



Hyper Hoare Logic: (Dis-)Proving Program Hyperproperties

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Hoare logics are proof systems that allow one to formally establish properties of computer programs. Traditional Hoare logics prove properties of individual program executions (such as functional correctness). Hoare logic has been generalized to prove also properties of multiple executions of a program (so-called hyperproperties, such as determinism or non-interference). These program logics prove the *absence* of (bad combinations of) executions. On the other hand, program logics similar to Hoare logic have been proposed to *disprove* program properties (e.g., Incorrectness Logic), by proving the *existence* of (bad combinations of) executions. All of these logics have in common that they specify program properties using assertions over a fixed number of states, for instance, a single pre- and post-state for functional properties or pairs of pre- and post-states for non-interference.

In this paper, we present Hyper Hoare Logic, a generalization of Hoare logic that lifts assertions to properties of arbitrary *sets* of states. The resulting logic is simple yet expressive: its judgments can express arbitrary *program hyperproperties*, a particular class of hyperproperties over the set of terminating executions of a program (including properties of individual program executions). By allowing assertions to reason about sets of states, Hyper Hoare Logic can reason about both the *absence* and the *existence* of (combinations of) executions, and, thereby, supports both proving and disproving program (hyper-)properties within the same logic, including (hyper-)properties that no existing Hoare logic can express. We prove that Hyper Hoare Logic is sound and complete, and demonstrate that it captures important proof principles naturally. All our technical results have been proved in Isabelle/HOL.

CCS Concepts: • Theory of computation → Logic and verification; Hoare logic.

Additional Key Words and Phrases: Hyperproperties, Program Logic, Incorrectness Logic, Non-Interference

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1 INTRODUCTION

Hoare Logic [Floyd 1967; Hoare 1969] is a logic designed to formally prove functional correctness of computer programs. It enables proving judgments (so-called *Hoare triples*) of the form $\{P\} C \{Q\}$, where C is a program command, and P (the *precondition*) and Q (the *postcondition*) are assertions over execution states. The Hoare triple $\{P\} C \{Q\}$ is valid if and only if executing C in an initial state that satisfies P can only lead to final states that satisfy Q .

Hoare Logic is widely used to prove the absence of runtime errors, functional correctness, resource bounds, etc. All of these properties have in common that they are properties of *individual* program executions. However, classical Hoare Logic cannot reason about properties of *multiple* program executions (so-called *hyperproperties* [Clarkson and Schneider 2008]), such as determinism

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(executing the program twice in the same initial state results in the same final state) or information flow security, which is often phrased as non-interference [Volpano et al. 1996] (executing the program twice with the same low-sensitivity inputs results in the same low-sensitivity outputs). To overcome such limitations and to reason about more types of properties, Hoare Logic has been extended and adapted in various ways. We refer to those extensions and adaptations collectively as *Hoare logics*.

Among them are several logics that can establish properties of two [Aguirre et al. 2017; Amtoft et al. 2006; Benton 2004; Costanzo and Shao 2014; Eilers et al. 2023; Ernst and Murray 2019; Francez 1983; Maillard et al. 2019; Naumann 2020; Yang 2007] or even k [D’Osualdo et al. 2022; Sousa and Dillig 2016] executions of the same program, where $k > 2$ is useful for properties such as transitivity and associativity. *Relational Hoare logics* are able to prove *relational properties*, i.e., properties relating executions of two (potentially different) programs, for instance, to prove program equivalence.

All of these logics have in common that they can prove only properties that hold *for all* (combinations of) executions, that is, they prove the *absence* of bad (combinations of) executions; to achieve that, their judgments *overapproximate* the possible executions of a program. Overapproximate logics cannot prove the *existence* of (combinations of) executions, and thus cannot establish certain interesting program properties, such as the presence of a bug or non-determinism.

To overcome this limitation, recent work [de Vries and Koutavas 2011; Murray 2020; O’Hearn 2019; Raad et al. 2020, 2022] proposed Hoare logics that can prove the *existence* of (individual) executions, for instance, to *disprove* functional correctness. We call such Hoare logics *underapproximate*. Tools based on underapproximate Hoare logics have proven useful for finding bugs on an industrial scale [Blackshear et al. 2018; Distefano et al. 2019; Gorogiannis et al. 2019; Le et al. 2022]. More recent work has proposed Hoare logics that combine underapproximate and overapproximate reasoning for single executions, such as Outcome Logic [Zilberstein et al. 2023] and Exact Separation Logic [Maksimović et al. 2023], and for $\forall^*\exists^*$ -hyperproperties, such as RHLE [Dickerson et al. 2022]. Another recent work, BiKAT [Antonopoulos et al. 2023], can be used to prove $\forall\exists$ -properties between two programs C_1 and C_2 , by providing an *alignment witness* W that overapproximates the behavior of C_1 and underapproximates the behavior of C_2 , and proving that W satisfies a relevant $\forall\forall$ -property, which the authors demonstrate by providing inference rules for forward and backward simulations ($\forall\exists$ -properties). BiKAT can also in principle be used to prove $\exists\forall$ -properties, by essentially proving the negation of a $\forall\exists$ -property, i.e., by proving that no such alignment witness W exists, but the authors provide no inference rules for $\exists\forall$ -properties.

The problem. Fig. 1 presents a (non-exhaustive) overview of the landscape of Hoare logics, where logics are classified in two dimensions: the type of properties they can establish, and the number of program executions those properties can relate. The table reveals two open problems. First, some types of hyperproperties cannot be expressed by any existing Hoare logic (represented by \emptyset). For example, to prove that a program violates generalized non-interference, one needs to show that there *exist* two executions τ_1 and τ_2 such that *all* executions with the same high-sensitivity input as τ_1 have a different low-sensitivity output than τ_2 .¹ Such $\exists^*\forall^*$ -hyperproperties cannot be proved by any existing Hoare logic. Second, the existing logics cover different, often disjoint program properties, which may hinder practical applications: reasoning about a wide spectrum of properties of a given program requires the application of several logics, each with its own judgments; properties expressed in different, incompatible logics cannot be composed within the same proof system.

¹Assuming no public (low-sensitivity) input.

Type	Number of executions			
	1	2	k	∞
Overapproximate (hypersafety)	✓ HL, OL, RHL, CHL, RHLE, MHRM, BiKAT	✓ RHL, CHL, RHLE, MHRM, BiKAT	✓ CHL, RHLE	✓ \emptyset
Backward underapproximate	✓ IL, InSec, BiKAT	✓ InSec, BiKAT	✓ \emptyset	✓ \emptyset
Forward underapproximate	✓ OL, RHLE, MHRM, BiKAT	✓ RHLE, MHRM, BiKAT	✓ RHLE	✓ \emptyset
$\forall^*\exists^*$	not applicable	✓ RHLE, MHRM, BiKAT	✓ RHLE	✓ \emptyset
$\exists^*\forall^*$	not applicable	✓ BiKAT	✓ \emptyset	✓ \emptyset
Set properties	not applicable	not applicable	not applicable	✓ \emptyset

Fig. 1. (Non-exhaustive) overview of Hoare logics, classified in two dimensions: The type of properties a logic can establish, and the number of program executions these properties can relate (column “ ∞ ” subsumes an unbounded and an infinite number of executions). In our extended version [Dardinier and Müller 2023], we explain the distinction between backward and forward underapproximate properties, and we give examples of (hypersafety and set) properties for an unbounded number of executions. $\forall^*\exists^*$ - and $\exists^*\forall^*$ -hyperproperties are discussed in Sect. 2. A green checkmark indicates that a property is handled by our Hyper Hoare Logic for the programming language defined in Sect. 3.1, and \emptyset indicates that no other Hoare logic supports it. The acronyms refer to the following. CHL: Cartesian Hoare Logic [Sousa and Dillig 2016], HL: Hoare Logic [Floyd 1967; Hoare 1969], IL: Incorrectness Logic [O’Hearn 2019] or Reverse Hoare Logic [de Vries and Koutavas 2011], InSec: Insecurity Logic [Murray 2020], OL: Outcome Logic [Zilberstein et al. 2023], RHL: Relational Hoare Logic [Benton 2004], RHLE [Dickerson et al. 2022], MHRM [Maillard et al. 2019], BiKAT [Antonopoulos et al. 2023].

This work. We present *Hyper Hoare Logic*, a novel Hoare logic that enables *proving or disproving* any *program hyperproperty*, a particular class of hyperproperties over the set of terminating executions of a program (formally defined in Sect. 3.5), which includes properties of individual program executions. In the rest of this paper, when the context is clear, we use *hyperproperties* to refer to program hyperproperties. As indicated by the green checkmarks in Fig. 1, these include many different types of properties, relating *any* (potentially unbounded or even infinite) number of program executions, and many hyperproperties that no existing Hoare logic can handle. Among them are $\exists^*\forall^*$ -hyperproperties such as violations of generalized non-interference (Sect. 4.3), and hyperproperties relating an unbounded or infinite number of executions such as quantifying information flow based on Shannon entropy or min-capacity [Assaf et al. 2017; Shannon 1948; Smith 2009; Yasuoka and Terauchi 2010] (we give an example in our extended version [Dardinier and Müller 2023]). Moreover, Hyper Hoare Logic offers rules to compose hyper-triples with different types of hyperproperties, such as $\exists\forall$ with $\forall\forall$, or $\forall\forall\exists$ with $\forall\forall$.

Hyper Hoare Logic is based on a simple yet powerful idea: We lift pre- and postconditions from assertions over a *fixed* number of execution states to *hyper-assertions* over *sets* of execution states. Hyper Hoare Logic then establishes *hyper-triples* of the form $\{P\} C \{Q\}$, where P and Q are hyper-assertions. Such a hyper-triple is valid iff for any set of initial states S that satisfies P , the set of all final states that can be reached by executing C in some state from S satisfies Q . By allowing assertions to quantify *universally* over states, Hyper Hoare Logic can express overapproximate properties, whereas *existential* quantification expresses underapproximate properties. Combinations of universal and existential quantification in the same assertion, as well as assertions over infinite sets of states, allow Hyper Hoare Logic to prove or disprove properties beyond existing logics.

Contributions. Our main contributions are:

- We present Hyper Hoare Logic, a novel Hoare logic that can prove or disprove arbitrary hyperproperties over terminating executions.
- We formalize our logic and prove soundness and completeness in Isabelle/HOL [Nipkow et al. 2002].

- We derive easy-to-use syntactic rules for a restricted class of *syntactic* hyper-assertions, as well as additional loop rules that capture different reasoning principles.
- We prove compositionality rules for hyper-triples, which enable the flexible composition of hyper-triples of different forms and, thus, facilitate modular proofs.
- We demonstrate the expressiveness of Hyper Hoare Logic, both on judgments of existing Hoare logics and on hyperproperties that no existing Hoare logic supports. We also prove in Isabelle/HOL that hyper-triples capture precisely program hyperproperties, and that any invalid hyper-triple can be disproved by proving another hyper-triple.

Outline. Sect. 2 informally presents hyper-triples, and shows how they can be used to specify hyperproperties. Sect. 3 introduces the rules of Hyper Hoare Logic, proves that these rules are sound and complete for establishing valid hyper-triples, defines program hyperproperties, proves that hyper-triples capture precisely those, and proves that invalid hyper-triples can be disproved by proving other hyper-triples. Secs. 4 and 5 derive additional rules that enable concise proofs in common cases. We discuss related work in Sect. 6 and conclude in Sect. 7. Our extended version [Dardinier and Müller 2023] contains further details and extensions. In particular, we show how to express judgments of existing logics in Hyper Hoare Logic, and present compositionality rules. All our technical results (Sects. 3, 4, 5, and the extended version) have been proved in Isabelle/HOL [Nipkow et al. 2002], and our mechanization is publicly available [Dardinier 2023; Dardinier and Müller 2024].

2 HYPER-TRIPLES, INFORMALLY

In this section, we illustrate how hyper-triples can be used to express different types of hyperproperties, including over- and underapproximate hyperproperties for single (Sect. 2.1) and multiple (Sect. 2.2 and Sect. 2.3) executions.

2.1 Overapproximation and Underapproximation

Consider the command $C_0 \triangleq (x := randIntBounded(0, 9))$, which generates a random integer between 0 and 9 (both included), and assigns it to the variable x . Its functional correctness properties include: (P1) The final value of x is in the interval $[0, 9]$, and (P2) every value in $[0, 9]$ can occur for every initial state (i.e., the output is not determined by the initial state).

