Considering Software Protection for Embedded Systems

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Software in modern embedded systems is often realized by using prefabricated reconfigurable computing devices such as Field Programmable Gate Arrays (FPGAs). Such devices support the use of portable hardware description languages and, as a result, have vulnerabilities consistent with normal software applications. In this article, we consider the nature of adversarial reverse-engineering attacks in this environment and measures of protection.

In our modern world, the meaning of a word can change quite often. Even the term *computer* previously referred to a human operator who crunches numbers while today we relate this term clearly to a machine. With the emergence of new reconfigurable computing technologies such as FPGAs, the definitions of software and hardware have become less clear. As Vahid suggests [1], we should stop calling circuits *hardware* and start broadening what we consider *software*.

In the traditional sense, software referred to the bits (1s and 0s) representing language statements that could be executed on hardware processors. Today, embedded systems utilizing FPGAs realize circuits merely by downloading a sequence of bits that instantiate gates, controllers, arithmetic logic units, crypto circuits, and even processors. Thus, a circuit implemented on embedded systems utilizing an FPGA is essentially software.

Considering the proliferation of embedded systems with reprogrammable hardware components in both commercial and military sectors, we can readily show the impact of malicious activity geared to reverse engineer, tamper, or copy critical technologies residing in those systems. In this article, we delineate protective transformations for such embedded logic and present a brief survey of reverse engineering attacks in this realm.

Characterizing Circuit Protection

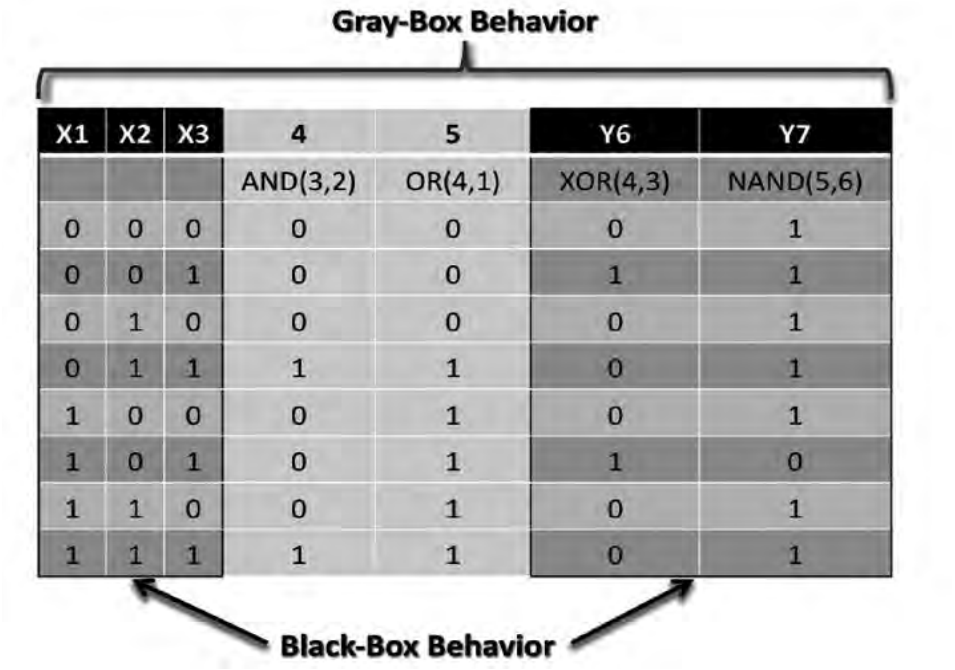
Both the DoD and the commercial sector have an interest in describing and measuring candidate protective measures, whether they derive from hardware anti-tamper realizations or software-based techniques. Adequately defining criteria for successful software *protection* in practice remains elusive mainly because full protection may not be possible, at least theoretically [2]. Collberg and Thomborson [3] describe three practical means of protecting software against copying, reverse-engineering, and malicious tampering; these include, respectively, watermarking, obfuscation, and tamper-proofing. In terms of analyzing protection mechanisms, they suggest measuring obfuscating transformations based on their obscurity (how much time is increased for understanding and reverse engineering), resilience (difficulty for reversing the transformation), stealth (the natural context of the transformation), and cost (overhead).

