PipeProof: Automated Memory Consistency Proofs for Microarchitectural Specifications

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Abstract—Memory consistency models (MCMs) specify rules which constrain the values that can be returned by load instructions in parallel programs. To ensure that parallel programs run correctly, verification of hardware MCM implementations would ideally be \textit{complete}; i.e., verified as being correct across all possible executions of all possible programs. However, no existing automated approach is capable of such complete verification.

To help fill this verification gap, we present PipeProof, a methodology and tool for complete MCM verification of an axiomatic microarchitectural (hardware-level) ordering specification against an axiomatic ISA-level MCM specification. PipeProof can automatically prove a microarchitecture correct in all cases, or return an indication (often a counterexample) that the microarchitecture could not be verified. To accomplish unbounded verification, PipeProof introduces the novel \textit{Transitive Chain Abstraction} to represent microarchitectural executions of an arbitrary number of instructions using only a small, finite number of instructions. With the help of this abstraction, PipeProof proves microarchitectural correctness using an automatic abstraction refinement approach. PipeProof’s implementation also includes algorithmic optimizations which improve runtime by greatly reducing the number of cases considered. As a proof-of-concept study, we present results for modelling and proving correct simple microarchitectures implementing the SC and TSO MCMs. PipeProof verifies both case studies in under an hour, showing that it is indeed possible to automate microarchitectural MCM correctness proofs.

Index Terms—Memory consistency models, automated verification, formal verification, happens-before graphs, abstraction refinement.

I. INTRODUCTION

Memory consistency models (MCMs) specify rules which constrain the values that can be returned by load instructions in parallel programs [1]. MCMs are defined at various levels of the hardware-software stack, including programming languages [15, 16, 25] and instruction set architectures (ISAs) [3, 14]. An ISA-level MCM like x86-TSO [14] serves as both a target for x86 compilers and a specification of what x86 hardware must implement. A key challenge in parallel hardware design is ensuring that a given microarchitecture (hardware design) obeys its ISA-level MCM. If the hardware does not respect its MCM in all possible cases, then the correct operation of parallel programs on that implementation cannot be guaranteed.

MCM bugs in hardware are becoming more common as parallel processing becomes ubiquitous and implementations increase in complexity. For example, two transactional memory bugs were discovered in recent Intel processors [11, 32]. One of these bugs was fixed by disabling the transactional memory functionality entirely, reducing processor capabilities. In addition, MCM bugs have been discovered in research simulators [18], coherence protocols [9], and open-source processors [23]. Furthermore, incorrect MCM implementations can be leveraged to create security exploits [10].

The ramifications of MCM bugs in parallel processors necessitate verifying that the hardware correctly implements its MCM. Such verification would ideally be \textit{complete}; i.e., it would cover all possible executions of all possible programs. However, truly complete verification is extremely difficult. The only existing complete consistency proofs of hardware are implemented in interactive theorem provers [7, 31], which require significant manual effort.

Automated approaches could make it much easier for microarchitects to verify their designs. However, no current automated approach is capable of complete MCM verification. Dynamic verification approaches [12, 26] only examine a subset of the possible executions of any program they test, so they are incomplete even for those programs. Formal MCM verification approaches look at all possible executions of the programs they check, but all such approaches that are automated have only been able to conduct verification of implementations for a \textit{bounded} set of programs. The verified programs in such an approach may be a suite of litmus tests\(^1\) which focus on the scenarios most likely to exhibit bugs [2, 18, 19, 23, 24, 30], or all programs smaller than a certain bound (\(~10\) instructions) [33].

Critically, litmus test-based or bounded verification only ensures that the implementation will correctly enforce orderings for the verified programs themselves. It does \textit{not} ensure that the implementation will correctly enforce required orderings for all possible programs. These incomplete approaches have missed important bugs because the set of programs they verified did not exercise those bugs [33]. This necessitates an automated approach capable of conducting \textit{complete} MCM verification of microarchitectural implementations.

To fill this need for complete microarchitectural MCM verification, we present PipeProof\(^2\), a methodology and automated tool for unbounded verification of axiomatic microarchitectural ordering specifications [19] against axiomatic ISA-level MCMs.

\(^1\)Litmus tests are small programs used to test MCM implementations.
\(^2\)open-source and publicly available at github.com/ymanerka/pipeproof.
specifications [2]. PipeProof uses an approach based on Satisfiability Modulo Theories (SMT) [4] and Counterexample-Guided Abstraction Refinement (CEGAR) [8]. PipeProof’s unbounded verification covers all possible programs, core counts, addresses, and values. The key to PipeProof’s unlimited verification is its novel Transitive Chain Abstraction, which allows PipeProof to inductively model and verify the infinite set of program executions that must be verified for a given microarchitecture. As its output, PipeProof either provides a guarantee that the microarchitecture is correct, or returns an indication that the microarchitecture could not be verified. The contributions of this paper are as follows:

- **Beyond Litmus Tests:** PipeProof is the first automated microarchitectural MCM verification tool that is capable of conducting complete verification of microarchitectural ordering specifications against axiomatic ISA-level MCM specifications.

- **Abstraction for Modelling an Infinite Set of Executions:** Verification of a microarchitectural design across all possible programs requires reasoning about an infinite number of possible executions. PipeProof’s Transitive Chain Abstraction allows this infinite set of executions to be modelled inductively, thus making complete microarchitectural verification feasible.

- **Comprehensive Automated Verification of General Microarchitectures:** PipeProof’s algorithms and its Transitive Chain Abstraction have broad applicability across microarchitectures and ISA-level patterns. They are not restricted to a particular microarchitecture or a particular ISA-level MCM.

The rest of this paper is organised as follows. Section II provides background on PipeProof’s two main inputs (ISA-level MCM specification and microarchitectural ordering specification). Section III covers PipeProof’s procedure for proving microarchitectural correctness. Section IV presents the supporting proofs and modelling techniques leveraged by the microarchitectural correctness proof. Section V covers optimizations that reduce PipeProof’s runtime, while Section VI discusses our methodology, results, and ideas for future work. Section VII discusses related work, and Section VIII, our conclusions.

II. BACKGROUND INFORMATION

A. ISA-Level MCMs and Their Axiomatic Specification

Figure 1a shows the message-passing (mp) litmus test, where core 0 communicates data (x) to core 1 by setting a flag (y) to indicate when the data is ready. In the outcome shown (r1=1, r2=0), core 1 observes the write to the flag but not the write to the data. The ISA-level MCM of the system dictates whether or not hardware should allow this behaviour. For example, sequential consistency (SC) [17] requires results that are consistent with a total order on all memory operations where (i) each load reads from the latest store to its address in the total order and (ii) each core performs its operations in program order. Thus, SC forbids the execution of mp where r1=1, r2=0.

