How to pair with a human

Stefan Dziembowski

Department of Computer Science
University of Rome
La Sapienza

Abstract. We introduce a protocol, that we call *Human Key Agreement*, that allows pairs of humans to establish a key in a (seemingly hopeless) case where no public-key infrastructure is available, the users do not share any common secret, and have never been connected by any physically-secure channel. Our key agreement scheme, while vulnerable to the *human*-in-the-middle attacks, is secure against any malicious *machine*-in-the middle. The only assumption that we make is that the attacker is a machine that is not able to break the Captcha puzzles (introduced by von Ahn et al., EUROCRYPT 2003).
Our main tool is a primitive that we call a *Simultaneous Turing Test*, which is a protocol that allows two users to verify if they are both human, in such a way that if one of them is not a human, then he does not learn whether the other one is human, or not.
To construct this tool we use a Universally-Composable Password Authenticated Key Agreement of Canetti et al. (EUROCRYPT 2005).

1 Introduction

One of the main reasons why digital crime is so difficult to combat is the fact that the attacks on digital devices are usually very easy to automatize and repeat for a large number of times. This makes the design of secure digital systems a completely different discipline than the design of physically-secure systems. Just observe that a physical attack on a bank that has probability 0.1% of succeeding may be infeasible, while, an *electronic* attack on a banking system that has the same probability of success may be feasible and profitable for the attacker.

The observation that certain types of malicious behavior are profitable only if they can be performed automatically and efficiently led to a construction of schemes where at some point one of the users has to prove that he is a human. This type of a "proof of being a human" was first proposed in [27], then independently discovered by [24], and finally formalized, and put in a general framework in [36], where it was given a name *Completely Automated Public Turing test to tell Computers and Humans Apart (Captcha).* In short, a Captcha scheme is a puzzle that is easy to solve by a human and hard to solve by a machine. The most common Captchas are computer-generated images containing a short string of characters written in such a way that they are unreadable for a computer, and still effortlessly readable by a human (cf. Fig. 1). Other Captchas that were proposed are based on: recognizing gender of a person on an image [27], understanding facial expression on an image [27], speech recognition [27], recognizing animal pictures [36], etc.

So far, Captcha schemes were mostly used as a method for preventing attacks in which the adversary simply floods the victim with a large number of unwanted requests. Examples of these include email spamming and automated posting to blogs, forums, on-line polls, wikis, etc. [27, 36]. Captchas are also used as a for thwarting the dictionary attacks on the password-based systems. In particular, [12] proposed to use Captcha for protecting local storage from such attacks. Also, some manufacturers of

Fig. 1. An example of a Captcha from Google.

home wifi routers recently started to use Captcha to prevent malicious software from getting access to their machines by simply guessing a password [31].

In this paper we propose a new application of the Captcha schemes. We show how Captchas can be used to construct a session key agreement between two humans that are connected by an insecure link. Our protocol, that we call a *Human Key Agreement* works in a (seemingly hopeless) case where no public-key infrastructure is available, and the users do not share any common secret, have never been connected by any physically-secure channel and do not even know each other personally (so they cannot, e.g., recognize each other's voice). The only assumption that we make is that the attacker is a machine that is not able to break the Captchas generated by the users.

1.1 Related work

Captcha Some work on Captchas was already described in Sect. 1. Both designing and breaking Captcha schemes is subject of intensive and active research. One of the interesting new research ideas in this field is the reCaptcha project [37], where the users solving Captchas are helping to digitize old books by deciphering scanned words on which the OCR methods failed. In this case Captcha consists of two images, (a) one that the creator of Captcha can solve himself (this is needed to verify the answer), and (b) one that is unreadable for him. The key point here is that the user who solves the Captcha does not know which image is (a) and which is (b), and hence he has to provide a solution for both.

Typically, the attacks on Captcha use the artificial intelligence methods (see e.g. [21]). An interesting exception is a so-called a *pornography attack*, where the the Captcha puzzles are forwarded to a pornographic web-site, and the web-site users have to solve the Captcha before being allowed to view the web-site contents [38]. For more information and references on Captcha see e.g. the Captcha web-site [34], or the wikipedia article [40].

Key agreement protocols Key agreement protocols were introduced by Diffie and Hellman in their seminal paper [14]. Informally, a key agreement protocol is a scheme that allows two parties that initially do not share any secret to agree on a common key. The protocol of [14] is secure only against an eavesdropping adversary, i.e. an adversary that can *passively* listen to the messages exchanged between the parties, and is not secure against a more powerful *active* adversary that fully controls the transmission (by modifying, coping, fabricating or destroying the messages). Such an active adversary is also called a *man-in-the middle*. Subsequently, several methods of protecting against the active attacks were proposed. A common one is to add message authentication to a passively-secure key agreement scheme. For example if the parties already share a common key K, they can authenticate their messages using Message Authentication Codes (see Sect. 3.1 for a definition). It may seem that the assumption that the parties from the beginning share a key trivializes the problem. The main point, however, is that such schemes allow to generate several fresh *session keys* from one long-term key K. An advantage of this method is that it provides *forward-security* [15, 18, 2], i.e. even if at some point the key K leaks to the adversary, the session keys generated in the past remain secret.

Other popular methods for authenticated key agreement are based on the public-key cryptography, or a trusted third party (for more on this, and for a general introduction to the area of key agreement see e.g. [6]). The drawback of the PKI approach is that it relays on a *public-key infrastructure*, that is usually non-trivial to set-up [16]. Using the trusted third party is often impractical, since it requires the parties to be connected to a party whom they both trust.

Some protocols are also based on the assumption that the agreeing parties share a common *password*, which may not be chosen uniformly at random, but has to be hard to guess for the adversary (we discuss it in more detail in Sect. 4). Yet another method, called *short string comparison*, assumes that the agreeing parties, after the protocol is completed, are able to securely compare, via a trusted channel if two short strings are equal [35, 29, 23, 9]. Such a comparison allows the parties to detect if the adversary performed the man-in-the middle attack, by verifying if both parties have the same view on the set of messages that were exchanged.

Secure pairing schemes *Secure device pairing* is a term used in the systems security community, referring to protocols whose goal is to establish a secret key between two electronic gadgets (mobile phones, PCs, routers, headsets, cameras and media players, etc.), usually connected with a wireless link. Hence, the meaning is similar to the term *key agreement* described above, and in fact some of the key agreement protocols can be directly used for pairing. The main difference is that the pairing protocols do not assume any shared secrets, trusted parties, or PKI. Moreover, the interfaces of the devices are often so constraint that they do not even permit the use of password protocols (since, e.g., they lack a keyboard or a screen). These protocols usually rely on a human user that is available to assist the pairing.

The first pairing pairing protocol [33] was based on an assumption that a user can actually connect the devices with a secure physical link. Later, several other schemes were proposed. Several of them rely on a so-called "out-of-band" (OOB) channels, which are channels whose security can be verified by the user. For example [3] uses an infrared channel as OOB, and [32] uses human body as the communication medium. Some protocols use essentially the "short string comparison" method. For example the protocol [30] requires the user to verify if the images (that are a graphical representations of the "short strings") displayed on both devices are the same. The protocol used in the *Zfone*, a secure VoIP system (see [41]), requires the users to read out to each other short strings, and to compare them (another example of such a protocol is [42]). The security of this system of course relies on the fact that the users can recognize each other's voice. For more examples of the pairing protocols see e.g. [22].

