Automating Analysis and Exploitation of Embedded Device Firmware

By: Malachi Jones, PhD

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About Me

https://www.linkedin.com/in/malachijonesphd

- **Education**
  - Bachelors Degree: Computer Engineering (Univ. of Florida, 2007)
  - Master's Degree: Computer Engineering (Georgia Tech, 2009)
  - PhD: Computer Engineering (Georgia Tech, 2013)
- **Cyber Security Experience**
  - Harris: Cyber Software Engineer (2013-2014)
  - Harris: Vulnerability Researcher (2015)
  - Booz Allen Dark Labs: Embedded Security Researcher (2016- Present)

About Dark Labs

Booz Allen Dark Labs is an elite team of security researchers, penetration testers, reverse engineers, network analysts, and data scientists, dedicated to stopping cyber attacks before they occur.[1]

(1 http://darklabs.bah.com)

Outline

- Motivation
- Background
  - Firmware Analysis
  - Automated Exploit Generation
  - Intermediate Representation (IR) Languages
- LLVM
- Architecture Independent Analysis and Exploitation
- Conclusion

Motivation

- Embedded in Society

Critical Infrastructure
(Nuclear Power Plant)

Life Critical Systems
(Pace Maker)

Transportation Systems
(Jeep)

Financial Infrastructure
(Banking & Investing)

Internet of Things (IoT)
(IoT Gadgets)

Commercial Products
(Network Switch)

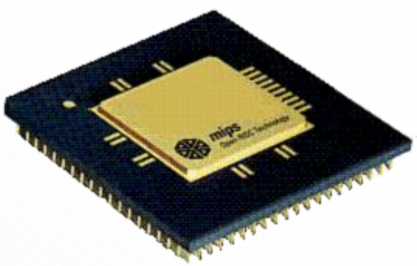
Motivation

- Workhorses Behind the Embedded Scene

Hexagon

MSP 430


SuperH



MIPS

ARM

PowerPC

Motivation

Why is embedded device security difficult? (vs. gen. purpose computing)

1. **Multi Architecture Support**:
   - Plethora of architectures that are utilized in embedded devices versus ubiquitous adoption of x86 & x86_64 for general purpose computing
   - ***This often requires security tool development for each architecture***

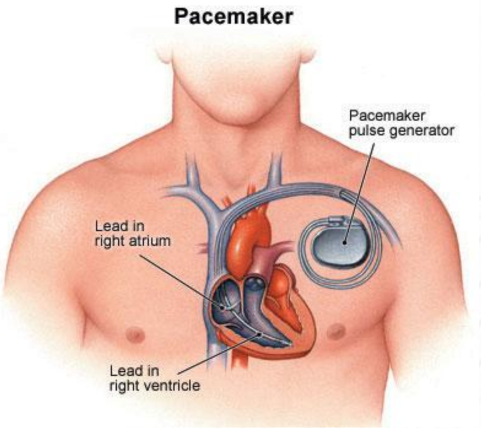
Motivation

Why is embedded device security difficult? (vs. gen. purpose computing)

2. **Custom Hardware**:
   - Embedded devices utilize custom and/or esoteric hardware (e.g. sensors) to perform specialized tasks
   - ***Difficult to emulate custom hardware, which is often required to achieve scale for dynamic analysis***

Motivation

Why is embedded device security difficult? (vs. gen. purpose computing)



3. **Environmental Constraints**:

- Depending on where the device is deployed, it may be constrained by mass, power, cost, or volume that can also impact performance and memory
- ***Mainstream features on general purpose devices such as ASLR or DEP may be sacrificed to satisfy environmental and/or computational constraints***

Motivation

Why is embedded device security difficult? (vs. gen. purpose computing)

4. **Security as an Afterthought**:
   - Often financially and/or technically infeasible to retrofit security capabilities to an embedded system that was not originally designed for it
   - ***Once deployed to target environment, embedded devices may be in operation for 10+ years. Because of (3), Moore's Law does not apply***

Objectives of Talk

- Discussion of an approach for addressing the challenge of building analysis tools that can ***support multiple embedded architectures***

- Specifically, we'll explore an approach for ***decoupling architecture specifics*** from the analysis by utilizing llvm, a widely supported intermediate representation (IR) language

Firmware Analysis

Background

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Background: Firmware Analysis

- Static Firmware Analysis:
  - Analysis of computer software that is performed without the actual execution of the software code
  - **Data Flow analysis** is a type of static analysis that can be used to understand and evaluate how "data flows" through the code paths of the program
  - **Taint analysis** is a specific application of data flow analysis that follows user controlled data to identify code paths that process that data

Background: Firmware Analysis

- Taint Analysis
  - Can be very instrumental in identifying user-controlled vulnerable code
  - **General Process**
    - **Step 1**: Identify source data inputs that originate from user
    - **Step 2**: Follow the code paths that process (e.g. transformations and reads) the user data inputs
    - **Step 3**: Keep track of code that reads the user data
  - A simple example to illustrate the concept of taint analysis can bee seen on the following slide

