Formally Verifiable Networking

Anduo Wang  
*University of Pennsylvania*, anduo@seas.upenn.edu

Limin Jia  
*University of Pennsylvania*, liminjia@seas.upenn.edu

Changbin Liu  
*University of Pennsylvania*, changbl@seas.upenn.edu

Boon Thau Loo  
*University of Pennsylvania*, boonloo@seas.upenn.edu

Oleg Sokolsky  
*University of Pennsylvania*, sokolsky@cis.upenn.edu

*See next page for additional authors*

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Abstract
This paper proposes Formally Verifiable Networking (FVN), a novel approach towards unifying the design, specification, implementation, and verification of networking protocols within a logic-based framework. In FVN, formal logical statements are used to specify the behavior and the properties of the protocol. FVN uses declarative networking as an intermediary layer between high-level logical specifications of the network model and low-level implementations. A theorem prover is used to statically verify the properties of declarative network protocols. Moreover, a property preserving translation exists for generating declarative networking implementations from verified formal specifications. We further demonstrate the possibility of designing and specifying well-behaved network protocols with correctness guarantees in FVN using meta-models in a systematic and compositional way.

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Author(s)
Anduo Wang, Limin Jia, Changbin Liu, Boon Thau Loo, Oleg Sokolsky, and Prithwish Basu
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Anduo Wang∗ Limin Jia∗ Changbin Liu∗
Boon Thau Loo∗ Oleg Sokolsky∗ Prithwish Basu†

University of Pennsylvania∗ BBN Technologies†

{anduo,liminjia,changbl,boonloo,sokolsky}@seas.upenn.edu, pbasu@bbn.com

ABSTRACT

This paper proposes Formally Verifiable Networking (FVN), a novel approach towards unifying the design, specification, implementation, and verification of networking protocols within a logic-based framework. In FVN, formal logical statements are used to specify the behavior and the properties of the protocol. FVN uses declarative networking as an intermediary layer between high-level logical specifications of the network model and low-level implementations. A theorem prover is used to statically verify the properties of declarative network protocols. Moreover, a property preserving translation exists for generating declarative networking implementations from verified formal specifications. We further demonstrate the possibility of designing and specifying well-behaved network protocols with correctness guarantees in FVN using meta-models in a systematic and compositional way.

1. INTRODUCTION

In recent years, there has been growing interest in the formal verification of network protocol design and implementation. On the theoretical front, algebraic models such as metarouting [9] are used to formalize routing protocols with convergence guarantees. Concurrently, several practical software tools and testing platforms have been proposed to facilitate the verification of existing networked systems. These include runtime verification platforms (e.g. [20]) that provide mechanisms for checking at runtime that a system does not violate expected properties; and model-checking tools (e.g. [5, 13, 19]) that use a collection of algorithmic techniques for checking temporal properties of system instances based on exhaustive state space exploration.

At one extreme, practical tools based on runtime verification or model checking are applied to actual protocol implementations. However, they are in general not complete. Any runtime verification scheme will incur additional runtime overheads, and subtle bugs may require a long time to be encountered. On the other hand, model-checking suffers from the state explosion problem, where the large state space persistent in network protocols often prevents complete exploration of the huge system states. While the heuristics used in exploration maximize the chances of detecting property violations, they are typically inconclusive and restricted to small network instances and temporal properties.

At the other extreme, formal models such as metarouting use a correct-by-construction approach: the verification of convergence is done once for the idealized algebra, and any routing protocol that implements the algebra is correct. The monotonicity requirements imposed by the idealized model limits the range of permissible protocols, and are unlikely to be adopted by actual routing protocol implementations.

In this paper, we aim to bridge the gap between formal verification of network protocols designs and the verification of actual implementations. Our proposed Formally Verifiable Networking (FVN) framework uses formal logical statements to specify the behavior and the properties of network protocols, and abstract network meta-models such as metarouting. The specified formal properties can be fed to a mechanized theorem prover such as PVS [17] or Coq [2] for static verification.

One advantage of using modern theorem proving techniques is that the logics of those provers can express properties beyond temporal properties that the majority of the model-checking techniques are bound to. Another advantage is that it is sound and complete: once a property is verified, it holds for all instances of the protocols. However, FVN does not exclude other incomplete techniques, such as model checking. In fact, one overarching goal of FVN is to smoothly integrate a variety of verification techniques for different classes of properties.

