Attempting to Hack The FiveM Client

The final project specification asked students to pick one target for bug hunting. When we were asked this we thought of many things but the main thing that crossed our minds was FiveM. One of the members in our group found bugs in several FiveM frameworks ranging from custom implementations to the second most popular framework, QBCore. But after all this, the target that fit best with the specification of this class was the FiveM client. Thus, we set out to see if we had what it takes to hack a open source project with 2900+ stars on github, hundreds of thousands of concurrent players, as well as hundreds of developers working to improve it.

Introduction on Target

Before diving into the technical details of attacking the FiveM client, you are probably curious what FiveM is. FiveM is a multiplayer game modification for the popular Rockstar Games product, Grand Theft Auto V (GTA 5). FiveM was developed by the team at CitizenFX who work to modify Rockstar Games' modern titles, all of which are open source and under the same repository. Unlike most game modifications (known as mods in these communities), FiveM does not create one standalone experience. Instead, it gives developers a whole framework to interact with the GTA 5 process through the user client. This is implemented by the Citizen API which allows developers to use front end runtimes/executables in Lua, Javascript, and even C# to make calls to the GTA 5 process. For example, a Javascript function `GetEntityHealth` will be passed in an ID of an in game object and return its health. This allows developers to script out playing certain animations at certain health thresholds and more. Owners will host servers where they have these developer create scripts interact with the GTA 5 process and FiveM client to provide users a unique and seamless multiplayer experience. This is a general overview of FiveM functionality, but there is a lot of moving parts to FiveM. The next section will cover what we focused on for the remainder of the project.

The Attack Model

Since our codebase is really massive, it makes researching the target very difficult. To minimize this, we set up an attack model to restrict the context of which we attacked the application and treated exterior implementation details of the project as a black box. This was extremely helpful as it limited the scope in which we could research and attack the application to something more manageable for a team of beginner low level bug hunters.

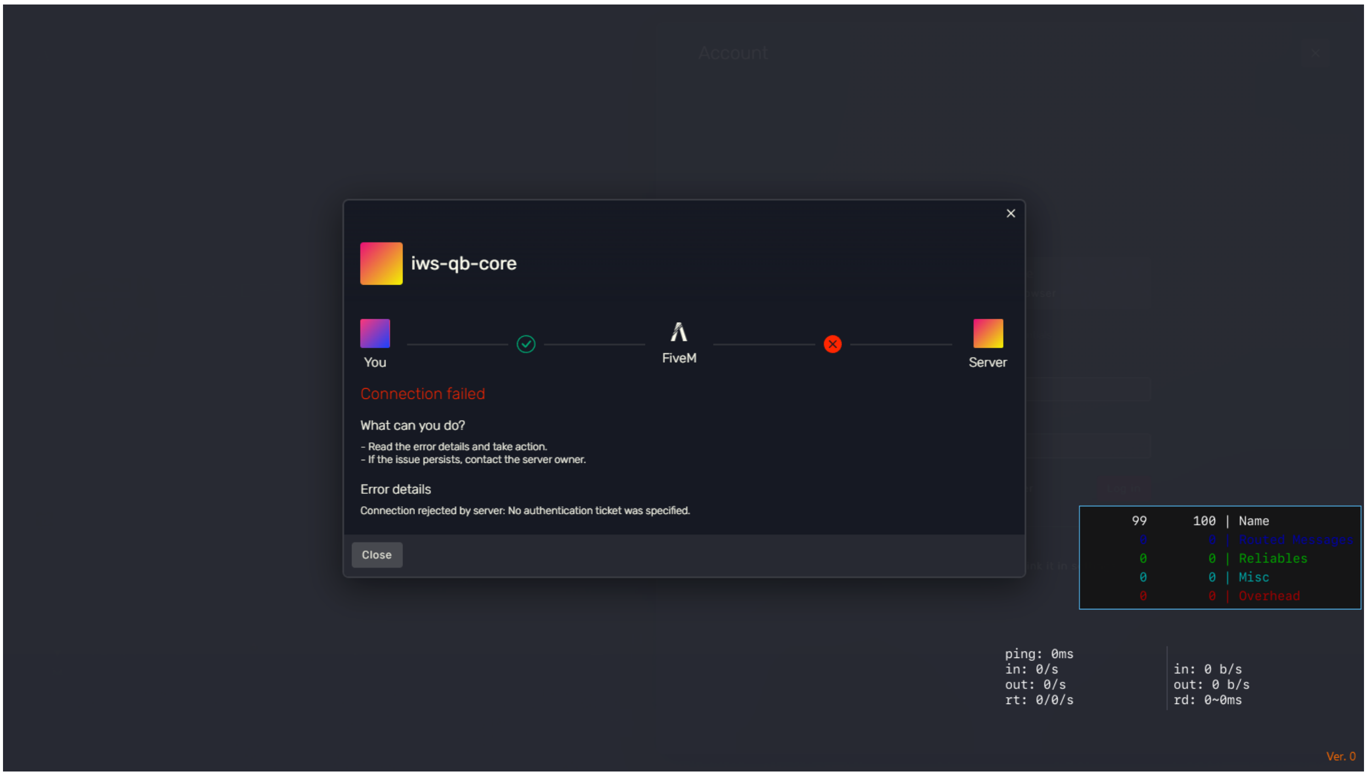
The attack model we established was a malicious server owner that sends users evil scripts that break out of the client runtime too run arbitrary code on the user system. This model relies on finding the C++ implementations of the Javascript V8 and Lua runtime and doing vulnerability analysis to discover bugs in them. During our assessment, we focused on the V8 Runtime because we had the most experience with Javascript, it is the least researched of the runtimes, and it is relatively straightforward to set up.