Taint Analysis Example

```
#include <stdio.h>
#include <stdlib.h>
#include <string.h>
int initializeArray(int * someArray, char * initiValues);

int main(int argc, char *argv[]){
    int myArray [10];

    if(argc !=  2)
    {
      printf("usage:Expected 2 arguments... Received:%d\n",argc);
      return 1;
    }
    char * values = argv[1];

    initializeArray(myArray, values);
    return 0;
}

int initializeArray(int * someArray, char *initializingValues){
    int length = strlen(initializingValues);

    for( int i =0; i <length; i++) {
        someArray[i] = (int) initializingValues[i] ;
        printf("someArray[%d] = %d\n",i, someArray[i]);
    }
  return 0;
}
```

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Step 1: Identify Originating User Controlled Input

```
#include <stdio.h>
#include <stdlib.h>
#include <string.h>
int initializeArray(int * someArray, char * initiValue

int main(int argc, char *argv[]){
    int myArray [10];

    if(argc !=  2)
    {
      printf("usage:Expected 2 arguments... Received:%d\n",argc);
      return 1;
    }
    char * values = argv[1];

    initializeArray(myArray, values);
    return 0;
}

int initializeArray(int * someArray, char *initializingValues){
    int length = strlen(initializingValues);

    for( int i =0; i <length; i++) {
        someArray[i] = (int) initializingValues[i] ;
        printf("someArray[%d] = %d\n",i, someArray[i]);
    }
  return 0;
}
```

User controlled input (via command line)

Step 2: Follow Code that Processes Data

```
#include <stdio.h>
#include <stdlib.h>
#include <string.h>
int initializeArray(int * someArray, char * initiValues);

int main(int argc, char *argv[]){
    int myArray [10];

    if(argc !=  2)
    {
      printf("usage:Expected 2 arguments... Received:%d\n",argc);
      return 1;
    }
    char * values = argv[1];

    initializeArray(myArray, values);
    return 0;
}

int initializeArray(int * someArray, char *initializingValues){
    int length = strlen(initializingValues);

    for( int i =0; i <length; i++) {
        someArray[i] = (int) initializingValues[i] ;
        printf("someArray[%d] = %d\n",i, someArray[i]);
    }
  return 0;
}
```

'values' holds a reference to user controlled data

Step 2: Follow Code that Processes Data

```
#include <stdio.h>
#include <stdlib.h>
#include <string.h>
int initializeArray(int * someArray, char * initiValues);

int main(int argc, char *argv[]){
    int myArray [10];

    if(argc !=  2)
    {
      printf("usage:Expected 2 arguments... Received:%d\n",argc);
      return 1;
    }
    char * values = argv[1];

    initializeArray(myArray, values);
    return 0;
}

int initializeArray(int * someArray, char *initializingValues){
    int length = strlen(initializingValues);

    for( int i =0; i <length; i++) {
        someArray[i] = (int) initializingValues[i] ;
        printf("someArray[%d] = %d\n",i, someArray[i]);
    }
  return 0;
}
```

Call to method that indirectly uses user controlled data

Step 2: Follow Code that Processes Data

```
#include <stdio.h>
#include <stdlib.h>
#include <string.h>
int initializeArray(int * someArray, char * initiValues);

int main(int argc, char *argv[]){
    int myArray [10];

    if(argc !=  2)
    {
      printf("usage:Expected 2 arguments... Received:%d\n",argc);
      return 1;
    }
    char * values = argv[1];

    initializeArray(myArray, values);
    return 0;
}

int initializeArray(int * someArray, char *initializingValues){
    int length = strlen(initializingValues);

    for( int i =0; i <length; i++) {
        someArray[i] = (int) initializingValues[i] ;
        printf("someArray[%d] = %d\n",i, someArray[i]);
    }
  return 0;
}
```

Alias of values, which is user controlled

Step 2: Follow Code that Processes Data

```
#include <stdio.h>
#include <stdlib.h>
#include <string.h>
int initializeArray(int * someArray, char * initiValues);

int main(int argc, char *argv[]){
    int myArray [10];

    if(argc !=  2)
    {
      printf("usage:Expected 2 arguments... Received:%d\n",argc);
      return 1;
    }
    char * values = argv[1];

    initializeArray(myArray, values);
    return 0;
}

int initializeArray(int * someArray, char *initializingValues){
    int length = strlen(initializingValues);

    for( int i =0; i <length; i++) {
        someArray[i] = (int) initializingValues[i] ;
        printf("someArray[%d] = %d\n",i, someArray[i]);
    }
  return 0;
}
```

'strlen' function reads value

Step 3: Identify read operations

```
#include <stdio.h>
#include <stdlib.h>
#include <string.h>
int initializeArray(int * someArray, char * initiValues);

int main(int argc, char *argv[]){
    int myArray [10];

    if(argc !=  2)
    {
      printf("usage:Expected 2 arguments... Received:%d\n",argc);
      return 1;
    }
    char * values = argv[1];

    initializeArray(myArray, values);
    return 0;
}

int initializeArray(int * someArray, char *initializingValues){
    int length = strlen(initializingValues);

    for( int i =0; i <length; i++) {
        someArray[i] = (int) initializingValues[i] ;
        printf("someArray[%d] = %d\n",i, someArray[i]);
    }
  return 0;
}
```

