Reverse Engineering a Bluetooth Application: Discovering the Secrets of a Makeup Printing Device

Independent Study Thesis

Presented in Partial Fulfillment of the Requirements for the Degree BS in the Computer Science at The College of Wooster

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THE COLLEGE OF
WOOSTER

Abstract

Include a short summary of your thesis, including any pertinent results. This section is *not* optional, and the reader should be able to learn the meat of your thesis by reading this (short) section.

This work is dedicated to the future generations of Wooster students.

Acknowledgments

I would like to acknowledge Prof. Lowell Boone in the Physics Department for his suggestions and code.

Vita

Publications

Fields of Study Major field: Major

Minor field: Minor

Specialization: Area of IS research

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CHAPTER 1

Introduction

1.1 What is Reverse Engineering?

Reverse Engineering is the process of disassembling something in order to understand how it works. It has been done long before it was used for technology. For example, the dissections that were a common high school experience. They were done to break down something as mystifying as life into clear components and functionalities. One of the best ways to fully understand how something works is to open it up.

Reverse engineering software can be done in many ways. The methods of analysis can be divided into two categories, static and dynamic analysis. Static analysis involves combing over a snapshot of the code in a single state. Dynamic analysis is done when the program is being executed and changing states. To start reverse engineering, usually a program's executable is passed to a disassembler which will break it down into the assembly level code. A programmer can use system monitoring tools to display information that was gathered by the operating system on the program and how it interacts with its environment. A debugger shows what happens in the CPU with the disassembled code one line at a time. Using these different tools, the programmer must use their intuition to guide the reversing process.

There are many reasons why someone might want to reverse engineer software. The only time that the workings of software is available to anyone is when that software is open source. Open source software is freely available source code that anyone can view, share, and modify. However, software developers sometimes opt out of publicly distributing the source code. There are a number of potential causes for this, including licensing and ownership issues, the need to preserve proprietary data, or other personal reasons.

Some of the most common reasons a person would choose to reverse engineer software is so that they can perform malware analysis, improve programming skills, recover lost source code, and implement interoperability between programs. My first introduction to reverse engineering was through a video where the creator was reverse engineering Apple's Facetime for Mac so he could reinstate closed captioning for his hearing impaired mother. The list of uses is as extensive as programs out there.

Most software developers know reverse engineering in the context of malware analysis. A classic example is a Trojan virus. Malicious developers can hide malware in programs that are designed to look innocuous. Breaking apart these programs will unveil the malware hidden inside. Developers also often call on external libraries. With large projects, keeping track of dependencies can be hard. Hackers can hide entry points in these libraries so they can access unauthorized information. Reverse engineering is the only foolproof way to reveal exactly what is happening at each step of a program's execution.

Learning how something is being done can be great to improve skills. Reverse engineering requires extensive knowledge of both assembly code and how high level code structuring. Reverse engineering someone else's code is no simple feat and will cause the reverser to need to learn in depth the possible ways a program could be constructed. This project will be an endeavor in learning both forward engineering and reverse engineering.

People may reverse engineer their own program to recover lost source code. While this is no easy task, it is possible to use reverse engineering to recover source code. Many software developers know the pain of losing source code and, with an executable, reverse engineering offers a potential solution.

Interoperability is one of the reasons a person might choose to reverse engineer something. This purpose is also only able to be accomplished through reverse engineering. When working with external libraries or operating systems that have documentation on usage but no source code, oftentimes documentation doesn't cover all use cases. While a programmer could keep throwing things at the wall or try to contact the vendor, reverse engineering provides a surefire way of figuring things out.

1.1.1 Purposes

1.1.1.1 Education

1.1.1.2 Legacy Systems

1.1.1.3 Security

1.1.1.4 Interoperability

CHAPTER 2

Bluetooth

2.1 Bluetooth

Bluetooth is a widely adopted wireless technology that has seen rapid growth over the past decade. Originally developed to eliminate the need for short-range wired connections, Bluetooth is now used in countless applications—from music and video streaming to medical devices requiring continuous data updates. While it operates similarly to WiFi in some respects, the key difference is its scope: WiFi connects multiple devices to the internet, whereas Bluetooth focuses on direct device-to-device communication and offers more diverse use cases [0].

Another distinction is how Bluetooth is optimized for low-latency applications that transmit small bursts of data quickly and efficiently. This makes it ideal for scenarios where power conservation and responsiveness are more important than high throughput.

2.1.1 Bluetooth Types

There are two main types of Bluetooth technology: *Bluetooth Basic Rate (BR)*, also referred to as *Bluetooth Classic*, and *Bluetooth Low Energy (BLE)*. Of the two, BLE has gained far more traction in modern applications.

Bluetooth Basic Rate is the older of the two technologies, supported in versions 1.0 through 3.0. It is primarily used for wireless audio streaming in devices like headphones, speakers, and in-car entertainment systems, and it relies on point-to-point communication.

Bluetooth Low Energy, introduced in version 4.0 and further enhanced in version 5.0, offers a broader range of capabilities. In addition to supporting audio and data transfer, BLE enables device networking and location services. It supports multiple communication topologies including point-to-point, mesh, and broadcast, making it far more versatile than its predecessor. One of BLE's standout features is its utility in high-accuracy location services. By leveraging nearby devices, BLE can determine relative positioning and provide precise location tracking.

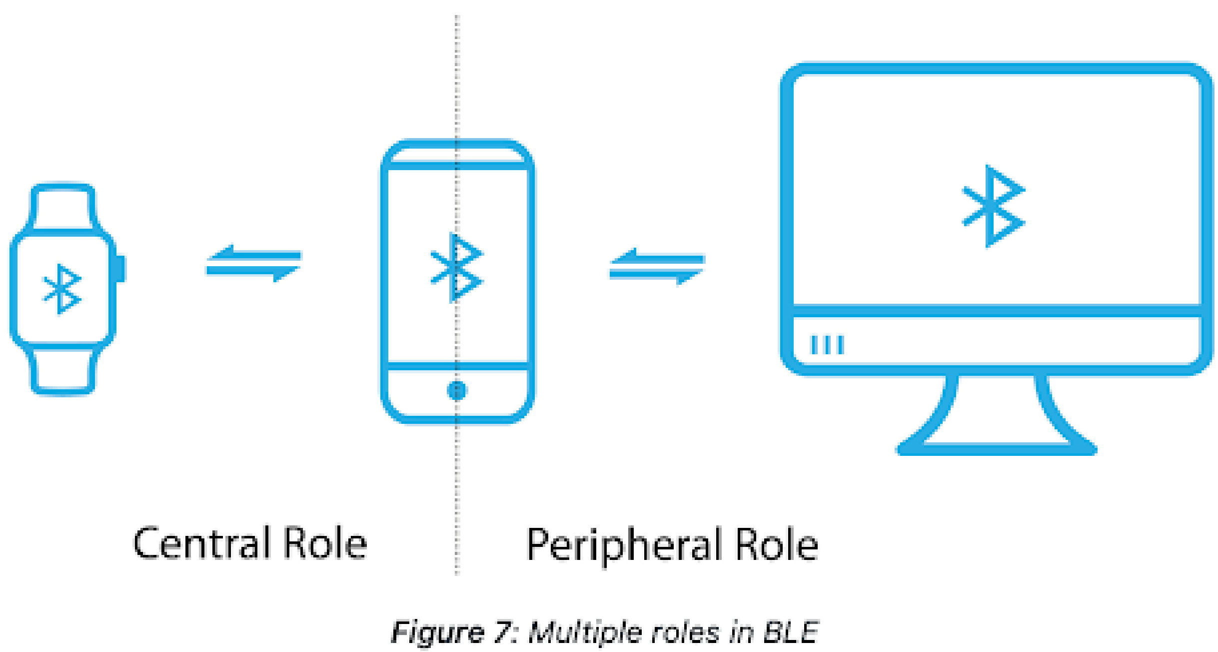
2.2 Pairing-Based Network

The core of Bluetooth is creating a network where two (or slightly more) devices pair with each other, since Bluetooth was designed to replace corded connections. The devices being paired can be broken down into the *Central* and *Peripheral(s)*. These terms are specific to newer Bluetooth standards and can be used interchangeably with the older terms *Master* and *Slave*.

The Central device coordinates the data being sent between it and any Slaves. This includes handling time synchronization, sleep scheduling, and configuring the channels used through frequency hopping [0]. Peripheral devices can communicate bi-directionally with the Master device, sending or receiving data depending on the request.

Figure **[insertnumbah from nextgenble]** shows an example of Central and Peripheral devices. Classic Bluetooth includes two network topology configurations: **Piconet** and **Scatternet**.

Figure 2.1: Central and Peripheral device relationship

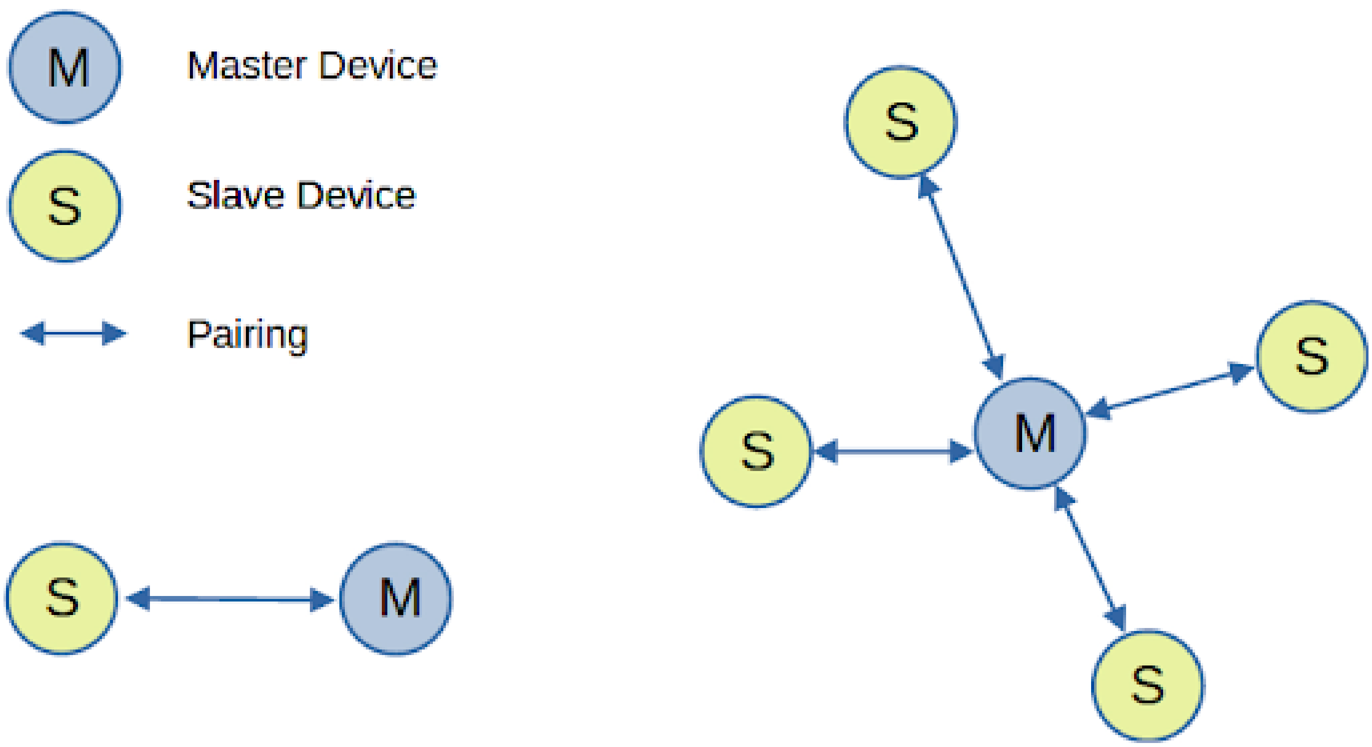


2.2.1 Piconet

A piconet is a type of ad hoc network topology that operates without preestablished infrastructure. Devices in a piconet communicate directly with one another without the need for a centralized device like a router or access point. The network is organized with one central device and one or more peripheral devices. A single central can support up to seven active peripherals, while each peripheral can only connect to one central [0]. The central manages the timing and synchronization of all devices in the piconet. Peripheral devices cannot communicate directly with each other; the central acts as a relay, forwarding data between them.

Figure **[insertfigurehere]** shows the structure of a piconet.