![Core 0](https://via.placeholder.com/150)

![Core 1](https://via.placeholder.com/150)

(a) Code for litmus test mp

(b) ISA-level execution of mp forbidden under SC, due to the cycle in the po, rf, and fr relations.

**Definition 1 (ISA-Level Execution):** An ISA-level execution (Instrs, Rels) is a graph. Nodes Instrs are instructions, and edges Rels between nodes represent ISA-level MCM attributes.

Figure 1b shows the ISA-level execution for the outcome of mp from Figure 1a. The po relation represents program order, so i1 po i2 and i3 po i4 represent that i1 is before i2 and i3 is before i4 in program order. The rf (reads-from) relation links each store to all loads which read from that store. For example, i2 rf i3 represents that i3 reads its value from i2 in this execution. The fr (from-reads) edge between i4 and i1 enforces that the store that i4 reads from comes before the store i1 in coherence order (a total order on same-address writes in an execution). The co relation (not present in Figure 1b) is used to represent coherence order. Other ISA-level MCMs require extra relations to model reorderings and fences [2].

In the relational framework of Alglave et al. [2], the permitted behaviours of the ISA-level MCM are defined in terms of the irreflexivity, acyclicity, or emptiness of certain relational patterns. For example, SC can be defined using relational modelling as acyclic(po ∪ co ∪ rf ∪ fr). This means that any execution with a cycle in these four relations is forbidden. The execution in Figure 1b contains such a cycle, and so is forbidden under SC.

B. µspec Microarchitectural Specifications

PipeProof models microarchitectural executions using the microarchitectural happens-before (µhb) graph model developed by the Check suite [18, 19, 23, 24, 30].

**Definition 2 (Microarchitectural Execution):** A microarchitectural execution is a µhb graph (Instrs, N, E). Nodes N represent individual sub-events in the execution of instructions Instrs. Edges E represent happens-before relationships between nodes.
In the case of the AddEdge predicate) to fulfill the requirements of the axiom. Execute also exist between their EdgeExists instructions, if an edge exists between their Fetch \( \sim \) SameMicroop \( a_1 a_2 \) instructions (\( \text{SameCore} a_1 a_2 \)).

\[ \text{AddEdge}((a_1,\text{Execute}),(a_2,\text{Execute})) \Rightarrow \text{EdgeExists}((a_1,\text{Fetch}),(a_2,\text{Fetch})) \]

Axiom "IF_FIFO":
\[
\forall a_1, a_2. ((\text{SameCore} a_1 a_2 \land \lnot \text{SameMicroop} a_1 a_2) \Rightarrow \text{EdgeExists}((a_1,\text{Fetch}),(a_2,\text{Fetch})) \Rightarrow \text{AddEdge}((a_1,\text{Execute}),(a_2,\text{Execute})))
\]

(a) \( \mu \text{hb} \) graph for \( mp \)'s forbidden outcome on simpleSC microarch.

(b) \( \mu \text{spec} \) expressing that the Fetch pipeline stage should be FIFO on simpleSC.

Fig. 2: Example \( \mu \text{hb} \) graph for the \( mp \) litmus test and example \( \mu \text{spec} \) axiom.

Fig. 3: High-level block diagram of PipeProof operation. Components are annotated with the sections in which they are explained.

Fig. 4: ISA-level relations can be analysed in terms of how a given microarchitecture enforces them. These four \( \mu \text{hb} \) graphs show the \( \mu \text{hb} \) edges between instructions that are enforced (directly or indirectly) by the mappings of ISA-level edges to the simpleSC microarchitecture.

III. PipeProof Operation

Figure 3 shows PipeProof’s high-level block diagram. The inputs to PipeProof are a set of \( \mu \text{spec} \) axioms describing microarchitectural orderings, an ISA-level MCM specification, mappings (to link ISA-level and microarchitectural execu-
Axiom "Mappings_po":
forall microop "i",forall microop "j", 
HasDependency po i j => AddEdge (((1, Fetch), (j, Fetch), "po_arch").

Fig. 5: Example mapping axiom for po ISA-level edges on simpleSC.

Fig. 6: A graphical example of the Transitive Chain (TC) Abstraction: all possible ISA-level chains connecting $i_1$ to $i_n$ (left) can be abstracted as some µhb edge (the transitive connection) between the nodes of instructions $i_1$ and $i_n$ (right). The red µhb edge is the microarchitectural mapping of the $fr$ edge from $i_n$ to $i_1$.

PipeProof’s overall operation has three high-level steps:
1) Prove chain invariants correct (Section IV-B).
Then for each forbidden ISA-level pattern in the ISA-level MCM specification:
2) Prove Transitive Chain (TC) Abstraction support for the microarchitecture and the ISA-level pattern (Section IV-A).
3) Prove Microarchitectural Correctness for the microarchitecture and the ISA-level pattern (this section).

The proofs of TC Abstraction support and chain invariants are supporting proofs on which PipeProof’s main Microarchitectural Correctness Proof builds. The Microarchitectural Correctness Proof proves Theorem 1 below.

Theorem 1 (Microarchitectural Correctness): For each ISA-level execution $ISA_{Exec} := (Instrs, Rel)$ where Rel exhibit a pattern forbidden by the ISA-level MCM, all microarchitectural executions $(Instrs, N, E)$ corresponding to $ISA_{Exec}$ are unobservable (i.e., their µhb graphs are cyclic).

This section describes the Microarchitectural Correctness Proof in detail, beginning with the structure of the ISA-level executions PipeProof verifies (Section III-A) and their translation to equivalent microarchitectural executions (Section III-B). The Microarchitectural Correctness proof uses an abstraction refinement approach that leverages the TC Abstraction (Section III-C) to model executions. PipeProof’s refinement process involves examining abstract counterexamples (Section III-D) and refining the abstraction through concretization and decomposition (Section III-E). The section concludes by explaining when PipeProof’s algorithm is able to terminate (Section III-F).

A. Symbolic ISA-Level Executions
PipeProof works with ISA-level executions that are similar to the ISA-level execution of $mp$ in Figure 1b, but it uses symbolic instructions. In other words, the instructions in such ISA-level executions do not have specific addresses or values. The symbolic version of the ISA-level execution in Figure 1b would consist of four instructions $i_1, i_2, i_3,$ and $i_4$, connected by the $po, rf,$ and $fr$ edges as shown, but nothing more would be known about the four instructions beyond the constraints enforced by the ISA-level relations. For instance, the instructions connected by $po$ would be known to be on the same core, and the $rf$ edge between $i_2$ and $i_3$ would enforce that $i_2$ and $i_3$ had the same address and value. However, the specific address and value of $i_2$ and $i_3$ could be anything. Such a symbolic ISA-level execution represents not only the ISA-level execution of $mp$ in Figure 1b, but any ISA-level execution comprised of the cycle$^3$ $po; rf; po; fr$. Thus, verifying such a symbolic ISA-level execution checks the instance of the ISA-level pattern in that execution across all possible addresses and values, as required for complete verification.

