

Definitional Issues in Functional Encryption

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Abstract

We provide a formalization of the emergent notion of “functional encryption,” as well as introduce various security notions for it, and study relations among the latter. In particular, we show that indistinguishability and semantic security based notions of security are *inequivalent* for functional encryption in general. This is alarming given the large body of work employing (special cases of) the former. We go on to show, however, that an equivalence does hold between indistinguishability and some form of semantic security for what we call *preimage sampleable* schemes. Our interpretation is that for preimage sampleable schemes an indistinguishability based notion is probably fine in practice. We show that some common functionalities considered in the literature satisfy this requirement.

1 Introduction

FUNCTIONAL ENCRYPTION. In recent years, a notion of “functional encryption” (FE) has emerged as a new paradigm for public-key encryption, wherein a receiver, given a ciphertext, is able to learn certain functions of the underlying message based on its secret keys (not necessarily the decryption). Special cases of FE include identity-based encryption [BF03], public-key encryption with keyword search [BCOP04, ABC⁺08], attribute-based encryption [SW05, GPSW06, BSW07], and predicate encryption [BW07, KSW08, LOS⁺10, OT10].¹ However, a general study of FE and its security seems not to have appeared. Here we initiate one, and in doing so we uncover some interesting definitional issues that have important implications for work in this area.

SYNTAX AND SECURITY NOTIONS. First we give a syntactic definition of FE, which extends that for predicate encryption introduced by Boneh and Waters [BW07]. We then formulate an “indistinguishability based” notion of privacy (IND), which again extends the security notion for predicate encryption introduced in [BW07]. Informally, the IND notion asks that it be hard for an adversary to distinguish between the encryptions of any two messages that agree on all the functions corresponding to the secret keys it requested. We go on to introduce a more complicated but more natural “semantic security based” (SS) notion of privacy in the spirit of the classical notion for public-key encryption [GM84], to capture the intuition that anything the adversary can compute from a ciphertext it could as well compute from the evaluations of the functions corresponding to the secret keys it requested on underlying message. We note that a novel feature of our definitions, which turns out to be important when considering relations among them, is that they distinguish

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¹We do not mean here to claim credit for the general concept of functional encryption and its generalizing these primitives; indeed, this view was present in prior work (e.g., [SW05, BW07, KSW08]) and in a talk by Waters [Wat].

between *adaptive* and *non-adaptive* access to the secret-key derivation oracle to aid in the adversary’s task (roughly, this distinction is analogous to that between access to the decryption oracle in adaptive versus non-adaptive chosen-ciphertext attack, see e.g. [BDPR98]).

RELATIONS AMONG SECURITY NOTIONS. In the classical setting of public-key encryption, semantic security and indistinguishability based formulations of security are well-known to be equivalent [MRS88]. We ask whether the same is true for FE. Surprisingly, we show that IND under adaptive access to the secret-key derivation oracle does not imply SS even under *non-adaptive* such access. To see why, consider a functional encryption scheme for a single function f . But suppose there is another function g that has the same “equality pattern” as f on the message space (i.e., two messages have the same f -value just when they have the same g -value). Furthermore, suppose $g(m)$ is hard to compute given $f(m)$. Now, if the functional encryption scheme is such that the secret keys created by the scheme, which are supposed to allow computing f , also allow computing g , the scheme is certainly not semantically secure. However, an IND adversary is “bound” to choosing messages that agree on f , hence also on g , and so cannot use computing g to its advantage. Our counter-example formalizes and generalizes this intuition. Another shortcoming of the IND notion we observe is that it is essentially vacuous² for some functions, such as a collision-resistant hash function. Then, it is hard for the adversary to find two messages that agree on the function.

ACHIEVABILITY. Finally, we ask the question of whether the SS notion for FE is *achievable*. In particular, we note that achieving SS under adaptive access to the key derivation oracle seems difficult. In the proof, the simulator seemingly must choose a “dummy” ciphertext on which to run the adversary *before* knowing what values the challenge message should have when evaluated under the functions for which the adversary will later request secret keys. Intuitively, this means the number of possible keys for a given function should at least be as large as the number of possible outputs of the latter. This situation is reminiscent of that for (non-interactive) non-committing encryption, for which impossibility results are known [Nie02].