Figure 2.2: Piconet Topology



All connections made using a BR/EDR controller occur within a piconet. BR/EDR devices communicate over the same physical channel by synchronizing with a shared clock and hopping sequence [0]. The piconet clock follows the central device's clock configuration, and the hopping sequence is also derived from the central's clock and Bluetooth device address.

Multiple independent piconets can exist in the same area. Each operates on a separate channel and is organized around a different central device. Bluetooth devices can also participate in multiple piconets simultaneously. While a Bluetooth device can only act as the central in one piconet at a time, it can serve as a peripheral in several.

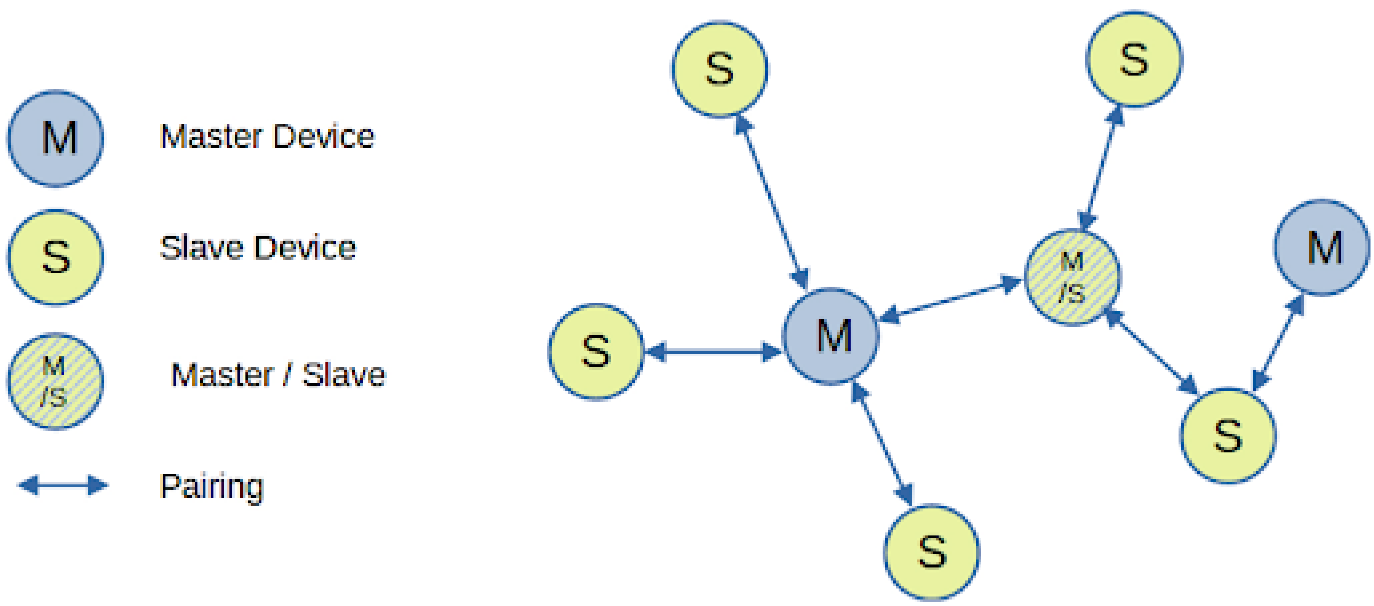
2.2.2 Scatternet

A scatternet is formed by connecting multiple piconets together. Unlike a piconet, a peripheral in a scatternet can connect to multiple central devices. Central devices can also connect to each other, sometimes serving dual roles as both central and peripheral.

For example, a scatternet might include a central laptop connected to a Bluetooth speaker, while also acting as a peripheral to a smartphone and printer. Figure **[insertnumber]** shows a diagram of a typical scatternet. Despite the increased complexity, peripherals still do not communicate directly with each other.

Piconets and scatternets are associated with Classic Bluetooth but are still supported in BLE and later Bluetooth versions [0]. Although BLE—with its advertising mode—has seen growing popularity, traditional Bluetooth methods still offer advantages such as added security during pairing. BLE services enhance the piconet and scatternet model, providing better security, more efficient pairing, and broader support for services.

Figure 2.3: Scatteret Topology



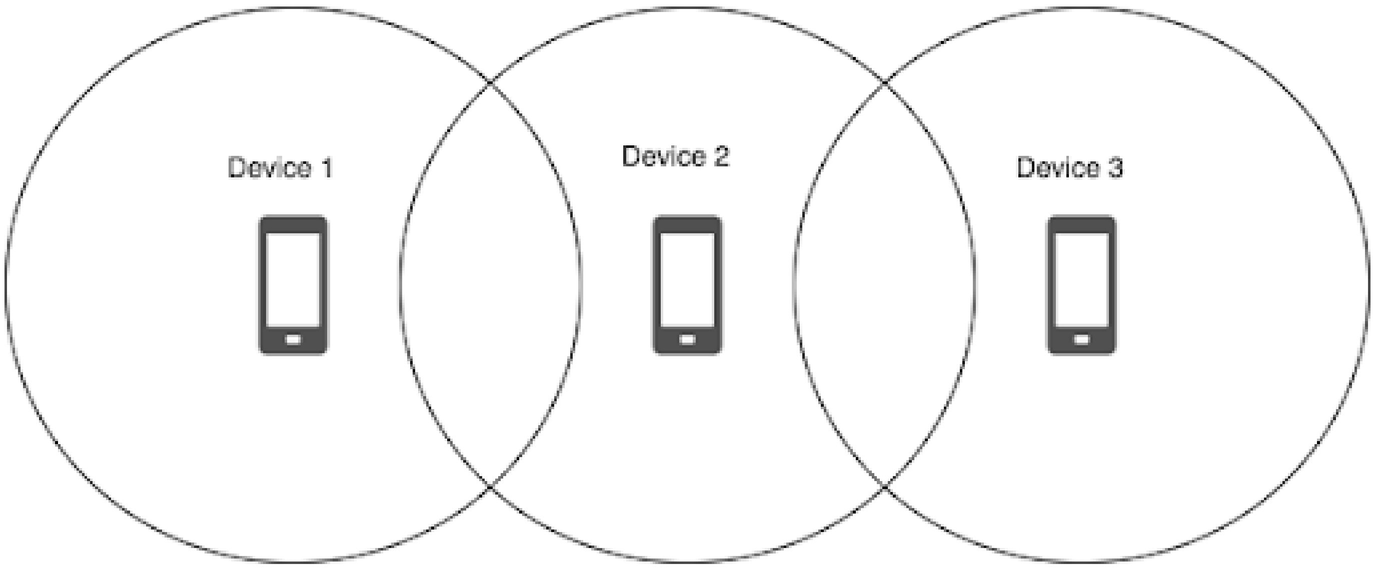
2.3 BLE Mesh Networks

Mesh networking, introduced with BLE, marks a significant evolution in Bluetooth topologies. In a mesh network, nodes are arranged in a self-configuring mesh, where each node relays traffic between peers when the destination is not directly connected [0].

This structure ensures a reliable path for data packets. If one path is blocked or unavailable, the network reroutes traffic dynamically. The self-organizing nature of mesh networks means they adapt in real-time to changes, such as nodes joining, leaving, or moving within the network.

For example, Figure **[insertnumbah]** shows Device 1 out of range of Device 3. Device 2, within range of both, acts as a router forwarding messages between them.

Figure 2.4: Mesh topology



2.4 Broadcast Network from LE

BLE introduces a new feature called *advertising mode*, which operates differently from the traditional pairing between a central and peripheral. In advertising mode, a device broadcasts data openly to any BLE devices within range that are tuned to the same channel. These listening devices can receive the data and use it as needed—without any pairing, connection, or formal association.

This topology loosely resembles a multi-peripheral piconet, but with a key difference: advertising mode removes the need for a dedicated central or established links. There's no synchronization or connection—just open broadcasting.

Advertising mode has been a major factor in expanding the possibilities of Bluetooth. By offloading the overhead of pairing, BLE made room for a wider variety of lightweight, low-latency applications. This performance shift is part of why so many modern devices—from smart beacons to virtual reality headsets—are feasible today. Devices like VR headsets, which require fast, efficient data sharing without constant handshaking, would be nearly impossible to build the same way without Bluetooth.

2.5 Connections and Mixed Topology

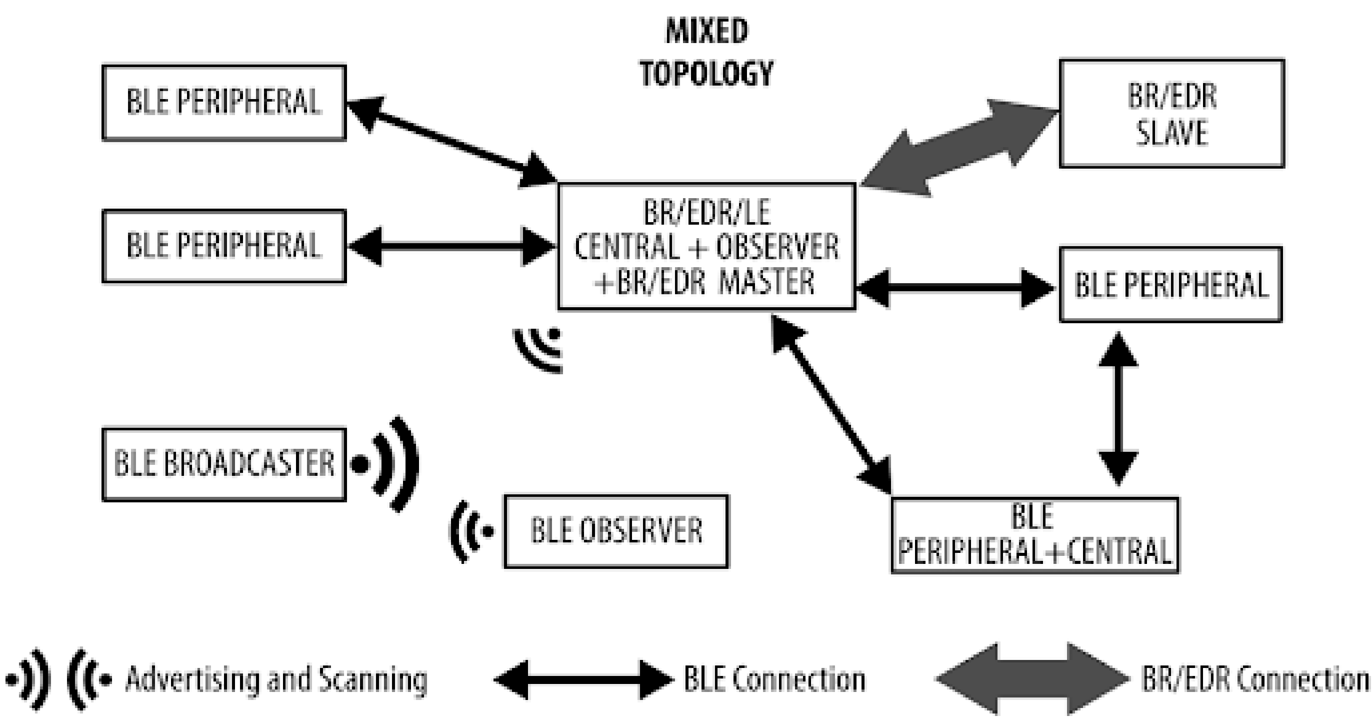
A connection becomes necessary when data needs to flow in both directions or when there's more data than can fit into the two available advertising payloads. Connections in BLE are more persistent—they allow devices to remember each other and avoid reestablishing the connection every time. Once established, connections support periodic data exchanges between two devices.

This connection-based pairing is what underpins piconets and scatternets. These connections are private by design: only the two participating devices exchange data (barring external sniffing). As covered earlier, connections involve one central device and one or more peripheral devices.

BLE networks can also incorporate mixed topology configurations depending on the use case. A device that supports both BR/EDR and LE can serve as a bridge between traditional Bluetooth and BLE communication, enabling broader interoperability across protocols. The possibilities for combining these configurations are only constrained by the capabilities of the individual devices' radios and protocol stacks.

Figure **[insertnumbah]** provides an example of a mixed topology Bluetooth network.

