
Verifying Temporal Heap Properties Specified via Evolution Logic

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Abstract

This paper addresses the problem of establishing temporal properties of programs written in languages, such as Java, that make extensive use of the heap to allocate—and deallocate—new objects and threads. Establishing liveness properties is a particularly hard challenge. One of the crucial obstacles is that heap locations have no static names and the number of heap locations is unbounded. The paper presents a framework for the verification of Java-like programs. Unlike classical model checking, which uses propositional temporal logic, we use first-order temporal logic to specify temporal properties of heap evolutions; this logic allows domain changes to be expressed, which permits allocation and deallocation to be modelled naturally. The paper also presents an abstract-interpretation algorithm that automatically verifies temporal properties expressed using the logic.

Keywords: verification, first-order logic, temporal logic, abstract interpretation

1 Introduction

Modern programming languages, such as Java, make extensive use of the heap. The contents of the heap may evolve during program execution due to dynamic allocation and deallocation of objects. Moreover, in Java, threads are first-class objects that can be dynamically allocated. Statically reasoning about temporal properties of such programs is quite challenging, because there are no *a priori* bounds on the number of allocated objects, or restrictions on the way the heap may evolve. In particular, proving liveness properties of such programs, e.g., that a thread is eventually created in response to each request made to a web server, can be a quite difficult task.

The contributions of this paper can be summarized as follows:

1. We introduce a first-order modal (temporal) logic [9, 8] that allows specifications of temporal properties of programs with dynamically evolving heaps to be stated in a natural manner.

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2. We develop an abstract interpretation [4] for verifying that a program satisfies such a specification.
3. We implement a prototype of the analysis using the TVLA system [11] and apply it to verify several temporal properties, including liveness properties of Java programs with evolving heaps.

We have used the framework for:

Specifying general heap-evolution properties: The framework has been used to specify in a general manner, various properties of heap evolution, such as properties of garbage-collection algorithms.

Verifying termination of sequential heap-manipulating programs: Termination is shown by providing a ranking function based on the set of items reachable from a variable iterating over the linked data structure. In particular, we have verified termination of all example programs from [6].

Verifying temporal properties of concurrent heap-manipulating programs: We have used the framework to verify temporal properties of concurrent heap-manipulating programs — in particular, liveness properties, such as the absence of starvation in programs using mutual exclusion, and response properties [13]. We have applied this analysis to programs with an unbounded number of threads.

The remainder of this paper is organized as follows: Section 2 gives an overview of the verification method and contrasts it with previous work. Section 3 introduces trace semantics based on first-order modal logic, and discusses how to state trace properties using the language of evolution logic. Section 4 defines an implementation of trace semantics via first-order logic. Section 5 shows how abstract traces are used to conservatively represent sets of concrete traces. Section 6 summarizes related work.

2 Overview

2.1 A Temporal Logic Supporting Evolution

The specification language, *Evolution Temporal Logic* (VTL), is a first-order linear temporal logic that allows specifying properties of the way program execution causes dynamically allocated memory (“the heap”) to evolve.

It is natural to consider the concrete semantics of a program as the set of its execution traces [5, 16], where each trace is an infinite sequence of *worlds*. First-order logical structures provide a natural representation of worlds with an unbounded number of objects: an individual of the structure’s domain (universe) corresponds to an anonymous, unique store location, and predicates represent properties of store locations. Such a representation allows properties of the heap contents to be maintained while abstracting away any information about the actual physical locations in the store.

This gives rise to traces in which worlds along the trace may have different domains. Such traces can be seen as models of a first-order modal logic with a varying-domain semantics [8]. This could be equivalently, but less naturally, modelled using constant-domain semantics.

This framework generalizes other specification methods that address dynamic allocation and deallocation of objects and threads. In particular, its descriptive power goes beyond Propositional LTL and finite-state machines (e.g., [1]).

Program properties can be verified by showing that they hold for all traces. Technically, this can be done by evaluating their first-order modal-logic formulae against all traces. We use a variant of Lewis’s counterpart theory [12] to cast modal models (and formula evaluation) in terms of classical predicate logic with transitive closure (FO^{TC}) [3].

Program verification using the above concrete semantics is clearly non-computable in general. We therefore represent potentially infinite sets of infinite concrete traces by one abstract trace. Infinite parts of the concrete traces are folded into cycles of the abstract traces. Termination of the abstract interpretation on an arbitrary program is guaranteed by bounding the size of the abstract trace. Two abstractions are employed: (i) representing multiple concrete worlds by a single abstract world, and (ii) creating cycles when an abstract world reoccurs in the trace.

Because of these abstractions, we may fail to show the correctness of certain programs, even though they are correct. Fortunately, we can use reduction arguments and progress monitors as employed in other program-verification techniques (e.g., [10]).

As in finite-state model checking (e.g., [16]), we let the specification formula affect the abstraction by making sure that abstract traces that fulfill the formula are distinguished from the ones that do not. However, our abstraction does not fold the history of the trace into a single state. This idea of using the specification to affect the precision of the analysis was not used in [15, 18], which only handle safety properties.

2.2 Overview of the Verification Procedure

First, the property φ is specified in VTL. The formula is then translated in a straightforward manner into an FO^{TC} logical formula, $(\varphi)^\dagger$, using a translation procedure described in Appendix A. An abstract-interpretation procedure is then applied to explore finite representations of the set of traces, using Kleene’s 3-valued logic to conservatively interpret formulae. The abstract-interpretation procedure essentially computes a greatest fixed point over the set of traces, starting with an abstract trace that represents all possible infinite traces from an initial state, and gradually increasing the set of abstract traces and reducing the set of represented concrete traces. Finally, the formula $(\varphi)^\dagger$ is evaluated on all of the abstract traces in the fixed point. If $(\varphi)^\dagger$ is satisfied in all of them, then the original VTL formula φ must be satisfied by all (infinite) traces of the program. However, it may be the case that for some programs that satisfy the VTL specification, our analysis only yields “maybe”.

2.3 Running Example

Consider a web server in which a new thread is dynamically allocated to handle each `http` request received. Each thread handles a single request, then terminates and is subject to garbage collection. Assume that worker threads compete for some exclusively shared resource, such as exclusive access to a data file. Fig. 1 shows fragments of a Java program that implements such a naive web server.

A number of properties for the naive web-server implementation are shown in Table 1 as properties P1–P4. For now you may ignore the formulae in the third column; these will become clear as VTL syntax is introduced in Section 3.

