An intentionally insecure Android Image against Inter Component Communication attacks

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Declaration

This work has not been previously accepted in substance for any degree and is not being concurrently submitted in candidature for any degree.

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Abstract

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Your abstract should be a couple or so paragraphs long, and roughly approximate the order and flow you then use for structuring the main document. If a viewer has read your abstract then they should already understand at a high level what it is you have created and delivered, and whether it is better than or comparable to existing methods. If your project is driven by a research hypothesis then the reader should know what that is at a high level from this section. Reading on, little should surprise the viewer.

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Chapter 1

Introduction

1.1 Current State of Mobile Cyber Security

Ever since the release of the iPhone in 2007, smart phones and other mobile devices have played an increasingly larger role in our lives. We are using mobile devices for education, social interaction, commerce, mobile banking, entertainment, work, and more.

In the first world, mobile device usage has become ubiquitous. In the UK, smartphones became the most widely owned internet-enabled device in 2015 [6]. Moreover, 52.6 percent of global web traffic came from mobile devices in 2019, up from 31.6 per cent in 2015 [7].

Given the statistics from above, you would hope that mobile app developers have learned lessons from their desktop counterparts, and therefore, the majority of mobile apps are reasonably secure.

That assertion proves to be false. A study done by cyber security consultancy Positive Technologies analysed 17 mobile apps, 8 for Android and 9 for iOS, through comprehensive penetration testing in 2018 [8]. On the client side, it found that only 11% of the apps had an acceptable level of security, with 56% having a low or below average level of security, and 43 percent of Android apps had critical vulnerabilities. On the server side, security was no better, with 57 percent of components having low or below average security, and a third of components had critical vulnerabilities. A more worrying piece of information from the report is that the average Android client app in the study contained 3.7 vulnerabilities, with 1.1 of those being of high risk.

Against the lacklustre security of mobile apps, attackers are becoming more relentless and cunning, and are using more elaborate techniques [1]. In figure 1.1 you can see how the

monthly number of reported cyber attacks has tended to increase since 2017. This situation has been exacerbated by the COVID-19 pandemic [9], [10], with coronavirus related cyberattacks targeting both mobile device users [11] and hospitals [12].

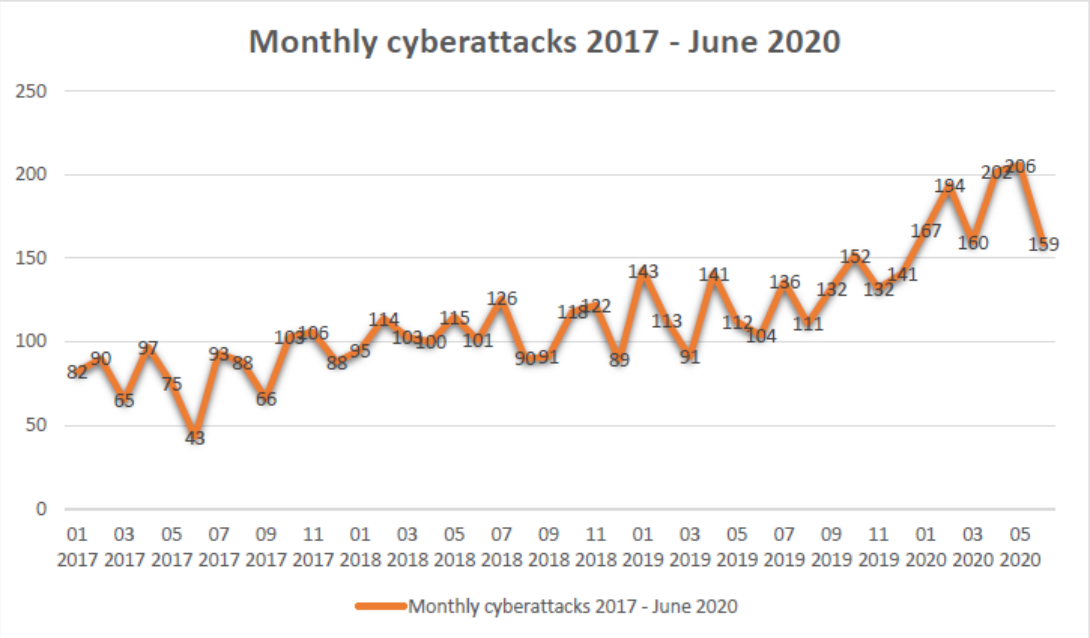


Figure 1.1: Increasing number of monthly cyber attacks since 2017. Data is compiled from [1], [2], [3] and [4].

Meanwhile, security of Android apps is not improving. A study conducted on over 400,000 APKs released between 2010 and 2016 belonging to over 28,000 apps used static analysis to see how Android app security evolved over time [13]. It discovered that critical vulnerabilities of various types have always been common in apps. Moreover, app updates generally do not improve security, and can even re-introduce previously fixed vulnerabilities. This is the largest and most comprehensive study of its time to date. Since it only considered APKs released before 2017, the situation might have improved since then, considering efforts by Google to combat malware [14]. Indeed, another study on the Google Play ecosystem found that the proportion of malware has dropped significantly in 2017 compared to 2014 [15], though it studied fewer APKs than [13].

1.2 Overview

The remainder of Chapter 1 outlines the document structure, the motivations behind undertaking this project, the aims and objectives of the project and the main contributions of this piece of work.

1.3 Motivations

I chose to explore Inter Component Communication vulnerabilities on Android in this project for reasons based on the current state of mobile application security and how this vulnerability category is touched upon in related work.

1.3.1 ICC-related vulnerabilities in current mobile apps

One of the categories of vulnerabilities that the authors of [8] analysed was Inter Process Communication related vulnerabilities. Inter Process Communication, abbreviated as IPC, refers to any exchange of information between two or more running processes on a computer system. In regards to Android, [8] also uses the term Inter Component Communication, or ICC, interchangeably with IPC. Android components are the logical building blocks of an app, and components can communicate with other components, which can belong to the same app or to another app on the same device. Android components, especially if they are of the same app, can run in the same process. Therefore, IPC and ICC are not synonymous, even though they often overlap.

In the study conducted in [8], 29 percent of client apps used insecure inter-process communication, and the average Android app had 1.1 ICC-related vulnerabilities [8].

Insecure inter-component communication is a high-risk vulnerability, and it is more dangerous than insecure storage or transmission of data, inadequate brute force protection or other common vulnerabilities [8], and therefore deserves significant attention from developers and cyber security specialists.

For Phil : Should the first and second paragraph of this subsection be moved to the Current State of Cyber Security section?

Moreover, while the overwhelming majority of vulnerabilities of other types are introduced in apps through the use of third-party libraries and rarely through developer code, ICC vulnerabilities differ in this regard. According to [13], between a third and a half of ICC vulnerabilities come from code written by the developer directly. Therefore, education regarding this type of

vulnerability addressed to the average developer would greatly help with minimizing the occurrence of these faults.

1.3.2 ICC-related vulnerabilities in related work

Vulnerabilities and cyber attacks concerning communication between Android components are not showcased in detail or intuitively in real word projects similar to mine. These projects either only cover some types of ICC related vulnerabilities, none at all, or are not easy to use, do not have good guidance, or do not show a realistic scenario.

Damn Insecure and Vulnerable App has challenges 9 and 10 that show examples of hijacking intents meant for a vulnerable activity [16]. DIVA also contains challenge 11 where a malicious user can send intents to extract data from an unprotected content provider.

Purposefully Insecure and Vulnerable Android Application, also called PIVAA from here on, has three challenges on components that are insecurely exported and thus can be sent malicious intents. The challenges show this vulnerability in a broadcast receiver, a service and a content provider, respectively.

Another intentionally insecure Android app used for educational purposes is InsecureBankv2 [17]. Similarly to PIVAA, it contains vulnerable components that can be started by a malicious app which injects a specially crafted intent, though it has a vulnerable activity, broadcast receiver and content provider and no service, unlike PIVAA [18]. Furthermore, another ICC related vulnerability it contains is intent sniffing, which allows a malware to intercept intents sent by components of the vulnerable app.

Damn Vulnerable Web Application, an intentionally insecure web application with vulnerabilities such SQL injection or Cross Site Scripting, does not cover any Inter Process vulnerabilities. TryHackMe.com is an interactive website for learning cyber security and penetration testing. Although easy to use and very useful, it has no dedicated activities on IPC.

