Resources: A Safe Language Abstraction for Money

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Smart contracts are programs that implement potentially sophisticated transactions on modern blockchain platforms. In the rapidly evolving blockchain environment, smart contract programming languages must allow users to write expressive programs that manage and transfer assets, yet provide strong protection against sophisticated attacks. Addressing this need, we present flexible and reliable abstractions for programming with digital currency in the Move language [Blackshear et al. 2019]. Move uses novel linear [Girard 1987] resource types with semantics drawing on C++11 [Stroustrup 2013] and Rust [Matsakis and Klock 2014]: when a resource value is assigned to a new memory location, the location previously holding it must be invalidated. In addition, a resource type can only be created or destroyed by procedures inside its declaring module. We present an executable bytecode language with resources and prove that it enjoys resource safety, a conservation property for program values that is analogous to conservation of mass in the physical world.

1 INTRODUCTION

The emergence of Bitcoin [Nakamoto 2008] and Ethereum [Wood 2014] has created significant interest in the computational model of a replicated state machine synchronized by a distributed consensus protocol. In this programming model, a command is executed as an atomic and deterministic transaction that is replicated consistently across all nodes participating in consensus. While cryptocurrency and decentralized finance are the most prominent applications of programmable blockchains, there are other important use-cases such as tracking supply chains [Casey and Wong 2017] and clearing global markets [Armstrong 2019].

Transactions are programmed as smart contracts, a catchy name [Szabo 1997] for program units installed for atomic execution on the blockchain. If the contract language is sufficiently expressive, then smart contracts are attractive implementaions for a wide variety of conventional functions such as bank deposit and withdrawal, cross-border funds transfer, point-of-sale online payment, escrow agreements, futures contracts, and derivatives. To meet these goals, a smart-contract programming language must allow users to write programs that manage and transfer assets while providing extremely trustworthy protection against sophisticated attacks.

In this paper, we describe and analyze flexible and reliable abstractions for programming with digital currency and other assets in the Move language [Blackshear et al. 2019]. Move uses novel linear [Girard 1987] resource types that draw on experience with C++11 [Stroustrup 2013] and Rust [Matsakis and Klock 2014] to preserve integrity and prevent copying of assets. When combined with other abstraction features of Move, linearity ensures resource conservation. Whereas data abstraction ensures that a resource may only be created and destroyed by the defining module, linearity further prevents duplication and unintended loss. We present an executable Move bytecode language with move semantics and show that it satisfies a set of resource safety guarantees.

Contributions. This paper adds rigor to the informal description of Move [Blackshear et al. 2019]. Its key contributions are:
• We introduce resources, an intuitive abstraction for currency-like values, and demonstrate their utility compared to existing language constructs (Section 2).
• We explain the key features of the Move bytecode language and explain how their design supports support resource-oriented programming (Section 3).
• We formalize the semantics of the Move bytecode interpreter for the subset of Move analyzed in this paper (Section 4).
• We formally define resource safety properties and prove that execution of Move bytecode programs is resource-safe (Section 5).
• We describe our implementation of the Move virtual machine, its integration in the Libra blockchain [Amsden et al. 2019], and the adoption of Move in other contexts (Section 6).

2 PROGRAMMING WITH MONEY
Move is designed to support a rich variety of economic and financial activities by supporting fundamental conservation properties, not only for built-in currencies, but also for programmer-defined assets. We believe this is essential. To begin with, smart contracts provide customizable logic for sending, receiving, storing, and apportioning digital funds that cannot be arbitrarily created, lost, or destroyed. Further, the internal balance in a bank account, the monetary value inherent in a contract for future payment, or an escrow contract all represent assets that must be conserved in the same ways as conventional currency. Thus, smart contracts must be able to implement new assets with expected conservation properties and appropriately control the exchange of one asset for another.

2.1 Savings Bank Example
With this goal in mind, we use a simple bank account contract to illustrate the key features of Move for programming with assets and demonstrate by example the advantages of Move over two alternative contract programming languages where notable problems have occurred in practice. Figure 1 implements a savings bank with the following requirements:
• A customer should be able to deposit money worth $N$ via the deposit procedure and subsequently extract money worth $N$ via the withdraw procedure.
• No customer should be able to withdraw money deposited by another customer.

Even in this simplest of examples, there are already two assets: the funds deposited into the bank contract, and the bank credit that the customer can use to withdraw the funds in the future. Most smart contract platforms have a native asset such as Ether in Ethereum [Wood 2014] that is implemented as part of the core platform and guarantees conservation. But even if the deposited funds are represented using the native asset, the bank contract must correctly implement deposit and withdraw to ensure conservation for the bank credit asset. Programming mistakes in this setting can be extremely costly: high-profile bugs in Ethereum, e.g., [Atzei et al. 2017; Buterin 2016; Palladino 2017], have resulted in the theft of digital assets worth tens of millions of dollars. To summarize, programming challenges in this environment include:

(1) **Conservation.** Transfers must preserve the total supply of money in the system, including custom assets defined by contracts.

(2) **Unique atomic transfer.** The sender of an asset must relinquish all control of the asset. This ownership transfer should be atomic because any non-atomic exchange risks leaving one or both parties empty-handed.

(3) **Authority.** Smart contract programmers must represent authority carefully and restrict access to privileged operations. Contracts are deployed on a public platform open to both benign customers and bad actors.
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---

```
contract Bank
field credit: Map Address Uint;  

transition deposit()
  accept;
  match credit[_sender] with
    Some(amt) => credit[_sender] := amt + _amount
    None => credit[_sender] := _amount
end
end

transition withdraw()
  match credit[_sender] with
    Some(amt) => 
      msg = {
        _recipient: _sender;
        _amount: amt ;
      };
      credit[_sender] := 0;
      send msg
    None => ()
end
end

module Bank
use @0x::Coin;
resource T { balance: Coin::T }
resource Credit { amt: u64, bank: address }

fun deposit(
  coin: Coin::T,
  bank: address
): Credit {
  let t = borrow_global<T>(copy bank);
  Coin::deposit(&mut t.balance, move coin);
  return Credit {
    amt: move amt, bank: move bank
  };
}

fun withdraw(credit: Credit): Coin::T {
  Credit { amt, bank } = move credit;
  let t = borrow_global<T>(move bank);
  return Coin::withdraw(&mut t.balance, move amt);
}
```

Fig. 1. A simple bank contract in Solidity (left), Scilla (middle), and Move (right). Each code snippet must implement bidirectional exchanges of the language’s native currency for a bank credit currency defined by the contract. In Solidity and Scilla, both native and custom currencies are represented indirectly via maps of identities to integers, whereas in Move, currency is represented directly with resources.

Move represents money using user-defined linear resource types. Move has ordinary types like integers and addresses that can be copied, but resources can only be moved. Linearity prevents “double spending” by moving a resource twice (e.g., into two different callees) and forces a well-typed procedure to move all of its resources, avoiding accidental loss.

Figure 1 provides a Move representation of the simple bank along with an implementation in Solidity [Foundation 2018a] and Scilla [Sergey et al. 2019]. Solidity is a source language for Ethereum [Wood 2014] and the first to provide an expressive smart contract programming model. Scilla is a newer language designed by programming language researchers to simplify formal verification of contracts and incorporate lessons learned from Solidity design flaws. Although many other contract languages have been proposed (see Section 7), these two represent the state of practice (Solidity) and the state of the art (Scilla).

Solidity, Scilla and other account-based languages often use a model in which each contract has an implicit balance in the platform’s native currency. This balance can only be modified by special instructions. However, the properties ensured by these special instructions are not available to programmers that wish to implement custom currencies such as bank credits. A common strategy used instead is illustrated in Figure 1: a map, credit, is employed to map creditor identities to integers. The integers in the range of the map represent money and must be manipulated carefully to provide the global conservation invariants associated with monetary assets. However, as we will see by examining the code samples, properties guaranteed by construction in Move are more difficult to ensure via ad hoc programming in other languages. Although the bank is a somewhat artificial example, it is adapted from similar examples in the Solidity/Scilla documentation and concisely captures the key idioms of typical contracts: sending/receiving/atomically exchanging money and implementing a new money-like construct.

