}_C)$.

Consequently, we are interested in proving that given $\mathtt{n}_S = \mathtt{n}_C$ at the procedure entries, $\mathtt{ret}_S \sim \mathtt{Clist}^{\mathtt{lnode}}_{\mathbb{m}}(\mathtt{ret}_C)$ holds at the exits of both procedures. Before going into the proof method, we

[1] We use S and C subscripts to refer to variables in the Spec and C procedures respectively.



(a) Product-CFG between CFGs in figs. 1.3a and 1.3b

PC-Pair	Invariants
(S0:C0)	Ⓟ $\mathtt{n}_S = \mathtt{n}_C$
(S3:C3)	(I1) $\mathtt{n}_S = \mathtt{n}_C$ (I2) $\mathtt{i}_S = \mathtt{i}_C$ (I3) $\mathtt{i}_S \leq_u \mathtt{n}_S$ (I4) $\mathtt{l}_S \sim \mathtt{Clist}^{\mathtt{lnode}}_{\mathbb{m}}(\mathtt{l}_C)$
(S3:C4) (S3:C5)	(I5) $\mathtt{n}_S = \mathtt{n}_C$ (I6) $\mathtt{i}_S = \mathtt{i}_C$ (I7) $\mathtt{i}_S <_u \mathtt{n}_S$ (I8) $\mathtt{l}_S \sim \mathtt{Clist}^{\mathtt{lnode}}_{\mathbb{m}}(\mathtt{l}_C)$
(SE:CE)	Ⓔ $\mathtt{ret}_S \sim \mathtt{Clist}^{\mathtt{lnode}}_{\mathbb{m}}(\mathtt{ret}_C)$

(b) Node invariants for product-CFG in fig. 1.4a

Figure 1.4: Product-CFG between the CFGs in figs. 1.3a and 1.3b. Figure 1.4b contains the corresponding node invariants for the product-CFG.

first introduce an alternate representation of IR, called the Control-Flow Graph (CFG for short). Figures 1.3a and 1.3b show the CFG representation of the Spec and C IRs in figs. 1.2a and 1.2b respectively. The CFG representation is fundamentally a labeled transition system representation of the corresponding IR, and is further explored in section 2.2. In essence, each node represents a PC location of its IR, and each edge represents (possibly conditional) transition between PCs through instruction execution. For brevity, we often represent a sequence of instructions with a single edge, e.g., in fig. 1.3b, the edge `C5`→`C3` represents the path `C5`→`C6`→`C7`→`C8`→`C3` in fig. 1.2b.

A common approach for showing equivalence between a pair of procedures involves finding a bisimulation relation across the said procedure-pair. Intuitively, a bisimulation relation (a) correlates program transitions across the specification and implementation procedures, and (b) asserts inductively-provable invariants between machine states of the two procedures at the endpoints of each correlated transition [43]. A bisimulation relation itself can be represented as a program, called a *product program* [53] and its CFG representation is called a *product*-CFG. Figure 1.4a shows a product-CFG between the Spec and C `mk_list` procedures in figs. 1.3a and 1.3b respectively.

At each node of the product-CFG, *invariants* relate the states of the Spec and C procedures respectively. Figure 1.4b lists the node invariants for the product-CFG in fig. 1.4a. At the start node ($\mathtt{S0{:}C0}$) of the product-CFG, the precondition (labeled $\textcircled{P}$) ensures equality of input arguments $\mathtt{n}_S$ and $\mathtt{n}_C$ at the procedure entries. Inductive invariants (labeled $\textcircled{I}$) need to be inferred at each intermediate product-CFG node (e.g., ($\mathtt{S3{:}C3}$)) relating both programs' states. For example, at node ($\mathtt{S3{:}C5}$), $\textcircled{I6}$ $\mathtt{i}_S = \mathtt{i}_C$ is an inductive invariant. The inductive invariant $\textcircled{I4}$ $\mathtt{l}_S \sim \mathtt{Clist}^{\mathtt{lnode}}_{\mathbb{m}}(\mathtt{l}_C)$ is another example of a recursive relation and asserts equality between the intermediate Spec and C lists at their respective loop heads. Assuming that the precondition ($\textcircled{P}$) holds at the entry node ($\mathtt{S0{:}C0}$), a bisimulation check involves checking that the inductive invariants hold too, and consequently the postcondition ($\textcircled{E}$) holds at the exit node ($\mathtt{SE{:}CE}$). Checking correctness of a bisimulation relation involves checking whether an invariant holds (among other things). These checks result in proof queries which must be discharged by a solver (aka theorem prover).

1.2 Our Contributions

As previously summarized in section 1.1, an algorithm to find a bisimulation based proof of equivalence between a Spec and C procedure involves three major algorithms: $\boxed{\text{A1}}$ An algorithm for construction of a product-CFG by correlating program executions across the Spec and C procedures respectively. $\boxed{\text{A2}}$ An algorithm for identification of inductively-provable invariants at intermediate correlated PCs. $\boxed{\text{A3}}$ An algorithm for solving proof obligations generated by $\boxed{\text{A1}}$ and $\boxed{\text{A2}}$ algorithms. Next we list our major contributions.

Proof Discharge Algorithm

Solving proof obligations ($\boxed{\text{A3}}$) involving recursive relations (generated by $\boxed{\text{A1}}$ and $\boxed{\text{A2}}$) is quite interesting and forms our primary contribution. We describe a *sound* proof discharge algorithm capable of tackling proof obligations containing recursive relations using off-the-shelf SMT solvers. Our proof discharge algorithm is also capable of reconstruction of counterexamples for the original proof query from models returned by the individual SMT queries. These counterexamples form the foundation of counterexample-guided heuristics for $\boxed{\text{A1}}$ and $\boxed{\text{A2}}$ algorithms as we will discuss shortly. As part of our proof discharge algorithm, we reformulate equality of ADT values (i.e. recursive relations) as equivalence of programs and discharge these proof queries using a nested (albeit much simpler) equivalence check.

Spec-to-C Automatic Equivalence Checker Tool

Our second contribution is S2C, a *sound* equivalence checker tool capable of proving equivalence between a Spec and a C program automatically. S2C either successfully finds a bisimulation relation implying equivalence or it provides a (sound but incomplete) unknown verdict. S2C builds upon the Counter tool[27] and uses specialized versions of (a) counterexample-guided correlation algorithm for incremental construction of a product-CFG ($\boxed{\text{A1}}$) and (b) counterexample-guided invariant inference algorithm for inference of inductive invariants at correlated PCs in the (partially constructed) product-CFG ($\boxed{\text{A2}}$) based on prior work on counterexample-guided equivalence checking [48]. S2C discharges the required verification conditions (i.e. proof obligations) using our Proof Discharge Algorithm. The counterexamples generated by the proof discharge algorithm help steer the search algorithms $\boxed{\text{A1}}$ and $\boxed{\text{A2}}$.

1.3 Outline of the Thesis

The rest of the thesis is divided into five chapters. We begin with a thorough presentation of the topics introduced thus far in chapter 2. The major topics discussed include our specification language, logical representation of programs, and bisimulation in the context of Spec-C equivalence. We finish chapter 2 with a logical encoding of proof obligations generated during an equivalence check.

The next chapter, chapter 3 illustrates our proof discharge algorithm ($\boxed{\text{A3}}$) through proof obligations originating from equivalence checks between previously shown program-pairs. In the context of our proof discharge algorithm, we introduce a decomposition procedure based on unification to reduce a recursive relation to an equivalent set of equalities. The proof discharge algorithm categorizes a proof obligation into three types, each of which is illustrated with the help of examples. We finish with a summary and pseudocode of the algorithm.

Chapter 4 gives an exhaustive overview of the major components of our Spec-to-C equivalence checker tool, S2C. We begin with a dataflow formulation of the points-to analysis introduced as part of our proof discharge algorithm in chapter 3. Next, we summarize the counterexample driven algorithms for product-CFG construction ($\boxed{\text{A1}}$) and invariant inference ($\boxed{\text{A2}}$) based on prior work [48]. Chapter 4 presents the pseudocode for the major subprocedures used as part of our proof discharge algorithm, in addition to details of SMT encoding of proof obligations and recovery of counterexamples from SMT models. We finish with a new representation of expressions, called 'Value Trees' which enables the consolidation of multiple subprocedures utilized as a component of our proof discharge algorithm. We also present an algorithm for converting an expression to its value tree representation along with illustrative examples of its applications.

We provide a comprehensive evaluation of S2C in chapter 5, followed by its limitations. Chapter 6 concludes our work by reiterating the key ideas presented, alongside additional related work.

Chapter 2

Preliminaries

2.1 The Specification Language : Spec

We start with an introduction to our specification language, called Spec. Spec supports recursive algebraic data types (ADT) [15] similar to the ones available in functional languages such as Haskell [36] and SML [45]. Spec supports mutually recursive ADTs but does *not* support universal types. Additionally, Spec is equipped with the following *scalar* types: `unit`, `bool` (boolean) and `i<N>` (fixed-width bitvectors). ADTs can be thought of as 'sum of product' types where each *data constructor* represents a variant (of the sum-type) and the arguments to each data constructor represents its *fields* (of the product-type). For example, the `List` type (defined at `A0` in fig. 1.1a) has two variants `LNil` and `LCons`. `LNil` has no fields while `LCons` has two fields `val` and `tail` of types `i32` and `List` respectively. Additionally, Spec follows *equirecursive* typing rules i.e. a `List` value l and $\texttt{LCons}(1_{\texttt{i32}}, l)$ have definitionally *equal* types. Later in section 4.4.9, we further expand on ADTs in the context of a graphical representation of values used as part of our proof discharge algorithm. The language also borrows its expression grammar heavily from functional languages. This includes `let-in`, `if-then-else`, `match` and function application. Pattern matching (i.e. deconstruction) of ADT values is achieved through `match`. Unlike functional languages, Spec only supports first order functions. Also, Spec does not support partial function application. Hence,

```
A0: type Str = SInvalid | SNil
A1:          | SCons (ch:i8, tail:Str).
A2:
A3: fn is_empty (s : Str) : bool =
A4:    assuming ¬(s is SInvalid) do
A5:      s is SNil.
```

(a) Spec program

```
B0: #include <stdbool.h>
B1:
B2: bool is_empty(char* s) {
B3:   if (!s) return false;
B4:   return *s == 0;
B5: }
```

(b) C program

```
S0: bool is_empty(Str s) {
S1:   assume ¬(s is Sinvalid);
S2:   return s is SNil;
SE: }
```

(c) (Abstracted) Spec IR

```
C0:  bool is_empty(i32 s) {
C1:    if ($s = 0_{i32}$): return false;
C2:    return $\mathbb{m}[0_{i32}]_{\texttt{i8}}$ = $0_{i8}$;
CE:  }
```

(d) (Abstracted) C IR

Figure 2.1: Spec and C programs along with corresponding IRs for the `is_empty` procedures.

$$
\begin{array}{rcl}
\langle\text{expr}\rangle & \rightarrow & \texttt{if}\ \langle\text{expr}\rangle\ \texttt{then}\ \langle\text{expr}\rangle\ \texttt{else}\ \langle\text{expr}\rangle \\
 & | & \texttt{let}\ \langle\text{id}\rangle\ \texttt{=}\ \langle\text{expr}\rangle\ \texttt{in}\ \langle\text{expr}\rangle \\
 & | & \texttt{match}\ \langle\text{expr}\rangle\ \texttt{with}\ \langle\text{match-clause-list}\rangle \\
 & | & \texttt{assuming}\ \langle\text{expr}\rangle\ \texttt{do}\ \langle\text{expr}\rangle \\
 & | & \langle\text{id}\rangle\ \texttt{(}\ \langle\text{expr-list}\rangle\ \texttt{)} \\
 & | & \langle\text{data-cons}\rangle\ \texttt{(}\ \langle\text{expr-list}\rangle\ \texttt{)} \\
 & | & \langle\text{expr}\rangle\ \texttt{is}\ \langle\text{data-cons}\rangle \\
 & | & \langle\text{expr}\rangle\ \langle\text{scalar-op}\rangle\ \langle\text{expr}\rangle \\
 & | & \langle\text{literal}_{\texttt{unit}}\rangle \mid \langle\text{literal}_{\texttt{bool}}\rangle \mid \langle\text{literal}_{\texttt{iN}}\rangle
\end{array}
\qquad
\begin{array}{rcl}
\langle\text{match-clause-list}\rangle & \rightarrow & \langle\text{match-clause}\rangle^{*} \\
\langle\text{match-clause}\rangle & \rightarrow & |\ \langle\text{data-cons}\rangle\ \texttt{(}\ \langle\text{id-list}\rangle\ \texttt{)}\ \Rightarrow \langle\text{expr}\rangle \\
\langle\text{expr-list}\rangle & \rightarrow & \epsilon \mid \langle\text{expr}\rangle\ \texttt{,}\ \langle\text{expr-list}\rangle \\
\langle\text{id-list}\rangle & \rightarrow & \epsilon \mid \langle\text{id}\rangle\ \texttt{,}\ \langle\text{id-list}\rangle \\
 & & \\
\langle\text{literal}_{\texttt{unit}}\rangle & \rightarrow & \texttt{()} \\
\langle\text{literal}_{\texttt{bool}}\rangle & \rightarrow & \texttt{false} \mid \texttt{true} \\
\langle\text{literal}_{\texttt{iN}}\rangle & \rightarrow & [\mathsf{0} \ldots \mathsf{2}^{\mathsf{N}} - \mathsf{1}]
\end{array}
$$

Figure 2.2: Simplified expression grammar of Spec language

we limit our attention to C programs containing only first order functions. Spec is equipped with a special `assuming-do` construct for explicitly providing assertions. Figure 2.1a shows a Spec program with the `assuming-do` construct, with its C equivalent shown in fig. 2.1b. The corresponding IRs are shown in figs. 2.1c and 2.1d respectively. The significance of explicit assertions in Spec is further discussed throughout this chapter. Spec also provides intrinsic scalar operators for expressing computation in C succintly yet explicitly. Examples of scalar operators include (a) logical operators (e.g., `and`), (b) bitvector arithmatic operators (e.g., `bvadd(+)`), and

```
A0: type List = LNil | LCons (val:i32, tail:List).
A1:
A2: fn sum_list_impl (l:List) (sum:i32) :i32 =
A3:    match l with
A4:    | LNil => sum
A5:    | LCons(x, rest) =>
A6:                  sum_list_impl(rest, sum + x).
A7:
A8: fn sum_list (l:List) : i32 =
A9:    sum_list_impl(l, $0_{i32}$).
```

(a) Spec program

```
S0: i32 sum_list (List l) {
S1:   i32 sum $:=$ $0_{i32}$;
S2:   while $\neg$(l is LNil):
S3:     // (l is LCons);
S4:     sum $:=$ sum + l.val;
S5:     l   $:=$ l.next;
S6:   return sum;
SE: }
```

(b) (Abstracted) Spec IR

```
B0:  typedef struct lnode {
B1:    unsigned val; struct lnode* next; } lnode;
B2:
B3:  unsigned sum_list(lnode* l) {
B4:    unsigned sum = 0;
B5:    while (l) {
B6:      sum += l→val;
B7:      l = l→next;
B8:    }
B9:    return sum;
B10: }
```

(c) C program

```
C0: i32 sum_list (i32 l) {
C1:   i32 sum $:=$ $0_{i32}$;
C2:   while l $\neq$ $0_{i32}$:
C3:     sum $:=$ sum + l $\xrightarrow{\mathfrak{m}}_{\texttt{lnode}}$ val;
C4:     l   $:=$ l $\xrightarrow{\mathfrak{m}}_{\texttt{lnode}}$ next;
C5:   return sum;
CE: }
```

(d) (Abstracted) C IR

Figure 2.3: Spec and C programs for traversing a Linked List along with corresponding IRs for the `sum_list` procedures.

(c) relational operators for comparing bitvectors interpreted as unsigned or signed integers (e.g., $\leq_{u,s}$). The equality operator (=) is only supported for scalar types.

Figure 2.2 shows the simplified expression grammar for Spec language. ⟨data-cons⟩ represents an ADT data constructor. The '⟨expr⟩ `is` ⟨data-cons⟩' construct returns a value of `bool` type and is used to test whether the value ⟨expr⟩ is of kind ⟨data-cons⟩. ⟨scalar-op⟩ includes the logical, arithmatic and relational operators supported by Spec.

2.2 Abstract Representation of Programs

As outlined in section 1.1, we convert both Spec and C programs to a common abstract representation called the *Control-Flow Graph* (CFG for short). This process involves first converting both programs to a linear representation called the IR. In this section, we present both IR and CFG representations of Spec and C procedures.

2.2.1 Conversion of Programs to Intermediate Representation

IR is a Three-Address-Code (3AC) style intermediate representation. We often omit intermediate registers in the IR for brevity, and refer to this as the *abstracted* IR. We have already seen the IRs (in figs. 1.2a and 1.2b) for the Spec and C programs that construct lists in figs. 1.1a and 1.1b. Figures 2.3a and 2.3c show Spec and C programs that traverse a list of integers and compute their sum. The corresponding IR programs for the above are shown in figs. 2.3b and 2.3d respectively.

The following major steps are performed during conversion of a Spec source to its IR representation:

1. `match` statements are converted to explicit `if-else` conditionals where each branch is associated with a `match` branch. The *sum-is* operator is used to query the top-level data constructor of an expression. The fields of the data constructor are bound to variables using the *product-access* or *accessor* operator. For example, the `match` statement at `A3` (in fig. 2.3a) is lowered to `if-else` in fig. 2.3b, where '`l` is `LCons`' is used to test whether `l` is of kind `LCons` and '`l.val`' is used to extract the `val` field of `LCons` data constructor. Importantly, the expression 'e.`fi`' is well-formed iff 'e is $V_{\texttt{fi}}$', where $V_{\texttt{fi}}$ represents the data constructor containing the field `fi`. The construction of the IR guarantees the well-formedness of all *accessor* expressions.

2. All tail-recursive calls are converted to loops in the IR. However, all non-tail procedure calls are preserved as is. This transformation enables direct correlation (during equivalence

checking) of tail-calls in Spec with native loops in C. For example, the tail recursive function `sum_list_impl` at `A2` (in fig. 2.3a) is converted to a non-recursive function with a loop.

3. All *helper* functions[1] are inlined at their call-site. We are only interested in proving equivalence of non-helper functions in Spec with their C counterparts. For example, the helper function `sum_list_impl` (now non-recursive due to previous step), is inlined at call-site `A7` in fig. 2.3a.

4. `assuming-do` statements are converted to their equivalent `assume` instruction in the IR. A Spec program is *well-defined* iff it satisfies all `assume` clauses encountered during its execution. These conditions are called *undefined behaviour assumes* or UB *assumes* for short. For example, the `assuming-do` statement at `A4` in fig. 2.1a is converted to an `assume` instruction at `S1` in fig. 2.1c.

Similarly, the following transformations are carried out during conversion of a C source to its IR:

1. Non-determinism in the original C program is determinized in the IR. This includes concretizing the size and memory layouts of both scalar (e.g. `int`) and compound (e.g., `struct`) types, along with fixing the order of evaluation in case it is unspecified. For example, during conversion of C program in fig. 1.1b to IR (in fig. 1.2b), the size of pointer types and `unsigned` is fixed to 32 bits (i.e. `i32`). Similarly, the memory layout (including alignment and offset) of `lnode` struct defined at `B0` (in fig. 1.1b) is chosen. The implications of determinizing the C program behaviour are further discussed in chapter 4. For now, it is sufficient to note that we are interested in equivalence between Spec and this determinized version of C.

2. The memory state of the C program is made explicit, represented using the byte-addressable array ‘`m`’. Memory loads and stores are represented using explicit operations on `m`, e.g., (a) memory loads at `C3` and `C4` in fig. 2.3d, and (b) memory stores at `C5` and `C6` in fig. 1.2b. The memory load and store operators are defined promptly in section 2.2.2

[1] We use a special marker to designate a function as ‘helper’ in Spec. For simplicity, this marker is omitted and instead helper function names are ended with the ‘`_impl`’ suffix.

3. We annotate calls to memory allocation functions (e.g., `malloc`) with their call-site, i.e., IR PC. For example, $\texttt{malloc}_{\texttt{C4}}$ is annotated with its call-site `C4` in fig. 1.2b. These annotations are used by a points-to analysis done as part of our equivalence checking procedure, and defined subsequently in section 4.1.

2.2.2 IR Instructions

Note that both Spec and C programs are converted to the common IR. For a Spec procedure, IR supports scalar types, as well as ADTs defined in its Spec source. The IR also inherits the scalar operators available as part of the Spec language. Each ADT value can be thought of as a key-value dictionary that maps each of its field names to their respective values. These key-value pairs are accessed using the previously introduced *accessor* operator, e.g., $l.\texttt{val}$ and $l.\texttt{next}$ represents the first and second fields of the `LCons` data constructor in fig. 2.3b. Recall that, the IR also allows querying the top-level variant of an ADT value using the *sum-is* operator, e.g., l is `LNil` at `S2` in fig. 2.3b. The `val` field is associated with the `LCons` data constructor and evidently, $l.\texttt{val}$ (and $l.\texttt{next}$) is only *well-formed* under l is `LCons`. As previously stated, the well-formedness of all *accessor* expressions are preserved during construction of IR for a Spec procedure. Using *accessor* and *sum-is* operators, a `List` value l can be expanded as:

$$U_S : l = \underline{\texttt{if}}\ l \text{ is } \texttt{LNil}\ \underline{\texttt{then}}\ \texttt{LNil}\ \underline{\texttt{else}}\ \texttt{LCons}(l.\texttt{val}, l.\texttt{next}) \tag{2.1}$$

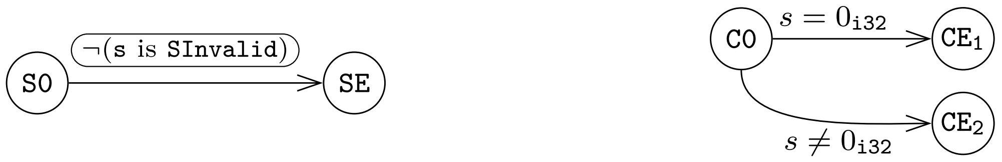
In this expanded representation of l, the *sum-deconstruction* operator '$\underline{\texttt{if}}$-$\underline{\texttt{then}}$-$\underline{\texttt{else}}$' conditionally deconstructs the sum type into its variants `LNil` and `LCons`. The *underlined* $\underline{\texttt{if}}$-$\underline{\texttt{then}}$-$\underline{\texttt{else}}$ operator is a stricter version of `if-then-else`, and is reserved for ADT values. An $\underline{\texttt{if}}$-$\underline{\texttt{then}}$-$\underline{\texttt{else}}$ expression e (for an ADT T) must satisfy the following properties: (a) e has exactly one branch for each data constructor of T (in the order they are defined), and (b) the branch associated with the data constructor V has the form $V(e_1, e_2, \dots)$ i.e. its top-level operator is V. For example, an $\underline{\texttt{if}}$-$\underline{\texttt{then}}$-$\underline{\texttt{else}}$ expression for the `List` type must be of the form: '$\underline{\texttt{if}}\ e_1\ \underline{\texttt{then}}\ \texttt{LNil}\ \underline{\texttt{else}}\ \texttt{LCons}(e_2, e_3)$' for some expressions e_1, e_2, e_3. Equation (2.1) is called the *unrolling procedure* for the `List` variable l. We can similarly define the unrolling procedure for any ADT variable (based on the definition of the ADT).

On the C side, the size of a pointer is fixed[2] and the memory state is modeled as a byte-addressable array over bitvectors (represented by $\mathbb{m}$). “$\mathbb{m}[p]_{\mathtt{T}}$” represents a memory load operation and is equal to the bytes at addresses $[p,\ p+\mathtt{sizeof(T)})$ in $\mathbb{m}$, interpreted as a value of type `T`. Similarly, “$\mathbb{m}[p \leftarrow v]_{\mathtt{T}}$” represents a memory store operation and is equal to $\mathbb{m}$ everywhere except at addresses $[p,\ p+\mathtt{sizeof(T)})$ which contains the value v of type `T` (e.g., `C5` in fig. 1.2b). We use the following two C-like syntaxes to represent more intricate memory loads succinctly:

1. “$p \xrightarrow{\mathbb{m}}_{\mathtt{T}} \mathtt{fi}$” is equivalent to “$\mathbb{m}[p + \mathtt{offsetof}(\mathtt{T}, \mathtt{fi})]_{\mathtt{typeof(T.fi)}}$” i.e., it returns the bytes in the memory array $\mathbb{m}$ starting at address ‘$p + \mathtt{offsetof}(\mathtt{T}, \mathtt{fi})$’ and interpreted as a value of type `typeof(T.fi)`.
2. “$p[i]^{\mathtt{T}}_{\mathbb{m}}$” is equivalent to “$\mathbb{m}[p+i\times\mathtt{sizeof}(\mathtt{T})]_{\mathtt{T}}$” i.e., it returns the bytes in the memory array $\mathbb{m}$ starting at address ‘$p+i\times\mathtt{sizeof}(\mathtt{T})$’ and interpreted as a value of type `T`. Interestingly, $\mathbb{m}[p]_{\mathtt{T}} = p[0]^{\mathtt{T}}_{\mathbb{m}}$.

Recall that the size and layout of each type in C is concretized in the IR, and hence the values ‘`offsetof(T,f)`’ and ‘`sizeof(T)`’ are constants. We use the ‘`addrof()`’ operator to extract the address of a memory load expression: “$\mathtt{addrof}(\mathbb{m}[p]_{\mathtt{T}})$” is equivalent to p. For example, at PC `C5` in fig. 1.2b, $\mathtt{addrof}(p \xrightarrow{\mathbb{m}}_{\mathtt{lnode}} \mathtt{val}) \Leftrightarrow p + \mathtt{offsetof}(\mathtt{lnode}, \mathtt{val})$. Additionally, given a bitvector expression e, “$e[\mathtt{ub} : \mathtt{lb}]$” represents a bitvector of size $(ub - lb + 1)$, such that the i^{th} bit is equal to the $(i + lb)^{th}$ bit in e.

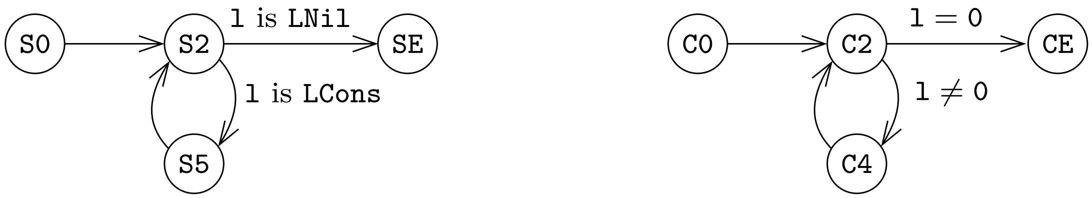
[2] We choose an address width of 4 bytes or 32 bits throughout this thesis.



(a) CFG of Spec procedure

(b) CFG of C procedure

Figure 2.4: CFG representation of Spec and C IRs in figs. 2.1c and 2.1d for the `is_empty` procedures in figs. 2.1a and 2.1b respectively.



(a) CFG of Spec procedure

(b) CFG of C procedure

Figure 2.5: CFG representation of Spec and C IRs in figs. 2.3b and 2.3d for the `sum_list` procedures in figs. 2.3a and 2.3c respectively.

2.2.3 Control-Flow Graph Representation

Figures 2.5a and 2.5b show the Control-Flow Graph (CFG) representation of the Spec and C IRs in figs. 2.3b and 2.3d respectively. Additionally, the CFG representation of IRs in figs. 2.1c and 2.1d are shown in figs. 2.4a and 2.4b respectively. The Control-Flow Graph is an alternate graphical representation of an IR program that emphasizes the control flow structures of the static program. Each CFG node represents a program point (i.e. IR PC) and is denoted by n. The CFG representation is analogous to a deterministic labeled transition systems and uses a symbolic state Ω_n to represent the machine state at node n. An edge ω from n to n' (denoted by $\omega[n \to n']$) represents transition from n to n' through execution of instructions and is associated with:

1. An *edge condition* representing the condition that must be satisfied by Ω_n to trigger the

edge ω.

2. A *transfer function* representing the symbolic state at n' ($\Omega_{n'}$) as a function of Ω_n i.e. how the machine state is mutated along the edge ω.

3. An UB *assume* representing the condition that must be satisfied by Ω_n for the transition ω to be well-defined. For a Spec procedure, the `assume` clauses form its UB assumes. Recall that, a C procedure is determinized during conversion to CFG and thus do not require UB assumes.

For brevity, we often represent a sequence of instructions with a single edge, e.g., in fig. 2.5a, the edge `S2`→`S5` represents the path `S2`→`S3`→`S4`→`S5` in fig. 2.3b. In such a case, the transfer function of the edge is the composition of the sequence of instructions. A CFG must contain exactly one entry node (representing the entry to the function) and (possibly) multiple exit nodes (each representing an exit from the function). For example, the CFG in fig. 2.4b contains an entry node `C0` and two exit nodes $\texttt{CE}_1$ and $\texttt{CE}_2$ representing exits through the IR PCs `C1` and `C2` in fig. 2.1d respectively. An edge incident on an exit node is called an *exit edge*, and is associated with an *action* representing the returned value as a function of the symbolic state at the source node. Actions form the observable behaviour of a CFG while transition through non-exit edges are internal to the program. For a C CFG, the action includes both the returned value (if non-void) and the memory state. We restrict ourselves to programs without calls to *external procedures* (except for `malloc` in $\mathcal{C}$), and thus the only observable action of a CFG are its returned values along exit edges. We often omit the transfer functions in the CFG figures (if they are shown in their corresponding IR) and only show the edge conditions (unless they are *true*). The UB assumes are shown inside curved rectangles (e.g., fig. 2.4b), unless they are *true*. Henceforth, we refer to the CFGs of Spec and C procedures as $\mathcal{S}$ and $\mathcal{C}$ respectively.

2.3 Equivalence Definition

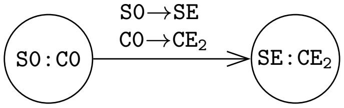
Given (1) a Spec function specification $\mathcal{S}$, (2) a C implementation $\mathcal{C}$, (3) a precondition *Pre* that relates the initial inputs $\texttt{Input}_S$ and $\texttt{Input}_C$ to $\mathcal{S}$ and $\mathcal{C}$ respectively, and (4) a postcondition *Post* that relates the final outputs $\texttt{Output}_S$ and $\texttt{Output}_C$ of $\mathcal{S}$ and $\mathcal{C}$ respectively[3]: $\mathcal{S}$ and $\mathcal{C}$ are *equivalent* if for all possible inputs $\texttt{Input}_S$ and $\texttt{Input}_C$ such that $Pre(\texttt{Input}_S, \texttt{Input}_C)$ holds, $\mathcal{S}$'s execution is well-defined on $\texttt{Input}_S$, *and* $\mathcal{C}$'s memory allocation requests during its execution on $\texttt{Input}_C$ are successful, then both $\mathcal{S}$ and $\mathcal{C}$ produce outputs such that $Post(\texttt{Output}_S, \texttt{Output}_C)$ holds.

$$Pre(\texttt{Input}_S, \texttt{Input}_C) \wedge (\mathcal{S}\ \texttt{def}) \wedge (\mathcal{C}\ \texttt{fits}) \Rightarrow Post(\texttt{Output}_S, \texttt{Output}_C)$$

The ($\mathcal{S}$ `def`) antecedent states that we are only interested in proving equivalence for well-defined executions of $\mathcal{S}$, i.e., executions that satisfy all assertions expressed using the `assuming-do` statement. The ($\mathcal{C}$ `fits`) antecedent states that we prove equivalence under the assumption that $\mathcal{C}$'s memory requirements fit within the available system memory i.e., only for those executions of $\mathcal{C}$ in which all memory allocation requests (through `malloc` calls) are successful.

Recall that the observables of $\mathcal{S}$ and $\mathcal{C}$ are the actions associated with their exit edges (i.e. returned values). For $\mathcal{S}$, observables include the explicit value returned. For $\mathcal{C}$, observables include the returned value (if non-void) along with the memory state at procedure exit. The postcondition *Post* relates these outputs of the two programs. The pair $(Pre, Post)$ represents the input-output behaviour of $\mathcal{C}$ in terms of the specification $\mathcal{S}$, and is called the *input-output specification*. In general, Spec and C sources may contain multiple top-level procedures, with calls to each other. In this case, we are interested in finding equivalence between the CFGs of each pair of S and C procedures with respect to their input-output specification.

[3] $\texttt{Input}_C$ and $\texttt{Output}_C$ include the initial and final memory state of $\mathcal{C}$ respectively.



(a) Product-CFG between figs. 2.4a and 2.4b

PC-Pair	Invariants
$(\mathtt{S0}\!:\!\mathtt{C0})$	Ⓟ $\mathtt{s}_S \sim \mathtt{Cstr}^{\mathtt{u8[]}}_{\mathtt{m}}(\mathtt{s}_C)$
$(\mathtt{SE}\!:\!\mathtt{CE}_2)$	Ⓔ $\mathtt{ret}_S = \mathtt{ret}_C$

(b) Note invariants for product-CFG in fig. 2.6a

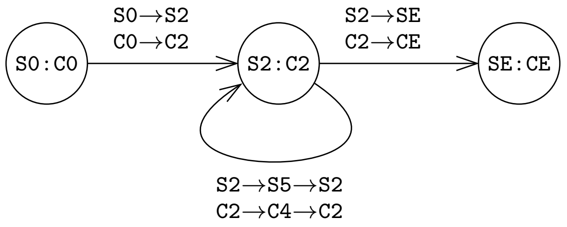
Figure 2.6: Product-CFG and its associated node invariants for CFGs in figs. 2.4a and 2.4b.

2.3.1 Constraining Inputs to C

Sometimes, the user may be interested in constraining the nature of inputs to $\mathcal{C}$ for the purpose of checking equivalence only for *well-formed* inputs. In those circumstances, we use a combination of ($\mathcal{S}$ `def`) and *Pre* to constrain the execution of $\mathcal{C}$ to inputs for which we are interested in proving equivalence. For example, consider the function `is_empty` (shown in figs. 2.1a and 2.1b) that accepts a string and checks if the string is empty. A string is represented as a list of characters (i.e. `i8`) in the Spec procedure. On the other hand, its C analogue expects a standard null-character[4] terminated string represented by a pointer to its first character, say $\mathtt{s}_C$. A *well-formed* nul-terminated string must point to an allocated region of memory terminating with a nul (i.e. *zero*) character and thus $\mathtt{s}_C$ must be non-null. Observe that the well-formedness of $\mathtt{s}_C$ is an entry assumption that must be ensured by the caller. Evidently, we are only interested in verifying the behaviour of the C procedure (against its specification) for well-formed inputs. Note that at `B3` in fig. 2.1b, we handle the case of $\mathtt{s}_C$ being null for safety, even though a well-formed input would never trigger it. Since Spec has no notion of pointers, we expose this conditional well-formedness of C input $\mathtt{s}_C$ through an explicit data constructor `SInvalid` for the `Str` ADT defined at `A0` in fig. 2.1a. Additionally, ($\mathcal{S}$ `def`) asserts $\neg(\mathtt{s}_S$ is `SInvalid`) (at `A4` and `S1`→`S2` in fig. 2.1c) and the precondition *Pre* (labeled Ⓟ in fig. 2.6b) relates ($\mathtt{s}_S$ is `SInvalid`) $\Leftrightarrow$ $(\mathtt{s}_C = 0_{\mathtt{i32}})$[5]. Combined, ($\mathcal{S}$ `def`) and *Pre* ensure that we constrain the inputs of $\mathcal{S}$ and in turn, $\mathcal{C}$ to only well-formed values during equivalence check. A similar strategy is employed for string functions from the

[4] We use *nul* and *null* to denote the zero character and the null pointer respectively.

[5] The relation is implied by the recursive relation $\mathtt{l}_S \sim \mathtt{Cstr}^{\mathtt{u8[]}}_{\mathtt{m}}(\mathtt{l}_C)$ as part of *Pre* shown in fig. 2.6b. The lifting constructor $\mathtt{Cstr}^{\mathtt{u8[]}}_{\mathtt{m}}$ is defined subsequently in section 2.5.



(a) Product-CFG between figs. 2.5a and 2.5b

PC-Pair	Invariants
(S0:C0)	$\textcircled{P}$ $\mathtt{l}_S \sim \mathtt{Clist}^{\mathtt{lnode}}_{\mathtt{m}}(\mathtt{l}_C)$
(S2:C2)	$\textcircled{I1}$ $\mathtt{l}_S \sim \mathtt{Clist}^{\mathtt{lnode}}_{\mathtt{m}}(\mathtt{l}_C)$ $\textcircled{I2}$ $\mathtt{sum}_S = \mathtt{sum}_C$
(SE:CE)	$\textcircled{E}$ $\mathtt{ret}_S = \mathtt{ret}_C$

(b) Node invariants for product-CFG in fig. 2.7a

Figure 2.7: Product-CFG between the CFGs in figs. 2.5a and 2.5b. Figure 2.7b contains the corresponding node invariants for the product-CFG.

standard library (e.g. `strchr`) and is explored in detail during evaluation in section 5.1.1.

2.4 Bisimulation Relation

Recall that, we construct a *bisimulation relation* to identify equivalence between the CFGs of Spec and C procedures. A bisimulation relation correlates the transitions of $\mathcal{S}$ and $\mathcal{C}$ in lockstep, such that the lockstep execution ensures identical observable behaviour. A bisimulation relation between two programs can be represented using a *product program* [53] and the CFG representation of a product program is called a *product*-CFG. Figure 2.7a shows a product-CFG, that encodes the lockstep execution (bisimulation relation) between the CFGs in figs. 2.5a and 2.5b.

A node in the product-CFG is formed by pairing nodes of $\mathcal{S}$ and $\mathcal{C}$, e.g., (S2:C2) is formed by pairing S2 and C2. If the lockstep execution of both programs is at node (S2:C2) in the product-CFG, then $\mathcal{S}$'s execution is at S2 and $\mathcal{C}$'s execution is at C2. The start node (S0:C0) of the product-CFG correlates the start nodes of CFGs of $\mathcal{S}$ and $\mathcal{C}$. Similarly, an exit node (SE:CE) correlates exit nodes of both programs.

An edge in the product-CFG is formed by pairing a *path* (a sequence of edges) in $\mathcal{S}$ with a path in $\mathcal{C}$[6]. A product-CFG edge encodes the lockstep execution of its correlated paths. For example,

[6] For ease of exposition, we present product-CFG in the context of *path* correlations. However, a more general

the product-CFG edge (`S2:C2`)→(`S2:C2`) is formed by pairing `S2`→`S5`→`S2` and `C2`→`C4`→`C2` in figs. 2.5a and 2.5b respectively, and represents that when $\mathcal{S}$ makes the transition `S2`→`S5`→`S2`, $\mathcal{C}$ makes the transition `C2`→`C4`→`C2` in lockstep. In general, a product-CFG edge e may correlate a finite path ρ_S in $\mathcal{S}$ with a finite path ρ_C in $\mathcal{C}$, written $e = (\rho_S, \rho_C)$. The empty path ϵ in $\mathcal{S}$ may be correlated with a finite path in $\mathcal{C}$, effectively simulating a *stuttering bisimulation* relation.

