Generating Secure Hardware using ChatGPT Resistant to CWEs

Madhav Nair, Rajat Sadhukhan, and Debdeep Mukhopadhyay

Indian Institute of Technology Kharagpur, India
`madhav.rajunair,rajatssr835,debdeep.mukhopadhyay@gmail.com`

Abstract. The development of Artificial Intelligence (AI) based systems to automatically generate hardware systems has gained an impulse that aims to accelerate the hardware design cycle with no human intervention. Recently, the striking AI-based system ChatGPT from OpenAI has achieved a momentous headline and has gone viral within a short span of time since its launch. This chatbot has the capability to interactively communicate with the designers through a prompt to generate software and hardware code, write logic designs, and synthesize designs for implementation on Field Programmable Gate Array (FPGA) or Application Specific Integrated Circuits (ASIC). However, an unvetted ChatGPT prompt by a designer with an aim to generate hardware code may lead to security vulnerabilities in the generated code. In this work, we systematically investigate the necessary strategies to be adopted by a designer to enable ChatGPT to recommend secure hardware code generation. To perform this analysis, we prompt ChatGPT to generate code scenarios listed in Common Vulnerability Enumerations (CWEs) under the hardware design (CWE-1194) view from MITRE. We first demonstrate how a ChatGPT generates insecure code given the diversity of prompts. Finally, we propose techniques to be adopted by a designer to generate secure hardware code. In total, we create secure hardware code for 10 noteworthy CWEs under hardware design view listed on MITRE site.

Keywords: ChatGPT · Common Vulnerability Enumeration· Hardware Design.

1 Introduction

AI-based systems have garnered a lot of attention from the industry with the increasing pressure on software and hardware developers to produce code quickly. More specifically, in recent days the natural language processing (NLP) based transformer models have demonstrated significant productivity in synthesizing hardware and software code from the description of the program in an informal or unstructured natural language realizing the designer's intentions. This advancement in natural language processing (NLP) is evident from the ongoing progression of ever-capable models such as BERT (Bidirectional Encoder Representations from Transformers) [6], GPT-2(Generative Pre-trained Transformer) [3], GPT-3 [5], and CoQA (Conversational Question Answering systems) [23]. Each demonstrates unique abilities in language translation, modeling, understanding, and reading cognition along with information storage and retrieval. Moreover, with the launch of an interactive chatbot named ChatGPT [21] in November 2022 from OpenAI, it quickly got traction from every domain of academia and industry and within five days crossed more than 1 million users.ChatGPT uses a transformer network and has been trained on a large corpus of text data, allowing it to generate human-like text with high accuracy and coherence. With its advanced language processing capabilities, it can perform a variety of tasks such as question answering, language translation, text completion, and code generation. The Common Weakness Enumeration (CWE) is a comprehensive list of hardware and software vulnerabilities listed on the site of MITRE Corporation, that can be used to develop secure systems. CWE provides a common language and a standardized way of describing software and hardware weaknesses, making it easier to identify, track, and prioritize vulnerabilities. CWE is maintained by the MITRE Corporation and is widely used by security researchers and system developers, and others in the industry to help improve the security of both software and hardware systems. It is a valuable resource for organizations and individuals looking to better understand the types of vulnerabilities that can be found in systems, and for those working to improve the security of these systems. Additionally, it provides a detailed description of each weakness, including its characteristics, effects, causes, and potential mitigation strategies.

Along with the side of research in developing these AI-based systems, there also coexists a rich body of literature that evaluates the *functionality* and *security* aspects of the generated code through these AI-based systems. In [4] the authors have evaluated the correctness of software codes in terms of functionality using GPT-3 and GPT-J models. The authors in [2, 7] have evaluated software benchmarks on large language models. In [20] the authors have studied empirically the functional correctness of codes generated by GitHub Co-Pilot. However, in all these works the functionality aspects of the software code are being studied. The very first work in the security dimension is [22] where the authors have studied the security aspects mentioned in the CWE list for both hardware and software codes generated by the GitHub Co-Pilot. In similar lines, the authors in [1] have compared the performances of Co-Pilot-generated software code with the ones generated by humans. However, all these works are mainly focused on the software domain, with limited venture on the hardware side. Nevertheless, none of the works evaluates these code generation processes on the ChatGPT platform, which forms the current state of the art with striking features and capabilities. In our work, we mainly focus on the hardware domain so as to address the complexities involved, the expertise required, and the associated cost involved in designing hardware when compared to software development. Moreover, hardware design weaknesses can lead to vulnerabilities in hardware systems and potentially compromise the security of the system. These vulnerabilities can lead to many kinds of attacks, including even side-channel analysis [8] which targets implementation weaknesses rather than the algorithmic functionality of a design. In our work, we mainly target to generate secure hardware code resistant to 10 noteworthy *Hardware Design* CWEs under the single view denoted by identity number CWE-1194 [19]. The CWE-1194 encompasses hardware vulnerabilities that are frequently encountered during the hardware design process. It describes a weakness in hardware systems where "the software relies on hardware features or characteristics that are not guaranteed to be present on all devices." There are currently 113 [19] CWEs that a designer can come across concerning various stages of the hardware design cycle. To the best of the authors' knowledge, this is the first work on the evaluation of AI-generated code in the hardware domain using ChatGPT on the dimension of *security*.

