Software Protection and Simulation on Oblivious RAMs

Oded Goldreich* Rafail Ostrovsky†

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Abstract

Software protection is one of the most important issues concerning computer practice. There exist many heuristics and ad-hoc methods for protection, but the problem as a whole has not received the theoretical treatment it deserves. In this paper we provide theoretical treatment of software protection[1]. We reduce the problem of software protection to the problem of efficient simulation on *oblivious* RAM.

A machine is *oblivious* if the sequence in which it accesses memory locations is equivalent for any two inputs with the same running time. For example, an oblivious Turing Machine is one for which the movement of the heads on the tapes is identical for each computation. (Thus, it is independent of the actual input.) *What is the slowdown in the running time of any machine, if it is required to be oblivious?* In 1979 Pippenger and Fischer showed how a two-tape *oblivious* Turing Machine can simulate, on-line, a one-tape Turing Machine, with a logarithmic slowdown in the running time. We show an analogue result for the random-access machine (RAM) model of computation. In particular, we show how to do an on-line simulation of an arbitrary RAM input by a probabilistic *oblivious* RAM with a poly-logarithmic slowdown in the running time. On the other hand, we show that a logarithmic slowdown is a lower bound.

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†University of California at Berkeley Computer Science Division, and International Computer Science Institute at Berkeley. E-mail: rafail@melody.berkeley.edu. Supported by NSF postdoctoral fellowship and ICSI. Part of this work was done at MIT.

[1]This paper unifies and extends abstracts of [G] and [Ost]. Applications of this work are described in U.S. Patent No. 07/395.882.

Contents

1 Introduction

In this paper, we present a theoretic treatment of software protection. In particular, we distill and formulate the key problem of *learning about a program from its execution*, and reduce this problem to the problem of on-line simulation of an arbitrary program on an *oblivious* RAM. We then present our main result: an *efficient* simulation of an arbitrary (RAM) program on a probabilistic *oblivious* RAM. Assuming that one-way functions exits, we show how one can make our software protection scheme *robust* against a polynomial-time adversary who is allowed to alter memory contents during execution in a dynamic fashion. We begin by discussing software protection.

1.1 Software Protection

Software is very expensive to create and very easy to steal. "Software piracy" is a major concern (and a major loss of revenue) to all software-related companies. Software pirates borrow/rent software they need, copy it to their computer and use it without paying anything for it. Thus, the question of *software protection* is one of the most important issues concerning computer practice. The problem is to sell programs that can be executed by the buyer, yet cannot be redistributed by the buyer to other users. Much engineering effort is put into trying to provide the "software protection", but this effort seems to lack theoretical foundations. In particular, there is no crisp definition of what the problems are and what should be considered as a satisfactory solution. In this paper, we provide a theoretic treatment of software protection, by distilling a key problem and solving it efficiently.

Before going any further, we distinguish between two folklore notions: the problem of *protection against illegitimate duplication* and the problem of *protection against redistribution* (or *fingerprinting software*). Loosely speaking, the first problem consists of ensuring that there is no efficient method for creating executable copies of the software; while the second problem consists of ensuring that only the software producer can prove in court that he has designed the program. In this paper we concentrate on the first problem.

1.1.1 The role of hardware

Let us examine various options which any computer-related company has when considering how to protect its software. We claim that a purely software-based solution is impossible. This is so, since any software (no matter how encrypted) is just a binary sequence which a pirate can copy (bit by bit) and run on his own machine. Hence, to protect against duplication, some hardware measures must be used: mere software (which is not physically protected) can always be duplicated. Carried to an extreme, the trivial solution is to rely solely on hardware. That is, to sell physically-protected special-purpose computers for each task. This "solution" has to be rejected as infeasible (in current technology) and contradictory to the paradigm of general purpose machines. We conclude that a real solution to protecting software from duplication should combine feasible software and hardware measures. Of course, the more hardware we must physically protect, the more expensive our solution is. Hence, we must also consider what is the minimal amount of the physically protected hardware we really need.

It has been suggested [Be, K] to protect software against duplication by selling a *physically shielded* Central Processing Unit (CPU) together with an *encrypted* program (hereafter called the *Software-Hardware-package* or the *SH-package*). The SH-package will be installed in a conventional computer system by connecting the shielded CPU to the address and data buses of the system and loading the encrypted program into the memory devices. Once installed and activated, the (shielded) CPU will run the (encrypted) program using the memory, I/O devices and other components of the computer. An instruction cycle of the (shielded) CPU will consist of *fetch*ing the next instruction, *decrypt*ing the instruction (using a cryptographic key stored in the CPU), and *execut*ing the instruction. In case the execution consists of reading from (resp. writing to) a memory location – the contents may be decrypted after reading it (resp. encrypted before writing). It should be stressed that the CPU itself will contain only a small amount of storage space. In particular, the CPU contains a constant number of registers, each capable of specifying memory addresses (i.e., the size of each register is at least equal to the logarithm of the number of storage cells), and a special register with a cryptographic key. We require only the CPU (with a fixed number of registers) to be physically shielded, while all the other components of the computer, including the memory in which the encrypted program and data are stored, need not be shielded. We note that the technology to physically shield (at least to some degree) the CPU (which, in practice, is a single computer *chip*) does already exist – indeed, every ATM bank machine has such a protected chip. Thus, the SH-package employs feasible software and hardware measures [Be, K].

Using encryption to keep the contents of the memory secret is certainly a step in the right direction. However, as we will shortly see, this does not provide the protection one may want. In particular, the *addresses* of the memory cells accessed during the execution are not kept secret. This may reveal to an observer essential properties of the program (e.g. its loop structure), and in some cases may even allow him to easily reconstruct it. Thus, we view the above setting (i.e. the SH-package) as the starting point for the study of software protection, rather than as a satisfactory solution. In fact, we will use this setting as the framework for our investigations, which are concerned with the following key question: *What can the user learn about the SH-package he bought?*

1.1.2 Learning by executing the SH-package

Our setting consists of an encrypted program, a shielded CPU (containing a constant number of registers), a memory module, and an "adversary" user trying to learn about the program. The CPU and memory communicate through a channel in the traditional manner. That is, in response to a $FETCH(i)$ message the memory answers with the contents of the i'th cell; while in response to a $STORE(v,j)$ the memory stores value v in cell j. Our "worst-case" adversary can read and alter the communication between CPU and memory, as well as inspect and modify the contents of the memory. However, the adversary cannot inspect or modify the contents of the CPU's registers.

The adversary tries to learn by conducting *experiments* with the hardware-software configuration. An *experiment* consists of initiating an execution of the (shielded) CPU on the encrypted program and a selected (by the adversary) input, and watching (and possibly modifying) both the memory contents and the communication between CPU and memory.

Given the above setting the question is what information should the adversary be prevented from learning, when conducting such experiments? To motivate the answer to this question, let us consider the following hypothetical scenario. Suppose you are a software producer selling a protected program which took you an enormous effort to write. Your competitor purchases your program, experiments with it widely and learns some partial information about your implementation. Intuitively, if the information he gains, through experimentation with your protected program, simplifies his task of writing a competing software package then the protection scheme has to be considered insecure. Thus, informally, software protection should mean that the task of reconstructing functionally equivalent copies of the SH-package is not easier when given the SH-package than when only given the specification for the package. That is, software protection is secure if whatever any polynomial-time adversary can do when having access to an (encrypted) program running on a shielded CPU, he can also do when having access to a "specification oracle" (such an oracle, on any input, answers with the "corresponding" output and running-time). Essentially, the protected program must behave like a black box which, on any input, "hums" for a while and returns an output such that no information except its I/O behavior and running time can be extracted. Jumping ahead, we note that in order to meet such security standards, not only the values stored in the general-purpose memory must be hidden (e.g., by using encryption), but also the *sequence* in which memory locations are accessed during program execution must be hidden. In fact, if the "memory access pattern" is not hidden then program characteristics such as its "loop structure" may be revealed to the adversary, and such information may be very useful in some cases for simplifying the task of writing a competing program. To prevent this, the memory *access pattern* should be *independent* of the program which is being executed.

Informally, we say that a *CPU defeats experiments with corresponding encrypted programs* if **no** probabilistic polynomial-time adversary can, on input an encrypted program, distinguish the following two cases:

- The adversary is *experimenting with the genuine shielded CPU*, which is trying to execute the encrypted program through the memory.

- The adversary is *experimenting with a fake CPU*. The interactions of the fake CPU with the memory are almost identical to those that the genuine CPU would have had with the memory when executing a (fixed) dummy program (e.g. *while* TRUE *do skip;*) The execution of the dummy program is timed-out by the number of steps of the real program. When timed-out, the fake CPU (magically) writes to the memory the same output that the genuine CPU would have written on the "real" program (and the same input).

We stress that, in the general case, the adversary may modify the communication between CPU and memory (as well as modify the contents of memory cells) in *any* way he wants. When we wish to stress that the SH-package defeats experiments by such adversaries, we say that the SH-package defeats *tampering* experiments. We shall refer to the special case, in which the adversary only inspects the CPU-memory communication and the contents of memory cells, as CH-package defeating *non-tampering* experiments.

1.1.3 An efficient CPU which defeats experiments

The problem of constructing a CPU which defeats experiments is not an easy one. There are two issues: The *first* issue is to hide from the adversary the *values* stored and retrieved from memory, and to prevent the adversary's attempts to change these *values*. This is done by an innovative use of traditional cryptographic techniques (e.g., probabilistic encryption [GM] and message authentication [GGM]). The *second* issue is to hide (from the adversary) the sequence of addresses accessed during the execution (hereafter referred as *hiding the access pattern*).

Hiding the (original) memory access pattern is a completely new problem and traditional cryptographic techniques are not applicable to it. The goal is to make it infeasible for the adversary to learn anything useful about the program from its access pattern. To this end, the CPU will not execute the program in the ordinary manner, but instead will replace each *original* fetch/store cycle by many fetch/store cycles. This will hopefully "confuse" the adversary and prevent him from "learning" the original sequence of memory-accesses (from the actual sequence of memory accesses). Consequently, the adversary can not improve his ability of reconstructing the program.

Nothing comes without a price. What is the price one has to pay for protecting the software? The answer is "speed". The protected program will run slower then the unprotected one. What is the minimal slowdown we can achieve without sacrificing the security of the protection? Informally, *software protection overhead* is defined as the number of steps the protected program makes per each step of the source-code program. In this paper, we show that this overhead is polynomially related to the security parameter. of a one-way function. Namely,

THEOREM A (Informal statement): Suppose that one-way functions exist, and let k be a security parameter. Then there exists an efficient way of transforming programs into pairs consisting of a physically protected CPU, with k bits of internal-("shielded")-memory, and a corresponding "encrypted" program, so that the CPU defeats $\mathrm{poly}(k)$-time experiments with the "encrypted" program. Furthermore, t instructions of the original program are executed using less than $t \cdot k^{O(1)}$ instructions (of the "encrypted" program), and the blowup in the size of the external memory is also bounded by a factor of k. (We stress that this scheme defeats **tampering** experiments.)

The above result is proved by reducing the problem of constructing CPU which defeats (tampering) experiments to the problem of hiding the access pattern, and solving the later problem efficiently. As a matter of fact, we formulate the latter problem as an on-line simulation of arbitrary RAMs by an oblivious RAM (see below).

1.2 Simulations by Oblivious RAMs

A machine is *oblivious* if the sequence in which it accesses memory locations is equivalent for any two inputs with the same running time. For example, an oblivious Turing Machine is one for which the movement of the heads on the tapes is identical for each computation (i.e., is independent of the actual input). We are interested in transformations of arbitrary machines into equivalent oblivious machines (i.e., oblivious machines computing the same

function). For every reasonable model of computation such a transformation does exist. The question is its cost: namely, the slowdown in the running time of the oblivious machine (when compared to the original machine). In 1979 Pippenger and Fischer [PF] showed how a one-tape Turing Machine can be simulated, on-line, by a two-tape *oblivious* Turing Machine, with a logarithmic slowdown in the running time. We study an analogue question for random-access machine (RAM) model of computation.

To see that it is *possible* to completely hide the access pattern consider the following solution: when a variable needs to be accessed, we read and rewrite the contents of *every* memory cell (in some fixed order). If the program terminates after t steps, and the size of memory is m, the above solution runs for $(t \cdot m)$ steps, thus, having a $O(m)$ *overhead*.

If the running time of the original program is smaller then the total memory size then we can do better. Instead of storing data in memory "directly", we build an address-value look-up table of size $\max\{n, t\}$, where n is the length of the input, and scan only this table. Thus, the scheme which we described above does not need to scan the entire memory for each original access — it can scan $O(t + n)$ locations only. (Moreover, the above algorithm need not know what t is. It simply builds a look-up table by adding a new entry for each original step, so that at any time t_i it has $O(t_i)$ entries in it.) Assuming $t > n$, this method runs for $O(t^2)$ steps, and yields an $O(t)$ overhead. Can the same level of "security" be achieved at a more moderate cost?

The answer is **no** if the scheme is deterministic. That is, the simulation is *optimal* if the CPU is *not allowed random moves* (or if obliviousness is interpreted in a deterministic manner). Fortunately, much more efficient simulation exist when allowing CPU to be *probabilistic*[2]. Thus, in defining an oblivious RAM, we interpret obliviousness in a probabilistic manner. Namely, we require that the probability distribution of certain actions (defined over the RAM's input and coin tosses) is independent of the input. Specifically, we define an *oblivious RAM* to be a probabilistic RAM for which the probability distribution of the sequence of (memory) addresses accessed during an execution depends only on the input length (i.e., is *independent* of the particular input.) In other words, the conditional probability for a particular input given a sequence of memory accesses, which occurs during an execution on that input, equals the a-priori probability for that particular input.

The solution of [PF] for making a single-tape Turing Machine oblivious heavily relies on the fact that the movement of the (single-tape Turing Machine) head is very "local" (i.e., immediately after accessing location i, a single-tape Turing-Machine is only able to access locations $i-1, i, i+1$). On the other hand, the main strength of a random-access machine (RAM) model is its ability to instantaneously access arbitrary locations of its memory. Nevertheless, we show an analogue result for the random-access machine model of computation:

THEOREM B (Main Result — Informal statement): Let RAM(m) denote a RAM with m memory locations and access to a random oracle. Then t steps of an arbitrary RAM(m) program can be simulated (on-line) by less than $O(t \cdot (\log_2 t)^3)$ steps of an oblivious RAM($m \cdot (\log_2 m)^2$).

