

Merkelized Abstract Syntax Trees

Jeremy Rubin, Manali Naik, Nitya Subramanian

{jlrubin, mnaik, nityas}@mit.edu
<https://github.com/JeremyRubin/MAST>

1. INTRODUCTION

In modern systems, it is critical to ensure the integrity and security of data transferred over the network. However, traditional methods like SSL/TLS can be a performance and cost bottleneck. As a result, data compression is a key factor in systems that heavily rely on networked communication. For this project, we created a new data structure called the Merkelized Abstract Syntax Tree (MAST) to address both data integrity and compression. MASTs can be used to compactly represent programs that will be executed remotely, and by using some of the properties of Merkle trees, they can also be used to verify the integrity of the code being executed. The project idea was developed with Bitcoin applications in mind, and the experiment we set up uses MASTs in a crypto currency network simulator. Using MASTs in the Bitcoin protocol [2] would reduce the amount of transaction data nodes would send over the network, while simultaneously maintaining the security of broadcasted data.

2. MAST DATA STRUCTURE

MASTs combine the traits of Merkle Trees [1] and Abstract Syntax Trees (ASTs) to compactly and securely represent programs. Merkle trees are data structures that can be used to efficiently verify the contents they store. Data blocks are stored in the leaf nodes, and every non-leaf node is the hash of the labels of its children nodes (see Figure 1). In the Bitcoin Blockchain, Merkle trees are used to check the integrity of data blocks transferred over untrusted networks with hash verification. ASTs, on the other hand, represent the syntactic structure of programs. Primitives are located at the leaf nodes of ASTs, and non-leaf nodes represent programmatic operations and control flow mechanisms.

In a MAST, the root of the tree represents the entirety of the program, while all other nodes represent subprograms. Each path in the tree is a different execution branch that the program can take. The structure is Merkelized in that leaf nodes are hashes of the subprogram code that they represent, and non-leaf nodes are hashes of the children labels. MASTs can therefore compactly represent the execution flow of a program with just a sequence of hashes that specify which child edge to follow at each node.

3. IMPLEMENTATION

3.1 MAST Nodes

A MAST node is constructed with string content and optional child node pointers. The string content is code that

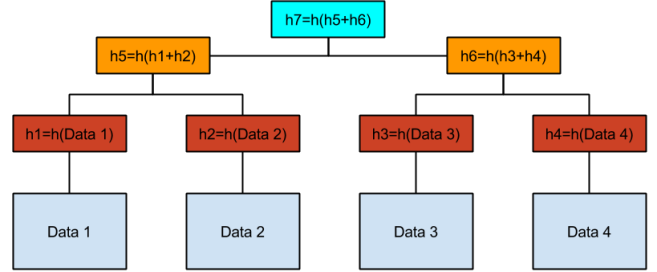


Figure 1: An example of the construction of a Merkle Tree

can be executed. A MAST node can have any number of children, each one representing a different branch of program execution, and new branches can be added via the `addBr` method. Joining all the string content from each node along a path in a MAST therefore yields the code for one possible path of execution for a program.

Since branches in a MAST don't have to be added in any particular order, maintaining the correct Merkle hash for each node during tree construction would be inefficient and require updating previously-set hash values. Instead, the hash function of a MAST node computes the correct Merkle hash using the current state of the tree. It does so by first forming a binary tree of all direct children nodes. As this tree is built, hashes are added up to compute a valid Merkle hash at each level of the binary tree. Then, the root hash of the binary tree is summed with the hash of the given node's content, producing a valid Merkle hash for the given node. By including the content hash in the sum, we can ensure integrity of code content later on. Figure 2a shows the structure used to calculate the Merkle hash of a given MAST node. The four children branches are placed in a binary tree whose root is the yellow "Branch Merkle Root." This Branch Merkle Root hash is summed with the content hash on the left to give the Merkle Root.