Figure 2.5: Mixed Topology



2.6 SCO and ACL Logical Transports

2.6.1 BR/EDR Asynchronous Connection-Oriented (ACL)

ACL links are the primary way Bluetooth devices using BR/EDR exchange general data. These links handle both control signals (like LMP and L2CAP) and typical user data. ACL is *asynchronous*, meaning data is sent when available rather than on a fixed schedule.

Every Peripheral in a Bluetooth piconet gets one default ACL link to the Central. This link is established when the device first connects and is identified by a Logical Transport Address (LT_ADDR) assigned by the Central. This LT_ADDR is also used when identifying the physical connection between devices.

However, because multiple types of logical transports (like SCO links, which are used for voice) might use the same LT_ADDR, it's not enough to identify the ACL connection by LT_ADDR alone. Devices also rely on the packet type to tell them which kind of transport is being used.

ACL links can also carry isochronous data—data that needs to arrive on time, like audio streams—by setting them to automatically drop old packets. At the same time, asynchronous traffic (like file transfers) can still be sent if it's marked not to auto-flush. This means both types of traffic can share the same ACL link if configured correctly.

If the ACL link is removed or if the device loses sync with the piconet, all other connections between the Central and that Peripheral (like SCO) are also dropped immediately [0].

2.6.2 BR/EDR Synchronous Connection-Oriented (SCO)

SCO links are designed specifically for real-time data like voice. They create a fixed, circuit-like connection between a Central and a Peripheral by reserving slots on the Bluetooth physical channel. These connections carry 64 kbps of data, usually for audio, and are synchronized with the piconet's clock.

There are several SCO configurations that balance audio quality, latency, and bandwidth usage. Every SCO connection uses the same LT_ADDR as the ACL link, so to identify an SCO packet, a device must look at the slot number, packet type, and LT_ADDR together.

Even though SCO reserves bandwidth, the system can override these slots if higher-priority data (like control messages over ACL) needs to get through. This helps maintain overall system reliability and meet Quality of Service (QoS) requirements.

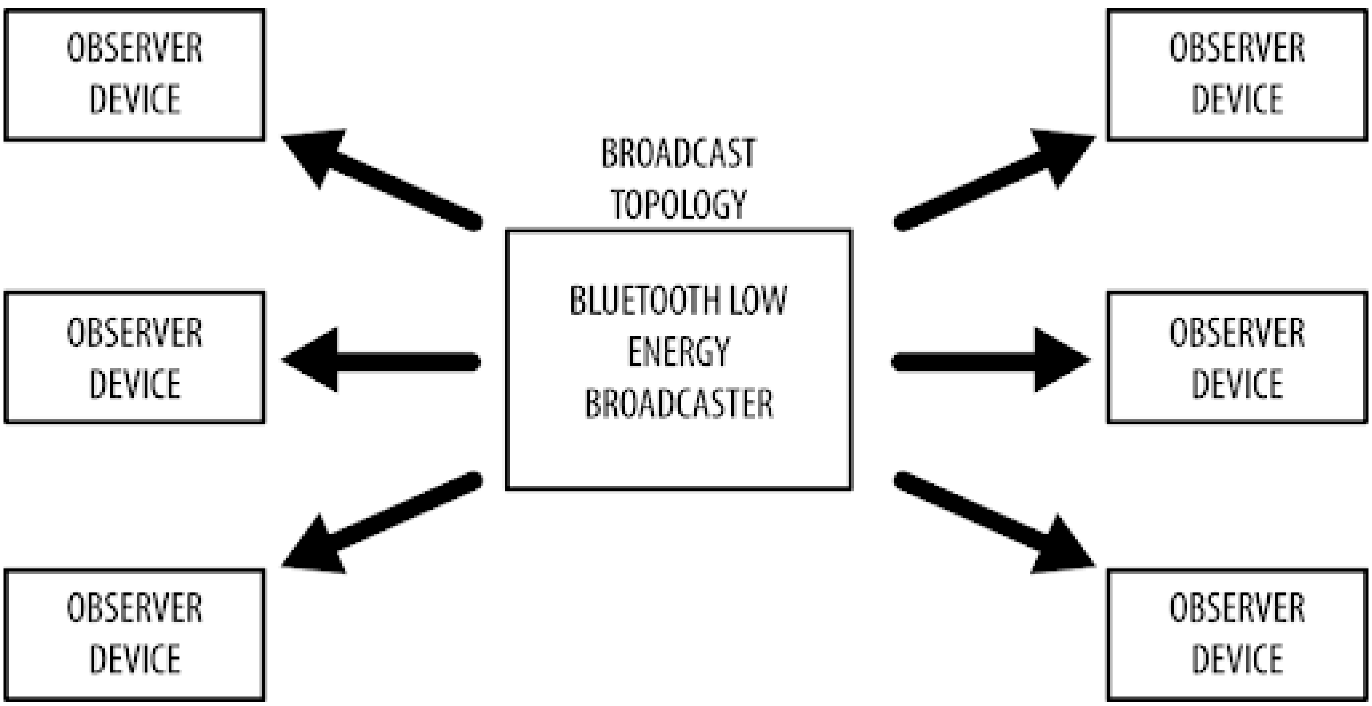
Unlike ACL links, SCO links don't carry complex protocols or layered data structures. They just send a steady stream of audio—either in a standard format or as raw data for the application to decode [0].

2.7 Bluetooth Low Energy Broadcasting and Observing

Bluetooth Low Energy devices communicate with the outside world in two primary ways: *broadcasting* and *connecting*. Both methods are governed by the Generic Access Profile (GAP), which outlines how devices discover and interact with each other [0].

Broadcasting enables BLE devices to send data one-way to any scanner or receiver within range. It's a form of open communication where any nearby device capable of listening can receive the broadcasted data. Figure **[insertnumbah]** illustrates this communication model. In the diagram, two roles are shown: the *Broadcaster*, which periodically sends non-connectable advertising packets, and the *Observer*, which continually scans for those packets [0].

Figure 2.6: Broadcasting and Observing



Broadcasting is a key concept in BLE because it's the only mechanism that allows a device to communicate with multiple other devices simultaneously. This functionality is made possible by BLE's advertising feature.

A standard advertising packet contains a 31-byte payload, which includes information about the broadcasting device and what it offers. This data can be customized to suit different applications, providing useful context to observing devices. If 31 bytes isn't enough, BLE allows for a secondary packet called a *Scan Response*, which provides an additional 31 bytes of payload. Observers can request this secondary data if they need more information [0].

Broadcasting is quick, efficient, and ideal for sending small amounts of data on a regular schedule to multiple receivers. However, it does come with limitations—particularly around security. Since any device within range can intercept a broadcast, there's virtually no privacy. Because of this, broadcasting isn't well-suited for transmitting sensitive or private data.

2.8 Bluetooth Protocols and Profiles

Bluetooth has always had a distinction between protocols and profiles. A protocol is a lower layer foundational block that gets used by all devices that have Bluetooth capabilities. They deal with the layers that implement the different packet formats, routing, encoding, decoding, and multiplexing that allows data to be properly sent between peers [0]. Profiles are "vertical slices" of functionality that encompass either fundamental modes of operation common to all devices (such as the Generic Access Profile and Generic Attribute Profile) or support specific use cases (like the Proximity Profile or Glucose Profile). They essentially define how protocols should be applied to accomplish a particular objective, whether general or specialized.

2.9 Bluetooth Low Energy Profiles

Profiles specify how BLE protocols are to be used to achieve interoperability and support a wide range of applications. These profiles fall into two primary categories: generic profiles, which are fundamental to all BLE operations, and use-case-specific profiles, which are built on top of the generic layers to support particular functionalities.

2.9.1 Generic Profiles

Generic profiles are defined by the Bluetooth Core Specification and provide the foundational mechanisms required for BLE communication. These profiles ensure that devices from different manufacturers can interoperate seamlessly. Two such profiles—Generic Access Profile (GAP) and Generic Attribute Profile (GATT)—are mandatory for all BLE-compliant devices and serve as the cornerstones of BLE communication.

2.9.1.1 Generic Access Profile (GAP)

The Generic Access Profile defines the roles, procedures, and operational modes required for device discovery, broadcasting, connection establishment, connection management, and security negotiation. GAP operates as the top-level control layer within the BLE protocol stack, orchestrating the basic behaviors necessary for device interaction. All BLE devices must implement and conform to the GAP specifications to ensure compatibility and reliable communication.

2.9.1.2 Generic Attribute Profile (GATT)

GATT focuses primarily on how data is exchanged. GATT defines a universal data model and a set of procedures that enable devices to discover, read, write, and notify data values. It functions as the uppermost data layer in BLE and serves as the foundational framework upon which most BLE applications and services are constructed.

Due to their foundational roles, GAP and GATT are commonly exposed through application programming interfaces (APIs), making them the primary entry points for developers interacting with the BLE protocol stack.

2.9.2 Use-Case-Specific Profiles

Beyond the generic profiles, the Bluetooth Special Interest Group (SIG) has defined a series of use-case-specific profiles. These profiles are designed to standardize behavior for specific applications and are exclusively built upon the GATT framework. At the time of writing, no BLE profiles exist outside the GATT structure. However, the introduction of connection-oriented L2CAP channels in Bluetooth version 4.1 may pave the way for future GATT-less profiles.

2.9.2.1 SIG-Defined GATT-Based Profiles

The Bluetooth SIG provides an extensive catalog of standardized profiles, each tailored to support a specific application or device type. These profiles fully specify the required procedures and data formats, facilitating rapid development and ensuring interoperability across implementations.

Examples of SIG-defined GATT-based profiles include:

- **Find Me Profile:** Enables physical location of nearby BLE devices (e.g., locating a lost phone or keyring).
- **Proximity Profile:** Detects when a connected device moves beyond a designated range, triggering alerts.
- **HID over GATT Profile:** Facilitates the transmission of Human Interface Device (HID) data over BLE for peripherals such as keyboards, mice, and remote controls.
- **Glucose Profile:** Securely transmits glucose measurement data for health monitoring applications.

- **Health Thermometer Profile:** Enables transfer of body temperature readings from wearable or medical devices.
- **Cycling Speed and Cadence Profile:** Allows cycling sensors to relay speed and cadence information to companion applications or devices.

A comprehensive list of SIG-adopted profiles is available on the Bluetooth SIG Specification Adopted Documents webpage. Developers may also consult the Bluetooth Developer Portal for up-to-date listings of adopted services and characteristics.

2.9.2.2 Vendor-Specific Profiles

While the SIG provides a broad range of standardized profiles, the BLE specification also permits the definition of vendor-specific profiles. These profiles are often developed to support proprietary use cases not covered by SIG standards. Vendor-specific profiles can be implemented privately between two devices (such as with a health accessory and a smartphone) or published to enable broader adoption.