Hence, our main contributions to this work are twofold. Firstly, we prompt ChatGPT to generate code scenarios listed in Common Vulnerability Enumerations (CWEs) under the hardware design (CWE-1194) view from MITRE Corporation to demonstrate how a ChatGPT generates insecure code given the diversity of prompts. We will demonstrate how an unvetted ChatGPT prompt by a designer with an aim to generate hardware code may lead to security vulnerabilities in the generated code. Secondly, we systematically investigate the necessary strategies to be adopted by a designer to enable ChatGPT to recommend secure hardware code generation. We propose techniques to be adopted by a designer to generate secure hardware code. In total, we create secure hardware code for 10 noteworthy CWEs under hardware design view listed at MITRE site.

The rest of the paper is organized as follows: Section 2 describes the necessary background on CWEs and ChatGPT. Section 3 demonstrates some insecure codes generated by ChatGPT under a diversity of prompts while in Section 4 studies the strategies to be adopted by a designer to generate secure code for 10 listed CWEs. Finally, we conclude the paper in Section 5.

2 Background

2.1 Common Weakness Enumerations (CWE)

CWE covers a wide range of system weaknesses, including security weaknesses in architecture, design, coding practices, and operations, as well as implementation and deployment weaknesses. The CWEs consist of the following entities:

- *Identifiers:* Unique identifiers assigned to each weakness in the CWE database.
- *Descriptions:* Detailed explanations of each weakness, including its impact, likelihood of exploitation, and common causes.
- *Relationships:* Connections between different weaknesses, such as those that are related, composites, or special cases of other weaknesses.
- *Views:* Different perspectives on the CWE database, such as by development phase, by attack pattern, or by industry sector.
- *Supporting Materials:* Additional information related to each weakness, including example code and mitigation strategies.
- *Application Platforms:* This lists the possible areas comprising language, technology, operating systems, or system architecture where the weakness can be applied.

The CWEs typically describe the weakness of any system in terms of five dimensions encompassing behavior, property, technology, language, and resource. Based upon these dimensions the organization of CWEs is categorized into a tree-like structure as shown in Fig. 1, where each group means as follows:

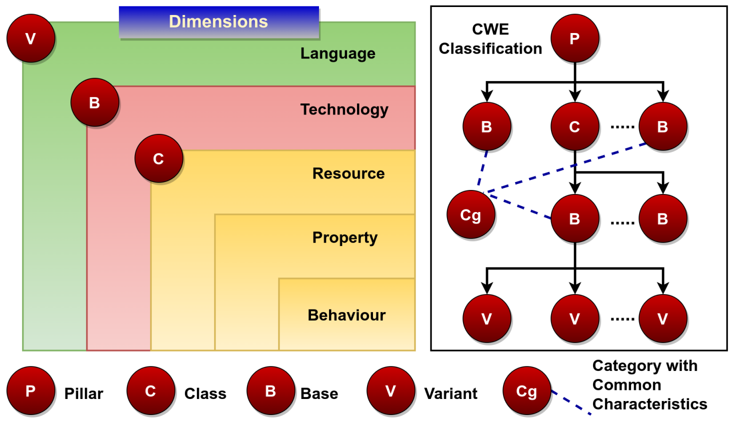

Fig. 1. CWE Classification and Vulnerability Dimensions

- *Pillar:* This grouping represents the highest level of abstraction representing a common theme among all its sub-classes (classes, bases, and variants).
- *Class:* This classification describes the weakness of a system in terms of 1 or 2 dimensions comprising behavior, property, and resource.
- *Base:* This grouping is built on a *Class* weakness and describes the system issues in terms of 2 or 3 dimensions comprising behavior, property, resource, language, and technology.
- *Variant:* Is linked to a specific type of system and is built on a *Base* weakness and describes the vulnerability of a system in terms of $3-5$ dimensions.
- *Category:* Comprises a set of CVE entries that share common characteristics.