Fortunately, we also bring some good news. In the case of non-adaptive SS, we identify a key property of functional encryption schemes that we call *preimage sampleability*. Intuitively, this means that, given the function values of some underlying message, it should always be possible to efficiently find some message consistent with them. (Thus, for non-adaptive security our above-mentioned counter-example is tight.) We show that for preimage sampleable FE schemes, IND is *equivalent* to SS (both under non-adaptive access to the key-derivation oracle). The reason we believe this is important is that non-adaptive SS suffices to rule out the “pathological” examples of schemes we gave that meet IND but not SS.³ Thus, our interpretation is that for preimage sampleable schemes, IND (under adaptive access to the key-derivation oracle) is probably fine in practice. We conclude by showing that some common function classes considered in the literature, including the powerful inner-product predicates realized in [KSW08, LOS⁺10, OT10], are preimage sampleable.

CONCURRENT AND INDEPENDENT WORK. Independently of our work, Boneh et al. [BSW10] also undertake a general study of FE. In particular they give a syntactic definition as well as indistinguishability and semantic security based formulations of privacy (their formulation of the latter

²At least, it is vacuous with respect to attacks that require the adversary to query its key derivation oracle; i.e., attacks where the adversary actually uses the secret keys. A functional encryption scheme may of course already not be semantically secure in the classical sense.

³On the other hand, it is possible to extend them to even more extreme examples that violate SS only under adaptive access to the key-derivation oracle, but these start to really stretch plausibility.

differs somewhat from ours; see the discussion in Section 2). Under their formulations, they give a (again, somewhat different⁴) example showing that IND does not imply SS. They also formalize the connection between SS under adaptive access to the key derivation oracle (although they do not distinguish between adaptive versus non-adaptive here) and non-committing encryption, showing via an argument in the style of [Nie02] that the former is not achievable at all without (programmable) random oracles but is achievable in the random oracle model. We feel this further highlights the importance of our results on the (standard model) achievability of non-adaptive SS.

2 Functional Encryption and its Security

We define the syntax of functional encryption and various security notions for it.

2.1 Syntax

A *functional encryption scheme* for the class of PT functions (aka. functionality) \mathcal{F} on message-space Σ is a tuple of algorithms $\mathcal{FE} = (\text{Setup}, \text{KDer}, \text{Enc}, \text{Eval})$ such that:

- **Setup** on input 1^k outputs a *master public key* pk and *master secret key* sk .
- **KDer** on input the master secret key sk and a (description of a) function $f \in \mathcal{F}$ outputs an *evaluation token* (aka. secret key) sk_f for f .
- **Enc** on input a public key pk and a message (aka. attribute) $m \in \Sigma$ outputs a ciphertext c .
- **Eval** on input an evaluation token sk_f and a ciphertext c outputs a string y or \perp .

For correctness we require that for all $k \in \mathbb{N}$, all $f \in \mathcal{F}$, and all $m \in \Sigma$,

$$\text{Eval}(sk_f, \text{Enc}(pk, m)) = f(m)$$

with probability 1 over $(pk, sk) \xleftarrow{\$} \text{Setup}(1^k)$ and $sk_f \xleftarrow{\$} \text{KDer}(sk, f)$.

Note that this notion is in particular a generalization of identity-based encryption (IBE) [BF03], public-key encryption with keyword search (PEKS) [BCOP04, ABC⁺08], attribute-based encryption (ABE) [SW05, GPSW06, BSW07], and predicate encryption (PE) [BW07, KSW08, LOS⁺10, OT10]. For example, in the case of identity-based encryption, the “message” would consist of the identity concatenated with the actual payload, and the secret key would be associated with the function $f_{ID}(ID' || x) = x$ if $ID = ID'$ and \perp otherwise.

2.2 Security Definitions

We present various formulations of privacy for functional encryption. Broadly, the definitions are either *indistinguishability based* or *semantic-security based*. In each case we also define a *token non-adaptive* (TNA) variant, where the adversary gets access to a token derivation oracle only before it sees the challenge ciphertext.

⁴Our counter-example is slightly more general. In particular, ours shows a separation even for schemes (such as those proposed in the literature) where the adversary can find two messages that agree on the functions corresponding to the secret keys it requested.