B. Mapping ISA-level Executions to Microarchitecture
To verify that a forbidden ISA-level execution is microarchitecturally unobservable, one needs to translate the ISA-level execution to its corresponding microarchitectural executions$^4$. PipeProof’s complete verification requires such translation for any arbitrary ISA-level execution, not just a particular program instance. PipeProof’s microarchitectural executions are similar to the µhb graph in Figure 2a, but like PipeProof’s ISA-level executions, they operate on symbolic instructions which do not have specific addresses and values.

An ISA-level execution’s instructions can be translated by instantiating the $μspec$ microarchitectural axioms for those instructions. Translating ISA-level relations to microarchitecture is harder because the microarchitectural implied by an ISA-level relation differ between microarchitectures. Thus, PipeProof requires user-provided $mappings$ to translate individual ISA-level edges to their corresponding microarchitectural constraints. These mappings are additional $μspec$ axioms that restrict the executions examined by PipeProof’s solver to the microarchitectural executions where the mapped ISA-level edge exists between its source and destination instructions.

$^3$A semicolon (;) denotes relational composition. For example, $r_1;r_2$ denotes a sequence of two ISA-level edges $r_1$ and $r_2$ where the destination instruction of $r_1$ is the source instruction of $r_2$.

$^4$There are usually multiple microarchitectural executions corresponding to a single ISA-level execution.
Fig. 7: PipeProof checking that non-unary ISA-level cycles forbidden by SC are unobservable on simpleSC with the help of the Transitive Chain Abstraction. This figure focuses on the cycles containing \( fr \) edges. Acyclic graphs like \( AbsCex \) are abstract counterexamples: they may be concretized into real counterexamples or broken down into possible decompositions which are each checked in turn. Decompositions A and B are valid decompositions (subsets) of \( AbsCex \), because they guarantee the edge from \( p \) to \( q \) in \( AbsCex \). Decomposition C does not guarantee this edge, and is thus invalid and not considered further. Decomposition A strengthens the TC Abstraction enough to make the graph cyclic (and thus unobservable) as required. Decomposition B is valid but acyclic, so its abstraction needs to be refined further.
Figure 4 shows the \( \mu lb \) edges enforced by mappings of the ISA-level edges \( fr, rf, po, \) and \( co \) on \textit{simpleSC}. Figure 5 shows the mapping axiom for \( po \) edges on \textit{simpleSC}, which translates a \( po \) edge between instructions \( i \) and \( j \) to a \( \mu lb \) edge between the \textit{Fetch} stages of those instructions. Such an edge can be seen between \( i1 \) and \( i2 \) in the \textit{po} case of Figure 4. This edge between the \textit{Fetch} stages indirectly induces edges between the \textit{Execute} and \textit{Writeback} stages of the instructions as well, through axioms like \texttt{IF_FIFO} from Figure 2b. These \( \mu lb \) edges are also shown in Figure 4, and reflect the in-order nature of \textit{simpleSC}'s pipeline.

C. The TC Abstraction: Representing Infinite ISA-level Chains

Symbolic analysis and the use of mappings for ISA-level edges allow a single ISA-level cycle to be translated to the microarchitectural level for all possible addresses and values. However, there are an infinite number of possible ISA-level cycles that match a forbidden ISA-level pattern like \( cyclic(po \cup co \cup rf \cup fr) \) (which are the executions forbidden by SC). Conceptually, all of these ISA-level cycles need to be verified as being unobservable in order to ensure that the microarchitecture is correct across all possible programs. Such unbounded verification is made possible by using inductive approaches. PipeProof achieves unbounded verification by inductively modelling executions using a novel \textit{Transitive Chain (TC) Abstraction}. Specifically, PipeProof uses the TC Abstraction to efficiently represent ISA-level chains (defined below):

\textbf{Definition 3}: An ISA-level chain is an acyclic sequence of ISA-level relations \( r_1; r_2; r_3; \ldots; r_n \). An example ISA-level chain is \( po; rf; po \) from Figure 1b.

The TC Abstraction is the representation of an ISA-level chain of arbitrary length between two instructions \( i_1 \) and \( i_n \) as a single \( \mu lb \) edge between \( i_1 \) and \( i_n \) at the microarchitecture level. None of the intermediate instructions in the chain are explicitly modelled. Abstract executions are those executions where the TC Abstraction is used to represent an ISA-level chain. Meanwhile, concrete executions are those executions where all instructions and ISA-level edges are explicitly modelled; that is, where nothing is abstracted using the TC Abstraction. (Instructions in concrete executions are still symbolic.)

Figure 6 illustrates the TC Abstraction for ISA-level cycles containing the \( fr \) edge. The left of the figure represents all possible non-unary ISA-level cycles (i.e. the cycles containing more than one instruction\(^5\)) that contain an \( fr \) edge. In these cycles, \( i_1 \) may be connected to \( i_n \) by a single ISA-level edge or by a chain of multiple ISA-level edges (the transitive chain). These cycles include the ISA-level cycle \( po; rf; po; fr \) from Figure 1b (since it contains an \( fr \) edge), as well as an infinite number of other cycles containing \( fr \). Using the TC Abstraction, any microarchitectural execution (as seen on the right) corresponding to such an ISA-level cycle represents the chain between \( i_1 \) and \( i_n \) by some \( \mu lb \) edge (the transitive connection) from a node of \( i_1 \) to a node of \( i_n \). (The red \( \mu lb \) edge from \( i_n \) to \( i_1 \) is the mapping of the \( fr \) edge to the microarchitecture.) Thus, if the \( \mu lb \) graph on the right is verified to be unobservable for all possible transitive connections from \( i_1 \) to \( i_n \), then the microarchitecture is guaranteed to be correct for all possible ISA-level cycles containing the \( fr \) edge. PipeProof automatically checks that the microarchitecture and ISA-level pattern support the TC Abstraction (Section IV-A) before using it to prove microarchitectural correctness.

The Transitive Chain Abstraction's capability to represent ISA-level chains of arbitrary length using a single transitive connection from the start to the end of the chain is the key insight underlying PipeProof's complete verification across all programs. This representation allows PipeProof to conduct unbounded verification while only explicitly modelling as many instructions as needed to prove microarchitectural correctness. The transitive connection models the effects of intermediate instructions in the ISA-level chain without explicitly modelling the instructions themselves, allowing for efficient modelling and verification of all possible ISA-level cycles. The TC Abstraction is both weak enough to apply to a variety of microarchitectures and also strong enough (with appropriate refinements discussed below) to prove microarchitectural MCM correctness.

