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Remote Attestation Protocol Synthesis and Verification with a Privacy Emphasis

by

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in the

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Declaration of Authorship

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"If you formulate a question properly, mathematics gives you the answer. It's like having a servant that is far more capable than you are. So you tell it 'do this,' and if you say it nicely, then it will do it."

Savas Dimopoulos, Stanford University

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Abstract

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Remote attestation is innately challenging and wrought with auxiliary challenges. Even determining what information to request can be a challenge. In cases when a presumptuous request is denied, mutual trust can be built incrementally to achieve the same result. All the while, we must 1) Respect our own privacy policy not revealing more than necessary; 2) Respond to counter-attestation requests to build trust slowly; 3) AvoidâĂIJMeasurement DeadlockâĂİ situations by handling cycles. In addition to these guidelines, there are basic properties of a remote attestation procedure that should be verified. One such property is ensuring parties send and receive messages harmoniously. Using the theorem prover Coq we explore designing, modeling, and verifying a mutual remote attestation procedure via an imperative protocol language that supports dynamically generating execution steps to perform a mutually agreeable attestation protocol from nothing other than a partyâĂŹs initial privacy policy.

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Abbreviations

TPM **T**rusted **P**latform **M**odule

PCR **P**latform **C**onfiguration **R**egister

Symbols

$\Rightarrow$	one-sided protocol	single-step eval one
$\Rightarrow^*$	one-sided protocol	multi-step eval
$\Rrightarrow$	dual-sided protocol	single-step eval
$\Rrightarrow^*$	dual-sided protocol	multi-step eval

For/Dedicated to/To my...

Chapter 1

1.1 Introduction

In a world increasingly dominated by computers, we are forced to place more and more trust in our devices regardless of whether or not that trust is well-founded. Often this trust has been misplaced or at best exaggerated. One reason for this is that there is often pressure to release software as soon as possible as opposed to as safe as possible. The trust problem is exacerbated by the trend of shifting operations from one's own machine to the cloud. The highly inter-machine nature of many operations complicates trust further. To address the need to establish trust in a remote machine, much research has been focused on how to execute *Remote Attestation* [1]. In simple terms, it is the process of learning information about the state of a remote machine with high assurance that the information gathered is true.

Remote attestation can more formally be defined as "the activity of making a claim about properties of a target by supplying evidence to an appraiser over a network" [2]. Though there is more that must be considered than inventing a way to send verifiably correct measurements to a remote party. Is it safe to reveal such information? Surely, we cannot simply comply with every attestation request from every party requesting sensitive measurements. We must have some sort of vetting process, or *Privacy Policy*, which dictates what information will be revealed upon request. While a Privacy Policy could simply be a list of revealable properties, we will use a more fluid approach. For example, a person may be willing to reveal their calendar events, but only after they learn some things about the requester– in other words, perform a *Counter Remote Attestation*. One would likely want to know the identity of the requester and if their terms of service allows them to sell the information or use it for advertising. Privacy Policies defined in this paper are a list of measurements each associated with a *Rule* which dictates under what conditions the measurement will be revealed. By "conditions" we mean the point in time when specific measurements are known about the requester and requirements on those measurements are met. In this paper we explore and attempt to verify a

schema which automatically performs Remote Attestations given a starting list of desired measurements while not violating any party's Privacy Policy. The schema inherently allows for mutual trust to be gained incrementally to obtain more sensitive measurements. The schema will have the following properties.

- In traditional remote attestation, one party is the appraiser and the other is the attester who attests to the state of the target. Note that we will often use the terms *target* and *attester* interchangeably since one often attests to the state of one's own system. Statically assigning the roles of attester and appraiser does not allow the attesting party to gain trust in the appraiser, only the inverse. The appraiser does not get the opportunity to gain the trust of an apprehensive attester, if necessary, to obtain all desired measurements. Therefore, who is attesting and who is appraising should be flexible as needed. This schema provides a way for *both* parties to incrementally build trust in each other by temporarily switching roles.
- Other formal models of remote attestation require entire protocols to be defined statically in order to verify their properties. While enumerating all possible paths of execution for protocols that build trust incrementally is theoretically possible if the cardinality of all possible measurement requests is finite, this computation is an unreasonable prerequisite. For example, if there are 10 possible properties to request and an appraiser desires to know 3 of them, there are well over 100 million unique message sequences that must be accounted for (see appendix A for this calculation). To compute this type and store it statically is a significant burden. Such static protocols certainly have their use in this model, however. Specifically, we abstract over most of the detail contained within a single property request and response. Each property request can be viewed as a small, static remote attestation with a rigid type.

Instead of defining an entire protocol statically, we abstractly define the meaning of taking one step in a remote attestation instance. We can then prove properties of this single step that hold for every occurrence. Parties can repeat this step as many times as necessary. We then go on to prove various correctness properties about a single step as well as answering bigger verification questions such as, "will participants ever stop taking steps?" "will participants stepping individually always create synchronized message sequences?" "Can a participant ever violate their privacy policy?"

1.2 Background

A practical use case for remote attestation occurs when a banking customer wishes to view their information remotely. It is in both the bank's and customer's best interests that this information remain confidential. Therefore prior to revealing sensitive information, an institution would prefer to be assured that the customer's computer has not been compromised in some way. For example, the bank may want assurance that the remote system is running an approved and updated anti-virus program on an approved version of an approved operating system. So the bank would send a request for this information and receive a response. But what stops the customer's computer from lying to the bank? A virus could have taken over and attested that everything is fine which is the exact scenario the bank is trying to detect and avoid. Researchers have devised a way for the appraiser to determine with a very high degree of confidence that the values received in remote attestations are (a) recent and (b) are the result of performing the requested measurement on the requested system (modulo hardware tampering). This process requires the target system to have a Trusted Platform Module (TPM) hardware chip. The properties of a TPM are numerous and will not be discussed in detail here (the specification is ~2,000 pages [3]). However, it is foundational for the ideas presented below to know of its existence and the basic services a TPM provides us when performing remote attestation.

1.2.1 TPM

The Trusted Platform Module or TPM was designed to address the fact that traditional computer platforms can't truly be trusted. The TPM is meant to provide a root of trust for software programs. The TPM earns this trust by physically being its own entity. It is a cryptoprocessor attached to the motherboard. Software running on the CPU communicates to the TPM via specially formed messages. The TPM can securely store a few cryptographic keys that cannot be read by any software running on the system. The only way to use the keys is by requesting the TPM to sign or encrypt or decrypt some data with them. For the key's entire life, it never leaves the confines of the TPM chip. In particular, a TPM securely stores at least a storage root key and platform identity also known as an endorsement key [1]. The TPM only has a small amount of space for storage and therefore opts to store keys securely and larger data can be securely stored on the system's hard drive after asking the TPM to encrypt it with the storage key and only provide the decryption under certain conditions. These conditions are a specific Platform Configuration Register or PCR state. PCRs are special registers inside the TPM that can be read from freely, but only written to by extending the

current register value by hashing it along with the hash of some other data. The TPM is intimately involved in the boot process storing measurements of each action taken and process started in a PCR that can only be modified during boot (see Intel's Trusted Execution Technology [4]). The endorsement key or EK is often not used directly, but instead certifies child keys which are then used to sign the contents of PCR registers upon request. Therefore, after boot in software an appraiser can request a signed data packet containing the requested PCR value(s) that can be compared to known "golden" hashes to gain assurance that the system is not running rouge software and only what we have pre-defined as acceptable. The target receives this request and forwards it to the TPM which returns the values in a signed message for the target system to report. Because the target does not have access to private keys used by the TPM to sign the values, the target cannot modify the contents of the message without detection. We chain trust outward from the boot process by storing the hash of a *measurer* program that will be executing the measurement requests received from an appraiser. The evidence sent to the appraiser includes the quote from the TPM regarding the measured values as well as the measured hash of the measurer program itself. With this information, the appraiser can examine the evidence, see that it came from a real TPM, and be confident the measured values are true. A more in-depth view of TPMs can be found in *The ten-page introduction to Trusted Computing* [1].

1.3 Remote Attestation

The procedure discussed in this paper requires the presence of a TPM in both the attesting and appraising parties. Particular measurement and evidence evaluation methods are held abstract since they are their own subjects of research. This includes the process of starting the trusted measurer program. Hence whenever we refer to the value of a measurement, know that this is in reality a complex value containing much more information (containing hashes, signatures, etc) than the primitive values used in this abstraction. Similarly, the evaluation of evidence is much more complicated and involves verifying keys; establishing, storing, and trusting a database of golden hashes; and establishing trust in one's own evidence evaluator program.

To give more detail on this abstraction, we encapsulate the process where an appraising party evaluates evidence provided in response to a measurement request by representing such an evaluation as a comparison of primitive values e.g. $x \stackrel{?}{=} 4$. We will also assume that all communication occurs in an encrypted session e.g. SSL. With these abstractions in mind, we can focus on higher level protocols that implement the listed abstractions.

We focus on what kinds of messages are sent back and forth and the procedure to arrive at a mutual state of trust.

As a general rule, one does not reveal more about oneself than necessary during the process of remote attestation. Therefore, a predetermined sequence of messages is insufficient to perform *mutual* attestation simply because one cannot know the privacy policy of another party. This knowledge would be necessary to know the order to request measurements satisfiably. For example, say appraiser A is a wireless access point that requires a singular measurement x of attesting party B, a client wishing to connect. Many clients acting in the role of B may be willing to reveal x without any counter-appraisal of entity A and readily perform and provide the measurement resulting in a grand total of two messages. However, there may be an occasional apprehensive client who only reveals property x when property y is obtained and scrutinized from the requesting party. This in turn may result in a counter-counter-appraiser from entity A if A's privacy policy dictates property y is reveal-able only if property z is measured and scrutinized. Obtaining the initially desired measurement x can be possible, though the exact sequence and quantity of messages must be prescribed dynamically from the privacy policies of the involved parties. We will refer to protocol *satisfiability* as an appraiser receiving measurement values for all initially desired measurements while both parties abide by their privacy policies. A satisfiable protocol may be unsatisfiable in a static context. Instead of attempting one large step, trust can be gained incrementally with an end result equivalent to the result of a static protocol. Note that sharing one's privacy policy with the requesting party may be possible (given the privacy policy allows its own sharing) to short-circuit the initial banter of requests by computing a resolving protocol, but this does not solve the general case since revealing one's privacy policy is considered a breach of privacy. Therefore we do not discuss this optimization further. Our procedure computes the same resolution dynamically.