At the start node (`S0:C0`) of the product-CFG in fig. 2.7a, the precondition *Pre* (labeled Ⓟ) ensures equality of input lists $\texttt{l}_S$ and $\texttt{l}_C$ at procedure entries. *Inductive invariants* (labeled Ⓘ) are inferred at each intermediate product-CFG node (e.g., (`S2:C2`)) that relate the values of $\mathcal{S}$ with values and memory state of $\mathcal{C}$. At an exit node (`SE:CE`) of the product-CFG, the postcondition *Post* (labeled Ⓔ) represents equality of observable outputs and forms our top-level proof obligation. Assuming that the precondition *Pre* (Ⓟ) holds at the entry node (`S0:C0`), a bisimulation check involves checking that the inductive invariants (Ⓘ) hold too (at all intermediate product-CFG nodes), and consequently the postcondition *Post* (Ⓔ) holds at each exit node (`SE:CE`). The input-output specification (i.e. (*Pre*, *Post*)) is manually provided by the user while all inductive invariants are identified by an invariant inference algorithm described in section 4.3.

2.4.1 Well-formedness of Product-CFG

A product-CFG is well-formed (i.e. represents a valid bisimulation relation) if it correlates every *possibly* executable edge (as part of a path) in $\mathcal{C}$ with a path in $\mathcal{S}$. An edge deemed to be unreachable (due to an unsatisfiable path condition) represents *dead code* and can be safely ignored and remain uncorrelated in the final product-CFG. For example, the ($\mathcal{S}$ `def`) and *Pre* conditions entail unreachability of the edge $\texttt{C0}\rightarrow\texttt{CE}_1$ in fig. 2.4b, and remain uncorrelated in the product-CFG in fig. 2.6a. Without ($\mathcal{S}$ `def`) and *Pre*, our equivalence checker would fail because the edge $\texttt{C0}\rightarrow\texttt{CE}_1$ is only triggered for ill-formed inputs and has no correlated paths in its specification.

Additionally, a well-formed product-CFG may not correlate a loop in $\mathcal{C}$ with the empty path ϵ in $\mathcal{S}$.

approach of pathset is used based on prior work [27] for improved completeness of our algorithm. We will explore pathsets and its consequences on the algorithm in more detail in section 4.2.1.

For example, fig. 1.4a shows the product-CFG between the programs in figs. 1.3a and 1.3b respectively. The edges $(\texttt{S3:C3}) \rightarrow (\texttt{S3:C4})$ and $(\texttt{S3:C4}) \rightarrow (\texttt{S3:C5})$ correlate the empty path ϵ with the non-empty paths C3→C4 and C4→C5 respectively. However, the only loop path C3→C4→C5→C3 in $\mathcal{C}$ is still correlated with the non-empty path S3→S5→S3 in $\mathcal{S}$ and thus, the product-CFG in fig. 1.4a satisfies this well-formedness criterion. This well-formedness condition ensures *divergence*, i.e. either both programs terminate or both continue indefinitely.

2.5 Recursive Relation

In section 1.1, we briefly introduced a lifting constructor ($\texttt{Clist}^{\texttt{lnode}}_{\mathbb{m}}$) and associated recursive relations. In fig. 2.7b, the precondition (Ⓟ) is another instance of a recursive relation: "$\texttt{l}_S \sim \texttt{Clist}^{\texttt{lnode}}_{\mathbb{m}}(\texttt{l}_C)$" where $\texttt{l}_S$ and $\texttt{l}_C$ represent the input arguments to the Spec and C procedures respectively, `lnode` is the C `struct` type that contains the `val` and `next` fields (defined at B0 in fig. 2.3c), and $\mathbb{m}$ is the byte-addressable array representing the current memory state of the C program. $l_1 \sim l_2$ is read l_1 *is recursively equal to* l_2 and is semantically equivalent to $l_1 = l_2$. The '$\sim$' simply emphasizes that l_1 and l_2 are (possibly recursive) ADT values. The lifting constructor $\texttt{Clist}^{\texttt{lnode}}_{\mathbb{m}}$ 'lifts' a C pointer value p (pointing to an object of type `struct lnode`) and memory state $\mathbb{m}$ to a (possibly infinite in case of a circular list) `List` value, and is defined through its *unrolling procedure* as follows:

$$U_C: \ \texttt{Clist}^{\texttt{lnode}}_{\mathbb{m}}(p : \texttt{i32}) = \underline{\texttt{if}}\ p = 0\ \underline{\texttt{then}}\ \texttt{LNil} \\ \underline{\texttt{else}}\ \texttt{LCons}(p \overset{\mathbb{m}}{\rightarrow}_{\texttt{lnode}} \texttt{val}, \texttt{Clist}^{\texttt{lnode}}_{\mathbb{m}}(p \overset{\mathbb{m}}{\rightarrow}_{\texttt{lnode}} \texttt{next})) \tag{2.2}$$

Note the recursive nature of the lifting constructor $\texttt{Clist}^{\texttt{lnode}}_{\mathbb{m}}$: if the pointer p is zero (i.e. p is the null pointer), then it represents the empty list `LNil`; otherwise it represents the list formed by `LCons`-ing the value stored at $p \overset{\mathbb{m}}{\rightarrow}_{\texttt{lnode}} \texttt{val}$ in memory $\mathbb{m}$ and the list formed by recursively lifting $p \overset{\mathbb{m}}{\rightarrow}_{\texttt{lnode}} \texttt{next}$ through $\texttt{Clist}^{\texttt{lnode}}_{\mathbb{m}}$. $\texttt{Clist}^{\texttt{lnode}}_{\mathbb{m}}(p)$ allows us to adapt a C linked list (formed by chasing pointers in the memory $\mathbb{m}$) to a `List` value and compare it with a Spec `List` value for equality.

Also, consider the $\mathtt{Str}$ lifting constructor $\mathtt{Cstr}^{\mathtt{u8[]}}_{\mathbb{m}}$ (in fig. 2.6b) used to lift a nul-terminated C string into a $\mathtt{Str}$ value. Similar to the $\mathtt{List}$ lifting constructor, $\mathtt{Cstr}^{\mathtt{u8[]}}_{\mathbb{m}}$ is also defined through its unrolling procedure as follows:

$$\begin{aligned} \mathtt{Cstr}^{\mathtt{u8[]}}_{\mathbb{m}}(p:\mathtt{i32}) = {} & \underline{\mathtt{if}}\ p = 0\ \underline{\mathtt{then}}\ \mathtt{SInvalid} \\ & \underline{\mathtt{elif}}\ p[0]^{\mathtt{i8}}_{\mathbb{m}} = 0\ \underline{\mathtt{then}}\ \mathtt{SNil} \\ & \underline{\mathtt{else}}\ \mathtt{SCons}(p[0]^{\mathtt{i8}}_{\mathbb{m}}, \mathtt{Cstr}^{\mathtt{u8[]}}_{\mathbb{m}}(p+1)) \end{aligned} \tag{2.3}$$

Observe that an ill-formed string is related to the pointer being null, whereas the nul character represents the empty string.

2.6 Proof Obligations

As previously discussed, algorithms for (a) incremental construction of a Product-CFG and (b) inference of invariants at intermediate PCs in the (partially constructed) product-CFG, are based on prior work[48] and discussed subsequently in sections 4.2 and 4.3. We discuss the proof obligations that arise from a given product-CFG. Recall that a bisimulation check involves checking that all inductive invariants (and the postcondition *Post*) hold at their associated product-CFG nodes.

We use relational Hoare triples to express these proof obligations [13, 28]. If ϕ denotes a predicate relating the machine states of $\mathcal{S}$ and $\mathcal{C}$, then for a product-CFG edge $e = (\rho_S, \rho_C)$, $\{\phi_s\}(e)\{\phi_d\}$ denotes the condition: if any machine states σ_S and σ_C of programs $\mathcal{S}$ and $\mathcal{C}$ are related through precondition $\phi_s(\sigma_S, \sigma_C)$ and the finite paths ρ_S and ρ_C are executed in $\mathcal{S}$ and $\mathcal{C}$ respectively without triggering undefined behaviour, then execution terminates in states $\sigma_S^{'}$ (for $\mathcal{S}$) and $\sigma_C^{'}$ (for $\mathcal{C}$) and postcondition $\phi_d(\sigma_S^{'}, \sigma_C^{'})$ holds.

For every product-CFG edge $e[s \to d] = (\rho_S, \rho_C)$, we are interested in proving: $\{\phi_s\}(\rho_S, \rho_C)\{\phi_d\}$, where ϕ_s and ϕ_d are the node invariants at the product-CFG nodes s and d respectively. The weakest-precondition transformer is used to translate a Hoare triple $\{\phi_s\}(\rho_S, \rho_C)\{\phi_d\}$ to the following first-order logic formula:

$$(\phi_s \wedge \mathtt{pathcond}_{\rho_S} \wedge \mathtt{pathcond}_{\rho_C} \wedge \mathtt{ubfree}_{\rho_S}) \Rightarrow \mathtt{WP}_{\rho_S,\rho_C}(\phi_d) \tag{2.4}$$

Here, $\mathtt{pathcond}_{\rho_X}$ represents the condition that path ρ is taken in program X and $\mathtt{ubfree}_{\rho_S}$ represents the condition that execution of $\mathcal{S}$ along path ρ_S is free of undefined behaviour. $\mathtt{WP}_{\rho_S,\rho_C}(\phi_d)$ represents the weakest-precondition of the predicate ϕ_d across the product-CFG edge $e = (\rho_S, \rho_C)$. From now on, we will use '$\mathtt{LHS}$' and '$\mathtt{RHS}$' to refer to the antecedent and consequent of the implication operator '$\Rightarrow$' in eq. (2.4).

For example, checking that the loop invariant $\textcircled{\small I1}$ $\mathtt{l}_S \sim \mathtt{Clist}^{\mathtt{lnode}}_{\mathbb{m}}(\mathtt{l}_C)$ holds at ($\mathtt{S2}$:$\mathtt{C2}$) in fig. 2.7a requires that $\textcircled{\small I1}$ is provable along the two product-CFG edges ($\mathtt{S0}$:$\mathtt{C0}$)$\rightarrow$($\mathtt{S2}$:$\mathtt{C2}$) and ($\mathtt{S2}$:$\mathtt{C2}$)$\rightarrow$($\mathtt{S2}$:$\mathtt{C2}$) terminating at ($\mathtt{S2}$:$\mathtt{C2}$), which further reduces to the following two proof obligations:

① $\{\phi_{\mathtt{S0:C0}}\}(\mathtt{S0}{\rightarrow}\mathtt{S2}, \mathtt{C0}{\rightarrow}\mathtt{C2})\{\mathtt{l}_S \sim \mathtt{Clist}^{\mathtt{lnode}}_{\mathbb{m}}(\mathtt{l}_C)\}$

② $\{\phi_{\mathtt{S2:C2}}\}(\mathtt{S2}{\rightarrow}\mathtt{S5}{\rightarrow}\mathtt{S2}, \mathtt{C2}{\rightarrow}\mathtt{C4}{\rightarrow}\mathtt{C2})\{\mathtt{l}_S \sim \mathtt{Clist}^{\mathtt{lnode}}_{\mathbb{m}}(\mathtt{l}_C)\}$

Using weakest precondition predicate transformer, the proof obligation ② reduces to the following first-order logic formula:

$$\begin{aligned} &\mathtt{l}_S \sim \mathtt{Clist}^{\mathtt{lnode}}_{\mathbb{m}}(\mathtt{l}_C) \wedge \mathtt{sum}_S = \mathtt{sum}_C \wedge (\mathtt{l}_S \text{ is } \mathtt{LCons}) \wedge (\mathtt{l}_C \neq 0) \\ &\qquad\qquad \Rightarrow \mathtt{l}_S.\mathtt{next} \sim \mathtt{Clist}^{\mathtt{lnode}}_{\mathbb{m}}(\mathtt{l}_C \xrightarrow{\mathbb{m}}_{\mathtt{lnode}} \mathtt{next}) \end{aligned} \tag{2.5}$$

Due to the presence of recursive relations, these proof queries (e.g., eq. (2.5)) cannot be solved directly by off-the-shelf solvers and require special handling. The next chapter illustrates our proof discharge algorithm for solving proof queries involving recursive relations.

Chapter 3

Proof Discharge Algorithm through Illustative Examples

This chapter demonstrates our proof discharge algorithm through examples. We consider proof obligations generated due to product-CFG invariants shown in figs. 1.4 and 2.7 representing bisimulation relations for the `mk_list` and `sum_list` procedures respectively. We start by describing the properties of the proof discharge algorthm. We also list the properties of the proof obligations generated by our equivalence checker; these properties are essential for the correctness of our proof discharge algorithm. Next, the proof discharge algorithm is explored using instances of proof obligations, and we finish with an overview of the algorithm.

3.1 Properties of Proof Discharge Algorithm

3.1.1 Soundness of Proof Discharge Algorithm

An algorithm that evaluates the truth value of a proof obligation is called a *proof discharge algorithm.* In case a proof discharge algorithm deems a proof obligation to be unprovable, it is expected to return *false* with a set of counterexamples that falsify the proof obligation. A proof discharge algorithm is *precise* if for all proof obligations, the truth value evaluated by the algorithm is identical to the proof obligation's *actual* truth value. A proof discharge algorithm is *sound* if: (a) whenever it evaluates a proof obligation to true, the actual truth value of that proof obligation is also true, and (b) whenever it generates a counterexample, that counterexample must falsify the proof obligation. However, it is possible for a sound proof discharge algorithm to return false (without counterexamples) when the proof obligation was actually provable.

For proof obligations generated by our equivalence checker, it is always safe for a proof discharge algorithm to return false (without counterexamples). Keeping this in mind, our proof discharge algorithm is designed to be *sound*. Conservatively evaluating a proof obligation to false (when it was actually provable) may prevent the equivalence proof from completing successfully. However, importantly, the overall equivalence procedure remains sound i.e. (a) either it successfully finds a valid proof of equivalence (bisimulation relation) or (b) it conservatively returns *unknown*.

3.1.2 Conjunctive Recursive Relation Property of Proof Obligations

Resolving the truth value of a proof obligation that contains a recursive relation such as $\mathtt{l}_S \sim \mathtt{Clist}^{\mathtt{lnode}}_{\mathbb{m}}(\mathtt{l}_C)$ is unclear. Fortunately, the shapes of the proof obligations generated by our equivalence checker are restricted. Our equivalence checking algorithm ensures that, for an invariant $\phi_s = (\phi^{\mathtt{1}}_{\mathtt{s}} \wedge \phi^{\mathtt{2}}_{\mathtt{s}} \wedge ... \wedge \phi^{\mathtt{k}}_{\mathtt{s}})$, at any node s of a product-CFG, if a recursive relation appears in ϕ_s, it must be one of ϕ^1_s, ϕ^2_s, ..., or ϕ^k_s. We call this the *conjunctive recursive relation* property of an invariant ϕ_s.

A proof obligation $\{\phi_s\}(e)\{\phi_d\}$, where $e[s \rightarrow d] = (\rho_S, \rho_C)$, gets lowered using $\mathtt{WP}_e(\phi_d)$ (as shown in eq. (2.4)) to a first-order logic formula of the following form:

$$(\eta^s_1 \wedge \eta^s_2 \wedge ... \wedge \eta^s_m) \Rightarrow (\eta^d_1 \wedge \eta^d_2 \wedge ... \wedge \eta^d_n) \tag{3.1}$$

Thus, due to the conjunctive recursive relation property of ϕ_s and ϕ_d, any recursive relation in eq. (3.1) must appear as one of η^s_i or η^d_j. To simplify proof obligation discharge, we break a first-order logic proof obligation P of the form in eq. (3.1) into multiple smaller proof obligations of the form $P_j : (\texttt{LHS} \Rightarrow \eta_j^d)$, for $j = 1..n$. Each proof obligation P_j is then discharged separately. We call this conversion from a bigger query to multiple smaller queries, RHS-*breaking*.

We provide a sound (but imprecise) proof discharge algorithm that converts a proof obligation generated by our equivalence checker into a series of SMT queries. Our algorithm begins by categorizing a proof obligation into one of three types; each type is discussed separately in subsequent sections. The categorization is based on a specialized unification procedure, which we describe next.

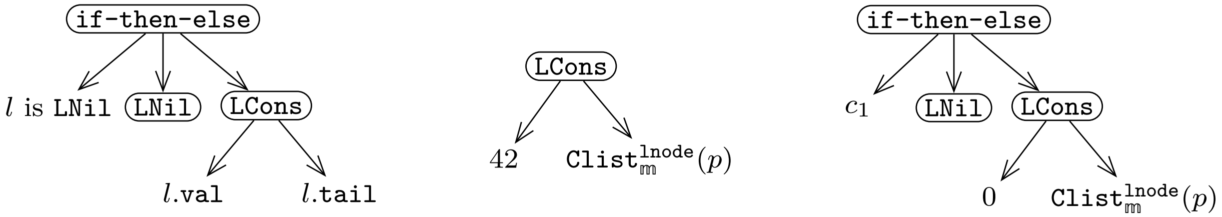
3.2 Iterative Unification and Rewriting Procedure

In this section, we introduce a unification procedure capable of decomposing an equality (e.g., a recursive relation) into an equivalent set of equalities (including scalar equalities and recursive relations).

3.2.1 Atomic Expression

We begin with some definitions. An expression e whose top-level constructor is a lifting constructor, e.g., $e = \texttt{Clist}_{\mathbb{m}}^{\texttt{lnode}}(\texttt{l}_C)$, is called a *lifted expression*. An expression e of the form $v.\texttt{a}_1.\texttt{a}_2...\texttt{a}_\texttt{n}$ i.e. a variable nested within *zero* or more *accessors*, is called a *pseudo-variable*. Note that, a variable is itself a pseudo-variable. Examples of pseudo-variable include the variable l and $l.\texttt{val}$.

Scalar expressions, pseudo-variables and lifted expressions are collectively called *atomic expressions*, or *atoms* for short. Hence, a List variable l, a bitvector expression $e_{\texttt{i32}}$ and a lifted expression $\texttt{Clist}_{\mathbb{m}}^{\texttt{lnode}}(p)$ are all examples of atoms. With each atom of an ADT type, we associate an *unrolling procedure*. By definition, an ADT atom is either a pseudo-variable or a lifted expression. Each (pseudo-)variable is associated with its unrolling procedure governed by its type. For example, the unrolling procedure for a List variable l is given by U_S (eq. (2.1)). For lifted expressions, the unrolling procedure is given by its definition, e.g., U_C (eq. (2.2)) for the lifting constructor $\texttt{Clist}_{\mathbb{m}}^{\texttt{lnode}}$.


if-then-else
l is LNil
LNil
LCons
l.val
l.tail
LCons
42
$\texttt{Clist}^{\texttt{lnode}}_{\mathbb{m}}(p)$
if-then-else
c_1
LNil
LCons
0
$\texttt{Clist}^{\texttt{lnode}}_{\mathbb{m}}(p)$

(a) if l is LNil then LNil else LCons$(l.\texttt{val}, l.\texttt{tail})$ **(b)** LCons(42, $\texttt{Clist}^{\texttt{lnode}}_{\mathbb{m}}(p)$) **(c)** if c_1 then LNil else LCons$(0, l)$

Figure 3.1: Expression trees corresponding to three canonical List expressions used in the context of unification.

3.2.2 Expression Trees

An expression e in which (a) each *accessor* (e.g., '_.tail') and (b) each *sum-is* operator (e.g., '_ is LCons') operate on a pseudo-variable, is called a *canonical expression*. It is possible to convert any expression e into its canonical form $\hat{e}$. For example, the canonical form of $a +$ LCons(b, l).tail.val is given by $a + l.\texttt{val}$, where $l.\texttt{val}$ is a pseudo-variable. The pseudocode for the canonicalization procedure is given in section 4.4.2.

Consider the expression tree of a canonical expression $\hat{e}$, as shown in fig. 3.1. The internal nodes of $\hat{e}$ represents ADT data constructors and the if-then-else sum-deconstruction operator. The leaves of $\hat{e}$ are the atomic subexpressions of $\hat{e}$. For example, in fig. 3.1a, (if-then-else), (LNil) and (LCons) are the internal nodes, whereas l is LNil, l.val and l.tail are the (atomic) leaf expressions. Note that nullary data constructors (e.g. LNil) are considered internal nodes even through they have no children.

The *expression path* to a node v in $\hat{e}$'s tree is the path from the root of $\hat{e}$ to the node v. The *expression path condition* represents the conjunction of all the if conditions (if the then branch of taken along the path), or their negation (if the else branch is taken along the path) for each if-then-else along the path. Consider the expression if c_1 then LNil else LCons$(0, l)$ and its associated expression tree in fig. 3.1c. The expression path condition of c_1 is true, of LNil is c_1 and of $\texttt{Clist}^{\texttt{lnode}}_{\mathbb{m}}(p)$ is $\neg c_1$.

3.2.3 Unification Procedure

For two expressions e_1 and e_2 under expression path conditions p_1 and p_2 respectively, a unification procedure $\theta(p_1, e_1, p_2, e_2)$ attempts to unify the canonical expression trees of e_1 and e_2 created by data constructors and the $\underline{\texttt{if}}$-$\underline{\texttt{then}}$-$\underline{\texttt{else}}$ operator (as shown in fig. 3.1). The unification procedure either fails to unify, or it returns *correlation tuples* $\langle p_1, a_1, p_2, e_2\rangle$ where atom a_1 at expression path condition p_1 in one expression is correlated with expression e_2 at expression path condition p_2 in the other expression.

If *at least* one of e_1 and e_2 (say e_2) is atomic, unification always succeeds and returns a single correlation tuple: $\langle p_2, e_2, p_1, e_1\rangle$. Recall that a variable is an atom and evidently, l and $\texttt{LCons}(42, \texttt{Clist}^{\texttt{lnode}}_{\mathbb{m}}(p))$ successfully unifies (under expression path conditions p_1 and p_2) yielding $\langle p_1, l, p_2, \texttt{LCons}(42, \texttt{Clist}^{\texttt{lnode}}_{\mathbb{m}}(p))\rangle$.

For two non-atomic expressions e_1 and e_2 to unify successfully, it must be true that either the top-level operator in e_1 and e_2 is the same data constructor (in which case an unification is attempted for each of their children), *or* the top-level operator in *at least* one of e_1 and e_2 is $\underline{\texttt{if}}$-$\underline{\texttt{then}}$-$\underline{\texttt{else}}$. For example, unification of $\texttt{LCons}(e_1, e_2)$ and $\texttt{LCons}(e'_1, e'_2)$ proceeds by recursive attempts to unify e_1 with e'_1, and e_2 with e'_2 respectively. On the other hand, unification of $\texttt{LCons}(e_1, e_2)$ and $\texttt{LNil}$ fails due to mismatched top-level data constructors.

If the top-level operator in *exactly one* of e_1 and e_2 (say e_2) is $\underline{\texttt{if}}$-$\underline{\texttt{then}}$-$\underline{\texttt{else}}$, then e_1 must have a data constructor at its root. Given $e_2 = \underline{\texttt{if}}\ c\ \underline{\texttt{then}}\ e_2^{\texttt{th}}\ \underline{\texttt{else}}\ e_2^{\texttt{el}}$, we first attempt to unify e_1 with the $\underline{\text{if}}$ branch $e_2^{\texttt{th}}$ — if unification succeeds, we also unify c ($\underline{\text{then}}$ condition) with *true*. Otherwise, we unify e_1 with the $\underline{\text{else}}$ branch $e_2^{\texttt{el}}$ and $\neg c$ ($\underline{\text{else}}$ condition) with *true*. Consider the unification of a $\texttt{List}$ variable l expanded through its unrolling procedure (i.e. $\underline{\texttt{if}}\ l$ is $\texttt{LNil}\ \underline{\texttt{then}}\ \texttt{LNil}\ \underline{\texttt{else}}\ \texttt{LCons}(l.\texttt{val}, l.\texttt{tail})$), and the expression $\texttt{LCons}(42, \texttt{Clist}^{\texttt{lnode}}_{\mathbb{m}}(p))$. The first unification attempt ($\underline{\text{then}}$ branch) unifying $\texttt{LNil}$ and $\texttt{LCons}(42, \texttt{Clist}^{\texttt{lnode}}_{\mathbb{m}}(p))$ fails due to mismatched data constructors. The second unification attempt ($\underline{\text{else}}$ branch) results in the unification of – (a) $\neg l$ is $\texttt{LNil}$ with *true*, and (b) $\texttt{LCons}(l.\texttt{val}, l.\texttt{tail})$ with $\texttt{LCons}(42, \texttt{Clist}^{\texttt{lnode}}_{\mathbb{m}}(p))$, which eventually succeeds and returns correlation tuples.

If the top-level operator in both e_1 and e_2 is `if`-`then`-`else`, we unify each child (condition and branch expressions) of the corresponding `if`-`then`-`else` operators. Recall that the `if`-`then`-`else` operator (introduced in section 2.2) for an ADT T must have exactly one branch for each data constructor of T, and the branch associated with the data constructor V has V in its top-level. Whenever we descend down an `if`-`then`-`else` operator, we conjunct the `if` condition (if `then` branch is taken) or its negation (if `else` branch is taken) with its associated expression path condition. This allows us to keep track of the expression path conditions for both expressions during recursive descent into their children. For example, consider the unification of `if` c_1 `then` `LNil` `else` $\texttt{LCons}(0, l)$ and `if` c_2 `then` `LNil` `else` $\texttt{LCons}(i, \texttt{Clist}^{\texttt{lnode}}_{\mathbb{m}}(p))$ under expression path conditions p_1 and p_2 respectively. The above results in the following three recursive calls to the unification procedure θ – (a) $\theta(p_1, c_1, p_2, c_2)$, (b) $\theta(p_1 \wedge c_1, \texttt{LNil}, p_2 \wedge c_2, \texttt{LNil})$, (c) $\theta(p_1 \wedge \neg c_1, \texttt{LCons}(0, l), p_2 \wedge \neg c_2, \texttt{LCons}(i, \texttt{Clist}^{\texttt{lnode}}_{\mathbb{m}}(p)))$. The pseudocode for the unification procedure is given in section 4.4.3.

3.2.4 Unification under Rewriting

Recall that our unification procedure θ either fails or successfully unifies two expressions yielding correlation tuples relating atoms to (possibly) non-atomic expressions. Given two *canonical* expressions e_a and e_b at expression path conditions p_a and p_b respectively, an *iterative unification and rewriting procedure* $\Theta(p_a, e_a, p_b, e_b)$ is used to identify a set of correlation tuples relating *only* atoms in the two expressions. This iterative procedure begins with an attempt to unify e_a and e_b. If this unification fails, we return a failure for the original expressions e_a and e_b. Else, we obtain correlation tuples between atoms and expressions (with their expression path conditions). If the unification correlates an atom a_1 at expression path condition p_1 with another atom a_2 at expression path condition p_2, we add $\langle p_1, a_1, p_2, a_2 \rangle$ to the final output. Otherwise, if the unification correlates an atom a_1 at expression path condition p_1 to a non-atomic expression e_2 at expression path condition p_2, we *rewrite* a_1 using its unrolling procedure to obtain expression e_1. The unification algorithm then proceeds by unifying e_1 and e_2 through a recursive call to $\Theta(p_1, e_1, p_2, e_2)$.

For example, consider the unification of a $\mathtt{List}$ variable l with $\mathtt{LCons}(42, \mathtt{Clist}^{\mathtt{lnode}}_{\mathbb{m}}(p))$ through θ, yielding the only correlation tuple $\langle p_1, l, p_2, \mathtt{LCons}(42, \mathtt{Clist}^{\mathtt{lnode}}_{\mathbb{m}}(p))\rangle$. The above tuple relates an atom with a non-atom, and hence Θ rewrites l using its unrolling procedure (in eq. (2.1)) to $\underline{\mathtt{if}}$ l is $\mathtt{LNil}$ $\underline{\mathtt{then}}$ $\mathtt{LNil}$ $\underline{\mathtt{else}}$ $\mathtt{LCons}(l.\mathtt{val}, l.\mathtt{tail})$. This is followed by another unification attempt which returns the correlation tuples: $\langle \mathit{true}, \neg l \text{ is } \mathtt{LNil}, \mathit{true}, \mathit{true}\rangle$, $\langle \neg l \text{ is } \mathtt{LNil}, l.\mathtt{val}, \mathit{true}, 42\rangle$ and $\langle \neg l \text{ is } \mathtt{LNil}, l.\mathtt{tail}, \mathit{true}, \mathtt{Clist}^{\mathtt{lnode}}_{\mathbb{m}}(p)\rangle$. The tuples relate only atomic expressions and thus Θ terminates successfully, yielding the same correlation tuples. In general, the maximum number of rewrites performed by $\Theta(p_a, e_a, p_b, e_b)$ (before termination) is bounded by the sum of number of ADT data constructors in e_a and e_b. The pseudocode for iterative unification and rewriting is given in section 4.4.4.

3.2.5 Decomposition of Recursive Relations

For a recursive relation $l_1 \sim l_2$, we unify the canonicalized trees of l_1 and l_2 through a call to $\Theta(\mathit{true}, l_1, \mathit{true}, l_2)$. If the n tuples obtained after a successful unification are $\langle p_1^i, a_1^i, p_2^i, a_2^i\rangle$ (for $i = 1 \ldots n$), then the *decomposition* of $l_1 \sim l_2$ is defined as:

$$l_1 \sim l_2 \Leftrightarrow \bigwedge_{i=1}^{n} ((p_1^i \wedge p_2^i) \to (a_1^i = a_2^i)) \tag{3.2}$$

Recall that the unification of l and $\mathtt{LCons}(42, \mathtt{Clist}^{\mathtt{lnode}}_{\mathbb{m}}(p))$ yields the correlation tuples: $\langle \mathit{true}, \neg l \text{ is } \mathtt{LNil}, \mathit{true}, \mathit{true}\rangle$, $\langle \neg l \text{ is } \mathtt{LNil}, l.\mathtt{val}, \mathit{true}, 42\rangle$ and $\langle \neg l \text{ is } \mathtt{LNil}, l.\mathtt{tail}, \mathit{true}, \mathtt{Clist}^{\mathtt{lnode}}_{\mathbb{m}}(p)\rangle$. Consequently, the recursive relation $l \sim \mathtt{LCons}(42, \mathtt{Clist}^{\mathtt{lnode}}_{\mathbb{m}}(p))$ decomposes into[1]:

$$(l \text{ is } \mathtt{LCons}) \wedge (l \text{ is } \mathtt{LCons} \to l.\mathtt{val} = 42) \wedge (l \text{ is } \mathtt{LCons} \to l.\mathtt{next} \sim \mathtt{Clist}^{\mathtt{lnode}}_{\mathbb{m}}(p))$$

In case of a failed unification, the *decomposition* is defined to be *false*, e.g., $\mathtt{LNil} \sim \mathtt{LCons}(0, l)$ decomposes into $false$. Each conjunctive clause of the form $((p_1^i \wedge p_2^i) \to (a_1^i = a_2^i))$[2] in the

[1] $(l \text{ is } \mathtt{LCons})$ is equivalent to $\neg(l \text{ is } \mathtt{LNil})$. In general, for an ADT value v of type T (with data constructors $V_1, V_2, \ldots, V_{\mathtt{k}}$), exactly one of $(v \text{ is } V_{\mathtt{i}})$ is true.

[2] If a_1^i and a_2^i are ADT values, we replace $a_1^i = a_2^i$ with $a_1^i \sim a_2^i$.

decomposition is called a *decomposition clause*. A decomposition clause may relate only atomic values, i.e., it may relate (a) two scalars or (b) two pseudo-variable(s) and/or lifted expressions. However, we restrict the shapes of recursive relation invariants such that each recursive relation in its decomposition *strictly* relates ADT pseudo-variables to lifted expressions. The invariant shapes along with the invariant inference procedure is presented in section 4.3. We *decompose* a recursive relation by replacing it with its decomposition. We *decompose* a proof obligation by decomposing all recursive relations in it.

3.3 Categorization of Proof Obligations

3.3.1 k-unrolling of Recursive Relations

Consider a recursive relation $l_1 \sim l_2$. We *unroll* $l_1 \sim l_2$ by rewriting the top-level lifted expressions in l_1 and l_2 using their respective unrolling procedures *and* decomposing the new recursive relation. We *unroll an expression* e by unrolling each recursive relation in e. More generally, the k-unrolling of e is found by unrolling the $(k-1)$-unrolling of e recursively. For example, the one-unrolling of $\texttt{LHS} \Rightarrow l \sim \texttt{Clist}_{\mathbb{m}}^{\texttt{lnode}}(p)$ is given by the decomposition of $\texttt{LHS} \Rightarrow l \sim \underline{\texttt{if}}\ p = 0\ \underline{\texttt{then}}\ \texttt{LNil}\ \underline{\texttt{else}}\ \texttt{LCons}(p \overset{\mathbb{m}}{\rightarrow}_{\texttt{lnode}} \texttt{val}, \texttt{Clist}_{\mathbb{m}}^{\texttt{lnode}}(p \overset{\mathbb{m}}{\rightarrow}_{\texttt{lnode}} \texttt{next}))$, which evaluates to:

$$\begin{aligned}\texttt{LHS} \Rightarrow (l \text{ is } \texttt{LNil}) = (p = 0) &\wedge (l \text{ is } \texttt{LCons} \wedge p \neq 0) \rightarrow (l.\texttt{val} = p \overset{\mathbb{m}}{\rightarrow}_{\texttt{lnode}} \texttt{val}) \\ &\wedge (l \text{ is } \texttt{LCons} \wedge p \neq 0) \rightarrow (l.\texttt{tail} \sim \texttt{Clist}_{\mathbb{m}}^{\texttt{lnode}}(p \overset{\mathbb{m}}{\rightarrow}_{\texttt{lnode}} \texttt{next}))\end{aligned}$$

3.3.2 Categorization Procedure

For a decomposed proof obligation $P_D : \texttt{LHS} \Rightarrow \texttt{RHS}$, we identify its k-unrolling (say P_K), where k is a fixed parameter of the algorithm called the *unrolling parameter*. We use a small value for k, e.g., five. After k-unrolling, we *eliminate* those decomposition clauses $(p_1 \wedge p_2) \rightarrow (a_1 = a_2)$ in P_K whose antecedent $(p_1 \wedge p_2)$ evaluates to false under $\texttt{LHS}$ (*ignoring* all recursive relations), yielding an equivalent proof obligation, say P_E. For example, the one-unrolling of $P : \texttt{LHS} \Rightarrow l \sim \texttt{Clist}_{\mathbb{m}}^{\texttt{lnode}}(0)$, after elimination, yields $P_E : \texttt{LHS} \Rightarrow l$ is $\texttt{LNil}$. We categorize a proof obligation $P : \texttt{LHS} \Rightarrow \texttt{RHS}$ based on the k-unrolled form of its decomposition (i.e. P_E) as follows:

- Type I: P_E does not contain recursive relations
- Type II: P_E contains recursive relations *only* in the LHS
- Type III: P_E contains recursive relations in the RHS

Observe that the process of elimination of decomposition clauses (i.e. $P_K \rightarrow P_E$) itself requires a precise solver to identify *all* decomposition clauses that may be eliminated. An imprecise (but sound) procedure may only identify a subset of these decomposition clauses and evidently classify a type I (and II) proof obligation as type II (and III). Our proof discharge algorithm ensures that it is sound as long as the conversion of P_K to P_E is sound, i.e. we *only* remove those decomposition clauses whose antecedent definitely evaluates to false. Henceforth, we will simply use k-unrolling of P to refer to P_E directly. Next, we describe the algorithm for each type of proof obligations in sections 3.4 to 3.6.

3.4 Handling Type I Proof Obligations

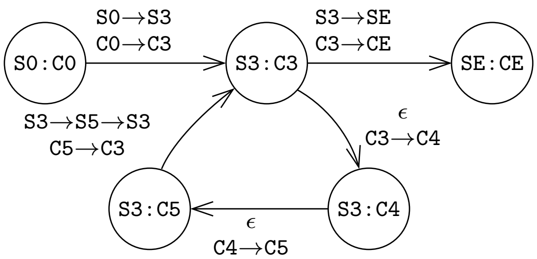
Recall the `mk_list` Spec and C procedures introduced in chapter 1 (figs. 1.1a and 1.1b). Figure 3.2 shows their corresponding IRs, along with the product-CFG and its associated node invariants representing a bisimulation relation. In fig. 3.2c, consider a proof obligation generated across the product-CFG edge $(\texttt{S0:C0}) \rightarrow (\texttt{S3:C3})$ while checking if the $\textcircled{\scriptsize I4}$ invariant in fig. 3.2d, $\texttt{l}_S \sim \texttt{Clist}_{\mathbb{m}}^{\texttt{lnode}}(\texttt{l}_C)$ holds at $(\texttt{S3:C3})$: $\{\phi_{\texttt{S0:C0}}\}(\texttt{S0}\rightarrow\texttt{S3}, \texttt{C0}\rightarrow\texttt{C3})\{\texttt{l}_S \sim \texttt{Clist}_{\mathbb{m}}^{\texttt{lnode}}(\texttt{l}_C)\}$. The precondition $\phi_{\texttt{S0:C0}} \equiv (\texttt{n}_S = \texttt{n}_C)$ does not contain a recursive relation. When lowered to first-order logic through $\texttt{WP}_{\texttt{S0}\rightarrow\texttt{S3},\texttt{C0}\rightarrow\texttt{C3}}$, this translates to $\texttt{n}_S = \texttt{n}_C \Rightarrow \texttt{LNil} \sim \texttt{Clist}_{\mathbb{m}}^{\texttt{lnode}}(0)$. Here, LNil is obtained for $\texttt{l}_S$ and 0 (null) is obtained for $\texttt{l}_C$. The one-unrolled form of this proof obligation yields $\texttt{n}_S = \texttt{n}_C \Rightarrow \textit{true}$ which trivially resolves to true.

```
S0: List mk_list (i32 n) {
S1:   List l ≔ LNil;
S2:   i32  i ≔ 0_i32;
S3:   while ¬(i ≥_u n):
S4:     l ≔ LCons(i, l);
S5:     i ≔ i + 1_i32;
S6:   return l;
SE: }
```

(a) (Abstracted) Spec IR

```
C0: i32 mk_list (i32 n) {
C1:   i32 l ≔ 0_i32;
C2:   i32 i ≔ 0_i32;
C3:   while i <_u n:
C4:     i32 p ≔ malloc_C4(sizeof(lnode));
C5:     𝕞 ≔ 𝕞[addrof(p →^𝕞_lnode val)←i]_i32;
C6:     𝕞 ≔ 𝕞[addrof(p →^𝕞_lnode next)←l]_i32;
C7:     l ≔ p;
C8:     i ≔ i + 1_i32;
C9:   return l;
CE: }
```

(b) (Abstracted) C IR



(c) Product-CFG between IRs in figs. 3.2a and 3.2b

PC-Pair	Invariants	
(S0:C0)	(P) $\mathtt{n}_S = \mathtt{n}_C$	
(S3:C3)	(I1) $\mathtt{n}_S = \mathtt{n}_C$ (I3) $\mathtt{i}_S \leq_u \mathtt{n}_S$	(I2) $\mathtt{i}_S = \mathtt{i}_C$ (I4) $\mathtt{l}_S \sim \mathtt{Clist}^{\mathtt{lnode}}_{\mathbb{m}}(\mathtt{l}_C)$
(S3:C4) (S3:C5)	(I5) $\mathtt{n}_S = \mathtt{n}_C$ (I7) $\mathtt{i}_S <_u \mathtt{n}_S$	(I6) $\mathtt{i}_S = \mathtt{i}_C$ (I8) $\mathtt{l}_S \sim \mathtt{Clist}^{\mathtt{lnode}}_{\mathbb{m}}(\mathtt{l}_C)$
(SE:CE)	(E) $\mathtt{ret}_S \sim \mathtt{Clist}^{\mathtt{lnode}}_{\mathbb{m}}(\mathtt{ret}_C)$	

(d) Node invariants for product-CFG in fig. 3.2c

Figure 3.2: Figures 3.2a and 3.2b shows the IRs for the Spec and C `mk_list` procedures in figs. 1.1a and 1.1b respectively. Product-CFG between the IRs in figs. 3.2a and 3.2b is shown in fig. 3.2c. Figure 3.2d contains the corresponding node invariants for the product-CFG.

