Secure Computation with Constant Communication Overhead using Multiplication Embeddings*

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Abstract

Secure multi-party computation (MPC) allows mutually distrusting parties to compute securely over their private data. The hardness of MPC, essentially, lies in performing secure multiplications over suitable algebras.

There are several cryptographic resources that help securely compute one multiplication over a large finite field, say $\mathbb{GF}[2^n]$, with linear communication complexity. For example, the computational hardness assumption like noisy Reed-Solomon codewords are pseudorandom. However, it is not known if we can securely compute, say, a linear number of AND-gates from such resources, i.e., a linear number of multiplications over the base field $\mathbb{GF}[2]$. Before our work, we could only perform $o(n)$ secure AND-evaluations.

Technically, we construct a perfectly secure protocol that realizes a linear number of multiplication gates over the base field using one multiplication gate over a degree-n extension field. This construction relies on the toolkit provided by algebraic function fields.

Using this construction, we obtain the following results. We provide the first construction that computes a linear number of oblivious transfers with linear communication complexity from the computational hardness assumptions like noisy Reed-Solomon codewords are pseudorandom, or arithmetic-analogues of LPN-style assumptions. Next, we highlight the potential of our result for other applications to MPC by constructing the first correlation extractor that has 1/2 resilience and produces a linear number of oblivious transfers.

Keywords and phrases Secure Computation, Multiplication Embeddings, Oblivious Transfer, Basis-independent Circuit Computation, Leakage-resilient Cryptography, Randomness Extractors

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Contents

1 Introduction

Secure multi-party computation [GMW87, Yao82] (MPC) allows mutually distrusting parties to compute securely over their private data. Even when parties follow the protocols honestly, but are curious to find additional information about other parties' private inputs, most functionalities cannot be securely computed [Bea89, IL89, Kil88, Kus89]. So, we rely on diverse forms of cryptographic resources to help parties perform computations over their private data. These cryptographic resources can either be computational hardness assumptions [GMW87, IPS08] or physical resources like noisy channels [BMM99, CK88, Kil91, Kil00], correlated private randomness [Kil00, WW06], trusted resources [CLOS02, IPS08, IPS09], and tamper-proof hardware [CGS08, DNW08, Kat07, MS08].

In this paper, for the simplicity of exposition of the key ideas, we consider 2-party secure computation against honest-but-curious adversaries. Suppose two parties are interested in securely computing a boolean circuit C that uses AND, and XOR, and represent the input, output, and the intermediate values of the computation in binary. Parties can use the oblivious transfer (OT) functionality to securely compute C (with perfect security and linear communication complexity) using the GMW protocol [GMW87]. The OT functionality takes as input a pair of bits (x_0, x_1) from the sender and a choice bit b from the receiver, and outputs the bit x_b to the receiver. Notice Alice does not know Bob's choice bit b, and Bob does not know Alice's other bit x_{1-b}. Parties perform m calls to the OT functionality to securely compute circuits that have m AND gates (and an arbitrary number of XOR gates) with $\Theta(m)$ communication complexity. In this work, we consider secure computation protocols that have communication complexity proportional to the size of the circuit C.[1]

Parties can also compute arithmetic circuits that use MUL and ADD gates over large fields by emulating the arithmetic gates using finite fields. In particular, using efficient bilinear multiplication algorithms [CC87], parties can securely compute one multiplication over the finite field $\mathbb{GF}[2^n]$ by performing m OT calls and linear communication complexity, where $n = \Theta(m)$. In general, using m OT calls, parties can securely compute any circuit C that has m_i arithmetic gates over $\mathbb{GF}[2^{n_i}]$, for $i \in \mathbb{N}$, such that $\sum_i m_i \cdot n_i = \Theta(m)$, which measures the *size of* C. Intuitively, the size of the arithmetic circuit C refers to the cumulative size of representing the elements of the (multiplication) gates in the circuit.

Summarizing this discussion, we conclude that m OT calls help the parties securely compute arithmetic circuits (over characteristic 2 fields) of size $\Theta(m)$ with communication complexity $\Theta(m)$. Several cryptographic resources can implement the m instances of the OT functionality using a linear communication complexity. For example, there are instantiations based on polynomial-stretch local pseudorandom generators [IKOS08], the Phi-hiding assumption [IKOS09], LWE [DHRW16], DDH-hard groups [BGI17], and noisy channels [IKO+11]. By composing these protocols, parties can use the corresponding cryptographic resources and securely compute linear-size circuits using only linear communication.

On the other hand, there are cryptographic resources that directly enable secure multiplication over a large extension field using communication that is proportional to the size of the field. For example, consider the constructions based on Paillier encryption [DJ01, Gil99, Pai99], LWE [DPSZ12, LPR10], pseudorandomness of noisy random Reed-Solomon codewords [IPS09, NP06], and arithmetic analogues of well-studied cryptographic assumptions [ADI+17]. The key functionality in this context is a generalization of the OT func-

[1] Network latency considerations typically motivate the study of MPC protocols with linear communication complexity.

tionality, namely the Oblivious Linear-function Evaluation [WW06] (OLE) over a field $\mathbb{K}$, say $\mathbb{K} = \mathbb{GF}[2^n]$. The OLE functionality takes as input a pair of field elements $(A, B) \in \mathbb{K}^2$ from the sender and an element $X \in \mathbb{K}$ from the receiver, and outputs the linear evaluation $Z = A \cdot X + B$ to the receiver. Note that, for $x_0, x_1, b \in \mathbb{GF}[2]$, we have $x_b = (x_0 + x_1)b + x_0$, i.e., OT is a particular instantiation of the OLE functionality. Using (the generalization of) the GMW protocol, parties can compute one multiplication over $\mathbb{K}$ with $\Theta(\lg|\mathbb{K}|)$ communication complexity. Note that the circuit with one MUL gate (over $\mathbb{K}$) has size $\lg|\mathbb{K}|$, so the communication complexity of the protocol is linear in the circuit size. However, using OLE over $\mathbb{K} = \mathbb{GF}[2^n]$, *can we securely compute boolean circuits such that the communication complexity is linear in the circuit size?*

The question motivated above with the illustrative example of $\mathbb{K} = \mathbb{GF}[2^n]$ and $\mathbb{F} = \mathbb{GF}[2]$ generalizes to any $\mathbb{K}$ that is an extension field of a constant-size base field $\mathbb{F}$. Before our work, the best solution securely evaluated size $m = o(n)$ boolean circuits using $\Theta(n) = \omega(m)$ communication complexity from one OLE over $\mathbb{GF}[2^n]$ (refer to Section 1.3 for the state-of-the-art construction). We present the first solution that securely evaluates size $m = \Theta(n)$ boolean circuits using one OLE over $\mathbb{GF}[2^n]$ and, thus, has communication complexity linear in the circuit size. Additionally, we found secure computation of size-m boolean circuits using linear communication from more diverse cryptographic resources. Because, any cryptographic resource that securely implements OLE over $\mathbb{K}$ with a linear communication complexity, also enables the secure computation of linear-size boolean circuits with a linear communication complexity. In particular, we provide the first linear communication protocols for m OTs from cryptographic hardness assumptions such as the pseudorandomness of noisy Reed-Solomon codewords [IPS09, NP06] and arithmetic analogues of well-studied cryptographic assumptions [ADI+17].

1.1 Multiplication Embedding Problem

Our approach to the MPC problem begins with the following combinatorial embedding problem, which was originally introduced by Block, Maji, and Nguyen [BMN17] in the context of leakage-resilient MPC. Let $\mathbb{F}$ be a finite field. Alice has private input $\mathbf{a} = (a_1, \ldots, a_m) \in \mathbb{F}^m$ and Bob has private input $\mathbf{b} = (b_1, \ldots, b_m) \in \mathbb{F}^m$. The two parties want Bob to receive the output $\mathbf{c} = (c_1, \ldots, c_m) \in \mathbb{F}^m$ such that $c_i = a_i \cdot b_i$, for all $i \in \{1, \ldots, m\}$.

Alice and Bob have access to an oracle that takes input $A \in \mathbb{K}$ from Alice and $B \in \mathbb{K}$ from Bob, where $\mathbb{K}$ is a degree-n extension of the field $\mathbb{F}$, and outputs $C = A \cdot B$ to Bob. Alice and Bob want to perform only one call to this oracle and enable Bob to compute $\mathbf{c}$. Note that Alice and Bob perform *no additional interactions*. Given a fixed value of n and a particular base field $\mathbb{F}$, how large can m be?

The prior work of Block et al. [BMN17] constructed an embedding that achieved $m = n^{1-o(1)}$ using techniques from additive combinatorics. This paper, using algebraic function fields, provides an asymptotically optimal $m = \Theta(n)$ construction. Section 1.2 summarizes our results and a few of its consequences for MPC.

Recent Independent Work. Recently, in an independent work, Cascudo et al. [CCXY18] (CRYPTO-2018) also studied this embedding problem as reverse multiplication-friendly embeddings (RMFE), and provide a constant-rate construction. They use this result to achieve new amortization results in MPC.

1.2 Our Contributions

Given two vectors $\mathbf{a} = (a_1, \ldots, a_m) \in \mathbb{F}^m$ and $\mathbf{b} = (b_1, \ldots, b_m) \in \mathbb{F}^m$, we represent their Schur product as the vector $\mathbf{a} * \mathbf{b} = (a_1 \cdot b_1, \ldots, a_m \cdot b_m)$. We prove the following theorem.

▶ **Theorem 1** (Embedding Theorem). *Let $\mathbb{F}_q$ be a finite field of size q, a power of a prime. There exist constants $c_q^* \in \{1, 2, 3, 4, 6\}$, $c_q > 0$, and $n_0 \in \mathbb{N}$ such that for all $n \geqslant n_0$ where c_q^* divides n, there exist (linear) maps $E \colon \mathbb{F}_q^m \to \mathbb{K}$ and $D \colon \mathbb{K} \to \mathbb{F}_q^m$, where $\mathbb{K}$ is the degree-n extension of the field $\mathbb{F}_q$, such that the following constraints are satisfied.*
1. *We have $m \geqslant c_q n$, and*
2. *For all $\mathbf{a}, \mathbf{b} \in \mathbb{F}_q^m$, we have: $D\big(E(\mathbf{a}) \cdot E(\mathbf{b})\big) = \mathbf{a} * \mathbf{b}$.*

Intuitively, an oracle that implements one multiplication over a degree-n extension field $\mathbb{K}$ facilitates the computation of $m = \Theta(n)$ multiplications over the base field $\mathbb{F}$. For instance, assuming the base field $\mathbb{F} = \mathbb{GF}[2]$, our result shows that we can implement $m = \Theta(n)$ AND gates, which are equivalent to the MUL arithmetic gates over the $\mathbb{GF}[2]$, by performing only one call to the functionality that implements MUL over $\mathbb{K} = \mathbb{GF}[2^n]$. Section 1.3 presents a summary of the intuition that inspired our construction, and Section 2 provides the required technical background, and Section 2.2 presents the proof of Theorem 1.