Let us examine another use case involving a customer and bank. In figure 1.1, a bank is

Required:
AntiVirus Version

Policy:
{}

Required:
{}

Policy:
{(AntiVirus *, free),
(identity,
yourIdent -> verified(yourIdent))
}

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FIGURE 1.1: Example 1 Privacy

requesting the anti-virus version of its customers when they wish to interact with their accounts. The empty privacy policy of the Bank indicates that under no circumstances will it reveal measurements about itself. If no rule is listed for a measurement the default behaviour is to deny the request. The customer has no initial measurement requests to ask of the appraising party. In the customer's privacy policy, we see that any information regarding anti-virus software will freely be given without verifying anything about the requesting system. The identity of this customer is only revealed once the identity of the requester is known and passes the 'verified' test. In figure 1.2, the customer Bob begins

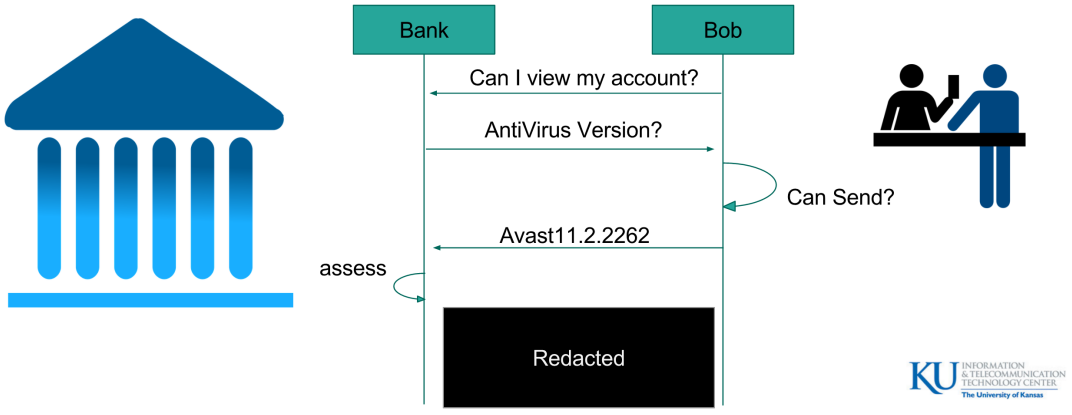


FIGURE 1.2: Example 1 Protocol

the conversation. In response, the bank requests to know the customer's anti-virus version. Bob checks his privacy policy to confirm he is able to reveal this information, performs the measurement, and responds. The bank assess the evidence provided, is satisfied with the values, and begins the process of sharing the sensitive information with a higher degree of certainty of the information's safety than without performing remote attestation.

We can make the example slightly more interesting if Bob first wants to confirm the identity of the requester before revealing his information as we see in figures 1.3 and 1.4.

A circumspect reader may have noticed a fatal flaw. What if we have the following slightly modified scenario in figure 1.5?

In figure 1.5, we have the notion of gaining incremental trust by countering requests with other requests, but as of yet we have no means of preventing such a regression. We refer to this situation as *measurement deadlock*. We will address this situation later.

In this section we have explored some use cases exemplifying the scenarios for which we wish to create a procedure and model using Coq. In summary, our remote attestation protocol must perform the following functions:

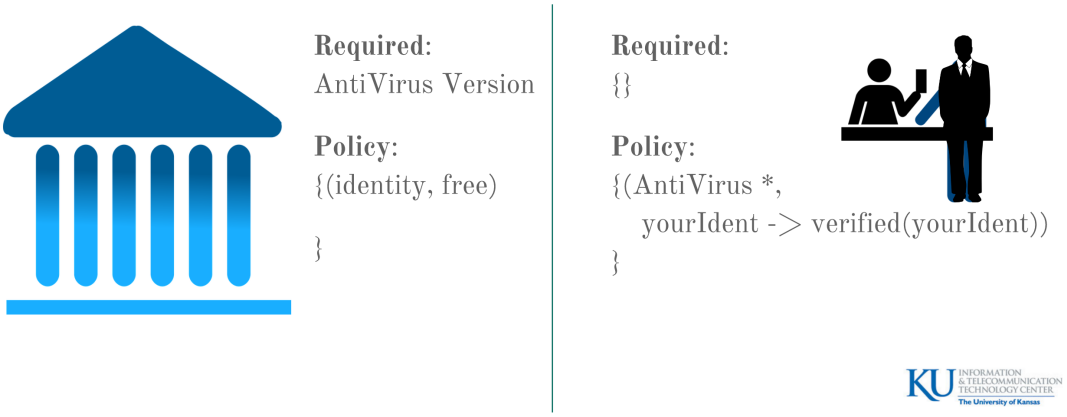


FIGURE 1.3: Example 2 Privacy

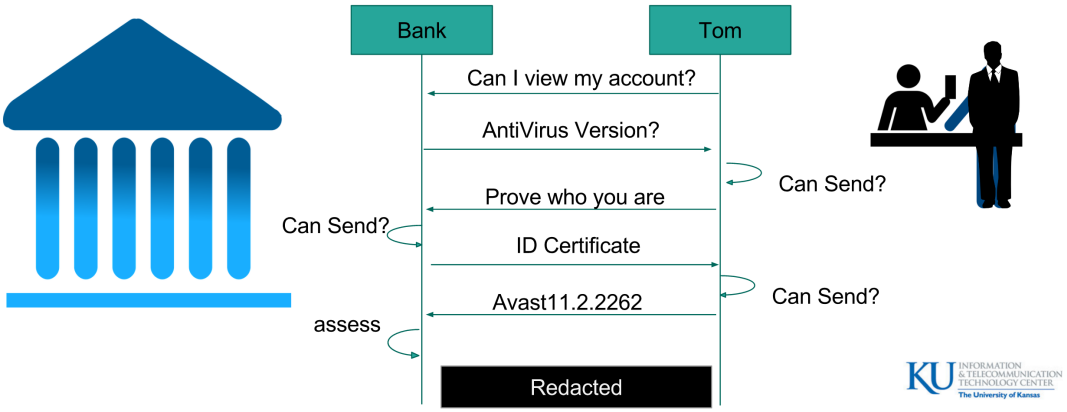


FIGURE 1.4: Example 2 Protocol

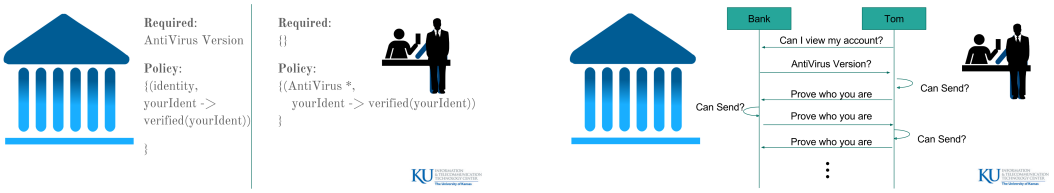


FIGURE 1.5: Infinite Regression

- Accomplish the initial attestation goal,
- Respond to counterattestation requests,
- Avoid *measurement deadlock* scenarios as the one in the previous example,
- Send and receive messages synchronously.

Chapter 2

Remote Attestation Procedure Representation in Coq

We have chosen Coq as our medium to model our protocol and procedure. We will first define a protocol language to represent all possible valid actions an attester or appraiser may take. The chaining together of these actions will constitute a party's *protocol*. We will then examine how each of these statements will be evaluated in what we call *one-sided* evaluation. Later, *Dual evaluation* will be defined to model the evaluation of an Attester and Appraiser's protocols simultaneously. In both cases, evaluation will be modeled via an inductive relation.

The choice to use an induction relation for evaluation as opposed to a computational model is not made lightly. There are a number of benefits and drawbacks to either computational or relational models as discussed in detail by Pierce [5]. In brief, a computational model would directly create runnable pieces of computation. A relational model requires the definition of a relation that maps terms to their simplification. That relation is then used to manually define term evaluations by repeatedly applying mappings from the relation. Though a computational model is simpler to implement, ultimately that benefit does not overcome its Achilles heel–its inability to examine individual terms for theorem proving. Most notably, pattern matching is only possible on inductive types and not possible for blocks of computation. Additionally, experience has shown that a computational representation tends to create incoherent and complex statements that are difficult to maintain. Therefore an inductive representation of evaluation is well worth the cost of having to manually define evaluation. Once a protocol language is defined and one-sided evaluation explored, we can use our protocol language to construct a well-crafted `Statement` we will refer to as a *single step*. The *single-step* protocol encapsulates the proper action for a party to take at each step of the remote attestation process. A

party's entire protocol can then simply be defined as repeating the single-step protocol as many times as necessary. The combination of an Attester and Appraiser each evaluating a sequence of single steps while sharing a network constitutes the entire model of the remote attestation protocol procedure.

2.1 The Protocol Language Definition

The language we have constructed to model a single protocol is defined as an inductive data type below:

```
Inductive Statement :=
  | SendStatement : Term → Participant → Participant → Statement
  | ReceiveStatement : VarID → Statement
  | EffectStatement : Effect → Statement
  | Compute : VarID → Computation → Statement
  | Assignment : VarID → Term → Statement
  | Choose : Condition → Statement → Statement → Statement
  | Chain : Statement → Statement → Statement
  | StopStatement : Statement
  | EndStatement : Statement
  | Skip : Statement
  | Wait : Statement.
```

This abstract syntax encompasses all possible actions that can be performed by one party during a remote attestation. Note that since this language is defined as `Statement` and it will be used to define protocols, we will sometimes use the terms 'Statement' and 'protocol' interchangeably. We will now explain the purpose of each `Statement` constructor.

2.1.1 Network Actions

The semantics of '`SendStatement`' and '`ReceiveStatement`' are relatively straightforward from their nomenclature. These are the only statements whose execution can modify the network state. Construction of a '`SendStatement`' requires three values: a `Term` to send (discussed later), the sender's identity, and the receiver's identity. '`ReceiveStatements`' require nothing more than a variable identifier which will be used to refer to the content of the received message. Later, we will verify that this schema always produces protocol pairs with synchronized sends and receives.

2.1.2 Effectful Statements

An ‘`EffectStatement`‘ is the only statement form allowed to modify the execution environment. The effect type contains the following constructors:

```
Inductive Effect :=
  | effect_StoreRequest : Term → Effect
  | effect_ReduceStatewithMeasurement : Term → Effect
  | effect_ReducePrivacyWithRequest : Term → Effect
  | effect_MvFirstDesire : Effect
  | effect_rmFstQueued : Effect
  | effect_cp_ppUnresolved : Term → Effect
  | effect_setAllGood : AllGood → Effect.
```

A ‘`StoreRequest`‘ modifies the executor’s state, preppending the measurement request to the current request queue. Storing multiple requests in the state at the same time is necessary to support counter-attestations for incremental trust. For example, when an attester responds to a measurement request with a counter-measurement request and receives another measurement request as the response, the attester must remember both of these requests and fulfill them once the prerequisites have been met. The length of this queue is bounded by the total number of possible unique requests. This is due to the fact that we will always reject a measurement request if that measurement request is received twice within one attestation instance. We will discuss this design choice in more detail later.