Consider the following example of a proof obligation: $\{\phi_{\mathtt{S0:C0}}\}(\mathtt{S0}\to\mathtt{S3}\to\mathtt{S5}\to\mathtt{S3}, \mathtt{C0}\to\mathtt{C3})\{\mathtt{l}_S \sim \mathtt{Clist}^{\mathtt{lnode}}_{\mathbb{m}}(\mathtt{l}_C)\}$. Notice, we have changed the path in $\mathcal{S}$ (with IR fig. 3.2a) to $\mathtt{S0}\to\mathtt{S3}\to\mathtt{S5}\to\mathtt{S3}$ here. In this case, the corresponding first-order logic formula evaluates to: $(\mathtt{n}_S = \mathtt{n}_C) \land (0 <_u \mathtt{n}_S) \Rightarrow \mathtt{LCons}(0, \mathtt{LNil}) \sim \mathtt{Clist}^{\mathtt{lnode}}_{\mathbb{m}}(0)$, where $(0 <_u \mathtt{n}_S)$ is the path condition for the path $\mathtt{S0}\to\mathtt{S3}\to\mathtt{S5}\to\mathtt{S3}$. One-unrolling of this proof obligation decomposes RHS into false due to failed unification of LCons and LNil. The proof obligation is further discharged using an SMT solver which provides a counterexample (model) that evaluates the formula to false. For example, the counterexample $\{\mathtt{n}_S \mapsto 42, \mathtt{n}_C \mapsto 42\}$ evaluates this formula to false. These counterexamples assist in faster convergence of our correlation search and invariant inference procedures (as we will discuss later in sections 4.2 and 4.3).

Thus for type I queries, k-unrolling reduces all (if any) recursive relations in the original proof obligation into scalar equalities. The resulting query is further discharged using an SMT solver. Section 4.4 contains a deeper analysis of the following aspects of our proof discharge algorithm: (a) translation of formula to SMT logic (section 4.4.7), and (b) reconstruction of counterexamples from models returned by the SMT solver (section 4.4.8). Assuming a capable enough SMT solver, all proof obligations in type I can be discharged precisely, i.e., we can always decide whether the proof obligation evaluates to true or false. If it evaluates to false, we also obtain counterexamples.

3.5 Handling Type II Proof Obligations

Recall the `sum_list` Spec and C procedures introduced in chapter 2 (figs. 2.3a and 2.3c). Figure 3.3 shows their corresponding IRs, along with the product-CFG and its associated node invariants representing a bisimulation relation. Consider the proof obligation for $\textcircled{\small I2}$ invariant $\mathtt{sum}_S = \mathtt{sum}_C$ across edge $(\mathtt{S2}\!:\!\mathtt{C2}) \rightarrow (\mathtt{S2}\!:\!\mathtt{C2})$ in fig. 3.3c: $\{\phi_{\mathtt{S2:C2}}\}(\mathtt{S2}\rightarrow\mathtt{S5}\rightarrow\mathtt{S2}, \mathtt{C2}\rightarrow\mathtt{C4}\rightarrow\mathtt{C2})\{\mathtt{sum}_S = \mathtt{sum}_C\}$, where the node invariant $\phi_{\mathtt{S2:C2}}$ contains the recursive relation $\mathtt{l}_S \sim \mathtt{Clist}^{\mathtt{lnode}}_{\mathbb{m}}(\mathtt{l}_C)$. The corresponding (simplified) first-order logic formula for this proof obligation is: $\mathtt{l}_S \sim \mathtt{Clist}^{\mathtt{lnode}}_{\mathbb{m}}(\mathtt{l}_C) \wedge (\mathtt{sum}_S = \mathtt{sum}_C) \wedge (\mathtt{l}_S \text{ is } \mathtt{LCons}) \wedge (\mathtt{l}_C \neq 0) \Rightarrow (\mathtt{sum}_S + \mathtt{l}_S.\mathtt{val}) = (\mathtt{sum}_C + \mathtt{l}_C \overset{\mathbb{m}}{\rightarrow}_{\mathtt{lnode}} \mathtt{val})$. We fail to remove the recursive relation on the `LHS` even after k-unrolling for any finite unrolling parameter k because both sides of $\sim$ represent list values of arbitrary length. In such a scenario, we do not know of an efficient SMT encoding for the recursive relation $\mathtt{l}_S \sim \mathtt{Clist}^{\mathtt{lnode}}_{\mathbb{m}}(\mathtt{l}_C)$. Ignoring this recursive relation will incorrectly (although soundly) evaluate the proof obligation to false; however, for a successful equivalence proof, we need the proof discharge algorithm to evaluate it to true. Let's call this requirement $\textcircled{\small R1}$.

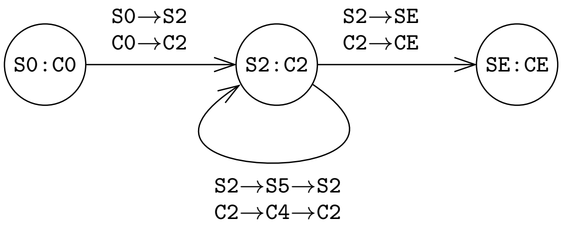
Now, consider the proof obligation formed by correlating two iterations of the loop in $\mathcal{S}$ (with IR

```
S0: i32 sum_list (List l) {
S1:   i32 sum := $0_{\texttt{i32}}$;
S2:   while ¬(l is LNil):
S3:     // (l is LCons);
S4:     sum := sum + l.val;
S5:     l   := l.next;
S6:   return sum;
SE: }
```

(a) (Abstracted) Spec IR

```
C0: i32 sum_list (i32 l) {
C1:   i32 sum := $0_{\texttt{i32}}$;
C2:   while l $\neq$ $0_{\texttt{i32}}$:
C3:     sum := sum + l $\xrightarrow{\mathbb{m}}_{\texttt{lnode}}$ val;
C4:     l   := l $\xrightarrow{\mathbb{m}}_{\texttt{lnode}}$ next;
C5:   return sum;
CE: }
```

(b) (Abstracted) C IR



(c) Product-CFG between IRs in figs. 3.3a and 3.3b

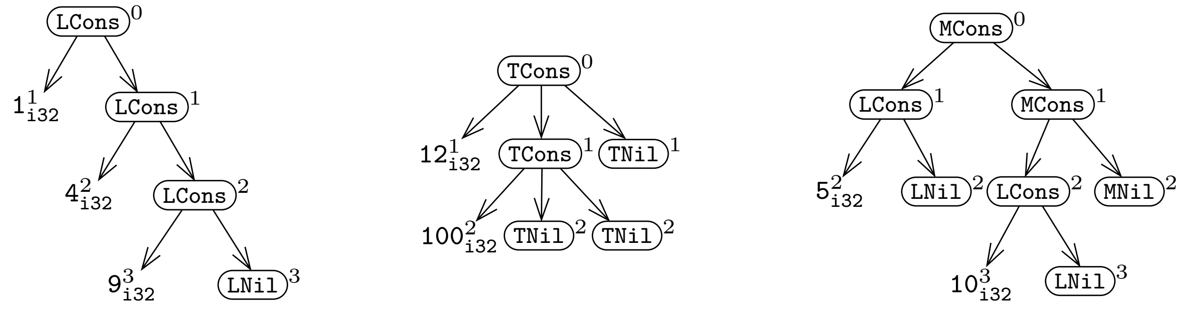
PC-Pair	Invariants
(S0:C0)	Ⓟ $\texttt{l}_S \sim \texttt{Clist}^{\texttt{lnode}}_{\mathbb{m}}(\texttt{l}_C)$
(S2:C2)	(I1) $\texttt{l}_S \sim \texttt{Clist}^{\texttt{lnode}}_{\mathbb{m}}(\texttt{l}_C)$ (I2) $\texttt{sum}_S = \texttt{sum}_C$
(SE:CE)	Ⓔ $\texttt{ret}_S = \texttt{ret}_C$

(d) Node invariants for product-CFG in fig. 3.3c

Figure 3.3: Figures 3.3a and 3.3b shows the IRs for the Spec and C `sum_list` procedures in figs. 2.3a and 2.3c respectively. Product-CFG between the IRs in figs. 3.3a and 3.3b is shown in fig. 3.3c. Figure 2.7b contains the corresponding node invariants for the product-CFG.

fig. 3.3a) with one iteration of the loop in $\mathcal{C}$ (with IR fig. 3.3b): $\{\phi_{\texttt{S2:C2}}\}(\texttt{S2}\rightarrow\texttt{S5}\rightarrow\texttt{S2}\rightarrow\texttt{S5}\rightarrow\texttt{S2}, \texttt{C2}\rightarrow\texttt{C4}\rightarrow\texttt{C2})\{\texttt{sum}_S = \texttt{sum}_C\}$. The equivalent first-order logic formula is: $\texttt{l}_S \sim \texttt{Clist}^{\texttt{lnode}}_{\mathbb{m}}(\texttt{l}_C) \wedge (\texttt{sum}_S = \texttt{sum}_C) \wedge (\texttt{l}_S \text{ is } \texttt{LCons}) \wedge (\texttt{l}_S.\texttt{tail} \text{ is } \texttt{LCons}) \Rightarrow (\texttt{sum}_S + \texttt{l}_S.\texttt{val} + \texttt{l}_S.\texttt{tail}.\texttt{val}) = (\texttt{sum}_C + \texttt{l}_C \xrightarrow{\mathbb{m}}_{\texttt{lnode}} \texttt{val})$. Similar to the prior proof obligation, its equivalent first-order logic formula contains a recursive relation in the LHS. Clearly, this proof obligation should evaluate to false. Whenever a proof obligation evaluates to false, we expect an ideal proof discharge algorithm to generate counterexamples that falsify the proof obligation. Let's call this requirement (R2). Recall that these counterexamples help in faster convergence of our correlation search and invariant inference procedures.

To tackle requirements (R1) and (R2), our proof discharge algorithm converts the original proof



(a) `List` = `LNil` | `LCons(i32, List)`

(b) `Tree` = `TNil` | `TCons(i32, Tree, Tree)`

(c) `Matrix` = `MNil` | `MCons(List, Matrix)`

Figure 3.4: Expression trees of three values, each of type `List`, `Tree` and `Matrix` respectively. The depths are shown as superscripts for each node in the trees.

obligation $P : \{\phi_s\}(e)\{\phi_d\}$ into two approximated proof obligations ($P_{pre-o} : \{\phi_s^{o_{d_1}}\}(e)\{\phi_d\}$) and ($P_{pre-u} : \{\phi_s^{u_{d_2}}\}(e)\{\phi_d\}$). Here $\phi_s^{o_{d_1}}$ and $\phi_s^{u_{d_2}}$ represent the over- and under-approximated versions of precondition ϕ_s respectively, and d_1 and d_2 represent *depth parameters* that indicate the degree of over- and under-approximation. To explain our over- and under-approximation scheme, we first introduce the notion of *depth* for an ADT value.

3.5.1 Depth of ADT Values

To define depth of an ADT value v, we view the value as its expression tree. The internal nodes represent ADT data constructors and the leafs (also called *terminals*) represent scalar constants (e.g. bitvector literals). The depth of a data constructor or a scalar literal in v is simply the depth of its associated node in the expression tree representation of v. The *depth* of ADT value v is defined as the depth of its expression tree. For example, the depth of $\texttt{LCons}(1, \texttt{LCons}(4, \texttt{LNil}))$ is 2. Figure 3.4 shows the expression tree and their corresponding node depths for three values, each of type `List`, `Tree` and `Matrix` respectively.

3.5.2 Approximation of Recursive Relations

The d-depth overapproximation of a recursive relation $l_1 \sim l_2$, denoted by $l_1 \sim_d l_2$, represents the condition that l_1 and l_2 are *recursively equal up to depth* d. i.e., l_1 and l_2 have identical structures and all *terminals* at depths $\leq d$ in the trees of both values are equal (under the precondition that the terminals exist); however, terminals at depths $> d$ may have different values. $l_1 \sim_d l_2$ (for finite d) is a weaker condition than $l_1 \sim l_2$ (i.e. overapproximation). The true equality i.e. $l_1 \sim l_2$ can be thought of as equality of structures and all terminals up to an unbounded depth i.e. $l_1 \sim_\infty l_2$.

The d-depth underapproximation of a recursive relation $l_1 \sim l_2$ is written as $l_1 \approx_d l_2$, where $\approx_d$ represents the condition that l_1 and l_2 are *recursively equal and bounded to depth* d, i.e., l_1 and l_2 have a maximum depth $\leq d$ *and* they are recursively equal up to depth d. Thus, $l_1 \approx_d l_2$ is equivalent to $\Gamma_d(l_1) \wedge \Gamma_d(l_2) \wedge l_1 \sim_d l_2$, where $\Gamma_d(l)$ represents the condition that the maximum depth of l is d. $l_1 \approx_d l_2$ (for finite d) is a stronger condition than $l_1 \sim l_2$ (i.e. underapproximation) as it bounds the depth to d while also ensuring equality till depth d. For arbitrary depths a and b ($a \leq b$), the approximations of $l_1 \sim l_2$ are related as follows:

$$l_1 \approx_a l_2 \Rightarrow l_1 \approx_b l_2 \Rightarrow l_1 \sim l_2 \Rightarrow l_1 \sim_b l_2 \Rightarrow l_1 \sim_a l_2 \tag{3.3}$$

3.5.3 Reduction of Approximate Recursive Relations

Unlike the original recursive relation $l_1 \sim l_2$, its approximations $l_1 \sim_d l_2$ and $l_1 \approx_d l_2$ can be reduced into equivalent conditions absent of recursive relations. Hence, these approximations can be encoded in and subsequently discharged by a SMT solver.

- $l_1 \sim_d l_2$ is equivalent to the condition that the tree structures of l_1 and l_2 are identical till depth d *and* the corresponding terminal values in both d-depth identical structures are also equal. Note that these conditions only require scalar equalities. $l_1 \sim_d l_2$ can be identified through unification of l_1 and l_2 till depth d. This algorithm is similar to the 'iterative unification and rewriting procedure' in section 3.2 and further described in section 4.4.6. In this modified unification algorithm, we eagerly expand atomic ADT expressions till depth d, in contrast to the 'iterative unification and rewriting procedure' which terminates whenever a correlation tuple relates (possibly ADT) atomic expressions. Finally, we only keep those correlation tuples at depth $\leq d$ that relate scalar values and discard the recursive relations.

For example, the condition $l \sim_1 \texttt{Clist}^{\texttt{lnode}}_{\mathbb{m}}(p)$ is computed through iterative unification and rewriting till depth one; yielding the correlation tuples: $\langle \mathit{true}, l \text{ is } \texttt{LNil}, \mathit{true}, p = 0 \rangle$, $\langle l \text{ is } \texttt{LCons}, l.\texttt{val}, p \neq 0, p \overset{\mathbb{m}}{\rightarrow}_{\texttt{lnode}} \texttt{val} \rangle$ and $\langle l \text{ is } \texttt{LCons}, l.\texttt{tail}, p \neq 0, \texttt{Clist}^{\texttt{lnode}}_{\mathbb{m}}(p \overset{\mathbb{m}}{\rightarrow}_{\texttt{lnode}} \texttt{next}) \rangle$. Keeping only those correlation tuples that relate scalar expressions, the above condition reduces to the SMT-encodable predicate:

$$((l \text{ is } \texttt{LNil}) = (p = 0)) \wedge ((l \text{ is } \texttt{LCons}) \wedge (p \neq 0) \rightarrow l.\texttt{val} = p \overset{\mathbb{m}}{\rightarrow}_{\texttt{lnode}} \texttt{val})$$

- Recall that $l_1 \approx_d l_2 \Leftrightarrow \Gamma_d(l_1) \wedge \Gamma_d(l_2) \wedge l_1 \sim_d l_2$. $\Gamma_d(l)$ is equivalent to the condition that the tree nodes at depths $> d$ are unreachable. This is achieved through expanding (canonicalized) l through rewriting till depth d and asserting the unreachability of $\underline{\texttt{if}}$-$\underline{\texttt{then}}$-$\underline{\texttt{else}}$ paths that reach nodes with depths $> d$ (i.e. asserting the negation of their expression path conditions). For example, for a `List` variable l, the condition $\Gamma_1(l)$ is equivalent to $(l \text{ is } \texttt{LNil}) \vee ((l \text{ is } \texttt{LCons}) \wedge (l.\texttt{tail} \text{ is } \texttt{LNil}))$. Similarly, $\Gamma_1(\texttt{Clist}^{\texttt{lnode}}_{\mathbb{m}}(p))$ is equivalent to $(p = 0) \vee ((p \neq 0) \wedge (p \overset{\mathbb{m}}{\rightarrow}_{\texttt{lnode}} \texttt{next} = 0))$. Finally, $l \approx_1 \texttt{Clist}^{\texttt{lnode}}_{\mathbb{m}}(p) \Leftrightarrow \Gamma_1(l) \wedge \Gamma_1(\texttt{Clist}^{\texttt{lnode}}_{\mathbb{m}}(p)) \wedge l \sim_1 \texttt{Clist}^{\texttt{lnode}}_{\mathbb{m}}(p)$. The algorithms for reduction of over- and under-approximate recursive relations are given in section 4.4.6.

3.5.4 Summary of Type II Proof Discharge Algorithm

We over- (under-) approximate a precondition ϕ till depth d by d-depth over- (under-) approximating each recursive relation occuring in ϕ. Due to the conjunctive recursive relation property (defined in section 3.1.2), the over- and under-approximation of ϕ are also weaker and stronger conditions compared to ϕ respectively. For a type II proof obligation $P : \{\phi_s\}(e)\{\phi_d\}$, we first submit the proof obligation $(P_{pre-o} : \{\phi_s^{o_{d_1}}\}(e)\{\phi_d\})$ to the SMT solver. Recall that the precondition ${\phi_s}^{o_{d_1}}$ is the d_1-depth overapproximated version of ϕ_s. If the SMT solver evaluates P_{pre-o} to true, then we return true for the original proof obligation P — if the Hoare triple with an overapproximate precondition holds, then the original Hoare triple also holds.

If the SMT solver evaluates P_{pre-o} to false, then we submit the proof obligation (P_{pre-u} : $\{{\phi_s}^{u_{d_2}}\}(e)\{\phi_d\}$) to the SMT solver. Recall that the precondition ${\phi_s}^{u_{d_2}}$ is the d_2-depth underapproximated version of ϕ_s. If the SMT solver evaluates P_{pre-u} to false, then we return false for the original proof obligation P — if the Hoare triple with an underapproximate precondition does not hold, then the original Hoare triple also does not hold. Further, a counterexample that falsifies P_{pre-u} would also falsify P, and is thus a valid counterexample for use in our correlation search and invariant inference procedures.

Finally, if the SMT solver evaluates P_{pre-u} to true, then we have neither proven nor disproven P. In this case, we imprecisely (but soundly) return false for the original proof obligation P (without counterexamples). Note that both approximations of P strictly fall in type I and are discharged as discussed in section 3.4.

Revisiting our examples, the proof obligation $\{\phi_{\texttt{S2:C2}}\}(\texttt{S2}\rightarrow\texttt{S5}\rightarrow\texttt{S2}, \texttt{C2}\rightarrow\texttt{C4}\rightarrow\texttt{C2})\{\texttt{sum}_S = \texttt{sum}_C\}$ is provable using a depth 1 overapproximation of the precondition $\phi_{\texttt{S2:C2}}$ — the depth 1 overapproximation retains the information that the first value in lists $\texttt{l}_S$ and $\texttt{Clist}^{\texttt{lnode}}_{\mathbb{m}}(\texttt{l}_C)$ are equal, and that is sufficient to prove that the new values of $\texttt{sum}_S$ and $\texttt{sum}_C$ are also equal (given that the old values are equal, as encoded in $\phi_{\texttt{S2:C2}}$).

Similarly, the proof obligation $\{\phi_{\texttt{S2:C2}}\}(\texttt{S2}\rightarrow\texttt{S5}\rightarrow\texttt{S2}\rightarrow\texttt{S5}\rightarrow\texttt{S2}, \texttt{C2}\rightarrow\texttt{C4}\rightarrow\texttt{C2})\{\texttt{sum}_S = \texttt{sum}_C\}$ successfully evaluates to false using a depth 2 underapproximation of the precondition $\phi_{\texttt{S2:C2}}$. In the depth 2 underapproximate version, we try to prove that if the equal lists $\texttt{l}_S$ and $\texttt{Clist}^{\texttt{lnode}}_{\mathbb{m}}(\texttt{l}_C)$ have exactly two nodes[3], then the sum of the two values in $\texttt{l}_S$ is equal to the value stored in the first node in $\texttt{l}_C$. This proof obligation will return counterexample(s) that map program variables to their concrete values. The following is a possible counterexample to the depth 2 underapproximate proof obligation.

[3] The underapproximation restricts both lists to have at most two nodes; the path condition for $\texttt{S2}\rightarrow\texttt{S5}\rightarrow\texttt{S2}\rightarrow\texttt{S5}\rightarrow\texttt{S2}$ additionally restricts $\texttt{l}_S$ to have at least two nodes. Together, this is equivalent to the list having exactly two nodes

$$\begin{array}{l}
\{\\
\quad \begin{array}{ll}
\texttt{sum}_S & \mapsto 3, \\
\texttt{sum}_C & \mapsto 3,\\
\texttt{l}_S & \mapsto \texttt{LCons(42,LCons(43,LNil))},\\
\texttt{l}_C & \mapsto \texttt{0x123},\\
\mathbb{m} & \mapsto \left\{ \begin{array}{l} \texttt{0x123} \mapsto_{\texttt{lnode}} (\texttt{.val} \mapsto 42,\ \texttt{.next} \mapsto \texttt{0x456}),\\ \texttt{0x456} \mapsto_{\texttt{lnode}} (\texttt{.val}\mapsto 43,\ \texttt{.next}\mapsto 0),\\ \texttt{()} \mapsto 77 \end{array}\right\}
\end{array}\\
\}
\end{array}$$

This counterexample maps variables to values (e.g., $\texttt{sum}_S$ maps to an `i32` value `3` and $\texttt{l}_S$ maps to a `List` value `LCons`(42,`LCons`(43,LNil))). Additionally, It maps the C program's memory state $\mathbb{m}$ to an array that maps the regions starting at addresses `0x123` and `0x456` (regions of size '`sizeof(lnode)`') to memory objects of type `lnode` (with the `val` and `next` fields shown for each object). All other addresses (except the ones for which an explicit mapping is available), $\mathbb{m}$ provides a default byte-value `77` (shown as `() ↦ 77`) in this counterexample.

This counterexample satisfies the preconditions $\texttt{l}_S \approx_2 \texttt{Clist}^{\texttt{lnode}}_{\mathbb{m}}(\texttt{l}_C)$, $\texttt{sum}_S = \texttt{sum}_C$ and the path conditions. Further, when the paths S2→S5→S2→S5→S2 and C2→C4→C2 are executed starting at the machine state represented by this counterexample, the resulting values of $\texttt{sum}_S$ and $\texttt{sum}_C$ are `3+42+43=88` and `3+42=45` respectively. Evidently, the counterexample falsifies the proof condition because these values are not equal (as required by the postcondition).

3.6 Handling Type III Proof Obligations

In fig. 3.2c, consider a proof obligation generated across the product-CFG edge (S3:C5) → (S3:C3) while checking if the $\textcircled{I4}$ invariant, $\texttt{l}_S \sim \texttt{Clist}^{\texttt{lnode}}_{\mathbb{m}}(\texttt{l}_C)$, holds at (S3:C3): $\{\phi_{\texttt{S3:C5}}\}(\texttt{S3}\rightarrow\texttt{S5}\rightarrow\texttt{S3}, \texttt{C5}\rightarrow\texttt{C3})\{\texttt{l}_S \sim \texttt{Clist}^{\texttt{lnode}}_{\mathbb{m}}(\texttt{l}_C)\}$. Here, a recursive relation is present both in the precondition $\phi_{\texttt{S3:C5}}$ ($\textcircled{I8}$) and in the postcondition ($\textcircled{I4}$) and we are unable to remove them after k-unrolling. When lowered to first-order logic through $\texttt{WP}_{\texttt{S3}\rightarrow\texttt{S5}\rightarrow\texttt{S3},\texttt{C5}\rightarrow\texttt{C3}}$, this translates to (showing only relevant relations):

$$(\texttt{i}_S = \texttt{i}_C \wedge \texttt{p}_C = \texttt{malloc}() \wedge \texttt{l}_S \sim \texttt{Clist}^{\texttt{lnode}}_{\mathbb{m}}(\texttt{l}_C)) \Rightarrow (\texttt{LCons}(\texttt{i}_S, \texttt{l}_S) \sim \texttt{Clist}^{\texttt{lnode}}_{\mathbb{m}'}(\texttt{p}_C)) \quad (3.4)$$

On the RHS of this first-order logic formula, $\texttt{LCons}(\texttt{i}_S, \texttt{l}_S)$ is compared for equality with the lifted expression $\texttt{Clist}^{\texttt{lnode}}_{\mathbb{m}'}(\texttt{p}_C)$; here $\texttt{p}_C$ represents the address of the newly allocated `lnode` object (through `malloc`) and $\mathbb{m}'$ represents the C memory state after executing the writes at lines C5 and C6 on the path C5→C3, i.e.,

$$\mathbb{m}' \Leftrightarrow \mathbb{m}[\texttt{addrof}(\texttt{p}_\texttt{C} \rightarrow_{\texttt{lnode}} \texttt{val}) \leftarrow \texttt{i}_C]_{\texttt{i32}}[\texttt{addrof}(\texttt{p}_\texttt{C} \rightarrow_{\texttt{lnode}} \texttt{next}) \leftarrow \texttt{l}_C]_{\texttt{i32}} \quad (3.5)$$

Recall that "$\mathbb{m}[a \leftarrow v]_{\texttt{T}}$" represents an array that is equal to $\mathbb{m}$ everywhere except at addresses $[a, a+\texttt{sizeof(T)})$ which contains the value v of type 'T'. Consequently, $\mathbb{m}'$ is equal to $\mathbb{m}$ everywhere except at the `val` and `next` fields of the `lnode` object pointed to by $\texttt{p}_C$. We refer to these memory writes that distinguish $\mathbb{m}$ and $\mathbb{m}'$, as the *distinguishing writes*.

3.6.1 LHS-to-RHS Substitution and RHS Decomposition

We start by utilizing the $\sim$ relationships in the LHS (antecedent) of '⇒' to rewrite eq. (3.4) so that the ADT variables (e.g., $\texttt{l}_S$) in its RHS (consequent) are substituted with the lifted $\mathcal{C}$ values (e.g., $\texttt{Clist}^{\texttt{lnode}}_{\mathbb{m}}(\texttt{l}_C)$). Thus, we rewrite eq. (3.4) to:

$$\begin{aligned}(\texttt{i}_S = \texttt{i}_C \wedge \texttt{p}_C = \texttt{malloc}() \wedge \texttt{l}_S \sim \texttt{Clist}^{\texttt{lnode}}_{\mathbb{m}}(\texttt{l}_C))\\ \Rightarrow (\texttt{LCons}(\texttt{i}_S, \texttt{Clist}^{\texttt{lnode}}_{\mathbb{m}}(\texttt{l}_C)) \sim \texttt{Clist}^{\texttt{lnode}}_{\mathbb{m}'}(\texttt{p}_C))\end{aligned} \quad (3.6)$$

Next, we decompose the RHS by decomposing the recursive relation in the RHS followed by RHS-breaking. This process reduces eq. (3.6) into the following smaller proof obligations (LHS denotes the antecedent of the proof obligation in eq. (3.6)): (a) $\texttt{LHS} \Rightarrow (\texttt{p}_C \neq 0)$, (b) $\texttt{LHS} \wedge (\texttt{p}_C \neq 0) \Rightarrow (\texttt{i}_S = \texttt{p}_C \overset{\mathbb{m}'}{\rightarrow}_{\texttt{lnode}} \texttt{val})$, and (c) $\texttt{LHS} \wedge (\texttt{p}_C \neq 0) \Rightarrow \texttt{Clist}^{\texttt{lnode}}_{\mathbb{m}}(\texttt{l}_C) \sim \texttt{Clist}^{\texttt{lnode}}_{\mathbb{m}'}(\texttt{p}_C \overset{\mathbb{m}'}{\rightarrow}_{\texttt{lnode}} \texttt{next})$.

The first two proof obligations fall in type II and are discharged through over- and under-approximation schemes as discussed in section 3.5.4:

1. The first proof obligation with postcondition ($\mathtt{p}_C \neq 0$) evaluates to *true* because the $\mathtt{LHS}$ ensures that $\mathtt{p}_C$ is the return value of an allocation function (i.e. $\mathtt{malloc}$) which must be non-zero due to the ($\mathcal{C}$ $\mathtt{fits}$) assumption.

2. The second proof obligation with postcondition ($\mathtt{i}_S = \mathtt{p}_C \overset{\mathbb{m}'}{\rightarrow}_{\mathtt{lnode}} \mathtt{val}$) also evaluates to *true* because $\mathtt{i}_C$ is written at address $\mathtt{p}_C + \mathtt{offsetof}(\mathtt{lnode}, \mathtt{val})$ in $\mathbb{m}'$ (eq. (3.5)) and the $\mathtt{LHS}$ ensures that $\mathtt{i}_S = \mathtt{i}_C$.

For ease of exposition, we simplify the postcondition of the third proof obligation by rewriting $\mathtt{Clist}^{\mathtt{lnode}}_{\mathbb{m}'}(\mathtt{p}_C \overset{\mathbb{m}'}{\rightarrow}_{\mathtt{lnode}} \mathtt{next})$ to $\mathtt{Clist}^{\mathtt{lnode}}_{\mathbb{m}'}(\mathtt{l}_C)$. This simplification is valid because $\mathtt{l}_C$ is written to address $\mathtt{p}_C + \mathtt{offsetof}(\mathtt{lnode}, \mathtt{next})$ in $\mathbb{m}'$ (eq. (3.5)). Also, we have already shown that ($\mathtt{p}_C \neq 0$) holds due to the ($\mathcal{C}$ $\mathtt{fits}$) assumption. This simplification-based rewriting is only done for ease of exposition, and has no effect on the completeness of the algorithm. Thus, the third proof obligation can be rewritten as a recursive relation between two lifted expressions:

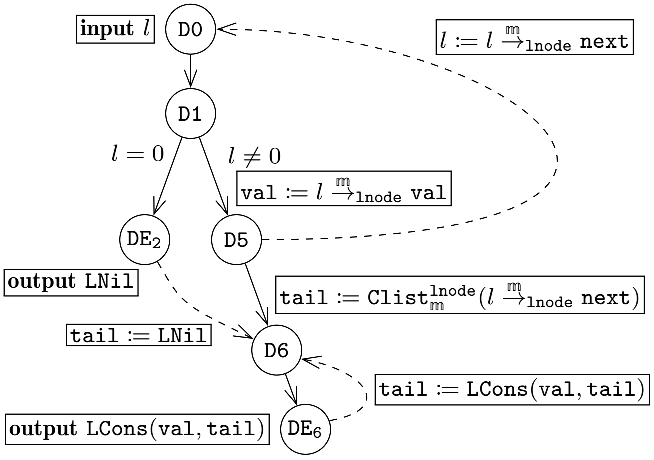
$$\mathtt{LHS} \Rightarrow \mathtt{Clist}^{\mathtt{lnode}}_{\mathbb{m}}(\mathtt{l}_C) \sim \mathtt{Clist}^{\mathtt{lnode}}_{\mathbb{m}'}(\mathtt{l}_C) \tag{3.7}$$

Hence, we are interested in proving equality between two $\mathtt{List}$ values lifted from $\mathcal{C}$ values under a precondition. Next, we show how the above can be reposed as the problem of showing equivalence between two procedures through bisimulation.

3.6.2 Deconstruction Programs for Lifted Values

Consider a program that recursively calls the definition (i.e. unrolling procedure) of $\mathtt{Clist}^{\mathtt{lnode}}_{\mathbb{m}}$ (eq. (2.2)) to deconstruct $\mathtt{Clist}^{\mathtt{lnode}}_{\mathbb{m}}(l)$. For example, $\mathtt{Clist}^{\mathtt{lnode}}_{\mathbb{m}}(l)$ may yield a recursive call to $\mathtt{Clist}^{\mathtt{lnode}}_{\mathbb{m}}(l \overset{\mathbb{m}}{\rightarrow}_{\mathtt{lnode}} \mathtt{next})$ and so on, until the argument becomes zero. This program essentially deconstructs $\mathtt{Clist}^{\mathtt{lnode}}_{\mathbb{m}}(l)$ into its terminal (scalar) values and reconstructs a $\mathtt{List}$ value equal to the value represented by $\mathtt{Clist}^{\mathtt{lnode}}_{\mathbb{m}}(l)$. We call this program a *deconstruction program* (denoted by $\mathcal{D}$) based on the lifting constructor $\mathtt{Clist}^{\mathtt{lnode}}_{\mathbb{m}}$. Figure 3.5 show the IR and CFG representations for the deconstruction program based on $\mathtt{Clist}^{\mathtt{lnode}}_{\mathbb{m}}$.

```
D0: List Clist^{lnode}_{m}(i32 l) {
D1:  if l = 0:
D2:   return LNil;
D3:  else:
D4:   i32  val  := l ->^{m}_{lnode} val;
D5:   List tail := Clist^{lnode}_{m}(l ->^{m}_{lnode} next);
D6:   return LCons(val, tail);
DE: }
```


input l
D0
$l := l \xrightarrow{\mathfrak{m}}_{\texttt{lnode}} \texttt{next}$
D1
$l = 0$
$l \neq 0$
$\texttt{val} := l \xrightarrow{\mathfrak{m}}_{\texttt{lnode}} \texttt{val}$
DE$_2$
D5
output LNil
$\texttt{tail} := \texttt{Clist}^{\texttt{lnode}}_{\mathfrak{m}}(l \xrightarrow{\mathfrak{m}}_{\texttt{lnode}} \texttt{next})$
tail := LNil
D6
tail := LCons(val, tail)
output LCons(val, tail)
DE$_6$

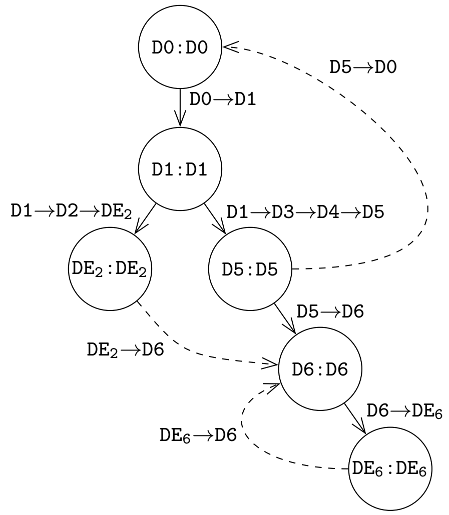
(a) (Abstracted) IR of deconstruction program **(b)** CFG of deconstruction program

Figure 3.5: IR and CFG representation of deconstruction program based on the lifting constructor $\texttt{Clist}^{\texttt{lnode}}_{\mathfrak{m}}$ defined in eq. (2.2). The edge D5→D6 contains a recursive function call. In fig. 3.5b, the square boxes show the transfer functions for the deconstruction program. The dashed edges represent the recursive function call in the CFG representation as shown in fig. 3.5b.

Theorem 1. *Under an antecedent* LHS*,* $\texttt{Clist}^{\texttt{lnode}}_{\mathfrak{m}}(\texttt{l}_C) \sim \texttt{Clist}^{\texttt{lnode}}_{\mathfrak{m}'}(\texttt{l}_C)$ *holds* if and only if *the two deconstruction programs* $\mathcal{D}_1$ *and* $\mathcal{D}_2$*, based on* $\texttt{Clist}^{\texttt{lnode}}_{\mathfrak{m}}(\texttt{l}_C)$ *and* $\texttt{Clist}^{\texttt{lnode}}_{\mathfrak{m}'}(\texttt{l}_C)$*, are equivalent. The equivalence must ensure that the observables generated by both programs (i.e. output* List *values) are equal, given that the input* $\texttt{l}_C$ *is provided to both programs respectively* and *the antecedent* LHS *holds at the program entries.*

Proof Sketch. The proof follows from noting that the only observables of $\mathcal{D}_1$ and $\mathcal{D}_2$ are their output List values. Also, the value represented by a lifted expression is equal to the output of its deconstruction program. Thus, a successful equivalence proof ensures equal values represented by the lifting constructors and vice versa. □

Thus, to check if $\texttt{Clist}^{\texttt{lnode}}_{\mathfrak{m}}(\texttt{l}_C) \sim \texttt{Clist}^{\texttt{lnode}}_{\mathfrak{m}'}(\texttt{l}_C)$ holds; we instead check if a bisimulation relation exists between their respective deconstruction programs $\mathcal{D}^{fst}$ and $\mathcal{D}^{snd}$ (implying equivalence). Theorem 1 generalizes to arbitrary lifted expressions with potentially different arguments and memory states.



(a) Decons-PCFG

PC-Pair	Invariants
(D0:D0)	$\textcircled{P}$ $\mathtt{l}^{fst} = \mathtt{l}^{snd}$
(D1:D1)	$\textcircled{I1}$ $\mathtt{l}^{fst} = \mathtt{l}^{snd}$
(D5:D5)	$\textcircled{I2}$ $\mathtt{val}^{fst} = \mathtt{val}^{snd}$ $\textcircled{I3}$ $\mathtt{l}^{fst} \xrightarrow{\mathbb{m}}_{\mathtt{lnode}} \mathtt{next} = \mathtt{l}^{snd} \xrightarrow{\mathbb{m}'}_{\mathtt{lnode}} \mathtt{next}$
(D6:D6)	$\textcircled{I4}$ $\mathtt{val}^{fst} = \mathtt{val}^{snd}$ $\textcircled{I5}$ $\mathtt{tail}^{fst} = \mathtt{tail}^{snd}$
(DE$_2$:DE$_2$) (DE$_6$:DE$_6$)	$\textcircled{E}$ $\mathtt{ret}^{fst} = \mathtt{ret}^{snd}$

(b) Node invariants for decons-PCFG in fig. 3.6a

Figure 3.6: Decons-PCFG and its associated node invariants for the deconstruction programs based on $\mathtt{Clist}^{\mathtt{lnode}}_{\mathbb{m}}(\mathtt{l}_C)$ and $\mathtt{Clist}^{\mathtt{lnode}}_{\mathbb{m}'}(\mathtt{l}_C)$ respectively.