Consequences for MPC. Recall that the OLE functionality over the field $\mathbb{K}$ takes as input (A, B) from the sender and X from the receiver, and outputs $Z = A \cdot X + B$ to the receiver. Essentially, OLE over the field $\mathbb{K}$ generates an additive secret share $(-B, Z)$ of the product $A \cdot X$. The embedding of Theorem 1 also helps Alice and Bob implement m independent OLEs over the base field $\mathbb{F}$, represented by the $\mathsf{OLE}(\mathbb{F})^m$ functionality, using one OLE over the extension field $\mathbb{K}$.

▶ **Theorem 2.** *Let $\mathbb{F}$ be a finite field, and $\mathbb{K}$ be a degree-n extension of $\mathbb{F}$. There exists a 2-party semi-honest secure protocol for the $\mathsf{OLE}(\mathbb{F})^m$ functionality in the $\mathsf{OLE}(\mathbb{K})$-hybrid, where $m = \Theta(n)$, that performs only one call to the $\mathsf{OLE}(\mathbb{K})$ functionality (and no additional communication).*

Section 3 provides the proof of Theorem 2 in the semi-honest setting. Continuing our working example of $\mathbb{F} = \mathbb{GF}[2]$, we can implement $m = \Theta(n)$ independent OT functionalities by performing one call to the $\mathsf{OLE}(\mathbb{K})$ functionality.

Using Theorem 2, we can implement a linear number of OTs at a constant communication overhead based on computational hardness assumptions like the pseudorandomness of noisy Reed-Solomon codewords [IPS09, NP06] and arithmetic analogues of well-studied cryptographic assumptions [ADI+17], which help construct an OLE over large (but finite) fields. In general, if a cryptographic resource supports the generation of one OLE over $\mathbb{K}$ using $\Theta(\lg |\mathbb{K}|)$ communication complexity, then the following result also applies to that resource.

▶ **Corollary 1.** *There exists a computationally secure protocol implementing m OTs using $\Theta(m)$ communication based on (any of) the following computational hardness assumptions.*
1. *Pseudorandomness of noisy random Reed-Solomon codewords [IPS09, NP06],*
2. *Arithmetic analogues of "LPN-style assumptions" and the existence of polynomial-stretch local arithmetic PRGs [ADI+17].*

In fact, we can leverage efficient bilinear multiplication algorithms [CC87] that incur a constant communication overhead, to obtain the following result.

▶ **Corollary 2.** *Let $\mathbb{F}$ be a finite field, and $\mathbb{K}$ be a degree-n extension of $\mathbb{F}$. Let $\mathbb{F}_1, \ldots, \mathbb{F}_k$ are finite fields such that $\mathbb{F}_i$ is a degree-n_i extension of the base field $\mathbb{F}$, for $i \in \{1, \ldots, k\}$. Let C*

be a circuit that uses m_i arithmetic gates over the field $\mathbb{F}_i$. If $m_1n_1 + \cdots + m_kn_k \leqslant \Theta(n)$, then there exists a secure protocol for C in the $\mathsf{OLE}(\mathbb{K})$-hybrid that performs only one call to the $\mathsf{OLE}(\mathbb{K})$ functionality.

Section 5 presents Corollary 2 and provides the outline of constant overhead secure computation of $\mathsf{OLE}(\mathbb{F}_i)$ by performing $\Theta(n_i)$ calls to the $\mathsf{OLE}(\mathbb{F})$ functionality, where $\mathbb{F}_i$ is a degree-n_i extension of the base field $\mathbb{F}$. We emphasize that Corollary 2 allows the flexibility to generate the (randomized version of the) $\mathsf{OLE}(\mathbb{K})$ in an offline phase of the computation without the necessity to fix the representation of the computation itself. We only fix the base field $\mathbb{F}$ and an upper-bound n estimating the size of the circuit C.

Finally, using our embedding, instead of the original multiplication embedding of [BMN17], we obtain the following result for correlation extractors (cf., [IKOS09] for definitions and an introduction).

▶ **Corollary 3.** *For every $1/2 \geqslant \varepsilon > 0$, there exists an n-bit correlated private randomness such that, despite $t = (1/2 - \varepsilon)n$ bits of leakage, we can securely construct $m = \Theta(\varepsilon n)$ independent OTs from this leaky correlation.*

Section 4 presents the details of the definition of correlation extractors and the proof of this corollary.

1.3 Technical Overview

To illustrate the underlying idea of our embedding, we use the example where $|\mathbb{F}| = 3n/2$, and $\mathbb{K}$ is a degree-n extension of $\mathbb{F}$. Note that in this intuition the size of the base field implicitly bounds the degree of the extension field $\mathbb{K}$ that we can consider. Ideally, our objective is to obtain multiplication embeddings for small constant-size $\mathbb{F}$ for infinitely many n, which our theorem provides. Nevertheless, we feel that the intuition presented in the sequel assists the reading of the details of Section 2.

Assume that n is even and $m := (n/2 - 1)$. We arbitrarily enumerate the elements in $\mathbb{F}$

$$\mathbb{F} = \{f_{-m}, \ldots, f_{-2}, f_{-1}, f_1, f_2, \ldots, f_{n-1}\}$$

Suppose the field $\mathbb{K}$ is isomorphic to $\mathbb{F}[t]/\pi(t)$, where $\pi(t) \in \mathbb{F}[t]$ is an irreducible polynomial of degree n.

Recall that Alice and Bob have private inputs $\mathbf{a} = (a_1, \ldots, a_m) \in \mathbb{F}^m$ and $\mathbf{b} = (b_1, \ldots, b_m) \in \mathbb{F}^m$. Alice constructs the unique polynomial $A(t) \in \mathbb{F}[t]/\pi(t)$ of degree $< m$ such that $A(f_{-i}) = a_i$, for all $i \in \{1, \ldots, m\}$ using Lagrange interpolation. Similarly, Bob constructs the unique polynomial $B(t) \in \mathbb{F}[t]/\pi(t)$ of degree $< m$ such that $B(f_{-i}) = b_i$, for all $i \in \{1, \ldots, m\}$.

Suppose the two parties have access to an oracle that multiplies two elements of $\mathbb{K}$ and outputs the result to Bob. Upon receiving the inputs $A(t)$ and $B(t)$ from Alice and Bob, respectively, which correspond to elements in $\mathbb{K}$, the oracle outputs the result $C(t) = A(t) \cdot B(t)$ to Bob.[2] Note that $C(t)$ is the convolution of the two polynomials $A(t)$ and $B(t)$. Moreover, it has the property that $C(f_{-i}) = a_i \cdot b_i$, for all $i \in \{1, \ldots, m\}$. So, Bob can evaluate the polynomial $C(t)$ at appropriate places to obtain $\mathbf{c} = \mathbf{a} * \mathbf{b}$.

[2] Note that this is exact polynomial multiplication because the degree of $A(t)$ and $B(t)$ are both $< m$. So, the degree of $C(t)$ is $< 2m - 1 = n$. This observation, intuitively, implies that "$\mod \pi(t)$" does not affect $C(t)$.

Note that this protocol crucially relies on the fact that the field $\mathbb{F}$ has sufficiently many *places* $\{f_{-1}, \dots, f_{-m}\}$ to enable the encoding of $a_1, \dots, a_m$ as the *evaluation* of polynomials at those respective places. For constant-size fields $\mathbb{F}$, this intuition fails to scale to large values of n. So, we use the toolkit of algebraic function fields for a more generalized and formal treatment of these intuitive concepts and construct these multiplication embeddings for *every* base field $\mathbb{F}$.

Prior Best Construction. [BMN17] showed that $(\lg |\mathbb{F}|)^{1-o(1)}$ OTs could be embedded into one OLE over $\mathbb{F}$ if $\mathbb{F}$ has characteristic 2. Overall, this construction yields $s(\log s)^{-o(1)}$ OTs from one OLE over $\mathbb{K}$, where $s = \lg |\mathbb{K}|$.

Reduction of our Construction to Chen and Cramer [CC06]. Chen and Cramer [CC06] construct algebraic geometry codes/secret sharing schemes that have properties similar to the Reed-Solomon codes, except that these linear codes are over finite fields of appropriate size. It is not clear how to rely solely on the distance and independence properties of these codes to get our results. However, the algebraic geometric techniques underlying the construction of [CC06] and our construction have a significant overlap.

2 Embedding Multiplications

Our goal is to embed m multiplications over $\mathbb{F}_q$ using a single multiplication over $\mathbb{F}_{q^n}$ such that $m = \Theta(n)$. To do so, we use algebraic function fields over $\mathbb{F}_q$ with appropriate parameters.

2.1 Preliminaries

We introduce the basics of algebraic function fields necessary for our construction. For explicit details we refer the reader to Appendix A, or works such as [Sti09]. Let $\mathbb{F}_q$ be a finite field of q elements, where q is a power of prime. Then an algebraic function field $K/\mathbb{F}_q$ of one variable over $\mathbb{F}_q$ is a finite algebraic extension of $\mathbb{F}_q(x)$ for some x transcendental over $\mathbb{F}_q$. Recall that $\mathbb{F}_q(x) = \{f(x)/g(x) \colon f, g \in \mathbb{F}_q[x], g \neq 0\}$. When clear from context, we write K in place of $K/\mathbb{F}_q$.

Every function field K has an infinite set of "points" called *places*, denoted by $P \in \mathbb{P}(K)$. Every place P has an associated *degree* $\deg P \in \mathbb{N}$, and for any $k \in \mathbb{N}$, the set $\mathbb{P}^{(k)}(K)$ denotes the set of places of degree k. In particular, for every $k \in \mathbb{N}$, this set is finite, and the set $\mathbb{P}^{(1)}(K)$ is called the set of *rational places*. For every element $f \in K$, and any place P, we can evaluate f at place P, denoted as $f(P)$. Then two cases occur: either f has a *pole* at P, which we denote as $f(P) = \infty$; or f is defined at P. For P which is not a pole of f and $\deg P = k$, we have that $f(P)$ is isomorphic to some element of $\mathbb{F}_{q^k}$. For any two functions f, g and place P such that P is not a pole of f or g, we have that $f(P) + g(P) = (f+g)(P)$, $f(P) \cdot g(P) = (f \cdot g)(P)$, and $xf(P) = (x \cdot f)(P)$ for any $x \in \mathbb{F}_q$. Every place P has an associated *valuation ring* $\mathcal{O}_P$. A valuation ring $\mathcal{O}$ of K is a ring such that $\mathbb{F}_q \subsetneq \mathcal{O} \subsetneq K$ and for every $z \in K$ either $z \in \mathcal{O}$ or $z^{-1} \in \mathcal{O}$.

