Secure Outsourced Garbled Circuit Evaluation for Mobile Devices

Henry Carter, *Georgia Institute of Technology;* Benjamin Mood, *University of Oregon;*
Patrick Traynor, *Georgia Institute of Technology;* Kevin Butler, *University of Oregon*

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Henry Carter
Georgia Institute of Technology
carterh@gatech.edu

Benjamin Mood
University of Oregon
bmood@cs.uoregon.edu

Patrick Traynor
Georgia Institute of Technology
traynor@cc.gatech.edu

Kevin Butler
University of Oregon
butler@cs.uoregon.edu

Abstract

Garbled circuits provide a powerful tool for jointly evaluating functions while preserving the privacy of each user's inputs. While recent research has made the use of this primitive more practical, such solutions generally assume that participants are symmetrically provisioned with massive computing resources. In reality, most people on the planet only have access to the comparatively sparse computational resources associated with their mobile phones, and those willing and able to pay for access to public cloud computing infrastructure cannot be assured that their data will remain unexposed. We address this problem by creating a new SFE protocol that allows mobile devices to securely outsource the majority of computation required to evaluate a garbled circuit. Our protocol, which builds on the most efficient garbled circuit evaluation techniques, includes a new outsourced oblivious transfer primitive that requires significantly less bandwidth and computation than standard OT primitives and outsourced input validation techniques that force the cloud to prove that it is executing all protocols correctly. After showing that our extensions are secure in the malicious model, we conduct an extensive performance evaluation for a number of standard SFE test applications as well as a privacy-preserving navigation application designed specifically for the mobile use-case. Our system reduces execution time by 98.92% and bandwidth by 99.95% for the edit distance problem of size 128 compared to non-outsourced evaluation. These results show that even the least capable devices are capable of evaluating some of the largest garbled circuits generated for any platform.

1 Introduction

Secure Function Evaluation (SFE) allows two parties to compute the result of a function without either side having to expose their potentially sensitive inputs to the other. While considered a generally theoretical curiosity even after the discovery of Yao's garbled circuit [43], recent advances in this space have made such computation increasingly practical. Today, functions as complex as AES-128 and approaching one billion gates in size are possible at reasonable throughputs, even in the presence of a malicious adversary.

While recent research has made the constructions in this space appreciably more performant, the majority of related work makes a crucial assumption - *that both parties are symmetrically provisioned with massive computing resources.* For instance, Kreuter et al. [25] rely on the Ranger cluster at the Texas Advanced Computing Center to compute their results using 512 cores. In reality, the extent of a user's computing power may be their mobile phone, which has many orders of magnitude less computational ability. Moreover, even with access to a public compute cloud such as Amazon EC2 or Windows Azure, the sensitive nature of the user's data and the history of data leakage from cloud services [40, 42] prevent the direct porting of known SFE techniques.

In this paper, we develop mechanisms for the secure outsourcing of SFE computation from constrained devices to more capable infrastructure. Our protocol maintains the privacy of both participant's inputs and outputs while significantly reducing the computation and network overhead required by the mobile device for garbled circuit evaluation. We develop a number of extensions to allow the mobile device to check for malicious behavior from the circuit generator or the cloud and a novel Outsourced Oblivious Transfer for sending garbled input data to the cloud. We then implement the new protocol on a commodity mobile device and reasonably provisioned servers and demonstrate significant performance improvements over evaluating garbled circuits directly on the mobile device.

We make the following contributions:

- **Outsourced oblivious transfer & outsourced consistency checks:** Instead of blindly trusting the cloud with sensitive inputs, we develop a highly

efficient Outsourced Oblivious Transfer primitive that allows mobile devices to securely delegate the majority of computation associated with oblivious transfers. We also provide mechanisms to outsource consistency checks to prevent a malicious circuit generator from providing corrupt garbled values. These checks are designed in such a way that the computational load is almost exclusively on the cloud, but cannot be forged by a malicious or "lazy" cloud. We demonstrate that both of our additions are secure in the malicious model as defined by Kamara et al. [21].

- **Performance Analysis:** Extending upon the implementation by Kreuter et al. [25], we conduct an extensive performance analysis against a number of simple applications (e.g., edit distance) and cryptographic benchmarks (e.g., AES-128). Our results show that outsourcing SFE provides improvements to both execution time and bandwidth overhead. For the edit distance problem of size 128, we reduce execution time by 98.92% and bandwidth by 99.95% compared to direct execution without outsourcing on the mobile device.
- **Privacy Preserving Navigation App:** To demonstrate the practical need for our techniques, we design and implement an outsourced version of Dijkstra's shortest path algorithm as part of a Navigation mobile app. Our app provides directions for a Presidential motorcade without exposing its location, destination, or known hazards that should be avoided (but remain secret should the mobile device be compromised). *The optimized circuits generated for this app represent the largest circuits evaluated to date.* Without our outsourcing techniques, such an application is far too processor, memory and bandwidth intensive for any mobile phone.

While this work is similar in function and provides equivalent security guarantees to the Salus protocols recently developed by Kamara et al. [21], our approach is dramatically different. The Salus protocol framework builds their scheme on a completely different assumption, specifically, that they are outsourcing work from low-computation devices with *high communication bandwidth*. With provider-imposed bandwidth caps and relatively slow and unreliable cellular data connections, this is not a realistic assumption when developing solutions in the mobile environment. Moreover, rather than providing a proof-of-concept work demonstrating that offloading computation is possible, this work seeks to develop and thoroughly demonstrate the practical potential for evaluating large garbled circuits in a resource-constrained mobile environment.

The remainder of this work is organized as follows: Section 2 presents important related work and discusses how this paper differs from Salus; Section 3 provides cryptographic assumptions and definitions; Section 4 formally describes our protocols; Section 5 provides security discussion - we direct readers to our technical report [6] for full security proofs; Section 6 shows the results of our extensive performance analysis; Section 7 presents our privacy preserving navigation application for mobile phones; and Section 8 provides concluding remarks.

2 Related Work

Beginning with Fairplay [32], several secure two-party computation implementations and applications have been developed using Yao garbled circuits [43] in the semi-honest adversarial model [3, 15, 17, 19, 26, 28, 31, 38]. However, a malicious party using corrupted inputs or circuits can learn more information about the other party's inputs in these constructions [23]. To resolve these issues, new protocols have been developed to achieve security in the malicious model, using cut-and-choose constructions [30], input commitments [41], and other various techniques [22,34]. To improve the performance of these schemes in both the malicious and semi-honest adversarial models, a number of circuit optimization techniques have also been developed to reduce the cost of generating and evaluating circuits [8, 11, 24, 35]. Kreuter et al. [25] combined several of these techniques into a general garbled circuit protocol that is secure in the malicious model and can efficiently evaluate circuits on the order of billions of gates using parallelized server-class machines. This SFE protocol is currently the most efficient implementation that is fully secure in the malicious model. (The dual execution construction by Huang et al. leaks one bit of input [16].)

Garbled circuit protocols rely on oblivious transfer schemes to exchange certain private values. While several OT schemes of various efficiencies have been developed [1, 30, 36, 39], Ishai et al. demonstrated that any of these schemes can be extended to reduce k^c oblivious transfers to k oblivious transfers for any given constant c [18]. Using this extension, exchanging potentially large inputs to garbled circuits became much less costly in terms of cryptographic operations and network overhead. Even with this drastic improvement in efficiency, oblivious transfers still tend to be a costly step in evaluating garbled circuits.

Currently, the performance of garbled circuit protocols executed directly on mobile devices has been shown to be feasible only for small circuits in the semi-honest adversarial model [5, 13]. While outsourcing general computation to the cloud has been widely considered for improving the efficiency of applications running on mobile devices, the concept has yet to be widely applied to cryp-

tographic constructions. Green et al. began exploring this idea by outsourcing the costly decryption of ABE ciphertexts to server-class machines while still maintaining data privacy [12]. Considering the costs of exchanging inputs and evaluating garbled circuits securely, an outsourcing technique would be useful in allowing limited capability devices to execute SFE protocols. Naor et al. [37] develop an oblivious transfer technique that sends the chooser's private selections to a third party, termed a proxy. While this idea is applied to a limited application in their work, it could be leveraged more generally into existing garbled circuit protocols. Our work develops a novel extension to this technique to construct a garbled circuit evaluation protocol that securely outsources computation to the cloud.

In work performed concurrently and independently from our technique, Kamara et al. recently developed two protocols for outsourcing secure multiparty computation to the cloud in their Salus system [21]. While their work achieves similar functionality to ours, we distinguish our work in the following ways: first, their protocol is constructed with the assumption that they are outsourcing work from devices with low-computation but high-bandwidth capabilities. With cellular providers imposing bandwidth caps on customers and cellular data networks providing highly limited data transmission speed, we construct our protocol without this assumption using completely different cryptographic constructions. Second, their work focuses on demonstrating outsourced SFE as a proof-of-concept. Our work offers a rigorous performance analysis on mobile devices, and outlines a practical application that allows a mobile device to participate in the evaluation of garbled circuits that are orders of magnitude larger than those evaluated in the Salus system. Finally, their protocol that is secure in the malicious model requires that all parties share a secret key, which must be generated in a secure fashion before the protocol can be executed. Our protocol does not require any shared information prior to running the protocol, reducing the overhead of performing a multiparty fair coin tossing protocol a priori. While our work currently considers only the two-party model, by not requiring a preliminary multiparty fair coin toss, expanding our protocol to more parties will not incur the same expense as scaling such a protocol to a large number of participants. To properly compare security guarantees, we apply their security definitions in our analysis.