3
**Solidity and Scilla** deposit. The first task of the deposit procedure in Figure 1 is to accept the language’s native currency. In Solidity, native currency sent by a caller is implicitly deposited into the contract’s balance before the callee code is executed, provided the receiving function is marked as payable. If not, an attempted deposit causes a runtime failure that reverts all changes performed by the current transaction.

In Scilla, money is transferred from caller to callee via an explicit accept construct which avoids runtime failures but introduces other problems. Although money not accepted by the callee will be silently returned, bugs may occur if the programmer forgets to accept funds. For example, accepting on one control-flow path but not another (e.g., only in the None branch) would allow the caller to steal funds deposited by another user by subsequently invoking Withdraw.

The second task of deposit is to update the caller’s bank credits by the transferred amount. In both languages, the amount sent by the caller is available through special integer-typed expressions: `msg.value` in Solidity and `_amount` in Scilla. The identity of the caller is represented by `msg.sender` or `_sender`, respectively. The programmer must be careful to increment the caller’s credit balance by the transferred quantity exactly once. Forgetting to update the balance is stealing funds from the caller, whereas updating more than once allows the caller to steal funds from other customers. There are no special checks on integer expressions to prevent either programmer error from violating conservation of funds.

**Solidity and Scilla** withdrawal. The withdraw procedure exchanges bank credits for native currency. Although this is logically the inverse of deposit, the implementation looks quite different. This is because Solidity and Scilla do not have language support for returning native or custom currency to the calling procedure. Instead, the code uses language primitives for sending currency to the address that stores the contract whose procedure invoked withdraw.

In Solidity, the relevant primitive is `msg.sender.transfer`. Subtly, this is a virtual call that invokes a user-defined procedure known as a fallback function in the callee. The decision to make every payment of native currency a virtual call has led to infamous re-entrancy vulnerabilities such as the DAO [Buterin 2016] attack that led to theft of digital assets worth over $60 million. The key issues are that (a) the update to the credit map via `credit[msg.sender] = 0` and the sending of funds via transfer are not atomic, and (b) the map update occurs after the virtual transfer call. If the virtual call invokes a user-defined function that calls back into withdraw, the caller can steal funds deposited by a different customer.

Scilla improves on Solidity by defining a more restricted message-passing primitive for sending money to addresses. The `_amount`: `amt` code snippet implicitly withdraws `amt` units of money from the contract’s available balance. Then, the `_sender`’s balance in the credit map is zeroed out before using the `send` primitive to transfer the money to its recipient. Scilla’s type system forces any global side effect like a message `send` to occur at the end of the procedure; for our example, it would not allow the update to `credit` to occur after the `send`. In addition, Scilla does not have virtual calls. These restrictions prevent re-entrancy issues.

However, the Scilla design introduces a new kind of issue: *using emit msg instead of send msg in the example would cause the money in the message to be destroyed*. The emit construct emits the message as a client-facing event rather than sending it to an address. This mistake permanently reduces the supply of money in the system. Scilla programmers have encountered this problem in practice ([Sergey et al. 2019], Section 5.2), though Scilla has an auxiliary “cashflow” static analyzer for detecting problems like this.

**Move Bank.** The Move implementations of the deposit and withdraw procedures are symmetric. The deposit procedure says that it requires payment by declaring a parameter of type `Coin::T` and that it intends to credit the caller by declaring a return value of type `Bank::Credit`. The withdraw
procedure does the inverse. Coin::T represents native currency; it is a resource type defined in a separate Coin module that we describe in Section 6.2. Since both Coin::T and Bank::Credit are resources, the type system will reject any implementation that fails to consume the input resource or return ownership of the output resource. Both resources can leverage the same language feature (move semantics) for atomic ownership transfer into and out of the procedure.

The deposit code consumes its input resource by acquiring a reference to a Bank::T value published in global storage and moving the coin resource into the bank’s balance via the call to Coin::deposit. It then packs (constructs) a Credit resource and returns it to the caller.

The withdraw code consumes its input Credit resource by unpacking it. Unpacking destroys a resource and returns its contents. Only the Bank module can pack, unpack, and acquire references to the fields of the Credit resource; code outside the module can only access Credit through the procedures exposed by Bank. Finally, withdraw extracts native currency from the bank’s balance via Coin::withdraw and returns it to the caller.

Resources as Capabilities. We conclude our discussion of the Move bank by noting that the advantage of an explicit type for money goes beyond safety: resources enable flexible programming patterns that would not be possible with an implicit representation of money. For example: say that Alice is a customer of the Bank and wants to give another user Bob permission to withdraw the funds she has deposited. Alice can simply transfer ownership of her Bank::Credit to Bob, who can use it to invoke withdraw at his leisure—no change to the Bank code is required. Bob could also choose to store his Bank::Credit in another resource that (e.g.) allows multiple parties to access it or prevents it from being redeemed until a certain time.

By contrast, the Solidity and Scilla implementations of the Bank cannot support this feature without modifying the original contract to support it. In essence, the credit map approach implements an access control list for withdrawing native currency, whereas the resource approach implements a linear capability for withdrawals [Hardy 1994; Miller et al. 2003; Swasey et al. 2017]. Capability-based programming enables some powerful design patterns, as we will see in Section 6.2.

3 MOVE OVERVIEW
This section provides an informal overview of the key concepts and design decisions of the Move language that support safe and expressive programming with resources.

3.1 Executable Bytecode With Resources
The Move execution platform relies on a compiler to transform source language programs into programs in the Move bytecode language. For example, Figure 1 contains Move source code that compiles to an executable bytecode representation (see Figure 2 for an example). Bytecode – not source code – is stored and executed on the Libra blockchain.

Because Move programs are deployed in the open alongside other (potentially untrusted) Move programs, it is important for key properties like resource safety to hold for all Move bytecode programs. If the safety guarantees were only enforced by the source language compiler, an adversary could subvert them by writing malicious bytecode directly and entering it into the execution environment without using a compiler. Thus, we focus on the design and semantic properties of the Move bytecode language here, although we write illustrative examples in the source language for readability.

The Move execution platform relies on a load-time bytecode verifier, in a manner similar to the Java Virtual Machine [Lindholm and Yellin 1997] and Common Language Runtime [Meijer et al. 2000]. The bytecode verifier enforces type, memory, and resource safety. Because the goal of the present paper is to explain and formalize properties of Move that provide key advantages over
prior smart contract languages (i.e. resource values with ironclad safety guarantees), we focus on a concrete semantics for Move with dynamic checks for type, resource, and memory safety and leave formalization of the bytecode verifier to future work. Our formalization and resource safety theorem (Theorem 5.10) therefore do not depend on any of the invariants ensured by the bytecode verifier; the presence of the verifier just allows an optimized implementation to skip these checks. The analyses performed by the bytecode verifier are sufficiently interesting and complex to fill a paper of their own (particularly reference safety, which has similarities to the Rust borrow checker; see Section 7).

Persistent Global State. Move execution occurs in the context of a persistent global state organized as a partial map from account addresses to resource data values. Each address can store an arbitrary number of resources, but at most one of any given type at the top level. For example, the account address 0x1 in Figure 2 holds two Coin::T resources, but one is at the top level and one is stored inside a Bank::T resource.

In addition, an address can store zero or more code modules. The global state is updated via transactions that contain a sender account address and a transaction script consisting of a single main procedure. Transaction scripts update the global state by invoking procedures of published modules that mutate stored resources, add new resources to an address, or remove existing resources from an address. A transaction has all-or-nothing semantics; either the entire script is executed without errors or it aborts and reverts all changes to the global state.