The ’`ReduceStatewithMeasurement`‘ constructor represents the effectful computation of modifying the executor’s state when the received message is a measurement value. We can then ‘reduce’ our execution environment in the following ways:

- The current list of unresolved requests is simplified with the result. i.e. the request that was sent for that measurement is marked as received. One of two things can happen after receiving a measurement: Either the measurement meets the requirements imposed upon it or it does not. The result of scrutinizing the received value is reduced to setting a Boolean flag in the execution state appropriately named ‘`AllGood`’ which can be set to ‘`Yes`’ or ‘`No`’ depending on if the requirement was met. We will later prove that modification of this flag is not possible by any ‘unauthorized’ `Statements`. This flag is checked by the ‘single-step’ protocol, and an `AllGood` state of `No` will trigger the termination of the remote attestation procedure.

- The privacy policy is reduced. Each remote attestation in which an attester participates begins with a 'fresh' copy of its privacy policy. Throughout the attestation process, the attester may become more willing to share information about itself when more knowledge is gained about the requesting party. Therefore, any privacy policy rules that request the received value for some value's release are lessened or severed depending on if that measurement meets each specified requirement. If the value does not meet the Privacy Rule's Requirement, we indicate that the measurement behind that rule should *never* be revealed should it by chance subsequently be requested. If the requirement is met, we remove that requirement from the rule and replace it with `Free`, simplifying its possible subsequent release.

- The list of measurement requests yet to be requested must also be reduced for the received measurement. It is possible that the value received was in response to a counter attestation which also happens to be an initially desired measurement. For example, an appraiser has the following initial requests $\{A, B, C\}$. The appraiser first sends request A. In response to A, the appraiser does not receive the measurement, but a counter-attestation for measurement X. The appraiser's privacy policy dictates measurement C must be known before releasing X so a counter-*counter* attestation is sent to the attester asking for measurement C. If the attester obliges and sends the value c for request C, not only must we reduce the privacy policy requirement to possibly release X which we must do for the appraiser to receive the initial goal measurement C, but we have received a value that by chance we were going to request anyway. Therefore the requirement in the initial request list imposed by C is also applied to measurement c and C is removed from our list of measurements to request.

  Not only does the above save time, but is required by our schema to maintain satisfiable protocols. A simple way to avoid Measurement Deadlock is for each party to always deny multiple requests for the same measurement should it occur more than once in a remote attestation session. Therefore, each party should ensure that they only request measurements as few times as possible.

The '`ReducePrivacyWithRequest`' statement will amend the executor's privacy policy such that should the received request be received again later, it will immediately be denied. The single step protocol executes this statement when fulfilling a request. This prevents 'Measurement Deadlock' cycles from occurring. Note that when a party receives a measurement value, the *entire* execution state is reduced including any potential privacy policy requirements in addition to pending requests of the other party. This ensures that a party will not request measurements more times than necessary.

'MvFirstDesire' is called after a measurement request is sent. The effect is simply to move the request from the toRequest list into the unresolved requests list.

'cp_ppUnresolved' represents the effect when a received measurement request cannot be fulfilled without the success of a counter measurement request as indicated by the privacy policy. In this case, the needed measurement request is simply added to the toRequest list.

'**setAllGood**' is used throughout the one-step protocol to indicate success or failure of the current branch.

2.1.3 Computations

Computations are encapsulated within this Statement type. Note that they do not effect the state other than bringing a variable into scope. The possible computations are defined as follows:

```
Inductive Computation :=
  | compGetMessageToSend
  | compGetNextRequest
  | compGetfstQueue.
```

'compGetMessageToSend' will perform the requested measurement. 'compGetNextRequest' can simply be thought of as a getter which returns the next measurement to request from the other party. Similarly, 'compGetfstQueue' is simply a getter for the first stored measurement request received in the executor's state.

2.1.4 Assignment

Occasionally, a 'vanilla' assignment may be needed which this statement provides. In subsequent statements wherever VarID occurs, the value that Term simplified to at the time of assignment is used. This is commonly referred to as Pass by Value.

2.1.5 Choose

This is our one and only branching construct. Upon evaluation of the Condition expression under the current state, either the first Statement is executed or the second. The following are the possible Condition expressions along with a brief description of their purpose.

```
Inductive Condition :=
 | IsMyTurntoSend : Condition -queries the state for the current action:  send or receive.
 | QueuedRequestsExist : Condition -queries the state for any queued requests from another entity.
 | ExistsNextDesire : Condition -queries the state for measurements that still need to be requested.
 | CanSend : Condition -queries the privacy policy for if the currently requested measurement can be revealed.
 | IsMeasurement : Term → Condition -checks if the given Term under the current state evaluates to a measurement value.
 | IsRequest : Term → Condition -checks if the given Term under the current state evaluates to a measurement request.
 | IsStop : Term → Condition -checks if the given Term under the current state evaluates to Stop message.
 | IsAllGood : Condition. -queries the state for AllGood flag that is set by the previous execution of single step.  For example, if an unacceptable measurement value is received, this flag indicates to the next execution of single step to signal attestation termination to the other party.
```

2.1.6 Chain

`Statements` can be sequenced into a new `Statement`. For example, if X, Y, and Z, are `Statements`, we can sequence them into a single statement using the chain C `Statement`. $S \rightarrow C;\rightarrow S;S;\rightarrow X;S;\rightarrow X;C;\rightarrow X;S;S;\rightarrow X;Y;S;->X;Y;Z;$.

2.1.7 Termination

Termination is indicated by both the `StopStatement` and the `EndStatement`. `StopStatement` indicates the early termination of the protocol due to a measurement request being denied or a requirement not being met. A `StopStatement` is also sent by the Appraiser to indicate no further requests are needed. The `EndStatement` indicates that there is simply no more protocol to run. The distinction is important when defining how to append two protocols into a single protocol. Branches that end in `StopStatement` are not appended to, only `EndStatements`.

2.1.8 Skip

`Skip` has no clear purpose until we focus on the evaluation of protocols. We use `Skip` to indicate successful execution of a statement. This is necessary since our evaluation relation will be from `Statement*State` $\rightarrow$ `Statement*State` which differs from the more common evaluation of `Statement` $\rightarrow$ `State`. The reason for this difference should become clear later and is necessary to include a network in our model.

2.1.9 Wait

It is possible that a `Receive` statement will not succeed (that is, evaluate to a `Skip`) if no message is present in the network. It is for this reason that evaluation leads to another statement rather than solely a new state. When a `Receive` is encountered with no corresponding message present in the network, a `Wait` Statement is prepended onto our statement chain which can only be removed by an evaluation rule which ensures the presence of a message. We will provide two evaluation relations: a one-sided evaluation relation which will simplify a `Statement` chain as far as it can, i.e. until an `End`, `Stop`, or `Wait`. We will also need a "larger" dual-sided evaluation relation to simplify both the Attester and Appraiser protocols along with a network. We will call the "large" evaluation relation `DualEval`. `DualEval` will mimic parallel, isolated execution by alternating execution between sides of the protocol when a `Stop`, `End`, or `Wait` is encountered. We will later prove that our method of generating Statements for our protocol will never end in a party waiting for a message. We will always end with both parties at one of `StopStatement` or `EndStatement`.

2.2 One sided Evaluation

Now that we have discussed the purpose of each statement, we will now view in more detail how these statements are evaluated in the one-sided evaluation. For brevity, we will refer to the statements `SendStatement`, `ReceiveStatement`, `StopStatement`, and `EndStatement` as `Send`, `Receive`, `Stop`, and `End` respectively.

2.2.1 Chaining

Perhaps most importantly we need to define how a chain is evaluated. The following rule defines how a sequence of statements is simplified. We will then explore how each

non-compound `Statement` is evaluated.

$$\frac{(stm1, st, n) \Rightarrow (Skip, st', n')}{(stm1 \gg stm2, st, n) \Rightarrow (stm2, st', n')} \quad \text{(EvalChain)}$$

The above notation to states, "Given $stm1$ under state st and network n evaluates ($\Rightarrow$) to $Skip$ with state st' and network n', then the chain of statements $stm1 \gg stm2$ under st and n evaluates to $stm2, st', n'$. We ensure that previous command succeeds before evaluating the next statement and propagate the new executor state and network. It is possible that evaluation of $Stm1$ does not evaluate so nicely. In this case we circumvent execution of the remainder of the chain with the following rule.

$$\frac{(stm1, st, n) \Rightarrow (Stop, st', n')}{(stm1 \gg stm2, st, n) \Rightarrow (Stop, st', n')} \quad \text{(EvalChainBad)}$$

If $stm1$ evaluates to a bad state indicated by `Stop`, any statements that were to follow $stm1$ are removed and not evaluated. `Stop` has no further evaluation rules and evaluation ends.

2.2.2 Send

We have two rules for evaluating a send. The following applies to sending any message other than a `StopMessage` abbreviated to `Stop`:

$$\frac{st[t \mapsto c] \wedge c \neq Stop}{(Send\ t, st, n) \Rightarrow (Skip, st, (c :: n))} \quad \text{(EvalSend)}$$

Sending a **Stop** is handled in the following rule:

$$\frac{st[t \mapsto c] \wedge c = Stop}{(Send\ t, st, n) \Rightarrow (Stop, st, (c :: n))} \quad \text{(EvalSendStop)}$$

With *EvalSendStop*, we prevent anyone from sending a `Stop` unless they plan on immediately stopping. In this way we can easily guarantee that the other side has stopped if one side receives a `Stop`. By choosing a relational model and encoding this requirement in the evaluation, we essentially get this proof for free since it is impossible to send a `Stop` (that is to evaluate a `Send Stop`) without immediately stopping oneself. There is only one rule which handles sending a stop, and it forces the evaluated term into a `Stop`. Note also that in both evaluation rules for `Send`, the state remains unmodified.

2.2.3 Receive

`Receive` has three evaluation rules. We use the function $\rho(n, st)$ to denote a message for an entity with state st on network n.