D. Abstract Counterexamples

The TC Abstraction guarantees the presence of some \( \mu lb \) edge between the start and end of an ISA-level chain, such as that between \( i_1 \) and \( i_n \) in Figure 6. To prove microarchitectural correctness using the TC Abstraction, PipeProof must show that for each possible transitive connection between \( i_1 \) and \( i_n \), all possible microarchitectural executions corresponding to the ISA-level cycles being checked are unobservable.

Figure 7 shows PipeProof’s procedure for proving Theorem 1 on \textit{simpleSC}. The figure focuses on the verification of ISA-level cycles containing at least one \( fr \) edge; the process is repeated for other types of cycles in the pattern (for SC, this equates to cycles containing \( po \), \( co \), or \( rf \) edges). For some transitive connections, like the one in the \texttt{NoDecomp} case, the initial \( \mu lb \) graph of the abstract execution is cyclic. This proves the unobservability of all concrete executions represented by \texttt{NoDecomp}, as required for microarchitectural correctness.

In most cases, however, the initial abstract execution graphs will be acyclic, as is the case for \texttt{AbsCex} in Figure 7. This is because the TC Abstraction’s guarantee of a single \( \mu lb \) edge (the transitive connection) between the start and end of an ISA-level chain is necessarily rather weak in order to be general across all possible ISA-level chains that match a forbidden ISA-level pattern. The weakness of the guarantee is also necessary in order for the TC Abstraction to be general enough to support a variety of microarchitectures.

In abstraction refinement \cite{abstraction}, cases such as \texttt{AbsCex} that appear to violate the property being checked but contain an abstraction are called abstract counterexamples. They may

\(^5\)The number of unary cycles (those where an instruction is related to itself) is small, so PipeProof explicitly enumerates and checks them separately.
correspond to concrete (real) counterexamples. They may also be spurious. When spurious, all concrete cases represented by the abstract counterexample are in fact correct.

In PipeProof, an abstract counterexample such as $AbsCex$ represents two types of concrete executions. First, $i_1$ and $i_n$ may be connected by a single ISA-level edge. On the other hand, $i_1$ and $i_n$ may be connected by a chain of multiple ISA-level edges. To check whether an abstract counterexample is spurious or not, PipeProof conducts concretization and decomposition (the refinement loop) to handle the aforementioned two cases.

E. Concretization and Decomposition: The Refinement Loop

In the concretization step, PipeProof checks the case where $i_1$ is connected to $i_n$ by a single ISA-level edge. PipeProof does so by replacing the transitive connection between $i_1$ and $i_n$ with a single ISA-level edge that causes the resultant ISA-level cycle to match the forbidden ISA-level pattern. This concrete execution must be microarchitecturally unobservable. For example, when trying to concretize $AbsCex$ in Figure 7, PipeProof checks the ISA-level cycle $po; fr$, then $co; fr$, then $rf; fr$, and finally $fr; fr$, since each of these are ISA-level cycles forbidden by SC that arise from replacing the transitive connection of $AbsCex$ with a single ISA-level edge. If any of these concrete executions is found to be observable, then the microarchitecture is buggy and PipeProof returns the observable ISA-level cycle as a counterexample.

If executions where the transitive connection is replaced by a single ISA-level edge are found to be unobservable, PipeProof then inductively checks the case where $i_1$ is connected to $i_n$ by a chain of multiple ISA-level edges through decomposition. PipeProof decomposes the transitive chain of $n-1$ ISA-level edges into a transitive chain of $n-2$ ISA-level edges represented by a transitive connection, and a single concrete ISA-level edge. This also results in the explicit modelling of an additional instruction. The concrete ISA-level edge and instruction added by the decomposition are “peeled off” the transitive chain. The key idea behind decomposition of the transitive chain is that the explicit modelling of an additional instruction and ISA-level edge enforces additional microarchitectural constraints that may be enough to create a cycle in the graph. If a cycle is created, the decomposition is unobservable, completing the correctness proof for that case. If all possible decompositions of an abstract counterexample are found to be cyclic (unobservable), then the abstract counterexample is spurious and can be ignored. If any decomposition is found to be acyclic, then that decomposition constitutes an abstract counterexample itself, and concretization and decomposition are repeated for it. Decomposing the chain one instruction at a time improves efficiency by ensuring that PipeProof does not explicitly model more instructions than needed to prove microarchitectural correctness.

Figure 7 shows three (of many) possible decompositions of $AbsCex$. In Decomposition A, an $rf$ edge has been peeled off the right end of the transitive chain. Peeling off the $rf$ edge strengthens the abstraction by connecting node $p$ to node $r$ (an edge not present in $AbsCex$). This creates a cycle in the $\mu$hb graph, rendering the execution unobservable. This completes the correctness proof for this decomposition.

Decomposition B in Figure 7 shows a case where a $co$ edge (rather than an $rf$ edge) is peeled off the transitive chain. Furthermore, the $co$ edge is peeled off the left end of the transitive chain rather than the right. Peeling off the $co$ edge refines the abstraction, but this is still not enough to create a cycle in the $\mu$hb graph. Thus, Decomposition B is itself an abstract counterexample, and the process of concretization and decomposition will be repeated for it.

To ensure completeness of verification when decomposing transitive chains, PipeProof enumerates all possibilities for the concrete ISA-level edge that could be peeled off (using the procedure from Section IV-E) and for the transitive connection representing the remaining chain of length $n-2$. Verifying a single decomposition is equivalent to verifying a subset of the executions of its parent abstract counterexample. As such, any valid decomposition must guarantee the transitive connections of its parent abstract counterexamples. Decompositions that violate this requirement do not represent executions that are modelled by their parent abstract counterexamples, and hence they are discarded.

For example, Decomposition C in Figure 7 is an invalid decomposition of $AbsCex$ because it does not guarantee the transitive connection of its parent $AbsCex$ (a $\mu$hb edge between nodes $p$ and $q$) as Decompositions A and B do. PipeProof filters out any such decompositions that do not guarantee the transitive connections of their parent abstract counterexamples; it does not consider them further.

PipeProof alternates between peeling from the left and peeling from the right when inductively decomposing transitive chains. For example, Decomposition B was created by peeling from the left of $AbsCex$, so when concretization and decomposition is rerun for Decomposition B, the next ISA-level edge will be peeled from the right. PipeProof alternates in this manner because creating a cycle in the graph through decomposition often requires connecting more nodes to either side of the transitive connection.

F. Termination of the PipeProof Algorithm

In many cases, repeatedly peeling off instructions from the transitive chain strengthens the TC Abstraction enough to prove microarchitectural correctness. For the remaining cases, PipeProof requires user-provided chain invariants (Section IV-B) to abstractly represent infinite repeated peelings of a specific pattern of ISA-level edges and ensure termination of the refinement loop. For the SC and TSO case studies detailed in Section VI, peeling off a maximum of 9 instructions from the transitive chain was sufficient (along with chain invariants) to prove correctness of the microarchitectures.