Procedure Calls. Execution of a Move program begins by executing the distinguished main procedure of the transaction script and proceeds via the evaluation mechanics shown in Figure 3. A procedure is defined by a type signature and an executable body comprising a linear sequence of Move bytecode commands. Procedure calls are implemented using a standard call stack containing frames with a procedure name, a set of local variables, and a return address. When one procedure calls another, the calling procedure pushes its callee’s arguments onto the operand stack and invokes the Call bytecode command, which pops the arguments off the stack and stores them in the actuals of the callee (which become a subset of the callee’s local variables). Before returning, the callee pushes its return values on the stack and invokes the Ret bytecode command, which pops the current stack frame and returns control to the return address.

Modules. A Move module such as our Bank from Figure 1 can declare both record types and procedures. Records can store primitive data values (including booleans, unsigned integers, and account addresses) as well as other record values, but not references. Each record is nominally declared as a resource or non-resource. Non-resource records cannot store resource records, and only resources can be stored in the global state.
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Fig. 3. Execution mechanics of the Move bytecode interpreter. The global state holds resources that can be moved onto the operand stack or borrowed by pushing a reference onto the stack. Resources can be published to the global state by moving them from the stack into an account address. Each call stack frame (blue) has its own local variables to store values popped off the stack. Formal parameters and return values are passed between caller and callee using the shared operand stack.

Fig. 4. List of Move instructions. The local variable instructions move or copy values between local variables and the operand stack. Reference instructions operate on reference values stored on the operand stack. The global state instructions move values between the operand stack and persistent global storage. Stack instructions manage the operand stack by popping unused values, pushing constants, and performing arithmetic/bitwise operations via Op. Finally, the procedure instructions create and destroy call stack frames.

Modules support strong encapsulation for their declared types. Consider the bytecode translation of the withdraw procedure from our running example shown in Figure 2. The struct definitions $s_i$ and field definitions $f_i$ used by the bytecode instructions are implemented as integer indexes into internal tables of the current module. This design ensures that privileged operations on the module’s declared types can only be performed by procedures in the module, encapsulating creation via Pack, destruction via Unpack, accessing fields via BorrowField, publishing via MoveTo, removing via MoveFrom, and accessing (either to read or write) via BorrowGlobal. For example: the withdraw bytecode is able to access a field of its declared $T$ type except via the API exposed by the Coin module.

A module may import a type or procedure declared in another module using its storing address as a namespace. For example, the use $0x0::Coin$ line from our running example indicates that the current module should link against the module named Coin stored at account address $0x0$. The combination of encapsulation and resource safety enables modules to safely interoperate while maintaining strong internal invariants.

References. Move supports references to records and primitive values (but not to other references). In a manner similar to Rust, references are either exclusive/mutable (written &mut) or read-only (written &). All reads and writes of record fields occur through a reference.
References are different from other Move values because they are transient: as explained above, persistent global state consists of resource records, which cannot have fields of reference type. This means that each reference must be created during the execution of a transaction script and released before the end of that transaction script. Thus, each individual record value is a tree, and the global state is a forest whose roots are account addresses.

3.2 Language Design for Resource Safety

At the beginning and end of a transaction script, all of the resources in the system reside in the global state $GS_{pre}$. Resource safety is a conservation property that relates the set of resources present in state $GS_{pre}$ before the script to the set of resources present in state $GS_{post}$ after the script. In general terms, we would like the language to guarantee that:

(1) A resource $M::T$ that is present in post-state $GS_{post}$ was also present in pre-state $GS_{pre}$ unless it is introduced by a Pack inside $M$ during script execution

(2) A resource $M::T$ that was present in pre-state $GS_{pre}$ is also present in post-state $GS_{post}$ unless it is eliminated by an Unpack inside $M$ during script execution

It is helpful to look at each of the instructions in Figure 4 and consider what precautions must be taken in order to ensure that properties (1) and (2) hold. For property (1), we must be careful not to introduce instructions that can duplicate a resource value. Move achieves this by providing both MvLoc and CpLoc instructions for transferring a value from a local variable to the operand stack. As the copy_resource_bad function in Figure 5 demonstrates, the CpLoc instruction cannot be applied to a resource value. The MvLoc, MoveTo, and MoveFrom instructions for transferring values prevent double moves that would allow a programmer to "spend" the same resource multiple times (see double_move_bad).

References must also be managed carefully to avoid duplication. The ReadRef for dereferencing a reference value can only be applied to a non-resource reference. Allowing a dereference of a resource like deref_resource_bad in Figure 5 would copy the resource value behind the reference.
Property (2) is further challenging because conventional languages provide a number of ways to indiscriminately discard values. At the instruction level, restrictions must be placed on \texttt{Pop}, \texttt{StLoc}, \texttt{WriteRef}, and \texttt{MoveTo}. Most obviously, popping a resource off the operand stack with \texttt{Pop} must be disallowed. If a local variable is of type resource, \texttt{StLoc} can only be applied when the variable is uninitialized. Code like \texttt{destroy\_via\_assign\_bad} in Figure 5 would violate property (2) by discarding the old value stored in the local. Similarly, a \texttt{WriteRef} like \texttt{*ref = move r} in \texttt{destroy\_via\_write\_bad} must not execute if \texttt{ref} points to a resource. This destructive update would destroy the value previously pointed to by \texttt{ref}. Finally, the \texttt{MoveTo} instruction for moving a resource into global storage aborts if the move would overwrite an existing resource at the given address. For example, \texttt{double\_move\_to\_bad} would fail at runtime because the memory 0x1.R is already occupied.

Instruction-level protections are not quite enough to ensure property (2). There are two remaining holes that could allow resource destruction: values left in local variables when a procedure returns (e.g., \texttt{unused\_resource\_local\_bad} in Figure 5), and values left on the operand stack at the end of script execution. Move prevents both with extra discipline in the calling convention:

- The values on the operand stack match the types of formal parameters/return values before a \texttt{Call}/\texttt{Ret} (respectively).
- \texttt{Ret} cannot be invoked if a local variable holds a resource value or the operand stack holds extra (non-return) values.
- A script terminates in a non-aborting state only when both the call stack and operand stack are empty.

The reader might wonder: can resources left on the stack and in locals be destroyed by a mid-script abort? This would be indeed be a problem in a conventional language, but the all-or-nothing semantics of Move transactions saves us. An aborting transaction script evaluates to the pre-state of the script, at which point all resources reside safely in global storage.

What Resource Safety Accomplishes for Programmers. At this point, it’s worthwhile to take a step back and briefly discuss what resource safety does and does not guarantee. For concreteness, let’s consider our running example in Figure 1 once more. Resource safety would not preclude an implementation of \texttt{deposit} whose first line was \texttt{let amt = 7}; that is, it cannot protect the programmer from mistakes in implementing a custom asset. It does, however, isolate and localize such decisions. For example, it prevents the \texttt{Bank} from violating the invariants established for the imported \texttt{Coin::T} type inside its own declaring module.

This observation suggests a clear division of responsibilities. It is the module author’s job to define and correctly implement safety invariants for the types inside her module. Once she has done so, encapsulation and resource safety will ensure that her local invariants are also global invariants—no possible client can ever violate them (similar to the “robust safety” of [Swasey et al. 2017]). This is quite powerful because Move modules give programmers an unusual amount of control over declared types (e.g., restricting publishing and destroying types as described above), and this control can be used to establish strong invariants. For example, it is possible to define a type that can only be created after a certain time, a type that can never be destroyed, or a type that can only be created by a caller that has paid ten coins. In Section 6.2, we will show how resource safety allows us to establish global conservation of native currency in the Libra platform via a local invariant of the \texttt{Coin} module.

4 MOVE BYTECODE INTERPRETER

Next, we present operational semantics for a call-free subset of the Move bytecode that simulates a single transaction of arbitrary length. Generalizing to multiple transactions with procedure calls is
conceptually straightforward, but would be significantly less concise. This semantics will be used in Section 5 to formalize and prove resource safety.