Regarding special cases, we note that our security notions yield the *anonymous* (aka. attribute-hiding) versions of IBE, ABE, and PE, where the identity or attribute is hidden by the ciphertext (or their “predicate-only” counterparts following the terminology of [KSW08]). The contemporaneous work of [BSW10] provides a more general and comprehensive treatment.

INDISTINGUISHABILITY BASED PRIVACY. The indistinguishability-based formulation follows [BW07] and tries to capture the intuition that the adversary is unable to distinguish between the encryptions of two different messages that it cannot trivially distinguish using its tokens. Let $\mathcal{FE} = (\text{Setup}, \text{KDer}, \text{Enc}, \text{Eval})$ be a functional encryption scheme for the class of functions \mathcal{F} over message-space Σ and let $A = (A_1, A_2)$ be an adversary. For $\text{mode} \in \{\text{full}, \text{tna}\}$ ⁵ and $k \in \mathbb{N}$ we associate to \mathcal{FE} and A the experiments

Experiment $\text{Exp}_{\mathcal{FE}, A}^{\text{ind-mode}}(k)$:
 $b \xleftarrow{\$} \{0, 1\}$
 $(pk, sk) \xleftarrow{\$} \text{Setup}(1^k)$
 $(m_0, m_1, st) \xleftarrow{\$} A_1^{\text{KDer}(sk, \cdot)}(pk)$
 $c \xleftarrow{\$} \text{Enc}(pk, m_b)$
 $b' \xleftarrow{\$} A_2^{\mathcal{O}(sk, \cdot)}(pk, c, st)$
 If $b = b'$ return 1 else return 0

where if $\text{mode} = \text{full}$ then $\mathcal{O}(sk, \cdot) = \text{KDer}(sk, \cdot)$ and if $\text{mode} = \text{tna}$ then $\mathcal{O}(sk, \cdot) = \varepsilon$ (the empty oracle). We require that $|m_0| = |m_1|$ and every query f that A_1 or A_2 makes to its oracle satisfies $f(m_0) = f(m_1)$. Denote by $\Pr[\mathbf{Exp}_{\mathcal{FE}, A}^{\text{ind-mode}}(k) = 1]$ the probability that the corresponding IND-MODE experiment outputs 1, and define

$$\mathbf{Adv}_{\mathcal{FE}, A}^{\text{ind-mode}}(k) = 2 \cdot \Pr[\mathbf{Exp}_{\mathcal{FE}, A}^{\text{ind-mode}}(k) = 1] - 1.$$

We say that \mathcal{FE} is *IND-MODE secure* if $\mathbf{Adv}_{\mathcal{FE}, A}^{\text{ind-mode}}(\cdot)$ is negligible for all PPT adversaries A .

SEMANTIC-SECURITY BASED PRIVACY. The semantic-security formulation is new and tries to capture the intuition that anything the adversary can compute from a ciphertext and the tokens it can compute from the tokens and the values of the corresponding functions on the underlying message. Let $\mathcal{FE} = (\text{Setup}, \text{KDer}, \text{Enc}, \text{Eval})$ be a functional encryption scheme for the class of functions \mathcal{F} over message-space Σ , let $A = (A_1, A_2, A_3)$ be an adversary, let S be a simulator. For $\text{mode} \in \{\text{full}, \text{tna}\}$ and $k \in \mathbb{N}$ we associate to \mathcal{FE} , A , and S the experiments

<p>Experiment $\text{Exp}_{\mathcal{FE}, A}^{\text{ss-real-mode}}(k)$: $(pk, sk) \xleftarrow{\\$} \text{Setup}(1^k)$ $st \xleftarrow{\\$} A_1^{\text{KDer}(sk, \cdot)}(pk)$ $(m, t) \xleftarrow{\\$} A_2(pk, st)$ $c \xleftarrow{\\$} \text{Enc}(pk, m)$ $t' \xleftarrow{\\$} A_3^{\mathcal{O}(sk, \cdot)}(pk, c, st)$ If $t = t'$ return 1 else return 0</p>	<p>Experiment $\text{Exp}_{\mathcal{FE}, A, S}^{\text{ss-ideal-mode}}(k)$: $(pk, sk) \xleftarrow{\\$} \text{Setup}(1^k)$ $st \xleftarrow{\\$} A_1^{\text{KDer}(sk, \cdot)}(pk)$ $(m, t) \xleftarrow{\\$} A_2(pk, st)$ Let f_1, \dots, f_q be the queries made by A_1 $t' \xleftarrow{\\$} S^{\mathcal{O}'(sk, \cdot)}(pk, f_1(m), \dots, f_q(m), st)$ If $t = t'$ return 1 else return 0</p>
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⁵We stress that our use of the terminology “full” security differs from the literature in that it refers to adaptive access to the key derivation oracle rather than adaptive choice of the challenge messages.