Like the `Send` evaluation rules, we have a special case for receiving a `Stop`. If the network provides a `Stop` message, a `Receive` evaluates to a `Stop` statement such that the state is only modified with the special variable R, the most recently received message, set to `Stop`. Forcing entities to stop after sending a stop and forcing entities to stop after receiving a stop will help us prove that entities walking through single-steps during remote attestation will always remain in sync. That is to say, no party will execute a `Send` without the other executing a `Receive` and vise versa. Note that the network is untouched other than the message being removed.

$$\frac{\rho(n, st) = Stop}{(Receive\ v, st, n) \Rightarrow (Stop, st[R \mapsto Stop], n - \rho(n, st))} \quad \text{(EvalReceiveStop)}$$

If a `Receive` is encountered before a message exists on the network for the participant, a `Wait` is inserted. Why not insert a `Wait` every time a `Receive` is encountered? Progress would never be made. A `Receive` becomes a `Wait >> Receive` which would reduce to `Receive` which once again evaluates to `Wait >> Receive`. Why not evaluate `Wait >> Receive` in its entirety? This makes our protocol language contextual, which we certainly do not want. Why not evaluate to something like `ReceivePending` instead of inserting a `Wait`? This a design choice. Rather than re-implement (or copy and paste) the definition for receiving a message to evaluate a `ReceivePending` statement, that logic exists already for evaluating `Receive`. Additionally, we would then have to prove that `Receive` and `ReceivePending` behave the same when a message is present. This burden is avoided by introducing a new statement `Wait` which encapsulates the single action of waiting while `Receive` encapsulates the single action of consuming a message. The important part is that there is some indication that `Receive` cannot receive just yet. In `DualEvaluation`, one party encountering a `Wait` indicates that we must evaluate the other party's protocol before evaluating further. In real life, `Receive`s would be implemented with timeouts, and both parties are evaluating their protocols simultaneously. However, to prove the properties we desire, we have to simulate this simultaneous evaluation within the Coq environment in a single thread by bouncing back and forth between evaluating protocol sides.

$$\frac{\rho(n, st) = \bot}{(Receive\ v, st, n) \Rightarrow (Wait >> Receive\ v, st, n)} \quad \text{(EvalReceiveWait)}$$

The above rule is yet another example for why a relational definition is preferred to the computational definition. Coq requires proof of termination for every functional definition. A functional definition of *eval* described thus far would be a significant burden on the designer since in the `Receive` case, the fix-point argument can actually *grow*. Such a definition is not impossible, but requires a lengthy manual proof to establish termination. This option was explored when modeling computationally, but was never completed before the switch to a relational model was made. Perhaps in the future, Coq will be able to deduce proof of termination from non-trivially reducing arguments. In the meantime, it is only for the truly desperate.

Finally in all other cases, we receive as normal.

$$\frac{\rho(n, st) = m}{(Receive\ v, st, n) \Rightarrow (Skip, st[R \mapsto m], n - \rho(n, st))} \quad \text{(EvalReceive)}$$

2.2.4 Wait

As stated, a `Wait` can be removed once a message is ready to be received. The state and network are preserved.

$$\frac{\rho(n, st) = m}{(Wait, st, n) \Rightarrow (Skip, st, n)} \quad \text{(EvalWait)}$$

Since evaluation is defined manually, we also need a case for propagating a `Wait` in a `Chain`. Recall that terms are evaluated individually so a single `Receive` becomes `Wait` >> `Receive`. We need a rule which takes an entire statement chain that began with a `Receive` and inserts the `Wait` to it as well.

$$\frac{(Stm1, st, n) \Rightarrow (Wait \gg Stm1, st', n')}{(Stm1 \gg Stm2, st, n) \Rightarrow (Wait \gg Stm1 \gg Stm2, st', n')} \quad \text{(EvalWait)}$$

The above rule states that if any statement $Stm1$ is prepended with a `Wait` and $Stm1$ occurs at the beginning of a Chain, then the entire new Chain is prepended with a `Wait`. Note that $Stm1$ could be a simple `Receive` statement or an arbitrarily long Chain that begins with a `Receive`. We know that it begins with a Receive because a `Wait` is inserted at the beginning, and evaluating a `Receive` is the only source of the `Wait` statement.

2.2.5 Effect

If an effect e modifies the state st into st', then an `Effect` evaluates into a `Skip` with the modified stated. $modify$ always succeeds so the prerequisite for EvalEffect is always met.

$$\frac{modify(st, e) = st'}{(EffectStatement\ e, st, n) \Rightarrow (Skip, st', n)} \quad \text{(EvalEffect)}$$

2.2.6 Compute

If a term t computes to constant c under state st, then a `Compute v t` statement evaluates to a `Skip`. Note that the state is unchanged other than looking up variable v will now return constant c.

$$\frac{compute(st, t) = c}{(Compute\ v\ t, st, n) \Rightarrow (Skip, st[v \mapsto c], n)} \quad \text{(EvalCompute)}$$

2.2.7 Assignment

Assignment is similar to `Compute` but the term is restricted to being only a constant or variable identifier. An `Assignment` can be used to store the result of a computation in multiple variable names. If a term t computes to constant c under state st, then an `Assignment v t` statement evaluates to a `Skip`. Note that the state is unchanged other than looking up variable v will now return constant c.

$$\frac{compute(st, t) = c}{(Assignment\ v\ t, st, n) \Rightarrow (Skip, st[v \mapsto c], n)} \quad \text{(EvalAssign)}$$

2.2.8 Choose

If a conditional expression c evaluates to $True$, `Choose c stm1 stm2` evaluates to `stm1`.

$$\frac{conditionEval(st, c) = True}{(Choose\ c\ stm1\ stm2, st, n) \Rightarrow (stm1, st, n)} \quad \text{(EvalChooseTrue)}$$

A similar rule exists for when the conditional evaluates to $False$.

$$\frac{conditionEval(st, c) = False}{(Choose\ c\ stm1\ stm2, st, n) \Rightarrow (stm2, st, n)} \quad \text{(EvalChooseFalse)}$$

Thus concludes our evaluation rules for the protocol language.

2.3 Attestation Protocol

Protocols are constructed by repeating a sequence of one-step protocols. We will define our attestation protocol by first defining what it means for one party to take one step. This attestation one step is not to be confused with small step semantics. One attestation protocol step is progress made by an attestation participant by completing one network action.

2.3.1 One Step

A single step denotes a single network action of `Send` or `Receive` in addition to any computation or effects needed. By composing our protocols this way, we can prove that adjacent steps always alternate between sending and receiving unless sending or receiving a **Stop** in which case we terminate. Therefore, if both participants' protocols are composed of nothing other than single steps and one party initially sends and the other receives, all possible protocols will line up. We will explore this proof later.

The first `Statement` in a one-step is a `Choose` which examines the state to see if the intention of the current step is to send or to receive. Initially, the appraiser will send the first message containing the first measurement request. The target's first step is to receive. This can be accomplished by every party running a server that listens for attestation requests. For a party to move from one step to the next, it is required that the action to perform in the state (send or receive) is flipped except in the cases of sending or receiving a **Stop** in which case no further actions are taken.

Sending State If the state tells us we must send, we will send *something*. The first action is to check if we have any current measurement requests queued up that we have yet to fulfill. If there is at least one, we check if we can answer the measurement request under our current privacy policy. If we can, we will preform the measurement and send it, completing the single step. There are two cases for which a privacy policy would not, at the time of request, allow a measurement to be taken: reconcilable and irreconcilable. The measurement request is irreconcilable if there is no level of trust which would allow the desired measurement to be taken and sent. The initial privacy policy could have forbade revealing said measurement, or revealing the measurement is not allowed because the simplification of that entry of the privacy policy with an earlier received measurement value forbids it. If we are irreconcilable, we send a `Stop` since the request in unfulfillable. Otherwise, we respond with a measurement request that when resolved could soften our privacy policy to reveal the initially requested value. If no current requirement exists for the requested measurement, the value can be sent directly.

We have now answered what we will send under all subcases of having a measurement request queued in the state. If there are no pending requests, we check our own list of desired measurements to see if there is anything more we would like to request of the other party. If there are no more, we send `Stop` to indicate that we are done. Otherwise, we make the request and remove it from our list.

The above case of sending a `Stop` may at first seem troubling since it appears that the target could short-circuit the attestation session by sending a **Stop** when it is its turn to

send and there are no more requests to fulfill or make. Though we can be sure that this will never happen from the following argument. The only difference we specify between an Attester and Appraiser is that (a) the Appraiser initiates the conversation by sending the first measurement request, and (b) the Attester has no initial measurement desires. Therefore, we know at least for the first message, the attester has a pending request in its state when sending. The attester will then either respond with the measurement or a counter request. If the measurement is sent, the appraiser will either send a `Stop` because they are done or a new measurement request. If a `Stop` is sent, attestation is over. If a new measurement request is sent, the attester will once again have a pending measurement request in its state. If the attester does not send the measurement but instead sends a counter-request, the pending request remains in its state. Therefore, a target is forever responding with measurement values or measurement requests from the privacy policy in effort to release requested measurements. An attester's state always contains at least one pending request from the appraiser otherwise the attestation session would have been ended by the appraiser by now.

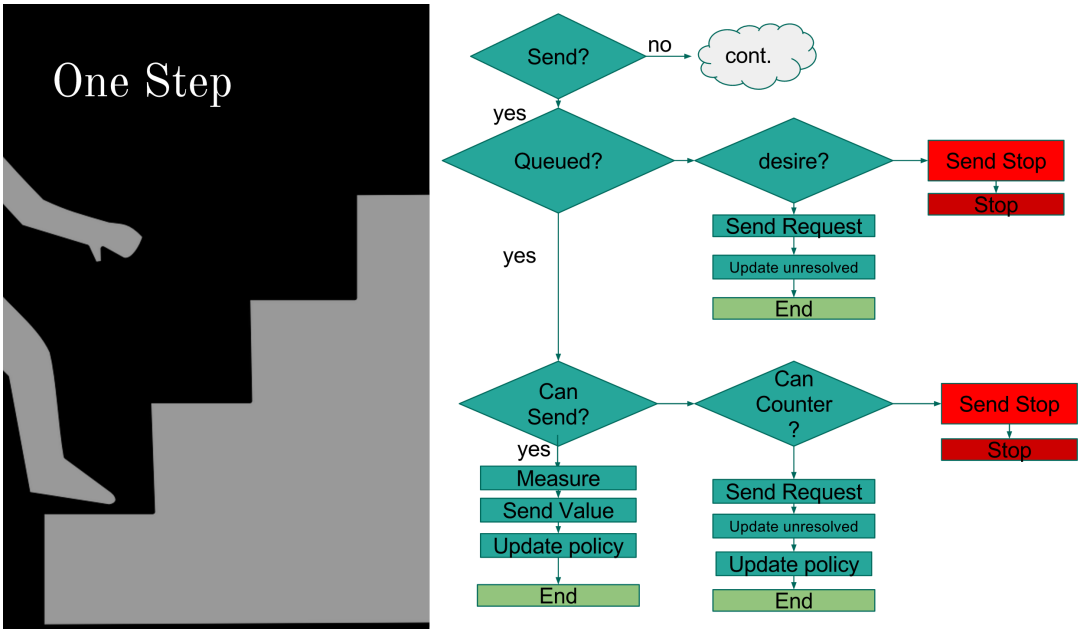


FIGURE 2.1: Control flow when a one-step protocol sends

Receiving State The execution path taken if we are to receive depends on the contents of the message. There are only three possibilities: a measurement value, a measurement request, or a stop message was received. If we receive a measurement value we reduce our state in two ways as seen in section 2.1.2, namely `ReduceStatewithMeasurement`.