2 Our contribution: Human Key Agreement

In this section we describe the *Human Key Agreement* protocol. Informally speaking that, our protocol, while vulnerable to the "man-in-the middle" attacks, is secure against the "*machine*-in-the-middle" attacks (i.e.: an attack in which the adversary in not a human). Moreover, the protocol will be designed in such a way that using a human-in-middle attack, will be very expensive, since it will require the adversary to use humans to constantly monitor the network, solving a large number of Captcha puzzles.

Consider a decentralized protocol for remote communication between the humans. For example, think of an internet instant messaging system, like XMPP[1], or in general, any system where pairs of humans need to establish secure connection. How can the users of such a protocol establish session keys in a way that is secure against the man-in-the-middle attacks, when the the Public-Key Infrastructure is not available? None of the methods described in Sect. 1.1 seems to be applicable in this case. It is usually infeasible for the users to meet in person in order to establish a shared secret password. Sometimes they do not know each other well, so they cannot recognize each other's voice, and hence they cannot use the "short string comparison" method used in the VoIP protocols [41, 42] (another reason may be that the voice link may simply not be available). Relying on a trusted server may also be a bad idea, as reported recently in the media [39]. Therefore, the adversary that controls the network can freely monitor, store and analyze all the messages that are transmitted by the users (as described in [39]).

Our *Human Key Agreement* permits the users to significantly increase security of their communication in this situation. The security of our protocol is based on the difficulty of solving the Captcha puzzles by a machine. More precisely the key established between each pair of participants will remain secret assuming that the adversary did not solve the Captcha puzzles that the users generated during the execution of the protocol. In addition, our protocol will be *forward-secure*, which means that, in order to break the security, the adversary will have to solve the Captcha puzzles *during* the execution of the protocol (solving the Captchas *after* the protocol is completed does not help him). Therefore the adversary will have to employ a significant amount of human power in order to decrypt users communication. Although, of course, this does not prevent him from targeting a concrete user, or a pair of users (if he is willing to spend some of his human time), at least it makes it very expensive to monitor and analyze the whole communication in the network. In some sense this is similar to the method based on voice recognition [41], since also there a very determined adversary may actually able to break the security, by using a *voice mimic attack* [42].

The details of the model are a little bit tricky, and we start with presenting them in a very informal way. Consider two parties, Alice (A) and Bob (B), that want to establish a secure connection. Intuitively, our protocol should satisfy the following requirements:

Requirement 1 *If the adversary is passive the protocol is completely secure, even against a human-adversary.*

Requirement 2 *If the adversary is performing a machine-in-the middle attack then this attack will be detected by the users.*

Therefore, of course, an active machine-adversary will always be able to prevent the parties from establishing a secure key, but he will not be able to convince the players that the key is secure, while it is not.

It is easy to observe that in order to satisfy Req. 1 both users themselves have to use the fact that their are humans, and demonstrate, during the execution of the protocol, their ability to solve the Captcha puzzles. This is because otherwise a machine-attacker would be completely indistinguishable from the honest users. On the other hand, solving a Captcha each time the protocol is executed would be very cumbersome. Therefore the protocol will have two modes: a *secure* one (during which the users

[1] XMPP stands for Extensible Messaging and Presence Protocol. It was formerly named *Jabber*. For more on XMPP see e.g. a wikipedia article `http://en.wikipedia.org/wiki/Extensible_Messaging_and_Presence_Protocol`

have to solve the Captcha puzzles) and both Req. 1 and 2 hold, and a *normal* one, where only Req. 1 holds.

The secure mode will only be activated if the users need to transmit some secret information, and otherwise they will use the normal mode. More precisely, each user $P \in \{A, B\}$ will be able to decide if he wants to establish a secure connection, or not, by setting his flag $human_P := 1$, or $human_P := 0$, resp. The secure mode will be used only if $human_A \wedge human_B = 1$.

Described this way, it may look like the protocol could actually deteriorate users' security, as the fact that one of the users wants to establish a secure connection could be a signal to the adversary that the user has some secret to hide (and in this case he could quickly call a human to help him solving the Captcha). Thus we introduce the third security condition:

Requirement 3 *A machine-adversary is not able to learn the values of $human_A$ and $human_B$. Moreover the values of $human_A$ and $human_B$ are* forward-secret *in a sense, that the adversary, in order to learn those values, needs to solve the Captcha puzzles* during *the execution of the protocol.*

The reason why the users may be interested in forward-secrecy of $human_P$ is that the fact that some pair of users used the secure mode, could draw the attention of the adversary to them, and hence he could use a human-attacker against them next time when they execute the key-agreement protocol. For this reason, the users should be advised to *always* encrypt their communication with the secret key that they established, no matter if they are in the secure mode or not (since otherwise they would reveal the values to the adversary).

Req. 3 implies that the computation of $human_A \wedge human_B$ has to be done in a "covert" way. In particular the parties cannot just send to each other their values $human_A$ and $human_B$, and in general none of them can send it to anyone who did not first prove to him that he is human (since the communication is not authenticated, and one never knows to him he is really talking).

A natural idea for a solution is as follows: let Alice reveal to Bob that $human_A = 1$ only if Bob proves to her that he is human. If we apply this in a naive way, then of course we enter a loop, since in turn Bob will be willing to prove this only if Alice proves to him that she is human. Fortunately, it turns out that we can construct a protocol in which Alice and Bob prove to each other that they are human *simultaneously*, i.e. they will prove to each other that they are human, in such a way that if one of them is *not* a human, he will not learn if the other party is a human or not. We call this a *Simultaneous Turing Test*[2] Moreover, also this proof will be *forward-secure* in the sense, that an adversary that solves the Captcha puzzles *after* the protocol was completed, will not have any information about the inputs $human_A$ and $human_B$. The main tool that we use is called Universally-Composable Password Based-Key Exchange (see Sect. 3.4 for more on this).

While from this description it may seem that our protocol is very complicated, the good news is that in fact from the user point of view the execution of the protocol is quite simple. In particular, each of the users will need to solve the Captcha puzzle only once, during the Simultaneous Turing Test, and the rest of the protocol will be fully automatic. Our protocol may be implemented in the following way. When the users start communicating, each of them has an option to choose a "secure connection" (by pressing some button in his interface, say). In this case his client shows him a Captcha

[2] In some sense this is similar in spirit to the problem of secure two-party computation of a conjunction. Recall that a secure evaluation of a two-party function $f : \{0,1\}^* \times \{0,1\}^* \to \{0,1\}^*$ is a protocol that allows Alice and Bob to learn $f(x_{\texttt{Alice}}, x_{\texttt{Bob}})$ without revealing to each other their respective inputs $x_{\texttt{Alice}}$ and $x_{\texttt{Bob}}$. This means in particular that if f is a conjunction of two bits then the following security guarantee holds for both $P \in \{\texttt{Alice}, \texttt{Bob}\}$: if $x_P = 0$ then P will not know if the input of the other party was 0 or 1. See e.g. [13] for an introduction to this area.

sent from the other user, and the user has 1 minute, say, to solve it. If also the other user solved the Captcha then the client displays an information "secure connection established", and otherwise it says "insecure connection". The user of course does not know if it is because the other user has not chosen "secure connection", or because the adversary interfered in the transmission, but this is unavoidable in our model.

