JOSEPH HALLETT

SECURITY POLICIES FOR HUMANS THESIS PROPOSAL

Contents

Introduction

When an app is installed on Android it prompts the user to accept a list of privileges granted to the app. The user makes the decision based on what they know about the app and their own security policies. In practice a large number of users accept the permissions whatever. This is problematic because some apps are over privileged[1] and some are malicious[2]. Other apps are considered to be potentially unwanted software (PUS) because though they are not malicious in themselves they handle data in a way that is not in the user's interests.

[1] Adrienne Porter Felt, Erika Chin, Steve Hanna, Dawn Song, and David Wagner. Android permissions demystified. *the 18th ACM conference*, pages 627–638, October 2011

[2] Yajin Zhou and Xuxian Jiang. Dissecting Android Malware: Characterization and Evolution. *Security and Privacy (SP), 2012 IEEE Symposium on*, pages 95–109, 2012

More generally users and computers make decisions, whether it update an app; whether to connect to a website, based on security policies and trust relationships. These security policies may include the use of tools or experts to decide whether something is malicious. For instance a user may trust a firewall program to enforce their network policy; and they may trust a tool like *Shorewall* to generate the actual policy for them. Alternately a user might wish to be able to install apps but only trust apps *Amazon* have vetted to be installed on their device. *The aim of this project is to formalize these security policies so they can be studied and enforced automatically.*

Mobile operating systems are similar to existing systems but come with a different trust model and are used in a different manner. Software is downloaded from app stores, Apps run within sandboxes and must collaborate and collude to share data with other apps. These devices contain more personal data than ever before: sensors tracking users' locations, gyroscopes measuring how users move, and microphones listening to users calls. The bring your own device (BYOD) movement empowers users to take the devices they have at home and bring them into work. This creates a tension between how the corporate IT department may require employees to use their devices and the user's policies on how they want to use their devices. These features add a novel challenge to modelling these devices and the stores and users surrounding them.

Formalizing the policies allows comparisons to be made between different systems and users. When comparisons are made between the two biggest mobile OSs, iOS and Android, the comparisons is informal: we say iOS is more closed, more of a *walled garden*, Android is more permissive. With a formal language to describe system policy we can make a precise comparison. It allows us to

There is decades of research on analysis tools. These tools can infer complex security properties about the code and systems they analyze. What there is missing is a glue layer between the assurances these tools can give and the policies users are trying to enforce. By using an *authorization logic* as the glue layer we can enforce the policy by building on the work on access control in distributed systems. Our static analysis tools can be trusted to give statements about code, with other principles, that can be combined to imple-

ment a security policy.

The aim of the thesis is to show how authorization logics can be used to make security decisions in mobile devices. Currently security decisions are made manually by smart phone users and it is our belief that by automating these choices users can avoid having to make security decisions and their overall security be improved. To do this we plan to look at the following areas:

- *To instantiate a logic of authorization that allows us to model the trust relationships between the components of an operating system and the users.* This will include analysis tools as principals and allow making decisions based on signed statements from them. The logic must be able to model what happens when apps can collude. The logic may be based off of earlier work on the *SecPAL language*[3] that was used for distributed access control decisions.
- *To explore how security policies change with time and when apps can collude.* A user's security policy need not be static. People change jobs and may bring old devices to new environments requiring new security policies. Apps can collude: two apps might meet a security policy when considered on their own but together they might act to share data inappropriately. Over time an app might want greater access and increased permissions to support new functionality. It is not obvious how to write and check security policies written in SecPAL for these scenarios and how to enforce the policy at runtime.
- *To implement an app store that serves users only the apps that meet their security policies.* This will include a user-study where we evaluate how well users comprehend their policies and the decisions made for them. This may lead into generating proof-carrying code certificates for apps that allow a device to check that their policy was met without having to do the full inference themselves.
- *To model the decisions and trust relationships inherent in Android and other mobile operating systems.* This will allow us to write a security policy that describes the current state in these systems and serve as a base to compare other systems against.
- *To study how users understand their security policies and the ways these policies are enforced.* One of the advantages of SecPAL is that it is more readable compared to other authorization logics and access control languages. Whilst end-users might not want to write their own policies they should be able to comprehend what a policy means, and they should be able to understand why their policy allows some decisions and not others.

[3] M Y Becker, C Fournet, and A D Gordon. SecPAL: Design and semantics of a decentralized authorization language. *Proc IEEE Computer Security . . .*, 2006

Project Context (App Guarden)

This thesis will form part of the *App Guarden*[4] project. The App Guarden project aims to improve the quality of mobile security by

[4] `http://groups.inf.ed.ac.uk/security/appguarden/Overview.html`

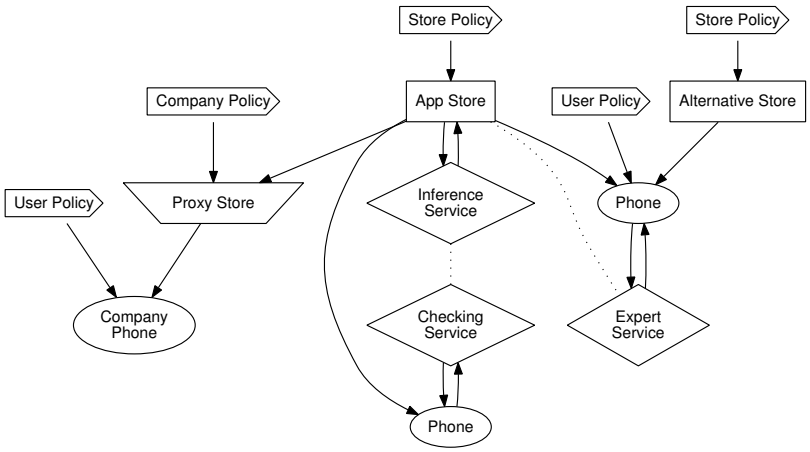

Figure 1: Overview of the different entities in App Guarden. Each of the ovals represents a different device inside the system; each rectangle or trapezium represents different supplier of apps, and each diamond is an authority that makes statements about apps and other software decisions. Arrow boxes show policies. Arrows represent transfers of information or apps, and dotted line indicate that the two entities are connected in some other way.

developing new tools to analyze apps and the app stores that sell them.

This work contributes to this by developing the security policies that describe what the user wants and showing how they can be enforced using the tools that can check security policies within the code. The end result might be a system as shown in Figure 1 where devices are interacting with stores and security services such as static analysis tools or proof checkers.

Between each of the nodes different policies could be enforced: for example consider an *app store* and *proxy store*. Here we have a master app store that sells a large number of apps. A company provides its employees each with a phone that they can install apps on but they have their own security and usage policy set by their IT department. They want to ensure that their employees can't install anything that breaks it so on all the devices they provide they install a special proxy app store. The proxy app store takes apps from the main store but discards any apps which might break the policy it is supplied with. Users may download apps from the company store, but they might exercise their own judgement and only download apps that meet their own policies. At each stage (as shown in Figure) judgements are being made about what is acceptable from an app store, and the policies are refined.