Before we could begin testing the Javascript runtime, we needed to first create out environment. For this we used IWS to create one Windows virtual machine to create a FiveM server running the default Cfx configuration and connected to it via any of the gaming capable desktops in the Cybersecurity room. With this setup, we created one manifest file to register commands in game and enabled them through our server. When we ran the commands our code would run in the client side engine. This allowed us to make edits and deploy them to the client without restarting the server or client. The demo video for this can be found here. With this set up, we can move into setting up a debug client.

Debugging the client

Debug build

Initially, we expect this to be a simple task: starting or attaching x64dbg and we can start debugging. Since the source code is available online, we successfully compiled a debug build from the repo. However, when running the debug build, we were not able to connect to the server. If the text box is true, the server we are hosting is not accepting and sending back authentication ticket to our debug client. We believe that the release build of FiveM has specific signature/key to link through Steam and FiveM signal server. Since we do not have them in our debug build, the connection process fails. After a bit of research, it seems that FiveM process is unable to communicate with Steam or the Source SDK process it uses for connecting.



Official release build

So we changed to working with the official build version. Unfortunately, as soon as we use WinDbg or x64dbg, the process terminates shortly after, before the RIP could reach breakpoint. We suspect that the process can detect debugger on start, so we switch to attaching to the running (sub)processes.

At normal start, `FiveM.exe` produces the following processes (XXXX is 4-letter build number):

```
FiveM_bXXXX_GTAProcess.exe
FiveM_bXXXX_DumpServer.exe
FiveM_ROSService
FiveM_ROSLauncher
FiveM_SteamChild.exe
FiveM_ChromeBrowser.exe
```

Given that our watch target is V8 engine and Lua runtime, we look for process that imports `citizen-scripting-v8client.dll`, `citizen-scripting-v8node.dll`, `citizen-scripting-lua54.dll`, `citizen-scripting-lua.dll`. Using Sysinternals Process Explorer, we found that only `FiveM_bXXXX_GTAProcess.exe` matches.

In few seconds after attaching to `FiveM_bXXXX_GTAProcess.exe`, exception such as `0xC0000005` (EXCEPTION_ACCESS_VIOLATION) occurred and we could not continue. Looking at the disassembly and call stack, the address and instructions looks irregular, suggesting that certain kind of anti-debugger measures were implemented.

Browsing x64dbg plugin, we found out ScyllaHide, an advanced user-mode anti-anti-debugger. Sadly, this would only lengthen the crash time, meaning there are multiple layers of anti-debugger. We list below the

IsDebuggerPresent

This is a simple Windows API call that returns non-zero if the current process is running in the context of a debugger. Internally, it checks for BeingDebugged flag in PEB (Process Execution Block).