Read operation performed on user controlled data

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Background: Firmware Analysis

- Dynamic Firmware Analysis:
  - Execution of software in an instrumented or monitored manner to garner more concrete information on behavior
  - Typically, software is executed in an instrumented emulator (e.g. QEMU) as the emulator offers fine grained execution control
  - **Emulators** also provide the ability to parallelize the analysis without the need of additional physical devices

Background: Firmware Analysis

- Complications of Dynamic Analysis in Embedded Systems
  - Dynamic analysis is most effective via an emulator, but ***emulation of embedded devices can be non-trivial***
  - Embedded devices often use many variations of esoteric hardware that have little to no documentation, which makes emulating hardware problematic
  - The emulators may have limited support for the firmware's processor architecture or the particular version of the processor

Background: Firmware Analysis

- Approaches to address emulation problem (Not exhaustive)
  - **Manual Static Analysis of Native Binary**
    - Popular approach that can require a significant amount of manual human analysis
    - Much manual effort spent identifying & filtering out false-positives
  - **Event Driven Dynamic Analysis Framework**: (Avatar) [1]
    - Firmware code is executed inside an emulator.
    - Any I/O access is then intercepted and forwarded to the physical device
  - **Firmware Adaption** [2]
    - Extracting limited parts of firmware code to emulate it in a generic emulator
    - The focus is typically on user code that does not require significant I/O access or system calls

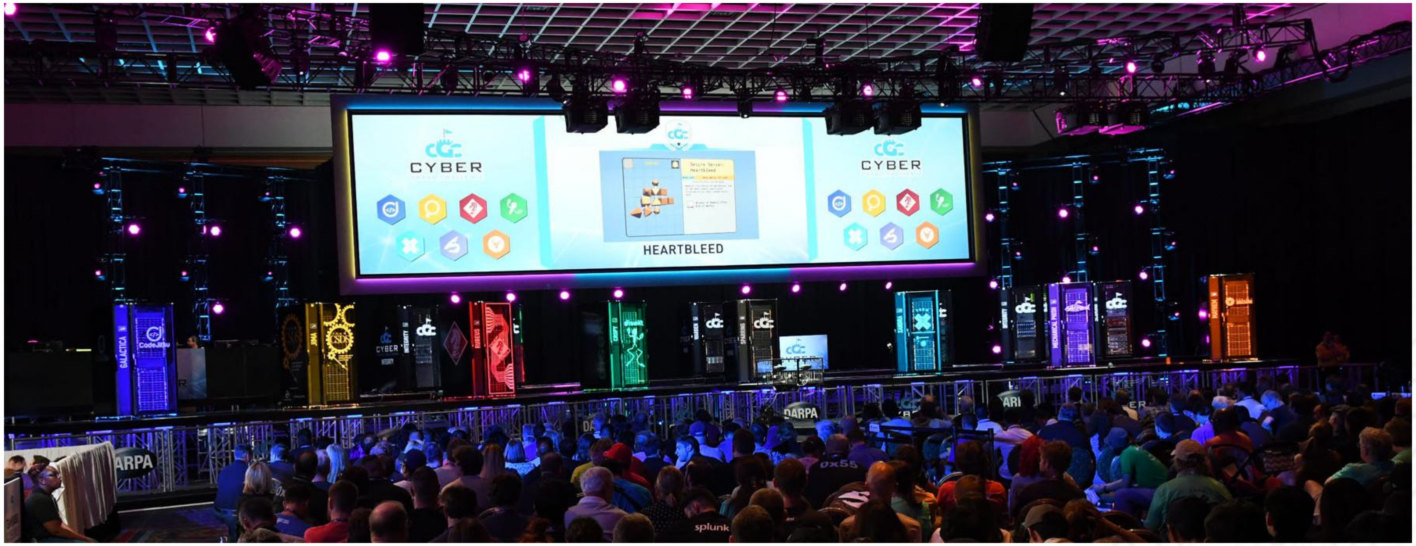
Background: Firmware Analysis

- Static vs. Dynamic Analysis
  - **Static analysis** scales well and can provide better code coverage
  - **Dynamic analysis** can uncover more “actual” vulnerabilities because only code paths that generate unexpected behavior during execution are analyzed
  - A potential code path marked as vulnerable during **static analysis** may not be reachable during actual execution
  - **Static analysis** requires that you know the type of vulnerability that you want to look for (e.g. buffer overflow and integer underflow)

Automated Exploit Generation

Background

Background: Automated Exploit Generation



- Automated Exploit Generation (AEG)
  - Given a program, ***automatically find vulnerabilities and generate exploits for them.***
  - One of the core objectives in DARPA's ***Cyber Grand Challenge***