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```
public class Worker implements Runnable {
    Request request;
    Resource resource; ...
    public void run() { ...
lw1        synchronized(resource) {
lwc            resource.processRequest(request);
lw2        }
    }
}
```

FIG. 1: Java fragment for worker thread in a web server with no explicit scheduling.

Due to the unbounded arrival of requests to the web server, and the fact that a thread is dynamically created for each request, absence of starvation (P2) does not hold in the naive implementation. To guarantee absence of starvation, we introduce a scheduler thread into the web server. The web server now consists of a listener thread (as before) and a queue of worker threads managed by the scheduler thread. The listener thread receives an `http` request, creates a corresponding worker thread, and places the new thread on a scheduling queue. The scheduler thread picks up a worker thread from the queue and starts its execution (which is still a very naive implementation).

When using a web server with a scheduler, a number of additional properties of interest exist, labeled P5–P8 (for additional properties of interest see [17]). Fig. 2 shows fragments of a web-server program in which threads use an explicit FIFO scheduler.

The ability of our framework to model explicit scheduling queues provides a mechanism for addressing issues of fairness in the presence of dynamic allocation of threads. (Further discussion of fairness is beyond the scope of this paper).

3 Trace-Based Evolution Semantics

In this section, we define a trace-based semantic domain for programs that manipulate unbounded amounts of dynamically allocated storage. This concrete semantics serves as a basis for the abstract traces semantics presented in the next section.

3.1 Representing Program Traces

To allow specifying temporal properties of heap-manipulating programs, we employ first-order modal logic [8]. Various such logics have been defined, and in general they can be given a *constant-domain* semantics, in which the domain of all worlds is fixed, or a *varying-domain* semantics, in which the domains of worlds can vary and domains of different worlds can overlap. In the most general setting, in both types of semantics an object can exist in more than a single world, and an equality relation is predefined to express global equality between individuals.

To model the semantics of languages such as Java, and to hide the implementation details of dynamic memory allocation, we use a semantics with varying domains. However, the semantics is deliberately restricted because of our intended application to program analysis. By design, our *evolution semantics* has a notion of equality

<pre> public class Scheduler implements Runnable { protected Queue schedQ; protected Resource resource; ... public void run() { ls1 while(true) { ... ls2 synchronized(resource) { ls3 while(resource.isAcquired()) ls4 resource.wait(); // may block until // queue not empty ls5 worker=schedQ.dequeue(); ls6 worker.start(); } } } </pre>	<pre> public class Listener implements Runnable { protected Queue schedQ; ... public void run() { la1 while(true) { ... la2 req=rqStream.readObject(); la3 worker=new Thread(new Worker(req)); la4 schedQ.enqueue(worker); ... } } } public class Worker implements Runnable { Request req; Resource resource; ... public void run() { lw1 synchronized(resource) { ... lw_c resource.processRequest(req); resource.notifyAll(); lw2 } } } </pre>
--	--

FIG. 2. Java code fragment for a web server with an explicit scheduler.

Pr.	Description	Formula
P1	mutual exclusion over the shared resource	$\square \forall t_1, t_2: thread.(t_1 \neq t_2) \rightarrow \neg(at[lw_c](t_1) \wedge at[lw_c](t_2))$
P2	absence of starvation for worker threads	$\square \forall t: thread.at[lw_1](t) \rightarrow \diamond at[lw_c](t)$
P3	a thread only created when a request is received	$\square (\forall t: thread. \neg \odot t) \vee (\forall t: thread. \neg \odot t) \mathcal{U} (\exists v: request. \odot v)$
P4	each request is followed by thread creation	$\square \exists v: request. \odot v \rightarrow \diamond \exists t: thread. \odot t$
P5	mutual exclusion of listener and scheduler over scheduling queue	$\square \forall t_1, t_2: thread.(t_1 \neq t_2) \rightarrow \neg(at[ls_3](t_1) \wedge at[la_3](t_2))$
P6	each created thread is eventually inserted into the scheduling queue	$\square \forall t: thread. \odot t \rightarrow \diamond \exists q: queue.rval[head.next^*](q, t)$
P7	each scheduled worker thread was removed from the scheduling queue	$\square \forall t: thread.at[lw_1](t) \rightarrow \neg \exists q: queue.rval[head.next^*](q, t)$
P8	each worker thread waiting in the queue eventually leaves the queue	$\exists q: queue. \square \forall t: thread.(rval[head.next^*](q, t) \rightarrow \diamond \neg(rval[head.next^*](q, t)))$

TABLE 1. Web server VTL specification using predicates of Table 2.

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in the presence of dynamic allocation and deallocation, without the need to update a predefined global-equality relation. Evolution semantics is adapted from Lewis's counterpart semantics [12]. In both evolution and counterpoint semantics, an individual *cannot* exist in more than a single world; each world has its own domain, and domains of different worlds are non-intersecting. Under this model, equality need only be defined within a single world's boundary; individuals of different worlds are unequal by definition.

To relate individuals of different worlds, an evolution mapping is defined; however, unlike Lewis, we are interested in an evolution mapping that is reflexive, transitive, and symmetric, which models the fact that, during a computation, an allocated memory cell does not change its identity until deallocated. In Section 5.3.1, we show how to track statically, in the presence of abstraction, the equivalence relation induced by the evolution mapping.

As is often done, we add a skip action from the exit of the program to itself, so that all terminating traces are embedded in infinite traces. The semantics of the program is its set of infinite traces.

In the rest of this paper, we work with a fixed set of predicates (or vocabulary) $\mathcal{P} = \{eq, p_1, \dots, p_k\}$. We denote by \mathcal{P}^k the set of predicates from \mathcal{P} with arity k .

DEFINITION 3.1 (World)

A **world** (program configuration) is represented via a first-order logical structure $W = \langle U_w, \iota_w \rangle$, where U_w is the domain (universe) of the structure, and ι_w is the interpretation function mapping predicates to their truth values; that is, for each $p \in \mathcal{P}^k$, $\iota_w(p): U_w^k \rightarrow \{0, 1\}$, such that for all $u \in U_w$, $\iota_w(eq)(u, u) = 1$, and for all $u_1, u_2 \in U_w$ such that u_1 and u_2 are distinct individuals $\iota_w(eq)(u_1, u_2) = 0$.

DEFINITION 3.2 (Trace)

A **trace** is an infinite sequence of worlds $\pi_1 \xrightarrow{D_{\pi_1}, e_{\pi_1}, A_{\pi_2}} \pi_2 \xrightarrow{D_{\pi_2}, e_{\pi_2}, A_{\pi_3}} \dots$, where: (i) each world represents a global state of the program, π_1 is an initial state, and for each π_i , its successor world π_{i+1} is derived by applying a single program action to π_i ; (ii) $D_{\pi_i} \subseteq U_{\pi_i}$ is the set of individuals deallocated at π_i , and $A_{\pi_{i+1}} \subseteq U_{\pi_{i+1}}$ is the set of individuals newly allocated at π_{i+1} ; (iii) each pair of consecutive worlds π_i, π_{i+1} is related by a stepwise **evolution function**, a bijective renaming function $e_{\pi_i}: U_{\pi_i} \setminus D_{\pi_i} \rightarrow U_{\pi_{i+1}} \setminus A_{\pi_{i+1}}$.

3.2 Extracting Trace Properties

To extract trace properties, we need a language that can relate information from different worlds in a trace. We define the language of evolution logic (VTL), which is a first-order linear temporal logic with transitive closure, as follows:

DEFINITION 3.3 (VTL Syntax)

A **VTL formula** is defined by

$$\begin{aligned} \varphi ::= & 0|1|p(v_1, \dots, v_n)| \odot v_1 | \otimes v_1 | \varphi_1 \vee \varphi_2 | \neg \varphi_1 | \exists v_1. \varphi_1 | (TC \ v_1, v_2: \varphi_1)(v_3, v_4) \\ & | \varphi_1 \mathcal{U} \varphi_2 | \bigcirc \varphi_1 \end{aligned}$$

where v_i are logical variables.

The set of free variables in a formula φ denoted by $FV(\varphi)$ is defined as usual.

Predicates	Intended Meaning
$thread(t)$	t is a thread
$\{at[lab](t) : lab \in Labels\}$	thread t is at label lab
$\{rval[fld](o_1, o_2) : fld \in Fields\}$	field fld of the object o_1 points to the object o_2
$heldBy(l, t)$	the lock l is held by the thread t
$blocked(t, l)$	the thread t is blocked on the lock l
$waiting(t, l)$	the thread t is waiting on the lock l

TABLE 2. Predicates used to record information about a single world

In a transitive closure formula, $FV((TC\ v_1, v_2 : \varphi_1)(v_3, v_4)) = (FV(\varphi_1) \setminus \{v_1, v_2\}) \cup \{v_3, v_4\}$.

The operators \odot and \oslash allow the specification to refer to the exact moments of birth and death (respectively) of an individual.¹ The transitive closure operator $(TC\ v_1, v_2 : \varphi_1)(v_3, v_4)$, allows the specification to naturally express transitive reachability along heap-paths.

Shorthand Formulae: For convenience, we also allow formulae to contain the shorthand notations $(v_1 = v_2) \triangleq eq(v_1, v_2)$, $(v_1 \neq v_2) \triangleq \neg eq(v_1, v_2)$, $\varphi_1 \wedge \varphi_2 \triangleq \neg(\neg\varphi_1 \vee \neg\varphi_2)$, $\varphi_1 \rightarrow \varphi_2 \triangleq \neg\varphi_1 \vee \varphi_2$, $\forall v. \varphi_1 \triangleq \neg(\exists v. \neg\varphi_1)$, $\diamond \varphi_1 \triangleq 1\mathcal{U}\varphi_1$, and $\square \varphi_1 \triangleq \neg(1\mathcal{U}\neg\varphi_1)$. We also use the shorthand $p^*(v_3, v_4)$ for $(TC\ v_1, v_2 : p(v_1, v_2))(v_3, v_4) \vee (v_3 = v_4)$, when p is a binary predicate.

In our examples, the predicates that record information about a single world include the predicates of Table 2, plus additional predicates defined in later sections. The set of predicates $\{at[lab](t) : lab \in Labels\}$ is parameterized by the set of program labels. Similarly, the set of predicates $\{rval[fld](o_1, o_2) : fld \in Fields\}$ is parameterized by the set of selector fields. We use the shorthand notation $rval[x.fld^*](v_1, v_2) \triangleq \exists v'. rval[x](v_1, v') \wedge rval[fld]^*(v', v_2)$. The transitive closure allows specifying properties relating to unbounded length of heap-allocated data structures (e.g., in $rval[fld]^*(v', v_2)$).

We use unary predicates, such as $thread(t)$, to represent type information. This could have been expressed using a many-sorted logic, but we decided to avoid this for expository purposes. Instead, for convenience we define the shorthands $\exists v: type. \varphi \triangleq \exists v. type(v) \wedge \varphi$ and $\forall v: type. \varphi \triangleq \forall v. type(v) \rightarrow \varphi$.

EXAMPLE 3.4

Property P2 of Table 1 specifies the absence of starvation for worker threads (Fig. 1). The formula $\exists t: thread. \diamond at[lw_c](t)$ states that some thread eventually enters the critical section. The formula $\square \exists t: thread. \diamond at[lw_c](t)$ expresses the fact that globally some thread eventually enters the critical section.