Another example might be an app store that supplies apps with *digital evidence*. When the app store sells an app it wants to reassure its users that it real guarantees that the app it is selling meets the security guarantees it claims. Being able to infer these properties is complex and takes both time and battery power; this is difficult as many phones are battery constrained. To avoid this the app store uses an inference service to produce digital evidence to be supplied with the app that shows (with the aid of a checking service that could be running on the device) that an app meets the policy (as shown in Figure). Other people in the App Guarden project are working on the development of such tools.

An alternative form of this could be where a store delegates to

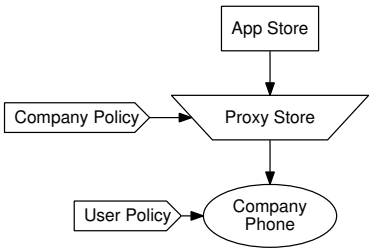

Figure 2: Security policies and the proxying store

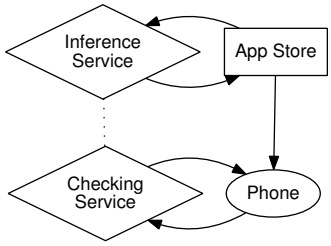

Figure 3: Checking services and an app store.

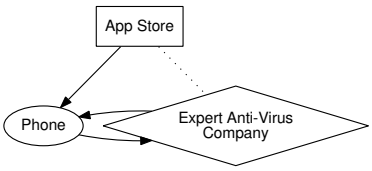

Figure 4: Use of an expert checker.

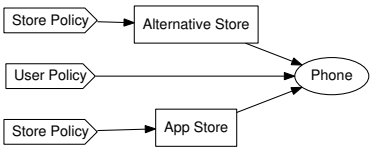

Figure 5: A device using multiple stores with different policies.

an expert third party to make statements about the apps it sells. One might imagine a scenario where an app store might claim *"We don't sell viruses in our store, but don't take our word for it: here's a well known anti-virus company that will verify our claim"* (as shown in Figure).

If a user is using multiple stores (for example a Jailbroken iPhone user might buy apps from both the App Store and the Cydia Store) then the policies the user might be applying become complex (as described in Figure). This leads to interesting questions around how policies should be composed and the equivalence of security policies when they are; as well as questions about the overall device policy in a system.

The work for this thesis will not concern itself with the development of tools to check the apps perform as they should; rather it will focus on modeling the trust relationships between these tools and the other entities in a mobile environment. This allows this part of the work to focus on the relationships and device policies rather than the intricacies of code analysis.

A Logic of Authorization For Mobile Devices

Logics of authorization are used to decide whether an entity can carry out a task. When we apply these logics to files and information we create an access control system; when we apply the logics to designing systems we create a security specification language. A review of the history and applications of the logics is given later in this proposal (page 11); but in summary they have shown themselves to be increasingly useful for modelling the complex security and trust policies in modern systems.

Mobile devices, whilst technically similar to traditional computers, have more information about their users, don't offer the user the traditional file system interfaces, sandbox everything, and use closed software markets (app stores) to distribute software. The app stores typically allow developers to sell their apps for money and are selective about what they will sell. Apps are vetted, usually in secret, for quality and security using (we believe) a combination of static and dynamic analysis tools as well as traditional manual inspection. The policies the app stores apply to their apps form an authorization decision (i.e. *the analysis team says app can be sold*) and their is a delegation of trust to the analysts and their tools but how these policies and trust relations filter through to the end users is not clear.

These differences amount to a different model of trust than the traditional machines, and a new set of authorization problems that it is not obvious how to express in other authorization logics.

To solve this we have taken an existing authorization logic, SecPAL[5], and extended it with a series of predicates that can describe how security policies are met inside a mobile ecosystem. Future work will include describing the current security policies for An-

[5] M Y Becker, C Fournet, and A D Gordon. SecPAL: Design and semantics of a decentralized authorization language. *Proc IEEE Computer Security . . .*, 2006

droid and other mobile OSs as well as some of the app stores. This will allow comparisons to be made between them, and (with a database of apps) comparing what kinds of apps different markets allow.

Compositional Policies Over Time

Consider the case where a user has a smart phone and they are buying apps. The user must decide if they want to install an app: to do this they apply a series of judgements called their *security policy*.

Whilst the user has their own security policy they apply they also have other security policies they implicitly follow. If they are downloading apps from an app store they are also subject to the security policy of the app store and what it is willing to sell. If the phone runs in a corporate environment then they may also be subject to the company's corporate policy. Finally the operating system itself may have certain restrictions on what it will allow: for example the APK app format used on Android can also be installed on Blackberry, and Mer operating systems. Each of these systems may add additional restrictions that may make some apps not installable. An example of how this kind of policy might be written is shown in Figure .

Phone **says** app is−installable
  if app **meets** UserSecurityPolicy,
  app **meets** AppStorePolicy,
  app **meets** ITDeptPolicy,
  app **meets** OSPolicy.

Phone **says** User **can**−**say** inf
  app **meets** UserSecurityPolicy.

Phone **says** PlayStore **can**−**say** 0
  app **meets** AppStorePolicy.

Phone **says** ITAdmin **can**−**say** inf
  app **meets** ITDeptPolicy.

Figure 6: A compositional security policy where an installation policy for a phone is dependent on other security policies.

The phone might use this policy for a while, but then the user changes jobs. Now they have to meet a new ITDeptPolicy set by a different administrator. Should any installed apps be uninstalled if they don't meet the new policy? If we already have a certificate showing the apps passed the old policy can we reuse it to create a new certificate that shows the app meets any additional restrictions?

Whilst other authorization logics have looked at making one-time decisions about whether to allow a computer to make a decision; there has been less work on modelling these policies over time and seeing how a changing security policy affects a changing device. This could add novelty.

Alternatively say there is an app which the developer is continually improving and adding new features. When the app is installed it may meet the security policy but with increasing features requiring access to more permissions and introducing more complexity or a change of advert library the app no longer meets the security policy.

Should the app be removed? If the app is used every day by then the user may not be pleased that the phone has decided to break their favorite app; though anecdotal evidence would suggest users tend to blame apps for failing rather than the frameworks they apps rely on; regardless of who is really to blame. Equally just stopping updates for the app increases app version fragmentation and reduces security by rejecting bug fixes. Allowing the update isn't correct either as it allows a means to break the security policy.

Whilst there have been several papers looking at (and proposing

methods to stop) excessive permissions in applications[6,7] there has not been a thorough review of how permissions change for apps over time and between versions of the same app.