Background: Automated Exploit Generation

- Steps for AEG [3]
  1. **Bug-finding**: Perform dynamic binary analysis to discover unsafe execution states
  2. **Exploit Generation**: For a specified unsafe execution state, generate a candidate exploit input (e.g. return-to-stack and return-to-libc)
  3. **Verification**: Feed in the exploit input into program to verify that control flow was altered in a desirable manner (e.g. spawn a shell)

Background: Automated Exploit Generation

- Commonly used bug-finding techniques for AEG
  - **Fuzzing**: Generate random permutations of a given input and monitor the program for crashes.
  - **Symbolic Execution**: Analysis of a program to determine the necessary inputs needed to reach a particular code path. Variables modeled as symbols
  - **Concolic Execution**: Used in conjunction with symbolic execution to generate concrete inputs (test cases) from symbolic variables to feed into program
  - **Selective Symbolic Execution*:** Fuzzing + Selective Concolic Execution

** Approach used by the CGC teams that include Shellphish [4]*

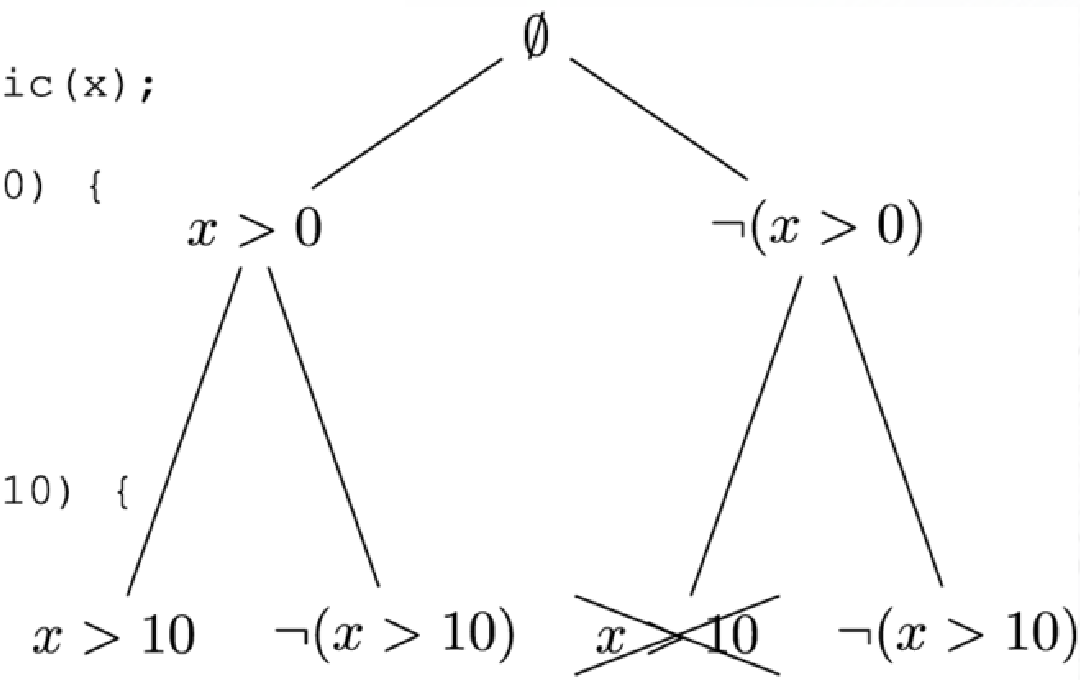
Background: Automated Exploit Generation

- **Example:** Symbolic Execution

```
int x;
mksymbolic(x);

if (x > 0) {
   ...
} else {
   ...
}

if (x > 10) {
   ...
} else {
   ...
}
```



Example taken from the following publication: *Symbolic Crosschecking of Data-Parallel Floating-Point Code (2014)*

Background: Automated Exploit Generation

- Complications with AEG (not exhaustive)
  - Not all bugs are exploitable (e.g. may not be able to alter control flow in a desirable manner)
  - Not all exploits are reliable (e.g. exploit requires an unlikely execution state)
  - Discovering the exploitable path among an infinite number of feasible paths is non-trivial
  - ***Requires dynamic analysis, which is also non-trivial for embedded systems***

Intermediate Representation (IR) Languages

Background

Background: IR Languages

- **Formal Definition**: The language of an abstract machine designed to aid in the analysis of computer programs[2]
- **IR Languages** (Not Exhaustive):
  1. Java Byte Code
  2. Microsoft's Common Intermediate Language (shared by .NET Framework compilers)
  3. ESIL[3] (radare2 disassembler)
  4. BAP [5] (Binary Analysis Platform)
  5. REIL [6] (Static Code Analysis)
  6. SWIFT[4]
  7. LLVM [7] (Compiler Optimization)

(2 https://en.wikipedia.org/wiki/Intermediate_representation)
(3 https://radare.gitbooks.io/radare2book/content/esil.html)
(4 https://github.com/apple/swift/blob/master/docs/SIL.rst)