The property $\square(\forall v. \odot v \rightarrow \diamond \oslash v)$ states that globally, each individual that is allocated during program execution is eventually deallocated. Note that the universal quantifier quantifies over individuals of the world in which it is evaluated. This property is an instance of the commonly used ‘‘Response structure’’ [13, 7], in which an allocation in a world has a deallocation response in some future world.

¹These operators could be extended to handle allocation and deallocation of a (possibly unbounded) set of individuals.

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The properties

$$\begin{aligned} \forall t: thread. \Box (at[l_{lh}](t) \rightarrow \exists v. rval[i.next^*](t, v) \wedge \Diamond (at[l_{lh}](t) \wedge \neg rval[i.next^*](t, v))) \\ \forall t: thread. \Box (\forall v. at[l_{lh}](t) \wedge \neg rval[i.next^*](t, v) \rightarrow \Box \neg at[l_{lh}](t) \vee \neg rval[i.next^*](t, v)) \end{aligned}$$

establish a ranking function for linked data structures based on transitive reachability. These properties state that at the loop head l_{lh} , the set of individuals transitively reachable from program variable i decreases on each iteration of the loop. (Typically i is a pointer that traverses a linked data structure during the loop.) Note that these properties relate an unbounded number of individuals of one world to another.

The property $\Box (\forall v. \Diamond \Box \forall t: thread. \bigwedge_{\substack{x \in Var \\ fld \in Fields}} \neg rval[x.fld^*](t, v) \rightarrow \Diamond \odot v)$ is a desired property of a garbage collector — that all non-reachable items are eventually collected.

3.3 Evolution Semantics

In the following definitions, $head(\pi)$ denotes the first world in a trace π , $tail(\pi)$ denotes the suffix of π without the first world, and π^i denotes the suffix of π starting at the i -th world. We also use $last(\tau)$ to denote the last world of a finite trace prefix τ .

DEFINITION 3.5 (Evolution mapping)

Let τ be the finite prefix of length k of the trace π . We say that an individual $u \in U_{head(\tau)}$ **evolves into** an individual $u' \in U_{last(\tau)}$ in the trace π in k steps, and write $\pi \models_k u \rightsquigarrow u'$ when there is a sequence of individuals u_1, \dots, u_k such that $u_1 = u$ and $u_k = u'$ and for each two successive worlds in τ , $u_{i+1} = e_{\tau_i}(u_i)$.

DEFINITION 3.6 (Assignment evolution)

Let τ be the finite prefix of length k of the trace π . Given a formula φ and an assignment Z mapping free variables of φ to individuals of a domain $U_{head(\tau)}$, we say that $\pi \models_k Z \rightsquigarrow Z'$ (Z **evolves into** Z' in π in k steps) if for each free variable fv_i of φ , $\pi \models_k Z(fv_i) \rightsquigarrow Z'(fv_i)$, $Z(fv_i) \in U_{head(\tau)}$, and $Z'(fv_i) \in U_{last(\tau)}$.

DEFINITION 3.7 (VTL evolution semantics)

We define inductively when an VTL formula φ is satisfied over a trace π with an assignment Z (denoted by $\pi, Z \models_t \varphi$) as follows:

- $\pi, Z \models_t \mathbf{1}$, and not $\pi, Z \models_t \mathbf{0}$.
- $\pi, Z \models_t p(v_1, \dots, v_k)$ when $\iota_{head(\pi)}(p)(Z(v_1), \dots, Z(v_k)) = 1$
- $\pi, Z \models_t \neg \varphi$ when not $\pi, Z \models_t \varphi$
- $\pi, Z \models_t \varphi \vee \psi$ when $\pi, Z \models_t \varphi$ or $\pi, Z \models_t \psi$
- $\pi, Z \models_t \exists v. \varphi(v)$ when there exists $u \in U_{head(\pi)}$ s.t. $\pi, Z[v \mapsto u] \models_t \varphi(v)$
- $\pi, Z \models_t (TC \ v_1, v_2: \varphi)(v_3, v_4)$ when there exists $u_1, \dots, u_{n+1} \in U_{head(\pi)}$, such that $Z(v_3) = u_1, Z(v_4) = u_{n+1}$, and for all $1 \leq i \leq n$, $\pi, Z[v_1 \mapsto u_i, v_2 \mapsto u_{i+1}] \models_t \varphi$.
- $\pi, Z \models_t \odot v$ when $Z(v) \in A_{head(tail(\pi))}$.
- $\pi, Z \models_t \odot v$ when $Z(v) \in D_{head(\pi)}$.
- $\pi, Z \models_t \bigcirc \varphi$ when there exists Z' such that $tail(\pi), Z' \models_t \varphi$ and $\pi \models_1 Z \rightsquigarrow Z'$.

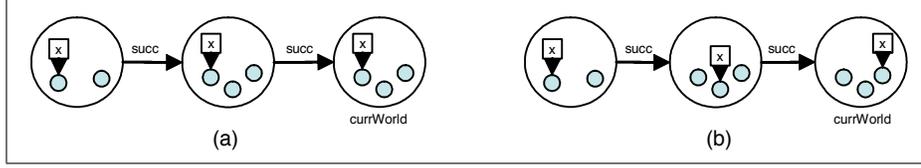


FIG. 3. Interaction of first-order quantifiers and temporal operators

- $\pi, Z \models_t \varphi \mathcal{U} \psi$ when there exists $k \geq 1$, Z' , and Z'' s.t.,
 $\pi^k, Z' \models_t \psi$ and $\pi \models_k Z \rightsquigarrow Z'$
 and for all $1 \leq j < k$, $\pi^j, Z'' \models_t \varphi$ and $\pi \models_j Z \rightsquigarrow Z''$

We write $\pi \models \varphi$ when $\pi, Z \models_t \varphi$ for every assignment Z .

It is worth noting that the first-order quantifiers in this definition only range over the individuals of a single world, yet the overall effect achieved by using the evolution mapping is the ability to reason about individuals of different worlds, and how they relate to each other. In essence, the assignment $Z[v \mapsto u]$ binds v to (the evolution of) an individual from the domain of the world over which the quantifier was evaluated (cf. the semantics of \bigcirc and \mathcal{U}).

The combination of first-order quantifiers and modal operators creates complications that do not occur in propositional temporal logics. In particular, the quantification domain of a quantifier may vary as the domain of underlying worlds varies. Verification of VTL properties therefore requires a mechanism for recording the domain related to each quantifier, and for relating members of quantification domains to individuals of future worlds. For VTL, this mechanism is provided by evolution-mappings, which relate individuals of a world to the individuals of its successor world. Transitively composing evolution-mappings captures the evolution of individuals along a trace.

EXAMPLE 3.8

The formula $\exists v. \Box x(v)$ states that the pointer variable x remains constant throughout program execution, and points to an object that existed in the program's initial world. On the other hand, the formula $\Box \exists v. x(v)$ merely states that x never has the value `null`; however, x is allowed to point to different objects at different times in the program's execution, and in particular x can point to objects that did not exist in the initial world. Examples illustrating the two situations are shown in Fig. 3, where in (a) x points to the same object in all worlds, and in (b) it points to different objects in different worlds.

DEFINITION 3.9

We say that a program **satisfies** an VTL formula φ when all (infinite) traces of the program satisfy φ .

The evolution semantics allows each world to have a different domain, thus conceptually representing a varying-domain semantics, which allows dynamic allocation and deallocation of objects and threads. In Section 4, we give a possible implementation of this semantics in terms of evolving first-order logical structures.

Separable Specifications

It is interesting to consider subclasses of VTL for which the verification problem is somewhat easier. Two such classes are: (i) *spatially separable specifications* — do not place requirements on the relationships between individuals of one world; this allows each individual to be considered separately, and the verification problem can be handled as a set of propositional verification problems; (ii) *temporally separable specifications* — do not relate individuals across worlds. Essentially, this corresponds to the extraction of propositional information from each world, and having temporal specifications over the extracted propositions. This class was addressed in [2, 19].

4 Expressing Trace Semantics using First-Order Logic

In this section, we use first-order logic to express a trace semantics; we encode temporal operators using standard first-order quantifiers. This allows us to automatically derive an abstract semantics in Section 5. This approach also extends to other kinds of temporal logic, such as the μ -calculus. Our initial experience is that we are able to demonstrate that some temporal properties, including liveness properties, hold for programs with dynamically allocated storage.

4.1 Representing Infinite Traces via First-Order Structures

We encode a trace via an infinite first-order logical structure using the set of designated predicates specified in Table 3. Successive worlds are connected using the *succ* predicate. Each world of the trace may contain an arbitrary number of individuals. The predicate *exists*(o, w) relates an individual o to a world w in which it exists. Each individual only exists in a single world. The *evolution*(o_1, o_2) predicate relates an individual o_1 to its counterpart o_2 in a successor world. The predicates *isNew* and *isFreed* hold for newly created or deallocated individuals and are used to model the allocation and deallocation operators.

DEFINITION 4.1

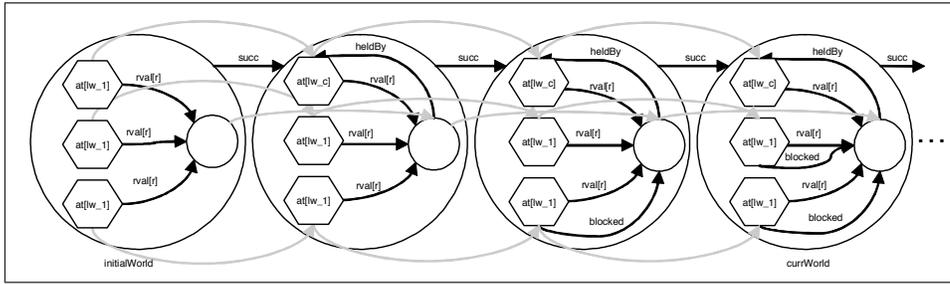
A **concrete trace** is a trace encoded as an infinite first-order logical structure $T = \langle U_T, \nu_T \rangle$, where U_T is the domain of the trace, and ν_T is the interpretation function mapping predicates to their truth value in the logical structure, i.e., for each $p \in \mathcal{P}^k$, $\nu_T(p): U_T^k \rightarrow \{0, 1\}$. To exclude structures that cannot represent valid traces, we impose certain integrity constraints [15]. For example, we require that each world has at most one successor (predecessor), and that equality (*eq*) is reflexive.

EXAMPLE 4.2

Fig. 4 shows four worlds of the trace T_4^{d} where each world is depicted as a large node containing other nodes and worlds along the trace are related by successor edges. Information in a single world is represented by a first-order logical structure, which is shown as a directed graph. Each node of the graph corresponds to a heap-allocated object. Hexagon nodes correspond to thread objects, and small round nodes to other types of heap-allocated objects. Predicates holding for an object are shown inside the object node, and binary predicates are shown as edges. For brevity, we use the label *rval*[r] to stand for *rval*[*resource*]. Grey edges, crossing world boundaries, are

Predicate	Intended Meaning
$world(w)$	w is a world
$currWorld(w)$	w is the current world
$initialWorld(w)$	w is the initial world
$succ(w_1, w_2)$	w_2 is the successor of w_1
$exists(o, w)$	object o is in world w
$evolution(o_1, o_2)$	object o_1 evolves to o_2
$isNew(o)$	object o is new
$isFreed(o)$	object o is freed

TABLE 3. Trace predicates.


 FIG. 4. A concrete trace T_4^h .

evolution edges, which relate objects of different worlds. Note that these are the only edges that cross world boundaries.

4.2 Exact Extraction of Trace Properties

Once traces are represented via first-order logical structures, trace properties can be extracted by evaluating formulae of first-order logic with transitive closure.

We translate a given VTL formula φ to an FO^{TC} formula $(\varphi)^\dagger$ by making the underlying trace structure explicit, and translating temporal operators to FO^{TC} claims over worlds of the trace. The translation procedure is straightforward, and given in Appendix A.

EXAMPLE 4.3

The property $\exists t: thread. \diamond at[lw_c](t)$ of Example 3.4 is translated to

$$\begin{aligned} & \exists w : world. \exists t : thread. initialWorld(w) \wedge \\ & exists(t, w) \wedge \exists w' \exists t' : thread. succ^*(w, w') \wedge \\ & exists(t', w') \wedge evolution^*(t, t') \wedge at[lw_c](t') \end{aligned}$$

which evaluates to 1 for the trace prefix of Fig. 4.

DEFINITION 4.4

The **meaning** of a formula φ over a concrete trace T , with respect to an assignment Z , denoted by $\llbracket \varphi \rrbracket_2^T(Z)$, yields a truth value in $\{0, 1\}$. The meaning of φ is defined inductively as follows:

```

explore() {
  Init = all possible traces
  F(T) = {x | τ ∈ T ∧ (ac is enabled for τ) ∧ x ∈ ac(τ)}
  Traces = GFP(F) // i.e., Traces = ⋂i=0∞ Fi(Init)
  for each τ ∈ Traces
    if τ ⊭2 (φ)† report an error
}

```

FIG. 5: A greatest fixed-point computation scheme for computing the set of (infinite) concrete traces and evaluating the property $(\varphi)^\dagger$. GFP is the greatest fixed-point operator.

- $\llbracket l \rrbracket_2^T(Z) = l$ (where $l \in \{0, 1\}$)
- $\llbracket p(v_1, \dots, v_k) \rrbracket_2^T(Z) = \iota^T(p)(Z(v_1), \dots, Z(v_k))$
- $\llbracket \varphi_1 \vee \varphi_2 \rrbracket_2^T(Z) = \max(\llbracket \varphi_1 \rrbracket_2^T(Z), \llbracket \varphi_2 \rrbracket_2^T(Z))$
- $\llbracket \neg \varphi_1 \rrbracket_2^T(Z) = 1 - \llbracket \varphi_1 \rrbracket_2^T(Z)$
- $\llbracket \exists v_1. \varphi_1 \rrbracket_2^T(Z) = \max_{u \in U^T} \llbracket \varphi_1 \rrbracket_2^T(Z[v_1 \mapsto u])$
- $\llbracket (TC \ v_1, v_2 : \varphi_1)(v_3, v_4) \rrbracket_2^T(Z) =$
 $\max_{\substack{n \geq 1, u_1, \dots, u_{n+1} \in U, \\ Z(v_3) = u_1, Z(v_4) = u_{n+1}}} \min_{i=1}^n \llbracket \varphi_1 \rrbracket_2^T(Z[v_1 \mapsto u_i, v_2 \mapsto u_{i+1}])$

We say that T and Z **satisfy** φ (denoted by $T, Z \models \varphi$) if $\llbracket \varphi \rrbracket_2^T(Z) = 1$. We write $T \models \varphi$ if for every Z we have $T, Z \models \varphi$.

The correctness of the translation is established by the following theorem:

THEOREM 4.5

For every closed VTL formula φ and a trace π , $\pi \models \varphi$ if and only if $rep(\pi) \models (\varphi)^\dagger$, where $rep(\pi)$ is the first-order representation of π , i.e., the first-order structure that corresponds to π , in which every world in π is mapped to a world in $rep(\pi)$, with the *succ* predicate holding for consecutive worlds.

4.3 Semantics of Actions

Informally, a program action ac consists of a *precondition* ac_{pre} under which the action is *enabled*, which is expressed as a logical formula, and a set of formulae for updating the values of predicates according to the effect of the action. An enabled action specifies that a possible next world in the trace is one in which the interpretations of every predicate p of arity k is determined by evaluating a formula $\varphi_p(v_1, v_2, \dots, v_k)$, which may use v_1, v_2, \dots, v_k and all predicates in \mathcal{P} (see [15]).

4.4 Exploring the Trace Space

Since liveness properties might be violated only by infinite traces, our verification procedure must reason about infinite traces. In this section, we present a non-computable

scheme for exploring the (infinite) space of program traces. In the next section, we show how to conservatively approximate this scheme using an abstract-interpretation algorithm that explores a finitely representable over-approximation of this space.

Fig. 5 shows a (non-computable) greatest fixed-point computation scheme for exploring the (infinite) space of program traces. In this scheme, we start with the (infinite) set of all possible infinite traces, and iteratively refine the set by eliminating traces that do not agree with the known explored prefixes of program traces.

On each step, we iteratively apply every possible enabled action on traces in the *Traces* set. When an action is applied on a trace, it extends its explored prefix, resulting in all possible extended prefixes, which are then added to the set of traces.

Each step of the scheme of Fig. 5 therefore replaces traces with a given explored prefix by a set of traces with longer explored prefixes. The process stabilizes when no more traces could be extended. Once the process has stabilized, we evaluate the violation property on every trace in the resulting set of traces. If a trace is found to satisfy the violation property, we report an error.

As noted earlier, this scheme operates on an infinite set of infinite traces, and is non-computable. To obtain a conservative solution to the verification problem, we therefore apply a conservative approximation as described in Section 5.

5 Exploring Finite Abstract Traces via Abstract Interpretation

In this section, we give an algorithm for conservatively determining the validity of a program with respect to a VTL property. A key difficulty in proving liveness properties is the fact that a liveness property might be violated only by an infinite trace. Therefore, our procedure for verifying liveness properties is a greatest fixed-point computation, which works down from an initial approximation that represents all infinite traces. In this section, we present the abstract-interpretation algorithm; procedure `explore` of Fig. 9.

This approach uses finite representations of infinite traces. Finite representations are obtained by abstraction to three-valued logical structures. The third logical value, $1/2$, represents “unknown” and may result from abstraction. The abstract semantics conservatively models the effect of actions on abstract representations. It should be noted that the abstract-interpretation algorithm is guaranteed to terminate and to produce sound results. That is, it never misses an error. However, because the algorithm over-approximates the set of possible program traces, it may report errors that do not occur in an execution of the program (also known as *false alarms*).

5.1 A Finite Representation of Infinite Traces

The first step in making the algorithm of Fig. 9 feasible is to define a finite representation of sets of infinite traces. Technically, we use 3-valued logical structures to finitely represent sets of infinite traces.

DEFINITION 5.1

An **abstract trace** is a 3-valued first-order logical structure $T = \langle U_T, \iota_T \rangle$, where U_T is the domain of the abstract trace, and ι_T is the interpretation, mapping predicates

to their truth values, i.e., for each $p \in \mathcal{P}^k$, $\iota_T(p): U_T^k \rightarrow \{0, 1, 1/2\}$. We refer to the values 0 and 1 as **definite values**, and to $1/2$ as a **non definite value**.

An individual u for which $\iota_T(eq)(u, u) = 1/2$ is called a **summary individual**;² a summary individual may represent more than one concrete individual.

The **meaning** of a formula φ over a 3-valued abstract trace T , with respect to an assignment Z , denoted by $\llbracket \varphi \rrbracket_3^T(Z)$, is defined exactly as in Def. 4.4, but interpreted over $\{0, 1, 1/2\}$.

We say that a trace T with an assignment Z **potentially satisfies** a formula φ when $\llbracket \varphi \rrbracket_3^T(Z) \in \{1, 1/2\}$ and denote this by $T, Z \models_3 \varphi$.

We now define how concrete traces are represented by abstract traces. The idea is that each individual of a concrete trace is mapped by the abstraction into an individual of an abstract trace. The new two definitions permit an (abstract or concrete) trace to be related to a less-precise abstract trace. Abstraction is a special case of this in which the first trace is a concrete trace. First, the following definition imposes an order on truth values of the 3-valued logic:

DEFINITION 5.2 (Information order)

For $l_1, l_2 \in \{0, 1, 1/2\}$, we define the **information order** on truth values as follows: $l_1 \sqsubseteq l_2$ if $l_1 = l_2$ or $l_2 = 1/2$.

The embedding ordering of abstract traces is then defined as follows:

DEFINITION 5.3 (Trace embedding)

Let $T = \langle U, \iota \rangle$ and $T' = \langle U', \iota' \rangle$ be abstract traces encoded as first-order structures. A function $f: T \rightarrow T'$ such that f is surjective is said to **embed T into T'** if for each predicate $p \in \mathcal{P}^k$, and for each $u_1, \dots, u_k \in U$:

$$\iota(p(u_1, u_2, \dots, u_k)) \sqsubseteq \iota'(p(f(u_1), f(u_2), \dots, f(u_k)))$$

We say that T' **represents** T when there exists such an embedding f .

One way of creating an embedding function f is by using *canonical abstraction*. Canonical abstraction maps individuals to an abstract individual based on the values of the individuals' unary predicates. All individuals having the same values for unary predicate symbols are mapped by f to the same abstract individual. We denote the canonical abstraction of a trace T by $t_embed(T)$. Canonical abstraction guarantees that each abstract trace is no larger than some fixed size, known *a priori*.

EXAMPLE 5.4

Fig. 6 shows an abstract trace, with four abstract worlds, that represents the concrete trace of Fig. 4. An individual with double-line boundaries is a summary individual representing possibly more than a single concrete individual. Similarly, the worlds with double-line boundaries are summary worlds that possibly represent more than a single world. Dashed edges are $1/2$ edges, that represent relations that may or may not hold. For example, a $1/2$ successor edge between two worlds represents the possible succession of worlds. The summary world following the initial world represents the two concrete worlds between the initial and the current world of T_4^b , which have the same values for their unary predicates. Similarly, the summary node labeled $at[lw_1]$ represents all thread individuals in these worlds that reside at label lw_1 .

²Note that for all $u \in U_T$, $\iota_T(eq)(u, u) = 1$ or $\iota_T(eq)(u, u) = 1/2$.

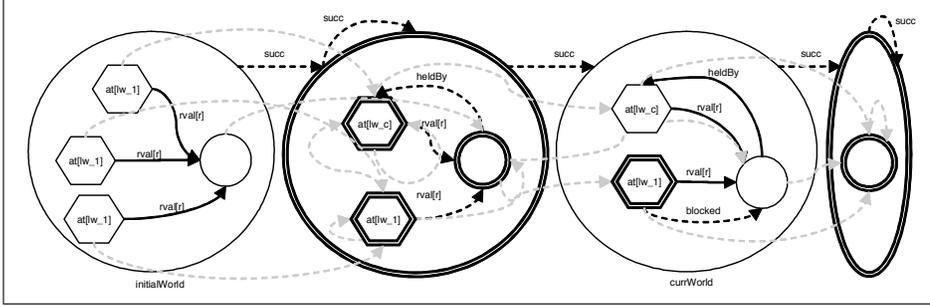


FIG. 6. An abstract trace T_4 that represents the concrete trace T_4^h .

Note that this abstract trace also represents other concrete traces besides T_4^h , for example, concrete traces in which in the current world some threads are blocked on the lock and some are not blocked.

5.2 Abstract Interpretation

The abstract semantics represents abstract traces using 3-valued structures. Intuitively, applying an action to an abstract trace unravels the set of possible successor worlds in the trace. That is, an abstract action elaborates an abstract trace by materializing a world w from the summary world at the tail of the trace; w becomes the definite successor of the current world $currWorld$, and w 's (indefinite) successor is the summary world at the tail of the trace. $currWorld$ is then advanced to w , which often causes the former $currWorld$ to be merged with its predecessor. When a trace is extended, we evaluate the formula's precondition and its update formulae using 3-valued logic (as in Def. 5.1).

EXAMPLE 5.5

Figures 6, 7, and 8 illustrate the application of the action that releases a lock. Fig. 7 shows the materialization of the next successor world for the trace T_4 of Fig. 6. In the successor world, the thread that was at label lw_c no longer holds the lock and has advanced to label lw_2 . The $currWorld$ predicate is then advanced, and the former $currWorld$ is merged with its predecessor, resulting in the abstract trace shown in Fig. 8.

The abstract-interpretation procedure **explore** is shown in Fig. 9. It computes a greatest fixed point starting with the set $\{T_1^\top, T_2^\top\}$; these two abstract traces represent all possible concrete (infinite) traces that start at a given initial state. T_1^\top and T_2^\top each have two worlds: an initial world that represents the initial program configuration connected by a $1/2$ -valued successor edge to a summary world that represents the unknown possible suffixes. The summary world w_{s1} of T_1^\top has a summary individual u_{s1} related to it. The summary individual u_{s1} has $1/2$ values for all of its predicates, including $exists(u_{s1}, w_{s1}) = 1/2$, meaning that future worlds of the trace do not necessarily contain any individuals. The summary world of T_2^\top has no summary individual related to it and represents suffixes in which all future worlds are empty. Fig. 10 shows an initial abstract trace (corresponding to T_1^\top) representing all traces

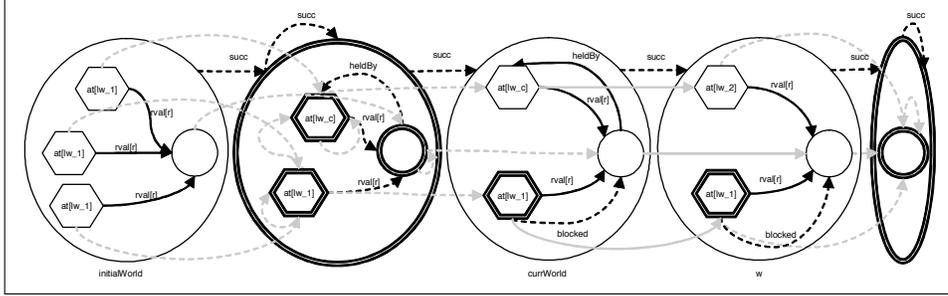


FIG. 7: An intermediate abstract trace, which represents the first stage of applying an action to T_4 .

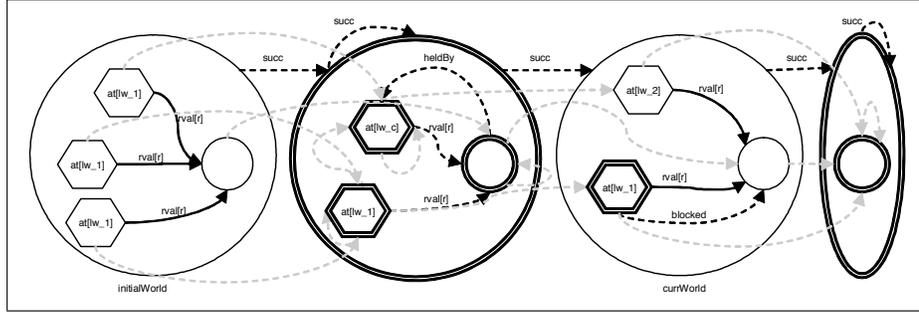


FIG. 8: The resulting abstract trace after applying an action over T_4 (after advancing *currWorld*).