One important piece of the design of FVN is the use of declarative networking [16, 15], a declarative logical framework for protocol implementation. We utilize the Network Datalog (NDlog) declarative networking language as the intermediary layer between high-level logical specifications of the network model and low-level implementations. NDlog naturally bridges formal network models and protocol implementations. In one direction, NDlog programs can be automatically translated into logical statements that capture the semantics of the NDlog program and can be fed directly into existing tools for verification. Conversely, the verified logical specifications can be used to generate NDlog programs for execution via a property-preserving translation.

Moreover, when NDlog is used in conjunction with expressive logics (e.g. linear logic), FVN can provide a better model for soft-state, and more importantly, the promise to directly produce system models for model checking tools.

FVN leverages two bodies of work that in conjunction has significantly lowered the barriers of adoption of formal reasoning techniques in networking research. First, there has been significant progress on the understanding of logic-based techniques for bridging the specification and implementation divide. In addition to metarouting and declarative networking, there are now logical frame-
works for reasoning about forwarding planes [12]. Second, modern theorem provers come with powerful proof engines that support a large portion of automated proof exploration which enable the proof of non-trivial difficulty problems with relatively modest human effort. Besides the built-in proof support, modern provers provide well-designed interfaces for customizing domain specific proof search strategies that can be further automated via user defined decision procedure, and integration with model-checkers, boolean satisfiability (SAT) solving and satisfiability modulo theories (SMT) [25].

2. OVERVIEW

We first present an overview of FVN framework, followed by a brief background on declarative networking.

2.1 FVN Framework

Figure 1 shows an overview of the FVN framework, which consists of the following four main components: design, specification, verification, and implementation. In the initial design phase, a network designer develops an abstract network model for the network protocol, and descriptions of the desired properties of the protocol, possibly informally. In practice, this step may be optional, but having such a model is often useful both from the implementation standpoint, and for verifying one’s protocol design. In fact, a formal specification of the model is desirable at the design phase for verifying the model itself. We will provide an example based on metarouting in Section 3.3.

![Figure 1: Overview of FVN](image)

After initial design, the designer writes down formal logical specification for properties of concern (arc 1), and verifies that the implementation indeed satisfies these properties. This is the place where declarative networking is relevant. Instead of verifying a low-level implementation, we use NDlog as an intermediary language that properties are verified against. The benefit of using NDlog has two folds: first, NDlog is in itself declarative, and there is a natural synergy between the formal logical specification of properties and NDlog programs; second, robust tools [18] are available for generating low-level implementation from NDlog programs (arc 7).

Due to the synergy between NDlog programs and logic, there exists a two-way translation between NDlog program and logical specifications (arc 3 and 4). In FVN, a protocol designer has the choice of either generating NDlog programs directly, and then compiling NDlog programs into its logical specifications (arc 4) via an automatic tool and verifying properties in an theorem prover (arc 5); or first generating the logical specifications of the protocol’s design (arc 1 and 2) and verifying the design using a theorem prover (arc 5), and then automatically generating the corresponding NDlog program from the verified logical specification (arc 3).

Ultimately, we envision that FVN will serve as a unifying framework, that uses formal logics as the specification language for properties, and eventually incorporate a number of different verification techniques, all of which share the specification language. For instance, aside from static verification using theorem provers, FVN can also take advantage of model-checking tools once it uses expressive logics such as linear logic for specifying protocols in the style of state transitions. We describe these opportunities (particularly arcs 6 and 8) in Section 4.

2.2 Background on Declarative Networking

Declarative networks are specified using Network Datadlog (NDlog), which is a distributed recursive query language used for querying network graphs. Declarative networking programs are compiled into distributed execution plans that are based on the Click [14] execution model. When executed, these declarative networks perform efficiently relative to imperative implementations. We present an example NDlog program that implements the path-vector protocol.

r1 path(@S,D,P,C):-link(@S,D,C), P=f_init(S,D).

r2 path(@S,D,P,C):-link(@S,Z,C1), path(@Z,D,P2,C2), C=C1+C2, P=f_concatPath(S,P2), f_inPath(P2,S)=false.

r3 bestPathCost (@S,D,MinCost):=path(@S,D,P,C).

r4 bestPath (@S,D,P,C):-bestPathCost (@S,D,C), path(@S,D,C).