3.2 Proof Lists

In order to verify the integrity of code, the MAST function `generateFullProofUpward` generates a proof list to a given Merkle root hash from the current node. It does so by crawling upwards in the tree, maintaining a list of the Merkle hashes and code content it passes along the way. The logic gets more complicated due to the fact that Merkle hashes are calculated using a binary tree (as described in Section

3.1). As a result, the proof list generator crawls up this binary tree until it hits the branch Merkle root (the parent MAST node), and then repeats the process until the destination node is reached. The content and hashes included in the proof list for a piece of content is shown in Figure 2b.

For the verification process, we assume that another machine (without the entire program code) has the Merkle hash of the MAST root node. With a proof list whose destination node is the MAST root hash, this other machine could verify the code in the proof list by iterating over it, summing up the hash values to make sure that they add up to the next hash value in the proof list. If the final summation yields the root hash, then the sequence of hashes provided is correct. Since content hashes get included in the proof list, we can also verify the integrity of the code content itself.

Additionally, scripts can be compiled to a proof that is compatible with opcodes used on the Blockchain via a script evaluator that interprets code in the context of Bitcoin opcodes. This further augments compatibility between our MAST implementation and the Bitcoin protocol and allows for potential future extensibility of this project to be integrated within the Blockchain.

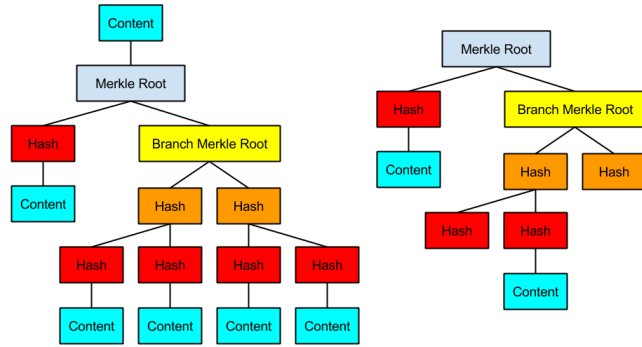


Figure 2: Some examples demonstrating functionalities of the MAST: the recursive data structure(left) and a proof for a particular branch of execution for a MAST(right)

3.3 Consensus Protocol Simulation

We implemented a crypto currency network simulator to use MASTs to verify and execute code transferred over the network. To simulate the transaction verification process used in Bitcoin, we created **ConsensusNodes** to execute and validate the code in a transaction. There are three different types of **ConsensusNodes**: **GoodNodes**, **EvilNodes**, and **InconsistentNodes**. **GoodNodes** execute code properly and include transactions in their local ledgers if they are valid. **EvilNodes** do the opposite, adding invalid transactions to their ledgers and excluding valid ones. **InconsistentNodes** behave correctly with some probability. With the three node types, we can simulate more realistic network conditions and the presence of adversaries.

Code for a transaction is stored in a MAST, and the transaction saves the corresponding root Merkle hash. The compression MASTs offer reduces the amount of data that has to be transferred between nodes during validation, as well as the amount of data that is stored in the ledgers. Rather than sending and saving the entire transaction code, we only transmit and save a path through the MAST (as a sequence

of Merkle hashes). Using an args array, we support passing arguments to transaction code and specifying the subsequent transactions to be run. Transactions also have associated amounts that are used to check whether the code is valid. A valid transaction is one whose amount is at least as large as the sum of amounts of its subsequent transactions.

After individual nodes validate/invalidate a set of transactions, the **GlobalConsensus** node determines the final outcome of a transaction; a transaction is valid if a majority of the **ConsensusNodes** validate it. The **GlobalConsensus** node updates a global ledger representing the correct state of the system, and **ConsensusNodes** can sync with this ledger to maintain an accurate picture of state.

4. APPLICATIONS AND EXPERIMENTS

4.1 Contractual Agreements

Using the previously discussed consensus protocol, we implemented a contract modeling a will that utilized the shared contract creation, verification, and execution functionalities of the MAST to create a multiparty execution environment. The will-based contract we implemented consisted of an agreement between three parties: Alice, Bob, and Carol. The branches of the tree represent approved expenditures both before and after Alices death, and present clauses of the contract as a series of branches that are unlocked upon the fulfillments of certain conditions in conjunction with the signatures of relevant signatories. This structure allows for sub-contracts to exist within the subset of the primary signatories and enables full transparency of the content of the contract while restricting execution of certain clauses to when necessary preconditions are satisfied.