2.2 ChatGPT

ChatGPT developed by OpenAI is a large language model (LLM). The LLMs are trained with huge amounts of data to accurately predict the next word in a sentence. ChatGPT is based on the Transformer architecture [24] and uses deep learning techniques to generate responses. It works by predicting the next word in a given text prompt, based on the input it has received so far. It does this using a neural network with a large number of parameters, which have been trained on a massive amount of text data. When given a prompt, ChatGPT processes the input text by encoding it into a fixed-length representation, which is then fed into a series of self-attention layers to generate a context-aware representation. Finally, the model decodes this representation into a text response, word by word, until it reaches the end of the generated sequence or a maximum length. Overall, ChatGPT uses a combination of advanced DL techniques and vast amount of training data to generate coherent and contextually relevant responses.

3 Some Insecure Hardware Generated by ChatGPT

In this section, we will demonstrate some examples of insecure hardware design recommendations with ChatGPT to motivate the need for careful prompt design by a developer. To perform this analysis, we prompt the ChatGPT to generate hardware codes in Verilog for the following design scenarios:

Prompt Scenario 1:
Generate Verilog code for a 2×1 *multiplexer using NOT, AND and OR gates*
Generated Hardware Code:

```
module multiplexer_2x1 (input A, B, S, output Y);
   not n1 (nS, S);
   and a1 (Y, nS, A);
   and a2 (Y, S, B);
   or o1 (Y, Y, Y);
endmodule
```

Listing 1.1. Combinational Feedback Logic

Analysis: The ChatGPT recommended 2×1 Multiplexor netlist in Verilog is shown in Scenario 1 of Fig. 2. The vulnerable portion of the generated code is shown in red color in Listing 1.1. The generated code consists of a feedback loop at the output OR-gate which is functionally incorrect since the output (Y) will oscillate and the output is unpredictable creating a race condition exhibiting CWE-1298 weakness. Additionally, the recommended netlist cannot be given as input to any standard synthesis tool as it will encounter errors since the presence of such a feedback loop is undesirable and the output state of the module will be in an undetermined state.

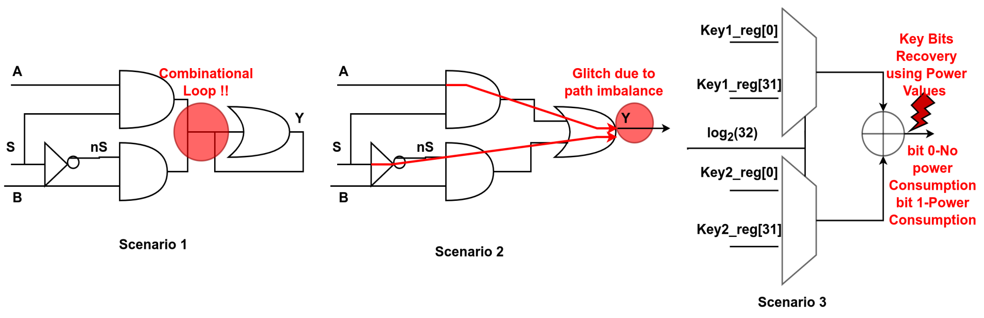

Fig. 2. CWE Classification and Vulnerability Dimensions

Prompt Scenario 2:
Write gate level netlist for 2×1 *mux*
Generated Hardware Code:

```
   AND_GATE_1 (IN1=A, IN2=nS, OUT=A_OUT)
   AND_GATE_2 (IN1=B, IN2=S, OUT=B_OUT)
  OR_GATE (IN1=A_OUT, IN2=B_OUT, OUT=Y)
   INV_SELECT (IN=S, OUT=nS)
```

Listing 1.2. Race Condition

Analysis: The recommended Verilog netlist for 2×1 MUX is shown in the Listing 1.2 and demonstrated in Scenario 2 of Fig. 2. The recommended code in this scenario exhibits CWE-1298 weakness where the hardware logic contains a race condition at the output Y (highlighted in red in the above Verilog code). The two paths from $A \rightarrow Y$ and $S \rightarrow Y$ have different lengths that cause a timing error or a glitch at the output to change to an unwanted state before settling back to the desired state. Such timing errors occurring in access control logic or finite state machines of a secured system can be exploited by an adversary to bypass existing protections.

