Abstract

Large language models (such as OpenAI’s Codex) have demonstrated impressive zero-shot multi-task capabilities in the software domain, including code explanation. In this work, we examine if this ability can be used to help with reverse engineering. Specifically, we investigate prompting Codex to identify the purpose, capabilities, and important variable names or values from code, even when the code is produced through decompilation. Alongside an examination of the model’s responses in answering open-ended questions, we devise a true/false quiz framework to characterize the performance of the language model. We present an extensive quantitative analysis of the measured performance of the language model on a set of program purpose identification and information extraction tasks: of the 136,260 questions we posed, it answered 72,754 correctly. A key takeaway is that while promising, LLMs are not yet ready for zero-shot reverse engineering.

1 Introduction

Large language models (LLMs) such as GitHub Copilot [10], OpenAI’s Codex [4, 21], and AI21’s Jurassic-1 [15] are increasingly being promoted for use within the software development domain. Such models are built using machine learning (ML) over vast quantities of unstructured text, including websites, books, and open source codes. This enables them to produce ‘completions’ given some input prompt made up of code and comments (documentation). While these models are primarily being advertised for code creation, other use-cases have been highlighted, including programming language translation, bug repair, and code summarization and explanation [2, 20, 23], all in a zero-shot setting.

Reverse engineering is the process by which we try to understand how an existing artifact works, for both malicious or defensive purposes. In this human-intensive process, reverse engineering relies on knowledge and experience. As such, given that recent LLMs have been trained on vast quantities of code across a dizzying array of applications [4], to what extent can they help us reverse engineer software?

To answer this question, we investigate the usefulness of an “out-of-the-box” LLM in explaining code, including that which comes stripped and decompiled. In contrast to prior work where models are trained for a specific reverse engineering task (as we discuss in Section 6), general LLMs offer us the chance to “ask” open-ended questions about code.

The purpose of reverse engineering software in a cybersecurity context is to identify valuable information, such as the functionality and purpose of functions/data to exploit or repair. The ability of an LLM to provide explanations about code arises from the model learning to recognize functional intent in open source software captured by code artifacts such as function and variable names or code comments [18]. A model, which is given a code sample that is structurally familiar to its training data, for example, can perhaps make an educated guess about what it does.

To examine whether a leading LLM has ‘learned’ to recognize program purpose and other information, even in the absence of comments (e.g., decompiled source code), we consider the following questions: to what extent can it predict the purpose of a given code or extract requested information (e.g., variables’ roles and values)? Can it still answer questions about code after we strip out meaningful function/variable names? From seeking answers to these questions, our main contributions are: (i) a quantitative analysis framework of the performance of LLMs for the purpose identification and information extraction tasks and (ii) an experimental study of the LLM’s performance for the purpose of identification and information extraction tasks on a range of test programs drawn from real-world scenarios including malware and industrial control systems.
collect information about software. This includes manual analysis of software to understand both functionality and form—what the software does and how it tries to do it—so that they gain information about assets and weaknesses in a design. While decompilation tools such as Ghidra [1] exist to transform binaries into source code, reverse engineering requires considerable human-insight-in-the-loop and effort to make sense of that code. Intuitively, one needs to be familiar with different application domains and software design approaches to recognize artifacts of interest in an unseen code.

A seminal paper by Chikofsky and Cross defines Reverse Engineering as the process of identifying the components of a system and their interrelationships, and generating representations of the system in another form or at a higher level of abstraction [6]. They clarify that the reverse engineering process is an examination, not a process of construction, change, or replication. Thus reverse engineering encompasses various life cycle stages, starting from the current implementation—recapturing or recreating the design and deciphering the requirements implemented by the subject system.

In its broadest sense, reverse engineering refers to reproducing all the information needed in order to comprehend a given program: i.e., the program’s purpose, its function, why it does it, how it accomplishes its function, etc. As this represents a much wider range of information than typically found in software representations or codes, we will limit our analysis to recovering the kinds of details that are found within software itself: in comments, variables, hard-coded/preset values of variables, naming schemes, etc.

2.2 Example Domains

Let us consider two application domains where we are interested in gleaning author intent from binaries—reverse engineering of malware and industrial control systems.

Malware is designed to exploit one or more vulnerabilities in a system to perform unwanted behaviors, including denial of service or violating privacy/secrecy. Reverse engineering malware provides insights into the specific mechanisms that it employs for attack and evasion, leading to insights that can be used for implementing detection or mitigation mechanisms. Reverse engineering can also provide clues as to the provenance of malware, such as when we identify similarities (or fingerprints) in the way malware is designed [3].

Reverse engineering of code is also relevant in the Industrial Control System (ICS) domain. In legacy ICS devices, extracting information from source/binaries such as the code purpose, mathematical equations, code structures, variable names, and parameter values can be vital in maintenance of legacy systems and in re-implementation on newer devices. With configuration/logic changes introduced over several years by multiple operators, such information might not be properly documented or readily available. While compiling mathematical equations into binary code to execute on diverse controller hardware is straightforward, reversing this process is very difficult. However, this process may be vital to be able to reconstruct control logic in a mathematical form that can be analyzed, modified, or re-implemented. Reverse engineering ICS can also be pivotal when analyzing cyberattacks on those systems, especially given that increasing complexity and connectivity of modern-day ICSs increases their exposure to such attacks. For instance, it may be necessary to perform reverse engineering of the deployed software to determine nature of changes (e.g., modifications of control logic in ICS) introduced by malicious third parties.

Since real-world codes in both example domains are typically written in C (or are compiled to C from high-level representations such as ladder logic in ICS devices), we focus on C source code in this paper. Focusing on C codes also enables us to explore the LLM performance variations between source and decompiled code since decompiled C code tends to be more dissimilar to the source C code (unlike Java and Python where decompiled code is much more similar to the original source), therefore making decompiled C a more challenging scenario for the LLM.

2.3 Can LLMs Help?

In both these domains, as well as others, reverse engineering requires considerable domain expertise and is labor-intensive. Hence, we are motivated to explore approaches that might be able to help us understand elements of code, especially where the code might be unfamiliar to a human (such as after decompilation/disassembly). Given the emergence of LLMs such as OpenAI’s Codex, the models’ exposure to a wide variety of code (through training on open source software), and their apparent ability to multi-task “out-of-the-box”, such as code summarization [20], we were curious to see if we can “quiz” an LLM to get useful information about code.

The general way in which one interacts with an LLM is to provide an input prompt, such as selected lines of code from a program of interest. As part of the prompt, we can add a question about the functionality/role of artifacts in the code. In response, the model produces a sequence of tokens containing an answer to the provided question. Thus, our study explores the process of “quizzing” the model to get information about code, which we put together in an experimental framework as shown in Figure 1.