Notable examples of vendor-defined profiles include:

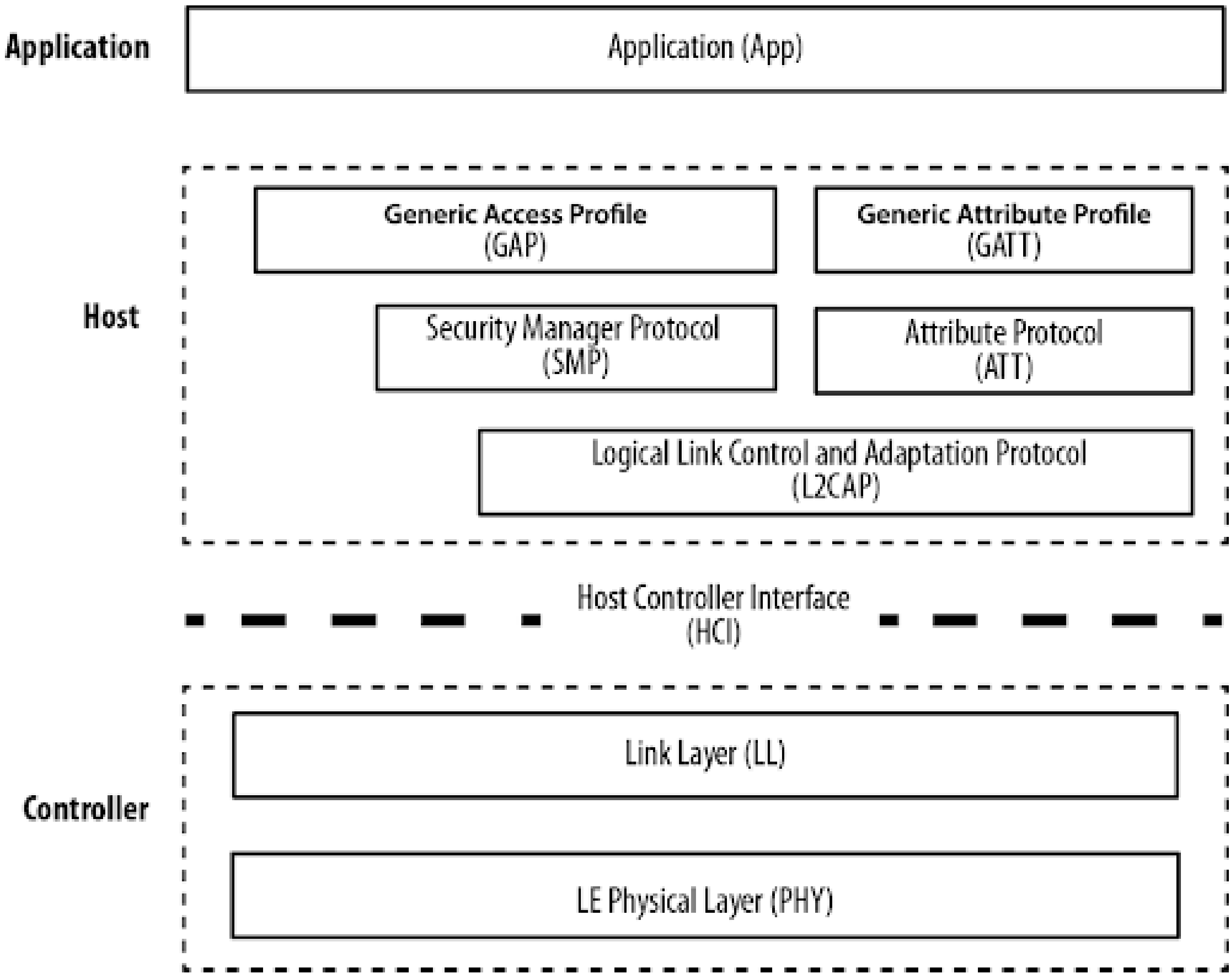
- **Apple iBeacon:** A proprietary proximity-sensing profile used for indoor positioning and location-based services.
- **Apple Notification Center Service (ANCS):** Enables wearable devices or external displays to access and display iOS notifications.

These profiles demonstrate the flexibility of the BLE specification in accommodating both standardized and proprietary communication models.

2.10 Bluetooth Low Energy (BLE) Architecture

Although most users will only ever interact with the top layers of the Bluetooth Low Energy (BLE) protocol stack, having a basic understanding of the full stack can provide helpful context. This overview lays the groundwork for understanding how BLE devices work and why each part of the system is important. A typical single-mode BLE device is made up of three main parts: the controller, the host, and the application. Each of these parts contains multiple layers, each responsible for specific tasks that allow the device to communicate and perform its intended functions. Figure [insertnumah] shows the BLE protocol stack.

Figure 2.7: BLE Protocol Stack



2.10.1 Application

The application layer sits at the top of the BLE protocol stack. It includes all the logic, data handling, and user interface components that define how a device behaves in a specific use case. This layer is highly customized and varies from one implementation to another [0].

2.10.2 Host

Below the application is the host, which includes several critical layers that manage communication and device behavior:

- **Generic Access Profile (GAP):** Controls how devices advertise themselves, discover others, establish connections, and manage roles and security [0].

- **Generic Attribute Profile (GATT):** Organizes and manages how data is exchanged between connected devices.
- **Logical Link Control and Adaptation Protocol (L2CAP):** Handles multiplexing and segmentation of data packets.
- **Attribute Protocol (ATT):** Supports data operations such as reads and writes via attribute handles.
- **Security Manager (SM):** Manages pairing, authentication, and encryption.
- **Host Controller Interface (HCI) – Host Side:** Facilitates communication between the host and controller [0].

2.10.3 Controller

At the bottom of the Bluetooth stack, the controller is responsible for radio operations and low-level data transport. It typically includes the following components:

- **Physical Layer (PHY):** Manages the actual transmission and reception of radio signals.
- **Link Layer (LL):** Controls advertising, scanning, and maintaining connections.
- **HCI (Controller Side):** Complements the host side of HCI to enable structured data flow between layers [0].

According to the Bluetooth Core Specification, a Bluetooth implementation includes a single controller, which may be configured as one of the following:

- A **BR/EDR controller**, containing the Radio, Baseband, Link Manager, and optionally HCI.
- An **LE controller**, including the LE PHY, Link Layer, and optionally HCI.
- A **dual-mode controller** that combines both BR/EDR and LE controller functions into a single unit.

Together, these layers ensure that BLE devices can connect reliably and communicate efficiently. This layered architecture is often described from the bottom up — starting at the antenna and PHY layer and moving up through the stack to the user-facing application.

2.11 BLE Link Layer and Device Addressing

In the Bluetooth Low Energy (BLE) protocol stack, the Link Layer serves as a crucial interface between the Physical Layer—which handles the actual radio transmission—and the upper protocol layers. It acts as the controller for radio operations and is essential for managing the states and timing mechanisms that define BLE communication. One of the key responsibilities of the Link Layer is to abstract the radio hardware, allowing higher-level layers to interact with it through the Host Controller Interface (HCI) [0].

In addition to timing and control, the Link Layer manages several hardware-accelerated tasks. These include generating cyclic redundancy checks (CRC) for error detection, producing random numbers for cryptographic operations, and performing encryption to secure data transfer [0]. These operations ensure the performance, integrity, and security of BLE communications.

2.11.1 Link Layer States

BLE devices operate in a well-defined set of five main states, each with specific behaviors and transitions:

- **Standby:** This is the default state, where the radio is idle and not transmitting or receiving any packets.
- **Advertising:** In this state, the device broadcasts data packets at regular intervals, making itself discoverable to other devices.
- **Scanning:** Devices in this state listen for advertising packets from others, searching for devices they might want to connect with.
- **Initiating:** When a scanning device decides to connect to an advertising device, it enters this state and sends a connection request.
- **Connected:** A persistent communication link is established. Devices in this state can exchange data regularly. The device that initiated the connection becomes the master, while the other becomes the slave [0].

This framework enables BLE to support dynamic and responsive device discovery and communication, while keeping energy consumption minimal.

2.12 Advertising, Scanning, and Connecting

Advertising and scanning are complementary operations: advertising devices periodically transmit small packets of data, while scanning devices listen for and interpret these packets. If the advertiser allows connections, and a scanning device decides to initiate one, both devices transition into the connected state [0]. These processes form the backbone of BLE interactions and are covered in more depth in subsequent chapters of most BLE technical literature.

2.13 Bluetooth Device Address

Every Bluetooth device is identified by a 48-bit device address, which serves a function similar to a MAC address in networking. BLE supports two major types of device addresses: public addresses and random addresses, which influence how discoverable and trackable a device is.

2.13.1 Public Address

A public address is a globally unique, fixed identifier that is factory-programmed and registered with the IEEE. Because of this registration requirement, it ensures uniqueness across all BLE devices worldwide. However, it can also present privacy concerns, since it does not change and is easily traceable [0].

2.13.2 Random Address

Random addresses, by contrast, provide more flexibility and are often preferred in consumer devices to protect user privacy. These addresses can either be static or private, and they do not require IEEE registration.

- **Static Address:** Used as a drop-in replacement for public addresses. A static address remains the same between sessions but can be regenerated at boot or kept for the lifetime of the device until a power cycle occurs.
- **Private Addresses:** These are designed to change regularly and enhance privacy. They come in two subtypes:
  - **Non-resolvable private addresses** are temporary, randomly generated, and cannot be traced back to a specific device. They are rarely used due to limited functionality.
  - **Resolvable private addresses** use an Identity Resolving Key (IRK) and a random number to generate temporary addresses. These change over time, making the device hard to track by unknown parties. However, trusted or bonded devices that have the IRK stored can resolve these addresses, allowing them to re-identify the device securely [0].

This system allows BLE to balance two key goals: persistent connectivity with trusted devices and protection against unwanted tracking or eavesdropping by unknown entities.

2.14 Host Controller Interface (HCI) Layer

The Host Controller Interface (HCI) serves as the communication bridge between the host and controller layers in a Bluetooth system. These components can be implemented on the same chipset or on separate chipsets. When they are on separate chipsets, HCI is critical for enabling interoperability and communication between them. In such cases, HCI defines both the standardized protocol and the physical transport mechanisms that facilitate message exchange. As shown in Figure [insertnumbah], the host, HCI, and controller are depicted as distinct components. HCI commonly uses transport technologies such as UART, USB, and SDIO to establish physical connections between the host and controller. When the host and controller are integrated on the same chipset, HCI functions as a logical interface rather than a physical one [0].

2.14.1 Universal Asynchronous Rx/Tx (UART)

UART is a serial communication protocol that uses wired connections to exchange data between devices. It is commonly found in integrated circuits and is especially favored in devices like mobile phones and laptops, where the entire Bluetooth stack is implemented on a single chipset. UART is also well-suited for small, resource-constrained devices powered by microcontrollers, as it is lightweight and efficient in its use of system resources [**nextgenble**].

In the context of the HCI UART protocol, four types of packet transmissions are defined: the Command packet (identified by 0x01), Event packet (0x04), Asynchronous Connection-Less (ACL) packet (0x02), and Synchronous Connection-Oriented (SCO) packet (0x03). Because the receiving HCI layer cannot distinguish these packet types based on content alone, each transmission begins with a leading byte — known as an indicator — which acts as a header to identify the type of packet that follows [0].

2.15 Connection

To establish a connection in Bluetooth Low Energy (BLE), the central device begins by scanning for advertising peripheral devices that are currently accepting connection requests. Advertising packets can be filtered based on the Bluetooth Address or the contents of the advertising data itself. Once a suitable advertiser is detected, the master sends a connection request packet. If the slave responds, a connection is established [0].

This connection request packet includes several critical parameters:

- **Frequency hop increment:** Defines the hopping sequence used for the duration of the connection.

- Three additional connection parameters:
  - **Connection interval:** The time between the start of two consecutive connection events. This can range from 7.5 ms (for high throughput) to 4 seconds (for minimal power usage).
  - **Slave latency:** The number of connection events the slave is allowed to skip without causing a disconnection.
  - **Connection supervision timeout:** The maximum allowed time between receiving valid packets before the connection is considered lost [0].

Once connected, communication happens through repeated connection events — periodic time slots where the master and slave take turns exchanging packets. A connection event:

- Always begins with a packet from the central.
- Requires the peripheral to respond if it receives a packet.
- Continues until both sides have no more data to send.
- Is repeated at the connection interval until the connection is either closed or lost.
- Can be closed by either the master or the slave. If the central sends a packet and does not receive a response, it waits until the next connection event to resume [0].

To manage interference and ensure privacy or security, BLE supports a white list mechanism at the Link Layer. This list defines which Bluetooth device addresses are of interest. Devices not on the list are ignored — their advertising (by scanners) or connection request packets (by advertisers) are simply dropped [0].

2.16 Services and Characteristics

2.16.1 Attribute Protocol (ATT)

The Attribute Protocol (ATT) defines how a server exposes its data to a client, and how that data is organized and accessed in a Bluetooth Low Energy (BLE) system [0].

2.16.1.1 Roles in ATT

There are two main roles in ATT communication:

- **Server:** The server is the device that stores and exposes data, and may allow certain behaviors to be remotely controlled. It receives commands from peer devices and sends responses, notifications, or indications in return. For example, a thermometer acts as a server when it provides access to its current temperature, unit of measurement, battery level, or the interval at which it records readings. Instead of requiring the client to repeatedly poll for changes, the server can proactively notify the client when data updates occur [0].

- **Client:** The client is the device that reads data from the server or controls the server's behavior. It sends commands and requests, and accepts incoming notifications and indications. In the thermometer example, a mobile device that connects to the thermometer and reads temperature values is operating as the client [0].

2.16.1.2 Data Format: Attributes

The data exposed by the server is organized into attributes. An attribute is a general term for any piece of data available on the server, such as services or characteristics (described later).

Each attribute consists of the following elements:

- **Attribute Type (UUID):** This is a Universally Unique Identifier (UUID) used to distinguish the type of data.
  - A 16-bit UUID is used for Bluetooth SIG-adopted attributes.
  - A 128-bit UUID is used for custom or vendor-specific attributes defined by developers [0].