That is, we show how to do an *on-line* simulation of an arbitrary RAM program by an

[2]By *probabilistic CPU* we mean a CPU which has access to a random oracle. Jumping ahead, we note that assuming the existence of one-way functions enables to implement such a random oracle by using only a short random seed, and hence our strong probabilistic machine can be implemented by an ordinary one.

Oblivious RAM incurring only a poly-logarithmic slowdown. We stress that the slowdown is a (poly-logarithmic) function of the program running time, rather than being a (poly-logarithmic) function of the memory size (which is typically much bigger than the program running time).

On the negative side, a simple combinatorial argument shows that any oblivious simulation of arbitrary RAMs should have an average $\Omega(\log t)$ overhead:

THEOREM C (Informal statement): Let RAM(m) be as in Theorem B. Every oblivious simulation of RAM(m) must make at least $\max\{m, (t-1)\cdot\log_2 m\}$ accesses in order to simulate t steps.

So far, we have discussed the issue of oblivious computation in a setting in which the observer is passive. A more challenging setting, motivated by some applications (e.g., software protection as treated in this paper), is one in which the observer (or *adversary*) is actively trying to get information by tampering with (i.e., modifying) the memory locations during computation. Clearly, such an active adversary can drastically affect the computation (e.g., by erasing the entire contents of the memory). Yet, the question is whether even in such a case we can guarantee that the affect of the adversary is oblivious of the input. Informally, we say that the simulation of a RAM on an oblivious RAM is *tamper-proof* if the simulation remains oblivious (i.e. does not reveal anything about the input except its length) even in case when an infinitely-powerful adversary examines and alters memory contents. A tamper-proof simulation means that either the tampered execution (of the oblivious machine) will equal the untempered execution for all the possible inputs of equal length or the tampered execution will be detected as faulty and suspended.

THEOREM D (Informal statement): Let RAM(m) be as in Theorem B. Then t steps of an arbitrary RAM(m) program can be tamper-proof simulated (on-line) by less than $O(t\cdot(\log_2 t)^3)$ steps of an oblivious RAM($m\cdot(\log_2 m)^2$).

We stress that there is no assumptions in the above theorems. In practice, we substitute access to a random oracle by a pseudo-random function, which assuming the existence of one-way functions, can be implemented using a short randomly chosen seed (cf. [BM, Y, ILL, H], and [GGM]). The resulting simulation will be oblivious with respect to adversaries which are restricted to time that is polynomial in the length of the seed.

1.3 Notes concerning the exposition

For simplicity of exposition, we present all the definitions and results, in the rest of the paper, in terms of machines having access to a random oracle. In practice, such machines can be implemented using pseudorandom functions, and the results will remain valid provided that the corresponding adversary is restricted to efficient computations. Detailed comments concerning such implementations will be given in the corresponding sections. Here, we merely recall that pseudorandom functions can be constructed using pseudorandom generators (cf. Goldreich et. al. [GGM]), and that the later can be constructed provided that one-way functions exist (cf. Blum and Micali [BM], Yao [Y], Impagliazzo et. al. [ILL], and Hastad [H]). Specifically, assuming the existence of one-way functions, one can construct a collection of pseudorandom functions with the following properties.

- For every n, the collection contains 2^n functions, each mapping n-bit strings to n-bit strings, and furthermore each function is represented by a unique n-bit long string.
- There exists a polynomial-time and linear-space algorithm that on input a representation of a function f and an admissible argument x, returns $f(x)$.
- No probabilistic polynomial-time machine can, on input 1^n and access to a function $f : \{0,1\}^n \mapsto \{0,1\}^n$, distinguish the following two cases:
  1. The function f is uniformly chosen in the pseudorandom collection (i.e., among the 2^n functions mapping n-bit strings to n-bit strings).
  2. The function f is uniformly chosen among all (2^{n2^n}) functions mapping n-bit strings to n-bit strings.

Another simplifying convention, used in the sequel, is the association of the size of the physically protected work space (internal to the CPU) with the size of the main memory. Specifically, we commonly consider a CPU with $O(k)$ bits of physically protected work space together with a main memory consisting of 2^k words (of size $O(k)$ each). In practice, the gap, between the size of protected work space and unprotected memory, may be smaller (especially since the protected space is used to store "cryptographic keys"). Specifically, we may consider a protected work space of size n and an physically unprotected memory consisting of 2^k words, provided $n \geq k$ (which guarantees that the CPU can hold pointers into the memory). It is easy to extend our treatment to this setting. In particular, all the transformations presented in the sequel do not depend on the size of the CPU (but rather on the size of the memory and on the running time).

2 Model and definitions

2.1 Overview

In this chapter we define the notions discussed in the introduction. To this end, we first present a definition which views the RAM model as a pair of (appropriately resource bounded) *interactive machines*. This definition is presented in subsection 2.2. Using the new way of looking at the RAM model, we define the two notions which are central to this paper: the notion of *software protection* (see subsection 2.3), and simulation by an *oblivious RAM* (see subsection 2.4). Subsections 2.3 and 2.4 can be read independently of each other.

2.2 RAMs as interactive machines

2.2.1 The Basic Model

Our concept of a RAM is the standard one (i.e., as presented in [AHU]). However, we decouple the RAM into two interactive machines, the CPU and the memory module, in order to explicitly discuss the interaction between the two. We begin with a definition of Interactive Turing-Machine (ITM), where the formalization of Interactive Turing-Machines is due to Manuel Blum (private communication), and first appeared in the work of Goldwasser, Micali anr Rackoff [GMR]. We modify it with explicit bounds on the length of "messages" and on the size of work tape.

Definition 1 (INTERACTIVE MACHINES WITH BOUNDED MESSAGES AND BOUNDED WORK SPACE): An **Interactive Turing Machine** is a multi-tape Turing Machine having the following tapes:

- a read-only **input tape**;
- a write-only **output tape**;
- a read-and-write **work tape**;
- a read-only **communication tape**; and
- a write-only **communication tape**.

where by $ITM(c,w)$ we denote a machine as specified above with a work tape of length w, and communication tapes each partitioned into c-bit long **blocks**, which operates as follows. The execution of $ITM(c,w)$ on input y starts with the ITM copying y into the first $|y|$ cells of its work tape. (In case $|y| > |w|$, execution is suspended immediately.) Afterwards, the machine works in **rounds**. At the beginning of each round, the machine reads the next c-bit block from its read-only communication tape. The block is called the **message received** in the current round. After some internal computation (utilizing its work tape), the round is completed with the machine writing c bits (called the **message sent** in the current round) onto its write-only communication tape. The execution of the machine may terminate at some point with the machine copying a prefix of its work tape to its output tape.

Now, we can define both the CPU and the memory as Interactive Turing Machines which "interact" with each other. To this end, we define both the CPU and the MEMORY as ITMs,

and associate the read-only communication tape of the CPU with the write-only communication tape of the MEMORY, and vice versa (cf. [GMR]). In addition, both CPU and MEMORY will have the same message length, however they will have drastically different work tape size and finite control. The MEMORY will have a work tape of size exponential in the message length, whereas the CPU will have a work tape of size linear in the message length. Intuitively, the MEMORY's work tape corresponds to a "memory" module in the ordinary sense; whereas the work tape of the CPU corresponds to a constant number of "registers", each capable of holding a pointer into the MEMORY's work tape. Each message may contain an "address" in the MEMORY's work tape and/or the contents of a CPU "register". The finite control of the MEMORY is unique, representing the traditional responses to the CPU "requests", whereas the finite control of the CPU varies from one CPU to another. Intuitively, different CPUs correspond to different universal machines. Finally, we use k as a parameter determining both the message length and work tape size of both MEMORY and CPU.

Definition 2 (MEMORY): For every $k \in \mathbb{N}$ we define MEM_k is the $ITM(O(k), 2^k O(k))$ operating as hereby specified. It partitions its work tape into 2^k **words**, each of size $O(k)$. After copying its input to its work tape, the machine MEM_k is message driven. Upon receiving a message (i, a, v), where $i \in \{$*"store"*, *"fetch"*, *"halt"*$\}$ (is an *instruction*), $a \in \{0,1\}^k$ (is an *address*) and $v \in \{0,1\}^{O(k)}$ (is a *value*), machine MEM_k acts as follows:

- if $i =$ *"store"* then machine MEM_k copies the value v from the current message into word number a of its work tape.
- if $i =$ *"fetch"* then machine MEM_k sends a message consisting of the current contents of word number a (of its work tape).
- if $i =$ *"halt"* then machine MEM_k copies a prefix of its work tape (until a special symbol) to its output tape, and halts.

The 2^k words of MEMORY correspond to a "virtual memory" consisting of all possible 2^k addresses that can be specified by a k-bit long "register". We remark that the "actual memory" available in hardware may be much smaller (say, have size polynomial in k). Clearly, "actual memory" of size S suffice in application which do not require to store concurrently more than S items.

Definition 3 (CPU): For every $k \in \mathbb{N}$ we define CPU_k is an $ITM(O(k), O(k))$ operating as hereby specified. After copying its input to its work tape, machine CPU_k conducts a computation on its work tape, and sends a message determined by this computation. In subsequent rounds, CPU_k is message driven. Upon receiving a new message, machine CPU_k copies the message to its work tape, and based on its computation on the work tape, sends a message. In case the CPU_k sends a "halt" message, the CPU_k halts immediately (with no output). The number of steps in each computation on the work tape is bounded by a fixed polynomial in k.

The only role of the input to CPU is to trigger its execution with CPU registers initialized, and this input may be ignored in the subsequent treatment. The ("internal") computation of the CPU, in each round, corresponds to elementary register operations. Hence, the number of

steps taken in each such computation is a fixed polynomial in the register length (recall that the register length is $O(k)$) corresponding to the primitive "hardwired" CPU computations. We can now define the RAM model of computation. We define RAM as a family of RAM_k machines for every k:

Definition 4 (RAM): For every $k \in \mathbb{N}$ we define RAM_k is a pair of (CPU_k, MEM_k), where CPU_k's read-only message tape coincides with MEM_k's write-only message tape, and CPU_k's write-only message tape coincides with MEM_k's read-only message tape. The **input** to RAM_k is a pair (s, y), where s is an (initialization) input for CPU_k, and y is input to MEM_k. (Without loss of generality, s may be a fixed "start symbol".) The **output** of RAM_k on input (s, y), denoted $RAM_k(s, y)$, is defined as the output of $MEM_k(y)$ when interacting with $CPU_k(s)$.

To view RAM as a universal machine, we separate the input y to MEM_k into "program" and "data". That is, the input y to the memory is partitioned (by a special symbol) into two parts, called the *program* (denoted by Π) and the *data* (denoted x).

Definition 5 (RUNNING PROGRAMS ON RAM): Given RAM_k, s, y where $y = (\Pi, x)$. We define the **output of program Π on data x**, denoted $\Pi(x)$, as $RAM_k(s, y)$. We define **the running time of Π on x**, denoted $t_\Pi(x)$, as the sum of $|y| + |\Pi(x)|$ and the number of rounds in the computation $RAM_k(s, y)$. We define the **storage-requirement of program Π on data x**, denote $s_\Pi(x)$, as the maximum of $|y|$ and the number of different addresses appearing in messages sent by CPU_k to MEM_k during the computation $RAM_k(s, y)$.

It is easy to see that the above formalization directly corresponds to Random-Access Machine model of computation. Hence, the "execution of Π on x" corresponds to the message exchange rounds in the computation of $RAM_k(\cdot, (\Pi, x))$. The additive term $|y| + |\Pi(x)|$ in $t_\Pi(x)$ account for the time spent in reading the input and writing the output, whereas each message exchange round represent a single cycle in the traditional RAM model. The term $|y|$ in $s_\Pi(x)$ account for the initial space taken by the input, whereas the other term accounts for "memory cells accessed by CPU during the actual computation".

Remark: Without loss of generality, we can assume that the running time, $t(y)$, is always greater than the length of the input (i.e., $|y|$). Under this assumption, we may ignore the "loading time" (represented by $|y| + |\Pi(x)|$), and count only the number of machine cycles in the execution of Π on x (i.e., the number of rounds of message exchange between CPU_k and MEM_k).

Remark: The memory consumption of Π at a particular point during the execution on data x, is defined in the natural manner. Initially the memory consumption equals $|(\Pi, x)|$, and the memory consumption may grow as computation progresses. However, after executing t machine cycles, the memory consumption is bounded by $\max\{t, |(\Pi, x)|\}$.

2.2.2 Augmentations to the Basic Model

Probabilistic RAMs

Probabilistic computations play a central role in this work. In particular, our results are stated for RAMs which are probabilistic in a very strong sense. Namely, the CPU in these

machines has access to a random oracle. We stress that providing RAM with access to a random oracle is more powerful than providing it with ability to toss coins. Intuitively, access to a random oracle allows the CPU to "record" the outcome of its coin tosses "for free"! However, as stated in the introduction, random oracles (functions) can be efficiently implemented by pseudorandom functions (and these can be constructed at the cost of tossing and storing in CPU registers only a small number of coins), provided that one-way function exist.

Remark: Notice that in practice, we utilize input to the CPU to store a seed of a pseudo-random function during initialization.

Definition 6 (ORACLE / PROBABILISTIC CPU): For every $k \in \mathbf{N}$ we define an **oracle-CPU_k** is a CPU_k with two additional tapes, called the **oracle tapes**. One of these tapes is read-only, whereas the other is write-only. Each time the machine enters a special **oracle invocation** state, the contents of the read-only oracle tape is changed *instantaneously* (i.e., in a single step), and the machine passes to another special state. The string written on the write-only oracle tape between two oracle invocations is called the **query** corresponding to the last invocation. We say that this CPU_k has access to the function f if when invoked with query q, the oracle replies by changing the contents of the read-only oracle tape to $f(q)$. A **probabilistic-CPU_k** is an oracle CPU_k with access to a uniformly selected function.

Definition 7 (ORACLE / PROBABILISTIC RAM): For every $k \in \mathbf{N}$ we define an **oracle-RAM_k** is a RAM_k in which CPU_k is replaced by an oracle-CPU_k. We say that this RAM_k has access to the function f if its CPU_k has access to the function f and we write RAM_k^f. A **probabilistic-RAM_k** is a RAM_k in which CPU_k is replaced by a probabilistic-CPU_k. (In other words, a *probabilistic-RAM_k* is a oracle-RAM_k with access to a uniformly selected function.)