```

explore() {
  Traces =  $\{T_1^\top, T_2^\top\}$ 
  while changes occur {
    select and remove  $\tau$  from Traces
    for each action  $ac$  enabled for  $\tau$ 
      Traces = Traces  $\cup$   $ac(\tau)$ 
  }
  for each  $\tau \in$  Traces
    if  $\tau \not\models_3 (\varphi)^\dagger$  report possible error
}
    
```

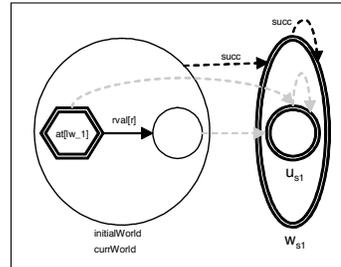


FIG. 9: Computing the set of abstract traces and evaluating the property $(\varphi)^\dagger$.

FIG. 10: An initial abstract trace T_1^\top .

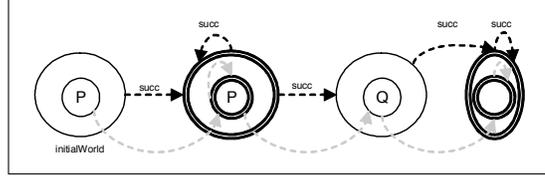


FIG. 11: $\exists v.P(v)\mathcal{U}Q(v)$ holds in all concrete traces that the abstract trace T_{11} represents, yet $\exists v.P(v)\mathcal{U}Q(v)$ evaluates to $1/2$ on T_{11} itself.

starting with an arbitrary number of worker threads at label lw_1 sharing a single lock.

The procedure `explore` accumulates abstract traces in the set $Traces$ until a fixed point is reached. Throughout this process, however, the set of concrete traces represented by the abstract traces in $Traces$ is actually decreasing. It is in this sense that `explore` is computing a greatest fixed point.

Once a fixed point has been reached, the property of interest is evaluated over abstract traces in the fixed point. Formula evaluation over an abstract trace exploits values of instrumentation predicates when possible (this is explained in the following section). This allows the use of recorded definite values, whereas re-evaluation might have yielded $1/2$.

We now show the soundness of the approach. We extend mappings on individuals to operate on assignments: If $f: U^T \rightarrow U^{T'}$ is a function and $Z: Var \rightarrow U^T$ is an assignment, $f \circ Z$ denotes the assignment $f \circ Z: Var \rightarrow U^{T'}$ such that $(f \circ Z)(v) = f(Z(v))$. One of the nice features of 3-valued logic is that the soundness of the analysis is established by the following theorem (which generalizes [15] for the infinite case):

THEOREM 5.6

[Embedding Theorem] Let $T = \langle U^T, \iota^T \rangle$ and $T' = \langle U^{T'}, \iota^{T'} \rangle$ be two traces encoded as first-order structures, and let $f: U^T \rightarrow U^{T'}$ be a function such that $T \sqsubseteq^f T'$. Then, for every formula φ and complete assignment Z for φ , $\llbracket \varphi \rrbracket_3^T(Z) \sqsubseteq \llbracket \varphi \rrbracket_3^{T'}(f \circ Z)$.

The algorithm in Fig. 9 must terminate. Furthermore, whenever it does not report an error, the program satisfies the original VTL formula φ .

It often happens that this approach to verifying temporal properties yields $1/2$, due to an overly conservative approximation. In the next section, we present machinery for refining the abstraction to allow successful verification in interesting cases.

EXAMPLE 5.7

For clarity and ease of presentation, we use an artificial example, which is also used in the next section. Fig. 11 shows an abstract trace in which the property $\exists v.P(v)\mathcal{U}Q(v)$ holds for all the concrete traces represented by the abstract trace, but the formula $\exists v.P(v)\mathcal{U}Q(v)$ evaluates to $1/2$ because the successor and evolution edges have value $1/2$.

5.3 Property-Guided Instrumentation

To refine the abstraction, we can maintain more precise information about the correctness of temporal formulae as traces are being constructed. This principle is referred to

Predicate	Intended Meaning	Formula
$twe(o_1, o_2)$	object o_1 is equal to object o_2 possibly across worlds	$(o_1 = o_2) \vee evolution^*(o_1, o_2) \vee evolution^*(o_2, o_1)$
$current(o)$	object o is a member of current world	$\exists w: world(o, w) \wedge currWorld(w)$

TABLE 4. Trace instrumentation predicates.

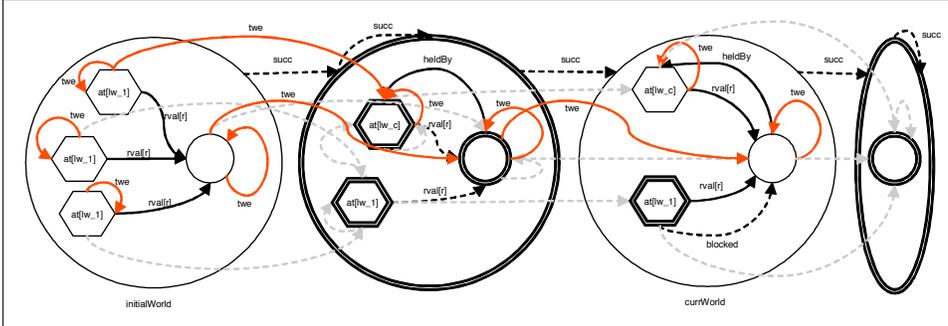


FIG. 12: Abstract trace with transworld equality instrumentation (Only 1-valued transworld equality edges are shown).

in [15] as the *Instrumentation Principle*. This work goes beyond what was mentioned there, by showing how one could actually obtain instrumentation predicates from the temporal specification.

5.3.1 Trace Instrumentation

The predicates in Table 4 are required for preserving properties of interest under abstraction. The instrumentation predicate $current(o)$ denotes that o is a member of the current world and should be distinguished from individuals of predecessor worlds. This predicate is required due to limitations of canonical embedding. The predicate $twe(o_1, o_2)$ records equality across worlds and is required due to the loss of information about concrete locations caused by abstraction.

Transworld Equality: In the evolution semantics, two individuals are considered to be different incarnations of the same individual when one may transitively evolve into the other. We refer to this notion of equality as *transworld equality* and introduce an instrumentation predicate $twe(v_1, v_2)$ to capture this notion.

Because the abstraction operates on traces (and not only single worlds), individuals of different worlds may be abstracted together. Transworld equality is crucial for distinguishing a summary node that represents different incarnations of the same individual in different worlds from a summary node that may represent a number of different individuals.

Transworld equality is illustrated in Fig. 12; the 1-valued twe self-loop to the summary thread-node at label lw_c records the fact that this summary node actually represents multiple incarnations of a single thread, and not a number of different threads.

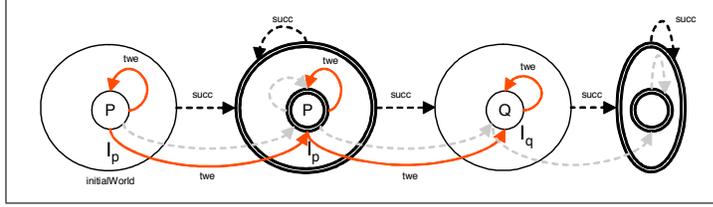


FIG. 13. In the abstract trace T_{13} , $\exists v.P(v)\mathcal{U}Q(v)$ evaluates to 1.

5.3.2 Temporal Instrumentation

Given a VTL specification formula, we construct a corresponding set of instrumentation predicates for refining the abstraction of the trace according to the property of interest. The set of instrumentation predicates corresponds to the sub-formulae of the original specification.

EXAMPLE 5.8

In Example 5.7, the property $\exists v.P(v)\mathcal{U}Q(v)$ evaluated to $1/2$ although it is satisfied by all concrete traces that T_{11} represents. We now add the temporal instrumentation predicates $I_p(v)$ and $I_q(v)$ to record the values of the temporal subformulae $P(v)$ and $Q(v)$. The predicates are updated according to their value in the previous worlds. Note the use of transworld equality instrumentation to more precisely record transitive evolution of objects. In particular, this provides the information that the summary node of the second world is an abstraction of different incarnations of the same single object. This is shown in Fig. 13.

6 Related Work

The Bandera Specification Language (BSL) [2] allows writing specifications via common high-level patterns. In BSL, it is impossible to relate individuals of different worlds, and impossible to refer to the exact moments of allocation and deallocation of an object.

In [14], a special case of the abstraction from [18, 19], named “counter abstraction”, is used to abstract an infinite-state parametric system into a finite-state one. They use static abstraction, i.e., they have a preceding model-extraction phase. In contrast, in our work abstraction is applied dynamically on every step of state-space exploration, which enables us to handle dynamic allocation and deallocation of objects and threads.

In [19], we have used observing-propositions defined over a first-order configuration to extract a propositional Kripke structure from a first-order one. The extracted structure was then subject to PLTL model-checking techniques. This approach is rather limited, because individuals of different worlds could not be specifically related.

7 Conclusion

We believe this work provides a foundation for specifying and verifying properties of programs manipulating the heap with dynamic allocation and deallocation of objects and threads. In the future, we plan to develop more scalable approaches, and in

particular abstract-interpretation algorithms that are tailored for VTL.

Acknowledgments

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A Translation of VTL to FO^{TC}

We say that a VTL sub-formula is temporally-bound if it appears under a temporal operator. Translations for temporally-bound and non-temporally-bound formulae are different, since non-temporally-bound formulae should be bound to the initial world of the trace.