Anticlimactic

When we were tracing anti-debug reference in the source code of FiveM, we came across this part ([code/client/citicore/SEHTableHandler.Win32.cpp, line 312-316]()):

```
static BOOLEAN WINAPI RtlDispatchExceptionStub(EXCEPTION_RECORD* record,
CONTEXT* context)
{
    // anti-anti-anti-anti-debug
    if (CoreIsDebuggerPresent() && (record->ExceptionCode == 0xc0000008 /*
|| record->ExceptionCode == 0x80000003*/))
    {
        return TRUE;
    }
```

`0xc0000008` exception code is STATUS_INVALID_HANDLE, meaning invalid handle. Based on the file name, an educated guess is that the program has custom code to handle Win32 SEH table. `CoreIsDebuggerPresent` is also called throughout the code base. As soon as the debugger is detected, this process force crashing itself and generating crash dump. Knowing that the program can hook to GTA safely, having this level of anti-debugging should not be surprising. At this point, we decide to give up debugging this mechanism and instead rely on outside observation.

NativeInvoke & InvokeNative

NativeInvoke

Before we established an attack model, we read through the source code to get an understanding of the project. In our initial readthrough of the source code, we noticed one class `NativeInvoke` had some code that *looked* a lot like some bugs we've seen in class. But before that, what is `NativeInvoke`. `NativeInvoke` is a class that includes a function `Invoke` that takes in an address to a GTA 5 method as well as the arguments to that method. Then the RAGE scripting engine will take these and execute the method in game. Afterwards it will return the response to the `NativeInvoke` which will in turn return it to the original caller. Let's see how it's implemented:

```
class NativeInvoke
{
public:
    template<uint32_t Hash, typename R, typename... Args>
    static inline R Invoke(Args... args)
    {
        NativeContext cxt;
        (cxt.Push(args), ...);

        static auto fn = rage::scrEngine::GetNativeHandler(Hash);
        if (fn != 0)
        {
            fn(&cxt);
        }

        if constexpr (!std::is_void_v<R>)
        {
            return cxt.GetResult<R>();
        }
    }
};
```

Okay, this is fine so far. How does the `NativeContext` look?

```
class NativeContext :
    public rage::scrNativeCallContext
{
private:
    // Configuration
    enum
    {
        MaxNativeParams = 16,
        ArgSize = 4,
    };

    // Anything temporary that we need
    uint8_t m_TempStack[MaxNativeParams * ArgSize];

public:
    inline NativeContext()
    {
        m_pArgs = &m_TempStack;
        m_pReturn = &m_TempStack;       // It's okay to point both args and
return at
                                        // the same pointer. The game
```

```
should handle this.
        m_nArgCount = 0;
        m_nDataCount = 0;
    }

    template <typename T>
    inline void Push(T value)
    {
        if (sizeof(T) > ArgSize)
        {
            // We only accept sized 4 or less arguments... that means no
double/f64 or large structs are allowed.
            throw "Argument has an invalid size";
        }
        else if (sizeof(T) < ArgSize)
        {
            // Ensure we don't have any stray data
            *reinterpret_cast<uintptr_t*>(m_TempStack + ArgSize *
m_nArgCount) = 0;
        }

        *reinterpret_cast<T*>(m_TempStack + ArgSize * m_nArgCount) = value;
        m_nArgCount++;
    }
/*...*/
}
```

The `Push` method correctly checks argument sizes but our `TempStack` is continually pushed into without regards for its size. Meaning, if we are able to push enough arguments onto the stack such that it is greater than the size of the buffer then a buffer exploit is possible. Unfortunately, as much as this *looks* like a buffer overflow it is unfortunately not, well not really. In the `Invoke` function definition we see `static inline R Invoke(Args... args)`, especially the `Args.. args` which is a function parameter pack that accepts zero or more function. In other words, this method will have a special definition for each number of possible arguments it can have *at compile time*. To exploit this, we must find any calls to `InvokeNative` with more than 16 arguments then we can actually cause an overflow. We'll go more into how we checked for this in the automated code analysis section.

Invoke Native

So, since this `NativeInvoke` had a buffer overflow and was a static (compile time), we decided to focus on the frontend scripting API. In this, we found that they had a similar function `InvokeNative` that did the same thing as `NativeInvoke` but was dynamic and implemented differently. However, our hopes were quickly crushed when we found that this was patched and previously exploited. In this we decided to focus on V8 since Lua was mostly exploited by the attacker in the blog. Similarly, we decided to read through the source of both `InvokeNative` as well as all other `Citizen` functions.