3.6.3 Checking Bisimulation between Deconstruction Programs

To check bisimulation, we attempt to show that both deconstructions proceed in lockstep, and the invariants at each step of this lockstep execution ensure equal observables. We use a product-CFG to encode this lockstep execution between $\mathcal{D}^{fst}$ and $\mathcal{D}^{snd}$ — to distinguish this product-CFG from the top-level product-CFG that relates $\mathcal{S}$ and $\mathcal{C}$, we call this product-CFG that relates two deconstruction programs, a *deconstruction product*-CFG or *decons*-PCFG for short.

The decons-PCFG for the proof obligation in eq. (3.7) is shown in fig. 3.6a. We distinguish states between the first and second programs using superscripts: fst and snd respectively. However, these are omitted in case the states are equal in both programs (e.g. $\mathtt{p}_C$). To check bisimulation between the programs that deconstruct $\mathtt{Clist}^{\mathtt{lnode}}_{\mathbb{m}}(\mathtt{l}_C)$ and $\mathtt{Clist}^{\mathtt{lnode}}_{\mathbb{m}'}(\mathtt{l}_C)$ (i.e. $\mathcal{D}^{fst}$ and $\mathcal{D}^{snd}$ respectively), the decons-PCFG correlates one unrolling of the first program with one unrolling of the second program, as defined by the unrolling procedure in eq. (2.2). Thus, the PC-transition correlations of $\mathcal{D}^{fst}$ and $\mathcal{D}^{snd}$ are trivially obtained by unifying the static program structures as shown in fig. 3.6a. A node is created in the decons-PCFG that encodes the correlation of the entries of both programs; we call this node the *recursive-node* in the decons-PCFG (e.g. $(\mathtt{D0}:\mathtt{D0})$ in fig. 3.6a). A recursive call becomes a back-edge in the decons-PCFG that terminates at the recursive-node. Furthermore, a bisimulation check involves identification of invariants at correlated PC-pairs strong enough to ensure observable equivalence. At the start of both deconstruction programs, $\textcircled{P}$ $\mathtt{l}^{fst} = \mathtt{l}^{snd} = \mathtt{l}_C$ — the same $\mathtt{l}_C$ is passed to both $\mathcal{D}^{fst}$ and $\mathcal{D}^{snd}$, only the memory states $\mathbb{m}$ and $\mathbb{m}'$ (defined in eq. (3.5)) are different. The observables include the returned `List` values at correlated program exits $(\mathtt{DE}_2:\mathtt{DE}_2)$ and $(\mathtt{DE}_6:\mathtt{DE}_6)$, which forms the postcondition (labeled $\textcircled{E}$ in fig. 3.6b). Next, the bisimulation check involves identification of inductive invariants (labeled $\textcircled{I}$ in fig. 3.6b) at correlated PC-pairs. The proof obligations arising due to this bisimulation check include:

1. The $\underline{\mathtt{if}}$ condition $(\mathtt{l}^{fst} = 0)$ in $\mathcal{D}^{fst}$ is equal to the corresponding $\underline{\mathtt{if}}$ condition $(\mathtt{l}^{snd} = 0)$ in $\mathcal{D}^{snd}$: $(\mathtt{l}^{fst} = 0) = (\mathtt{l}^{snd} = 0)$.

2. If the $\underline{\mathtt{if}}$ condition evaluates to false in both $\mathcal{D}^{fst}$ and $\mathcal{D}^{snd}$, then observable values $\mathtt{val}^{fst}$ and $\mathtt{val}^{snd}$ along the path $(\mathtt{D1}:\mathtt{D1})\rightarrow(\mathtt{D5}:\mathtt{D5})$ (used in the construction of the output lists) are equal. This forms the invariant $\textcircled{I2}$ in fig. 3.6b and lowers to the following proof obligation:
   $(\mathtt{l}^{fst} \neq 0) \wedge (\mathtt{l}^{snd} \neq 0) \Rightarrow \mathtt{l}^{fst} \xrightarrow{\mathbb{m}}_{\mathtt{lnode}} \mathtt{val} = \mathtt{l}^{snd} \xrightarrow{\mathbb{m}'}_{\mathtt{lnode}} \mathtt{val}$.

3. If the $\underline{\mathtt{if}}$ condition evaluates to false in both $\mathcal{D}^{fst}$ and $\mathcal{D}^{snd}$, then the preconditions are satisfied at the beginning of the programs invoked through the recursive call. This involves checking that, along the path $(\mathtt{D1}:\mathtt{D1})\rightarrow(\mathtt{D5}:\mathtt{D5})$, the actual arguments to the recursive call satisfies the precondition $\textcircled{P}$ at the beginning of the procedure i.e. the recursive-node $(\mathtt{D0}:\mathtt{D0})$. This forms the invariant $\textcircled{I3}$ in fig. 3.6b and lowers the following proof obligation:
   $(\mathtt{l}^{fst} \neq 0) \wedge (\mathtt{l}^{snd} \neq 0) \Rightarrow \mathtt{l}^{fst} \xrightarrow{\mathbb{m}}_{\mathtt{lnode}} \mathtt{next} = \mathtt{l}^{snd} \xrightarrow{\mathbb{m}'}_{\mathtt{lnode}} \mathtt{next}$.

   A successful discharge of the above invariant ($\textcircled{I3}$), by induction, ensures that postcondition ($\textcircled{E}$) is satisfied by the values returned by the recursive call at product-CFG node $(\mathtt{D6}:\mathtt{D6})$. Hence, we can assume that invariant $\textcircled{I5}$ holds at $(\mathtt{D6}:\mathtt{D6})$. This special case of correlating procedure call edges is further discussed in section 4.2.3 as part of our overall product-CFG construction algorithm.

The first check succeeds due to the precondition $\textcircled{P}$ $\mathtt{l}^{fst} = \mathtt{l}^{snd}$ at the recursive-node. For the second and third checks, we additionally need to reason that the memory objects $\mathtt{l}^{snd} \overset{\mathbbm{m}'}{\rightarrow}_{\mathtt{lnode}} \mathtt{val}$ and $\mathtt{l}^{snd} \overset{\mathbbm{m}'}{\rightarrow}_{\mathtt{lnode}} \mathtt{next}$ cannot alias with the writes in $\mathbbm{m}'$ (eq. (3.5)) to the newly allocated objects $\mathtt{p}_C \overset{\mathbbm{m}'}{\rightarrow}_{\mathtt{lnode}} \mathtt{val}$ and $\mathtt{p}_C \overset{\mathbbm{m}'}{\rightarrow}_{\mathtt{lnode}} \mathtt{next}$. We capture this aliasing information using a points-to analysis described next in section 3.6.4.

Notice that a bisimulation check between the deconstruction programs is significantly easier than the top-level bisimulation check between $\mathcal{S}$ and $\mathcal{C}$: here, the correlation of PC transitions is trivially identified by unifying the unrolling procedures of both lifted expressions, and the candidate invariants are obtained by equating each pair of terminal values that form the observables of both programs.

3.6.4 Points-to Analysis

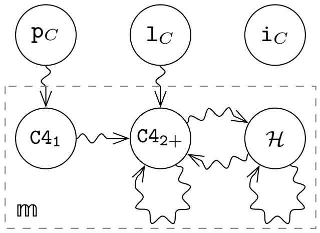
To reason about aliasing (as required during bisimulation check in section 2.4), we conservatively compute *may-point-to* information for each program value using an interprocedural flow-sensitive version of Andersen's algorithm [10]. The range of this computed may-point-to function is the set of *region labels*, where each region label identifies a set of memory objects. The sets of memory objects identified by two distinct region labels are necessarily disjoint. We write $p \rightsquigarrow \{R_1, R_{2+}\}$ to represent the condition that value *p may point to* an object belonging to one of the region labels R_1 or R_{2+} (but may not point to any object outside of R_1 and R_{2+}).

We populate the set of all region labels using *allocation sites* of C i.e., PCs where a call to `malloc` occurs. For example, `C4` in fig. 3.2b is an allocation site. For each allocation site A, we create two region labels: (a) the first region label, called A_1, identifies the set of memory objects that were allocated by the most recent execution of A, and (b) the second region label, called A_{2+}, identifies the set of memory objects that were allocated by older (not the most recent) executions of A. We also include a special heap region, $\mathcal{H}$ to represent the rest of the memory not covered by the allocation site regions associated with `malloc` calls.

For example, at the start of PC `C7` in fig. 3.2b, $\mathtt{i}_C \rightsquigarrow \emptyset$, $\mathtt{p}_C \rightsquigarrow \{\mathtt{C4}_1\}$, and $\mathtt{l}_C \rightsquigarrow \{\mathtt{C4}_{2+}\}$. Since the

Points-to Invariants	
J1 $\mathtt{p}_C \rightsquigarrow \{\mathtt{C4}_1\}$	J2 $\mathtt{C4}_1 \rightsquigarrow \{\mathtt{C4}_{2+}\}$
J3 $\mathtt{l}_C \rightsquigarrow \{\mathtt{C4}_{2+}\}$	J4 $\mathtt{C4}_{2+} \rightsquigarrow \{\mathtt{C4}_{2+}, \mathcal{H}\}$
J5 $\mathtt{i}_C \rightsquigarrow \emptyset$	J6 $\mathcal{H} \rightsquigarrow \{\mathtt{C4}_{2+}, \mathcal{H}\}$

(a) Points-to invariants at C5 of fig. 1.2b



(b) Points-to graph at C5 of fig. 1.2b

Figure 3.7: Points-to invariants at C5 of $\mathcal{C}$ in fig. 1.2b. Figure 3.7b shows the graphical representation of the relations in fig. 3.7a. Each node represents a $\mathcal{C}$ pseudo-register or a memory region in $\mathbb{m}$. An edge $A \rightarrow R$ represents the condition that A (or objects in A in case of a memory region) may point to the memory region R.

may-point-to analysis determines the sets of objects pointed-to by $\mathtt{p}_C$ and $\mathtt{l}_C$ to be disjoint, ($\mathtt{C4}_1$ against $\mathtt{C4}_{2+}$), any memory accessed through $\mathtt{p}_C$ and $\mathtt{l}_C$ cannot alias at C7 (for accesses within the bounds of the allocated objects).

The may-point-to information is computed not just for program values (e.g., $\mathtt{p}_C$, $\mathtt{l}_C$) but also for each region label. For region labels R_1, R_2 and R_3: $R_1 \rightsquigarrow \{R_2, R_3\}$ represents the condition that the values (pointers) stored in objects identified by R_1 may point to objects identified by either R_2 or R_3 (but not to any other object outside R_2 and R_3). In fig. 3.2b, at PC C7, we get $\mathtt{C4}_1 \rightsquigarrow \{\mathtt{C4}_{2+}\}$ and $\mathtt{C4}_{2+} \rightsquigarrow \{\mathtt{C4}_{2+}, \mathcal{H}\}$. The condition $\mathtt{C4}_1 \rightsquigarrow \{\mathtt{C4}_{2+}\}$ holds because the next pointer of the object pointed-to by $\mathtt{p}_C$ (which is a $\mathtt{C4}_1$ object at C7) may point to a $\mathtt{C4}_{2+}$ object (e.g., object pointed to by $\mathtt{l}_C$). On the other hand, pointers within a $\mathtt{C4}_{2+}$ object may not point to a $\mathtt{C4}_1$ object.

3.6.5 Transferring Points-to Information to Decons-PCFG

Recall that in section 3.6.3, we reduce the condition $\mathtt{Clist}^{\mathtt{lnode}}_{\mathbb{m}}(\mathtt{l}_C) \sim \mathtt{Clist}^{\mathtt{lnode}}_{\mathbb{m}'}(\mathtt{l}_C)$ to an equivalence check between their deconstruction programs: $\mathcal{D}^{fst}$ and $\mathcal{D}^{snd}$. Also, recall that we discharge the equivalence check through construction of a decons-PCFG encoding the lockstep execution of the two deconstruction programs. During this bisimulation check, we need to prove that,

$\mathtt{l}^{fst} \overset{\mathbb{m}}{\rightarrow}_{\mathtt{lnode}} \{\mathtt{val}, \mathtt{next}\}$ and $\mathtt{l}^{snd} \overset{\mathbb{m}'}{\rightarrow}_{\mathtt{lnode}} \{\mathtt{val}, \mathtt{next}\}$ are equal in decons-PCFG node ($\mathtt{D1{:}D1}$) shown in fig. 3.6b. Recall that the invariant $\textcircled{I1}$ asserts $\mathtt{l}^{fst} = \mathtt{l}^{snd}$. Thus, to successfully discharge these proof obligations, it suffices to show that $\mathtt{l}^{snd}$ cannot alias with the memory writes that distinguish $\mathbb{m}$ and $\mathbb{m}'$.

Figure 3.7a shows the may-point-to relations identified by our points-to analysis on $\mathcal{C}$ in fig. 3.2b at the program point $\mathtt{C5}$. The points-to analysis determines that at $\mathtt{C5}$ (i.e. start of the product-CFG edge $(\mathtt{S3{:}C5}) \rightarrow (\mathtt{S3{:}C3})$ across which the proof obligation is generated), the pointer to the *head* of the list, i.e. $\textcircled{J3}$ $\mathtt{l}_C \rightsquigarrow \{\mathtt{C4}_{2+}\}$. It also determines that the distinguishing writes (in eq. (3.5)) modify memory regions belonging to $\mathtt{C4}_1$ only ($\textcircled{J1}$). Further, we get $\textcircled{J4}$ $\mathtt{C4}_{2+} \rightsquigarrow \{\mathtt{C4}_{2+}, \mathcal{H}\}$ at PC $\mathtt{C5}$. Figure 3.7b shows the points-to graph for the $\mathcal{C}$ variables and the memory regions (in $\mathbb{m}$). This graphical representation clearly illustrates that the objects pointed to by $\mathtt{p}_C$ (i.e. $\mathtt{C4}_1$) and $\mathtt{l}_C$ (i.e. $\mathtt{C4}_{2+}$) are mutually isolated.

However, notice that these determinations only rule out aliasing of the list-head with the distinguishing writes. We also need to confirm non-aliasing of the internal nodes of the linked list with the distinguishing writes. For this, we need to identify a points-to invariant: $\mathtt{l}^{snd} \rightsquigarrow \{\mathtt{C4}_{2+}, \mathcal{H}\}$, at the recursive-node of the decons-PCFG (shown in fig. 3.6a). To identify such points-to invariants, we run our points-to analysis on the deconstruction programs (i.e. $\mathcal{D}^{fst}$ and $\mathcal{D}^{snd}$) before comparing them for equivalence. To model procedure calls, A *supergraph* is created with edges representing control flow to (and from) the entry (and exits) of the program respectively (e.g., dashes edges in fig. 3.5b). To see why $\mathtt{l}^{snd} \rightsquigarrow \{\mathtt{C4}_{2+}, \mathcal{H}\}$ is an inductive invariant at ($\mathtt{D0{:}D0}$):

> (base case) The invariant holds at entry of the decons-PCFG because $\mathtt{l}^{snd} = \mathtt{l}_C$ at entry and $\textcircled{J3}$ $\mathtt{l}_C \rightsquigarrow \{\mathtt{C4}_{2+}\}$, which is a stronger condition.
>
> (inductive step) If $\mathtt{l}^{snd} \rightsquigarrow \{\mathtt{C4}_{2+}, \mathcal{H}\}$ holds at the entry node, it also holds at the start of a recursive call. This follows from $\textcircled{J4}$ $\mathtt{C4}_{2+} \rightsquigarrow \{\mathtt{C4}_{2+}, \mathcal{H}\}$ and $\textcircled{J6}$ $\mathcal{H} \rightsquigarrow \{\mathtt{C4}_{2+}, \mathcal{H}\}$ (points-to information at PC $\mathtt{C5}$), which ensures that $\mathtt{l}^{snd} \overset{\mathbb{m}'}{\rightarrow}_{\mathtt{lnode}} \mathtt{next}$ may point to only $\mathtt{C4}_{2+}$ and $\mathcal{H}$ objects.

The same analysis is run for both $\mathcal{C}$, and the deconstruction programs $\mathcal{D}^{fst}$ and $\mathcal{D}^{snd}$. For a deconstruction program $\mathcal{D}$, the boundary condition (at entry) for the points-to analysis is based on the results of the points-to analysis on $\mathcal{C}$ at the PC where the proof obligation is being discharged. For example, the points-to information of $\mathcal{C}$ PC `C5` (in fig. 3.2b) is used during the points-to analysis on $\mathcal{D}^{fst}$ and $\mathcal{D}^{snd}$.

During proof query discharge, the points-to invariants are encoded as SMT constraints. This allows us to complete the bisimulation proof on the decons-PCFG in fig. 3.6a, and consequently, successfully discharge the proof obligation $\{\phi_{\mathtt{S3:C5}}\}(\mathtt{S3}\rightarrow\mathtt{S5}\rightarrow\mathtt{S3},\mathtt{C5}\rightarrow\mathtt{C3})\{\mathtt{l}_S \sim \mathtt{Clist}_{\mathbb{m}}^{\mathtt{lnode}}(\mathtt{l}_C)\}$ in fig. 3.2d. The points-to analysis is further discussed in section 4.1.

3.6.6 Summary of Type III Proof Discharge Algorithm

Before the start of an equivalence check, a points-to analysis is run on the $\mathcal{C}$ program (IR) once. During equivalence check, to discharge a type III proof obligation P : $\mathtt{LHS} \Rightarrow \mathtt{RHS}$ (expressed first-order logic), we substitute ADT values (in $\mathcal{S}$) in the `RHS` with lifted C values (in $\mathcal{C}$), based on the recursive relations present in the `LHS`. This is followed by decomposition of `RHS` and `RHS`-breaking.

Upon `RHS`-breaking, we obtain several smaller proof obligations, say P_i : $\mathtt{LHS}_i \Rightarrow \mathtt{RHS}_i$ (for $i = 1 \dots n$). To prove P, we require *all* of these smaller proof obligations P_i to be provable. However, a counterexample to *any* one of these proof obligations would also be a counterexample to the original proof obligation P. Due to decomposition and `RHS`-breaking, each $\mathtt{RHS}_i$ must be a decomposition clause and hence, relate atomic expressions. If $\mathtt{RHS}_i$ relate two scalar values, then P_i is a type II proof obligation and discharged using the algorithm summarized in section 3.5.4.

If $\mathtt{RHS}_i$ relates two lifted expressions (i.e. a recursive relation), we check if the deconstruction programs of the two ADT values being compared can be proven to be equivalent (assuming $\mathtt{LHS}_i$ holds at the correlated entry nodes on the first invocation). Similar to the top-level equivalence check, we attempt to find a bisimulation relation. To improve the precision during bisimilarity check, we transfer points-to invariants of the $\mathcal{C}$ program (at the PC where the proof obligation is being discharged) to the entry of the deconstruction programs. The same points-to analysis is run on the deconstruction programs before the equivalence check begins, (through construction of decons-PCFG) to identify points-to invariants in the deconstruction programs.

If the bisimilarity check succeeds, we return *true* for P; otherwise, we imprecisely return *false* (without counterexamples).

3.7 Overview of Proof Discharge Algorithm

Figure 3.8 gives the pseudocode of our proof discharge algorithm. The top-level function responsible for discharging Hoare triple proof obligations is *prove*(). It accepts a proof obligation along with the categorization (k) and approximation (d_o and d_u) parameters, and either returns `True` representing a successful proof attempt, or `False`(Γ), where Γ is a set of counterexamples. Recall that our proof discharge algortihm is *sound* and may return `False`($\emptyset$) to indicate a failed (proof and counterexample generation) attempt. As discussed in section 2.6, we lower the Hoare triple into a first-order logic formula using weakest-precondition predicate transformer (`lowerWP()` in L2). This is followed by `RHS`-breaking (introduced in section 3.1), which results in multiple smaller proof obligations (`RHSBreak()` in L3). Next, we attempt to prove each of these proof obligations individually through a call to *solve*(). If any one of these queries fail, we immediately stop and return `False` with the counterexamples in Γ — a counterexample to one of the smaller queries is also a counterexample to the original query.

solve() is responsible for discharging these smaller queries. The inputs include `LHS`, `RHS` (representing the proof obligation P : `LHS` $\Rightarrow$ `RHS`); along with the parameters k, d_o and d_u. We start by decomposing and finding the k-unrolled form of P, say P_E : $\texttt{LHS}_k \Rightarrow \texttt{RHS}_k$ through `decomposeAndUnroll()` in L11. Next, we categorize P_E into one of the three types (`categorize()` in L12). As discussed in section 3.4, we simply discharge a type I query using SMT solvers (through `solveSMT()` in L14). `solveSMT()` is responsible for (a) translating the input formula (absent of recursive relations) to SMT logic, (b) discharging SMT solver queries, and (c) reconstructing counterexamples from the models returned by the SMT solvers. The steps (a) and (c) are further explored in sections 4.4.7 and 4.4.8 respectively. As summarized in section 3.5.4, for a type II query, we overapproximate `LHS` into $\texttt{LHS}_o$ (through `overapproximate()` in L16)

Algorithm 1: Algorithm for discharging proof obligations containing recursive relations

```
Function $prove(\{\phi_s\}(\rho_S, \rho_C)\{\phi_d\}, k, d_o, d_u)$
    $F \mapsfrom$ lowerWP($\{\phi_s\}(\rho_S, \rho_C)\{\phi_d\}$)
    foreach LHS $\Rightarrow$ RHS$_i$ in RHSBreak($F$) do
        if $solve$(LHS, RHS$_i$, $k, d_o, d_u$) = False($\Gamma$) then
            return False($\Gamma$)
        end
    end
    return True
end
Function $solve$(LHS, RHS, $k, d_o, d_u$)
    (LHS$_k$, RHS$_k$) $\mapsfrom$ decomposeAndUnroll(LHS, RHS, $k$)
    switch categorize(LHS$_k$, RHS$_k$) do
        case Type I do
            return solveSMT(LHS$_k$ $\Rightarrow$ RHS$_k$)
        case Type II do
            LHS$_o$ $\mapsfrom$ overapproximate(LHS, $d_o$)
            if solveSMT(LHS$_o$ $\Rightarrow$ RHS$_k$) = True then
                return True
            end
            LHS$_u$ $\mapsfrom$ underapproximate(LHS, $d_u$)
            if solveSMT(LHS$_u$ $\Rightarrow$ RHS$_k$) = False($\Gamma$) then
                return False($\Gamma$)
            end
            return False($\emptyset$)
        case Type III do
            RHS$'$ $\mapsfrom$ rewriteRHSUsingLHS(LHS, RHS)
            foreach P$_i$ $\Rightarrow$ RHS$_i$ in decompose(RHS$'$) do
                if RHS$_i$ $= l_1 \sim l_2$ then
                    $(\mathcal{D}_1, \mathcal{D}_2)$ $\mapsfrom$ getDeconstructionPrograms($l_1, l_2$)
                    if checkEquivalence(LHS $\wedge$ P$_i$, $\mathcal{D}_1, \mathcal{D}_2$) = False then
                        return False($\emptyset$)
                    end
                else if $solve$(LHS $\wedge$ P$_i$, RHS$_i$, $k, d_o, d_u$) = False($\Gamma$) then
                    return False($\Gamma$)
                end
            end
            return True
        end
    end
end
```

Figure 3.8: Pseudocode of the algorithm responsible for discharging proof obligations containing recursive relations.

and attempt to prove $\texttt{LHS}_o \Rightarrow \texttt{RHS}_k$ through `solveSMT()` in L17. In case the proof attempt fails, we underapproximate `LHS` into $\texttt{LHS}_u$ (through `underapproximate()` in L20) and attempt to disprove (i.e. generate counterexamples) $\texttt{LHS}_u \Rightarrow \texttt{RHS}_k$ through `solveSMT()` in L21. If both attempts fail, we *soundly* return `False` (without counterexamples). Lastly, a type III query P_E is discharged as detailed in section 3.6.6. In brief, we rewrite `RHS` using recursive relations in `LHS` (`rewriteRHSUsingLHS()` in L26) and decompose (`decompose()` in L27) P_E. This results in smaller proof obligations; ones without a recursive relation in its `RHS` are type II queries and discharged through a recursive call to *solve*. For those containing a recursive relation $l_1 \sim l_2$ in their `RHS`, we attempt to show equivalence (through `checkEquivalence()` in L30) between the deconstruction programs of l_1 and l_2 constructed through `getDeconstructionPrograms()` in L29. If any one of these queries fail, we immediately return `False` with the counterexamples (if available). Otherwise, we have successfully proven a type III query and return `True`.

Chapter 4

Spec-to-C Equivalence Checker

This chapter presents our automatic equivalence checker S2C. Given a Spec and a C program along with the input-output specification for each function-pair, S2C searches for a proof of equivalence between the CFGs of each Spec and C procedures: $\mathcal{S}$ and $\mathcal{C}$. Recall that CFGs represent deterministic programs and evidently, the C procedure is determinized during conversion to $\mathcal{C}$. Hence, S2C checks equivalence between a Spec procedure and the determinized C procedure. A translation validator (such as the Counter tool [27]) can be used to check equivalence between the same determinized C procedure against its generated assembly. By restricting the deterministic choices made by the C compiler to the same choices made during construction of $\mathcal{C}$, we can effectively establish end-to-end equivalence between a Spec procedure against its assembly. We start with a dataflow formulation of the points-to analysis used as part of S2C on $\mathcal{C}$ as well as deconstruction programs during discharge of type III proof obligations in section 4.1. As stated in section 1.2, S2C is based on three major algortihms: $\boxed{\text{A1}}$ an algorithm to incrementally construct a product-CFG by correlating program executions across $\mathcal{S}$ and $\mathcal{C}$, $\boxed{\text{A2}}$ an algorithm to identify inductive invariants at intermediate PCs in the (partially constructed) product-CFG, and $\boxed{\text{A3}}$ an algorithm for solving proof obligations generated by $\boxed{\text{A1}}$ and $\boxed{\text{A2}}$ algorithms. We describe our counterexample-guided best-first search algorithm for construction of a product-CFG ($\boxed{\text{A1}}$) in section 4.2. This is followed by a dataflow formulation of our counterexample-guided invariant inference algorithm ($\boxed{\text{A2}}$) in section 4.3. Recall that algorithms $\boxed{\text{A1}}$ and $\boxed{\text{A2}}$ are based on prior

Table 4.1: Dataflow Formulation of the Points-to Analysis

Domain	$\Delta^C : (\mathbb{S}^C \cup \mathbb{R}) \rightarrow 2^{\mathbb{R}}$ $\quad\quad \Delta^D : (\mathbb{S}^C \cup \mathbb{R} \cup \mathbb{S}^D) \rightarrow 2^{\mathbb{R}}$
Direction	Forward
Boundary Condition	Δ_n for start node : $\Delta_n^C(t) = \begin{cases} \emptyset & t \in \mathbb{S}^C \\ \mathbb{R} & t \in \mathbb{R} \end{cases} \quad\quad \Delta_n^D(t) = \begin{cases} \Delta_{n_C}^C(t) & t \in (\mathbb{S}^C \cup \mathbb{R}) \\ \emptyset & t \in \mathbb{S}^D \end{cases}$
Initialization to $\top$	Δ_n for non-start nodes : $\Delta_n(t) = \emptyset \;\; t \in \texttt{Domain}(\Delta_n)$
Transfer function across edge $e = (s \rightarrow d)$	$\Delta_d = f_e(\Delta_s)$ (described in section 4.1)
Meet operator $\otimes$	$\Delta_n \leftarrow \Delta_n^1 \otimes \Delta_n^2$ $\Delta_n(t) = \Delta_n^1(t) \cup \Delta_n^2(t) \;\; t \in \texttt{Domain}(\Delta_n)$

work on equivalence checking between unoptimized IR (aka determinized C) and assembly [48]. We only summarize these procedures in addition to the primary modifications made in the context of Spec-C equivalence. The previous chapter walked through our proof discharge algorithm ($\boxed{\text{A3}}$) using examples, ending with the pseudocode of proof discharge algorithm (fig. 3.8). In this chapter, we present pseudocode for multiple subprocedures utilized by our proof discharge algorithm in section 4.4. Additionally, we describe the process of encoding queries in SMT logic as well as the recovery of counterexamples from models returned by SMT solvers. We finish with a new representation of expressions, which allows us to simplify a number of steps performed by the proof discharge algorithm.

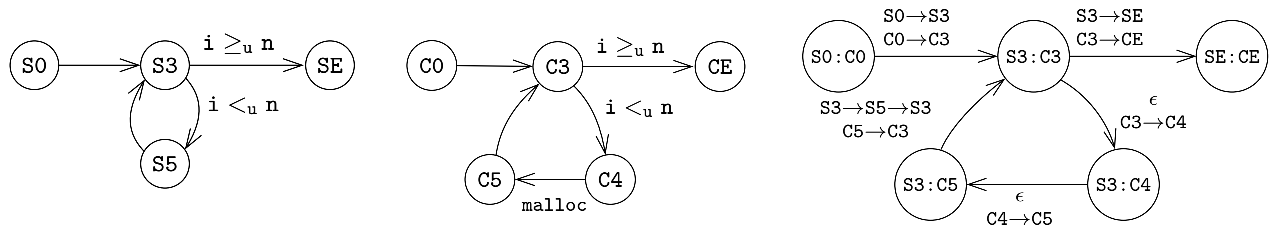
4.1 Points-to Analysis

Recall that in section 3.6.3, we needed to reason about aliasing to successfully discharge a type III proof obligation. These aliasing relationships are introduced in section 3.6.4 and subsequently used in section 3.6.5 to successfully discharge a type III proof obligation. An interprocedural, flow-sensitive, untyped points-to analysis is used to identify these relationships in $\mathcal{C}$ as well as each deconstruction program $\mathcal{D}$. Table 4.1 presents the dataflow formulation of our points-to analysis. We start by identifying the set $\mathbb{R}$ of all region labels representing mutually non-overlapping regions of the $\mathcal{C}$ memory $\mathtt{m}$. For each call to `malloc()` at PC A of $\mathcal{C}$'s IR, we add A_1 and A_{2+} to $\mathbb{R}$. Recall that A_1 represents the region of memory returned by the *most recent* execution of A. A_{2+} represents the region of memory returned by older (i.e. all but most recent) executions of A. $\mathbb{R} = \bigcup_A \{A_1, A_{2+}\} \cup \{\mathcal{H}\}$, where $\mathcal{H}$ is the region of memory $\mathtt{m}$ not covered by the labels associated with allocation sites.

Let $\mathbb{S}^C$ be the set of all scalar pseudo-registers in $\mathcal{C}$'s IR. We use a forward dataflow analysis to identify a may-point-to function $\Delta^C : (\mathbb{S}^C \cup \mathbb{R}) \mapsto 2^{\mathbb{R}}$ at each program point in $\mathcal{C}$'s IR. For a deconstruction program $\mathcal{D}$, we are also interested in finding the may-point-to function for all scalar pseudo-registers in $\mathcal{D}$'s IR, say $\mathbb{S}^D$. Thus, the domain of the may-point-to function for $\mathcal{D}$ (Δ^D) contains $\mathbb{S}^D$ in addition to the domain of Δ^C i.e. $\Delta^D : (\mathbb{S}^C \cup \mathbb{R} \cup \mathbb{S}^D) \mapsto 2^{\mathbb{R}}$. The '$\rightsquigarrow$' operator introduced in section 3.6.4 is called the *element-wise* may-point-to function and is related to the may-point-to function Δ as follows: $p \rightsquigarrow S \Leftrightarrow \Delta(p) \subseteq S$.

The meet operator is element-wise set-union e.g., $p \rightsquigarrow S_1$ and $p \rightsquigarrow S_2$ combines into $p \rightsquigarrow S_1 \cup S_2$. Evidently, the $\top$ value is the constant function that returns $\emptyset$. At entry of $\mathcal{C}$, we conservatively assume that all memory regions may point to each other. However, at entry of a deconstruction program $\mathcal{D}$, created during a proof obligation at product-CFG node $(n_S{:}n_C)$, we use $\mathcal{C}$'s precomputed may-point-to function at n_C ($\Delta^C_{n_C}$) to initialize the points-to relationships for all state elements in $\mathcal{C}$'s IR (i.e. $\mathbb{S}^C \cup \mathbb{R}$). This is a crucial step for proving equality of $\mathcal{C}$ values under different memory states as seen in section 3.6.5.

Next, we discuss the transfer function f_e for our points-to analysis. For an IR instruction $\mathtt{x} \coloneqq \mathtt{c}$, for constant $\mathtt{c}$, the transfer function updates $\Delta(\mathtt{x}) \coloneqq \emptyset$. For instruction $\mathtt{x} \coloneqq \mathtt{y}\ \mathtt{op}\ \mathtt{z}$ (for some arithmetic or logical operator $\mathtt{op}$), we update $\Delta(\mathtt{x}) \coloneqq \Delta(\mathtt{y}) \cup \Delta(\mathtt{z})$. For a load instruction $\mathtt{x} \coloneqq \mathtt{m}[y]_{\mathtt{T}}$, we update $\Delta(\mathtt{x}) \coloneqq \bigcup_{t \in \Delta(y)} \Delta(t)$. For a store instruction $\mathtt{m} \coloneqq \mathtt{m}[x \leftarrow y]_{\mathtt{T}}$, for all $t \in \Delta(\mathtt{x})$, we update $\Delta(t) \coloneqq \Delta(t) \cup \Delta(y)$. For a malloc instruction $\mathtt{x} \coloneqq \mathtt{malloc}_A()$ (where A represents the allocation site), we perform the following steps (in order):



(a) CFG of Spec procedure **(b)** CFG of C procedure **(c)** Product-CFG

Figure 4.1: Figures 4.1a and 4.1b shows the CFG representation of Spec and C IRs in figs. 3.2a and 3.2b for the `mk_list` procedures in figs. 1.1a and 1.1b. The product-CFG representing path correlations between figs. 4.1a and 4.1b is shown in fig. 4.1c.

1. Convert all existing occurrences of A_1 to A_{2+}, i.e., for all $t \in (\mathbb{S}^C \cup \mathbb{R})$, if $A_1 \in \Delta(t)$, then update $\Delta(t) \coloneqq (\Delta(t) \setminus \{A_1\}) \cup \{A_{2+}\}$.

2. Update $\Delta(\mathtt{x}) \coloneqq \{A_1\}$.

3. Update $\Delta(A_{2+}) \coloneqq \Delta(A_{2+}) \cup \Delta(A_1)$.

4. Update $\Delta(A_1) \coloneqq \emptyset$.

For function calls, a *supergraph* is created by adding control flow edges from the call-site to the procedure head (copying actual arguments to the formal arguments) and from the procedure exit to the program point just after the call-site (copying returned value to the variable assigned at the callsite), e.g., in fig. 3.5b, the dashed edges represent supergraph edges.

The allocation-site abstraction (with a bounded-depth call stack) is known to be effective at disambiguating memory regions belonging to different data structures [29, 16, 11]. In our work, we also need to reason about non-aliasing of the most-recently allocated object (through a `malloc` call) and the previously-allocated objects (as in the `List` construction example). The coarse-grained $\{1, 2+\}$ categorization of allocation recency is effective for such disambiguation.

Algorithm 2: Best-first search algorithm for incremental construction of a product-CFG between $\mathcal{S}$ and $\mathcal{C}$

```
Function $bestFirstSearch(\mathcal{S}, \mathcal{C}, \mu_S)$
    $\pi_{init} \mapsfrom$ createInitProductCFG($\mathcal{S}, \mathcal{C}$);
    $Q \mapsfrom \{\pi_{init}\}$;
    while $Q$ is not empty do
        $\pi_{cur} \mapsfrom$ extractMostPromising($Q$);
        InferInvariantsAndCounterexamples($\pi_{cur}$);
        if getPathsetToCorrelateInC($\mathcal{C}, \pi_{cur}$) = Found($\xi_C$) then
            foreach $\xi_S$ in enumeratePathsetsInS($\mathcal{S}, \xi_C, \mu_S$) do
                $\pi_{next} \mapsfrom$ extendProductCFG($\pi_{cur}, \xi_S, \xi_C$);
                $Q \mapsfrom Q \cup \{\pi_{next}\}$;
            end
        else if productCFGRepresentsBisim($\pi_{cur}$) then
            return Found($\pi_{cur}$);
        end
    end
    return NotFound;
end
```

Figure 4.2: Pseudocode of the best-first search algorithm responsible for incremental construction of a product-CFG between $\mathcal{S}$ and $\mathcal{C}$.

4.2 Counterexample-guided Product-CFG Construction

S2C constructs a product-CFG incrementally to search for a bisimulation relation between the Spec and C CFGs : $\mathcal{S}$ and $\mathcal{C}$. Multiple candidate product-CFGs are partially constructed during this search; the search completes when one of these candidates yield an equivalence proof. Recall that the incremental product-CFG construction algorithm is based on prior work [48] and we simply summarize the relevant components in the context of Spec-C equivalence. Figure 4.2 shows the pseudocode of the incremental construction algorithm.

Anchor nodes are identified in $\mathcal{S}$ and $\mathcal{C}$, and represents the CFG nodes (i.e. IR PCs) being considered for correlation. The algorithm ensures that every cycle in both $\mathcal{S}$ and $\mathcal{C}$ contains at least one anchor node. The start and exit nodes are always anchor nodes. Also, for every function call, the nodes just before and after its callsite are considered anchor nodes. For example, in fig. 4.1b, C4 and C5 are anchor nodes around the call to malloc. A valid selection of anchor nodes for the CFGs in figs. 4.1a and 4.1b are: $\{\texttt{S0}, \texttt{S3}, \texttt{SE}\}$ and $\{\texttt{C0}, \texttt{C3}, \texttt{C4}, \texttt{C5}, \texttt{CE}\}$ respectively. For each anchor node in $\mathcal{C}$, our search algorithm searches for a correlated anchor node in $\mathcal{S}$ — if a (partially constructed) product-CFG π contains a product-CFG node $(n_S : n_C)$, then π correlates node n_C in $\mathcal{C}$ with node n_S in $\mathcal{S}$. The search procedure begins with a single partially-constructed product-CFG π_{init}. π_{init} contains exactly one node (S0:C0) that encodes the correlation of the entry nodes (i.e. S0 and C0) of $\mathcal{S}$ and $\mathcal{C}$.