3 Assumptions and Definitions

To construct a secure scheme for outsourcing garbled circuit evaluation, some new assumptions must be considered in addition to the standard security measures taken in a two-party secure computation. In this section, we discuss the intuition and practicality of assuming a non-colluding cloud, and we outline our extensions on standard techniques for preventing malicious behavior when evaluating garbled circuits. Finally, we conclude the section with formal definitions of security.

3.1 Non-collusion with the cloud

Throughout our protocol, we assume that none of the parties involved will ever collude with the cloud. This requirement is based in theoretical bounds on the efficiency of garbled circuit evaluation and represents a realistic adversarial model. The fact that theoretical limitations exist when considering collusion in secure multiparty computation has been known and studied for many years [2, 7, 27], and other schemes considering secure computation with multiple parties require similar restrictions on who and how many parties may collude while preserving security [4, 9, 10, 20, 21]. Kamara et al. [21] observe that if an outsourcing protocol is secure when both the party generating the circuit and the cloud evaluating the circuit are malicious and colluding, this implies a secure two-party scheme where one party has sub-linear work with respect to the size of the circuit, which is currently only possible with fully homomorphic encryption. However, making the assumption that the cloud will not collude with the participating parties makes outsourcing securely a theoretical possibility. In reality, many cloud providers such as Amazon or Microsoft would not allow outside parties to control or affect computation within their cloud system for reasons of trust and to preserve a professional reputation. In spite of this assumption, we cannot assume the cloud will always be semi-honest. For example, our protocol requires a number of consistency checks to be performed by the cloud that ensure the participants are not behaving maliciously. Without mechanisms to force the cloud to make these checks, a "lazy" cloud provider could save resources by simply returning that all checks verified without actually performing them. Thus, our adversarial model encompasses a non-colluding but potentially malicious cloud provider that is hosting the outsourced computation.

3.2 Attacks in the malicious setting

When running garbled circuit based secure multiparty computation in the malicious model, a number of well-documented attacks exist. We address here how our system counters each.

Malicious circuit generation: In the original Yao garbled circuit construction, a malicious generator can garble a circuit to evaluate a function f' that is not the function f agreed upon by both parties and could compromise the security of the evaluator's input. To counter this, we

employ an extension of the random seed technique developed by Goyal et al. [11] and implemented by Kreuter et al. [25]. Essentially, the technique uses a cut-and-choose, where the generator commits to a set of circuits that all presumably compute the same function. The parties then use a fair coin toss to select some of the circuits to be evaluated and some that will be re-generated and hashed by the cloud given the random seeds used to generate them initially. The evaluating party then inspects the circuit commitments and compares them to the hash of the regenerated circuits to verify that all the check circuits were generated properly.

Selective failure attack: If, when the generator is sending the evaluator's garbled inputs during the oblivious transfer, he lets the evaluator choose between a valid garbled input bit and a corrupted garbled input, the evaluator's ability to complete the circuit evaluation will reveal to the generator which input bit was used. To prevent this attack, we use the input encoding technique from Lindell and Pinkas [29], which lets the evaluator encode her input in such a way that a selective failure of the circuit reveals nothing about the actual input value. To prevent the generator from swapping garbled wire values, we use a commitment technique employed by Kreuter et al. [25].

Input consistency: Since multiple circuits are evaluated to ensure that a majority of circuits are correct, it is possible for either party to input different inputs to different evaluation circuits, which could reveal information about the other party's inputs. To keep the evaluator's inputs consistent, we again use the technique from Lindell and Pinkas [29], which sends all garbled inputs for every evaluation circuit in one oblivious transfer execution. To keep the generator's inputs consistent, we use the malleable claw-free collection construction of shelat and Shen [41]. This technique is described in further detail in Section 4.

Output consistency: When evaluating a two-output function, we ensure that outputs of both parties are kept private from the cloud using an extension of the technique developed by Kiraz [23]. The outputs of both parties are XORed with random strings within the garbled circuit, and the cloud uses a witness-indistinguishable zero-knowledge proof as in the implementation by Kreuter et al. [25]. This allows the cloud to choose a majority output value without learning either party's output or undetectably tampering with the output. At the same time, the witness-indistinguishable proofs prevent either party from learning the index of the majority circuit. This prevents the generator from learning anything by knowing which circuit evaluated to the majority output value.

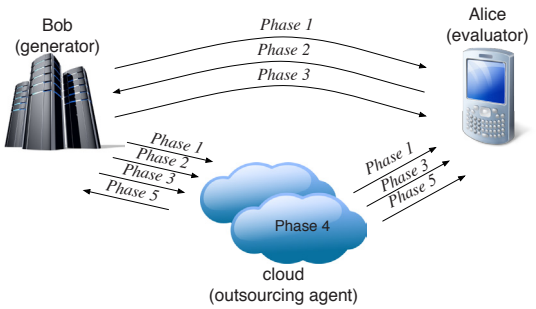


Figure 1: The complete outsourced SFE protocol.

3.3 Malleable claw-free collections

To prevent the generating party from providing different inputs for each evaluation circuit, we implement the malleable claw-free collections technique developed by shelat and Shen [41]. Their construction essentially allows the generating party to prove that all of the garbled input values were generated by exactly one function in a function pair, while the ability to find an element that is generated by both functions implies that the generator can find a claw. It is composed of a four-tuple of algorithms (G,D,F,R), where G is the index selection algorithm for selecting a specific function pair, D is an algorithm for sampling from the domain of the function pair, F is the algorithm for evaluating the functions in the pair (in which it should be difficult to find a claw), and R is the "malleability" function. The function R maps elements from the domain of F to the range of F such that for $b \in \{0,1\}$, any I in the range of G, and any m_1, m_2 in the domain of F, we have for the function indexed by I and b $f_I^b(m_1 \star m_2) = f_I^b(m_1) \diamond R_I(m_2)$, where $\star$ and $\diamond$ represent the group operations over the domain and range of F. We provide full definitions of their construction in our technical report [6].

3.4 Model and Definitions

The work of Kamara et al. [21] presents a definition of security based on the ideal-model/real-model security definitions common in secure multiparty computation. Because their definition formalizes the idea of a non-colluding cloud, we apply their definitions to our protocol for the two-party case in particular. We summarize their definitions below.

Real-model execution. The protocol takes place between two parties (P_1,P_2) executing the protocol and a server P_3, where each of the executing parties provides input x_i, auxiliary input z_i, and random coins r_i and the server provides only auxiliary input z_3 and random coins r_3. In the execution, there exists some subset of independent parties $(A_1,..,A_m), m \leq 3$ that are malicious adversaries. Each adversary corrupts one executing party and

does not share information with other adversaries. For all honest parties, let OUT_i be its output, and for corrupted parties let OUT_i be its view of the protocol execution. The i^{th} partial output of a real execution is defined as:

$$REAL^{(i)}(k,x;r) = \{OUT_j : j \in H\} \cup OUT_i$$

where H is the set of honest parties and r is all random coins of all players.

Ideal-model execution. In the ideal model, the setup of participants is the same except that all parties are interacting with a trusted party that evaluates the function. All parties provide inputs x_i, auxiliary input z_i, and random coins r_i. If a party is semi-honest, it provides its actual inputs to the trusted party, while if the party is malicious (and non-colluding), it provides arbitrary input values. In the case of the server P_3, this means simply providing its auxiliary input and random coins, as no input is provided to the function being evaluated. Once the function is evaluated by the trusted third party, it returns the result to the parties P_1 and P_2, while the server P_3 does not receive the output. If a party aborts early or sends no input, the trusted party immediately aborts. For all honest parties, let OUT_i be its output to the trusted party, and for corrupted parties let OUT_i be some value output by P_i. The *ith* partial output of an ideal execution in the presence of some set of independent simulators is defined as:

$$IDEAL^{(i)}(k,x;r) = \{OUT_j : j \in H\} \cup OUT_i$$

where H is the set of honest parties and r is all random coins of all players. In this model, the formal definition of security is as follows:

Definition 1. *A protocol securely computes a function f if there exists a set of probabilistic polynomial-time (PPT) simulators $\{Sim_i\}_{i\in[3]}$ such that for all PPT adversaries $(A_1,...,A_3)$, x, z, and for all $i \in [3]$:*

$$\{REAL^{(i)}(k,x;r)\}_{k\in N} \overset{c}{\approx} \{IDEAL^{(i)}(k,x;r)\}_{k\in N}$$

Where $S = (S_1,...,S_3)$, $S_i = Sim_i(A_i)$, and r is random and uniform.

4 Protocol

Our protocol can be divided into five phases, illustrated in Figure 1. Given a circuit generator Bob, and an evaluating mobile device Alice, the protocol can be summarized as follows:

- Phase 1: Bob generates a number of garbled circuits, some of which will be checked, others will be evaluated. After Bob commits to the circuits, Alice and Bob use a fair coin toss protocol to select which circuits will be checked or evaluated. For the check circuits, Bob sends the random seeds used to generate the circuits to the cloud and the hashes of each circuit to Alice. These are checked to ensure that Bob has not constructed a circuit that is corrupted or deviates from the agreed-upon function.
- Phase 2: Alice sends her inputs to Bob via an outsourced oblivious transfer. Bob then sends the corresponding garbled inputs to the cloud. This allows the cloud to receive Alice's garbled inputs without Bob or the cloud ever learning her true inputs.
- Phase 3: Bob sends his garbled inputs to the cloud, which verifies that they are consistent for each evaluation circuit. This prevents Bob from providing different inputs to different evaluation circuits.
- Phase 4: The cloud evaluates the circuit given Alice and Bob's garbled inputs. Since the cloud only sees garbled values during the evaluation of the circuit, it never learns anything about either party's input or output. Since both output values are blinded with one-time pads, they remain private even when the cloud takes a majority vote.
- Phase 5: The cloud sends the encrypted output values to Alice and Bob, who are guaranteed its authenticity through the use of commitments and zero-knowledge proofs.