Background: IR Languages

- **IR Utilization in Disassemblers**
  - An approach that disassemblers (e.g. IDA Pro, Binary Ninja, and radare2) utilize is to convert the binaries to IR for control flow and data flow analysis
  - For example, **radare2** supports the following architectures[4]: 6502, 8051, CRIS, H8/300, LH5801, T8200, arc, ***arm***, avr, bf, blackfin, xap, dalvik, dcpu16, gameboy, i386, i4004, i8080, m68k, malbolge, ***mips***, msil, msp430, nios II, ***powerpc***, rar, sh, snes, sparc, tms320 (c54x c55x c55+), V810, ***x86-64***, zimg, risc-v.
  - Instead of creating an analysis tool for each architecture, radare2 performs analysis on its custom IR, ESIL (Evaluable Strings Intermediate Language)
  - Example x86 to ESIL Translation:

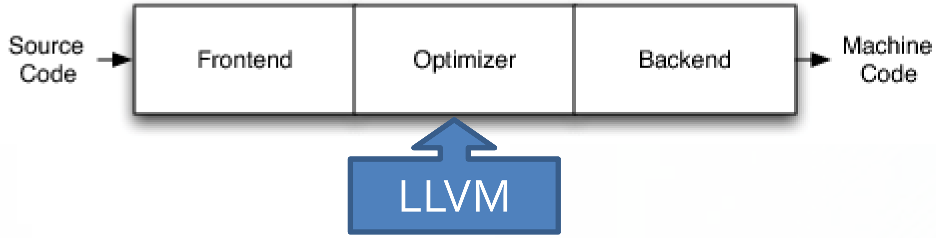
```
mov eax, [0x80480]   →   0x80480,[],eax,=, #8
```

(4 https://github.com/radare/radare2)

LLVM

LLVM

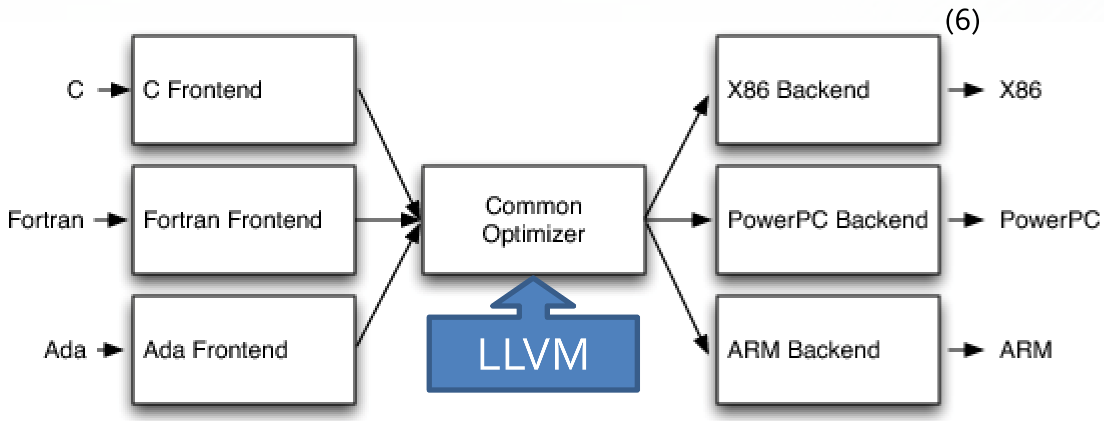
(5)



- **LLVM** is a common infrastructure to implement a broad variety of compiled languages that include[5]
  - The family of languages supported by GCC (e.g. C, and C++)
  - Java
  - .NET
  - Python (via Cpython)

(5 http://www.aosabook.org/en/llvm.html)

LLVM



- Typical use case
  1. Translate programming language (e.g. C) to llvm IR *(Front end)*
  2. Perform compiler optimizations on llvm IR *(Optimization)*
  3. Translate llvm to target machine language, e.g. x86 *(Back end)*

(6 http://www.aosabook.org/en/llvm.html)

LLVM

- Example "hello world" llvm IR[7]

```
; Declare the string constant as a global constant.
@.str = private unnamed_addr constant [13 x i8] c"hello world\0A\00"

; External declaration of the puts function
declare i32 @puts(i8* nocapture) nounwind

; Definition of main function
define i32 @main() {   ; i32()*
  ; Convert [13 x i8]* to i8  *...
  %cast210 = getelementptr [13 x i8], [13 x i8]* @.str, i64 0, i64 0

  ; Call puts function to write out the string to stdout.
  call i32 @puts(i8* %cast210)
  ret i32 0
}

; Named metadata
!0 = !{i32 42, null, !"string"}
!foo = !{!0}
```

(7 http://llvm.org/docs/LangRef.html)