4.2.1 Correlating Pathsets

Recall that a product-CFG edge correlates transitions in $\mathcal{S}$ and $\mathcal{C}$. The examples presented so far only considers correlations between *paths* in $\mathcal{S}$ and $\mathcal{C}$. However, we consider a more general approach of *pathset* correlations in the context of product-CFG construction. Pathsets are based on earlier work on the Counter tool [27, 48] and help improve the completeness of the bisimulation search by considering correlations of a single path in $\mathcal{C}$ with a set of paths in $\mathcal{S}$ and vice versa, where individual paths may be uncorrelated. An example of such a scenario is depicted in section 5.1.1. For now, we briefly summarize pathsets in the context of Spec-C bisimulation search. A *pathset* ξ is essentially a set of paths with the following additional properties: (a) all paths $\rho \in \xi$ begin at the same node and terminate at the same node, and (b) all paths $\rho \in \xi$ are mutually exclusive i.e. *at most* one of $\texttt{pathcond}_\rho$ can be true. A (μ, δ)-*unrolled pathset* ξ is a pathset from n_s to n_d such that: (a) all paths $\rho \in \xi$ contains *at most* μ occurrences of *any* node except n_d as the end node (to-PC) of an edge in ρ, and (b) all paths $\rho \in \xi$ contains *exactly* δ occurrences of n_d as the end (to-PC) of an edge in ρ. Intuitively, δ represents the number of iterations of a loop (ending at n_d) considered as part of a path in ξ, whereas μ bounds the number of times any node is visited by a path in ξ. (μ, δ)-unrolled pathsets have been shown to be quite effective at identifying correlations in the presence of compiler transformations such as unrolling and vectorization [48] and we also found it to be suitable in the context of Spec-C equivalence.

At each step of the incremental construction process, a node $(n_S : n_C)$ is chosen in a product-CFG π and a (1,1)-unrolled pathset ξ_C in $\mathcal{C}$ starting at n_C (and ending at an anchor node) is selected (`getPathsetToCorrelateInC()` in L7). Then, we enumerate (μ_S, δ)-unrolled pathsets in $\mathcal{S}$ (for

$\delta \in [0, \mu_S]$) as potential correlations for the pathset ξ_C in $\mathcal{C}$ (`enumeratePathsetsInS()` in L8). μ_S is a fixed parameter of S2C and is called the *unroll factor*. For example, during construction of the product-CFG shown in fig. 4.1c, say we select the product-CFG node (`S3:C3`). We choose the $\mathcal{C}$ path(set) `C3`→`C4` and enumerate its potential correlations (i.e. (μ_S, δ)-unrolled pathsets in $\mathcal{S}$ starting at `S3`): ϵ, `S3`→`S5`→`S3`, ..., `S3`→(`S5`→`S3`)$^{\mu_S}$. Importantly, for pathsets ξ_S (in $\mathcal{S}$) and ξ_C (in $\mathcal{C}$) to be considered for correlation, they must originate and terminate at anchor nodes, i.e. the path `S3`→`S5` is skipped during enumeration. Moreover, the pathset ξ_C may only contain anchor nodes as its source and destination. Thus, the path `C3`→`C4`→`C5` is not considered for ξ_C, instead we attempt to correlate the subpaths `C3`→`C4` and `C4`→`C5` individually. Section 4.4.1 briefly discusses the techniques of handling Hoare triples (i.e. proof obligations) involving pathsets.

For each enumerated correlation possibility (ξ_S, ξ_C), a separate product-CFG π' is created (by cloning π) and a new product-CFG edge $e = (\xi_S, \xi_C)$ is added to π' (`extendProductCFG()` in L9). The head of the product-CFG edge e is the (potentially newly added) product-CFG node representing the correlation of the end-points of pathsets ξ_S and ξ_C. For example, the node (`S3:C4`) is added to the product-CFG if it correlates pathsets ϵ and `C3`→`C4` starting at (`S3:C3`). Recall that, we consider ϵ as a candidate for ξ_S, but not ξ_C. The algorithm ensures that no cycle in $\mathcal{C}$ is correlated with ϵ in $\mathcal{S}$ (to preserve divergence discussed in section 2.4). For each node n in a product-CFG π, we maintain a small number of concrete machine state pairs (of $\mathcal{S}$ and $\mathcal{C}$). The concrete machine state pairs at s are obtained as counterexamples to unsucessful proof obligations $\{\phi_s\}(s \rightarrow d)\{\phi_d\}$ (for some edge $s \rightarrow d$ and node d in π). Thus, by construction, these counterexamples represent concrete state pairs that may potentially occur at n during the lockstep execution encoded by π.

4.2.2 Best-First Ranking of Partial Product-CFGs

To evaluate the promise of a possible correlation (ξ_S, ξ_C) starting at node n in product-CFG π, we examine the execution behaviour of the counterexamples at n on the product-CFG edge $e = (s \rightarrow d) = (\xi_S, \xi_C)$. If the counterexamples ensure that the machine states remain related at d, then that candidate correlation is ranked higher. This ranking criterion is based on prior work [27]. A best-first search (BFS) procedure based on this ranking criterion is used to incrementally construct a product-CFG (starting from π_{init}). For each intermediate candidate product-CFG π generated during this search procedure, an automatic invariant inference procedure (discussed next in section 4.3) is used to identify invariants at all the nodes in π (`InferInvariantsAndCounterexamples()` in L6). The counterexamples obtained from the proof obligations generated by this invariant inference procedure are added to the respective nodes in π; these counterexamples help rank future correlations starting at those nodes.

If after invariant inference, we realize that an intermediate candidate product-CFG π_1 is not promising enough, we backtrack and choose another candidate product-CFG π_2 and explore the potential correlations that can be added to π_2 (`extractMostPromising()` in L5). Thus, a product-CFG is constructed one edge at a time. If at any stage, a product-CFG π satisfies the well-formedness conditions (introduced in section 2.4.1) and invariants ensure equal observables (i.e. *Post* holds at correlated exit nodes), we have successfully shown equivalence (`productCFGRepresentsBisim()` in L12). This counterexample-guided BFS procedure is similar to the one described in prior work on the Counter algorithm [27].

4.2.3 Correlation in the Presence of Function Calls

Recall that $\mathcal{S}$ and $\mathcal{C}$ may make function calls (including self calls), e.g., C memory allocation, recursive traversal of a tree data structure. Recall that the nodes just before and after a function call are always considered anchor nodes. Calls to memory allocation functions in $\mathcal{C}$ (i.e. `malloc`) are handled by correlating the function call edge with the empty path (ϵ) in $\mathcal{S}$. For example, in the product-CFG shown in fig. 4.1c, the `malloc` edge `C4`→`C5` in $\mathcal{C}$ is correlated with ϵ in $\mathcal{S}$.

For all other calls, our correlation algorithm (in section 4.2) ensures that the anchor nodes around such a callsite are correlated one-to-one across both procedures. For example, let there be a call to procedure δ in $\mathcal{S}$ at PC n_S, i.e. n_S is the call-site. Let us denote the program point just after this call-site as n'_S. Let $\texttt{args}_{n_S}$ represent the values of the actual arguments of this function call (at n_S). Let $\texttt{ret}_{n'_S}$ represent the value returned by this function call (at n'_S). Similarly, for a procedure call δ in $\mathcal{C}$, let n_C, n'_C, $\texttt{args}_{n_C}$ and $\texttt{ret}_{n'_C}$ represent the function call-site, program point

Table 4.2: Dataflow Formulation of the Invariant Inference Algorithm

Domain	$\left\{ (\phi_n, \Gamma_n) \;\middle\|\; \begin{array}{c} \phi_n \text{ is a conjunction of predicates drawn from} \\ \mathbb{G} \text{ (in fig. 4.3b)}, \Gamma_n \text{ is a set of counterexamples} \end{array} \right\}$
Direction	Forward
Boundary Condition	(ϕ_n, Γ_n) for start node : $\phi_n \leftarrow Pre, \quad \Gamma_n \leftarrow \emptyset$
Initialization to $\top$	(ϕ_n, Γ_n) for non-start nodes : $\phi_n \leftarrow \texttt{false}, \quad \Gamma_n \leftarrow \emptyset$
Transfer function across edge $e = (s \rightarrow d)$	$(\phi_d, \Gamma_d) = f_e(\phi_s, \Gamma_s)$ (shown in fig. 4.3a)
Meet operator $\otimes$	$(\phi_n, \Gamma_n) \leftarrow (\phi_n^1, \Gamma_n^1) \otimes (\phi_n^2, \Gamma_n^2)$ $\Gamma_n \leftarrow \Gamma_n^1 \cup \Gamma_n^2, \quad \phi_n \leftarrow \texttt{strongestInvCover}(\Gamma_n)$

just after the call-site, the values of the actual arguments and the value returned respectively. Our algorithm ensures that the only correlation possible in a product-CFG π for these program points are $(n_S : n_C)$ and $(n'_S : n'_C)$.

We utilize the user-supplied input-output specification for δ, say $(Pre_\delta, Post_\delta)$, to obtain the desired invariants at nodes $(n_S : n_C)$ and $(n'_S : n'_C)$ in the product-CFG. A successful proof must *ensure* that $Pre_\delta(\texttt{args}_{n_S},\texttt{args}_{n_C})$ holds at $(n_S : n_C)$. Further, the proof can *assume* that $Post_\delta(\texttt{ret}_{n'_S},\texttt{ret}_{n'_C})$ holds at $(n'_S : n'_C)$. Note that $\texttt{args}_{n_C}$ and $\texttt{ret}_{n'_C}$ includes the $\mathcal{C}$ memory states $\mathbb{m}_{n_C}$ (at n_C) and $\mathbb{m}_{n'_C}$ (at n'_C) respectively. Thus, for function calls, we inductively prove the precondition (on the arguments) at $(n_S : n_C)$ and assume the postcondition (on the returned values) at $(n'_S : n'_C)$.

4.3 Invariant Inference and Counterexample Generation

We formulate our counterexample-guided invariant inference algorithm as a forward dataflow analysis as shown in table 4.2. Figure 4.3a shows the pseudocode for the transfer function for the said dataflow analysis. The invariant inference procedure is responsible for inferring invariants

```
1  Function $f_e(\phi_s, \Gamma_s)$
2      $\Gamma_d^{can} \hookleftarrow \Gamma_d \cup \mathtt{exec}_e(\Gamma_s)$
3      $\phi_d^{can} \hookleftarrow \mathtt{strongestInvCover}(\Gamma_d^{can})$
4      while $\mathtt{prove}(\{\phi_s\}(e)\{\phi_d^{can}\}) = \mathtt{False}(\gamma_s)$ do
5          $\gamma_d \hookleftarrow \mathtt{exec}_e(\gamma_s)$
6          $\Gamma_d^{can} \hookleftarrow \Gamma_d^{can} \cup \gamma_d$
7          $\phi_d^{can} \hookleftarrow \mathtt{strongestInvCover}(\Gamma_d^{can})$
8      end
9      return $(\phi_d^{can}, \Gamma_d^{can})$
10 end
```

(a) Transfer function f_e across edge $e = (s \rightarrow d)$.

$$\begin{array}{lll} \mathtt{Inv} & \rightarrow & \sum_i c^i v^i = c \mid v^1 \odot v^2 \\ & \mid & \alpha_S \sim \mathtt{Clift}^{\mathtt{T}}_{\mathbb{m}}(v_C \ldots) \end{array}$$

(b) Predicate grammar $\mathbb{G}$ for constructing invariants. v represents a bitvector variable in either $\mathcal{S}$ or $\mathcal{C}$. c represents a bitvector constant. $\odot \in \{<, \leq\}$. α_S represents an ADT variable in $\mathcal{S}$. v_C represents a bitvector variable in $\mathcal{C}$. $\mathbb{m}$ represents the current $\mathcal{C}$ memory state.

Figure 4.3: Transfer function f_e and predicate grammar $\mathbb{G}$ for invariant inference dataflow analysis in table 4.2. Given invariants ϕ_s and counterexamples Γ_s at node s, f_e returns the updated invariants ϕ_d and counterexamples Γ_d at node d. $\mathtt{strongestInvCover}(\Gamma)$ computes the strongest invariant cover for counterexamples Γ. $\mathtt{exec}_e(\Gamma)$ (concretely) executes counterexamples Γ over edge e. $\mathtt{prove}(P)$ (in fig. 3.8) discharges a proof obligation P, and returns either `True` or $\mathtt{False}(\gamma_s)$.

ϕ_n at each intermediate node n of a (partially constructed) product-CFG, while also generating a set of counterexamples Γ_n that represents the potential concrete machine states at n. Recall that the invariant inference algorithm is based on prior work [48] and we simply summarize the relevant components in the context of Spec-C equivalence.

Given the invariants and counterexamples at node s: (ϕ_s, Γ_s), the transfer function initializes the new candidate set of counterexamples at d (Γ_d^{can}) with the current set of counterexamples at d (Γ_d) *union*-ed with the counterexamples obtained by executing Γ_s on edge e (through $\mathtt{exec}_e$). The candidate invariant at d (ϕ_d^{can}) is computed as the strongest cover of Γ_d^{can} (`strongestInvCover()` in L7). At each step, the transfer function attempts to prove $\{\phi_s\}(e)\{\phi_d^{can}\}$ (through a call to `prove()` in L4). If the proof succeeds (`prove()` returns `True`), the candidate invariant ϕ_d^{can} is returned along with the counterexamples Γ_d^{can} learned so far. Otherwise, `prove()` returns $\mathtt{False}(\gamma_s)$. The candidate invariant ϕ_d^{can} is weakened using the counterexamples obtained (i.e. γ_s) and the proof attempt is repeated. The candidate invariants are drawn from the predicate grammar $\mathbb{G}$ shown in fig. 4.3b. In addition to affine and inequality relations between bitvectors in $\mathcal{S}$ and $\mathcal{C}$, $\mathbb{G}$ supports recursive relations between an ADT variable in $\mathcal{S}$ and a lifted expression in $\mathcal{C}$. The candidate lifting constructors of the form $\mathtt{Clift}^{\mathtt{T}}_{\mathbb{m}}$ (where $\mathbb{m}$ is the current memory state in $\mathcal{C}$) are derived from the lifting constructors present in the precondition *Pre* and the postcondition *Post*, as supplied by the user. More sophisticated strategies for inference of new lifting constructors is left as future work.

`strongestInvCover()` for affine relations involve identifying the basis vectors of the kernel of the matrix formed by the counterexamples in the bitvector domain [37, 18]. For inequality relations, `strongestInvCover`() returns *true* (i.e. the weakest invariant) iff any counterexample in Γ evaluates the relation to false — this effectively simulates the Houdini approach [25]. Similarly, in case of a recursive relation $l_1 \sim l_2$, `strongestInvCover`() returns *true* iff any counterexample in Γ evalutes its η-depth over-approximation $l_1 \sim_\eta l_2$ to false (effectively falsifying a weaker condition and thus $l_1 \sim l_2$ itself), where η is a fixed parameter of the algorithm.

4.4 More on Proof Discharge Algorithm

4.4.1 Handling Proof Obligations on Pathsets

Recall that our correlation algorithm attempts to correlate pathsets (instead of paths) between $\mathcal{S}$ and $\mathcal{C}$. Evidently, each edge of a (partially constructed) product-CFG π is associated with a pair of pathsets (ξ_S, ξ_C). A proof obligation originating across a product-CFG edge $e[s \to d] = (\xi_S, \xi_C)$ is of the form $\{\phi_s\}(\xi_S, \xi_C)\{\phi_d\}$. A Hoare triple of the above form can be broken down into a conjunction of Hoare triples involving only path correlations as follows:

$$\{\phi_s\}(\xi_S, \xi_C)\{\phi_d\} \Leftrightarrow \bigwedge_{\substack{\rho_S \in \xi_S \\ \rho_C \in \xi_C}} \{\phi_s\}(\rho_S, \rho_C)\{\phi_d\} \tag{4.1}$$

Recall that our proof discharge algorithm requires that proof obligations satisfy the conjunctive recursive relation property (section 3.1). If the original proof obligation $\{\phi_s\}(\xi_S, \xi_C)\{\phi_d\}$ satisfies

Algorithm 3: Algorithm for discharging proof obligations over pathset correlations

```
1  Function $prove(\{\phi_s\}(\xi_S, \xi_C)\{\phi_d\}, k, d_o, d_u)$
2      foreach $(\rho_S, \rho_C)$ in $(\xi_S, \xi_C)$ do
3          if areSimultaneouslyActive($\rho_S, \rho_C$) then
4              if prove($\{\phi_s\}(\rho_S, \rho_C)\{\phi_d\}$) = False($\Gamma$) then
5                  return False$\Gamma$
6              end
7          end
8      end
9      return True
10 end
```

Figure 4.4: Pseudocode of the algorithm responsible for discharging proof obligations over pathset correlations between $\mathcal{S}$ and $\mathcal{C}$.

this property, so does each of $\{\phi_s\}(\rho_S, \rho_C)\{\phi_d\}$. Hence, the proof discharge algorithm presented in chapter 3 is capable of handling these smaller proof obligations and by extension (eq. (4.1)), the original proof obligation $\{\phi_s\}(\xi_S, \xi_C)\{\phi_d\}$. If $|\xi|$ represents the number of paths in a pathset ξ, the proof obligation $\{\phi_s\}(\xi_S, \xi_C)\{\phi_d\}$ results in $|\xi_S| \times |\xi_C|$ smaller proof obligations.

Figure 4.4 shows the pseudocode for discharging proof obligations over pathsets. The function $prove(\{\phi_s\}(\xi_S, \xi_C)\{\phi_d\}, k, d_o, d_u)$ is responsible for discharging $\{\phi_s\}(\xi_S, \xi_C)\{\phi_d\}$ with parameters k, d_o and d_u. Consider a product-CFG edge $e[s \to d] = (\xi_S, \xi_C)$. We call a pair of paths $\rho_S \in \xi_S$ and $\rho_C \in \xi_C$ *simultaneously active* if there exists a combined machine state at s (satisfying the node invariants ϕ_s) for which $\mathcal{S}$ and $\mathcal{C}$ takes the paths ρ_S and ρ_C respectively. In practice, the number of paths in $\mathcal{S}$ that are simultaneously active with a path in $\mathcal{C}$ (and vice versa) is quite low and consequently, most of these proof obligations usually end up with an unsatisfiable `LHS` when lowered to first-order logic (through eq. (2.4)) due to presence of $\texttt{pathcond}_{\rho_S}$ and $\texttt{pathcond}_{\rho_C}$. Our proof discharge procedure begins with an attempt to disprove `LHS` (0-depth overapproximate) which trivially resolves the smaller proof obligations to `true` for path pairs that are not simultaneously active (`areSimultaneouslyActive()` in L3). For path pairs that are simultaneously active, we discharge the smaller Hoare triple queries through `prove()` in L4 (in fig. 3.8). Additionally, a counterexample to any one of $\{\phi_s\}(\rho_S, \rho_C)\{\phi_d\}$ is also a counterexample to the original proof obligation $\{\phi_s\}(\xi_S, \xi_C)\{\phi_d\}$.

Algorithm 4: Algorithm for converting an expression to its canonical form

```
Function $canonicalize(e)$
    $\hat{e} \mapsfrom e$
    while $e$ contains $e' = e_1.\texttt{a}^{\texttt{i}}$ where $e_1$ is $foldable$ do
        if $e_1 = V_1^{(n)}(e_1^1, e_1^2, \ldots, e_1^n)$ then
            $\hat{e} \mapsfrom \{e' \mapsto e_1^i\}\hat{e}$
        else if $e_1 = \underline{\texttt{if}}\ c_1\ \underline{\texttt{then}}\ V_1^{(n)}(e_1^1, e_1^2, \ldots, e_1^n)\ \underline{\texttt{else}}\ e_1^{\texttt{el}}$ then
            if $V_1^{(n)}$ contains $\texttt{a}^{\texttt{i}}$ then $\hat{e} \mapsfrom \{e' \mapsto e_1^i\}\hat{e}$
            else $\hat{e} \mapsfrom \{e' \mapsto e_1^{\texttt{el}}.\texttt{a}^{\texttt{i}}\}\hat{e}$
        else $e_1 = \texttt{Clift}^{\texttt{T}}_{\mathbb{m}}(e^1, e^2, \ldots, e^n)$
            $\hat{e} \mapsfrom \{e' \mapsto \texttt{rewrite}(e_1).\texttt{a}^{\texttt{i}}\}\hat{e}$
        end
    end
    while $e$ contains $e' = e_1$ is $V_2^{(m)}$ where $e_1$ is $foldable$ do
        if $e_1 = V_1^{(n)}(e_1^1, e_1^2, \ldots, e_1^n)$ then
            if $V_1^{(n)} = V_2^{(m)}$ then $\hat{e} \mapsfrom \{e' \mapsto true\}\hat{e}$
            else $\hat{e} \mapsfrom \{e' \mapsto false\}\hat{e}$
        else if $e_1 = \underline{\texttt{if}}\ c_1\ \underline{\texttt{then}}\ V_1^{(n)}(e_1^1, e_1^2, \ldots, e_1^n)\ \underline{\texttt{else}}\ e_1^{\texttt{el}}$ then
            if $V_1^{(n)} = V_2^{(m)}$ then $\hat{e} \mapsfrom \{e' \mapsto c_1\}\hat{e}$
            else $\hat{e} \mapsfrom \{e' \mapsto \neg c_1 \wedge (e_1^{\texttt{el}} \text{ is } V_2^{(m)})\}\hat{e}$
        else $e_1 = \texttt{Clift}^{\texttt{T}}_{\mathbb{m}}(e^1, e^2, \ldots, e^n)$
            $\hat{e} \mapsfrom \{e' \mapsto \texttt{rewrite}(e_1).\texttt{a}^{\texttt{i}}\}\hat{e}$
        end
    end
    return $\hat{e}$
end
```

Figure 4.5: Pseudocode of the canonicalization procedure responsible for converting an expression to its canonical form.

4.4.2 Canonicalization Procedure

Figure 4.5 shows the pseudocode for the canonicalization procedure. *canonicalize*(e) is responsible for converting an expression e to its canonical form $\hat{e}$ (introduced in section 3.2.2). Recall that a pseudo-variable is an expression of the form $v.\texttt{a}_1.\texttt{a}_2...\texttt{a}_\texttt{n}$, where v is a variable. Also recall that, an expression e is canonical iff each *accessor* and *sum-is* expression operate on a pseudo-variable. An ADT expression with a data constructor, a lifting constructor or the $\underline{\texttt{if}}$-$\underline{\texttt{then}}$-$\underline{\texttt{else}}$-operator at its top-level, is called a *foldable* expression. *canonicalize*(e) iteratively folds each *accessor*

Algorithm 5: Algorithm for unifying two expressions

```
Function $\theta(p_1, e_1, p_2, e_2)$
    if $e_1$ is atomic then
        return $\mathtt{Succ}(\{\langle p_1, e_1, p_2, e_2\rangle\})$
    else if $e_2$ is atomic then
        return $\mathtt{Succ}(\{\langle p_2, e_2, p_1, e_1\rangle\})$
    else if $e_1 = V_1^{(n)}(e_1^1, e_1^2, \ldots, e_1^n)$ and $e_2 = V_2^{(m)}(e_2^1, e_2^2, \ldots, e_2^m)$ then
        if $V_1^{(n)} \neq V_2^{(m)}$ then
            return Fail
        end
        return $\bigsqcup_{i\in[1,n]} \theta(p_1, e_1^i, p_2, e_2^i)$
    else if $e_1 = V_1^{(n)}(e_1^1, e_1^2, \ldots, e_1^n)$ and $e_2 = \underline{\mathtt{if}}\ c_2\ \underline{\mathtt{then}}\ e_2^{\mathtt{th}}\ \underline{\mathtt{else}}\ e_2^{\mathtt{el}}$ then
        $R^{\mathtt{th}} \hookleftarrow \theta(p_1, true, p_2, c_2) \sqcup \theta(p_1, e_1, p_2 \mathbin{\underline{\wedge}} c_2, e_2^{\mathtt{th}})$
        if $R^{\mathtt{th}} = \mathtt{Succ}(S)$ then return $\mathtt{Succ}(S)$
        $R^{\mathtt{el}} \hookleftarrow \theta(p_1, true, p_2, \neg c_2) \sqcup \theta(p_1, e_1, p_2 \mathbin{\underline{\wedge}} \neg c_2, e_2^{\mathtt{el}})$;
        if $R^{\mathtt{el}} = \mathtt{Succ}(S)$ then return $\mathtt{Succ}(S)$
        return Fail
    else if $e_1 = \underline{\mathtt{if}}\ c_1\ \underline{\mathtt{then}}\ e_1^{\mathtt{th}}\ \underline{\mathtt{else}}\ e_1^{\mathtt{el}}$ and $e_1 = V_2^{(m)}(e_2^1, e_2^2, \ldots, e_2^m)$ then
        $R^{\mathtt{th}} \hookleftarrow \theta(p_1, c_1, p_2, true) \sqcup \theta(p_1 \mathbin{\underline{\wedge}} c_1, e_1^{\mathtt{th}}, p_2, e_2)$
        if $R^{\mathtt{th}} = \mathtt{Succ}(S)$ then return $\mathtt{Succ}(S)$
        $R^{\mathtt{el}} \hookleftarrow \theta(p_1, \neg c_1, p_2, true) \sqcup \theta(p_1 \mathbin{\underline{\wedge}} \neg c_2, e_1^{\mathtt{el}}, p_2, e_2)$;
        if $R^{\mathtt{el}} = \mathtt{Succ}(S)$ then return $\mathtt{Succ}(S)$
        return Fail
    else $e_1 = \underline{\mathtt{if}}\ c_1\ \underline{\mathtt{then}}\ e_1^{\mathtt{th}}\ \underline{\mathtt{else}}\ e_1^{\mathtt{el}}$ and $e_2 = \underline{\mathtt{if}}\ c_2\ \underline{\mathtt{then}}\ e_2^{\mathtt{th}}\ \underline{\mathtt{else}}\ e_2^{\mathtt{el}}$
        $R_1 \hookleftarrow \theta(p_1, c_1, p_2, c_2)$;
        $R_2 \hookleftarrow \theta(p_1 \mathbin{\underline{\wedge}} c_1, e_1^{\mathtt{th}}, p_2 \mathbin{\underline{\wedge}} c_2, e_2^{\mathtt{th}})$
        $R_3 \hookleftarrow \theta(p_1 \mathbin{\underline{\wedge}} \neg c_1, e_1^{\mathtt{el}}, p_2 \mathbin{\underline{\wedge}} \neg c_2, e_2^{\mathtt{el}})$
        return $R_1 \sqcup R_2 \sqcup R_3$
    end
end
```

Figure 4.6: Pseudocode of the algorithm responsible for unifying two expressions yielding correlation tuples relating atoms with (possibly) non-atoms in case of a successful unification.

and *sum-is* subexpressions of e that operate on a foldable argument. Thus, *canonicalize*(e) returns an expression where none of the *accessor* or *sum-is* subexpressions is foldable. This condition implies the requirements of the canonical form. For example, $a + \mathtt{LCons}(b, l).\mathtt{tail}.\mathtt{val}$ and $\mathtt{Clist}^{\mathtt{lnode}}_{\mathbb{m}}(p)$ is $\mathtt{LNil}$ canonicalizes to $a + l.\mathtt{val}$ and $(p = 0)$ respectively. $\{e_1 \mapsto e_2\}e$ represents the expression obtained by substituting all instances of e_1 with e_2 in e.

Algorithm 6: Algorithm for unifying two expressions under rewriting of ADT atoms

```
Function $\Theta(p_a, e_a, p_b, e_b)$
    $R \mapsfrom \emptyset$
    $S \mapsfrom \theta(p_a, e_a, p_b, e_b)$
    if $S =$ Fail then return Fail
    foreach $\langle p_1, a_1, p_2, e_2 \rangle$ in $S$ do
        if $e_2$ is atomic then
            $R \mapsfrom R \cup \{\langle p_1, a_1, p_2, e_2 \rangle\}$
        else
            $e_1 \mapsfrom$ rewrite($a_1$)
            $R_1 \mapsfrom \Theta(p_1, e_1, p_2, e_2)$
            if $R_1 =$ Fail then return Fail
            $R \mapsfrom R \cup R_1$
        end
    end
    return Succ($R$)
end
```

Figure 4.7: Pseudocode of the algorithm responsible for unifying two expressions yielding correlation tuples relating only atoms in case of a successful unification.

4.4.3 Unification Procedure

Figure 4.6 shows the pseudocode for the unification algorithm introduced in section 3.2.3. The function $\theta(p_1, e_1, p_2, e_2)$ is responsible for unifying expressions e_1 and e_2 under the expression path conditions p_1 and p_2 respectively. θ either fails to unify with the `Fail` output, or it successfully returns `Succ`(S), where S is the set of correlation tuples that relate (a) either two atomic expressions, or (b) an atom with an non-atomic expression. $\theta(p_1, e_1, p_2, e_2)$ terminates when one of e_1 and e_2 is an atomic expression. In case both e_1 and e_2 contains a data constructor at their top-level, θ attempts to recursively unify the data constructors and their corresponding children. If exactly one of e_1 and e_2 is a `if`-`then`-`else` expression, θ attempts to unify both branches of `if`-`then`-`else` with the other expression. Additionally, θ unifies the `if`-`then`-`else` condition of the successful branch (if any) with `true`. If both e_1 and e_2 are `if`-`then`-`else` expressions, θ attempts to recursively unify their children. θ uses the $\sqcup$ -operator to combine the results of successive self-calls. $A \sqcup B$ is equal to `Succ`($S_1 \cup S_2$) if $A =$ `Succ`(S_1) and $B =$ `Succ`(S_2); otherwise (if one of A and B is `Fail`), $A \sqcup B =$ `Fail`. Additionally, for a `if`-`then`-`else` expression with `if`

Algorithm 7: Algorithm for decomposing a recursive relation

```
Function decompose($l_1, l_2$)
    $P \hookleftarrow true$
    $\hat{l}_1 \hookleftarrow$ canonicalize($l_1$)
    $\hat{l}_2 \hookleftarrow$ canonicalize($l_2$)
    $R \hookleftarrow \Theta(true, \hat{l}_1, true, \hat{l}_2)$
    if $R =$ Fail then return $false$
    foreach $\langle p_1, a_1, p_2, a_2 \rangle$ in $R$ do
        if $a_1$ is $scalar$ then
            $P \hookleftarrow P \wedge ((p_1 \wedge p_2) \rightarrow (a_1 = a_2))$
        else
            $P \hookleftarrow P \wedge ((p_1 \wedge p_2) \rightarrow (a_1 \sim a_2))$
        end
    end
    return $P$
end
```

Figure 4.8: Pseudocode of the algorithm responsible for decomposing a recursive relation through unification.

condition c, c is well-formed under the expression path condition. Hence, when conjuncting c to the expression path condition, we use an 'ordered and' operator $\underline{\wedge}$, where $e_1 \underline{\wedge} e_2$ is equivalent to $e_1 \wedge (e_1 \rightarrow e_2)$.

4.4.4 Iterative Unification and Rewriting Procedure

Figure 4.7 shows the pseudocode for the iterative unification and rewriting procedure introduced in section 3.2.4. $\Theta(p_a, e_a, p_b, e_b)$ is responsible for unifying expressions e_a and e_b under the expression path conditions p_a and p_b respectively. Θ either fails to unify with the `Fail` output, or it successfully returns $\texttt{Succ}(S)$, where S is the set of correlation tuples that relate *only* atomic expressions. Θ attempts to iteratively (a) unify the expressions (through a call to the unification procedure θ in section 4.4.3), and (b) perform rewriting (of atom a_1 for those correlation tuples $\langle p_1, a_1, p_2, e_2 \rangle$ where e_2 is non-atomic), followed by a recursive call to Θ. For example, the unification of l and $\texttt{LCons}(42, \texttt{Clist}^{\texttt{lnode}}_{\mathbb{m}}(p))$ yields the correlation tuples: $\langle true, l \text{ is } \texttt{LCons}, true, true \rangle$, $\langle l \text{ is } \texttt{LCons}, l.\texttt{val}, true, 42 \rangle$ and $\langle l \text{ is } \texttt{LCons}, l.\texttt{tail}, true, \texttt{Clist}^{\texttt{lnode}}_{\mathbb{m}}(p) \rangle$.

4.4.5 Decomposition Procedure for Recursive Relations

Figure 4.8 shows the pseudocode for the decomposition algorithm defined in section 3.2.5. The function $\mathit{decompose}(l_1, l_2)$ is responsible for computing the decomposition of the recursive relation $l_1 \sim l_2$. Recall that, decomposition of a recursive relation $l_1 \sim l_2$ requires the unification of (canonicalized) l_1 and l_2 through the top-level invocation of $\Theta(\mathit{true}, l_2, \mathit{true}, l_2)$. If the n correlation tuples obtained after a successful unification are $\langle p_1^i, a_1^i, p_2^i, a_2^i\rangle$ (for $i = 1 \ldots n$), then the decomposition of $l_1 \sim l_2$ is defined as:

$$l_1 \sim l_2 \Leftrightarrow \bigwedge_{i=1}^{n}((p_1^i \wedge p_2^i) \rightarrow (a_1^i = a_2^i)) \tag{4.2}$$

If the unification fails (with a `Fail` output), the decomposition is defined to be `false`. For example, recall that the unification of l and $\mathtt{LCons}(42, \mathtt{Clist}^{\mathtt{lnode}}_{\mathbb{m}}(p))$ yields the correlation tuples: $\langle \mathit{true}, l \text{ is } \mathtt{LCons}, \mathit{true}, \mathit{true}\rangle$, $\langle l \text{ is } \mathtt{LCons}, l.\mathtt{val}, \mathit{true}, 42\rangle$ and $\langle l \text{ is } \mathtt{LCons}, l.\mathtt{tail}, \mathit{true}, \mathtt{Clist}^{\mathtt{lnode}}_{\mathbb{m}}(p)\rangle$. Consequently, $l_1 \sim \mathtt{LCons}(42, \mathtt{Clist}^{\mathtt{lnode}}_{\mathbb{m}}(l_2))$ decomposes into the conjunctive predicate: $(l \text{ is } \mathtt{LCons}) \wedge (l \text{ is } \mathtt{LCons} \rightarrow l.\mathtt{val} = 42) \wedge (l \text{ is } \mathtt{LCons} \rightarrow l.\mathtt{next} \sim \mathtt{Clist}^{\mathtt{lnode}}_{\mathbb{m}}(p))$.

4.4.6 Reduction Procedures for Approximate Recursive Relations

Recall that type II proof obligations (summarized in section 3.5.4) are discharged by over- and under-approximating the `LHS` (resulting in a weaker and a stronger proof obligation respectively), followed by discharging both proof obligations through SMT solvers. We overapproximate `LHS` by substituting each recursive relation $l_1 \sim l_2$ in the `LHS` with its d_o-depth overapproximation $l_1 \sim_{d_o} l_2$. Similarly, the `LHS` is underapproximated by substituting each recursive relation $l_1 \sim l_2$ with its d_u-depth underapproximation $l_1 \sim_{d_u} l_2$.

Algorithm 9: Pseudocode for the algorithm responsible for unifying two expressions yielding depth-augmented correlation tuples relating atoms with (possibly) non-atoms in case of a successful unification.

```
Function $\theta_D(p_1, e_1, p_2, e_2, d)$
    if $e_1$ is atomic then
        return $\texttt{Succ}(\{\langle p_1, e_1, p_2, e_2 \rangle_d\})$
    else if $e_2$ is atomic then
        return $\texttt{Succ}(\{\langle p_2, e_2, p_1, e_1 \rangle_d\})$
    else if $e_1 = V_1^{(n)}(e_1^1, e_1^2, \ldots, e_1^n)$ and $e_2 = V_2^{(m)}(e_2^1, e_2^2, \ldots, e_2^m)$ then
        if $V_1^{(n)} \neq V_2^{(m)}$ then
            return $\texttt{Fail}$
        end
        return $\bigsqcup_{i \in [1,n]} \theta_D(p_1, e_1^i, p_2, e_2^i, d+1)$
    else if $e_1 = V_1^{(n)}(e_1^1, e_1^2, \ldots, e_1^n)$ and $e_2 = \underline{\texttt{if}}\ c_2\ \underline{\texttt{then}}\ e_2^{\mathtt{th}}\ \underline{\texttt{else}}\ e_2^{\mathtt{el}}$ then
        $R^{\mathtt{th}} \mapsfrom \theta_D(p_1, true, p_2, c_2, d) \sqcup \theta_D(p_1, e_1, p_2 \underline{\triangle} c_2, e_2^{\mathtt{th}}, d)$
        if $R^{\mathtt{th}} = \texttt{Succ}(S)$ then return $\texttt{Succ}(S)$
        $R^{\mathtt{el}} \mapsfrom \theta_D(p_1, true, p_2, \neg c_2, d) \sqcup \theta_D(p_1, e_1, p_2 \underline{\triangle} \neg c_2, e_2^{\mathtt{el}}, d)$
        if $R^{\mathtt{el}} = \texttt{Succ}(S)$ then return $\texttt{Succ}(S)$
        return $\texttt{Fail}$
    else if $e_1 = \underline{\texttt{if}}\ c_1\ \underline{\texttt{then}}\ e_1^{\mathtt{th}}\ \underline{\texttt{else}}\ e_1^{\mathtt{el}}$ and $e_1 = V_2^{(m)}(e_2^1, e_2^2, \ldots, e_2^m)$ then
        $R^{\mathtt{th}} \mapsfrom \theta_D(p_1, c_1, p_2, true, d) \sqcup \theta_D(p_1 \underline{\triangle} c_1, e_1^{\mathtt{th}}, p_2, e_2, d)$
        if $R^{\mathtt{th}} = \texttt{Succ}(S)$ then return $\texttt{Succ}(S)$
        $R^{\mathtt{el}} \mapsfrom \theta_D(p_1, \neg c_1, p_2, true, d) \sqcup \theta_D(p_1 \underline{\triangle} \neg c_2, e_1^{\mathtt{el}}, p_2, e_2, d)$
        if $R^{\mathtt{el}} = \texttt{Succ}(S)$ then return $\texttt{Succ}(S)$
        return $\texttt{Fail}$
    else $e_1 = \underline{\texttt{if}}\ c_1\ \underline{\texttt{then}}\ e_1^{\mathtt{th}}\ \underline{\texttt{else}}\ e_1^{\mathtt{el}}$ and $e_2 = \underline{\texttt{if}}\ c_2\ \underline{\texttt{then}}\ e_2^{\mathtt{th}}\ \underline{\texttt{else}}\ e_2^{\mathtt{el}}$
        $R_1 \mapsfrom \theta_D(p_1, c_1, p_2, c_2, d)$
        $R_2 \mapsfrom \theta_D(p_1 \underline{\triangle} c_1, e_1^{\mathtt{th}}, p_2 \underline{\triangle} c_2, e_2^{\mathtt{th}}, d)$
        $R_3 \mapsfrom \theta_D(p_1 \underline{\triangle} \neg c_1, e_1^{\mathtt{el}}, p_2 \underline{\triangle} \neg c_2, e_2^{\mathtt{el}}, d)$
        return $R_1 \sqcup R_2 \sqcup R_3$
    end
end
```

D-depth Iterative Unification and Rewriting Procedure

Section 3.5.3 briefly describes the process of reducing an overapproximate recursive relation into its SMT-encodable equivalent absent of recursive relations. We use modified versions of unification and 'iterative unification and rewriting' algorithms (defined in sections 4.4.3 and 4.4.4 respectively) to reduce an approximate recursive relation into its SMT-equivalent. The D-depth unification and 'iterative unification and rewriting' procedures are represented by $\Theta_D(p_a, e_a, p_b, e_b, d)$

Algorithm 10: Algorithm for D-depth unifying two expressions under rewriting of ADT atoms

```
Function $\Theta_D(p_a, e_a, p_b, e_b, d)$
    $R \hookleftarrow \emptyset$
    $S \hookleftarrow \Theta_D(p_a, e_a, p_b, e_b, d)$
    if $S = \mathtt{Fail}$ then return Fail
    foreach $\langle p_1, a_1, p_2, e_2 \rangle_{d'}$ in $S$ do
        if $e_2$ is atomic then
            if $d' \le D$ and $a_1$ is not scalar then
                $e_1 \hookleftarrow \mathtt{rewrite}(a_1)$
                $e_2^r \hookleftarrow \mathtt{rewrite}(e_2)$
                $R_1 \hookleftarrow \Theta_D(p_1, e_1, p_2, e_2^r, d')$ if $R_1 = \mathtt{Fail}$ then return Fail
                $R \hookleftarrow R \cup R_1$
            else
                $R \hookleftarrow R \cup \{\langle p_1, a_1, p_2, e_2 \rangle_{d'}\}$
            end
        else
            $e_1 \hookleftarrow \mathtt{rewrite}(a_1)$
            $R_1 \hookleftarrow \Theta_D(p_1, e_1, p_2, e_2, d')$
            if $R_1 = \mathtt{Fail}$ then return Fail
            $R \hookleftarrow R \cup R_1$
        end
    end
    return $\mathtt{Succ}(R)$
end
```

Figure 4.9: Pseudocode of the algorithm responsible for D-depth unifying two expressions yielding depth-augmented correlation tuples relating only atoms in case of a successful unification.

and $\theta_D(p_1, e_1, p_2, e_2, d)$ respectively, where D is a parameter of the algorithm. The pseudocode for these two procedures are shown in algorithm 9 and fig. 4.9 respectively. The D-depth 'iterative unification and rewriting' returns depth-augmented correlation tuples of the form $\langle p_1, a_1, p_2, a_2 \rangle_d$ such that $d \ge D$ for all correlation tuples relating ADT values. Unlike Θ which terminates unification iff both expressions are atomic, Θ_D performs rewriting of both ADT atomic expressions and continues to unify deeper into their respective expression trees until all correlation tuples relate ADT expressions at depth $\ge D$. For example, the 1-depth unification of l and $\mathtt{Clist}^{\mathtt{lnode}}_{\mathbb{m}}(p)$ yields the (depth augmented) correlation tuples: $\langle true, l \text{ is } \mathtt{LNil}, true, p = 0 \rangle_0$, $\langle l \text{ is } \mathtt{LCons}, l.\mathtt{val}, p \ne 0, p \xrightarrow{\mathbb{m}}_{\mathtt{lnode}} \mathtt{val} \rangle_1$ and $\langle l \text{ is } \mathtt{LCons}, l.\mathtt{tail}, p \ne 0, \mathtt{Clist}^{\mathtt{lnode}}_{\mathbb{m}}(p \xrightarrow{\mathbb{m}}_{\mathtt{lnode}} \mathtt{next}) \rangle_1$.