None of the projects mentioned in this subsection cover all types of ICC vulnerabilities. Furthermore, DIVA, PIVAA and InsecureBankv2 only offer one application which has various components for each individual vulnerability they implement, they do not offer standalone apps for each vulnerability. More importantly, these applications are meant to be used together with other tools such as ADB or Dozer on a computer in order to perform each cyber attack. Thus, these projects do not offer real examples of malicious apps that can attack vulnerable apps. Another area in which these projects are lacking in is the educational instructions provided in the app. They provide little to no instructions, and only some hints as to how to solve each

vulnerability, they do not show detailed explanations and code examples of the vulnerability and how to fix it. In addition, they do not provide much interactivity, and have to be used together with a computer. Finally, some of the apps contain major UI bugs, such as the About project activity in PIVAA.

Damn Vulnerable Web Application, or DVWA, had multiple security levels for each vulnerability, where in each one the vulnerable program uses code that is increasingly secure. It tells the user what each level does, why it is not perfect, and shows source code for it. This is a very useful feature that is not shared by the three insecure Android app projects mentioned above in this subsection.

1.3.3 Motivation Conclusion

We have shown how vulnerabilities related to Inter Component Communication in Android are widespread and that they offer a dangerous attack surface through which applications can be hacked. Furthermore, current projects that implement intentionally insecure Android apps do not cover the domain of Inter Component Communication well and have a lot of room for improvement.

I have therefore chosen to create an educational tool that explores vulnerabilities related to insecure Inter Component Communication in Android that provides clear guidance, is interactive and combines the best parts from each of the related projects that I have looked into.

For Phil: Is the above paragraph good? Is this whole Motivation section too long? Do I add personal motivations?

1.4 Project Aims and objectives

In this section, we will discuss the causes of the precarious security of apps and why intentionally insecure programs are a good solution. Following that, I will present the aim of this project, and the actions or objectives that will be undertakes to achieve said aims.

1.4.1 Overview

Why is it that Android app security is often neglected? The reality is that software developers are not always trained in cybersecurity, may lack costly automatic analysis tools, or do not have the time to design and implement secure software due to tight deadlines [19]. These issues can be caused by upper management not being aware of the importance of cyber security. There-

fore, there needs to be more awareness of cyber security, and of vulnerabilities related to ICC in particular, in the software development industry, especially among developers, penetration testers and project managers.

To solve these issues, more education regarding the importance of cyber security in Android is needed. An Android image that is intentionally insecure could be designed as an educational tool. Such software could be used to highlight how android malware works and what it can do. It could teach people how to exploit vulnerabilities and how to fix them.

Such a product would be aimed at developers, penetration testers and senior technical management. For developers, it would make them aware of ICC vulnerabilities, what attackers can do and how to fix these issues. Penetration testers would be able to practice how to hack vulnerable apps using inter component communication. For the upper technical management of businesses, it would raise awareness of cyber security and the need to train staff and allocate proper resources.

1.4.2 Project Aims and Objectives

The aim of this project is to create an educational tool that can be used by penetration testers, developers, and tech savvy people alike to learn about Android mobile application vulnerabilities related to Inter Component Communication.

The primary objectives of the project, that will make up the minimal viable product, are:

- Develop an intentionally insecure Android image that will let the user explore various Inter Component Communication vulnerabilities, how to exploit them, and how to fix them. This will consist of a home application through which the user can access all educational material and can interactively learn about each vulnerability, and a series of apps that act as either a vulnerable app or a malicious app. Each challenge has two apps, one that is vulnerable and the other being the malware that exploits the former.
- Make sure that the experience of using the product is cohesive and pleasant.

1.5 Contributions

The main contributions of this work can be seen as follows:

• **An intentionally insecure Android image focused on Inter Component Communication**

During this project, we developed a series of Android apps that showcase a wide range of vulnerabilities related to Inter Component Communication, which are not the main focus of existing related work.

- **An educational tool for Android vulnerabilities that does not require the use of ADB shell**

  The finished product can be used to learn about ICC vulnerabilities on one's smartphone, and does not require one to use the ADB shell in order to attack the vulnerable app.

- **An intentionally insecure Android image which includes malware**

  Unlike existing projects of this type, our project has developed real malware apps that attack other apps in the image, and does not rely on the user to use ADB Shell to attack the app.

- **An intentionally insecure Android image with multiple security levels for each vulnerability**

  DVWA has multiple security levels for each vulnerability, as mentioned in subsection 1.3.2. No other related work on Android except ours implements this, to our knowledge.

For Phile: Is the contirbutions section good?

Chapter 2

Background

This chapter will cover the necessary technical background regarding Inter Component Communication. It will first explain Inter Process Communication (IPC) in computing in general. Next, it will give an overview of important concepts of the Android Operating System. Following that, we will explain what components and permissions are in Android, and then go on to discuss in detail Inter Component Communication, which is a type of IPC specific to this OS. Subsequently, we explore the various types of vulnerabilities related to Inter Component Communication.

2.1 Inter Process Communication

In the context of computing, a process refers to a running instance of a computer program. A process has its own section of computer memory that it has access to. By default, processes cannot access the memory address space of another process. Processes have one or more threads, which are individual sequences of instructions executed by the computer at a given time.

Inter Process Communication refers to the ways in which processes communicate and share data between each other. Using various means of IPC, computer programs can enhance their functionality greatly. For example, a word processing software like Microsoft Office Word can get data from a spreadsheet through Excel.

IPC can be accomplished through a variety of means: sharing files, sharing memory via various APIs, pipes, network sockets, the clipboard, and various means specific to each Operating System.

2.2 Basics of the Android Operating System

Android is an open source operating system designed for use on mobile devices released in September of 2008 [20]. It is built around a customised version of the Linux kernel. The UI and API are written in Java [21], which was also the primary development language for apps until 2019 when it was replaced by Kotlin [22]. Developer tools package compiled code along with any necessary resource files into an archive file called an APK, or Android package, which is then used by a mobile device to install the application.

In Android, each application is by default assigned a unique user ID known only by the OS. The files of an app can only be accessed by a Linux user with the same ID as that of the app. Moreover, each app runs in its own process by default, and each process runs in its own virtual machine [23]. Consequently, each Android application runs in its own sandbox, which enhances the security of the system, as apps are generally separated from each other.

Throughout the continuous development of Android, the API is modified to introduce new features and improve security or performance. Therefore, in order to identify each incremental version of the API, a unique integer is assigned to each version or level. Over the years, there have been changes to the API that improved software security, and therefore some vulnerabilities are harder or impossible to exploit in current API levels.

The manifest of an Android app is an XML file that gives the system information about the app's structure, capabilities and needs. All Android app components, except broadcast receivers, need to be declared in the manifest file, and for each component you can define permission requirements and the capabilities of the component [23]. Moreover, the developer can say in the manifest file what hardware or software system features the app uses, whether those features are required, and what is the minimum API level the app requires. For example, an app would not be installed on a device if the app's manifest said it required a microphone and the mobile device did not posses microphone hardware.

The manifest also specifies the target SDK version of the app, which refers to the API version for which the is built to run on. Android apps can run on devices with a different API version as well.

Components will be explained in detail later in section 3.3, and permissions in section 3.4.

2.3 Android Components

Android mobile apps are made up of logical building blocks called components. A component is an entity which allows the user or the operating system to access the application [23]. Therefore, a component does not necessarily correlate with other computing concepts such as processes or threads. When any component of an app needs to be run, the system starts a process for that app.

There are four types of components in Android: activities, services, broadcast receivers and content providers. We will detail these in the rest of section 2.3

2.3.1 Activities

Activities represent the individual app UI screens through which a user interacts with the app. For example, a news aggregator application might have an activity for viewing a list of news articles.

Activities are used by the operating system to keep track of what the user sees on screen, what information they are interested in, and the information of minimized apps that might be needed later [23].

Activities are independent components [23], and therefore it is possible that activities of different apps collaborate. This is what happens in a browser when the user wants to share a link and they choose between various messaging applications.

