Benchmarking Obfuscators of Functionality

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Abstract—We propose a set of benchmarks for evaluating the practicality of software obfuscators which rely on provably-secure methods for functional obfuscation.

Note to SPRO referees: this paper is one page longer than the 7-page limit for a regular submission. I will prepare a 7-page version, if this is required for publication.

Index Terms—Indistinguishability obfuscation, virtual black boxes, benchmarking.

I. INTRODUCTION

Recent advances in cryptographic theory have pointed the way toward constructions of provably-secure indistinguishability obfuscators for Boolean functions [1]. However, as with many other theoretical advances, the reduction to practice may be problematic. The constructions may be very difficult to implement; the constructions may “leak” information through side-channels that are not considered by the theoretical proofs; and the obfuscated functions may be “bloated” to the point that they are not feasibly computable on a handheld device, a desktop computer, or even on a supercomputer.

This article is an early response to the 30 September 2014 announcement of the SafeWare research program, managed by the US Defense Advanced Research Projects Agency (DARPA) [2], which will explore the practical feasibility of provably-secure obfuscation, as well as to advance the theory of such obfuscations.

Any obfuscators which are constructed under SafeWare will be evaluated for their runtime overhead (average and worst-case), their obfuscation security level (e.g. an adversary work factor), and any potential side-channel vulnerabilities. In this article we propose a framework for evaluating runtime overheads.

SafeWare-funded researchers will attempt to construct obfuscated programs which are provably secure, i.e. programs whose de-obfuscation would involve the solution of a problem which is known, or generally believed, to be computationally infeasible. Currently, the only plausible candidates for such constructions are what we would call functional obfuscators, as opposed to control-flow obfuscators, data obfuscators, system-call obfuscators, communication obfuscators, or semantic obfuscators (in which portions of the program are expressed in a programming language that is initially unknown to the adversary).

Current techniques in control-flow flattening, opaque predicates, and the breaking of abstractions [3] are specifically excluded from attention in SafeWare, because programs obfuscated by these techniques may be de-obfuscated without solving a computationally-hard problem. It remains an open question, to be addressed by SafeWare-funded theoreticians, whether or how the control-flow graph of a program could be encoded into an obfuscated function which does not leak important information about control flow to a reverse engineer who performs a dynamic analysis on the obfuscated program.

Our focus in this article is on what we call functionally-obscure programs. We say a program is functionally-obscure if it contains an obfuscated function whose behaviour is required for program correctness, i.e. if a change to its value at any point might cause the program to behave incorrectly. Functional obscurity is not, in and of itself, a solution to digital rights management of software, because an attacker may replace an obfuscated password-recognition function by a stub which returns true for any input, or they may invert the comparison logic so that the program accepts any password except the correct one [4]. However functional obscurity may still be an important line of defense in a digital rights management system, and it may also be used to meet other security goals. In particular, functional obscurity would significantly mitigate the risk of password leakage, if password-recognition functions are securely obfuscated in a computational environment which is well-secured against adversarial observation and control.

The most promising line of research into functionally-obscure obfuscators is, at present, based on the security model of “indistinguishability obfuscation” with respect to a set of circuits, such as NC$^1$. This set of functions may be, informally, considered to be a “crowd” of functions within which any individual function of practical interest would be “anonymous” (i.e. indistinguishable from any other member of the crowd) – even after an attacker has spent a long time probing its behaviour (by observing its output on adversarially-controlled inputs) in an effort to determine its secret identity.

Indistinguishability obfuscation is an appropriate security concept for password-recognition functions, and for all other “point” functions (such as signature-verifiers). An attacker who is unable to deobfuscate, or to exploit a side-channel, must perform an exhaustive search over all likely inputs to the obfuscated function to discover the point at which its
output changes. If a securely-obfuscated password-recognition function can be efficiently evaluated on low-cost computing platforms, and if it can be economically produced by an obfuscation process, this would be of great practical utility. However if the obfuscation is weak, then the obfuscation is a dangerous waste of computational resource. This line of reasoning suggests that the provision of adequate security is the primary requirement on a functional obfuscator.

In this article, we do not attempt to evaluate the adequacy of security – this is a very challenging technical problem which includes the construction of a valid security model. Instead, we focus on the easier, but still quite challenging and important, problem of evaluating the performance of an obfuscated function.