Repeated executions of RAMs

For our treatment of software protection, we use repeated execution of the "same" RAM on several inputs. Our intention is that the RAM starts its next execution with the work tapes of both CPU and MEMORY having contents identical to their contents at termination of the previous execution. This is indeed what happens in practice, yet the standard abstract formulation usually ignore this point, which requires cumbersome treatment.

Definition 8 (REPEATED EXECUTIONS OF RAM): For every $k \in \mathbf{N}$, by **repeated executions** of RAM_k, on the inputs sequence $y_1, y_2, ...$, we mean a sequence of computations of RAM_k so that the first computation starts with input y_1 when the work tapes of both CPU_k and MEM_k are empty, and the i^{th} computation starts with input y_i when the work tape of each machine (i.e., CPU_k and MEM_k) contains the same string it has contained at termination of the $i-1^{\text{st}}$ computation.

2.3 Definition of Software Protection

In this section we define software protection. Loosely speaking, a scheme for software protection is a transformation of RAM programs into functionally equivalent programs for a corresponding RAM so that the resulting program-RAM pair "foils adversarial attempts to learn something substantial about the original program (beyond its specifications)". Our formulation of software protection should answer the following questions:

1. *What can the adversary do (in course of its attempts to learn)?*
2. *What is substantial knowledge about a program?*
3. *What is a specification of a program?*

Our approach in answering the above questions is the most pessimistic (and hence conservative) one: among all possible malicious behavior, we consider the most difficult, and most malicious, *worst case* scenario. That is, we assume that the adversary can run the transformed program on the RAM on arbitrary data of its choice, and can modify the messages between the CPU and MEMORY in an arbitrary and adaptive manner[3]. Moreover, since we consider the *worst case* scenario, we interpret the release of *any* information about the original program, which is not implied by its input/output relation and time/space complexity as substantial learning. Clearly, the input/output relation and time/space complexity of the program are not secret (as the software is purchased based an announcement of this information).

2.3.1 Experimenting with a RAM

We consider two types of adversaries. Both can repeatedly initiate RAM on inputs of their choice. The difference between the two types of adversaries is in their ability to modify the CPU-MEMORY communication tapes during these computation (which correspond to interactions of CPU with MEMORY). A *tampering* adversary is allowed, both to read and write to these tapes (i.e., inspect and alter the messages sent in an adaptive fashion), whereas a *non-tampering* adversary is only allowed to read these tapes (i.e., inspect the messages).

Remark: In both cases it is redundant to allow the adversary to have the same access rights to the MEMORY's work tape, since the contents of this tape is totally determined by the initial input and the messages sent by the CPU.

We stress that in both cases the adversary has no access to the internal tapes of the CPU (i.e., the work tape and the oracle tape of the CPU).

For sake of simplicity, we concentrate on adversaries with exponentially bounded running-time. Specifically, the running-time of the adversary is bounded above by 2^n, where n is the size of the CPU's work tape. We note that the time bound on the adversary is used only in order to bound the number of steps taken by the RAM with which ADV experiments. In practice, the adversary will be even more restricted (specifically to working in time polynomial in the length of the CPU's work tape).

[3] Recall that in our model, even worst-case adversary is not allowed to read the internal work tape of the CPU since the CPU models a "physically shielded" CPU (see Introduction).

Definition 9 (A NON-TAMPERING ADVERSARY): A **non-tampering adversary**, (which we denote as ADV), is a probabilistic machine that, on input k (a parameter) and α (an "encrypted program"), is given the following access to an oracle-RAM_k. Machine ADV can initiate repeated execution of RAM_k on inputs of its choice, as long as its total running time is bounded by $2^{O(k)}$. During each of these executions, machine ADV has *read-only access* to the communication tapes between CPU_k and MEM_k.

Definition 10 (A TAMPERING ADVERSARY): A **tampering adversary**, (which we debnote as ADV), is a probabilistic machine that, on input k (a parameter) and α (an "encrypted program"), is given the following access to an oracle-RAM_k. Machine ADV can initiate repeated execution of RAM_k on inputs of its choice, as long as its total running time is bounded by $2^{O(k)}$. During each of these executions, machine ADV has *read and write access* to the communication tapes between CPU_k and MEM_k.

2.3.2 Software protecting transformations

We define transformations on programs (i.e., compilers) which given a program, Π, produce a pair (f, Π_f) so that f is a randomly chosen function and Π_f is an "encrypted program" which corresponds to Π and f. Jumping ahead, we have in mind an oracle-RAM that on input (Π_f, x) and access to oracle f, simulates the execution of Π on data x, so that this simulation "protects" the original program Π. The reader may be annoyed, at this point, of the fact that the transformation produces a random function f which may have an unbounded (or "huge") description. However, in practice, the function f will be pseudorandom [GGM], and will have a succinct description as discussed in the introduction.

We start by defining compilers as transformations of programs into (program,oracle) pairs, which when executed by an oracle-RAM are functionally equivalent to executions of the original programs.

Definition 11 (COMPILER): A **compiler**, (which we denote as C), is a probabilistic mapping that on input an integer parameter k and a program Π, for RAM_k, returns a pair (f, Π_f), so that

- f is a randomly selected Boolean function (i.e., mapping bit-strings into a bit);
- $|\Pi_f| = O(|\Pi|)$.
- For some $k' = k + O(\log k)$ there exists an oracle-$RAM_{k'}$ so that, for every Π, every f and every $x \in \{0,1\}^*$, initiating $RAM_{k'}$ on input (Π_f, x) and access to the oracle f yields output $\Pi(x)$.

The oracle-$RAM_{k'}$ differs from RAM_k in several aspects. Most noticeably, $RAM_{k'}$ has access to an oracle whereas RAM_k does not. It is also clear that $RAM_{k'}$ has a larger memory: $RAM_{k'}$'s memory consists of $2^{k'} = \text{poly}(k) \cdot 2^k$ words, whereas RAM_k's memory consists of 2^k words. In addition, the length of the memory words in the two RAMs may differ (and in fact will differ in the transformations we present), and so may the *internal computations* of the CPU *conducted in each round*. Still, both RAMs have memory words of length linear in the parameter (i.e., k' and k, respectively), and conduct internal CPU computations which are polynomial in this parameter.

Compilers as defined above transform *deterministic* programs into "encrypted programs" which run on probabilistic-RAM (i.e., into "probabilistic programs"). It is worthwhile noting that we can extend the above definition so that compilers can be applied also to programs which make calls to oracles, and in particular to programs which make calls to random oracles. The results in this paper will remain valid for such *probabilistic* programs as well. However, for simplicity of exposition we restrict ourselves to compilers which are applied only to deterministic programs.

We now turn to define software-protecting compilers. Intuitively, a compiler protects software if whatever can be computed after experimenting with the "encrypted program" can be computed, in about the same time, by a machine which merely has access to a specification of the original program. We first define what is meant by access to a specification of a program.

Definition 12 (SPECIFICATION OF PROGRAMS): **A specification oracle for a program** Π is an oracle that on query x returns the triple $(\Pi(x), t_\Pi(x), s_\Pi(x))$.

Recall that $t_\Pi(x)$ and $s_\Pi(x)$ denote the running-time and space requirements of program Π on data x. We are now ready for the main definition concerning software protection. In this definition ADV may be either a tampering or a non-tampering adversary.

Definition 13 (SOFTWARE-PROTECTING AGAINST A SPECIFIC ADVERSARY): Given a compiler (denoted as C) and an adversary (denoted as ADV), we say that the the compiler, C, **protects software against the adversary** ADV if there exists a probabilistic oracle machine (in the standard sense), M, satisfying the following.

- (M operates in about the same time as ADV): There exists a polynomial $p(\cdot)$ so that, for every string α, the running-time of M on input $(k', |\alpha|)$ (and access to an arbitrary oracle) is bounded by $p(k') \cdot T$, where T denotes the running time of ADV when experimenting with $RAM_{k'}$ on input α.
- (M with access to a specification oracle produces output almost identical to the output of ADV after experimenting with the result of the compiler): For every program, Π, the statistical distance between the following two probability distributions is bounded by $2^{-k'}$.

  1. The output distribution of ADV when experimenting with $RAM^f_{k'}$ on input Π_f, where $(f, \Pi_f) \leftarrow C(\Pi)$. By $RAM^f_{k'}$ we mean an interactive $(CPU_{k'}, MEM_{k'})$ pair where $CPU_{k'}$ has access to oracle f. The distribution is over the probability space consisting of all possible choices of the function f, and all possible outcomes of the coin tosses of ADV, with uniform probability distribution.
  2. The output distribution of the oracle machine M on input $(k', O(|\Pi|))$ and access to a specification oracle for Π. The distribution is over the probability space consisting all possible outcomes of the coin tosses of machine M, with uniform probability distribution.

Definition 14 (SOFTWARE-PROTECTING COMPILERS): The compiler, (which we denote as C), **provides (weak) software protection** if C protects software against any non-tampering

adversary. The compiler, C, **provides tamper-proof software protection** if C protects software against any tampering adversary.

Next, we define the cost of software protection. We remind the reader that, for sake of simplicity, we confine ourselves to programs Π with running time, t_Π, satisfying $t_\Pi(x) > |\Pi| + |x|$, for all x.

Definition 15 (OVERHEAD OF COMPILERS): Let C be a compiler, and $g : \mathbb{N} \mapsto \mathbb{N}$ be a function. We say that the **overhead of C is at most g** if for every Π, every $x \in \{0,1\}^*$, and every randomly selected f, the expected running time of $RAM_{k'}$, on input (Π_f, x) and access to the oracle f, is bounded above by $g(T) \cdot T$, where $T = t_\Pi(x)$.

Remark: An alternative definition of the overhead of compilers follows. We say that the *overhead of C is at most g* if for every Π, every $x \in \{0,1\}^*$, and a randomly selected f, the running time of $RAM_{k'}$, on input (Π_f, x) and access to the oracle f, is greater than $g(T) \cdot T$ with probability bounded above by 2^{-T}, where $T = t_\Pi(x)$. The results presented in this paper hold for this definition as well.

2.4 Definition of oblivious RAM and oblivious simulations

The final goal of this section is to define oblivious simulations of RAMs. To this end we first define oblivious RAMs. Loosely speaking, the "memory access pattern" in an oblivious RAM, on each input, depends only on their running time (on this input). We next define what is meant by a simulation of one RAM on another. Finally, we define oblivious simulation as having a "memory access pattern" which depends only on the running time of the original (i.e., "simulated") machine.

2.4.1 Oblivious RAMs

We begin by defining the *access pattern* as the sequence of MEMORY locations which CPU accesses during computation. This definition applies also to an oracle-CPU.

Definition 16 (ACCESS PATTERNS): The **access pattern**, denoted $\mathcal{A}^k(y)$, of a (*deterministic*) RAM_k **on input** y is a sequence $(a_1, \ldots, a_i, \ldots)$, such that for every i, the i^{th} message sent by CPU_k, when interacting with $MEM_k(y)$, is of the form $(\cdot, a_i, \cdot)$. (Similarly, we can define the *access pattern* of an *oracle-*RAM_k on a specific input y and access to a specific function f.)

Considering probabilistic-RAMs, we define a random variable which for every possible function f assigns the access pattern which corresponds to computations in which the RAM has access to this function. Namely,

Definition 17 (ACCESS PATTERN OF A PROBABILISTIC-RAM): The **access pattern**, denoted $\widetilde{\mathcal{A}}^k(y)$, of a **probabilistic-**RAM_k **on input** y is a random variable which assumes the value of the access pattern of RAM_k on a specific input y and access to a uniformly selected function f.

Now, we are ready the define an *oblivious* RAM. We define an *oblivious RAM* to be a probabilistic RAM for which the probability distribution of the sequence of (memory) addresses accessed during an execution depends only on the running time (i.e., is independent of the particular input).

Definition 18 (OBLIVIOUS RAM): For every $k \in \mathbb{N}$ we define an **oblivious** RAM_k is a probabilistic-RAM_k satisfying the following condition. For every two strings, y_1 and y_2, if $|\widetilde{\mathcal{A}}^k(y_1)|$ and $|\widetilde{\mathcal{A}}^k(y_2)|$ are identically distributed then so are $\widetilde{\mathcal{A}}^k(y_1)$ and $\widetilde{\mathcal{A}}^k(y_2)$.

Intuitively, the sequence of memory accesses of an oblivious RAM_k reveals no information about the input (to the RAM_k), beyond the running-time for the input.

2.4.2 Oblivious Simulation

Now, that we have defined both RAM and oblivious RAM, it is left only to specify what is meant by an *oblivious simulation* of an arbitrary RAM program on an oblivious RAM. Our notion of simulation is a minimal one: it only requires that both machines compute the

same function. The RAM simulations presented in the sequel are simulations in a much stronger sense: specifically, they are "on-line". On the other hand, an oblivious simulation of a RAM is *not* merely a simulation by an oblivious RAM. In addition we require that inputs having identical running time on the original RAM, maintain identical running-time on the oblivious RAM (so that the obliviously condition applies to them in a non-vacuous manner). For sake of simplicity, we present only definitions for oblivious simulation of deterministic RAMs.

Definition 19 (OBLIVIOUS SIMULATION OF RAM): Given probabilistic-$RAM'_{k'}$, and RAM_k, we say that a probabilistic-$RAM'_{k'}$, **obliviously simulates** RAM_k if the following conditions hold.

- The probabilistic-$RAM'_{k'}$ simulates RAM_k with probability 1. In other words, for every input y, and every choice of a (oracle) function f, the output of oracle-$RAM'_{k'}$, on input y and access to oracle f, equals the output of RAM_k on input y.
- The probabilistic-$RAM'_{k'}$ is oblivious. *(We stress that we refer here to the access pattern of $RAM'_{k'}$ on fixed input and randomly chosen oracle function.)*
- The expected running-time of probabilistic-$RAM'_{k'}$ (on input y) is determined by the running-time of RAM_k (on input y). *(Here, again, we refer to the behavior of $RAM'_{k'}$ on a fixed input and a randomly chosen oracle function.)*

Hence, the access pattern in an oblivious simulation (which is a random variable defined over the choice of the random oracle) has a distribution depending only on the running-time of the original machine. Namely, let $\widetilde{\mathcal{A}}^{k'}(y)$ denote the access pattern in an oblivious simulation of the computation of RAM_k on input y. Then, $\widetilde{\mathcal{A}}^{k'}(y_1)$ and $\widetilde{\mathcal{A}}^{k'}(y_2)$ are identically distributed if the running time of RAM_k on these inputs is identical.