2.3.2 Services

Services are components used for running long-term operations in the background. Importantly, a service does not represent a separate process or thread, but an interface for the system to let the app work in the background [24]. A service does not have a user interface itself. Examples of the usage of services include VPN apps that maintain a VPN connection in the background.

There are three types of services: foreground services, which perform tasks that are noticeable to the user and must display a notification, background services, which do things that are not noticeable to the user, and bound services, which act as servers responding to requests made by client components [25].

2.3.3 Broadcast Receivers

Broadcast receivers are components that an app uses to receive system wide broadcasts. These broadcasts are messages sent by the operating system or by other apps. Applications can react to various events by using broadcast receivers. For example, the system can send a broadcast to let apps know that the device's battery is low or that airplane mode has been activated. An app can use a broadcast receiver to listen for an event even when the app is not running. Broadcast receivers do not have a user interface but can display notifications in the device's status bar. In addition, it is worth noting that they do not have to be declared in the manifest but can be created programmatically as well.

There are three types of broadcasts:

- Normal broadcasts – These are sent to all receivers at the same time, and each receiver can react independently of other receivers.
- Ordered broadcasts – These are sent to receivers one at a time. Unlike with a normal broadcast, the receiver currently processing the broadcast can change what information the broadcast contains, and can even cancel the broadcast, so that it will not be sent to further receivers [26]. Broadcast receivers can be registered with a certain priority for getting broadcasts.
- Sticky broadcasts – They are persistent broadcasts, they remain after they have been broadcast to all receivers and are re-broadcast to any new receivers. They have been deprecated since API level 21, because they are very insecure [27].

2.3.4 Content Providers

Content providers are interfaces through which apps can access data stored in persistent storage such as a remote server, an SQL database or local file storage. A provider can be used by components of the same app or by components of other apps. Therefore, they are used by the system to manage access to shared data. Content providers can restrict access to the data to apps with certain permissions and give temporary access to certain files only [23].

2.4 Permissions

Android follows the principle of least privilege. This means that, by default, each app only has access to the resources that it needs to complete its job. This principle is enforced through

a system of permissions, meaning that an application can only access sensitive data, system features or components of other applications if it possesses the necessary requirements [28]. For instance, an application needs the correct permission if it wants to access the user's contacts or the device's camera.

The developer can protect the components of an app with permission requirements by adding an android:permission tag in the manifest file. These elements can be added once for the whole application, or on a per component basis.

2.4.1 Types of permissions

There are four types of permissions, based on the level of protection they allow:

- Normal permissions – Permissions for unimportant resources, such as the permission to set the time zone [28]. They are granted automatically at install time.
- Dangerous permissions – These permissions are for important resources such as private user information, or that can affect the state of the system or of other apps. The user needs to give explicit permission in the app to utilise these resources.
- Signature permissions – These are special permissions designed for use among a group of apps created by the same developer. An app is automatically granted a signature permission at install time only if it is signed by the same certificate as the app that defined the permission. The certificate does not have to be signed by a certificate authority, they can be self-signed by the developer. Their purpose is to identify the author of an app [29].
- Signature or System permissions - a deprecated type of permission since API level 23 [30]. It is automatically granted only if the app is signed by the same certificate as the app that declared the permission or if the app is in the system folder. Apps in the system folder are installed by the mobile device's vendor.

2.4.2 Custom permissions

Applications can declare their own permissions. These can be used to restrict access to components of an application, or protect broadcasts of that app. This is done by declaring a permission in the manifest file of the app.

```
1 <permission
2   android:name="uk.ac.swansea.alexandru.icc_education.permission.BANKING_ACTIVITY"
```

```
3   android:label="@string/lab _bankingActivity"
4   android:description="@string/desc_bankingActivity"
5   android:protectionLevel="dangerous" />
```

Listing 2.1: A declaration of a custom permission in an Android manifest.

2.5 Inter Component Communication

So far, we have seen that each Android application runs in its own sandbox, and by default can not see what other applications are doing. Sometimes, we need the system to communicate with the apps, and applications can enrich the users experience by collaborating. Moreover, an application component can be used by other apps to provide extra functionality. For example, a browser lets you select which social media or messaging app to use for sharing a link.

Intents are a class in the Android API that are used as messages for communication between application components. More specifically, intents are used to start new activities, start and stop services, bind or unbind a component to a service, and they also represent the broadcasts that are sent to receivers.

2.5.1 Exported Components

By default, app components are not accessible to outside apps through intents. However, a component can be exported and thus receive intents from other applications. To export a component, you can set the `<exported>` tag in a component in the app's manifest to true. However, if the component has an intent filter defined in the manifest, the component will become automatically exported unless the exported tag is explicitly set to false. Intent Filters will be fully explained in section 3.5.3.

Further complicating component exportation is that developers can configure an application to use the same Android User ID as other applications created by them. This means these apps can run in the same process, and they can access each other's components regardless of the exported tag or the presence of intent filters, as can be seen in figure 2.1

2.5.2 Explicit Intents

Explicit intents directly specify the application that should receive the intent and handle it. This is done by setting either the package name of the receiving application, or the full name of a

Activity configuration		*Application configuration*	*Consequence*	
Exported	*Intent filter*	*SharedUid*	*Callers accepted*	*Risk level*
Exported="true"	Present	Any	Any	High
Exported="true"	Absent	Any	Any	High
Exported="false"	Present	Set	From same developer	Low
Exported="false"	Absent	Set	From same developer	Low
Default	Present	Any	Any	High
Default	Absent	Set	From same developer	Low

Figure 2.1: Exportation of components in various circumstances. Taken from [5].

component of said app [31]. Explicit intents can contain other information, such as data or the intended action to be performed, as you can see in Listing 2.2.

Using an explicit intent means that only the targeted app or component can receive the intent. Explicit intents are usually used for communication between components of the same app, such as when one activity starts another when the user clicks a button. That being said, explicit intents can be used to start components of other apps as well. As explained in subsection 2.5.1, an app component must be exported so that other apps can send explicit intents to it.

```
1 val noPaymentUri : Uri = Uri.parse("santander_pay://uk.ac.swansea.dascalu.dvmicc.
      santander/pay")
2 val intent = Intent(this, LogInActivity::class.java)
3 intent.setDataAndType(noPaymentUri, "text/plain")
4 startActivity(intent)
```

Listing 2.2: Kotlin code to make an explicit intent, add data to it and start an activity with it

2.5.3 Implicit Intents

Unlike explicit intents, implicit intents do not directly specify what application or component it should be sent to. Instead, the Android system decides who to send it to based on the information in the intent and what other components have declared they can handle.

A component defines what intents it can handle by specifying Intent Filters in the manifest file, with an example in Listing 2.3. An Intent Filter defines the type of intents an application can handle. A filter can say what actions the component can perform, what intent categories it accepts, the MIME data types it accepts or the kind of URI resources it can handle. A component may declare multiple Intent Filters, and it is recommended that this is done for each task the component can do [31].

```
<activity android:name=".LogInActivity">
    <intent-filter>
        <action android:name="uk.ac.swansea.dascalu.dvmicc.santander.intent.action
            .LOGIN" />
        <category android:name="android.intent.category.DEFAULT" />
        <category android:name="android.intent.category.HOME"/>
        <data android:mimeType="text/plain"
            android:scheme="santander_pay"
            android:host="uk.ac.swansea.dascalu.dvmicc.santander"/>
    </intent-filter>
</activity>
```

Listing 2.3: Declaration of an intent filter that the intent in Listing 2.4 will match.

When an implicit intent is sent, like you can see in Listing 2.4, the Android System compares its attributes against all intent filters of all components. For the intent to be matched with a filter, three tests are performed: the Action test, the Category test, and the Data test [31]. In order to pass the Action test, the Intent's action must be amongst the actions of the filter. It passes the Category Test if all of its categories are found in the filter's declaration, and the Data Test is passed if the data URI or MIME type of the intent matches one of the data elements in the filter. If the component has multiple filters, the intent only needs to match one of them for it to be passed to the component.

```
val noPaymentUri : Uri = Uri.parse("santander_pay://uk.ac.swansea.dascalu.dvmicc.
    santander/pay")
val intent = Intent("uk.ac.swansea.dascalu.dvmicc.santander.intent.action.LOGIN")
intent.addCategory(Intent.CATEGORY_HOME)
intent.setDataAndType(noPaymentUri, "text/plain")
startActivity(intent)
```

Listing 2.4: Kotlin code to make an implicit intent, add data to it and start an activity with it

If only one intent filter matches the implicit intent, the operating system will start that filter's component automatically. However, if there are multiple matches, a dialog will be displayed to the user so they can manually select the component to handle the intent.