The runtime performance of a securely-obfuscated function is always a satisficing requirement for its end-users: rapidly-evaluating functions are preferable to slowly-evaluating functions. However, in any given application, the maximally-acceptable runtime performance is a feasibility constraint. This constraint may be extremely challenging, or even infeasible, to satisfy. For example, in the specific case of password-recognition functions, end-users will not wait years, and they may not even be willing to wait seconds, for a program to accept or reject their password.

We cannot predict the most important applications of obfuscated function, so we cannot benchmark a general technique for secure obfuscation against a fixed-time threshold. However we can establish some indicative runtime constraints, e.g. we might insist that the recognition of an 8-character password must be accomplished within 1 second on a mid-spec smartphone such as a Samsung Galaxy S III. Highly-specific performance requirements of this nature are very important in acceptance-testing, but they would provide little or no guidance to theoreticians whose insights and theorems are based on asymptotic analysis.

It is technically challenging – and this is the primary technical focus of our article – to construct an easily-assessed measure of runtime performance which is valid, at least as a rough approximation, on a wide variety of contemporary computing platforms, for a wide variety of functions which might plausibly be obfuscated.

In Section 2, we argue that the runtime cost of functional obfuscators should be estimated as $n\sqrt{w}$, where $n$ is the number of 2- or 3-input gates in the obfuscated circuit, and $w$ is the width of a program which represents the obfuscated circuit. We believe that this functional form is simple enough to guide asymptotic analyses, while being accurate enough to provide appropriate guidance.

Our definition of the width of a program is a significant restriction on the usual notion of circuit width, because (in version 1 of our file format) a program of declared width $w$ which represents a Boolean circuit may have at most $w^2$ Boolean inputs and at most $w^2$ Boolean outputs. In subsequent versions of our file format, after experimentation on the range of contemporary computational platforms and functions of practical interest, we may relax this restriction, perhaps allowing as many as $w^4$ inputs and outputs (with a significant time-penalty for such extended-IO) to a width-$w$ program.

We have not parameterised our cost function on the depth of the circuit, even though such cost functions have been researched extensively in circuit complexity theory, because we are benchmarking low-cost computational platforms which are evaluating Boolean functions with billions or trillions of logic gates. Our cost estimate is intended to model the effects of the memory (or I/O) bottleneck that will arise when the platform’s evaluation of a Boolean function requires a working set which exceeds the cache (or main-memory) capacity of the platform. Circuit depth would only become important if it were impossible to avoid a CPU bottleneck, i.e. in the case of very narrow circuits. We do not expect this case to arise in practical applications of obfuscated functions, for the reasons discussed in Section 2.

In Section 3, we propose a space-efficient and computationally-appropriate file format (BPW) for the evaluation of very large Boolean functions with bounded program width. There are many existing formats for describing Boolean circuits, and any of these might be used for describing obfuscated functions. Some formats are restricted to combinational logic, and therefore may be more compact than formats which support sequential logic or those which specify implementations such as programmable logic arrays or full-custom integrated circuitry. Some formats are designed to help designers create attractive visual representations of small circuits. We encourage future researchers on functionally-obscure software to consider using any convenient representation when generating their circuits, then translate into our representation when storing a very large circuit in a computer file, or when evaluating a very large circuit in software. If we are funded to contribute to SafeWare, we would envisage implementing routines to a translate circuit-description files from our BPW format into a (very small subset of) IEEE VHDL [5], and vice versa. By our preference, and because SafeWare “emphasizes the idea of creating and leveraging open source architecture technology”[2], our translation routines will be open-sourced. We claim no intellectual-property rights over the BPW format disclosed in this article.

In Section 4, we propose an experimental method for evaluating our proposed cost metric, to determine its range of validity for contemporary computing platforms such as smartphones, laptops, and desktop computers.

We summarise our contributions in Section 5.

II. COST METRIC

Obfuscated functions may be deployed occasionally on supercomputers, however we believe most commercially-important functionally-obscure programs will be on mass-market platforms such as smart sensors, smart phones, battery-powered laptops, and desktop computers. Functionally-obscure programs could conceivably be used in cloud-computing environments, and in ad-hoc distributed computing environments, however the secure evaluation of a Boolean function in a
distributed environment has quite a different set of cost drivers due to the latency and bandwidth limitations of communication links. Readers who are interested in communication-limited functional evaluations should review the literature on distributed secure computations [6], whereby geographically-separated parties can provide secret inputs to a collaboratively-evaluated function such as the result of an auction or a democratic vote.