Though embedded systems may encompass a wide variety of custom processors and components, our discussion focuses on more fundamental logic programs represented as combinations of gate-level logic. In describing such circuits, we use two primary analysis paradigms: how they behave, and how they are constructed. We express the black-box behavior of a circuit by enumeration of all inputs, subsequent evaluation and propagation of signals on all intermediate gates, and the recording of the corresponding output. Figure 1 illustrates an input/output representation of a small combinational logic circuit with three inputs (X1, X2, X3), four intermediate gates (4, 5, 6, 7), and two distinguished intermediate gates (Y6, Y7) known as outputs.

We define a signal as a vertical reading of a column in the truth table (a fully enumerated input/output behavior, based on canonical ordering of inputs) and call the signature of a circuit the collection of its output signals. Given the full truth table of a circuit, we define its gray-box behavior as signals of all intermediate logic gates based on the enumeration of all possible inputs.

The white-box structure of a circuit may be represented by textual description languages (Bench, Verilog, VHDL, etc.), which are regular grammars that support expression of gates, electrical signals, components, and gate interconnections. Textual representations translate into graphical forms, which are referred to as

Figure 1: *Black-Box and Gray-Box Circuit Behavior*



the circuit topology. Figure 2 illustrates the circuit seen in Figure 1 in corresponding graphical representation and a Bench textual description [4]. We define a component within the circuit as a collection of lower-level elements (such as gates) that form a distinct sub-circuit.

The semantics (or black-box behavior) of a circuit consists of only the input and output signal pairs (the X and Y signals seen in Figure 1). Intuitively, one way to think of circuit protection is the act *hiding* all intermediate transitions that transform input to output. The collection of these transitions, in essence, represents the intellectual property of a circuit. Without knowledge of the original intermediate transitions, no human or automated process may derive other information about the original circuit such as topology, signal definitions, or component definitions. Many define the essence of circuit reverse engineering as the ability to correctly identify topology or components of the original circuit [4, 5].

To protect a circuit, replace the original circuit with a semantically equivalent version (one which does the same function) that hides the intellectual property of the original in some definable or measurable way. For the circuit in Figures 1 and 2, a replacement circuit would have identical signals for inputs and outputs (*X1, X2, X3, Y6, Y7*), but would have some other internal white-box construction (represented by gates 4 and 5 in Figures 1 and 2).

This formulation restates the essence of a virtual black box [2] because it defines full protection as a replacement circuit that does not leak any more information relative to an original circuit (other than its input/output characteristics). In more practical settings [3], the goal of using a replacement circuit becomes obscuring the original circuit in some way so that the cost of reverse engineering is maximized while operation characteristics of the circuit are not degraded beyond an acceptable level. Next, we delineate the permissible transformations on a circuit when obfuscation is in view.

Characterizing Circuit Transformations

We define an obfuscating transformation $O(\cdot)$ as an efficient, terminating program that takes circuit P as input and returns another circuit P': $O(P) = P'$. Of this assertion, all theoreticians and practitioners (that we are aware of) would agree. Beyond that, the majority of theoretical and practical models for obfuscation have