where if $\text{mode} = \text{full}$ then $\mathcal{O}(sk, \cdot) = \text{KDer}(sk, \cdot)$ and for any f oracle $\mathcal{O}'(sk, f)$ returns $(sk_f, f(m))$ where $sk_f \stackrel{\$}{\leftarrow} \text{KDer}(sk, f)$, and if $\text{mode} = \text{tna}$ then $\mathcal{O}(sk, \cdot) = \mathcal{O}'(sk, \cdot) = \varepsilon$ (the empty oracle). We assume for simplicity that A_1 's output (the state st) includes its oracle queries and the responses.⁶ Think of the string $t \in \{0, 1\}^*$ in the output of A_2 as partial information on m . Note that in the above formalization of semantic security, even in the ideal experiment we run A_1 and A_2 . A more standard formalization would have the simulator also run at these stages. However, we want to “bind” the simulator to making the same key derivation queries as the adversary.⁷ Denote by $\Pr [\mathbf{Exp}_{\mathcal{F}\mathcal{E}, A}^{\text{ss-real-mode}}(k) = 1]$ the probability that the SS-REAL-MODE experiment outputs 1 and by $\Pr [\mathbf{Exp}_{\mathcal{F}\mathcal{E}, A, S}^{\text{ss-ideal-mode}}(k) = 1]$ the probability that the SS-IDEAL-MODE experiment outputs 1. Define

$$\mathbf{Adv}_{\mathcal{F}\mathcal{E}, A, S}^{\text{ss-mode}}(k) = \Pr [\mathbf{Exp}_{\mathcal{F}\mathcal{E}, A}^{\text{ss-real-mode}}(k) = 1] - \Pr [\mathbf{Exp}_{\mathcal{F}\mathcal{E}, A, S}^{\text{ss-ideal-mode}}(k) = 1] .$$

We say that $\mathcal{F}\mathcal{E}$ is *SS-MODE secure* if for every PPT adversary A there exists a PPT simulator S such that $\mathbf{Adv}_{\mathcal{F}\mathcal{E}, A, S}^{\text{ss-mode}}(\cdot)$ is negligible.

3 Inequivalence of the Definitions in General

We investigate relations among the notions of security we introduced for FE. First, we note that when giving the adversary adaptive access to the token derivation oracle (i.e., what we call FULL security), one reason semantic security seems stronger than indistinguishability is that the simulator apparently needs to commit to a “dummy” ciphertext on which to run the adversary *before* knowing what values the challenge message should have when evaluated under the functions for which the adversary will later request tokens.

But we show that there is actually a more subtle reason for inequivalence of the definitions. In fact, we show that in general IND-FULL security does not even imply SS-TNA security. To show the separation we start with a IND-FULL secure functional encryption scheme for any class of functions \mathcal{F} of a certain form. We then modify it to construct a new scheme that is still IND-FULL secure for \mathcal{F} but *not* SS-TNA secure. We show the latter by presenting a concrete attack. We first describe a concept our counter-example scheme employs.