The computational platforms of relevance to our context have limited parallelism at any level of their memory hierarchy. At any given instant, there may be thousands or even tens of thousands of register-level operations in progress; dozens of cache operations; a few main-memory operations; and one or two secondary-storage operations. Cache, main-memory, and secondary-storage operations are of particular relevance, whenever a computer is evaluating a Boolean function with millions or trillions of gate-equivalents, unless the function is narrow enough that the working set of the evaluation process will fit in the registers.

We base the analysis in the remainder of this section on the premise that securely obfuscated programs must have widths of 50 or more.

We define the term “width of a program” only informally in this section, as a rough measure of its working set. We will give this term a formal definition in Section 3, when we define our BPW format.

Seven-character passwords, and (generally) cryptographic keys that are shorter than 50 bits are susceptible to a brute-force attack; so we use \( w = 50 \) as the lower limit of our range of interest. We encourage SafeWare-funded security analysts to critically examine this lower bound on \( w \) for validity, that is, to determine whether or not there is a general method of feasible attack on a width-49 BPW program.

The width of a circuit is well-established analytic concept [7, 8, 9]. If the gates of a circuit are arranged in levels (or rows), such that each level has at most \( w \) gates, and such that the gate-outputs at each level are connected only to gate-inputs on the next level, then the circuit has width \( w \).

The width of a function is the width of its narrowest gate-level implementation in any circuit, in a given logic family (e.g. in 2-AND, 2-OR, and NOT gates).

A program which describes a circuit implementing a function may have a width that greatly exceeds the width of the function. We believe that such unnecessarily-wide programs are the most promising candidates for functional obfuscations, because the process of circuit analysis is impeded very significantly by its width, and because it may be very difficult, or even computationally infeasible, for an adversary to discover a narrower implementation.

Wide circuits can be evaluated efficiently on parallel computers. For example, a circuit of width 50 or more may be evaluated by a 50-thread computation of the following form. Each thread runs a straight-line program in which it fetches a few Boolean inputs, computes a simple Boolean function, and writes a Boolean value into a shared memory area. It is not necessary to write programs with such explicit parallelism, in order to exploit much of the parallelism available on a modern CPU. Hundreds or thousands of machine instructions may be concurrently in the execution pipeline of a single CPU core, and a single-threaded computation which relies on the instruction-scheduling hardware is (in many cases) more efficient than a multithreaded computation with explicit locks.

The CPUs on high-end desktop computers may soon have some transactional memory features [10] which could allow an extremely efficient multithreaded evaluation of Boolean circuits – if the evaluation state is small enough to be held in L1 cache.

As indicated in the previous paragraph, modern computers have widely differing numbers of CPU cores, and they have widely differing organisations of their memory systems. This diversity implies that a circuit evaluator which is highly tuned for efficiency on one platform may be very poorly optimised for another platform. Our response to this engineering challenge is to propose a special-purpose programming language for the evaluation of large and wide Boolean circuits. Our language should be efficiently interpretable on any platform, and it may be compiled with platform-specific optimisations if even higher performance is required. In the remainder of this section, we identify the most important factors which affect the runtime performance of a circuit evaluator on any platform, and we develop some rough estimates of performance in particular cases, with the goal of developing a general formula for predicting runtime performance on any platform.

One of the key factors in any performance estimation is the size of the working set of the program. If the working set can be held entirely in CPU registers, the computation will never be stalled on cache accesses. If the working set is cache-local, then the computation will never be stalled on main memory accesses. If the working set is small enough to fit in main memory, then the computation will not thrash the secondary storage device. Accordingly: our programming language has a wordsize of 1 bit, so that its interpreter may (depending on the platform) minimise the size of its working set by packing and unpacking bits into machine words. This is a CPU-memory tradeoff, for the pack/unpack operations may result in a CPU-bottlenecked evaluation which could be avoided (at the cost of occasional cache faults) by storing Boolean values in machine bytes or words rather than in machine bits.