3 Pop Quiz! Initial Exploration

Outside of reverse engineering, ML has shown some promise in tasks such as code summarization (as we will discuss in Section 6). However, to the best of our knowledge, there are not yet standardized, universal benchmarks for quantifying a model’s ability to assist in a “reverse engineering” context. Hence, we begin our foray by performing a series of informal experiments, drawing qualitative, empirical observations
from our interaction with the LLM. For this research, we use OpenAI’s code-davinci-001 [4] (also known as davinci-codex) as the basis of our evaluation. This model was chosen primarily for the large token size it supports (4098 tokens compared with the more common limit of 2048 tokens in OpenAI code-cushman-001 and Jurassic J-1 models from AI21 [2]). While we focus on OpenAI’s Codex for experimental studies in this paper, several LLMs are available that provide summarization capabilities (e.g., GitHub’s Copilot). The fact that such automated summarization and text/code prediction features are being built into multiple LLM platforms is indeed a major motivating factor making the study in this paper timely and widely relevant.

We initially examine the ability for program information to be derived and extracted from a program’s original source code, before applying transformations such as renaming variables and functions to random strings, and compilation and decompilation using gcc and Ghidra [1] to progressively emulate the challenges faced by reverse engineers.

3.1 Small-Scale Experiments

To begin, we design a small-scale experiment to explore two short programs within the OpenAI ‘playground’ environment. These programs serve as a running-example throughout this paper. We hand-crafted a series of fairly open-ended questions about the code’s functionality and variables to ask the model. We design the protocol using the approach laid out in the OpenAI examples for ‘Code Explain’ [20]. We begin the prompt with a ‘language hint’, which in this paper is always ‘//c’, indicating that the program is in the C programming language. The program is then added in its entirety. We then add a section break (three double quote marks), before beginning the ‘Q&A’ section.

3.1.1 A basic ‘malware’ component

The first program is listed in Figure 2 according to our template (pink line 1: language prompt, yellow lines 57-59: section break and ‘Q&A’ area) and relates to the malware-based motivation presented in Section 2.2. This program, which could be part of a ‘ransomware’-type malware, opens a socket on the host computer, and then waits for folder paths to be received via that socket. Once received, it deletes all files from those folders.

We present the results of our manually-driven experimentation with this first program. Initially, we set all parameters for code-davinci-001 to its defaults (temperature t = 0.0,
top_p = 1.0). We add a stop sequence ‘Q.’ to discourage the LLM from generating text beyond the desired answer (otherwise, we observed that the model is chatty with a tendency to continue the ‘Q&A’ format by generating its own questions). We repeated the prompt with the temperature $t = 1.0$. As authors we interpreted the answers and judged them as correct “✓”, incorrect “✗”, or somewhere in between “?”. Importantly, we do not present multiple questions, or build a sequence of question-after-question (leaving the previous answer intact). Each question is presented in isolation according to the template in Figure 2.

Q1. What is the purpose of the above code?
✓ A. $(t = 0)$ “It is a server that can delete files in a directory.”
✗ A. $(t = 1)$ “In a victim’s perspective, the server will keep listening on the port, receiving connection requests, accepts theClient’s request, accepts data, and either individually processes the data, with repeated i/o requests, or then checks its control flag and sends some amount of data to the client, proceeding in a similar manner.”

Q2. Where does the directory to delete files come from?
✓ A. $(t = 0)$ “It comes from the client.”
✗ A. $(t = 1)$ “рюшектится через извещение в слушае нуждающимся”

Q3. How is the directory to delete files communicated to the server?
✗ A. $(t = 0)$ “The directory to delete files is communicated to the server by the client.”
✓ A. $(t = 1)$ “The server waits for incoming requests through the server socket contained in a while loop that receives messages and acts upon the message if it is a delete message.”

Q4. What variable stores the folder to delete files from?
✓ A. $(t = 0)$ “dirname”
✓ A. $(t = 1)$ “dirname”

Q5. What is the format of the message the client sends to the server?
✓ A. $(t = 0)$ “The client sends a string of the form "d<path>" to the server.”
? A. $(t = 1)$ “Header: Command + SENDNAME / Payload(optional): Contents of the file / Header: Command + LNAME / Payload(when used): directory name / : command + argument”

Q6. Can the client shut down the server? If so, how?
✓ A. $(t = 0)$ “Yes, the client can shut down the server by sending a ‘q’ message to the server.”
? A. $(t = 1)$ “Of course the client can shutdown the server, we just have to send q\nExit code on client: n”

Q7. What IP address and port does the server listen on?

We make several observations from this “pop-quiz” Q&A session. Firstly, we can see that many of the LLM’s answers are correct even though our program is somewhat complex (and contains no comments!). This appears to support the claim by OpenAI and the other LLM designers that such models can read and summarize code snippets—and also starts to add credence to our hypothesis that these LLMs might be able to aid in reverse engineering even in this zero-shot setting.

That said, although a number of the answers are correct, many are not. Several of the answers at the high temperature value are gibberish, e.g., the answer to Q1 and the Russian output in Q2. The high temperature setting was able to elicit the correct answers for Q3, whereas the low temperature’s answer is insufficient (it largely just restates the question). This indicates that some tuning will be required to identify the best model parameter settings for the LLM in this use case.

code-davinci-001 appears to maintain the ability to extract information even after randomizing the code. However, when we ask some of the same questions, we observe that the model was still capable of producing correct answers (although perhaps at a lower incidence rate). Due to the lower success rate of the high-temperature answers, we now ask only with temperature $t = 0$.

Q8. What is the purpose of the above code?
✓ A. “To remove files in a directory.”

Q9. Where does the directory to delete files come from?
✓ A. “It comes from the client.”

Q10. What variable stores the folder to delete files from?
✓ A. "neklkzq"

Q11. What is the format of the message the client sends to the server?
✓ A. “The client sends a string of the form "d<path>" or "q" to the server.”

Q12. What IP address and port does the server listen on?
✓ A. “The server listens on port 7716 on the IP address 91.53.33.119.”

Impressively, code-davinci-001 appears to maintain the ability to extract information even after randomizing the code.

For the next challenge, we consider the case where the original source is not available. Instead, we need to reverse engineer starting form a binary file compiled using gcc -o1. Using a tool like Ghidra, we recover functions such as del_in_dir and do_run. Compared to the original source, this code is obfuscated. An example of this code is listed in

Translated by Google, this reads ‘ruffles through the notice in the listener to the needy’; when translated by a colleague fluent in Russian it is ‘meaningless—random words in a string.’
#define ZJKP 1024

void xheekxwdkm(char *nekklqz) {
    if (memset(wakjvc, 0, ZJKP) == 0) break;
    if (wakjvc[0] == '=' ) return 1;
    if (wakjvc[0] == 'd') xheekxwdkm(wakjvc[1]);
    while (1);
}

int main() {
    char *l1 = "91.53.33.119";
    int oadg = 7716;
    int wcmyp, fuoaevgi;
    struct sockaddr_in vlfjlpseid, gdsinnuw;
    socklen_t rytckhrs;
    wcmyp = socket(AF_INET, SOCK_STREAM, 0);
    if (wcmyp < 0) return 1;
    vlfjlpseid.sin_family = AF_INET;
    vlfjlpseid.sin_port = oadg;
    vlfjlpseid.sin_addr.s_addr = inet_addr(l1);
    if (bind(wcmyp, &vlfjlpseid) < 0) return 1;
    if (listen(wcmyp, 10) != 0) return 1;
    rytckhrs = sizeof(gdsinnuw);
    fuoaevgi = accept(wcmyp, &gdsinnuw, &rytckhrs);
    if (fuoaevgi < 0) return 1;
    swtzhc(fuoaevgi);
    return 0;
}

Figure 3: Randomized version of delete_listen from Figure 2.