[6] Adrienne Porter Felt, Erika Chin, Steve Hanna, Dawn Song, and David Wagner. Android permissions demystified. *the 18th ACM conference*, pages 627–638, October 2011

[7] T Vidas, N Christin, and L Cranor. Curbing android permission creep. In *Proceedings of the Web*, 2011

Personally Curated App Stores

The primary method of software distribution on mobile devices is through an app store. On iOS users have the *App Store*: a curated market place run by Apple (though other, albeit clunkier, distribution mechanisms do exist for even non-jailbroken phones) that is perceived as being picky about the apps it sells.

On Android users have a far greater choice of marketplace. The *Play Store* is the standard app store distributed by Google and is less moderated than Apple's store. Amazon have their own app store that serves as a more curated version of Google's offering and the default on their Kindle tablets. Other app stores target specific regions: such as *gFan* in China, and the *SK T-Store* in Korea. Some, such as *Yandex.Store, AppsLib and SlideMe*, are pre-installed by OEMS who can't or don't want to meet Google's requirements for the PlayStore. The *F-Droid* store only delivers open source apps. Others exist to distribute pirated apps. On average eight percent[8] of the apps in each of these alternative market places is malware. The Play Store contains very little malware however (0.1% of total apps), whilst a third of the app in the Android159 store were found to be malicious.

[8] BRODERICK AQUILINO, KARMINA AQUINO, CHRISTINE BEJERASCO, EDILBERTO CAJUCOM, SU GIM GOH, ALIA HILYATI, MIKKO HYYKOSKI, TIMO HIRVONEN, MIKKO HYPPONEN, SARAH JAMALUDIN, CHOON HONG LIM, ZIMRY ONG, MIKKO SUOMINEN, SEAN SULLIVAN, MARKO THURE, and JUHA YLIPEKKALA. Threat Report H2. Technical report, F-Secure Labs, 2013

Each of these app stores have a different security policy. They enforce these policies when they pick which apps to sell to their users. By using an authorization logic to decide whether apps will meet a security policy we have the ability to create a new kind of app store where offerings are tailored to the user's security policy. By creating app stores tailored to a security policy we also give ourselves a way to empirically measure how restrictive a security policy is: we can measure the number of apps offered inside the stores.

To enhance the trust in the store by the user digital evidence could be offered with the app which would give devices a practical means to check that the app is supported by their security policy without having to re-run all the checks themselves; this should also save device battery life. Proof-carrying authentication[9] and authorization logics such as BLF[10] have already introduced ideas from proof-carrying code into authorization logics. The focus of this work, however, has been on access control where a user is providing a proof that they have the credentials to access a resource. In the scenario we propose the role of the user is reversed: the store offers many proofs to the user to increase their trust in its wares; rather than the user offering one specific proof to prove they have the right to complete a certain action.

[9] Andrew W Appel and Edward W Felten. *Proof-carrying authentication*. ACM, New York, New York, USA, November 1999

[10] N Whitehead, M Abadi, and G Necula. By reason and authority: a system for authorization of proof-carrying code. In *Computer Security Foundations Workshop, 2004. Proceedings. 17th IEEE*, pages 236–250. IEEE, 2004

Review of Android Security

Android is a Linux-based operating system designed for mobile phones and increasingly used in consumer electronics. It comes with a large software market that distributes apps. These apps are built on top of a virtual machine, called Dalvik, and run within a sandbox provided by the OS that is based on Linux's permissions model[11].

Permissions and Apps

On top of the traditional permissions level Android has API permissions that apps must request at install time. API permissions control access to functionality such as the internet, reading or writing external storage, or to learn about the state of the phone. These permissions are displayed to users at install time and must be accepted if the app is to be installed. Most users do not pay attention to these permissions and okay them no matter what is asked for[12]. This has led to malware and PUS that requests excess permissions; which leads to apps sending premium text messages (a common monetization strategy[13]) or stealing private information.

There are tools which can detect when an app is over privileged (like the app in Figure). The *Stowaway* tool[14] mapped Android permissions onto the API calls to access the functionality they enabled. This allowed them to detect when apps were over privileged by looking for apps which had the permissions but none of the associated API calls. The *PScout* tool[15] improved upon Stowaway by increasing the accuracy of the permissions map and by deriving the map from the Android source code, rather than the fuzzing based methods Stowaway used.

One criticism of the API permissions is that they are quite broad. For instance the *internet* permission allows an app to send or receive anything on the internet. Several people have proposed a *fine grained permissions model* and developed tools to support it. The *RefineDroid, Dr. Android & Mr. Hyde* tools[16] are a suite designed to discover which permissions can be made fine-grained, rewrite apps to use these permissions and then enforce them at runtime; they do this on a stock Android system without requiring rooting or kernel modification. Alternately the *AppFence* tool[17] works without modifying apps. It allows users to write fine grained policies for what data an app can receive: if an app exceeds its bounds then the request is either denied or fake data supplied in its place. This does require modifications to the Android OS however. The *AppGuard* tool[18] offers something in between: it rewrites apps to use a security monitor to enforce security policies at runtime.

Intents and Collusion

Android uses a novel IPC mechanism called *Binder*. Apps use *intents* to share data and handle events. For instance if an app wishes

[11] Joshua J Drake, Zach Lanier, Collin Mulliner, Pau Oliva Fora, Stephen A Ridley, and Georg Wicherski. *Android Hacker's Handbook*. John Wiley & Sons, March 2014

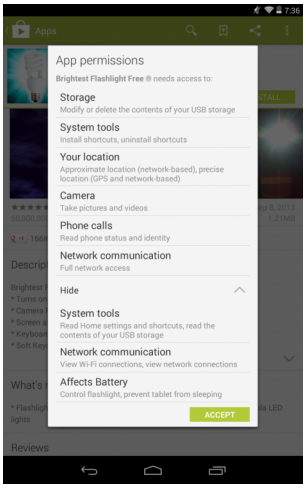

Figure 7: The *Brightest Flashlight Free* app prompting for it's permissions at install time. This app is over privileged as a flashlight app should have no need for GPS or phone data, or network access.