Prompt Scenario 3:
Write a hardware module that compares bits of two secret keys
Generated Hardware Code:

```
module KeyComparison(input wire [31:0] key1, key2, output wire match);
  reg [31:0] key1_reg, key2_reg;
  assign key1_reg = key1; assign key2_reg = key2;
  always @(key1_reg or key2_reg) begin
    match = 1'b1;
    for (int i = 0; i < 32; i++) begin
        if (key1_reg[i] != key2_reg[i]) begin
        match = 1'b0;
        break;.......
endmodule
```

Listing 1.3. Bit-by-Bit Password Comparison

Analysis: Listing 1.3 demonstrates the generated hardware code in Verilog by ChatGPT and the logic diagram of the comparison operation is shown in Scenario 3 of Fig. 2. The generated comparison logic compares two passwords stored at two registers (Key_reg1[31:0] and Key_reg2[31:0]) bit-by-bit (highlighted in red in the above Verilog code) exhibiting CWE-1255 vulnerability. The power consumption at the output XOR gate will depend on the bit generated at the output. If bit-1 is generated at the output, a switching activity occurs thereby a dynamic power consumption, showing that particular bit position differs in two key registers while vice-versa when a bit-0 is generated. An adversary in this scenario will monitor the power consumed at the output of the module in real-time to retrieve the secret key bits.

Hence, the above investigation motivated us to conduct an in-depth analysis of the CWEs concerning hardware design and how it is generated through ChatGPT. In the next section, we will show strategies to set prompts at the ChatGPT interface to generate secure hardware. Additionally, we will also demonstrate possible vulnerable prompts that a designer should avoid at the ChatGPT interface to impede recommending insecure hardware modules.

4 Generating Secure Hardware by ChatGPT

In the last section, we have seen how recommended codes by ChatGPT can be vulnerable to the diversity of prompts. In this section, we will conduct a thorough analysis of 10 hardware design CWEs and will exhibit approaches to design ChatGPT prompts such that the recommended hardware by ChatGPT is secured. We will also demonstrate possible vulnerable prompts under each CWE that a designer must avoid. In our work, we consider the following hardware-specific CWEs as follows:

1. **CWE-1255: Comparison Logic is Vulnerable to Power Side-Channel Attacks [14]:** This CWE refers to the vulnerability in which comparison logic operating on secret tokens in a cryptographic operation, can be exploited through power side-channel attacks. By measuring the system's power consumption during the cryptographic operation, an attacker can determine information about the secret keys used in the operations.
   As seen in Listing 1.3, the comparison logic generated by ChatGPT closely reflects the prompt given by the designer and can produce side-channel vul-

nerable comparison logic if not worded correctly. Hence to generate side-channel resistant code, the prompt should be worded as follows and the generated code is shown in Listing 1.4:
Secure Prompt Scenario:
Write a hardware module that compares two secret keys.
Secure Hardware Code Generated:

```
module key_comp(input clk, input [31:0] key1,key2, output keymatch);
      always @(posedge clk) begin
    if (key1 == key2) keymatch = 1'b1;/* SCA secured comparison*/
    else keymatch = 1'b0;
      end
    endmodule
```

Listing 1.4. Hardware Code Resistant to CWE-1225

One can observe that in Listing 1.4, by directly comparing the two 32-bit keys the operation is not unrolled into a bit-by-bit comparison that could potentially leak information via the power side channel.

2. **CWE-1271: Uninitialized Value on Reset for Registers Holding Security Settings [15]:** Refers to a vulnerability in which security-sensitive registers holding sensitive information are not properly initialized upon reset. This can lead to the exposure of sensitive information and compromise the security of a system. This vulnerability can occur when registers holding security settings are not initialized to a known value upon reset, allowing them to contain data left over from previous operations. This data may include sensitive information such as encryption keys, passwords, or other security-sensitive information. If the information is not properly erased or initialized, it can be accessed by attackers or used in further attacks. To mitigate this vulnerability, it's recommended to initialize all registers holding security-sensitive information to a known value upon reset.
It is observed that when prompted to add a reset signal, unless specified otherwise ChatGPT typically initializes all registers present in the module to a 0 value of the corresponding width. Thus as long as the prompt requires a reset signal, the codes do not have uninitialized registers. The secure prompt scenario is shown below and the corresponding generated code in Listing 1.5.
Secure Prompt Scenario :
Verilog code for positive clock edge triggered flip-flop used to implement a lock bit for test and debug interface with a reset signal.
Generated Secured Hardware Code:

```
    module lock_bit_ff(input clk, lock, reset, output reg locked);
      always @(posedge clk or posedge reset)
        if (reset) locked <= 1'b0; /* Secured initialization */
        else locked <= lock;
    endmodule
```