Inputs: Alice has a string of encoded input bits ea of length $\ell \cdot n$ and Bob has pairs of input values $(x_{0,j}, x_{1,j})$ for $j = 1...\ell \cdot n$.

1. **Setup:** Alice generates random matrix T of size $\ell \cdot n \times t$, Bob generates random string s of length t.
2. **Primitive OT:** Alice and Bob execute t 1-out-of-2 oblivious transfers with Alice inputting $(T^i, T^i \oplus ea)$ and Bob inputting selection bits s (T^i denotes the i^{th} column of the T matrix). Bob sets the resulting columns as matrix Q.
3. **Permuting the output:** Alice generates random string p of length $\ell \cdot n$ and sends it to Bob.
4. **Encrypting the output:** Bob sets the encrypted output pairs $y_{0,j}, y_{1,j}$ where $y_{b,j} = x_{b,j} \oplus H_1(j, Q_j \oplus (b \cdot s))$ (Q_j denotes the j^{th} row of the Q matrix).
5. **Permuting the outputs:** Bob permutes the encrypted output pairs as $y_{0\oplus p_j,j}, y_{1\oplus p_j,j}$ and sends the resulting set of pairs Y to the cloud.
6. **Decrypting the output:** Alice sends $h = ea \oplus p$ and T to the cloud. The cloud recovers $z_j = y_{h_j,j} \oplus H_1(j, T_j)$ for $j = 1...\ell \cdot n$ (T_j denotes the j^{th} row of the T matrix).

Figure 2: The Outsourced Oblivious Transfer protocol

4.1 Participants

Our protocols reference three different entities:
Evaluator: The evaluating party, called Alice, is assumed to be a mobile device that is participating in a secure two-party computation.
Generator: The party generating the garbled circuit, called Bob, is an application- or web- server that is the second party participating with Alice in the secure computation.
Proxy: The proxy, called cloud, is a third party that is performing heavy computation on behalf of Alice, but is not trusted to know her input or the function output.

4.2 Outsourced Protocol

Common inputs: a function $f(x,y)$ that is to be securely computed, a claw-free collection $(G_{CLW}, D_{CLW}, F_{CLW}, R_{CLW})$, two hash functions $H_1 : \{0,1\}^* \rightarrow \{0,1\}^n$ and $H_2 : \{0,1\}^* \rightarrow \{0,1\}^w$, a primitive 1-out-of-2 oblivious transfer protocol, a perfectly hiding commitment scheme $com_H(key, message)$, and security parameters for the number of circuits built k, the number of primitive oblivious transfers t, and the number of encoding bits for each of Alice's input wires ℓ.
Private inputs: The generating party Bob inputs a bit string b and a random string of bits b_r that is the length of the output string. The evaluating party Alice inputs a bit string a and a random string of bits a_r that is the length of the output string. Assume without loss of generality that all input and output strings are of length $|a| = n$.
Output: The protocol outputs separate private values fa for Alice and fb for Bob.
Phase 1: Circuit generation and checking

1. *Circuit preparation:* Before beginning the protocol, both parties agree upon a circuit representation of the function $f(a,b)$, where the outputs of the function may be defined separately for Alice and Bob as $f_A(a,b)$ and $f_B(a,b)$. The circuit must also meet the following requirements:
   (a) Additional XOR gates must be added such that Bob's output is set to $fb = f_B(a,b) \oplus b_r$ and Alice's output is set to $fa = f_A(a,b) \oplus a_r$.
   (b) For each of Alice's input bits, the input wire w_i is split into ℓ different input wires $w_{j,i}$ such that $w_i = w_{1,i} \oplus w_{2,i} \oplus ... \oplus w_{l,i}$ following the input encoding scheme by Lindell and Pinkas [29]. This prevents Bob from correlating a selective failure attack with any of Alice's input bit values.

2. *Circuit garbling:* the generating party, Bob, constructs k garbled circuits using a circuit garbling technique $Garble(\cdot,\cdot)$. When given a circuit representation C of a function and random coins rc, $Garble(C, rc)$ outputs a garbled circuit GC that evaluates C. Given the circuit C and random coins $rc_1...rc_k$, Bob generates garbled circuits $Garble(C, rc_i) = GC_i$ for $i = 1...k$. For Bob's j^{th} input wire on the i^{th} circuit, Bob associates the value $H_2(\beta_{b,j,i})$ with the input value b, where $\beta_{b,j,i} = F_{CLW}(b, I, \alpha_{b,j,i})$. For Alice's j^{th} input wire, Bob associates the value $H_2(\delta_{b,j,i})$ with the input value b, where $\delta_{b,j,i} = F_{CLW}(b, I, \gamma_{b,j,i})$. All the values $\alpha_{b,j,i}$ and $\gamma_{b,j,i}$ for $b = \{0,1\}, j = 1...n, i = 1...k$ are selected randomly from the domain of the claw-free pair using D.

3. *Circuit commitment:* Bob generates commitments for all circuits by hashing $H_1(GC_i) = HC_i$ for $i = 1...k$. Bob sends these hashes to Alice. In addition, for every output wire $w_{b,j,i}$ for $b = \{0,1\}$, $j = 1...n$ and $i = 1...k$, Bob generates commitments $CO_{j,i} = com_H(ck_{j,i}, (H_2(w_{0,j,i}), H_2(w_{1,j,i})))$ using commitment keys $ck_{j,i}$ for $j = 1...n$ and $i = 1...k$ and sends them to both Alice and the cloud.

4. *Input label commitment:* Bob commits to Alice's garbled input values as follows: for each generated circuit $i = 1...k$ and each of Alice's input wires $j = 1...\ell \cdot n$, Bob creates a pair of commitment keys $ik_{0,j,i}, ik_{1,j,i}$ and commits to the input wire label seeds $\delta_{0,j,i}$ and $\delta_{1,j,i}$ as $CI_{b,j,i} = com_H(ik_{b,j,i}, \delta_{b,j,i})$. For each of Alice's input wires $j = 1...\ell \cdot n$, Bob randomly permutes the commitments within the pair $CI_{0,j,i}, CI_{1,j,i}$ across every $i = 1...k$. This prevents the cloud from correlating the location of the commitment with Alice's input value during the OOT phase.

5. *Cut and choose:* Alice and Bob then run a fair coin toss protocol to agree on a set of circuits that will be evaluated, while the remaining circuits will be checked. The coin toss generates a set of indices $Chk \subset \{1,...,k\}$ such that $|Chk| = \frac{3}{5}k$, as in shelat and Shen's cut-and-choose protocol [41]. The remaining indices are placed in the set Evl for evaluation, where $|Evl| = e = \frac{2}{5}k$. For every $i \in Chk$, Bob sends rc_i and the values $[\alpha_{b,1,i}, ..., \alpha_{b,n,i}]$ and $[\gamma_{b,1,i}, ..., \gamma_{b,\ell \cdot n,i}]$ for $b = \{0,1\}$ to the cloud. Bob also sends all commitment keys $ck_{j,i}$ for $j = 1...n$ and $i \in Chk$ to the cloud. Finally, Bob sends the commitment keys $ik_{b,j,i}$ for $b = \{0,1\}$, $i \in Chk$, and $j = 1...\ell \cdot n$ to the cloud. The cloud then generates $Garble(C, rc_i) = GC'_i$ for $i \in Chk$. For each $i \in Chk$, the cloud then hashes each check circuit $H_1(GC'_i) = HC'_i$ and checks that:

- each commitment $CO_{j,i}$ for $j = 1...n$ is well formed
- the value $H_2(\beta_{b,j,i})$ is associated with the input value b for Bob's j^{th} input wire
- the value $H_2(\delta_{b,j,i})$ is associated with the input value b for Alice's j^{th} input wire
- for every bit value b and input wire j, the values committed in $CI_{b,j,i}$ are correct

If any of these checks fail, the cloud immediately aborts. Otherwise, it sends the hash values HC'_i for $i \in Chk$ to Alice. For every $i \in Chk$, Alice checks if $HC_i = HC'_i$. If any of the hash comparisons fail, Alice aborts.

Phase 2: Outsourced Oblivious Transfer (OOT)

1. *Input encoding:* For every bit $j = 1...n$ in her input a, Alice sets encoded input ea_j as a random string of length ℓ such that $ea_{1,j} \oplus ea_{2,j} \oplus ... \oplus ea_{l,j} = a_j$ for each bit in ea_j. This new encoded input string ea is of length $\ell \cdot n$.

2. *OT setup:* Alice initializes an $\ell \cdot n \times t$ matrix T with uniformly random bit values, while Bob initializes a random bit vector s of length t. See Figure 2 for a more concise view.

3. *Primitive OT operations:* With Alice as the sender and Bob as the chooser, the parties initiate t 1-out-of-2 oblivious transfers. Alice's input to the i^{th} instance of the OT is the pair $(T^i, T^i \oplus ea)$ where T^i is the i^{th} column of T, while Bob's input is the i^{th} selection bit from the vector s. Bob organizes the t selected columns as a new matrix Q.