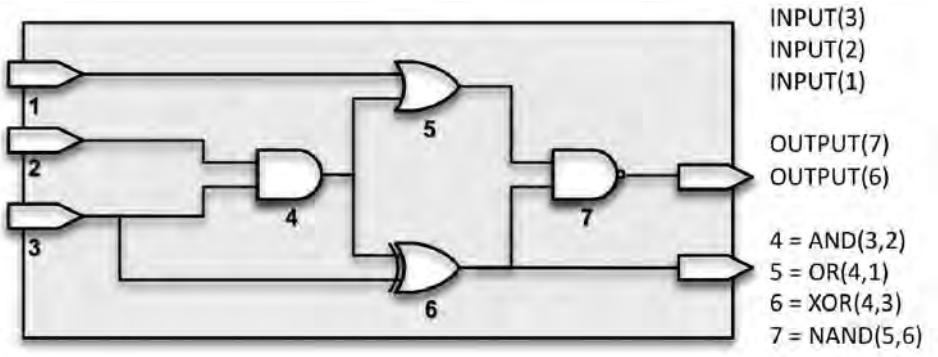


Figure 2: *White-Box Circuit Description*

at least two other requirements for the obfuscating program $O(\cdot)$: semantic equivalence and security.

We believe security may be provable in some circumstances if we are allowed to expand the semantic equivalence requirement (in other words, if an obfuscator can change the [white-box] structure of a circuit so that [black-box] input/output relationships of the original circuit *P* are also changed). We refer to black-box transformation with this meaning in mind. Likewise, the obfuscator may change (white-box) structure in such a way so that semantic equivalence with *P* is preserved. We refer to white-box transformation with this meaning in view.

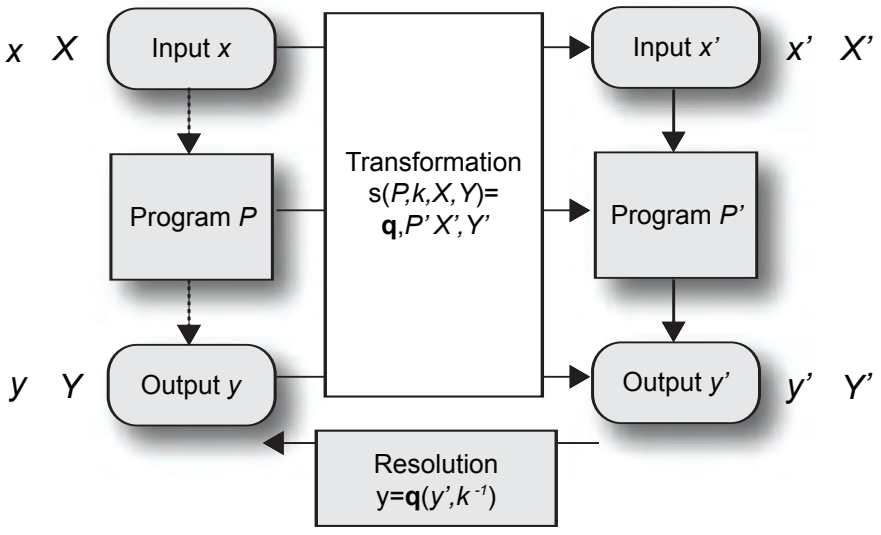
Black-Box Transformations

Sander and Tschudin [6] were one of the first to recognize the value of a black-box transformation as a means to hide functional intent. In discussing black-box changes to *P*, we assume there are certain programmatic environments where the output of the obfuscated circuit *P'* is conducive for off-line analysis and, therefore, open to the possibility of recovering the intended output of the original circuit *P*. In certain environments, this may not be possible. Black-box transformations, however, may be necessary to achieve stronger guarantees of security. In order to achieve a useful black-box transformation by some specific white-box changes to the structure of a circuit, an obfuscating operation must meet two requirements:

1. **Change in Black-Box Behavior.** The functional behavior changes for some majority of values in the domain x, $P(x) \neq P'(x)$. This leaves open the possibility that some transformations may produce equivalent values for certain values of x.
2. **Recovery of Black-Box Intent.** In order to recover the original functional output of *P*, some function $S(\cdot)$ must allow inversion: $V(x):P(x)=S(P'(x))$.