LLVM

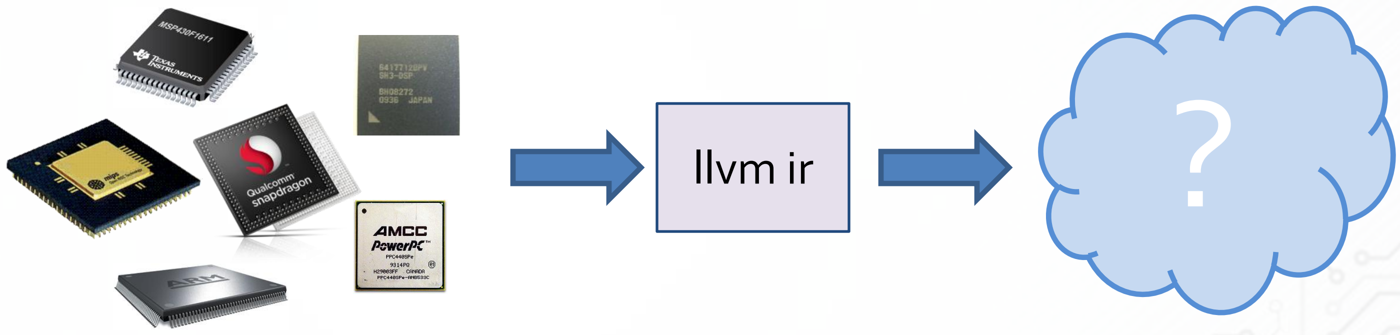
- Supported back end targets include
  - x86 & x86_64
  - ARM
  - MIPS
  - PowerPC
  - Hexagon
- ***Back end code is typically maintained by the processor's designers*** (e.g. Intel maintains the x86 & x86_64 llvm back end)

LLVM

- Analysis Libraries
  - One of the core functions of LLVM is to perform optimizations (e.g. eliminate dead code and redundant stores) on its IR to produce efficient code
  - It uses a powerful set of libraries written in C++ to analyze the code to identify optimizations
  - ***These libraries can also be used for static analysis to find potential vulnerabilities***
  - **Example:** We can perform loop analysis on any llvm instruction to determine the following
    - If the instruction is in a loop
    - What are the exit conditions for the loop (e.g. i<10)
  - Could be useful in identifying buffer overflows

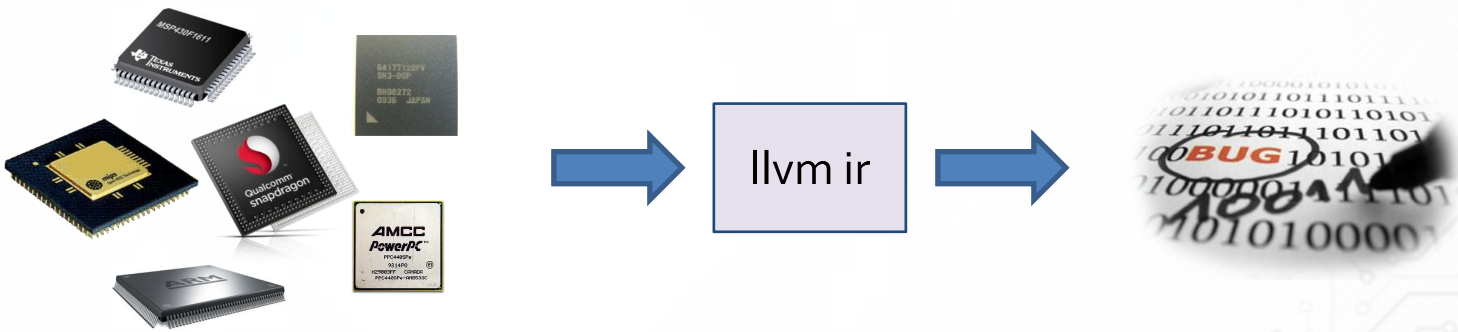
Architecture Independent Analysis and Exploitation

Architecture Independent Analysis and Exploitation



- So how can we utilize LLVM to analyze & exploit firmware?
  - Build a tool that can perform automated static analysis on the IR to find potential bugs
  - In particular, we can exploit the fact that static analysis can provide us with more ***comprehensive code coverage***
  - Bugs that we may be interested in identifying include use-after-free, buffer overflow, and buffer underflow

Architecture Independent Analysis and Exploitation



- Static Analysis Example
  - Suppose we have a binary 'simpleArray' that has a potential buffer overflow vulnerability in one of its functions
  - The vulnerable code in its C representation can be seen on the next slide

simpleArray.c

```
#include <stdio.h>
#include <stdlib.h>
#include <string.h>
int initializeArray(int * someArray, char * initiValues);

int main(int argc, char *argv[]){
    int myArray [10];

    if(argc !=  2)
    {
      printf("usage:Expected 2 arguments... Received:%d\n",argc);
      return 1;
    }
    char * values = argv[1];

    initializeArray(myArray, values);
    return 0;
}

int initializeArray(int * someArray, char *initializingValues){
    int length = strlen(initializingValues);

    for( int i =0; i <length; i++) {
        someArray[i] = (int) initializingValues[i] ;
        printf("someArray[%d] = %d\n",i, someArray[i]);
    }
  return 0;
}
```

