Correlation-Robust Hashing and OT Extension from One-Way Functions

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April 16, 2024

Abstract

This document contains a proof that the PAKE protocol of Katz, Ostrovsky and Yung (2001) is not UC-secure.

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1 Overview

At a high level, our attack relies on an adversary $\mathcal{A}$ that completely disregards the presence of Server and instead interacts with User while executing Server's algorithm on its own. In particular, once the protocol is initiated by User, $\mathcal{A}$ assumes the role of the server (discarding the actual server in the process, which plays no part in the protocol) and receives $\mathsf{msg}_1 = \mathsf{VK}|A|B|C|D$. After this, $\mathcal{A}$ runs the server's algorithm on User's password pw and computes $\mathsf{msg}_2 = E|F|G|I|J$. User then runs its session-key generating algorithm and outputs its session key $\mathsf{sk} = E^{r_1}F^{x_1}G^{y_1}(I')^{z_1}J^{w_1}$. We note that at this point, $\mathcal{A}$ (and $\mathcal{Z}$) have all the information they need to run the server's session-key generating algorithm locally, which computes a session key equal to sk generated by User.

To see why a PPT simulator $\mathcal{S}$ cannot simulate this adversary, we attempt an ideal-world execution and pinpoint where it fails. Since $\mathcal{S}$ is allowed to choose $\mathsf{crs} = (g_1, g_2, h, c, d)$, it can sample g_1 at random and set h such that $h = g_1^{\ell}$. After receiving the $\mathsf{NewSession}$ command from $\mathcal{F}_{\mathsf{PAKE}}$, $\mathcal{S}$ must simulate User's first message msg_1. Since $\mathcal{S}$ does not know the password, at this point it must (effectively) guess some pw^* at random; that is, in msg_1, $C = h^{r_1} \cdot \mathsf{pw}^*$ where pw^* can be no better than a random password sampled from the dictionary. After $\mathcal{Z}$ responds with $\mathsf{msg}_2 = E|F|G|I|J$, since $F = g_1^{r_2}$ and $I = h^{r_2} \cdot \mathsf{pw}$, $\mathcal{S}$ can extract pw as I/F^{ℓ}. Once this has been done, $\mathcal{S}$ can send a $\mathsf{TestPwd}$ command to $\mathcal{F}_{\mathsf{PAKE}}$ on the correct pw; $\mathcal{F}_{\mathsf{PAKE}}$ would mark the User session $\mathsf{compromised}$ and thus allow $\mathcal{S}$ to choose User's session key sk.[1] The problem is that even with this information, $\mathcal{S}$ still cannot determine what sk is.

To determine sk, $\mathcal{S}$ can either run Server's algorithm or User's algorithm to generate session keys. Recalling that $\mathsf{msg}_2 = E|F|G|I|J$ is provided to $\mathcal{S}$ directly from the environment, $\mathcal{S}$ cannot use Server's algorithm since it would require the determination of all of x_2, y_2, z_2, r_2, w_2, which is computationally infeasible under the hardness of CDH. Alternately, $\mathcal{S}$ can run User's algorithm to determine sk, for which it already has access to x_1, y_1, z_1, r_1, w_1 and E, F, G, I, J. However, we recall that this sk output by $\mathcal{S}$ must be equal to that which $\mathcal{Z}$ determines using its own execution of Server's algorithm (this is what happens in the real world). The problem here is that the password guess pw^* that $\mathcal{S}$ uses while generating msg_1 is likely incorrect; in fact, we can show that the output of Server's algorithm on $\mathsf{msg}_1, \mathsf{msg}_2$ and msg_3 by $\mathcal{Z}$ will have $(\mathsf{pw}^*/\mathsf{pw})^{z_2}$ as a factor, and except in the $1/|\mathcal{D}|$ probability case that $\mathsf{pw}^* = \mathsf{pw}$, $\mathcal{S}$ cannot determine z_2 assuming the hardness of CDH and thus will be unable to determine sk.

2 Proof

Theorem 2.1. *Assuming the hardness of fixed-CDH, the protocol of [KOY] does not UC-realize $\mathcal{F}_{\mathsf{pake}}$ in the $\mathcal{F}_{\mathsf{crs}}$-hybrid model.*

Proof. Consider the environment $\mathcal{Z}$ in Figure 1 and the dummy adversary. It follows from the correctness of the protocol that in the real-world protocol execution $\mathcal{Z}$ always outputs 1, since the algorithm of $\mathcal{Z}$ and $\mathcal{A}$ is the same as that of an honest server. At a high level, we will show that any simulator that successfully simulates the protocol against $\mathcal{Z}$ in the ideal world can be used to solve arbitrary instances of fixed-CDH.

[1] Recall that a $\mathsf{TestPwd}$ *must* be run, since we require that msg_1 and msg_2 together with the randomness of the User and $\mathcal{A}$ together determine sk; allowing the simulation to proceed without a $\mathsf{TestPwd}$ would result in $\mathcal{F}_{\mathsf{PAKE}}$ outputting a uniformly random key.