As explained in Section 3.1, Move uses a bytecode verifier to ensure type safety and memory safety of smart contracts. Our formalism here, focusing on resource safety, does not depend on the bytecode verifier. Instead, our semantics gets stuck in erroneous states, e.g., when encountering a dangling reference or an ill-typed operation. The bytecode verifier ensures additional invariants (e.g., no dangling references, well-typedness) such that programs that pass the bytecode verifier cannot get stuck due to memory or type errors. As a result, our resource safety theorem (Theorem 5.10) does not depend on the bytecode verifier.

We will begin with preliminary definitions and notation for values, types, memory, and persistent global state, before introducing evaluation rules. The notation is summarized in Figure 6.

### 4.1 Definitions and Notation

**Notation for partial functions and lists.** We use standard operations on partial functions (used to represent record values or mappings in local and global states); operations on lists are similarly standard and used in several ways.

Following common convention, if $f : A \rightarrow B$ is a partial function from $A$ to $B$, then $\text{dom}(f)$ is the set of all $a \in A$ for which $f(a)$ is defined, and $\text{img}(f)$ is the set of all $b \in B$ for which $f(a) = b$ for some $a \in A$. We use $f \downarrow \{ a \mapsto b \}$ to denote the function that is equivalent to $f$ on every input except $a$ and which maps $a$ to $b$. Similarly, $f \setminus a$ is the partial function equivalent to $f$ except that it is undefined at $a$. 

---

| locations   | $\mathcal{L}$ |
| primitive data values | $P$ |
| addresses   | $\mathcal{A} \subseteq P$ |
| resource types | $T$ |
| resource tags | $R$ |
| tags        | $T = R \cup \{U\}$ |
| field names | $F$ (finite) |
| paths       | $F^*$ |
| values      | $V$ (see Definition 4.1) |
| tagged values | $TV$ (see Definition 4.1) |
| record values | $V \setminus P$ |
| memories    | $M = \mathcal{L} \rightarrow TV$ |
| references  | $\text{Ref} = \mathcal{L} \times F^* \times \{\text{mut, immut}\}$ |
| stack values | $SV = TV \cup \text{Ref}$ |
| local values | $LV = \mathcal{L} \cup \text{Ref}$ |
| local variables | $\mathcal{V}$ |
| local states | $M \times (\mathcal{V} \rightarrow LV) \times SV^*$ |
| global resource ids | $\mathcal{G} = \mathcal{A} \times T$ |
| global states | $GS = M \times (\mathcal{G} \rightarrow \mathcal{L}) \times (\mathcal{V} \rightarrow LV) \times SV^*$ |
| program locations | $PC$ |
| program states | $PC \times GS$ |

Fig. 6. Definitions for the semantics of Move. For a set $X$, $X^*$ denotes the set of (finite) lists of elements from $X$. 


We use lists to represent a sequence of field accesses and in components of semantic states. We write \([\ ]\) for the empty list and \(e :: l\) for the result of placing \(e\) at the front of list \(l\). Similarly, \(l :: e\) is the list with \(e\) appended to \(l\) and, by slight abuse of notation, \(l :: l'\) the concatenation of lists \(l\) and \(l'\).

**Values and their types.** We begin with primitive types, field names, and tags, using these three elements to define the values used in computation. While tags are used to state and prove semantic properties, tags are not needed in the Move virtual machine.

Let \(P\) be the set of primitive data values, including Booleans, integers, and addresses, \(F\) a fixed, finite set of *field names* and \(T\) the set of *tags*, where each tag may be a resource tag from a set \(R\) or the distinguished element \(U\) indicating a value that is not a resource.

**Definition 4.1.** The set \(V\) of *values* and the set \(TV\) of *tagged values* are defined together from the primitive values, tags and field names as the least sets satisfying:

(i) \(P \subseteq V\);
(ii) for every \(v \in V\) and \(t \in T\), \(\langle v, t \rangle \in TV\); and
(iii) if \(n \geq 1, f_1 \ldots f_n \in F\) are pair-wise distinct, and \(tv_1 \ldots tv_n \in TV\), then \({(f_i, tv_i) \mid 1 \leq i \leq n}\} \in V\).

The values arising from condition (iii) are non-empty partial functions from \(F\) to \(TV\), which we call *record values*. We use ordinary function notation when using them (e.g., when writing \(v(f)\) to refer to the value associated with field \(f\) in the record value \(v\)).

Although types are not used extensively in this paper, we leverage the fact that typing distinguishes resource values from non-resource values. We write \(\nu : s\) to indicate that value \(\nu\) has a type \(s\). If \(T\) is the set of resource types, \(\nu : s\), and \(s \in T\), then we say that \(\nu\) is a *resource value* and \(\langle \nu, t \rangle\) is a *resource tagged value*, or simply *resource*; otherwise, \(\nu\) is a *non-resource value* and \(\langle \nu, t \rangle\) is a non-resource tagged value.\(^1\)

**Paths and Trees.** In the semantics, a path is a possibly empty list of field names, which we think of as representing a sequence of field selections.

A tagged value may be regarded as a labeled tree, in the usual way that expressions are parsed as trees, with nodes labeled by tags and edges labeled by field names. Specifically, a primitive value is a tree consisting of a leaf. The tree associated with a tagged record value consists of a node labeled with the tag and a subtree for each record component. If \(r\) is a record value, then for each \((f, tv) \in r\), there is an edge from \(r\) to the subtree for \(tv\) labeled by \(f\).

Two useful operations on values and paths are (i) the subterm \(tv[p]\) of \(tv\) located at path \(p\), and (ii) the term \(tv[p := tv']\) obtained by replacing the subterm at path \(p\) with term \(tv'\). The subterm identified by following the empty path is the term itself, i.e. \(tv[[]] = tv\). These operations are formalized as follows.

**Definition 4.2.** If \(tv = \langle \nu, t \rangle \in TV\), then \(tv[p]\) is defined inductively by:

1. \(tv[[]] = tv\)
2. \(tv[f :: p'] = v(f)[p']\) if \(v\) is a record value and \(f \in dom(v)\)
3. undefined otherwise

Similarly, if \(tv = \langle \nu, t \rangle\) and \(tv'\) are both tagged values, then \(tv[p := tv']\) is defined inductively by:

1. \(tv[[]] := tv'\) = \(tv'\)
2. \(tv[f :: p' := tv'] = \langle v [f \mapsto v(f)[p' := tv']], t \rangle\) if \(v\) is a record value and \(f \in dom(v)\)
3. undefined otherwise

\(^1\) In a well-formed tagged value, the type of the value must be consistent with the tag (see Definition 5.1).
States. In the Move semantics, a state comprises persistent global storage, local memory, operand stack and local variables.

If \( L \) is the set of memory locations, then a reference is a triple \( \text{ref} \langle c, p, q \rangle \) consisting of a location \( c \in L \), path \( p \), and mutability qualifier \( q \in \{\text{mut, immut}\} \).

Local states and global states include memories, which are mappings from locations to values, and stacks. Specifically, a memory \( M \) is a partial function from \( L \) to \( TV \). Defining local values to be locations or references, a local memory is similarly a partial function from \( V \) to local values, where \( V \) is a set of local variables. A local stack is a list of stack values, which may be tagged values or references.

Global resources are identified by an address and a resource type. If \( A \) is the set of addresses, then the set \( G = A \times T \) of global resource ids consists of pairs \( \langle a, R \rangle \), each associating a primitive value \( a \in A \) of address type with a resource type \( R \in T \). A global store \( G \) is a partial function from global resource ids \( G \) to \( L \).

A global state is a tuple \( \langle M, G, L, S \rangle \), where \( M \) is a memory, \( L \) is a local memory, \( S \) is a local stack, and \( G \) is a global store. A local state is similar with the global store omitted.

A Move program \( P \) is a mapping from program locations \( PC \) to operations and, if \( pc \in PC \) represents the current program counter, then \( P[pc] \) is the current instruction and \( P[pc + 1] \) is the next instruction under normal execution. A program state consists of a program counter \( pc \in PC \) and a global state.