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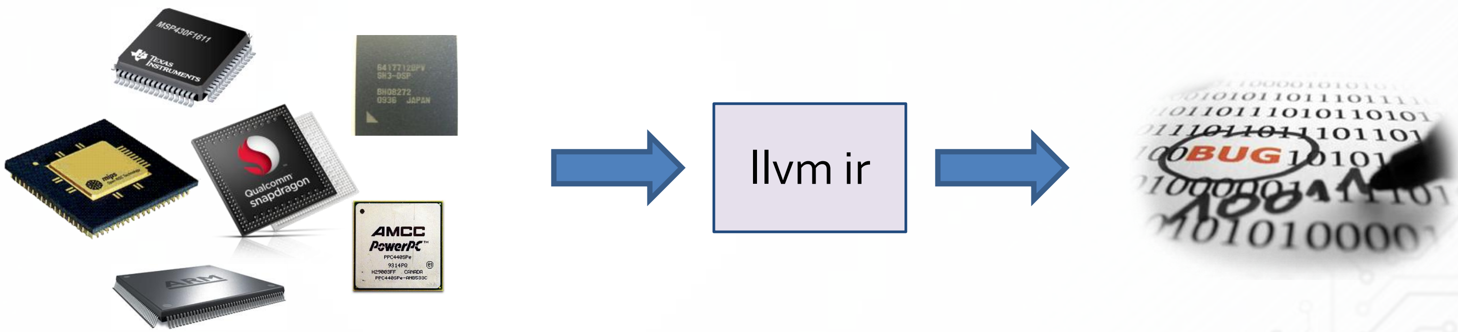
Architecture Independent Analysis and Exploitation

- Snippet of llvm ir (Static Analysis Example)

```
define i32 @initializeArray(i32* %someArray, i8* %initializingValues) #0 {
  %1 = alloca i32*, align 8
  %2 = alloca i8*, align 8
  %length = alloca i32, align 4
  %i = alloca i32, align 4
  store i32* %someArray, i32** %1, align 8
  store i8* %initializingValues, i8** %2, align 8
  %3 = load i8** %2, align 8
  %4 = call i64 @strlen(i8* %3) #3
  %5 = trunc i64 %4 to i32
  store i32 %5, i32* %length, align 4
  store i32 0, i32* %i, align 4
  br label %6

 ………………………………
; <label>:31                                      ; preds = %6
  ret i32 0
}
```

Architecture Independent Analysis and Exploitation



- Static Analysis Example
  - ***Objective is to identify buffer overflows that occur on fixed size arrays***
  - Next few slides will demonstrate how we can use our tool to accomplish this

Buffer Overflow Detection Example

```
Terminal
!tbaa !4"
--------------------Loop Analysis-------------------
**User performs write in loop "  store i32 %9, i32* %10, align 4, !tbaa !4" **
"---------Values that the target value :'  %lftr.wideiv = trunc i64 %indvars.iv
to i32' is dependent on-----------"
"---------Values that the target value :'  %5 = add i32 %4, -1' is dependent on-
-----------"
Value Dependency:  "  %1 = tail call i64 @strlen(i8* %initializingValues) #4"


(3.1) Performing loop analysis
"---------Values that the target value :'  %lftr.wideiv = trunc i64 %indvars.iv
to i32' is dependent on-----------"
"---------Values that the target value :'  %5 = add i32 %4, -1' is dependent on-
-----------"
Value Dependency:  "  %1 = tail call i64 @strlen(i8* %initializingValues) #4"


(3.2)Loop exit condition:  "  %exitcond = icmp eq i32 %lftr.wideiv, %5"

 (3.3) User controls the following operand of exit condition: "  %5 = add i32 %4
, -1"
Therefore, exit condition is controlled by user
```

Buffer Overflow Detection Example

```
int initializeArray(int * someArray, char *initializingValues){
    int length = strlen(initializingValues);

    for( int i =0; i <length; i++) {
        someArray[i] = (int) initiali ingValues[
        printf("someArray[%d] = %d\n",i, someArr
    }
  return 0;
}
```