[12] Adrienne Porter Felt, Elizabeth Ha, Serge Egelman, Ariel Haney, Erika Chin, and David Wagner. *Android permissions: user attention, comprehension, and behavior*. ACM, July 2012

[13] E Chien. Motivations of recent android malware. *Symantec Security Response*, 2011

[14] Adrienne Porter Felt, Erika Chin, Steve Hanna, Dawn Song, and David Wagner. Android permissions demystified. *the 18th ACM conference*, pages 627–638, October 2011

[15] Kathy Wain Yee Au, Yi Fan Zhou, Zhen Huang, and David Lie. PScout: analyzing the Android permission specification. *the 2012 ACM conference*, pages 217–228, October 2012

[16] Jinseong Jeon, Kristopher K Micinski, Jeffrey A Vaughan, Ari Fogel, Nikhilesh Reddy, Jeffrey S Foster, and Todd Millstein. *Dr. Android and Mr. Hide: fine-grained permissions in android applications*. ACM, October 2012

[17] P Hornyack, S Han, J Jung, and S Schechter. These aren't the droids you're looking for: retrofitting android to protect data from imperious applications. In *Proceedings of the 18th . . .*, 2011

[18] M Backes, S Gerling, C Hammer, and M Maffei. AppGuard–Enforcing User Requirements on Android Apps. *Tools and Algorithms for . . .*, 2013

to handle an SMS_RECEIVED action it can declare itself a *broadcast receiver* for it and the app will be started when the event occurs. Alternatively if an app wants to open a URL in the browser it can send an ACTION_VIEW intent and the user's chosen browser will take open the URL. Apps can create their own intents and can restrict usage of them (if they wish) to only a limited number of other apps (or those signed with a specific key).

These mechanisms also allow apps to collude to increase their privilege levels, or share data inappropriately. To do this consider the case where there are two apps communicating: one which can use the network and another which cannot. If the unprivileged app asks the privileged app to send data on its behalf, and the privileged app forwards the network responses back to it; then the unprivileged app has the network permission without needing to declare it to the user. Alternately if a privileged app does not secure its intents then they may break the protections offered by permissions. An example of this was the *Kies* app on Samsung Galaxy S3 phones that could be exploited to allow any app to install other apps[19].

Several tools have been developed to detect these privilege escalation attacks such as *Quire*[20] that added origin tracing to intents. Other tools such as *ScanDroid*[21] statically analyze apps to find data-flows across components and produce a series of constraints that should be satisfied to guarantee information security. The *Kirin*[22] tool certifies apps at install time against a policy based on the potential data-flows introduced by the permissions they request.

The *TaintDroid*[23] and *FlowDroid*[24] have both had a large impact. Both tools both use taint analysis to track the data passed between apps and detect when sensitive data is being leaked to an app that should not have access to it through intents, however others have shown that the approach is not perfect[25] and can be defeated by malicious apps.

[19] Andre shka Moulu. From 0 perm app to INSTALL_PACKAGES on Samsung Galaxy S3, July 2012. URL `http://sh4ka.fr/android/galaxys3/from_0perm_to_INSTALL_PACKAGES_on_galaxy_S3.html`

[20] S Bugiel, L Davi, and A Dmitrienko. Towards taming privilege-escalation attacks on Android. *19th Annual . . .*, 2012

[21] A P Fuchs, A Chaudhuri, and J S Foster. SCanDroid: Automated security certification of Android applications. . . . , 2009

[22] William Enck, Machigar Ongtang, and Patrick McDaniel. *On lightweight mobile phone application certification.* ACM, New York, New York, USA, November 2009

[23] W Enck, P Gilbert, B G Chun, L P Cox, and J Jung. TaintDroid: An Information-Flow Tracking System for Realtime Privacy Monitoring on Smartphones. *OSDI*, 2010

[24] C Fritz, S Arzt, and S Rasthofer. Highly precise taint analysis for android applications. *EC SPRIDE*, 2013

[25] G Sarwar, O Mehani, and R Boreli. On the effectiveness of dynamic Taint analysis for protecting against private information leaks on android-based devices. *International Conference on Security and Cryptography*, 2013

Review of Policy Languages

Logics of Authorization

When an action is performed, such as reading a file or installing an app, there are a set of conditions that must be met for the action to go ahead. These conditions form the *authorization policy* for that decision. When these policies describe what actions are permissible in order to maintain a secure system then we call it the *security policy*.

The policies often contain a notion of *trust* where certain principals may be trusted to make statements about other principals and what is permissible. To model the relationships many logics have been proposed that can be implemented to decide whether an action can be authorized automatically.

Early authorization logics, such as *PolicyMaker*[26] grew out of the logics of authentication proposed by Wobber, Abadi, Burrows, and

[26] M Blaze, J Feigenbaum, and J Lacy. Decentralized trust management. *Security and Privacy*, 1996

Lampson[27,28]. PolicyMaker allowed authorities to declare trust in other principles (identified through asymmetric keys) for certain actions or to declare further trust relationships. The language was designed to be minimal and did not specify how the policies should be checked: they suggested by using regular expressions, or checking programs written in a sandboxed version of AWK however any language could have been used. The author suggested that the language might be good as a model for the public-key infrastructure. Later work introduced *KeyNote*[29] which they claimed was a simplified version of PolicyMaker designed to support public-key infrastructure.

[27] B Lampson, M Abadi, and M Burrows. Authentication in distributed systems: Theory and practice. *ACM Transactions on ...*, 1992

[28] E Wobber, M Abadi, M Burrows, and B Lampson. Authentication in the Taos operating system. *ACM Transactions on ...*, 12(1):3–32, 1994

[29] Matt Blaze, Joan Feigenbaum, and Angelos D Keromytis. KeyNote: Trust Management for Public-Key Infrastructures. In *Security Protocols*, pages 59–63. Springer Berlin Heidelberg, Berlin, Heidelberg, January 1999

Later other languages such as *RT*[30] were introduced. RT allowed principals to be given roles (in a manner similar to an role based access control (RBAC) access-control system) and for decisions to be made based on which roles an entity held. This meant that RT could express general statements that were not expressible in the PolicyMaker languages such as:

> "Anyone who is a preferred customer and a student can get a discount."

[30] N Li and J C Mitchell. Design of a role-based trust-management framework. *Security and Privacy*, 2002

Several different versions of RT were described: the simplest being RT_0[31] and with RT_1 and RT_2 adding support for parameterized-roles and logical-objects respectively; each with extensions to provide other features.

[31] N Li, W H Winsborough, and J C Mitchell. Distributed credential chain discovery in trust management. *Journal of computer security*, 2003

By providing a translation into *Datalog* (specifically *Datalog with constraints* or *Datalog*^{C}[32]), the RT family of languages was shown to be tractable, unlike earlier languages. Datalog is a query language similar to *Prolog* but that doesn't support nested sub-queries or functions and has a safety condition that all variables in the head must occur in the body. Datalog is a subset of first-order logic and is known to be tractable: i.e. all queries can be done in polynomial time.

[32] Ninghui Li and John C Mitchell. Datalog with Constraints: A Foundation for Trust Management Languages. In *Practical Aspects of Declarative Languages*, pages 58–73. Springer Berlin Heidelberg, Berlin, Heidelberg, January 2003

Influences form the RT family of languages and Datalog^C can be seen in the *Cassandra* policy rule language[33]. Cassandra was a trust management system that could be used to model large complicated systems. In his doctoral thesis Becker showed how the NHS Spine (a complex and informally defined system concerning access control and roles in health care) could be formally modelled in the Cassandra language.