We note that in order to define oblivious simulations of oracle-RAMs, we have to supply the simulating RAM with two oracles (i.e., one identical to the oracle of the simulated machine and the other being a random oracle). Of course, these two oracles can be incorporating into one, but in any case the formulation will be slightly more cumbersome.

We now turn to define the *overhead* of oblivious simulations.

Definition 20 (OVERHEAD OF OBLIVIOUS SIMULATIONS): Given probabilistic-$RAM'_{k'}$, RAM_k, and suppose that a probabilistic-$RAM'_{k'}$ obliviously simulates the computations of RAM_k, and let $g : \mathbf{N} \mapsto \mathbf{N}$ be a function. We say that the **overhead of the simulation is at most** g if, for every y, the expected running time of $RAM'_{k'}$ on input y is bounded above by $g(T) \cdot T$, where T denotes the running-time of RAM_k on input y.

2.4.3 Time-labeled simulations

Finally, we present a property of some RAM simulations. This property is satisfied by the oblivious simulations we present in the sequel, and is essential to our solution to tamper-proof software-protection[4] (since this solution is reduced to oblivious simulations having

[4] Our solution to the problem of weak software-protection (i.e., protection against non-tampering adversaries) does not rely on this extra property, since it is reduced to ordinary oblivious simulations (as defined above).

this extra property). Loosely speaking, the property requires that whenever retrieving a value from a MEMORY cell, the CPU "knows" how many times the contents of this cell has been updated. Again, we consider only simulation of deterministic RAMs.

Definition 21 (TIME-LABELED SIMULATION OF RAM): Given oracle-$RAM'_{k'}$, RAM_k, and suppose that an oracle-$RAM'_{k'}$, with access to oracle f', simulates the computations of RAM_k. We say that the simulation is **time-labeled** if there exists an $O(k')$-time algorithm $Q(\cdot,\cdot)$ computable as an elementary $CPU'_{k'}$ computation such that the following holds. Let (i,a,v) be the j^{th} message sent by $CPU'_{k'}$ (during REPEATED EXECUTIONS of $RAM'_{k'}$). Then, the number of previous messages of the form $(\texttt{store},a,\cdot)$, sent by $CPU'_{k'}$ is exactly $Q(j,a)$. ($Q(j,a)$ is hereafter referred as the $version(a)$ **number** at round j.)

3 Reducing Software Protection to Oblivious Simulation of RAMs

In this section, we reduce the problem of software protection to the problem of simulation of RAM on Oblivious RAM. Note that the problem of simulation of RAM on Oblivious RAM only deals with the problem of hiding the access pattern, and completely ignores the fact that the memory contents and communication between CPU and memory is accessible to the adversary. To make matters worse, a tampering adversary is not only capable of inspecting the interaction between CPU and memory during the simulation, but is also capable of *modifying* them. We start by reducing the problem of achieving weak software protection (i.e., protection against non-tampering adversaries) to the construction of oblivious RAM simulation. We latter augment our argument so that (tamper-proof) software protection is reduced to the construction of oblivious *time-labeled* simulation.

3.1 Software protection against non-tampering adversaries

Recall that an adversary is called *non-tampering* if all he does is selects inputs, initiates executions of the program on them and reads memory contents and communications between the CPU and the memory in such executions. Without loss of generality, it suffices to consider adversaries which only read the communication tapes (since the contents of memory cells is determined by the input and the communication with the CPU). Using an oblivious simulation of a universal RAM, it only remains to hide the contents of the "value field" in the messages exchanged between CPU and MEMORY. This is done using encryption which in turn is implemented using the random oracle.

Theorem 1 Let $\{RAM_k\}_{k\in\mathbf{N}}$ be a probabilistic RAM which constitutes an oblivious simulation of a universal RAM. Furthermore, suppose that t steps of the original RAM are simulated by less than $t \cdot g(t)$ steps of the oblivious RAM. Then there exists a compiler, that protects software **against non-tampering adversaries**, with overhead at most $O(g(t))$.

Proof: The information available to a non-tampering adversary consists of the messages exchanged between CPU and MEMORY. Recall that messages from CPU_k to MEM_k have the form (i, a, v), where $i \in \{\texttt{fetch}, \texttt{store}, \texttt{halt}\}$, $a \in \{1, 2, ..., 2^k\}$ and $v \in \{0,1\}^{O(k)}$, whereas the messages from MEM_k to CPU_k are of the form $v \in \{0,1\}^{O(k)}$. In an oblivious simulation, by definition, the "address field" (i.e., a) yields no information about the input $y = (\Pi_f, x)$. It is easy to eliminate the possibility that the "instruction field" (i.e., i) yield any information, by modifying the CPU so that it always accesses a memory location by first fetching it and next storing in it (possibly the same but "re-encrypted" value). Hence, all that is left is to "encrypt" the contents of the value field (i.e. v), so that CPU can retrieve the original value. The idea is to implement an encryption, using the oracle available to the CPU. In particular, the "encrypted program" will consist of the original program encrypted in the same manner.

For encryption purposes, CPU_k maintains a special counter, denoted `encount`, initialized to 0. We modify RAM_k by providing it with an additional random oracle, denoted f. (Clearly, the new random oracle can be combined with the random oracle used in the

oblivious simulation[5].) Whenever CPU_k needs to store a value (either an old value which was just read or a new value) into memory MEM_k, the counter `encount` is incremented, and the value v is encrypted by the pair $(v \oplus f(\texttt{encount}), \texttt{encount})$ (where $\oplus$ denotes an "exclusive-or" operation). When retrieving a pair (u, j) the encrypted value is retrieved by computing $u \oplus f(j)$. We stress that both encryption and decryption can be easily computed with access to the oracle f.

Hence, the software protecting compiler, C, operates as follows. On input a parameter k and a program Π, consisting of a sequence of instructions $\pi_1, ..., \pi_n$, the compiler uniformly selects a function f, and sets

$$\Pi_f = (\pi_1 \oplus f(2^k + 1), 2^k + 1), \ldots, (\pi_n \oplus f(2^k + n), 2^k + n)$$

Since the total running time of RAM_k, in all experiments initiated by the adversary, is at most 2^k, we never use the same argument (to f) for two different encryptions. It follows that the encryption (which is via a "one-time pad") is perfectly secure (in the information theoretic sense), and hence the adversary gains no information about the original contents of the value field. ■

We remark that, in practice, one has to substitute the random oracle by a pseudo-random one. Consequently, the result will hold only for adversaries restricted to polynomial-time. Specifically, the compiler on input parameter k and program Π, uniformly select a pseudorandom function f, and the description of f is hard-wired into CPU_k. Hence, CPU_k is able to evaluate f on inputs of length k, and no poly(k)-time adversary can distinguish the behavior of this CPU from the CPU described in the proof of the theorem above. Hence, whatever a poly(k)-time adversary can compute after a non-tampering experiment, can be computed in poly(k)-time with access to only the specification oracle (i.e., the two are indistinguishable in poly(k)-time). A similar remark will apply also to the following theorem.

3.2 Software protection against tampering adversaries

Theorem 2 Let $\{RAM_k\}_{k \in \mathbb{N}}$ be a probabilistic RAM which constitutes an oblivious *time-labeled* simulation of a universal RAM. Furthermore, suppose that t steps of the original RAM are simulated by less than $t \cdot g(t)$ steps of the oblivious RAM. Then there exists a compiler, that protects software **against tampering adversaries**, with overhead at most $O(g(t))$.

Proof: In addition to the ideas used above, we have to prevent the adversary from modifying the contents of the messages exchange between CPU and MEMORY. This is achieved by using authentication. Without loss of generality, we may restrict our attention to adversaries that only alter messages in the MEMORY-to-CPU direction.

Authentication is provided by augmenting the values stored in MEMORY with authentication tags. The authentication tag will depend on the value to be stored, on the actual MEMORY location (in which the value is to be stored), and on the number of previous store instructions to this location. (Hence, the fact that the simulation is time-labeled is crucial to our reduction.) Intuitively, such an authentication tag will prevent the possibility of

[5] E.g., to combine functions f_1 and f_2 define $f(i, x) \stackrel{\text{def}}{=} f_i(x)$.

modifying the value, substituting it by a value stored in a different location, or substituting it by a value which has been stored in the same location (before the current value).

The CPU_k resulting from the above theorem, is hence further modified as follows. The modified CPU_k has access to yet another random function, denoted f. (Again this function can be combined with the other ones.) In case CPU_k needs to store the (encrypted) value v, in MEMORY location a, it first determines the current version number of location a. (Notice that *version*(a) *number* can be computed by the CPU_k according to the definition of time-labeled simulation). The modified CPU_k now sends the message $(\texttt{store}, a, (v, f(a, \textit{version(a)}, v)))$ (instead of the message $(\texttt{store}, a, v)$ sent originally). Upon receiving a message (v, t) from MEMORY, in response to a $(\texttt{fetch}, a, \cdot)$ request, the modified CPU_k determines the current version number, and compares t against $f(a, \textit{version(a)}, v)$. In case the two values are equal, CPU_k proceeds as before. Otherwise, CPU_k halts immediately (and "forever"). Thus, attempts to alter the messages from MEMORY to CPU will be detected with very high probability. ■

4 Towards the solution: the "square root" solution

Recall that the trivial solution to oblivious simulation of RAM is to scan the entire actual RAM_k memory for each virtual memory access. We now describe the first non-trivial oblivious simulation of RAM_k on probabilistic ${RAM'}_{k'}$ in order to develop some intuition about the more efficient solution. We further simplify our problem by assuming that we know, ahead of time, the amount of memory m required by the program (we note that we do not make this additional assumption in the final solution). We show below how to simulate such a RAM by an oblivious RAM of size $m + 2\sqrt{m}$, such that t steps of the original RAM are simulated by approximately $t \cdot \sqrt{m}$ steps of the oblivious RAM.

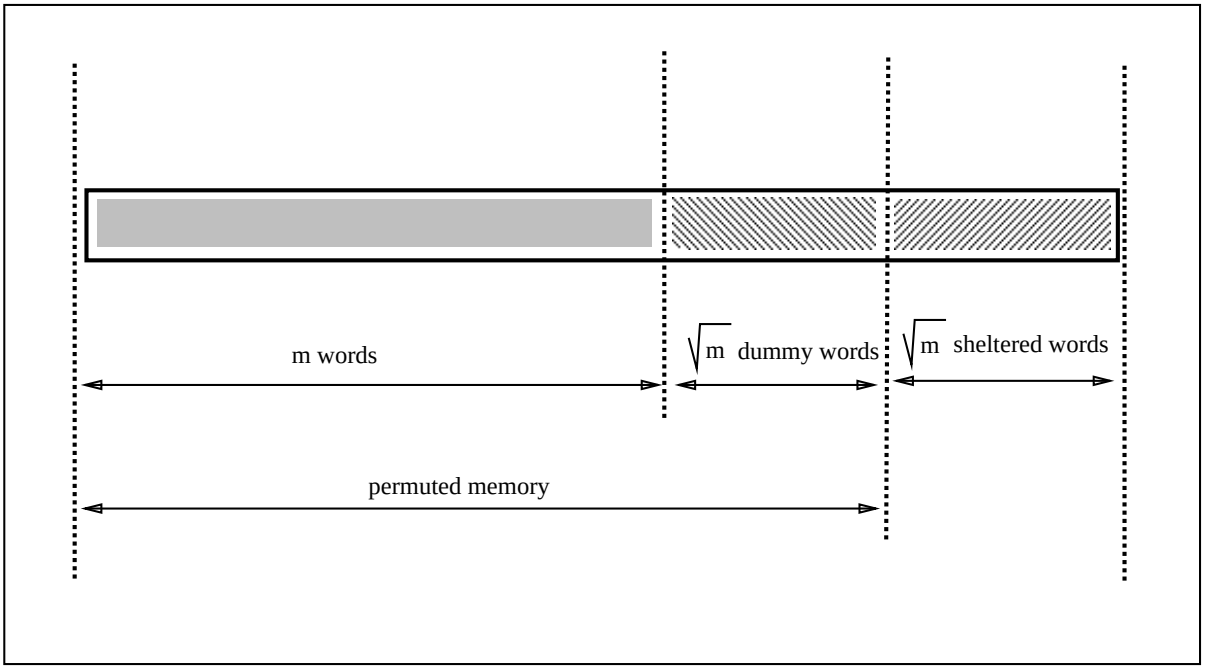
Intuitively, if we completely hide the virtual access pattern, then the following must also be hidden:

(1) *which* virtual locations are accessed, and in what order?

(2) *how many times (if any)* a particular virtual location is accessed?

Informally, to deal with the first problem, it is sufficient to somehow "shuffle" the memory, so that the adversary does not know which actual memory address corresponds to which virtual address. To deal with the second problem, we make sure that any (shuffled) memory location is accessed at most once. The high-level steps of the simulation are as follows:

- Initially, the first m words of the oblivious RAM contain the contents of the words of the original RAM. The other $\sqrt{m}$ words are called "dummy" and the last $\sqrt{m}$ words are called "shelter":



- *while* TRUE *do begin*:

  (1) Randomly permute the contents of locations 1 through $m+\sqrt{m}$. That is, select a permutation π over the integers 1 through $m+\sqrt{m}$ and relocate the contents of word i into word $\pi(i)$ (later, we show how to do this *obliviously*)

  (2) Simulate $\sqrt{m}$ memory accesses of the original RAM. During the simulation we maintain the values previously retrieved (during the current execution of step (2)) in the "sheltered locations" $(m+\sqrt{m}+1)$ through $(m+2\sqrt{m})$ (i.e. locations which are not shuffled, but rather used as a buffer in which we store values once we retrieve them from the permuted memory.) A memory access of the original RAM, say an access to word i, is simulated as follows: first we scan through the "sheltered" $\sqrt{m}$ words and check whether the contents of the original i-th word is in one of these words. If the ith word is not found there then we retrieve it from virtual word tagged by $\pi(i)$; else we access the next "dummy word" (i.e. one of the permuted dummy words $\pi(m+1)$ through $\pi(m+\sqrt{m})$ which was not accessed before).

  (3) Finally, we return the memory contents to their initial locations.