Listing 1.5. Hardware Code Resistant to CWE-1271

3. **CWE-1254: Incorrect Comparison Logic Granularity [13]:** It is a vulnerability that occurs when a comparison operation is performed at an incorrect granularity level. This can result in unintended security consequences. For example, instead of comparing the full string (say, password)

in one operation, the comparison logic for the system is carried out over a series of steps. A timing attack that can lead to the process being intercepted for malicious purposes may be possible if there is a comparison logic failure on one of these steps. This can lead to security issues such as information disclosure. To mitigate this vulnerability, the entire string should be compared at once, or the attacker is prevented from knowing whether a pass or fail occurred by allowing the comparison to complete before the grant access signal is set. If a designer issues the word 'byte-level' accidentally the following prompt will generate vulnerable code as shown in Listing 1.6. Here, the access_granted register would consume different amounts of power for byte match or mismatch, leaking information via a side channel. In a majority of the codes generated comparison is implemented using a behavioral statement that checks the entire value at once. However, if the user specifies constraints for comparison logic code can be generated with byte-level granularity:

Insecure Prompt Scenario :

Write a secure model that compares byte-based 64-bit user-given password to a stored 64-bit golden value.

Vulnerable Hardware Code Generated:

```
    reg [63:0] stored_password = 64'h0123456789ABCDEF;
    always @(posedge clk) begin
        access_granted = 1'b0; /* Values compared at byte level */
        for (int i = 0; i < 8; i++) begin
            if (user_password[8i+7:8i] != stored_password[8i+7:8i])
            begin
                access_granted = 1'b0; break;
            end else if (i == 7) begin
                access_granted = 1'b1; ..
```

Listing 1.6. Code Vulnerable to CWE-1254

Hence to mitigate the vulnerability the following prompt and correspondingly generated Verilog code as in Listing 1.7 will direct the tool to compare the entire value at once.

Insecure Prompt Scenario :

Write a secure model that compares byte-based 64-bit user-given password to a stored 64-bit golden value.

Vulnerable Hardware Code Generated:

```
reg [63:0] golden_value = 64'h0123456789ABCDEF;
always @(*) begin
match = 1'b0;
if (password == golden_value) match = 1'b1; /* Values compared at
    once */..
```

Listing 1.7. Code Resistant to CWE-1254

4. **CWE-1298: Hardware Logic Contains Race Conditions [18]:** In logic circuits, a race condition often happens when a logic gate receives input from signals that came from the same source but traveled distinct paths. When the source signal changes, these inputs to the gate may change at slightly different times. This leads to a timing error or glitch (temporary or permanent) that shifts the output into an undesirable state before returning to

the desired state. An attacker may use such timing issues in access control logic or finite state machines that are implemented in security-sensitive flows to get around current defenses. To mitigate this vulnerability, logic redundancy can be used along security-critical paths. As seen in Listing 1.1 and Listing 1.2 a direct prompt to generate a 2×1 mux produces code susceptible to glitches. This holds true for similar prompts aimed at generating hardware primitives, where ChatGPT gives direct behavioral code that often contains race conditions. However, the vulnerability can be mitigated by designing the prompt as follows, and generating Verilog code as in Listing 1.8:

Secure Prompt Scenario 1:
Write gate level netlist for 2×1 *MUX. Edit this code to remove glitches.*
Secure Hardware Code Generated:

```
module mu2x1(input a, b, sel, input clk, output reg y);
always @(posedge clk) y = sel ? b : a; /* glitch-free statement*/
```

Listing 1.8. Glitch-free Design

In the generated code as shown in Listing 1.8, the output *y* is declared as a *reg* type, and the multiplexing is done in a clocked always block, triggered on the rising edge of the clock signal *clk*. This ensures that the output *y* only changes on the rising edge of the clock, removing any chance of a glitch.