[33] M Y Becker and P Sewell. Cassandra: flexible trust management, applied to electronic health records. *Proceedings. 17th IEEE Computer Security Foundations Workshop, 2004.*, pages 139–154, 2004

In Cassandra principals activate and deactivate roles. Actions can only be completed if the principal holds the required roles. Delegation is allowed through an appointment mechanism where one principal can activate a role on another principal. Like the RT languages Cassandra is tractable as it can be translated to Datalog^C.

$$\texttt{canActivate}(mgr, \texttt{AppointEmployee}(emp)) \leftarrow \texttt{hasActivated}(mgr, \texttt{Manager}())$$

$$\texttt{canActivate}(emp, \texttt{Employee}(app)) \leftarrow \texttt{hasActivated}(app, \texttt{AppointEmpolyee}(emp))$$

Figure 8: Role delegation in the *Cassandra* policy language. A manager is allowed to activate the employee role for an arbitrary entity by appointing them.

The *Binder* language[34] was designed for authorization decisions[35] and implemented as an extension of Datalog. Properties are given to entities by creating arbitrary predicates for them, and a special *says* modality allows statements to be imported from third parties.

[34] J DeTreville. Binder, a logic-based security language. In *Security and Privacy, 2002. Proceedings. 2002 IEEE Symposium on*, pages 105–113. IEEE Comput. Soc, 2002

[35] M Abadi. Logic in access control. In *Logic in Computer Science, 2003. Proceedings. 18th Annual IEEE Symposium on*, pages 228–233. IEEE Comput. Soc, 2003

Authorisation is granted by checking to see if a predicate can

be deduced from the knowledge base, however because Binder does not add any special predicates, and Datalog does not allow functions there can be no notion of state.

The *SecPAL* authorization language[36] is an authorization logic for decentralized systems. Early experiments indicate that it is highly suitable for modeling the distributed nature of software installation, app stores and mobile devices so we will describe it in more detail than other authorization languages.

[36] M Y Becker, C Fournet, and A D Gordon. SecPAL: Design and semantics of a decentralized authorization language. *Proc IEEE Computer Security ...*, 2006

```
can(X, read, file ) :−
  employee(X, company).
employee(X, company) :−
  hr says empolyee(X, company).
hr says employee(john, company).
```

Figure 9: Statements in *Binder* to say that in the current context only employees can read a file, and that an employee they must have a statement from HR to prove they are an employee.

Syntactically SecPAL appears similar to Binder, however it has a richer syntax that allows for constraints and decisions to be made based on state (such as the time). SecPAL was designed to be readable and has a more verbose, English like, language than other authorization logics.

Like Binder it contains a *says* statement however unlike Binder it requires that all statements are said by a principal explicitly rather than relying on a default context. SecPAL also allows arbitrary predicates to be created, and also adds two additional special modalities to the logic. The *can-say* statement allows for explicit delegation and has two varieties. The *can-say*$_\infty$ phrase allows for nested delegation, whereas the *can-say*$_0$ statement does not. SecPAL also adds a *can-act-as* phrase that allows for aliasing entities.

Later extensions of SecPAL[37] add support for guarded universal quantification and remove the *can-act-as* statement. Other languages such as *DKAL*[38] built and eventually split from SecPAL. DKAL was designed to express distributed knowledge between principals by adding to the trust delegation mechanisms already in SecPAL. They also showed how any SecPAL statement could be translated into DKAL. The *SecPAL4P* language[39] was an instantiation of (the extended version of) SecPAL designed to specify how users' wished their personally identifiable information (PII) to be handled.

[37] M Y Becker. SecPAL: Formalization and Extensions. 2009

[38] Yuri Gurevich and Itay Neeman. DKAL: Distributed-Knowledge Authorization Language. *Computer Security Foundations*, pages 149–162, 2008

[39] M Y Becker, A Malkis, and L Bussard. A framework for privacy preferences and data-handling policies. ... *Cambridge Technical Report*, 2009

The inference rules for SecPAL are shown in Figure 10. Queries are evaluated against a set of known statements (the assertion context (AC)) and an initially infinite delegation level (D). If the rules show that the query is valid then SecPAL says the statement is okay else it is rejected.

$$\frac{\begin{array}{l}(A \text{ says } fact \text{ if } fact_1, \ldots, fact_k, c) \in AC \\ AC, D \models A \text{ says } fact_i\theta \ \forall i \in \{1 \cdots k\}\end{array} \quad \models c\theta \quad \text{vars}(fact\theta) = \emptyset)}{AC, D \models A \text{ says } fact\theta}\ \text{cond}$$

$$\frac{AC, \infty \models A \text{ says } B \text{ can say}_D fact \quad AC, D \models B \text{ says } fact}{AC, \infty \models A \text{ says } fact}\ \text{can say}$$

$$\frac{AC, D \models A \text{ says } B \text{ can act as } C \quad AC, D \models A \text{ says } C\ verbphrase}{AC, D \models A \text{ says } B\ verbphrase}\ \text{can act as}$$

Figure 10: The inference rules used to evaluate SecPAL. All SecPAL rules are evaluated in the context of a set of other assertions AC as well as an allowed level of delegation D which may be 0 or ∞.

Access Control Systems

TODO

Review of Datalog

Datalog is a database language created from a simplification of logic programming. It is based on first order logic and is known to be both sound and complete. Since Datalog is used as the basis for several of the authorization logics, including SecPAL, we will review some of the evaluation strategies used for querying Datalog knowledge bases.

Datalog programs are presented as series of Horn clauses in the syntactically same way as the Prolog language (see Figure). There are additional restrictions, however, that all variables in the head of a clause must be present in the body; and that no parameter can be a nested predicate.

When considering a Datalog program we split statements in it into two sets: into the extensional database (EDB) we place the set of ground (containing no free variables) facts, and into the intensional database (IDB) we place the rules for deriving more facts.

```
person(alice).
person(bob).
person(claire).
person(david).
mother(alice, claire).
father(alice, david).
mother(bob, claire).
father(bob, david).
sibling(X,Y) :- person(X),   person(Y),
                person(M),   person(F),
                mother(X,M), mother(Y,M),
                father(X,F), father(Y,F).
```

Figure 11: A simple Datalog program and describing a family, and a relation describing what it means to be a sibling.

Evaluation Strategies

The *bottom-up* or *Gauss-Seidel* method is one of the simplest evaluation strategies[40]. Given a Datalog program; try each of the known constants in the program as parameters to each of the rules in the IDB. When a rule is found to be true add it to the set of known facts. Repeat this process until a fixed point (or the required fact) is known. If a queried fact is still unknown when the process terminates then it is assumed to be false by the closed world assumption (CWA). The bottom-up strategy is known to be complete and to always terminate; and querying the database is fast once all facts have been inferred. Once all facts have been computed it allows for fast querying of the database and large joins to be calculated quickly.