4. *Permuting the selections:* Alice generates a random bit string p of length $\ell \cdot n$, which she sends to Bob.

5. *Encrypting the commitment keys:* Bob generates a matrix of keys that will open the committed garbled input values and proofs of consistency as follows: for Alice's j^{th} input bit, Bob creates a pair $(x_{0,j}, x_{1,j})$, where $x_{b,j} = [ik_{b,j,Evl_1}, ik_{b,j,Evl_2}, ..., ik_{b,j,Evl_e}]||[\gamma_{b_j,j,Evl_2} \star (\gamma_{b_j,j,Evl_1})^{-1}, \gamma_{b_j,j,Evl_3} \star (\gamma_{b_j,j,Evl_1})^{-1}, ..., \gamma_{b_j,j,Evl_e} \star (\gamma_{b_j,j,Evl_1})^{-1}]$ and Evl_i denotes the i^{th} index in the set of evaluation circuits. For $j = 1...\ell \cdot n$, Bob prepares $(y_{0,j}, y_{1,j})$ where $y_{b,j} = x_{b,j} \oplus H_1(j, Q_j \oplus (b \cdot s))$. Here, Q_j denotes the j^{th} row in the Q matrix. Bob permutes the entries using Alice's permutation vector as $(y_{0 \oplus p_j,j}, y_{1 \oplus p_j,j})$. Bob sends this permuted set of ciphertexts Y to the cloud.

6. *Receiving Alice's garbled inputs:* Alice blinds her input as $h = ea \oplus p$ and sends h and T to the cloud. The cloud recovers the commitment keys and consistency proofs $x_{b,j} = y_{h_j,j} \oplus H_1(j, T_j)$ for $j = 1...\ell \cdot n$. Here, h_j denotes the j^{th} bit of the string h and T_j denotes the j^{th} row in the T matrix. Since for every $j \in Evl$, the cloud only has the commitment key for the b garbled value (not the $b \oplus 1$ garbled value), the cloud can correctly decommit only the garbled labels corresponding to Alice's input bits.

7. *Verifying consistency across Alice's inputs:* Given the decommitted values $[\delta_{b,1,i}, ..., \delta_{b,\ell \cdot n,i}]$ and the modified pre images $[\gamma_{b_j,j,Evl_2} \star (\gamma_{b_j,j,Evl_1})^{-1}, \gamma_{b_j,j,Evl_3} \star (\gamma_{b_j,j,Evl_1})^{-1}, ..., \gamma_{b_j,j,Evl_e} \star (\gamma_{b_j,j,Evl_1})^{-1}]$, the cloud checks that:

$$\delta_{b_j,j,i} = \delta_{b_j,j,Evl_1} \diamond R_{CLW}(I, \gamma_{b_j,j,i} \star (\gamma_{b_j,j,Evl_1})^{-1})$$

for $i = 2...e$. If any of these checks fails, the cloud aborts the protocol.

Phase 3: Generator input consistency check

1. *Delivering inputs:* Bob delivers the hash seeds for each of his garbled input values $[\beta_{b_1,1,i}, \beta_{b_2,2,i}, ..., \beta_{b_n,n,i}]$ for every evaluation circuit $i \in Evl$ to the cloud, which forwards a copy of these values to Alice. Bob then proves the consistency of his inputs by sending the modified preimages $[\alpha_{b_j,j,Evl_2} \star (\alpha_{b_j,j,Evl_1})^{-1}, \alpha_{b_j,j,Evl_3} \star (\alpha_{b_j,j,Evl_1})^{-1}, ..., \alpha_{b_j,j,Evl_e} \star (\alpha_{b_j,j,Evl_1})^{-1}]$ such that $F_{CLW}(b_i, I, \alpha_{b_i,j,i}) = \beta_{b_i,j,i}$ for $j = 1...n$ and $i \in Evl$ such that GC_i was generated with the claw-free function pair indexed at I.

2. *Check consistency:* Alice then checks that all the hash seeds were generated by the same function by checking if:

$$\beta_{b_j,j,i} = \beta_{b_j,j,Evl_1} \diamond R_{CLW}(I, \alpha_{b_j,j,i} \star (\alpha_{b_j,j,Evl_1})^{-1})$$

for $i = 2...e$. If any of these checks fails, Alice aborts the protocol.

Phase 4: Circuit evaluation

1. *Evaluating the circuit:*For each evaluation circuit, the cloud evaluates $GC_i(ga_i, gb_i)$ for $i \in Evl$ in the pipelined manner described by Kreuter et al. in [25]. Each circuit produces two garbled output strings, (gfa_i, gfb_i).

2. *Checking the evaluation circuits:* Once these output have been computed, the cloud hashes each evaluation circuit as $H_1(GC_i) = HC'_i$ for $i \in Evl$ and sends these hash values to Alice. Alice checks that for every $i, HC_i = HC'_i$. If any of these checks do not pass, Alice aborts the protocol.

Phase 5: Output check and delivery

1. *Committing the outputs:*The cloud then generates random commitment keys ka_i, kb_i and commits the output values to their respective parties according to the commitment scheme defined by Kiraz [23], generating $CA_{j,i} = commit(ka_{j,i}, gfa_{j,i})$ and $CB_{j,i} = commit(kb_{j,i}, gfb_{j,i})$ for $j = 1...n$ and $i = 1...e$. The cloud then sends all *CA* to Alice and *CB* to Bob.

2. *Selection of majority output:* Bob opens the commitments $CO_{j,i}$ for $j = 1...n$ and $i = 1...e$ for both Alice and the Cloud. These commitments contain the mappings from the hash of each garbled output wire $H_2(w_{b,j,i})$ to real output values $b_{j,i}$ for $j = 1...n$ and $i = 1...e$. The cloud selects a circuit index maj such that the output of that circuit matches the majority of outputs for both Alice and Bob. That is, $fa_{maj} = fa_i$ and $fb_{maj} = fb_i$ for i in a set of indices *IND* that is of size $|IND| > \frac{e}{2}$

3. *Proof of output consistency:* Using the OR-proofs as described by Kiraz [23], the cloud proves to Bob that *CB* contains valid garbled output bit values based on the de-committed output values from the previous step. The cloud then performs the same proof to Alice for her committed values *CA*. Note that these proofs guarantee the output was generated by one of the circuits, but the value maj remains hidden from both Alice and Bob.

4. *Output release:* The cloud then decommits gfa_{maj} to Alice and gfb_{maj} to Bob. Given these garbled outputs and the bit values corresponding to the hash of each output wire, Alice recovers her output string fa, and Bob recovers his output string fb.

5. *Output decryption:* Alice recovers her output $f_A(a,b) = fa \oplus a_r$, while Bob recovers $f_B(a,b) = fb \oplus b_r$.

5 Security Guarantees

In this section, we provide a summary of the security mechanisms used in our protocol and an informal security discussion of our new outsourced oblivious transfer primitive. Due to space limitations, we provide further discussion and proofs of security in our technical report [6].

Recall from Section 3 that there are generally four security concerns when evaluating garbled circuits in the malicious setting. To solve the problem of malicious circuit generation, we apply the random seed check variety of cut-&-choose developed by Goyal et al. [11]. To solve the problem of selective failure attacks, we employ the input encoding technique developed by Lindell and Pinkas [29]. To prevent an adversary from using inconsistent inputs across evaluation circuits, we employ the witness-indistinguishable proofs from shelat and Shen [41]. Finally, to ensure the majority output value is selected and not tampered with, we use the XOR-and-prove technique from Kiraz [23] as implemented by Kreuter et al. [25]. In combination with the standard semi-honest security guarantees of Yao garbled circuits, these security extensions secure our scheme in the malicious security model.

Outsourced Oblivious Transfer: Our outsourced oblivious transfer is an extension of a technique developed by Naor et al. [37] that allows the chooser to select entries that are forwarded to a third party rather than returned to the chooser. By combining their concept of a proxy oblivious transfer with the semi-honest OT extension by Ishai et al. [18], our outsourced oblivious transfer provides a secure OT in the malicious model. We achieve this result for four reasons:

1. First, since Alice never sees the outputs of the OT protocol, she cannot learn anything about the garbled values held by the generator. This saves us from having to implement Ishai's extension to prevent the chooser from behaving maliciously.
2. Since the cloud sees only random garbled values and Alice's input blinded by a one-time pad, the cloud learns nothing about Alice's true inputs.
3. Since Bob's view of the protocol is almost identical to his view in Ishai's standard extension, the same security guarantees hold (i.e., security against a malicious sender).
4. Finally, if Alice does behave maliciously and uses inconsistent inputs to the primitive OT phase, there is a negligible probability that those values will hash to the correct one-time pad keys for recovering *either* commitment key, which will prevent the cloud from de-committing the garbled input values.

It is important to note that this particular application of the OOT allows for this efficiency gain since the evaluation of the garbled circuit will fail if Alice behaves maliciously. By applying the maliciously secure extension by Ishai et al. [18], this primitive could be applied generally as an oblivious transfer primitive that is secure in the malicious model. Further discussion and analysis of this general application is outside the scope of this work.

We provide the following security theorem here, which gives security guarantees identical to the Salus protocol by Kamara et al. [21]. However, we use different constructions and require a completely different proof, which is available in our technical report [6].

Theorem 1. *The outsourced two-party SFE protocol securely computes a function $f(a,b)$ in the following two*

corruption scenarios: (1)The cloud is malicious and non-cooperative with respect to the rest of the parties, while all other parties are semi-honest, (2)All but one party is malicious, while the cloud is semi-honest.