The program takes as input link(@S,D,C) tuples, where each tuple represents an edge from the node itself (s) to one of its neighbors (z) of cost c. NDlog supports a location specifier in each predicate, expressed with "@" symbol followed by an attribute. This attribute is used to denote the source location of each corresponding tuple. For example, link tuples are stored based on the value of the s field.

Rules r1-r2 recursively derive path(@S,D,P,C) tuples, where each tuple represents the fact that there is a path P from S to D with cost C. Rule r1 computes one-hop reachability trivially given the neighbor set of S stored in link(@S,D,C). Rule r2 computes transitive reachability as follows: if there exists a link from s to z with cost c1, and z knows about a path to D with cost c2, then transitively, s can reach D via the path f_concatPath(S,P2) with cost C1+C2. Note that r1-r2 also utilize two list manipulation functions to maintain path vector: P=f_init(S,D) initializes a path vector with two elements s and D, while f_concatPath(S,P2) prepends s to path vector P2. To prevent computing paths with cycles, an extra predicate f_inPath(P,S)=false is used in rule r2, where f_inPath(P,S) returns true if s is in the path vector P.

Rules r3-r4 take as input hop tuples generated by rules r1-r2, and then derive the hop along the path with the
minimal cost for each source/destination pair. The program outputs the set of bestPath(S,D,P,C) tuples, each of which stores the shortest path \( P \) from \( S \) to \( D \).

3. VERIFICATION IN FVN

To demonstrate FVN’s verification mechanisms concretely, we show the verification of NDlog programs (arc 4) in Section 3.1 via examples, and discuss the generation of NDlog programs from verified specifications (arc 3) in Section 3.2 where verified component-based specifications can be directly translated into executable NDlog programs. In Section 3.3 we demonstrate that the network meta-model itself can be formally specified in design phase, by using metarouting as our driving example. While we use PVS as the theorem prover, the methods are general, and other theorem provers such as Coq will work similarly.

3.1 NDlog Verification

One method to carry out the formal verification process, proposed by Wang et al. [22], is to automatically compile declarative networking programs written in NDlog into formal specifications recognizable by a theorem prover. This translation is depicted by arc 4 in Figure 1.

The verification is made possible by the natural mapping from NDlog rules to PVS axioms. We provide the following high-level intuitions behind the translation from NDlog to PVS formalizations. The translation leverages the proof-theoretic semantics of Datalog [1], the set of NDlog rules defining a predicate is equivalent to an inductively defined data type in PVS [1]. For instance, the following inductive definition in PVS is logically equivalent to rule \( r_1 \) and \( r_2 \) from Section 2.2.

\[
\text{path}(S,D,(P:\text{Path}),C): \text{INDUCTIVE Bool} = (\text{link}(S,D,C) \text{ AND } P=f_{\text{init}}(S,D)) \text{ OR } \\
(\exists (C_1,C_2:\text{Metric}) \text{ (P2:Path) (Z:Node)):} \\
\text{link}(S,Z,C_1) \text{ AND } \text{path}(Z,D,P_2,C_2) \text{ AND } \text{C=C1+C2} \\
\text{ AND } P=f_{\text{concatPath}}(S,P_2) \text{ AND } f_{\text{inPath}}(S,P_2) \Rightarrow \text{FALSE})
\]

The universal quantifiers over the attributes of \( \text{path} \) (i.e., \( S,D,P,C \)) are implicitly embedded and existential quantifiers such as \( C_1 \) and \( C_2 \) are explicitly stated. Next, the protocol designer specifies high-level properties of the protocol directly as theorems in the theorem prover. For instance, the route optimality property in the path-vector protocol can be expressed as follows:

\[
\text{bestPathStrong: THEOREM} \\
\forall (S,D:\text{Node}): \text{bestPath}(S,D,P,C) \Rightarrow \\
(\not\exists (C_2:\text{Metric}) \text{ (P2:Path):} \\
\text{link}(S,D,C) \text{ AND path}(S,D,P_2,C_2) \text{ AND } C=C_2+C)
\]

The above theorem states that \( P \) is the optimal path from \( S \) to \( D \) with cost \( C \) implies that there does not exist another path \( P_2 \) from \( S \) to \( D \) with cost lower than \( C \).