For example, if there are multiple browsers installed on a device, and within an app the user clicks on a web link, they will then see an Android dialog letting them choose what browser to use to open that page. This is because the parent app sent an implicit intent, and all browsers had filters that matched with the intent.

2.6 Inter Component Communication Vulnerabilities and Attacks

In this section, we will explain how the way components communicate using Intents can be exploited by attackers, and what developers can do to fix these vulnerabilities.

Most of the vulnerabilities that will be explored in this project happen due to the misuse of implicit intents or intent filters. Because implicit intents do not directly state what component they target, it is possible that an intent is delivered to a malicious app. Moreover, an attacker could create malicious intents that could launch other components in ways that could compromise the victim app.

2.6.1 Unauthorised Intent Receipt

The Android documentation recommends that explicit intents are used for intra-app communication, and implicit intents for inter-application communication [31]. However, developers sometimes use implicit intents to start a component within the same app. An attacker can make an app with an intent filter designed to match with said implicit intents, which can direct the intent to the malicious application. When receiving an intent, a component can read all of its data. Therefore, even if the implicit intent is meant for external use, if the developer puts sensitive information in it, that data could be intercepted.

In general, vulnerabilities against this class of attacks are fixed by using explicit intents instead of implicit intents in order to send broadcasts, start activities or services or grant access to a content provider [32]. Another way to mitigate these attacks is to not put sensitive information in implicit intents.

The rest of subsection 2.6.1 explains various types of the Unauthorised Intent Receipt attack.

2.6.1.1 Broadcast Theft

When a broadcast is sent, the sender does not receive any indication of what components have received that broadcast. A malicious app could register a broadcast receiver with as many intent filters as possible to listen to many public broadcasts [32]. The malware would be able to read the data in the broadcasts without the user knowing it, and could therefore be used as spyware. Moreover, if an implicit intent is used for a broadcast meant for an app's internal use, that broadcast will be sent to any receiver on the device with a matching filter.

Ordered broadcast are sent to receivers one at a time, as explained in subsection 2.3.3. The use of ordered implicit broadcasts can not only enabled eavesdropping as described above, but denial of service and man in the middle attacks as well [32]. A malicious app could register a broadcast receiver with a very high priority to ensure it is the first to receive it. It could extract the data from the broadcast, and then abort the broadcast, ensuring the intended receivers do not get it and thus perform a Denial of Service attack. Otherwise, the malicious receiver could replace the original data with malicious data, and perform a Man In the Middle attack. This could be used to corrupt data or crash other applications.

When making a broadcast, the developer can specify the permission that a broadcast receiver needs to have in order to be able to get it. This can be used to guard against Broadcast Theft. A developer can declare their own custom permission, as seen in section 2.4, which must be obtained by receivers to be able to get broadcasts sent by the developer's app.

However, if the developer does not set the protection level of the permission, it will default to "normal", and the malware will get it automatically at install time. The developer can set the protection level to "dangerous", meaning the malware needs to ask the user to grant that permission. This is quite secure, but a careless user may still grant it. The most secure protection level for the custom permission is "signature", but if the private key of the certificate is not stored securely, it can be stolen and be used to sign the malware, which would be able to get the permission. In order to make broadcast theft impossible, the broadcast should be sent as an explicit intent, or as an implicit intent which specifies the package of components that can receive it [32]. Other ways for a developer to guard against these attacks is to not put sensitive information in a broadcast unless necessary.

2.6.1.2 Activity Intent Hijacking

In this type of attack, a hacker takes advantage of the use implicit intents so that a malicious activity is launched instead of the intended one, by registering the right intent filters for their malicious activity.

In a sophisticated version of this attack, the attacker could use phishing to steal user credentials [32]. For example, consider an application with a log in screen. If that application uses an implicit intent to start the Log In activity, a hacker could create an identical looking Log In activity in their app. They could then use an identical intent filter for their fake activity. This means that the implicit intent will match both the fake Log In activity and the legitimate one as well, and thus prompt the user to choose between them. The attacker can give a confusing

or identical name to their malware, or make the icons of the two apps similar in order to make the user choose the malware. The unaware user would then type in their credentials on the fake Log In screen, which could then be sent to the hacker.

This type of attack is most dangerous when it intercepts implicit intents meant to launch an activity within the same app. This is because it disrupts the workflow of that app, and the attacker can get data that should be private.

2.6.1.3 Service Intent Hijacking

This type of attack is similar to the Activity Intent Hijacking attack, but it concerns the malicious start of unwanted services. If a mobile application uses an implicit intent to start a service, then the Android system will search for services with intent filters that match the intent. A key difference between activities and services is that when multiple services have filters matching the same intent, then the OS chooses a service to start at random [33], the user does not get to choose. This, combined with the fact that services give at most a notification in the Android status bar, means that it is harder for the user to be aware of this attack.

Once the malicious service is started, a multitude of things can happen. It could steal any sensitive data in the intent and lie about completing the intended task. Even more dangerous is the scenario where the implicit intent is used start a bound services, which can return information to the client components more easily and frequently. Thankfully, since Android 5.0 it is impossible to start a bound service with an implicit intent [34], and therefore we have not covered Intent Hijacking for bound services. A malicious service could return false information to clients, and this could be used to crash other apps and thus perform a Denial of Service Attack, pollute other components with fake data or manipulate the client components to perform other attacks [32].

To give an example, consider a messaging app like WhatsApp. This app would use a service for making periodical backups of the user's messages. If it used an implicit intent to start this service, an attacker could make a service in their app with a matching intent filter. The malicious service could be started at random instead of the legitimate one. This service could then get access to the user's messages and upload them in the background to the attacker's server. The malicious service could be hidden in an app that appears to have an unrelated functionality, and thus be hidden.

2.6.1.4 Content Provider URI Hijacking

We have discussed that intents can transmit data using a URI. These URIs can point to data stored using a Content Provider. We have also explained that permissions can be set on a per component basis. However, when declaring a Content Provider in the manifest file, the developer can set the `android:grantUriPermissions` tag of the `<provider>` element to true. This means that the content provider can allow temporary access to data linked to in a URI for a component that does not otherwise have the permission required by the provider.

In order to do this, the intent that transmits the URI link must have the `FLAG_GRANT_READ_URI_PERMISSION` or `FLAG_GRANT_WRITE_URI_PERMISSION` flags added to it. If this intent is an implicit intent and is intercepted by a malicious component, then that component can read the data and perhaps modify it. This attack can put private information, such as debit card information or a phone number, in the hands of attackers.

2.7 Intent Spoofing

While the Intent Hijacking attacks that we have detailed worked by accidentally activating a malicious component when an intent is intercepted, Intent Spoofing attacks happen when a victim component is unexpectedly activated by an attacking component using an Intent. Often, this attack targets components that are not meant to be accessible outside of their apps, but because they have an intent filter and the `<exported>` tag is not set, they are exported automatically. Because exported components are accessible to other apps, the attacker can create an explicit intent targeting it and does not need to worry about having to match intent filters. The developers are usually unaware of this.

This attack is dangerous because components often extract information from the intents they receive. An Intent Spoofing attack could insert malicious information into the victim component. The attacker could send invalid information to crash the victim's app (a DoS attack), corrupt the user's data, or inject commands to retrieve data. Often, the launch of an activity, service or broadcast receiver leads a change in the application's state [32], even if the victim component takes no input from the intent. And since activities and services can return information to the component that activated them, they could leak sensitive information. This attack is often done against components that were not meant to be accessible to other apps, and these components are thus less likely to check the input data of the intent or make sure they do not return private data.

Developers can secure their application from this class of attacks in a number of ways [32]. First, they should not declare intent filters for internal components, and they should use explicit intents to launch them. Secondly, if they need to use intent filters for internal components, they should explicitly declare them as not exported in the manifest. Thirdly, they can protect components with permissions of various types. Fourthly, state-changing operations should not be done in exported components. And finally, developers should make sure that exported components do not return information that should be private.