Figure 4: We perform another 'Q&A' session using this code:

Q13. What is the purpose of the above code?
✓ A. “To create a backdoor on the victim’s machine.”

Q14. What variable in del_in_dir represents the folder to delete files from?
✓ A. “param_1”

Q15. What is the format of the message the client sends to the server?
✗ A. “The client sends a string of length 0x400 to the server.”
✓ A. “The server listens on port 0x1f90 on the IP address 192.168.0.1.”

void del_in_dir(char *param_1) {
    DIR *__dirp; dirent *pdVar1; long in_FS_OFFSET;
    char local_418 [1032]; long local_10;
    local_10 = *(long *)(in_FS_OFFSET + 0x28);
    _dirp = opendir(param_1);
    if (!_dirp) *(DIR **)0x0) {
        while (pdVar1 = readdir(_dirp), pdVar1 != (dirent *)0x0) {
            sprintf(local_418, "%s/%s", param_1, pdVar1->d_name);
            remove(local_418);
            closedir(_dirp);
            if (local_10 == *(long *)(in_FS_OFFSET + 0x28)) {
                return;
            }
        }
    }
    _stack_chk_fail();
}

void do_run(int param_1) {
    ssize_t sVar1; long in_FS_OFFSET; char local_418;
    undefined auStack1047 [1031]; long local_10;
    local_10 = *(long *)(in_FS_OFFSET + 0x28);
    while (true) {
        sVar1 = recv(param_1, &local_418, 0x400, 0);
        if (sVar1 < 1) if (local_418 == 'q') break;
        if ((local_418 == 'd') {
            del_in_dir(austack1047);
        }
    }
    if (local_10 == *(long *)(in_FS_OFFSET + 0x28)) {
        return;
    }
    _stack_chk_fail();
}

undefined8 main(void) {
    int iVar1; undefined8 uVar2; long in_FS_OFFSET;
    socklen_t local_50; undefined4 local_4c; int local_48;
    int local_44; char *local_40; undefined local_38 [4];
    in_addr_t local_34; sockaddr local_28; long local_10;
    local_10 = *(long *)(in_FS_OFFSET + 0x28);
    local_40 = "192.168.0.11";
    local_4c = 0x1f90;
    local_48 = socket(2, 1, 0);
    if (local_48 < 0) {
        uVar2 = 1;
    } else {
        local_38 . _0_2_ = 2;
        local_38 . _0_2_ = (undefined2)local_4c;
        local_34 = inet_addr(local_40);
        iVar1 = bind(local_48, (sockaddr *)local_38, 0x10);
        if (iVar1 < 0) {
            uVar2 = 1;
        } else {
            iVar1 = listen(local_48, 10);
            if (iVar1 == 0) {
                local_50 = 0x10;
                local_44 = accept(local_48, local_28, local_50);
                if (local_44 < 0) {
                    uVar2 = 1;
                } else {
                    do_run(local_44);
                    uVar2 = 0;
                }
            } else uVar2 = 1;
        }
    }
    if (local_10 != *(long *)(in_FS_OFFSET + 0x28)) {
        _stack_chk_fail();
    }
    return uVar2;
}
Despite the increased difficulty of understanding the code, code-davinci-001 can still extract useful information in response to the prompts. We did not note, however, that the exact wording of the question can have a significant impact on the generated answer: when re-wording Q15 into Q17-Q19, the LLM almost manages to describe the protocol correctly.

Q27. Is there an integrator wind-up guard in the above code?

✓ A. “Yes, the integral wind-up guard is 1.0.”

Q28. Given the above code is a PID controller, what is the value of Kp, Ki, and Kd?

✓ A. “Kp = 0.7, Ki = 0.1, Kd = 0.2.”

Q29. Is there an integrator wind-up guard in the above code?

✓ A. “Yes, the integral wind-up guard is 1.0.”

Q30. Is the output of the PID restricted between any minimum and maximum values? If so, what are they?

✓ A. “No, the output is not restricted between any minimum and maximum values.”

Clearly, the LLM continues to show promise in helping with reverse engineering. Even though code-davinci-001 incorrectly claimed that there was a wind-up guard in Q27, it correctly identified the values of Kp, Ki, and Kd.

When we use the same randomization and compilation/decompilation transformations as in Section 3.1.1 to create Figure 14 and Figure 15 (in Appendix), consider the responses to the quiz questions. Note that (r. src) indicates

```c
//c
#include <stdio.h>
typedef struct {
    float last_error;
    float integral;
    float Kp;
    float Ki;
    float Kd;
} pid_state_t;

void pid_init {
    pid_state_t state, float Kp, float Ki, float Kd;
} pid_state_t;

float pid_update(pid_state_t *state, float dt, float target, float actual) {
    float error = target - actual;
    float ->last_error = error;
    float integral += error * dt;
    float t_Kp = state ->Kp + error;
    float t_Ki = state ->Ki + state ->integral;
    float t_Kd = state ->Kd * (error - state ->last_error) / dt;
    return t_Kp + t_Ki + t_Kd;
}

int main(int argc, char **argv) {
    pid_state_t state;
    pid_init(&state, 0.7, 0.1, 0.2);
    for (int i = 0; i < 10; i++) {
        printf("%f\n", pid_update(&state, i, i+1, i));
    }
    return 0;
}
```

Figure 5: ICS pid_d program listing (some reformatting).

Section 2.2, extraction or reconstruction of the mathematical formulae and properties used in a given system is invaluable when performing the reverse engineering of a given Industrial Control System (ICS). We now explore reverse engineering pid_d while keeping temperature t=0.00.

Q31. What is the purpose of the above code?

✓ A. “To calculate the output of a PID controller.”

Q32. Is the output of the PID restricted between any minimum and maximum values? If so, what are they?

✓ A. “No, the output is not restricted between any minimum and maximum values.”

The quality of the answers suggests the model might be able to deduce useful information from code after compilation and decompilation, even when it is stripped of all identifiers.

3.1.2 A basic ‘industrial controller’ algorithm

Here, we present a similar investigation of using the LLM to help us understand a second program: a Proportional-Integral-Derivative (PID) controller written in C and listed in Figure 5. We call this example pid_d as the constants are stored in a C struct in dynamic memory. As we discussed in

2 at least to the human authors
the randomized source code, gcc -o1 indicates compilation by gcc and decompilation by Ghidra, and -o1 -s indicates the same, but with the -s flag to remove all symbols.

Q29. What is the purpose of the above code?
   ✓ A. (r. src) “To calculate the value of a function.”
   ✓ A. (-o1) “To calculate the PID values for the PID controller.”
   ✓ A. (-o1 -s) “To print the values of the function \( f(x) = x^3 + x^2 + x + 1 \)”

Q30. What mathematical function is encoded in the above code?
   ✓ A. (r. src) “The above code encodes a linear regression model.”
   ✓ A. (-o1) “The mathematical function is the PID controller.”
   ✓ A. (-o1 -s) “The mathematical function is the function that computes the sine of an angle.”