One way of hiding or masking input/output relationships is to do so through transformation that keeps the input/output values hidden in plain sight. We refer to such techniques as a black-box refinement of the original circuit *P* and present its algorithmic description in Figure 3. From the viewpoint of a circuit and its corresponding truth table, we can visualize at least five distinct operations that may be a part of a black-box refine-

Figure 3: *Black-Box Refinement*



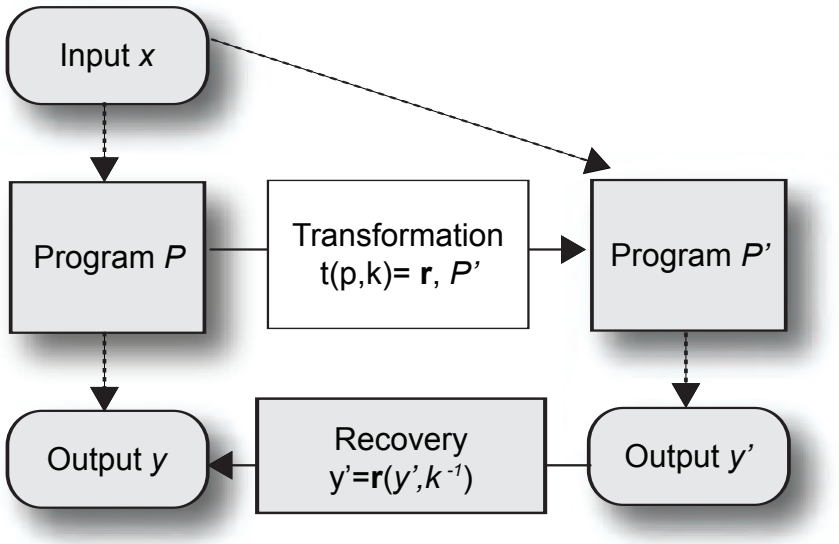


Figure 4: *Semantic Transformation*

ment. We envision that all five would be applied in a probabilistic manner based on configurable properties found in a (secret) key. If we let *X* represent the domain of the original *P* and confine it to a fixed number of bits, a black-box refinement may do any of the following:

1. Add input bits so that a new domain with a larger possible bit string *X'* is created.
2. Randomly permute the input bits themselves, resulting in a virtual reordering of the bits.
3. Introduce intermediate gates that would result in new truth table columns for *P'*.
4. Introduce a random number of output gates.
5. Randomly permute any of the output bits themselves.

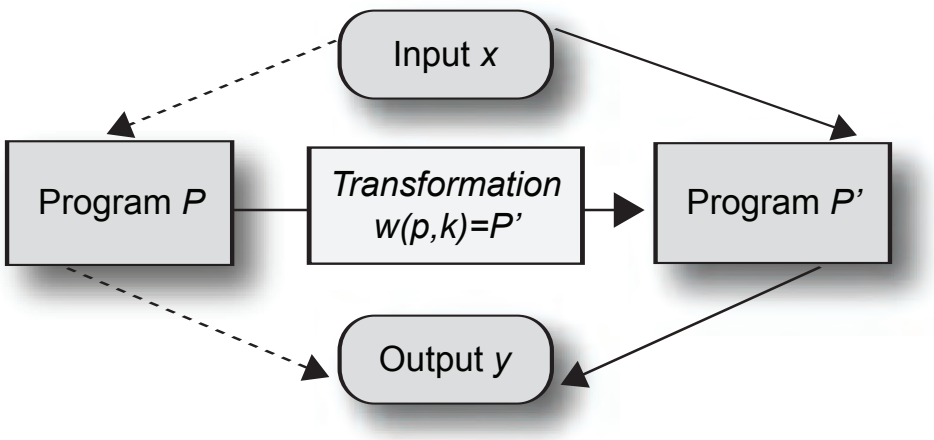
Changing the full input/output relationships of a circuit may truly hide the original black-box intent of a circuit. By composing a circuit with a semantically strong data encryption algorithm, the resulting program exhibits input/output relationships with desirable cryptographic properties. Figure 4 depicts this black-box change, known as *semantic transformation*.