The option to switch to the secure mode may be permanently available for the users (i.e. the clients can, invisibly for the users, execute the key agrement scheme every minute, say). Of course, the users should not explicitly say (over an insecure link) that they want to establish a secure connection, since it would violate Req. 3. The user can, however, indicate it in some non-explicit way, hoping that the other player will understand it, but an inattentive adversary will not.

One of the possible weaknesses of this model is that it does not distinguish between a user that makes an error while solving Captcha, and an adversary. Fortunately, we have an extended version of the protocol (see Sect. 4.5), where the user has a right to a couple of tries when solving Captcha.

3 Tools

3.1 Message Authentication Codes

Message Authentication Codes (MACs) is a tool for guaranteeing integrity of communication between two paries that share a key. An introduction to MACs and a complete security definition can be found, e.g., in [19]. We will use a following definition of MACs. MAC is a pair of algorithms $(\mathit{Tag}, \mathit{Vrfy})$, such that Tag takes as an input a random secret key $S \in \{0,1\}^k$ and a message $M \in \{0,1\}^*$. It outputs an *authentication tag* $\mathit{Tag}_S(M)$. We require that always $\mathit{Vrfy}_S(M, \mathit{Tag}_S(M)) = 1$. It is *secure against chosen-message attack* if any polynomial probabilistic time adversary (taking as input 1^k) has negligible[3] (in k) chances of producing a pair (M, T) such that $\mathit{Vrfy}_S(M, T) = 1$, even after seeing an arbitrary number of pairs

$$(M_1, \mathit{Tag}_S(M_1)), (M_2, \mathit{Tag}_S(M_2)) \ldots$$

(where $M \notin \{M_1, M_2, \ldots\}$) and even when $M_1, M_2, \ldots$ were adaptively chosen by the adversary.

In our construction we will use a special type of MACs, that have the following non-standard feature: informally, it should be infeasible to discover if two tags were computed with the same key. More precisely, we require that for $S_0, S_1 \in \{0,1\}^k$ chosen uniformly at random, and for any $M_0 \neq M_1$ no polynomial-time adversary that knows $\mathit{Tag}_{S_0}(M_0)$ can distinguish between $\mathit{Tag}_{S_0}(M_1)$ (i.e. M_1 encrypted with the same key) and $\mathit{Tag}_{S_1}(M_1)$ (i.e. M_1 encrypted with a fresh key). This can be formalized as follows: for every polynomial-time machine $\mathcal{A}$ and every M_0 and M_1 we have that

$$\begin{aligned} &|P\left(\mathcal{A}(\mathit{Tag}_{S_0}(M_0), \mathit{Tag}_{S_0}(M_1) = 1)\right) \\ &-P\left(\mathcal{A}(\mathit{Tag}_{S_0}(M_0), \mathit{Tag}_{S_1}(M_1) = 1)\right)| \\ &\text{is negligible.} \end{aligned} \tag{1}$$

The standard definition of MACs does not guarantee this. This is because the definition of MACs does not require that no information about the key leaks to the adversary. For example, it may be possible that a MAC is secure, but the first 10 bits of S can be computed from $\mathit{Tag}_S(M)$ (and hence it can be easily checked if two tags were computed with the same key). Luckily, concrete examples of MACs satisfy this extended definition. One example is the standard construction of a MAC from

[3] A $f : \mathcal{N} \to \mathcal{R}$ function is *negligible in k* if for every $c \geq 1$ there exists k_0 such that for every $k \geq k_0$ we have $|f(k)| \leq k^{-c}$.

a pseudorandom function (cf. e.g. [19], Sect. 4.4). Recall, that a pseudorandom function (which is essentially the same as a *block-cipher*) is a function f that takes as input some key S, and a (fixed-length) *block* M and outputs a *ciphertext* $C = f_S(M)$ of the same length. Informally speaking, the security of the pseudorandom functions is defined as follows: for every sequence of blocks $M_1, \dots, M_t$ the string $f_S(M_1), \dots, f_S(M_t)$ should be indistinguishable from random (even is the blocks $M_1, \dots, M_t$ are chosen adaptively by the adversary). It is easy to see that a function $Tag_S^{prf}(M) = f_S(M)$ (with $Vrfy^{prf}$ defined in a straightforward way) is a secure MAC that works on messages of fixed length. It can be extended to work on messages of arbitrary length by first hashing a message with a collision-resistant hash function H, and then applying f, i.e. setting $Tag_S^{prf,H}(M) := f_S(H(M))$ (this method is called *hash-and-authenticate*, cf. [19]).

The reason why for any polynomial-time $\mathcal{A}$ the scheme Tag^{prf} satisfies (1) is that, from the definition of a pseudorandom function, both $Tag_{S_0}^{prf}(M_0), Tag_{S_0}^{prf}(M_1)$ and $Tag_{S_0}^{prf}(M_0), Tag_{S_1}^{prf}(M_1)$ are indistinguishable from random strings, and hence, obviously, they are indistinguishable from each other. The same holds for $Tag^{prf,H}$.

3.2 Key Agreement

Key Agreement is a scheme that allows two parties, Alice and Bob, that initially share no secret, to establish a common key. For simplicity, in this paper we restrict ourselves to one-round key agreement protocols. Hence, for us a key agreement protocol is a triple of randomized interactive algorithms $(KA_{\texttt{Alice}}, KA_{\texttt{Bob}}, KA_{Key})$. Let $r_{\texttt{Alice}}$ and $r_{\texttt{Bob}}$ denote the respective random inputs of the players. In the first step each algorithm $P \in \{\texttt{Alice}, \texttt{Bob}\}$ sends to the other one a message $m_P = KA_P(r_P)$. Then, `Alice` calculates her output $K_{\texttt{Alice}} = KA_{Key}(r_{\texttt{Alice}}, m_{\texttt{Bob}})$ and `Bob` calculates his output $K_{\texttt{Bob}} = KA_{Key}(r_{\texttt{Bob}}, m_{\texttt{Alice}})$. We require that always $K_{\texttt{Alice}} = K_{\texttt{Bob}}$. Security of $(\texttt{Alice}, \texttt{Bob})$ is defined in the following way: for any polynomial time adversary that can see $m_{\texttt{Alice}}$ and $m_{\texttt{Bob}}$ the key $K_{\texttt{Alice}}$ should be indistinguishable from a random string of the same length. Of course, if the adversary is active, then he can cause $K_{\texttt{Alice}} \neq K_{\texttt{Bob}}$, or $K_P = error$ (for $P \in \{\texttt{Alice}, \texttt{Bob}\}$).

An example of a key agreement protocol is the protocol of Diffie and Hellman [14]. Let G be a cyclic group, and let g be its generator. The protocol works as follows: each user P selects a random exponent $r_P \in Z_{|G|}$, calculates $m_P := g^{r_P}$ and sends it to the other player. Then, each player calculates $K := (m_P)^{r_P}$. The protocol is correct, since $(g^{r_{\texttt{Alice}}})^{r_{\texttt{Bob}}} = (g^{r_{\texttt{Bob}}})^{r_{\texttt{Alice}}}$. The protocol is secure under a so-called *Decisional Diffie-Hellman Assumption* in (G, g). See, e.g., [19] for more on this.