How are these frontend functions implemented though? Essentially, there is a struct that holds keys that the names of these citizen functions and the values are the pointer to each respective function. Additionally, these functions are patched directly into the Runtime meaning they are callable via `Citizen.[FunctionName]`. With this, we looked through the code and scanned for memory bugs and our eyes found basically **nothing**. We also attempted to call these `Citizen` functions from the frontend with weird or edge case parameters but did not get any weird behavior or erros from the output logs. With these failiures, we decided to move onto automated vulnerability analysis to push us in the right direction. At this point due to time and resource constraints we attempted to do automated static analysis.

Automated Static Analysis

Introduction

Since we determined dynamic analysis is not optimal given the circumstances we can try our hand with some static analysis tools. We took two main strategies for bug hunting with our tool Joern. Joern brings our code into nodes with additional information associated such as callers, callees, args, etc.. that we can interact with from our scala CLI/scripts to find bugs in the codebase. In our case, we had two strategies when looking for bugs in the program. The first involved scanning with Joern to find all places where `NativeInvoke` is used in the code and checking these locations to find where we can either find a place with 17+ arguments or dangerously passing user controlled data. The second strategy was to create *sink and source* model where our sources were all of the Citizen V8 functions while our sinks were any dangerous or potentialy dangerous C++ functions that could introduce bugs.

Finding NativeInvoke

C++ Templates

At a very high level, C++ templates allow for generics for C++ classes and functions at compile time. So very unlucky for us, `NativeInvoke` uses a template so we cannot use `joern` easily. Normally in Joern, we can run the following command to get the callers of a function:

```
cpg.method.filter(_.name=="printf").caller.l
```

```
),
Method(
  id = 8529977L,
  astParentFullName = "code/components/tool-vehrec/src/VehicleRecordingTool.cpp:<global>",
  astParentType = "TYPE_DECL",
  code = """static void DoFile(const boost::filesystem::path& path)

      static_assert(sizeof(VehicleRecordingEntry) == 32, "size");

      std::wstring fileNameStr = path.wstring();
      const wchar_t* fileName = fileNameStr.c_str();

      FILE* f = _wfopen(fileName, L"rb");

      if (!f)
      {
              wprintf(L"couldn't open input file %s...\n", path.filename().c_str());
              return;
      }

      std::vector<VehicleRecordingEntry> entries;

      fseek(f, 0, SEEK_END);
      entries.resize(ftell(f) / sizeof(VehicleRecordingEntry));
      fseek(f, 0, SEEK_SET);

      fread(&entries[0], sizeof(VehicleRecordingEntry), entries.size(), f);

      fclose(f);

      auto bm = rage::five::pgStreamManager::BeginPacking();

      auto file = new(false) VehicleRecordingFile();
      file->SetBlockMap();
      file->SetEntries(entries.size(), &entries[0]);

      rage::five::pgStreamManager::EndPacking();

      std::wstring outFileName(fileName);
      outFileName = outFileName.substr(0, outFileName.length() - 3) + L"yvr";

      f = _wfopen(outFileName.c_str(), L"wb");

      if (!f)
      {
              printf("... couldn'...""",
  columnNumber = Some(value = 1),
  columnNumberEnd = Some(value = 1),
  filename = "code/components/tool-vehrec/src/VehicleRecordingTool.cpp",
  fullName = "DoFile",
  hash = None,
  isExternal = false,
  lineNumber = Some(value = 46),
  lineNumberEnd = Some(value = 109),
  name = "DoFile",
  order = 3,
  signature = "void DoFile (ANY)"
),
Method(
  id = 8530212L,
  astParentFullName = "code/components/tool-vehrec/src/VehicleRecordingTool.cpp:<global>",
  astParentType = "TYPE_DECL",
  code = """static void Run(const boost::program_options::variables_map& map)

      if (map.count("filename") == 0)
      {
              printf("Usage:\n\n   fivem tool:vehrec *.rrr...\n");
              return;
      }

      auto& entries = map["filename"].as<std::vector<boost::filesystem::path>>();

      for (auto& filePath : entries)
      {
              DoFile(filePath);
      }
""",
```

Since Joern doesn't know about these generics and is matching with strings of functions and signatures to eachother this means we actually cannot get the callers of our function.

```
  }

  joern> cpg.method.filter(_.fullName=="NativeInvoke.Invoke").caller.l
  res14: List[Method] = List()

  joern> 
```