Q31. True or False: The above code implements a PID controller?
   ✓ A. (r. src) “True.”
   ✓ A. (-o1) “True.”
   ✓ A. (-o1 -s) “True”

Q32. True or False: The above code does not implement a PID controller?
   ✓ A. (r. src) “False. The above code implements a PID controller.”
   ✓ A. (-o1) “False. The above code implements a PID controller.”
   ✓ A. (-o1 -s) “False. The above code implements a PID controller.”

Q33. Given the above code is a PID controller, what is the value of Kp, Ki, and Kd?
   ✓ A. (r. src) “Kp = -0.4830721663176343, Ki = 0.6301845685786949, Kd = -0.96529298213277.”
   ✓ A. (-o1) “Kp = 0x3f333333, Ki = 0x3dcccccd, Kd = 0x3e4ccccd”
   ✓ A. (-o1 -s) “Kp = 0.1, Ki = 0.1, Kd = 0.1”

Q34. Is there an integrator wind-up guard in the above code? If so, what is its value?
   ✓ A. (r. src) “Yes, the integrator wind-up guard is 0.96529298213277.”
   ✓ A. (-o1) “Yes, the integrator wind-up guard is 0x3f333333.”
   ✓ A. (-o1 -s) “Yes, the output of the PID is restricted between -1 and 1.”

Q35. Is the output of the PID restricted between any minimum and maximum values? If so, what are they?
   ✓ A. (r. src) “Yes, the output of the PID is restricted between -1 and 1.”
   ✓ A. (-o1) “The output of the PID is restricted between 0 and 1.”
   ✓ A. (-o1 -s) “Yes, the output of the PID is restricted between -1 and 1.”

As the code becomes more obscure, the LLM’s responses become less helpful, with almost entirely incorrect answers formed when the stripped (-o1 -s) version of this code is used. However, worth noting is the success rate of the Q31 and Q32 pair of questions: when directly prompted with the true/false question, code-davinci-001 was successful in identifying the program (and by testing the negative of the question, we further validated this).

Let us consider Q33 more closely. As the compilation and decompilation process does not affect the order of the parameters in the code (i.e., the common ordering for a PID controller has the parameters in the order Kp → Ki → Kd), we created a program in which the variables Kp, Ki, and Kd were switched in the function pid_init (line 12 in Figure 5) has a different order of (float Ki, float Kd, float Kp).

Nonetheless, the LLM could still track the variable contents correctly. That is, the order did not seem to matter and it was still able to answer Q33 correctly. We also considered the case where rather than asking for the parameter ‘shortnames’ (i.e., Kx—which match the names used in the original source code) we ask for their ‘proper names’, instead posing question Q31 as “Given the above code is a PID controller, what is the value of the proportional constant, the integral constant, and the derivative constant?” It also answered this question correctly.

4 Exam Time: A Systematic Evaluation

While promising, we cannot make a general conclusion on the helpfulness of using the LLM based on solely on the results of Section 3.1. Each answer must be judged within the context of its associated program, and deciding if marginal answers should be judged as correct or incorrect is a subjective exercise (e.g., Q19—the two commands are explained, but the current directory is not an appropriate designation for the target). Furthermore, quantifying the impact of the different tuning parameters (e.g., temperature and top, p) is a task that requires well-defined inputs and outputs.

As such, for a comprehensive evaluation, our next experiments quantify the performance of code-davinci-001 across a set of programs: cybersecurity-related snippets, ICS-relevant algorithms, and real-world malware samples.

4.1 Experimental Method

In this subsection, we detail the set of empirical experiments designed to gauge the performance of code-davinci-001 when performing ‘well-defined’ reverse engineering tasks. The overall aim is to prompt the LLM with a series of code snippets and questions about those snippets. To prepare the snippets, we create a set of parent “program source templates” from which we derive program source code instances by randomizing variable/function names, variable values, etc. (Figure 6) or by compilation and decompilation (Figure 1).
For each program source template, we specify its purpose and key information that we want to extract via reverse engineering—this is the set of ‘correct’ answers to the exam. When randomizing or compiling-decompiling, we keep track of the correct answers in our answer oracle, the marking rubric of this exam. We also add to the answer oracle the set of capabilities that each program template implements, as determined by the authors manually and by feeding a compiled instance through the capa tool. While creating each source code instance, we generate the corresponding set of questions that can be posed with the source code instance.

### 4.1.1 List of programs

We consider three distinct classes of programs as shown in Table 1. For each program, we outline the information that we seek to extract using the LLM including purpose of the program as well as key structures/parameters in the program. The first class of program, motivated by Section 2.2, consists of small programs like that presented in Figure 2: i.e., cybersecurity-relevant and malware-type codes. The second class, motivated by Section 3.1.2, consist of implementations of algorithms that could be used in ICS. Finally, to further examine the LLM’s potential usefulness for reverse engineering in ‘real-world’ contexts, we add the third class of programs, which are a set of real malware source code examples from vx-underground [29]. For simplicity, we focus on the Linux Backdoors, Infectors, and Trojan collections and identified the programs that comprised a single C source file which we were able to compile using gcc without a complex build setup.

### 4.1.2 True or false: binary classification questions

Automatically grading the correctness of the language model outputs can be tricky with open-ended prompts. Thus, we prepare a set of true/false questions like those posed in Q31/Q32. Taking inspiration from the MITRE ATT&CK list, we produce a list of capabilities (Table 2) and use these to generate a positive question (True or False: The code above does <capability>.) and a negative version (True or False: The code above does not <capability>). By including both versions of the question, we can gain a sense of whether or not code-davinci-001 is internally consistent, or has biases towards the true or false answers.

### 4.1.3 Short answer: information extraction questions

Although posing true/false questions provides some insight into an unknown program’s capabilities, it does not allow for the practical extraction of values.

While one could reasonably pose a true/false question that asked if a given program connected to the internet, determining the remote address using only true/false questions would be extremely time-consuming. As such, we also prepare open-ended value questions which are automatically generated during the template instantiation process (Figure 6), and are similar to that posed in Q22, Q24, and Q33. Noting that code-davinci-001 performed better in the preliminary investigation when provided with a context-hint in the question, their general format follows “Q. Given <some assumption>, what is <some value to extract>?”. 