4.2 Local State Rules
Each rule in Figure 7 operates on local states (global storage is unchanged and thus omitted to keep the presentation simple) and takes the form

\[
\varphi \quad \frac{}{\langle \langle M, L, S \rangle, op \langle \cdot \rangle \rangle \rightarrow_0 \langle M', L', S' \rangle} \quad \text{Rule1}
\]

where Rule1 is the name of the rule, \( \varphi \) is a precondition for applying it, \( \langle M, L, S \rangle \) and \( \langle M', L', S' \rangle \) are local states, and \( op \langle \cdot \rangle \) is an operation parameterized by a field, variable, or record declaration of the current module. When there are no parameters, we simply write \( op \). We use the following variable conventions: \( c \in L; x \in V; t \in T; v \in V; tv \in TV; f \in F; p \) is a path; \( q \) is a mutability qualifier; \( r \) is a stack value; and \( s \) is a type.

The \text{MvLoc} rules show how the state changes when a local value is moved from a local variable \( x \) onto the stack. Note that if the value moved is not a reference, it is removed from memory when it is placed on the stack. The \text{CpLoc} rules copy local values to the stack. In this case, the local variable \( x \) (and memory if applicable) retain their values. Note that these rules can only be applied if the local value is not a resource. The \text{StLoc} rules take the top stack value and store it in the local variable \( x \). There are two versions of the rule, depending on the current local value of \( x \). If \( x \) has no value or contains a reference, it is always possible to store the stack value in \( x \) (note that we can always choose a \( c' \) not currently in the domain of \( M \)). However, if \( x \) contains a tagged value, then the rule can only be applied if the tagged value is not a resource.

\text{BorrowLoc} pushes a reference to the local value in \( x \) onto the stack. \text{BorrowField} takes a reference \( r \) from the top of the stack and pushes a new reference onto the stack that points to the tagged value in field \( f \) of the record pointed to by \( r \). \text{FreezeRef} turns a mutable reference into an immutable reference. \text{ReadRef} makes a copy of the tagged value pointed to by a reference on top of the stack and pushes it onto the stack (note that the value must be a non-resource). \text{ReadRef} can be applied to either a mutable reference or an immutable reference. \text{WriteRef} takes a non-resource tagged value \( tv' \) and a reference \( r \) from the stack, and replaces the tagged value \( tv \) pointed to by \( r \) (which must also be a non-resource and of the same type) by \( tv' \). It can only be applied when \( r \) is a
Fig. 7. Operational Semantics of Move: operations on local state
And finally, exists (e.g. that the divisor is non-zero for a division operation).

The rules of Figure 8 lift the small-step semantics presented so far to semantics of call-free Move programs. The rules of Figure 8 are similar except that they operate on global states. The combined global, local, and memory state (represented in the rule Step as \( \sigma \)) is extended with the pc to obtain a program state, and the rules simply implement sequential and branching control flow in a straightforward way.

These evaluation rules intentionally get stuck in the presence of resource, type, or memory errors (e.g., \( \text{CpLoc} \) on a variable that contains a resource). As we mentioned in Section 3.1, the Move bytecode verifier performs checks that preclude these errors. However, there are two kinds of program locations over which a program counter \( \text{PC} \) ranges. A program \( \text{P} \) is a mapping from such program locations to operations. The combined global, local, and memory state (represented in the rule Step as \( \sigma \)) is extended with the \( \text{pc} \) to obtain a program state, and the rules simply implement sequential and branching control flow in a straightforward way.

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of runtime errors not caught by the bytecode verifier that we also model as stuck execution for convenience:

1. Errors in Op such as division by zero and arithmetic over/underflow (which Move chooses to treat as errors);
2. Overwriting an existing global resource id in MoveTo or accessing a global resource id that does not exist in MoveFrom or BorrowGlobal.

In practice, these runtime errors trigger an abort that terminates the current transaction and reverts any changes to global state.

5 RESOURCE SAFETY

In this section, we prove that the operational semantics introduced above enforces a conservation property: a resource cannot be created or destroyed except by the privileged Pack and Unpack constructs available in its declaring module. We define a set of well-formed states (Definition 5.5), show that the semantic rules preserve well-formedness (Proposition 5.7), and finally, that well-formedness guarantees resource safety (Theorem 5.10). We start by introducing the parts of a well-formed state.

Definition 5.1 (Well-formed tagged value). A tagged value \( tv = \langle v, t \rangle \) with \( v : s \) is well-formed if \( s \in T \) iff \( t \in R \), and in addition, one of the following holds: (i) \( v \) is primitive; (ii) \( v = \{ f_i, tv_i \} \ | \ 1 \leq i \leq n \) such that every \( tv_i \) is well-formed, and if \( s \notin T \) then for every \( i \), \( tv_i \) is not a resource.

Intuitively, in a well-formed tagged value, a resource value is never nested inside of an non-resource value, and the tag corresponds to the type.

Definition 5.2 (Globally consistent state). We say that a state \( \langle M, G, L, S \rangle \) is globally consistent if the following holds: (i) Every tagged value in \( img(M) \) or in \( S \) is well-formed; (ii) \( \text{dom}(M) = img(G) \cup (img(L) \cap L) \); (iii) For every \( \langle a, s \rangle \in \text{dom}(G), M(G(\langle a, s \rangle)) = \langle v, t \rangle \) with \( v : s \).

Intuitively, (i) means that tagged values in the state are well-formed; (ii) means that global resource ids and local variables only point to locations in the memory (no dangling references) and the memory only contains locations pointed to by some global resource id or local variable (no garbage); (iii) means that global values have their expected types.

Definition 5.3 (Tag-consistent state). A state \( \langle M, G, L, S \rangle \) is tag-consistent if the following holds: (i) if \( M(c_1)[p_1] = \langle v_1, t \rangle, M(c_2)[p_2] = \langle v_2, t \rangle \), and \( t \neq U \), then \( c_1 = c_2 \) and \( p_1 = p_2 \); (ii) If \( S = [s_1, s_2, \ldots] \), \( s_i[p_1] = \langle v_1, t \rangle, s_i[p_2] = \langle v_2, t \rangle \), and \( t \neq U \), then \( i_1 = i_2 \) and \( p_1 = p_2 \); and (iii) It is never the case that \( S = [s_1, s_2, \ldots], M[c][p] = \langle v_1, t \rangle, s_i[p] = \langle v_2, t \rangle \), and \( t \neq U \).

Intuitively, being tag-consistent means that resource tags are unique, i.e. a resource tag can appear in the memory and the stack at most once.
Definition 5.4 (Non-aliasing). A state \( \langle M, G, L, S \rangle \) is non-aliasing if the following holds: (i) If \( x_1, x_2 \in \text{dom}(L) \) with \( x_1 \neq x_2 \) and \( L(x_1), L(x_2) \in L \), then \( L(x_1) \neq L(x_2) \); (ii) If \( g_1, g_2 \in G \) with \( g_1 \neq g_2 \), then \( G(g_1) \neq G(g_2) \); and (iii) If \( g \in G \) and \( x \in \text{dom}(L) \) then \( G(g) \neq L(x) \).

Intuitively, a state is non-aliasing if different global or local identifiers cannot point to the same memory location.

Definition 5.5 (Well-formed state). A state \( \langle M, G, L, S \rangle \) is well-formed if it is globally consistent, tag-consistent, and non-aliasing.

Well-formed states ensure that global resource identifiers and local variables only point to locations that are in the memory, and do not alias. Note, however, that according to these semantics, a well-formed state may still contain dangling references i.e., \( \text{ref} \langle c, p, q \rangle \in \text{img}(L) \cup S \) s.t. \( c \notin \text{dom}(M) \), as well as aliasing between references. As explained in Section 3.1, the bytecode verifier ensures stronger guarantees (e.g., no dangling references), but in this section we do not depend on these stronger invariants.

We now show that the operational semantics preserves well-formedness of states.