Authenticated Key Agreement (AKA) is a protocol between Alice and Bob that share a common key K that allows them to generate a fresh *session key*. It can be constructed from the Key Agreement Scheme described, by asking both users to authenticated their messages with a MAC (using the key K). In our construction we will need a stronger version of this notion, that we call a *Covert-AKA*. This is described below.

3.3 Covert-AKA

As a building-block for our main construction we introduce a scheme that we call *Covert-AKA*. It is a protocol between Alice and Bob. The players have as input two keys sk_A and sk_B. The protocol is executed either with $sk_A = sk_B$ (this is called the "equal keys" case), or with sk_A independent from sk_B (this is called the "independent keys" case). The properties of the protocol are as follows. If the adversary is passive, then

– in the "equal keys" case both parties output the same output: $(secure, K)$,

– in the "independent keys" case both parties output $(normal, K)$.

If the adversary is active then

– in the "equal keys" case he can cause each party (independently) to output $(normal, K')$ (for some K', that can be different for both parties), or *error*
– in the "independent keys" case he can cause each party (independently) to output *error*.

The security conditions are as follows: (1) no polynomial-time adversary that attacks the protocol (even actively) can distinguish between the "equal keys" and "independent keys" case, and (2) whenever one of the parties outputs $(secure, K)$, the key K is indistinguishable from random, for a polynomial-time adversary.

Covert-AKA can be implemented in a similar way to the normal AKA, namely both players execute a passively secure key agreement, authenticating their messages in with the keys sk_A and sk_B, resp. The complete protocol is presented on Fig. 2.

Obviously, if $sk_A = sk_B$ then the players just executed a normal authenticated key agreement, and hence whenever the adversary tampers with the messages he can cause the parties to output $(normal, K')$ (by tampering just with the tag), or *error* (by, e.g., destroying the whole message). If the keys are independent then obviously the verification of the tag will fail.[4] Therefore the adversary cannot force any parties to output *secure*. Moreover, if he is passive, then both parties will always output $(normal, K)$.

Observe, that if the players use a standard MAC scheme for authentication, then the adversary that observes the transcript can in principle see if the keys are equal or independent, since, as explained in Sect. 3.1 a MAC does not even need to hide the entire key. Hence, we use Tag^{prf} constructed in Sect. 3.1, that has exactly the property that the adversary, after seeing the messages $m_{\texttt{Alice}}$ and $m_{\texttt{Bob}}$, and the *Tag*s on them, cannot distinguish (with a non-negligible advantage) if they were authenticated with the same key, or two independent keys.

3.4 Universally-Composable Password Authenticated Key Exchange

As briefly mentioned in Sect. 1.1 there exist key-agreement protocols, where it is enough that the users share a *password*. Such schemes, introduced in [5], are called *Password Authenticated Key Exchange* protocols. The main difference between a password, and a cryptographic key is that the latter is usually assumed to have a unform distribution over some set $\{0, 1\}^m$, and the distribution of the former can be very far from uniform over $\{0, 1\}^m$, e.g., it can be known to the adversary that the password is a word from a dictionary. It is particularly important that such schemes offer protection against the *off-line password guessing attacks*, i.e. the attacks, where the adversary can perform an exhaustive search for a correct password, after he saw the transcript of the communication. The design of such schemes attracted a considerable interest [4, 7, 26, 17, 28, 20, 8] during the last two decades, and has proven to be a challenging task. It has even been non-trivial to come up with the right security definitions. For example, most of the definitions made an unrealistic assumption that the passwords are chosen according to some pre-determined distribution, and that the passwords between different pairs of parties are chosen independently.

In this paper we will use a very strong version of such a protocol, called *Universally-Composable Password Authenticated Key Exchange (UC PAK)*, defined and constructed in [11]. Its definition follows

[4] Actually, here we really need the assumption that the keys are independent, since otherwise the adversary could in principle be able to exploit the correlations between the keys, and launch a related-key attack.

`Alice`		`Bob`
$m_{\texttt{Alice}} := KA_{\texttt{Alice}}(r_{\texttt{Alice}})$ $t_{\texttt{Alice}} := Tag^{prf}_{sk}(\texttt{Alice}, m_{\texttt{Alice}})$	$\xrightarrow{((\texttt{Alice}, m_{\texttt{Alice}}), t_{\texttt{Alice}})}$ $\xleftarrow{((\texttt{Bob}, m_{\texttt{Bob}}), t_{\texttt{Bob}})}$	$m_{\texttt{Bob}} := KA_{\texttt{Bob}}(r_{\texttt{Bob}})$ $t_{\texttt{Bob}} := Tag^{prf}_{sk}(\texttt{Bob}, m_{\texttt{Bob}})$
if $KA_{Key}(r_{\texttt{Alice}}, m_{\texttt{Bob}}) = error$ then output *error* otherwise: if $Vrfy^{prf}_{sk}((\texttt{Bob}, m_{\texttt{Bob}}), t_{\texttt{Bob}}) = 1$ then output $(secure, KA_{Key}(r_{\texttt{Alice}}, m_{\texttt{Bob}}))$ otherwise output $(normal, KA_{Key}(r_{\texttt{Alice}}, m_{\texttt{Bob}}))$.		if $KA_{Key}(r_{\texttt{Bob}}, m_{\texttt{Alice}}) = error$ then output *error* otherwise: if $Vrfy^{prf}_{sk}((\texttt{Alice}, m_{\texttt{Alice}}), t_{\texttt{Bob}}) = 1$ then output $(secure, KA_{Key}(r_{\texttt{Bob}}, m_{\texttt{Alice}}))$ otherwise output $(normal, KA_{Key}(r_{\texttt{Bob}}, m_{\texttt{Alice}}))$.

Fig. 2. The Covert-AKA scheme. $(KA_{\texttt{Alice}}, KA_{\texttt{Bob}}, KA_{Key})$ is the passively secure key agreement from Sect. 3.2. Tag^{prf} is the Message Authentication Code from Sect. 3.1.

the *Universal Composability* (UC) paradigm of Canetti [10]. There is no space here for a general introduction to the UC framework. Let us just highlight that in the UC framework a protocol Π is defined secure with respect to an *ideal functionality* F which it is supposed to "emulate". The security definition guarantees that if another protocol uses Π as a subroutine one can simply replace each call to Π with a call to F. This holds if the protocols are executed in an arbitrary way, and even if several instances of the same protocol are executed concurrently. To achieve this strong property the security definition has to take into account that the inputs of the honest parties can be chosen in an arbitrary way. This is modeled by introducing a machine called *environment* $\mathcal{Z}$ that is responsible for choosing the inputs.

The ideal functionality of the UC PAK is presented on Fig. 4 in the appendix. Informally, the main security guarantees of the UC PAK are as follows. Suppose that the parties are Alice and Bob, each of them holding a password $\pi_{\texttt{Alice}}$, and $\pi_{\texttt{Bob}}$, resp. At the end of the execution both parties obtain either

1. the same uniformly-random session key sk — if $\pi_{\texttt{Alice}} = \pi_{\texttt{Bob}}$ and the adversary did not attempt to compromise the session,
2. two different uniformly-random keys $sk_{\texttt{Alice}}$ and $sk_{\texttt{Bob}}$ (resp.), chosen independently — if $\pi_{\texttt{Alice}} \neq \pi_{\texttt{Bob}}$ or the adversary attempted to compromise the session,

The adversary can compromise the session either by guessing a password (he has a right to *one* such guess), or by corrupting one of the parties. In both cases he has a right to choose the keys that the parties receive. Unless the adversary compromised the session, the only information that he obtains is the fact the the parties executed the protocol. He does not even learn what was the output of the protocol, i.e. if the parties agreed on the same key *sk* (Case 1 above) or if each of them received a different key chosen independently (Case 2). We will use this property in our construction.[5]

An important feature of the UC framework is that the inputs of the users (in this case: $\pi_{\texttt{Alice}}$ and $\pi_{\texttt{Bob}}$) are chosen by the environment $\mathcal{Z}$ and hence, for example, it may be the case that $\pi_{\texttt{Alice}}$ and $\pi_{\texttt{Bob}}$, although not equal, are in some way correlated. In reality some correlation like this is not an unusual case, since it happens, for example, if a user mistypes his password. Another usefull feature of the UC PAK is that it provides the *forward-security*, in other words, guessing the password after the session was completed does not give the adversary any additional information.