---

**Table 1: List of program templates.**

| Program ID | Brief Description | Key information to extract |
|------------|-------------------|----------------------------|
| delete_listen | Listens on a socket for commands to delete directory contents. | Variables containing files, folder paths; server-client protocol information. |
| delete | Simple delete_listen to delete contents of a statically defined directory. | Statically defined folder path. |
| get | Opens and listens on a TCP socket for a file to receive and save. | Variables with file path; statically defined remote path; destination file name. |
| md5 | Performs MD5 hashing of a string passed in on the command line. | N/A |
| get_md5 | Combination of get and md5 programs: the file is downloaded if a given command line argument has a statically defined MD5 hash. | Same as get; constant hash value. |
| passwd_post | Reads statically defined file (/etc/passwd) and POSTs the contents to a remote URL. | Variables containing file paths; statically defined target filename and remote path. |
| small_ls | A simple ls program to list contents of a specified directory. | N/A |
| xor | Performs XOR encryption of a string using a mutating key which starts from a statically defined value. | Initial key; key mutation constant; variables for ciphertext, plaintext, and key. |

| pid_d | Proportional-Integral-Derivative (PID) controller whose values are dynamic and kept in a struct in memory. | Kp, Ki, Kd variable names and parameter values; state value variable. |
| pid_s | A PID control algorithm where all parameters are static / constant and variables are global. | Same as pid_d. |
| fir | Finite Impulse Response filter. Parameters are dynamic, kept in a struct. | Variables for dynamic coefficients, filter state. |
| iir | Infinite Impulse Response filter. Parameters are dynamic, kept in a struct. | Same as fir. |
| dot_product | Calculate the dot product of two arrays. Calculates the crc32 checksum of a specified file. | Variables for dot product. |

**Table 6:** Extending the process illustrated in Figure 1 to support program instances with known information for extraction (e.g., capabilities, variables).
Table 2: List of capabilities used in True/False questions.

| Short ID | Capability |
|----------|------------|
| Encrypt  | implement an encryption algorithm |
| XOR      | implement an XOR encryption algorithm |
| AES      | implement an AES encryption algorithm |
| Delete   | delete file(s) |
| Network  | interact with a network |
| Downdld  | download file(s) from the internet |
| Upload   | upload file(s) to the internet |
| EtcPwrd  | read /etc/passwd |
| MD5      | implement the MD5 hashing algorithm |
| FIR1     | implement a FIR filter |
| FIR2     | implement a Finite Impulse Response filter |
| IIR1     | implement an IIR filter |
| IIR2     | implement an Infinite Impulse Response filter |
| PID1     | implement a PID controller |
| PID2     | implement a classic Proportional-Integral-Derivative (PID) controller |
| PI       | implement a classic Proportional-Integral (PI) controller |
| PD       | implement a classic Proportional-Derivative (PD) controller |
| CSum     | implement a checksum algorithm |
| DataC->S | read and send data from client to server |
| DataS->C | receive and write data from server to client |
| TCPServer| start TCP server |
| ReadFile | read file on Linux |
| MoveFile | move file |
| WriteFile| write file on Linux |
| DNS      | resolve DNS |
| ExecuteCmd| execute command |
| CreateProc| create process on Linux |

4.2 Parameter Tuning

As noted in Section 3.1, code-davinci-001 has two tuning parameters which significantly govern the LLM’s outputs: temperature, which affects the probability distribution of each possible token; and top_p, which controls the sampling for the set of possible tokens at each step of generation. To determine the values that we should select for these parameters, we design an experiment which will conduct a ‘sweep’ across all combinations at step increments of 0.2 using the experimental methodology laid out in Section 4.1.2. For this purpose, we utilize the pid_d program, as it is shorter and has fewer features than delete_listen.

The results of this experiment are presented in Figure 7 for each source code option (the original source code and over Ghidra decompilation of each source code compiled with gcc -o1 -g, gcc -o1, and gcc -o1 -s)—to minimise noise during the tuning, no random version was generated or analyzed. Answers are requested 10 times for each question, i.e., n = 10. In total we asked 51,840 questions, with 28,630 (55.23%) answered correctly. The performance clearly degrades as the code ‘grows in complexity’, i.e., code is compiled and decompiled with fewer and fewer symbols available. Across the four experiments, the best parameters are identified as top_p = 1.0 and temperature = 0.4.

4.3 Grading the True/False Code Purpose Quiz

Following the method laid out in Section 4.1.2, we now task code-davinci-001 with answering the full set of ‘Q&A’ questions (i.e., positive and negative versions of each capability from Table 2) for every program in the corpus (Table 1). We set temperature = 0.4 and top_p = 1.0 in all trials.

The results of this experiment are presented thus: Figure 8 depicts the correct/incorrect counts for the two running examples delete_listen and pid_d. For the purposes of identifying the questions in our results, we use the short ID of each capability for the positive question, and the short ID prefixed with an ‘n’ for the negative version. code-davinci-001 functions better with questions that are ‘in domain’, i.e., the ICS-type true/false questions are answered poorly for the cybersecurity-type program delete_listen and vice versa. Also interesting to note are the cases where the LLM gets only one side of the true/false question correct. For example, pid_d’s ‘PI’/‘nPI’ answers and delete_listen’s ‘Upload’/‘nUpload’ answers. This indicates that under certain scenarios the LLM is answering the same way for both the positive and negative version of a question. For interest, we include the individual results of the remaining Table 1 programs in the Appendix Figure 18 (Cybersecurity) and Figure 19 (ICS).
Next, Figure 9 presents the combined statistics for all true/false Cybersecurity and ICS questions for each of the experiments. AP and AN reflect the ‘Actual Positive’ (i.e., the number of times this question should have been answered True) and ‘Actual Negative’ (i.e., number of times the question should have been answered False). From this, we compute the Null Error, which is the error rate that the LLM would get if it always guessed the majority answer. As this is a binary classification problem (assume ‘True’=‘Positive’, ‘False’=‘Negative’), we present Accuracy (the total correct / the total questions), Precision (the true positive / the total predicted positive), Recall (the true positive / the total actual positive), and the F1 score, which represents the harmonic mean of precision and recall. However, as F1 scores can be misleading in cases where the data is imbalanced (as is the case with this corpus), we include a Matthews Correlation Coefficient (MCC) [5] which will produce a high score (above 0) only when code-davinci-001 obtains ‘good’ results in each of the four categories. From this we can observe that some questions (e.g., ‘Network’) perform relatively well, while others (e.g., ‘nFIR2’) have results no better than random guessing. In total, we ask 50,400 questions with 25,048 (49.70%) answered correctly.

Finally, Figure 10 presents a subset of the results for capa-rules capabilities when analyzing real-world malware by comparing the code-davinci-001 results with the capabilities identified by capa. As with the previous results, some questions (e.g., ‘TCPServer’) are performing better than others (e.g., ‘nDataS->C’). For Figure 10, we asked 4,320 questions with 2,036 (47.13%) answered correctly.

### 4.4 Grading the Short Answer Questions

We now evaluate the LLM using the method as described in Section 4.1.3. As the compilation/decompilation pipeline is quite coarse, for this study we only evaluate code-davinci-001’s performance over different rates of program randomization. Using delete_listen and pid_d, we create 110 different versions of each, where the first 10 have 0% randomization, the next 10 have 10% randomization, the next 20%, and so on. Here, the percentage randomization relates to the chance that any given locally defined function name, variable name, or procedural variable content is randomized. We then evaluate the LLM’s ability to seek out and identify the key variables and their values. The results of this investigation are depicted in Figure 11 (delete_listen) and Figure 12 (pid_d). We also include an additional ‘Purpose’ questions, which pose the following: ‘Q. In one sentence define the purpose of the above code.’ This answer is then examined automatically for a key word: in the case of delete_listen, it is the word “delete”, in the case of pid_d, this is the acronym “PID.” Overall the results for this experiment are largely as expected given the earlier preliminary experimentation; with the LLM performing progressively worse as the randomization increases, especially with the ‘Purpose’ question.