As indicated earlier, we are restricting our attention to circuits with width at least 50. We are also restricting our attention to circuits with at least millions (\( 10^6 \)) of 2- or 3-input gates. Smaller circuits seem unlikely to be securely obfuscated. Furthermore, initial constructions from an asymptotically-valid theory such as indistinguishability obfuscation are rarely, if ever, efficient with respect to constant factors and additive constants.

If a circuit with a million 3-input gates is not organised for temporal locality during its evaluation, then its width will be 500000 or more, and every gate-evaluation will require three fetches and one store on a million-bit state vector. This vector, even if it is stored bitwise in 128 KB, is too large for L1-locality on most contemporary computers. However this
state vector, and thus the working-data set of the evaluation, will fit comfortably in the L2 cache of a smartphone, laptop, or desktop computer. The evaluation of each logic gate will thus involve four L1 misses: three reads and one write. A tightly-written inner loop for an interpreted evaluation might execute thirty machine instructions per gate-evaluation, so we estimate one L1 miss per eight machine instructions. Modern processors are very inefficient with such high L1 miss rates; their memory systems are tuned for miss rates not exceeding a small fraction of a percent, very roughly 1/300. We conclude that a disorganised evaluation will have a slowdown of a factor of approximately 300/8 = 40 in comparison to a memory-local (CPU-bottlenecked) evaluation of a narrower circuit on the same platform.

High-end GPUs in desktop computers may support very rapid evaluations of Boolean circuits, so long as the circuit description is compressed well enough to avoid a communication bottleneck at the GPU-CPU interface. We expect that a disorganised billion-gate circuit would be evaluated by a high-end GPU at a rate approaching one gate-evaluation per four DRAM cycles, that is, at (very roughly) 10 million gate-evaluations per second. Note that, due to the disorganisation, each a DRAM word in the 128 MB working set of this billion-gate evaluation contains only a single bit of relevance to its current stage of computation.

NVIDIA’s Fermi architecture for its GPUs has 32k general-purpose registers and 512 ALU cores [11]. We thus expect the working set of a well-optimised interpreter to be held in GPU registers, if the Boolean circuit has width 10000 or less. The description of the billion-gate circuit will not be register-local, but it could be streamed from main memory at a rate of perhaps 3 GB/s, using DMA over its PCIe channel. Our BPW format will encode gates in very large circuits at (roughly) 8B/gate, so we estimate high-end GPU performance on moderately-organised billion-gate Boolean circuits to be 3/8 billion evaluations per second. This is roughly 40 times faster than our estimated performance for GPUs on disorganised billion-gate circuits.

Based on the preceding performance estimates, we tentatively identify $n$ (circuit size) and $w$ (program width) as the most important factors controlling runtime performance on any platform, under the constraints that $w \geq 50$ (so that the computation is at least 50-way parallelisable) and $10^6 \leq n \leq 10^9$ (so that it is reasonable to assume the circuit description is in main memory, thereby avoiding I/O bottlenecks). If we aim only at predicting the relative performance for two different evaluations on the same platform, we need not encumber our predictions with platform-specific parameters if we adopt a general model of memory system performance. In prior work, we suggested one such model [12]. We will use this model to develop a performance estimate, immediately after describing it briefly in the next paragraph. In Section 4 we propose a set of experiments which would validate (or invalidate) our performance model.

Our general model of memory system performance is based on the assumption of a hierarchical memory system which may be visualised as a triangle. At the apex of the triangle are the CPU registers; at the base is a very small number of secondary storage devices such as solid-state or magnetic disks. The hierarchy has two to four intermediate layers: main memory (typically DRAM), and one to three levels of CPU cache (typically SRAM). The memory at the top of the hierarchy is very fast, with a small blocksize: a word in a CPU register typically holds 4 to 8 bytes. The memory at the bottom of the hierarchy is very slow, and it has a very large blocksize to enable a generally-appropriate tradeoff of bandwidth for latency. If the blocksize of a disk transfer is too small, then any random or linear access would deliver only a few bytes of useful data, and the latency on this access might be millions of times larger than the CPU cycle time – so a computation that is bottlenecked at this level will proceed at a rate of only a few bytes per millions of CPU cycles. However if the blocksize is too large, then only a tiny fraction of a randomly-accessed block will be useful. As a general rule of thumb, the blocksize of a layer of memory is the square root of its capacity. The capacity $S_i$ of the $i$-th layer also seems to be a power function (perhaps $S_i = (S_{i-1})^{1.4}$) of the capacity of the layer immediately above it, with the random-access latency $L_i$ of each level also growing as a power function (perhaps $L_i = (L_{i-1})^{0.6}$) [12].