6 Performance Analysis

We now characterize how garbled circuits perform in the constrained-mobile environment with and without outsourcing.[1] Two of the most important constraints for mobile devices are computation and bandwidth, and we show that order of magnitude improvements for both factors are possible with outsourced evaluation. We begin by describing our implementation framework and testbed before discussing results in detail.

6.1 Framework and Testbed

Our framework is based on the system designed by Kreuter et al. [25], hereafter referred to as *KSS* for brevity. We implemented the outsourced protocol and performed modifications to allow for the use of the mobile device in the computation. Notably, *KSS* uses MPI [33] for communication between the multiple nodes of the multi-core machines relied on for circuit evaluation. Our solution replaces MPI calls on the mobile device with sockets that communicate directly with the Generator and Proxy. To provide a consistent comparison, we revised the *KSS* codebase to allow for direct evaluation between the mobile device (the Evaluator) and the cloud-based Generator.[2]

Our deployment platform consists of two Dell R610 servers, each containing dual 6-core Xeon processors with 32 GB of RAM and 300 GB 10K RPM hard drives, running the Linux 3.4 kernel and connected as a VLAN on an internal 1 Gbps switch. These machines perform the roles of the Generator and Proxy, respectively, as described in Section 4.1. The mobile device acts as the Evaluator. We use a Samsung Galaxy Nexus phone with a 1.2 GHz dual-core ARM Cortex-A9 processor and 1 GB of RAM, running the Android 4.0 "Ice Cream Sandwich" operating system. We connect an Apple Airport Express wireless access point to the switch attaching the servers, The Galaxy Nexus communicates to the Airport Express over an 802.11n 54Mbps WiFi connection in an isolated environment to minimize co-channel interference. All tests are run 10 times with error bars on figures representing 95% confidence intervals.

[1] We contacted the authors of the Salus protocol [21] in an attempt to acquire their framework to compare the performance of their scheme with ours, but they were unable to release their code.

[2] The full technical report [6] describes a comprehensive list of modifications and practical improvements made to *KSS*, including fixes that were added back into the codebase of *KSS* by the authors. We thank those authors for their assistance.

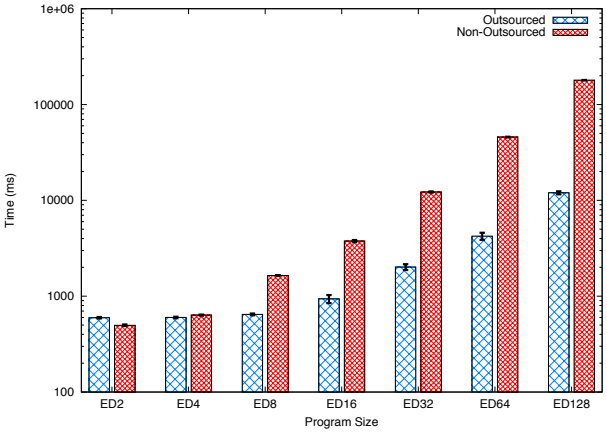


Figure 3: Execution time for the Edit Distance program of varying input sizes, with 2 circuits evaluated.

We measured both the total execution time of the programs and microbenchmarks for each program. All results are from the phone's standpoint. We do not measure the time the programs take to compile as we used the standard compiler from Kreuter et al. For our microbenchmarks, the circuit garbling and evaluation pair is referred to as the 'evaluation'.

6.2 Execution Time

Our tests evaluated the following problems:

Millionaires: This problem models the comparison of two parties comparing their net worth to determine who has more money without disclosing the actual values. We perform the test on input values ranging in size from 4 to 8192 bits.

Edit (Levenshtein) Distance: This is a string comparison algorithm that compares the number of modifications required to covert one string into another. We performed the comparison based on the circuit generated by Jha et al. [19] for strings sized between 4 and 128 bytes.

Set Intersection: This problem matches elements between the private sets of two parties without learning anything beyond the intersecting elements. We base our implementation on the SCS-WN protocol proposed by Huang et al. [14], and evaluate for sets of size 2 to 128.

AES: We compute AES with a 128-bit key length, based on a circuit evaluated by Kreuter et al. [25].

Figure 3 shows the result of the edit distance computation for input sizes of 2 to 128 with two circuits evaluated. This comparison represents worst-case operation due to the cost of setup for a small number of small circuits—with input size 2, the circuit is only 122 gates in size. For larger input sizes, however, outsourced computation becomes significantly faster. Note that the graph is logarithmic such that by the time strings of size 32 are evaluated, the outsourced execution is over 6 times

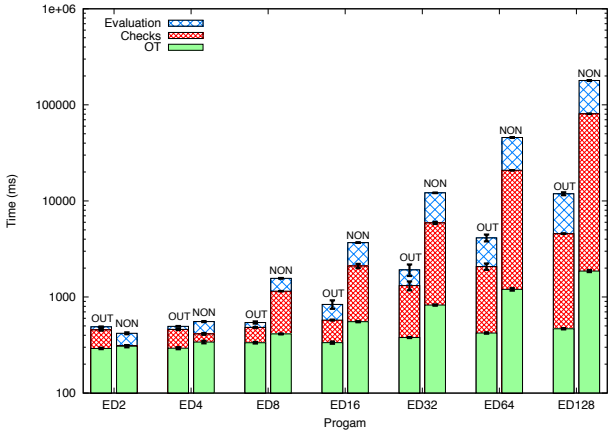


Figure 4: Execution time for significant stages of garbled circuit computation for outsourced and non-outsourced evaluation. The Edit Distance program is evaluated with variable input sizes for the two-circuit case.

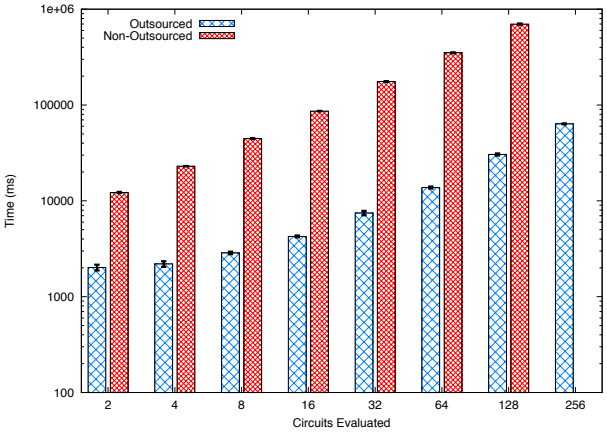


Figure 5: Execution time for the Edit Distance problem of size 32, with between 2 and 256 circuits evaluated. In the non-outsourced evaluation scheme, the mobile phone runs out of memory evaluating 256 circuits.

faster than non-outsourced execution, while for strings of size 128 (comprising over 3.4 million gates), outsourced computation is over 16 times faster.

The reason for this becomes apparent when we examine Figure 4. There are three primary operations that occur during the SFE transaction: the oblivious transfer (OT) of participant inputs, the circuit commit (including the circuit consistency check), and the circuit generation and evaluation pair. As shown in the figure, the OT phase takes 292 ms for input size 2, but takes 467 ms for input size 128. By contrast, in the non-outsourced execution, the OT phase takes 307 ms for input size 2, but increases to 1860 ms for input size 128. The overwhelming factor, however, is the circuit evaluation phase. It increases from 34 ms (input size 2) to 7320 ms (input size 128) for the outsourced evaluation, a 215 factor increase. For non-outsourced execution however, this phase increases from 108 ms (input size 2) to 98800 ms (input size 128), a factor of 914 increase.

6.3 Evaluating Multiple Circuits

The security parameter for the garbled circuit check is $2^{-0.32k}$ [25], where k is the number of generated circuits. To ensure a sufficiently low probability (2^{-80}) of evaluating a corrupt circuit, 256 circuits must be evaluated. However, there are increasing execution costs as increasing numbers of circuits are generated. Figure 5 shows the execution time of the Edit Distance problem of size 32 with between 2 and 256 circuits being evaluated. In the outsourced scheme, costs rise as the number of circuits evaluated increases. Linear regression analysis shows we can model execution time T as a function of the number of evaluated circuits k with the equation $T = 243.2k + 334.6$ ms, with a coefficient of determination R^2 of 0.9971. However, note that in the non-outsourced scheme, execution time increases over 10 times as quickly compared to outsourced evaluation. Regression analysis shows execution time $T = 5435.7k + 961$ ms, with $R^2 = 0.9998$. Because in this latter case, the mobile device needs to perform all computation locally as well as transmit all circuit data to the remote parties, these costs increase rapidly. Figure 6 provides more detail about each phase of execution. Note that the OT costs are similar between outsourced and non-outsourced execution for this circuit size, but that the costs of consistency checks and evaluation vastly increase execution time for non-outsourced execution.

Note as well that in the non-outsourced scheme, there are no reported values for 256 circuits, as the Galaxy Nexus phone ran out of memory before the execution completed. We observe that a single process on the phone is capable of allocating 512 MB of RAM before the phone would report an out of memory error, providing insight into how much intermediate state is required for non-outsourced evaluation. Thus, to handle circuits of any meaningful size with enough check circuits for a strong security parameter, the *only way* to be able to perform these operations is through outsourcing.