Definition 5.6 (Well-formed execution sequence). Let \( P \) be a program. An execution sequence of \( P \) is \( \pi = \langle p_{c_0}, \sigma_0 \rangle, \ldots, \langle p_{c_n}, \sigma_n \rangle \) such that \( p_{c_{i+1}} \in \text{dom}(P) \) for every \( 0 \leq i \leq n \) and \( P \vdash \langle p_{c_i}, \sigma_i \rangle \rightarrow \langle p_{c_{i+1}}, \sigma_{i+1} \rangle \) for every \( 0 \leq i < n \). An execution sequence is called well-formed if each \( \sigma_i \) is well-formed.

Proposition 5.7. Let \( P \) be a program and \( \pi = \langle p_{c_0}, \sigma_0 \rangle, \ldots, \langle p_{c_n}, \sigma_n \rangle \) an execution sequence of \( P \). If \( \sigma_0 \) is well-formed, then \( \pi \) is well-formed, i.e., \( \sigma_1, \ldots, \sigma_n \) are all well-formed.

Proof. The proof is by induction on \( n \), and amounts to a routine check that the rules of Figure 7 and Figure 8, as well as the Branch-F and Branch-T rules of Figure 9 preserve well-formedness. We explicitly prove this for MvLoc. The rest are verified similarly. Global Consistency: (i) follows from the induction hypothesis since the set of tagged values in the memory and the stack are not changed. (ii) is also preserved: by the induction hypothesis, \( \langle M, G, L, S \rangle \) is non-aliasing. Thus, the fact that \( x \) is removed from \( L \) also means that \( c \) is removed from \( \text{img}(G) \cup \text{img}(L) \cap L \). Since \( c \) is also removed from \( M \), it follows that (ii) holds. (iii) is preserved since \( G \) is unchanged and no locations are added to \( M \). Tag Consistency: (i) is preserved as the memory only gets smaller after MvLoc. (ii) and (iii) hold initially by the induction hypothesis; it is easy to see that both must also hold after moving a value from memory to the stack. Non-Aliasing: (ii) holds since the global state is unchanged. Additionally, (i) and (iii) are preserved as \( L \) only gets smaller after MvLoc. \( \square \)

Next, we define the resources of a state, and what it means for resources to be introduced or eliminated in an execution sequence. We can then prove the resource safety theorem.

Definition 5.8 (State Resources). Let \( \sigma = \langle M, G, L, S \rangle \) be a state. The resources of \( \sigma \), denoted \( \mathcal{R}(\sigma) \), are defined as follows: \( \mathcal{R}(\langle M, G, L, S \rangle) = \{ t \in R \mid \langle \nu, t \rangle \in \text{img}(M) \cup S \} \)

Intuitively, resources of a state are the resource tags that occur in a tagged value of the state.

Definition 5.9 (Resources Introduced and Eliminated). Let \( P \) be a program and \( \pi = \langle p_{c_0}, \sigma_0 \rangle, \ldots, \langle p_{c_n}, \sigma_n \rangle \) an execution sequence of \( P \). The set of resources introduced in \( \pi \), denoted \( \mathcal{R}_I(\pi) \), is: \( \{ t \in R \mid \exists 0 \leq i < n. \; P[p_{c_i}] = \text{Pack} \text{ and } \sigma_{i+1} = \langle M, G, L, \langle \nu, t \rangle; S \rangle \} \). The set of resources eliminated in \( \pi \), denoted \( \mathcal{R}_E(\pi) \), is: \( \{ t \in R \mid \exists 0 \leq i < n. \; P[p_{c_i}] = \text{UnPack} \text{ and } \sigma_i = \langle M, G, L, \langle \nu, t \rangle; S \rangle \} \).
Intuitively, $R_I(\pi)$ collects all resource tags that were created (using Pack) during the execution; similarly, $R_E(\pi)$ collects all resource tags that were consumed (using Unpack) during the execution. Notice that these sets are not necessarily disjoint. That is, a resource that is created and later consumed during $\pi$ will appear both in $R_I(\pi)$ and in $R_E(\pi)$.

**Theorem 5.10 (Resource Safety).** Let $P$ be a program and $\pi = (pc_0, \sigma_0), \ldots, (pc_n, \sigma_n)$ a well-formed execution sequence of $P$. Then, $R(\sigma_n) = R(\sigma_0) \cup R_I(\pi) \setminus R_E(\pi)$.

**Proof.** The proof is by induction on $n$. The base case ($n = 0$) is straightforward (in this case, $R_I(\pi) = R_E(\pi) = \emptyset$). For the induction step, the induction hypothesis provides:

$$(*) R(\sigma_{n-1}) = R(\sigma_0) \cup R_I(\pi') \setminus R_E(\pi')$$

where $\pi' = (pc_0, \sigma_0), \ldots, (pc_{n-1}, \sigma_{n-1})$. If $P[pc_{n-1}] \not\in \{\text{Pack } (s), \text{ Unpack}\}$, then examination of the rules shows that $R(\sigma_{n-1}) = R(\sigma_{n-1})$ (i.e. for all rules other than the Pack and Unpack rules, the set of resource tags in the global state remains the same after the application of the rule). By Definition 5.9, $R_I(\pi) = R_I(\pi')$ and $R_E(\pi) = R_E(\pi')$. Using $(*)$, we get $R(\sigma_{n-1}) = R(\sigma_{n-1}) \cup R_I(\pi') \setminus R_E(\pi')$. The proof is similar if $P[pc_{n-1}] = \text{Pack } (s)$ and $s \not\in T$ or if $P[pc_{n-1}] = \text{Unpack}$ and $\sigma_{n-1} = \langle M, G, L, \langle v, U :: S \rangle \rangle$. If $P[pc_{n-1}] = \text{Pack } (s)$ for a resource type $s$, then the Pack-R rule shows that $R(\sigma_{n-1}) = R(\sigma_{n-1}) \cup \{t\}$ where $\sigma_{n} = \langle M, G, L, \langle v, t :: S \rangle \rangle$. We know $t$ is fresh, so it is not in $R_E(\pi')$. By Definition 5.9, $R_I(\pi) = R_I(\pi')$ and $R_E(\pi) = R_E(\pi')$. Thus, by $(*)$, $R(\sigma_{n-1}) = R(\sigma_{n-1}) \cup R_I(\pi') \setminus R_E(\pi')$. The proof is similar if $P[pc_{n-1}] = \text{Unpack}$ and $\sigma_{n-1} = \langle M, G, L, \langle v, t :: S \rangle \rangle$, $t \not\in U$. □

### 6 EXPERIENCE WITH MOVE

In this section, we describe the open-source implementation of the Move language, report on our experience using Move in the Libra blockchain, and mention efforts that have adopted or built on the language.

#### 6.1 Implementation

**Move Compiler.** We have implemented$^2$ a compiler from the Move source code used in Figure 1 and Figure 5 to the Move bytecode language. The source language adds structured control flow for convenience and expressions to abstract away the operand stack, but the programming model otherwise matches the bytecode language. Although all of the examples in this paper use explicit **copy** and **move** directives when accessing variables (e.g., `let x = copy r`), the compiler does not require these directives. In the absence of a directive, the compiler uses liveness analysis to emit a **move** for the last usage of a variable and a **copy** for all other uses. In addition, the compiler implements source code equivalents of the bytecode verifier analyses with friendly error messages.

**Move Virtual Machine.** The Move virtual machine implements a superset of the bytecode interpreter semantics described in Section 4. The implemented interpreter includes gas metering similar to the EVM [Wood 2014], support for a limited form of generics, and a **vector** type. The virtual machine also includes the bytecode verifier, which performs static checks for type safety, usage of uninitialized variables, reference safety, and stack balancing (to ensure that the callee cannot illegally access stack locations belonging to a caller). The bytecode verifier has a linker for ensuring that the usage of external types in a module are consistent with their declarations (e.g., procedure $p$ invoked in module $m1$ exists and matches the type signature of its declaring module $m2$). The implementation$^3$ of both components consists of about 17K lines of Rust code.