We can not predict absolute performance from a general model such as the one above. However we can predict relative performance, to an accuracy of perhaps a factor of 10. We do not believe it is feasible to devise a general model that is more accurate than this, given the diversity of contemporary computing platforms. Indeed, we believe that estimating relative performance within a factor of 10 in a general model is a very challenging technical problem, even when the computational workload is limited to the evaluation of Boolean circuits. On a general workload, a computation may be bottlenecked in many different ways: by CPU instruction bandwidth, by CPU instruction latency, by memory latency, by memory bandwidth, by latency or bandwidth of interprocessor communication, or by power consumption (for heat- or battery-limited computations). We tentatively identify memory latency as the most critical constraint, on most platforms, when they are evaluating large Boolean circuits. Memory latency bottlenecks arise when the working set is overly large.

We can measure the speed of a circuit evaluation in gate-evaluations per second. We expect our experimentation to confirm that this rate is nearly constant, after a brief startup transient – if the program width (and thus the working set of its evaluator) does not vary significantly by level. We are moderately confident that the obfuscated functions constructed under SafeWare will conform to this expectation. However, if constructions of obfuscated functions are compositions of moderately-wide functions with very wide functions, then (in subsequent work) we will adjust our programming language to accomodate series-parallel functional compositions with
declared widths on each subcircuit [1].

Evaluation rates will almost surely be nondecreasing in the size of the working set, but there will be very significant nonlinearities in this relationship whenever the working set is almost equal to the capacity of a layer of memory. A fully-accurate timing model would be parameterised on the threshold values of \( w \) which (for a particular evaluation method and a particular platform) are likely to cause this evaluation method to become memory-bottlenecked at that level. A generally-valid timing model cannot have any platform-specific parameters, so we restrict our attention to cost functions of the form \( nw^\alpha \).

Earlier in this section, we performed two platform-specific estimations which suggested a factor of 40 difference between the per-gate-evaluation time for a circuit which is too wide to be efficiently evaluated, in comparison to a circuit which is narrow enough to be efficiently evaluated. The range of interest in circuit width is 50 to 500000 – a factor of 10000. A factor of 40 difference is, very roughly, a square root of this range; so we have seized on the square root as a convenient exponent \( \alpha = 0.5 \) for the effect of circuit width \( w \) on gate-evaluation rate, on any given platform, for any given family of circuits.

Our proposed cost metric is thus \( n \sqrt{w} \). We may revise the exponent on \( w \), if experiments (such as the ones described in Section 4) on contemporary platforms of interest suggest that such revision would be appropriate. However we see very little chance that the best-fit exponent \( \alpha \), as determined by experimentation, will be below 0.4 or above 0.7, except perhaps for long-running computations on battery-powered platforms where (for theoretical reasons [12]) we would expect to observe power-limited computations with runtimes proportional to \( nw^\alpha \).

III. FILE FORMAT

In this section, we briefly sketch an efficient format for describing large Boolean circuits of bounded width. These files have the extension .BPW, as an acronym for “bounded program width”, so the corresponding “magic bytes” must appear first in their header: 0x42, 0x50, 0x57. The fourth byte is a version number. Version 0x01 is described in this article.

Four 8-byte integer parameters appear next in the file: \( w \), \( n \), \( a \), \( b \). The first parameter is the declared width \( w \) of the circuit, as represented in this BPW program. The next parameter is the declared number of gates \( n \) in the circuit. The third parameter is its number of Boolean inputs. Runtime arguments to the evaluation function would supply these inputs, in order to determine the values of the circuit’s \( b \) (the fourth parameter) Boolean outputs.

We require \( a \leq w^2 \) and \( b \leq w^2 \). These may seem very unnatural restrictions to a circuit-complexity theorist, because a width-\( w \) circuit of \( n \) 3-input gates could naturally be allowed to have up to \( 2w \) external inputs per level, with different inputs being accepted on each of \( \Omega(n/w) \) levels. Such a circuit might produce \( n \) output bits. However our emphasis is not on theoretical elegance, but is instead on representing circuits so that they can be evaluated efficiently on a contemporary computer system such as a handheld device.