HIDDEN FUNCTIONS. Let $\mathcal{G} = \{g_k\}_{k \in \mathbb{N}}$ and $\mathcal{F} = \{f_k\}_{k \in \mathbb{N}}$ be families of functions on a common domain $D = D(k)$. We say \mathcal{G} is *hidden* by \mathcal{F} if any PPT adversary A on inputs $f_k, f_k(x)$ where $x \stackrel{\$}{\leftarrow} D$ outputs $g_k(x)$ with only negligible probability in k . Note that such functions can be constructed under standard assumptions; for example, let f_k be a one-way function applied to the first half of the bits of the input and let g_k just output these bits (that is, the first half of the bits of the input).⁸ We say \mathcal{F} and \mathcal{G} are *isomorphic* if f_k and g_k are isomorphic for every k , meaning

$$f_k(d_1) = f_k(d_2) \Leftrightarrow g_k(d_1) = g_k(d_2) .$$

⁶We do not consider a notion of *function hiding* (cf. [SSW09]).

⁷On the other hand, in the case of FULL security this is not enforced by the definition. This was an oversight on our part that we leave in here, since we only noticed it after [BSW10] appeared. Other differences between their SS definition and ours include: theirs considers only adaptive access to the key derivation oracle whereas ours distinguishes between adaptive and non-adaptive, and theirs considers the encryption of multiple messages whereas ours considers only a single message (in particular, the former is important for the proof of impossibility they give for meeting their notion without random oracles).

⁸Indeed, a simpler example is to take f_k to be a one-way function and g_k to be the identity. However, in our counter-example this will prevent the adversary from even being able to *find* two messages that agree on f_k . We believe this points to a separate shortcoming of the IND definition.

for all $d_1, d_2 \in D$. In other words, f_k and g_k have the same equality pattern across the domain. This is the case, for example, if f_k in the example above is an *injective* one-way function on the first half of the input bits. We suppress dependence on k below for convenience, just talking of functions rather than function families.

THE COUNTER-EXAMPLE SCHEME. Let $\mathcal{AE}^* = (\text{KDer}^*, \text{Enc}^*, \text{Dec}^*)$ be a (standard) public-key encryption scheme, and let $\mathcal{FE}' = (\text{Setup}', \text{KDer}', \text{Enc}', \text{Eval}')$ be a functional encryption scheme over message-space Σ for a class of functions $\mathcal{F} = \{f_1, \dots, f_n\}$ satisfying the following: there is a function g on Σ such that the pointwise concatenated function⁹ $f = f_1 \parallel \dots \parallel f_n$ is isomorphic to g and moreover g is hidden by f . (For simplicity, we assume here that n is polynomial in k . The counter-example can easily be extended to larger function sets by instead requiring the forgoing condition on some fixed *subset* of the f_i 's.) Then we define a new functional encryption scheme $\mathcal{FE} = (\text{Setup}, \text{KDer}, \text{Enc}, \text{Eval})$ over Σ for \mathcal{F} as follows.

- **Setup** on input 1^k first runs $(pk', sk') \xleftarrow{\$} \text{Setup}'(1^k)$, and $(pk^*, sk^*) \xleftarrow{\$} \text{KDer}^*(1^k)$. It then selects $w_1, \dots, w_{n-1} \xleftarrow{\$} \{0, 1\}^{|sk^*|}$ and computes $w_n \leftarrow sk^* \oplus w_1 \oplus \dots \oplus w_{n-1}$. Finally, it returns master public key $pk = pk' \parallel pk^*$ and master secret key $sk = sk' \parallel w_1 \parallel \dots \parallel w_n$.
- **KDer** on input the master secret key $sk = sk' \parallel w_1 \parallel \dots \parallel w_n$ and a (description of a) function $f_i \in \mathcal{F}$ first runs $\text{KDer}'_{sk'}(f_i)$ to obtain sk'_{f_i} . Then, it outputs $sk_{f_i} = sk'_{f_i} \parallel w_i$.
- **Enc** on input the master public key $pk = pk' \parallel pk^*$ and a message $m \in \Sigma$ first computes $c' \xleftarrow{\$} \text{Enc}'(pk', m)$ and $c^* \xleftarrow{\$} \text{Enc}^*(pk^*, g(m))$. It returns $c' \parallel c^*$.
- **Eval** on input a secret key $sk_{f_i} = sk'_{f_i} \parallel w_i$ and a ciphertext $c = c' \parallel c^*$ computes $d \leftarrow \text{Eval}'(sk'_{f_i}, c')$, and outputs d .