DEFINITION A.1 (VTL translation to FO^{TC})

We denote by $(\varphi)^{\dagger w}$ the bounded translation of a formula φ in a world w and by $(\varphi)^{\dagger}$ the non-bounded translation.

- $(\varphi)^{\dagger} = \exists w: world.initialWorld(w) \wedge (\varphi)^{\dagger w}$
- if φ is an atomic formula other than $\odot x$ and $\oslash x$ then $(\varphi)^{\dagger w} = \varphi$. If $\varphi = \odot x$ then $(\varphi)^{\dagger w} = isNew(x)$. If $\varphi = \oslash x$ then $(\varphi)^{\dagger w} = isFreed(x)$.
- $(\varphi \wedge \psi)^{\dagger w} = (\varphi)^{\dagger w} \wedge (\psi)^{\dagger w}$, $(\varphi \vee \psi)^{\dagger w} = (\varphi)^{\dagger w} \vee (\psi)^{\dagger w}$, $(\neg \varphi)^{\dagger w} = \neg(\varphi)^{\dagger w}$
- $(\exists x \varphi)^{\dagger w} = \exists x.exists(w, x) \wedge (\varphi)^{\dagger w}$
- $((TC \ x_1, x_2: \varphi)(x_3, x_4))^{\dagger w} = (TC \ x_1, x_2: (\varphi)^{\dagger w} \wedge exists(w, x_1) \wedge exists(w, x_2))(x_3, x_4)$
- $(\varphi(x_1, \dots, x_n) \mathcal{U} \psi(y_1, \dots, y_k))^{\dagger w} =$

$$\begin{aligned} & \exists w': world. \exists y'_1, \dots, y'_k. succ^*(w, w') \wedge (\psi(y'_1, \dots, y'_k))^{\dagger w'} \\ & \wedge \bigwedge_{1 \leq i \leq k} evolution^*(y_i, y'_i) \wedge \forall \tilde{w}: world. \exists x'_1, \dots, x'_n. (succ^*(w, \tilde{w}) \\ & \wedge succ^*(\tilde{w}, w') \rightarrow (\varphi(x'_1, \dots, x'_n))^{\dagger \tilde{w}} \wedge \bigwedge_{1 \leq j \leq n} evolution^*(x_j, x'_j)) \end{aligned}$$
- $(\bigcirc \varphi(x_1, \dots, x_n))^{\dagger w} =$

$$\begin{aligned} & \exists w': world. \exists x'_1, \dots, x'_n. succ(w, w') \\ & \wedge (\varphi(x'_1, \dots, x'_n))^{\dagger w'} \wedge \bigwedge_{1 \leq j \leq n} evolution(x_j, x'_j) \wedge exists(x'_j, w') \end{aligned}$$

Note that x_i and y_i are not necessarily distinct. Simplified translations may be used for the \diamond and \square temporal operators.

B 2 and 3-valued FO^{TC}

In this appendix, we give a brief summary of 2 and 3 valued FO^{TC} . The material presented here is fairly standard and included only for completeness of presentation.

B.1 Syntax

Formally, the syntax of first-order formulae with transitive closure is defined as follows:

DEFINITION B.1

A **formula** over the **vocabulary** $\mathcal{P} = \{eq, p_1, \dots, p_n\}$ is defined inductively, as follows:

Atomic Formulae The **logical literals** **0** and **1** are atomic formulae with no free variables.

For every predicate symbol $p \in \mathcal{P}$ of arity k , $p(v_1, \dots, v_k)$ is an atomic formula with free variables $\{v_1, \dots, v_k\}$.

Logical Connectives If φ_1 and φ_2 are formulae whose sets of free variables are V_1 and V_2 , respectively, then $(\varphi_1 \wedge \varphi_2)$, $(\varphi_1 \vee \varphi_2)$, and $(\neg \varphi_1)$ are formulae with free variables $V_1 \cup V_2$, $V_1 \cup V_2$, and V_1 , respectively.

Quantifiers If φ_1 is a formula with free variables $\{v_1, v_2, \dots, v_k\}$, then $(\exists v_1 : \varphi_1)$ and $(\forall v_1 : \varphi_1)$ are both formulae with free variables $\{v_2, v_3, \dots, v_k\}$.

Transitive Closure If φ_1 is a formula with free variables V such that $v_3, v_4 \notin V$, then $(TC\ v_1 : v_2)(\varphi_1)v_3v_4$ is a formula with free variables $(V - \{v_1, v_2\}) \cup \{v_3, v_4\}$. A formula is **closed** when it has no free variables.

B.2 2-valued Interpretation

In this section, we define the (2-valued) semantics for first-order logic with transitive closure in the standard way.

DEFINITION B.2

A **2-valued interpretation** of the language of formulae over \mathcal{P} is a **2-valued logical structure** $S = \langle U^S, \iota^S \rangle$, where U^S is a set of **individuals** and ι^S maps each predicate symbol p of arity k to a truth-valued function:

$$\iota^S(p) : (U^S)^k \rightarrow \{0, 1\}.$$

An **assignment** Z is a function that maps free variables to individuals (i.e., an assignment has the functionality $Z : \{v_1, v_2, \dots\} \rightarrow U^S$). An assignment that is defined on all free variables of a formula φ is called **complete** for φ . In the sequel, we assume that every assignment Z that arises in connection with the discussion of some formula φ is complete for φ .

The **(2-valued) meaning** of a formula φ , denoted by $\llbracket \varphi \rrbracket_2^S(Z)$, yields a truth value in $\{0, 1\}$. The meaning of φ is defined inductively as follows:

Atomic Formulae For an atomic formula consisting of a logical literal $l \in \{0, 1\}$, $\llbracket l \rrbracket_2^S(Z) = l$ (where $l \in \{0, 1\}$).

For an atomic formula of the form $p(v_1, \dots, v_k)$,

$$\llbracket p(v_1, \dots, v_k) \rrbracket_2^S(Z) = \iota^S(p)(Z(v_1), \dots, Z(v_k))$$

Logical Connectives When φ is a formula built from subformulae φ_1 and φ_2 ,

$$\begin{aligned} \llbracket \varphi_1 \wedge \varphi_2 \rrbracket_2^S(Z) &= \min(\llbracket \varphi_1 \rrbracket_2^S(Z), \llbracket \varphi_2 \rrbracket_2^S(Z)) \\ \llbracket \varphi_1 \vee \varphi_2 \rrbracket_2^S(Z) &= \max(\llbracket \varphi_1 \rrbracket_2^S(Z), \llbracket \varphi_2 \rrbracket_2^S(Z)) \\ \llbracket \neg \varphi_1 \rrbracket_2^S(Z) &= 1 - \llbracket \varphi_1 \rrbracket_2^S(Z) \end{aligned}$$

Quantifiers When φ is a formula that has a quantifier as the outermost operator,

$$\begin{aligned} \llbracket \forall v_1 : \varphi_1 \rrbracket_2^S(Z) &= \min_{u \in U^S} \llbracket \varphi_1 \rrbracket_2^S(Z[v_1 \mapsto u]) \\ \llbracket \exists v_1 : \varphi_1 \rrbracket_2^S(Z) &= \max_{u \in U^S} \llbracket \varphi_1 \rrbracket_2^S(Z[v_1 \mapsto u]) \end{aligned}$$

Transitive Closure When φ is a formula of the form $(TC\ v_1 : v_2)(\varphi_1)v_3v_4$,

$$\begin{aligned} \llbracket (TC\ v_1 : v_2)(\varphi_1)v_3v_4 \rrbracket_2^S(Z) &= \\ &= \max_{\substack{n \geq 1, u_1, \dots, u_{n+1} \in U, \\ Z(v_3) = u_1, Z(v_4) = u_{n+1}}} \min_{i=1}^n \llbracket \varphi_1 \rrbracket_2^S(Z[v_1 \mapsto u_i, v_2 \mapsto u_{i+1}]) \end{aligned}$$

We say that S and Z **satisfy** φ (denoted by $S, Z \models \varphi$) if $\llbracket \varphi \rrbracket_2^S(Z) = 1$. We write $S \models \varphi$ if for every Z we have $S, Z \models \varphi$.

B.3 3-valued Interpretation

We now generalize Defn. B.2 to define the meaning of a formula with respect to a 3-valued structure.

DEFINITION B.3

A **3-valued interpretation** of the language of formulae over \mathcal{P} is a **3-valued logical structure** $S = \langle U^S, \iota^S \rangle$, where U^S is a set of individuals and ι^S maps each predicate symbol p of arity k to a truth-valued function:

$$\iota^S(p) : (U^S)^k \rightarrow \{0, 1, 1/2\}.$$

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For an assignment Z , the **(3-valued) meaning** of a formula φ , denoted by $\llbracket \varphi \rrbracket_3^S(Z)$, now yields a truth value in $\{0, 1, 1/2\}$. The meaning of φ is defined inductively as in Defn. B.2.

We say that S and Z **potentially satisfy** φ , denoted by $S, Z \models_3 \varphi$, if $\llbracket \varphi \rrbracket_3^S(Z) = 1/2$ or $\llbracket \varphi \rrbracket_3^S(Z) = 1$. We write $S \models_3 \varphi$ if for every Z we have $S, Z \models_3 \varphi$.

C Proofs

For proving Theorem 4.5 we need a few additional definitions.

We first have to formally define $rep(\pi)$, and also introduce an intermediate assignment Z which will be used to record values of intermediate assignments through evaluation.

DEFINITION C.1 (Trace representation)

Given a trace π , we define $rep(\pi) = \langle U_{rep(\pi)}, \iota_{rep(\pi)} \rangle$ to be the representation of π as a first-order logical structure, where:

- for every world π_i in π , there exists a world individual $w_i \in U_{rep(\pi)}$ s.t. $\iota_{rep(\pi)}(world)(w_i) = 1$.
- for every individual u in the universe U_{π_i} of a world π_i in the trace, there exists a corresponding non-world individual $\tilde{u} \in U_{rep(\pi)}$, s.t. $\iota_{rep(\pi)}(world)(\tilde{u}) = 0$.
- for every two successive worlds π_i and π_{i+1} in π , having corresponding world individuals $w_i, w_{i+1} \in U_{rep(\pi)}$, $\iota_{rep(\pi)}(succ)(w_i, w_{i+1}) = 1$.
- for the first world of the trace π_0 in π , having a corresponding world individual $w_0 \in U_{rep(\pi)}$, $\iota_{rep(\pi)}(initialWorld)(w_0) = 1$.