Property P1 expresses the *absence* of bad executions, in which the output x is outside the interval $[0, 9]$. This property can be expressed in classical Hoare logic, with the triple $\{\top\} C_0 \{0 \leq x \leq 9\}$. In Hyper Hoare Logic, where assertions are properties of sets of states, we express it using a postcondition that *universally* quantifies over all possible final states: In all final states, the value of x should be in $[0, 9]$. The hyper-triple $\{\top\} C_0 \{\forall \langle \varphi' \rangle. 0 \leq \varphi'(x) \leq 9\}$ expresses this property. The postcondition, written in the syntax that will be introduced in Sect. 4, is semantically equivalent to $\{\lambda S'. \forall \varphi' \in S'. 0 \leq \varphi'(x) \leq 9\}$. This hyper-triple means that, for any set S of initial states φ (satisfying the trivial precondition \top), the set S' of all final states φ' that can be reached by executing C_0 in some initial state $\varphi \in S$ satisfies the postcondition, i.e., all final states $\varphi' \in S'$ have a value for x between 0 and 9. This hyper-triple illustrates a systematic way of expressing classical Hoare triples as hyper-triples (as shown in our extended version [Dardinier and Müller 2023]). Property P2 expresses the *existence* of desirable executions and can be expressed using an underapproximate Hoare logic. In Hyper Hoare Logic, we use a postcondition that *existentially* quantifies over all possible final states: For each $n \in [0, 9]$, there exists a final state where $x = n$. The hyper-triple $\{\exists \langle \varphi \rangle. \top\} C_0 \{\forall n. 0 \leq n \leq 9 \Rightarrow \exists \langle \varphi' \rangle. \varphi'(x) = n\}$ expresses P2. The precondition is semantically equivalent to $\{\lambda S. \exists \varphi \in S\}$. It requires the set S of initial states to be non-empty (otherwise the set of states reachable from states in S by executing C_0 would also be empty, and the

postcondition would not hold). The postcondition ensures that, for any $n \in [0, 9]$, it is possible to reach at least one state φ' with $\varphi'(x) = n$.

This example shows that hyper-triples can express both under- and overapproximate properties, which allows Hyper Hoare Logic to reason about both the *absence* of bad executions and the *existence* of good executions. Moreover, hyper-triples can also be used to prove the existence of *incorrect* executions, which has proven useful in practice to find bugs without false positives [Le et al. 2022; O’Hearn 2019]. To the best of our knowledge, the only other Hoare logics that can express both properties P1 and P2 are Outcome Logic [Zilberstein et al. 2023], Exact Separation Logic [Maksimović et al. 2023], and BiKAT [Antonopoulos et al. 2023].² However, the two first are limited to properties of single executions, and the latter to properties relating two executions. Thus, these logics cannot handle the general class of k -safety hyperproperties, which we discuss next.

2.2 (Dis-)Proving k -Safety Hyperproperties

A k -safety hyperproperty [Clarkson and Schneider 2008] is a property that characterizes *all combinations of k executions of the same program*. An important example is information flow security, which requires that programs that manipulate secret data (such as passwords) do not expose secret information to their users. In other words, the content of high-sensitivity (secret) variables must not leak into low-sensitivity (public) variables. For deterministic programs, information flow security is often formalized as *non-interference* (NI) [Volpano et al. 1996], a 2-safety hyperproperty: Any two executions of the program with the same low-sensitivity (*low* for short) inputs (but potentially different high-sensitivity inputs) must have the same low outputs. That is, for all pairs of executions τ_1, τ_2 , if τ_1 and τ_2 agree on the initial values of all *low* variables, they must also agree on the final values of all *low* variables. This ensures that the final values of *low* variables are not influenced by the values of *high* variables. Assuming for simplicity that we have only one *low* variable l , the hyper-triple $\{low(l)\} C_1 \{low(l)\}$, where $low(l) \triangleq (\forall \langle\varphi_1\rangle, \langle\varphi_2\rangle. \varphi_1(l) = \varphi_2(l))$, expresses that C_1 satisfies NI: If all states in S have the same value for l , then all final states reachable by executing C_1 in any initial state $\varphi \in S$ will have the same value for l . Note that this set-based definition is equivalent to the standard definition based on pairs of executions; Instantiating S with a set of two states directly yields the standard definition.

Non-interference requires that all final states have the same value for l , irrespective of the initial state that leads to any given final state. Other k -safety hyperproperties need to relate initial and final states. For example, the program $y := f(x)$ is *monotonic* iff for any two executions with $\varphi_1(x) \geq \varphi_2(x)$, we have $\varphi'_1(y) \geq \varphi'_2(y)$, where φ_1 and φ_2 are the initial states φ'_1 and φ'_2 are the *corresponding* final states. To relate initial and final states, Hyper Hoare Logic uses *logical variables* (also called *auxiliary variables* [Kleymann 1999]). These variables cannot appear in a program, and thus are guaranteed to have the same values in the initial and final states of an execution. We use this property to tag corresponding states, as illustrated by the hyper-triple for monotonicity: $\{\text{mono}_x^t\} y := f(x) \{\text{mono}_y^t\}$, where $\text{mono}_x^t \triangleq (\forall \langle\varphi_1\rangle, \langle\varphi_2\rangle. \varphi_1(t) = 1 \wedge \varphi_2(t) = 2 \Rightarrow \varphi_1(x) \geq \varphi_2(x))$. Here, t is a logical variable used to distinguish the two executions of the program.

Disproving k -safety hyperproperties. As explained in the introduction, being able to prove that a property does *not* hold is valuable in practice, because it allows building tools that can find bugs without false positives. Hyper Hoare Logic is able to *disprove* hyperproperties by proving a hyperproperty that is essentially its negation. For example, we can prove that the insecure program $C_2 \triangleq (\text{if } (h > 0) \{l := 1\} \text{ else } \{l := 0\})$, where h is a high variable, violates non-interference (NI), using the following hyper-triple: $\{low(l) \wedge (\exists \langle\varphi_1\rangle, \langle\varphi_2\rangle. \varphi_1(h) > 0 \wedge \varphi_2(h) \leq 0)\} C_2 \{\exists \langle\varphi'_1\rangle, \langle\varphi'_2\rangle. \varphi'_1(l) \neq \varphi'_2(l)\}$.

²While RHLE [Dickerson et al. 2022] can in principle reason about the existence of executions, it is unclear how to express the existence for *all* numbers n .

The postcondition is the negation of the postcondition for C_1 above, hence expressing that C_2 violates NI. Note that the precondition needs to be stronger than for C_1 . Since the postcondition has to hold for *all* sets that satisfy the precondition, we have to require that the set of initial states includes two states that will definitely lead to different final values of l .

The general class of k -safety hyperproperties includes properties that relate more than 2 executions, such as transitivity ($k = 3$) and associativity ($k = 4$) [Sousa and Dillig 2016]. The only other Hoare logic that can be used to both prove and disprove arbitrary k -safety hyperproperties is RHLE [Dickerson et al. 2022], since it supports $\forall^*\exists^*$ -hyperproperties, which includes both hypersafety (that is, \forall^* properties and their negation (that is, \exists^* -hyperproperties). However, RHLE does not support $\exists^*\forall^*$ -hyperproperties, and thus cannot disprove $\forall^*\exists^*$ -hyperproperties such as generalized non-interference, as we discuss next.

2.3 Beyond k -Safety

NI is widely used to express information flow security for deterministic programs, but is overly restrictive for non-deterministic programs. For example, the command $C_3 \triangleq (y := \text{nonDet}(); l := h + y)$ is information flow secure. Since the secret h is added to an unbounded non-deterministically chosen integer y , any secret h can result in any³ value for the public variable l and, thus, we cannot learn anything certain about h from observing the value of l . However, because of non-determinism, C_3 does not satisfy NI: Two executions with the same initial values for l could get different values for y , and thus have different final values for l .

Information flow security for non-deterministic programs (such as C_3) is often formalized as *generalized non-interference* (GNI) [McCullough 1987; McLean 1996], a security notion weaker than NI. GNI allows two executions τ_1 and τ_2 with the same low inputs to have *different* low outputs, provided that there is a third execution τ with the same low inputs that has the same high inputs as τ_1 and the same low outputs as τ_2 . That is, the difference in the low outputs between τ_1 and τ_2 cannot be attributed to their secret inputs.⁴ The non-deterministic program C_3 satisfies GNI, which can be expressed via the hyper-triple⁵ $\{\text{low}(l)\} C_3 \{\forall \langle\varphi'_1\rangle, \langle\varphi'_2\rangle. \exists \langle\varphi'\rangle. \varphi'(h) = \varphi'_1(h) \wedge \varphi'(l) = \varphi'_2(l)\}$. The final states φ'_1 and φ'_2 correspond to the executions τ_1 and τ_2 , respectively, and φ' corresponds to execution τ .

As before, the expressivity of hyper-triples enables us not only to express that a program *satisfies* complex hyperproperties such as GNI, but also that a program *violates* them. For example, the program $C_4 \triangleq (y := \text{nonDet}(); \text{assume } y \leq 9; l := h + y)$, where the first two statements model a non-deterministic choice of y smaller or equal to 9, leaks information: Observing for example $l = 20$ at the end of an execution, one can deduce that $h \geq 11$ (because $y \leq 9$). We can formally express that C_4 violates GNI using the following hyper-triple:⁶

$$\{\text{low}(l) \wedge (\exists \langle\varphi_1\rangle, \langle\varphi_2\rangle. \varphi_1(h) \neq \varphi_2(h))\} C_4 \{\exists \langle\varphi'_1\rangle, \langle\varphi'_2\rangle. \forall \langle\varphi'\rangle. \varphi'(h) = \varphi'_1(h) \Rightarrow \varphi'(l) \neq \varphi'_2(l)\}$$

The postcondition implies the negation of the postcondition we used previously to express GNI. As before, we had to strengthen the precondition to prove this violation.

GNI is a $\forall\forall\exists$ -hyperproperty, whereas its negation is an $\exists\exists\forall$ -hyperproperty. To the best of our knowledge, Hyper Hoare Logic is the only Hoare logic that can both prove and disprove GNI. In

³This property holds for both unbounded and bounded arithmetic.

⁴GNI is often formulated without the requirement that τ_1 and τ_2 have the same low inputs, e.g., in Clarkson and Schneider [2008]. This alternative formulation can also be expressed in Hyper Hoare Logic, with the hyper-triple $\{\forall \langle\varphi\rangle. \varphi(l_{in}) = \varphi(l)\} C_3 \{\forall \langle\varphi'_1\rangle, \langle\varphi'_2\rangle. \exists \langle\varphi'\rangle. \varphi'(h) = \varphi'_1(h) \wedge \varphi'(l_{in}) = \varphi'_2(l_{in}) \wedge \varphi'(l) = \varphi'_2(l)\}$. The precondition binds, in each state, the initial value of l to the logical variable l_{in} , which enables the postcondition to refer to the initial value of l .

⁵We assume here for simplicity that h is not modified by C_3 .

⁶Still assuming that h is not modified.

fact, we will see in Sect. 3.5 that all hyperproperties over terminating program executions can be proven or disproven with Hyper Hoare Logic.

3 HYPER HOARE LOGIC

In this section, we present the programming language used in this paper (Sect. 3.1), formalize hyper-triples (Sect. 3.2), present the core rules of Hyper Hoare Logic (Sect. 3.3), prove soundness and completeness of the logic w.r.t. hyper-triples (Sect. 3.4), formally characterize the expressivity of hyper-triples (Sect. 3.5), and discuss additional rules for composing proofs (Sect. 3.6). All technical results presented in this section have been formalized in Isabelle/HOL.

3.1 Language and Semantics

We present Hyper Hoare Logic for the following imperative programming language:

DEFINITION 1. *Program states and programming language.* A program state (*ranged over by* σ) is a mapping from local variables (in the set $PVars$) to values (in the set $PVals$): The set of program states $PStates$ is defined as the set of total functions from $PVars$ to $PVals$: $PStates \triangleq PVars \rightarrow PVals$.