- **Attribute Handle:** This is a 16-bit value that acts like an address assigned by the server to each of its attributes. The handle uniquely identifies an attribute during the lifetime of the connection, allowing the client to reference it directly. Handle values range from 0x0001 to 0xFFFF, while 0x0000 is reserved [0].

- **Attribute Permissions:** Permissions control whether an attribute can be read, written, notified, or indicated, and what security requirements are necessary for each operation. These permissions are not specified within ATT itself, but are defined at a higher layer—typically the GATT (Generic Attribute Profile) or application layer [0].

2.17 Profiles

2.17.1 Generic Attribute Profile (GATT)

The Generic Attribute Profile (GATT) defines how BLE devices organize, expose, and exchange data over a connection. It builds directly on top of the Attribute Protocol (ATT), using it as the transport layer for transmitting structured data known as attributes [0].

GATT introduces a hierarchical data model centered around three key concepts:

- **Services**
- **Characteristics**
- **Profiles** [0]

These elements allow BLE devices to encapsulate user-facing data and device functionality in a standardized, interoperable way. All BLE application-level interactions happen within the framework defined by GATT [0].

2.17.2 GATT Roles

Like ATT, GATT supports client and server roles, which are dynamic per transaction rather than fixed per device. This means a single device can simultaneously act as a GATT server for one connection and a GATT client in another [0].

- **GATT Server:** Stores and exposes attributes to the client. It responds to requests and may send unsolicited updates via notifications or indications. Every BLE device must at least support a minimal GATT server, even if only to respond with error codes [0].
- **GATT Client:** Initiates communication by performing service discovery, reading/writing attributes, and subscribing to updates. The client has no prior knowledge of the server's structure—it learns through discovery procedures [0].

2.17.3 Services

A service is a logical grouping of one or more attributes that collectively provide a certain function on the server. A service always includes at least one characteristic, and often contains supporting attributes like declarations, descriptors, and included services (used to reference other services) [0].

- **Primary Services:** Represent core functionality (e.g., Battery Service).

- **Secondary Services:** Offer auxiliary support and must be referenced by primary services (rarely used) [0].

The Bluetooth SIG maintains a set of adopted services with published specifications to ensure interoperability across vendors. If a product claims compliance with one of these services, it must strictly follow its specification [0].

2.17.4 Characteristics

A characteristic is the smallest logical unit of user-accessible data on a BLE server. It always belongs to a service and includes:

- **Value:** The actual data being exposed.
- **Properties:** Operations permitted on the value (e.g., read, write, notify, indicate).
- **Descriptors:** Metadata about the value (e.g., format, units, configuration settings) [0].

For example, the battery level characteristic within the Battery Service lets clients read the device's current power level [0].

2.17.5 Profiles

While services and characteristics define how data is stored and exposed on the server, profiles describe how clients and servers interact, including service usage, connection procedures, and security requirements. Profiles are not discovered over BLE connections like services are; instead, they exist as specification documents, often adopted by the Bluetooth SIG. These define how multiple services should be used together to achieve specific use cases (e.g., Heart Rate Profile, Blood Pressure Profile) [0].

Each profile specification includes:

- Required services and characteristics
- Interaction behaviors for both server and client
- Connection and security requirements
- Example usage diagrams and workflows [0]

2.18 Nordic Semiconductor

2.18.1 nRF Connect

nRF Connect for Mobile—formerly known as the nRF Master Control Panel—is a feature-rich application designed for developers working with Bluetooth Low Energy (BLE) devices. Created by Nordic Semiconductor, this free app is available on both Android and iOS platforms and is widely regarded as one of the most powerful tools for BLE development and testing [0].

The application supports numerous Bluetooth SIG-adopted profiles, including Over-the-Air Device Firmware Updates (OTA DFU), making it especially useful for firmware deployment and debugging [0].

2.18.1.1 Key Features

[0]:

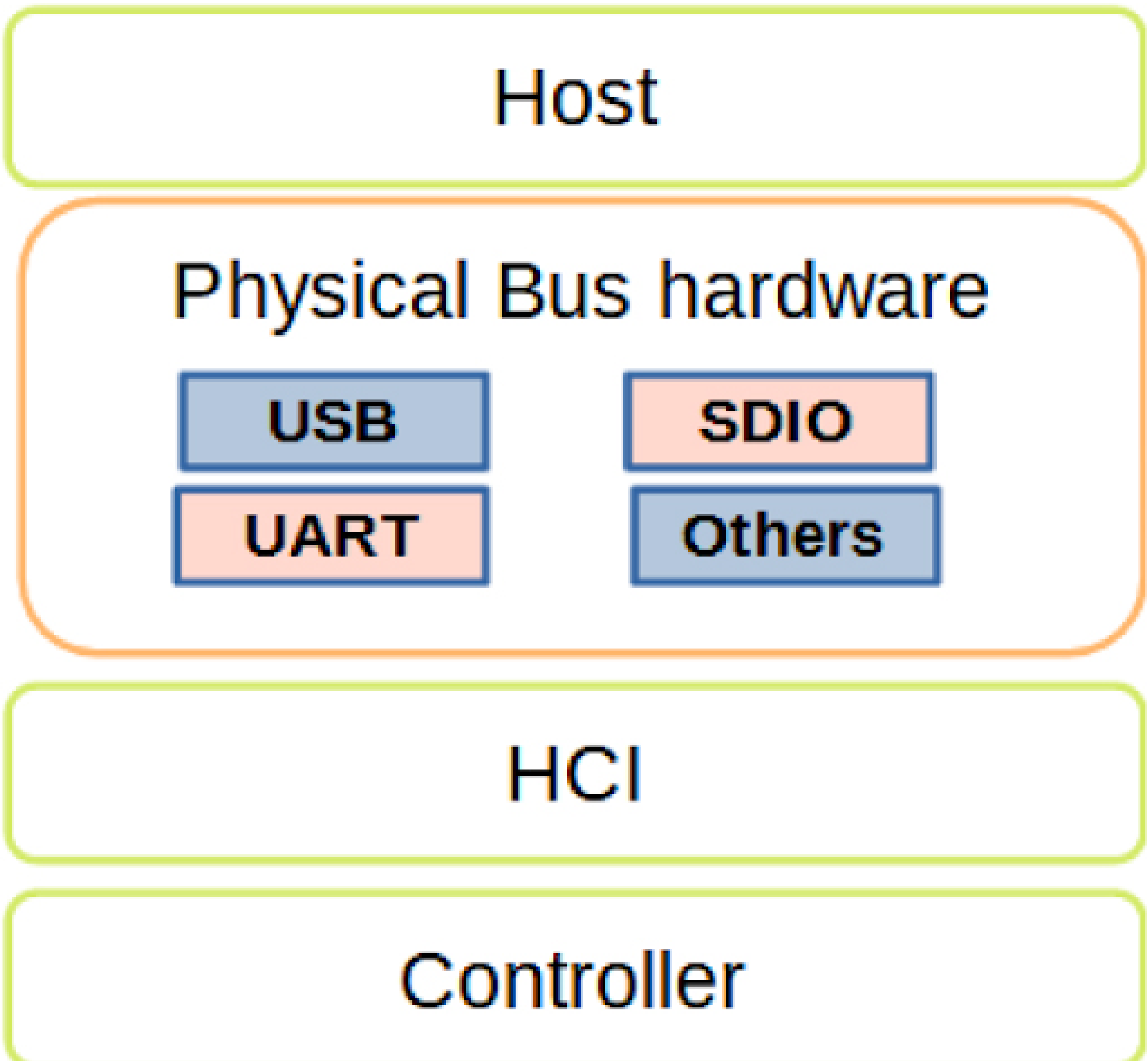
- **BLE Device Scanning with RSSI Graphs:** Visualize signal strength (RSSI) for nearby devices in real-time.
- **Advertisement Data Parsing:** Inspect general advertisements and manufacturer-specific payloads.
- **GATT Client Functionality:** Connect to BLE peripherals and display their services and characteristics.
- **Characteristic Interaction:** Perform reads, writes, and observe values from server-side characteristics.
- **Support for Notifications and Indications:** Enable and receive updates directly from connected devices.
- **GATT Server Emulation:** Simulate a GATT server with built-in configuration presets.
- **OTA Firmware Updates:** Flash firmware over-the-air for supported devices.
- **Automated Testing:** Execute test cases defined in XML scripts for BLE device behavior validation.
- **UART Service Support:** Communicate via UART-over-BLE channels.

2.18.1.2 Compatibility:

- **Android:** Version 4.3 and higher
- **iOS:** Version 8.0 and higher

With its comprehensive feature set, nRF Connect is an essential tool for BLE developers, from prototyping and debugging to final deployment [0].

Figure 2.8: Host, HCI, and Controller components



CHAPTER 3

Reverse Engineering

3.1 Analysis Methods and Tools

3.1.1 Static Analysis

Static analysis is a practice of analyzing code without executing it. It can be used to help inform dynamic analysis. Static analysis tools can analyze at either the source code level with code that hasn't been compiled yet or machine language level with code that has. Static analysis tools can be used by reverse engineers to retrieve and comb over assembly level code. This is one of the most basic functions of any static analysis tool, but many of them offer a lot more functionality to help reverse engineers. Most static analysis tools are designed to help give the reverse engineer a starting off point with interpreting assembly level functions.

3.1.1.1 Disassembler

One of the most key static analysis tools for a reverse engineer is a disassembler. Disassemblers are applications that take in a program's executable file and generate a file with the assembly code. This isn't too difficult because assembly is just a text translation of the machine readable binary code. Unfortunately, that makes it a lot less clear than higher level programming languages. Disassembly is also unique to a person's processor, but there are disassemblers that can support more than one CPU architecture. Some examples of disassemblers are IDA, Binary Ninja, Hopper, Ollydbug, Radare2, and Ghidra.

3.1.1.2 Decompiler

Decompilers are similar but more complex than disassemblers. Instead of just producing the assembly language code, decompilers attempt to produce high-level readable code. They attempt to produce something that looks as close to the source code as possible by reversing the compilation process [0]. The front end of the decompiler decodes low-level assembly instructions and translates it into an intermediate representation specific to the decompiler. The intermediate representation is then iterated on to remove as many extraneous details as possible while preserving the important details. Lastly the back end takes the polished up intermediate representation and translates it again into a high level language.

While this may sound like a simple way to retrieve the source code, it is highly unlikely the high level language returned will be something that actually matches. Anyone who has ever run text through a translation website multiple times knows that each iteration causes a loss in fidelity and oftentimes the end result will be gibberish. Decompilers go a step further and have no immediate knowledge of things like function or variable names and structures. This does not make them useless, though. For example, a text translator will usually return your original result when given a simple phrase. Similarly a decompiler will most likely be able to pick up on more straightforward functions such as adding a + b. Decompilers offer hints and snippets into what the source code may look like which is valuable information for a reverse engineer. Most of the examples for disassemblers listed also count as decompilers.

3.1.1.3 Dumping Tools

Executable dumping is usually the first step in reverse engineering a program. Executable dumping helps inform a reverse engineer what a program does, how it interacts with external elements, and general knowledge of how a file is structured. Using dumping tools, a reverse engineer will start by figuring out what type of file they're dealing with. They will then start to unpack the format. Extracting strings will immediately offer insight into what language the source code is written in, what library modules it uses, what kinds of data it is dealing with, and what the goals of program functions may be. Other useful information we can retrieve is the layout of the file in memory and what the general logical structure of the file is. Once we know the type of file we also know which tools we can use. For example, some debuggers only work with certain high and low level languages. Some popular executable dumping programs are ones already built into your machine like DUMPBIN for windows or otool for mac.

Otool is identifies a file's mach header. On systems with a Mach kernel like macOS and iOS, the executable binaries they use will have a mach header. All headers have a magic number to identify them. T hin binaries only have that number while fat binaries with fat headers will have locations of the other executable's headers in them

3.1.2 Dynamic Analysis

Dynamic Analysis occurs when the program or section being analyzed is run during the analysis process. Because dynamic analysis requires the program to execute with unknown results, it is safest to do it in an enclosed or sandboxed environment to protect the rest of the system. Thus easily manipulated virtual machines are usually set up during the dynamic analysis process. Many tools can be part of the dynamic analysis process. Anything that needs to run and monitor some output is considered dynamic. Tools may run the full program, a portion of the program, or even just a single line. Tools that monitor the external environment while the program runs are also considered dynamic.