Table 1 presents the execution time of a representative subset of circuits that we evaluated. It spans circuits from small to large input size, and from 8 circuits evaluated to the 256 circuits required for a 2^{-80} security parameter. Note that in many cases it is impossible to evaluate the non-outsourced computation because of the mobile device's inability to store sufficient amounts of state. Note as well that particularly with complex circuits such as set intersection, even when the non-outsourced evaluation is capable of returning an answer, it can require orders of

	8 Circuits		32 Circuits		128 Circuits		256 Circuits	
Program	Outsourced	KSS	Outsourced	KSS	Outsourced	KSS	Outsourced	KSS
Millionaires 128	2150.0 ± 1%	6130.0 ± 0.6%	8210.0 ± 3%	23080.0 ± 0.6%	38100.0 ± 7%	91020.0 ± 0.8%	75700.0 ± 1%	180800.0 ± 0.5%
Millionaires 1024	4670.0 ± 6%	46290.0 ± 0.4%	17800.0 ± 1%	180500.0 ± 0.3%	75290.0 ± 1%	744500.0 ± 0.7%	151000.0 ± 1%	1507000.0 ± 0.5%
Millionaires 8192	17280.0 ± 0.9%	368800.0 ± 0.4%	76980.0 ± 0.5%	1519000.0 ± 0.4%	351300.0 ± 0.7%	-	880000.0 ± 20%	-
Edit Distance 2	1268.0 ± 0.9%	794.0 ± 1%	4060.0 ± 1%	2125.0 ± 0.7%	19200.0 ± 2%	7476.0 ± 0.5%	42840.0 ± 0.4%	14600.0 ± 0.8%
Edit Distance 32	2860.0 ± 3%	44610.0 ± 0.7%	7470.0 ± 5%	175600.0 ± 0.5%	30500.0 ± 3%	699000.0 ± 2%	63600.0 ± 1%	-
Edit Distance 128	12800.0 ± 2%	702400.0 ± 0.5%	30300.0 ± 2%	2805000.0 ± 0.8%	106200.0 ± 0.6%	-	213400.0 ± 0.3%	-
Set Intersection 2	1598.0 ± 0.8%	1856.0 ± 0.9%	5720.0 ± 0.7%	6335.0 ± 0.4%	26100.0 ± 2%	24420.0 ± 0.6%	56350.0 ± 0.8%	48330.0 ± 0.6%
Set Intersection 32	5200.0 ± 10%	96560.0 ± 0.6%	13800.0 ± 1%	400800.0 ± 0.6%	59400.0 ± 1%	-	125300.0 ± 0.9%	-
Set Intersection 128	24300.0 ± 2%	1398000.0 ± 0.4%	55400.0 ± 3%	5712000.0 ± 0.4%	1998000.0 ± 0.5%	-	395200.0 ± 0.8%	-
AES-128	2450.0 ± 2%	15040.0 ± 0.7%	9090.0 ± 5%	58920.0 ± 0.5%	39000.0 ± 2%	276200.0 ± 0.6%	81900.0 ± 1%	577900.0 ± 0.5%

Table 1: Execution time (in ms) of outsourced vs non-outsourced (KSS) evaluation for a subset of circuits. Results with a dash indicate evaluation that the phone was incapable of performing.

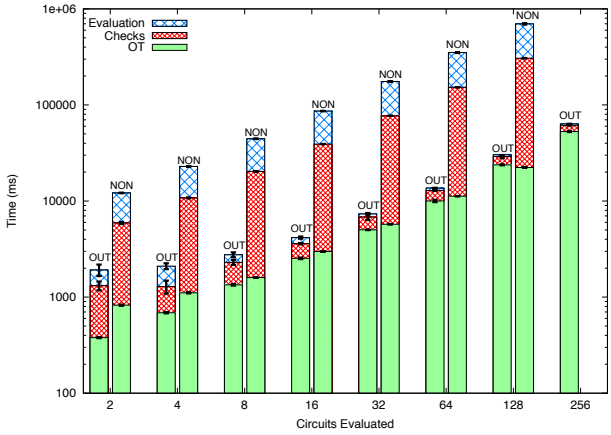


Figure 6: Microbenchmarks of execution time for Edit Distance with input size 32, evaluating from 2 to 256 circuits. Note that the y-axis is log-scale; consequently, the vast majority of execution time is in the check and evaluation phases for non-outsourced evaluation.

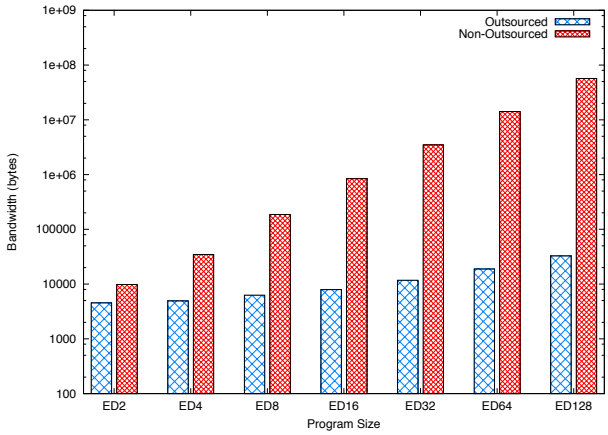


Figure 7: Bandwidth measurements from the phone to remote parties for the Edit Distance problem with varying input sizes, executing two circuits.

magnitude more time than with outsourced evaluation. For example, evaluating the set intersection problem with 128 inputs over 32 circuits requires just over 55 seconds for outsourced evaluation but *over an hour and a half* with the non-outsourced *KSS* execution scheme. Outsourced evaluation represents a time savings of 98.92%. For space concerns, we have omitted certain values; full results can be found in our technical report [6].

Multicore Circuit Evaluation We briefly note the effects of multicore servers for circuit evaluation. The servers in our evaluation each contain dual 6-core CPUs, providing 12 total cores of computation. The computation process is largely CPU-bound: while circuits on the servers are being evaluated, each core was reporting approximately 100% utilization. This is evidenced by regression analysis when evaluating between 2 and 12 circuit copies; we find that execution time $T = 162.6k + 1614.6$ ms, where k is the number of circuits evaluated, with a coefficient of determination R^2 of 0.9903. As the number of circuits to be evaluated increases beyond the number of available cores, the incremental costs of adding new circuits becomes higher; in our observation of execution time for 12 to 256 circuits, our regression analysis provided the equation $T = 247.4k - 410.6$ ms, with $R^2 = 0.998$. This demonstrates that evaluation of large numbers of circuits is optimal when every evaluated circuit can be provided with a dedicated core.

The results above show that as many-way servers are deployed in the cloud, it becomes easier to provide optimal efficiency computing outsourced circuits. A 256-core machine would be able to evaluate 256 circuits in parallel to provide the accepted standard 2^{-80} security parameter. Depending on the computation performed, there can be a trade-off between a slightly weaker security parameter and maintaining *optimal* evaluation on servers with lower degrees of parallelism. In our testbed, optimal evaluation with 12 cores provides a security parameter of $2^{-3.84}$. Clearly more cores would provide stronger security while keeping execution times proportional to our results. A reasonable trade-off might be 32 circuits, as 32-core servers are readily available. Evaluating 32 circuits provides a security parameter of $2^{-10.2}$, equivalent to the adversary having less than a $\frac{1}{512}$ chance of causing the evaluator to compute over a majority of corrupt circuits. Stronger security guarantees on less par-

	32 Circuits		Factor
Program	Outsourced	KSS	Improvement
Millionaires 128	336749	1445369	4.29X
Millionaires 1024	2280333	11492665	5.04X
Millionaires 8192	17794637	91871033	5.16X
Edit Distance 2	56165	117245	2.09X
Edit Distance 32	134257	41889641	312.01X
Edit Distance 128	350721	682955633	1947.29X
Set Intersection 2	117798	519670	4.41X
Set Intersection 32	1173844	84841300	72.28X
Set Intersection 128	4490932	1316437588	293.13X
AES-128	367364	9964576	27.12X

Table 2: Total Bandwidth (Bytes) transmitted to and from the phone during execution.

allel machines can be achieved at the cost of increasing execution time, as individual cores will not be dedicated to circuit evaluation. However, if a 256-core system is available, it will provide optimal results for achieving a 2^{-80} security parameter.

6.4 Bandwidth

For a mobile device, the costs of transmitting data are intrinsically linked to power consumption, as excess data transmission and reception reduces battery life. Bandwidth is thus a critical resource constraint. In addition, because of potentially uncertain communication channels, transmitting an excess of information can be a rate-limiting factor for circuit evaluation. Figure 7 shows the bandwidth measurement between the phone and remote parties for the edit distance problem with 2 circuits. When we compared execution time for this problem in Figure 3, we found that trivially small circuits could execute in less time without outsourcing. Note, however, that *there are no cases where the non-outsourced scheme consumes less bandwidth than with outsourcing*.

This is a result of the significant improvements garnered by using our outsourced oblivious transfer (OOT) construction described in Section 4. Recall that with the OOT protocol, the mobile device sends inputs for evaluation to the generator; however, after this occurs, the majority of computation until the final output verification from the cloud occurs between the generator and the cloud, with the mobile device only performing minor consistency checks. Figure 7 shows that the amount of data transferred increases only nominally compared to the non-outsourced protocol. Apart from the initial set of inputs transmitted to the generator, data demands are largely constant. This is further reflected in Table 2, which shows the vast bandwidth savings over the 32-circuit evaluation of our representative programs. In particular, for large, complex circuits, the savings are vast: outsourced AES-128 requires 96.3% less bandwidth, while set intersection of size 128 requires 99.7% less bandwidth than in the non-outsourced evaluation. Remarkably, the edit distance 128 problem requires 99.95%, *over 1900 times less bandwidth*, for outsourced execution. The full table is in our technical report [6].