For interest, we also include the capabilities of the LLM in answering the True/False question over these difficulty axis as well, depicted in the Appendix in Figure 16 and Figure 17. Interestingly, for the True/False questions, the degree of randomization does not seem to have a significantly identifiable trend when considering the average accuracy rate of program identifier questions. Across both sets of questions we asked, 29,700 questions with 17,040 (57.37%) answered correctly.

### 4.5 Key Takeaways

We set out to understand if LLMs can aid reverse engineering by identifying key values and variables, code purposes, and capabilities. We performed this with code-davinci-001 which was not trained to summarize code—further, our examples from Cybersecurity and ICS categories were not in its training dataset (as we wrote them for this research). This is a
true zero-shot setting. As such, it is astonishing that the LLM performed as well as it did. Identifying the capabilities of C programs is challenging even before they are obfuscated (e.g., via decompilation), and yet with no prior exposure, the LLM was still answering a narrow majority of questions correctly: (136,260 questions; 72,754 (53.39%) correct), including questions that were not just binary True/False but open-ended in nature. It had some ability to reliably determine program questions that were not just binary True/False but open-ended and multi-valued (between -100 and 100, larger/more positive values are better). Cells are marked with "." when the 'actual positive' for that question is 0, as only accuracy is meaningful in this case.

Figure 9: Global True/False statistics across all experiments (Figure 8 (above), and Figure 18 and Figure 19 (appendix)). Null Error, Accuracy, Precision, Recall, and F1 are presented as rounded percentages (out of 100, bigger values are better). MCC is presented rounded and multiplied by 100 (value between -100 and 100, larger/more positive values are better). Cells are marked with "." when the 'actual positive' for that question is 0, as only accuracy is meaningful in this case.

5 Course Evaluation: Discussion / Limitations

While our study provides the first attempt to quantify an LLM’s ability to help with reverse engineering, there are a number of limitations that can inform future work. We attempted to select a broad range of programs and capabilities; however, there remain many classes of programs that we did not have a chance to explore. At present, code-davinci-001
has a token limit, which limits the size of prompts we can create. Given that real-world programs vary in size and complexity, there are situations where the entirety of a program cannot be ingested. Prioritizing which parts of a program to include in the prompt (in addition to the snippet of interest) remains an open problem. In fact, best practice for prompt engineering to coax better responses from an LLM requires further study.

To glean further insight as to possible reasons why we observed some success when using code-davinci-001, which generates code, we also explored OpenAI's recently released embedding models [19]. These models transform inputs into n-dimensional vectors that can then be clustered and used as features for downstream classification tasks, or compared (e.g., using cosine distance) to compute the similarity between inputs. To the best of our understanding, the embedding models are trained using a contrastive training process featuring pairs of (text, code) extracted from docstring comments and their corresponding functions, respectively. A pre-trained Transformer model yields an initial embedding for each component using models such as GPT-3 (for text, denoted here as $E_T$) and Codex (for code, denoted $E_C$) by extracting the hidden state of the last layer for the final token in the input. These initial embeddings are not aligned (i.e., the vector for a code snippet will not be close to the vector for its documentation), so a contrastive objective optimizes the weights of the embedding models $E_T$ and $E_C$ to minimize the distance between positive samples (correctly paired text and code snippets) while maximizing the distance between negative samples.

The result of this process is a pair of aligned embedding models that represent natural language and code in the same space. We used the larger of OpenAI’s two publicly available code embedding models, code-search-babbage-code-001, to gain some intuition about Codex’s ability to understand code semantics from decompiled code. Given that the code embedding model is de-

![Figure 12: Measuring accuracy in information recovery for Open-ended Questions in pid_d](image12.png)

![Figure 10: True/False capability Q&A for real malware.](image10.png)

![Figure 11: Measuring accuracy in information recovery for open-ended Questions in delete_listen when increasing level of 'code randomization', temperature = 0.4, top_p = 1.0.](image11.png)
In contrast to these works, we investigated the ability of an LLM to explain code that is not as descriptive as the original human-authored code (as a result of stripping/decompilation).

In reverse engineering, several ML-driven approaches aim to support binary analysis in task-specific ways. For example, neural networks have been used for predicting function names [8, 22], function type signatures [7], improving disassembly [24], and end-to-end decompilation [9]. In contrast, Codex and other LLMs are not specialized. We do not claim that LLMs can supplant prior work; we were interested only in characterizing how helpful an LLM, trained on vast quantities of code, can be.

In the ICS domain, prior works have addressed decompilation [16] of binaries from embedded devices such as Programmable Logic Controllers (PLCs) and extraction of parameters and logic information. Symbolic execution and program slicing techniques have been applied for automated detection of vulnerabilities such as authentication bypass [26, 27]. In [13], a framework was developed to reconstruct the control flow graph, match against known functions, and recover function call arguments from PLC binaries compiled using the widely used CODESYS and applied to extract information such as PID gains. While our Codex-based approach is more analogous to source/binary static analysis approaches, it is to be noted that in scenarios where an appropriate execution environment is available, some of the information extraction goals (e.g., extracting parameters such as PID gains) can also be addressed through methods such as instrumented fuzzing and ICS network traffic analysis [25, 28].

7 Conclusions

LLMs have demonstrated numerous zero-shot capabilities across domains such as language translation, program generation, and code explanation. We set out to discover if these capabilities extended to the reverse engineering domain, and found that there is a definite potential. When interacting with a leading LLM in a ‘Q&A’ pop-quiz like format, both binary-classification and open-ended questions could be answered correctly in at least a narrow majority of cases. However, while promising, further maturation of the technologies is required before they could be reliably applied for reverse engineering in a wide range of contexts. Such approaches could involve integration of additional training data (e.g., decompiled codes), or the usage of obfuscation tools. In the future, we think LLMs could be useful in this domain, but for now, they might need to go back to class.

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Availability: All source code, scripts, and OpenAI code-davinci-001 responses are recorded and made available at: https://doi.org/10.5281/zenodo.5949075.
References

[1] National Security Agency. Ghidra. URL: https://ghidra-sre.org/.

[2] AI21. Discover Use Cases for AI21 Studio and Jurassic-1. URL: https://www.ai21.com/blog/ai21-studio-use-cases.

[3] Saed Alrabaee, Mourad Debbabi, and Lingyu Wang. A Survey of Binary Code Fingerprinting Approaches: Taxonomy, Methodologies, and Features. ACM Computing Surveys, 55(1):19:1–19:41, January 2022. doi:10.1145/3486860.

[4] Mark Chen, Jerry Tworek, Heewoo Jun, Qiming Yuan, Henrique Ponde de Oliveira Pinto, Jared Kaplan, Harri Edwards, Yuri Burda, Nicholas Joseph, Greg Brockman, Alex Ray, Raul Puri, Gretchen Krueger, Michael Petrov, Heidy Khlaf, Girish Sastry, Pamela Mishkin, Brooke Chan, Scott Gray, Nick Ryder, Mikhail Pavlov, Alethea Power, Lukasz Kaiser, Mohammad Bavarian, Clemens Winter, Philippe Tillet, Felipe Petroski Such, Dave Cummings, Matthias Plappert, Fotios Chantzis, Elizabeth Barnes, Ariel Herbert-Voss, William Hebgen Guss, Alex Nichol, Alex Paino, Nikolas Tezak, Jie Tang, Igor Babuschkin, Suchir Balaji, Shantanu Jain, William Saunders, Christopher Hesse, Andrew N. Carr, Jan Leike, Josh Achiam, Vedant Misra, Evan Morikawa, Alec Radford, Matthew Knight, Miles Brundage, Mira Murati, Katie Mayer, Peter Welinder, Bob McGrew, Dario Amodei, Sam McCandlish, Ilya Sutskever, and Wojciech Zaremba. Evaluating Large Language Models Trained on Code. arXiv:2107.03374 [cs], July 2021. arXiv: 2107.03374. URL: http://arxiv.org/abs/2107.03374.