Given the above theorem, one can utilize PVS to carry out the proof process interactively, PVS, and other interactive theorem provers, provide some degree of automation to aid the process of proof construction.

The bestPathStrong theorem takes 7 proof steps. We omit the details of the proof process. The main takeaways is that PVS requires only a fraction of a second to carry out the actual proof, and built-in commands are available to mechanically advance the proof. When the proof is completed, it covers all instances of the network. In addition to the route optimality property above, reference [22] demonstrates additional proofs, for instance, the presence of count-to-infinity loops in the distance-vector protocol.

3.2 Verified Code Generation

The previous approach requires one to specify protocols in NDlog prior to verification. In this section, we demonstrate that reverse translation: given a conceptual network model at design phase, logical specifications are generated from the network model. This process corresponds to arc 2 in Figure 1. Once the logical specifications are verified, they are translated into NDlog programs for execution (arc 3).

We further observe that component-based network models are particularly amenable to the generation of NDlog programs from verified specifications. When formalized as logical specifications for verification, there is a straightforward translation to NDlog programs for execution (see Section 3.3).

3.2.1 Component-based BGP Model

As our driving example, we demonstrate FVN’s facility for generating executable NDlog programs from verified logical specifications based on a component conceptual model of routing protocols, with a focus on policy-based routing in BGP. Note that while our treatment of the model itself in this section is conceptual, one can formalize and verify this model itself at design phase, as we demonstrate in Section 3.3.

We adopt Griffin’s BGP model [8][7] which views BGP protocol as a series of route transformations. Each transformation is represented by a component that takes as input received routes, performs internal transformation based on the component specifications, and produces the output routes.

The bestPathStrong theorem takes 7 proof steps. We omit the details of the proof process. The main takeaways is that PVS requires only a fraction of a second to carry out the actual proof, and built-in commands are available to mechanically advance the proof. When the proof is completed, it covers all instances of the network. In addition to the route optimality property above, reference [22] demonstrates additional proofs, for instance, the presence of count-to-infinity loops in the distance-vector protocol.

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The above translation works for a single component that is connected with one other input and output component. The translation can however be easily generalized to a component connected to multiple input and output components. In this case, each input component will generate one \( t_{\text{in}} \) predicate in the rule body, and for each output component, a NDlog rule is generated with the corresponding rule head denoting the output.

Given a component with sub-components, one can recursively define the rules in a top-down fashion. Consider the compositional component \( tc \) shown in Figure 3 that consists of three subcomponents \( t_1, t_2, t_3 \), each of which has additional constraints \( C_1, C_2, C_3 \). The PVS definitions are as follows:

\[
\begin{align*}
& t_{\text{out}}(O_1) :- t_{\text{in}}(I_1), C_1(I_1,O_1). \\
& t_{\text{out}}(O_2) :- t_{\text{in}}(I_2), C_2(I_2,O_2). \\
& t_{\text{out}}(O_3) :- t_{\text{in}}(I_3), C_3(I_3,O_3).
\end{align*}
\]

To annotate the above NDlog program with the appropriate location specifiers for each predicate, additional predicate schema information is required as input for the translation process. Reference [24] validates distributed executions of translated NDlog programs implementing a path-vector protocol with export and import policies within a local cluster environment, and observe delayed convergence in the presence of policy conflicts.

### 3.3 Meta-Theoretic Model

Section 3.2 demonstrates that verified NDlog programs can be generated from a conceptual BGP model. However, the model itself is not formally specified and checked. To develop complex models in a systematic and compositional way with correctness guarantee, one would like to also formally specify the network model and verify the model directly at design phase.

FVN aims to provide a meta-theoretic framework for specifying new formal network models at the design stage. Once verified, it can be used to generate logical specifications for additional verification, and NDlog programs for implementation. To illustrate this process, we demonstrate a subset of FVN's built-in network meta-model based on metarouting [9]. Our goal here is to demonstrate the use of FVN to define new routing protocols given the built-in meta-model. Detailed description and formalism is available in reference [24].