Chapter 3

Finding and citing resources

The university has subscriptions to a vast number of major academic journals spanning a wide range of subject areas. By accessing the internet from a university network connection (Eduroam or Ethernet), the paywalls of many journals will simply vanish without any need for login credentials.

3.1 Tunnel your internet connection via the university internet

When you are working from outside of the university then connecting to an on campus machine via remote desktop (RemoteDesktopProtocol, TeamViewer, ect) or via port forwarding (ssh, ssh tunnel, ect) can allow you to access papers that would otherwise be behind a paywall.

If you do not have individual access to a machine that is exposed for ssh on the university network you can always use the computers in Linux Lab CF204[1] for the purpose of setting up an ssh port tunnel to proxy your internet through. These machines have fixed IPv4 addresses and respond to ssh using your student account credentials. While in use your internet will be routed[2] to the university and then out to the internet, granting you transparent access to journals without a paywall.

[1] One caveat of using computer lab machines for remote tunnelling is that a environmentally conscious student who has worked late in the computer lab might choose to switch off the machine you were using...

[2] Painfully slowly.

3.2 Practice your Google Fu

The internet is big [35]. Knowing how to phrase a question to a search engine is therefore an invaluable skill. If the request is simple enough, even a poorly structured query will likely return usable results. For more difficult to find resources you can leverage the language of the search engine to gather relevant papers and resources for your research more efficiently.

`https://www.gwern.net/Search`

"Internet Search Tips" [36] provides an excellent review of methods and tips for scouring the internet for hard to find resources. You will also be less likely to get caught behind journal paywalls when working remotely without a tunnel as your queries can be made to look for raw pdfs that are often released by the authors directly.

3.3 Organizing your citations in BibTeX

BibTeX is a language for specifying resource citations. Every time you access and read an academic paper, take code from an online repository, or source the media such as images from existing works you should create a BibTeX entry in a file that you keep throughout your research. Software such as Mendeley [37] can help automate the process of building your BibTeX library of citations.

```
@INPROCEEDINGS{kaj86,
    author    = {Kajiya, James T.},
    title     = {The Rendering Equation},
    booktitle = {Proceedings of the 13th Annual Conference on Computer Graphics
        and Interactive Techniques},
    year      = {1986},
    series    = {SIGGRAPH '86},
    pages     = {143--150},
    address   = {New York, NY, USA},
    publisher = {ACM},
    isbn      = {0-89791-196-2},
    numpages  = {8},
    acmid     = {15902}
}
```

Listing 3.1: An example BibTeX entry for an academic paper published in conference proceedings [38].

The BibTeX code listing above (listing 3.1) shows an example of how to cite an academic paper, in this case one of the central papers in Computer Graphics research. The key **kaj86** is

an arbitrary name chosen as a meaningful identifier for the resource. In the document text we can call on this resource as an inline citation using the LaTeX command `\cite{kaj86}` which produces [38] at the location it is called. As long as a citation has been used at least once somewhere within the document then a formatted full citation will be created in the bibliography at the end of the document with the same citation number that is shown inline.

It is considerably easier to be disciplined in methodically taking note of the resources you access and make use of as you access them, than it is to try and hunt them all down again at the time you need to write about them in your document. Invest time in being organized and consistent up front and it will be easier when you come to write up.

3.4 Properly using and formatting citations within the text

Usually you would not put the URL of the resource you are citing directly in the text like is done previously in section 3.2. The citation for the resource [36] is sufficient to reference it within the text given that full details of its location are then kept neatly within the bibliography at the end of the document.

In normal usage the purpose of a citation is not to direct the reader away from your thesis, but to justify and back up assertions you are making about the state of the domain. If a reader questions your assertions then they can follow the rabbit hole of papers which will likely also make and justify assertions with even earlier papers from the literature.

In the above case the intention is for the reader of this template to actually go to that resource and read what it has to say directly. The link is therefore shown clearly within the main text to indicate that the reader should visit it. This as opposed to wanting the reader to purely acknowledge that the facts which are within the resource legitimize the points made in this document, in which case a simple inline citation is the best way to back up your assertions. Section 4.3.7 specifically touches on the best practice for how to cite images which you are importing from existing work.

Chapter 4

Typesetting your thesis

This document is intended as both a LaTeX thesis template and as a tutorial on structuring and typesetting your thesis in the LaTeX programming language.

The following are some powerful online resources for learning about LaTeX:

- **Overleaf Documentation for LaTeX**

  Overleaf [39] is an online browser-based LaTeX IDE which stores your document in the cloud and provides live recompilation as you type. The documentation on Overleaf's website has a good knowledge base of examples for how to typeset things cleanly and simply in LaTeX code.

  See: `https://www.overleaf.com/learn`

- **TeX StackExchange, the StackOverflow site dedicated to TeX questions**

  TeX StackExchange [40] is sub-community of the StackOverflow network dedicated to questions about the TeX family of typesetting tools including LaTeX, BibTeX and others. A vast majority of the time it is unlikely that the question or issue you are facing is one that has not been encountered before, and this site more than likely to be able to point you in the correct direction.

  See: `https://tex.stackexchange.com`

4.1 Referencing items within this document

In section 3.3 we saw examples of how to typeset citations for resources we had stored in an external BibTeX file. However, often we would like to accurately refer to the location of a resource or region of text stored somewhere else within this document[1]. To do this we need to annotate our LaTeX code with `\label{key}` statements which will take on the numeric (or otherwise formatted) identifier for the current chapter, section, figure, table, equation, ect where they are directly defined. To insert an inline reference to the label you can use the `\ref{key}` command which works similarly to the `\cite{key}` used for external references. In the event we chose to reorder or add additional content to the document, which would change the section numbering, the document will still compile to a pdf with the correct references inserted for each `\ref{key}` command.

4.2 Equations

Typesetting equations is one of the things that LaTeX does best. It has packages for different fonts and symbols for many different mathematical notations. However, to person learning how to typeset in LaTeX for the first time it can be a daunting and unwieldy user experience. Almost all LaTeX packages have documentation available in pdf format online, and documentation for packages specifically relating to fonts and symbols usually have tables enumerating the names and codes for all of the fonts symbols, organized by intended usage.

4.2.1 Inline equations

Small equations like $x = 0$ can be written directly within the text by using LaTeX's maths mode shorthand controlled by dollar signs `$ math mode $`. As long as it is not becoming cumbersome to the reader, equations such as $\mathbb{P}(A \cap B) = \mathbb{P}(B \cap A)$ are quite neatly displayed in this fashion.

[1] Like at the beginning of the last sentence when we referred to section 3.3.

4.2.2 Block equations

For long equations it is best to provide a break in the main text of the document and format the equation using a `\begin{equation}...\end{equation}` environment.

$$|a| = \left\| \begin{bmatrix} a_0 \\ a_1 \\ \vdots \\ a_n \end{bmatrix} \right\| = \sqrt{a_0^2 + a_1^2 + \ldots + a_n^2} \tag{4.1}$$

Equation 4.1 demonstrates formatting a larger equation and uses an `\begin{array}...\end{array}` environment to structure a column vector of sub-equations. Block equations should be located at a relevant point directly as they are being referred to in the text. When referred to from other locations in the document you should use the `\ref{key}` command to insert the correct equation number.

4.2.2.1 Aligning multi-line block equations

When equations become even larger they may need cross over multiple new lines. When this happens it is desirable to align relevant parts of the equation on each line to one another for aesthetic reasons and to help imply structure to the reader.

$$\begin{aligned} \mathscr{L}_o(x,\omega_o,\lambda,t) &= \mathscr{L}_e(x,\omega_o,\lambda,t) \\ &\quad + \int_\Omega f(x,\omega_i,\omega_o,\lambda,t)\,\mathscr{L}_i(x,\omega_i,\lambda,t)\,(\omega_i \bullet n)\,d\omega_i \\ &\quad \text{where} \quad \mathscr{L}_i(x,\omega_i,\lambda,t) = \mathscr{L}_o\left(x',-\omega_i,\lambda,t\right) \end{aligned} \tag{4.2}$$

Equation 4.2, known as Kajiya's Rendering Equation [38] demonstrates the use of the `\begin{split}...\end{split}` environment which uses a single un-escaped & symbol placed on each line of the equations LaTeX code to indicate where each line should be co-aligned. In this example the &'s were placed on the =, +, and w (in where) characters.