Program commands C are defined by the following syntax, where x ranges over variables in the set $PVars$, e over expressions (modeled as total functions from $PStates$ to $PVals$), and b over predicates over states (total functions from $PStates$ to Booleans):

$$C ::= \text{skip} \mid x := e \mid x := \text{nonDet}() \mid \text{assume } b \mid C; C \mid C + C \mid C^*$$

The **skip**, assignment, and sequential composition commands are standard. The command **assume** b acts like **skip** if b holds and otherwise stops the execution. Instead of including deterministic if-statements and while loops, we consider a *non-deterministic* choice $C_1 + C_2$ and a *non-deterministic* iteration C^* , which are more expressive. Combined with the **assume** command, they can express deterministic if-statements and while loops as follows:

$$\begin{aligned} \text{if } (b) \{C_1\} \text{ else } \{C_2\} &\triangleq (\text{assume } b; C_1) + (\text{assume } \neg b; C_2) \\ \text{if } (b) \{C\} &\triangleq (\text{assume } b; C) + (\text{assume } \neg b) \\ \text{while } (b) \{C\} &\triangleq (\text{assume } b; C)^*; \text{assume } \neg b \end{aligned}$$

Our language also includes a non-deterministic assignment $y := \text{nonDet}()$ (also called *havoc*), which allows us to model unbounded non-determinism. Together with **assume**, it can for instance model the generation of random numbers between bounds: $y := \text{randIntBounded}(a, b)$ can be modeled as $y := \text{nonDet}(); \text{assume } a \leq y \leq b$.

The big-step semantics of our language is standard, and formally defined in our extended version [Dardinier and Müller 2023]. The rule for $x := \text{nonDet}()$ allows x to be updated with any value v . **assume** b leaves the state unchanged if b holds; otherwise, the semantics gets stuck to indicate that there is no execution in which b does *not* hold. The command $C_1 + C_2$ non-deterministically executes either C_1 or C_2 . C^* non-deterministically either performs another loop iteration or terminates.

Note that our language does not contain any command that could fail (in particular, expression evaluation is total, such that division-by-zero and other errors cannot occur). Runtime failures could easily be modeled by instrumenting the program with a special Boolean variable err that tracks whether a runtime error has occurred and skips the rest of the execution if this is the case.

3.2 Hyper-Triples, Formally

As explained in Sect. 2, the key idea behind Hyper Hoare Logic is to use *properties of sets of states* as pre- and postconditions, whereas traditional Hoare logics use properties of individual states

(or of a given number k of states in logics for hyperproperties). Considering arbitrary sets of states increases the expressivity of triples substantially; for instance, universal and existential quantification over these sets corresponds to over- and underapproximate reasoning, respectively. Moreover, combining both forms of quantification allows one to express advanced hyperproperties, such as generalized non-interference (see Sect. 2.3).

To allow the assertions of Hyper Hoare Logic to refer to logical variables (motivated in Sect. 2.2), we include them in our notion of state.

DEFINITION 2. *Extended states.* An extended state (ranged over by φ) is a pair of a logical state (a total mapping from logical variables to logical values) and a program state:

$$\text{ExtStates} \triangleq (L\text{Vars} \rightarrow L\text{Vals}) \times P\text{States}$$

Given an extended state φ , we write φ^L to refer to the logical state and φ^P to refer to the program state, that is, $\varphi = (\varphi^L, \varphi^P)$.

We use the same meta variables (x, y, z) for program and logical variables. When it is clear from the context that $x \in P\text{Vars}$ (resp. $x \in L\text{Vars}$), we often write $\varphi(x)$ to denote $\varphi^P(x)$ (resp. $\varphi^L(x)$).

The assertions of Hyper Hoare Logic are predicates over sets of extended states:

DEFINITION 3. *Hyper-assertions.* A hyper-assertion (ranged over by P, Q, R) is a total function from $\mathbb{P}(\text{ExtStates})$ to Booleans.

A hyper-assertion P entails a hyper-assertion Q , written $P \models Q$, iff all sets that satisfy P also satisfy Q :

$$(P \models Q) \triangleq (\forall S. P(S) \Rightarrow Q(S))$$

We formalize hyper-assertions as semantic properties, which allows us to focus on the key ideas of the logic. In Sect. 4, we will define a syntax for hyper-assertions, which will allow us to derive simpler rules than the ones presented in this section.

To formalize the meaning of hyper-triples, we need to relate them formally to the semantics of our programming language. Since hyper-triples are defined over extended states, we first define a semantic function sem that lifts the operational semantics to extended states; it yields the set of extended states that can be reached by executing a command C from a set of extended states S :

DEFINITION 4. *Extended semantics.*

$$\text{sem}(C, S) \triangleq \{\varphi \mid \exists \sigma. (\varphi^L, \sigma) \in S \wedge \langle C, \sigma \rangle \rightarrow \varphi^P\}$$

The following lemma states several useful properties of the extended semantics.

LEMMA 1. *Properties of the extended semantics.*

- (1) $\text{sem}(C, S_1 \cup S_2) = \text{sem}(C, S_1) \cup \text{sem}(C, S_2)$
- (2) $S \subseteq S' \Rightarrow \text{sem}(C, S) \subseteq \text{sem}(C, S')$
- (3) $\text{sem}(C, \bigcup_x f(x)) = \bigcup_x \text{sem}(C, f(x))$
- (4) $\text{sem}(\text{skip}, S) = S$
- (5) $\text{sem}(C_1; C_2, S) = \text{sem}(C_2, \text{sem}(C_1, S))$
- (6) $\text{sem}(C_1 + C_2, S) = \text{sem}(C_1, S) \cup \text{sem}(C_2, S)$
- (7) $\text{sem}(C^*, S) = \bigcup_{n \in \mathbb{N}} \text{sem}(C^n, S)$ where $C^n \triangleq \underbrace{C; \dots; C}_{n \text{ times}}$

Using the extended semantics, we can now define the meaning of hyper-triples.

DEFINITION 5. *Hyper-triples.* Given two hyper-assertions P and Q , and a command C , the hyper-triple $\{P\} C \{Q\}$ is valid, written $\models \{P\} C \{Q\}$, iff for any set S of initial extended states that satisfies P , the set $\text{sem}(C, S)$ of extended states reachable by executing C in some state from S satisfies Q :

$$\models \{P\} C \{Q\} \triangleq (\forall S. P(S) \Rightarrow Q(\text{sem}(C, S)))$$

$$\begin{array}{c}
\frac{}{\vdash \{P\} \text{ skip } \{P\}} (\text{Skip}) \quad \frac{\vdash \{P\} C_1 \{R\} \quad \vdash \{R\} C_2 \{Q\}}{\vdash \{P\} C_1; C_2 \{Q\}} (\text{Seq}) \quad \frac{\vdash \{P\} C_1 \{Q_1\} \quad \vdash \{P\} C_2 \{Q_2\}}{\vdash \{P\} C_1 + C_2 \{Q_1 \otimes Q_2\}} (\text{Choice}) \\
\\
\frac{P \models P' \quad Q' \models Q \quad \vdash \{P'\} C \{Q'\}}{\vdash \{P\} C \{Q\}} (\text{Cons}) \quad \frac{}{\vdash \{\lambda S. P(\{\varphi \mid \varphi \in S \wedge b(\varphi^P)\})\} \text{ assume } b \{P\}} (\text{Assume}) \\
\\
\frac{\forall x. (\vdash \{P_x\} C \{Q_x\})}{\vdash \{\exists x. P_x\} C \{\exists x. Q_x\}} (\text{Exist}) \quad \frac{}{\vdash \{\lambda S. P(\{\varphi \mid \exists \alpha \in S. \varphi^L = \alpha^L \wedge \varphi^P = \alpha^P[x \mapsto e(\varphi^P)]\})\} x := e \{P\}} (\text{Assign}) \\
\\
\frac{\vdash \{I_n\} C \{I_{n+1}\}}{\vdash \{I_0\} C^* \{\bigotimes_{n \in \mathbb{N}} I_n\}} (\text{Iter}) \quad \frac{}{\vdash \{\lambda S. P(\{\varphi \mid \exists \alpha \in S. \exists v. \varphi^L = \alpha^L \wedge \varphi^P = \alpha^P[x \mapsto v]\})\} x := \text{nonDet}() \{P\}} (\text{Havoc})
\end{array}$$

Fig. 2. Core rules of Hyper Hoare Logic. The meaning of the operators \otimes and $\bigotimes_{n \in \mathbb{N}} I_n$ are defined in Def. 6 and Def. 7, respectively.

This definition is similar to classical Hoare logic, where the initial and final states have been replaced by sets of extended states. As we have seen in Sect. 2, hyper-assertions over sets of states allow our hyper-triples to express properties of single executions and of multiple executions (hyperproperties), as well as to perform overapproximate reasoning (like e.g., Hoare Logic) and underapproximate reasoning (like e.g., Incorrectness Logic).

3.3 Core Rules

Fig. 2 shows the core rules of Hyper Hoare Logic. *Skip*, *Seq*, *Cons*, and *Exist* are analogous to traditional Hoare logic. *Assume*, *Assign*, and *Havoc* are straightforward given the semantics of these commands. All three rules work backward. In particular, the precondition of *Assume* applies the postcondition P only to those states that satisfy the assumption b . By leaving the value v unconstrained, *Havoc* considers as precondition the postcondition P for all possible values for x . The three rules *Assume*, *Assign*, and *Havoc* are optimized for expressivity; we will derive in Sect. 4 syntactic versions of these rules, which are less expressive, but easier to apply.

The rule *Choice* (for non-deterministic choice) is more involved. Most standard Hoare logics use the same assertion Q as postcondition of all three triples. However, such a rule would not be sound in Hyper Hoare Logic. Consider for instance an application of this hypothetical *Choice* rule where both P and Q are defined as $\lambda S. |S| = 1$, expressing that there is a single pre- and post-state. If commands C_1 and C_2 are deterministic, the antecedents of the rule can be proved because a single pre-state leads to a single post-state. However, the non-deterministic choice will in general produce two post-states, such that the postcondition is violated.

To account for the effects of non-determinism on the sets of states described by hyper-assertions, we obtain the postcondition of the non-deterministic choice by combining the postconditions of its branches. As shown by Lemma 1 (point 6), executing the non-deterministic choice $C_1 + C_2$ in the set of states S amounts to executing C_1 in S and C_2 in S , and taking the union of the two resulting sets of states. Thus, if $Q_1(\text{sem}(C_1, S))$ and $Q_2(\text{sem}(C_2, S))$ hold then the postcondition of $C_1 + C_2$ must characterize the union $\text{sem}(C_1, S) \cup \text{sem}(C_2, S)$. The postcondition of the rule *Choice*, $Q_1 \otimes Q_2$, achieves that:

DEFINITION 6. A set S satisfies $Q_1 \otimes Q_2$ iff it can be split into two (potentially overlapping) sets S_1 and S_2 (the sets of post-states of the branches), such that S_1 satisfies Q_1 and S_2 satisfies Q_2 :

$$(Q_1 \otimes Q_2)(S) \triangleq (\exists S_1, S_2. S = S_1 \cup S_2 \wedge Q_1(S_1) \wedge Q_2(S_2))$$

The rule *Iter* for non-deterministic iterations generalizes our treatment of non-deterministic choice. It employs an indexed loop invariant I , which maps a natural number n to a hyper-assertion I_n . I_n characterizes the set of states reached after executing n times the command C in a set of initial states that satisfies I_0 . Analogously to the rule *Choice*, the indexed invariant avoids using the same hyper-assertion for all non-deterministic choices. The precondition of the rule's conclusion and its premise prove (inductively) that the triple $\{I_0\} C^n \{I_n\}$ holds for all n . I_n thus characterizes the set of reachable states after exactly n iterations of the loop. Since our loop is non-deterministic (i.e., has no loop condition), the set of reachable states after the loop is the union of the sets of reachable states after each iteration. The postcondition of the conclusion captures this intuition, by using the generalized version of the \otimes operator to an indexed family of hyper-assertions:

DEFINITION 7. A set S satisfies $\bigotimes_{n \in \mathbb{N}} I_n$ iff it can be split into $\bigcup_i f(i) = f(0) \cup \dots \cup f(i) \cup \dots$, where $f(i)$ (the set of reachable states after exactly i iterations) satisfies I_i (for each $i \in \mathbb{N}$):

$$(\bigotimes_{n \in \mathbb{N}} I_n)(S) \triangleq (\exists f. (S = \bigcup_{n \in \mathbb{N}} f(n)) \wedge (\forall n \in \mathbb{N}. I_n(f(n))))$$

Note that this rule makes Hyper Hoare Logic a partial correctness logic: it only considers an unbounded, but finite number n of loop iterations. In our extended version [Dardinier and Müller 2023], we present an alternative, stronger definition of hyper-triples, which express the existence of a terminating execution from any initial state, and corresponding inference rules (proven sound in our Isabelle/HOL mechanization) such as a rule for while loops based on a loop variant. We also discuss a possible extension of Hyper Hoare Logic to prove non-termination, i.e., the existence of non-terminating executions.