White-Box Transformations

We define a structural white-box change to a circuit as a change to the topology of the underlying directed acyclic graph, which represents the circuit. Topological changes may involve textual renaming of signals or gates, changing the Boolean function type of particular gates, reordering input or output signals, introducing additional inputs, introducing additional outputs, concatenating the serial composition of the entire circuit with another circuit, merging the parallel composition of the circuit with another circuit, or replacing one or more gates within the circuit with a functionally equivalent set of gates.

Figure 5 shows the traditional meaning of obfuscation as understood in both theoretical and practical study: A transformation $w(P, k) = P'$ takes as input a circuit *P* with some (possibly) probabilistic information embodied in key *k*. We consider any random choices made by an obfuscation process to be part of this key. The output of $w(\cdot)$ is a circuit *P'* that remains functionally equivalent to the original circuit *P* and represents a different version of the original. Current obfuscation research centers on the transformation algorithm and defining the security that is achieved by its use.

Figure 5: *White-Box Transformation*



Reverse-Engineering Attacks

In the world of real circuit analysis, the typical goal of a reverse engineer is to recover the input/output of the circuit in question by some method less than full exponential enumeration. As we have already alluded to with black-box refinement or semantic transformation, such transformations would (at a minimum) prevent this form of reverse engineering while simultaneously introducing the need for output recovery in order to maintain functional utility. There are a number of different ways to discover and alter the functionality of a circuit. The term *tampering* refers to broad categories of circuit exploitation, including subversion, modification, and reverse engineering. Reverse engineers typically target reproduction of a circuit's functionality, usually for capital gain or malicious intent. Specific attacks can be roughly categorized as brute force, white-box/gray-box, side-channel, and fault injection.

Brute Force Attacks

Brute force attacks are based on black-box circuit behavior and are performed either while the circuit is in its natural environment or standalone in a simulator. Such attacks can be categorized as either *general* or *passive*.

- **General black-box attacks.** Traditionally, black-box attacks are the first and simplest means to reverse engineer a circuit. Adversaries glean black-box behavior by enumerating all possible input combinations and recording corresponding outputs. Using a large truth table, data analysis algorithms—or in some cases visual inspection—the adversary may re-create the underlying Boolean equations that define the circuit's logic; this type of attack works well on circuits with well-defined inputs and outputs.

  There exists potentially $2n$ input combinations to fully characterize any combinational circuit and potentially $2n + m$ or more input combinations for sequential circuits with m sequen-

tial elements. For a typical circuit with 100 or more inputs, a conventional black-box attack is not practical due to an enormously large search space. For example, a simple 64-bit adder with a carry-in pin has a total of 129 input pins and 65 output pins. If the reverse engineer, with no prior knowledge of the circuit applies the inputs, it would take 2^{129} attempts or 2^{99} seconds, roughly 2×10^{22} years, using a state-of-the-art 1 gigahertz automatic test equipment costing well over $1 million.

- **Passive attacks.** In passive attacks, adversaries examine circuits in their native environment (i.e., while they are being used in an actual circuit). Input and output pins are monitored, using either an oscilloscope or logic analyzer, and data is recorded giving a good picture of the chip's functionality. Typically, adversaries use passive attacks to provide focus for later black-box attacks that require a smaller distribution of input values.