A *divisor* D of K is a formal sum of places. Namely, $D = \sum_{P \in \mathbb{P}(K)} m_P P$ where $m_P \in \mathbb{Z}$ and $m_P = 0$ for all but finitely many places P. The set of places P where $m_P \neq 0$ is called the *support* of D and is denoted as $\mathsf{Supp}(D)$. Any divisor D also has associated degree $\deg D := \sum_{P \in \mathbb{P}(K)} m_P(\deg P) \in \mathbb{Z}$. Note that every place is also a divisor; namely $P = 1 \cdot P$. Such divisors are called *prime divisors*. For any two divisors $D = \sum m_P P$ and $D' = \sum n_P P$, we define $D + D' = \sum (m_P + n_P)P$. We say that $D \leqslant D'$ if $m_P \leqslant n_P$ for all places P.

For any $f \in K \setminus \{0\}$, the *principal divisor* associated to f is denoted as (f). Informally, the principal divisor $(f) = \sum a_P P$ for places P, where $a_P = 0$ if P is not a zero or a pole of f, $a_P > 0$ if P is a pole of f of order a_P, and $a_P < 0$ if P is a zero of f of order $|a_P|$. Given any divisor D, we can define the *Riemann-Roch space* associated to D. This space is defined as $\mathscr{L}(D) := \{f \in K : (f) + D \geqslant 0\} \cup \{0\}$. The Riemann-Roch space of any divisor D is a vector space over $\mathbb{F}_q$ and has dimension $\ell(D)$. This dimension is bounded by the degree of the divisor.

▶ **Imported Lemma 1** ([Cas10, Lemma 2.51]). *For any $D \in \mathrm{Div}(K)$, we have $\ell(D) \leqslant \deg D + 1$. In particular, if $\deg D < 0$, then $\ell(D) = 0$.*

Every function field K has associated $g(K) \in \mathbb{N}$ called the *genus*. In particular, $g(K) := \max_D \deg D - \ell(D) + 1$, where the max is taken over all divisors D of K. When clear from context, we simply write $g := g(K)$.

2.2 Our Construction

In this section we present our construction that proves Theorem 1. We need three results to prove our result. First, we need Imported Lemma 1. The second needed result shows that there always exists a prime divisor of degree n for large enough n. This is given by the following lemma.

▶ **Imported Lemma 2** ([BCS97, Lemma 18.21]). *Let $K/\mathbb{F}_q$ be an algebraic function field of one variable of genus g and degree at least n satisfying $n \geqslant 2\log_q g + 6$. Then there exists a prime divisor of degree n of $K/\mathbb{F}_q$.*

Finally, we need the following result.

▶ **Lemma 1.** *Let V be a subspace of dimension m of $\mathbb{F}_q^r$. Then there exists a linear mapping $\psi : \mathbb{F}_q^r \to \mathbb{F}_q^m$ such that ψ is a bijection from V to $\mathbb{F}_q^m$ and that $\psi(x) * \psi(y) = \psi(x * y)$ for every $x, y \in \mathbb{F}_q^r$.*

Proof. Let G be a generator matrix of $V \subseteq \mathbb{F}_q^r$, then $V = \{uG\colon u \in \mathbb{F}_q^m\}$ and for any $x \in V$ there exists a unique $z \in \mathbb{F}_q^m$ such that $x = zG$. Let G_T denote the columns of G indexed by set $T \subseteq \{1, \ldots, r\}$ and x_T denote the entries of $x \in \mathbb{F}_q^r$ indexed by T. Choose $S \subseteq \{1, \ldots r\}$ such that $G \setminus G_S$ has full rank. Note that $|S| = r - m$. Let $G' = G \setminus G_S$ and $S' = \{1, \ldots, r\} \setminus S$. Define $\psi\colon \mathbb{F}_q^r \to \mathbb{F}_q^m$ as $\psi(x) = x_{S'}$. Now, for any $x, y \in \mathbb{F}^r$, we have $\psi(x) * \psi(y) = x_{S'} * y_{S'} = (x * y)_{S'} = \psi(x * y)$. Finally, it follows that ψ is a bijection from V to $\mathbb{F}^m$ since G' has full rank and for any $x \in V$ there exists a unique $z \in \mathbb{F}^m$ such that $x = zG$. ◀

At a high level, the proof of Theorem 1 follows from Figure 1, and the intuition presented in Section 1.3 carries over, with the main difference being now the base field $\mathbb{F}$ here is of constant size.

Proof of Theorem 1 . We consider two cases for the size q of the field: (1) q is an even power of a prime and $q \geqslant 49$, and (2) $q < 49$ or q is an odd power of a prime.

Case 1. Suppose $q \geqslant 49$ and q is an even power of a prime. In this case we choose $c_q^* = 1$. Suppose there exists an algebraic function field $K/\mathbb{F}_q$ of genus g and degree $n \geqslant \max\{2\log_q g + 6, 6g\}$. Let P be a prime divisor of degree one of $K/\mathbb{F}_q$. By Imported Lemma 2 there exists a prime divisor Q of degree n. Let $s = \lfloor (n-1)/2 \rfloor$ and consider the Riemann-Roch space $\mathscr{L}(2sP) = \{z \in K/\mathbb{F}_q \mid (z) + 2sP \geqslant 0\}$ and the valuation ring $\mathcal{O}_Q$ of Q. The vector space $\mathscr{L}(2sP)$ is contained in $\mathcal{O}_Q$, which yields that the map $\kappa : \mathscr{L}(2sP) \to \mathbb{F}_{q^n}$ defined as $z \mapsto z(Q)$ is a ring homomorphism. The kernel of κ is $\mathscr{L}(2sP - Q)$, which has dimension 0 by Imported Lemma 1 (since $\deg(2sP - Q) = 2s - n < 0$). This implies that κ

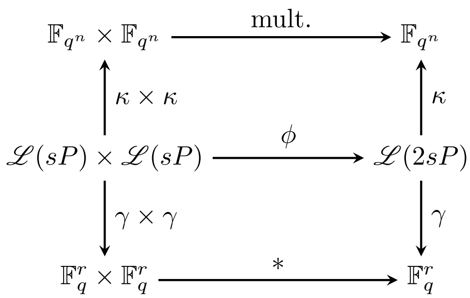

Figure 1 Commutative diagram for performing r pointwise multiplications (the Schur product) over $\mathbb{F}_q$ using one multiplication over $\mathbb{F}_{q^n}$. The map ϕ represents polynomial multiplication.

is injective. Since $\mathscr{L}(sP) \subseteq \mathscr{L}(2sP)$, the evaluation map κ restricted to $\mathscr{L}(sP)$, represented by $\kappa|_{\mathscr{L}(sP)}$, is a homomorphism from $\mathscr{L}(sP)$ to $\mathbb{F}_{q^n}$ and is injective.

Let $r > s$ and suppose $K/\mathbb{F}_q$ has at least $r+1$ distinct prime divisors of degree one. Let $P_1, P_2, \ldots, P_r$ be distinct prime divisors of degree one other than P. Consider the evaluation map $\gamma : \mathscr{L}(2sP) \to \mathbb{F}_q^r$ defined by $x \mapsto (x(P_1), x(P_2), \ldots, x(P_r))$. Since $\deg(sP - \sum P_i) = s - r < 0$, the kernel of $\gamma|_{\mathscr{L}(sP)}$ is $\mathscr{L}(sP - \sum P_i)$, which has dimension 0. Note that γ is a linear map, therefore by the rank-nullity theorem we have $\dim(\ker(\gamma|_{\mathscr{L}(sP)})) + \dim(\operatorname{Im}(\gamma|_{\mathscr{L}(sP)})) = \dim(\mathscr{L}(sP))$. So $\dim(\operatorname{Im}(\gamma|_{\mathscr{L}(sP)})) = \dim(\mathscr{L}(sP)) = s - g + 1$ since $\deg(sP) = s > 2g - 1$. Let $m = s - g + 1$ and $V = \operatorname{Im}(\gamma|_{\mathscr{L}(sP)})$. Then V is a vector subspace of $\mathbb{F}_q^r$ of dimension m. By Lemma 1, there exists a bijection $\psi : V \to \mathbb{F}_q^m$ such that it preserves the point-wise product operation; that is, $\psi(x) * \psi(y) = \psi(x * y)$ for every $x, y \in V$.

We define $E : \mathbb{F}_q^m \to \mathbb{K}$ such that $E = \kappa \circ \gamma^{-1} \circ \psi^{-1}$, and $D : \operatorname{Im}(\kappa) \subseteq \mathbb{F}_{q^n} \to \mathbb{F}_q^m$ such that $D = \psi \circ \gamma \circ \kappa^{-1}$, where $\mathbb{K} = \mathbb{F}_{q^n}$.

▶ **Claim 1.** *The maps E and D are well-defined.*

Proof. The definitions of E and D have inversion of functions and the fact is that not all functions have inverse functions. So we need to prove that we can always perform the inversions γ^{-1}, ψ^{-1}, and κ^{-1}. Since ψ is a bijection from from V to $\mathbb{F}_q^m$ and γ is also a bijection from $\mathscr{L}(sP)$ to V, the mapping E is well-defined. Next, since κ is injective it is a bijection from $\mathscr{L}(2sP)$ to $\operatorname{Im}(\kappa)$. Thus, the mapping D is also well-defined. ◀

▶ **Claim 2.** *E and D are linear maps.*

This follows directly from the fact that ψ, κ, and γ are all linear maps. Next we will show that $D\big(E(\mathbf{a}) \cdot E(\mathbf{b})\big) = \mathbf{a} * \mathbf{b}$ for every $\mathbf{a}, \mathbf{b} \in \mathbb{F}_q^m$. Let $x, y \in \mathscr{L}(sP)$ such that $\mathbf{a} = \psi(x(P_1), x(P_2), \ldots, x(P_r)) = \psi(\gamma(x))$ and $\mathbf{b} = \psi(y(P_1), y(P_2), \ldots, y(P_r)) = \psi(\gamma(y))$ (such x and y always exist by properties of ψ and γ). Note that $(x \cdot y) \in \mathscr{L}(2sP)$ because $\mathscr{L}(sP) \cdot \mathscr{L}(sP) \subseteq \mathscr{L}(2sP)$, so γ has the following property.

$$\begin{aligned}\gamma(x \cdot y) &= ((x \cdot y)(P_1), \ldots, (x \cdot y)(P_r)) = (x(P_1) \cdot y(P_1), \ldots, x(P_r) \cdot y(P_r)) \\ &= (x(P_1), \ldots, x(P_r)) * (y(P_1), \ldots, y(P_r)) = \gamma(x) * \gamma(y).\end{aligned}$$

Therefore, we have

$$\begin{aligned}D(E(\mathbf{a}) \cdot E(\mathbf{b})) &= D(\kappa(x) \cdot \kappa(y)) = D(\kappa(x \cdot y)) \\ &= \psi(\gamma(x \cdot y)) = \psi(\gamma(x) * \gamma(y)) \\ &= \psi(\gamma(x)) * \psi(\gamma(y)) = \mathbf{a} * \mathbf{b}.\end{aligned}$$

Finally, since $s = \lfloor (n-1)/2 \rfloor$ and $n \geqslant 6g$, we have that $m = s - g + 1 = \Theta(n)$. This completes the proof of Case 1.