[40] S Ceri, G Gottlob, and L Tanca. What you always wanted to know about Datalog (and never dared to ask). *IEEE Transactions on Knowledge and Data ...*, 1(1):146–166, 1989

However since this strategy ends up computing all known facts, it is less than optimal when only a subset of them will ever be interesting. The *magic sets*[41] rewriting rule avoids this problem by marking interesting constants as being *magic* and then considering the knowledge base as a graph: nodes related to a magic node are also considered magic. Rules in the IDB are then rewritten to include a predicate that constants used in the inference must also be magic. This cuts down on irrelevant results as anything that isn't interesting will not be in the magic set.

[41] Francois Bancilhon, David Maier, Yehoshua Sagiv, and Jeffrey D Ullman. *Magic sets and other strange ways to implement logic programs (extended abstract)*. ACM, New York, New York, USA, June 1985

The selective linear definite clause (SLD) resolution strategy works in the opposite direction. Rather than computing a set of all known facts it starts with a goal and then constructs a tree where

transitions are applications of rules from the IDB and nodes are either facts (the leaves) or further branches. If there is a subtree from the query node to leaves and all the leaves are true then the query is true. The Prolog language (which Datalog is a more constrained form of) uses this strategy and to keep its use of memory efficient searches the tree in a depth-first manner (though breadth-first and other tree traversal searches are also possible including parallel strategies). The *top-down* strategy is a less commonly used evaluation strategy for Datalog programs that is very similar to SLD resolution. Tabling is often used with this strategy to speed queries by memoizing previously inferred facts.

In the case of Prolog SLD resolution may not terminate if there is a set of rules that set up an infinite loop (for instance the rule `a(X) :- a(X).`), alternatively it is possible because Prolog has an infinite number of constants (i.e. the integers) it is possible to construct queries which return an infinite number of answers.

Whilst the bottom up strategy is more commonly used with Datalog programs; Becker's paper describing SecPAL[42] points out that since their programs may change dramatically from query to query recomputing every possible fact each time will not be efficient and is not appropriate. The SLD resolution strategy is also not appropriate (despite Datalog's finite Herbrand universe) as SecPAL's *can-say* and *can-act-as* assertions allow a potentially infinite recursion.

They present an algorithm for efficiently evaluating the Datalog translation of SecPAL programs. The algorithm uses the top-down strategy and tabling to speed the inference; they also show the algorithm is sound, complete and always terminates.

[42] M Y Becker, C Fournet, and A D Gordon. SecPAL: Design and semantics of a decentralized authorization language. *Journal of computer security*, 2010

Datalog Variants

Datalog does not support negation, and it is not possible to write inference rules which depend upon facts being false. This can be inconvenient as it is natural sometimes to write rules which rely upon a negative result: for example an app is safe to run if it uses a finite amount of memory, and is not malware.

A version Datalog with negation called *Datalog*$^{\neg}$[43] is achieved by allowing negation it clause bodies and defining two sets of known facts: those that are known to be true and those that are known to be false. When deciding if a fact is satisfied by a Datalog program if the fact is not negated then it must be inferable by the rules of the program; if the fact is negated then it must not be satisfiable.

[43] S Ceri, G Gottlob, and L Tanca. What you always wanted to know about Datalog (and never dared to ask). *IEEE Transactions on Knowledge and Data . . .*, 1(1):146–166, 1989

This is problematic because in the unmodified Datalog if the bottom-up strategy is used and all possible facts inferred then these facts form a single, minimal model of the Datalog program. In Datalog$^{\neg}$ the program `safe(game) :- ¬ malware(game).` has two minimal models that are inconsistent with each other: `safe(game)` and `malware(game)`. This can make analysis problematic as the CWA is broken. A further variant called *Stratified Datalog*$^{\neg}$ avoids this by

further restricting what can be negated and defining an evaluation order[44].

Constraint Datalog (Datalog^C[45]) is a version of Datalog based on constraint logic programming. Constraint logic programming allows relationships to be defined in terms of more general relationships (for example $<$) rather than in terms of explicitly defined predicates. Being able to define relations in terms of more general relations is very convenient for authorization logics as it allows relations to be defined in terms of time or other general (and infinite) predicates.

An example of this might be a scenario where there are two guards who can open a gate; the day guard can open it from 6 am to 6 pm, and the night guard can open it from 6 pm to 6 am; alternately an access control policy may allow a user to view all files whose path is within a specific directory. Expressing these relations in traditional Datalog is tricky as the number of files within that directory or sub-directories is infinite and the number of different specific times in the watchmen's shifts is also large. Traditional Datalog would require each of these times and files to be instantiated which is not ideal as it makes programs unwieldy. Several policy languages, such as Cassandra[46], SecPAL[47] and RT_1^C[48] use a form of Datalog^C as their evaluation engine to allow for this extra expressiveness.

Unfortunately while some constraints applied to domains are tractable (such as trees, ordering and discrete domains) Li and Mitchell could not show all were. Consequently policy languages that use constraint Datalog often apply additional restrictions to how constraints can be used. Variable independence conditions[49] have been suggested as a *middle-ground* as they can simplify the query evaluation while still keeping the extra expressiveness Datalog with constraints allows.

Proposal

Work Done In First Year

During the first year of my studies we have focussed on developing an authorization logic that can express the security policies a user might have for their smart phone; in particular the policies when the user is installing apps. We have considered what kinds of policies and trust relationships a user might wish to express and shown how they can be expressed in the language.

To do this we initially looked at a variety of authorization logics including BLF[50] and Binder[51] before settling on SecPAL as it was both simple, extensible and readable. SecPAL's decentralized nature was felt to be ideal for describing a mobile-device and app-store ecosystem as there isn't a single authority making decisions about what can and cannot be installed onto a device.