Algorithm 11: Algorithm for reducing an overapproximate recursive relation into an equivalent SMT-encodable condition

```
Function $overapprox_D(l_1, l_2)$
    $P \mapsfrom true$
    $\hat{l}_1 \mapsfrom \mathtt{canonicalize}(l_1)$
    $\hat{l}_2 \mapsfrom \mathtt{canonicalize}(l_2)$
    $R \mapsfrom \Theta_D(true, \hat{l}_1, true, \hat{l}_2, 0)$
    if $R = \mathtt{Fail}$ then return $false$
    foreach $\langle p_1, a_1, p_2, a_2 \rangle_d$ in $R$ do
        if $a_1$ is $scalar$ and $d \leq D$ then
            $P \mapsfrom P \wedge ((p_1 \wedge p_2) \rightarrow (a_1 = a_2))$
        end
    end
    return $P$
end
```

Figure 4.10: Pseudocode of the algorithm responsible for reducing an overapproximate recursive relation into an equivalent SMT-encodable condition free of recursive relations.

Reduction Procedure for Overapproximate Recursive Relations

$overapprox_D(l_1, l_2)$ is responsible for reducing the overapproximation $l_1 \sim_D l_2$ into its SMT-encodable equivalent condition. $overapprox_D$ is similar to the decomposition procedure in section 4.4.5 except it only preserves scalar equalities till a maximum depth of D (inclusive). This essentially asserts that both l_1 and l_2 have identical structures (by equating expression path conditions) and equal scalar values (by equating scalar leaf expressions) till a depth of D. For example, recall that l and $\mathtt{Clist}^{\mathtt{lnode}}_{\mathbb{m}}(p)$ 1-depth unifies into the correlation tuples: $\langle true, l \text{ is } \mathtt{LNil}, true, p = 0 \rangle_0$, $\langle l \text{ is } \mathtt{LCons}, l.\mathtt{val}, p \neq 0, p \overset{\mathbb{m}}{\rightarrow}_{\mathtt{lnode}} \mathtt{val} \rangle_1$ and $\langle l \text{ is } \mathtt{LCons}, l.\mathtt{tail}, p \neq 0, \mathtt{Clist}^{\mathtt{lnode}}_{\mathbb{m}}(p \overset{\mathbb{m}}{\rightarrow}_{\mathtt{lnode}} \mathtt{next}) \rangle_1$. Keeping only the scalar clauses till depth 1, $l \sim_1 \mathtt{Clist}^{\mathtt{lnode}}_{\mathbb{m}}(p)$ reduces to: $((l \text{ is } \mathtt{LNil}) = (p = 0)) \wedge ((l \text{ is } \mathtt{LCons}) \wedge (p \neq 0) \rightarrow l.\mathtt{val} = p \overset{\mathbb{m}}{\rightarrow}_{\mathtt{lnode}} \mathtt{val})$.

Algorithm 12: Algorithm for computing a predicate bounding the maximum depth of a value to D

```
Function $\mathit{isDepthBounded}_D(l, p, d)$
    if $d > D$ then return $\neg p$
    if $l$ is atomic then
        if $l$ is scalar then return true
        else
            $l_r \mapsfrom \texttt{rewrite}(l)$
            return $\mathit{isDepthBounded}_D(l_r, p, d)$
        end
    else if $l = V^{(n)}(l^1, l^2, \ldots, l^n)$ then
        return $\bigwedge_{i \in [1,n]} \mathit{isDepthBounded}_D(l^i, p, d+1)$
    else $l = \underline{\texttt{if}}\ c\ \underline{\texttt{then}}\ l^{\texttt{th}}\ \underline{\texttt{else}}\ l^{\texttt{el}}$
        $c^{\texttt{th}} \mapsfrom \mathit{isDepthBounded}_D(l^{\texttt{th}}, p \,\underline{\triangle}\, c, d)$
        $c^{\texttt{el}} \mapsfrom \mathit{isDepthBounded}_D(l^{\texttt{el}}, p \,\underline{\triangle}\, \neg c, d)$
        return $c^{\texttt{th}} \wedge c^{\texttt{el}}$
    end
end
```

Figure 4.11: Pseudocode of the algorithm responsible for computing an SMT-encodable predicate bounding the maximum depth of a value to D.

Reduction Procedure for Underapproximate Recursive Relations

Recall that, an underapproximate recursive relation $l_1 \approx_{d_u} l_2$ is equivalent to $\Gamma_{d_u}(l_1) \wedge \Gamma_{d_u}(l_2) \wedge l_1 \sim_{d_u} l_2$, where $\Gamma_d(l)$ asserts that l has a maximum depth of d (defined in section 3.5.2). The function responsible for computing $\Gamma_D(l)$ is $\mathit{isDepthBounded}_D(l, p, d)$, where p and d represents the current expression path condition and depth of l, and D is a parameter of the algorithm. Figure 4.11 gives the pseudocode for $\mathit{isDepthBounded}_D$. The top-level invocation is given by $\mathit{isDepthBounded}_D(l, \mathit{true}, 0)$. $\mathit{isDepthBounded}_D$ recursively traverses the expression tree of l (while rewriting as necessary), until it reaches a node at depth $> D$, at which point it returns the condition asserting the unreachability of such a node. For example, for a `List` variable l, $\Gamma_1(l)$ (i.e. $\mathit{isDepthBounded}_1(l, \mathit{true}, 0)$) returns the predicate: $\neg(l \text{ is } \texttt{LCons} \,\underline{\triangle}\, l.\texttt{tail} \text{ is } \texttt{LCons})$. Expanding $e_1 \,\underline{\triangle}\, e_2$ to $e_1 \wedge (e_1 \rightarrow e_2)$ and using the identity $\neg(e \text{ is } \texttt{LNil}) = e \text{ is } \texttt{LCons}$, the above reduces to the equivalent condition: $(l \text{ is } \texttt{LNil}) \vee ((l \text{ is } \texttt{LCons}) \wedge (l.\texttt{tail} \text{ is } \texttt{LNil}))$.

Finally, $\mathit{underapprox}_D(l_1, l_2)$ is responsible for reducing the underapproximation $l_1 \approx_D l_2$ into

Algorithm 13: Algorithm for reducing an underapproximate recursive relation to an equivalent SMT-encodable condition

```
Function $underapprox_D(l_1, l_2)$
    $\hat{l}_1 \mapsfrom \texttt{canonicalize}(l_1)$;
    $\hat{l}_2 \mapsfrom \texttt{canonicalize}(l_2)$;
    $overapprox \mapsfrom \texttt{overapprox}_D(\hat{l}_1, \hat{l}_2)$;
    $depthbound_1 \mapsfrom \texttt{isDepthBounded}_D(\hat{l}_1, true, 0)$;
    $depthbound_2 \mapsfrom \texttt{isDepthBounded}_D(\hat{l}_2, true, 0)$;
    return $overapprox \wedge depthbound_1 \wedge depthbound_2$;
end
```

Figure 4.12: Pseudocode of the algorithm responsible for reducing an underapproximate recursive relation to an equivalent SMT-encodable condition free of recursive relations.

its SMT-encodable equivalent condition. The pseudocode for $underapprox_D$ is given in fig. 4.12. For example, $l \approx_1 \texttt{Clist}^{\texttt{lnode}}_{\mathbb{m}}(p) \Leftrightarrow \Gamma_1(l) \wedge \Gamma_1(\texttt{Clist}^{\texttt{lnode}}_{\mathbb{m}}(p)) \wedge l \sim_1 \texttt{Clist}^{\texttt{lnode}}_{\mathbb{m}}(p)$. $\Gamma_1(l)$ and $\Gamma_1(\texttt{Clist}^{\texttt{lnode}}_{\mathbb{m}}(p))$ reduces to the conditions $(l \text{ is } \texttt{LNil}) \vee ((l \text{ is } \texttt{LCons}) \wedge (l.\texttt{tail} \text{ is } \texttt{LNil}))$ and $(p = 0) \vee ((p \neq 0) \wedge (p \xrightarrow{\mathbb{m}}_{\texttt{lnode}} \texttt{next} = 0))$ respectively. Finally, $l \approx_1 \texttt{Clist}^{\texttt{lnode}}_{\mathbb{m}}(p)$ reduces to:

$$\begin{gathered}(l \text{ is } \texttt{LNil}) \vee ((l \text{ is } \texttt{LCons}) \wedge (l.\texttt{tail} \text{ is } \texttt{LNil})) \wedge \\ (p = 0) \vee ((p \neq 0) \wedge (p \xrightarrow{\mathbb{m}}_{\texttt{lnode}} \texttt{next} = 0)) \wedge \\ ((l \text{ is } \texttt{LNil}) = (p = 0)) \wedge ((l \text{ is } \texttt{LCons}) \wedge (p \neq 0) \rightarrow l.\texttt{val} = p \xrightarrow{\mathbb{m}}_{\texttt{lnode}} \texttt{val})\end{gathered}$$

4.4.7 SMT Encoding of First Order Logic Formula

As summarized in fig. 3.8, our proof discharge algorithm solves a proof obligation $P : \texttt{LHS} \Rightarrow \texttt{RHS}$, through a sequence of queries $(P_i : \texttt{LHS}_i \Rightarrow \texttt{RHS}_i)$ to off-the-shelf SMT solvers. Recall that P may contain recursive relations. However, our algorithm ensures that each P_i is free of recursive relations and only contain scalar equalities. We encode each query P_i in SMT logic with bitvector and array theories. We begin by converting P_i to its canonical form $\hat{P}_i$ (as described in section 4.4.2). Although $\hat{P}_i$ does not contain recursive relations, it may still contain ADT variables, as well as *accessor* and *sum-is* expressions. Recall that in the canonicalized form, all *accessor* and *sum-is* expressions are of the forms $v.\texttt{a}_1.\texttt{a}_2...\texttt{a}_\texttt{n}$ and $v.\texttt{a}_1.\texttt{a}_2...\texttt{a}_\texttt{n}$ is V respectively.

Such an expression e is called *flattenable* and the *name* of the ADT variable v is called the *index* of e. $\hat{P}_i$ is lowered into an intermediate expression $\hat{P}_i^f$ through a process called *flattening*. This involves 'flattening' all flattenable subexpressions of $\hat{P}_i$ to variables such that $\hat{P}_i^f$ only contains scalar values with scalar and memory operations (but importantly not ADT values). Flattening is a two step process as described next.

1. For each *accessor* expression $e = v.\mathtt{a_1}.\mathtt{a_2}...\mathtt{a_n}$, we replace it with a variable named $v \,\|\, \mathtt{a_1} \,\|\, \mathtt{a_2} \,\| \ldots \|\, \mathtt{a_n}$, where $\|$ concatenates two strings with a '_' character in between i.e. "a"$\|$"b" = "a_b".
2. For each ADT T with data constructors $V_1, V_2, \ldots, V_k$, we define an enumeration type $\mathcal{E}(T)$ in SMT logic with items $\mathcal{E}(V_1), \mathcal{E}(V_2), \ldots, \mathcal{E}(V_k)$ respectively. The last step guarantees that each *sum-is* expression e must be of the form: v is V. We replace e with the its SMT equivalent: $(v \,\|\, \text{"}tag\text{"}) = \mathcal{E}(V)$ [1].

For example, the canonical expression $a + l.\mathtt{val}$ flattens to $a + \mathtt{l\_val}$. Similarly, ($l.\mathtt{tail}$ is $\mathtt{LCons}$) flattens to $\mathtt{l\_tail\_tag} = \mathcal{E}(\mathtt{LCons})$. Due to flattening, each flattenable subexpression e in $\hat{P}_i$ with index "str" gets lowered into a variable in $\hat{P}_i^f$ whose name begins with "$str\_$". For the ADT variable v, let $\mathcal{F}(v)$ be the set of all such lowered variables in $\hat{P}_i^f$. For example, flattening of an expression with $l.\mathtt{val}$ and l is $\mathtt{LCons}$ results in $\mathcal{F}(l) = \{\mathtt{l\_val}, \mathtt{l\_tag}\}$. Importantly, $\hat{P}_i^f$ may only contain scalar and memory operations (but not ADT values).

Scalar types and their operations map one-to-one with their SMT equivalents. The memory element $\mathbb{m}$ is represented as a byte-addressable (i.e. i8) array. A memory load $\mathbb{m}[a]_\mathtt{T}$ is expanded into the concatenation of sizeof(T) *array-select* operations. A memory write $\mathbb{m}[a \leftarrow v]_\mathtt{T}$ is expanded into sizeof(T) nested *array-store* operations.

4.4.8 Reconciliation of Counterexamples

As previously discussed in section 4.4.7, each ADT variable v gets lowered into a set of scalar variables $\mathcal{F}(v)$ in its SMT encoding. Evidently, the models returned by SMT solvers map these

[1] Spec does not allow naming a field of a data constructor tag. Furthermore, fields cannot contain the '_' character. Combined, these two conditions prevent collision between variable names obtained due to flattening.

Algorithm 14: Algorithm for reconciling a constant valuation for variable v from a model γ returned by an SMT solver

```
Function reconcile($v, T, \gamma$)
    if $T$ is scalar then
        if $\gamma$ maps $v$ then return $\gamma[v]$
        else return rand($T$)
    else
        if $\gamma$ maps $v \parallel "tag"$ then
            $\mathcal{E}(V) \hookleftarrow \gamma[v \parallel "tag"]$
            $args \hookleftarrow []$
            let $[\mathtt{a_1} : T_1, \mathtt{a_2} : T_2, \ldots, \mathtt{a_n} : T_n]$ be the fields of $V$.
            foreach $\mathtt{a}' : T'$ in $[\mathtt{a_1} : T_1, \mathtt{a_2} : T_2, \ldots, \mathtt{a_n} : T_n]$ do
                $arg \hookleftarrow reconcile(v \parallel \mathtt{a}', T', \gamma)$
                $args$.append($arg$)
            end
            return $V(args \ldots)$
        else
            return rand($T$)
        end
    end
end
```

Figure 4.13: Pseudocode of the algorithm responsible for reconciling a constant valuation for a variable v from model γ returned by an SMT solver.

variables (in $\mathcal{F}(v)$ instead of v) to constant values. We are interested in recovering a counterexample for the original query from a model returned by an SMT solver. Recall that, these counterexamples help guide the correlation search (in section 4.2) and invariant inference (in section 4.3) procedures. The process of constructing a concrete value for v from the constants returned for $\mathcal{F}(v)$ by an SMT solver is called *reconciliation*. Obviously, the reconciled counterexample must be a valid counterexample to the original proof obligation.

The function *reconcile*(v, T, γ) is responsible for reconciling a concrete value for the variable v (of type T) from the model γ (returned by an SMT solver). `rand`(T) returns an arbitrary constant of type T. For example, consider the rather contrived proof obligation P : `true` $\Rightarrow$ l is `LNil`. Clearly, any valuation of l where l is a non-empty list is a valid counterexample to P. However, a counterexample γ returned by an SMT solver would instead map `l_tag` to $\mathcal{E}$(`LCons`). *reconcile*() identifies that `l_tag` maps to the data constructor `LCons` and attempts to recursively reconcile values for each of its fields `val` and `tail`. Since γ do not contain a mapping for either of these fields (`l_val` and `l_tail_tag`), we soundly generate random constants for these instead (through `rand()`). *reconcile*() returns a non-empty but otherwise arbitrary list for l, which is indeed a valid counterexample to the original proof obligation P.

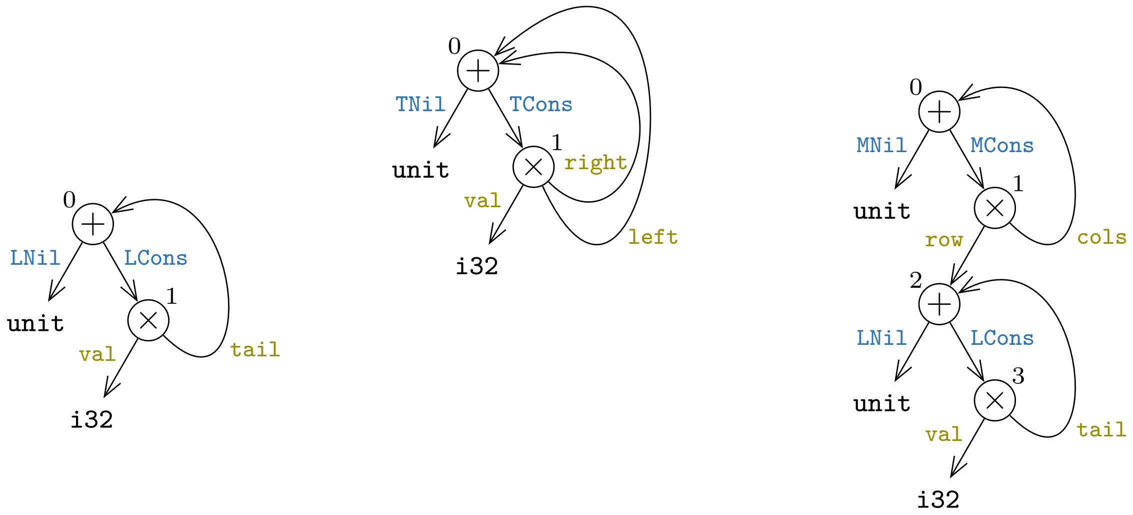
4.4.9 Value Tree Representation

This section presents a graphical representation of expressions that helps us simplify the implementation of multiple subprocedures used by our proof discharge algorithm. This includes the process of canonicalization, reduction of approximate recursive relations, as well as the creation of deconstruction programs as part of type III proof obligations. We call this the *value tree* representation and use $\mathcal{V}(e)$ to denote a value tree associated with e. We give an algorithm to convert an expression e into $\mathcal{V}(e)$ and list its applications.

Before diving into value trees, we start by introducing an analogous (but simpler) representation for types, called *type trees*. We use $\mathcal{T}(\tau)$ to denote a type tree associated with τ. Recall that ADTs are simply 'sum of product' types where each data constructor represents a variant (of the sum-type) and contains values for each of its fields (of the product-type). On top of ADTs, IR has build-in scalar types: `unit`, `bool` and `i<N>`. Types in IR can be represented in *first order recursive types* [26] using the product ($\times$) and sum ($+$) type constructors; and the scalar types (i.e. nullary type constructors). The type system is characterized by the grammar $\mathbb{T}$ as follows:

$$T \rightarrow \mu\alpha.\, T \mid T \times \cdots \times T \mid T + \cdots + T \mid \texttt{unit} \mid \texttt{bool} \mid \texttt{i}\langle\texttt{N}\rangle \mid \alpha$$

Every IR type can be encoded as a closed term (i.e. term without free variables) in $\mathbb{T}$. For example, the `List` type can be written as $\mu\alpha.\texttt{unit} + (\texttt{i32} \times \alpha)$. Note the use of a type variable α which is bound using μ to represent recursion. Similarly, the `Matrix` type is represented by the term $\mu\alpha.\texttt{unit} + ((\mu\beta.\texttt{unit} + (\texttt{i32} \times \beta)) \times \alpha)$, where the type variables α and β are used to bind recursive types `Matrix` and `List` at their definitions respectively.



(a) `List` = `LNil` | `LCons(i32, List)`

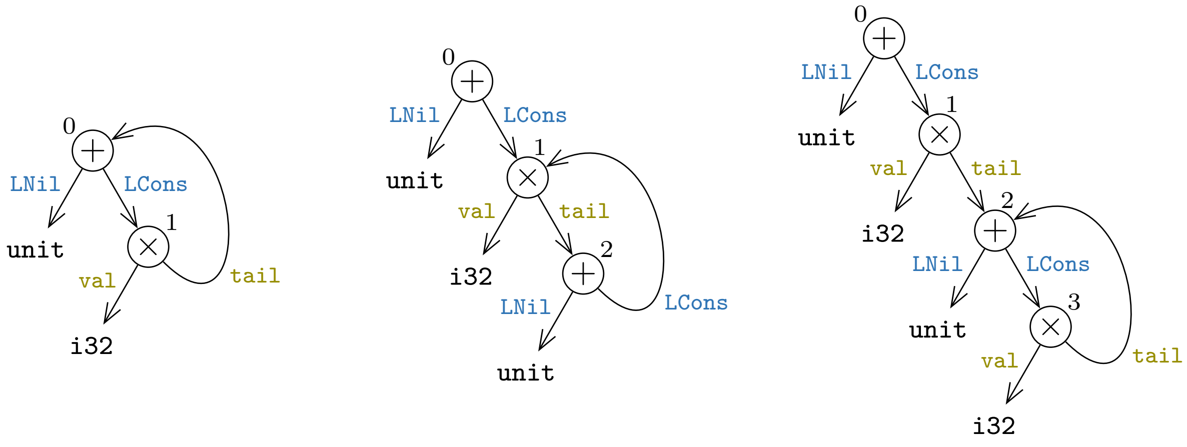
(b) `Tree` = `TNil` | `TCons(i32, Tree, Tree)`

(c) `Matrix` = `MNil` | `MCons(List, Matrix)`

Figure 4.14: Type tree representation for the ADTs – `List`, `Tree` and `Matrix` respectively.

Figure 4.14 shows the type trees for three ADTs – `List`, `Tree`, and `Matrix` respectively. In a type tree, each internal node represents either a product ($\otimes$) or a sum ($\oplus$) type constructor. The leaf nodes are the scalar types. Each outgoing edge of a $\oplus$ node is associated with a data constructor of the corresponding ADT (i.e. `LCons` for `List`). Similarly, each outgoing edge of a $\otimes$ node is associated with a field of the corresponding data constructor (i.e. `val` for `LCons`). We assign integer indices to the internal nodes and use $[v\!:\!\texttt{label}]$[2] to identify the edge outgoing at v associated with `label`, where `label` is either a data constructor or a field name. The root node is denoted by v_0. The edges going outward from the root node are called *tree-edges*, e.g., $[0\!:\!\texttt{LCons}]$ and $[1:\texttt{val}]$ in fig. 4.14a. Edges that are not tree-edges, are called *backedges*, e.g., $[1:\texttt{cols}]$ in fig. 4.14c. Every backedge induces an unique simple cycle in the type tree representation.

[2] The $[v:\texttt{label}]$ syntax is chosen over $v_1 \rightarrow v_2$ because type trees may have multi-edges (e.g. fig. 4.14b), in

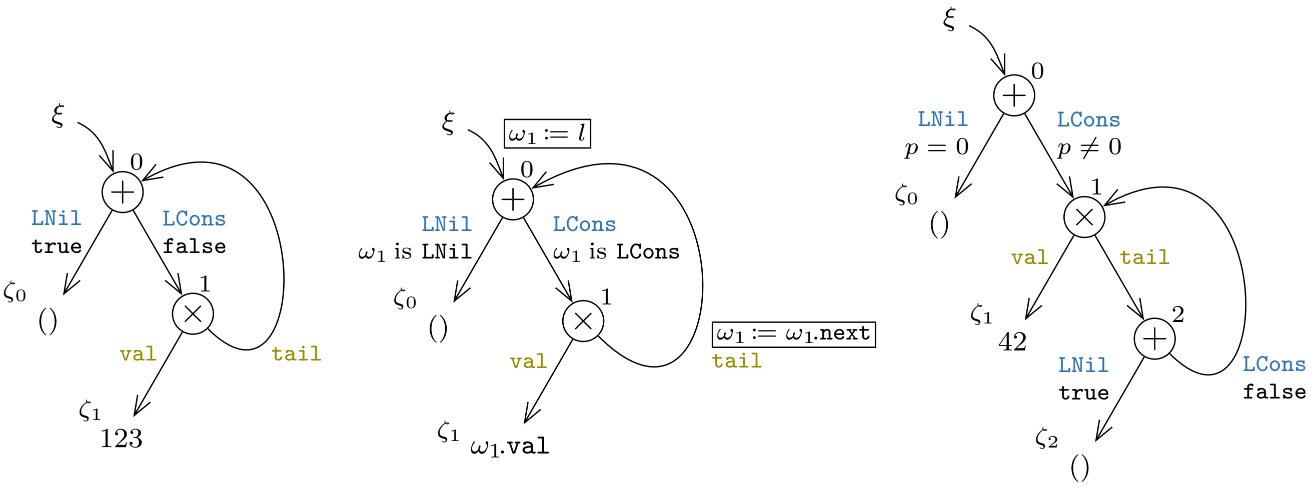


(a) Canonical `List` ADT **(b)** Peeled `List` ADT **(c)** Unrolled `List` ADT

Figure 4.15: Three type trees representing the ADT `List`. Figure 4.15a shows the type tree for the canonical form of `List`. Figure 4.15b is obtained by peeling the back-edge [1 : `tail`] in fig. 4.15a. Figure 4.15c is obtained by unrolling the back-edge [1 : `tail`] in fig. 4.15a or by peeling the back-edge [2 : `LCons`] in fig. 4.15b respectively.

Recall that types in Spec (and in IR) follow equirecursive typing rules i.e. types $\mu\alpha.T$ and $T[\mu\alpha.T/\alpha]$ in $\mathbb{T}$ are *equal* types, where $T[\mu\alpha.T/\alpha]$ represents the new type obtained by substituting all free instances of α with $\mu\alpha.T$, and is defined as the *unfolding* of $\mu\alpha.T$. In general, under equirecursive typing, two types are equal iff their infinite expansions (through unfolding) are equal. In the type tree representation, two types are equal iff their infinite expansions are equal. Such type trees are called isomorphic and two types are isomorphic iff they represent the same type. An unfolding in the term representation corresponds to *unrolling* one iteration of a simple cycle in its type tree. Figure 4.15 shows three type trees for the `List` type. Figure 4.15a corresponds to the canonical (intuitively the 'smallest') type tree for the `List` type. The type trees figs. 4.15b and 4.15c are obtained by *peeling* and unrolling the backedge [1 : `tail`] (in fig. 4.15a) respectively. Peeling is a form of partial unrolling which only extracts the head of a cycle. In practice, equality of two types (encoded in $\mathbb{T}$) can be reposed as syntactic equality of their *canonical forms* [19]. In general, type trees may contain cycles (due to backedges) and

which case $v_1 \rightarrow v_2$ no longer represents an unique edge.



(a) `LNil` **(b)** l : `List` **(c)** $\underline{\texttt{if}}\ p = 0\ \underline{\texttt{then}}\ \texttt{LNil}$ $\underline{\texttt{else}}\ \texttt{LCons}(42, \texttt{LNil})$

Figure 4.16: Value trees of three `List`-typed expressions

hence are not quite 'trees'. However, they represent the actual (possibly infinite) trees obtained through repeated unrolling of cycles.

With type trees out of the way, we are ready to present their value analogue called 'value trees'. Figure 4.16 shows the value trees for three `List` expressions. Note that, all three value trees are isomorphic to one of the `List` type trees shown in fig. 4.15, e.g., fig. 4.16c is isomorphic to fig. 4.15b. In general, for an expression e of type τ, its value tree $\mathcal{V}(e)$ resembles a type tree $\mathcal{T}(\tau)$ with the following distinctions:

1. Similar to a type tree, each internal node in $\mathcal{V}(e)$ is either a ⊕ or a ⊗ node.
2. Each node v in $\mathcal{V}(e)$ is associated with a symbolic state Ω_v similar to the control-flow graph representation (presented in section 2.2.3) of a program.
3. Recall that an edge leaving a ⊕ node is labeled with a data constructor. These edges are additionally labeled with an *edge condition* (a boolean valued function over Ω_n). We identify such an edge with $[v : V; c]$, where v is the ⊕ node, V is a data constructor and

c is the edge condition. The set of edge conditions of all edges leaving a $\oplus$ node must be mutually exclusive and exhaustive.

4. Recall that an edge $v \to v'$ leaving a $\otimes$ node is labeled with a field name. Such an edge is also associated with a transfer function ($\Omega_{v'}$ as a function of Ω_v), and is denoted by $[v\!:\!\texttt{fi};\texttt{tf}]$, where v is the $\otimes$ node, `fi` is a field name and `tf` is the transfer function.

5. Instead of a scalar type τ_s, each leaf node v in $\mathcal{V}(e)$ contains an expression of type τ_s (as a function of Ω_v).

6. Additionally, a value tree contains a special node (called the *entry node*), and a special edge (called the *entry edge*) from the entry node to v_0 (i.e. the root of the tree). We use ξ to denote the entry node. The entry edge is associated with a transfer function $\texttt{tf}_\xi$. We often omit the entry node in figures for brevity.

7. A value tree $\mathcal{V}(e)$ can be converted to a type tree $\mathcal{T}$ as follows: (a) remove the entry node and edge pair, (b) remove edge conditions and transfer functions associated with all edges, and (c) replace each leaf node expression of (scalar) type τ_s with τ_s itself. The resulting type tree $\mathcal{T}$ represents the type τ of the expression e.

Intuitively, a value tree simultaneously represents the value of the expression as well as the canonical CFG of its deconstruction program. We will subsequently discuss these properties along with their applications in the context of our proof discharge algorithm. First, we give an algorithm to convert an expression e to its value tree representation $\mathcal{V}(e)$.

4.4.10 Conversion of Expressions to their Value Trees

In this section, we present an algorithm to recursively construct a value tree for any arbitrary expression e. We take a visual approach to align with the graphical nature of value trees.

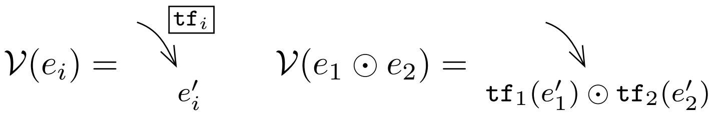

$\mathcal{V}(e_i) =$
tf$_i$
e'_i
$\mathcal{V}(e_1 \odot e_2) =$
tf$_1(e'_1) \odot$ tf$_2(e'_2)$

Figure 4.17: Construction of $\mathcal{V}(e_1 \odot e_2)$ from $\mathcal{V}(e_1)$ and $\mathcal{V}(e_2)$. $\odot$ represents an arbitrary scalar operator.

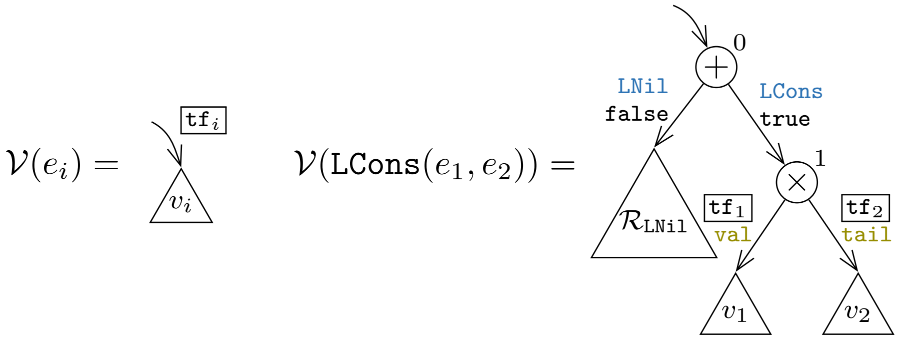


Figure 4.18: Construction of $\mathcal{V}(\texttt{LCons}(e_1, e_2))$ from $\mathcal{V}(e_1)$ and $\mathcal{V}(e_2)$. $\mathcal{R}_{\texttt{LNil}}$ represents an arbitrary value tree corresponding to the product-type (in $\mathbb{T}$) associated with `LNil`.

Scalar Operators

Given an expression $e = e_1 \odot e_2$, fig. 4.17 shows the construction of $\mathcal{V}(e)$ from $\mathcal{V}(e_1)$ and $\mathcal{V}(e_2)$ respectively. Since e_1 and e_2 have scalar types, their value trees must have exactly one node (i.e. a leaf node) containing an expression (e'_1 and e'_2 respectively) of the same type. $\odot$ represents an aribtrary scalar operator, i.e. an operator that accepts scalar values and produce another scalar value. Importantly, arrays over bitvectors are considered scalar types and thus memory load and store satisfy the properties of scalar operators. Given an expression s and a transfer function `tf`, `tf`(s) represents the expression obtained by applying `tf`, interpreted as a substitution, to s. This is equivalent to the weakest-precondition of s along an edge associated with `tf`. The construction shown in fig. 4.17 can be generalized to n-ary scalar operators for $n > 2$.

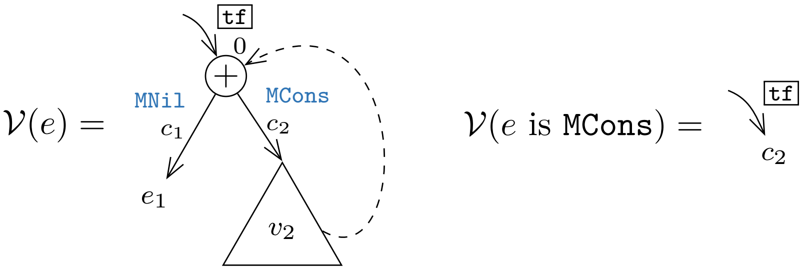


Figure 4.19: Construction of $\mathcal{V}(e \text{ is } \texttt{MCons})$ from $\mathcal{V}(e)$. The dashed edge represents the (possibly empty) set of backedges originating in the subtree rooted at v_2 that terminates at 0.

ADT Data Constructors

Given an expression $e = \texttt{LCons}(e_1, e_2)$, fig. 4.18 depicts the construction of $\mathcal{V}(e)$ from $\mathcal{V}(e_1)$ and $\mathcal{V}(e_2)$ respectively. In general, for an arbitrary data constructor V of ADT T, the construction begins with a $\oplus$ node (0 in fig. 4.18) such that the outgoing edge associated with the value constructor V (`LCons` in fig. 4.18) has an edge condition of `true` while all other edges are assigned the edge condition `false`. For each data constructor $V' \neq V$ of T, we append a random value tree corresponding to the product-type associated with V' in $\mathbb{T}$. For example, given `List` is associated with the sum-type $\mu\alpha.\texttt{Unit} + (\texttt{i32} \times \alpha)$, the product-types associated with `LNil` and `LCons` are: `Unit` and $\mu\alpha.\texttt{i32} \times (\texttt{Unit} + \alpha)$ respectively. We use $\mathcal{R}_\tau$ to denote an arbitrary (i.e. random) value tree of type τ. For the outgoing edge associated with the data constructor V ($[0 : \texttt{LCons}; \texttt{true}]$ in fig. 4.18), we construct a product node (1 in fig. 4.18) and append the value trees corresponding to the arguments e_i as children of the product node.

Sum-Is Operator

Given a *sum-is* expression $e' = e$ is `MCons`, fig. 4.19 shows the construction of $\mathcal{V}(e')$ from $\mathcal{V}(e)$. The process is rather straightforward and for a general expression e is $V_\texttt{i}$, entails extracting the edge condition c (c_2 in fig. 4.19) from $\mathcal{V}(e \text{ is } V_\texttt{i})$ edge $[v_0 : V; c]$ ($[0 : \texttt{MCons}; c_2]$ in fig. 4.19). Notice that the entry transfer function `tf` is preserved during this construction.

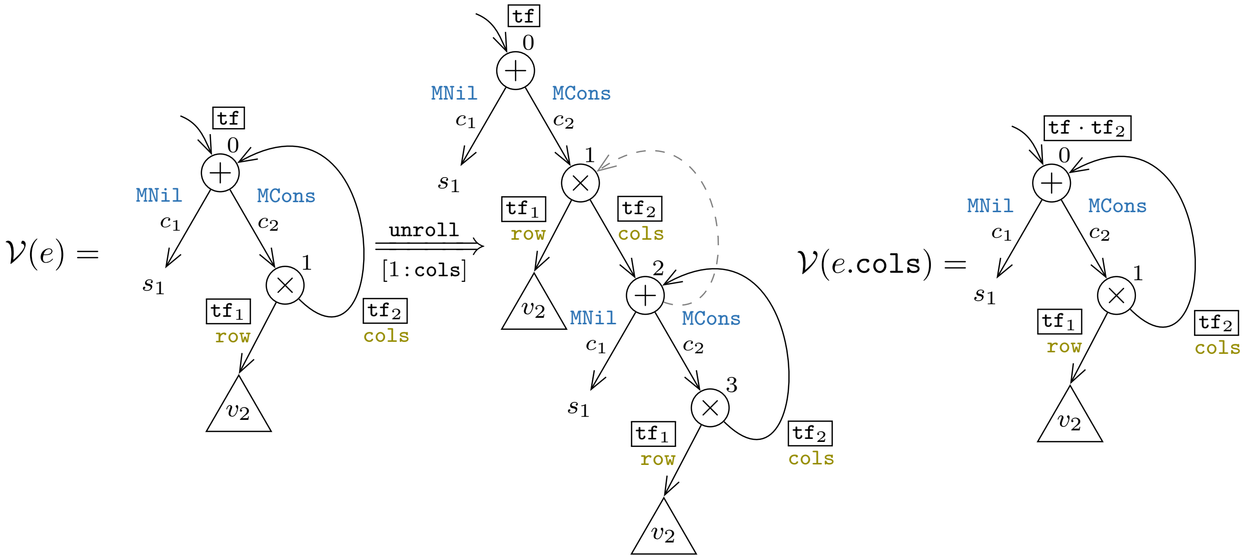


Figure 4.20: Construction of $\mathcal{V}(e.\texttt{cols})$ from $\mathcal{V}(e)$. Similar to type trees, $\texttt{unroll}$ $[1:\texttt{cols}]$ represents the operation of hoisting one iteration of the cycle 0→1→0.