Case 2. Suppose $q < 49$ is a power of prime or q is an odd power of a prime. Then Figure 2 presents how to choose c_q^* such that $q^{c_q^*}$ is an even power of a prime and is at least 49.

	q												
	$q < 49$											$q \geqslant 49$	
	2	4	8	16	32	3	9	27	5	25	$q \geqslant 7$	$q = p^{2a+1}$	$q = p^{2a}$
c_q^*	6	3	2	2	2	4	2	2	4	2	2	2	1

Figure 2 Table for our choices of c_q^* for Theorem 1. The value of c_q^* is chosen minimally such that $q^{c_q^*}$ is an even power of a prime and $q^{c_q^*} \geqslant 49$.

Let $q^* := q^{c_q^*}$. Suppose that n is sufficiently large and is divisible by c_q^*, and that $n/c_q^* \geqslant \max\{2\log_{q^*} g + 6, 6g\}$. Now q^* is an even power of a prime and $q^* \geqslant 49$, so we are in Case 1 with the following parameters. Let $n^* := n/c_q^*$, let $K/\mathbb{F}_{q^*}$ be an algebraic function field of genus g, and let Q be a prime divisor of degree n^*. Divisor Q exists since $n^* \geqslant 2\log_{q^*} g + 6$. Let $s = \lfloor (n^*-1)/2 \rfloor$ and set $m = s - g + 1$.

Notice for every $x \in \mathbb{F}_q$, it holds that $x \in \mathbb{F}_{q^*}$ since $\mathbb{F}_q$ is a subfield of $\mathbb{F}_{q^*}$. Now consider any $\mathbf{a}, \mathbf{b} \in \mathbb{F}_q^m$. Again we have $\mathbf{a}, \mathbf{b} \in \mathbb{F}_{q^*}^m$. We define the maps of Case 1 with respect to q^* and n^*. In particular, we apply the algorithm from Case 1 with appropriate changes to q and n. Concretely, let $\kappa \colon \mathscr{L}(2sP) \to \mathbb{F}_{(q^*)^{n^*}}$, let $\gamma \colon \mathscr{L}(2sP) \to \mathbb{F}_{q^*}^r$, and let $V = \mathrm{Im}(\gamma|_{\mathscr{L}(sP)})$. Let $\psi \colon V \to \mathbb{F}_{q^*}^m$ be a bijection defined by Lemma 1. Let $E = \kappa \circ \gamma^{-1} \circ \psi^{-1}$ and $D = \psi \circ \gamma \circ \kappa^{-1}$. Consequently, we have $D(E(\mathbf{a}) \cdot E(\mathbf{b})) = \mathbf{a} * \mathbf{b}$.

We now have $s = \lfloor (n^*-1)/2 \rfloor = \lfloor (n/c_q^* - 1)/2 \rfloor = \Theta(n)$ and $g = \Theta(n^*) = \Theta(n)$. Therefore, we have $m = s - g + 1 = \Theta(n)$. This completes the proof of case 2. Finally, Imported Theorem 1 gives concrete constructions of function fields with degree n prime divisors and $r+1$ distinct rational places, which gives the result. ◀

2.3 Function Field Instantiation using Garcia-Stichtenoth Curves

In the proof of Theorem 1, we assume that there exists at least $r+1$ distinct places of degree one and there exists a prime divisor of degree n. We use appropriate Garcia-Stichtenoth curves to ensure this is indeed the case. Formally, we have the following theorem.

▶ **Imported Theorem 1** (Garcia-Stichtenoth [GS96]). *For every q that is an even power of a prime, there exists an infinite family of curves $\{C_u\}_{u \in \mathbb{N}}$ such that:*

1. *The number of rational places $\#C_u(\mathbb{F}_q) \geqslant q^{u/2}(\sqrt{q} - 1)$, and*
2. *The genus of the curve $g(C_u) \leqslant q^{u/2}$.*

For Theorem 1, we want the following conditions to be satisfied.

1. The number of distinct degree one places is at least $r+1$
2. There exists a prime divisor of degree n.

Let $q \geqslant 49$ be an even power of a prime. Then for any $u \in \mathbb{N}$, we choose $n = q^{u/2}(\sqrt{q} - 1) \in \mathbb{N}$ and consider the function field given by the curve C_u. By Imported Theorem 1, we have that the number of rational points $\#C_u(\mathbb{F}_q) \geqslant q^{u/2}(\sqrt{q} - 1) = n$ and $g(C_u) \leqslant q^{u/2} = \frac{n}{\sqrt{q}-1}$. In particular, for $s = \left\lfloor \frac{n-1}{2} \right\rfloor$, we have $s < n$ and we can always choose r such that $s < r \leqslant n$.

Setting $r = n - 1$, we have that the map γ in the proof of Theorem 1 defines a suitable Goppa code [Gop81] over $\mathbb{F}_q$. With $r = n - 1$, we in fact have that there are at least $r + 1$ distinct prime divisors of degree one. Furthermore, we have $n \geqslant 6g$ and since $g \leqslant \frac{n}{\sqrt{q}-1}$, so

$$2 \log_q g + 6 \leqslant 2 \log_q \left(n/(\sqrt{q} - 1)\right) + 6 \leqslant n.$$

So there exists a prime divisor of degree n by Imported Lemma 2. Finally we have

$$m = s - g + 1 \geqslant \lfloor (n-1)/2 \rfloor - n/(\sqrt{q} - 1) + 6 = \Theta(n).$$

Note that $g \geqslant 0$, so we also have $m \leqslant \left\lfloor \frac{n-1}{2} \right\rfloor + 6 = \Theta(n)$.

2.4 Efficiency

There are efficient algorithms to generate the places on the Garcia-Stichtenoth curves in Imported Theorem 1. In particular, the evaluation and the interpolation algorithms are efficient. The existence of such algorithms is one of the primary motivations for using Garcia-Stichtenoth curves instead of other alternate constructions.

For example, the cost of creating the generator matrices for multiplication-friendly linear secret sharing schemes as introduced by the seminal work of Chen-Cramer [CC06] corresponds to the cost of the encoding in our construction. The result of Shum-Aleshnikov-Kumar-Stichtenoth-Deolalikar [SAK+01], for instance, provides such an efficient encoding algorithm. The reconstruction/decoding problem has an efficient algorithm using the Berlekamp-Massey-Sakata algorithm with Feng-Rao majority voting.

3 Realizing $\mathsf{OLE}(\mathbb{F})^m$ using one $\mathsf{ROLE}(\mathbb{K})$

In this section, we show how to securely realize m independent copies of $\mathsf{OLE}(\mathbb{F})$ using one sample of $\mathsf{ROLE}(\mathbb{K})$ (Random-OLE), for field $\mathbb{F} = \mathbb{F}_q$ and $\mathbb{K}$ a degree n extension field of $\mathbb{F}$. Intuitively, the $\mathsf{ROLE}(\mathbb{K})$ functionality is an inputless functionality that samples A, B, X uniformly and independently at random from $\mathbb{K}$, and outputs (A, B) to one party and (X, Z) to the other party. This secure realization is achieved by composing two steps. First, we securely realize one $\mathsf{OLE}(\mathbb{K})$ from one $\mathsf{ROLE}(\mathbb{K})$ using a standard protocol (cf. the randomized self-reducibility of the OLE functionality [WW06]). Then, we embed m copies of $\mathsf{OLE}(\mathbb{F})$ into one $\mathsf{OLE}(\mathbb{K})$. Formally, we have the following theorem.

▶ **Theorem 3** (Realizing multiple small OLE using one large ROLE). *Let $\mathbb{F}$ be a field of size q, a power of a prime. Let $\mathbb{K}$ be a degree n extension field of $\mathbb{F}$. There exists a perfectly secure protocol for $\mathsf{OLE}(\mathbb{F})^m$ in the $\mathsf{ROLE}(\mathbb{K})$-hybrid that performs only one call to the $\mathsf{ROLE}(\mathbb{K})$ functionality, $m = \Theta(n)$, and has communication complexity $3 \lg |\mathbb{K}|$.*

3.1 Preliminaries

We introduce the functionalities we are interested in.

Oblivious Linear-function Evaluation. For a field $(\mathbb{F}, +, \cdot)$, oblivious linear-function evaluation over $\mathbb{F}$, represented by $\mathsf{OLE}(\mathbb{F})$, is a two-party functionality that takes as input $(a, b) \in \mathbb{F}^2$ from Alice and $x \in \mathbb{F}$ from Bob and outputs $z = ax + b$ to Bob. In particular, OLE refers to the $\mathsf{OLE}(\mathbb{GF}[2])$ functionality.

Random Oblivious Linear-function Evaluation. For a field $(\mathbb{F}, +, \cdot)$, random oblivious linear-function evaluation over $\mathbb{F}$, represented by $\mathsf{ROLE}(\mathbb{F})$, is a correlation that samples $a, b, x \in \mathbb{F}$ uniformly and independently at random. It provides Alice the secret share

$r_A = (a, b)$ and provides Bob the secret share $r_B = (x, z)$, where $z = ax + b$. In particular, ROLE refers to the $\mathsf{ROLE}(\mathbb{GF}[2])$ correlation.

3.2 Securely realizing $\mathsf{OLE}(\mathbb{K})$ using one $\mathsf{ROLE}(\mathbb{K})$

The protocol presented in Figure 3 is the standard protocol that implements the $\mathsf{OLE}(\mathbb{K})$ functionality in the $\mathsf{ROLE}(\mathbb{K})$-hybrid with perfect semi-honest security (cf. [WW06]).

Given. Alice has $(\widetilde{A}_0, \widetilde{B}_0)$ and Bob has $(\widetilde{X}_0, \widetilde{Z}_0)$, where $\widetilde{A}_0, \widetilde{B}_0, \widetilde{X}_0$ are random elements in $\mathbb{K}$ and $\widetilde{Z}_0 = \widetilde{A}_0\widetilde{X}_0 + \widetilde{B}_0$.

Private Inputs. Alice has private input $(A^*, B^*) \in \mathbb{K}^2$ and Bob has $X^* \in \mathbb{K}$.

Hybrid. Parties are in $\mathsf{ROLE}(\mathbb{K})$-hybrid.

Interactive Protocol.