White-Box/Gray-Box Attacks

In physical realizations, white-box attacks focus on the structure of a circuit. An adversary attempts to gain access to the internal nodes of a circuit without having to go through input/output evaluation, allowing a better functional understanding. Even though adversaries may risk destroying delicate circuit internals, these techniques are the only way to get direct access to the underlying white-box structure of a circuit in the real world. In order to extract white-box descriptions, adversaries focus attention on silicon characteristics using specific technologies such as ion beams and optical equipment:

- **Focused Ion Beam.** The focused ion beam is a semiconductor fabrication device similar to the scanning electron microscope (SEM), but it uses gallium ions instead of electrons. Unlike the SEM, it has a destructive effect as the gallium ions are implanted into the sample surface. This method allows an adversary to set specific intermediate nodes to specific values (0 or 1), including modifying existing connections to bypass normal input signal propagation. Likewise, an adversary does not have to rely on the actual output of the circuit in order to examine intermediate propagation values.
- **Optical Equipment.** Optical attacks rely on the interaction of photons with silicon devices and take two forms: optical probe and optical attack. Optical probing focuses on circuit examination by looking at transistor states. Adversaries essentially use pictures to observe signals that are propagated by means of applied input values.

Side-Channel Attacks

We observe that even circuits that may be provably secure according to a theoretical model—based on static white-box and dynamic black-box behavior—may still leak critical information relative to the circuit's function (based on real-world implementation issues). Rather than use brute force (to glean black-box behavior) or physically probe the internals of a circuit (to glean white-box and gray-box behavior), side-channel attacks use secondary information to create a picture of circuit functionality. Side channels are areas of a circuit that leak unintended information. They include power consumption and timing analysis:

- **Power Consumption.** Power consumption attacks mainly focus on breaking cryptographic schemes. The concept is that through an examination of the power used by a circuit, the underlying encryption algorithm can be found. This approach gives an attacker insight into the data values that are being manipulated on a chip. It is possible to then correlate this collected data to known functions in order to see exactly what is happening.
- **Timing Analysis.** With brute force attacks, synchronous circuits add additional complexity in the reverse-engineering process due to the timing constraints that are introduced. Timing attacks focus on taking the circuit outside of normal parameters by modifying the speed of the clock, either speeding it up or slowing it down. Because timing is linked directly to real-world physical implementations of various circuit technologies, our existing obfuscation framework requires additional information regarding structural characteristics of the circuit implementation.

Fault Injection

Fault injection is a generic term describing the injection of faults into digital systems using a variety of attacks: raising voltage higher or lower than system tolerances, inducing voltage spikes, or introducing clock glitches. An adversary may use any of these methods to cause the system to malfunction with intentions of revealing information useful in further attacks. The adversary performs fault injection dynamically at circuit run-time combined with power analysis techniques. Encryption algorithms, such as the Advanced Encryption Standard (AES), provide strength against brute-force key discovery from black-box behavioral analysis. However, an adversary may use fault injections with realized AES circuits in order to reduce encryption strength via key-space reduction. This exploit requires internal circuit access and reduces the goal of the adversary from using brute-force methods to interrupt the successful encryption/decryption process itself.

Software Defense Application

Considering the proliferation of embedded systems with reprogrammable hardware components in both commercial and military sectors, we can readily show the impact of malicious activity geared to reverse engineer, tamper, or copy critical technologies resident in those systems. Both the DoD and industry have interest in understanding how to describe and measure candidate protective measures, whether they derive from hardware anti-tamper realizations or software-based techniques. This article deals specifically with the characteristics of protection, possible transformations, and the delineation of malicious attacks.

Conclusion

Given the current trend of reprogrammable embedded devices within the DoD and industry, attention needs to be refocused on the benefits or measurability of software protection applied to this domain. Modern reconfigurable embedded systems now require us to consider circuits as software and the tamper methods applicable to physical circuits as new threats to a broadened definition of software. This article has presented a brief overview of the characteristics, transformations, and attacks possible in the realm of software implemented as circuits on an embedded system. Ultimately, we must turn our attention to the protection of critical technology resident in such an embedded system, mindful of the possible threats and techniques at our disposal.◆

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Note

1. The views expressed in this article are those of the authors and do not reflect the official policy or position of the U.S. Air Force, DoD, or U.S. government.

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