IV. SUPPORTING PROOFS AND TECHNIQUES

PipeProof’s Microarchitectural Correctness proof relies on a number of supporting proofs and modelling techniques in or-
If \( r_n \in \{po, co, rf, fr\} \), show that

\[
\begin{array}{c}
\text{IF} \\
\text{EX} \\
\text{WB}
\end{array}
\quad \overset{\text{Some Tran. Conn.}}{\Rightarrow} \\
\begin{array}{c}
\text{IF} \\
\text{EX} \\
\text{WB}
\end{array}
\]

Fig. 8: Graphical depiction of the inductive case of the TC Abstraction support proof for simpleSC. Extending a transitive chain by an additional instruction and ISA-level edge \( r_n \) should extend the transitive connection to the new instruction as well.

A. Ensuring Microarchitectural TC Abstraction Support

As discussed in Section III-C, PipeProof uses the Transitive Chain (TC) Abstraction to represent the infinite set of ISA-level cycles that match a pattern like cyclic(po ∪ co ∪ rf ∪ fr). The TC Abstraction enables PipeProof to abstract away most of the instructions and ISA-level relations in these ISA-level cycles and represent them with a single µhb edge (the transitive connection) at the microarchitecture level.

The TC Abstraction is key to PipeProof’s complete verification. However, to use the TC Abstraction in its Microarchitectural Correctness proof (Section III), PipeProof must first ensure that the microarchitecture and ISA-level pattern being verified support the TC Abstraction. If the TC Abstraction cannot be proven to hold for a given microarchitecture, then PipeProof cannot prove the microarchitecture correct. PipeProof’s verification is sound; it will never falsely claim that the TC Abstraction holds without proving it.

Theorem 2: If instructions \( i_A \) and \( i_B \) are connected by a transitive chain (i.e. a subchain of a forbidden ISA-level cycle), then there exists at least one µhb edge (the transitive connection) from a node of \( i_A \) to a node of \( i_B \) in all microarchitectural executions in which that subchain is present.

PipeProof tries to automatically prove Theorem 2 inductively for each microarchitecture and ISA-level pattern for which the TC Abstraction is used.

Base Case: In the base case, we need to show that any single ISA-level edge isaEdge that could be the start of the ISA-level chain to be abstracted guarantees a µhb edge between its source and destination instructions \( i_1 \) and \( i_2 \). For example, for simpleSC, PipeProof checks whether a po, co, rf, or fr edge between instructions \( i_1 \) and \( i_2 \) guarantees a µhb edge between them. As Figure 4 shows, the microarchitectural mappings of these ISA-level edges do indeed guarantee edges from \( i_1 \) to \( i_2 \) for simpleSC, so the base case passes.

Inductive Case: Figure 8 illustrates the inductive case for simpleSC. Given an ISA-level transitive chain between \( i_1 \) and \( i_n \), if \( i_1 \) implies a µhb transitive connection from \( i_1 \) to \( i_n \), the inductive case must show that extending the transitive chain with an additional instruction \( i_{n+1} \) and ISA-level edge \( r_n \) matching the forbidden pattern extends the transitive connection. In other words, the inductive case must show that a µhb edge from some node of \( i_1 \) to some node of \( i_{n+1} \) exists.

If the combination of a transitive connection from \( i_1 \) to \( i_n \) and the microarchitectural mapping of \( r_n \) is not enough to guarantee a transitive connection from \( i_1 \) to \( i_{n+1} \), this constitutes an abstract counterexample to Theorem 2. PipeProof then attempts to concretize and decompose the transitive chain between \( i_1 \) and \( i_n \) (as explained in Section III-E) to discover whether the abstract counterexample is spurious or whether a concrete ISA-level chain violating Theorem 2 exists. ISA-level chains that fail Theorem 2 are henceforth referred to as failing fragments.

As in the Microarchitectural Correctness proof (Section III), chain invariants (Section IV-B) are used to abstractly represent cases where an infinite number of edges could be peeled off without terminating. The abstraction refinement through decomposition continues until either the abstraction is strong enough to guarantee a transitive connection between \( i_1 \) and \( i_{n+1} \) in all cases (thus proving Theorem 2), or a failing fragment is found and returned to the user as failing the proof of Theorem 2.

Strength of Theorem 2: Theorem 2 is stronger than what the Microarchitectural Correctness proof (Section III) needs. Theorem 2 requires the transitive chain to guarantee a transitive connection both when the transitive chain is part of a forbidden ISA-level cycle in the overall execution (as the Microarchitectural Correctness proof requires) and when it is not part of such an ISA-level cycle (as seen in Figure 8). This enables Theorem 2 to be proven by induction. As Figure 8 shows, the inductive case consists of adding an extra instruction and ISA-level edge to the case guaranteed by the induction hypothesis, resulting in a proof by induction.

On the other hand, proving the existence of a transitive connection only in the presence of a forbidden ISA-level cycle is not as straightforward. In the inductive case of such a
As a result of Theorem 2 being stronger than required, if a failing fragment is found, the microarchitecture may or may not be buggy. If the microarchitecture is buggy, PipeProof can generate an ISA-level cycle that exhibits the bug as a counterexample through its Cyclic Counterexample Generation procedure. This procedure checks all possible forbidden ISA-level cycles of length 1, then length 2, and so on for microarchitectural observability. At each iteration, if any of the cycles are microarchitecturally observable, the observable cycle is returned to the user as a counterexample. Otherwise, the procedure increases the size of the examined cycles by 1 and repeats the process.

B. The Need for Chain Invariants and their Proofs

When decomposing TC Abstractions instruction-by-instruction as outlined in Section III-E, it is possible to peel off concrete ISA-level edges that match a repeating pattern, but for the abstraction to never be strong enough to prove the required property (Theorem 1 or 2). For example, Figure 9a shows an abstract counterexample to Theorem 2 on simpleSC where there is no \( \mu \)hb connection between instructions \( i_1 \) and \( i_5 \). When decomposing this abstract counterexample, it is possible to peel off a \( po \) edge from the transitive chain, as shown in Figure 9b, and still have no \( \mu \)hb connection between \( i_1 \) and \( i_5 \). In fact, one can continue peeling off \( po \) edges in this manner ad infinitum, while never being able to guarantee a \( \mu \)hb edge between \( i_1 \) and \( i_5 \). Such a case will result in the refinement loop of the Microarchitectural Correctness proof or TC Abstraction support proof being unable to terminate.

For refinement loops to terminate in such cases, PipeProof needs a way to efficiently represent such repeating patterns. To do so, PipeProof utilises user-provided\(^7\) chain invariants. These chain invariants are additional \( \mu \)spec axioms which specify microarchitectural guarantees about repeated ISA-level edge patterns. Users can examine PipeProof’s status updates to detect when the peeling off of repeated edge patterns is preventing termination of a refinement loop. This is a sign that the user needs to provide PipeProof with a chain invariant for the repeated edge pattern in question.