[5] Davide Chicco and Giuseppe Jurman. The advantages of the Matthews correlation coefficient (MCC) over F1 score and accuracy in binary classification evaluation. BMC Genomics, 21(1):6, January 2020. doi:10.1186/s12864-019-6413-7.

[6] E.J. Chikofsky and J.H. Cross. Reverse engineering and design recovery: a taxonomy. IEEE Software, 7(1):13–17, January 1990. Conference Name: IEEE Software. doi:10.1109/52.43044.

[7] Zheng Leong Chua, Shiqi Shen, Prateek Saxena, and Zhenkai Liang. Neural Nets Can Learn Function Type Signatures From Binaries. pages 99–116, Vancouver, BC, August 2017. USENIX Association. URL: https://www.usenix.org/conference/usenixsecurity17/technical-sessions/presentation/chua.

[8] Yaniv David, Uri Alon, and Eran Yahav. Neural reverse engineering of stripped binaries using augmented control flow graphs. Proceedings of the ACM on Programming Languages, 4(OOPLSA):1–28, November 2020. URL: https://dl.acm.org/doi/10.1145/3428293, doi:10.1145/3428293.

[9] Cheng Fu, Huili Chen, Haolan Liu, Xinyun Chen, Yuandong Tian, Farinaz Koushanfar, and Jishen Zhao. Coda: An End-to-End Neural Program Decompiler. In Advances in Neural Information Processing Systems, volume 32. Curran Associates, Inc., 2019. URL: https://papers.nips.cc/paper/2019/hash/093b60fd0557804c8ba0cbf1453da22f-Abstract.html.

[10] GitHub. GitHub Copilot · Your AI pair programmer. URL: https://copilot.github.com/.

[11] Sonia Haiduc, Jairo Aponte, Laura Moreno, and Andrian Marcus. On the Use of Automated Text Summarization Techniques for Summarizing Source Code. In 2010 17th Working Conference on Reverse Engineering, pages 35–44, October 2010. ISSN: 2375-5369. doi:10.1109/WCRE.2010.13.

[12] Sakib Haque, Alexander LeClair, Lingfei Wu, and Collin McMillan. Improved Automatic Summarization of Subroutines via Attention to File Context. In Proceedings of the 17th International Conference on Mining Software Repositories, pages 300–310, Seoul Republic of Korea, June 2020. ACM. URL: https://dl.acm.org/doi/10.1145/3379597.3387449, doi:10.1145/3379597.3387449.

[13] Anastasis Keliris and Michail Maniatakos. ICSREF: A Framework for Automated Reverse Engineering of Industrial Control Systems Binaries. In Proceedings of the Network and Distributed System Security Symposium (NDSS), 2019. URL: https://www.ndss-symposium.org/wp-content/uploads/2019/02/ndss2019_07A_5_Keliris_paper.pdf.

[14] Alexander LeClair and Collin McMillan. Recommendations for Datasets for Source Code Summarization. In Proceedings of the 2019 Conference of the North, pages 3931–3937, Minneapolis, Minnesota, 2019. Association for Computational Linguistics. URL: http://aclweb.org/anthology/N19-1394, doi:10.18653/v1/N19-1394.

[15] Opher Lieber, Or Sharir, Barak Lentz, and Yoav Shoham. Jurassic-1: Technical Details and Evaluation. Technical report, AI21 Labs, August 2021. URL: https://uploads-ssl.webflow.com/61f4503684b466578c0d307/
[16] Xuefeng Lv, Yaobin Xie, Xiaodong Zhu, and Lu Ren. A technique for bytecode decompilation of PLC program. In Proceedings of the IEEE Advanced Information Technology, Electronic and Automation Control Conference (IAEAC), pages 252–257, March 2017. URL: https://ieeexplore.ieee.org/document/8054016, doi:10.1109/IAEAC.2017.8054016.

[17] Antonio Mastropaolo, Simone Scalabrino, Nathan Cooper, David Nader Palacio, Denys Poshyvanyk, Rocco Oliveto, and Gabriele Bavota. Studying the Usage of Text-To-Text Transfer Transformer to Support Code-Related Tasks. In 2021 IEEE/ACM 43rd International Conference on Software Engineering (ICSE), pages 336–347, May 2021. ISSN: 1558-1225. doi:10.1109/ICSE43902.2021.00041.

[18] Vishal Misra, Jakku Sai Krupa Reddy, and Sridhar Chimalakonda. Is there a correlation between code comments and issues? an exploratory study. In Proceedings of the 35th Annual ACM Symposium on Applied Computing, SAC ’20, pages 110–117, New York, NY, USA, March 2020. Association for Computing Machinery. doi:10.1145/3341105.3374009.

[19] Arvind Neelakantan, Tao Xu, Raul Puri, Alec Radford, Jesse Michael Han, Jerry Twood, Qiming Yuan, Nicholas Tezak, Jong Wook Kim, Chris Hallacy, Johannes Heidecke, Pranav Shyam, Boris Power, Tyna Eloundou Nekoul, Girish Sastry, Gretchen Kruegel, David Schnurr, Felipe Petroski Such, Kenny Hsu, Madeleine Thompson, Tabarak Khan, Toki Sherbakov, Joanne Jang, Peter Welinder, and Lilian Weng. Text and Code Embeddings by Contrastive Pre-Training. arXiv:2201.10005 [cs], January 2022. arXiv: 2201.10005. URL: http://arxiv.org/abs/2201.10005.

[20] OpenAI. Examples - OpenAI API. URL: https://beta.openai.com/examples/?category=code.

[21] OpenAI. OpenAI Codex, August 2021. URL: https://openai.com/blog/openai-codex/.

[22] James Patrick-Evans, Lorenzo Cavallaro, and Johannes Kinder. Probabilistic Naming of Functions in Stripped Binaries. In Annual Computer Security Applications Conference, ACSAC ’20, pages 373–385, New York, NY, USA, December 2020. Association for Computing Machinery. doi:10.1145/3427228.3427265.

[23] Hammond Pearce, Benjamin Tan, Baleegh Ahmad, Ramesh Karri, and Brendan Dolan-Gavitt. Can OpenAI Codex and Other Large Language Models Help Us Fix Security Bugs? arXiv:2112.02125 [cs], December 2021. arXiv: 2112.02125. URL: http://arxiv.org/abs/2112.02125.