4.2.3 A masochistic approach to learning to typeset mathematics in LaTeX

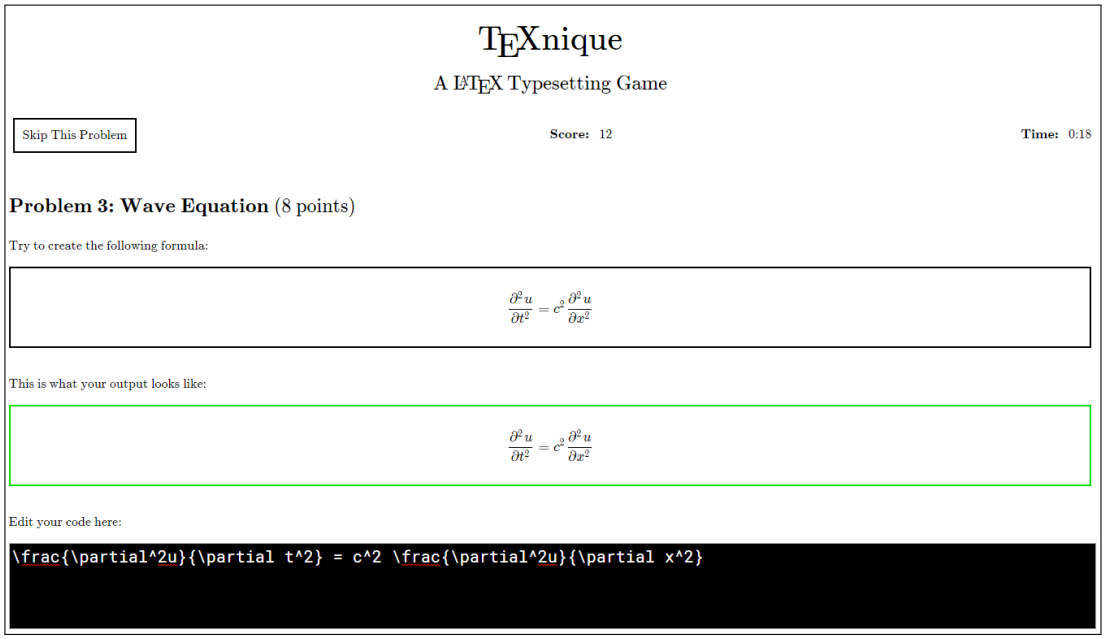


Figure 4.1: TeXnique, a game about typesetting equations [41]. (Top) The game presents you with a rendered equation, (Bottom) the task is to enter LaTeX code that produces the same rendered equation. The green border on the lower rendering indicates it is a valid solution.

TeXnique [41] is web-browser based game for practising how to typeset equations in LaTeX. The game will present you with a rendered equation and your task is to type LaTeX code into the box below it such that your code produces the same (or closely matching / pixel equivalent) rendered equation. Figure 4.1 shows the game during play, the bottom rendered equation is bordered in green to indicate it is a valid match with the target.

`https://texnique.xyz`

This is one of the more painful parts of typesetting a document, so it really takes a special kind of sadism to come up with such a game. Least to say, graduate students and researchers can be an odd bunch, and when we found this it was surprisingly addictive to compete over.

4.3 Figures

In this template figures are numbered starting with the current chapter number followed by a figure number that resets to 1 each new chapter. As you can see below, the first figure is

labelled Figure 4.2 because we are in Chapter 4.

Figures in LaTeX are defined using a `\begin{figure}...\end{figure}` environment and often immediately begin rendering in centre aligned mode by calling `\centering`. Listing 4.1 below shows the LaTeX code used to typeset figure 4.2. Figures 4.3 and 4.4 are defined similarly and make additional use of the `\subfloat` command to position multiple images within a single figure environment, each with their own automatically incremented labels and individual captions.

```
\begin{figure}[H]
  % [H] means put the figure HERE, directly when you input this code.
  \centering

  % We set the width of the figure based on the width of one line
  % of text on the page. The value can be tuned to any value in
  % [0.0, 1.0] to scale the image while maintaining its aspect ratio.
  \includegraphics[width=1.0\linewidth]{./graphics/dragon.png}

  % Caption is defined with a short and long version. The short
  % version is shown in the List of Figures section, and the long
  % version is used directly with the figure.
  \caption[Short caption.]{Long caption and citation \cite{whittle15_dragons}.}

  % For figures, \label should be defined after the caption to ensure
  % proper figure numbering.
  \label{fig:dragon}
\end{figure}
```

Listing 4.1: An example LaTeX excerpt demonstrating how to typeset figure 4.2 with a simple caption.

4.3.1 Consistent presentation throughout the document

Figures work best in a document when you use a consistent style for formatting and captioning them and make sure that figures always actively support the content of the main text.

4.3.2 Justified use of space in the document

All figures must be referred to directly in the main text of the document and discussed with meaningful and in depth critical analysis. If you don't need to use the figure to leverage and support your discussion then it is just taking up space and padding out the document. For example, you can use a command like `\ref{fig:dragon}` to automatically get the figure number for Figure 4.2.

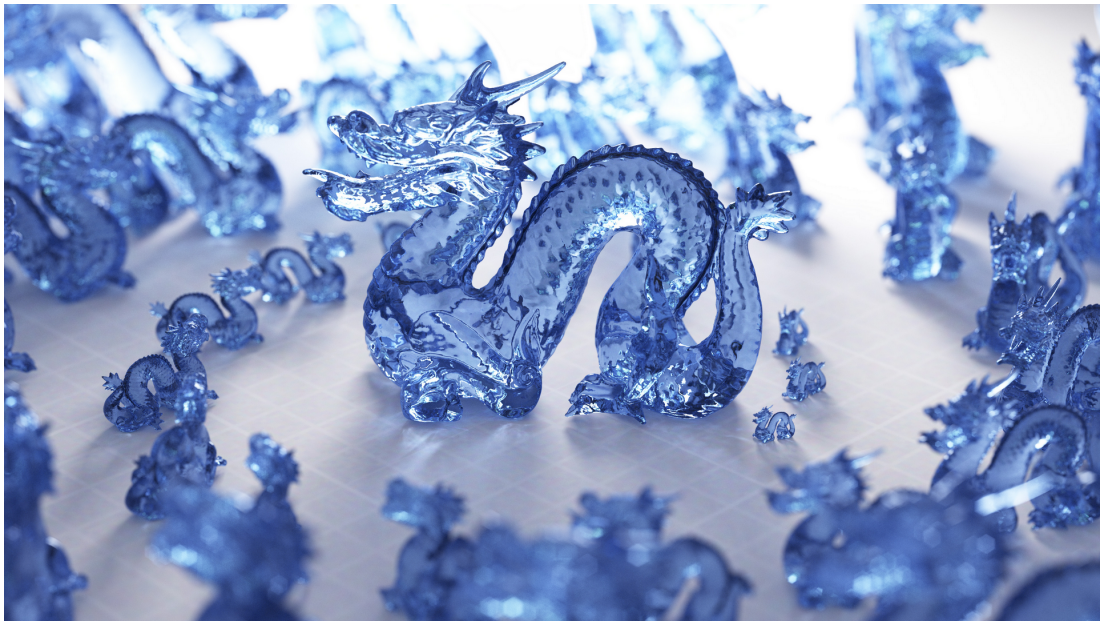


Figure 4.2: A good caption should be sufficient enough to put the figure in context even if the reader has randomly flicked to the current page and looked only at the figure in isolation. All figures should also be referred to directly within the main text of your document. You can use the LaTeX **\ref{key}** command to insert the correct figure number when you refer to it in the main text. By the very logic of this caption, this is a very poor caption because we still don't know why on earth is there an picture of glass dragons here. Image of glass dragons rendered using Path Tracing [42].

4.3.3 Placement that supports and enhances the flow of the document

All figures shown in your document should be displayed in relevant locations, ideally just after that have been alluded to in the main text. Although there are many times where it is best to force a figure to the top or bottom of a nearby page.