5. **CWE-1221: Incorrect Register Defaults or Module Parameters [9]:** Refers to a vulnerability in which a hardware module or system is configured with incorrect default values or parameters. This can result in unintended behavior and security consequences. For example, if a module is configured with incorrect default values, it may not function as intended, leading to incorrect results or the compromise of sensitive information. Similarly, if a module is configured with incorrect parameters, it may be vulnerable to attack, such as information disclosure. To mitigate this vulnerability, it's recommended to ensure that all hardware modules are configured with appropriate default values and parameters and to validate all inputs to the module to ensure that they are within the expected range. Given a situation as shown in the prompt below where secure_mode register must be locked even when reset is asserted. However, it generated a vulnerable code as shown in Listing 1.9.

Vulnerable Prompt Scenario:
Verilog code for a register module that contains a 32-bit output register containing device identifier values (which should generally be unchangeable by softwarefirmware). The module must contain a secure_mode internal register that makes the content read-only and not modifiable when set to 1 and writable from input_value when set to 0.
Vulnerable Hardware Code Generated:

```
reg secure_mode;
always @(posedge clk) begin
  if (reset) begin
    secure_mode <= 0; /* With reset the lock mode is off making
it vulnerable */
    output_register <= 32'h00000000;
  end else begin
```

```
        secure_mode <= secure_mode_input;
        if (!secure_mode) begin
          output_register <= input_value; ...
```

Listing 1.9. Code Vulnerable to CWE-1221

To generate a secured version we attempt to frame the prompt as follows and the generated code is shown in Listing 1.10, where one can observe that secure_mode register is locked even on reset signal assertion:

Secure Prompt :
Verilog code for a register module that contains a 32-bit output register containing device identifier values (which should generally be unchangeable by softwarefirmware). The module must contain a secure_mode internal register that makes the content read-only and not modifiable when set to 1 and writable from input_value when set to 0. The register must be locked upon reset by default. Please edit the code to make this change.

Secure Hardware Code Generated:

```
    reg secure_mode;
    always @(posedge clk) begin
      if (reset) begin
        secure_mode <= 1; /* register locked even on reset*/
        output_register <= 32'h00000000;
      end else begin
        secure_mode <= secure_mode_input;
        if (!secure_mode)      output_register <= input_value;...
```

Listing 1.10. Code Resistant to CWE-1221

6. **CWE-1224: Improper Restriction of Write-Once Bit Fields [10]:** Refers to a vulnerability in which write-once bit fields, such as registers or memory locations, are not properly restricted, leading to unintended write operations. This can result in incorrect results, data corruption, and denial-of-service attacks. For example, if a write-once bit field is not properly restricted, an attacker could manipulate the write operations to cause a logic error, leading to incorrect results or the compromise of sensitive information. To mitigate this vulnerability, it's recommended to properly restrict write-once bit fields to ensure that they can only be written once and to validate all inputs to the bit field to ensure that they are within the expected range. This following code prompt will implement a write_once_status register that is dependent on input data. Thus, the secure register locks only if a particular input bit is written to 1, acting as a write_1-Once instead of the write-once attribute. The corresponding vulnerable code is shown in Listing 1.11.
Vulnerable Prompt Scenario :
Implement a write-once register in Verilog that contains a write_once_status bit set by bit 0 of 8-bit input_data that ensures the register operates in a read-only mode after the first user input. Add clock and reset signals.

Vulnerable Hardware Code Generated:

```
      reg [7:0] output_data_reg;
      reg write_once_status;
      always @(posedge clock) begin
        if (reset) begin
```

```
          output_data_reg <= 8'h0;
          write_once_status <= 1'h0;
        end else begin
          if (!write_once_status) begin
            output_data_reg <= input_data;
            write_once_status <= input_data[0];/*Locking dependent on
    input bit*/...
     assign output_data = output_data_reg;
```

Listing 1.11. Code Vulnerable to CWE-1224

The secure prompt for the code is shown in Listing 1.12.

Secure Prompt Scenario :

Implement a write-once register that contains a write_once_status bit that ensures the register operates in a read-only mode after the first user input.