Before getting to the implementation details of the above steps, we provide some hints as to why they constitute an oblivious simulation. We are going to show how to make memory accesses of step (1) fixed and thus independent of the input and the access pattern of the original RAM. The memory accesses executed in step (2) are of two types: scanning through all "sheltered" words from the $m+\sqrt{m}+1$-th to the $m+2\sqrt{m}$-th, and accessing $\sqrt{m}$ locations which seem to the observer (not knowing the permutation employed at step (1)) as being chosen at random among the yet unaccessed words between 1 and $m+\sqrt{m}$ in the "permuted memory". It is easy to see that Step (3) creates no difficulties, as it can be handled by reversing the accesses of steps (1) and (2).

We now turn to details. First, we show how to choose and store a random permutation over $\{1,2,...,t\}$, using $O(\log t)$ storage and a random oracle. The idea is to use the oracle in order to tag the elements with randomly chosen distinct (with high probability) integers from a set of tags, denoted T_t. The permutation is obtained by sorting the elements by their tags. (It suffice to have the tags being drawn at random from the set $T_t = \{1,2,...,t^{\log t}\}$.) Let $f : \{1,2,...,t\} \rightarrow T_t$ be a random function trivially constructed by the random oracle. Then $\pi(i) = k$ if and only if $f(i)$ is the k-th smallest element in $\{f(j) : 1 \leq j \leq t\}$. Now we face the problem of obliviously sorting the t elements (by their tags). The crucial condition is that the RAM which executes the sorting can store only a fix number of values (say 2) at a time. The idea is to "implement" Batcher's Sorting Network [Bat], which allows to sort t elements by $t \cdot \lceil \log_2 t \rceil^2$ comparisons. Each comparison is "implemented" by accessing both corresponding words, reading their contents, and then writing these values back in the desired order. The sequence of memory accesses generated for this purpose is fixed and independent of the input. Note that the oblivious RAM can easily compute at each point which comparison it needs to implement next. This is due to the simple structure of Batcher's network, which is uniform with respect to logarithmic space[6].

[6]The simplicity of Batcher sorting network is the main reason we prefer it (in practice) upon the asymptotically superior Ajtai-Komlos-Szemeredi sorting network [AKS].

Next we specify how to access a virtual location i. Notice that after step (1), the virtual locations 1 through $m + \sqrt{m}$ are sorted according to their tag (i.e. $\pi(\cdot)$). Thus, we must access actual location which contains tag $\pi(i)$ when looking for virtual location i. It is not immediately obvious how to find a location with tag $\pi(i)$ as we do not know its exact address. However, we do know that actual locations are sorted by their tags. Therefore, in order to access actual location with a tag $\pi(i)$ we perform a binary search of actual locations 1 through $m + \sqrt{m}$ searching for location with the tag $\pi(i)$. We claim that the actual location $j \in \{1, \ldots, m + \sqrt{m}\}$ (in which $\pi(i)$ tag is stored), completely specifies the access pattern performed during binary search which stops at location j.

In particular, given actual location j we can specify access pattern done during binary search as follows:

- In each actual memory location $i \in \{1 \ldots m + \sqrt{m}\}$ store as its value its own actual address i.
- Perform binary search, looking for j.

Notice that this simulation has *exactly* the same access pattern as the original binary search. Thus, the accesses done in the binary search does not add any information except j (which is determined by $\pi(i)$).

Next, we describe how to implement step 2 (i.e. obliviously simulate a single access). We remind the reader that the main idea of this simulation is that we access each virtual memory location in the "permuted memory" only once between each permutation step. Once we access some virtual location, we keep track of this virtual location in "sheltered memory" in case we need to access it again. Since "sheltered memory" (which we constantly scan) has only $\sqrt{m}$ capacity, we do permutations with frequency $\sqrt{m}$. Thus, throughout step (2), *count* maintains the number of single accesses simulated in the current run. The variable *count* is initially 0 and is incremented until it reaches $\sqrt{m}$. The boolean variable $found$ will record whether the required value was found in one of the "sheltered" $\sqrt{m}$ words. When the original RAM accesses its i-th virtual word the oblivious RAM proceeds as follows:

(2a) Scans through "sheltered locations" $m + \sqrt{m} + 1$ to $m + 2\sqrt{m}$. If the contents of the original i-th word is in either of these words then the oblivious RAM fetches it, and sets $found \leftarrow 1$, else set $found \leftarrow 0$.

(2b) If $found = 1$ then the oblivious RAM accesses the word with tag $\pi(m + count)$ (which is "dummy"); else the oblivious RAM accesses the word with tag $\pi(i)$, retrieves its contents (which is the desired original word i).

(2c) It scans through "sheltered locations" again and writes the (possibly) updated value of the original i-th word. Increment *count* by 1.

In order to rearrange the memory, we simply do an oblivious sort of all $m + 2\sqrt{m}$ words by the original word location. It should be stressed that only the last accessed word containing the value of an original is considered as bearing this word. (Note that during step (2) we can mark words which no longer contain the last accessed version of an original word.) All other words are considered empty and will be sorted to the last $2\sqrt{m}$ words.

The reader may easily verify that the sequence of memory accesses of the oblivious RAM indeed yields no information about the sequence of memory accesses of the original RAM. It is left to calculate the overhead of the simulation (i.e the ratio of number of accesses done by the oblivious RAM over the number of original accesses). The permutation applied after every $\sqrt{m}$ original accesses causes an overhead of $O(m \cdot \log^2 m)$, which amounts to an amortized overhead of $O(\sqrt{m} \cdot \log^2 m)$ actions per each original access. In addition, each of the original accesses causes $O(\sqrt{m})$ actions to be taken in step (2). Other actions taken in step (3) are negligible in number. The total overhead thus amounts to $O(\sqrt{m} \cdot \log^2 m)$ actions per instruction (actually, the above choice of parameters is not optimal. Repermuting the words after every $O(\sqrt{m} \cdot \log m)$ instructions, yields an overhead of $O(\sqrt{m} \cdot \log m)$ actions per instruction.) Thus, we have shown that there exist an oblivious simulation of m-size RAMs with $O(\sqrt{m} \cdot \log_2 m)$ overhead.

Our next step makes an exponential improvement: we eliminate a $\sqrt{m}$ factor in the simulation and thus reduce overhead from linear to poly-logarithmic. Thus, now that we developed some tools and intuition, we turn to a much more efficient solution.

5 The Hierarchical Solution

First, we state our main theorem, which is proved in this section:

Theorem 3 (MAIN RESULT:) For all $k \in \mathbf{N}$, for any RAM_k and for all y of length $\leq 2^k$, any $t \leq 2^k$ steps of the computation of RAM_k on y can be obliviously simulated by probabilistic-$RAM'_{k+2\log\log k}$ with overhead $O((\log_2 t)^3)$. Furthermore, the simulation is on-line and time-labeled.

5.1 Overview

In this section we give a high-level description of our algorithm together with some intuition. The hierarchical solution presented in this section is a generalization of the solution presented in the previous section. One can view the solution of the previous section as consisting of two parts: the random shuffling and re-shuffling of the memory contents every $\sqrt{m}$ original accesses (steps (1) and (3)), and the simulation of the original accesses through their randomized locations (step (2)). Substeps (2a) and (2c) actually simulates a "powerful" RAM in which the CPU can hold up to $\sqrt{m}$ values in its local registers at any time: The CPU looks whether he already holds the required value in its $\sqrt{m}$ registers (which we call a "buffer"). If the answer is negative then the CPU fetches the value, else it reaches for a "new" empty cell. When trying to generalize the solution, we want to decrease the amortized cost of the random shuffling. The idea, intuitively, is to have buffers of different sizes according to the *frequency* with which they are accessed. That is, we will have a small-size buffer which we frequently access and frequently shuffle. We will have bigger and bigger buffers which are not as frequently accessed and hence will not have to be shuffled as frequently, striking a balance in the (amortized) cost. Hence, our approach, intuitively, is to design a solution using a "powerful" RAM with CPU which can hold *a constant fraction of the original memory*, and then simulate such a RAM by s smaller RAMs in a recursive fashion. Thus, we introduce hierarchy of buffers of different sizes, where essentially we are going to "shuffle" buffers with frequency roughly proportional to their sizes.

For exposition purposes, we again make (another) simplifying assumption about the possible access pattern and first present a solution for this simpler problem.

Remark: At first reading, it will not be clear why we select this particular solution for the simplified problem. The reason, however, will become obvious, once we show how to extend it to the general case.

5.2 The restricted Problem

Suppose somebody guarantees to us that *every* memory location in a contiguous block A of memory of length n is going to be read once and only once (we assume that each memory location $\mathcal{V}_i$ ($\mathcal{V}$ stands for "virtual") in A contains a value $\mathcal{X}_i$. Thus, $A = ((\mathcal{V}_1, \mathcal{X}_1), \ldots, (\mathcal{V}_n, \mathcal{X}_n))$.) In this section we consider the problem of hiding the access pattern into A. That is, we hide the *order* (i.e. the permutation!) in which words in A are examined. Instead of taking a simple approach of the previous section, we introduce a new data-structure, which will

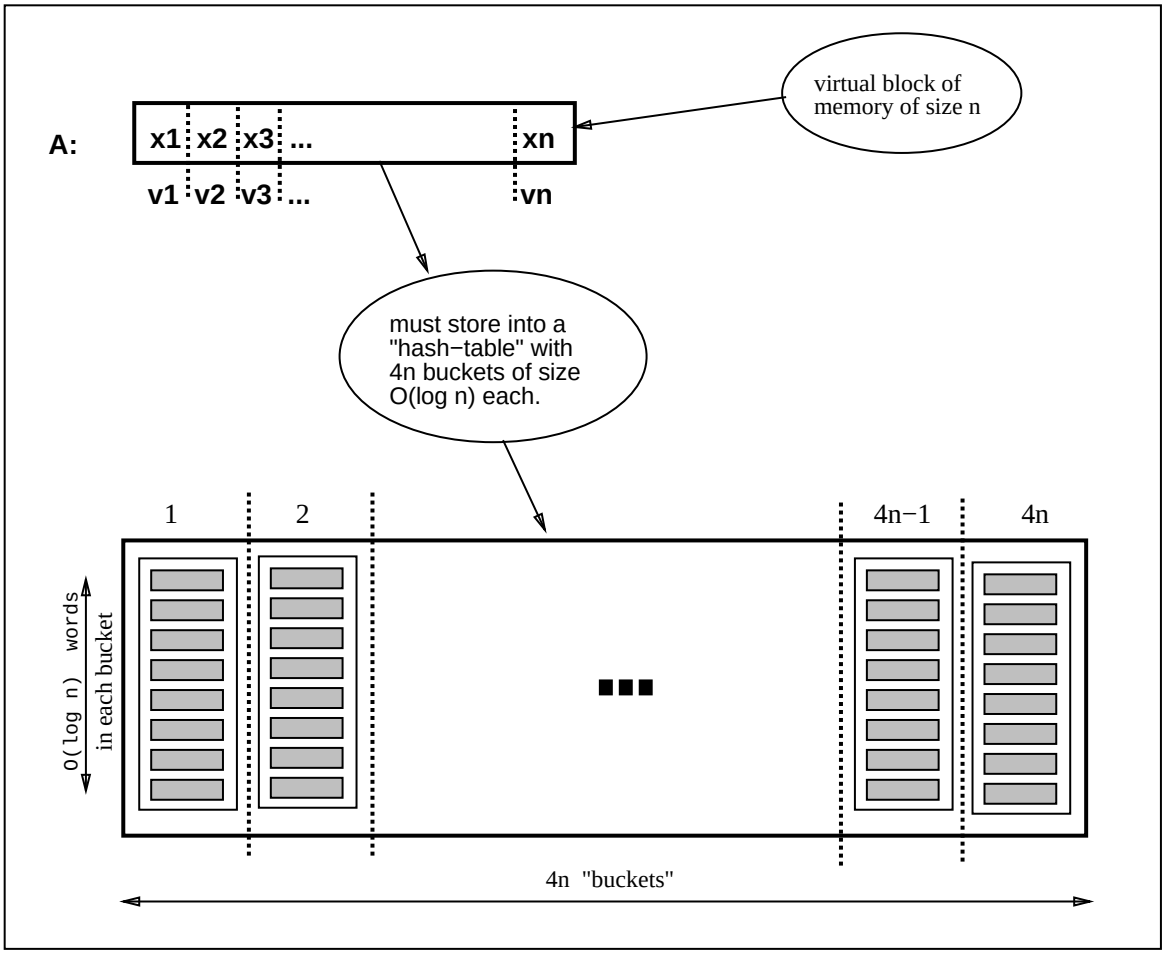


Figure 1: The restricted problem.

be proved useful for our general problem. In particular, instead of just permuting memory contents, we create a hash-table with $4n$ "buckets", where each bucket will contain $O(\log n)$ words (as indicated on the figure of the restricted problem).

We are going to treat the above data structure as a hash-table with keys from 1 to $4n$, where with each key a "bucket" of size $O(logn)$ is allocated. We are going to map virtual memory addresses to keys in the hash table, using the random oracle to compute our hash function. That is, we define our hash function $h(\mathcal{V})$ to be $F(\mathcal{V})$ mod $4n$. (Recall that we denote by $F(i)$ a call to a random oracle on input i.) The pre-processing step works as follows:

(1) Allocate a new block of memory of size $4n \cdot O(\log n)$ words. In this block, we call each consecutive sub-block of size $O(\log n)$ a *bucket*, and we number our buckets from 1 to $4n$.

(2) Pick a random index s. Given s, we define a hash-function $h_s(\cdot)$ to map any address $\mathcal{V}$ in A to an address $h_s(\mathcal{V})$ which we define as $h_s(\mathcal{V}) = F(s \circ \mathcal{V})$ mod $4n$.

(3) ("Oblivious hash"): For i from 1 to n do: obliviously store a pair $(\mathcal{V}_i, \mathcal{X}_i)$. into a bucket $h_s(\mathcal{V}_i)$ (i.e. into the first available word in a bucket $h_s(\mathcal{V}_i)$).

Remark: At this point, we do not describe how step (3) could be implemented *obliviously* and efficiently. We only note that using techniques developed in the previous section, this could be achieved in time $O(n \cdot (\log n)^2)$. We postpone the details of step (3) until after we present our main algorithm. We call (a generalization of) the procedure describe in step (3) an "oblivious hash" according to s.

Remark: Notice that we store n items into a hash table with $4n$ entries according to a random oracle. Hence, the probability that any bucket will overflow (taken over the choice of the randomly chosen function) is negligible.