When considering the policies we wanted to allow users to del-

[44] K R Apt, H A Blair, and A Walker. Towards a theory of declarative knowledge, 1986

[45] Ninghui Li and John C Mitchell. Datalog with Constraints: A Foundation for Trust Management Languages. In *Practical Aspects of Declarative Languages*, pages 58–73. Springer Berlin Heidelberg, Berlin, Heidelberg, January 2003

[46] M Y Becker and P Sewell. Cassandra: flexible trust management, applied to electronic health records. *Proceedings. 17th IEEE Computer Security Foundations Workshop, 2004.*, pages 139–154, 2004

[47] M Y Becker, C Fournet, and A D Gordon. SecPAL: Design and semantics of a decentralized authorization language. *Proc IEEE Computer Security . . .*, 2006

[48] Ninghui Li and John C Mitchell. Datalog with Constraints: A Foundation for Trust Management Languages. In *Practical Aspects of Declarative Languages*, pages 58–73. Springer Berlin Heidelberg, Berlin, Heidelberg, January 2003

[49] J Chomicki, D Goldin, G Kuper, and D Toman. Variable independence in constraint databases. *constraints*, 2000

[50] N Whitehead, M Abadi, and G Necula. By reason and authority: a system for authorization of proof-carrying code. In *Computer Security Foundations Workshop, 2004. Proceedings. 17th IEEE*, pages 236–250. IEEE, 2004

[51] J DeTreville. Binder, a logic-based security language. In *Security and Privacy, 2002. Proceedings. 2002 IEEE Symposium on*, pages 105–113. IEEE Comput. Soc, 2002

egate decisions to experts who might be third party certification services or static analysis services running on a remote server or on the device itself. There should be the ability to use digital evidence[52] as a means of increasing trust in an external tool as this might allow proof checking to be done with less strain on a mobile's battery. We also wanted to have a clear separation between the checking of the user's security policy for the device (the *device policy*) and the policies any tool was checking for an app (the *application policy*). This means that any analysis tool needn't use the same logic for checking the application policy, as the device uses for checking it's own policy. In the security policy static analysis tools are treated as oracles: they can utter statements about their inputs but we do not know (or care) how they came to these conclusions.

[52] I Stark. Reasons to Believe: Digital Evidence to Guarantee Trustworthy Mobile Code. In *The European FET Conference*, pages 1–17, September 2009

To do this we extended SecPAL with two new predicates. The *meets* predicate is used to state that some entity believes an app meets an application policy. For instance if Alice believed that the *Angry-Birds* app met her policy to not leak information about her then we would have the statement:

Alice **says** AngryBirds **meets** NoInfoLeaks.

To express the notions of proof carrying code[53] and digital evidence we want to say that some evidence *shows* a policy is met. To do this we introduce the *shows-meets* predicate (whose notation we sugar somewhat). As an example consider again Alice who this time has managed to get some digital evidence to show Angry-Birds won't leak her information.

[53] G C Necula and P Lee. Proof-carrying Code. Carniegie Mellon University, 1996

Alice **says** Evidence **shows** AngryBirds **meets** NoInfoLeaks.

Alice Installs An App

To provide a better idea of the logic might be used we will describe a story where a user is trying to install an app on their mobile phone. This example is built from our work that was presented as a paper at the ESSoS Doctoral Symposium[54] and as a poster at the FMATS workshop.

[54] Joseph Hallett and David Aspinall. Towards an authorization framework for app security checking. In *ESSoS Doctoral Symposium*, pages 1–6. University of Edinburgh, February 2014

Suppose Alice has a smart phone. Alice has a security policy that says:

> "No app installed on my phone will send my location to an advertiser, and I wont install anything that Google says is malware."

Alice trusts Google to decide whether something is malware or not (or at at least recommend an anti-virus vendor who can be trusted), and she trusts the *NLLTool* to decide whether an app will leak her location data. Alice has heard about digital evidence and is happy that if an app can come with a proof of it meeting a policy then she will believe it.

She translates her policy into SecPAL thus:

Alice **says** app is−installable

```
    if app meets NotMalware,
       app meets NoLocationLeaks.

Alice says Google can−say inf app meets NotMalware.
Alice says NLLTool can−say 0 app meets NoLocationLeaks.

anyone says app meets policy
   if evidence shows app meets policy.
```

Alice wishes to install Angry Birds. To do so she downloads the app from a modified app store where apps come with statements about their security. Alice takes the statements from the store and builds her assertion context. These statements include a delegation from Google to say McAfee can be trusted to decide whether an app is malware or not, as well as some statements from McAfee and the NLLTool about the app itself. The full assertion context is shown in Figure .

Alice then uses SecPAL to decide whether or not the assertion context supports the idea that Alice says app is−installable.

```
Alice says app is−installable
   if app meets NotMalware,
   app meets NoLocationLeaks.
anyone says app meets policy
   if evidence shows app meets policy.
Alice says Google can−say inf
   app meets NotMalware.
Alice says NLLTool can−say 0
   app meets NoLocationLeaks.
Google says McAfee can−say 0
   app meets NotMalware.
McAfee says
   AngryBirds meets NotMalware.
NLLTool says ABProof shows
   AngryBirds meets NoLocationLeaks.
```

Figure 12: The full assertion context used to evaluate Alice's query.

Implementation

To evaluate her security policy we implemented the SecPAL logic. The implementation was done in the Haskell programming language and is around a thousand lines of code plus five hundred lines of test cases (including comments).

Whilst in the original SecPAL paper[55] Becker, Fournet, and Gordon describe an efficient implementation using Datalog; this implementation uses a simpler goal-oriented *brute-force* approach. It was written in this way to quickly evaluate whether SecPAL is a good fit for the problem, rather than to be an efficient production ready inference engine. In fact it could not currently be used on a phone as most Android devices run using ARM processors which are poorly supported by Haskell compilers. That said it supports command history, dynamically loaded constraint-functions, comes with syntax highlighting plugins for Vim, and has handled simple assertion contexts with over a thousand statements: whilst it is not ideal it can serve as a reference for a later efficient implementation if required.

[55] M Y Becker, C Fournet, and A D Gordon. SecPAL: Design and semantics of a decentralized authorization language. *Journal of computer security*, 2010

An example of a proof generated by the tool is shown in Figure 13. The proof is presented as an inverted inference tree where indented statements are the proofs for each condition of the unindented line above. Underlining indicates something is known to be true as it either exists in the assertion context or is true in itself. Variable substitutions are shown in brackets to aid debugging.

Thesis Proposal

I would like to focus on developing security policies for mobile systems in the remaining years of my PhD. My first year has focussed

```
AC, inf [app\AngryBirds] |= Alice says AngryBirds is-installable.
 AC, inf [app\AngryBirds] |= Alice says AngryBirds meets NotMalware.
  AC, inf [app\AngryBirds] |= Alice says Google can-say inf app meets NotMalware.
  ------------------------------------------------------------------------------
  AC, inf [app\AngryBirds] |= Google says AngryBirds meets NotMalware.
   AC, inf [app\AngryBirds] |= Google says McAfee can-say 0 app meets NotMalware.
   ------------------------------------------------------------------------------
   AC, 0 |= McAfee says AngryBirds meets NotMalware.
    AC, 0 |= True
    -------------
 AC, inf [app\AngryBirds] |= Alice says AngryBirds meets NoLocationLeaks.
  AC, inf [app\AngryBirds] |= Alice says NLLTool can-say 0 app meets NoLocationLeaks.
  --------------------------------------------------------------------------------
  AC, 0 [anyone\NLLTool, ...] |= NLLTool says AngryBirds meets NoLocationLeaks.
   AC, 0 [evidence\ABProof] |= NLLTool says ABProof shows AngryBirds meets NoLocationLeaks.
    AC, 0 |= True
    -------------
   AC, 0 |= True
   -------------
 AC, inf |= True
 ---------------
```

Figure 13: Proof output by the SecPAL tool when evaluating Alice's query.

on exploring SecPAL and ensuring it is the right logic to model the issues surrounding smart phones. The next two years will be spent exploring what happens when these policies interact with users.