Figure 10 shows an example chain invariant for \( po \) edges (i.e. \( po_{\text{plus}} \)) on the simpleSC microarchitecture.

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\(^7\)Future work could also use known invariant generation techniques to automatically discover invariants for a given concrete repeating ISA-level pattern. The search space of possible chain invariants is relatively small, and can be reduced further by restricting the search to specific invariant templates.

\(^8\)The \( \text{plus} \) in \( po_{\text{plus}} \) is from Kleene plus.
each iteration of the refinement loop. The search for patterns matching available invariants is conducted edge by edge, similar to regex matching. Supported invariant patterns are repeated single edges (e.g., $po$) or repeated chains (e.g., $po; rf$). If PipeProof finds a concrete ISA-level pattern matching an invariant, it replaces the pattern with its invariant version. On subsequent decompositions, PipeProof’s ISA Edge Generation procedure (Section IV-E) restricts the ISA-level edges that can be peeled off to those that cannot be subsumed within an adjacent chain invariant. For example, any edge peeled off from the right of the transitive chain in Figure 9c cannot be a $po$ edge, as any such $po$ edge is already subsumed within the $po; plus$ edge between $i2$ and $i4$. This prevents edges matching an invariant pattern from being peeled off a transitive chain endlessly, allowing the refinement loop to terminate in such cases.

To help ensure verification soundness, PipeProof proves chain invariants inductively before using them in its proofs. If the proof of any chain invariant fails, PipeProof informs the user of the failure and does not proceed further. As an example of a chain invariant proof, consider Figure 10’s invariant. PipeProof first checks the base case—whether a single $po$ edge between two instructions $i$ and $j$ guarantees that they will be on the same core and have an edge between their Fetch stages. The $po$ edge mapping and theory lemmas (Section IV-C) guarantee this. For the inductive case, PipeProof assumes that $i$ and $j$ are connected by a chain of a single $po$ edge followed by a $po; plus$ edge (i.e. a $po$-chain of arbitrary length), and that the invariant holds for the $po; plus$ portion of the chain. It then checks if $i$ and $j$ are on the same core and have an edge between their Fetch stages. This property is guaranteed by the $po$ edge mapping, theory lemmas, and the invariant from the induction hypothesis, completing the proof.

### C. Theory Lemmas

The symbolic analysis conducted by PipeProof can allow inconsistent assignments to $\mu$spec predicates that are incompatible with any microarchitectural execution. For example, in any execution containing three instructions $i$, $j$, and $k$, if $i$ and $j$ have the same data ($\text{SameData } i \ j$ is true), and $j$ and $k$ have the same data ($\text{SameData } j \ k$ is true), then logically $i$ and $k$ must have the same data ($\text{SameData } i \ k$ must be true). In other words, the $\text{SameData}$ predicate is transitive. However, naive symbolic analysis will not require $\text{SameData } i \ k$ to be true in such a case. Thus, to enforce such constraints, PipeProof provides a set of Theory Lemmas\(^9\) for $\mu$spec predicates that is included in every call to PipeProof’s solver. These constraints enforce universal rules (like the transitivity of $\text{SameData}$) that must be respected by every microarchitectural execution.

### D. Over-Approximating to Ensure an Adequate Model

PipeProof verifies executions of an arbitrary number of instructions while only modelling a small subset of those instructions and their constraints on the execution. Some of the instructions in an ISA-level cycle may be abstractly represented using the TC Abstraction or chain invariants, while other instructions in the execution that are not part of the ISA-level cycle are also not explicitly modelled. For its verification to be sound, PipeProof must ensure that the subset of an execution’s constraints that it models is adequate: the subset must be an over-approximation of the constraints on the entire execution. In other words, it should never be the case that an execution is deemed to be unobservable when modelling only the subset of its constraints, but is actually observable.

For example, consider the abstract execution $\text{SubsetExec}$ on $\text{simpleSC}$ in Figure 11, where an ISA-level cycle is abstractly represented with the help of the TC Abstraction. Consider also the constraint (henceforth called $\text{LoadSource}$) on every ISA-level execution that for every load $l$ which does not read the initial value of memory, there exists a store $s$ for which $s \rightarrow l$, corresponding to $s$ being the store from which $l$ reads its value. Instruction $i2$ in $\text{SubsetExec}$ is a load (since it is the source of an $fr$ edge), and so must satisfy the $\text{LoadSource}$ constraint. If PipeProof attempted to satisfy $\text{LoadSource}$ for $i2$ using only the explicitly modelled instructions, $i2$ could be sourced either from $i1$ (i.e. $i1 \rightarrow i2$) or from $i3$ ($i3 \rightarrow i2$). If sourcing from $i1$, the microarchitectural mapping of the $rf$ edge adds a $\mu hb$ edge from node $t$ to node $u$, giving us a cycle in the $\mu hb$ graph. Likewise, if $i3$ is used as the source, $i3 \rightarrow i2$ maps to a $\mu hb$ edge from node $v$ to node $u$, once again creating a cycle in the graph. Thus, if the analysis only considered explicitly modelled instructions, it would deduce that all graphs for this case are cyclic (i.e. unobservable), and that this case need not be concretized and decomposed.

However, this reasoning would be incorrect. For instance, it is perfectly valid for an execution containing the ISA-

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\(^9\)These lemmas are very similar to the lemmas produced by a theory solver in an SMT setup.
level cycle from SubsetExec to have an additional instruction 
i4 that is not part of the ISA-level cycle but sources the value of 
i2 (i.e. 
i4 → \text{LoadSource} → \text{ISA} → \text{ISA} → \text{ISA} → \text{ISA} → \text{i2}). Figure 11 depicts this variant as SubsetWithExternal, which satisfies LoadSource while maintaining an acyclic graph. This indicates (correctly) that the ISA-level cycle from SubsetExec is actually an abstract counterexample and must be concretized and decomposed.

To avoid unsoundly flagging executions such as SubsetExec as unobservable, PipeProof conservatively over-approximates by replacing every exists clause in the µspec with a Boolean true. This suffices to guarantee an adequate model, since exists clauses are the only µspec clauses whose evaluation can change from false to true when an additional instruction is explicitly modelled. In the case of SubsetExec, the over-approximation results in LoadSource always evaluating to true, ensuring that SubsetExec is treated as an abstract counterexample as required for soundness.

This over-approximation forces PipeProof to work only with a subset of the overall true microarchitectural ordering constraints; these may or may not be sufficient to prove the design correct. There exist microarchitectures for which this subset is not sufficient, and PipeProof currently cannot prove the correctness of those designs. However, the over-approximation of microarchitectural constraints is sufficient to prove the correctness of the designs in this paper.