3.4 Soundness and Completeness

We have proved in Isabelle/HOL that Hyper Hoare Logic is sound and complete. That is, every hyper-triple that can be derived in the logic is valid, and vice versa. Note that Fig. 2 contains only the *core rules* of Hyper Hoare Logic. These are sufficient to prove completeness; all rules presented later in this paper are only useful to make proofs more succinct and natural.

THEOREM 1. *Soundness.* Hyper Hoare Logic is sound:

$$\text{If } \vdash \{P\} C \{Q\} \text{ then } \models \{P\} C \{Q\}.$$

PROOF SKETCH. We prove $\forall P, Q. \vdash \{P\} C \{Q\} \Rightarrow \models \{P\} C \{Q\}$ by straightforward structural induction on C . The cases for `skip`, C_1 ; C_2 , $C_1 + C_2$, and C^* , directly follow from Lemma 1. \square

THEOREM 2. *Completeness.* Hyper Hoare Logic is complete:

$$\text{If } \models \{P\} C \{Q\} \text{ then } \vdash \{P\} C \{Q\}.$$

PROOF SKETCH. We prove $H(C) \triangleq (\forall P, Q. \models \{P\} C \{Q\} \Rightarrow \vdash \{P\} C \{Q\})$ by structural induction over C . We show the case for $C \triangleq C_1 + C_2$; the proof for the non-deterministic iteration is analogous, and the other cases are standard or straightforward.

We assume $H(C_1)$ and $H(C_2)$, and want to prove $H(C)$ where $C \triangleq C_1 + C_2$. As we illustrate after this proof sketch, we need to consider each possible value V of the set of extended states S separately. For an arbitrary value V , we define $P_V \triangleq (\lambda S. P(S) \wedge S = V)$, $R_V^1 \triangleq (\lambda S. S = \text{sem}(C_1, V) \wedge P(V))$, and $R_V^2 \triangleq (\lambda S. S = \text{sem}(C_2, V))$. We get $\vdash \{P_V\} C_1 \{R_V^1\}$ from $H(C_1)$ and $\vdash \{P_V\} C_2 \{R_V^2\}$ from $H(C_2)$. By applying the rule *Choice*, we get $\vdash \{P_V\} C \{R_V^1 \otimes R_V^2\}$. Since we prove this triple for an arbitrary value V (that is, for all V), we can apply the rule *Exist*, to obtain $\vdash \{\exists V. P_V\} C \{\exists V. R_V^1 \otimes R_V^2\}$. P clearly entails $\exists V. P_V$, and the postcondition $\exists V. R_V^1 \otimes R_V^2$ entails $(\lambda S. \exists V. P(V) \wedge S = \text{sem}(C_1, V) \cup \text{sem}(C_2, V))$, which precisely describes the sets of states $\text{sem}(C_1 + C_2, V)$ (see Lemma 1(6)) where V satisfies P , and thus entails Q . By rule *Cons*, we get $\vdash \{P\} C \{Q\}$, which concludes the case. \square

Note that our completeness theorem is not concerned with the expressivity of the assertion language because we use *semantic* hyper-assertions (i.e., functions, see Def. 3). Similarly, by using semantic entailments in the rule *Cons*, we decouple the completeness of Hyper Hoare Logic from the completeness of the logic used to derive entailments.

Interestingly, the logic would *not* be complete without the core rule *Exist*, as we illustrate with the following simple example:

EXAMPLE 1. Let φ_v be the state that maps x to v and all other variables to 0. Let $P_v \triangleq (\lambda S. S = \{\varphi_v\})$. Clearly, the hyper-triples $\{P_0\}$ skip $\{P_0\}$, $\{P_2\}$ skip $\{P_2\}$, $\{P_0\} x := x + 1 \{P_1\}$, and $\{P_2\} x := x + 1 \{P_3\}$ are all valid. We would like to prove the hyper-triple $\{P_0 \vee P_2\}$ skip + $(x := x + 1) \{P_1 \vee P_3\}$. That is, either P_0 holds before, and then we have $S = \{\varphi_0, \varphi_1\}$ afterwards, or P_2 holds before, and then we have $S = \{\varphi_2, \varphi_3\}$ afterwards. However, using the rule *Choice* only, the most precise triple we can prove is

$$\frac{\vdash \{P_0 \vee P_2\} \text{ skip } \{P_0 \vee P_2\} \quad \vdash \{P_0 \vee P_2\} x := x + 1 \{P_1 \vee P_3\}}{\vdash \{P_0 \vee P_2\} \text{ skip } + (x := x + 1) \{(P_0 \vee P_2) \otimes (P_1 \vee P_3)\}} \text{ (Choice)}$$

The postcondition $(P_0 \vee P_2) \otimes (P_1 \vee P_3)$ is equivalent to $(P_0 \otimes P_1) \vee (P_0 \otimes P_3) \vee (P_2 \otimes P_1) \vee (P_2 \otimes P_3)$, i.e., $\lambda S. S = \{\varphi_0, \varphi_1\} \vee S = \{\varphi_0, \varphi_3\} \vee S = \{\varphi_2, \varphi_1\} \vee S = \{\varphi_2, \varphi_3\}$. We thus have two spurious disjuncts, $P_0 \otimes P_3$ (i.e., $S = \{\varphi_0, \varphi_3\}$) and $P_2 \otimes P_1$ (i.e., $S = \{\varphi_2, \varphi_1\}$).

This example shows that the rule *Choice* on its own is not precise enough for the logic to be complete; we need at least a *disjunction* rule to distinguish the two cases P_0 and P_2 . In general, however, there might be an infinite number of cases to consider, which is why we need the rule *Exist*. The premise of this rule allows us to fix a set of states S that satisfies some precondition P and to prove the most precise postcondition for the precondition $\lambda S'. S = S'$; combining these precise postconditions with an existential quantifier in the conclusion of the rule allows us to obtain the most precise postcondition for the precondition P .

For our example, we can use the rule *Exist* with a Boolean b that records whether P_0 or P_2 is satisfied initially, as follows:

$$\frac{\vdash \{(b \Rightarrow P_0) \wedge (\neg b \Rightarrow P_2)\} \text{ skip } \{(b \Rightarrow P_0) \wedge (\neg b \Rightarrow P_2)\} \quad \vdash \{(b \Rightarrow P_0) \wedge (\neg b \Rightarrow P_2)\} x := x + 1 \{(b \Rightarrow P_1) \wedge (\neg b \Rightarrow P_3)\}}{\vdash \{(b \Rightarrow P_0) \wedge (\neg b \Rightarrow P_2)\} \text{ skip } + (x := x + 1) \{((b \Rightarrow P_0) \wedge (\neg b \Rightarrow P_2)) \otimes ((b \Rightarrow P_1) \wedge (\neg b \Rightarrow P_3))\}} \text{ (Choice)}$$

$$\frac{\vdash \{\exists b. (b \Rightarrow P_0) \wedge (\neg b \Rightarrow P_2)\} \text{ skip } + (x := x + 1) \{\exists b. ((b \Rightarrow P_0) \wedge (\neg b \Rightarrow P_2)) \otimes ((b \Rightarrow P_1) \wedge (\neg b \Rightarrow P_3))\}}{= P_0 \vee P_2} \text{ (Exist)}$$

3.5 Expressivity of Hyper-Triples

In the previous subsection, we have shown that Hyper Hoare Logic is sound and complete to establish the validity of hyper-triples, and, thus, Hyper Hoare Logic is as expressive as hyper-triples. We now show that hyper-triples are expressive enough to capture arbitrary hyperproperties over finite program executions. A *hyperproperty* [Clarkson and Schneider 2008] is traditionally defined as a property of sets of *traces* of a system, that is, of sequences of system states. Since Hoare logics typically consider only the initial and final state of a program execution, we use a slightly adapted definition here:

DEFINITION 8. Program hyperproperties. A program hyperproperty is a set of sets of pairs of program states, i.e., an element of $\mathbb{P}(\mathbb{P}(P\text{States} \times P\text{States}))$.

A command C satisfies the program hyperproperty \mathcal{H} iff the set of all pairs of pre- and post-states of C is an element of \mathcal{H} : $\{(\sigma, \sigma') \mid \langle C, \sigma \rangle \rightarrow \sigma' \} \in \mathcal{H}$.

Equivalently, a program hyperproperty can be thought of as a predicate over $\mathbb{P}(P\text{States} \times P\text{States})$. Note that this definition subsumes properties of single executions, such as functional correctness properties.

In contrast to traditional hyperproperties, our program hyperproperties describe only the *finite* executions of a program, that is, those that reach a final state. An extension of Hyper Hoare Logic to infinite executions might be possible by defining hyper-assertions over sets of traces rather than sets of states; we leave this as future work. In the rest of this paper, when the context is clear, we use *hyperproperties* to refer to *program hyperproperties*.

Any program hyperproperty can be expressed as a hyper-triple in Hyper Hoare Logic:

THEOREM 3. *Expressing hyperproperties as hyper-triples.* Let \mathcal{H} be a program hyperproperty. Assume that the cardinality of $L\text{Vars}$ is at least the cardinality of $P\text{Vars}$, and that the cardinality of $L\text{Vals}$ is at least the cardinality of $P\text{Vals}$.

Then there exist hyper-assertions P and Q such that, for any command C , $C \in \mathcal{H}$ iff $\models \{P\} C \{Q\}$.

PROOF SKETCH. We define the precondition P such that the set of initial states contains all program states, and the values of all program variables in these states are recorded in logical variables (which is possible due to the cardinality assumptions). Since the logical variables are not affected by the execution of C , they allow Q to refer to the initial values of any program variable, in addition to their values in the final state. Consequently, Q can describe all possible pairs of pre- and post-states. We simply define Q to be true iff the set of these pairs is contained in \mathcal{H} . \square

We also proved the converse: every hyper-triple describes a program hyperproperty. That is, hyper-triples capture exactly the hyperproperties over finite executions.

THEOREM 4. *Expressing hyper-triples as hyperproperties.* For any hyper-assertions P and Q , there exists a hyperproperty \mathcal{H} such that, for any command C , $C \in \mathcal{H}$ iff $\models \{P\} C \{Q\}$.

PROOF SKETCH. We define $\mathcal{H} \triangleq \{\Sigma \mid \forall S. P(S) \Rightarrow Q(\{(l, \sigma') \mid \exists \sigma. (l, \sigma) \in S \wedge (\sigma, \sigma') \in \Sigma\})\}$. \square

Combined with our completeness result (Thm. 2), this theorem implies that, if a command C satisfies a hyperproperty \mathcal{H} then there exists a proof of it in Hyper Hoare Logic. More surprisingly, our logic also allows us to *disprove* any hyperproperty: If C does *not* satisfy \mathcal{H} then C satisfies the *complement* of \mathcal{H} , which is also a hyperproperty, and thus can also be proved. Consequently, Hyper Hoare Logic can prove or disprove any *program hyperproperty* as defined in Def. 8.

Since hyper-triples express hyperproperties (Thm. 3 and Thm. 4), the ability to disprove any hyperproperty implies that Hyper Hoare Logic can also disprove any *hyper-triple*. More precisely, one can *always* use Hyper Hoare Logic to prove that some hyper-triple $\{P\} C \{Q\}$ is *invalid*, by proving the validity of another hyper-triple $\{P'\} C \{\neg Q\}$, where P' is a satisfiable hyper-assertion that entails P . Conversely, the validity of such a hyper-triple $\{P'\} C \{\neg Q\}$ implies that all hyper-triples $\{P\} C \{Q\}$ (with P weaker than P') are *invalid*. The following theorem precisely expresses this observation:

THEOREM 5. *Disproving hyper-triples.* Given P , C , and Q , the following two propositions are equivalent:

- (1) $\models \{P\} C \{Q\}$ does not hold.
- (2) There exists a hyper-assertion P' that is satisfiable, entails P , and $\models \{P'\} C \{\neg Q\}$.