Theorem 3.1 If \mathcal{AE}^* is IND-CPA secure and \mathcal{FE}' is IND-FULL secure for $\mathcal{F} = \{f_1, \dots, f_n\}$ as above (i.e., where g is hidden by $f_1 \parallel \dots \parallel f_n$), then \mathcal{FE} is also IND-FULL secure for \mathcal{F} . However, it is not SS-TNA secure.

Note that the assumptions of the theorem do not constitute any additional complexity assumptions beyond the (minimal) one of \mathcal{FE}' being IND-FULL secure for \mathcal{F} , meaning based on the latter we can construct the other schemes and functions that are assumed.

We also remark that the separation also holds in the case of “selective-security,” where the challenge messages are chosen up-front by the adversary, as considered in e.g. [BW07, KSW08]. It also holds in the case of predicate encryption [BW07, KSW08], since we can take f_i for $1 \leq i \leq n$ to output the i -th bit of a function f such that g is hidden by f (i.e., a function can always be decomposed bit-wise into predicates).

Proof: (Sketch.) To see \mathcal{FE} is IND-FULL secure for \mathcal{F} , first consider an adversary A that does not request tokens for all of f_1, \dots, f_n . Then in addition to interacting with \mathcal{FE}' in the IND-FULL experiment, the adversary is just given additional random strings when it requests tokens, which in particular are independent of b , so security of \mathcal{FE} follows from that of \mathcal{FE}' . Now consider A that requests tokens for all of f_1, \dots, f_n . In this case, in addition to interacting with \mathcal{FE}' the adversary obtains $g(m_b)$ where m_b is the challenge message. But by the rules of the experiment we know that

⁹By pointwise concatenation $f \parallel g$ of functions f and g on a set D we mean that $f \parallel g(x) = f(x) \parallel g(x)$ for all $x \in D$.

$f_1(m_0) \parallel \dots \parallel f_n(m_0) = f_1(m_1) \parallel \dots \parallel f_n(m_1)$ and thus by assumption $g(m_0) = g(m_1)$, meaning again this information is independent of b and so IND security of \mathcal{FE} follows from that of \mathcal{FE}' .

To show that \mathcal{FE} is not SS-TNA secure, we describe an SS-TNA adversary $B = (B_1, B_2, B_3)$ for which there is no simulator with comparable probability of guessing $t = t'$. Namely, B_1 requests evaluation tokens for all of f_1, \dots, f_n and passes them along as the state, and B_2 chooses a random challenge message $m \in \Sigma$, sets $t \leftarrow g(m)$, and outputs (m, t) . Then, by construction B_3 can always output $t = t'$ by decrypting the part of the challenge ciphertext formed by \mathcal{AE}^* (note that B_3 makes no queries itself as required). However, a simulator who outputs $t = t'$ with non-negligible probability would contradict the fact that g is hidden by f since the simulator is not given any ciphertext but just the value of $f_1(m) \parallel \dots \parallel f_n(m)$ (also pk and the evaluation tokens for f_1, \dots, f_n , but a hidden function adversary can generate these itself). \blacksquare

4 An Equivalence under Preimage Sampleability

We show that for token non-adaptive (TNA) security the counter-example in Section 3 is tight. Namely, we show an *equivalence* between indistinguishability and semantic-security under TNA security for what we call *preimage sampleable* (PS) schemes. Note that TNA security seems reasonable in practical applications where what tokens a party receives does not depend on the encrypted messages.

PREIMAGE SAMPLEABILITY. Let $\mathcal{FE} = (\text{Setup}, \text{KDer}, \text{Enc}, \text{Eval})$ be a functional encryption scheme over message-space Σ for the class of functions \mathcal{F} . We call \mathcal{FE} *preimage sampleable* (PS) if there is a PPT algorithm that given $(f_1, y_1 = f_1(m)), \dots, (f_i, y_i = f_i(m))$ for any polynomial $i = i(k)$, any $f_1, \dots, f_i \in \mathcal{F}$ and any $m \in \Sigma$ outputs some message (not necessarily m) in the set

$$S_{y_1, \dots, y_i} = \{m' \in \Sigma \mid f_1(m') = y_1, \dots, f_i(m') = y_i\}.$$

Note that preimage sampleability as we have defined it is thus a property of \mathcal{F} and we sometimes refer to it as such.