First, we reduce our own pending requests of the other party. If the measurement does not meet our specified requirement, we modify our state to trigger a `Stop` message in the next step to end the attestation session. The justification for this is as follows. If we

receive a measurement value, it is in response to requesting it. The two ways we could have requested it are (a) it was part of our initial desires as an appraiser or (b) as a counter request in response to some number of steps ago an initial request. In either case if the measurement value does not satisfy the condition attached to it, an initial desire of the appraiser is unsatisfiable and attestation terminates.

The second state reduction is to search our privacy policy for any requirements containing this measurement and apply the value. For example, privacy policy entries are of the form $M : M', R(v : M')$. M is the protected value, M' is the value that first must be known of the requester before revealing measurements of type M, and R is the requirement that the value of an M' measurement must meet in order to reveal M. For all entries for which the received measurement v has type M', the entry is reduced to either $M : FREE$ or $M : NEVER$ depending on if v satisfied requirement R. We do this reduction now instead of requesting the measurement M' if M is requested for 2 reasons. 1) We may end up requesting the same measurement M' many times if it is a requirement in a privacy policy for many measurement values, wasting time and network resources. 2) To avoid measurement deadlocks, executors of this protocol schema will reject measurement requests if they appear a second time in a remote attestation. Therefore, an attestation participant must take full advantage of learning a measurement value to avoid needing to request it a second time.

We should address the possibility that an Appraiser is flexible and wants to know just one of several measurements which is not handled by the above short circuiting action which would end in mutual termination. An 'or' may very well be needed, and the solution is simple. Each set of measurements desired by the appraiser logically separated by an 'or' are each split up into their own sub-attestation protocol session instances. Then at a higher level, we can evaluate the satisfaction of one of them. Therefore, it is useful that this attestation protocol indicates the satisfiablilty of the initial requests as a whole.

If the message we receive is a measurement request, we store it in the state for the subsequent `Send` step to handle. In the last case that we have received a `StopMessage`, we stop– an indication that the appraiser has all the information desired or an indication that the other party has determined this session is unsatisfiable either due to (a) a request is unsatisfiable, or (b) a measurement value was unsatisfactory.

The entire unfolded definition of one step written in our protocol EDSL can be seen in listing 2.1. However, the control flow is probably best understood by examining figures 2.1 and 2.2 as well as the aforementioned sending and receiving states. Note that a single-step protocol is constructed from a state argument. In this way, a participant constructs a new step from their old state each time the previous single-step evaluated in an `End`.

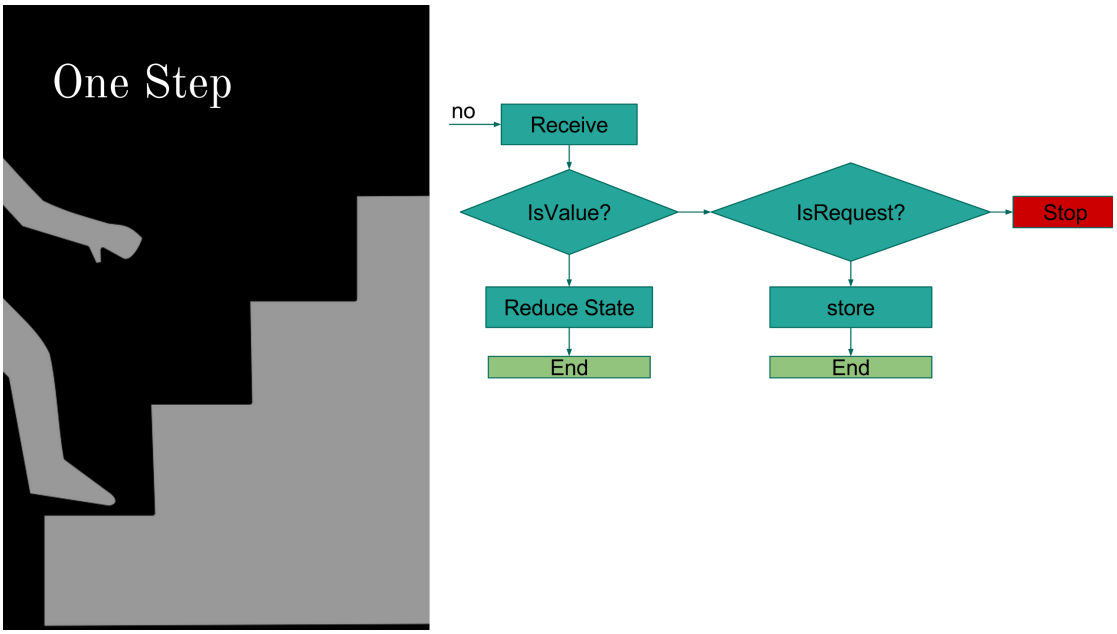


FIGURE 2.2: Receiving step continued from previous

```
Definition OneProtocolStep (st : State) : Statement :=
IFS IsMyTurntoSend THEN
  IFS IsAllGood THEN
    EffectStatement (effect_setAllGood Unset) >>
    IFS QueuedRequestsExist THEN
      IFS CanSend THEN
        Compute toSendMESSAGE compGetMessageToSend >>
        SendStatement (variable toSendMESSAGE) (getMe st) (notMe (getMe st)) >>
        Compute (variden 1) compGetfstQueue >>
        EffectStatement (effect_ReducePrivacyWithRequest (variable (variden 1))) >>
        EffectStatement effect_rmFstQueued >>
        EffectStatement (effect_setAllGood Yes) >> (*all good here! *)
        EndStatement
      ELSE (*Can't send and queued request exists *)
        EffectStatement (effect_setAllGood No) >> (* no, this is bad! *)
        SendStatement (const constStop) (getMe st) (notMe (getMe st)) >>
        StopStatement (*Give up!*)
    ELSE (*No queued up things for me. So I can continue down my list of things I want. *)
      IFS ExistsNextDesire THEN
        Compute toSendMESSAGE compGetNextRequest >>
        EffectStatement effect_MvFirstDesire >>
        SendStatement (variable toSendMESSAGE) (getMe st) (notMe (getMe st)) >>
        EffectStatement (effect_setAllGood Yes) >>
        EndStatement
      ELSE (* I must send, nothin queued, nothin left I want, quit! *)
        EffectStatement (effect_setAllGood Yes) >> (*all is well, just out! *)
        SendStatement (const constStop) (getMe st) (notMe (getMe st)) >>
        StopStatement
  ELSE
    SendStatement (const constStop) (getMe st) (notMe (getMe st)) >>
    StopStatement
ELSE
```

```
ReceiveStatement (receivedMESSAGE) >>
IFS (IsMeasurement (variable (receivedMESSAGE))) THEN
  EffectStatement (effect_ReduceStatewithMeasurement (variable (receivedMESSAGE)) ) >>
  EndStatement
ELSE
  IFS (IsRequest (variable (receivedMESSAGE))) THEN
    EffectStatement (effect_StoreRequest (variable (receivedMESSAGE))) >> EndStatement
  ELSE (*we must have received a stop *)
    StopStatement.
```

Listing 2.1: One Step

The following properties ensure that step repeating is always valid. 'Valid' in this context means that no party sends a message out of turn or attempts to receive more or fewer messages than will be sent.

- A *OneProtocolStep* will always perform exactly one send or exactly one receive. A formal proof of this can be found in the next section.
- For a remote attestation, the appraiser sends the first message. That is to say, the appraiser's first single-step is to send, while the attester's is to receive. The first step of both parties line up.
- A new step is only created if the previous step ended in a good state. Recall `End` is a good terminator and `Stop` is our bad/abrupt terminator.
- The only way for *OneProtocolStep* to end with a `Stop` instead of an `End` is either
  - a `Stop` was sent
  - a `Stop` was received.
- Every time a party creates a new step, the network action to take is flipped from the previous step's state.
- If a `Stop` is sent, the sender does not create a new step because `Send Stop` evaluates to a `Stop` as enforced by the evaluation rule *EvalSendStop*.
- If a `Stop` is received, the receiver does not create a new step because `Receive Stop` evaluates to a `Stop` as enforced by the evaluation rule *EvalReceiveStop*.
- It is impossible for the two parties to get out of step since each step is not computed until the previous completes and with the previous' result. That is to say, if a party sends any message other than `Stop`, it will always create a next step which receives. It cannot work ahead because all further action depends on the value of the message received. If a party receives any message other than `Stop`, it will always switch to send. The farthest two parties could get out of sync is an attempt to receive

before a send from the other party. This scenario is safely captured by the *Wait* evaluation rules.

2.3.2 Correctness of a Single Step

We will now discuss in more detail the correctness of the *OneProtocolStep*. Absolute correctness is hard to even define–what does it mean to be correct? Therefore when verifying a system's correctness, many smaller properties are verified which make the system's absolute correctness highly likely. In this fashion, there are particular properties about our model for which we can prove correctness and gain a higher confidence in the model's overall correctness.

2.3.2.1 Language Properties

Before we examine the correctness of *OneProtocolStep*, we will first examine more general properties about the language and evaluation rules used to define it.

We can formally prove that **Effect** Statements are the only statements which modify the execution state. More formally, we state this as

```
Theorem thm_onlyEffect_effects : ∀ (stm stm': Statement) (st st': State)
(n n' : Network),
 (stm,st,n) ⇒ (stm',st',n') →
 getProState st = getProState st' ∨ ∃ e, (headStatement stm) = EffectStatement
e.
```

getProState is an accessor so that we ignore any particular execution variable differences. In all cases, either the state remains unchanged, or the very first statement was an `Effect`. The full proof, along with all full proofs for formal proof listed here, can be viewed in the git repository [6].