Environment $\mathcal{Z}$:

0. Jiayu: $\mathcal{Z}$ receives the CRS (g_1, g_2, h, c, d).

1. $\mathcal{Z}$ selects $\mathsf{pw} \xleftarrow{\$} \mathcal{PW}$, where $\mathcal{PW} \subseteq \mathbb{G}$ is the password dictionary. It then sends $(\mathsf{NewSession}, \mathsf{sid}, \mathsf{User}, \mathsf{Server}, \mathsf{pw})$ to User.

2. $\mathcal{Z}$ receives $\mathsf{msg}_1 = \mathsf{sid}|\mathsf{VK}|A|B|C|D$ from $\mathcal{A}$ and samples $x_2, y_2, z_2, w_2, r_2 \xleftarrow{\$} \mathbb{Z}_q$. It then sets
$$\begin{aligned} \alpha' &:= H(A|B|C|D) \\ E &:= g_1^{x_2} g_2^{y_2} h^{z_2} (cd^{\alpha'})^{w_2} \\ F &:= g_1^{r_2} \\ G &:= g_2^{r_2} \\ I &:= h^{r_2} \cdot \mathsf{pw} \\ \beta &:= H(\mathsf{msg}_1|E|F|G|I) \\ J &:= (cd^{\beta})^{w_2} \end{aligned}$$
and instructs $\mathcal{A}$ to send $\mathsf{msg}_2 := \mathsf{sid}|E|F|G|I|J$ to User.

3. $\mathcal{Z}$ receives $\mathsf{msg}_3 = \mathsf{sid}|K|\sigma$ from $\mathcal{A}$ and $(\mathsf{sid}, \mathsf{sk})$ from User.

4. $\mathcal{Z}$ sets $C' := C/\mathsf{pw}$ and then checks if $\mathsf{Vrfy}_{\mathsf{VK}}(\mathsf{msg}_1|\mathsf{msg}_2|K, \sigma) = 1$. If yes, it computes $\mathsf{sk}_S := A^{x_2} B^{y_2} (C')^{z_2} D^{w_2} K^{r_2}$ and outputs 1 if $\mathsf{sk}_S = \mathsf{sk}$. If either of the two checks fails, it outputs 0.

Figure 1: Our Setup.

Assume that there exists a negligible function $\varepsilon := \varepsilon(\lambda)$ such that there exists a "successful" simulator $\mathcal{S}$ for which $\mathcal{Z}$ outputs 1 with probability $1 - \varepsilon$ in the ideal world. First, assume that CDH is hard over $(\mathbb{G}, p, h)$. Consider reduction $\mathcal{R}$ which does the following. Jiayu: that runs the simulator $\mathcal{S}$ as follows (note that $\mathcal{R}$ plays the role of the environment $\mathcal{Z}$, the PAKE functionality $\mathcal{F}_{\mathsf{PAKE}}$, and the dummy parties User and Server combined):

Naman: I'm not completely convinced if this is the best way to write this; the proof is correct in the essentials, but I think this needs to be rewritten since I'm not sure what formal part $\mathcal{R}$ is playing here...

0. $\mathcal{R}$ receives $\mathsf{crs} = (g_1, g_2, h, c, d)$ from $\mathcal{S}$, outputs h to its challenger, and receives (h^a, h^b) where $a, b \xleftarrow{\$} \mathbb{Z}_p$. Jiayu: I moved "receiving the CRS" as the 0th step of the formal description of the reduction (and the environment) Jiayu: Is the group order p or q? It is called p in this step but q in the second step

1. $\mathcal{R}$ sends $(\mathsf{NewSession}, \mathsf{sid}, \mathsf{User}, \mathsf{Server})$ to $\mathcal{S}$.

2. $\mathcal{R}$ waits to receive $\mathsf{msg}_1 = \mathsf{sid}|\mathsf{VK}|A|B|C|D$ in response (as the first message from User to Server).

It then sets $\mathsf{pw} := C/h^b$ and samples $x_2, y_2, w_2, r_2 \xleftarrow{\$} \mathbb{Z}_q$, setting

$$\begin{aligned}
\alpha' &:= H(PIDs|A|B|C|D) \\
E &:= g_1^{x_2} g_2^{y_2} h^a (cd^{\alpha'})^{w_2} \\
F &:= g_1^{r_2} \\
G &:= g_2^{r_2} \\
I &:= h^{r_2} \cdot \mathsf{pw} \\
\beta &:= H(\mathsf{msg}_1|E|F|G|I) \\
J &:= (cd^{\beta})^{w_2}
\end{aligned}$$

i.e., the same computation as that of the honest server with a special choice of pw and z_2 Jiayu: the special choice of $\mathsf{pw} = C/h^b$ and $z_2 = a$, and sends $\mathsf{msg}_2 := \mathsf{sid}|E|F|G|I|J$ to $\mathcal{S}$.