In essence, we show that preimage sampleability provides a “test” of whether equivalence between the IND and SS definitions is maintained in the case of TNA security.

Theorem 4.1 Let \mathcal{FE} be an PS functional encryption scheme. Then \mathcal{FE} is SS-TNA secure if and only if it is IND-TNA secure.

Proof: (Sketch.) (SS-TNA \Rightarrow IND-TNA) Suppose that \mathcal{FE} is not IND-TNA secure, in particular let $A = (A_1, A_2)$ be a successful IND-TNA adversary against it. Consider a SS-TNA adversary $B = (B_1, B_2, B_3)$ that works as follows. B_2 runs A_1 on pk to receive messages m_0, m_1 . It then chooses $d \in \{0, 1\}$ at random and returns (m_d, d) . B_3 runs A_2 on its input and outputs the result. Note that no SS-TNA simulator can output d with probability better than $1/2$ in the SS-TNA-REAL experiment because it gets no information about it (recall that A only makes key-derivation queries whose results are independent of b , and the simulator makes no queries).

(IND-TNA \Rightarrow SS-TNA) Now suppose \mathcal{FE} is IND-TNA secure. Let $A = (A_1, A_2, A_3)$ be an SS-TNA adversary against \mathcal{FE} . We construct a simulator S with comparable probability of outputting $t = t'$ in the SS-IDEAL-TNA experiment to A in the SS-REAL-TNA experiment, meaning \mathcal{FE} is

SS-TNA secure. Simulator S works as follows: given the queries f_1, \dots, f_q made by A_1 and their values y_1, \dots, y_q on the challenge message m , S will sample a “dummy” message $m' \in \Sigma$ such that $f_1(m') = y_1, \dots, f_q(m') = y_q$ using the sampler guaranteed by the definition of PS. It runs A_3 on the encryption of m' and outputs the result. If $m = m'$ with overwhelming probability then A_3 's success probability in the simulated environment remains negligibly different from in the real one. Otherwise, we can use A to construct a successful IND-TNA adversary B , as follows. B runs A_1, A_2 on the appropriate inputs to receive m, t . Let f_1, \dots, f_q be the queries made by A_1 . Using the sampler guaranteed by the definition of PS, B samples a message m' such that $f_1(m') = f_1(m), \dots, f_q(m') = f_q(m)$. It then submits m, m' as its challenge messages, runs A_3 on the result and checks whether it returns $t' = t$ or not; if so, it outputs 0, and otherwise 1. Note that it is important here that $m \neq m'$, which holds with non-negligible probability in this case. This contradicts our assumption. ■

It is interesting to note how the proof of the second implication accounts for the fact that IND-TNA may be “vacuously” satisfied when the adversary is not able to find two messages that agree on the given functionality. Indeed, in this case, our simulator samples from the corresponding preimage set of size 1, and thus the simulation trivially works.

5 On Preimage Sampleability of Some Functionalities

We examine whether specific functionalities considered in the literature satisfy our PS condition. For inner-product predicates [KSW08, LOS⁺10, OT10], IBE [BF03], and PEKS [BCOP04, ABC⁺08], we show that the answer is “yes.” On the other hand, for ABE [SW05, GPSW06, BSW07] it seems hard to show PS; we leave this as an open problem.

INNER-PRODUCTS. We first show that PS is satisfied by the important class of *inner-product predicates* realized in prior work [KSW08, LOS⁺10, OT10]. Hence, by Theorem 4.1, schemes in the literature for this functionality proven secure relative to the IND notion also meet SS, at least under non-adaptive access to the token-derivation oracle. Namely, consider the evaluation of inner products over \mathbb{Z}_N for a composite N (of which it assumed hard to find a non-trivial factor). More formally, let $n \in \mathbb{N}$ be given and let N be such a composite. Let $\Sigma = \mathbb{Z}_N^n \setminus \{0^n\}$ and define the associated class of *inner-product predicates* $\mathcal{P}_{iprod} = \{p_{\mathbf{x}} \mid \mathbf{x} \in \mathbb{Z}_N^n\}$ where $p_{\mathbf{x}}(\mathbf{y}) = 1$ if $\langle \mathbf{x}, \mathbf{y} \rangle = \sum_{i=1}^n x_i \cdot y_i = 0 \pmod N$, and 0 otherwise. (Note that in the terminology of [KSW08] we thus consider the “predicate-only” version of the scheme for simplicity.)