- for every world π_i with a corresponding world individual w_i , and for every individual $u \in U_{\pi_i}$ with a corresponding individual $\tilde{u} \in U_{rep(\pi)}$, $\iota_{rep(\pi)}(exists)(\tilde{u}, w_i) = 1$, and for every other world $\pi_j, j \neq i$ with a corresponding world individual w_j , $\iota_{rep(\pi)}(exists)(\tilde{u}, w_j) = 0$.
- for every two consecutive worlds π_i, π_{i+1} in π , and for every two individuals $u_i \in U_{\pi_i}$ and $u_{i+1} \in U_{\pi_{i+1}}$ with corresponding individuals $\tilde{u}_i, \tilde{u}_{i+1} \in U_{rep(\pi)}$, $\iota_{rep(\pi)}(evolution)(\tilde{u}_i, \tilde{u}_{i+1}) = 1$ iff $e_{\pi_i}(u_i) = u_{i+1}$.
- for every world π_i and an individual $u \in \pi_i$ with a corresponding individual $\tilde{u} \in U_{rep(\pi)}$, $\iota_{rep(\pi)}(isNew)(\tilde{u}) = 1$ iff $u \in A_{\pi_i}$.
- for every world π_i and an individual $u \in \pi_i$ with a corresponding individual $\tilde{u} \in U_{rep(\pi)}$, $\iota_{rep(\pi)}(isFreed)(\tilde{u}) = 1$ iff $u \in D_{\pi_i}$.

We augment the notion of assignment as follows: an assignment Z assigns individuals from the universe to logical variables, and assigns a world of the trace to the designated logical variable w .

DEFINITION C.2

Given a trace π , a VTL formula φ , an assignment Z , and a world of the trace π_i for some i , we say that $\pi, Z \models_t [\varphi]_w$ when:

- $Z(w) = \pi_i$
- $\pi^i, Z \models_t \varphi$

That is, when the suffix of π starting from the world assigned to w satisfies the property.

LEMMA C.3 (Prefix Redundancy)

Given a trace π and an assignment Z assigning a world π_i to w ,

$$\pi, Z \models_t [\varphi]_w \iff \pi^i, Z \models_t [\varphi]_w$$

PROOF.

$$\begin{aligned} \pi, Z \models_t [\varphi]_w &\iff \text{(by Definition C.2)} \\ \pi^i, Z \models_t \varphi &\iff \text{(by Definition C.2)} \\ \pi^i, Z \models_t [\varphi]_w & \end{aligned}$$

■

DEFINITION C.4

We define an additional operation on traces, $\triangleright_w(\pi)$ that takes a trace and a logical variable assigned by Z to a world in the trace. The operation returns the suffix of the trace starting at the given world.

The initial assignment Z assigns w to the first world of the trace.

PROOF. [Theorem 4.5]

We need to prove that for every closed VTL formula φ and a trace π , $\pi \models \varphi$ if and only if $rep(\pi) \models (\varphi)^\dagger$, where $rep(\pi)$ is the first-order representation of π . We will now show that:

$$\pi, Z \models_t [\varphi]_w \text{ if and only if } rep(\triangleright_w(\pi)), Z \models (\varphi)^{\dagger w}$$

0,1 trivially holds.

p($\mathbf{v}_1, \dots, \mathbf{v}_k$)

$$\begin{aligned} rep(\triangleright_w(\pi)), Z \models (p(v_1, \dots, v_k))^{\dagger w} &\iff && \text{(Definition A.1)} \\ rep(\triangleright_w(\pi)), Z \models p(v_1, \dots, v_k) &\iff && \text{(Definition B.2)} \\ \iota_{head(\triangleright_w(\pi))}(p)(Z(v_1), \dots, Z(v_k)) = 1 &\iff && \text{(Definition 3.7)} \\ \pi^i, Z \models_t p(v_1, \dots, v_k) \text{ where } Z(w) = \pi_i &\iff && \text{(Definition C.2)} \\ \pi, Z \models_t [p(v_1, \dots, v_k)]_w &&& \end{aligned}$$

$\varphi \wedge \psi$

$$\begin{aligned} rep(\triangleright_w(\pi)), Z \models (\varphi \wedge \psi)^{\dagger w} &\iff && \text{(Definition A.1)} \\ rep(\triangleright_w(\pi)), Z \models (\varphi)^{\dagger w} \text{ and } rep(\triangleright_w(\pi)), Z \models (\psi)^{\dagger w} &\iff && \text{inductive assumption} \\ \pi, Z \models_t [\varphi]_w \text{ and } \pi, Z \models_t [\psi]_w &\iff && \text{(Definition 3.7)} \\ \pi, Z \models_t [\varphi \wedge \psi]_w &&& \end{aligned}$$

$\varphi \vee \psi$

$$\begin{aligned} rep(\triangleright_w(\pi)), Z \models (\varphi \vee \psi)^{\dagger w} &\iff && \text{(Definition A.1)} \\ rep(\triangleright_w(\pi)), Z \models (\varphi)^{\dagger w} \text{ or } rep(\triangleright_w(\pi)), Z \models (\psi)^{\dagger w} &\iff && \text{inductive assumption} \\ \pi, Z \models_t [\varphi]_w \text{ or } \pi, Z \models_t [\psi]_w &\iff && \text{(Definition 3.7)} \\ \pi, Z \models_t [\varphi \vee \psi]_w &&& \end{aligned}$$

$\exists v. \varphi(\mathbf{v})$

$$\begin{aligned} rep(\triangleright_w(\pi)), Z \models (\exists v. \varphi(v))^{\dagger w} &\iff && \text{(Definition A.1)} \\ rep(\triangleright_w(\pi)), Z \models \exists v. exists(w, v) \wedge (\varphi(v))^{\dagger w} &\iff && \\ \text{(assume only } v \text{ is free without loss of generality)} &&& \\ \text{exists } u \in U_{head(\triangleright_w(\pi))} \text{ s.t. } rep(\triangleright_w(\pi)), Z[v \mapsto u] \models (\varphi(v))^{\dagger w} &&& \\ \text{exists } u \in U_{head(\triangleright_w(\pi))} \text{ s.t. } \pi, Z[v \mapsto u] \models_t [\varphi(v)]_w &\iff && \text{(Definition 3.7)} \\ \pi, Z \models_t [\exists v. \varphi(v)]_w &&& \end{aligned}$$

(TC $\mathbf{v}_1, \mathbf{v}_2 : \varphi$)($\mathbf{v}_3, \mathbf{v}_4$)

$$\begin{aligned} rep(\triangleright_w(\pi)), Z \models ((TC \ v_1, v_2 : \varphi)(v_3, v_4))^{\dagger w} &\iff && \text{(Definition A.1)} \\ rep(\triangleright_w(\pi)), Z \models (TC \ v_1, v_2 : \varphi)^{\dagger w} \wedge exists(w, v_1) \wedge exists(w, v_2)(v_3, v_4) &\iff && \\ \text{exists } u_1, \dots, u_k \in U_T. \text{ s.t. } Z(v_3) = u_1 \wedge Z(v_4) = u_k &&& \\ \text{and for all } 1 \leq i \leq k. rep(\triangleright_w(\pi)), Z[v_1 \mapsto u_i, v_2 \mapsto u_{i+1}] \models (\varphi)^{\dagger w} &&& \\ \wedge exists(w, v_1) \wedge exists(w, v_2) &\iff && \\ \text{exists } u_1, \dots, u_k \in U_{head(\triangleright_w(\pi))}. \text{ s.t. } Z(v_3) = u_1 \wedge Z(v_4) = u_k &&& \\ \text{and for all } 1 \leq i \leq k. rep(\triangleright_w(\pi)), Z[v_1 \mapsto u_i, v_2 \mapsto u_{i+1}] \models (\varphi)^{\dagger w} &\iff && \\ \pi, Z \models_t [(TC \ v_1, v_2 : \varphi)(v_3, v_4)]_w &&& \end{aligned}$$

$\bigcirc \varphi(\mathbf{x}_1, \dots, \mathbf{x}_n)$

$$\begin{aligned} rep(\triangleright_w(\pi)), Z \models (\bigcirc \varphi(x_1, \dots, x_n))^{\dagger w} &\iff && \text{(Lemma C.5)} \\ rep(\triangleright_{w'}(\pi)), Z' \models (\varphi(x_1, \dots, x_n))^{\dagger w'} \text{ where } succ(w, w'), Z' \text{ is an evolution of } Z &\iff && \\ \pi, Z' \models_t [\varphi]_{w'} &\iff && \text{chop worlds before } w', \text{ Lemma C.3} \\ tail(\pi), Z' \models_t [\varphi]_{w'} &\iff && \text{(Definition 3.7)} \\ \pi, Z \models_t [\bigcirc \varphi]_w &&& \end{aligned}$$

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$\varphi(\mathbf{x}_1, \dots, \mathbf{x}_n) \mathcal{U} \psi(\mathbf{y}_1, \dots, \mathbf{y}_n)$
 $rep(\triangleright_w(\pi)), Z \models (\varphi(x_1, \dots, x_n) \mathcal{U} \psi(y_1, \dots, y_n))^{\dagger w} \iff$ (Definition A.1)
 $rep(\triangleright_w(\pi)), Z \models \exists w': world. \exists y'_1, \dots, y'_k. succ^*(w, w') \wedge (\psi(y'_1, \dots, y'_k))^{\dagger w'}$
 $\wedge \bigwedge_{1 \leq i \leq k} evolution^*(y_i, y'_i) \wedge \forall \tilde{w}: world. \exists x'_1, \dots, x'_n. (succ^*(w, \tilde{w})$
 $\wedge succ^*(\tilde{w}, w') \rightarrow (\varphi(x'_1, \dots, x'_n))^{\dagger \tilde{w}} \wedge \bigwedge_{1 \leq j \leq n} evolution^*(x_j, x'_j)) \iff$
exists $w', rep(\triangleright_w(\pi)), Z \models succ^*(w, w')$ and
exists $Z', rep(\triangleright_w(\pi)), Z' \models (\psi(y_1, \dots, y_k))^{\dagger w'}$ and
for all $\tilde{w}, rep(\triangleright_w(\pi)), Z \models (succ^*(w, \tilde{w}) \wedge succ^*(\tilde{w}, w'))$ implies
exists $\tilde{Z}, rep(\triangleright_w(\pi)), Z \models (\varphi(x_1, \dots, x_n))^{\dagger \tilde{w}} \iff$ (Lemma C.6)
exists $w', k \geq 0, s.t. Z(w') = \pi_k$ and
exists $Z', rep(\triangleright_w(\pi)), Z' \models (\psi(y_1, \dots, y_k))^{\dagger w'}$ and
for all $\tilde{w}, rep(\triangleright_w(\pi)), Z \models (succ^*(w, \tilde{w}) \wedge succ^*(\tilde{w}, w'))$ implies
exists $\tilde{Z}, rep(\triangleright_w(\pi)), Z \models (\varphi(x_1, \dots, x_n))^{\dagger \tilde{w}} \iff$
exists $w', k \geq 0, s.t. Z(w') = \pi_k$ and exists $Z', rep(\triangleright_w(\pi)), Z' \models (\psi(y_1, \dots, y_k))^{\dagger w'}$ and
for all $\tilde{w}, Z(\tilde{w}) = \pi_i, 1 \leq i \leq k$, there exists $\tilde{Z}, rep(\triangleright_w(\pi)), Z \models (\varphi(x_1, \dots, x_n))^{\dagger \tilde{w}} \iff$
exists $w', k \geq 0, s.t. Z(w') = \pi_k$ and exists $Z', rep(\triangleright_{w'}(\pi)), Z' \models (\psi(y_1, \dots, y_k))^{\dagger w'}$ and
for all $\tilde{w}, Z(\tilde{w}) = \pi_i, 1 \leq i \leq k$, there exists $\tilde{Z}, rep(\triangleright_{\tilde{w}}(\pi)),$
 $Z \models (\varphi(x_1, \dots, x_n))^{\dagger \tilde{w}} \iff$ (ind.)