1. **First Round.** Bob sends $M = \widetilde{X}_0 - X^*$ to Alice.
2. **Second Round.** Alice sends $\alpha = \widetilde{A}_0 + A^*$ and $\beta = \widetilde{A}_0 M + B^* + \widetilde{B}_0$.

Output Computation. Bob outputs $Z^* = \alpha X^* + \beta - \widetilde{Z}_0$.

Figure 3 Perfectly secure protocol realizing $\mathsf{OLE}(\mathbb{K})$ in the $\mathsf{ROLE}(\mathbb{K})$ correlation hybrid.

3.3 Securely realizing $\mathsf{OLE}(\mathbb{F})^m$ using one $\mathsf{OLE}(\mathbb{K})$

This section presents the realization of Theorem 2. Our goal is to embed m independent copies of $\mathsf{OLE}(\mathbb{F})$ into one $\mathsf{OLE}(\mathbb{K})$, where $m = \Theta(n)$. More concretely, suppose we are given an oracle that takes as input $A^*, B^* \in \mathbb{K}$ from Alice and $X^* \in \mathbb{K}$ from Bob, and outputs $Z^* = A^* \cdot X^* + B^*$ to Bob. Our aim is to implement the following functionality. Alice has inputs $\mathbf{a} = (a_1, \dots, a_m) \in \mathbb{F}_q^m$ and $\mathbf{b} = (b_1, \dots, b_m) \in \mathbb{F}_q^m$, and Bob has input $\mathbf{x} = (x_1, \dots, x_m) \in \mathbb{F}_q^m$. We want Bob to obtain $\mathbf{z} = (z_1, \dots, z_m)$, where $\mathbf{z} = \mathbf{a} * \mathbf{x} + \mathbf{b}$, in other words, $z_i = a_i \cdot x_i + b_i$ for every $i \in [m]$. To do that, we extend our multiplication embedding with addition using a standard technique like in [BMN17, GIMS15]. We define a randomized encoding function E_2 needed for our protocol as the following.

Definition of the (randomized) encoding function E_2

$E_2 : \mathbb{F}_q^m \to \mathbb{F}_{q^n}$. $E_2(\mathbf{b})$ returns a uniformly random $B \in \mathrm{Im}(\kappa) \subseteq \mathbb{F}_{q^n}$ such that $D(B) = \mathbf{b}$; that is, $\psi(\gamma(\kappa^{-1}(B))) = \mathbf{b}$.

We show that the protocol presented in Figure 4 achieves $m = \Theta(n)$ and realizes Theorem 2.

Correctness. We argue the correctness of the protocol by showing that $D(Z^*) = \mathbf{a} * \mathbf{x} + \mathbf{b}$. In the protocol, Alice creates $A^* = E(\mathbf{a})$ and $B^* = E_2(\mathbf{b})$, and Bob creates $X^* = E(\mathbf{x})$. Calling the $\mathsf{OLE}(\mathbb{K})$ functionality, Bob receives $Z^* = A^* \cdot X^* + B^*$. In particular, Bob receives $Z^* = E(\mathbf{a}) \cdot E(\mathbf{x}) + E_2(\mathbf{b})$. Then Bob computes $D(Z^*)$. Since D is a linear map and by Theorem 1, we have $m = \Theta(n)$ and the following.

$$D(Z^*) = D\left(E(\mathbf{a}) \cdot E(\mathbf{x}) + E_2(\mathbf{b})\right) = D\left(E(\mathbf{a}) \cdot E(\mathbf{x})\right) + D(E_2(\mathbf{b})) = \mathbf{a} * \mathbf{x} + \mathbf{b}$$

Security. We argue the security for our protocol. The security relies on the observation that $E(\mathbf{a}) \cdot E(\mathbf{x}) + E_2(\mathbf{b})$ is uniformly distributed over the set

$$\{Z \colon Z \in \mathrm{Im}(\kappa) \text{ and } D(Z) = \mathbf{z}\},$$

Given. Linear maps E and D as in Theorem 1, and the linear map E_2 defined above.

Private input. Alice has private inputs $\mathbf{a} = (a_1, \dots, a_m) \in \mathbb{F}_q^m$ and $\mathbf{b} = (b_1, \dots, b_m) \in \mathbb{F}_q^m$. Bob has private input $\mathbf{x} = (x_1, \dots, x_m) \in \mathbb{F}_q^m$.

Hybrid. Parties are in the $\mathsf{OLE}(\mathbb{K})$-hybrid.

Private Input Construction.

1. Alice creates private inputs $A^* = E(\mathbf{a})$ and $B^* = E_2(\mathbf{b})$.
2. Bob creates private input $X^* = E(\mathbf{x})$.
3. Both parties invoke the $\mathsf{OLE}(\mathbb{K})$ functionality with respective Alice input (A^*, B^*) and Bob input X^*. Bob receives $Z^* = A^*X^* + B^* = E(\mathbf{a}) \cdot E(\mathbf{x}) + E_2(\mathbf{b})$.

Output Decoding. Bob outputs $\mathbf{z} = D(Z^*) = D(E(\mathbf{a}) \cdot E(\mathbf{x}) + E_2(\mathbf{b}))$.

Figure 4 Protocol for embedding m copies of $\mathsf{OLE}(\mathbb{F})$ into one $\mathsf{OLE}(\mathbb{K})$, where $\mathbb{K}$ is a degree n extension field of $\mathbb{F}$.

where $\mathbf{z} = \mathbf{a} * \mathbf{b} + \mathbf{c}$. Note that Alice does not receive any message, so the simulation of semi-honest corrupt Alice is trivial.

Consider the case that Bob is semi-honest corrupt. In this case, the simulator receives $\mathbf{x}$ from the environment, sends $\mathbf{x}$ to the external functionality, and receives $\mathbf{z}$ as output. It samples $Z^* = E_2(\mathbf{z})$, and sends $(X^* = E(\mathbf{x}), Z^*, \mathbf{z})$ as the view of Bob to the environment.

We shall show that this simulation is perfect. Note that $E(\mathbf{a}) \cdot E(\mathbf{x}) \in \mathrm{Im}(\kappa)$. Observe that $E_2(\mathbf{b})$ is a uniform distribution over a coset of $E_2(0^m)$. Now, $E(\mathbf{a}) \cdot E(\mathbf{x}) + E_2(\mathbf{b})$ is a uniform distribution over the coset $\{Z \colon Z \in \mathrm{Im}(\kappa) \text{ and } D(Z) = \mathbf{z}\}$, where $\mathbf{z} = \mathbf{a} * \mathbf{x} + \mathbf{b}$. That is, the distribution of $E(\mathbf{a}) \cdot E(\mathbf{x}) + E_2(\mathbf{b})$ is identical to the distribution of $E_2(\mathbf{z})$.

3.4 Realization of $\mathsf{OLE}(\mathbb{F})^m$ in the $\mathsf{ROLE}(\mathbb{K})$-hybrid

The protocol that realizes Theorem 3 is the parallel composition of the protocols presented in Figure 3 and Figure 4 (Theorem 2). The composition of these protocols in parallel gives an optimal two-round protocol for realizing $\mathsf{OLE}(\mathbb{F})^m$ in the $\mathsf{ROLE}(\mathbb{K})$-hybrid with perfect security and $m = \Theta(n)$ by Theorem 1, as desired.

4 Linear Production Correlation Extractors in the High Resilience Setting

This section provides the necessary background of correlation extractors and proves Corollary 3. In particular, Corollary 3 is achieved by the construction of a suitable correlation extractor. A *correlated private randomness*, or *correlation* in short, is a joint distribution (R_A, R_B) which samples shares (r_A, r_B) according to the distribution and sends secret shares r_A to Alice and r_B to Bob. Correlations are given to parties in an offline preprocessing phase. Parties then use their respective secret shares in an online phase in an interactive protocol to securely compute an intended functionality. Correlation extractors take *leaky* shares of correlations and distill them into *fresh* randomness to be used to securely compute the intended functionality. Formally, we define a correlation extractor below.

▶ **Definition 1** (Correlation Extractor [IKOS09]). Let (R_A, R_B) be a correlated private randomness such that the secret share size of each party is n'-bits. An (n', m, t, ε)-*correlation* *extractor for* (R_A, R_B) is a two-party interactive protocol in the $(R_A, R_B)^{[t]}$-hybrid that securely implements m copies of the OT functionality against information-theoretic semi-honest adversaries with ε-simulation error.

Using this definition we restate Corollary 3 as follows.

▶ **Theorem 4** (Half Resilience, Linear Production Correlation Extractor). *For all constants $0 < \delta < g \leqslant 1/2$, there exists a correlation (R_A, R_B), where each party gets n'-bit secret shares, such that there exists a two-round (n', m, t, ε)-correlation extractor for (R_A, R_B), where $m = \Theta(n')$, $t = (1/2 - g)n'$, and $\varepsilon = 2^{-(g-\delta)n'/2}$.*

The construction of this correlation extractor achieves linear production $m = \Theta(n')$ and 1/2 leakage resilience by composing our embedding (Theorem 1, Theorem 2) with the correlation extractor of Block, Maji, and Nguyen (BMN) [BMN17]. Prior correlation extractors either achieved sub-linear production, (significantly) less than 1/2 resilience, or were not round-optimal.

4.1 Preliminaries

We introduce some useful functionalities and correlations.

Random Oblivious Transfer Correlation. Random oblivious transfer, represented by ROT, is a correlation that samples x_0, x_1, b uniformly and independently at random. It provides Alice the secret share $r_A = (x_0, x_1)$ and provides Bob the secret share $r_B = (b, x_b)$.

Recall also the **Oblivious Linear-function Evaluation** and **Random Oblivious Linear-function Evaluation** functionalities from Section 3.1. We denote $\mathsf{ROLE}(\mathbb{GF}[2])$ by ROLE. Note that ROT and ROLE are identical (functionally equivalent) correlations.

Inner-product Correlation. For a field $(\mathbb{K}, +, \cdot)$ and $n' \in \mathbb{N}$, inner-product correlation over $\mathbb{K}$ of size n', represented by $\mathsf{IP}\left(\mathbb{K}^{n'}\right)$, is a correlation that samples random $r_A = (x_0, \ldots, x_{n'-1}) \in \mathbb{K}^{n'}$ and $r_B = (y_0, \ldots, y_{n'-1}) \in \mathbb{K}^{n'}$ subject to the constraint that $x_0 + y_0 = \sum_{i=1}^{n'-1} x_i y_i$. The secret shares of Alice and Bob are, respectively, r_A and r_B.