After the pre-processing step, we can easily hide the access pattern, utilizing the assumption that every virtual memory location $\mathcal{V}$ in A is referenced once and only once. To do so, when looking for a value stored under a virtual address $\mathcal{V}$ we completely scan bucket $h(\mathcal{V})$ looking for a tuple $(\mathcal{V}, \cdot)$. Notice that any two distinct virtual memory locations are assigned independent buckets and every virtual memory location (by our assumption) is accessed at most once. Thus, the (actual memory) access pattern (i.e. bucket-access pattern) is independent of the virtual memory access pattern. Moreover, the probability of an overflow is negligible.

Claim 1 Assume that every element in a block A of memory of length n is accessed once and only once. Then there exists an (off-line) oblivious simulation with $\Theta((\log n)^2)$ overhead.

Remark: We emphasize a crucial point of the above solution: our procedure is allowed to access the same bucket more than once. In fact, it will do so when collisions occur. Notice, however, that the distribution is the same as if we select (for n times) one of the $4n$ buckets uniformly at random and sequentially scan it.

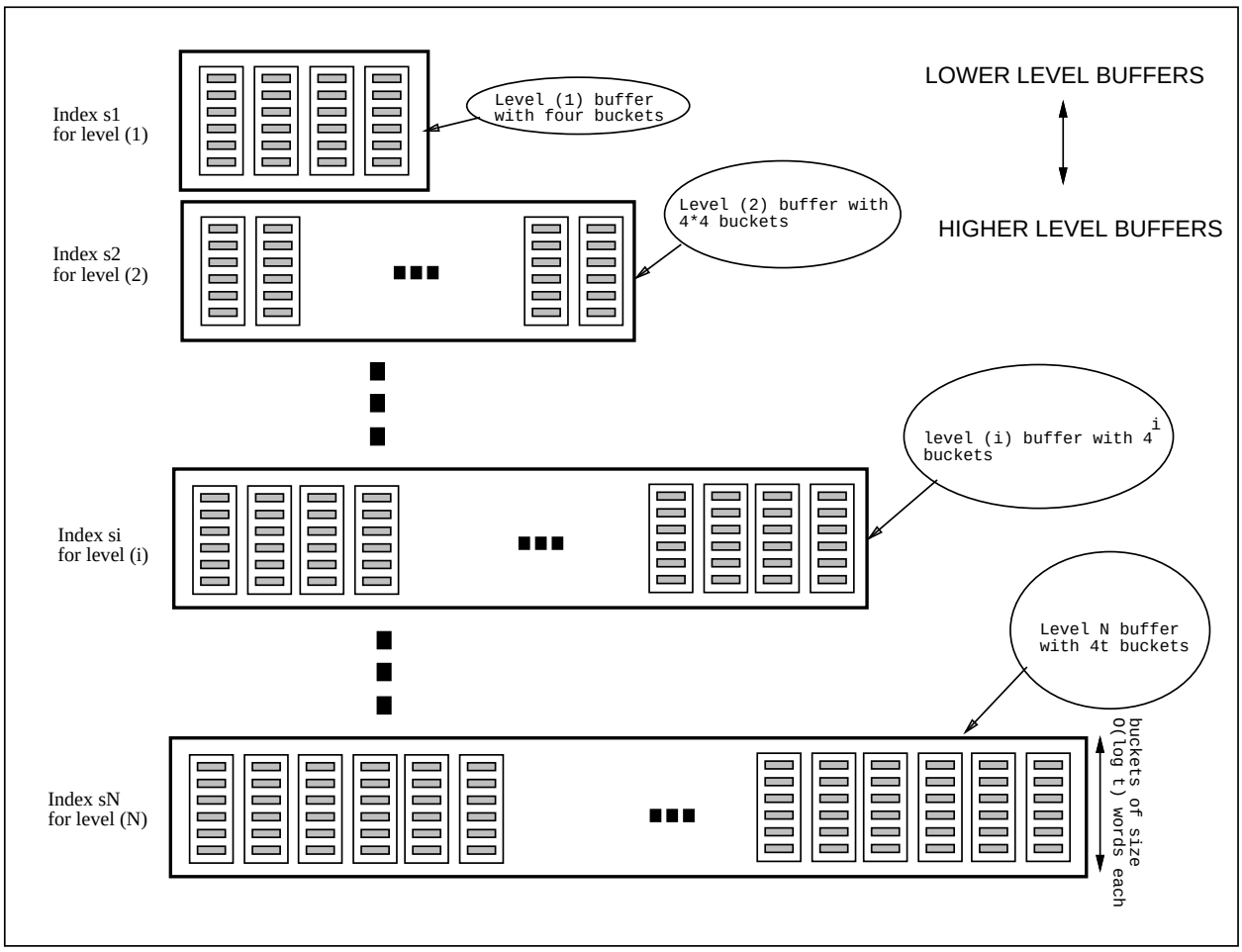


Figure 2: Hierarchical data-structure.

5.3 The algorithm

In this section we show how to hide the access pattern with just *polylog*(t) slowdown in the running time. We waive all the previous restrictions, and allow multiple accesses to the same location and do not rely on the a-priory knowledge of the total (RAM) memory size.

Instead of a single hash-table introduced in the previous section, we use several hash-tables of different sizes. With each hash-table, we associate a different hash-function (i.e. a different *index* s_i. We call this hash-tables "buffers". We number them from 1 to N and refer to the i'th "level" buffer when we talk about buffer number i, $1 \leq i \leq N$ (see "hierarchical data-structure" figure.) We "obliviously hash" contents of buffers at different intervals, according to their sizes (for smaller buffers we do so more often than for bigger ones.) The idea is to ensure that for each buffer, no element in that buffer is accessed more than once in between two consecutive "oblivious hashes", thus reducing the general problem to the simplified problem of the previous section.

Let t be the current length of the access sequence, (i.e., the current running time of

the program which is being simulated). Note that initially, t is equal to input length. We allocate memory for $N = (1 + \lceil \log_4 t \rceil)$ distinct "buffers", where the i'th level buffer, $i = 1, \ldots, N$ is a hash-table of size 4^i buckets, each bucket of size $m = O(\log t)$). (The largest, N'th level buffer will be of size $4t$.) For each buffer of level i, we pick s_i at random and associate a hash-function $h_{s_i}(\cdot)$, where $h_{s_i}(\mathcal{V}) \stackrel{\text{def}}{=} F(s_i \circ \mathcal{V}) \bmod 4^i$. Before we explain what our algorithm does, let us mention how our simulation is going to look to an "adversary": during simulation we will be adding more and more buffers at some predetermined intervals of time. At a very high level, during on-line simulation, for every virtual memory reference, we scan all (four) buckets of level one and for all the other (already created) levels (access and) scan a single bucket, "random" to the adversary.

Initially, all the buffers are empty. In the beginning of the simulation we store (i.e. "obliviously hash") the program and the input into the biggest, N'th level buffer according to the value of s_N and answers of the random oracle.) During on-line simulation, when we need to access virtual memory reference $\mathcal{V}$, we first completely scan the level (1) buffer, looking for it. If we have not found $(\mathcal{V}, \mathcal{X})$ at level (1), then we scan bucket $h_{s_2}(\mathcal{V})$ of level (2). If we have not found it there, we scan $h_{s_3}(\mathcal{V})$ if level (3), etc. Say we find the virtual memory reference we been looking for at some level (j), then for all the higher (i.e., bigger) levels, we access and scan a randomly chosen bucket. At the end, we store the found virtual "address-value" pair $(\mathcal{V}, \mathcal{X})$ at the level (1) buffer. (We stress that we store in the level (1) buffer only the "address-value" pair we been looking for, and not the entire bucket in which we have found it.)

In summary, here is how the value of the virtual location $\mathcal{V}$ is retrieved:

- Set boolean variable *found* to *false* and change it to "true" only when contents of virtual location $\mathcal{V}$ is found, as specified below.

(1) Sequentially scan the level (1) buffer, looking for $(\mathcal{V}, \mathcal{X})$; (we remark that once found, the CPU keeps $(\mathcal{V}, \mathcal{X})$ pair in its work tape (i.e. in its registers) until step (3) below.)

(2) For i from 2 to n do:

  - Retrieve the i'th level index s_i (of the current hash function associated with buffer level (i)) and compute $h_{s_i}(\mathcal{V})$.
  - IF virtual location $\mathcal{V}$ has already been found THEN access a "random" location. Namely, pick a random integer r between 1 and 4^i and scan bucket r.
  - ELSE scan bucket number $h_{s_i}(\mathcal{V})$, looking for a tuple $(\mathcal{V}, \mathcal{X})$. If found, set *found* to true, and copy $(\mathcal{V}, \mathcal{X})$ onto CPU work tape. (We remark that we scan entire bucket even if we already found the tuple, and for each element of the bucket, we perform an access pattern as if we copy it into CPU work tape)

(3) Copy $(\mathcal{V}, \mathcal{X})$ from CPU work tape into the first empty bucket of the level (1) buffer.

Note that in the above description, the data is is always "moved up" to the level (1) buffer. Thus, after four accesses, the level (1) buffer may become full. To avoid potential

"overflow" we must "move" contents of the first level buffer to the second level buffer. Then (at longer intervals) we must move contents of the second level buffer to the third level buffer, etc. When we "move" contents of buffer level (i) to buffer level $(i+1)$, (every 4^{i-1} retrieves) we "obliviously hash" the contents of buffer level i and the contents of buffer level $i+1$ to the buffer $i+1$ according to a new, randomly chosen index s'_{i+1}. Thus, every time when a buffer at level (i) is at most quarter-full (i.e. has the number of stored virtual memory references equal to at most a quarter of the number of the buckets) we empty it into the higher level. If the higher level does not yet exists, we allocate it.

Remark: Notice that at round 4^i, the total number of entries in the first i buffers is at most 4^i, and hence merging their contents into the i'st buffer (of size 4^{i+1} buckets) can have only a quarter (of the total number of buckets) of the entries!

Remark: Note that when we move contents of lower level buffer into the larger buffer, we pick a new hash-function and put into the bigger buffer the content of the smaller buffer and the contents of the bigger buffer according to this new hash function. Thus, the collisions which occurred in the smaller buffer do not influence collisions which may occur in the bigger buffer. That is, collisions do not *accumulate*.

Remark: Note that we do not need to know a-priori the length of the request sequence. Instead, we do an adaptive simulation, starting with twice the size of the input and adding more memory "as needed", (but obliviously of the real access.) That is, after t steps we use $O(t \cdot (\log t)^2)$ memory. Notice that this *does not* reveal the rate at which the memory is actually used up by the program.

5.4 Obliviousness of Access Pattern

From our examination of the restricted problem, we know that as long as we look for any memory reference at most once, the choice of the hash-bucket accessed appears completely random to the adversary. Notice that there may be "collisions" (i.e. we scan the same bucket more the once), but since different memory locations are assigned independent buckets, the choice of a bucket (for an unaccessed-before memory reference) appears random to the adversary.

The crucial observation is that for all the buffers (except for (1)), we never look for the same virtual memory $\mathcal{V}$ more then once (in the same level) in between hashing stages of that buffer. This is so, since once we have found a tuple containing $\mathcal{V}$, we move it into the first level buffer, and due to the order in which we access buffers, we will find it in a smaller-level buffer unless it has already "migrated" to the same level. However, every time something is migrated to a same level, this level is hashed according to a new, randomly selected hash-function. Thus, for all buffers $i \geq 2$ and any $\mathcal{V}$, whenever we pick a new s_i, we compute $h_{s_i}(\mathcal{V})$ at most once. Thus, we can now utilize our study of the restricted problem: for every level at which we find $\mathcal{V}$, the (position of) bucket in which we have found $\mathcal{V}$ appears completely random to the adversary.

Suppose we found $(\mathcal{V}, \mathcal{X})$ at some buffer level (j). What we have just shown is that the bucket $h_{s_j}(\mathcal{V})$ scanned at level (j) appears random to the adversary. Next, we argue that

for all the buffers smaller then (j), and for all the buffers bigger then (j), the choice of the buckets which is scanned appears random to the adversary as well. (Note that if this is the case, the adversary has no information as to which buffer level the virtual memory reference has been found on.)

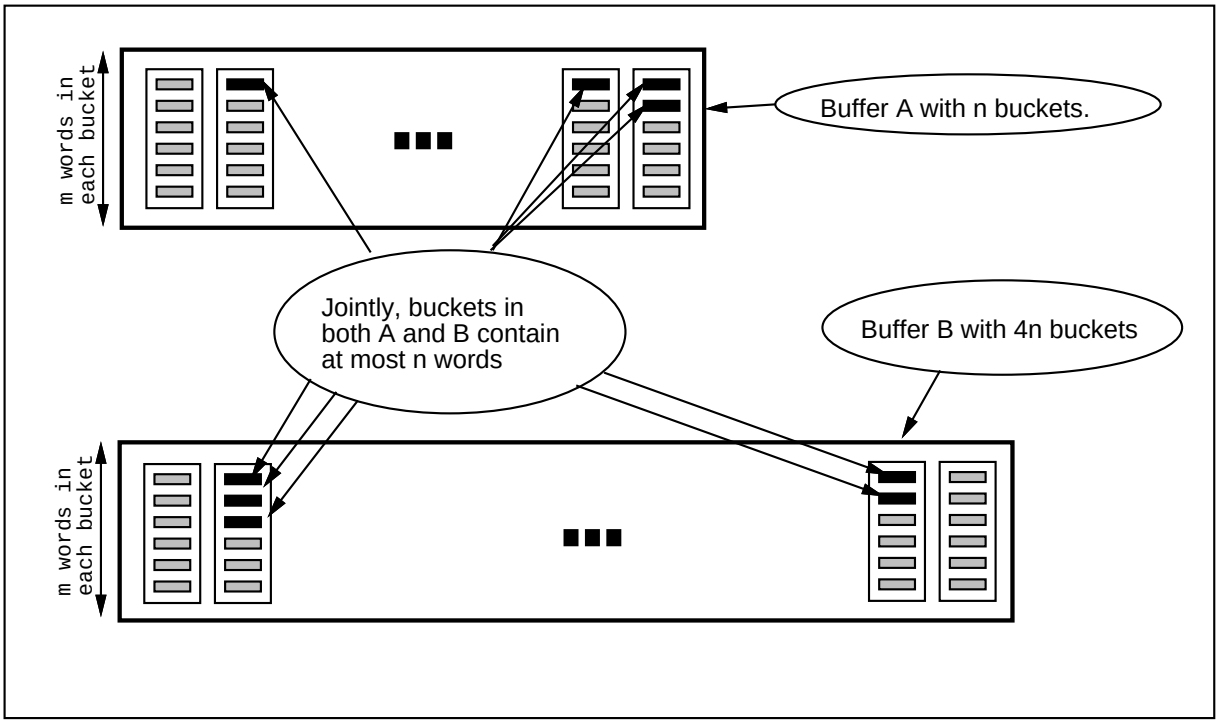
Suppose we found $\mathcal{V}$ at level (j). First, we wish to show that for all the smaller (than j) level buffers, the accessed bucket appears to the adversary to be uniformly distributed. Note that due to the order in which we examine buffers, the bucket number is computed by applying a random function to a key which has not been accessed before at this level (otherwise, we would have found it at some smaller level!) Thus, it is equivalent to applying a random function with a new (unused before) argument in order to decide which bucket to scan. Thus, it appears random to the adversary.