In a similar fashion, we can prove that `Send` and `Receive` Statements are the only Statements which affect the network.

```
Theorem thm_onlySendOrReceiveChangesNetwork : ∀ (stm stm': Statement) (st
st': State) (n n' : Network),
 (stm,st,n) ⇒ (stm',st',n') →
 n = n' ∨
 (∃ t p1 p2, headStatement stm = SendStatement t p1 p2) ∨
```

```
(∃ vid, headStatement stm = ReceiveStatement vid)
.
```

Either the networks are identical or a **Send** or **Receive** occurred.

We will not list all proofs here and now shift our attention to verifying properties about the single-step protocol. A full list of formal proofs can be viewed in appendix B.

2.3.2.2 Single Step Properties

We have claimed that each side of our one-step will always line up. We now prove this formally. We begin by defining methods for counting the maximum and minimum number of network actions taken by a statement in our language.

```
Fixpoint countMaxNetworkActions (stm : Statement) : nat :=
match stm with
 | SendStatement x x0 x1 ⇒ 1
 | ReceiveStatement x ⇒ 1
 | Choose x x0 x1 ⇒ max (countMaxNetworkActions x0) (countMaxNet-
workActions x1)
 | Chain x x0 ⇒ (countMaxNetworkActions x) + (countMaxNetworkAc-
tions x0)
 | _ ⇒ 0
end.
```

countMinNetworksActions is defined similarly.

We then show that the maximum actions for *OneProtocolStep* is equal to the minimum is equal to 1.

```
Lemma onestepProtocolmaxAction_eq_minAction : ∀ st,
countMinNetworkActions (OneProtocolStep st) = (countMaxNetworkAc-
tions (OneProtocolStep st)).
Theorem onestepProtocolmaxAction_eq_1 : ∀ st,
(countMaxNetworkActions (OneProtocolStep st)) = 1.
```

We would like to speak more specifically about the network action being taken. For example that the action is `Send`. We can define functions that count only sends and only receives. Using these, we can define an inductive type which certifies a particular

statement to perform precisely one network action of either send or receive throughout all possible branches.

```
Inductive SingularNetworkAction :Statement → Action → Prop :=
 | s_Send (stm :  Statement):  (countMaxReceives stm) = 0 ∧
                               (countMinSends stm) = 1 ∧
                               (countMaxSends stm) = 1 → Singular-
NetworkAction stm ASend
 | s_Receive (stm :  Statement):  (countMaxSends stm) = 0 ∧
                               (countMinReceives stm) = 1 ∧
                               (countMaxReceives stm) = 1 → Singu-
larNetworkAction stm AReceive.
```

This new inductive proposition allows us to state our proofs clearly.

```
Theorem oneStepSend :  ∀ st stm' n,
 evalChoose IsMyTurntoSend st = true →
 (OneProtocolStep st, st, n) ⇒ (stm', st, n) →
 SingularNetworkAction stm' ASend.

Theorem oneStepReceives :  ∀ st stm' n,
 evalChoose IsMyTurntoSend st = false →
 (OneProtocolStep st, st, n) ⇒ (stm', st, n) →
 SingularNetworkAction stm' AReceive.
```

We would like to formally prove that a single-step which receives will always end in a good state so long as the message was not a `Stop`. We introduce the notation $\Rightarrow^*$ to denote multistep evaluation of a `Statement`.

```
Theorem thm_receiveAlwaysFinishes :  ∀ vars prst n m n', evalChoose IsMyTurn-
toSend (state vars prst) = false →
 receiveN n (getMe (state vars prst)) = Some (m, n') →
 m ≠ constStop → ∃ prst',
 (OneProtocolStep (state vars prst), (state vars prst), n) ⇒* (EndStatement,
(state ((receivedMESSAGE,m)::vars) prst'), n').
```

In all cases that we receive a `Stop`, we will stop.

```
Theorem thm_oneStepProtoStopsWhenTold :∀ v p n n', evalChoose IsMyTurntoSend (state
v p) = false →
receiveN n (getMe (state v p)) = Some (constStop, n') →
```

((OneProtocolStep (state v p) , (state v p), n) $\Rightarrow^*$ (StopStatement, assign receivedMESSAGE constStop (state v p), n')) .

We have mentioned that a simple solution to avoid measurement deadlock is to simply remove items from one's privacy policy as they are requested. If there is no rule for a measurement, it is always denied. Recall that each attestation session begins with a 'fresh' version of the executors privacy policy. By learning things about the requester, a privacy policy can become more relaxed. Removing an item, if present, from the privacy policy after it is requested ensures that the second time a measurement is requested, the request is denied. *handleRequestST* is the function encapsulating this functionality. It modifies the privacy policy in the returned state to no longer contain an entry for the requested item description d. The fact that $findAndMeasureItem$ returns `None` is indicative of the fact that once a request has been handled, additional measuring is not allowed by the privacy policy.

```
Theorem thm_isRemovedFromPrivacyhandleST : ∀ st d,
findandMeasureItem (getPrivacy (handleRequestST st d)) d = None.
```

Another property we would like to formally prove is that we never send a measurement value without permission from the privacy policy. An exact formal proof of this is elusive. The difficulty stems from the fact the privacy policy check must occur in a Choose Statement that is "far away" from the actual send. Some simple proofs are difficult in proof assistants. Though we make the correctness argument below.

- Recall within the definition of *OneProtocolStep*:

```
IFS CanSend THEN
        Compute toSendMESSAGE compGetMessageToSend >>
        SendStatement (variable toSendMESSAGE) (getMe st) (notMe (getMe st)) >>
        Compute (variden 1) compGetfstQueue >>
        EffectStatement (effect_ReducePrivacyWithRequest (variable (variden 1))) >>
        EffectStatement effect_rmFstQueued >>
        EffectStatement (effect_setAllGood Yes) >> (*all good here! *)
        EndStatement
```

- *CanSend*'s evaluation performs the privacy policy check which we wish to associate with sending the associated measurement.
- Within this if branch is the only occurrence of *compGetMessageToSend* which performs the measurement.
- Therefore, the only way to send a measurement value is if the privacy policy has first allowed it to be measured.

We have so far discussed only one-sided evaluation. In the next section we examine how both sides of the protocol procedure can be evaluated.

2.4 Dual Evaluation

The Dual Evaluation rules dictate how both sides of the protocol can be executed in tandem. In brief, we model the simultaneous execution of protocols by alternating a one-step evaluation as far as possible and then switching, repeating until both sides arrive at the `Stop` state. We will use the notation $\Big(\big[stmL, stL\big], \big[stmR, stR\big], n\Big) \Rrightarrow \Big(\big[stmL', stL'\big], \big[stmR', stR'\big], n'\Big)$ to denote that the left participant's statement chain $stmL$, state stL; right participant's statement chain $stmR$, state stR; both under network n evaluate to left participant's statement chain $stmL'$, state stL'; right participants statement chain $stmR'$, state stR'; and new network n'.

2.4.1 Stepping

$$\frac{(stmL, stL, n) \Rightarrow^* (End, stL', n')}{\Big(\big[stmL, stL\big], \big[stmR, stR\big], n\Big) \Rrightarrow \Big(\big[oneStep(r(stL')), r(stL')\big], \big[stmR, stR\big], n'\Big)} \text{(DualLeft)}$$

If the left side of the protocol multi-steps to an `End` then the pair evaluates to the left side starting a new step with the network action reversed and resultant network. We have a symmetric rule DualRight for evaluating the right side.

2.4.2 Stopping

The only way for two valid protocols to complete is if both sides do so simultaneously. That is to say that the total network actions taken by each side are the same and the final network is empty. We have already established that one party sending a **Stop** will result in both parties stopping.

$$\frac{(stmL, stL, n) \Rightarrow^* (Stop, stL', n') \wedge (stmR, stR, n') \Rightarrow^* (Stop, stR', n'')}{\Big(\big[stmL, stL\big], \big[stmR, stR\big], n\Big) \Rrightarrow \Big(\big[Stop, stL'\big], \big[Stop, stR'\big], n''\Big)} \text{(DualStopLeft)}$$

Again, we have a dual for this rule where the right side finishes first and passes the network for the left side to finish. Every Remote Attestation/Dual Evaluation will end by a party sending a `Stop` message. Recall that a `Stop` is sent in response to one of the following state conditions:

- A measurement value m_{v1} has been received that does not meet its associated requirement, req_m_{v1}. This requirement arrived in our state in one of two ways:
  - req_m_{v1} was attached to a measurement in the initial list of desired measurements. Therefore, the entity is the Appraiser and has learned enough negative information about the target to end Remote Attestation.

– A measurement request for m_{v0} was initially made, but the entity's privacy policy dictated that the value could not be released until m_{v1} is known from the opposite party and meets requirement req_m_{v1}. Note that it makes no difference if m_{v0} was requested initially or as a counter request itself. In either case, failure to meet the requirement propagates into failure of a requirement on an initial request or failure of a requirement that would eventually lead to the release of an initially requested measurement value.

In either case, the Remote Attestation session terminates.

- The current pending request in the execution environment would irreconcilably violate the privacy policy.
- Finally, if the single-step's action is to send, yet there are no pending measurement requests to fulfill nor measurement requests to send, a `Stop` is sent to indicate termination (see One-step figure above). This could only be the Appraiser. We have already discussed that the Attesting party will always have something to send, otherwise attestation would have ended before that point.

Therefore, simultaneous **Stop**s is the only valid termination of Dual Evaluation.

2.4.3 Waiting

The rules `DualLeft` and `DualRight` do not address potentially valid evaluations that result in prepending a `Wait` to the protocol. Therefore we must have additional rules to eliminate `Wait`s. The following rule states that if the multi-step evaluation of the left side protocol results in network n' and some Statement prepended with `Wait`, and the right side protocol, under the resultant n' network, multi-steps to an `End` resulting in network n'', then our Dual evaluates to the result from the left side sans `Wait` and the right takes another step while reversing its network action. A symmetric rule exists for the right side.

$$\frac{(stmL, stL, n) \Rightarrow^* (Wait >> stL', stL', n') \wedge (stmR, stR, n') \Rightarrow^* (End, stR', n'')}{\Big(\big[stmL, stL\big], \big[stmR, stR\big], n\Big) \Rrightarrow \Big(\big[stmL', stL'\big], \big[oneStep(r(stmR')), stR'\big], n''\Big)} \text{(DualWaitLeft)}$$

At first examination, these wait rules may appear to let the protocols become out of sync since the right side takes another step before the left side has finished the previous. Before we discuss the rule's validity, we must first introduce the two other Dual Wait

rules we have so we can reference them.

$$\frac{(stmL, stL, n) \Rightarrow^* (Wait >> stL', stL', n') \wedge (stmR, stR, n') \Rightarrow^* (Stop, stR', n'')}{\Big(\big[stmL, stL\big], \big[stmR, stR\big], n\Big) \Rrightarrow \Big(\big[stmL', stL'\big], \big[Stop, stR'\big], n''\Big)}$$

(DualWaitLeftStopRight)

As always, there is a right version of this rule as well. We may wish to add another Dual Stop Evaluation rule to avoiding having to make the following progress-less evaluation valid: $(Stop, st, n) \Rightarrow^* (Stop, st, n)$

We know that the DualWaitLeft/Right rules are valid in creating another single step from the following argument.