3.1.2.1 Debugger

Debuggers are a tool usually used for developers to locate and work through errors in their programs, but they're also vital tools in reverse engineering. Many debuggers can work through assembly language. While assembly language may be difficult for a human to parse through, it is the exact same logic that gets broken down and sent to a computer meaning that the computer can show what each assembly instruction is intended to do. Most debuggers software engineers use were actually designed from the ground up with the purpose of stepping through assembly code. The debugger can show the state of CPU registers along with a memory dump that shows what's in the stack. Debuggers usually contain disassemblers which as discussed is a vital reverse engineering tool. Many debuggers also contain both software and hardware breakpoints. Software breakpoints are instructions added into the code during runtime to pause and hand control over to the debugger. Hardware breakpoints are a CPU feature which allow the processor to pause execution when a certain memory address is reached and hand control over to the debugger. A reverse engineer can use insert breakpoints at data structures of interest and use the debugger to reveal what they are. Debuggers also offer a clear view of registers and memory to aid in a reverse engineer's ability to process low level information.

3.1.2.1.1 User Mode Debuggers Most debuggers that a programmer will use are user mode debuggers. They run on a system like any other application then seize control of the target program to debug [0]. An advantage to them is that they are easier to set up and navigate than their kernel-mode counterparts. Usually it's fine to stay limited to user mode viewing of an application. It only creates troublesome limitations when the target application has kernel mode components such as device drivers. User mode debuggers are also not always sufficient when trying to debug a program before it reaches the main entry point. These kinds of programs are usually ones that have a lot of statically linked libraries in the executable. The final and most likely to be problematic issue is that user-mode debuggers can only view a single process in a program. This can cause issues when the target application has processes that interact in unknown ways. The user may not know which process to zero in on that has the code of interest.

3.1.2.1.2 Kernel Mode Debuggers Kernel mode debuggers are different from user-mode debuggers because they capture the entire system and not just a single process. Instead of running atop the operating system, kernel mode debuggers sit alongside the system kernel and stay ready to capture the entire system's stats. Kernel mode debuggers can be more helpful to reverse engineers because they offer more clues as to what's going on with the system. A key tool for kernel-mode debuggers is that they allow the placement of low level code breakpoints. As a reverse engineer working with assembly code, being able to test different sets of assembly instructions that may be the code section a reverser is looking for is incredibly useful.

For example, picture a scenario where a reverse engineer is looking for the API responsible for handling moving windows? That will need to be managed by a windows manager in the kernel. The complexity is introduced when trying to identify which API moves a particular window. Since there are multiple APIs that can be used to move a window, pinpointing the one you are trying to focus on is a difficult task. This is where kernel mode debuggers come in handy. Low level breakpoints in the operating system responsible for shifting windows around will help you identify which API is getting called when a window is moved [0]. From there the reverse engineer will be able to hone in on that API.

Unfortunately, kernel mode debuggers come with their own drawbacks. Setting them up can be challenging because they require access to the full system. They need to suspend the entire system while running so they can go line by line, which means the system can no longer have multiple threads going [0]. They will also usually need to be set up inside a Virtual Machine which will be discussed in a later section [**PracticalRE**]. These are reasons why a reverser should exhaust their other options before jumping into using a kernel mode debugger. Still, they are powerful tools when the scenario calls for it.

3.1.2.2 System Monitor

System monitoring can be a crucial part of the reverse engineering process. In some cases, a reverse engineer can figure out what they need through system monitoring tools without ever looking at the decompiled code. System monitoring tools can capture what happens between the code and hardware using the intermediate channels of input/output [0]. For local system monitoring, tools monitor things such as file operations (creating, deleting, moving, etc). For programs that communicate over networks, system monitoring might look like recording all TCP/UDP network traffic. System monitoring tools are commonly used in virtual machines.

3.1.2.3 Virtual Machine

Many programmers will encounter virtual machines (VM) at some point during their career. It's not uncommon for an application to interface exclusively with one type of operating system. One reason is because writing applications to work with different operating systems adds time and complexity that not all programmers can afford. Choosing to write in a high level language may make code more portable because there's more verbose built-in libraries or interpreters that deal with the specifics of the systems without the need for any programmer intervention. But high level languages often trade performance for convenience which is not a trade that a developer working with large amounts of data can necessarily afford to take. What happens when a developer has an application that runs on Windows while they have a Mac? This is where a virtual machine enters into the mix. Virtual machines are safe sandboxed environments that work as miniature computers with their own operating systems within a computer. They are constructed with an interpreter and bytecode. During compile time, select code snippets are compiled specific for the VM target architecture and then inserted into the program along with the interpreter. During run-time, the interpreter begins executing the bytecode. Virtual machines are costly to implement because they are so expansive which is why only the necessary code snippets get rendered [0]. Because virtual machines work in their own isolated environment, they offer powerful protections against unknown or potentially malicious software. This makes them a useful tool for reverse engineers who deal with software that they do not know the contents of. The level of control over virtual machines also makes them a useful tool because there is ultimate knowledge of system conditions.

3.2 Compiled Code RE

It is important for a reverser to understand the different goals of high level and low level languages. Understanding these differences will help with interpretation of why code is structured a certain way.

3.2.1 High level languages

High level languages exist to take away the complexity of system specific programming. High level languages work so that a programmer can focus on specifying the clean structural logic without needing to dedicate time to figuring out system specific details. While writing in something like assembly can be very performative, it would be nearly impossible for a standalone human to write a modern application in assembly. Because high level languages favor simplicity over the flexibility to do exactly what is the most efficient for achieving a program's goals, many programmers don't even know what is going on at the assembly level. A reverse engineer will be forced to pick apart what potentially roundabout ways a program's goals are being achieved. The main goal of a reverse engineer is to use what they know about what the program was trying to do, potential ways that can be accomplished in high level code, and how to read assembly code to make their best educated guess on what's happening where. For reverse engineers, the most important thing to know about a high level language is to what level does it abstract or conceal the underlying machine code [0]. Languages like Python that have a built in interpreter will abstract it a lot. These programs may be full of extraneous machine code. On the other hand, languages like C are written much closer to the target processor and won't have nearly as much separation between the source and machine code.

3.2.1.1 Control Flow

Control flow is what makes code more user friendly. This manifests through statements like conditionals that give general instructions for what a program should do when. ' A processor has no knowledge what statements like 'if' or 'while' mean. Under the hood, these statements translate into verbose and daunting assembly code. This is because high level conditional statements are often broken down into operation sequences because it would otherwise overwhelm the processor [0].

Other typical structural components of programs that aid in control flow are switch blocks and loops. Switch blocks, or $n - way$ conditionals, take in an input and have n number of code blocks that are potentially executed depending on the input value. Each block of code gets assigned at least one value prior to runtime. The compiler also generates code to receive the input value and search for the proper code block to execute. The values for the code blocks are usually stored in a lookup table that has pointers to each corresponding code block. Depending on the input value, the program will go through the process of searching the lookup table then jumping to the proper code block at runtime [0]. Loops work to allow a program to repeatedly execute a certain code block multiple times. A loop has a counter to keep track of how many iterations it has performed. There is also a conditional statement that determines when the loop will stop. Loops and conditionals are inherently intertwined. The difference is that loops execute over and over until the condition is no longer met.

To understand control flow sequences, one must understand how low level control flow is implemented. This means that a reverse engineer needs to know the specific rules of each kind of low level architecture because low level control flow is individual to the platform and therefore the language.

3.2.2 Low level languages

Earlier we mentioned that complexity is introduced when working with low level system specific details. This is especially true when the goal is to translate high level logic into something that will be understood by your machine. Of course, there must be a way to do this because the CPU does it anytime a modern application is run. But it often involves keeping track of more details than a sole human is capable of. That is why a reverse engineer must develop the skill of parsing through assembly code and being able to create a kind of 'mental image' of how it relates to high level constructs. Data management is one of the things that a person's computer keeps track of that would be difficult for a human to do. To understand why this is, we can look at the data management of a relatively low level language, C, versus the assembly representation. Consider the code:

```
int divide(int a, int b) {
    int result;
    result = a // b;
    return result;
}
```

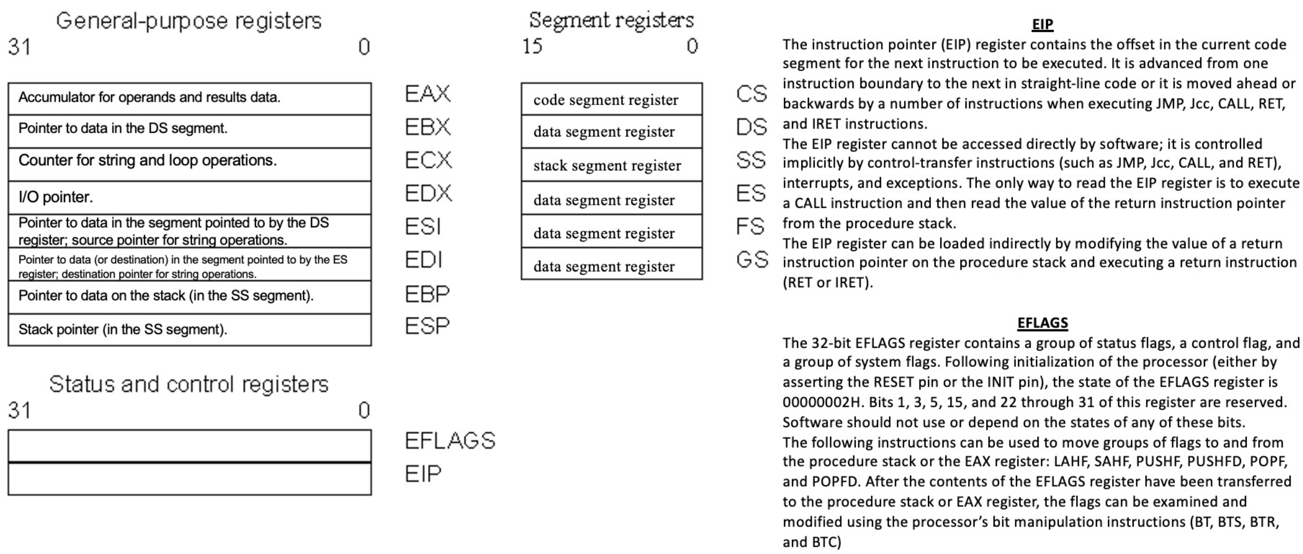
While this function may seem incredibly simple, there is no direct translation into a machine code representation. To execute this in a low level language, it would require first storing the machine state. Then memory would need to get allocated for result. Variables a and b would need to get loaded from memory into a register. Then a would need to be divided by b and the result would need to get stored in the register that got loaded in the beginning. The machine state from before would need to get reloaded. The pointer would need to return to the caller and bring back result [0]. One line of high level code could result in any number of assembly instructions. Managing data is one of the biggest challenges of reverse engineering.

3.2.2.1 Registers

To keep from needing to constantly access RAM, microprocessors have a smaller internal memory that can be accessed with barely any performance cost [0]. There are multiple types of internal memories that microprocessors keep and registers are one of them. Registers are little pieces of internal memory that live within the processor and are able to be accessed with an imperceptible cost to performance [**PracticalRE**]. The biggest problem with registers is that there are not very many of them. One of the most popular processors, the IA-32, only has eight 32-bit registers that can be used for anything. It does have more registers, but they all have highly specific use cases. Assembly language is written around utilizing registers because they're so performant. They are not good for long term storage, though, that is when RAM becomes the better choice. One of the most important things to take away is that CPUs do not automatically manage this. Data management is outlined in the assembly code which is what reverse engineers will need to get comfortable sorting through.

One thing that reverse engineers will need to do is focus on figuring out what kind of values are getting loaded into a register. For example, it is easy to see when a register is only being used to grant instructions access to a specific value because that register will only show up when transferring value from memory to the instruction or vice versa. Another example is when a register shows up many times in one function. This is a good clue that one of the function's local variables is being stored in that register.

Figure 3.1: Figure modified using Intel® 64 and IA-32 Architectures Software Developer's Manual and https://flint.cs.yale.edu/cs422/doc/pc-arch.html#register



3.2.2.2 The Stack

The stack is one of two places that a value can be set aside. Registers are not managed by a processor and to use one you just need to load a value in it. Often there will not be registers available or there is a particular reason a variable will need to reside in RAM instead of in a register. That's when you'd put a variable on the stack instead [0].