PROOF SKETCH. By negating Def. 5, we get that point (1) is equivalent to the existence of a set of extended states S such that $P(S)$ holds but $Q(\text{sem}(C, S))$ does not, i.e., $\neg Q(\text{sem}(C, S))$ holds. Let $P' \triangleq (\lambda S'. S = S')$. P' is clearly satisfiable. Moreover, point (1) implies that P' entails P , and that $\models \{P'\} C \{\neg Q\}$ holds. Thus, (1) implies (2).

Assuming (2), we get that there exists a set of extended states S such that $P'(S)$ (since P' is satisfiable) and $\neg Q(\text{sem}(C, S))$ hold. Since P' entails P , $P(S)$ holds, which implies (1). \square

We need to strengthen P to P' in point (2), because there might be some sets S, S' that both satisfy P , such that $Q(\text{sem}(C, S))$ holds, but $Q(\text{sem}(C, S'))$ does not. This was the case for our examples in Sect. 2.2 and Sect. 2.3; for instance, one of the preconditions there was strengthened to include $\exists \langle \varphi_1 \rangle, \langle \varphi_2 \rangle. \varphi_1(h) \neq \varphi_2(h)$.

Thm. 5 is another illustration of the expressivity of Hyper Hoare Logic. The corresponding result does *not* hold in traditional Hoare logics. For example, (1) the classical Hoare triple $\{\top\} x := \text{nonDet}() \{x \geq 5\}$ does not hold, but (2) there is *no* satisfiable P such that $\{P\} x := \text{nonDet}() \{\neg(x \geq 5)\}$ holds. Moreover, to disprove this triple, one needs to show the *existence* of an execution that satisfies the negated postcondition, which is not expressible in HL. In contrast, Hyper Hoare Logic can disprove the classical Hoare triple by proving the hyper-triple $\{\exists \langle \varphi \rangle. \top\} x := \text{nonDet}() \{\neg(\forall \langle \varphi \rangle. \varphi(x) \geq 5)\}$.

The correspondence between hyper-triples and program hyperproperties (Thm. 3 and Thm. 4), together with our completeness result (Thm. 2) precisely characterizes the expressivity of Hyper Hoare Logic. In our extended version [Dardinier and Müller 2023], we show systematic ways to express the judgments of existing over- and underapproximating Hoare logics as hyper-triples.

3.6 Compositionality

The core rules of Hyper Hoare Logic allow one to prove any valid hyper-triple, but not necessarily *compositionally*. As an example, consider the sequential composition of a command C_1 that satisfies *generalized non-interference* (GNI) with a command C_2 that satisfies non-interference (NI). We would like to prove that $C_1; C_2$ satisfies GNI (the weaker property). As discussed in Sect. 2.3, a possible postcondition for C_1 is $\text{GNI}_l^h \triangleq (\forall \langle \varphi_1 \rangle, \langle \varphi_2 \rangle. \exists \langle \varphi \rangle. \varphi_1(h) = \varphi(h) \wedge \varphi(l) = \varphi_2(l))$, while a possible precondition for C_2 is $\text{low}(l) \triangleq (\forall \langle \varphi_1 \rangle, \langle \varphi_2 \rangle. \varphi_1(l) = \varphi_2(l))$. Unfortunately, the corresponding hyper-triples for C_1 and C_2 cannot be composed using the core rules. In particular, rule *Seq* cannot be applied (even in combination with *Cons*), since the postcondition of C_1 does not imply the precondition of C_2 . Note that this observation does *not* contradict completeness: By Thm. 2, it is possible to prove *more precise* triples for C_1 and C_2 , such that the postcondition of C_1 matches the precondition of C_2 . However, to enable modular reasoning, our goal is to construct the proof by composing the given triples for the individual commands rather than deriving new ones.

We have proved (in Isabelle/HOL) a number of useful *compositionality rules* for hyper-triples [Dardinier and Müller 2023]. These rules are *admissible* in Hyper Hoare Logic, in the sense that they do not modify the set of valid hyper-triples that can be proved. Rather, they enable flexible compositions of hyper-triples. As an example, we have proved the following compositionality rule

$$\frac{\vdash \{P\} C \{Q\}}{\vdash \{\bigotimes P\} C \{\bigotimes Q\}} \text{ (BigUnion)}$$

where $\bigotimes P \triangleq (\lambda S. \exists F. (S = \bigcup_{S' \in F} S') \wedge (\forall S' \in F. P(S')))$. This rule is useful when we have a set of states S that does not directly satisfy the precondition P , but that can be decomposed as a *union* of smaller sets S' that individually satisfy P . After executing C , we get a set of states that is a union of smaller sets that individually satisfy Q .

In our aforementioned example, we have a set of states S that satisfies the postcondition $\forall \langle \varphi_1 \rangle, \langle \varphi_2 \rangle. \exists \langle \varphi \rangle. \varphi_1(h) = \varphi(h) \wedge \varphi(l) = \varphi_2(l)$ of C_1 . While S does not necessarily satisfy the precondition $\text{low}(l)$ of C_2 , S can be seen as a union of smaller sets of states $\{\varphi, \varphi_2\}$ that individually satisfy the precondition of C_2 . Thus, using the compositionality rule *BigUnion*, we obtain after C_2 a set of states that is a union of smaller sets that all satisfy the postcondition of C_2 , from which we

$$\frac{}{\vdash \{A_x^e[P]\} x := e \{P\}} \text{(AssignS)} \quad \frac{}{\vdash \{H_x[P]\} x := \text{nonDet}(_)\{P\}} \text{(HavocS)} \quad \frac{}{\vdash \{\Pi_b[P]\} \text{assume } b \{P\}} \text{(AssumeS)}$$

Fig. 3. Some syntactic rules of Hyper Hoare Logic. The syntactic transformations $A_x^e[A]$ and $H_x[A]$ are defined in Def. 10, and the syntactic transformation $\Pi_b[_]$ is defined in Def. 11.

can then prove the desired postcondition GNI_l^h for $C_1; C_2$.⁷ The full proof of this example is shown in our extended version [Dardinier and Müller 2023], along with another challenging example.

4 SYNTACTIC RULES

The core rules presented in Sect. 3 are optimized for expressivity: They are sufficient to prove *any* valid hyper-triple (Thm. 2), but not necessarily in the simplest way. In particular, the rules for atomic statements *Assume*, *Assign*, and *Havoc* require a set comprehension in the precondition, which is necessary when dealing with arbitrary semantic hyper-assertions. However, by imposing syntactic restrictions on hyper-assertions, we can derive simpler rules, as we show in this section. In Sect. 4.1, we define a syntax for hyper-assertions, in which the set of states occurs only as range of universal and existential quantifiers. As we have seen in Sect. 2 and formally show in our extended version [Dardinier and Müller 2023], this syntax is sufficient to capture many useful hyperproperties. Moreover, it allows us to derive simple rules for assignments (Sect. 4.2) and assume statements (Sect. 4.3). All rules presented in this section have been proven sound in Isabelle/HOL.

4.1 Syntactic Hyper-Assertions

We define a restricted class of syntactic hyper-assertions, which can interact with the set of states only through universal and existential quantification over its states:

DEFINITION 9. *Syntactic hyper-expressions and hyper-assertions.*

Hyper-expressions e are defined by the following syntax, where φ ranges over states, x over (program or logical) variables, y over quantified variables, c over literals, \oplus over binary operators (such as $+$, $-$, $*$ for integers, $++$ for lists, etc.), and f denotes functions from values to values (such as len for lists):

$$e ::= c \mid y \mid \varphi^P(x) \mid \varphi^L(x) \mid e \oplus e \mid f(e)$$

Syntactic hyper-assertions A are defined by the following syntax, where e ranges over hyper-expressions, b over boolean literals, and \geq over binary operators (such as $=$, \neq , $<$, $>$, \leq , \geq , \dots):

$$A ::= b \mid e \geq e \mid A \vee A \mid A \wedge A \mid \forall y. A \mid \exists y. A \mid \forall \langle \varphi \rangle. A \mid \exists \langle \varphi \rangle. A$$

Note that *hyper-expressions* are different from *program* expressions, since the latter can only refer to program variables of a *single* implicit state (e.g., $x = y + z$), while the former can explicitly refer to different states (e.g., $\varphi(x) = \varphi'(x)$). Negation $\neg A$ is defined recursively in the standard way. We also define $(A \Rightarrow B) \triangleq (\neg A \vee B)$, $\text{emp} \triangleq (\forall \langle \varphi \rangle. \perp)$, and $\Box p \triangleq (\forall \langle \varphi \rangle. p(\varphi))$, where p is a *state*⁸ expression. The evaluation of hyper-expressions and satisfiability of hyper-assertions are formally defined in our extended version [Dardinier and Müller 2023].

4.2 Syntactic Rules for Deterministic and Non-Deterministic Assignments

In classical Hoare logic, we obtain the precondition of the rule for the assignment $x := e$ by substituting x by e in the postcondition. The Hyper Hoare Logic syntactic rule for assignments

⁷We also need to prove that C_2 does not drop executions depending on the value of h .

⁸State expressions refer to a single (implicit) state. In contrast to program expressions, they may additionally refer to logical variables and use quantifiers over values.

AssignS (Fig. 3) generalizes this idea by repeatedly applying this substitution for *every quantified state*. This syntactic transformation, written $\mathcal{A}_x^e[_]$ is defined below. As an example, for the assignment $x := y + z$ and postcondition $\exists\langle\varphi\rangle. \forall\langle\varphi'\rangle. \varphi(x) \leq \varphi'(x)$, we obtain the precondition $\mathcal{A}_x^{y+z}[\exists\langle\varphi\rangle. \forall\langle\varphi'\rangle. \varphi(x) \leq \varphi'(x)] = (\exists\langle\varphi\rangle. \forall\langle\varphi'\rangle. \varphi(y) + \varphi(z) \leq \varphi'(y) + \varphi'(z))$.

Similarly, our syntactic rule for non-deterministic assignments *HavocS* substitutes every occurrence of $\varphi(x)$, for every quantified state φ , by a fresh quantified variable v . This variable is universally quantified for universally-quantified states, capturing the intuition that we must consider all possible assigned values. In contrast, v is existentially quantified for existentially-quantified states, because it is sufficient to find one suitable behavior of the non-deterministic assignment. As an example, for the non-deterministic assignment $x := \text{nonDet}()$ and the aforementioned postcondition, we obtain the precondition $\mathcal{H}_x[\exists\langle\varphi\rangle. \forall\langle\varphi'\rangle. \varphi(x) \leq \varphi'(x)] = (\exists\langle\varphi\rangle. \exists v. \forall\langle\varphi'\rangle. \forall v'. v \leq v')$.

DEFINITION 10. Syntactic transformations for assignments.

$\mathcal{A}_x^e[A]$ yields the hyper-assertion A , where $\varphi(x)$ is syntactically substituted by $e(\varphi)$ for all (existentially or universally) quantified states φ . The two main cases are:

$$\mathcal{A}_x^e[\forall\langle\varphi\rangle. A] \triangleq (\forall\langle\varphi\rangle. \mathcal{A}_x^e[A[e(\varphi)/\varphi(x)]]) \quad \mathcal{A}_x^e[\exists\langle\varphi\rangle. A] \triangleq (\exists\langle\varphi\rangle. \mathcal{A}_x^e[A[e(\varphi)/\varphi(x)]])$$

where $A[y/x]$ refers to the standard syntactic substitution of x by y . Other cases apply \mathcal{A}_x^e recursively (e.g., $\mathcal{A}_x^e[A \wedge B] \triangleq \mathcal{A}_x^e[A] \wedge \mathcal{A}_x^e[B]$). See [Dardinier and Müller \[2023\]](#) for the full definition.