The body of a BPW file is a sequence of \( n \) gate-descriptors. Syntax errors are clearly possible, for example the body of a BPW file may not have exactly \( n \) gate-descriptors. A formal syntax for BPW is outside of the scope of this article – because our intent is to sketch the initial (pre-release) version of this language in sufficient detail that its design can be discussed, in a workshop setting, prior to the finalisation of a first production version.

Each gate-descriptor starts with a 4-bit nibble encoding its type, with the following possibilities (enumerated from 0 to 0xF): NOT, AND2, OR2, NAND2, NOR2, XOR2, AND3, OR3, NAND3, NOR3, XOR3, XNOR3, MUX3, COPY, undefined. Note that gate type 0xF is undefined in version 0x01 of the BPW format. Future formats may use 0xF as a prefix for multiple-nibble gate-type descriptors.

Version 0x01 of BPW has one type of 1-input gate, six types of 2-input gates, seven types of 3-input gates, and a three-input ‘COPY’ pseudogate which is used for extended-length IO operations as well as to represent width-\( w \) parallel compositions while maintaining locality in the state vector of the evaluation process. We take the (positive-logic) convention that 0 encodes a FALSE value and 1 encodes a TRUE value. The third input of MUX3 controls which of its first two inputs should be copied onto its output, with a control of 0 selecting the first input of this 2-input multiplexor. The logic function of every other gate type should be clear from its mnemonic. We will explain the semantics of the COPY pseudogate, immediately after discussing the detailed semantics of logic-gate evaluation.

Gate input-specifiers are references to:

- any of \( w \) external inputs (indexed as 0 to \( w-1 \)),
- any bit in a length-\( w \) circular queue of results from prior gate-evaluations (indexed as \( w \) to \( 2w-1 \)),
- any (single-bit) result of an evaluation of a gate on the previous level of gates. These results are stored in a length-2\( w \) circular queue, indexed as \( 2w \) to \( 4w-1 \) in gate-descriptors; and these registers are locked against reads during the virtual-machine cycle in which they are being written. Gate evaluations are done in a \( w \)-way parallel fashion, so only \( w \) of these bit-registers are available as inputs while the other \( w \) are being updated.

Summarising the above, input-specifiers are indexes into the register file of a virtual machine with \( 4w \) bits of storage. The virtual machine state also has an instruction pointer (into the input stream of the BPW file), and two register-pointers (of length \( \lceil \log 2w \rceil \) ) which maintain the states of the two circular queues.

The reservations on bit-registers give BPW the flavour of a VLIW instruction set, in which it is the programmer’s responsibility to schedule operations in order to achieve \( w \)-way parallelism. The resulting “forbidden” values of input-
evaluations. First, \(PR = (PR + 1) \mod 2w + w\). The output of the \(i\)-th gate on the \(j\)-th preceding level is accessible as \(COPY(j, 1, i)\). The latency of a \(COPY\) operation is \(\sqrt{w}\), as measured in VLIW instruction times; it is \(w\sqrt{w}\), if measured in gate-evaluation instructions. This latency is enforced by syntactic restrictions on BPW version 0x01. We call such programs BPW1 for convenience. Subsequent versions of BPW may have different restrictions. A BPW1 program is invalid if

- it contains more than one \(COPY\) operation per \(w\) instructions, or
- if the result of a \(COPY\) by a BPW instruction at level \(i\) is referenced by a gate-evaluation instruction at level \(j < i + \sqrt{w}\).

Levels are defined by counting the non-\(COPY\) instructions in a program, with level 0 being the initial level, and the level counter being incremented after every \(w\) non-\(COPY\) instructions. As previously indicated, a gate-evaluation has latency 1, that is, its result is unavailable to gate-evaluations in the same level but is available to gate-evaluations in the subsequent level.

If the first operand of a \(COPY\) is in the range \(2w..3w - 1\), then its semantics are undefined in version 0x01 of BPW. In future versions, BPW semantics may be extended to allow more external inputs (perhaps up to \(w^4\)) and more prior-results (perhaps up to \(w^4\)) to be accessible, with an appropriately-high latency (perhaps \(w^2\)).