The first step will be to complete the work done in the first year and show that a logic of authorization can model the security decisions made inside Android, and that it is capable of describing complex security policies. This will culminate in a technical report that describes the authorization logic, why it was chosen over other policy languages and showing some of the applications of the logic to mobile systems and the problems associated with them.

The next step will be to develop an app store that uses security policies as a filtering mechanism for it's users. Authorization logics have not been used in this application before and current markets are not filtering by a user's policies (though the Play Store is at least advertising apps to users on the basis of past app selections).

Creating an app store also allows users to interact with the research. Encouraging users to sign up for and use an app store with security policies increases the impact of the research, provides a practical example to illustrate how it can be applied to a real world problem. It also will offer a platform to test real policies against and show how different analysis tools can make different guarantees.

The store can also act as a framework and baseline to compare different store's policies against. By doing the policy checks at the app store level it avoid the need for users to root their phone (thereby reducing their device security) and allows for a wider range of users to interact with the project.

Creating a secure app store is a non-trivial engineering challenge; especially when combined with the danger provided by user

supplied policy files. The engineering difficulty in developing such a store can be mitigated by sensible software development practices.

The second stage of the project will be to increase the complexity of the policies and to show how the policies interact with the user. One area will be on compositional policies where a user might have one policy for apps at home and another for how they should use their phone at work. Showing that SecPAL could support policies of this kind is, as hinted earlier, easy in SecPAL or many other authorization languages; however it is not clear what to do when these policies change, or when new policies are composed with them, or when two composed policies contradict each other.

Another area to look at will be to show how policies can be written to take into account of the *app collusion problem*. Whilst tools have been written to detect and attempt to prevent these kinds of attacks there has not been an attempt to model the decisions to collude and with whom in a logic of authorization. Collusion is not, in itself, a sign of malicious intent. By developing an authorization logic to model these decisions will allow for a richer policy language for mobile devices.

The final area to look at to do with policy language will be to ensure the language is flexible enough to handle different scenarios when handling updates to applications. This will include looking at the whether permissions increase over time or if developers actively prune the lists; as well as developing policies that can describe what to do when a well-used app no longer meets the security policy.

At the end of the project I want to have shown how authorization logics can be extended to describe and mitigate decision making problems on mobile devices.

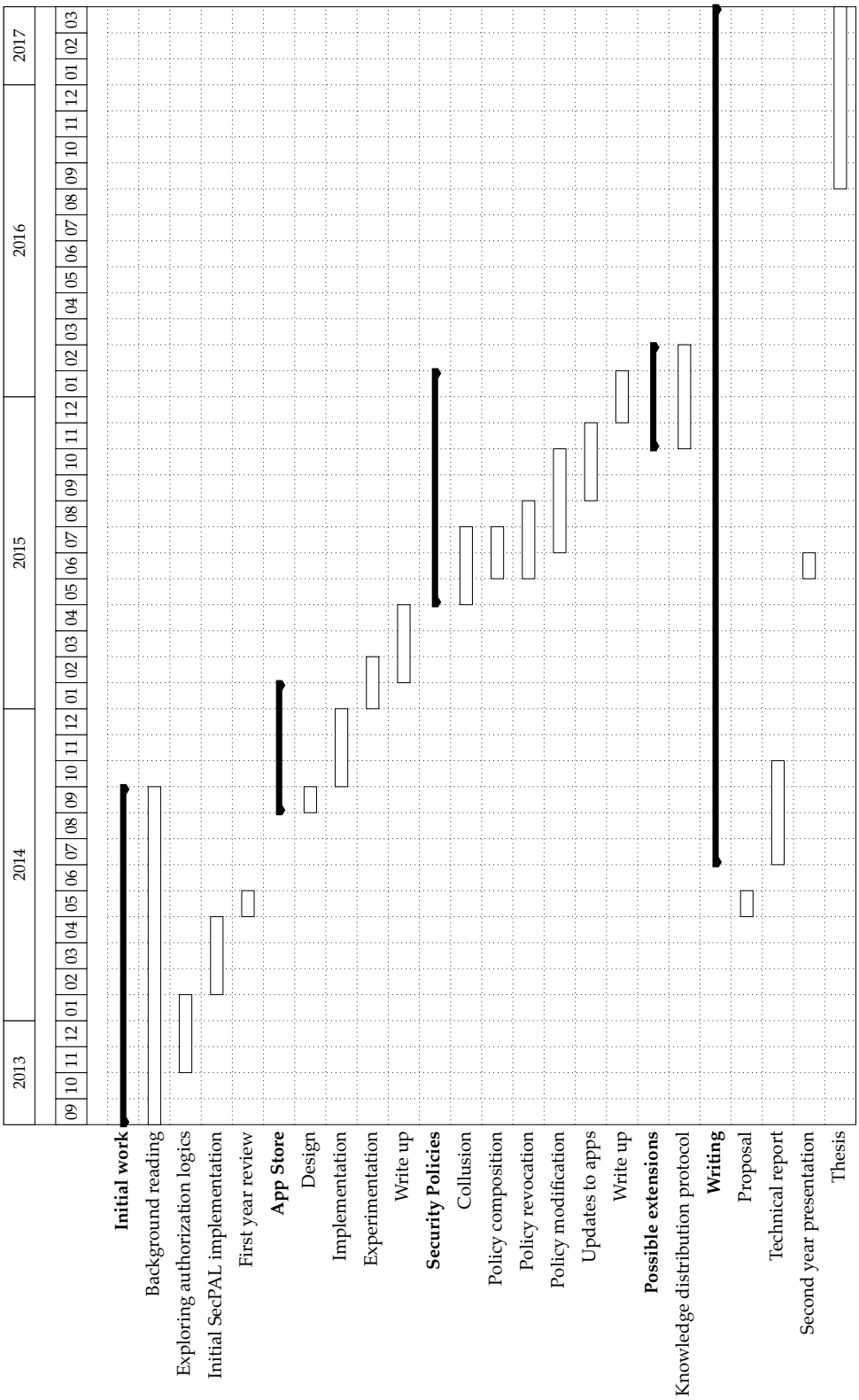

Figure 14: Gantt chart showing progress plans through out funded period of PhD study.

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