The stack is a short term storage space in memory that gets utilized by both the CPU and the program. It is the spot where short term information gets put when a register can not be used for whatever reason. Registers are for the shortest term data while the stack is for the second shortest. The stack lives in RAM like all other data and is just a carved out section for intermediate term data. Modern operating systems tend to manage multiple stacks at the same time. Each of the concurrently running stacks is a representation of a program or thread [0].

Stacks use Last In First Out data management. Items are pushed on the top of the stack and popped from the bottom of the stack. Memory in stacks is allocated from the top down where the first in address is allocated and used first while the stack grows backwards towards lower addresses [0].

3.2.2.3 Flags

One of the registers you may have noticed from the previous figure is the EFLAGS register. This is a collection of special IA-32 registers that contain system and status flags. The system flags' job is to manage the different modes and states of the processor. The status flags are what a reverse engineer will typically be more interested in and are used by the processor to record its current logical state [0]. They are often updated by various logical and integer instructions so they can record the outcome of these actions. There are also instructions whose operation conditions are dependent on the values for the status flags. This is what allows sequences of instructions to run different operations depending on what different input values may be, etc.

Flags in IA-32 are the crux of conditional code. Arithmetic instructions check operand conditions and then set processor flag conditions based on the resulting values. There are also sets of instructions designed to read the flags and do different operations based on the value. An example of a popular instruction set is Jcc or the Conditional Jump. It tests for predefined flag values and then jump depending on whether or not it matches with the specified conditional code [0].

3.2.2.4 Functions

Instructions are the actual actions specified in assembly code. They are formatted with operation code (opcode) and one or two operands [0] The opcode is what you are asking the computer to do such as MOV or JMP. The operand is the parameters that get passed to the opcode or the data being manipulated. Certain instructions will have no parameters. Data in assembly comes in three basic forms. There are register names, immediate data, and memory addresses. Register names are the names of the general purpose registers to be read from or written to like the EAX, EBX, etc. Immediate data is constant values that are embedded into the code and usually indicates there was a hard coded value in the source code. Memory addresses are the locations of operands stored in RAM. It can be hard coded and tell the processor where to read to and write from. It could also be a register with a value that will be used as a memory address. It is also possible to combine a register with an arithmetic operation and a constant so that there is some base address and then an index offset [0].

General purpose instructions are the ones that deal with program flow, logic, arithmetic, string operations, and basic data movement. They deal with data stored in memory at the general purpose registers, EFLAGS register, segment registers, and address information stored in memory [0].

The MOV instruction shows up most frequently in most IA-32 instruction sets. This one deals with basic data movement. It takes in a destination operand and a source operand then moves the data from the source to the destination. The sources can be registers, immediate, or memory addresses. It is important to note that MOV cannot transfer data through memory, it can only take it out or put it in. The destination address can be a memory address (using a register or an immediate) or a register [0].

3.3 Example Problems

3.3.1 Reversing Hello World

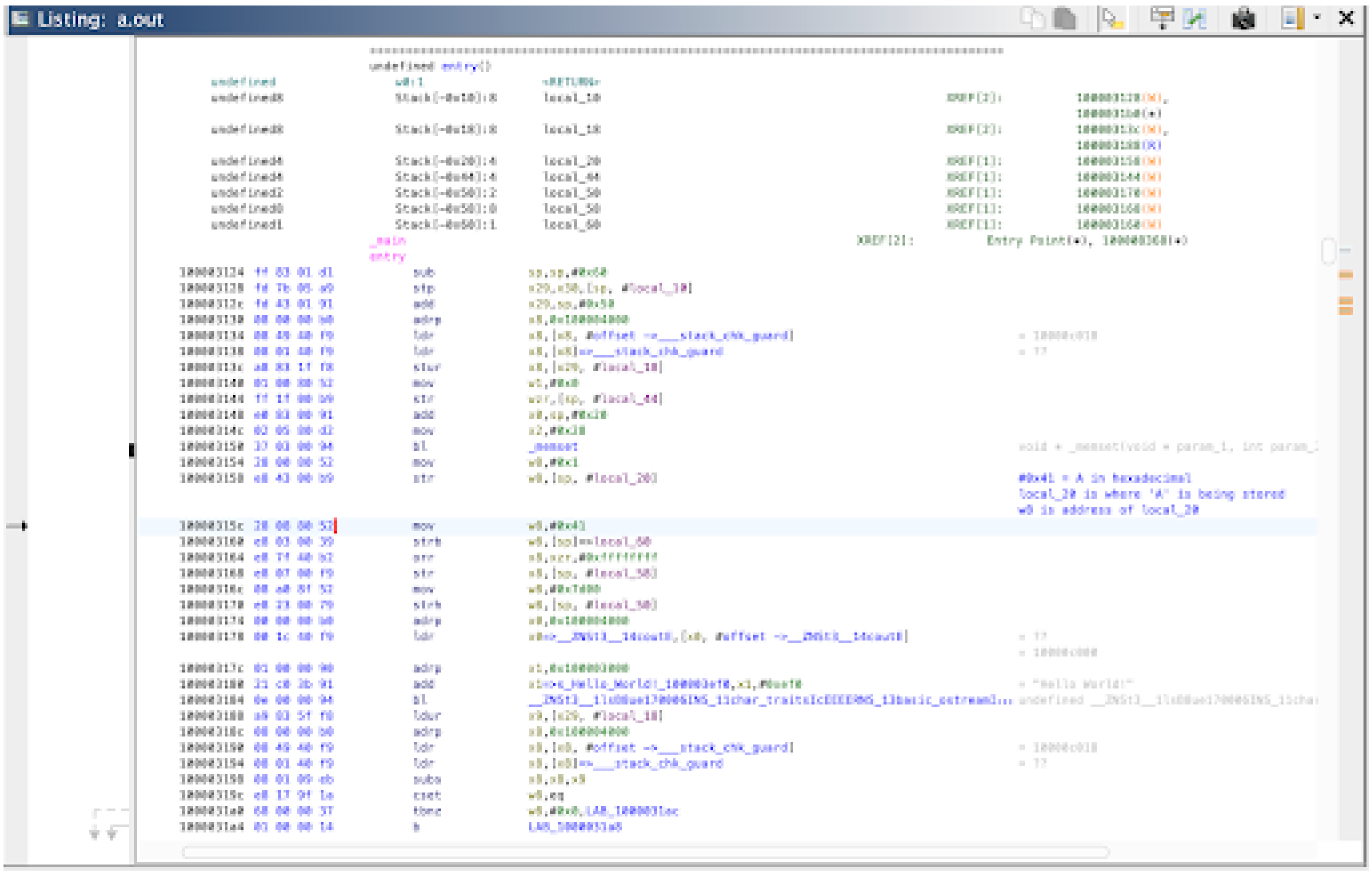
Before taking on the larger endeavor of reversing a program written in a declarative language (SwiftUI), it's important to start with the basics. Figure [insert figure here] shows a simple 'Hello World' program in C. To add some complexity, a few random variables and data structures were thrown in as Easter eggs. This is the program whose decompilation will be used as a jumping off point. Figure 3 is the decompilation of

Figure 3.2: Hello World Program


```
#include <iostream>

struct dope{
    char b;
    unsigned long long val;
    short val2;
};

int main() {
    int array[10] = {0};
    array[8] = 1;
    struct dope local_dope;
    local_dope.b = 'A';
    local_dope.val = 0xffffffff;
    local_dope.val2 = 32000;

    std::cout << "Hello World!";
    return 0;
}
```

the program once it was put through Ghidra. The first thing to note is how with even a relatively low level language like C, the instructions in the code more than doubled. The disassembly being shown in the figure is also only a portion of Ghidra's output. The figure only shows the function section of the program output when imports, exports, labels, classes, etc take up the large majority of the program. One important part of reverse engineering is sorting through all of the information to find out what exactly is important to the reverser. Some reverse engineers refer to this process as finding the shape and edges of the data. With the

Figure 3.3: Hello World Disassembly



important section identified, it is time to analyze the assembly code. One thing to keep in mind with the disassembled code is that all the values will be stored in hexadecimal. A good place to start is with the values we know will need to be stored. In the array there are 10 variables which all get set to 0, except for the eighth array member which is changed to equal 1. In our local_dope struct there are three variables equal to 'A', '0xffffffff', and 32000. The highlighted line in the figure shows 'A' being stored in the register w8. Shortly after, #0xfffffff shows up without needing to be translated into hexadecimal. #0x7d000 is the hex for 32000. This surface level analysis offers a glimpse into the methodology of more complex reverse engineering. Lastly, the 'Hello_World!' gives us the final piece of information we need to know about what the program is.

3.3.2 Crack Me

The next step in practicing reverse engineering is trying a Crack Me problem. Crack Me problems are toy problems designed by other software developers to help reverser's practice their skills. Usually there's an executable that opens up a little puzzle. The puzzles usually involve finding a password but can involve any number of things like decryption, key generation, etc. This section will cover the process of reverse engineering a simple crack me.

The first step I took in reversing this program was checking the header and libraries as shown in Figure 4 and 5.

Figure 3.4: Crack Me Header

```
nataliepargas@Natalies-MBP downloads % otool -hv crackme0x00
crackme0x00:
Mach header
      magic  cputype cpusubtype  caps    filetype ncmds sizeofcmds      flags
MH_MAGIC_64   X86_64        ALL  0x00     EXECUTE    16       1368   NOUNDEFS DY
LDLINK TWOLEVEL PIE
```

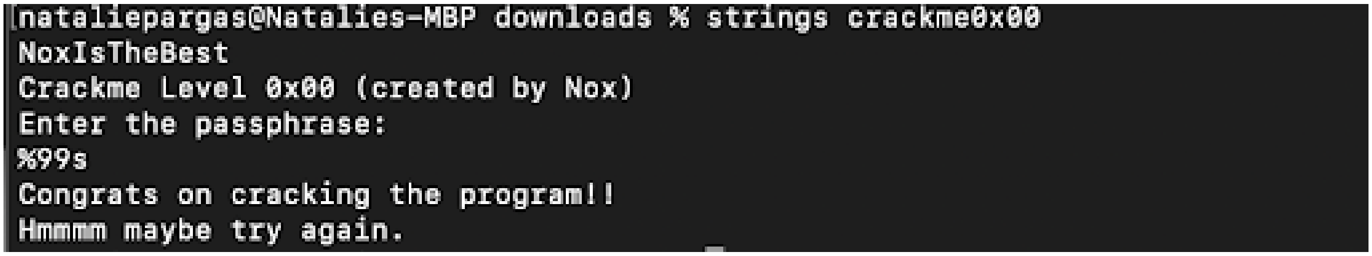
Figure 3.5: Crack Me Libraries

```
nataliepargas@Natalies-MBP downloads % otool -L crackme0x00
crackme0x00:
        /usr/lib/libSystem.B.dylib (compatibility version 1.0.0, current version
 1319.0.0)
```

Both of these steps were done with an executable dumping tool called 'otool'. The header information shows that the assembly language being used is x86. The library dump shows that the only library being linked is the system library. While these tools didn't offer that much information about this particular program, they are very useful in programs that have more dependencies and more specific assembly languages. These dumping tools ended up being vital later in the project because they offered insight into what libraries were being linked from the project's declarative language as well as what assembly language was being used with Apple's modified version of ARM64. Next, otool was used once again to list the strings. This is a vital part of reverse engineering and is useful to be able to refer back to during the process. Figure 6 shows the result of the string dump.