Moreover, for all the bigger-level buffers, we always select the bucket number to scan at random. Hence, as far as adversary is concerned, we scan a random bucket on all the levels, and completely scan the level (1) bucket. Thus, provided that we can perform oblivious hashing, then for any simulated access pattern, the distribution of accessed buckets is the same, making the access pattern *oblivious*.

5.5 How to perform the oblivious hash

In this sub-section we give details of how to perform oblivious hash, which we used all-along.

Recall that in out algorithm, the data is is always "moved up" to the level (1) buffer. Thus, after four accesses, the level (1) buffer may become full. To avoid potential "overflow" we must "move" contents of the first level buffer to the second level buffer. Then (at longer intervals) we must move contents of the second level buffer to the third level buffer, etc. When we "move" contents of buffer level (i) to buffer level $(i+1)$, (every 4^{i-1} retrieves) we "obliviously hash" the contents of buffer level i and the contents of buffer level $i+1$ to the buffer $i+1$ according to a new, randomly chosen index s'_{i+1}. Thus, every time when a buffer at level (i) is at most quarter-full (i.e. has the number of stored virtual memory references equal to at most a quarter of the number of the buckets) we empty it into the higher level. If this potentially makes the next level more then quarter full, we empty it into a bigger buffer as well. Notice that at round 4^i, the total number of entries in the first i buffers is at most 4^i, and hence merging their contents into the i'st buffer (of size 4^{i+1} buckets) can have only a quarter (of the total number of buckets) of the entries! Thus, problem is always as follows: we have 2 hash-tables, A and B. A has n buckets, while B has $4n$ buckets, each bucket has size m words. Jointly, both A and B contain not more then n entries, where each (non-empty) entry is a pair $(\mathcal{V}_i, \mathcal{X}_i)$:



Our goal is to efficiently and obliviously transfer all such pairs into B, using a new random hash-function h', so that all non-empty entries $(\mathcal{V}_i, \mathcal{X}_i)$ from both A or B end up in buckets $h'(\mathcal{V}_i)$.

The requirement of making this transfer oblivious demands access pattern of our algorithm to be independent (among all other things) of the number of entries in each (old or new) bucket. In particular, the issue is the following. What we know is to obliviously sort

n distinct elements into n cell, whereas what we need to do now is obliviously hash n not necessarily distinct elements into n cells. Furthermore, the elements will be independently and uniformly assign a cell number and they should be obliviously put in the cell. Note that it is expected that a constant fraction of the cells are assigned no element, a constant fraction are assigned one element, a (smaller) constant fraction are assigned two elements, and it is likely that there is a cell assigned $\log_2 n$ elements. The hashing should be performed so that, in particular, the number of elements in each target cell is kept secret.

Recall that in the "square root" solution we assigned "tags" to element and then sorted according to these "tags". Here, the "tag" indicates the specific bucket in which the the elements (i.e. virtual words) must be put. Notice that we want to place up to n words into designated random $4n$ buckets (of B), where each word is assigned a destination "tag" which corresponds to the bucket number into which this word must be obliviously put. This can not be obtained by just obliviously sorting these words by their tags since the words do not necessarily get unique tags (and in fact, with high probability collisions **do** occur, as indicated above.) Notice that if the tags were indeed unique then there would be no issue, as we could of just applied the approach developed in out "square root" solution for the case of the permutation. That is, while sorting (obliviously) we already know how to achieve (i.e, in the square-root solution), it is not clear that the ability to obliviously sort will allow us to *obliviously* put elements in the right buckets (instead of just sorting them). Thus, the approach of the "square root" solution does not work here directly.

The problem, intuitively, is that even after the valid entries are sorted by their new keys, it is not clear how they can be efficiently and obliviously put into their appropriate buckets. Thus, what we wish to do is to first somehow initialize all the *buckets* to have the correct contents, and then obliviously put these buckets into the right position. In fact, one of the things we are going to do is to first sort valid entries by their new keys. Notice that since collisions do occur, there will be many entries with the same key. Next, we must put this entries in the appropriate buckets. The way we are going to achieve this is to use many applications of "oblivious sorting" using different "granularity" of elements which we are sorted — the idea, in essence, is to reduce the above problem to the already known case of obliviously sorting a permutation. In particular, we are going to to use "oblivious sorting" for the following purposes:

(a) *sorting elements within a bucket:* we mark all the "empty" entries as zero and all the "full" entries as one and then perform an oblivious sorting. As a result, all the "empty" and "full" entries are grouped together.

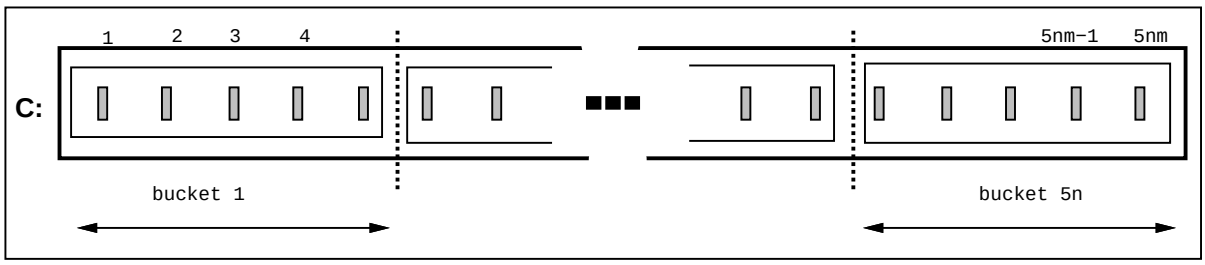
(b) *sorting elements within two buckets:* Again, the idea is to mark all the empty elements in both buckets as zero and all the non-empty elements as one and then obliviously sort. Since we are going to be guaranteed (with high probability) that the number of non-empty entries will be less then the size of a bucket, we essentially manage to "move" all the non-empty entries into one of the buckets, while keeping access pattern completely oblivious.

(c) *sorting buckets as individual elements:* we can now put buckets (as individual elements) according to their numbering, provided that all buckets are represented.

In order to make sure that we are dealing with all the buckets, (i.e. that we are dealing

with the *permutation*), we introduce a "dummy" entry for each bucket. This way, we are guaranteed that there is at least one item that we must put into each bucket. Then we sort all the entries by their keys. Then we put the designated words (and "dummy" entries) into buckets according to their tags (step 5) using oblivious sorting (sorting two buckets at a time as in (b)) and then put buckets into their appropriate places obliviously sorting then as in in (c) above and then just copying them into B in the open (as it does not release any information as this point). Now we turn to a detailed description. The steps of oblivious hash algorithm are as follows:

1. Create a new hash-table C, of size $5n$ buckets, and copy contents of A and B into C, bucket by bucket (i.e. treating each bucket as indivisible block of memory of size m words.)

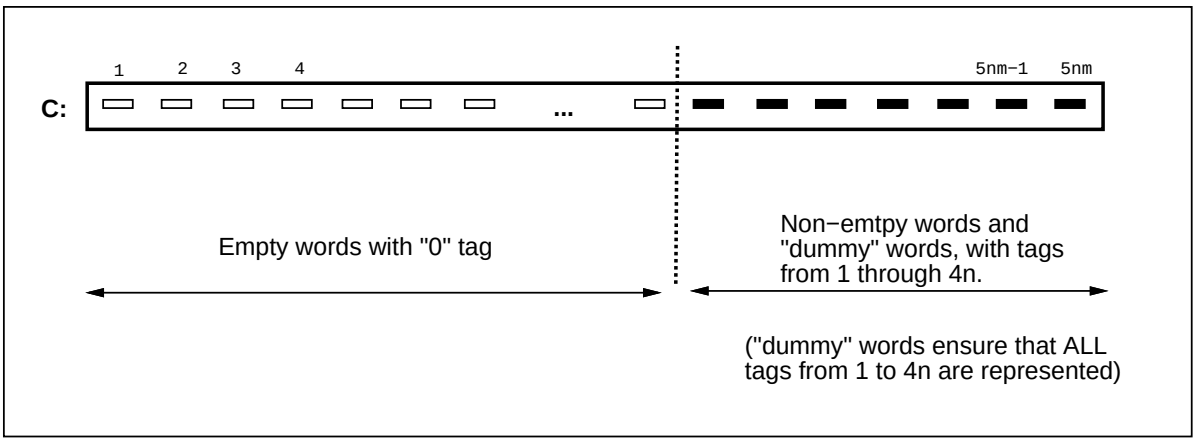


Remark: the intuition here is that we put all the data from A and B to a "temporary" bucket C, in which we "garbage-collect" all the empty words in an oblivious manner. In order to do so, we essentially "mark" all the empty words with "0", all the non-empty words with positive numbers and then perform an oblivious sort. In step 2 below, we do essentially this, and (at the same time) pre-compute hash-values (which are in random from 1 to $4n$) of all the non-empty words.

Remark: We must hide (among other things) which buckets will contain (one or more) elements, and which buckets will remain empty. To make sure that this information is not revealed, we store at least one element into *each* bucket. In order to do so, we, introduce an additional "dummy" entry for each bucket.

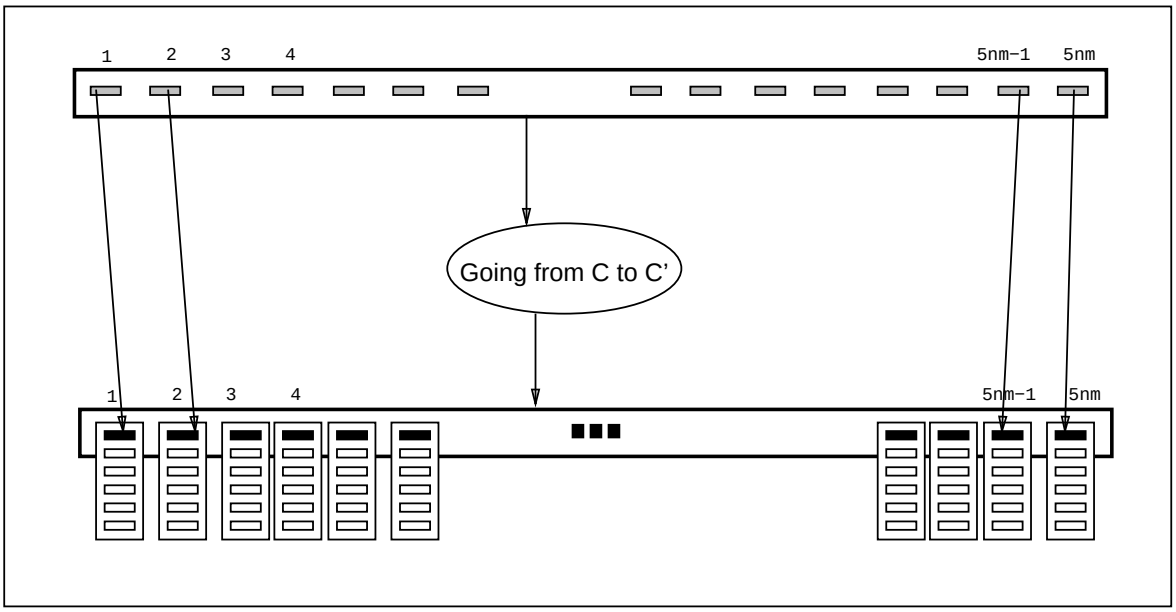
2. Scan each bucket of C and for each non-empty word, assign a "tag" corresponding to the new hash-function h'. In addition, for each i from 1 to $4n$ add a "dummy" virtual-address entry with "tag" i, while scanning C. (Since C has $5mn$ word size, there is always sufficient space to add "dummy" tags). While scanning, mark all the remaining "empty" words with "0 tag".

3. Sort C at a word level (i.e. treating C as a single-dimensional array which contains $5nm$ words to be sorted.) The data in C now looks as follows:



Remark: At this point, in array "C" contains all the entries sorted by their tags. Each tag corresponds to a final destination of a bucket into which this element must be stored. In addition, there are "dummy" entries for each bucket as explained above. Our next goal is to somehow accumulate all the elements with the same "tag" into a single "bucket" (steps 4 and 5) and then put these buckets into their appropriate positions (steps 6 and 7).

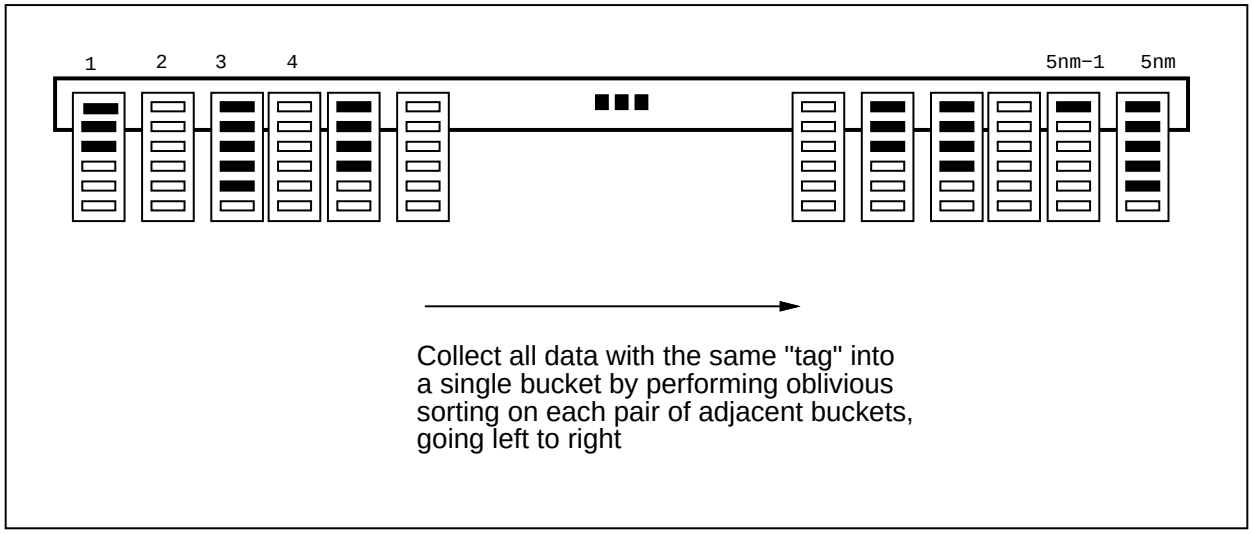
4. Allocate C' which has the same number of *buckets* as there are words in C (i.e. $5mn$ buckets.). Copy each word of C into a new top-most word of each bucket of C'.