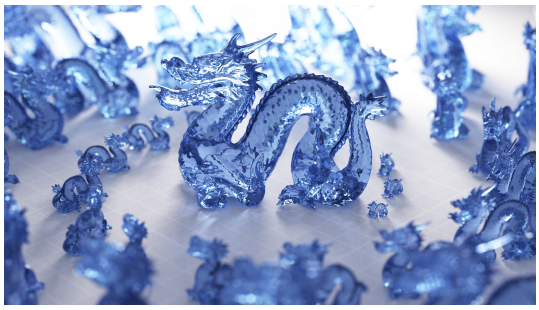
4.3.4 Avoid directly importing other peoples images

You should avoid using other peoples figures whenever possible, and instead create your own figures for visualizing the specific methods and data you are working with in a way directly relevant to your project.

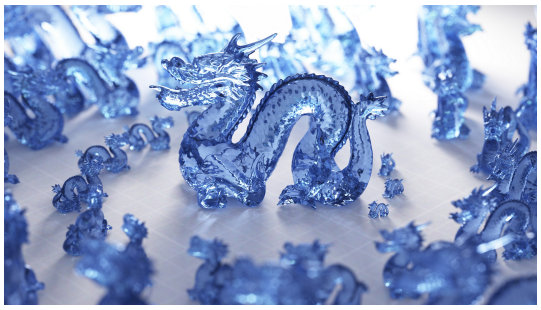
4.3.5 Format sub-figures in LaTeX, not in the image itself

Construct sub-figures from multiple image files in LaTeX not in the image file itself. This allows you to tweak the positioning and layout without having to modify the images. It also

allows for automatic formatting and numbering of captions and sub-captions. Figures 4.3 and 4.4 show examples of side-by-side and quad layouts respectively.

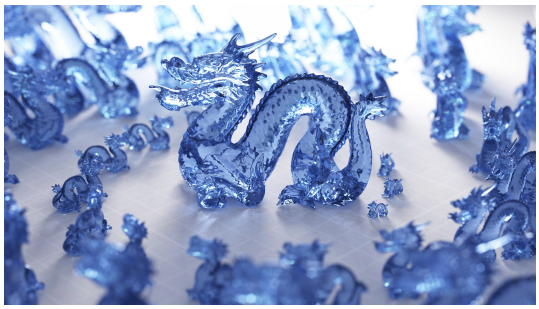


A. Left image sub-caption.

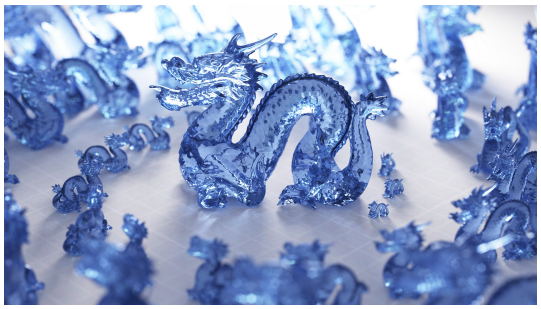


B. Right image sub-caption.

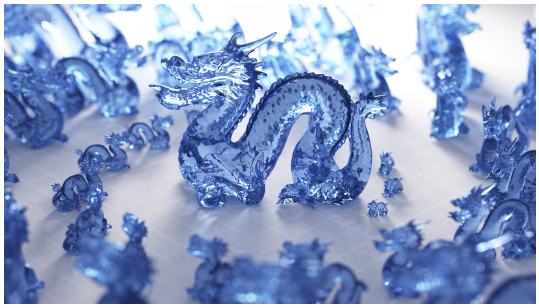
Figure 4.3: Construct sub-figures from multiple image files in LaTeX not in the image file itself. This allows you to tweak the positioning and layout without having to modify the images. It also allows for automatic formatting and numbering of captions and sub-captions. Image of glass dragons rendered using Path Tracing [42].



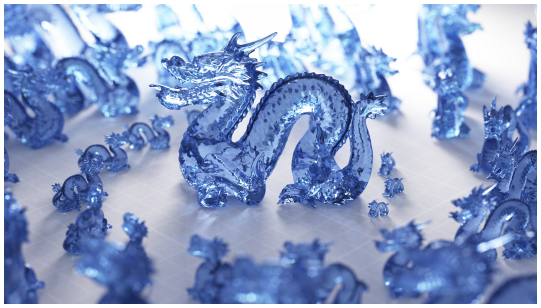
A. Top-Left image sub-caption.



B. Top-Right image sub-caption.



C. Bottom-Left image sub-caption.



D. Bottom-Right image sub-caption.

Figure 4.4: A demonstration of a 2x2 sub-figure layout. Between A-B and C-D we use tilde symbols and between B-C we use a new line. Image of glass dragons rendered using Path Tracing [42].

4.3.6 Robust captions that can stand in isolation

Figures need to be captioned such that they can be viewed in isolation and still be meaningful to the viewer. There will likely be some duplication of information that is written in the main text, but this is intended.

4.3.7 Proper attribution and citation of images

If an image does not belong to you it **must** be cited directly in the figure caption. **It is not correct to put a URL in the figure caption directly.** A URL in isolation is not an accurate or reliable way of directing a future reader to the exact content you are referencing. Instead make a new entry in your `citations.bib` file and then reference that citation in the caption using the `\cite{key}` command. Figures 4.2, 4.3, and 4.4 each include a statement in the caption stating "Image of glass dragons rendered using Path Tracing [42].". When adding the BibTeX entry, try to find the proper information about the original author and source document to strengthen the citation in case the URL changes.

4.4 Code Listings

Code listings should be formatted in the same style as figures and inline equations. It is important to use a monospace font so that characters line up vertically. Syntax highlighting is also extremely important for effectively displaying complicated code segments. To format inline code listings you can use the `\lstinline|the_code|` command[2].

```
#include <stdio.h>

int main(int argc, char *argv[]) {
  printf("Hello world.\n");
  return 0;
}
```

Listing 4.2: An implementation of an important algorithm from our work.

In LaTeX the "Listings" package can be used to properly format code and provide basic syntax highlighting, line numbering, and captioning of embedded code excerpts. Listing 4.3 shows examples of how to properly format code using the listings package.

[2] So meta.

```
% The lstinline command can be used to insert monospace formatted code directly
% inline within the documents main text. You can optionally specify a programming
% language to enable syntax highlighting.
\lstinline|the_code|
\lstinline[language={the_language}]|the_code|

% The lstinputlisting command is used to insert an external file containing
% code into the document formatted in the same manner as a figure or table.
% All stand alone listings should have a label and caption. You can optionally
% specify a programming language to enable syntax highlighting.
\lstinputlisting[label={lst:my_label_name}, caption={The caption.}]{the_file}
\lstinputlisting[language={the_language}, label={lst:the_label}, caption={The
    caption.}]{the_file}

% An example showing how Listing 3.1 is formatted in LaTeX code.
% The C code is stored in its own file as C code, allowing it to be modified
% and prepared separately using a dedicated code IDE to ensure correctness and
% proper formatting.
\lstinputlisting[language={c}, label={lst:c_hello_world}, caption={An
    implementation of an important algorithm from our work.}]{./listings/
    hello_world.c}
```

Listing 4.3: Examples of methods for typesetting code listings within a LaTeX document.

4.5 Tables

Tables are also quite predictably captioned and formatted the same way. It is important to decide on a style for how you will organize your data and apply that style consistently for all of your tables. Table 4.1 shows one possible way of styling your data but is by no means the only way of doing so neatly. Consistency is the key.

Table 4.1: An example of a table formatted with caption.

Some	Relevant	Fields	From	Your	Data
0	0	0	0	0	0
1	1	1	1	1	1
2	2	2	2	2	2

Chapter 5

Conclusions and Future Work

In this document we have demonstrated the use of a LaTeX thesis template which can produce a professional looking academic document.

5.1 Contributions

The main contributions of this work can be summarized as follows:

- **A LaTeX thesis template**

  Modify this document by adding additional top level content chapters. These descriptions should take a more retrospective tone as you include summary of performance or viability.

- **A typesetting guide of useful primitive elements**

  Use the building blocks within this template to typeset each part of your document. Aim to use simple and reusable elements to keep your document neat and consistently styled throughout.

- **A review of how to find and cite external resources**

  We review techniques and resources for finding and properly citing resources from the prior academic literature and from online resources.