E. Inductive ISA Edge Generation

There are often an infinite number of ISA-level executions that can match a forbidden ISA-level pattern. Thus, PipeProof must reason about these ISA-level executions inductively to make verification feasible. PipeProof’s refinement loop inductively models additional instructions through concretization and decomposition (Section III-E and Figure 7). As such, PipeProof must also inductively generate the possible ISA-level relations that could connect these modelled instructions such that the overall execution matches the forbidden ISA-level pattern being checked.

Given an ISA-level pattern \textit{pat}, PipeProof’s ISA Edge Generation procedure returns all possible choices \textit{(edge, remain)}, where \textit{edge} is a possible initial or final edge of \textit{pat}, and \textit{remain} is the part of \textit{pat} that did not match \textit{edge}. If peeling from the left of a transitive chain, the procedure returns cases where \textit{edge} is an initial edge. If peeling from the right, the procedure returns cases where \textit{edge} is a final edge.

For example, if decomposing a transitive chain representing the pattern \textit{(po ∪ co):rf;fr}, the ISA Edge Generation procedure would return \textit{(po,rfr)} and \textit{(co,rf;fr)} if peeling from the left, so either \textit{po} or \textit{co} could be peeled off. Likewise, if peeling from the right, the procedure would return \textit{(fr,(po ∪ co):rf)} so only \textit{fr} could be peeled off.

V. PipeProof Optimizations

PipeProof implements two optimizations that improve its runtime by greatly reducing the number of cases considered. This section explains these optimizations.

A. Covering Sets Optimization

The TC Abstraction guarantees at least one transitive connection between the start and end of an ISA-level chain that it represents. Thus, PipeProof needs to verify correctness for each possible transitive connection when using the TC Abstraction to represent an ISA-level chain. As seen in Figure 7, a new set of transitive connections comes into existence each time a transitive chain is decomposed. This can quickly lead to a large number of cases to consider. Even the simpleSC microarchitecture has 9 possibilities (3 nodes * 3 nodes) for transitive connections between any two instructions.

To mitigate this case explosion, PipeProof implements the Covering Sets Optimization to eliminate redundant transitive connections.

The key idea behind the Covering Sets Optimization is that if in a given scenario, \textit{a} and \textit{b} are possible transitive connections, and every µhb graph containing \textit{a} also contains \textit{b}, then it is sufficient to just check correctness when \textit{b} is the transitive connection. In other words, \textit{b} covers \textit{a}. For example, AbsCex in Figure 7 has a transitive connection between nodes \textit{p} and \textit{q}. This transitive connection covers other possible transitive connections such as the one from \textit{p} to \textit{r} used in NoDecomp. This is because there is no possible µhb graph satisfying the microarchitectural axioms that contains an edge from \textit{p} to \textit{r} without also having an edge from \textit{p} to \textit{q} (by transitivity). Given a set of transitive connections \textit{conns} for a given scenario along with all other scenario constraints, the Covering Sets Optimization eliminates transitive connections in \textit{conns} that are covered by other transitive connections in the set. This optimization significantly improves PipeProof runtime (details in Section VI-A).

B. Eliminating Redundant Work Using Memoization

Figure 7 shows PipeProof’s procedure for proving that simpleSC is a correct implementation of SC. PipeProof first checks that all ISA-level cycles containing \textit{fr} are microarchitecturally unobservable, and then does the same for cycles containing \textit{rf}, \textit{po}, and \textit{co}. However, there is notable overlap between these four cases. For example, the ISA-level cycle \textit{po:rf:po:rf} from Figure 1b contains \textit{po}, \textit{rf}, and \textit{fr} edges.

A naïve PipeProof implementation would verify this cycle (directly or indirectly through the TC Abstraction) 3 times: once as a cycle containing \textit{po}, once as a cycle containing \textit{rf}, and once as a cycle containing \textit{fr}. The second and third checks of the cycle are redundant and can be eliminated.

PipeProof filters out cases that have already been verified by restricting the edges that can be peeled off during decompositio. For example, if all ISA-level cycles containing \textit{fr} have been verified for simpleSC, then when checking all ISA-level cycles containing \textit{po}, \textit{fr} edges should be excluded from the choices of edges to peel off. This is because peeling off an \textit{fr} edge would turn the ISA-level cycle being considered into a cycle containing \textit{fr} (which has already been verified).

Stated formally, given an ISA-level MCM property \textit{acyclic(r1 ∪ r2 ∪...∪ r_n)}, if all ISA-level cycles containing \textit{ri} have been verified ∀i < j, then the only choices for edges
to peel off when verifying cycles containing $r_j$ should be
\{r_j, r_{j+1}, ..., r_n\}. This optimization enables our TSO case
study (Section VI-A) to be verified in under an hour.

VI. METHODOLOGY, RESULTS, AND DISCUSSION

A. Methodology and Results

PipeProof is written in Gallina, the functional programming
language of the Coq proof assistant [29]. PipeProof reuses the
Check suite’s \(\mu\)spec parsing and axiom simplification [19],
and extends the Check suite solver to be able to model and
verify executions of symbolic instructions. Writing PipeProof
in Gallina allows for future formal analysis of the code, such
as proving PipeProof’s solver or proof procedures correct.
PipeProof is an automated tool; we do not use the interactive
theorem proving capabilities of Coq to prove microarchitec-
tures. We use the built-in extraction functionality of Coq to
extract our Gallina code to OCaml so it can be compiled and
run as a standalone binary.

We ran PipeProof on two microarchitectures. The
simpleSC microarchitecture has a 3-stage in-order pipeline
and Store→Load ordering enforced. The simpleTSO mi-
croarchitecture is simpleSC with Store→Load ordering rel-
daxed for different addresses. We verified simpleSC against
the SC ISA-level MCM, while simpleTSO was verified
against the TSO ISA-level MCM. The overall specification of
TSO consists of two properties: acyclic(po\textunderscore loc∪co∪rf∪fr)
and acyclic(ppo∪loc∪rfe∪fr∪fence) [2]. The po\textunderscore loc relation
models same-address program order, while ppo (preserved
program order) relates instructions in program order except
for Store→Load pairs (which can be reordered under TSO).
The rfe (reads-from external) edge represents when a store
sources a load on another (“external”) core, and fence relates
instructions separated by a fence in program order.

Experiments were run on an Ubuntu 16.04 machine with
an Intel Core i7-4870HQ processor. Table I breaks down
PipeProof runtimes for five cases. We present results for
simpleSC when (i) using vanilla PipeProof algorithms, (ii)
with the Covering Sets Optimization (Section V-A), and
(iii) with Covering Sets and Memoization (Section V-B).
We also present results for simpleTSO when (iv) using
Covering Sets, and (v) with Covering Sets and Memoization.