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$^2$https://github.com/libra/libra/tree/master/language/move-lang

$^3$https://github.com/libra/libra/tree/master/language
Although the Move language was originally created to serve as the execution layer for the Libra blockchain, we have maintained a clean separation between the platform-agnostic Move language layer implemented in the virtual machine and the Libra-specific layer implemented in the Libra adapter component and Libra’s Move standard library. This flexible architecture has facilitated adoption of Move outside of Libra (see Section 6.3).

**Tooling.** In addition to the compiler and virtual machine, we have implemented several tools\(^4\) to facilitate testing and analysis of Move code:

- A testing framework\(^5\) that allows users to write multi-transaction test scenarios.
- A bytecode code coverage tool that attaches to the testing framework and records the bytecode instructions exercised by each test.
- A Move bytecode disassembler similar to the `javap` utility for Java bytecode. The disassembler prints raw bytecode, but can also accept an optional source to bytecode map that augments the result with variable names and line numbers.

### 6.2 Integration With the Libra Blockchain

The Move VM implements the transaction execution layer in the Libra blockchain [Amsden et al. 2019]. At a high level, a blockchain is a simple replicated state machine [Lamport 1984]. Libra validators (replicas) collectively maintain a distributed database that encodes the global state structure described in Section 3. Users submit transactions to the system that are batched into a block, or ordered list of transactions. The role of the transaction execution layer is to take a block of transactions and the current global state as input and execute each transaction to produce a write set representing the effects of the transaction on the global state. The effect of the block is the ordered composition of the effects of each of its transactions.

The logic for Libra execution lives in two separate places: the Libra adapter, and Libra’s Move standard library. The Libra adapter contains about 1K lines of Rust code that wrap the Move virtual machine. The adapter implements logic for splitting a Libra block into transactions, checking a cryptographic signature on the transaction, extracting a Move transaction script, arguments, and gas budget to pass to the Move virtual machine, and applying the effects of executing the transaction to the storage layer.

**Move Standard Library.** Libra’s Move standard library consists of 40 modules totalling about 3K lines of Move source code that compile to 44KB of bytecode. Broadly speaking, these modules implement four categories of functionality:

1. Coins: implementations of both single-currency stablecoins and the multi-currency LBR coin as described in [The Libra Association 2020]
2. Accounts: several different account types, sequence number logic to prevent replay attacks, sender authentication, key rotation, events for notifying clients
3. Validator management: adding/removing validators, paying gas fees to validators, rotating validator cryptographic keys
4. Utility modules such as `Option`, `Compare`, and `FixedPoint32`

We will present a subset of the Coin and Account APIs to give the reader a sense of how Move’s resources give us the flexibility to implement our own version of concepts that must be baked into the semantics of other smart contract languages.

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\(^4\)https://github.com/libra/libra/tree/master/language/tools
\(^5\)https://libra.org/en-US/blog/how-to-use-the-end-to-end-tests-framework-in-move/
Resources: A Safe Language Abstraction for Money

```rust
resource T { value: u64 }  
resource MarketCap { total_value: u64 }

// create a Coin with value=0
fun zero(): Coin::T

// Consume c and increment c_ref by its value
fun deposit(c_ref: &mut Coin::T, c: Coin::T)

// Decrement c_ref by amt, create Coin with value=amt
fun withdraw(c_ref: &mut Coin::T, amt: u64): Coin::T

// create Coin with value=amt, update MarketCap by amt. privileged operation
fun mint(amt: u64): Coin::T
```

Fig. 10. A subset of the Coin module API.

```rust
resource T { bal: Coin::T, seq_num: u64, auth_key: vector<u8>, has_withdraw_cap: bool, ... }  
resource WithdrawCap { account: address }

fun create(addr: address) // publish a T under addr

fun withdraw_from_sender(amt: u64): Coin::T

fun deposit(recipient: address, c: Coin::T)

fun rotate_sender_auth_key(new_auth_key: bytes)

fun extract_sender_withdraw_cap(): Account::WithdrawCap

fun withdraw(amt: u64, cap: &Account::WithdrawCap): Coin::T
```

Fig. 11. A subset of the Account module API.

Coin Module. The Coin module in Figure 10 implements the native currency of the Libra platform by wrapping an integer value with a safe API. This module clearly illustrates the value of combining linearity with traditional modularity. Any user can create a coin worth zero, combine two coins with deposit, or split a single coin into two coins with withdraw. The reader might wonder why withdraw chooses to mutate a &mut Coin::T rather than expose a functional API that takes two Coin::T’s and returns a new one. The answer is that the reference parameter provides needed flexibility for updating a Coin::T object stored in the field of another resource. For example: the functional API could not be used to update the balance field of the Bank::T resource in Figure 1.

The privileged mint operation allows a privileged user (the body contains a permission check) to create new currency and update the integer value stored in the MarketCap resource. The body of the procedure also ensures that there is a single MarketCap resource in the system published at address $a$.

The conservation of currency in the Libra system can thus be stated as a local invariant of the Coin module: the sum of the values of each Coin::T resource in the system must be equal to the total_value field of the MarketCap resource. The combination of the strong encapsulation described in Section 3.1 and resource safety guarantees defined in Section 5 ensure that Coin::T’s cannot be created, destroyed, or modified by code outside the Coin module. The Coin module needs only to ensure that deposit and withdraw conserve the value fields of the input/output field and that the MarketCap is updated appropriately whenever new coins are created. This can be verified with straightforward local reasoning over the Coin module.

To the best of our knowledge, no other blockchain platform has made a rigorous argument for the conservation of its native currency. We note that there are known counterexamples for conservation such as the Scilla emit bug described in Section 2.
Account Module. A Libra user account at address $a$ is represented by storing an Account::T resource under $a$. This resource holds all of the information a user needs to transact: a balance, a sequence number to prevent replay attacks, and an authentication key. The module exposes procedures for withdrawing funds and rotating authentication keys (for the transaction sender only) and depositing funds (to any address).

In addition, the module allows the holder of the WithdrawCap capability to debit an account (similar to the Bank::Credit resource in Figure 1). The implementation of extract_sender_withdraw_cap (not shown) uses the has_withdraw_cap field to ensure that there is at most one WithdrawCap for each account in the system. An account whose WithdrawCap has been extracted can no longer use withdraw_from_sender—using the unique capability for account address $a$ is the only way to debit the balance of $a$. Similar to native currency conservation in Coin, the uniqueness property for WithdrawCap can be established with simple local reasoning in the Account module.

In addition, using a resource to explicitly represent the permission to withdraw from an account provides significant flexibility for users of Libra. A common use-case for contracts is placing preconditions on the funds stored in certain addresses; for example:

- Funds should only be sent to recipients in a whitelist
- Funds should only be transferred after a certain date
- Funds should only be withdrawn with the approval of a quorum

Each of these policies can be implemented by creating a resource that stores a WithdrawCap and restricts access accordingly. Platforms like Ethereum [Wood 2014] support this use case by implementing payments with dynamic dispatch and allowing contracts to override the default payment behavior, but (as we explained in Section 2), this is a dangerous pattern because payment to an unknown address can call arbitrary code. The capability-based approach of WithdrawCap enables custom payment logic without dynamic dispatch by moving the dynamism to the withdrawal code (known and trusted by the sender) instead of the recipient code (unknown and not trusted by the sender).

Deployment in the Libra Testnet. The Move VM is currently running as part of the public Libra testnet\(^6\) that previews the functionality of the Libra payment system (expected to launch in 2020 pending regulatory approval). The testnet supports a whitelist of transaction scripts that exercise all of the modules in the Move standard library. To limit the scope and risk of the launch, the testnet does not currently allow users to publish new modules. We hope that this will change in time as the Libra Association works with regulators to define appropriate safeguards for third-party publishing of smart contracts.

6.3 Move Usage Outside of Libra

The flexibility of the Move language and the modularity of the Move VM has facilitated external interest in/adoptions of Move in both academic and industrial contexts.