The consensus protocol to verify valid construction and execution of the will was implemented using a group of nodes (comprised of representative **ConsensusNodes** from the **GoodNode**, **EvilNode**, and **InconsistentNode** classes discussed above), each of which verified the validity of a transaction.

4.2 Code Compression

The primary benchmarks used to quantify code compression were a series of python scripts, which can be found in our repo at the location MAST/bin. The file longcode.py (Figure 3) generates a Merkle tree with tens of thousands of branches, yielding a total code length of 2M characters. The post-compression result after applying our algorithms was under 23,500 characters, indicating a compression rate of over 98%. We cannot compare the code compression we saw directly to compressing with another algorithm such as LZW because such algorithms employ frequency based compression and longcode uses repeated segments again and again. However, this repetition is OK to do because we perform structural compression. Instead, we compared it to using zip to compress the Linux kernel. This took it from roughly 6115332 characters in length to 1754665 characters, a compression rate of 70%. It is important to note that compression algorithms could also be used in several places within the MAST data structure itself: per code block, and on the complete proof list. Additionally, we currently use an unoptimized message format to send MASTs which is essentially a list of $[[subproof], data, mroot]]$. This could be further optimized to rely on less punctuation and whitespace and use more efficient character encodings.

```
#!/usr/bin/python
import mast.mast as mast
import mast.crypto as crypto
import mast.sim as sim
import mast.script as script
from pprint import pprint
from base64 import b64encode as enc

ex = lambda x: ""
def testfn(x, y, z):
    if x > y:
        print x, y, z
    else:
        print %s
ret = Valid("print 1")
"""%(x)
if __name__ == "__main__":
    code = map(ex, xrange(20))
    m = mast.Mast("compile", "print 1")
    n = m
    for i, c in enumerate(code):
        if i%10000 == 0:
            print '.'
            for i in xrange(100):
                n.addBr(c)
            n = n.addBr(c)
    mt = mast.MerkleTreeList(m.children)

    orig_len = len("".join(code))*101*20.0
    print "original length", orig_len
    pr = n.generateFullProofUpward(m.hash())
    code, _script = mast.toScript(pr, m.hash())
    together = enc("".join(map(chr, code+_script
    )))
    comp_len = len(str(pr))
    pct_comp = 1 - comp_len/orig_len
    print sim.merkleVerifyExec(None, m.hash(),
    [pr], 10)
    print script.run("".join(map(chr, code+
    _script)))
    print "compression length", comp_len
    print "compression length for blockchain
    ready version", len(together)
    print "compression percentage", pct_comp
    print "compression percentage for
    blockchain version", 1-len(together)/
    orig_len
```

Figure 3: An example demonstrating code compression on a Merkle tree with millions of characters. Conversion to a MAST representation yielded a compression score of over 98.9%

5. SIGNIFICANCE AND FUTURE WORK

The primary impact of this projects is in its applications to established environments utilizing contracts. The introduction of MASTs has potential to greatly impact existing problems ranging from bitcoin contracts to code transfer between distributed nodes on a network. Potential improvements to this implementation of the MAST could include greater support for distributed construction and execution or the addition of a framework allowing greater extensibility by users of this data structure. Complete integration with Bitcoin would reduce the amount of data that is stored in the Blockchain, and will make it possible to perform more complex transactions like the will we modeled.

6. REFERENCES

- [1] R. Merkle. Protocols for public key cryptosystems. In *Proc. 1980 Symposium on Security and Privacy, IEEE Computer Society*, pages 122–133. IEEE Computer Society, 1980.
- [2] S. Nakamoto. Bitcoin: A peer-to-peer electronic cash system. 2008.