The first UC PAK was constructed in [11], and proven secure in the common reference string model under the standard number-theoretic assumptions. In [1] the authors prove (in the random oracle model) that one of the existing, more efficient protocols [8] is also UC-secure.

3.5 Private Equality Test

We will also use a tool called a *Private Equality Test (PET)* (also known as "Socialist Millionaires Protocol"), which is a scheme executed between two parties, Alice and Bob, holding some inputs $x_{\texttt{Alice}}$, and $x_{\texttt{Bob}}$, resp. The output of Bob is just one bit, namely the information whether $x_{\texttt{Alice}} = x_{\texttt{Bob}}$, and Alice learns nothing from the protocol. Such protocol can be constructed using generic methods for the secure two-party computations (see, e.g. [13]). Also, concrete, efficient PET protocols exist (see e.g. [25]).

4 The construction

4.1 Modeling captcha

It is non-trivial to model Captcha in a proper way. We define a *captcha scheme* to be a pair (G, H), where G is a randomized algorithm called a *captcha generator* that takes as input a string $x \in \{0,1\}^*$ and outputs a *captcha* $G(x)$, and H is a solution function such that we always have $H(G(x)) = x$. We say that (G, H) is secure if for every poly-time adversary $\mathcal{A}$ and for x chosen uniformly at random from $\{0,1\}^m$ we have that

$$|P\left(\mathcal{A}(G(x)) = x\right)| \text{ is negligible in } m. \tag{2}$$

Our model is inspired by [12], the main difference being that we explicitly assume that for any solution x one can efficiently generate the Captcha puzzles that have x as their solution (by calculating $y := G(x)$). This makes the description of our protocol a bit simpler, and it also excludes the Captchas where the creator of the puzzle does not know the entire solution to it (an example of such a system is the reCaptcha scheme described in Sect. 1.1). In fact, our protocol works only with the Captchas were the complete solution is known to its creator. Observe that we do not assume anything about the non-malleability of the Captcha puzzles, i.e. it may be possible for the adversary that knows some puzzle $z = G(x)$ to produce (without decoding x) a puzzle that z' such that $H(z')$ is in some way related to x. This corresponds to the real-life situation, where the Captcha puzzles are indeed malleable (for example, removing the first letter from a graphical representation of a text may be easy, even if the whole text is unreadable — consider e.g. the image on Fig. 1). Observe also, that the only thing that

[5] In [11] the authors say that they are not aware of any application where this is needed. In fact, it may the first application when this feature is used.

we require in (2) is that the *whole* solution x is hard to compute, and a Captcha scheme may satisfy our definition even if some part of x is not hidden from the adversary.

To make our model more realistic, we could relax this definition a little bit and require that the probability in (2) is smaller than some $p(m)$ (where p is a function that would be a parameter in the definition, and could be non-negligible). We do not do it since it would complicate our exposition.

A subtle point is how to model the human adversary. As explained in Sect. 2 the adversary can always break the security of some sessions if he uses a human to solve the Captchas, and an important property of our scheme is that only those sessions get broken. Therefore, we need somehow to capture the fact that an adversary "used a human" in some session. To do it, we introduce a *captcha oracle* $\Omega_{G,H}$, which is a machine that accepts requests

- $\mathit{captcha}(x)$ – in this case the oracle replies with $G(x)$,
- $\mathit{solve}(y)$ — in this case the oracle replies with $H(y)$.

In this way we will be able to attach a formal meaning to the expression: "the adversary broke a Captcha of a user P_i": we will say it if the user sent a $\mathit{solve}(y)$ request to the oracle, where y was an output of $G(x)$ and x was $\mathit{captcha}(x)$ was sent to the oracle by P_i. Since we did not assume that Captchas are non-malleable, the adversary could of course "cheat" and send a *solve* request with a slightly modified y, to circumvent this definition. In order to prevent it, we require that the adversary is only allowed to send $\mathit{solve}(y)$ queries for those y's that in the past were produced as output by the oracle in a response to a $\mathit{captcha}(x)$ query. This restriction may look quite arbitrary, but it is hard to think about any alternative. Observe that, since the Captchas are malleable, in principle there can exist a way to combine several Captchas $y_1 = \mathit{captcha}(x_1), \ldots, y_t = \mathit{captcha}(x_t)$ into one "super-Captcha" whose solution would solve all $y_1, \ldots, y_t$. Therefore to reason formally about it, we would somehow need to be able to measure the "amount of human work" that the adversary invested into breaking the protocol. Since the goal of this paper is to present the protocol, not to introduce a new formal model, we do not investigate it further.

4.2 An informal description of the Human Key Agreement protocol

The high-level description of the model was already presented in Sect. 2. Before defining it formally we give an informal description of the protocol. Recall that the key point of the protocol is the *Simultaneous Turing Test*, which is a procedure that allows two parties to test if they are both human, in such a way that if one of them is not human he will not learn weather the other is human or not. Before defining the model formally, we provide an informal description of the protocol. Consider two players, Alice and Bob, holding inputs $\mathit{human}_{\texttt{Alice}}$ and $\mathit{human}_{\texttt{Bob}}$, resp., where for $P \in \{\texttt{Alice}, \texttt{Bob}\}$ we have $\mathit{human}_P = 1$ if and only if the player P wants to use the secure mode (and hence is willing to solve Captchas).

At the beginning Alice and Bob select randomly two strings $x_{\texttt{Alice}}$ and $x_{\texttt{Bob}}$, resp. Then each of them creates a Captcha whose solution is the string that he has chosen, i.e. Alice calculates $y_{\texttt{Alice}} := \mathit{captcha}(x_{\texttt{Alice}})$ and Bob calculates $y_{\texttt{Bob}} := \mathit{captcha}(x_{\texttt{Bob}})$. Afterwards, they send to each other, over an insecure link, the values $y_{\texttt{Alice}}$ and $y_{\texttt{Bob}}$, together with their identities (`Alice` and `Bob`), and a bit indicating their roles in the protocol (Alice sends 0 and Bob sends 1). Now, Alice does the following: if $\mathit{human}_{\texttt{Alice}} = 1$ then she solves the Captcha $y_{\texttt{Bob}}$, and sets $x'_{\texttt{Bob}} := \mathit{solve}(y_{\texttt{Bob}})$, and otherwise she sets $x'_{\texttt{Bob}}$ to be equal to some default value $((0, \ldots, 0)$, say). Bob does a symmetric thing, i.e. he solves $y_{\texttt{Alice}}$ if and only if $\mathit{human}_{\texttt{Bob}} := 1$, setting $x'_{\texttt{Alice}} := \mathit{solve}(y_B)$ and setting $x'_{\texttt{Alice}} := (0, \ldots, 0)$. Denote $\pi_{\texttt{Alice}} = (x_{\texttt{Alice}}, x'_{\texttt{Bob}})$ and $\pi_{\texttt{Bob}} = (x'_{\texttt{Alice}}, x_{\texttt{Bob}})$.