In version 1 of BPW, we emphasise programming convenience (and CPU cycle-timing) over file compression; so we nibble-align all of the input-specifiers (rather than bit-aligning them for optimal compression). The length, in nibbles, of each input-specifier is \(\lceil \lg 4w/2 \rceil\). For example, a width-50 circuit requires 1 byte (2 nibbles) for each input-specifier. If it were composed entirely of 2-input gates, then each gate (with its 1-nibble type) is encoded in 2.5 bytes. A disorganised circuit with a million gates could be declared to have width 500,000; so it would require 5 nibbles for each input-specifier, for a total of 5.5 bytes per gate.

IV. EXPERIMENTAL DESIGNS

In this section, we briefly sketch some experimentation which would validate (or invalidate) our cost function and our BPW language design.

A. Workload

The experimental workload consists of two types of BPW programs at varying \(n\) (size), \(w\) (width), and \(d\) (density of \(COPY\) operations), for all

\[
\begin{align*}
\{ & 5, 10, 50, 100, 500, 1000, 5000, 10000, \\
& 50000, 100000, 500000\}, \\
n & = \{10^6, 10^7, 10^8, 10^9\}, \\
d & = \{ \frac{1}{w}, \frac{1}{2w}, \frac{1}{4w}, \ldots, \frac{1}{2\lceil\lg(n/w)\rceil w} \}. 
\end{align*}
\]

The first type of program implements a randomly-chosen function with \(k = \min(w, 50)\) inputs and \(k\) outputs. The second type of program is a lightly obfuscated password recogniser, for the very insecurely-chosen \(k\)-bit password
0x1555...555. The output of the password recogniser is 1 if the input matches the password, 0 otherwise.

The first type of program consists of a sequence of \( nd/(1 + d) \) repetitions of the following subcircuit: \( 1/d \) randomly-generated NAND2 gates, a randomly-generated COPY pseudogate-specifier. The input-specifiers on the NAND2 gates are generated from i.u.d. variates on \( \{0, 1, ..., 4w-1\} \), discarding any generated values which are invalid due to the uninitialised or unavailable bit-registers at this point in the BPW program. The first input-specifier on each COPY pseudogate appears in a BPW program at density \( \lfloor \sqrt{w} \rfloor \). The second input-specifier of each COPY pseudogate is \( \lfloor \sqrt{w}/w \rfloor \) when \( w = 50 \). The output of the password recogniser is 1 if the input matches the password, 0 otherwise.

The second input-specifier of each COPY pseudogate is \( \lfloor \sqrt{w}/w \rfloor \) when \( w = 50 \). When such COPY pseudogates appear in a BPW program at density \( d = 1/w \), then (due to the latency of COPY operations) about half of the prior-results cache is being updated at any time during the program execution. The other half of the prior-results cache may be referenced by input-specifiers.

The password-recogniser should compute \( w \) copies of its output bit in its last \( \lceil \lg \min(w, 50) \rceil \) levels, using XOR2 and XNOR2 gates on the first of these levels and using AND2 gates for the remaining levels. Note that the \( i \)-th bit of the secret password is encoded in the type (XOR2 or XNOR2) of the gate which receives two copies of the \( i \)-th input bit. The input bits are permuted in the intermediate levels of the password-recogniser. Each intermediate level is composed of \( w \) NOT gates with input-specifiers which (collectively) define a random permutation on \( w \) elements – so that each intermediate level is a very weak obfuscation (by bit-scrambling) of the input. The first level of the password-recogniser is also composed of NOT gates, with the \( i \)-th gate having input-specifier \( i \mod \min(w, 50) \).

**B. Systems under test**

A BPW execution environment should be set up on a mid-spec smartphone (such as a Samsung Galaxy III S), a mid-spec laptop computer, a mid-spec desktop computer (using its CPU as the function evaluator), and a mid-spec desktop computer using its CUDA-enabled GPU as the function evaluator.

**C. Primary measurements**

The experimenter should measure the runtime and total energy consumption of the function evaluator, exclusive of loading the circuit description into the primary memory of the computing platform. The function evaluator should be coded in three different ways:

1) For ease of programming, with the \( 4w \) bits of evaluation state (\( w \) inputs, \( w \) prior subcircuit outputs, \( w \) current subcircuit outputs, \( w \) copied outputs from a prior subcircuit in a parallel composition) stored in a single machine-addressable array of \( 4w \) bytes or words;
2) For memory latency, with the \( 4w \) bits of evaluation state in a bit-packed array;
3) To avoid CPU and GPU bottlenecks, if the resourcing of the experimental team permits this: BPW programs should be compiled into machine code that is well-optimised for each platform. We expect such compilations to avoid CPU bottlenecks on any platform, except for very small \( w \); whereas the byte-by-byte interpretations of the first two codings may introduce CPU bottlenecks for \( w \) up to 500, and GPU bottlenecks may be unavoidable unless the code is compiled.