4.2 Realizing Theorem 4

The realization of Theorem 4 is the parallel composition of two protocols. First, we utilize the BMN $\mathsf{ROLE}(\mathbb{K})$ extraction protocol [BMN17, Figure 7]. Informally, the BMN extraction protocol takes leaky shares of the inner-product correlation over the field $\mathbb{K}$, and securely extracts one sample of $\mathsf{ROLE}(\mathbb{K})$. In particular, the BMN extraction protocol is resilient to $t = (1/2 - g)n'$ bits of leakage, for any $g \in (0, 1/2]$.

Second, we utilize our new embedding protocol of Theorem 3 which produces m copies of $\mathsf{OLE}(\mathbb{F})$ from one $\mathsf{ROLE}(\mathbb{K})$, and compose it in parallel with the BMN extraction protocol for $\mathsf{ROLE}(\mathbb{K})$. Previously, the BMN embedding achieved $m = (n')^{1-o(1)}$ production, whereas with Theorem 3 we achieve $m = \Theta(n')$ production with the following parameters. We take $\mathbb{F} = \mathbb{GF}[2]$ and $\mathbb{K} = \mathbb{GF}[2^{\delta n'}]$, where n' and δ are given, $\eta := \frac{1}{\delta} - 1$, and $n := \frac{n'}{(\eta+1)}$. In particular, $\mathbb{K}$ is a degree-n extension of $\mathbb{F}$, and n here corresponds to the n of Corollary 3. So $m = \Theta(n') = \Theta(n)$. We then take $(R_A, R_B) = \mathsf{IP}\left(\mathbb{K}^{1/\delta}\right)$ to be the input correlation for the BMN extraction protocol.

The BMN extraction protocol is a perfectly secure semi-honest protocol for extracting one $\mathsf{ROLE}\left(\mathbb{GF}[2^{\delta n'}]\right)$ in the $\left(\mathsf{IP}\left(\mathbb{GF}[2^{\delta n'}]^{1/\delta}\right)\right)^{[t]}$-hybrid which is resilient to $t = (1/2 - g)n'$ bits of leakage, for all $0 < \delta < g \leqslant 1/2$ (cf. [BMN17, Theorem 1]). Then the parallel composition of the protocols of Figure 3 and Figure 4 is a perfectly secure semi-honest protocol for realizing m copies of $\mathsf{OLE}\left(\mathbb{GF}[2]\right)$ in the $\mathsf{ROLE}\left(\mathbb{GF}[2^{\delta n'}]\right)$-hybrid, and $m = \Theta(n') = \Theta(n)$. This proves Theorem 4, and thus Corollary 3.

4.3 Comparison with Prior Works

Correlation extractors were introduced by Ishai, Kushilevitz, Ostrovsky, and Sahai [IKOS09] as a natural generalization of privacy amplification and randomness extraction. Since the initial feasibility result of [IKOS09], there have been significant qualitative and quantitative improvements in correlation extractor constructions. Figure 5 summarizes the current state-of-the-art of correlation extractors.

	Correlation Description	Message Complexity	Number of OTs Produced ($m/2$)	Number of Leakage bits (t)	Simulation Error (ε)
[IKOS09]	$\mathsf{ROT}^{n/2}$	4	$\Theta(n)$	$\Theta(n)$	$2^{-\Theta(n)}$
[GIMS15]	$\mathsf{ROT}^{n/2}$	2	$n/\operatorname{poly}\lg n$	$(1/4 - g)n$	$2^{-gn/m}$
	$\mathsf{IP}\left(\mathbb{K}^{n/\lg\lvert\mathbb{K}\rvert}\right)$	2	1	$(1/2 - g)n$	2^{-gn}
[BMN17]	$\mathsf{IP}\left(\mathbb{K}^{n/\lg\lvert\mathbb{K}\rvert}\right)$	2	$n^{1-o(1)}$	$(1/2 - g)n$	2^{-gn}
[BGMN18]	$\mathsf{ROT}^{n/2}$	2	$\Theta(n)$	$\Theta(n)$	$2^{-\Theta(n)}$
	$\mathsf{ROLE}\left(\mathbb{F}\right)^{n/2\lg\lvert\mathbb{F}\rvert}$	2	$\Theta(n)$	$\Theta(n)$	$2^{-\Theta(n)}$
Our Results	$\mathsf{IP}\left(\mathbb{K}^{n/\lg\lvert\mathbb{K}\rvert}\right)$	2	$\Theta(n)$	$(1/2 - g)n$	2^{-gn}

Figure 5 A qualitative summary of prior relevant works in correlation extractors and a comparison to our correlation extractor construction. Here $\mathbb{K}$ is a finite field and $\mathbb{F}$ is a finite field of constant size. All correlations have been normalized so that each party gets an n-bit secret share. The parameter g is defined as the gap to leakage resilience such that $t \geqslant 0$.

Prior to our work, the Block, Gupta, Maji, and Nguyen correlation extractors [BGMN18] achieve the best qualitative and quantitative parameters. For example, starting with $n/2$ independent samples of the ROT correlation, they construct the first round-optimal correlation extractor that produces $m = \Theta(n)$ secure ROT samples despite $t = (1/4 - \varepsilon)n$ bits of leakage, for any $\varepsilon > 0$. Note that any correlation extractor for $n/2$ ROT samples can have at most $t = n/4$ resilience [IMSW14].

Our correlation extractor is also round optimal. However, the BMN [BMN17] correlation extractor and our correlation extractor have resilience in the range $t/n \in [1/4, 1/2)$. Intuitively, our correlation extractor is ideal where high resilience is necessary. Our correlation extractor needs a large correlation, for example, the inner-product correlation over large fields. Contrast this with the case of BGMN extractor that uses multiple samples of the ROT correlation. To achieve $t = (1/2 - g)n$ resilience, where $g \in (0, 1/4]$, we use the inner-product correlation over fields of size (roughly) 2^{gn}. Using the multiplication embedding in Theorem 1, our work demonstrates the feasibility of extracting $m = \Theta(gn)$ independent ROT samples when the fractional resilience is in the range $t/n \in [1/4, 1/2)$.

5 Chudnovsky-Chudnovsky Bilinear Multiplication

We discuss the reverse problems of Theorem 1 and Theorem 3. We assume familiarity with Section 2. First we consider the problem of computing one large field multiplications using many small field multiplications. This is given by the following theorem.

▶ **Theorem 5** (Field Extension Multiplication via Pointwise Base Field Multiplication). *Let $\mathbb{F}$ be a finite field of size q, a power of a prime. For sufficiently large n, there exists a constant $c' > 0$ and (linear) maps $E' \colon \mathbb{K} \to \mathbb{F}^m$ and $D' \colon \mathbb{F}^m \to \mathbb{K}$, where $\mathbb{K}$ is the degree-n extension of the field $\mathbb{F}$, such that the following constraints are satisfied.*

1. *We have $m \geqslant c'n$, and*
2. *For all $A, B \in \mathbb{K}$, the following identity holds*

$$D'\left(E'(A) * E'(B)\right) = A \cdot B$$

where "$*$" is pointwise multiplication over $\mathbb{F}^m$.

Note that since the maps E' and D' are linear, the following holds.

▶ **Corollary 4.** *For all $A, B, C \in \mathbb{K}$, we have*

$$D'\big(E'(A) * E'(B) + E'(C)\big) = D'\big(E'(A) * E'(B)\big) + D'\big(E'(C)\big).$$

Theorem 5 follows from the results of Chudnovsky-Chudnovsk [CC87]. In particular, they show that the rank of bilinear multiplication is $\Theta(n)$.

▶ **Imported Theorem 2** (Chudnovsky and Chudnovsky [BCS97, Theorem 18.20]). *For every power of a prime q there exists a constant c_q such that $R(\mathbb{F}_{q^n}/\mathbb{F}_q) \leqslant c_q n$, where R is the rank of the $\mathbb{F}_q$-bilinear map that is multiplication over $\mathbb{F}_{q^n}$.*

The theorem states that if $\mathbb{K}$ is a degree n extension of $\mathbb{F}_q$, then the bilinear complexity of multiplication over $\mathbb{K}$ is $\Theta(n)$. This result is due to the Chudnovsky-Chudnovsky interpolation algorithm (cf. Imported Lemma 3) and the following result of Garcia and Stichtenoth.

▶ **Imported Theorem 3** (Garcia and Stichtenoth [GS95], [BCS97, Theorem 18.24]). *Let p be a power of prime, X_1 be an indeterminate over $\mathbb{F}_{p^2}$, and $K_1 := \mathbb{F}_{p^2}(X_1)$. For $i \geqslant 1$ let $K_{i+1} := K_i(Z_{i+1})$, where Z_{i+1} satisfies the Artin-Schreier equation $Z_{i+1}^p + Z_{i+1} = X_m^{p+1}$ and $X_i := Z_i/X_{i-1} \in K_i$ (for $i \geqslant 2$). Then K_i/F_{p^2} has genus g_i given by*

$$g_i = \begin{cases} p^i + p^{i-1} - p^{\frac{i+1}{2}} - 2p^{\frac{i-1}{2}} + 1 & \text{if } i \equiv 1 \bmod 2, \\ p^i + p^{i-1} - \frac{1}{2}p^{\frac{i}{2}+1} - \frac{3}{2}p^{\frac{i}{2}} - p^{\frac{i}{2}-1} + 1 & \text{if } i \equiv 0 \bmod 2, \end{cases}$$

and $|\mathbb{P}^{(1)}(K_i/\mathbb{F}_{p^2})| \geqslant (p^2-1)p^{i-1} + 2p \geqslant (p-1)g_i$.

▶ **Imported Lemma 3** (Chudnovsky-Chudnovsky Interpolation Algorithm [BCS97, Proposition 18.22]). *Let $K/\mathbb{F}_q$ be an algebraic function field of one variable of genus g, $n \geqslant 2\log_q g + 6$, and assume that there exist at least $4g + 2n$ prime divisors of degree one of $K/\mathbb{F}_q$. Then we have $R(\mathbb{F}_{q^n}/\mathbb{F}_q) \leqslant 3g + 2n - 1$.*

Imported Lemma 3 gives rise to the commutative diagram of Figure 6 which defines the interpolation method. This interpolation method implements multiplication over $\mathbb{F}_{q^n}$ using r' pointwise multiplications over $\mathbb{F}_q^{r'}$. This gives that $r' = 3g + 2n - 1 = \Theta(n)$. Setting $m = r'$ and setting E' and D' according to the interpolation algorithm directly yields Theorem 5. Concretely, we have the maps E' and D' defined as follows.

$$E' := \kappa' \circ (\gamma')^{-1} \qquad\qquad D' := \gamma' \circ (\kappa')^{-1}.$$

Note both κ' and γ' are linear maps, so E' and D' are also linear maps.

Given E' and D' of Theorem 5, we compute the reverse problem of Theorem 3. That is, we can use multiple small ROLE to realize one large OLE.