- We can assume that the very first statements created were done so using the *oneStep* constructor.
- One protocol's first action will be to send and the other will receive.
- We assume that our protocols are in sync up to this point (inductive argument).
- A `Wait` is only inserted on a receiving action. Therefore since the protocols are in sync, the right side will send a message on the network. Recall that we have proved one steps will always perform exactly one network action.
- Since we know that the right side has ended in a good state by evaluating to `End` and not `Stop`, we know that the right side has not sent a `Stop` message. Sending a `Stop` would trigger the other side to stop and take no more steps.
- Therefore, we know the left side will at least send one more message since worst case scenario will send a `Stop` message, and the right side is safe to take another step which will receive.

However, this doesn't appear to address the out-of-step issue in full. We have only proved that `Wait` evaluation rules will not create two protocol sides with differing numbers of network actions. After the application of the rule $DualWaitLeft$(or Right) we have two choices: we can choose to evaluate the left side as far as it can go or the right side. If the right side is chosen, it will soon be forced to wait on the evaluation of the left side since we have yet to evaluate the left side to send a message the right is expecting, or even evaluate the left side far enough to receive the last message we were waiting for. If we are forced to evaluate the left side or chose to evaluate the left side first and avoid the right side `Wait` insertion makes little difference. The left side will soon evaluate to the end of its single-step. Again, the two possible final statements are `End` and `Stop`. If `End` is encountered, $DualLeft$ applies, and another step is created for the left side. The only way for a sending single-step to arrive at a `Stop` is to send a `Stop`, thus consuming the remaining step on the right side.

Interestingly, it can be argued that these wait rules are not needed since carefully choosing DualLeft or DualRight can avoid all insertions of `Wait`. In practice, however, these waiting elimination rules prevent the need to backtrack in proofs. No matter which side is evaluated first, a valid evaluation path to completion exists.

2.5 Overall Correctness

To approach overall correctness, we prove many smaller properties about our system which paint a picture of the system's overall correctness.
We have discussed a number of proofs already as they were relevant. We also get a number of smaller verification properties "for free" without needing to write any proofs simply from the expressive nature of Coq. For example, let us look at how we defined measurement values. Recall that a measurement value is the measurement taken in response to a measurement request. In Coq we use `Description` to refer to a valid property description.

```
Inductive Const :=
 | constValue (d: Description) : (measurementDenote d) → Const
 | constRequest : Description → Const
 | constStop : Const.
```

The term `Const` holds constants (values) as opposed to variables. Indeed the the three constructors listed above are the only three values needed in this schema since these are the three valid message types. A `constValue` actually holds two values: a `Description` and a value. The value is meant to be the result of measuring what was described. We take advantage of the expressiveness of Coq's specification language and create the type level function `measurementDenote` to *compute* the correct type that this measurement must be. For example, if `Description` A is known to have a measurement type of `String`, it is impossible to create a `constValue` A that holds a `Boolean`. We are guaranteed to contain a measurement value of the correct type. A note to Coq programmers: By placing the dependent type within a constructor rather than at the type level, we are able to list the simple type `Const` wherever it is used rather than dealing with the headache of not even being able to ask if two `Const`s are the same because they are of different types. Avoiding dependent types by wrapping them in a constructor is a common practice used throughout our Coq code to achieve some of the benefits of dependent types without most of the headache.

2.6 Step Termination

Since our schema involves repeatedly taking single steps, it is worthwhile to prove that in all cases we eventually stop taking the next step. The proof is as follows:

- If any party receives a `Stop`, both parties cease taking steps.
- Therefore, we need only prove that eventually some party will send a `Stop`.
- What is sent is dependent on:
  - the list of currently requested measurements Q_s. If empty, we will send the first from..
  - the list of desired property measurements D_s. If empty, we will send `Stop`
- We want to prove that each send step makes progress towards emptying these lists.
- Recall that we first check if $|Q_s| >= 1$. If so there are three possibilities:
  - The desired measurement is unobtainable. We send a **Stop**, finishing the proof for this case.
  - The desired measurement is obtainable and we take and send the measurement, shrinking $|Q_s|$ by 1 and finishing the proof for this case.
  - A counter-request is sent that must be fulfilled before the measurement is revealed.
  - In response, the counter-request can be: (i) denied, a `Stop` received; (ii) answered, a measurement value received, in which case either a `Stop` is sent for an unsatisfactory value or the desired measurement is taken and $|Q_s|$ shrinks by 1; or (iii) more interestingly, a counter-request could also be countered. Therefore we must prove that the depth of counter requests is finite. This would indicate that the initial request will eventually be answered with a stop or a value shrinking $|Q_s|$ by 1.
    - Let P_p be the set of all properties in the requirements section of the executor's privacy policy.
    - Let $S_p = P_p \cup Q_s$
    - $|S_p|$ is finite since it is the union of two finite sets.
    - Then the maximum depth of counter-requests possible which hold back a single property measurement is $|S_p| - 1$. Recall that if a property is ever requested twice, the second request is always denied and a `Stop` is sent. Therefore the deepest possible chain of counter requests is $|S_p| - 1$. This will either result in a `Stop` being sent or the initial property request being measured and sent, shrinking $|Q_s|$ by 1.
  - In all cases, a `Stop` is sent or $|Q_s|$ shrinks by 1.
- If $|Q_s| = 0$, the first element from D_s is sent, shrinking $|D_s|$ by 1.

- If both are empty, a `Stop` is sent.
- In all cases, a Stop is eventually sent, ending remote attestation.

In Chapter 2 we defined a protocol EDSL inside the Coq Environment and inductive evaluation rules for this language. With this language, we defined a one-step protocol who's repeated application constitutes one side of a remote attestation. To avoid measurement deadlock, measurements are only requested once per attestation session. We saw that each party can safely repeat steps individually without getting out of sync with the creation and examination of dual protocol evaluation. We also discussed the correctness properties of this schema. In the next sections, we will explore possible extensions as well as concluding remarks.

Chapter 3

Future Work

3.1 Design amendments

This model is not perfect which is why some proofs remain elusive. It is not that they are not true under the current model–I believe that they are. Some structure tweaking could get rid of some of the difficulties that have arose in theorem proving under this model. For example, The Dual Evaluation rules listed in the previous chapter are ambiguous: more than one rule could be chosen for evaluation for a given configuration. Not only that, but attempting to apply a Dual Evaluation rule that is doomed to fail is not immediately obvious in such a large proof state as this model creates. Attempting its application can lead to hours of fruitless time. Proof automation can help, but still needs to know which rules to apply. Even with ambiguity removed, knowing which rules to apply is non-trivial due to the heavy single-step evaluation needed in the preconditions. Once a better solution is found, proof automation could be used more so than it is.

3.2 Extensions

This work could be modified into a 'negotiation' protocol which finds a mutually satisfiable remote attestation session *type*. The main difference would be a simplification in that measurements are not taken or sent upon request, but rather a placeholder indicating that, given all previously requested measurements in the protocol thus far meet their requirements, this particular measurement is releasable at this time. This could be desirable for two reasons.

Once we have a protocol type, simplification can occur to lessen network traffic. For instance if it is known that there are many targets with roughly the same privacy policy and 'baby stepping' is not necessary, all requests could be sent at once instead of request, measurement; request, measurement; etc.

The second reason has many of the prerequisites of the first. If no 'baby stepping' is necessary so request aggregation can occur, we can remove the short-circuiting functionality from an instance of a remote attestation session type. This may be desirable for a paranoid appraiser that considers it too revealing that just after receiving a measurement value it indicates to stop. If an attester were to remember the order of all messages exchanged it would be possible for the attester to deduce the precise measurement value the appraiser did not like–though it is still a mystery to the attester why the value was rejected. Without short-circuiting, the appraiser quietly makes a judgment call of the attester the result of which remains a complete mystery to the attester. Then the 'sensitive' information can begin with false values if it is undesirable that the attester be aware of the dissatisfied appraiser.

Many defined inductive evaluation steps include an *exists* statement due to the multiplicative growth of evaluation proofs necessary to account for all evaluation cases. At the time of creation this was not seen as an issue, but proved to be one when attempting larger proofs which depend on the evaluation proofs. Ideally, the use of 'exists' would be stricken from all evaluation proofs and perhaps more significant properties could be verified.

As mentioned early on, many details are overlooked because they are out of scope of our focus (TMP quotes, encryption, etc). An obvious extension would be to incrementally add detail to this representation until fully instantiated.

The privacy policy is currently implemented with a one-for-one mentality. Meaning at most, you can only require one other measurement before releasing what was requested of you. Initially, we had an AND requirement and OR requirement. However, implementing this evaluation added undesirable complexity for an initial model. Adding this back in is a clear extension.

Chapter 4

Conclusion

Here we have designed a protocol procedure for Remote Attestation that supports the integration of a dynamic privacy policy of both parties which adapt to the current level of trust in the opposing party. Additionally, the protocol procedure allows for trust to be built incrementally over a dynamically determined sequence of messages which allows for any number of counter attestations instead of attempting bulk requests. This is achieved by starting each attestation session with a fresh copy of the privacy policy. Requirements in the policy are then relaxed as more and more information is learned of the opposite party. Thereby, the opposing party can request increasingly sensitive information that would otherwise be inaccessible. This schema, properties, and evaluation were modelled within the theorem prover Coq. Specifically, we built the protocol language, its evaluation, and modeling valid execution of the protocols of both parties simultaneously. We also successfully proved a number of properties about this model. Some larger proofs we would have liked to have seen formally unfortunately remain informal verbal arguments based on smaller formal and informal proofs. The main cause of this incomplete formality can be attributed to the following observations:

- A perceived correct though non-optimum model creates undesirable complexity in proof states.
- A non-expert Coq Programmer (me)
- Immature proving tools. This divisive opinion is my own. Though Coq has been around for over 30 years and is considered an industry standard in the field, if automated theorem proving is to the evolution of programming languages, I would say Coq is somewhere between C and C++. It has a long way to go before we see something as equivalently powerful as Haskell. For example, one of Coq's most powerful features, dependent types, is also its worst. In fact, some professional Coq programmers actively avoid and advise others to avoid using them due to.. their inability to be used. As a result, many elegant definitions feel like hacks in

> opposition to the design of Coq rather than in sync. A proving system should aid in proving after all, not hinder it. Elegant definitions should live on the surface instead of having to dig deeply for them. Though in all fairness, could I design a better system? Most certainly not. Despite these downfalls, Coq has been steadily advancing. For example, in the comparatively short time I have programmed in it I have seen an order of magnitude improvement to the bundled CoqIDE. With each update come a number of algorithmic improvements to proof tactics. If these improvements continue along with more out-of-the-box automation, I have no doubt Coq will become a tool with little to complain about.