$\mathcal{H}_x[A]$ yields the hyper-assertion A where $\varphi(x)$ is syntactically substituted by a fresh quantified variable v , universally (resp. existentially) quantified for universally (resp. existentially) quantified states. The two main cases are (where v is fresh):

$$\mathcal{H}_x[\forall\langle\varphi\rangle. A] \triangleq (\forall\langle\varphi\rangle. \forall v. \mathcal{H}_x[A[v/\varphi(x)]]) \quad \mathcal{H}_x[\exists\langle\varphi\rangle. A] \triangleq (\exists\langle\varphi\rangle. \exists v. \mathcal{H}_x[A[v/\varphi(x)]])$$

Other cases apply \mathcal{H}_x recursively. See [Dardinier and Müller \[2023\]](#) for the full definition.

4.3 Syntactic Rules for Assume Statements

Intuitively, **assume** b provides additional information when proving properties for *all* states, but imposes an additional requirement when proving *the existence* of a state. This intuition is captured by the rule *AssumeS* shown in Fig. 3. The syntactic transformation Π_b adds the state expression b as an assumption for universally-quantified states, and as a proof obligation for existentially-quantified states. As an example, for the statement **assume** $x \geq 0$ and the postcondition $\forall\langle\varphi\rangle. \exists\langle\varphi'\rangle. \varphi(x) \leq \varphi'(x)$, we obtain the precondition $\Pi_{x \geq 0}[\forall\langle\varphi\rangle. \exists\langle\varphi'\rangle. \varphi(x) \leq \varphi'(x)] = (\forall\langle\varphi\rangle. \varphi(x) \geq 0 \Rightarrow (\exists\langle\varphi'\rangle. \varphi'(x) \geq 0 \wedge \varphi(x) \leq \varphi'(x)))$.

DEFINITION 11. Syntactic transformation for assume statements.

The two main cases of Π_b are

$$\Pi_b[\forall\langle\varphi\rangle. A] \triangleq (\forall\langle\varphi\rangle. b(\varphi) \Rightarrow \Pi_b[A]) \quad \Pi_b[\exists\langle\varphi\rangle. A] \triangleq (\exists\langle\varphi\rangle. b(\varphi) \wedge \Pi_b[A])$$

Other cases apply Π_b recursively. See [Dardinier and Müller \[2023\]](#) for the full definition.

Example. We now illustrate the use of our three syntactic rules for atomic statements in Fig. 4, to prove that the program $C_4 \triangleq (y := \text{nonDet}(); \text{assume } y \leq 9; l := h + y)$ from Sect. 2.2 violates GNI. This program leaks information about the secret h through its public output l because the pad it uses (variable y) is upper bounded. From the output l , we can derive a lower bound for the secret value of h , namely $h \geq l - 9$.

To see why C_4 violates GNI, consider two executions with different secret values for h , and where the execution for the larger secret value sets y to exactly 9. This execution will produce a larger public output l (since the other execution adds at most 9 to its smaller secret). Hence, these executions can be *distinguished* by their public outputs.

```

{ $\exists \langle\varphi_1\rangle, \langle\varphi_2\rangle. \varphi_1(h) \neq \varphi_2(h)$ } 
{ $\exists \langle\varphi_1\rangle. (\exists \langle\varphi_2\rangle. (\forall \langle\varphi\rangle. \forall v. v \leq 9 \Rightarrow (\varphi(h) = \varphi_1(h) \Rightarrow \varphi_2(h) + 9 > \varphi(h) + v)))$ } (Cons)
{ $\exists \langle\varphi_1\rangle. \exists v_1. v_1 \leq 9 \wedge (\exists \langle\varphi_2\rangle. \exists v_2. v_2 \leq 9 \wedge (\forall \langle\varphi\rangle. \forall v. v \leq 9 \Rightarrow ((\varphi(h) \neq \varphi_1(h)) \vee (\varphi(h) + v \neq \varphi_2(h) + v_2))))$ } (Cons)
y := nonDet();
{ $\exists \langle\varphi_1\rangle. \varphi_1(y) \leq 9 \wedge (\exists \langle\varphi_2\rangle. \varphi_2(y) \leq 9 \wedge (\forall \langle\varphi\rangle. \varphi(y) \leq 9 \Rightarrow (\varphi(h) \neq \varphi_1(h) \vee \varphi(h) + \varphi(y) \neq \varphi_2(h) + \varphi_2(y))))$ } (HavocS)
assume y ≤ 9;
{ $\exists \langle\varphi_1\rangle, \langle\varphi_2\rangle. \forall \langle\varphi\rangle. \varphi(h) \neq \varphi_1(h) \vee \varphi(h) + \varphi(y) \neq \varphi_2(h) + \varphi_2(y)$ } (AssumeS)
l := h + y
{ $\exists \langle\varphi_1\rangle, \langle\varphi_2\rangle. \forall \langle\varphi\rangle. \varphi(h) \neq \varphi_1(h) \vee \varphi(l) \neq \varphi_2(l)$ } (AssignS)

```

Fig. 4. Proof outline showing that the program *violates* generalized non-interference. The rules used at each step of the derivation are shown on the right (the use of rule *Seq* is implicit).

Our proof outline in Fig. 4 captures this intuitive reasoning in a natural way. We start with the postcondition that corresponds to the negation of GNI, and work our way backward, by successively applying our syntactic rules *AssignS*, *AssumeS*, and *HavocS*. We conclude using the rule *Cons*: Since the precondition implies the existence of two states with different values for h , we first instantiate φ_1 and φ_2 such that φ_1 and φ_2 are both members of the set of initial states, and $\varphi_2(h) > \varphi_1(h)$.⁹ We then instantiate $v_2 = 9$, such that, for any $v \leq 9$, $\varphi_2(h) + v_2 > \varphi(h) + v$, which concludes the proof.

5 PROOF PRINCIPLES FOR LOOPS

To reason about standard while loops, we can derive from the core rule *Iter* in Fig. 2 the rule *WhileDesugared*, shown in Fig. 5 (recall that $\text{while } (b) \{C\} \triangleq (\text{assume } b; C)^*$; $\text{assume } \neg b$). While this derived rule is expressive, it has two main drawbacks for usability: (1) Because of the use of the infinitary $\bigotimes_{n \in \mathbb{N}}$, it requires non-trivial *semantic* reasoning (via the consequence rule), and (2) the invariant I_n relates only the executions that perform *at least* n iterations, but ignores executions that perform fewer.

To illustrate problem (2), imagine that we want to prove that the hyper-assertion $low(l) \triangleq (\forall \langle\varphi\rangle. \forall \langle\varphi'\rangle. \varphi(l) = \varphi'(l))$ holds after a while loop. A natural choice for our loop invariant I_n would be $I_n \triangleq low(l)$ (independent of n). However, this invariant does *not* entail our desired postcondition $low(l)$. Indeed, $\bigotimes_{n \in \mathbb{N}} low(l)$ holds for a set of states iff it is a *union* of sets of states that all *individually* satisfy $low(l)$. This property holds trivially in our example (simply choose one set per possible value of l) and, in particular, does not express that the entire set of states after the loop satisfies $low(l)$. Note that this does not contradict completeness (Thm. 2), but simply means that a stronger invariant I_n is needed.

In this section, we thus present three more convenient loop rules, shown in Fig. 5, which capture powerful reasoning principles, and overcome those limitations: The rule *WhileSync* (Sect. 5.1) is the easiest to use, and can be applied whenever all executions of the loop have the same control flow. Two additional rules for while loops can be applied whenever the control flow differs. The rule *While- $\forall^*\exists^*$* (Sect. 5.2) supports $\forall^*\exists^*$ postconditions, while the rule *While- \exists* (Sect. 5.3) handles postconditions with a top-level existential quantifier. In our experience, these loop rules cover all practical hyper-assertions that can be expressed in our syntax. We are not aware of any practical program hyperproperty that requires multiple quantifier alternations.

⁹Note that the quantified states φ_1 , φ_2 and φ from different hyper-assertions can be unrelated. That is, the witnesses for φ_1 and φ_2 in the first hyper-assertion [$\exists \langle\varphi_1\rangle, \langle\varphi_2\rangle. \varphi_1(h) \neq \varphi_2(h)$] are not necessarily the same as the ones in the second hyper-assertion [$\exists \langle\varphi_1\rangle. \exists \langle\varphi_2\rangle. \varphi_2(h) > \varphi_1(h)$], which is why the entailment holds.

$$\begin{array}{c}
 \frac{\vdash \{I_n\} \text{ assume } b; C \{I_{n+1}\} \quad \vdash \{\bigotimes_{n \in \mathbb{N}} I_n\} \text{ assume } \neg b \{Q\}}{\vdash \{I_0\} \text{ while } (b) \{C\} \{Q\}} \text{ (WhileDesugared)} \\
 \\
 \frac{I \models low(b) \quad \vdash \{I \wedge \square b\} C \{I\} \quad P \models low(b) \quad \vdash \{P \wedge \square b\} C_1 \{Q\} \quad \vdash \{P \wedge \square(\neg b)\} C_2 \{Q\}}{\vdash \{P\} \text{ if } (b) \{C_1\} \text{ else } \{C_2\} \{Q\}} \text{ (IfSync)} \\
 \\
 \frac{\vdash \{I\} \text{ if } (b) \{C\} \{I\} \quad \vdash \{I\} \text{ assume } \neg b \{Q\} \quad \text{no } \forall \langle _ \rangle \text{ after any } \exists \text{ in } Q}{\vdash \{I\} \text{ while } (b) \{C\} \{Q\}} \text{ (While-V* } \exists^*) \\
 \\
 \frac{\forall v. \vdash \{\exists \langle \varphi \rangle. P_\varphi \wedge b(\varphi) \wedge v = e(\varphi)\} \text{ if } (b) \{C\} \{\exists \langle \varphi \rangle. P_\varphi \wedge e(\varphi) < v\} \quad \forall \varphi. \vdash \{P_\varphi\} \text{ while } (b) \{C\} \{Q_\varphi\} \quad < \text{wf}}{\vdash \{\exists \langle \varphi \rangle. P_\varphi\} \text{ while } (b) \{C\} \{\exists \langle \varphi \rangle. Q_\varphi\}} \text{ (While-} \exists)
 \end{array}$$

Fig. 5. Hyper Hoare Logic rules for while loops (and branching). Recall that $low(b) \triangleq (\forall \langle \varphi \rangle, \langle \varphi' \rangle. b(\varphi) = b(\varphi'))$ and $\square b \triangleq (\forall \langle \varphi \rangle. b(\varphi))$. In the rule *WhileSync*, $<$ must be *well-founded* (*wf*).

5.1 Synchronized Control Flow

Standard loop invariants are sound in relational logics if all executions exit the loop *simultaneously* [Benton 2004; Terauchi and Aiken 2005]. In our logic, this synchronized control flow can be enforced by requiring that the loop guard b has the same value in all states (1) before the loop and (2) after every loop iteration, as shown by the rule *WhileSync* in Fig. 5. After the loop, we get to assume $(I \vee emp) \wedge \square(\neg b)$. That is, the loop guard b is false in all executions, and the invariant I holds, or the set of states is empty. The *emp* disjunct corresponds to the case where the loop does not terminate (i.e., *no* execution terminates). Going back to our motivating example, the natural invariant $I \triangleq low(l)$ with the rule *WhileSync* is now sufficient for our example, since we get the postcondition $(low(l) \vee emp) \wedge \square(\neg b)$, which implies our desired (universally-quantified) postcondition $low(l)$. In the case where the desired postcondition quantifies existentially over states at the top-level, it is necessary to prove that at least one execution terminates. We show the corresponding rule in our extended version [Dardinier and Müller 2023].

We also provide a rule for if statements with synchronized control flow (rule *IfSync* in Fig. 5), which can be applied when all executions take the same branch. This rule is simpler to apply than the core rule *Choice*, since it avoids the \otimes operator, which usually requires semantic reasoning.