#### 3.3.1 Background on Metarouting

Metarouting is an algebraic framework for specifying routing protocols in a restricted fashion such that the protocols are guaranteed to converge. Metarouting provides base algebras as the atomic building blocks, together with composition operators that generate complex protocol algebras from existing ones.

Metarouting uses abstract routing algebra as the mathematical model for routing. An abstract routing algebra
A is denoted by a tuple \( A = (\Sigma, \preceq, \mathcal{L}, \oplus, \mathcal{O}, \phi) \). \( \Sigma \) is the set of paths in the network totally ordered by \( \preceq \). Intuitively, the preference relation is used by the routing protocol algorithm to select the most desirable path; \( \mathcal{L} \) is a set of labels describing links between immediate neighbors. Note that the labels may denote complicated policies associated with the corresponding link; \( \oplus \) is a mapping from \( \mathcal{L} \times \Sigma \) to \( \Sigma \), which is the label application operation that generates new paths by concatenating existing paths and adjacent links; \( \mathcal{O} \) is a subset of \( \Sigma \) called origination that represents the initial routes stored at network nodes; Finally \( \phi \) is a special element in \( \Sigma \) denoting prohibited paths that will not be propagated.

The semantics of routing algebra is given by four axioms on maximality, absorption, monotonicity, and isotonicity. The maximality and absorption axioms describe the behavior of prohibited paths as the least preferred path that is closed under path concatenation; monotonicity imposes the restriction that a path becomes less preferred when "grows" (i.e. path concatenation occurs), and isotonicity states that the preference relation over two paths is preserved when concatenated with the same link.

Unlike previous combinatorial models \( \text{[8]} \), the routing algebra identifies and proves that the properties of monotonicity and isotonicity are sufficient conditions for network convergence. Convergence verification of routing protocols implementation are hence reduced to proofs of monotonicity and isotonicity of the routing algebra.

Based on abstract routing algebra, metarouting further defines a set of base (atomic) algebras and composition operators which serve as the building blocks in the construction of routing algebras. For instance, metarouting provides instances of base algebras for adding link costs \( (add) \) during path concatenation, and for specifying local preferences \( (lp) \) used in route selection. These algebras are then used by composition operators such as the lexical product operator that models lexicographical comparisons of multiple attributes in route selection.

### 3.3.2 Example Protocol Formalization

Given the above basic framework, a protocol designer formalizes a routing protocol in terms of the metarouting algebras, and prove that the above four axioms hold for the protocol. This is tedious work: mistakes in the hand-written proofs yield faulty designs, which defeat the purpose of formal modeling. \( \text{FVN} \) instead uses a theorem prover to automatically check that the protocol is correctly formalized.

Our encoding uses a module system called theory interpretation in PVS \( \text{[2]} \). An analogy of module systems is the use of .h files and .c files in C. We first encode the abstract metarouting algebra as abstract signatures in a PVS theory called \text{routeAlgebra} (a .h file). The \text{routeAlgebra} theory contains the type declarations of the abstract algebra, based on the tuple \( A \) that we introduced earlier: \( A = (\Sigma, \preceq, \mathcal{L}, \oplus, \mathcal{O}, \phi) \). The \text{routeAlgebra} theory also contains additional definitions for maximality, absorption, monotonicity, and isotonicity axioms.

Next, the network designer instantiates an algebra instance as an implementation of the abstract routeAlgebra, similar to a predefined routeAlgebra. In order for the instantiation to be valid, the designer must carry out the proofs for the above four axioms. Using PVS, network designers are freed from such tedious low-level proof obligations. The proof obligations are automatically discharged for all the base algebras developed in \( \text{[2]} \).

Furthermore, it is straightforward to encode the composition operators provided in \( \text{[2]} \). Again, the proofs that protocols obtained from composing two well-behaved protocols using these composition operations satisfy all the necessary axioms are automatically discharged by PVS’s type checker.