Other Blockchains. Solana\(^7\) is a multi-language blockchain that supports Move smart contracts and has publicly launched. The dfinance\(^8\) and OpenLibra\(^9\) blockchain platforms are using Move, but have not yet launched. The Flow blockchain is an upcoming project from Dapper Labs, the creator of the popular CryptoKitties project in Ethereum. Dapper is considering using the Move

\(^6\)https://developers.libra.org/docs/my-first-transaction
\(^7\)https://solana-labs.github.io/book/embedding-move.htm
\(^8\)https://docs.dfinance.co/move_vm
\(^9\)https://www.openlibra.io/
bytecode as the compilation target for its Cadence source language. PRISM [Yang et al. 2019] is an academic project that seeks to significantly enhance the scalability of existing blockchain platforms. PRISM has recently implemented smart contract support for both Move and the EVM [Wang et al. 2020].

Verification Tools. The Move Prover [Zhong et al. 2020] implements a specification language and functional verification tool for Move. It has been used to specify and verify pre- and post-conditions for several of the Libra standard library modules. A verification startup called Synthetic Minds verified key properties of an earlier version of the Coin/Account Libra modules and wrote/verified several new modules.\textsuperscript{11}

7 RELATED WORK

Rust. Mozilla’s Rust [Matsakis and Klock 2014] language is used at large companies such as Google, Amazon, and Facebook. Rust uses a clever affine type system to provide type and memory safety along with data-race freedom. Move is strongly influenced by Rust, but there are several important differences:

(1) Affine vs linear: Rust structs can be silently discarded, but Move resources must be explicitly Unpack’ed. This is a profound difference that is required for resource safety, but presents complications in the design of many language features (see Section 3.2).

(2) A subset of Move without the persistent global state $GS$ is superficially similar to a linear variant of Rust with many features removed (e.g., references in structs, heap allocation, collections, traits, generics, concurrency, \texttt{unsafe}). However, the persistent global state of Move gives programmers access to a shared, mutable global state. There is no equivalent feature in Rust, and the restrictions of Rust’s borrow checker make it impossible to emulate this feature in safe Rust. A key contribution of Move is a representation of global state expressive enough to represent complex smart contracts, yet simple enough to preserve the safety guarantees we desire.

(3) Rust is a source language that compiles to an executable representation, whereas Move bytecode is itself an executable representation. The key difference is that the guarantees enforced by the Move language hold directly on the executable representation (no need to trust a compiler) and continue to hold when Move programs are linked against untrusted code. This property is a requirement for smart contracts, which are deployed in the open and must tolerate arbitrary interactions with untrusted code. Thus, even if the Rust language (or a subset) had exactly the properties we wanted, it would not be usable as a smart contract language.

Substructural Type Systems and Ownership Types. Rust is the most mainstream language with a substructural type system, but it follows in the footsteps of other cleverly designed languages such as Cyclone [Grossman et al. 2002], Clean [Smetsers et al. 1994], Pony [Clebsch et al. 2015], and Alms [Tov and Pucella 2011]. A related line of work involves ownership type systems [Clarke et al. 2013] for controlling aliasing in languages with reference semantics. A common theme in both areas is leveraging types for safe memory management to avoid undefined behavior due to data races or accessing deallocated/uninitialized memory, but without relying on garbage collection.

Move also builds on this tradition, but our usage of linearity is broader and more ambitious than memory management: linear resources are a natural abstraction for digital money and other programmer-defined assets. The resource safety guarantee from Section 5 is a novel semantic

\textsuperscript{10}https://medium.com/dapperlabs/libra-and-flow-combining-resources-for-open-source-40530e53fa01

\textsuperscript{11}https://synthetic-minds.com/pages/blog/blog-2019-09-11.html
conservation property similar to (e.g.) conservation of mass, stated in a way that is independent from any particular enforcement mechanism (e.g., linear type or dynamic checks).

**Linear Logic.** The modern era of substructural logics and associated type systems began with Girard’s linear logic [Girard 1987]. In his early explanation of its resource sensitivity, Girard used an intuitive representation of money. In that account, each number of fixed-value coins has a different type: two coins would have type $C \otimes C$ and three coins $C \otimes C \otimes C$. While this encoding of money illustrates a fundamental difference between linear and intuitionistic logic, the approach resembles giving each individual integer a different type. (If each integer has a different type, then any straightforward type system would prohibit a single addition function from being used to add arbitrary pairs of integers.) Instead of segregating different monetary values in different types, we need resource types (such as the `Coin` module in Section 6.2) that create coins of any value which cannot be duplicated or destroyed outside the control of their defining module. Thus, while Move draws on Girard’s key insight relating linearity to assets, Move resources give programmers both provable resource safety and flexibility in representing money-like types.

**Account-based Blockchain Languages.** Account-based blockchain languages mimic a classic bank ledger by representing global state as a map from account addresses to integer balances and exposing language primitives for debiting one balance and crediting another. We discussed two prominent executable account-based languages [Sergey et al. 2019; Wood 2014] in Section 2; many others like IELE [Kasampalis et al. 2019], Agoric JS [Agoric 2019], Michelson [Foundation 2018b], and Pact [Popejoy 2017] have been proposed in the past few years. Move implements a more expressive variant of the account-based model where account addresses are associated with a direct representation of money (programmable resources) instead of an indirect one (integer balances).

**UTXO-based Blockchain Languages.** UTXO (unspent transaction output) blockchain languages represent the global state as a set of (authentication policy, amount) pairs. Programs transfer money by satisfying the authentication policy of one or more input UTXOs and creating a set of fresh output UTXOs whose amounts sum to the amounts included in the inputs. Program execution removes the input UTXOs from the state and adds the fresh ones. This model was pioneered by Bitcoin’s [Nakamoto 2008] Script [Wiki line] language, and has been adopted by a few more recent languages such as Simplicity [OâĂŹConnor 2017] and Plutus [Foundation 2019]. Though UTXOs are a good choice for a platform with a single native currency and limited programmability, they are cumbersome to use for general-purpose state changes. We feel that Move’s resources are a more flexible approach to implementing diverse financial assets with customizable behaviors.

**Blockchain Source Languages with Linear Types.** Flint [Schrans et al. 2019] and Obsidian [Coblenz 2017; Coblenz et al. 2019] are contract programming languages that use linear types as an explicit representation of assets. These languages enforce linearity at the source level, but compile to an executable representation (EVM bytecode [Wood 2014] and a Java subset used by Hyperledger Fabric [Foundation 2018c], respectively) without the same protections. Nomos [Das et al. 2019] uses session types to achieve even stronger static protections, but also does not consider the problem of applying the type system to an executable blockchain representation. The Cadence source language has linear types and is considering Move bytecode as a compilation target (see Section 6.3).

The distinguishing feature of Move is an executable bytecode representation with resource safety guarantees for all programs. This is crucially important given the open deployment model for contracts—recall that any contract must tolerate arbitrary interactions with untrusted code.

12https://docs.onflow.org/docs/cadence
Source-level linearity has limited value if it can be violated by untrusted code at the executable level (e.g., untrusted code that duplicates a source-level linear type).

8 CONCLUSION

We have introduced language support for a specific form of linear resource types, formalized corresponding semantic resource safety properties, and proved that they hold for successful concrete execution of Move programs. The language construct provides a safe abstraction for currency-like values in the Move language, as illustrated by example in Section 2 and through more extensive experience summarized in Section 6. In future work, we plan to describe and formalize the Move bytecode verifier, which involves interesting and novel static analyses for ensuring type, resource, and reference safety invariants. One goal of the verifier is to ensure progress for concrete execution of Move programs in the checking semantics of the present paper, complementing the safety guarantees proved here. Overall, we believe the semantic guarantees and successful programming experience presented in this paper suggest that the language design and implementation provide better language support and more effective design patterns for the growing range of resource-sensitive applications of blockchain and related platforms.

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