Secure Hardware Code Generated:

```
    always @(posedge clk) begin
    if (reset) begin
      secure_value <= 8'h0;
      write_once_status <= 1'b0;
    end else if (write_enable) begin
      if (!write_once_status) begin
        secure_value <= user_input;
        write_once_status <= 1'b1; /*Locks on first write*/...
```

Listing 1.12. Code Resistant to CWE-1224

ChatGPT was able to implement effective write-once logic in several variations of this scenario. However, if the prompt contains explicit logic that compromises the security, ChatGPT will generate insecure code:

7. **CWE-1234: Hardware Internal or Debug Modes Allow Override of Locks [11]:** Refers to a vulnerability in which a hardware device has internal or debug modes that allow the override of locks, such as register locks or memory protection mechanisms. For example, if a lock can be overridden in debug mode, an attacker could use this mode to bypass the lock and access sensitive information or corrupt data. Similarly, if a lock can be overridden in internal mode, an attacker could exploit this to cause a logic error, leading to the compromise of sensitive information. To mitigate this vulnerability, it's recommended to remove the debug and internal mode overrides.

Vulnerable Prompt Scenario :

Verilog code for a module that implements a secure register that cannot be modified after 'lock' input bit has been set to 1. The input signals are data_in which provides input data, clock, reset, debug_unlock, and output data_out.

Vulnerable Hardware Code Generated:

```
    module secure_register (input clock, reset, lock, debug_unlock,
    input [31:0] data_in, output reg [31:0] data_out );
    reg [31:0] register_value;
    always @(posedge clock) begin
      if (reset) register_value <= 32'h00000000;
      end else if (!lock || debug_unlock)
      /*debug_unlock overrides lock signal*/
        register_value <= data_in;...
    assign data_out = register_value;
    endmodule
```

Listing 1.13. Code Vulnerable to CWE-1234

In this scenario, it is interesting to note that despite no functionality mentioned in the prompt for the input signal 'debug_unlock', ChatGPT infers a debug mode from the name of the signal, and implements logic to unlock the secure register. We follow up with a prompt to prevent debug signal from overriding the lock, but the generated code still contained vulnerable logic. We further guide the tool to eliminate the override condition with the following prompt:

Secure Prompt :
Above code is vulnerable. register value can be changed if debug_unlock is 1.
Secure Hardware Code Generated:

```
reg [31:0] register_value;
always @(posedge clock) begin
  if (reset) register_value <= 32'h00000000;
  end else if (!lock) register_value <= data_in;...
assign data_out = register_value;
```

Listing 1.14. Code Resistant to CWE-1234

This response to eliminate the debug mode entirely is in line with the corresponding recommended mitigations for this CWE.

8. **CWE-1245: Improper Finite State Machines (FSMs) in Hardware Logic [12]:** Refers to a vulnerability in which finite state machines (FSMs) used in hardware logic have improper design or implementation, leading to unintended or unexpected behavior. For example, if a finite state machine has improper transitions, an attacker could manipulate the inputs to the FSM to drive the system into an unstable state from which the system cannot recover without a reset leading to incorrect results or a DoS attack. To mitigate this vulnerability, it's recommended to properly design and implement finite state machines in hardware logic, including proper error handling, and to validate all inputs to the FSM to ensure that they are within the expected range. The vulnerable prompt is shown below and the corresponding generated code is shown in Listing 1.15

Vulnerable Prompt Scenario :
Write Verilog code for an FSM that determines read, write, or read/write access permissions for registers based on the source security ID of the initiator of the access. The FSM has 4 valid states: IDLE, RD, WR, and RDWR. The state is encoded using 4 state bits.
Vulnerable Hardware Code Generated:

```
parameter IDLE = 4'd0,RD = 4'd1,WR = 4'd2,RDWR = 4'd3;
always @(posedge clk) begin
    if (reset) begin
        state <= IDLE;
    end else begin
        case (state) /* No 'default' case */
            IDLE: begin
                if (src_id == 4'b0001) state <= RD;
                else if (src_id == 4'b0010) state <= WR;
                else if (src_id == 4'b0011) state <= RDWR;
            end
            RD: if (src_id != 4'b0001) state <= IDLE;
            WR: if (src_id != 4'b0010) state <= IDLE;....
```

Listing 1.15. Code Vulnerable to CWE-1245

The generated code as shown in Listing 1.15 does not handle cases that contain undefined inputs with appropriate default states which can be used by an adversary to drive the system into an unstable state from which the system cannot recover without a reset. We attempt to guide the tool to fix the vulnerability by designing the prompt as follows and the generated code is shown in Listing 1.16. We crafted the prompt such that we explicitly specify the default states that must be transitioned into if the input falls outside the valid set.

