ABSTRACT
This paper first describes an ‘obfuscating’ compiler technology developed for encrypted computing, then examines if the trivial case without encryption produces much-sought indistinguishability obfuscation.

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1 INTRODUCTION
Encrypted computing [1] means running on a processor that ‘works profoundly encrypted’ in user mode, taking encrypted inputs to encrypted outputs via encrypted intermediate values in registers and memory. Encryption keys for such processors are installed at manufacture, as with Smartcards [10], or uploaded in public view to a write-only internal store via a Diffie-Hellman circuit [5], and are not accessible to the operator and operating system, who are the unprivileged user’s potential adversaries in this context. Prototype processors supporting encrypted computing include HEROIC [12], CryptoBlaze [8] and the authors’ own KPU (Krypto Processing Unit) [4]. The latter, clocked at 1 GHz, measures on the industry-standard Dhrystones benchmark [13] with AES (American Encryption Standard) 128-bit encryption [6] as equivalent to a 433 MHz classic Pentium. HEROIC and CryptoBlaze use the much slower Paillier [11] (partially homomorphic) encryption at 2048 bits or more.

A context in which an attack by the operator may be a risk, for example, is where scenes from animation cinematography are being rendered in a server farm. On-site operators have an opportunity to pirate for profit portions of the movie before release and may be tempted. Another possible risk scenario is processing in a specialised facility of satellite photos of a foreign power’s military installations to reveal changes since a previous pass. If an operator (or a hacked operating system) can modify the data to show no change where there has been some, then that is an option for espionage. A successful attack by the operator in both cases is one that discovers the plaintext of user data or alters it to order. It is shown in [3] that, given that the encryption is independently secure:

\[
\Delta E[x + y] = E[x] + E[y] \mod m, \text{ Pailler encryption } E, \text{ public key } m.
\]

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THEOREM. There is no method, deterministic or stochastic, that can read a bit of plaintext data from a program trace or rewrite the program to generate a target bit to order, with any probability above random chance.

The method that is ruled out is not restricted to polynomial complexities (in the encryption block size), but apart from that and the extra hypothesis, that is classic ‘cryptographic semantic security’ [7] and the meaning here is ‘encrypted computing does not compromise encryption’. The result also depends on stochastically-based compilation, as follows.

An appropriate ‘obfuscating’ compilation \( C[-] \) for encrypted computing and ANSI C [9] takes an expression \( r \) of the source language and compiles it to machine code \( mc \) that puts it in register \( r \) but deliberately misses the nominal value by an offset \( \Delta r \) that it generates, as set out in [2]:

\[
C[r] = (mc, \Delta r)
\]

The operational semantics of the generated object code \( mc \) is such that it changes processor state \( s_0 \) to \( s_1 \) with a ciphertext \( s_1(r) \) in \( r \) whose plaintext value beneath the encryption \( E \) differs by \( \Delta r \) from the nominal value

\[
s_0 \xrightarrow{mc} s_1 \text{ where } s_1(r) = E[r + \Delta r]
\]

The following lemma encapsulates the compiler specification:

LEMMA. Object codes \( mc \) from the same source are identical apart from identified constants. The runtime traces are also identical apart from the ciphertext values read and written, such that, for any particular plaintext 32-bit value \( x \), the probability across different compilations that \( E[x] \) is in a given register or memory location at any given point in the trace is uniformly \( 1/2^{32} \), independently to the maximum extent permitted by copy instructions and loops in the code.

The proviso is because a plain copy (‘mov’) instruction always has precisely the same input and output, and a loop means the ‘delta’ variations introduced by the compiler must be the same at the beginning as at the end of the loop.

The set of deltas generated by the compiler as above, one per register and memory location per point in the control graph is an obfuscation scheme \( O \). The user knows the scheme, so can interpret the program output after decryption, but ‘the processor’ does not know it, nor does the operator or operating system, in addition to not having access to the encryption key. The compiler can also generate schemes in which the input and final output deltas are zero. Then different object codes that look the same apart from constants, whose traces look the same apart from values written and read, end up with the same (correct, encrypted) values from

\[\text{Syntax } r \text{ vs. value } s(r) \text{ are not distinguished for succinctness here.}\]
the same inputs. That is a kind of obfuscation, limited to different programs from the same source by the same compiler.