Now, observe that if the adversary did not disturb the communication then we have that

$$\pi_{\texttt{Alice}} = \pi_{\texttt{Bob}}$$
$$\text{if and only if}$$
$$\mathit{human}_{\texttt{Alice}} = \mathit{human}_{\texttt{Bob}} = 1.$$

If this is the case then we will denote the value of $\mathit{human}_{\texttt{Alice}}(= \mathit{human}_{\texttt{Bob}})$ with $\pi_{\texttt{Alice,Bob}}$. If the adversary did disturb the communication then he can always cause $(x_{\texttt{Alice}}, x'_{\texttt{Bob}}) \neq (x'_{\texttt{Alice}}, x_{\texttt{Bob}})$, just by modifying one of the Captchas that were sent over the insecure network, but as long as he is *not* a human it is infeasible for him to cause $(x_{\texttt{Alice}}, x'_{\texttt{Bob}}) = (x'_{\texttt{Alice}}, x_{\texttt{Bob}})$, if $\mathit{human}_{\texttt{Alice}} \neq 1$, or $\mathit{human}_{\texttt{Bob}} \neq 1$, since to do this he would need to solve a Captcha himself.

Observe also that a *machine*-adversary has negligible chances of deciphering $x_{\texttt{Alice}}$ and $x_{\texttt{Bob}}$, and hence, if $\mathit{human}_{\texttt{Alice}} = \mathit{human}_{\texttt{Bob}} = 1$ then the value of $\pi_{\texttt{Alice,Bob}}$ is hidden from him. Moreover, observe that until this point the players did not send to each other the Captcha solutions, and hence the values of human_P remain secret.

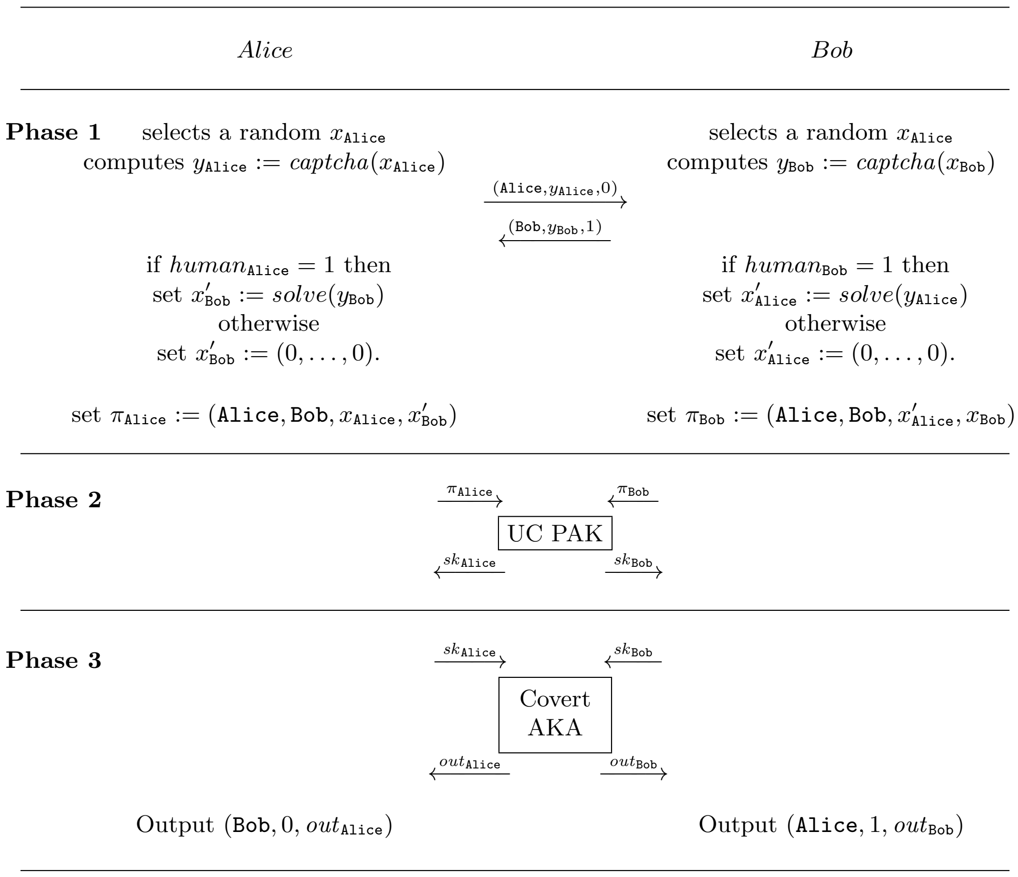
In the second phase, the players execute a UC PAK with Alice setting her password to $(\texttt{Alice}, \texttt{Bob}, \pi_{\texttt{Alice}})$, and Bob setting his password to $(\texttt{Alice}, \texttt{Bob}, \pi_{\texttt{Bob}})$. From the properties of UC PAK if $\pi_{\texttt{Alice}} = \pi_{\texttt{Bob}}$ and the execution of the protocol was not disturbed actively by the adversary, then the parties will agree on a common key sk. If $\pi_{\texttt{Alice}} \neq \pi_{\texttt{Bob}}$ then the parties will receive two independent and uniformly-chosen keys sk and sk'. The adversary can cause the same effect by actively disturbing the communication during the execution of PAK. The important thing is, however, that he does not get any information about the inputs $\pi_{\texttt{Alice}}$ and $\pi_{\texttt{Bob}}$, which in turn implies that, no matter what his actions are, he does not know the inputs $\mathit{human}_{\texttt{Alice}}$ and $\mathit{human}_{\texttt{Bob}}$. Hence, after the second phase the players either share the same key sk, or have to independent keys $sk_{\texttt{Alice}}$ and $sk_{\texttt{Bob}}$, resp. Now:

– If $sk_{\texttt{Alice}} \neq sk_{\texttt{Bob}}$ (which happened either because $\mathit{human}_{\texttt{Alice}} \wedge \mathit{human}_{\texttt{Bob}} = 0$, or because the adversary disturbed the communication), then the users will generate a new fresh key for communication. Of course this key will be secure only against a passive adversary (since the users do not share any secret)
– If the users share the same key (i.e. $sk_{\texttt{Alice}} = sk_{\texttt{Bob}}$) then they can use this key to establish a common session key, using an authenticated key agreement.

Of, course the adversary should not be able to distinguish which was the case (since it would give him information about $\mathit{human}_{\texttt{Alice}} \wedge \mathit{human}_{\texttt{Bob}}$). Here we use the Covert-AKA (see Sect. 3.3), that is constructed exactly for this purpose: it allows Alice and Bob, that have keys keys sk_A and sk_B, resp. to establish a common key. If $sk_A = sk_B$ then it is a normal AKA, if sk_A and sk_B are independent, then it is a passively secure key agreement. The users are notified which was the case, while the adversary does not know it. The Human Key Agreement protocol is depicted on Fig. 3.