**D. Secondary measurements**

The experimenter should collect a timeseries, at 10 msec intervals, of the temperature and cycle rate of the CPU or GPU. These timeseries should be annotated, to indicate the start-time, stop-time, and identity (program type, \( n, w, d \), type of evaluation method) of each BPW evaluation in the experimental sequence. The platform under test should be allowed to cool down to a baseline temperature before starting another evaluation.

**E. Hypotheses under test**

1) On each platform, for both program types, and for each of its available evaluation routines: confirm that the runtime for each \( w \) is linear in \( n \), and is nondecreasing in \( w \), with a factor of about \( 5/500000 = 320 \) separating the runtime curve for \( w = 50 \) from the runtime curve for \( w = 500000 \). Fail to accept the hypothesis if the computed separation in runtime for small and large \( w \) is either less than 32 or greater than 3200, for any platform, circuit type, or evaluation routine.

2) Compute a best-fit value of a speedup ratio \( R \) for each platform, function type, and evaluation type, where \( R \) is the average speedup (over all feasible \( n \)) for the evaluation of a width-50 circuit as compared to the evaluation of a width-500000 circuit. Confirm that the best-fit value for \( R \) is not significantly affected by platform, function, or evaluation method.

3) Compute a ratio of the total energy consumption of each computation to the value \( nw \), this formula being a theoretical prediction of the energy consumption of a memory-limited computation on a computational device that is optimised for energy efficiency \([12]\). Confirm that, for \( w = 500000 \), this ratio (a measure of peta-reference-bytes per watt-hour) is within a factor of 10 across all platforms.

4) If experimental resources permit, perform additional experimentation on larger \( n \) with very large \( w \) to confirm that a power bottleneck is possible i.e. that the CPU or GPU speed has been throttled to avoid overheating. If power bottlenecks are commonly observed within the range of practical interest, then the cost function \( nw \) should be considered as a possible replacement for the proposed \( n\sqrt{w} \).

**V. Summary and Discussion**

We have discussed the promise of indistinguishability obfuscation (iO) as a technique for obfuscating programs, we have proposed a method for estimating the time required to evaluate
an obfuscated function, and we have proposed an experimental method for validating our proposed estimation method.

At the time of writing, iO is a very promising theory that has not yet been reduced to practice. There are no published methods for producing feasibly-computable IO circuits for any functions of practical importance, such as the recognition of a 50-bit password.

Our BPW language is directly comparable to Barrington’s a $w$-BP language [13]. Regrettably, Barrington’s programs do not have easily-predictable performance on real-world computer systems, because their unrestricted references to inputs may result in IO bottlenecks. In Barrington’s circuit-theoretical context, any charge for access to inputs “would lead to a class far too restricted to be interesting” [13].

In a possible variant of BPW (or $w$-BP) which models online computations, an input stream of unbounded length may be presented on a one-way read-only tape. If such IO streams ever become a promising line of theoretical enquiry for functional obfuscation, then a future version of BPW should allow streamed-IO – at some blocksize and latency that has been experimentally determined to be feasibly achievable, on a wide variety of contemporary mass-market computing platforms in typical networking environments.

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Barrington has proved that any language recognised by an NC$^1$ circuit can be recognised by 5-PBP, that is, by a restricted 5-BP in which all of the $w$-maps are permutations. Each instruction in a 5-PBP could be implemented in $3w$ BPW instructions in a computation of declared width $4w$, if the length of the input is bounded by $w$. This construction may be devoid of practical relevance, because of its very restrictive input bound, and because Barrington’s 5-PBP program is exponential in the depth of the NC$^1$ circuit.

We suspect that partial evaluations will be important in many applications of functional obfuscation. This could be handled via the syntax of the call to the functional evaluator, whereby the output of the partial evaluation is a new BPW program which describes an efficiently-computable projection of the original program with a correspondingly-reduced set of inputs.

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