That is the established theory. The question here is [i] if encryption \( E \) is really necessary, and [ii], what happens if a virtual machine (VM) is compiled to machine codes \( v'_1, v'_2 \) conforming to obfuscation schemes \( O_1, O_2 \) respectively along with data \( E[p_1], E[p_2] \) interpreted by \( v'_1, v'_2 \) as programs, and data \( E[d] \) for them. The data \( d \) is the same for both because it is compiled with delta zero, but deltas for \( p_1, p_2 \) differ.

Looking at [ii] first, by definition, on a processor for encrypted computing:

\[
v'_1(E[p_1], E[d]) = E[o], \quad v'_2(E[p_2], E[d]) = E[o]
\]  

Examining that for [i], on an unencrypted platform, where \( v_1 \) and \( v_2 \) are the versions of the programs that embed unencrypted constants in the machine code instructions instead of encrypted constants, gives

\[
v_1(p_1, d) = o = v_2(p_2, d)
\]

Both programs produce the same results. The traces are those of the repetitive virtual machine cycle interpreting the incoming data as instructions and modifying components of its state (which may be thought of as a finite array representing memory) to suit. They take the same time to finish. The different obfuscation schemes will have scrambled the access patterns (the compiler changes the delta in force for a pointer or array index at every increment to it). It is impossible to tell which is which, but both come from the same source.

What happens with different source codes with the same functionality? One expects traces to be different lengths and show different patterns, but suppose now that instructions are ordered/numbered arbitrarily in \( p_1, p_2 \) and there is only one instruction type for the VM: add, compare and jump:

\[
L_0 : \text{if } (Y = X + A) < Z + B \text{ goto } L_1 \text{ else goto } L_2
\]

There, \( A, B \) are constants, \( X, Y, Z \) are program variables, \( L_0, L_1, L_2 \) are instruction locations. Comparisons and additions wrap in the 2's complement arithmetic. This one instruction suffices for all computation: it is the instruction in HEROIC’s encrypted ‘one instruction computing’ (OIC) system.

An instruction (5) can also be interpreted via \( x=x+a, Y=y+b, Z=z+c \), where \( x, y, z \) are ‘virtual variables’ and \( a, b, c \) are secret constants, as follows:

\[
L_0 : \text{if } (y = x + A') < z + B' \text{ goto } L_1 \text{ else goto } L_2
\]

where \( A' = A + a - b, B' = B + c - b \).

Our compiler for encrypted computing already randomly generates deltas \( a, b, c \) by varying \( A, B, C \) per instruction and manages the deltas over the course of translation of a given program to maintain the intended source code semantics. Here the ‘virtual variables’ \( x, y, z \) in (6) have no physical existence so cannot be directly observed, but that is abstractly the same situation as on an encrypted computing platform, where encryption protects register and memory contents. Theory developed for the compiler in the encrypted computing context then applies. The Lemma affirms the compiler can design instruction constants \( A, B, C \) to vary secret \( a, b, c \) deltas independently and arbitrarily.

Only the user who knows those ‘program keys’ \( a, b, c \) can interpret the program’s functioning, and they can only run the program code correctly as data \( p \) for a virtual machine \( v \) that is supplied with it if they know the ‘master key’ consisting of the obfuscation scheme \( O \) for \( v \). The VM \( v \) can have been customised for \( p \) with a different interpretation unit for each instruction internal to \( p \), plus the compiler’s obfuscations.

**SUMMARY**

A compiler for encrypted computing, on each recompilation of the same source, generates object code of the same structure for which the runtime traces also have the same structure but for which the data (beneath the encryption if there is any) differs at each point in the trace and memory with flat stochastic distribution, independently to the maximal extent.

The full paper looks at what that compiler does in an unencrypted context where it translates source to machine code for a virtual machine. Instead of encrypted registers and memory, virtual content is hidden via secret deltas from physical values. Translation of a particular source code constructs are examined very carefully to see if this mechanism can possibly amount formally to ‘indistinguishability obfuscation’.

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