exists $w', k \geq 0, s.t. Z(w') = \pi_k$ and exists $Z', \pi, Z' \models_t [\psi(y_1, \dots, y_k)]_{w'}$ and
for all $\tilde{w}, Z(\tilde{w}) = \pi_i, 1 \leq i \leq k$, there exists $\tilde{Z}, \pi, \tilde{Z} \models_t [\varphi(x_1, \dots, x_n)]_{\tilde{w}}$
 \iff (Lemma C.3)
exists $w', k \geq 0, s.t. Z(w') = \pi_k$ and exists $Z', \pi^k, Z' \models_t [\psi(y_1, \dots, y_k)]_{w'}$ and
for all $\tilde{w}, Z(\tilde{w}) = \pi_i, 1 \leq i \leq k$, there exists $\tilde{Z}, \pi^i, \tilde{Z} \models_t [\varphi(x_1, \dots, x_n)]_{\tilde{w}} \iff$
(Def. C.2 + Definition 3.7)
 $\pi, Z \models_t [\varphi(x_1, \dots, x_n) \mathcal{U} \psi(y_1, \dots, y_n)]_w$

■

LEMMA C.5

$$rep(\triangleright_w(\pi)), Z \models (\bigcirc \varphi(x_1, \dots, x_n))^{\dagger w} \iff rep(\triangleright_{w'}(\pi)), Z' \models (\varphi(x_1, \dots, x_n))^{\dagger w'}$$

where $succ(w, w')$ and Z' is the evolution of Z .

PROOF.

$$\begin{aligned}
rep(\triangleright_w(\pi)), Z \models (\bigcirc \varphi(x_1, \dots, x_n))^{\dagger w} &\iff \\
rep(\triangleright_w(\pi)), Z \models \exists w': world. \exists x'_1, \dots, x'_n. succ(w, w') \wedge (\varphi(x'_1, \dots, x'_n))^{\dagger w'} \wedge \\
&\bigwedge_{1 \leq j \leq n} evolution(x_j, x'_j) \wedge exists(x'_j, w') \iff \\
&\text{(when } succ(w, w') \text{)} \\
rep(\triangleright_{w'}(\pi)), Z \models \exists x'_1, \dots, x'_n. (\varphi(x'_1, \dots, x'_n))^{\dagger w'} \\
&\wedge \bigwedge_{1 \leq j \leq n} evolution(x_j, x'_j) \wedge exists(x'_j, w') \iff \\
&\text{(when } Z' \text{ is the evolution of } Z \text{)} \\
rep(\triangleright_{w'}(\pi)), Z' \models (\varphi(x_1, \dots, x_n))^{\dagger w'}
\end{aligned}$$

■

LEMMA C.6

Given a trace π , an assignment Z assigning a world individual to the logical variable w , for any w' ,

$$rep(\triangleright_w(\pi)), Z \models succ^*(w, w') \iff \text{there exists } k \geq 0, Z(w') = \pi_k$$

PROOF. Trivial from definition of TC operator. This lemma is provided to emphasize that $succ^*(w, w')$ corresponds to the existence of a successor within a *finite future*. ■

PROOF. [Theorem 5.6] This theorem generalizes the embedding theorem of [15] for the infinite case. The proof is by structural induction on φ :

Basis: For atomic formula $p(v_1, v_2, \dots, v_k), u_1, u_2, \dots, u_k \in U^S$,

and $Z = [v_1 \mapsto u_1, v_2 \mapsto u_2, \dots, v_k \mapsto u_k]$ we have

$$\begin{aligned} & \llbracket p(v_1, v_2, \dots, v_k) \rrbracket_3^S(Z) \\ &= \iota^S(p)(u_1, u_2, \dots, u_k) && \text{(Definition B.3)} \\ &\sqsubseteq \iota^{S'}(p)(f(u_1), f(u_2), \dots, f(u_k)) && \text{(Definition 5.3)} \\ &= \llbracket p(v_1, v_2, \dots, v_k) \rrbracket_3^{S'}(f \circ Z) && \text{(Definition B.3)} \end{aligned}$$

Also, for $l \in \{0, 1, 1/2\}$, we have:

$$\begin{aligned} & \llbracket \mathbf{I} \rrbracket_3^S(Z) \\ &= l && \text{(Definition B.3)} \\ &\sqsubseteq l && \text{(Definition 5.2)} \\ &= \llbracket \mathbf{I} \rrbracket_3^{S'}(f \circ Z) && \text{(Definition B.3)} \end{aligned}$$

Induction step: Suppose φ is a formula with free variables v_1, v_2, \dots, v_k . Let Z be a complete assignment for φ . If $\llbracket \varphi \rrbracket_3^S(Z) = 1/2$, then the theorem holds trivially. Therefore assume that $\llbracket \varphi \rrbracket_3^{S'}(f \circ Z) \in \{0, 1\}$. We distinguish between the following cases:

Logical-and $\varphi \equiv \varphi_1 \wedge \varphi_2$. The proof splits into the following subcases:

Case 1: $\llbracket \varphi_1 \wedge \varphi_2 \rrbracket_3^{S'}(f \circ Z) = 0$.

In this case, either $\llbracket \varphi_1 \rrbracket_3^{S'}(f \circ Z) = 0$ or $\llbracket \varphi_2 \rrbracket_3^{S'}(f \circ Z) = 0$. Without loss of generality assume that $\llbracket \varphi_1 \rrbracket_3^{S'}(f \circ Z) = 0$. Then, by the induction hypothesis for φ_1 , we conclude that $\llbracket \varphi_1 \rrbracket_3^S(Z) = 0$. Therefore, by Definition B.3, $\llbracket \varphi_1 \wedge \varphi_2 \rrbracket_3^S(Z) = 0$.

Case 2: $\llbracket \varphi_1 \wedge \varphi_2 \rrbracket_3^{S'}(f \circ Z) = 1$.

In this case, both $\llbracket \varphi_1 \rrbracket_3^{S'}(f \circ Z) = 1$ and $\llbracket \varphi_2 \rrbracket_3^{S'}(f \circ Z) = 1$. Then, by the induction hypothesis for φ_1 and φ_2 , we conclude that $\llbracket \varphi_1 \rrbracket_3^S(Z) = 1$ and $\llbracket \varphi_2 \rrbracket_3^S(Z) = 1$. Therefore, by Definition B.3, $\llbracket \varphi_1 \wedge \varphi_2 \rrbracket_3^S(Z) = 1$.

Logical-negation $\varphi \equiv \neg \varphi_1$. The proof splits into the following subcases:

Case 1: $\llbracket \neg \varphi_1 \rrbracket_3^{S'}(f \circ Z) = 0$.

In this case, $\llbracket \varphi_1 \rrbracket_3^{S'}(f \circ Z) = 1$.

Then, by the induction hypothesis for φ_1 , we conclude that $\llbracket \varphi_1 \rrbracket_3^S(Z) = 1$.

Therefore, by Definition B.3, $\llbracket \neg \varphi_1 \rrbracket_3^S(Z) = 0$.

Case 2: $\llbracket \neg \varphi_1 \rrbracket_3^{S'}(f \circ Z) = 1$.

In this case, $\llbracket \varphi_1 \rrbracket_3^{S'}(f \circ Z) = 0$.

Then, by the induction hypothesis for φ_1 , we conclude that $\llbracket \varphi_1 \rrbracket_3^S(Z) = 0$.

Therefore, by Definition B.3, $\llbracket \neg \varphi_1 \rrbracket_3^S(Z) = 1$.

Existential-Quantification $\varphi \equiv \exists v_0 : \varphi_1$. The proof splits into the following subcases:

Case 1: $\llbracket \exists v_1 : \varphi_1 \rrbracket_3^{S'}(f \circ Z) = 0$.

In this case, for all $u \in U^S$, $\llbracket \varphi_1 \rrbracket_3^{S'}((f \circ Z)[v_1 \mapsto f(u)]) = 0$. Then, by the induction hypothesis for φ_1 , we conclude that for all $u \in U^S$ $\llbracket \varphi_1 \rrbracket_3^S(Z[v_1 \mapsto u]) = 0$. Therefore, by Definition B.3, $\llbracket \exists v_1 : \varphi_1 \rrbracket_3^S(Z) = 0$.

Case 2: $\llbracket \exists v_1 : \varphi_1 \rrbracket_3^{S'}(f \circ Z) = 1$.

In this case, there exists a $u' \in U^{S'}$ such that $\llbracket \varphi_1 \rrbracket_3^{S'}((f \circ Z)[v_1 \mapsto u']) = 1$. Because f is surjective, there exists a $u \in U^S$ such that $f(u) = u'$ and $\llbracket \varphi_1 \rrbracket_3^{S'}((f \circ Z)[v_1 \mapsto f(u)]) = 1$. Then, by the induction hypothesis for φ_1 , we conclude that $\llbracket \varphi_1 \rrbracket_3^S(Z[v_1 \mapsto u]) = 1$. Therefore, by Definition B.3, $\llbracket \exists v_1 : \varphi_1 \rrbracket_3^S(Z) = 1$.

Transitive Closure $\varphi \equiv (TC \ v_1, v_2 : \varphi_1)(v_3, v_4)$. The proof splits into the following subcases:

Case 1: $\llbracket (TC \ v_1, v_2 : \varphi_1)(v_3, v_4) \rrbracket_3^{S'}(f \circ Z) = 1$.

By Definition B.3, there exist $u'_1, u'_2, \dots, u'_{n+1} \in U^{S'}$ such that for all $1 \leq i \leq n$, $\llbracket \varphi_1 \rrbracket_3^{S'}((f \circ Z)[v_1 \mapsto u'_i, v_2 \mapsto u'_{i+1}]) = 1$, $(f \circ Z)(v_3) = u'_1$, and $(f \circ Z)(v_4) = u'_{n+1}$. Because f is surjective, there exist $u_1, u_2, \dots, u_{n+1} \in U^S$ such that for all $1 \leq i \leq n+1$, $f(u_i) = u'_i$. Therefore, $Z(v_3) = u_1$, $Z(v_4) = u_{n+1}$, and by the induction hypothesis, for all $1 \leq i \leq n$, $\llbracket \varphi_1 \rrbracket_3^S(Z[v_1 \mapsto u_i, v_2 \mapsto u_{i+1}]) = 1$. Hence, by Definition B.3, $\llbracket (TC \ v_1, v_2 : \varphi_1)(v_3, v_4) \rrbracket_3^S(Z) = 1$.

Case 2: $\llbracket (TC \ v_1, v_2 : \varphi_1)(v_3, v_4) \rrbracket_3^{S'}(f \circ Z) = 0$.

We need to show that $\llbracket (TC \ v_1, v_2 : \varphi_1)(v_3, v_4) \rrbracket_3^S(Z) = 0$. Assume on the

contrary that $\llbracket (TC \ v_1, v_2 : \varphi_1)(v_3, v_4) \rrbracket_3^{S'}(f \circ Z) = 0$, but $\llbracket (TC \ v_1, v_2 : \varphi_1)(v_3, v_4) \rrbracket_3^S(Z) \neq 0$.

Because $\llbracket (TC\ v_1, v_2 : \varphi_1)(v_3, v_4) \rrbracket_3^S(Z) \neq 0$, by Definition B.3 there exist $u_1, u_2, \dots, u_{n+1} \in U^S$ such that $Z(v_3) = u_1$, $Z(v_4) = u_{n+1}$, and for all $1 \leq i \leq n$, $\llbracket \varphi_1 \rrbracket_3^S(Z[v_1 \mapsto u_i, v_2 \mapsto u_{i+1}]) \neq 0$. Hence, by the induction hypothesis there exist $u'_1, u'_2, \dots, u'_{n+1} \in U^{S'}$ such that $(f \circ Z)(v_3) = u'_1$, and $(f \circ Z)(v_4) = u'_{n+1}$ and for all $1 \leq i \leq n$, $\llbracket \varphi_1 \rrbracket_3^{S'}((f \circ Z)[v_1 \mapsto u'_i, v_2 \mapsto u'_{i+1}]) \neq 0$. Therefore, by Definition B.3, $\llbracket (TC\ v_1, v_2 : \varphi_1)(v_3, v_4) \rrbracket_3^{S'}(f \circ Z) \neq 0$, which is a contradiction. ■

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