PipeProof proves the correctness of simpleSC in under four minutes using vanilla PipeProof algorithms. The Covering Sets Optimization brings runtime down to under a
minute, and Memoization reduces runtime further to under
20 seconds. Meanwhile, proving that simpleTSO correctly
implements TSO takes just over five and a half hours with the
Covering Sets Optimization. With the addition of Memoiza-
tion, simpleTSO is verified in under 41 minutes.

While runtimes under an hour are quite acceptable, the
verification of simpleTSO takes more than the verification of
simpleSC because TSO’s additional relations increase
the number of possibilities for ISA-level edges that can be
peeled off a transitive chain. This has a multiplicative effect
on the number of cases that need to be verified; each peele-
d-off instruction may require verification across many transitive
connections, each of which may require further instructions
to be peeled off. Nevertheless, with the help of its optimiza-
tions, PipeProof’s verification of simpleTSO in under an
hour shows that complete automated MCM verification of
microarchitectures can indeed be tractable.

With regard to chain invariants, verifying simpleSC re-
quired one invariant (ppo\textunderscore plus) to be provided to model re-
peated ppo edges. Meanwhile, verifying simpleTSO required
five invariants, for repetitions of ppo, fence, po\textunderscore loc, ppo
followed by fence, and fence followed by ppo.

PipeProof’s detection of microarchitectural bugs was quite
fast. As an example, we introduced a flaw into simpleSC
relaxing Store→Load ordering. PipeProof produced a coun-
terexample to that flaw in under a second (both with and with-
out the Covering Sets optimization). Similarly, if Store→Load
ordering for the same address was relaxed on simpleTSO,
the bug was detected in under 2 seconds from the begin-
ing of the check of the relevant ISA-level pattern.

B. Scalability

To scale performance to more complicated microarchitec-
tures, we can parallelize the implementation of PipeProof’s
algorithm (Section III). The only dependency in the algorithm
is that a given abstract execution (such as AbsCex from
Figure 7) must be checked before any concretizations or
decompositions of it are checked. Apart from this depen-
dency, each abstract or concrete execution can be checked
independently of the others, making the algorithm highly
parallelizable and well-suited to the use of multicore machines
and clusters to improve performance.

C. Future Work

We intend to build on PipeProof in future work by paral-
elizing it, handling read-modify-write instructions, the RISC-
V [28], Power [13], and ARM [3] ISA-level MCMs, and chain
invariant auto-generation. We would also like to modify the
TC Abstraction support proof (Section IV-A) to only require
that a microarchitecture guarantee a transitive connection when
the transitive chain is part of a forbidden ISA-level cycle in
the overall execution. Likewise, we also intend to derive a
more accurate over-approximation (Section IV-D) that allows
PipeProof to utilise more of the axioms from a microarchitec-
tural ordering specification. These modifications would help
PipeProof scale to more microarchitectures than it currently
does.

VII. RELATED WORK

ISA-level MCMs are often specified in the format used by the
herd tool [2], consisting of irreflexivity, acyclicity, and
emptiness requirements for certain relational patterns. Such
specifications can be created by hand based on consultation
with system architects and dynamic or formal analysis of im-
plementations using litmus tests (e.g.: x86-TSO [2], Power [2],

\[ \text{Read-ᴍ} \text{from External edge}\]
ARM [2, 27], and RISC-V [28]). Relational logic-based ISA-level MCM specifications can also be automatically generated based on litmus test outcomes [5].

MCM verification of hardware implementations has mostly been conducted using litmus test-based approaches, both static [2, 18, 19, 23, 24, 30] and dynamic [12]. Schemes for generating better suites of litmus tests have also been developed [5, 20, 21]. ISA-level MCM analysis has also been conducted using approaches which check all programs up to a certain bounded size [33]. All these approaches suffer from the flaw of being incomplete and possibly missing bugs. Mador-Haim et al. [22] established a bound on litmus test completeness when comparing certain consistency models, but it is still unknown how to detect whether a test suite is complete with respect to a given parallel system implementation. As such, there is no way to tell whether passing a suite of litmus tests means that a design is correct for all programs. PipeProof surpasses these approaches by conducting complete, unbounded verification of all possible programs on a microarchitecture, giving users the confidence that their microarchitecture is indeed completely correct.

Chatterjee et al. [6] verify operational models of processor implementations against operationally specified ISA-level MCMs. Their approach has two main steps. The first step creates an abstract model of the microarchitectural implementation by abstracting away the external memory hierarchy, and verifies it by checking a refinement relation between the two models using model checking. The second step verifies this abstract model against an ISA-level MCM specification using theorem-proving. They only verify small instances (restricted to two processors, addresses, and values), while PipeProof’s verification is complete across different core counts, addresses, and values. They also target verification of operational models, while PipeProof targets axiomatic models. Finally, they handle visibility order specifications, whereas PipeProof uses more general MCM specifications such as the acyclicity of certain ISA-level edge patterns.

The only complete proofs of microarchitectural MCM correctness that have been conducted to date are those of the Kami project [7, 31]. However, Kami utilizes the Coq interactive theorem prover [29] for its proofs, which requires designers to know proof techniques and requires manual effort. This is not amenable for many computer architects. In contrast, PipeProof automatically proves microarchitectural MCM correctness when provided with an ISA-level MCM specification, μspec axioms, mappings, and invariants.

<table>
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<th>Component</th>
<th>simpleSC</th>
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TABLE I: PipeProof runtimes for simpleSC and simpleTSO with and without Covering Sets and Memoization.

VIII. CONCLUSIONS

Memory consistency models and their verification are paramount to correct parallel system operation. The MCM verification of a hardware design must be complete in order to guarantee the correct execution of parallel programs on that hardware. However, prior automated microarchitectural MCM verification approaches only conduct bounded or litmus-test-based verification, which can miss bugs.

In response, this paper introduces PipeProof, the first methodology and tool for automated complete verification of axiomatic microarchitectural ordering specifications with respect to axiomatic ISA-level MCM specifications. PipeProof can either automatically prove a specified microarchitecture correct with respect to its ISA-level MCM or it can inform the user that that the microarchitecture could not be verified, often providing a counterexample to illustrate the relevant bug in the microarchitecture. PipeProof’s novel Transitive Chain Abstraction allows it to inductively model and verify all microarchitectural executions of all possible programs. This enables efficient yet complete microarchitectural MCM verification; PipeProof is able to prove the correctness of microarchitectures implementing SC and TSO in under an hour. With PipeProof, verification can be moved much earlier in the design process. Furthermore, architects no longer have to restrict themselves to manual proofs of correctness of their designs in interactive theorem provers to achieve complete verification. Instead, they can use PipeProof to automatically prove microarchitectural MCM correctness for all possible programs, addresses, and values.

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