The takeaway from our evaluation is simple: outsourcing the computation allows for faster and larger circuit evaluation than previously possible on a mobile device. Specifically, outsourcing allows users to evaluate garbled circuits with adequate malicious model security (256 circuits), which was previously not possible on mobile devices. In addition, outsourcing is by far the most efficient option if the bandwidth use of the mobile devices is a principle concern.

7 Evaluating Large Circuits

Beyond the standard benchmarks for comparing garbled circuit execution schemes, we aimed to provide compelling applications that exploit the mobile platform with large circuits that would be used in real-world scenarios. We discuss public-key cryptography and the Dijkstra shortest path algorithm, then describe how the latter can be used to implement a privacy-preserving navigation application for mobile phones.

7.1 Large Circuit Benchmarks

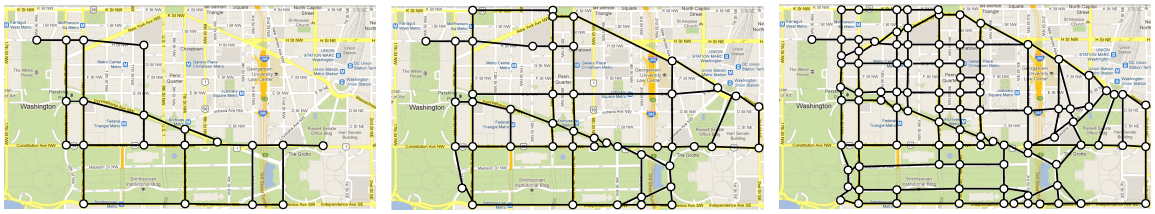
Table 3 shows the execution time required for a blinded RSA circuit of input size 128. For these tests we used a more powerful server with 64 cores and 1 Terabyte of memory. Our testbed is able to give dedicated CPUs when running 32 circuits in parallel. Each circuit would have 1 core for the generation and 1 core for the evaluation. As described in Section 6, larger testbeds capable of executing 128 or 256 cores in parallel would be able to provide similar results for executing the 256 circuits necessary for a 2^{-80} security parameter as they could evaluate the added circuits in parallel. The main difference in execution time would come from the multiple OTs from the mobile device to the outsourced proxy. The RSA circuit has been previously evaluated with *KSS*, but never from the standpoint of a mobile device.

We only report the outsourced execution results, as the circuits are far too large to evaluate directly on the phone. As with the larger circuits described in Section 6, the phone runs out of memory from merely trying to store a representation of the circuit. Prior to optimization, the blinded RSA circuit is $192,537,834$ gates and afterward, comprises $116,083,727$ gates, or 774 MB in size.

The implementation of Dijkstra's shortest-path algorithm results in very large circuits. As shown in Table 3, the pre-optimized size of the shortest path circuit for 20 vertices is $20,288,444$ gates and after optimization is $1,653,542$ gates. The 100-node graph is even larger, with $168,422,382$ gates post optimization, 1124 MB in size. This final example is among the largest evaluated

	32 Circuits Time (ms)	64 Circuits (ms)	128 Circuits (ms)	Optimized Gates	Unoptimized Gates	Size (MB)
RSA128	505000.0 ± 2%	734000.0 ± 4%	1420000.0 ± 1%	116,083,727	192,537,834	774
Dijkstra20	25800.0 ± 2%	49400.0 ± 1%	106000.0 ± 1%	1,653,542	20,288,444	11
Dijkstra50	135000.0 ± 1%	197000.0 ± 3%	389000.0 ± 2%	22,109,732	301,846,263	147
Dijkstra100	892000.0 ± 2%	1300000.0 ± 2%	2560000.0 ± 1%	168,422,382	2,376,377,302	1124

Table 3: Execution time for evaluating a 128-bit blinded RSA circuit and Dijkstra shortest path solvers over graphs with 20, 50, and 100 vertices. All numbers are for outsourced evaluation, as the circuits are too large to be computed without outsourcing to a proxy.



(a) 20 identified intersections. (b) 50 identified intersections. (c) 100 identified intersections.

Figure 8: Map of potential presidential motorcade routes through Washington, DC. As the circuit size increases, a larger area can be represented at a finer granularity.

garbled circuits to date. While it may be possible for existing protocols to evaluate circuits of similar size, it is significant that we are evaluating comparably massive circuits from a resource-constrained mobile device.

7.2 Privacy-Preserving Navigation

Mapping and navigation are some of the most popular uses of a smartphone. Consider how directions may be given using a mobile device and an application such as Google Maps, without revealing the user's current location, their ultimate destination, or the route that they are following. That is, the navigation server should remain oblivious of these details to ensure their mutual privacy and to prevent giving away potentially sensitive details if the phone is compromised. Specifically, consider planning of the motorcade route for the recent Presidential inauguration. In this case, the route is generally known in advance but is potentially subject to change if sudden threats emerge. A field agent along the route wants to receive directions without providing the navigation service any additional details, and without sensitive information about the route loaded to the phone. Moreover, because the threats may be classified, the navigation service does not want the holder of the phone to be given this information directly. In our example, the user of the phone is trying to determine the shortest path.

To model this scenario, we overlay a graph topology on a map of downtown Washington D.C., encoding intersections as vertices. Edge weights are a function of their distance and heuristics such as potential risks along a graph edge. Figure 8 shows graphs generated based on vertices of 20, 50, and 100 nodes, respectively. Note that the 100-node graph (Figure 8c) encompasses a larger area and provides finer-grained resolution of individual intersections than the 20-node graph (Figure 8a).

There is a trade-off between detail and execution time, however; as shown in Table 3, a 20-vertex graph can be evaluated in under 26 seconds, while a 100-vertex graph requires almost 15 minutes with 32 circuits in our 64-core server testbed. The 64 circuit evaluation requires more time: almost 50 seconds for the 20-vertex graph, and almost 22 minutes for a 100-vertex graph. We anticipate that based on the role a particular agent might have on a route, they will be able to generate a route that covers their particular geographical jurisdiction and thus have an appropriately sized route, with only certain users requiring the highest-resolution output. Additionally, as described in Section 6.3, servers with more parallel cores can simultaneously evaluate more circuits, giving faster results for the 64 circuit evaluation.

Figure 9 reflects two routes. The first, overlaid with a dashed blue line, is the shortest path under optimal conditions that is output by our directions service, based on origin and destination points close to the historical start and end points of the past six presidential inaugural motorcades. Now consider that incidents have happened along the route, shown in the figure as a car icon in a hazard zone inside a red circle. The agent recalculates the optimal route, which has been updated by the navigation service to assign severe penalties to those corresponding graph edges. The updated route returned by the navigation service is shown in the figure as a path with a dotted purple line. In the 50-vertex graph in Figure 8, the updated directions would be available in just over 135 seconds for 32-circuit evaluation, and 196 and a half seconds for 64-circuit evaluation.

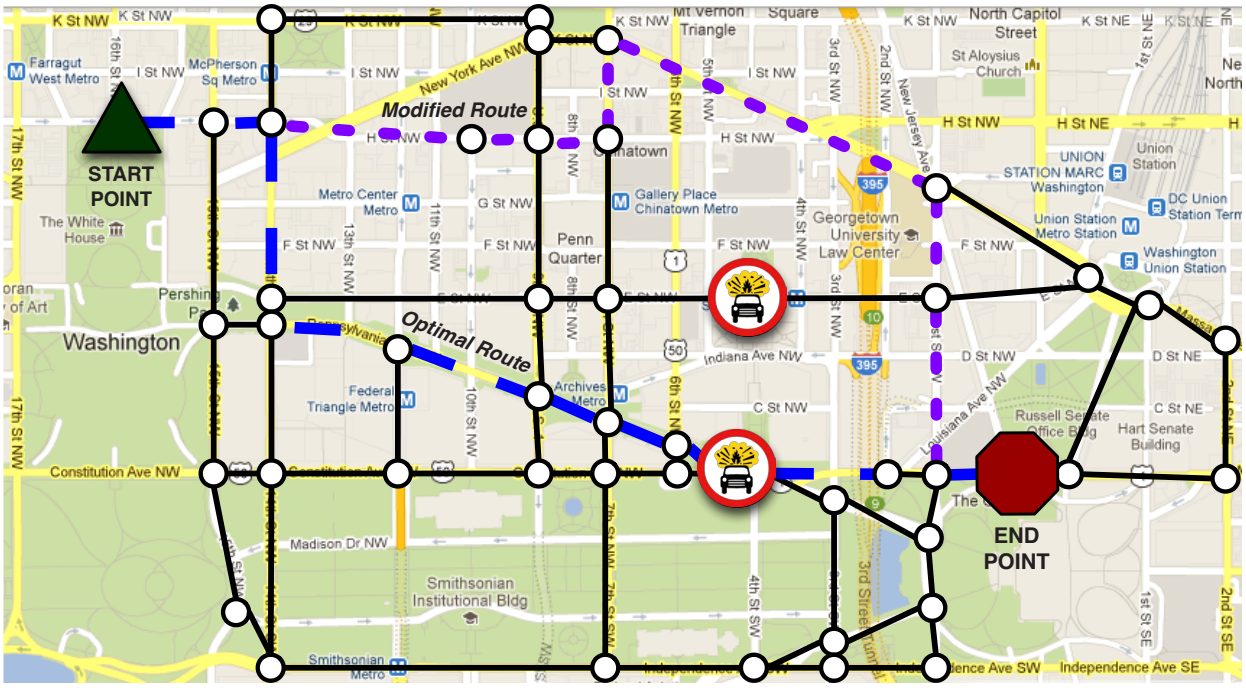


Figure 9: Motorcade route with hazards along the route. The dashed blue line represents the optimal route, while the dotted violet line represents the modified route that takes hazards into account.