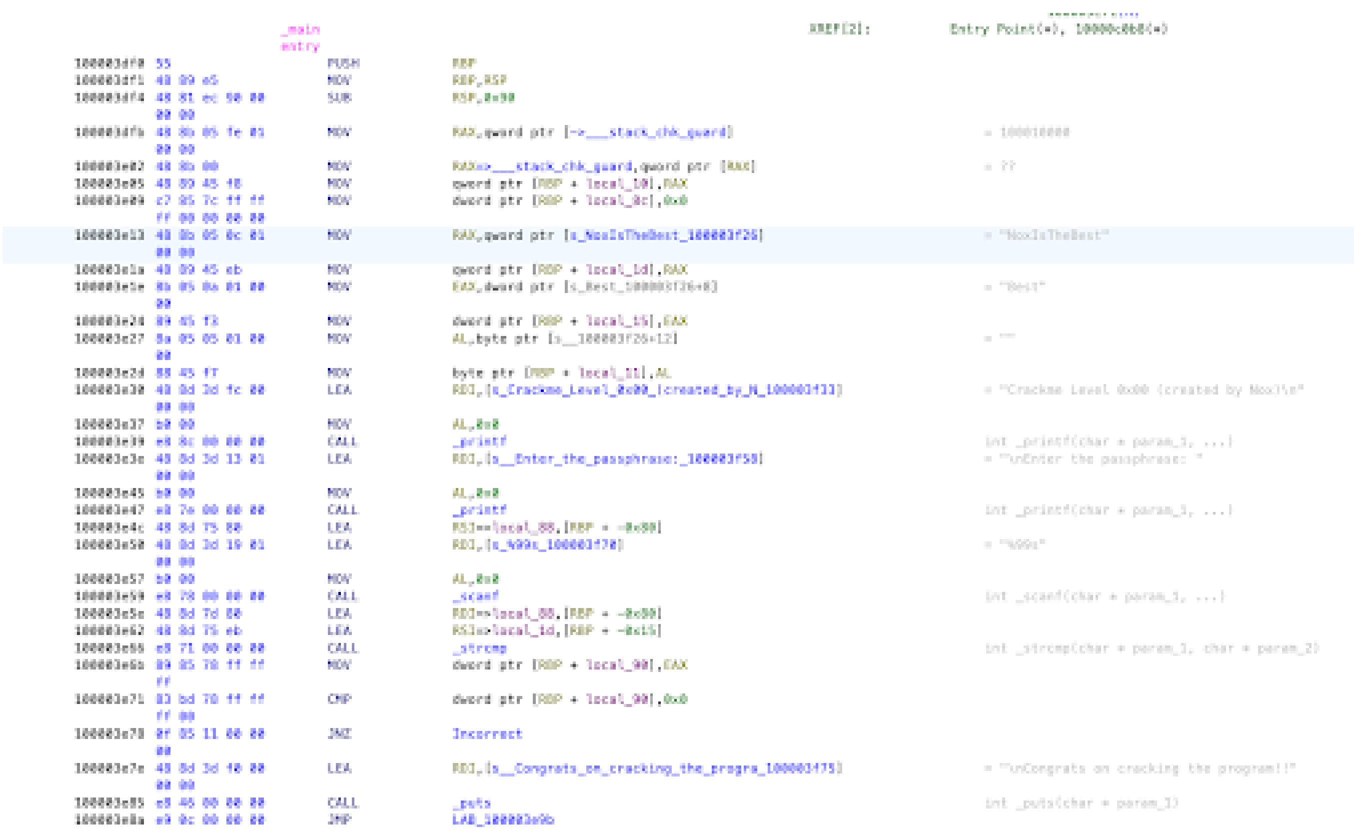
Examining this more closely, you can see that there's only a few strings that give a very clear idea of what the program is designed to do. There's a random string, the title of the program, a passphrase prompt, a string indicating the expected input, a congratulations message, and an incorrect guess message. With just this information, you could easily make an educated guess on what the password is. Most likely the

Figure 3.6: Crack Me Strings



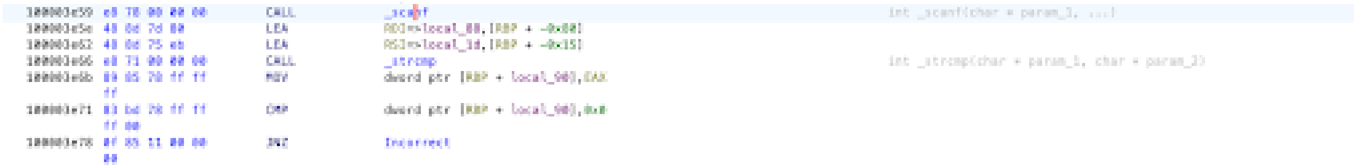
passphrase will be the one random string that doesn't get given easily in the executable. But for the sake of gaining understanding of the process, it's good to go over the decompiled code. Figure 7 shows the decompiled code.

Figure 3.7: Crack Me Ghidra Disassembly



The first thing to do is find the entrance into the program. Ghidra already labeled the '_main' at the top but the strings and function calls reaffirm this as the right section to be looking over. Next, thinking back to the string dump, it's likely that the password will be near whatever function takes input. Prior knowledge of programming informs the reverser that after getting the user input, the input string will need to be compared to the right answer. Thankfully Ghidra was able to identify the function 'scanf'.

Figure 3.8: Crack Me Code Section 1

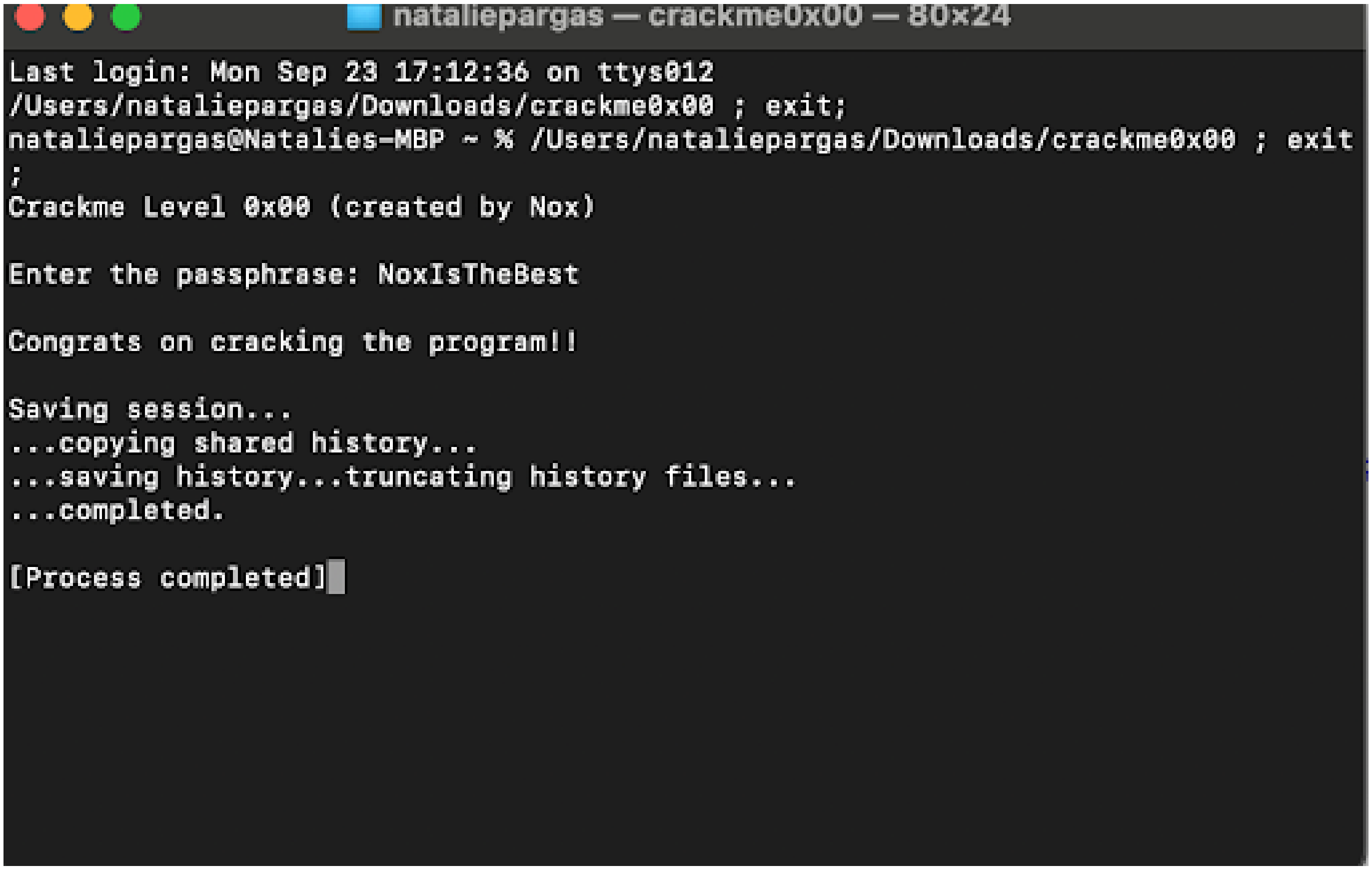


Inspecting the code section at figure 8, it shows that the variable local_88 contains the user input. This is because it loads a %99s into the RDI register to prepare for the input directly above where scanf is called. RSI has local_1d loaded into it and that variable is immediately 'strcmp' compared to local_88. Using these clues, one could infer that local_1d contains the password. To verify, a reverser should always retrace and check.

Figure 3.9: Crack Me Code Section 2

The first instance of local_1d contains the register RAX 9. RAX has the qword ptr ' s_NoxIsTheBest_100003f26' moved into it right above. s_NoxIsTheBest_100003f25 only contains the string "NoxIsTheBest". That string is probably the password, but all that's left is to check. Figure 10 shows the result.

Figure 3.10: Crack Me Code Executable



The attempt was a success and the crack me was successfully reverse engineered!

3.4 Java RE

3.4.1 JVM

3.4.2 Reversing Bytecode

3.4.3 Java Name Obfuscation

3.4.3.1 Obfuscating names for .class file

3.5 Mobile RE

3.5.1 Hybrid Approach

3.5.2 Symbolic Execution

3.5.3 Generating UML Diagram

3.5.4 Android

3.5.4.1 Tools

3.5.4.1.1 Dalvik VM Android

3.5.4.1.2 APK Tools

3.5.5 Apple?

3.5.5.1 Obj C tools

CHAPTER 4

Methods

I would highly recommend that you use BibLaTeX for your bibliography, and that is what this class uses as of August 2022. BibLaTeX supports foreign languages and UTF-8 and provides several styles for formatting references (ACS, Chicago, APA, Turabian). For many people it also is easier to customize than BibTeX with natbib, should you need to customize the formatting of references. BibLaTeX also can make use of the Biber reference processing application which provides support for foreign languages and more sophisticated sorting options than BibTeX. You still process a special .bib file. The .bib file is where you enter your bibliographic information. Sample entries look something like

```
@article{feu02,
author=  {Thomas Feuerstack},
title=   {Introduction to pdf{\TeX{}}},
journal=  {TUGboat},
volume=  {23},
pages=  {329--334},
number=  {3/4},
url=   {http://www.tug.org/TUGboat/Articles/tb23-3-4/tb75feu.pdf},
year=   2002}
```

or

```
@book{mgbcr04,
author=  {Frank Mittelbach and Michel Goossens and
Johannes Braams and David Carlisle and Chris Rowley},
title=   {The \LaTeX\ Companion},
publisher=  {Addison Wesley Professional},
edition=  {2nd},
address=  {New York},
year=   2004}
```

For a Web site I would recommend the following

```
@misc{brei04,
author =   {Jon Breitenbucher},
title =   {{W}ooster related {L}a{T}e{X} files},
url =    {https://woolatex.spaces.wooster.edu},
howpublished= {World Wide Web},
year=   2021,
note =   {Accessed on 09/27/2021}}
```

You can make a reference by typing `\citet{mgbcr04}` to produce **mgbcr04**. Other forms for citation include `\citep{mgbcr04}` or `\citeauthor {mgbcr04}` to produce [**mgbcr04**] or **mgbcr04** respectively. You can consult **kd03** or **mgbcr04** to find out how to format entries in the .bib file and what options each reference type has.[1]

Indicies are also relatively easy to create. If I wanted to have Wooster show up in the index, I would enter `Wooster\index{Wooster}` in my source file. I could create a subentry for User Services by entering `User Services\index{Wooster!User Services}`. A subsubentry for Help Desk would be entered as `\index{Wooster!User Services!Help Desk}`.

To create the index, one needs to make sure to uncomment the `\makeindex` command in the `main.tex` file. One also needs to uncomment the makeidx entry in the `styles/packages.tex` file and then run the Makeindex program. Consult **kd03** or **mgbcr04** for further information.

[1]You could also use footnotes if your department called for that.

4.1 Environment Setup (components)

4.1.1 Virtual Machine

4.1.2 Tools

4.1.2.1 JADX

4.1.2.2 Ghidra

4.1.2.3 APK Tools

4.1.2.4 JBSE (symbolic Java VM)

4.1.2.5 UML Diagram Creator (Ask Dr.Guarnera)

4.1.2.6 Emulator ?

4.2 Scripting

4.3 App Interoperability

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