4.3 A formal model

In this section we present a formal definition of our model. An important point is that we have to take into account that several players may execute the protocol concurrently. Since in our model the adversary fully controls the network, we cannot prevent him from hijacking a message that some player P_i to sent to P_j, and forwarding it to some other P_k. Therefore, the players, during the execution of the protocol have to exchange their identities. Of course, if P_k is malicious then he can falsely claim to be P_i (we cannot prevent it). So, from the point of view of P_i the security guarantee is as follows: he knows that either he is talking to P_j, or he is talking to some malicious *human* (since an honest



Alice
Bob
Phase 1
selects a random $x_{\texttt{Alice}}$
computes $y_{\texttt{Alice}} := \mathit{captcha}(x_{\texttt{Alice}})$
selects a random $x_{\texttt{Alice}}$
computes $y_{\texttt{Bob}} := \mathit{captcha}(x_{\texttt{Bob}})$
$\xrightarrow{(\texttt{Alice}, y_{\texttt{Alice}}, 0)}$
$\xleftarrow{(\texttt{Bob}, y_{\texttt{Bob}}, 1)}$
if $\mathit{human}_{\texttt{Alice}} = 1$ then
set $x'_{\texttt{Bob}} := \mathit{solve}(y_{\texttt{Bob}})$
otherwise
set $x'_{\texttt{Bob}} := (0, \ldots, 0)$.
if $\mathit{human}_{\texttt{Bob}} = 1$ then
set $x'_{\texttt{Alice}} := \mathit{solve}(y_{\texttt{Alice}})$
otherwise
set $x'_{\texttt{Alice}} := (0, \ldots, 0)$.
set $\pi_{\texttt{Alice}} := (\texttt{Alice}, \texttt{Bob}, x_{\texttt{Alice}}, x'_{\texttt{Bob}})$
set $\pi_{\texttt{Bob}} := (\texttt{Alice}, \texttt{Bob}, x'_{\texttt{Alice}}, x_{\texttt{Bob}})$
Phase 2
$\xrightarrow{\pi_{\texttt{Alice}}}$
$\xleftarrow{\pi_{\texttt{Bob}}}$
UC PAK
$\xleftarrow{sk_{\texttt{Alice}}}$
$\xrightarrow{sk_{\texttt{Bob}}}$
Phase 3
$\xrightarrow{sk_{\texttt{Alice}}}$
$\xleftarrow{sk_{\texttt{Bob}}}$
Covert AKA
$\xleftarrow{out_{\texttt{Alice}}}$
$\xrightarrow{out_{\texttt{Bob}}}$
Output $(\texttt{Bob}, 0, out_{\texttt{Alice}})$
Output $(\texttt{Alice}, 1, out_{\texttt{Bob}})$

Fig. 3. The Human Key Agreement Protocol. Each out_P is equal to (secure, K), (normal, K) or error. The reason why `Alice` outputs $(\texttt{Bob}, 0, out_{\texttt{Alice}})$ instead of just outputting $out_{\texttt{Alice}}$ is required by the formal model (that we define in Sect. 4.3) to make sure that the parties have a consistent view on who started the protocol, and what is the identity of the other party.

P_k would reveal to him that his identity is P_k, not P_j). Hence, in our model there is no difference between a malicious participant, and a human-adversary. Therefore, for simplicity, we assume that all the players are honest.

Other simplifying assumption that we make is that we will consider only two variants of the adversary: *passive* or *active* — in principle the adversary could passively attack some pairs of users, and actively attack the others, but modeling if formally would just complicate the presentation.

We also assume that the each user P_i decides at the beginning of the protocol if he wants to connect securely to all the other users (by setting his flag $human_i := 1$). We in fact assume that $human_i = 1$ with probability $1/2$. This choice is made just not to make the mode too complicated. In fact, our protocol is secure also secure if the users can decide adaptively during the execution of the protocol that to which users they want to connect securely, and to which not.

The adversary in our model is very powerful: he fully controls the network, and he can initiate the sessions between the players by sending request $start(P_i, P_j, role)$ (where $role$ is a bit indicating which party initiates the protocol). For simplicity, we assume that each pair of users generates the key at most one with the same roles (hence, at most twice in total).

Formally, a *Human Key Agreement protocol* is a set of players $\mathcal{P} = \{P_1, \ldots, P_n\}$ represented as interactive randomized machines. An *adversary* is a randomized poly-time interactive machine. The adversary may be *passive* or *active*. Let 1^m be a security parameter that all the players and the adversary take as input. At the beginning each player P_i selects a random bit $human_i \in \{0, 1\}$. Each player P_i is allowed to send to the oracle $\Omega_{G,H}$ the *captcha* queries. If $human_i = 1$ then P_i is also allowed to send to the oracle the *solve* queries. The adversary can send to the oracle *captcha* and *solve* queries, with the restriction that he can only send a query $solve(y)$, if some player P_i received y as a response to his *captcha* query. In this case we say that the adversary *solved a captcha of* P_i.

The players start executing the protocol. The execution is divided into rounds. At the beginning of the execution the players are idle. During the execution the players just wait for the requests from the adversary. The adversary can *wake up* each P_i by sending to it a requests $start(P_i, P_j, role)$, where $P_j \in \mathcal{P}$ and $role \in \{0, 1\}$. We assume that $\mathcal{A}$ never sends twice the same message $start(P_i, P_j, role)$. If the adversary is passive then whenever he sends a request $start(P_i, P_j, 0)$ to some P_i in the same round he also sends $start(P_j, P_i, 1)$ to some P_j. After P_i receives a $start(P_i, P_j, role)$ request it wakes up and starts interacting with P_j (we say that P_i *starts a session with* P_j), for a number of rounds. At the beginning of each round P_i can issue a pair (P_j, m) and $m \in \{0, 1\}^*$. These values are passed to the adversary. If the adversary is *passive* then he has to deliver m to P_j, i.e. he has to send a pair (m, P_i) to P_j. If the adversary is *active* he can also prevent m from reaching P_j, modify it, send it to someone else, or fabricate new messages. At the end of the interaction P_i outputs one of the following values (suppose P_i was woken up by a $start(P_i, P_j, role)$ message):

– $(P_j, role, (secure, K_{i,j}))$, where key $K_{i,j} \in \{0, 1\}^m$,
– $(P_j, role, (normal, K_{i,j}))$, where key $K_{i,j} \in \{0, 1\}^m$,
– a message $(P_j, role, error)$.

After producing the output P_i enters again the idle mode (we say that P_i *ended the session*), and waits for the next *start* message from the adversary. At some point the adversary sends to every player P_i a message *end* which causes the players to terminate, and a *post-execution game* starts. During this game the adversary can start interacting with an oracle $\Omega_{G,H}$. In particular, he can issue *solve* requests to the oracle. For every P_i the adversary outputs $human_i^{\mathcal{A}}$. We say that the protocol *humanity-hiding* if for every P_i such that the adversary did not solve P_i's captcha *before the protocol terminated*, the probability that $human_i^{\mathcal{A}} = human_i$ is at most $1/2 + \epsilon(m)$, where m is negligible.