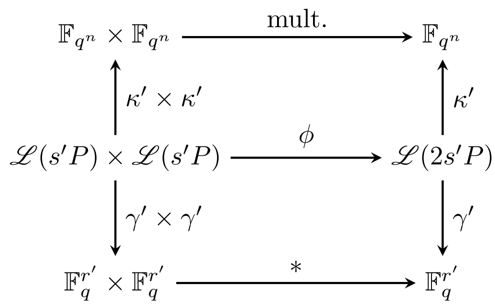

Figure 6 Chudnovsky-Chudnovsky interpolation algorithm for performing multiplication over $\mathbb{F}_{q^n}$ using r' pointwise multiplications over $\mathbb{F}_q^{r'}$, where $r' = \Theta(n)$ and $s' = n + 2g - 1$.

▶ **Theorem 6** (Realizing one large OLE using multiple small ROLE). *Let $\mathbb{F}$ be a field of size q, a power of a prime. Let $\mathbb{K}$ be a degree n extension field of $\mathbb{F}$. There exists a perfectly secure protocol for $\mathsf{OLE}(\mathbb{K})$ in the $\mathsf{ROLE}(\mathbb{F})^m$-hybrid that performs only one call to the $\mathsf{ROLE}(\mathbb{F})^m$ functionality, $m = \Theta(n)$, and has communication complexity $3m \lg |\mathbb{F}|$.*

To realize Theorem 6, we compose two steps in parallel. First we securely realize $\mathsf{OLE}(\mathbb{F})^m$ from $\mathsf{ROLE}(\mathbb{F})^m$ using a standard protocol. Then we use m copies of $\mathsf{OLE}(\mathbb{F})$ to implement a single $\mathsf{OLE}(\mathbb{K})$.

5.1 Securely realizing $\mathsf{OLE}(\mathbb{F})^m$ using $\mathsf{ROLE}(\mathbb{F})^m$

The protocol presented in Figure 7 is an extension of the standard protocol that implements the $\mathsf{OLE}(\mathbb{F})$ functionality in the $\mathsf{ROLE}(\mathbb{F})$-hybrid with perfect semi-honest security. In particular, it is the m parallel composition of the $\mathsf{OLE}(\mathbb{F})$ functionality in the $\mathsf{ROLE}(\mathbb{F})$-hybrid.

Pseudocode of the $\mathsf{OLE}(\mathbb{F})^m$ protocol

Given. Alice has $(\mathbf{a}', \mathbf{b}')$ and Bob has $(\mathbf{x}', \mathbf{z}')$, where $\mathbf{a}', \mathbf{b}', \mathbf{x}'$ are random elements in $\mathbb{F}^m$ and $\mathbf{z}' = \mathbf{a}' * \mathbf{x}' + \mathbf{b}'$.

Private Inputs. Alice has private input $(\mathbf{a}^*, \mathbf{b}^*) \in \mathbb{F}^{2m}$ and Bob has $\mathbf{x}^* \in \mathbb{F}^m$.

Hybrid. Parties are in $\mathsf{ROLE}(\mathbb{F})^m$-hybrid.

Interactive Protocol.
1. **First Round.** Bob sends $\mathbf{m} = \mathbf{x}' - \mathbf{x}^*$ to Alice.
2. **Second Round.** Alice sends $\boldsymbol{\alpha} = \mathbf{a}' + \mathbf{a}^*$ and $\boldsymbol{\beta} = \mathbf{a}' * \mathbf{m} + \mathbf{b}^* + \mathbf{b}'$.

Output Computation. Bob outputs $\mathbf{z}^* = \boldsymbol{\alpha} * \mathbf{x}^* + \boldsymbol{\beta} - \mathbf{z}'$.

Figure 7 Perfectly secure protocol realizing $\mathsf{OLE}(\mathbb{F})^m$ in the $\mathsf{ROLE}(\mathbb{F})^m$ correlation hybrid.

5.2 Securely realizing $\mathsf{OLE}(\mathbb{K})$ from $\mathsf{OLE}(\mathbb{F})^m$

The goal is to use m copies of $\mathsf{OLE}(\mathbb{F})$ to compute one $\mathsf{OLE}(\mathbb{K})$, where $m = \Theta(n)$. Concretely, suppose we are given an oracle which takes as input $\mathbf{a}, \mathbf{b} \in \mathbb{F}^m$ from Alice and $\mathbf{x} \in \mathbb{F}^m$ from Bob, and outputs $\mathbf{z} = \mathbf{a} * \mathbf{x} + \mathbf{b}$ to Bob. Our aim is to implement the following functionality. Alice has private inputs $A \in \mathbb{K}$ and $B \in \mathbb{K}$, and Bob has input $X \in \mathbb{K}$. We want Bob to obtain $Z = AX + B \in \mathbb{K}$. We show that if Alice and Bob use the protocol presented in Figure 8, we can achieve $m = \Theta(n)$. More formally, we have the following lemma.

▶ **Lemma 2** (Performing one large OLE using multiple small OLE)**.** *Let $\mathbb{K}$ be an extension field of $\mathbb{F}$ of degree n. There exists a perfectly secure protocol for $\mathsf{OLE}(\mathbb{K})$ in the $\mathsf{OLE}(\mathbb{F})^m$-hybrid that performs only one call to the $\mathsf{OLE}(\mathbb{F})^m$ functionality and $m = \Theta(n)$.*

Given. Two linear maps E' and D' as in Theorem 5.

Private input. Alice has private inputs $A \in \mathbb{K}$ and $B \in \mathbb{K}$. Bob has private input $X \in \mathbb{K}$.

Hybrid. Parties are in the $\mathsf{OLE}(\mathbb{F})^m$-hybrid.

Private Input Construction.
1. Alice creates private inputs $\mathbf{a} = E'(A)$ and $\mathbf{b} = E'(B)$.
2. Bob creates private inputs $\mathbf{x} = E'(X)$.
3. Both parties invoke the the $\mathsf{OLE}(\mathbb{F})^m$ functionality with respective Alice input $(\mathbf{a}, \mathbf{b})$ and Bob input $\mathbf{x}$. Bob receives $\mathbf{z} = \mathbf{a} * \mathbf{x} + \mathbf{b} = E'(A) * E'(X) + E'(B)$.

Output Decoding. Bob outputs $Z = D'(\mathbf{z}) = D'\big(E'(\mathbf{a}) * E'(\mathbf{x}) + E'(\mathbf{b})\big) = AX + B$.

Figure 8 Protocol for computing one $\mathsf{OLE}(\mathbb{K})$ using m copies of $\mathsf{OLE}(\mathbb{F})$, where $\mathbb{K}$ is a degree n extension field of $\mathbb{F}$.

Figure 8 realizes Lemma 2. In the protocol, Alice creates $\mathbf{a} = E'(A)$ and $\mathbf{b} = E'(B)$, and Bob creates $\mathbf{x} = E'(X)$. Calling the $\mathsf{OLE}(\mathbb{F})^m$ functionality, Bob receives $\mathbf{z} = \mathbf{a} * \mathbf{x} + \mathbf{b}$. In particular, he receives $\mathbf{z} = E'(A) * E'(X) + E'(B)$. Bob then computes $D'(\mathbf{z})$. Since D' is a linear map and by Theorem 5, we have the following.

$$\begin{aligned} D'(\mathbf{z}) &= D'\big(E'(A) * E'(X) + E'(B)\big) = D'\big(E'(A) * E'(X)\big) + D'\big(E'(B)\big) \\ &= AX + B \end{aligned}$$

5.3 Proof of Theorem 6

The protocol which satisfies Theorem 6 is the parallel composition of the protocols presented in Figure 7 and Figure 8 (Lemma 2). The composition of these protocols in parallel gives an optimal two-round protocol for realizing $\mathsf{OLE}(\mathbb{K})$ in the $\mathsf{ROLE}(\mathbb{F})^m$-hybrid with perfect security and $m = \Theta(n)$ by Theorem 5, as desired.

5.4 Prior Work

Chudnovsky-Chudnovsky [CC87] gave the first feasibility result on the bilinear complexity of multiplication, showing $\Theta(n)$ multiplications in $\mathbb{F}_q$ suffice to perform one multiplication over

$\mathbb{F}_{q^n}$. Since then there have been several works on explicit constructions and variants of the bilinear multiplication algorithms and improved the bounds on the bilinear complexity.

The works of [GS95, GS96, STV92] discuss the construction of appropriate function fields such that there is sufficient number of rational points for interpolation. Improvement on the bounds for the bilinear complexity of multiplication and generalizations of the Chudnovsky-Chudnovsky method appear in [BR04, BBBT17, BPR16, Ran12]. Explicit construction of multiplication algorithms are discussed in [ABBR15, BBBT17, CÖ10], and in the particular case of function fields over elliptic curves in [BBT13, Cha12].

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A Detailed Basics of Algebraic Function Fields

We introduce the basics of algebraic function fields in detail which are necessary for our construction. We follow the conventions of [Sti09, Cas10]. Let $\mathbb{F}_q$ be a finite field of q elements, where q is a power of prime.

▶ **Definition 2** (Algebraic Function Field)**.** An *algebraic function field* (or function field for simplicity) $K/\mathbb{F}_q$ of one variable over $\mathbb{F}_q$ is an extension field $K \supseteq \mathbb{F}_q$ and a finite algebraic extension of $\mathbb{F}_q(x)$ for some element x which is transcendental over $\mathbb{F}_q$.

We let $\widetilde{\mathbb{F}}_q$ denote the field of constants of $K/\mathbb{F}_q$. In the remainder of this paper, we only consider function fields $K/\mathbb{F}_q$ such that $\mathbb{F}_q = \widetilde{\mathbb{F}}_q$. For ease of presentation, we assume $\mathbb{F}_q$ to always be the field of constants and denote $K/\mathbb{F}_q$ by K. The simplest example of a function field is the *rational function field*. The function field K is called *rational* if $K = \mathbb{F}_q(x)$ for $x \in K$ which is transcendental over $\mathbb{F}_q$. Explicitly, the rational function field K is written as

$$K = \{f(x)/g(x) \ : \ f, g \in \mathbb{F}_q[x], g \not\equiv 0\} .$$

▶ **Definition 3** (Valuation Ring)**.** A valuation ring of the function field K is a ring $\mathcal{O} \subseteq K$ such that

- $\mathbb{F}_q \subsetneq \mathcal{O} \subsetneq K$, and
- for every $z \in K$, either $z \in \mathcal{O}$ or $z^{-1} \in \mathcal{O}$.

Valuation rings are used to define a more general "point" of a function field, namely *places*.

▶ **Definition 4** (Places)**.** A *place* P of K is the maximal ideal of some valuation ring $\mathcal{O}$ of K. We denote the set of all places of K by $\mathbb{P}(K)$.

Places uniquely define their corresponding valuation rings, and valuation rings uniquely define their corresponding places. This is given by the following lemmas.