3. $\mathcal{R}$ receives $\mathsf{msg}_3 = \mathsf{sid}|K|\sigma$ (as the second message from User to Server) and $(\mathsf{sid}, \mathsf{sk})$ from $\mathcal{S}$ (as User's output to $\mathcal{Z}$), and checks if $\mathsf{Vrfy}_{\mathsf{VK}}(\mathsf{msg}_1|\mathsf{msg}_2|K, \sigma) = 1$. If yes, Jiayu: If not, $\mathcal{R}$ aborts. Otherwise it calculates
$$h' = \frac{\mathsf{sk}}{A^{x_2} B^{y_2} D^{w_2} K^{r_2}}.$$

4. $\mathcal{R}$ outputs h'.

We recall that $\mathsf{sk}_C = \mathsf{sk}_S$ with probability $1 - \varepsilon$ by the assumption. Clearly in the protocol execution, we have, setting $C' = C/\mathsf{pw} = h^b$,

$$\mathsf{sk}_S = A^{x_2} B^{y_2} (C')^{z_2} D^{w_2} K^{r_2} = A^{x_2} B^{y_2} (h^b)^a D^{w_2} K^{r_2}$$

which clearly gives $h' = h^{ab}$ with probability $1 - \varepsilon$, as claimed, contradicting the hardness of fixed-CDH. Jiayu: Note that $\mathcal{S}$'s view while interacting with $\mathcal{R}$ is identical to $\mathcal{S}$'s view in the ideal world with environment $\mathcal{Z}$ in Figure 1; the difference is that $\mathcal{Z}$ samples pw and z_2 on its own, whereas $\mathcal{R}$ sets $\mathsf{pw} = C/h^b$ and $z_2 = a$ — which cannot be detected by $\mathcal{S}$. Let $C' = C/\mathsf{pw} = h^b$ and

$$\mathsf{sk}_S = A^{x_2} B^{y_2} (C')^{z_2} D^{w_2} K^{r_2} = A^{x_2} B^{y_2} (h^b)^a D^{w_2} K^{r_2}$$

as what $\mathcal{Z}$ would compute in its step 4; $\mathcal{Z}$ outputs 1 if and only if $\mathsf{sk}_S = \mathsf{sk}$, so by our assumption on $\mathcal{S}$, in $\mathcal{R}$'s interaction with $\mathcal{S}$, $\mathsf{sk}_S = \mathsf{sk}$ with probability $1 - \varepsilon$. But this gives $h' = h^{ab}$ with probability $1 - \varepsilon$, i.e., $\mathcal{R}$ wins with probability $1 - \varepsilon$, contradicting the hardness of fixed-CDH. □

//everything below is deprecated comments.

First, we will assume the hardness of CDH over the group $(\mathbb{G}, g, p)$. Let Let g^a, g^b be two elements where $a, b \xleftarrow{\$} \mathbb{Z}_p$.
Formally, assume that there exists a simulator $\mathcal{S}$ such that $\mathcal{Z}$ always outputs 1 in the ideal world. Jiayu: Formally we cannot really assume this; need to say "such that $\mathcal{Z}$ outputs 1 with all but negligible probability in the ideal world". I am not entirely sure for now, but we probably need to be more specific and say "there is a negligible function ϵ such that $\mathcal{Z}$ outputs 1 with probability $1 - \epsilon$ in the ideal world." We will use this simulator to compute g^{ab}. Jiayu: We will construct a reduction $\mathcal{R}$ that uses $\mathcal{S}$ to solve the CDH problem in $(\mathbb{G}, g, p)$. (I think it's better to explicitly mention a reduction.) Our technique works as follows: first, we send Jiayu: everywhere you say "we do something", change it to "$\mathcal{R}$ does something" $(\mathsf{NewSession}, \mathsf{sid}, \mathsf{User}, \mathsf{Server}, \mathsf{pw})$ to $\mathcal{F}_{\mathsf{PAKE}}$ Jiayu: conceptually I think $\mathcal{R}$ should play the role of $\mathcal{F}_{\mathsf{PAKE}}$

(if you are not sure what I am talking about, chat with me in our meeting or on Slack) and recieve $\mathsf{msg}_1 = \mathsf{sid}|\mathsf{VK}|A|B|C|D$ in response from $\mathcal{S}$. We set $\mathsf{pw} = C/g^b$ and sample $x_2, y_2, z_2, w_2, r_2 \xleftarrow{\$} \mathbb{Z}_q$.

$$\begin{aligned}
\alpha' &:= H(PIDs|A|B|C|D) \\
E &:= g_1^{x_2} g_2^{y_2} h^{z_2} (cd^{\alpha'})^{w_2} \\
F &:= g_1^{r_2} \\
G &:= g_2^{r_2} \\
I &:= h^{r_2} \cdot \mathsf{pw} \\
\beta &:= H(\mathsf{msg}_1|Server|E|F|G|I) \\
J &:= (cd^{\beta})^{w_2}
\end{aligned}$$

i.e., the same computation as that of the honest server with a special choice of pw. Forwarding this to $\mathcal{F}_{\mathsf{PAKE}}$, we recieve $\mathsf{msg}_3 = K|\mathsf{Sig}$ and $(\mathsf{sid}, \mathsf{sk})$ in return.