Remark: At step 4 we created a correct data-structure to accumulate all the entries with the same "tag" into a single bucket of C', which we can now do in step 5 as follows:

5. Scan C' buckets left to right, performing oblivious sort between words of every two adjacent buckets, and in the process, "accumulating" all the data with the same "tag"

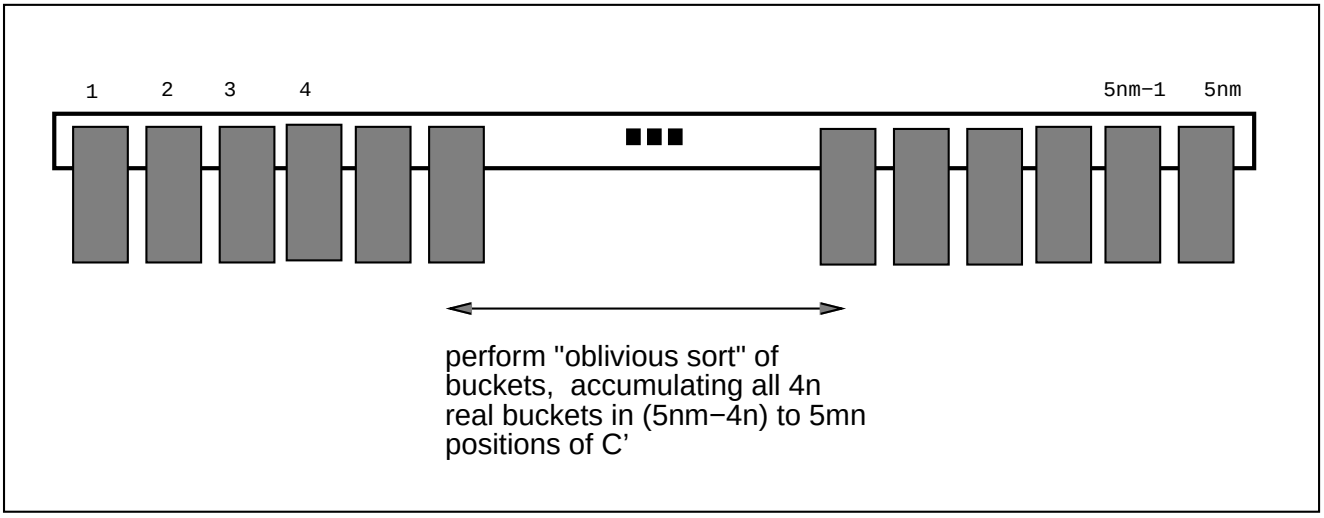
into unique buckets of C' (Note that due to "dummy" entries, all "tags" from 1 to $4n$ are represented.) That is for every two pair of buckets, if they contain different tags, execute oblivious hash but do nothing. If they have the same tags, treat all non-empty entries as 1's and all empty entries as zeros as perform oblivious hash. This way, all the empty entries are left in the first bucket, while all the non-empty entries are moved to the next bucket, as explained in step (c) above.



Remark: Notice that step 5 is the key to our solution, as we now have all the "buckets" represented, and hence, we are back to an already solved problem of obliviously re-arranging the permutation of the buckets as single entities.

Remark: After executing step 5 we know that there are exactly $4n$ non-empty buckets, thanks to our "dummy" entries. Now, the only remaining task is to put this buckets into the right positions into B. This is achieved in steps 7 and 8 in a straightforward manner:

6. Perform oblivious sort of C' buckets (i.e, now treating each bucket of C' as an indivisible unit.) and treating all the "empty" buckets (i.e. those without even one entry) as "-1". Notice that as a result, all the non-empty buckets are accumulated in the last $4n$ positions of C'.



7. Scan the last 4n positions of C' left to right, and put each good "bucket" (i.e. with "tags" from 1 to $4n$ into the correct place in B. Now scan B and eliminate "dummy" entries.

Remark: We note that the point of creating dummy entries is to prevent the adversary from learning how many buckets in B are non-empty. It should be clear from the above description, that the oblivious hash procedure is both oblivious and achieves its desired goal. Moreover, taking $m = O(\log n)$ the running time of the above procedure is $O(n \cdot (\log n)^2)$.

5.6 Cost

Recall that there are $N = O(\log t)$ buffers. For every step in the original sequence s_t we scan all the buckets of the level (1) buffer and then scan a single bucket of size $O(\log t)$ on every other level, getting $O((\log t)^2)$ actual accesses for each virtual access. In addition, during on-line simulation of s_t we hash the level (i) and level $(i-1)$ buffers into the level (i) buffer a total of 4^{n-i+1} times, $i = 2, \ldots n$. Since the joint size of the level $(i-1)$ and level (i) buffers is $O(4^i)$ buckets of size $O(\log t)$, it takes $O(4^i \cdot \log t \cdot \log(4^i \cdot m))$ steps to obliviously hash them. Thus, the total number of steps we have to perform for all the hashing of all the buffers is equal to:

$$\sum_{i=2}^{N} 4^{n-i+1} \cdot 4^i \cdot \log t \cdot \log(4^i \cdot \log t) \;=\; O\left(t \cdot (\log t)^3\right)$$

Therefore, we have an amortized poly-logarithmic (i.e. $O((\log t)^3)$) overhead of hiding the access pattern (with a negligible probability of an overflow.)

Remark: Our negligible probability of error can be substituted to expected (polylog) running time by requiring the running time to be an expected polylog overhead, and hashing whenever overflow occurs.

Remark: Notice that there is a trade-off between the size of the CPU and the overhead of the simulation. That is, given more ("protected" from the adversary) memory in the CPU, we can always speed-up our simulation.

5.7 Making hierarchical simulation time-labeled

Recall that we need to make our simulation *time-labeled* in order to prevent an adversary from substituting values previously stored in the *same* actual location. Before we present our solution we make a crucial observation:

Lemma 1 During our (hierarchical) simulation, for all buffers of levels bigger then one we do not change the contents of these buffers except by oblivious hashing.

Proof: Notice that we do not have to modify the bucket when we scan it. Modifications happen only during re-hashing (and on buffer level (1)). Recall that this is possible since whenever we wish to "change" some location, we always move it to the first level buffer, and hence, can change it there. Hence, we do not "touch" the bucket where we have found it. ∎

Due to the above lemma, our simulation is trivially time-labeled, as we touch each level with a fixed frequency which depends only on the size of that level and total elapsed time of the simulation. This completes the proof of theorem 3.

5.8 Software protection

We can now combine theorem 3 and 2 to establish that:

Theorem 4 SOFTWARE PROTECTION (information-theoretic case): There exists a software-protecting compiler C such that for any *probabilistic-RAM* C protects software against tampering adversaries with overhead $O((\log_2)^3)$.

The above theorem holds in the information-theoretic sense on a *probabilistic-RAM* (which uses a random oracle.) As noted in the introduction, instead of random oracle we can use pseudo-random functions [GGM], and state a practical analogue of the above theorem. That is, assuming the existence of a strong one-way function, the above algorithm can be implemented in practice using $O(t \cdot (\log_2 t)^3 \cdot k^c)$ steps. However, the *security parameter* k implies that 2^k is infeasible. Hence, in practice, $(t) << 2^k$, and $(\log_2 t)^3 < k^c$ for $c \geq 3$. Thus, we can state a practical analogue of theorem 4 as follows:

Theorem 5 SOFTWARE PROTECTION (polynomial case): Suppose one-way functions exist, with k a security parameter of a strong one-way function. Then there exists a software-protecting compiler C secure against *all* polynomial-time adversaries with compilation overhead $k^{O(1)}$.

Proof : Analogous to the information-theoretic case, but substituting random oracle by a pseudo-random one. ∎

6 A lower bound

Theorem 6 Every oblivious simulation of RAM on input y by probabilistic-RAM must make at least $(\max\{|y|, \Omega(t \cdot \log t)\}$ accesses in order to simulate t steps.

Proof : The task of simulating RAM on an oblivious RAM can be modeled by the following game between three players:

- the CPU *player* who can hold at one time at most c "balls" and has access to random function f.
- the *program request sequence*: $(r_1, \ldots, r_t)$ of length t.
- an *observer*.

The *player* is allowed at any point in time to inspect the entire *program request sequence*. The game takes place on a memory consisting of m cells, each capable of storing a single ball. Balls are numbered, from 1 to m. Initially, ith cell contains ball number i, for $1 \leq i \leq m$. (By m we denote the maximal amount of memory that RAM can use on input y and t steps of the execution. Notice that m is at most $\max\{|y|, t\}$.)

The game proceeds for t rounds. In each round j, the *program request sequence* secretly specifies to the *player* a request r_j which is a ball number from 1 to m (say i). The goal of the player is to hold the ball r_j but in such a way that the *observer* does not know the value of r_j. That is, the obliviousness condition requires that the observer can learn nothing about the sequence of requests initiated by the *program* from the sequence of addresses accessed by the *player*. We note that the *program* request sequence is collaborating with neither the *player* nor *observer*.

In order to achieve the above goal, the *player* "answers" by a sequence of exchanges of balls that he currently has and balls stored in memory (or just touches of balls stored in memory). The current round ends when the *player* holds ball i. The *observer* sees the sequence of (memory) addresses accessed, but does not see any of the ball numbers nor whether the balls in memory are just touched or exchanged.

Consider a probabilistic mapping of t-element long request sequence (i.e. the request made by the *program*) into a pair of two q-element sequences determining the behavior of the CPU player. The first sequence V_q describes the *visible* access pattern while the second sequence H_q describes the *hidden* sequence of actions (elements of $\{\text{EXCHANGE(l)}_{1 \leq l \leq c}$, $\text{DROP(l)}_{1 \leq l \leq c}, \text{TAKE(l)}_{1 \leq l \leq c}, \text{DO-NOTHING}\}$). Hence, in response to request sequence $(r_1, ..., r_t)$ and access to random function f, the *player* conducts actions $(v_1, h_1), \ldots, (v_q, h_q)$ where v_i is a cell number from V_q and h_i denotes above mentioned $3c + 1$ actions from H_q (i.e., whether the *player* "takes (a ball from the cell)", "drops (a ball into it)" or "keeps (the balls he holds)".

We can now specify exactly the notion of "rounds": we say that a sequence of actions $(v_1, h_1), ..., (v_q, h_q)$ satisfies the request sequence $r_1, ..., r_t$ if there exists a sequence $i_1, ..., i_t$ (i.e., when rounds are "finished") so that, for every (round) j $(1 \leq j \leq t)$, after actions

$(v_1, h_1), ..., (v_{i_j}, h_{i_j})$ the *player* holds ball r_j (i.e., request to get ball r_j is satisfied). Note that this definition does not depend on the function f (which might have been used to determine the action sequence).

Note that a fixed sequence of player actions $(v_1, h_1), ..., (v_q, h_q)$ may satisfy at most c^q *program request sequences*, as after each step the *player* holds at most c balls. Moreover, for a fixed V_q there are $(3c+1)^q$ possible request sequences. Therefore, each V_q of length q may satisfy at most $c^q \cdot (3c+1)^q$ request sequences. By obliviousness condition, the V_q sequence should be statistically independent of the particular request sequence (except for its length). But there are m^t requests, calling for at least this number of hidden actions. Thus, for any constant c (which corresponds to the oblivious RAM that has probabilistic CPU with c registers) it must be the case that $q > t \cdot \Omega(\log m)$. ∎

Remark: The above proof does not use the fact that the simulation needs to be done on-line. That is, the above lower bound holds even if the simulation is performed with the entire program request sequence given to the oblivious RAM before the simulation begins!

7 Concluding Remarks

Summarizing, we provided theoretical treatment of software protection in terms of formalizing what the problem is, and establishing poly-logarithmic upper bound and logarithmic lower bound.

Moreover, we have established the analog of Pippenger and Fisher result [PF] for random-access machines, despite the fact that random-access machines can access its memory in an arbitrary manner, whereas the result of [PF] relies on the fact that single-tape Turing machine memory-access is severely limited.

On a practical side, we have presented a compiler which translates RAM-programs to equivalent programs which defeat attempts to learn anything about the program by executing it. The translation was carried-out on the instruction level: namely, we have replaced the memory access of each instruction by a sequence of redundant memory accesses. Clearly, all statements and results appearing above, apply to any other level of execution granularity. For example, on the "paging" level this would mean dealing with "get page" and "store page" as atomic access instructions, and substituting single "page access" by a sequence of "page accesses". In general, we have provided a mechanism for obliviously accessing a large number of unprotected cites when using a single protected cite. This has several applications.

One possible application of our work is protection of traffic-patterns in a distributed database. In this application we deal with a distributed database in which no user can hold at one time more then a small part of the database, and in which a polynomial-time adversary can monitor all communication lines. Encryption hides the contents of the messages, but does not hide which communication lines are used. Thus, indirectly, some information about the database is revealed to an adversary. For example, an adversary can learn which part of the database is most useful (i.e., most frequently read and updated), and which part of the database is most useful to a particular user. How can users hide the access sequence without sending too many additional messages? It can be shown that a

solution to the "obliviously accessed data base" problem reduces to simulation of arbitrary RAMs by oblivious RAMs. We note that further work in this direction, dealing with a more powerful adversary was addressed in [SR].

Another application of our technique is for data-structure checking [B, BK, BEGKN], where assuming that a data-structure has small reliable memory we can guarantee that it was not modified by an adversary.

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