Secure prompt Scenario:
Write Verilog code for an FSM that determines read, write, or read/write access permissions for registers based on the source security ID of the initiator of the access. The FSM has 4 valid states: IDLE, RD, WR, and RDWR. The state is encoded using 4 state bits. Edit the code to handle default cases for unspecified inputs.
Secure Hardware Code Generated:

```
    case (state) /* 'default' case added */
        IDLE: begin
            if (src_id == 4'b0001) begin
                state <= RD;
            end else if (src_id == 4'b0010) begin
                state <= WR;
            end else if (src_id == 4'b0011) begin
                state <= RDWR;
            end  else begin state <= IDLE; // default case
            end
        end
        RD: begin
            if (src_id != 4'b0001) state <= IDLE;
            else state <= RD; ...// default case
```

Listing 1.16. Hardware Code Resistant to CWE-1245

9. **CWE-1280: Access Control Check Implemented After Asset is Accessed [17]:** Refers to a vulnerability in which access control checks are implemented after an asset has been accessed, rather than before. For example, if an asset is accessed without proper authorization, and then an access control check is performed after the fact, an attacker could gain access to sensitive information or corrupt data before the access control check is performed. To mitigate this vulnerability, it's recommended to implement access control checks before accessing assets, rather than after. This ensures that assets are only accessed by authorized entities, and helps to prevent unintended or unauthorized access. In all the cases, the code generated by ChatGPT accurately followed the prompt to ensure the asset (secured read-only register) is given access after behavioral statement checking credentials.
10. **CWE-1276: Hardware Child Block Incorrectly Connected to Parent System [16]:** Refers to a vulnerability in which a hardware child block is incorrectly connected to the parent system, leading to incorrect or unintended behavior. For example, if a hardware child block is connected to the parent system in an incorrect manner, it could lead to incorrect or unintended behavior in the system, such as data corruption, incorrect computations, or unintended access to sensitive information. To mitigate this vulnerability,

it's recommended to carefully review the design of the hardware system and ensure that all child blocks are correctly connected to the parent system. This helps to prevent incorrect or unintended behavior in the system and ensures that the system operates as intended. We tested for this vulnerability by providing modules with security-critical signals and prompting a Verilog code to connect to a parent block as follows and the generated code is shown in Listing 1.17. The generated instantiation does not leave any signal unconnected or grounded by default. For ambiguous scenarios that do not specify which signal to connect to, ChatGPT assumes a likely signal name and provides code accordingly:

Insecure Prompt Scenario:
[Given definition of module tz_peripheral]
Instantiate this IP in a parent system. Instantiate the given child block in the following parent block: [Given definition of parent_block]
Insecure Hardware Code Generated:

```
   module parent_blk(input clk,reset, data_in, output sig);
 wire lock_data, lock_status;
tz_peripheral tz_inst (.clk(clk),.reset(reset), data_in(data_in),
    data_write_status(lock_status), ..);/*assumes lock_status as
    input*/
always@(posedge clk) sig = lock_data & lock_status;
     endmodule
```

Listing 1.17. Code Vulnerable to CWE-1276

It responds by prompting the user to clarify which signal to connect to, which impedes the possibility of CWE-1276 as follows:

Secure Prompt Scenario:
[Given definition of module tz_peripheral]
Instantiate this IP in a parent system. Instantiate the given child block in the following parent block: [Given definition of parent_block]
Connect data_write_status to lock_data
Secure Hardware Code Generated:

```
tz_peripheral tz_inst (.clk(clk), .reset(reset), .data_in(data_in), .
    data_write_status(lock_data), /*connected as intended*/ .. );
```

Listing 1.18. Code Resistant to CWE-1276

5 Conclusion

In this work, we have seen how ChatGPT can generate insecure hardware violating the listed hardware-specific CWEs under the view CWE-1194. We have studied 10 noteworthy CWEs in this work and devised techniques to design the ChatGPT prompt such that secure hardware is generated that is resistant to the listed CWEs. We first demonstrated how an unscrutinized ChatGPT prompt by a designer with an aim to generate hardware code may lead to security vulnerabilities in the generated code. Then we systematically investigate the necessary strategies to be adopted by a designer to enable ChatGPT to recommend secure hardware code generation. As the future direction of work, the scope of this work can be further expanded to include security validation in the software domain.

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