A workaround for this was to write a custom scala script to go iterate through all the base methods in the program and recursively iteratte through the methods of their callers and return any point where we find a `NativeInvoke` call in the code. The code looked like the following:

```
def getInvokeCalls(max: Int=5): Unit = {
    def addRecurse(cur: Traversal[Method],count: Int){
        cur.foreach({res=>
            if(res.size > 0 && count<max){
                if(res.code.contains("NativeInvoke")){
                    print("NativeInvoke @ ")
                    print(res.filename)
                    print(":" )
                    print(res.lineNumber)
                    println()
                }
                addRecurse(res.callee,count+1)
            }
        })
    }
    addRecurse(cpg.method,0)
}
```

And running it in the code we get the following output:

```
joern> getInvokeCalls()
NativeInvoke @ code/components/extra-natives-five/src/NuiAudioSink.cpp:Some(1940)
NativeInvoke @ code/components/scripthookv/src/VishCompat.cpp:Some(121)
NativeInvoke @ code/components/loading-screens-five/src/LoadingScreens.cpp:Some(71)
NativeInvoke @ code/components/loading-screens-five/src/LoadingScreens.cpp:Some(71)
NativeInvoke @ code/components/loading-screens-five/src/LoadingScreens.cpp:Some(354)
NativeInvoke @ code/components/scrbind-formats/src/Drawable.cpp:Some(269)
NativeInvoke @ code/components/lovely-script/src/Lovely.cpp:Some(67)
NativeInvoke @ code/components/lovely-script/src/Lovely.cpp:Some(139)
NativeInvoke @ code/components/lovely-script/src/Lovely.cpp:Some(67)
NativeInvoke @ code/components/gta-net-ny/src/HostSystemNY.cpp:Some(24)
NativeInvoke @ code/components/gta-net-ny/src/HostSystemNY.cpp:Some(71)
NativeInvoke @ code/components/extra-natives-rdr3/src/ShapeTestNatives.cpp:Some(62)
NativeInvoke @ code/components/citizen-level-loader-rdr3/src/LevelLoader.cpp:Some(60)
NativeInvoke @ code/components/gta-net-five/src/MumbleVoice.cpp:Some(605)
NativeInvoke @ code/components/gta-net-five/src/MumbleVoice.cpp:Some(790)
NativeInvoke @ code/components/gta-net-five/src/MumbleVoice.cpp:Some(814)
NativeInvoke @ code/components/extra-natives-rdr3/src/DoorExtraNatives.cpp:Some(58)
NativeInvoke @ code/components/citizen-level-loader-five/src/LevelLoader.cpp:Some(68)
NativeInvoke @ code/components/citizen-devtools/src/ResourceTimeWarnings.cpp:Some(30)
NativeInvoke @ code/components/scripting-gta/src/ScriptEngine.cpp:Some(96)
```

Now when we individually look at all of these calls we do not find anything out of the ordinary. Therefore, we moved to our second strategy.