Proposition 5.1 The class \mathcal{P}_{iprod} as defined above is preimage sampleable.

Proof: (Sketch.) For any polynomial $r = r(k)$, given $(p_{\mathbf{x}_1}, y_1 = p_{\mathbf{x}_1}(m)), \dots, (p_{\mathbf{x}_r}, y_r = p_{\mathbf{x}_r}(m))$ for any $p_{\mathbf{x}_1}, \dots, p_{\mathbf{x}_r} \in \mathcal{P}_{iprod}$ and $m \in \Sigma$, we construct an algorithm A that samples from S_{y_1, \dots, y_r} in the definition of PS. Let I_b denote the set $\{i \in [r] \mid y_i = b\}$ for $b \in \{0, 1\}$, and let B be an $|I_1| \times n$ matrix where each row is a unique element of $\{\mathbf{x}_i \mid i \in I_1\}$.

The sampling algorithm A first finds a “basis” $W = \{\mathbf{w}_1, \dots, \mathbf{w}_s\}$ for $\ker(B)$ in the space \mathbb{Z}_N^n . This can be done by solving the homogeneous system of equations $B\mathbf{x} = \mathbf{0}$ using Gaussian elimination over \mathbb{Z}_N . (Note that while \mathbb{Z}_N is not a field, if Gaussian elimination fails we have found a non-trivial factor of N .) Next, A samples a uniformly random element $\mathbf{w} \in \ker(B)$ by taking a random \mathbb{Z}_N -combination of the basis vectors in W . A then tests if $\langle \mathbf{w}, \mathbf{x}_i \rangle \neq 0$ for all $i \in I_0$. If so, A outputs

w and terminates, and if not, then A continues to re-sample w from $\ker(B)$ until this is true (but halts after say a maximum k attempts).

Observe that A is a PPT algorithm, since a random vector from $\ker(B)$ is overwhelmingly likely to be non-orthogonal to each \mathbf{x}_i , $i \in I_0$, and thus by a union bound the termination condition is achieved with overwhelming probability in each attempt. ■

IBE AND PEKS. The functionalities for IBE [BF03] and PEKS [BCOP04, ABC⁺08] are also preimage sampleable. For example, in the case of IBE, given the functions and their values on the underlying “message,” there are two cases: if we know that $f_{ID}(ID' \| x) = x$ then there is only one possible preimage, namely $ID \| x$; otherwise, we can sample from the set of possible “messages” by choosing an identity other than those for which the adversary has requested secret keys and any payload. (an analogous argument applies in the case of PEKS). We omit the formal statements. By Theorem 4.1, we conclude that such schemes in the literature proven secure under an IND notion also meet SS-TNA under this condition.

ATTRIBUTE-BASED ENCRYPTION. For the functionalities of ABE [SW05, GPSW06, BSW07], we do not know if PS holds. For example, consider the case of (anonymous) Fuzzy IBE [SW05, KSW08]. Namely, let U be a finite set and let Σ be the power-set of U , i.e., $\Sigma = \{S \mid S \subseteq U\}$. For $1 \leq d \leq |U|$ and $S, T \subseteq U$ define $p_{S,d}(T) = 1$ if $S \cap T \geq d$ and 0 otherwise. (As before, let us consider this “predicate-only” counterpart to Fuzzy IBE for simplicity.) Typically, one considers an FE scheme over Σ for the class $\mathcal{P}_d = \{p_{S,d} \mid S \subseteq U\}$ where d is fixed. To show PS, we would basically need to give an efficient algorithm that, given “good” sets $G_1, \dots, G_n \subseteq U$ and “bad sets” $B_1, \dots, B_m \subseteq U$ for polynomials $n = n(k), m = m(k)$, as well as d such that $1 \leq d \leq |U|$, outputs a set $X \subseteq U$ such that $|X \cap G_i| \geq d$ for all $1 \leq i \leq n$ and $|X \cap B_j| < d$ for all $1 \leq j \leq m$. We are not sure if such an algorithm exists and leave this for future work.

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