User controls operand `length' of exit condition

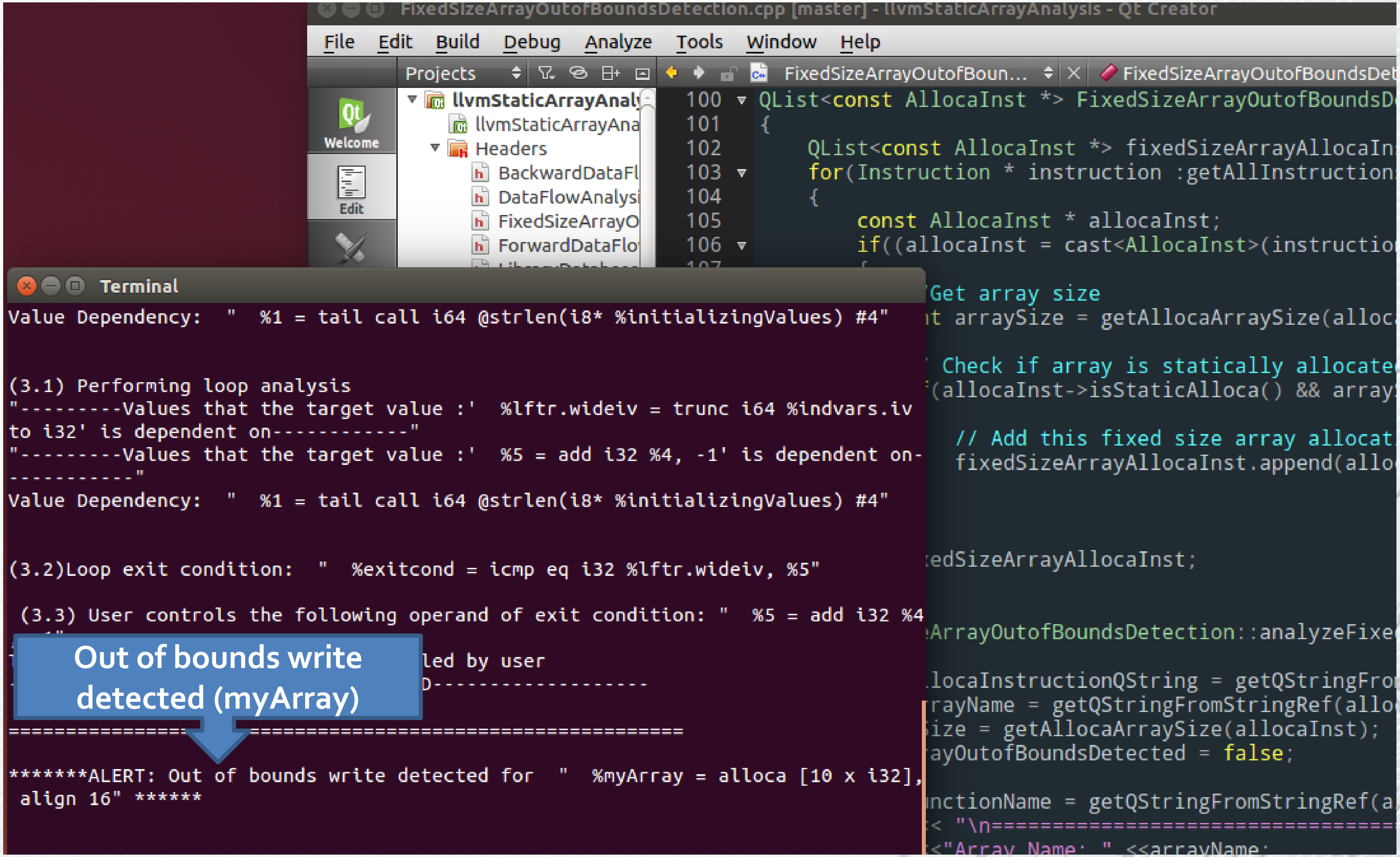
```
Value Dependency:  "  %1 = tail call i64 @strlen(i8* %in


(3.2)Loop exit condition:  "  %exitcond = icmp eq i32 %lftr.wideiv, %5"

 (3.3) User controls the following operand of exit condition: "  %5 = add i32 %4
, -1"
Therefore, exit condition is controlled by user
```

User Controlled operand of exit condition

Buffer Overflow Detection Example



SimpleArray.c

```c
#include <stdio.h>
#include <stdlib.h>
#include <string.h>
int initializeArray(int * someArray, char * initiValues);

int main(int argc, char *argv[]){
    int myArray [10];

    if(argc !=  2)
    {
      printf("usage:Expected 2 arguments... Received:%d\n",argc);
      return 1;
    }
    char * values = argv[1];

    initializeArray(myArray, values);
    return 0;
}

int initializeArray(int * someArray, char *initializingValues){
    int length = strlen(initializingValues);

    for( int i =0; i <length; i++) {
        someArray[i] = (int) initializingValues[i] ;
        printf("someArray[%d] = %d\n",i, someArray[i]);
    }
  return 0;
}
```

Overflowed buffer

Buffer overflow occurs if user passes in a string with length > 10

- Open Source Analysis Tool (Klee)
  - **Klee** is a popular analysis tool that takes as input llvm bitcode
  - Applied to all 90 programs in the GNU COREUTILS utility suite, which forms the core user-level environment installed on most Unix systems [9]
  - When program execution branches based on a symbolic value, klee follows both branches at once, maintaining on each path a set of constraints called the path condition
  - ***When a path terminates or hits a bug, a test case can be generated by using the current path condition to find concrete values that can generate the bug***

Conclusion

- Automated vulnerability analysis tools have the potential to allow the larger embedded community to conduct effective analysis, at scale, that has historically been limited to a small group of security experts

- However, there are some challenges (e.g. hardware emulation and multi-architecture support) that will need to addressed before the potential can be realized

- In this talk, we've discussed an approach to address the multi-architecture support challenge by utilizing LLVM IR

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Questions?

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