Example. The program in Fig. 6 takes as input a list h of secret values (but whose length is public), computes its prefix sum $[h[0], h[0] + h[1], \dots]$, and encrypts the result by performing a one-time pad on each element of this prefix sum, resulting in the output $[h[0] \oplus k_0, (h[0] + h[1]) \oplus k_1, \dots]$. The keys k_0, k_1, \dots are chosen non-deterministically at each iteration, via the variable k .¹⁰

Our goal is to prove that the encrypted output l does not leak information about the secret elements of h , provided that the attacker does not have any information about the non-deterministically chosen keys. We achieve this by formally proving that this program satisfies GNI. Since the length of the list h is public, we start with the precondition $\forall \langle \varphi_1 \rangle, \langle \varphi_2 \rangle. len(\varphi_1(h)) = len(\varphi_2(h))$. This implies that all our executions will perform the same number of loop iterations. Thus, we use the rule *WhileSync*, with the natural loop invariant $I \triangleq (\forall \langle \varphi_1 \rangle, \langle \varphi_2 \rangle. \varphi_1(i) = \varphi_2(i) \wedge len(\varphi_1(h)) = len(\varphi_2(h)) \wedge (\exists \langle \varphi \rangle. \varphi(h) = \varphi_1(h) \wedge \varphi(l) = \varphi_2(l)))$. The last conjunct corresponds to the postcondition we want to prove, while the former entails $low(i < len(h))$, as required by the rule *WhileSync*.

The proof of the loop body starts at the end with the loop invariant I , and works backward, using the syntactic rules *HavocS* and *AssignS*. From $I \wedge \square(i < len(h))$, we have to prove that there exists a value v such that $\varphi(l) ++ [(\varphi(s) + \varphi(h)[\varphi(i)]) \oplus v] = \varphi_2(l) ++ [(\varphi_2(s) + \varphi_2(h)[\varphi_2(i)]) \oplus v_2]$. Since

¹⁰In practice, the keys used in this program should be stored somewhere, so that one is later able to decrypt the output.

```

 $\{\forall \langle\varphi_1\rangle, \langle\varphi_2\rangle. \text{len}(\varphi_1(h)) = \text{len}(\varphi_2(h))\}$ 
 $\{\forall \langle\varphi_1\rangle, \langle\varphi_2\rangle. 0 = 0 \wedge \text{len}(\varphi_1(h)) = \text{len}(\varphi_2(h)) \wedge (\exists \langle\varphi\rangle. \varphi(h) = \varphi_1(h) \wedge [] = [])\}$  (Cons)

 $s := 0$ 
 $l := []$ 
 $i := 0$ 
 $\{\forall \langle\varphi_1\rangle, \langle\varphi_2\rangle. \varphi_1(i) = \varphi_2(i) \wedge \text{len}(\varphi_1(h)) = \text{len}(\varphi_2(h)) \wedge (\exists \langle\varphi\rangle. \varphi(h) = \varphi_1(h) \wedge \varphi(l) = \varphi_2(l))\}$  (AssignS)
while ( $i < \text{len}(h)$ ) {
   $\{\forall \langle\varphi_1\rangle, \langle\varphi_2\rangle. \varphi_1(i) = \varphi_2(i) \wedge \text{len}(\varphi_1(h)) = \text{len}(\varphi_2(h)) \wedge (\exists \langle\varphi\rangle. \varphi(h) = \varphi_1(h) \wedge \varphi(l) = \varphi_2(l)) \wedge \square(i < \text{len}(h))\}$ 
   $\{\forall \langle\varphi_1\rangle. \forall v_1. \forall \langle\varphi_2\rangle. \forall v_2. \varphi_1(i) + 1 = \varphi_2(i) + 1 \wedge \text{len}(\varphi_1(h)) = \text{len}(\varphi_2(h))\}$ 
   $\{\exists \langle\varphi\rangle. \exists v. \varphi(h) = \varphi_1(h) \wedge \varphi(l) \text{++} [(\varphi(s) + \varphi(h)[\varphi(i)]) \oplus v] = \varphi_2(l) \text{++} [(\varphi_2(s) + \varphi_2(h)[\varphi_2(i)]) \oplus v_2]\}$  (Cons)
   $s := s + h[i];$ 
   $k := \text{nonDet}();$ 
   $l := l \text{++} [s \oplus k];$ 
   $i := i + 1;$ 
   $\{\forall \langle\varphi_1\rangle, \langle\varphi_2\rangle. \varphi_1(i) = \varphi_2(i) \wedge \text{len}(\varphi_1(h)) = \text{len}(\varphi_2(h)) \wedge (\exists \langle\varphi\rangle. \varphi(h) = \varphi_1(h) \wedge \varphi(l) = \varphi_2(l))\}$  (HavocS, AssignS)
}
 $\{((\forall \langle\varphi_1\rangle, \langle\varphi_2\rangle. \varphi_1(i) = \varphi_2(i) \wedge \text{len}(\varphi_1(h)) = \text{len}(\varphi_2(h)) \wedge (\exists \langle\varphi\rangle. \varphi(h) = \varphi_1(h) \wedge \varphi(l) = \varphi_2(l))) \vee \text{emp}) \wedge \square(i \geq \text{len}(h))\}$  (WhileSync)
 $\{\forall \langle\varphi_1\rangle, \langle\varphi_2\rangle. \exists \langle\varphi\rangle. \varphi(h) = \varphi_1(h) \wedge \varphi(l) = \varphi_2(l)\}$  (Cons)

```

Fig. 6. A proof that the program in black satisfies generalized non-interference (where the elements of list h are secret, but its length is public), using the rule *WhileSync*. $[]$ represents the empty list, ++ represents list concatenation, $h[i]$ represents the i -th element of list h , and \oplus represents the XOR operator.

$\varphi(l) = \varphi_2(l)$, this boils down to proving that $(\varphi(s) + \varphi(h)[\varphi(i)]) \oplus v = (\varphi_2(s) + \varphi_2(h)[\varphi_2(i)]) \oplus v_2$, which we achieve by choosing $v \triangleq (\varphi_2(s) + \varphi_2(h)[\varphi_2(i)]) \oplus v_2 \oplus (\varphi(s) + \varphi(h)[\varphi(i)])$.

5.2 $\forall^*\exists^*$ -Hyperproperties

Let us now turn to the more general case, where different executions might exit the loop at different iterations. As explained at the start of this section, the main usability issue of the rule *WhileDesugared* is the precondition $\bigotimes_{n \in \mathbb{N}} I_n$ in the second premise, which requires non-trivial semantic reasoning. The $\bigotimes_{n \in \mathbb{N}}$ operator is required, because I_n ignores executions that exited the loop earlier; it relates only the executions that have performed *at least* n iterations. In particular, it would be unsound to replace the precondition $\bigotimes_{n \in \mathbb{N}} I_n$ by $\exists n. I_n$.

The rule *While- $\forall^*\exists^*$* in Fig. 5 solves this problem for the general case of $\forall^*\exists^*$ -postconditions. The key insight is to reason about the successive *unrollings* of the while loop: The rule requires to prove an invariant I for the conditional statement **if** (b) { C }, in contrast to **assume** b ; C in the rule *WhileDesugared*. This allows the invariant I to refer to *all* executions, i.e., executions that are still running the loop (which will execute C), and executions that have already exited the loop (which will not execute C).

Example. The program C_{fib} in Fig. 7 takes as input an integer $n \geq 0$ and computes the n -th Fibonacci number (in variable a). We want to prove that C_{fib} is monotonic, i.e., that the n -th Fibonacci number is greater than or equal to the m -th Fibonacci number whenever $n \geq m$, without making explicit what C_{fib} computes. Formally, we want to prove the hypertriple

$\{\forall \langle\varphi_1\rangle, \langle\varphi_2\rangle. \varphi_1(t) = 1 \wedge \varphi_2(t) = 2 \Rightarrow \varphi_1(n) \geq \varphi_2(n)\} C_{fib} \{\forall \langle\varphi_1\rangle, \langle\varphi_2\rangle. \varphi_1(t) = 1 \wedge \varphi_2(t) = 2 \Rightarrow \varphi_1(a) \geq \varphi_2(a)\}$,
where t is a logical variable used to track the execution (as explained in Sect. 2.2).

```

 $a := 0;$ 
 $b := 1;$ 
 $i := 0;$ 
while ( $i < n$ ) {
   $tmp := b;$ 
   $b := a + b;$ 
   $a := tmp;$ 
   $i := i + 1$ 
}

```

Fig. 7. The program C_{fib} , which computes the n -th Fibonacci number.

Intuitively, this program is monotonic because both executions will perform at least $\varphi_2(n)$ iterations, during which they will have the same values for a and b . The first execution will then perform $\varphi_1(n) - \varphi_2(n)$ additional iterations, during which a and b will increase, thus resulting in larger values for a and b .

We cannot use the rule *WhileSync* to make this intuitive argument formal, since both executions might perform a different number of iterations. Moreover, we cannot express this intuitive argument with the rule *WhileDesugared* either, since the invariant I_k only relates executions that perform *at least k iterations*, as explained earlier: After the first $\varphi_2(n)$ iterations, the loop invariant I_k cannot refer to the values of a and b in the second execution, since this execution has already exited the loop.

However, we can use the rule *While- $\forall^*\exists^*$* to prove that C_{fib} is monotonic, with the intuitive loop invariant $I \triangleq (\forall\langle\varphi_1\rangle,\langle\varphi_2\rangle. \varphi_1(t)=1 \wedge \varphi_2(t)=2 \Rightarrow (\varphi_1(n)-\varphi_1(i) \geq \varphi_2(n)-\varphi_2(i) \wedge \varphi_1(a) \geq \varphi_2(a) \wedge \varphi_1(b) \geq \varphi_2(b)) \wedge \Box(b \geq a \geq 0))$. The first part captures the relation between the two executions: a and b are larger in the first execution than in the second one, and the first execution does at least as many iterations as the second one. The second part $\Box(b \geq a \geq 0)$ is needed to prove that the additional iterations lead to larger values for a and b . The proof of this example is in our extended version [Dardinier and Müller 2023].

Restriction to \forall^\exists^* -hyperproperties.* The rule *While- $\forall^*\exists^*$* is quite general and powerful, since it can be applied to prove any postcondition of the shape $\forall^*\exists^*$, which includes *all* safety hyperproperties, as well as some liveness hyperproperties such as GNI. However, it cannot be applied for postconditions with a top-level existential quantification over states, because this would be unsound. Indeed, a triple such as $\vdash \{\exists\langle\varphi\rangle. \forall\langle\varphi'\rangle. I\}$ if (b) $\{C\} \{\exists\langle\varphi\rangle. \forall\langle\varphi'\rangle. I\}$ implies that, for any n , there exists a state φ such that I holds for all states φ' reached after *unrolling the loop n times*. The key issue is that φ might not be a valid witness for states φ' reached after *more than n loop unrollings*, and therefore we might have different witnesses for φ for each value of n . We thus have no guarantee that there is a *global* witness that works for all states φ' after any *number* of loop unrollings. To handle such examples, we present a rule for $\exists^*\forall^*$ -hyperproperties next.

5.3 $\exists^*\forall^*$ -Hyperproperties

The rule *While- $\forall^*\exists^*$* can be applied for any postcondition of the form $\forall^*\exists^*$, which includes all safety hyperproperties as well as some liveness hyperproperties such as GNI, but cannot be applied to prove postconditions with a top-level existential quantifier, such as postconditions of the shape $\exists^*\forall^*$ (e.g., to prove the existence of minimal executions, or to prove that a $\forall^*\exists^*$ -hyperproperty is violated). In this case, we can apply the rule *While- \exists* in Fig. 5. To the best of our knowledge, this is the first program logic rule that can deal with $\exists^*\forall^*$ -hyperproperties for loops. This rule splits the reasoning into two parts: First, we prove that there is a *terminating* state φ such that the hyper-assertion P_φ holds after some number of loop unrollings. This is achieved via the first premise of the rule, which requires a well-founded relation $<$, and a variant $e(\varphi)$ that strictly decreases at each iteration, until $b(\varphi)$ becomes false and φ exits the loop.¹¹ In a second step, we fix the state φ (since it has exited the loop), which corresponds to our global witness, and prove $\vdash \{P_\varphi\} \text{while } (b) \{C\} \{Q_\varphi\}$ using any loop rule. For example, if P_φ has another top-level existential quantifier, we can apply the rule *While- \exists* once more; if P_φ is a $\forall^*\exists^*$ -hyper-assertion, we can apply the rule *While- $\forall^*\exists^*$* .

¹¹Note that the existentially-quantified state φ in the postcondition of the first premise of the rule *While- \exists* does *not* have to be from the same execution as the one in the precondition.