▶ **Imported Lemma 4** ([Cas10, Proposition 2.5])**.** *A valuation ring $\mathcal{O}$ of K is a local ring; that is, its only maximal ideal is $P = \mathcal{O} \setminus \mathcal{O}^*$, where $\mathcal{O}^*$ denotes the group of units of $\mathcal{O}$.*

▶ **Imported Lemma 5** ([Cas10, Proposition 2.8])**.** *Given $P \in \mathbb{P}(K)$, there is a unique valuation ring $\mathcal{O}_P$ such that P is its maximal ideal. This valuation ring is precisely $\mathcal{O}_P = \{f \in K \ : \ f^{-1} \notin P\}$.*

These two imported lemma state that places and valuation rings are interchangeable. In fact, a place P is the principle ideal of its corresponding valuation ring $\mathcal{O}_P$.

▶ **Imported Lemma 6** ([Cas10, Proposition 2.9])**.** *Any valuation ring $\mathcal{O}$ of K is a principal ideal domain. Therefore any place $P \in \mathbb{P}(K)$ is a principle ideal and can be written in the form $P = t_P\mathcal{O}_P$ for some $t_P \in P$.*

Any $t_P \in P$ which satisfies $P = t_p\mathcal{O}_P$ is called a *uniformizing parameter* for P. Valuation rings give rise to valuation maps.

▶ **Definition 5** (Valuation Map)**.** For any $P \in \mathbb{P}(K)$ with any uniformizing parameter t_P, define the function $v_P \colon K \to \mathbb{Z} \cup \{\infty\}$ by

$$v_P(f) := \begin{cases} n & \text{if } 0 \neq f \in \mathcal{O}_P, \text{ and } f = t_P^n u, u \in \mathcal{O}_P^* \\ -n & \text{if } f \in K \setminus \mathcal{O}_P, \text{ and } f^{-1} = t_P^n u, u \in \mathcal{O}_P^* \\ \infty & \text{if } f = 0 \end{cases}$$

The value $v_P(f)$ is the *valuation* of f at P.

This map is well-defined since $\mathcal{O}_P$ is a valuation ring and by the following lemma.

▶ **Imported Lemma 7** ([Cas10, Proposition 2.12]). *For any $P \in \mathbb{P}(K)$ and uniformizing parameter t_P for P, every element $0 \neq f \in \mathcal{O}_P$ can be uniquely written as $f = t_P^n u$ for $n \in \mathbb{N}$ and $u \in \mathcal{O}_P^*$. Furthermore, for any $0 \neq f \in \mathcal{O}_P$ and any two uniformizing parameters t_P and t'_P of P, if $f = t_P^n u = (t'_P)^{n'} u'$, then $n' = n$.*

Note that Definition 5 gives an equivalent definition of a valuation ring $\mathcal{O}_P$ for place P.

▶ **Imported Theorem 4** ([Sti09, Theorem 1.1.13]). *For any $P \in \mathbb{P}(K)$, we have $\mathcal{O}_P = \{z \in K : v_P(z) \geqslant 0\}$.*

We can now define evaluation of a function at a place.

▶ **Definition 6** (Evaluation at a Place). For any $P \in \mathbb{P}(K)$, the *residue class field* of P is $K_P := \mathcal{O}_P/P$. The *evaluation* of $f \in \mathcal{O}_P$ at P is its residue class in K_P and is denoted by $f(P)$. For $f \notin \mathcal{O}_P$, its evaluation at P is defined to be $f(P) = \infty$.

In other words, evaluation of a function f at place P yields the residue class of f in K_P. In fact, K_P is isomorphic to a finite field extension of $\mathbb{F}_q$, where the degree of the extension depends on the place P.

▶ **Imported Lemma 8** ([Cas10, Proposition 2.17]). *Let $P \in \mathbb{P}(K)$. Then $\mathbb{F}_q \subseteq \mathcal{O}_P$ and $\mathbb{F}_q \cap P = \{0\}$. Hence there is a canonical embedding of $\mathbb{F}_q$ into K_P, so $\mathbb{F}_q$ can be considered as a subfield of K_P. Furthermore the degree $|K_P : \mathbb{F}_q|$ of the field extension satisfies $|K_P : \mathbb{F}_q| \leqslant |K : \mathbb{F}_q(x)| < \infty$, for any $0 \neq x \in P$.*

In particular, if $|K_P : \mathbb{F}_q| = a$, then we have $K_P \cong \mathbb{F}_{q^a}$ and $f(P) \equiv \alpha \in \mathbb{F}_{q^a}$ for $f \in \mathcal{O}_P$. Imported Lemma 8 naturally defines the degree of a place P.

▶ **Definition 7** (Degree of a place). For every $P \in \mathbb{P}(K)$, the *degree* of P is $\deg P := |K_P : \mathbb{F}_q|$.

We denote the set of all places of degree k by $\mathbb{P}^{(k)}(K)$. Note that the set $\mathbb{P}^{(1)}(K)$ is called the *set of rational places* (or rational points). Places are used to define the divisors of a function field K.

▶ **Definition 8** (Divisors). A *divisor* D of a function field K is a formal sum $D = \sum_{P \in \mathbb{P}(K)} m_P P$ where $m_P \in \mathbb{Z}$ and $m_P = 0$ except for a finite number of places $P \in \mathbb{P}(K)$. We define $\mathsf{Supp}(D) := \{P \in \mathbb{P}(K) : m_P \neq 0\}$ to be the *support* of divisor D. The set of all divisors of K is denoted $\mathrm{Div}(K)$.

Note that from Definition 8, it is clear that every place $P \in \mathbb{P}(K)$ is also a divisor, namely $P = 1 \cdot P \in \mathrm{Div}(K)$. Such divisors are called *prime divisors*. Any divisor $D \in \mathrm{Div}(K)$ has corresponding degree depending on places $P \in \mathsf{Supp}(D)$.

▶ **Definition 9** (Degree of a Divisor). For any divisor $D = \sum_{P \in \mathbb{P}(K)} m_P P$, the *degree* of D is $\deg D := \sum_{P \in \mathbb{P}(K)} m_P (\deg P) \in \mathbb{Z}$.

This definition is consistent with the degree of place P for the case where divisor D is also a place. We can naturally define the summation of two divisors.

▶ **Definition 10** (Sum of Divisors). Let $D = \sum_{P \in \mathbb{P}(K)} m_P P$ and $D' = \sum_{P \in \mathbb{P}(K)} n_P P$ be two divisors. Then $D + D' := \sum_{P \in \mathbb{P}(K)} (m_P + n_P) P$.

We use Definition 10 to define a partial ordering of divisors.

▶ **Definition 11** (Divisor Partial Ordering). For divisors $D = \sum_{P\in\mathbb{P}(K)} m_P P$ and $D' = \sum_{P\in\mathbb{P}(K)} n_P P$, we say that $D \leqslant D'$ if $m_P \leqslant n_P$ for all $P \in \mathbb{P}(K)$. We say that a divisor D is *effective* (or positive) if $D \geqslant 0$.

Every $f \in K \setminus \{0\}$ can be associated with a divisor by the following theorem.

▶ **Imported Theorem 5** ([Cas10, Theorem 2.32]). *Every $f \in K \setminus \{0\}$ has finitely many zeros and poles. That is, we have $v_P(f) = 0$ except for finitely many $P \in \mathbb{P}(K)$.*

We now define the divisor associated to $f \in K \setminus \{0\}$.

▶ **Definition 12** (Principal Divisors). For any $f \in K \setminus \{0\}$, the divisor

$$(f) := \sum_{P\in\mathbb{P}(K)} v_P(f)P$$

is the *principal divisor* associated to f. We let $\mathrm{Prin}(K) := \{D \in \mathrm{Div}(K) \colon \exists f \in K\setminus\{0\},\ D = (f)\}$ denote the set of principal divisors.

Associating every nonzero function f with divisor (f) allows us to define the Riemann-Roch space.

▶ **Definition 13** (Riemann-Roch Space). For a divisor $G \in \mathrm{Div}(K)$, the *Riemann-Roch space* associated with G is defined as

$$\mathscr{L}(G) := \{f \in K : (f) + G \geqslant 0\} \cup \{0\}.$$

Note that $\mathscr{L}(G)$ is a vector space over $\mathbb{F}_q$ for any $G \in \mathrm{Div}(K)$. We denote the dimension of $\mathscr{L}(G)$ over $\mathbb{F}_q$ by $\ell(G)$. In particular, the dimension of the Riemann-Roch space is bounded by the degree of its divisor, given by Imported Lemma 1 and the following lemma.

▶ **Imported Theorem 6** (Riemann's Theorem [Cas10, Theorem 2.53]). *There exists $M \in \mathbb{Z}$ such that for all $D \in \mathrm{Div}(K)$, we have $\ell(D) \geqslant M + \deg D$.*

We now define the genus of the function field K.

▶ **Definition 14** (Genus). The *genus* of the function field K is defined as

$$g(K) := \max_{D\in\mathrm{Div}(K)} \deg D - \ell(D) + 1 \in \mathbb{N}.$$

When clear from context, we let $g := g(K)$.

The genus always exists and is a non-negative integer by Imported Theorem 6. Next we define canonical divisors. First we need the following definition.

▶ **Definition 15** (Space of Differential Forms). The *space of differential forms* $\Omega(K)$ of K is the K-vector space generated by the symbols df, $f \in K$, such that

- $d(f + g) = df + dg$ for all $f, g \in K$,
- $d(fg) = f \cdot dg + df \cdot g$ for all $f, g \in K$,
- $df = 0$ for all $f \in \mathbb{F}_q$.

Now we can associate a divisor to any $w \in \Omega(K) \setminus \{0\}$.

▶ **Definition 16** (Canonical Divisor). For any $w \in \Omega(K)\setminus\{0\}$, the *canonical divisor* associated to w is the divisor

$$(w) := \sum_{P\in\mathbb{P}(K)} v_P(w)P.$$

Canonical divisors are well-defined by the following lemma.

▶ **Imported Lemma 9** ([Cas10, Proposition 2.62]). *For $w \in \Omega(K) \setminus \{0\}$, we have $v_P(w) = 0$ for all but a finite number of places $P \in \mathbb{P}(K)$.*

Next we state an important result about canonical divisors.

▶ **Imported Theorem 7** ([Cas10, Theorem 2.65]). *For any canonical divisor $W \in \mathrm{Div}(K)$, we have $\deg W = 2g - 2$ and $\ell(W) = g$.*

We have the tools in place to state the Riemann-Roch Theorem.

▶ **Imported Theorem 8** (Riemann-Roch Theorem [Sti09, Theorem 1.5.15]). *Let W be a canonical divisor of $K/\mathbb{F}_q$. Then for each divisor $A \in \mathrm{Div}(K)$,*

$$\ell(A) = \deg A + 1 - g + \ell(W - A).$$