5.2 Future Work

Future editions of this template may include additional references to Futurama.

Bibliography

[1] P. Technologies. (2018) Cybersecurity threatscape 2017 trends and forecasts. [Online]. Available: https://www.ptsecurity.com/upload/corporate/ww-en/analytics/Cybersecurity-threatscape-2017-eng.pdf

[2] ——. (2019) Cybersecurity threatscape 2018 trends and forecasts. [Online]. Available: https://www.ptsecurity.com/upload/corporate/ww-en/analytics/Cybersecurity-threatscape-2018-eng.pdf

[3] ——. (2020) Cybersecurity threatscape 2019. [Online]. Available: https://www.ptsecurity.com/upload/corporate/ww-en/analytics/cybersecurity-threatscape-2019-eng.pdf

[4] ——. (2020) Cybersecurity threatscape q2 2020. [Online]. Available: https://www.ptsecurity.com/upload/corporate/ww-en/analytics/cybersecurity-threatscape-2020-q2-eng.pdf

[5] D. Sbîrlea, M. G. Burke, S. Guarnieri, M. Pistoia, and V. Sarkar, "Automatic detection of inter-application permission leaks in android applications," *IBM Journal of Research and Development*, vol. 57, no. 6, pp. 10:1–10:12, 2013.

[6] Ofcom. (2015) The communications market report. [Online]. Available: https://www.ofcom.org.uk/__data/assets/pdf_file/0022/20668/cmr_uk_2015.pdf

[7] Statista.com. (2020) Percentage of mobile device website traffic worldwide from 1st quarter 2015 to 2nd quarter 2020. [Online]. Available: https://www.statista.com/statistics/277125/share-of-website-traffic-coming-from-mobile-devices/

[8] P. Technologies. (2019) Vulnerabilities and threats in mobile applications. [Online]. Available: https://www.ptsecurity.com/upload/corporate/ww-en/analytics/Mobile-Application-Vulnerabilities-and-Threats-2019-eng.pdf

[9] F. B. of Investigation. (2020) Covid-19 fraud: Law enforcement's response to those exploiting the pandemic. [Online]. Available: https://www.fbi.gov/news/testimony/covid-19-fraud-law-enforcements-response-to-those-exploiting-the-pandemic

[10] J. Jolly. (2020) Huge rise in hacking attacks on home workers during lockdown. [Online]. Available: https://www.theguardian.com/technology/2020/may/24/hacking-attacks-on-home-workers-see-huge-rise-during-lockdown

[11] L. Stefanko. (2020) New ramsomware posing as covid-19 tracing app targets canada. [Online]. Available: https://www.welivesecurity.com/2020/06/24/new-ransomware-uses-covid19-tracing-guise-target-canada-eset-decryptor/

[12] D. Ahmed. (2020) Coronavirus related cyber attacks hit hhs in us, testing center in czech. [Online]. Available: https://www.hackread.com/coronavirus-cyber-attacks-us-hhs-czech-testing-center/

[13] J. Gao, L. Li, P. Kong, T. F. Bissyandé, and J. Klein, "Understanding the evolution of android app vulnerabilities," *IEEE Transactions on Reliability*, vol. 70, no. 1, pp. 212–230, 2019.

[14] D. Kleidermacher. (2019) The app defense alliance: Bringing the security industry together to fight bad apps. [Online]. Available: https://security.googleblog.com/2019/11/the-app-defense-alliance-bringing.html

[15] H. Wang, H. Li, and Y. Guo, "Understanding the evolution of mobile app ecosystems: A longitudinal measurement study of google play," in *The World Wide Web Conference*, ser. WWW '19. New York, NY, USA: Association for Computing Machinery, 2019, p. 1988–1999. [Online]. Available: https://doi.org/10.1145/3308558.3313611

[16] Srinivas. (2016) Cracking damn insecure and vulnerable app (diva) – part 4. [Online]. Available: https://resources.infosecinstitute.com/topic/cracking-damn-insecure-and-vulnerable-app-diva-part-4/

[17] dineshshetty. (2019) Android-insecurebankv2. [Online]. Available: https://github.com/dineshshetty/Android-InsecureBankv2

[18] Hacktivities. (2020) Android insecurebankv2 walkthrough: Part 2. [Online]. Available: https://infosecwriteups.com/android-insecurebankv2-walkthrough-part-2-429b4ab4a60f

[19] J. Umawing. (2018) Why bad coding habits die hard—and 7 ways to kill them. [Online]. Available: https://blog.malwarebytes.com/101/2018/05/bad-code-wont-die-7-ways-kill/

[20] A. D. Blog. (2008) Announcing the android 1.0 sdk, release 1. [Online]. Available: https://android-developers.googleblog.com/2008/09/announcing-android-10-sdk-release-1.html

[21] OpenHub.net. (2020) Android latest languages. [Online]. Available: https://www.openhub.net/p/android/analyses/latest/languages_summary

[22] C. Haase. (2019) Google i/o 2019: Empowering developers to build the best experiences on android + play. [Online]. Available: https://android-developers.googleblog.com/2019/05/google-io-2019-empowering-developers-to-build-experiences-on-Android-Play.html

[23] Developer.android.com. (2021) Application fundamentals. [Online]. Available: https://developer.android.com/guide/components/fundamentals

[24] ——. (2021) What is a service. [Online]. Available: https://developer.android.com/reference/android/app/Service#what-is-a-service

[25] ——. (2021) Services overview. [Online]. Available: https://developer.android.com/guide/components/services

[26] ——. (2021) Broadcasts overview. [Online]. Available: https://developer.android.com/guide/components/broadcasts

[27] ——. (2021) Send sticky broadcast. [Online]. Available: https://developer.android.com/reference/android/content/Context#sendStickyBroadcast(android.content.Intent)

[28] ——. (2021) Permissions on android. [Online]. Available: https://developer.android.com/guide/topics/permissions/overview)

[29] ——. (2021) Define a custom app permission. [Online]. Available: https://developer.android.com/guide/topics/permissions/defining

[30] ——. (2021) Permission manifest element. [Online]. Available: https://developer.android.com/guide/topics/manifest/permission-element

[31] ——. (2021) Intents and intent filters. [Online]. Available: https://developer.android.com/guide/components/intents-filters

[32] E. Chin, A. P. Felt, K. Greenwood, and D. Wagner, "Analyzing inter-application communication in android," in *Proceedings of the 9th International Conference on Mobile Systems, Applications, and Services*, ser. MobiSys '11. New York, NY, USA: Association for Computing Machinery, 2011, p. 239–252. [Online]. Available: https://doi.org/10.1145/1999995.2000018

[33] Developer.android.com. (2021) Starting a service. [Online]. Available: https://developer.android.com/reference/android/content/Context#startService(android.content.Intent)

[34] ——. (2021) Bound services overview. [Online]. Available: https://developer.android.com/guide/components/bound-services.html

[35] Internet Live Stats. (2020). [Online]. Available: https://www.internetlivestats.com

[36] G. Branwen. (2020) Internet search tips. [Online]. Available: https://www.gwern.net/Search

[37] RELX Group. (2019) Mendeley. [Online]. Available: https://www.mendeley.com

[38] J. T. Kajiya, "The rendering equation," in *Proceedings of the 13th Annual Conference on Computer Graphics and Interactive Techniques*, ser. SIGGRAPH '86. New York, NY, USA: ACM, 1986, pp. 143–150.

[39] Overleaf. (2020) Overleaf documentation. [Online]. Available: https://www.overleaf.com/learn

[40] Stack Overflow. (2008) Tex stackexchange. [Online]. Available: https://tex.stackexchange.com

[41] A. Ravikumar. (2019) Texnique. [Online]. Available: https://texnique.xyz

[42] J. Whittle. (2015) Path traced glass dragons.

Appendix A

Implementation of a Relevant Algorithm

```
#include <stdio.h>

int main(int argc, char *argv[]) {
  printf("Hello world.\n");
  return 0;
}
```

Listing A.1: An implementation of an important algorithm from our work.

Appendix B

Supplementary Data

The results of large ablative studies can often take up a lot of space, even with neat visualization and formatting. Consider putting full results in an appendix chapter and showing excerpts of interesting results in your chapters with detailed analysis. You can use labels and references to refer the reader here for the full data.