As an example, consider proving that the program C_m in Fig. 8 has a final state with a minimal value for x and y . Formally, we want to prove the triple $\{\neg \text{emp} \wedge \square(k \geq 0)\} C_m \{\exists \langle\varphi\rangle. \forall \langle\alpha\rangle. \varphi(x) \leq \alpha(x) \wedge \varphi(y) \leq \alpha(y)\}$. Since the set of initial states is not empty and k is always non-negative, we know that there is an initial state with a minimal value for k . We prove that this state leads to a final state with minimal values for x and y , using the rule *While- \exists* . For the first premise, we choose the variant¹² $k - i$, and the invariant $P_\varphi \triangleq (\forall \langle\alpha\rangle. 0 \leq \varphi(x) \leq \alpha(x) \wedge 0 \leq \varphi(y) \leq \alpha(y) \wedge \varphi(k) \leq \alpha(k) \wedge \varphi(i) = \alpha(i))$, capturing both that φ has minimal values for x and y , but also that φ will be the first state to exit the loop. We prove that this is indeed an invariant for the loop, by choosing $r = 2$ for the non-deterministic assignment for φ . Finally, we prove the second premise with $Q_\varphi \triangleq (\forall \langle\alpha\rangle. 0 \leq \varphi(x) \leq \alpha(x) \wedge 0 \leq \varphi(y) \leq \alpha(y))$ and the rule *While- $\forall^*\exists^*$* . The proof of this example is in our extended version.

```

x := 0;
y := 0;
i := 0;
while (i < k) {
    r := nonDet();
    assume r ≥ 2;
    t := x;
    x := 2 * x + r;
    y := y + t * r;
    i := i + 1
}

```

Fig. 8. A program with a final state with minimal values for x and y .

6 RELATED WORK

Overapproximate (relational) Hoare logics. Hoare Logic originated with the seminal works of Floyd [1967] and Hoare [1969], with the goal of proving programs functionally correct. Relational Hoare Logic [Benton 2004] (RHL) extends Hoare Logic to reason about (2-safety) hyperproperties of a single program as well as properties relating the executions of two different programs (e.g., semantic equivalence). RHL’s ability to relate the executions of two different programs is also useful in the context of proving 2-safety hyperproperties of a single program, in particular, when the two executions take different branches of a conditional statement. In comparison, Hyper Hoare Logic can prove and disprove hyperproperties of a single program (Sect. 3.5), but requires a program transformation to express relational properties (see our extended version [Dardinier and Müller 2023]). Extending Hyper Hoare Logic to multiple programs is interesting future work.

RHL has been extended in many ways, for example to deal with heap-manipulating [Yang 2007] and higher-order [Aguirre et al. 2017] programs. A family of Hoare and separation logics [Amtoft et al. 2006; Costanzo and Shao 2014; Eilers et al. 2023; Ernst and Murray 2019] designed to prove non-interference [Volpano et al. 1996] specializes RHL by considering triples with a single program, similar to Hyper Hoare Logic. Naumann [2020] provides an overview of the principles underlying relational Hoare logics. Cartesian Hoare Logic [Sousa and Dillig 2016] (CHL) extends RHL to reason about hyperproperties of k executions, with a focus on automation and scalability. CHL has recently been reframed [D’Osualdo et al. 2022] as a weakest-precondition calculus, increasing its support for proof compositionality. Hyper Hoare Logic can express the properties supported by CHL, in addition to many other properties; automating Hyper Hoare Logic is future work.

Underapproximate program logics. Reverse Hoare Logic [de Vries and Koutavas 2011] is an underapproximate variant of Hoare Logic, designed to prove the existence of good executions. The recent Incorrectness Logic [O’Hearn 2019] adapts this idea to prove the presence of bugs. Incorrectness Logic has been extended with concepts from separation logic to reason about heap-manipulating sequential [Raad et al. 2020] and concurrent [Raad et al. 2022] programs. It has also been extended to prove the presence of insecurity in a program (i.e., to disprove 2-safety hyperproperties) [Murray 2020]. Underapproximate logics have been successfully used as foundation of industrial bug-finding tools [Blackshear et al. 2018; Distefano et al. 2019; Gorogiannis et al. 2019; Le et al. 2022]. Hyper Hoare Logic enables proving and disproving hyperproperties within the same logic.

¹²We interpret $<$ as $<$ between natural numbers, i.e., $a < b$ iff $0 \leq a$ and $a < b$, which is well-founded.

Several recent works have proposed approaches to unify over- and underapproximate reasoning. Exact Separation Logic [Maksimović et al. 2023] can establish both overapproximate and (backward) underapproximate properties over single executions of heap-manipulating programs, by employing triples that describe *exactly* the set of reachable states. Local Completeness Logic [Bruni et al. 2021, 2023] unifies over- and underapproximate reasoning in the context of abstract interpretation, by building on Incorrectness Logic, and enforcing a notion of *local completeness* (no false alarm should be produced relative to some fixed input). HL and IL have been both embedded in a Kleene algebra with diamond operators and countable joins of tests [Möller et al. 2021]. Dynamic Logic [Harel 1979] is an extension of modal logic that can express both overapproximate and underapproximate guarantees over single executions of a program.

Outcome Logic [Zilberstein et al. 2023] (OL) unifies overapproximate and (forward) underapproximate reasoning for heap-manipulating and probabilistic programs, by combining and generalizing the standard overapproximate Hoare triples with forward underapproximate triples. OL (instantiated to the powerset monad) uses a semantic model similar to our extended semantics (Def. 4), and a similar definition for triples (Def. 5). Moreover, a theorem similar to our Thm. 5 holds in OL, i.e., invalid OL triples can be disproven within OL. The key difference with Hyper Hoare Logic is that OL does not support reasoning about hyperproperties. OL assertions are composed of atomic unary assertions, which can express the existence and the absence of certain states, but not relate states with each other, which is key to expressing hyperproperties. OL does not provide logical variables, on which we rely to express certain hyperproperties (see Sect. 2.2).

Logics for \forall^\exists^* -hyperproperties.* Maillard et al. [2019] present a general framework for defining relational program logics for arbitrary monadic effects (such as state, input-output, nondeterminism, and discrete probabilities), for two executions of two (potentially different) programs. Their key idea is to map *pairs* of (monadic) computations to relational specifications, using relational effect observations. In particular, they discuss instantiations for $\forall\forall$ -, $\forall\exists$ -, and $\exists\exists$ -hyperproperties. RHLE [Dickerson et al. 2022] supports overapproximate and (a limited form of) underapproximate reasoning, as it can establish $\forall^*\exists^*$ -hyperproperties, such as generalized non-interference (Sect. 2.3) and program refinement. BiKAT [Antonopoulos et al. 2023], an algebra of alignment for relational verification, can be used directly to prove $\forall\forall$ -properties. Moreover, $\forall\exists$ -properties between two programs C_1 and C_2 can also be proved with BiKAT, by proving that a corresponding $\forall\forall$ -property holds for some *alignment witness*, i.e., a program that overapproximates the behavior of C_1 while underapproximating the behavior of C_2 . All three frameworks can be used to reason about relational properties of multiple programs, whereas Hyper Hoare Logic requires a program transformation to handle such properties. On the other hand, our logic supports a wider range of underapproximate reasoning and can express properties not handled by any of them, e.g., $\exists^*\forall^*$ -hyperproperties and hyperproperties relating an unbounded or infinite number of executions. Moreover, even for $\forall^*\exists^*$ -hyperproperties, Hyper Hoare Logic provides while loop rules that have no equivalent in these logics, such as the rules *While*- \exists (useful in this context for \exists^* -hyperproperties) and *While*- $\forall^*\exists^*$ (Sect. 5).

Note that one can in principle use BiKAT to prove $\exists\forall$ -properties, by essentially proving the negation of $\forall\exists$ -properties: To prove that an $\exists\forall$ -property between two programs C_1 and C_2 holds, one needs to consider all programs W that overapproximate the behavior of C_1 and underapproximate the behavior of C_2 , and prove that W does *not* satisfy a $\forall\forall$ -property.

Probabilistic Hoare logics. Many assertion-based logics for probabilistic programs have been proposed [Barthe et al. 2018, 2019b; Corin and Den Hartog 2006; Den Hartog and de Vink 2002; Ramshaw 1979; Rand and Zdancewic 2015]. These logics typically employ assertions over *probability (sub-)distributions* of states, which bear some similarities to hyper-assertions: Asserting the existence

(resp. absence) of a state is analogous to asserting that the probability of this state is strictly positive (resp. zero). Taking the union of two sets of states is analogous to taking the sum of two sub-distributions. Our operator \otimes (Def. 6) used in the rule *Choice* is thus similar to the operator \oplus from Barthe et al. [2018]. Notably, our loop rule *While*- $\forall^*\exists^*$ draws some inspiration from the rule *While* of Barthe et al. [2018], which also requires an invariant that holds for all *unrollings* of the loop. These probabilistic logics have also been extended to the relational setting [Barthe et al. 2009], for instance to reason about the equivalence of probabilistic programs.

Verification of hyperproperties. The concept of hyperproperties has been formalized by Clarkson and Schneider [2008]. Verifying that a program satisfies a k -safety hyperproperty can be reduced to verifying a safety property of the *self-composition* of the program [Barthe et al. 2011b; Terauchi and Aiken 2005] (e.g., by sequentially composing the program with renamed copies of itself). Self-composition has been generalized to product programs [Barthe et al. 2011a; Eilers et al. 2019]. (Extensions of) product programs have also been used to verify relational properties such as program refinement [Barthe et al. 2013] and probabilistic relational properties such as differential privacy [Barthe et al. 2014]. The temporal logics LTL, CTL, and CTL*, have been extended to HyperLTL and HyperCTL* [Clarkson et al. 2014] to specify hyperproperties, and model-checking algorithms [Beutner and Finkbeiner 2022, 2023; Coenen et al. 2019; Hsu et al. 2021] have been proposed to verify hyperproperties expressed in these logics, including hyperproperties outside the safety class. Unno et al. [2021] propose an approach to automate relational verification (including $\forall^*\exists^*$ -properties such as GNI) based on an extension of constrained Horn-clauses. Relational properties of imperative programs can be verified by reducing them to validity problems in trace logic [Barthe et al. 2019a]. Finally, the notion of hypercollecting semantics [Assaf et al. 2017] (similar to our extended semantics) has been proposed to statically analyze information flow using abstract interpretation [Cousot and Cousot 1977]. One major difference between our extended semantics and this hypercollecting semantics is the treatment of loops. The former is defined directly on top of the big-step semantics (Def. 4), whereas the latter is defined inductively, and, in the case of loops, as a fixpoint over sets of sets of traces, which is more suitable for abstract interpretation, but less precise than the extended semantics. This difference in precision matters for hyperproperties that are not subset-closed (such as GNI) [Naumann and Ngo 2019; Pasqua 2019].

7 CONCLUSION AND FUTURE WORK

We have presented Hyper Hoare Logic, a novel, sound, and complete program logic that supports reasoning about a wide range of hyperproperties. It is based on a simple but powerful idea: reasoning directly about the *set* of states at a given program point, instead of a fixed number of states. We have demonstrated that Hyper Hoare Logic is very expressive: It can be used to prove or disprove *any* program hyperproperty over terminating executions, including $\exists^*\forall^*$ -hyperproperties and hyperproperties relating an unbounded or infinite number of executions, which goes beyond the properties handled by existing Hoare logics. Moreover, we have presented syntactic rules, compositionality rules, and rules for loops that capture important proof principles naturally.

We believe that Hyper Hoare Logic is a powerful foundation for reasoning about the correctness and incorrectness of program hyperproperties. We plan to build on this foundation in our future work. First, we will explore automation for Hyper Hoare Logic by developing an encoding into an SMT-based verification system such as Boogie [Leino 2008]. Second, we will extend the language supported by the logic, in particular, to include a heap. The main challenge will be to adapt concepts from separation logic to hyper-assertions, e.g., to find a suitable definition for the separating conjunction of two hyper-assertions. Third, we will explore an extension of Hyper Hoare Logic that can relate multiple programs.

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DATA AVAILABILITY STATEMENT

All technical results presented in this paper have been formalized and proven in Isabelle/HOL, and our formalization is publicly available [Dardinier 2023; Dardinier and Müller 2024].

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