We hope that this schema can provide a formal basis for designing remote attestation protocols that focus on privacy and incremental trust. With modification, practical code can be generated from this model. Some verification properties remain informal proofs, but many useful properties have formal proofs. As Coq advances, we expect more properties to have formal arguments, and this model to gain expressiveness.

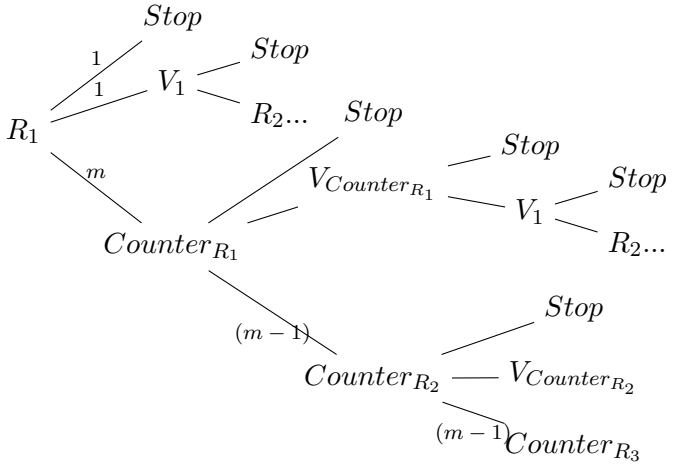
Appendix A

Cardinality of possible message paths

The formula for computing all possible communication paths for an appraiser and attester is as follows. Let m be the cardinality of requestable properties and n be the number of requests an appraiser would like to make. In response to a request, the appraiser may receive:

- a **stop** ending that path
- a **value** of the measurement, in which case we stop (if the value is bad) or continue on to the next property request.
- a **counter-request** which must be fulfilled before the desired property measurement is released.

The following tree provides a nice visual for the possible cases in response to $Request_1$.



We will not expand this and further. We have explored the tree far enough to approximate the cardinality in the following function. We can approximate the size of this tree in the following way:

```
size :: Measurements -> Requests -> Integer
size 0 _ = 2
size _ 0 = 0
size m n =  1 + value + counterRequest where
     value = 1 + (size (m-1) (n-1))
     counterRequest = m * (size (m-1) n)
```

If we recursively reach $m = 0$, our base case is 2: A **stop** or a **value**; no further measurements can be requested. If we reach $n = 0$, there are no more requests to be made. Otherwise, we could receive a **stop**, a **value**, or a **counterRequest**. As we saw in the tree, a value can be responded to with a **stop**, or continuing the attestation: thereby decreasing m and n by one. Remember that we remove the possibility of requesting a property twice to avoid Measurement Deadlock hence the $m - 1$. There are m counterRequests we could receive. Note that the recursive call to *size* does not decrement n since we have not yet received the value we desire and have not moved on. Example cardinalities include:

- $size(2, 1) = 14$
- $size(3, 1) = 44$
- $size(5, 2) = 1,930$
- $size(10, 3) = 114,190,992$

Hence it is certainly unfeasible to enumerate all possible protocol paths statically to arrive at well-typed protocol (Session Types).

Appendix B

Proof list

B.1 Formal Proofs

B.1.1 Network Related Proofs

Description: If findandMeasureItem returns a constValue, it is, in fact, the result of the initial request (d=d0).

Formal Statement:

```
Theorem thm_findAndMeasureItemL : ∀ pp d d0 val x, findandMeasureItem pp d
= Some (constValue d0 val, x) → d = d0.
```

Description: If an item has been removed from the privacy policy, findAndMeasureItemL will never succeed.

Formal Statement:

```
Theorem thm_youCantFindit : ∀ pp d, findandMeasureItem (rmAllFromPolicy pp d)
d = None.
```

Description: After handling a request, subsequent requests of that description will fail.

Formal Statement:

```
Theorem thm_removedFromPrivacy : ∀ pp d pp' c ri,
 handleRequest' pp d = (pp',c,ri) →
 findandMeasureItem pp' d = None.
```

Description: Ensures that we are, in fact, returning the head of the request list, if we canSend.

Formal Statement:

```
Theorem thm_canSendL : ∀ pp ls d, (canSend ls pp = Some d )-> (head ls)
=Some d.
```

Description: If a message exists on the network for the participant, then removing that message from the network results in shrinking the network in size by exactly 1.

Formal Statement:

```
Lemma thm_rmMessSmallerL : ∀ n p, existsMessageForMe n p → S (length (rmMess
n p))= length n.
```

Description: Calling `receiveMess` will shrink the network by exactly 1.

Formal Statement:

```
Theorem thm_receivingShrinks' : ∀ c n p, receiveMess n p = Some c →
length n = length (rmMess n p) + 1.
```

Description: The resultant network from calling `receiveN` is the same network returned by removing a message by calling `rmMess`.

Formal Statement:

```
Theorem thm_receiveN_NewNetworkrmMessage : ∀ c n n' p, receiveN n p = Some
(c, n') → n' = rmMess n p.
```

Description: The resulting network from calling `receiveN` shrinks the network by exactly 1.

Formal Statement:

```
Theorem thm_receivingShrinks : ∀ n c p n', receiveN n p = Some (c,n') →
length n = S (length n') .
```

Description: The `Send` statement increases the number of messages in the network by 1. **Formal Statement:**

```
Theorem thm_sendOnNetworkAppends : ∀ f t c n, length (sendOnNetwork f t
c n) = length n + 1.
```

B.1.2 One Step Related Proofs

Description: The maximum number of network actions taken by any branch of `OneProtocolStep` is equal to the minimum number of network actions taken by any branch. i.e. All execution paths through `OneProtocolStep` perform exactly the same number of network actions.

Formal Statement:

```
Theorem thm_onestepProtocolmaxAction_eq_minAction : ∀ st,
countMinNetworkActions (OneProtocolStep st) = (countMaxNetworkActions (OneProtocolStep st)).
```

Description: The maximum number of actions taken by `OneProtocolStep` is 1. With the previous proof, we have that every `OneProtocolStep` will always perform exactly 1 network action.

Formal Statement:

```
Theorem thm_onestepProtocolmaxAction_eq_1 : ∀ st,
(countMaxNetworkActions (OneProtocolStep st)) = 1.
```

Description: If a `OneProtocolStep` is instructed to Send, the network action performed will be Send. With the previous proof, we know that if the step is to send, exactly one send will occur and no receives. Refer to 2.3.2.2 for the Propositional definition of `SingularNetworkAction`.

Formal Statement:

```
Theorem thm_oneStepSend : ∀ st stm' n,
 evalChoose IsMyTurntoSend st = true →
 (OneProtocolStep st, st, n) ⇒ (stm', st, n) →
 SingularNetworkAction stm' ASend.
```

Description: Similar to the above proof, we prove that if the action is to Receive, exactly one Receive will occur and no Sends.

Formal Statement:

```
Theorem thm_oneStepReceives : ∀ st stm' n,
 evalChoose IsMyTurntoSend st = false →
 (OneProtocolStep st, st, n) âĞŠ (stm', st, n) →
 SingularNetworkAction stm' AReceive.
```

Description: If `CanSend` *st*, which checks the privacy policy if the desired measurement can be taken and sent, evaluates to `true`, then computing the message to send will always succeed.

Formal Statement:

```
Theorem thm_canSendST_implies_handleExists : ∀ st, evalChoose CanSend st = true
→ ∃ c, handleCompute compGetMessageToSend st = Some c.
```

Description: If there is still at least 1 property to request of the other party, then computing the message to send will always succeed.

Formal Statement:

```
Theorem thm_ifwillthenway : ∀ st, evalChoose ExistsNextDesire st = true →∃ c,
handleCompute compGetNextRequest st = Some c .
```

Description: As discussed in 2.3.2.1, this proof states that the `effect` statements are the only ones which modify the execution state.

Formal Statement:

```
Theorem thm_onlyEffect_effects : ∀ (stm stm': Statement) (st st': State)
(n n' : Network),
 (stm,st,n) ⇒ (stm',st',n') →
 getProState st = getProState st' ∨ ∃ e, (headStatement stm) = EffectStatement
e.
```

Description: Only the `Send` or `Receive` statements modify the network.

Formal Statement:

```
Theorem thm_onlySendOrReceiveChangesNetwork : ∀ (stm stm': Statement) (st
st': State) (n n' : Network),
 (stm,st,n) âĞŠ (stm',st',n') →
 n = n' ∨
 (∃ t p1 p2, headStatement stm = SendStatement t p1 p2) ∨
 (∃ vid, headStatement stm = ReceiveStatement vid)
 .
```

Description: The `Action` to take, `Send` or `Receive`, is not modified by any statement

in the language.

Formal Statement:

```
Theorem thm_noOneTouchesAction : ∀ stm stm' n n' st st',
(stm,st,n) ⇒ (stm',st',n') → getAction st = getAction st'.
```

Description: From the previous proof, it follows that any multi-step also does not modify the `Action`

Formal Statement:

```
Theorem thm_noOneTouchesAction_m : ∀ stm stm' n n' st st',
(stm,st,n) ⇒* (stm',st',n') → getAction st = getAction st'.
```

Description: When a `OneProtocolStep`'s action is to Receive and a `Stop` is not the received message, the `OneProtocolStep` always evaluates to `End`.

Formal Statement:

```
Theorem thm_receiveAlwaysFinishes : ∀ vars prst n m n', evalChoose IsMyTurn-
toSend (state vars prst) = false →
 receiveN n (getMe (state vars prst)) = Some (m, n') →
 m ≠ constStop → ∃ prst',
 (OneProtocolStep (state vars prst), (state vars prst), n) ⇒* (EndStatement,
(state ((receivedMESSAGE,m)::vars) prst'), n').
```

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