Mapping Sinks to Sources

The next strategy involves us declaring two lists, one for our sources (Citizen functions) and the other for our sinks (dangerous C++) functions. This part is simple enough, we write a script to iterate through all our source functions and recursively search through their callees for any sinks. If we find one we print the call stack to get to it as well as where we can find it. The script is below:

```
def sink2src(max: Int=5) {
    val sinks = List("printf", "memcpy",
"scanf","free","Delete","strcpy","malloc","calloc","execve","sprintf","vspr
intf","gets","fgets","read")
    val sources =
List("V8_Trace","V8_SetTickFunction","V8_SetEventFunction","V8_SetCallRefFu
nction","V8_SetDeleteRefFunction","V8_SetDuplicateRefFunction","V8_Canonica
lizeRef","V8_MakeFunctionReference","V8_GetTickCount","V8_InvokeNative<Stri
ngHashGetter>","V8_InvokeNative<IntHashGetter>","V8_InvokeNativeRaw","V8_Sn
ap","V8_StartProfiling","V8_StopProfiling","V8_SetUnhandledPromiseRejection
Routine","V8_SubmitBoundaryStart","V8_SubmitBoundaryEnd","V8_SetStackTraceR
outine","V8_GetPointerField<V8MetaFields::PointerValueInt>","V8_GetPointerF
ield<V8MetaFields::PointerValueFloat>","V8_GetMetaField<V8MetaFields::Point
erValueInt>","V8_GetMetaField<V8MetaFields::PointerValueFloat>","V8_GetMeta
Field<V8MetaFields::PointerValueVector>","V8_GetMetaField<V8MetaFields::Ret
urnResultAnyway>","V8_GetMetaField<V8MetaFields::ResultAsInteger>","V8_GetM
etaField<V8MetaFields::ResultAsLong>","V8_GetMetaField<V8MetaFields::Result
AsFloat>","V8_GetMetaField<V8MetaFields::ResultAsString>","V8_GetMetaField<
V8MetaFields::ResultAsVector>","V8_GetMetaField<V8MetaFields::ResultAsObjec
t>","V8_GetResourcePath")

    def recurseSearch(cur: Traversal[Method], count: Int): Boolean = {
    cur.filter(!_.name.contains("<operator>")).foreach { res =>
        if (res.size > 0 && count < max) {
        if (sinks.contains(res.name)) {
            println(s"${res.method.name} @
${res.filename}:${res.lineNumber}")
            println("Call Stack:")
            println(s"  -> ${res.name}")
            return true
        } else {
            val found = recurseSearch(res.callee, count + 1)
            if (found) {
            println(s"  -> ${res.name}")
            return true
            }
        }
        }
    }
    false
    }


    cpg.method.filter{method=>sources.contains(method.name)}
        .foreach{res=>
            var found = recurseSearch(res,0)
            if(found){
                println(s"  -> ${res.name}")
            }
```

```
        }
    }
```

The output of this script finds a couple `free` and many `Delete` but again, we did not find anything that stood out:

```
free @ code/components/citizen-scripting-mono/deps/server/include/glib.h:Some(148)
Call Stack:
  -> free
  -> fwFree
  -> V8_CanonicalizeRef
  -> V8_CanonicalizeRef
Delete @ <empty>:None
Call Stack:
  -> Delete
  -> V8_StopProfiling
  -> V8_StopProfiling
Delete @ <empty>:None
Call Stack:
  -> Delete
  -> V8_Snap
  -> V8_Snap
free @ code/components/citizen-scripting-mono/deps/server/include/glib.h:Some(148)
Call Stack:
  -> free
  -> fwFree
  -> V8_CanonicalizeRef
  -> V8_CanonicalizeRef
Delete @ <empty>:None
Call Stack:
  -> Delete
  -> V8_StopProfiling
  -> V8_StopProfiling
Delete @ <empty>:None
Call Stack:
  -> Delete
  -> V8_Snap
  -> V8_Snap
free @ code/components/citizen-scripting-mono/deps/server/include/glib.h:Some(148)
Call Stack:
  -> free
  -> fwFree
  -> V8_CanonicalizeRef
  -> V8_CanonicalizeRef
Delete @ <empty>:None
Call Stack:
  -> Delete
  -> V8_StopProfiling
  -> V8_StopProfiling
```

With that, we exhausted the time and ideas we had for static analysis and presented our findings to the class. However, there are still ideas we didn't try that will definitely be interesting if we attempt to attack this target in the future.

Future Plans

For the future, we hope to employ more dynamic techniques like taint analysis and fuzzing. Specially, we believe fuzzing the target would bring the most success. To fuzz this target we would have two options.

The first is to fuzz the V8Runtime directly by writing a harness to interact with the DLL and execute our Javascript. The fuzzer would be grammar based to generate valid Javascript and call the Citizen functions with the correct arguments. In this example, we would take our crashes and usee the same input in our previous manual set up to debug what caused the crashes and if it led to anything exploitable. Alternatively we could do the same thing but create a custom snapshot based fuzzer that uses the FiveM server API to update the Javascript for each mutation and load the client at the point it finished loading into the game and executes the script. We would verify crashes the same way as our other fuzzer.

Final Remarks

With this have finished cataloging our assessment of the target and concluded a few things. *Attacking large targets is hard*. If we were to redo this whole project we would pick a smaller target we could really dive into and get to understand entirely. *Time is key*. Good vulnerability research takes time and if we had more time and experience we could have evaluated this target better. *Pick something easy to debug*. Debugging is very important, and when you can't properly debug it sucks. Picking a target that had less debug protections would have made it a lot easier. All in all, this was a fun project to get to know how real world vulnerability research is done and what we can expect from real life targets.