[24] Kexin Pei, Jonas Guan, David Williams-King, Junfeng Yang, and Suman Jana. XDA: Accurate, Robust Dis-assembly with Transfer Learning. In Proceedings 2021 Network and Distributed System Security Symposium, Virtual, 2021. Internet Society. URL: https://www.ndss-symposium.org/wp-content/uploads/ndss2021_1B-3_23112_paper.pdf, doi:10.14722/ndss.2021.23112.

[25] Syed Ali Qasim, Jared M. Smith, and Irfan Ahmed. Control logic forensics framework using built-in decompiler of engineering software in industrial control systems. Forensic Science International: Digital Investigation, 33:301013, 2020.

[26] Yan Shoshitaishvili, Ruoyu Wang, Christophe Hauser, Christopher Kruegel, and Giovanni Vigna. Firmalice - automatic detection of authentication bypass vulnerabilities in binary firmware. In Proceedings of the Network and Distributed System Security Symposium (NDSS), 2015. URL: https://www.ndss-symposium.org/wp-content/uploads/2017/09/11_1_2.pdf.

[27] Yan Shoshitaishvili, Ruoyu Wang, Christopher Salls, Nick Stephens, Mario Polino, Audrey Dutcher, John Grosen, Siji Feng, Christophe Hauser, Christopher Kruegel, and Giovanni Vigna. SoK: (state of) the art of war: Offensive techniques in binary analysis. In Proceedings of the IEEE Symposium on Security and Privacy (IEEE S&P), 2016. URL: https://doi.org/10.1109/SP.2016.17.

[28] Dimitrios Tychalas, Hadjer Benkraouda, and Michail Maniatakos. ICSFuzz: Manipulating i/os and repurposing binary code to enable instrumented fuzzing in ics control applications. In USENIX Security Symposium, pages 2847–2862, 2021.

[29] vxunderground. vxunderground/MalwareSourceCode: Collection of malware source code for a variety of platforms in an array of different programming languages., January 2022. original-date: 2020-10-10T02:48:57Z. URL: https://github.com/vxunderground/MalwareSourceCode.
Appendix: Additional Figures

#include <stdio.h>

typedef struct {
    float pttjdywbh;
    float xbbchhomt;
    float in;
    float la;
    float st;
} mzxywounks;

void syyttirvr(mzxywounks yrfsf, float in, float la, float st) {
    yrfsf->pttjdywbh = 0;
    yrfsf->xbbchhomt = 0;
    yrfsf->in = in;
    yrfsf->la = la;
    yrfsf->st = st;
}

float ccnspszai(mzxywounks *yrfsf, float in, float la, float st) {
    float vzhre = in - st;
    float t = (((yrfsf->in - vzhre) * yrfsf->la + vzhre) * yrfsf->xbbchhomt) / in;
    return t;
}

int main(int argc, char **argv) {
    mzxywounks yrfsf;
    syyttirvr(&yrfsf, 0.2, 0.4, 0.6, 0.8, 1.0);
    for (int i = 0; i < 10; i++) {
        printf("%f
", ccnspszai(&yrfsf, 1.0, i + 1, i));
    }
    return 0;
}

float pid_update(string param_1, float param_2, float param_3, float *param_4) {
    float fVar1 = pid_update(0x3f800000, param_2, param_3, param_4);
    return fVar1;
}

void pid_init(string param_1, undefined4 param_2, undefined4 param_3, undefined4 *param_4) {
    param_4 = param_2;
    return;
}

Figure 14: Randomized pid_d program (original in Figure 5).

Figure 15: Decompiled (from gcc -o1) pid_d program (original in Figure 5). Slightly reformatted here for clarity.

Figure 16: Measuring accuracy in information recovery for True/False Questions in delete_listen when increasing the level of ‘code randomization’, temp. = 0.4, top_p = 1.0.

Figure 17: Measuring accuracy in information recovery for True/False Questions in pid_d program when increasing the level of ‘code randomization’, temp. = 0.4, top_p = 1.0.
| Scenario | Encrypt? | XOR? | AES? | nDelete? | md5 | nUpload? | nIIR1? | PD? | CSum? | nCSum? | Question ID |
|----------|---------|------|------|----------|-----|----------|-------|-----|-------|--------|-------------|
| (o. src) | 10      | 3    | 9    | 4       | 5   | 2        | 6     | 5   | 10    | 6      | 297         |
| (r. src) | 8       | 2    | 7    | 4      | 9    | 5       | 10    | 5   | 6     | 2      | 390         |
| -o1-g   | 9       | 2    | 4    | 2      | 3    | 9        | 4     | 9   | 10    | 8      | 301         |
| -o1     | 8       | 3    | 7    | 5      | 4    | 7        | 6     | 8   | 9     | 5      | 302         |
| -o1-g   | 7       | 4    | 6    | 5      | 3    | 8        | 4     | 8   | 9     | 7      | 303         |
| (o. src) | 8       | 5    | 1    | 3      | 2    | 9        | 10    | 5   | 6     | 6      | 304         |
| (r. src) | 7       | 5    | 3    | 9      | 4    | 10       | 6     | 7   | 8     | 8      | 305         |
| -o1-g   | 8       | 2    | 7    | 4      | 9    | 5        | 10    | 5   | 6     | 2      | 306         |
| -o1     | 8       | 4    | 5    | 1      | 3    | 2        | 9     | 5   | 6     | 3      | 307         |
| -o1-g   | 8       | 3    | 7    | 5      | 4    | 7        | 6     | 8   | 9     | 5      | 308         |
| (o. src) | 9       | 7    | 5    | 4      | 10   | 8        | 6     | 6   | 10    | 7      | 309         |
| (r. src) | 9       | 8    | 6    | 5      | 9    | 1        | 7     | 8   | 3      | 9      | 310         |

Figure 18: True/False heatmaps for ‘Cybersecurity’ programs. Values are number of correct answers for that question (max: 10).
### True/False Question ID

| Scenario | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|----------|---|---|---|---|---|---|---|---|---|---|----|
| XOR?     |   |   |   |   |   |   |   |   |   |   | 0  |
| AES?     |   |   |   |   |   |   |   |   |   |   | 1  |
| Downld?  |   |   |   |   |   |   |   |   |   |   | 2  |
| EtcPswd? |   |   |   |   |   |   |   |   |   |   | 3  |
| MD5?     |   |   |   |   |   |   |   |   |   |   | 4  |
| nFIR1?   |   |   |   |   |   |   |   |   |   |   | 5  |
| nIIR1?   |   |   |   |   |   |   |   |   |   |   | 6  |
| nIIR2?   |   |   |   |   |   |   |   |   |   |   | 7  |
| PID1?    |   |   |   |   |   |   |   |   |   |   | 8  |
| nPID2?   |   |   |   |   |   |   |   |   |   |   | 9  |
| PI?      |   |   |   |   |   |   |   |   |   |   | 10 |
| nPI?     |   |   |   |   |   |   |   |   |   |   |    |
| PD?      |   |   |   |   |   |   |   |   |   |   |    |
| CSum?    |   |   |   |   |   |   |   |   |   |   |    |
| nCSum?   |   |   |   |   |   |   |   |   |   |   |    |

**Figure 19**: True/False heatmaps for ICS-type programs. Values are number of correct answers for that question (max: 10).