Product-Access Operator

Given an expression $e' = e.\texttt{cols}$, fig. 4.20 depicts the construction of $\mathcal{V}(e')$ from $\mathcal{V}(e)$. Intuitively, $\mathcal{V}(e')$ represents the subtree of $\mathcal{V}(e)$ rooted at the $\oplus$ node reached by taking the edges $[0 : \texttt{MCons}; c_2]$ followed by $[1:\texttt{cols}; \texttt{tf}_2]$. However, this path may contain backedges or the subtree itself may contain backedges leaving the subtree. In such a case, we perform peeling until all such backedges strickly terminate within this subtree. For example, in fig. 4.20, the edge $[1:\texttt{cols}; \Omega_2]$ is a backedge and hence we peel it once. In the resulting (equivalent) value tree, the subtree (rooted at 2) contains a backedge leaving the subtree (dashed edge $[2:\texttt{MCons}]$) which requires one more peeling operation. The resulting value tree contains the subtree rooted at the $\oplus$ node 2 which satisfies the two conditions above and hence $\mathcal{V}(e')$ is simply constructed by extracting the subtree rooted at node 2. Note that we preserve the transfer functions from the entry to node 2 during extraction. $\texttt{tf}_1 \cdot \texttt{tf}_2$ represents the composition of the transfer functions $\texttt{tf}_1$ and $\texttt{tf}_2$ respectively.

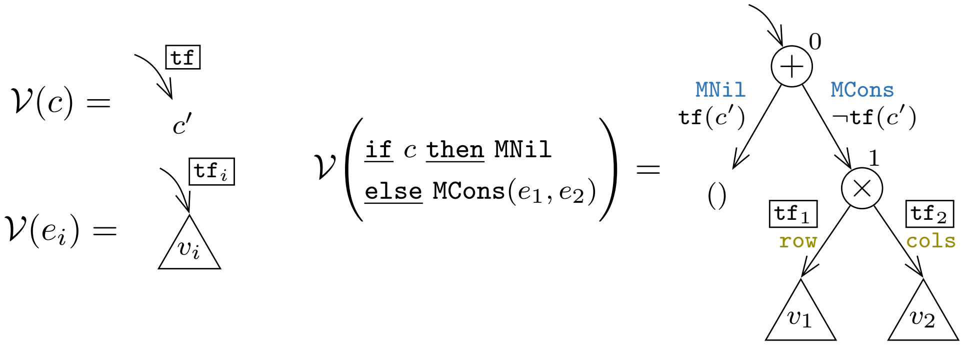

$\mathcal{V}(c) =$
tf
c'
$\mathcal{V}(e_i) =$
$\texttt{tf}_i$
v_i
$\mathcal{V}\left(\begin{array}{l}\underline{\texttt{if}}\ c\ \underline{\texttt{then}}\ \texttt{MNil}\\ \underline{\texttt{else}}\ \texttt{MCons}(e_1, e_2)\end{array}\right) =$
0
MNil
$\texttt{tf}(c')$
MCons
$\neg\texttt{tf}(c')$
()
1
$\texttt{tf}_1$
row
$\texttt{tf}_2$
cols
v_1
v_2

Figure 4.21: Construction of $\mathcal{V}(\ \underline{\texttt{if}}\ c\ \underline{\texttt{then}}\ \texttt{MNil}\ \underline{\texttt{else}}\ \texttt{MCons}(e_1, e_2)\ )$ from $\mathcal{V}(c)$, $\mathcal{V}(e_1)$ and $\mathcal{V}(e_2)$.

If-Then-Else Operator

Given an expression $e = \underline{\texttt{if}}\ c\ \underline{\texttt{then}}\ \texttt{MNil}\ \underline{\texttt{else}}\ \texttt{MCons}(e_1, e_2)$, fig. 4.21 describes the construction of $\mathcal{V}(e)$ using $\mathcal{V}(c)$, $\mathcal{V}(e_1)$ and $\mathcal{V}(e_2)$. Let us consider a general $\underline{\texttt{if}}$-$\underline{\texttt{then}}$-$\underline{\texttt{else}}$ expression e (associated with the ADT T with data constructors $V_1, V_2, \ldots, V_n$) such that the branch associated with V_i is given by $V_i(e_i^1, e_i^2, \ldots)$. We begin with the construction of a $\oplus$ root node (0 in fig. 4.21) such that the outgoing edge associated with V_i has the edge condition equal to the expression path condition of the branch $V_i(e_i^1, e_i^2, \ldots)$ ($\texttt{tf}(c')$ and $\neg\texttt{tf}(c')$ for MNil and MCons respectively in fig. 4.21). For each outgoing edge associated with the data constructor V_i, we construct a $\otimes$ node (1 for MCons in fig. 4.21) and append the value trees corresponding to the arguments e_i^j as its children.

Lifting Constructor

Given an expression $e = \texttt{Clist}^{\texttt{lnode}}_{\mathbb{m}}(p)$, fig. 4.22 shows the construction of $\mathcal{V}(e)$ from $\mathcal{V}(p)$. Recall the recursive definition of the lifting constructor $\texttt{Clist}^{\texttt{lnode}}_{\mathbb{m}}$ given in eq. (2.2). We start by assuming that $v^{\texttt{Clist}}_{\omega_1}$ is the value tree for the lifted expression $\texttt{Clist}^{\texttt{lnode}}_{\mathbb{m}}(\omega_1)$. Hence, the value tree of $\texttt{Clist}^{\texttt{lnode}}_{\mathbb{m}}(p)$ is identical to $v^{\texttt{Clist}}_{\omega_1}$ except we assign the actual argument (i.e. $\texttt{tf}(p')$) to the formal argument ω_1 along the entry edge. Next, we expand the subtree $v^{\texttt{Clist}}_{\omega_1}$ based on the

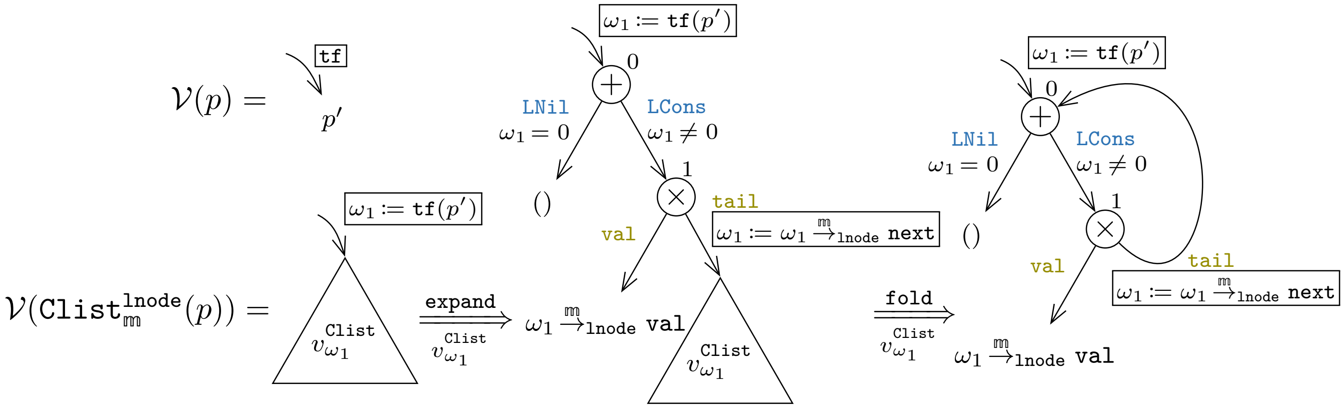

$\mathcal{V}(p) =$
tf
p'
$\mathcal{V}(\mathtt{Clist}^{\mathtt{lnode}}_{\mathbb{m}}(p)) =$
$\omega_1 := \mathtt{tf}(p')$
$v^{\mathtt{Clist}}_{\omega_1}$
expand
0
1
LNil
$\omega_1 = 0$
LCons
$\omega_1 \neq 0$
()
val
tail
$\omega_1 := \omega_1 \xrightarrow{\mathbb{m}}_{\mathtt{lnode}} \mathtt{next}$
$\omega_1 \xrightarrow{\mathbb{m}}_{\mathtt{lnode}} \mathtt{val}$
fold

Figure 4.22: Construction of $\mathcal{V}(\mathtt{Clist}^{\mathtt{lnode}}_{\mathbb{m}}(p))$ from $\mathcal{V}(p)$. The process involves assuming that $v^{\mathtt{Clist}}_{\omega_1}$ is the value tree of $\mathtt{Clist}^{\mathtt{lnode}}_{\mathbb{m}}(\omega_1)$, followed by expansion of $v^{\mathtt{Clist}}_{\omega_1}$ using the definition of $\mathtt{Clist}^{\mathtt{lnode}}_{\mathbb{m}}$ (in eq. (2.2)) and, finally folding the tree-edge $[1:\mathtt{tail}]$ incident on the self-referencial subtree $v^{\mathtt{Clist}}_{\omega_1}$ into a backedge.

unrolling procedure of $\mathtt{Clist}^{\mathtt{lnode}}_{\mathbb{m}}$ (defined in eq. (2.2)) until the entire value tree becomes a self-referencial structure. For example, after expanding through eq. (2.2) once in fig. 4.22, the value tree contains a tree-edge $[1:\mathtt{tail}]$ incident on the self-referencial subtree $v^{\mathtt{Clist}}_{\omega_1}$. In the last step, we fold all self-referencial tree-edges ($[1:\mathtt{tail}]$ in fig. 4.22) by converting them into backedges terminating at the root of the subtree being referenced (0 for $v^{\mathtt{Clist}}_{\omega_1}$ in fig. 4.22).

Variables

Finally, we are interested in constructing the value tree for a variable. Recall that, every ADT (pseudo-)variable is associated with an unrolling procedure characterized by the ADT itself, e.g., eq. (2.1) for the `List` variable l. The `Matrix` ADT is defined as $\mathtt{Matrix} = \mathtt{MNil} \mid \mathtt{MCons}(\mathtt{List}, \mathtt{Matrix})$, and thus the unrolling procedure for a `Matrix` variable m is given by:

$$m = \underline{\mathtt{if}}\ m \text{ is } \mathtt{MNil}\ \underline{\mathtt{then}}\ \mathtt{MNil}\ \underline{\mathtt{else}}\ \mathtt{MCons}(m.\mathtt{row}, m.\mathtt{cols}) \tag{4.3}$$

Figure 4.23 illustrates the construction $\mathcal{V}(m)$ for the `Matrix` variable m. The process consists of the same three steps used to construct the value tree for a lifted expression – assume, expand

and fold. First, we assume that $v^{\texttt{Mat}}_{\omega_1}$ and $v^{\texttt{Lis}}_{\omega_2}$ are the value trees corresponding to the pseudo-variables ω_1 and ω_2 of `Matrix` and `List` types respectively. Thus, $\mathcal{V}(m)$ is equal to $v^{\texttt{Mat}}_{\omega_1}$ except for $\texttt{tf}_\xi = \{\omega_1 \hookleftarrow m\}$. We expand the definitions of $v^{\texttt{Mat}}_{\omega_1}$ and $v^{\texttt{Lis}}_{\omega_2}$ once each before the value tree becomes self-referencial. Finally, we fold the tree-edges $[1\!:\!\texttt{cols}]$ and $[3\!:\!\texttt{tail}]$ into the backedges terminating at the roots of the subtrees representing $v^{\texttt{Mat}}_{\omega_1}$ and $v^{\texttt{Lis}}_{\omega_2}$ respectively (nodes 0 and 3 in fig. 4.23).

4.4.11 Applications of Value Trees

With the conversion algorithm out of the way, we next discuss a handful of properties of value trees along with their applications, in the context of our proof discharge algorithm. This allows us to formulate the value tree construction algorithms for approximate recursive relations.

Program Interpretation of Value Trees

A value tree $\mathcal{V}$ can be interpreted as a *non-deterministic* Control-Flow Graph corresponding to a program. Similar to the CFG representation, every node v is associated with a symbolic state Ω_n. In this interpretation, edges without an edge condition (e.g. outgoing at a $\otimes$ node) are assigned the `true` edge condition. Similarly, edges without a transfer function (e.g. outgoing at a $\oplus$ node) are assigned an identity transfer function. The entry node ξ is the start node and each leaf node ζ represents an exit node. An edge incident on a leaf node ζ (containing an expression e) is called an exit edge and is associated with an observable action that returns e.

Canonical Deconstruction Property

A path originating at the entry node ξ and terminating at an exit node ζ is called an *execution path* and is denoted by `ep`. Generalizing the edge syntax, $[v\!:\!\texttt{label}_1, \texttt{label}_2, \ldots, \texttt{label}_\texttt{n}]$ represents the path starting at v such that its n consecutive edges are associated with the labels $\texttt{label}_i \forall i \in [1, n]$. Hence, an execution path `ep` can be written as $\xi \rightarrow [v_0\!:\!\texttt{label}_1, \texttt{label}_2, \ldots, \texttt{label}_\texttt{n}]$, or

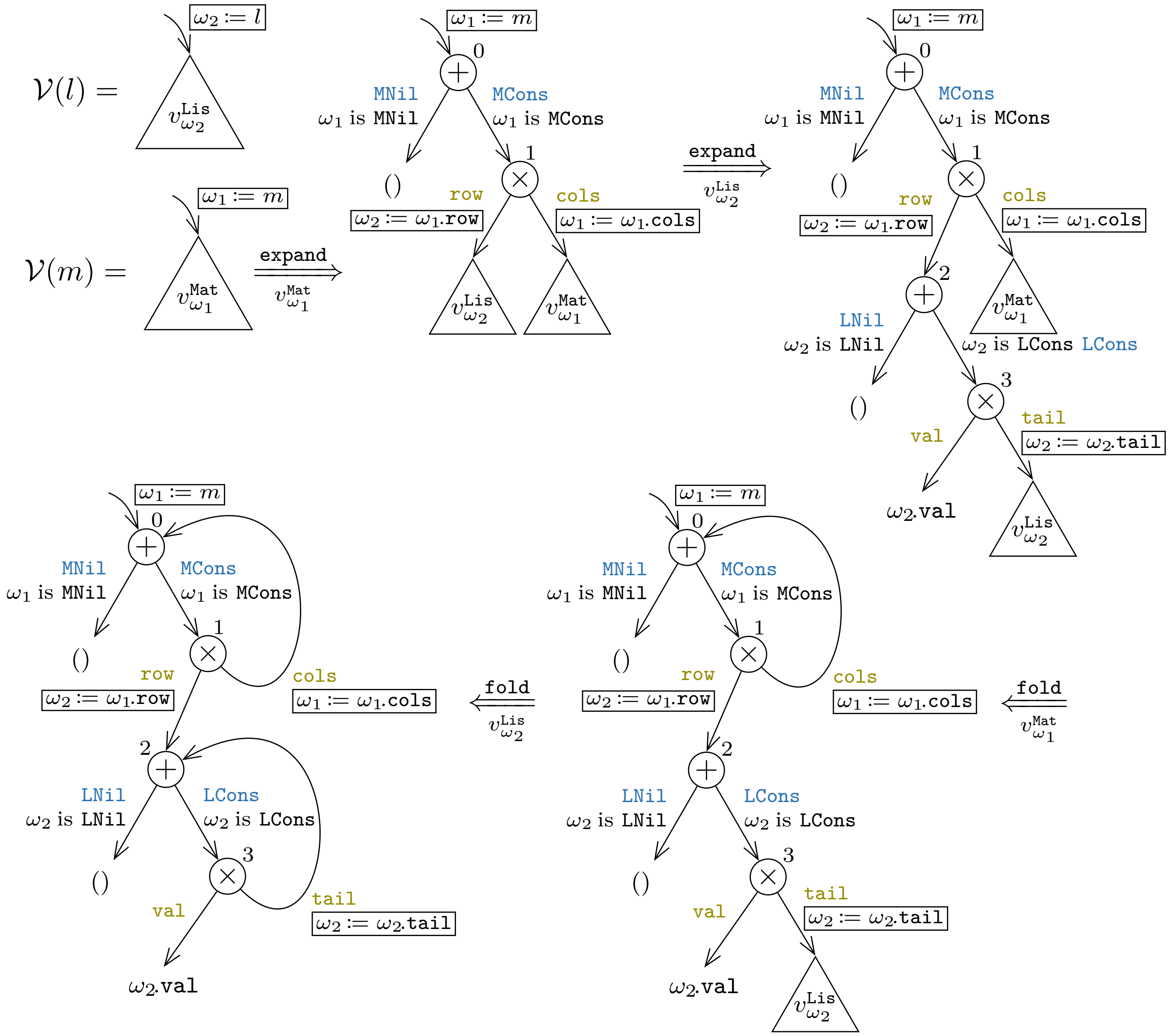
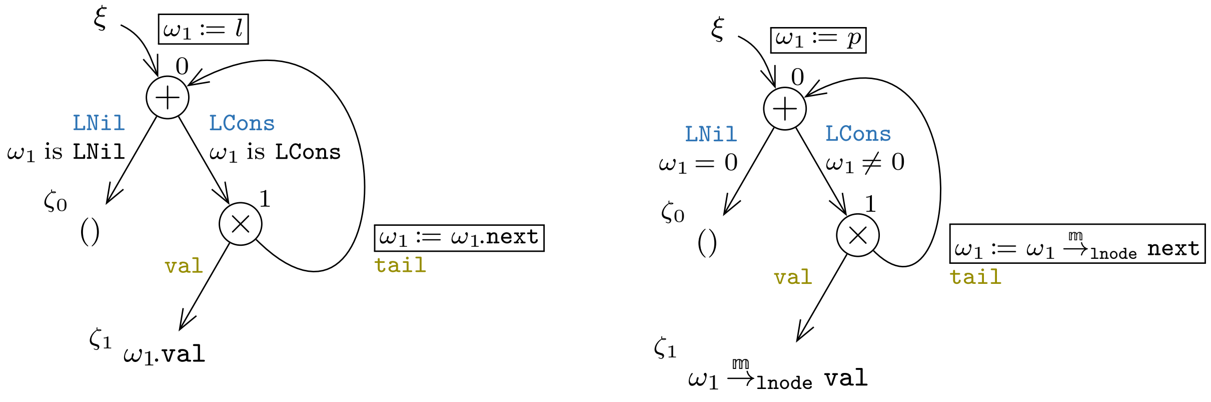

$\mathcal{V}(l) =$
$\omega_2 := l$
$v^{\texttt{Lis}}_{\omega_2}$
$\mathcal{V}(m) =$
$\omega_1 := m$
$v^{\texttt{Mat}}_{\omega_1}$
expand
$v^{\texttt{Mat}}_{\omega_1}$
0
MNil
ω_1 is MNil
MCons
ω_1 is MCons
1
()
row
$\omega_2 := \omega_1$.row
cols
$\omega_1 := \omega_1$.cols
$v^{\texttt{Lis}}_{\omega_2}$
expand
$v^{\texttt{Lis}}_{\omega_2}$
2
LNil
ω_2 is LNil
ω_2 is LCons LCons
3
val
tail
$\omega_2 := \omega_2$.tail
ω_2.val
fold
$v^{\texttt{Lis}}_{\omega_2}$
fold
$v^{\texttt{Mat}}_{\omega_1}$
LCons
ω_2 is LCons

Figure 4.23: Construction of $\mathcal{V}(m)$ for a `Matrix` variable m. The process is analogous to the construction of value trees for lifted expressions as shown in fig. 4.22. First, we assume that $v^{\texttt{Mat}}_{\omega_1}$ and $v^{\texttt{Lis}}_{\omega_2}$ represents the value trees of `Matrix` and `List`-typed pseudo-variables ω_1 and ω_2 respectively. Next, we expand both subtrees using the unrolling procedures in eqs. (2.1) and (4.3) until the value tree becomes self-referencial. Finally, we fold tree-edges incident on the self-referencial subtrees into backedges.



(a) $\mathcal{V}(l)$

(b) $\mathcal{V}(\texttt{Clist}^{\texttt{lnode}}_{\mathbb{m}}(p))$

Figure 4.24: Value trees for a `List` variable l and a lifted expression $\texttt{Clist}^{\texttt{lnode}}_{\mathbb{m}}(p)$ respectively.

$\texttt{ep}[\texttt{label}_1, \texttt{label}_2, \ldots, \texttt{label}_\texttt{n}]$ in short. Recall that, edges leaving a $\otimes$ node are associated with field names. The *field trace of* `ep`, `Ftrace(ep)` is defiend as the ordered list of field names associated with edges in the path `ep`. For an execution path $\texttt{ep}[\texttt{LCons}, \texttt{tail}, \texttt{LCons}, \texttt{val}]$ in the value tree shown in fig. 4.24a, `Ftrace(ep)` is given by $[\texttt{tail}, \texttt{val}]$. Given a value tree $\mathcal{V}(e)$ and an execution path `ep` with a field trace $[\texttt{a}_1, \texttt{a}_2, \ldots, \texttt{a}_\texttt{n}]$, $e.\texttt{a}_1.\texttt{a}_2 \ldots \texttt{a}_\texttt{n}$ is defined as the component of e with respect to `ep`, denoted by $\texttt{Comp}_\texttt{ep}(e)$. The *canonical deconstruction property* for a value tree ensures that:

1. The condition under which $\texttt{Comp}_\texttt{ep}(e)$ is accessible (i.e. is well-formed as discussed in section 2.2.1) is equal to the path condition of `ep`, denoted by `Pathcond(ep)`.

2. The value of $\texttt{Comp}_\texttt{ep}(e)$ is equal to the value returned by $\mathcal{V}(e)$ (interpreted as a program) along the execution path `ep`. This is equivalent to the weakest-precondition of the value returned along the path `ep` and is denoted by `Retval(ep)`.

3. Both `Pathcond(ep)` and `Retval(ep)` are in the canonical form (section 4.4.2).

Consider the value tree corresponding to the lifted expression $e = \texttt{Clist}^{\texttt{lnode}}_{\mathbb{m}}(p)$ as shown in fig. 4.24b. The execution path $\mathtt{ep}[\mathtt{LCons}, \mathtt{val}]$ corresponds to the component $\mathtt{Comp}_{\mathtt{ep}}(e) = \mathtt{Clist}_{\mathtt{m}}^{\mathtt{lnode}}(p).\mathtt{val}$. The path condition and the value returned along $\mathtt{ep}$ are given by $\mathtt{Pathcond}(\mathtt{ep}) = (p \neq 0)$ and $\mathtt{Retval}(\mathtt{ep}) = p \overset{\mathtt{m}}{\rightarrow}_{\mathtt{lnode}} \mathtt{val}$ respectively. Note that $\mathtt{Comp}_{\mathtt{ep}}(e)$ is well-formed iff $\mathtt{Pathcond}(\mathtt{ep})$ is true and $\mathtt{Comp}_{\mathtt{ep}}(e) = \mathtt{Retval}(\mathtt{ep})$. Furthermore, both are in canonical forms.

Reduction of Approximate Recursive Relations

Since an ADT represents a 'sum of product' type, each level of an ADT value (in its expression tree as shown in section 3.5.1) corresponds to two levels – $\oplus$ and $\otimes$ in the value tree representation. Combining the above observation with the value tree properties discussed above (section 4.4.11) allow us to reformulate approximate recursive relations between l_1 and l_2 as *bounded* equivalence [14] between $\mathcal{V}(l_1)$ and $\mathcal{V}(l_2)$. The d-depth over-approximation $l_1 \sim_d l_2$ asserts that $\mathcal{V}(l_1)$ and $\mathcal{V}(l_2)$ are equivalent for all execution paths up to a depth[3] of $2 \cdot d$. Clearly, this is a weaker condition because $\mathcal{V}(l_1)$ and $\mathcal{V}(l_2)$ may behave differently for longer execution paths. The d-depth under-approximation $l_1 \approx_d l_2$ asserts that $\mathcal{V}(l_1)$ and $\mathcal{V}(l_2)$ are equivalent for all execution paths up to a depth of $2 \cdot d$ and all other execution paths are unreachable. This is a stronger condition than general equivalence because paths deeper than $2 \cdot d$ may indeed be reachable. Let $\mathtt{EP}_\delta(l_1, l_2)$ be the set of all execution path pairs $\langle \mathtt{ep}_1, \mathtt{ep}_2 \rangle$ in l_1 and l_2, such that $\mathtt{Ftrace}(\mathtt{ep}_1) = \mathtt{Ftrace}(\mathtt{ep}_2)$ and depths of $\mathtt{ep}_1$ and $\mathtt{ep}_2$ are equal to δ. For example, consider the value trees shown in fig. 4.24 corresponding to the $\mathtt{List}$ values $e_1 = l$ and $e_2 = \mathtt{Clist}_{\mathtt{m}}^{\mathtt{clnode}}(p)$ respectively. Then, $\mathtt{EP}_0(e_1, e_2) = \emptyset$, $\mathtt{EP}_1(e_1, e_2) = \{\langle \xi \rightarrow 0 \rightarrow \zeta_0, \xi \rightarrow 0 \rightarrow \zeta_0 \rangle\}$ and $\mathtt{EP}_2(e_1, e_2) = \{\langle \xi \rightarrow 0 \rightarrow 1 \rightarrow \zeta_1, \xi \rightarrow 0 \rightarrow 1 \rightarrow \zeta_1 \rangle\}$. Finally, the d-depth approximations of $l_1 \sim l_2$ are given by:

[3] The depth of an execution path $\mathtt{ep}$ is defined as the depth of the exit node in the unrolled (executable) value tree. If $\mathtt{ep}$ contains n edges (including the entry edge), then its depth is equal to $(n - 1)$.

$$l_1 \sim_d l_2 = \sum_{\delta=0}^{2\cdot d} \left(\bigwedge_{\substack{\langle \mathtt{ep}_1,\mathtt{ep}_2\rangle \\ \in \mathtt{EP}_\delta(l_1,l_2)}} \begin{matrix} \mathtt{Pathcond}(\mathtt{ep}_1) = \mathtt{Pathcond}(\mathtt{ep}) \\ \mathtt{Retval}(\mathtt{ep}_1) = \mathtt{Retval}(\mathtt{ep}_2) \end{matrix} \right) \tag{4.4}$$

$$l_1 \approx_d l_2 = \sum_{\delta=0}^{2\cdot d} \left(\bigwedge_{\substack{\langle \mathtt{ep}_1,\mathtt{ep}_2\rangle \\ \in \mathtt{EP}_\delta(l_1,l_2)}} \begin{matrix} \mathtt{Pathcond}(\mathtt{ep}_1) = \mathtt{Pathcond}(\mathtt{ep}) \\ \mathtt{Retval}(\mathtt{ep}_1) = \mathtt{Retval}(\mathtt{ep}_2) \end{matrix} \right) \wedge \left(\bigwedge_{\substack{\langle \mathtt{ep}_1,\mathtt{ep}_2\rangle \\ \in \mathtt{EP}_{2\cdot d+1}(l_1,l_2)}} \begin{matrix} \neg\mathtt{Pathcond}(\mathtt{ep}_1) \\ \neg\mathtt{Pathcond}(\mathtt{ep}_2) \end{matrix} \right) \tag{4.5}$$

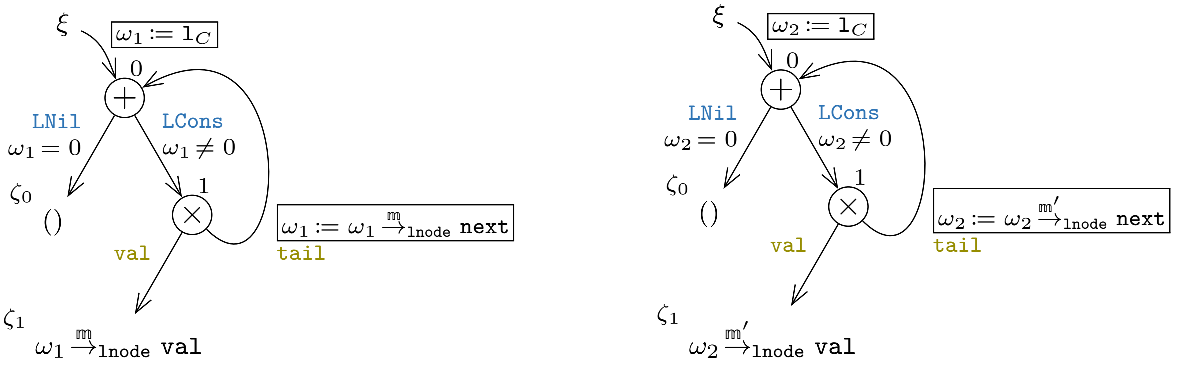
Recall that the canonical deconstruction property ensures that the reductions in eqs. (4.4) and (4.5) are in the canonical form. Thus, the value trees corresponding to $l_1 \sim_d l_2$ and $l_1 \approx_d l_2$ are constructed by creating a single (leaf) node with the boolean expressions given in eqs. (4.4) and (4.5) respectively. The conversion algorithm presented in section 4.4.10 together with the handling of approximate recursive relations described above enables the reduction of a proof obligation P without recursive relations directly to its canonical form by – (a) constructing $\mathcal{V}(P)$ and (b) extracting the boolean expression at its root.

Bisimilarity of Value Trees

Unlike its approximations, a recursive relation $l_1 \sim l_2$ asserts general equivalence between $\mathcal{V}(l_1)$ and $\mathcal{V}(l_2)$ respectively. Similar to our top-level equivalence check between $\mathcal{S}$ and $\mathcal{C}$, we attempt to prove that $\mathcal{V}(l_1)$ and $\mathcal{V}(l_2)$ are bisimilar. To make the search for a bisimulation relation easier, we peel $\mathcal{V}(l_1)$ and $\mathcal{V}(l_2)$ to unify their static structures. Once unified, the bisimulation relation requires the inference of inductive invariants at correlated nodes such that under the precondition at $(\xi : \xi)$, inductive invariants hold and both $\mathcal{V}(l_1)$ and $\mathcal{V}(l_2)$ have equal observables at correlated exit nodes $(\zeta_i : \zeta_i)$.

Recall the type III proof obligation illustrated in section 3.6:

$$\begin{aligned} (\mathtt{i}_S = \mathtt{i}_C) \wedge \mathtt{p}_C = \mathtt{malloc}() \wedge \mathtt{l}_S \sim \mathtt{Clist}^{\mathtt{lnode}}_{\mathfrak{m}}(\mathtt{l}_C) \wedge (\mathtt{p}_C \neq 0) \\ \Rightarrow \mathtt{Clist}^{\mathtt{lnode}}_{\mathfrak{m}}(\mathtt{l}_C) \sim \mathtt{Clist}^{\mathtt{lnode}}_{\mathfrak{m}'}(\mathtt{l}_C) \end{aligned} \tag{4.6}$$



(a) $\mathcal{V}(\texttt{Clist}^{\texttt{lnode}}_{\mathfrak{m}}(\texttt{l}_C))$ **(b)** $\mathcal{V}(\texttt{Clist}^{\texttt{lnode}}_{\mathfrak{m}'}(\texttt{l}_C))$

Node Pair	Invariants		
$(\xi : \xi)$	(P) LHS in eq. (4.6)		
$(0:0)$ $(1:1)$	(I1) $\omega_1 = \omega_2$	(I2) $\omega_1 \rightsquigarrow \{\texttt{C4}_{2+}, \mathcal{H}\}$	(I3) $\omega_2 \rightsquigarrow \{\texttt{C4}_{2+}, \mathcal{H}\}$
	(I4) $\texttt{p}_C \rightsquigarrow \{\texttt{C4}_{2+}\}$	(I5) $\texttt{l}_C \rightsquigarrow \{\texttt{C4}_{2+}\}$	
	(I6) $\texttt{C4}_1 \rightsquigarrow \{\texttt{C4}_{2+}\}$	(I7) $\texttt{C4}_{2+} \rightsquigarrow \{\texttt{C4}_{2+}, \mathcal{H}\}$	(I8) $\mathcal{H} \rightsquigarrow \{\texttt{C4}_{2+}, \mathcal{H}\}$
$(\zeta_0 : \zeta_0)$	(E1) $() = ()$		
$(\zeta_1 : \zeta_1)$	(E2) $\omega_1 \overset{\mathfrak{m}}{\rightarrow}_{\texttt{lnode}} \texttt{val} = \omega_2 \overset{\mathfrak{m}'}{\rightarrow}_{\texttt{lnode}} \texttt{val}$		

(c) Invariants table for bisimulation relation between fig. 4.25a and fig. 4.25b.

Figure 4.25: Value trees of $\texttt{Clist}^{\texttt{lnode}}_{\mathfrak{m}}(\texttt{l}_C)$ and $\texttt{Clist}^{\texttt{lnode}}_{\mathfrak{m}'}(\texttt{l}_C)$ along with their associated node invariants at correlated node pairs.

The memory $\mathfrak{m}'$ is defined as:

$$\mathfrak{m}' \Leftrightarrow \mathfrak{m}[\texttt{addrof}(\texttt{p}_\texttt{C} \rightarrow_{\texttt{lnode}} \texttt{val}) \leftarrow \texttt{i}_C]_{\texttt{i32}}[\texttt{addrof}(\texttt{p}_\texttt{C} \rightarrow_{\texttt{lnode}} \texttt{next}) \leftarrow \texttt{l}_C]_{\texttt{i32}}$$

The points-to invariants available at C5 (in fig. 3.2b) are discussed in Section 3.6.5. The relevant ones for a successful bisimulation are as follows: $\texttt{p}_C \rightsquigarrow \{\texttt{C4}_1\}$ $\texttt{l}_C \rightsquigarrow \{\texttt{C4}_{2+}\}$, $\texttt{C4}_1 \rightsquigarrow \{\texttt{C4}_{2+}\}$, $\texttt{C4}_{2+} \rightsquigarrow \{\texttt{C4}_{2+}, \mathcal{H}\}$, and $\mathcal{H} \rightsquigarrow \{\texttt{C4}_{2+}, \mathcal{H}\}$. Similar to a deconstruction program, we run our points-to analysis on the value trees to identify potentially beneficial points-to invariants at all correlated nodes. Figure 4.25 shows the value trees of $\texttt{Clist}_{\mathbb{m}}^{\texttt{lnode}}(\texttt{l}_C)$ and $\texttt{Clist}_{\mathbb{m}'}^{\texttt{lnode}}(\texttt{l}_C)$ along with the table of invariants required for a successful bisimulation check. Unlike deconstruction programs, value trees do not contain procedure calls and instead represent values of arbitrary depth using cycles.

Chapter 5

Evaluation

We have implemented S2C on top of the Counter tool [27]. We use *four* SMT solvers running in parallel for solving SMT proof obligations discharged by our proof discharge algorithm: `z3-4.8.7`, `z3-4.8.14` [22], `Yices2-45e38fc` [23], and `cvc4-1.7` [1]. An unroll factor of *four* is used to handle loop unrolling in the C implementation. We use a default value of *eight* for over- and under-approximation depths (d_o and d_u). The default values for unrolling parameter k (used for categorization of proof obligations) and η (used by `strongestInvCover()` during weakening of recursive relation invariants) are *five*.

S2C requires the user to provide a Spec program S (specification), a C implementation C, and a file that contains their input-output specifications. For each function pair, S2C attempts to find equivalence between their CFGs $\mathcal{S}$ and $\mathcal{C}$ under their respective *Pre* and *Post* (given as part of input-output specification). An equivalence check requires the identification of lifting constructors to relate $\mathcal{C}$ values to the ADT values in $\mathcal{S}$ through recursive relations. Such relations may be required at the entry of both programs (i.e. in the precondition *Pre*), in the middle of both programs (i.e. as invariants at intermediate product-CFG nodes), and at the exit of both programs (i.e. in the postcondition *Post*). *Pre* and *Post* are user-specified, whereas the inductive invariants are inferred automatically by our algorithm. During invariant inference, S2C derives the candidate lifting constructors from the user-specified *Pre* and *Post*. More sophisticated approaches to finding lifting constructors are left as future work.