8 Conclusion

While garbled circuits offer a powerful tool for secure function evaluation, they typically assume participants with massive computing resources. Our work solves this problem by presenting a protocol for outsourcing garbled circuit evaluation from a resource-constrained mobile device to a cloud provider in the malicious setting. By extending existing garbled circuit evaluation techniques, our protocol significantly reduces both computational and network overhead on the mobile device while still maintaining the necessary checks for malicious or lazy behavior from all parties. Our outsourced oblivious transfer construction significantly reduces the communication load on the mobile device and can easily accommodate more efficient OT primitives as they are developed. The performance evaluation of our protocol shows dramatic decreases in required computation and bandwidth. For the edit distance problem of size 128 with 32 circuits, computation is reduced by 98.92% and bandwidth overhead reduced by 99.95% compared to non-outsourced execution. These savings are illustrated in our privacy-preserving navigation application, which allows a mobile device to efficiently evaluate a massive garbled circuit securely through outsourcing. These results demonstrate that the recent improvements in garbled circuit efficiency can be applied in practical privacy-preserving mobile applications on even the most resource-constrained devices.

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References

[1] M. Bellare and S. Micali. Non-interactive oblivious transfer and applications. In *Advances in Cryptology–CRYPTO*, 1990.

[2] M. Ben-Or, S. Goldwasser, and A. Wigderson. Completeness theorems for non-cryptographic fault-tolerant distributed computation. In *Proceedings of the annual ACM symposium on Theory of computing*, 1988.

[3] J. Brickell and V. Shmatikov. Privacy-preserving graph algorithms in the semi-honest model. In *Proceedings of the international conference on Theory and Application of Cryptology and Information Security*, 2005.

[4] R. Canetti, Y. Lindell, R. Ostrovsky, and A. Sahai. Universally composable two-party and multi-party secure computation. In *Proceedings of the annual ACM symposium on Theory of computing*, 2002.

[5] H. Carter, C. Amrutkar, I. Dacosta, and P. Traynor. Efficient oblivious computation techniques for privacy-preserving mobile applications. *Journal of Security and Communication Networks (SCN)*, To appear 2013.

[6] H. Carter, B. Mood, P. Traynor, and K. Butler. Secure outsourced garbled circuit evaluation for mobile devices. Technical Report GT-CS-12-09, College of Computing, Georgia Institute of Technology, 2012.

[7] D. Chaum, C. Crépeau, and I. Damgard. Multiparty unconditionally secure protocols. In *Proceedings of the annual ACM symposium on Theory of computing*, 1988.

[8] S. G. Choi, J. Katz, R. Kumaresan, and H.-S. Zhou. On the security of the "free-xor" technique. In *Proceedings of the international conference on Theory of Cryptography*, 2012.

[9] I. Damgård and Y. Ishai. Scalable secure multiparty computation. In *Proceedings of the annual international conference on Advances in Cryptology*, 2006.

[10] I. Damgård and J. B. Nielsen. Scalable and unconditionally secure multiparty computation. In *Proceedings of the annual international cryptology conference on Advances in cryptology*, 2007.

[11] V. Goyal, P. Mohassel, and A. Smith. Efficient two party and multi party computation against covert adversaries. In *Proceedings of the theory and applications of cryptographic techniques annual international conference on Advances in cryptology*, 2008.

[12] M. Green, S. Hohenberger, and B. Waters. Outsourcing the decryption of abe ciphertexts. In *Proceedings of the USENIX Security Symposium*, 2011.

[13] Y. Huang, P. Chapman, and D. Evans. Privacy-Preserving Applications on Smartphones. In *Proceedings of the USENIX Workshop on Hot Topics in Security*, 2011.

[14] Y. Huang, D. Evans, and J. Katz. Private set intersection: Are garbled circuits better than custom protocols? In *NDSS '12: Proceedings of the 19th ISOC Symposium on Network and Distributed Systems Security*, San Diego, CA, USA, Feb. 2012.

[15] Y. Huang, D. Evans, J. Katz, and L. Malka. Faster secure two-party computation using garbled circuits. In *Proceedings of the USENIX Security Symposium*, 2011.

[16] Y. Huang, J. Katz, and D. Evans. Quid-pro-quotocols: Strengthening semi-honest protocols with dual execution. In *Proceedings of the IEEE Symposium on Security and Privacy*, 2012.

[17] A. Iliev and S. W. Smith. Small, stupid, and scalable: Secure computing with faerieplay. In *The ACM Workshop on Scalable Trusted Computing*, 2010.

[18] Y. Ishai, J. Kilian, K. Nissim, and E. Petrank. Extending oblivious transfers efficiently. In *Proceedings of the Annual International Cryptology Conference*, 2003.

[19] S. Jha, L. Kruger, and V. Shmatikov. Towards practical privacy for genomic computation. In *Proceedings of the IEEE Symposium on Security and Privacy*, 2008.

[20] S. Kamara, P. Mohassel, and M. Raykova. Outsourcing multi-party computation. Cryptology ePrint Archive, Report 2011/272, 2011. `http://eprint.iacr.org/`.

[21] S. Kamara, P. Mohassel, and B. Riva. Salus: A system for server-aided secure function evaluation. In *Proceedings of the ACM conference on Computer and communications security (CCS)*, 2012.

[22] M. S. Kiraz. *Secure and Fair Two-Party Computation*. PhD thesis, Technische Universiteit Eindhoven, 2008.

[23] M. S. Kiraz and B. Schoenmakers. A protocol issue for the malicious case of yaos garbled circuit construction. In *Proceedings of Symposium on Information Theory in the Benelux*, 2006.

[24] V. Kolesnikov and T. Schneider. Improved garbled circuit: Free xor gates and applications. In *Proceedings of the international colloquium on Automata, Languages and Programming, Part II*, 2008.

[25] B. Kreuter, a. shelat, and C. Shen. Billion-gate secure computation with malicious adversaries. In

Proceedings of the USENIX Security Symposium, 2012.

[26] L. Kruger, S. Jha, E.-J. Goh, and D. Boneh. Secure function evaluation with ordered binary decision diagrams. In *Proceedings of the ACM conference on Computer and communications security (CCS)*, 2006.

[27] Y. Lindell. Lower bounds and impossibility results for concurrent self composition. *Journal of Cryptology*, 21(2):200–249, 2008.

[28] Y. Lindell and B. Pinkas. Privacy preserving data mining. In *Proceedings of the Annual International Cryptology Conference on Advances in Cryptology*, 2000.

[29] Y. Lindell and B. Pinkas. An efficient protocol for secure two-party computation in the presence of malicious adversaries. In *Proceedings of the annual international conference on Advances in Cryptology*, 2007.

[30] Y. Lindell and B. Pinkas. Secure two-party computation via cut-and-choose oblivious transfer. In *Proceedings of the conference on Theory of cryptography*, 2011.

[31] L. Malka. Vmcrypt: modular software architecture for scalable secure computation. In *Proceedings of the 18th ACM conference on Computer and communications security*, 2011.

[32] D. Malkhi, N. Nisan, B. Pinkas, and Y. Sella. Fairplay–a secure two-party computation system. In *Proceedings of the USENIX Security Symposium*, 2004.

[33] Message Passing Interface Forum. The message passing interface (mpi) standard. `http://www.mcs.anl.gov/research/projects/mpi/`, 2009.

[34] P. Mohassel and M. Franklin. Efficiency tradeoffs for malicious two-party computation. In *Proceedings of the Public Key Cryptography conference*, 2006.

[35] B. Mood, L. Letaw, and K. Butler. Memory-efficient garbled circuit generation for mobile devices. In *Proceedings of the IFCA International Conference on Financial Cryptography and Data Security (FC)*, 2012.

[36] M. Naor and B. Pinkas. Efficient oblivious transfer protocols. In *Proceedings of the annual ACM-SIAM symposium on Discrete algorithms*, 2001.

[37] M. Naor, B. Pinkas, and R. Sumner. Privacy preserving auctions and mechanism design. In *Proceedings of the ACM conference on Electronic commerce*, 1999.

[38] N. Nipane, I. Dacosta, and P. Traynor. "Mix-In-Place" anonymous networking using secure function evaluation. In *Proceedings of the Annual Computer Security Applications Conference (ACSAC)*, 2011.

[39] C. Peikert, V. Vaikuntanathan, and B. Waters. A framework for efficient and composable oblivious transfer. In *Advances in Cryptology (CRYPTO)*, 2008.

[40] W. Rash. Dropbox password breach highlights cloud security weaknesses. `http://www.eweek.com/c/a/Security/Dropbox-Password-Breach-Highlights-Cloud-Security-Weaknesses-266215/`, 2012.

[41] a. shelat and C.-H. Shen. Two-output secure computation with malicious adversaries. In *Proceedings of the Annual international conference on Theory and applications of cryptographic techniques*, 2011.

[42] K. Thomas. Microsoft cloud data breach heralds things to come. `http://www.pcworld.com/article/214775/microsoft_cloud_data_breach_sign_of_future.html`, 2010.

[43] A. C. Yao. Protocols for secure computations. In *Proceedings of the Annual Symposium on Foundations of Computer Science*, 1982.