To provide a flavor of the formalism, we show the code snippet of a route selection policy used in a BGP system.

```
LP: THEORY = \text{routeAlgebra}
\{\text{sig=lpA.SIG, label=lpA.LABEL, }\
\text{labelApply(l:lpA.LABEL, s:lpA.SIG)=1, }\
\text{prohibitPath=4, prefRel(s1, s2:int) = (s1<=s2)}\}
```

The above definition species that \( LP \) is an instantiation of the abstract theory \( \text{routeAlgebra} \), and that \( LP \) inherits from another predefined algebra instance \( lpA \). In particular \( \text{prefRel}(\preceq) \), which is used to specify a total ordering of all routes, specifies a preference for smaller local preference values. Accordingly, sub-component \( RC \) can be defined in terms of base algebra \( addA \) in a similar fashion.

By extending PVS specification logic with metarouting theory, \( \text{FVN} \) can leverage PVS’s powerful type checker and built-in proof engine to ensure routing model consistency. As a result, the network designer can focus on high-level protocol design (i.e. customize the policies using existing base algebras, such as the sub-components \( LP \) and \( RC \) shown above) and the conceptual decomposition of their routing protocols, and shift the low-level details of ensuring consistency of the derived protocol model with respect to metarouting theory to the proof engine.

### 4. DISCUSSION

To conclude, we outline our ongoing research efforts.

#### 4.1 Network Models and Implementation

\( \text{FVN} \) uses \text{NDlog} as an intermediary layer between high-level logical specifications of the network model and low-level implementations. However, it is still up
to the network designer to define the conceptual network model. Our initial effort in Section 3 demonstrates the promise of using formal tools to automate the process of defining and verifying a network model. We plan to expand upon this initial effort and explore a range of alternative meta-models in FVN. For example, metarouting, as an idealized model for a constrained class of protocols, cannot represent well-behaved converging protocols that violate monotonicity. FVN, by leveraging PVS’s proof checker, can aid in the design and analysis of relaxed algebraic models for a wider range of routing protocols.

In Section 3.2, we observe a natural mapping between a component-based conceptual model of BGP and equivalent NDlog programs. However, in the case of the metarouting formalism in Section 3.3 the translation is less clearly defined. We however are optimistic that given the close logical relationships between metarouting algebraic objects and declarative networking specifications, a property-preserving translation can be achieved.

Beyond routing, we are interested in exploring network models based on component-based abstractions (e.g., [14, 10]) that are also amenable to the translation into NDlog programs for direct execution.

4.2 Modeling Soft-state

Soft-state [4] is central in the design of many network protocol. Declarative networking incorporates soft-state by allowing tuples in tables to timeout after a specified lifetime. To reason about protocols with soft-state, Wang et al. [22] utilize a rule rewrite strategy that translate soft-state to hard-state rules via the introduction of explicit timestamps and lifetime attributes to soft-state predicates. The resulting encoding is heavy-weight and cumbersome to prove, and consequently, non-ideal for reasoning about eventual consistency of protocols.

We are currently exploring the use of linear logic [6] as the semantics foundation for verification of NDlog programs with soft-state data. To this end, we are interested in extending NDlog specification with linear logic so that the semantics of soft-states can be explicitly modeled. The characteristics of linear logic is that logical facts will be consumed once it is used in a proof. Consequently, linear logic is known to be able to reason about state transition and resource consumption elegantly, and have wide-applicability in security protocol verification [3] and memory update models [11].

4.3 Combining Verification Techniques

An important aspect of this work is to develop a holistic understanding of various verification techniques, and develop a verification methodology that combines them in the most effective manner.

Unlike model checking, theorem proving is complete, and it is also more expressive in the types of properties that it can express and verify. In terms of proof effort, model checking typically requires less human intervention compared to theorem proving. We however note that typically two-thirds of the proof steps can be automated by the theorem prover’s default proof strategies, and in some cases, can be further automated [25].

An advantage of model checking over theorem proving is its ability to simulate runs of the protocols and explore all possible states to detect automatically if some run will reach an undesirable state. The proof process can be automated via integration with model checking to explore the proof search space. Another useful method to combine the two techniques is via a counter-example approach. When verification fails, most model checkers provide a counter-example (that is, a trace that illustrates why the formula evaluates to false) to aid in the theorem proving process.

Extending NDlog with linear logic has the added benefit that it would allow us to view the declarative networking specification as a set of transition rules that determine the updates of the underlying routing tables. We can leverage such transition system representation to directly interface with model checkers, hence providing an additional verification mechanism for FVN.

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5. REFERENCES