Table 5.1: String lifting constructors and their definitions

Lifting Constructor	**Definition**
$\boxed{\text{T1}}$ `Str = SInvalid | SNil | SCons(ch:i8, tail:Str)` `OptStr = NotFound | Found(str:Str)`	
$\mathtt{Cstr}^{\mathtt{u8[]}}_{\mathbb{m}}(p\,{:}\,\mathtt{i32})$	$\underline{\mathtt{if}}\ p = 0_{\mathtt{i32}}\ \ \underline{\mathtt{then}}\ \mathtt{SInvalid}$ $\underline{\mathtt{elif}}\ p[0_{\mathtt{i32}}]^{\mathtt{i8}}_{\mathbb{m}} = 0_{\mathtt{i8}}\ \ \underline{\mathtt{then}}\ \mathtt{SNil}$ $\underline{\mathtt{else}}\ \mathtt{SCons}(p[0_{\mathtt{i32}}]^{\mathtt{i8}}_{\mathbb{m}}, \mathtt{Cstr}^{\mathtt{u8[]}}_{\mathbb{m}}(p + 1_{\mathtt{i32}}))$
$\mathtt{Coptstr}^{\mathtt{u8[]}}_{\mathbb{m}}(p\,{:}\,\mathtt{i32})$	$\underline{\mathtt{if}}\ p = 0_{\mathtt{i32}}\ \ \underline{\mathtt{then}}\ \mathtt{NotFound}\ \underline{\mathtt{else}}\ \mathtt{Found}(\mathtt{Cstr}^{\mathtt{u8[]}}_{\mathbb{m}}(p))$
$\mathtt{Cstr}^{\mathtt{lnode(u8)}}_{\mathbb{m}}(p\,{:}\,\mathtt{i32})$	$\underline{\mathtt{if}}\ p = 0_{\mathtt{i32}}\ \ \underline{\mathtt{then}}\ \mathtt{SInvalid}$ $\underline{\mathtt{elif}}\ p \overset{\mathbb{m}}{\rightarrow}_{\mathtt{lnode}} \mathtt{val} = 0_{\mathtt{i8}}\ \ \underline{\mathtt{then}}\ \mathtt{SNil}$ $\underline{\mathtt{else}}\ \mathtt{SCons}(p \overset{\mathbb{m}}{\rightarrow}_{\mathtt{lnode}} \mathtt{val}, \mathtt{Cstr}^{\mathtt{lnode(u8)}}_{\mathbb{m}}(p \overset{\mathbb{m}}{\rightarrow}_{\mathtt{lnode}} \mathtt{next}))$
$\mathtt{Coptstr}^{\mathtt{lnode(u8)}}_{\mathbb{m}}(p\,{:}\,\mathtt{i32})$	$\underline{\mathtt{if}}\ p = 0_{\mathtt{i32}}\ \ \underline{\mathtt{then}}\ \mathtt{NotFound}\ \underline{\mathtt{else}}\ \mathtt{Found}(\mathtt{Cstr}^{\mathtt{lnode(u8)}}_{\mathbb{m}}(p))$
$\mathtt{Cstr}^{\mathtt{clnode(u8)}}_{\mathbb{m}}(p\,{:}\,\mathtt{i32}, i\,{:}\,\mathtt{i2})$	$\underline{\mathtt{if}}\ p = 0_{\mathtt{i32}}\ \ \underline{\mathtt{then}}\ \mathtt{SInvalid}$ $\underline{\mathtt{elif}}\ p \overset{\mathbb{m}}{\rightarrow}_{\mathtt{lnode}} \mathtt{chunk}[i]^{\mathtt{i8}}_{\mathbb{m}} = 0_{\mathtt{i8}}\ \ \underline{\mathtt{then}}\ \mathtt{SNil}$ $\underline{\mathtt{else}}\ \mathtt{SCons}(p \overset{\mathbb{m}}{\rightarrow}_{\mathtt{lnode}} \mathtt{chunk}[i]^{\mathtt{i8}}_{\mathbb{m}}, \mathtt{Cstr}^{\mathtt{clnode(u8)}}_{\mathbb{m}}(i = 3_{\mathtt{i2}} ? p \overset{\mathbb{m}}{\rightarrow}_{\mathtt{clnode}} \mathtt{next} : p, i + 1_{\mathtt{i2}}))$
$\mathtt{Coptstr}^{\mathtt{clnode(u8)}}_{\mathbb{m}}(p\,{:}\,\mathtt{i32}, i\,{:}\,\mathtt{i2})$	$\underline{\mathtt{if}}\ p = 0_{\mathtt{i32}}\ \ \underline{\mathtt{then}}\ \mathtt{NotFound}\ \underline{\mathtt{else}}\ \mathtt{Found}(\mathtt{Cstr}^{\mathtt{clnode(u8)}}_{\mathbb{m}}(p, i))$

5.1 Experiments

We consider programs involving four distinct ADTs, namely, $\boxed{\text{T1}}$ `Str`, $\boxed{\text{T2}}$ `List`,, $\boxed{\text{T3}}$ `Tree`, and $\boxed{\text{T4}}$ `Matrix`. For each Spec program specification, we consider multiple C implementations that differ in their (a) memory layout of ADTs, and (b) algorithmic strategies. For example, a `Matrix` in C may be laid out in a two-dimensional array, a one-dimensional array using row or column major layouts etc. On the other hand, an optimized implementation may choose manual vectorization of an inner-most loop. Next, we consider each ADT in more detail. For each, we discuss (a) its corresponding programs, (b) C memory layouts and their lifting constructors, and (c) varying algorithmic strategies.

5.1.1 String

We wrote a single specification in Spec for each of the following common string library functions: `strlen`, `strchr`, `strcmp`, `strspn`, `strcspn`, and `strpbrk`. For each specification program, we took multiple C implementations of that program, drawn from popular libraries like `glibc` [3], `klibc` [4], `newlib` [7], `openbsd` [8], `uClibc` [9], `dietlibc` [2], `musl` [5], and `netbsd` [6]. These library implementations use a nul-terminated array to represent a string, and the corresponding lifting constructor is $\texttt{Cstr}^{\texttt{u8[]}}_{\mathbb{m}}$. `u<N>` represents the N-bit unsigned integer type in C. For example, `u8` represents `unsigned char` type.

Further, we implemented custom C programs for these functions that uses linked list and *chunked linked list* data structures to represent a string. In a chunked linked list, a single list node (linked through a `next` pointer) contains a small array (chunk) of values. We use a default chunk size of four for our benchmarks. The corresponding lifting constructors are $\texttt{Cstr}^{\texttt{lnode(u8)}}_{\mathbb{m}}$ and $\texttt{Cstr}^{\texttt{clnode(u8)}}_{\mathbb{m}}$ respectively. These lifting constructors are defined in table 5.1. $\texttt{Cstr}^{\texttt{lnode(u8)}}_{\mathbb{m}}$ requires a single argument p representing the pointer to the list node. On the other hand, $\texttt{Cstr}^{\texttt{clnode(u8)}}_{\mathbb{m}}$ requires two arguments p and i, where p represents the pointer to the chunked linked list node and i represents the position of the initial character in the chunk.

An Example : strchr

Additionally, we define an optional string type `OptStr` to specify behaviour of functions that conditionally return a string (e.g. `strchr`, `strpbrk`). The `OptStr` ADT along with three (pairs of) lifting constructors for the three layouts of the `Str` ADT are shown in table 5.1. `strchr` accepts a string t and a character c[1] and returns the longest suffix of t that begins with c, otherwise it returns the null pointer to indicate failure to find c in the string t. In case c is the null character (i.e. nul), `strchr` is defined to return the empty string (instead of the null pointer). Figures 5.1a and 5.1b show the IRs of the `strchr` specification and a generic C implementation respectively. We demonstrate two important aspects of S2C using this example – (a) use of ($\mathcal{S}$ `def`) and *Pre* to constrain the C implementation to only well-formed inputs (in section 2.3.1), and (b) need for correlating pathsets (instead of paths) (in section 4.2.1).

Recall that a nul-terminated C string is only well-formed if the string itself does not belong to a region of memory containing the null pointer. This well-formedness condition is necessary to

[1] Due to historical reasons, the type of c is declared as `int` to maintain backward compatibility with pre C-98 code. However, the function is specified to cast it to a character and use it instead.

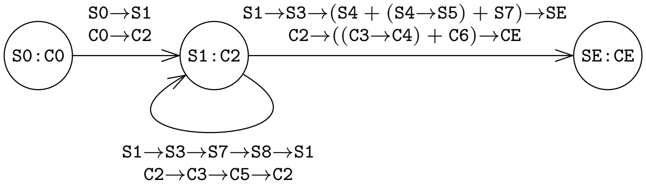
```
S0: OptStr strchr (Str s, i8 c) {
S1:   while true:
S2:     assume ¬(s is SInvalid);
S3:     if s is SNil:
S4:       if c = 0i8: return Found(s);
S5:       return NotFound();
S6:     i8 ch := s.ch; // (s is SCons)
S7:     if c = ch: return Found(s);
S8:     s := s.tail;
SE: }
```

(a) Strchr specification

```
    char* strchr(char* t, int c);

C0: i32 strchr (i32 t, i32 c) {
C1:   i8 ch := c[7:0];
C2:   while t[0i32]i8m ≠ ch:
C3:     if t[0i32]i8m = 0i8:
C4:       return 0i32;
C5:     t := t + 1i32
C6:   return t;
CE: }
```

(b) Strchr implementation



(c) Product-CFG for programs figs. 5.1a and 5.1b

PC-Pair	Invariants
(S0:C0)	(P1) $\mathtt{s}_S \sim \mathtt{Cstr}^{\mathtt{u8[]}}_{\mathbb{m}}(\mathtt{t}_C)$ (P2) $\mathtt{c}_S = \mathtt{c}_C[7:0]$
(S1:C2)	(I1) $\mathtt{s}_S \sim \mathtt{Cstr}^{\mathtt{u8[]}}_{\mathbb{m}}(\mathtt{t}_C)$ (I2) $\mathtt{c}_S = \mathtt{ch}_C$
(SE:CE)	(E) $\mathtt{ret}_S \sim \mathtt{Coptstr}^{\mathtt{u8[]}}_{\mathbb{m}}(\mathtt{ret}_C)$

(d) Node invariants for product-CFG in fig. 5.1c

Figure 5.1: Figures 5.1a and 5.1b show the (abstracted) IRs for the Spec specification and a generic nul-terminated array based C implementation of `strchr`. Figure 5.1c shows the product-CFG representing a bisimulation relation between figs. 5.1a and 5.1b. The node invariants for the product-CFG in fig. 5.1c are given in fig. 5.1d.

prove that the pointer to the string returned at `C6` (in fig. 5.1b) is non-null (used uniquely to indicate a failure to find the character c in the string t). As previously discussed in section 2.3, we expose this well-formedness condition in the specification using the explicit `Str` data constructor `SInvalid`. Finally, we assert that $\mathtt{s}_S$ in fig. 5.1a is well-formed using the `assuming-do` statement (`S3` in fig. 5.1a) and relate the non-null well-formedness condition of the C input string $\mathtt{t}_C$ with the condition of $\mathtt{s}_S$ being `SInvalid` using *Pre* (labeled (P1) in fig. 5.1d). Note the use of $\mathtt{Coptstr}^{\mathtt{u8[]}}_{\mathbb{m}}$ in the postcondition (labeled (E) in fig. 5.1d).

Figure 5.1c shows the product-CFG showing the path correlations between $\mathcal{S}$ and $\mathcal{C}$. Consider the product-CFG edge $(\texttt{S1}:\texttt{C2}) \to (\texttt{SE}:\texttt{CE})$ correlating the pathsets: $\texttt{S1}\to\texttt{S3}\to(\texttt{S4} + (\texttt{S4}\to\texttt{S5}) + \texttt{S7})\to\texttt{SE}$ (in $\mathcal{S}$) and $\texttt{C2}\to((\texttt{C3}\to\texttt{C4}) + \texttt{C6})\to\texttt{CE}$ (in $\mathcal{C}$). The $\to$ and $+$ operators are used to represent 'series' and 'parallel' path combinations. The above two pathsets represent the following two sets $\{\texttt{S1}\to\texttt{S3}\to\texttt{S4}\to\texttt{SE},\ \texttt{S1}\to\texttt{S3}\to\texttt{S4}\to\texttt{S5}\to\texttt{SE},\ \texttt{S1}\to\texttt{S3}\to\texttt{S7}\to\texttt{SE}\}$ and $\{\texttt{C2}\to\texttt{C3}\to\texttt{C4}\to\texttt{CE},\ \texttt{C2}\to\texttt{C6}\to\texttt{CE}\}$ respectively. In $\mathcal{S}$, the case of $\texttt{c}_{\mathcal{S}}$ being nul is handled explicitly at S4, whereas S7 handles the case of $\texttt{s}_{\mathcal{S}}$ containing the (non-nul) character $\texttt{c}_{\mathcal{S}}$. Interestingly in $\mathcal{C}$, both these cases are taken care of by the singular exit edge outgoing at C6. This is an example where a path in $\mathcal{C}$ (i.e. $\texttt{C2}\to\texttt{C6}\to\texttt{CE}$) is simultaneously active with two paths in $\mathcal{S}$ (i.e. $\texttt{S1}\to\texttt{S3}\to\texttt{S4}\to\texttt{SE}$ and $\texttt{S1}\to\texttt{S3}\to\texttt{S7}\to\texttt{SE}$). Evidently, for a successful bisimulation proof, we are required to correlate the $\mathcal{C}$ path $\texttt{C2}\to\texttt{C6}\to\texttt{CE}$ with the $\mathcal{S}$ pathset $\{\texttt{S1}\to\texttt{S3}\to\texttt{S4}\to\texttt{SE}, \texttt{S1}\to\texttt{S3}\to\texttt{S7}\to\texttt{SE}\}$. Such situations are rather frequent because the strongly-typed specification is forced to handle each case explicitly while a C implementation may take advantage of the underlying representation to generalize multiple explicit cases into one.

Another Example : strlen

Figure 5.2 shows the strlen specification and two vastly different C implementations. Figure 5.2b is a generic implementation using a C-style nul-terminated array to represent a string. The second implementation in fig. 5.2c differs from fig. 5.2b in the following: (a) it uses a chunked linked list data layout for the input string and (b) it uses specialized bit manipulations to identify whether a (4 byte) chunk contains the nul character simultaneously. S2C is able to automatically find a bisimulation relation for both implementations against the unaltered specification. Figure 5.3 shows the product-CFG and its associated node invariants for each implementation.

Lifting constructors are named based on the C data layout being lifted and the type of the lifted value. For example, $\texttt{Cstr}^{\texttt{u8[]}}$ represents a Str lifting constructor for an array layout. In general, we use the following naming convention for different C data layouts: T[] represents an array of type T (e.g., u8[]). lnode(T) represents a linked list node type containing a value of type T. Similarly, clnode(T) and tnode(T) represent a chunked linked list and a tree node with values of type T respectively.

```
S0: i32 strlen (Str s) {
S1:   i32 len := $0_{i32}$;
S2:   while ¬(s is SNil):
S3:     assume ¬(s is SInvalid);
S4:     // (s is SCons)
S5:     s   := s.tail;
S6:     len := len + $1_{i32}$;
S7:   return len;
SE: }
```

(a) Strlen specification

```
    size_t strlen(char* s);

C0: i32 strlen (i32 s) {
C1:   i32 i := $0_{i32}$;
C2:   while $s[0_{i32}]^{i8}_{\mathfrak{m}} \neq 0_{i8}$:
C3:     s := s + $1_{i32}$;
C4:     i := i + $1_{i32}$;
C5:   return i;
CE: }
```

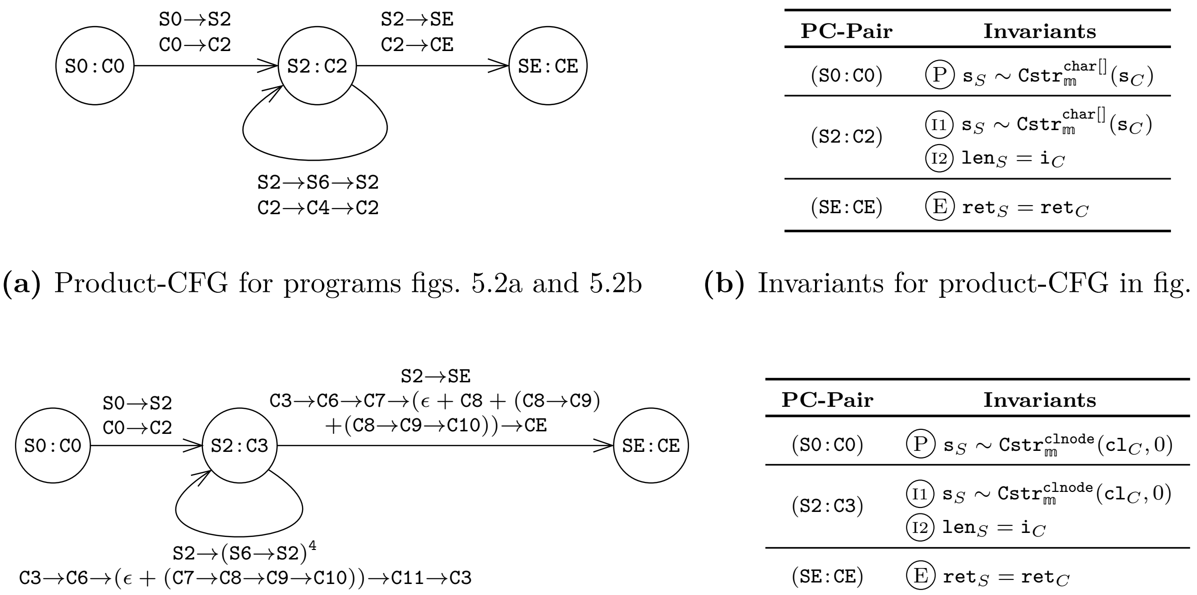
(b) Generic strlen implementation using array

```
     typedef struct clnode {
       char chunk[4]; struct clnode* next; } clnode;
     size_t strlen(clnode* cl);

C0 : i32 strlen (i32 cl) {
C1 :   i32 hi := $0x80808080_{i32}$; i32 lo := $0x01010101_{i32}$;
C2 :   i32 i  := $0_{i32}$;
C3 :   while true:
C4 :     i32 dword_ptr := addrof(cl $\xrightarrow{\mathfrak{m}}_{clnode}$ chunk);
C5 :     i32 dword     := $dword\_ptr[0_{i32}]^{i32}_{\mathfrak{m}}$;
C6 :     if $((dword - lo)\ \&\ (\sim dword)\ \&\ hi) \neq 0_{i32}$:
C7 :       if $dword\_ptr[0_{i32}]^{i8}_{\mathfrak{m}} = 0_{i8}$: return i;
C8 :       if $dword\_ptr[1_{i32}]^{i8}_{\mathfrak{m}} = 0_{i8}$: return $i + 1_{i32}$;
C9 :       if $dword\_ptr[2_{i32}]^{i8}_{\mathfrak{m}} = 0_{i8}$: return $i + 2_{i32}$;
C10:       if $dword\_ptr[3_{i32}]^{i8}_{\mathfrak{m}} = 0_{i8}$: return $i + 3_{i32}$;
C11:     cl := cl $\xrightarrow{\mathfrak{m}}_{clnode}$ next; i  := $i + 4_{i32}$;
CE : }
```

(c) Optimized strlen implementation using chunked linked list

Figure 5.2: Figure 5.2a shows the (abstracted) IR for the Spec specification of `strlen`. Figures 5.2b and 5.2c show the (abstracted) IRs for two C implementations of `strlen`. Figure 5.2b is a generic implementation using a nul-terminated array to represent a string, whereas fig. 5.2c is an optimized implementation with a chunked linked list memory layout for a string.



(a) Product-CFG for programs figs. 5.2a and 5.2b

PC-Pair	Invariants
(S0:C0)	$\textcircled{P}$ $\mathtt{s}_S \sim \mathtt{Cstr}^{\mathtt{char[]}}_{\mathbb{m}}(\mathtt{s}_C)$
(S2:C2)	$\textcircled{I1}$ $\mathtt{s}_S \sim \mathtt{Cstr}^{\mathtt{char[]}}_{\mathbb{m}}(\mathtt{s}_C)$ $\textcircled{I2}$ $\mathtt{len}_S = \mathtt{i}_C$
(SE:CE)	$\textcircled{E}$ $\mathtt{ret}_S = \mathtt{ret}_C$

(b) Invariants for product-CFG in fig. 5.3a

(c) Product-CFG for programs figs. 5.2a and 5.2c

PC-Pair	Invariants
(S0:C0)	$\textcircled{P}$ $\mathtt{s}_S \sim \mathtt{Cstr}^{\mathtt{clnode}}_{\mathbb{m}}(\mathtt{cl}_C, 0)$
(S2:C3)	$\textcircled{I1}$ $\mathtt{s}_S \sim \mathtt{Cstr}^{\mathtt{clnode}}_{\mathbb{m}}(\mathtt{cl}_C, 0)$ $\textcircled{I2}$ $\mathtt{len}_S = \mathtt{i}_C$
(SE:CE)	$\textcircled{E}$ $\mathtt{ret}_S = \mathtt{ret}_C$

(d) Invariants for product-CFG in fig. 5.3c

Figure 5.3: Product-CFGs and their node invariants representing bisimulation relations between the specification fig. 5.2a and its two implementations in figs. 5.2b and 5.2c respectively.

5.1.2 List

We wrote a Spec program specification that creates a list, a program that traverses a list to compute the sum of its elements and a program that computes the dot product of two lists. We use three different data layouts for a list in C: array ($\mathtt{Clist}^{\mathtt{u32[]}}_{\mathbb{m}}$), linked list ($\mathtt{Clist}^{\mathtt{lnode(u32)}}_{\mathbb{m}}$), and a chunked linked list ($\mathtt{Clist}^{\mathtt{clnode(u32)}}_{\mathbb{m}}$). The lifting constructors are shown in table 5.2. Although similar to the string lifting constructors, these lifting constructors differ widely in their data encoding. For example, $\mathtt{Clist}^{\mathtt{u32[]}}_{\mathbb{m}}(p, i, n)$ represents a `List` value constructed from a C array of size n, pointed to by p and starting at the i^{th} index. The list becomes empty when we are at the end of the array. $\mathtt{Clist}^{\mathtt{lnode(u32)}}_{\mathbb{m}}$ and $\mathtt{Clist}^{\mathtt{clnode(u32)}}_{\mathbb{m}}$, on the other hand, encodes the empty list (i.e. `LNil`) using the null pointer. These layouts are in contrast to the `Str` layouts, all of which uses the nul character to indicate the empty string.

Table 5.2: List lifting constructors and their definitions

Lifting Constructor	Definition
(T2) `List = LNil | LCons(val:i32, tail:List)`	
$\texttt{Clist}_{\mathbb{m}}^{\texttt{u32[]}}(p\ i\ n : \texttt{i32})$	$\underline{\texttt{if}}\ i \geq_u n\ \ \underline{\texttt{then}}\ \texttt{LNil}$ $\underline{\texttt{else}}\ \texttt{LCons}(p[i]_{\mathbb{m}}^{\texttt{i32}}, \texttt{Clist}_{\mathbb{m}}^{\texttt{u32[]}}(p, i + 1_{\texttt{i32}}, n))$
$\texttt{Clist}_{\mathbb{m}}^{\texttt{lnode(u32)}}(p : \texttt{i32})$	$\underline{\texttt{if}}\ p = 0_{\texttt{i32}}\ \ \underline{\texttt{then}}\ \texttt{LNil}$ $\underline{\texttt{else}}\ \texttt{LCons}(p \overset{\mathbb{m}}{\rightarrow}_{\texttt{lnode}} \texttt{val}, \texttt{Clist}_{\mathbb{m}}^{\texttt{lnode}}(p \overset{\mathbb{m}}{\rightarrow}_{\texttt{lnode}} \texttt{next}))$
$\texttt{Clist}_{\mathbb{m}}^{\texttt{clnode(u32)}}(p : \texttt{i32}, i : \texttt{i2})$	$\underline{\texttt{if}}\ p = 0_{\texttt{i32}}\ \ \underline{\texttt{then}}\ \texttt{LNil}$ $\underline{\texttt{else}}\ \texttt{LCons}(p \overset{\mathbb{m}}{\rightarrow}_{\texttt{clnode}} \texttt{chunk}[i]_{\mathbb{m}}^{\texttt{i32}}, \texttt{Clist}_{\mathbb{m}}^{\texttt{clnode}}(i = 3_{\texttt{i2}} ? p \overset{\mathbb{m}}{\rightarrow}_{\texttt{clnode}} \texttt{next} : p, i + 1_{\texttt{i2}}))$

Table 5.3: Tree lifting constructors and their definitions

Lifting Constructor	Definition
(T3) `Tree = TNil | TCons(val:i32, left:Tree, right:Tree)`	
$\texttt{Ctree}_{\mathbb{m}}^{\texttt{u32[]}}(p\ i\ n : \texttt{i32})$	$\underline{\texttt{if}}\ i \geq_u n\ \ \underline{\texttt{then}}\ \texttt{TNil}$ $\underline{\texttt{else}}\ \texttt{TCons}(p[i]_{\mathbb{m}}^{\texttt{i32}}, \texttt{Ctree}_{\mathbb{m}}^{\texttt{u32[]}}(p, 2_{\texttt{i32}} \times i + 1_{\texttt{i32}}, n), \texttt{Ctree}_{\mathbb{m}}^{\texttt{u32[]}}(p, 2_{\texttt{i32}} \times i + 2_{\texttt{i32}}, n))$
$\texttt{Ctree}_{\mathbb{m}}^{\texttt{tnode(u32)}}(p : \texttt{i32})$	$\underline{\texttt{if}}\ p = 0_{\texttt{i32}}\ \ \underline{\texttt{then}}\ \texttt{TNil}$ $\underline{\texttt{else}}\ \texttt{TCons}(p \overset{\mathbb{m}}{\rightarrow}_{\texttt{tnode}} \texttt{val}, \texttt{Ctree}_{\mathbb{m}}^{\texttt{tnode(u32)}}(p \overset{\mathbb{m}}{\rightarrow}_{\texttt{tnode}} \texttt{left}), \texttt{Ctree}_{\mathbb{m}}^{\texttt{tnode(u32)}}(p \overset{\mathbb{m}}{\rightarrow}_{\texttt{tnode}} \texttt{right}))$

5.1.3 Tree

We wrote a Spec program that computes the sum of the elements of a binary tree through an inorder traversal using recursion. We use two different data layouts for a tree: (a) a flat array where a *complete* binary tree is laid out in breadth-first search order commonly used for heaps ($\texttt{Ctree}_{\mathbb{m}}^{\texttt{u32[]}}$), and (b) a linked tree node with two pointers for the left and right children ($\texttt{Ctree}_{\mathbb{m}}^{\texttt{tnode(u32)}}$) (shown in table 5.3). Both Spec and C programs contain non-tail recursive procedure calls for left and right children. S2C is able to correlate these recursive calls using user-provided *Pre* and *Post* as discussed in section 4.2.3. At the entry of the recursive calls, S2C is required to prove that *Pre* holds for the arguments and at the exit of the recursive calls, S2C assumes *Post* on the values returned.

Table 5.4: Matrix and auxiliary List lifting constructors with their definitions

Lifting Constructor	**Definition**
$\boxed{\text{T4}}$ `Matrix = MNil | MCons(row:List, cols:Matrix)`	
$\texttt{Cmat}_{\mathbb{m}}^{\texttt{u32[][]}}(p\ i\ u\ v : \texttt{i32})$	$\underline{\texttt{if}}\ i \geq_u u\ \ \underline{\texttt{then}}\ \texttt{MNil}$ $\underline{\texttt{else}}\ \texttt{MCons}(\texttt{Clist}_{\mathbb{m}}^{\texttt{u32[]}}(p[i]_{\mathbb{m}}^{\texttt{i32}}, 0_{\texttt{i32}}, v), \texttt{Cmat}_{\mathbb{m}}^{\texttt{u32[][]}}(p, i + 1_{\texttt{i32}}, u, v))$
$\texttt{Clist}_{\mathbb{m}}^{\texttt{u32[r]}}(p\ i\ j\ u\ v : \texttt{i32})$	$\underline{\texttt{if}}\ j \geq_u v\ \ \underline{\texttt{then}}\ \texttt{LNil}$ $\underline{\texttt{else}}\ \texttt{LCons}(p[i \times v + j]_{\mathbb{m}}^{\texttt{i32}}, \texttt{Clist}_{\mathbb{m}}^{\texttt{u32[r]}}(p, i, j + 1_{\texttt{i32}}, u, v))$
$\texttt{Cmat}_{\mathbb{m}}^{\texttt{u32[r]}}(p\ i\ u\ v : \texttt{i32})$	$\underline{\texttt{if}}\ i \geq_u u\ \ \underline{\texttt{then}}\ \texttt{MNil}$ $\underline{\texttt{else}}\ \texttt{MCons}(\texttt{Clist}_{\mathbb{m}}^{\texttt{u32[r]}}(p, i, 0_{\texttt{i32}}, u, v), \texttt{Cmat}_{\mathbb{m}}^{\texttt{u32[r]}}(p, i + 1_{\texttt{i32}}, u, v))$
$\texttt{Clist}_{\mathbb{m}}^{\texttt{u32[c]}}(p\ i\ j\ u\ v : \texttt{i32})$	$\underline{\texttt{if}}\ j \geq_u v\ \ \underline{\texttt{then}}\ \texttt{LNil}$ $\underline{\texttt{else}}\ \texttt{LCons}(p[i + j \times u]_{\mathbb{m}}^{\texttt{i32}}, \texttt{Clist}_{\mathbb{m}}^{\texttt{u32[c]}}(p, i, j + 1_{\texttt{i32}}, u, v))$
$\texttt{Cmat}_{\mathbb{m}}^{\texttt{u32[c]}}(p\ i\ u\ v : \texttt{i32})$	$\underline{\texttt{if}}\ i \geq_u u\ \ \underline{\texttt{then}}\ \texttt{MNil}$ $\underline{\texttt{else}}\ \texttt{MCons}(\texttt{Clist}_{\mathbb{m}}^{\texttt{u32[c]}}(p, i, 0_{\texttt{i32}}, u, v), \texttt{Cmat}_{\mathbb{m}}^{\texttt{u32[c]}}(p, i + 1_{\texttt{i32}}, u, v))$
$\texttt{Cmat}_{\mathbb{m}}^{\texttt{lnode(u32[])}}(p\ v : \texttt{i32})$	$\underline{\texttt{if}}\ p = 0_{\texttt{i32}}\ \underline{\texttt{then}}\ \texttt{MNil}$ $\underline{\texttt{else}}\ \texttt{MCons}(\texttt{Clist}_{\mathbb{m}}^{\texttt{u32[]}}(p \overset{\mathbb{m}}{\rightarrow}_{\texttt{lnode}} \texttt{val}, 0_{\texttt{i32}}, v), \texttt{Cmat}_{\mathbb{m}}^{\texttt{lnode(u32[])}}(p \overset{\mathbb{m}}{\rightarrow}_{\texttt{lnode}} \texttt{next}, v))$
$\texttt{Cmat}_{\mathbb{m}}^{\texttt{lnode(u32)[]}}(p\ i\ u : \texttt{i32})$	$\underline{\texttt{if}}\ i \geq_u u\ \underline{\texttt{then}}\ \texttt{MNil}$ $\underline{\texttt{else}}\ \texttt{MCons}(\texttt{Clist}_{\mathbb{m}}^{\texttt{lnode(u32)}}(p[i]_{\mathbb{m}}^{\texttt{i32}}), \texttt{Cmat}_{\mathbb{m}}^{\texttt{lnode(u32)[]}}(p, i + 1_{\texttt{i32}}, u))$
$\texttt{Cmat}_{\mathbb{m}}^{\texttt{clnode(u32)}}(p\ i\ u : \texttt{i32})$	$\underline{\texttt{if}}\ i \geq_u u\ \underline{\texttt{then}}\ \texttt{MNil}$ $\underline{\texttt{else}}\ \texttt{MCons}(\texttt{Clist}_{\mathbb{m}}^{\texttt{clnode(u32)}}(p[i]_{\mathbb{m}}^{\texttt{i32}}, 0_{\texttt{i2}}), \texttt{Cmat}_{\mathbb{m}}^{\texttt{clnode(u32)[]}}(p, i + 1_{\texttt{i32}}, u))$

5.1.4 Matrix

We wrote a Spec program to count the frequency of a value appearing in a 2D matrix. A matrix is represented as an ADT that resembles a `List` of `List`s ($\boxed{\text{T4}}$ in table 5.4). The C implementations for a `Matrix` object include (a) a two-dimensional array ($\texttt{Cmat}_{\mathbb{m}}^{\texttt{u32[][]}}$), (b) a flattened row-major array ($\texttt{Cmat}_{\mathbb{m}}^{\texttt{u32[r]}}$), (c) a flattened column-major array ($\texttt{Cmat}_{\mathbb{m}}^{\texttt{u32[c]}}$), (d) a linked list of 1D arrays ($\texttt{Cmat}_{\mathbb{m}}^{\texttt{lnode(u32[])}}$), (e) a 1D array of linked lists ($\texttt{Cmat}_{\mathbb{m}}^{\texttt{lnode(u32)[]}}$) and (f) a 1D array of chunked linked list ($\texttt{Cmat}_{\mathbb{m}}^{\texttt{clnode(u32)[]}}$) memory layouts. Note that both `T[r]` and `T[c]` represent a 1D array of type `T`; r and c emphasizes that these arrays are used to represent matrices in row-major and column-major encodings respectively. We also introduce two auxiliary lifting constructors $\texttt{Clist}_{\mathbb{m}}^{\texttt{u32[r]}}$ and $\texttt{Clist}_{\mathbb{m}}^{\texttt{u32[c]}}$ for lifting each row of matrices lifted using the corresponding $\texttt{Cmat}_{\mathbb{m}}^{\texttt{u32[r]}}$ and $\texttt{Cmat}_{\mathbb{m}}^{\texttt{u32[c]}}$ `Matrix` lifting constructors. These lifting constructors are listed in table 5.4.

Data Layout	Variant	Time(s)	($\mathbf{d}_u, \mathbf{d}_o$)	Data Layout	Variant	Time(s)	($\mathbf{d}_u, \mathbf{d}_o$)
	list				**tree**		
u32[]	sum naive	16	(1,2)	u32[]	sum	264	(1,2)
	sum opt	49	(4,5)	tnode(u32)	sum	204	(1,2)
	dot naive	65	(1,2)		**matfreq**		
	dot opt	176	(4,5)	u8[][]	naive	974	(1,3)
lnode(u32)	sum naive	8	(1,2)		opt	1.8k	(4,8)
	sum opt	54	(4,5)	u8[r]	naive	958	(1,3)
	dot naive	37	(1,2)		opt	1.9k	(4,8)
	dot opt	120	(4,5)	u8[c]	naive	984	(1,3)
	construct	426	(1,1)		opt	1.9k	(4,6)
clnode(u32)	sum opt	39	(4,5)	lnode(u8[])	naive	753	(1,3)
	dot opt	118	(4,5)		opt	1.7k	(4,6)
	strlen			lnode(u8)[]	naive	1.5k	(1,2)
u8[]	dietlibc$_s$	9	(1,2)		opt	2.3k	(4,6)
	dietlibc$_f$	44	(3,2)	clnode(u8)[]	opt	1.8k	(4,6)
	glibc	52	(3,2)		**strpbrk**		
	klibc	9	(1,2)	u8[],u8[]	dietlibc	398	(1,2)
	musl	49	(3,2)		opt	494	(4,2)
	netbsd	9	(1,2)	u8[],lnode(u8)	naive	392	(1,2)
	newlib	50	(3,2)		opt	540	(4,2)
	openbsd	8	(1,2)	u8[],clnode(u8)	opt	523	(4,2)
	uClibc	8	(1,2)	lnode(u8),u8[]	naive	497	(1,2)
lnode(u8)	naive	13	(1,2)		opt	602	(4,2)
	opt	49	(3,5)	lnode(u8),lnode(u8)	naive	345	(1,2)
clnode(u8)	opt	45	(3,5)		opt	503	(4,2)
	strchr			lnode(u8),clnode(u8)	opt	572	(4,2)
u8[]	dietlibc$_s$	16	(1,1)		**strcspn**		
	dietlibc$_f$	89	(4,1)	u8[],u8[]	dietlibc	462	(1,2)
	glibc	127	(4,1)		opt	538	(4,2)
	klibc	23	(1,1)	u8[],lnode(u8)	naive	395	(1,2)
	newlib$_s$	15	(1,1)		opt	521	(4,2)
	openbsd	24	(1,1)	u8[],clnode(u8)	opt	527	(4,2)
	uClibc	22	(1,1)	lnode(u8),u8[]	naive	601	(1,2)
lnode(u8)	naive	19	(1,1)		opt	660	(4,2)
	opt	146	(4,1)	lnode(u8),lnode(u8)	naive	349	(1,2)
	strcmp				opt	502	(4,2)
u8[],u8[]	dietlibc$_s$	39	(1,1)	lnode(u8),clnode(u8)	opt	595	(4,2)
	freebsd	39	(1,1)		**strspn**		
	glibc	41	(1,1)	u8[],u8[]	dietlibc	277	(1,2)
	klibc	41	(1,1)		opt	388	(4,2)
	musl	41	(1,1)	u8[],lnode(u8)	naive	405	(1,2)
	netbsd	39	(1,1)		opt	682	(4,2)
	newlib$_s$	42	(1,1)	u8[],clnode(u8)	opt	535	(4,2)
	newlib$_f$	405	(4,1)	lnode(u8),u8[]	naive	409	(1,2)
	openbsd	40	(1,1)		opt	553	(4,2)
	uClibc	38	(1,1)	lnode(u8),lnode(u8)	naive	357	(1,2)
lnode(u8),lnode(u8)	naive	47	(1,1)		opt	514	(4,2)
	opt	293	(4,1)	lnode(u8),clnode(u8)	opt	616	(4,2)
clnode(u8),clnode(u8)	opt	254	(4,1)				

Table 5.5: Time taken by S2C for successful equivalence checks between specifications and their C implementations. Additionally, we show the minimum under- and over-approximation depths at which these equivalence checks succeed.

5.2 Results

Table 5.5 lists the various C implementations and the time S2C took to compute equivalence with their specifications. For functions that take two or more data structures as arguments, we show results for different combinations of data layouts for each argument. We also show the minimum under-approximation (d_u) and over-approximation (d_o) depths at which the equivalence proof completed (keeping all other parameters to their default values).

5.3 Limitations

S2C is not without limitations. Since S2C is only interested in finding a bisimulation relation, a whole class of non-bisimilar but equivalent program pairs is beyond our scope. In addition to recursive relations based on the lifting constructors provided as part of *Pre* and *Post*, S2C currently only supports bitvector affine and inequality relations. Consequently, non-linear bitvector invariants (such as polynomial invariants) are not supported. More importantly, S2C does not attempt to infer lifting constructors and merely uses the lifting constructors (with different arguments) provided as part of the input-output characteristics. While our correlation and invariant inference algorithms are based on the Counter tool [27], which is designed primarily for equivalence checking between (C-like) unoptimized IR and assembly, we found them to be quite effective for equivalence checking between Spec and deterministic C as well. However, S2C inherits many of the limitations of the Counter tool.

For example, S2C fails to find a proof of equivalence if the unrolling in the C implementation is higher than the unrolling parameter μ_S used during path enumeration as part of the product-CFG construction algorithm. Larger values of μ_S would significantly increase the correlation search space and likely have negative implications on the runtime of the algorithm. Additionally, S2C suffers from a similar trade-off with regards to the approximation parameters d_o and d_u – a smaller than necessary value would cause a failed equivalence check while a larger value may have major impact on the size of queries and counterexamples for reasons discussed next. Consider a recursive relation relating values of a non-linear ADT such as `Tree`. It's d-depth approximation reduces into $\mathcal{O}(2^d)$ scalar equalities resulting in large SMT queries, which to our experience is a major source of SMT solver timeouts during evaluation. We partially subvert this issue by using an iterative deepening strategy for type II queries – we try prove and disprove attempts with approximation parameters smaller than the maximum d_o and d_u, in hopes that either attempt would succeed saving valuable time waiting on SMT solvers. We found this strategy to be rather helpful during our evaluation.

Also, the completeness of type III proof obligations is highly contingent on the precision of our points-to analysis on $\mathcal{C}$ as well as the deconstruction programs being checked for equivanece as part of the nested bisimulation check. We found our coarse-grained `{1,2+}` categorization of allocation recency combined with allocation-site based points-to analysis to be quite good at identifying required points-to invariants. However, such an abstraction is far from complete.

Chapter 6

Conclusion

As introduced in chapter 1, most of the current solutions to the problem of equivalence checking between a functional specification and a C program relies heavily on manually provided correlation, inductive invariants as well as proof assistants for discharging said obligations. While the size of programs considered in our work is quite small, we hope the ideas in S2C will help automate the proofs for such systems to some degree.

Prior work on push-button verification of specific systems [17, 42, 40, 41] involves a combination of careful system design and automatic verification tools like SMT solvers. Constrained Horn Clause (CHC) Solvers [21] encode verification conditions of programs containing loops and recursion, and raise the level of abstraction for automatic proofs. Comparatively, S2C further raises the level of abstraction for automatic verification from SMT queries and CHC queries to lifting constructors and automatic discharge of proof obligations involving recursive relations.

A key idea in S2C is the conversion of proof obligations involving recursive relations to bisimulation checks. Thus, S2C performs *nested* bisimulation checks as part of a 'higher-level' bisimulation search. This approach of identifying recursive relations as invariants and using bisimulation to discharge the associated proof obligations may have applications beyond equivalence checking.

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