For each $K_{i,j}$ that was output by some of the players during the execution of the protocol a random bit $b \in \{0,1\}$ is selected, and the following is calculated and sent to the adversary:

$$K' = \begin{cases} K_{i,j} & \text{if } b = 0 \\ \text{uniformly random } K \in \{0,1\}^m & \text{otherwise.} \end{cases}$$

The adversary outputs $b^{\mathcal{A}} \in \{0,1\}$. We say that he *distinguished* $K_{i,j}$ *from random* if $b = b^{\mathcal{A}}$. We say that the $K_{i,j}$*-session key is secret* if the probability (taken over the randomness of the adversary and the players) that the adversary distinguishes the $K_{i,j}$ from random is at most $1/2 + \epsilon(m)$, where ϵ is negligible. We say that $(\pi, \Omega_{G,H})$ is *secure* if both following conditions holds

- if the adversary is passive then at the end of a session between P_i and P_j player P_i outputs $(P_j, 0, (\mathit{secure}, K_{i,j}))$, and player P_j outputs $(P_i, 1, (\mathit{secure}, K_{i,j}))$. Moreover, the key $K_{i,j}$ is secret.
- if the adversary is active then whenever some P_i outputs $(P_j, \mathit{role}, (\mathit{secure}, K_{i,j}))$, and the adversary did not solve P_i's captcha during the session that led to producing this output, then:
  - with overwhelming probability in the same round P_j outputs $(P_i, \mathit{role}, (\mathit{secure}, K_{i,j}))$, or $(P_i, \mathit{role}, \mathit{error})$, and
  - the key $K_{i,j}$ is secret.

Moreover, the protocol has to be humanity-hiding.

4.4 The implementation

The implementation was already discussed informally in Sect. 4.2, and depicted on Fig. 3). We now present our protocol in the framework from Sect. 4.3. To make our description consistent with the description in Sect. 4.2 we call the two parties Alice and Bob, instead of P_j and P_j.

The Human Key Agreement protocol

1. Alice receives $\mathit{start}(\mathtt{Alice}, \mathtt{Bob}, 0)$ message, and Bob receives $\mathit{start}(\mathtt{Bob}, \mathtt{Alice}, 1)$ message,
2. Alice generates a random $x_{\mathtt{Alice}} \in \{0,1\}^m$ and asks the oracle to compute $y_{\mathtt{Alice}} = \mathit{captcha}(x_{\mathtt{Alice}})$. She sends $(\mathtt{Alice}, y_{\mathtt{Alice}}, 0)$ to Bob.
3. Bob generates a random $x_{\mathtt{Bob}} \in \{0,1\}^m$ and asks the oracle to compute $y_{\mathtt{Bob}} = \mathit{captcha}(x_{\mathtt{Bob}})$. He sends $(\mathtt{Bob}, y_{\mathtt{Bob}}, 1)$ to Alice.
4. If $\mathit{human}_{\mathtt{Alice}} = 1$ then after receiving this message Alice asks the oracle to compute $x'_{\mathtt{Bob}} = \mathit{solve}(x_{\mathtt{Bob}})$ (in this case $x'_{\mathtt{Bob}} = x_{\mathtt{Bob}})$). Otherwise Alice sets $x'_{\mathtt{Bob}} := 0^m$.
   She sets $\pi_{\mathtt{Alice}} = (\mathtt{Alice}, \mathtt{Bob}, x_{\mathtt{Alice}}, x'_{\mathtt{Bob}})$.
5. If $\mathit{human}_{\mathtt{Bob}} = 1$ then after receiving this message Bob asks the oracle to compute $x'_{\mathtt{Alice}} = \mathit{solve}(x_{\mathtt{Alice}})$ (in this case $x'_{\mathtt{Alice}} = x_{\mathtt{Alice}})$). Otherwise Bob sets $x'_{\mathtt{Alice}} := 0^m$.
   He sets $\pi_{\mathtt{Bob}} = (\mathtt{Alice}, \mathtt{Bob}, x'_{\mathtt{Alice}}, x_{\mathtt{Bob}})$.
6. Alice and Bob execute the UC PAK protocol setting their passwords to $\pi_{\mathtt{Alice}}$ and $\pi_{\mathtt{Bob}}$, resp.
7. Alice and Bob execute the Covert-AKA protocol, let $\mathit{out}_{\mathtt{Alice}}$ and $\mathit{out}_{\mathtt{Bob}}$ be their respective outputs. Then, Alice outputs $(\mathtt{Bob}, 0, \mathit{out}_{\mathtt{Alice}})$ and Bob outputs $(\mathtt{Alice}, 1, \mathit{out}_{\mathtt{Bob}})$.

We now have the following:

Lemma 1. *The Human Key Agreement protocol constructed above is secure.*

Proof (Proof (sketch)). The security of this scheme as a stand-alone protocol was already informally argued in Sect. 4.2. Now we just argue informally why the protocol is secure in the framework from Sect. 4.3, i.e. when executed in a large group of players, possibly concurrently with other executions. First, if the adversary concurrently initiated several sessions of this protocol with Alice and Bob in the same roles, then the players themselves will detect it, since by the rules of or model, each pair can execute the protocol at most once (with the same roles).

If the adversary starts several instances of the protocol, with different players, then he can either

– faithfully make the users execute UC PAK with the same passwords ($\pi_{\texttt{Alice}} = \pi_{\texttt{Bob}}$), in which case they end up with a common key that is unknown to him, or
– he can try to, e.g., start many parallel sessions and forward the messages between them, however, if even if he forwards the messages between the sessions, the players will detect it during the execution of PAK.

Moreover, it is easy to see that injecting the messages from other sessions in the Covert-AKE protocol does not help the adversary (since the tags in the sessions are computed with independent keys).

4.5 Extensions

Multiple tries One of the common problems with Captcha is that even the human users often fail to solve them correctly. In the protocol presented above, unfortunately, the user cannot distinguish between the case when the other user made a mistake solving Captcha, or the case when he is talking to a malicious machine.

We now show how to extend our protocol in such a way that it permits the user to attempt to solve the Captchas t times (each time he will be challenged with a different Captcha). Our protocol uses the Private Equality Test (see Sect. 3.5) in the following way. In Step 2 of the Human Key Agreement protocol from Sect. 4.4 Alice prepares t Captchas $y_{\texttt{Alice},1}, \ldots, y_{\texttt{Alice},t}$. In Step 3 (if $human_{\texttt{Bob}} = 1$) the players execute a following procedure $PET^{\texttt{Bob}}_{\ell}$ for $\ell = 1, \ldots, t$:

1. Bob attempts to solve $y_{\texttt{Alice},\ell}$, let $x'_{\texttt{Alice},\ell}$ be his solution,
2. the players execute the PET protocol with Bob's input equal to $x'_{\texttt{Alice},\ell}$ and Alice's input equal to $x_{\texttt{Alice}_\ell}$. Recall that as a result of PET Bob learns if $x'_{\texttt{Alice},\ell} = x_{\texttt{Alice}_\ell}$, and Alice learns nothing. If indeed $x'_{\texttt{Alice},\ell} = x_{\texttt{Alice}_\ell}$ then Bob knows that he correctly solved $y_{\texttt{Alice},\ell}$. Let $\ell_{\texttt{Bob}}$ denote the current value of ℓ. In this moment Bob may stop participating actively in the remaining procedures $PET^{\texttt{Bob}}_{\ell_{\texttt{Bob}}+1}, \ldots, PET^{\texttt{Bob}}_{t}$. However, since we want to hide the fact that $human_{\texttt{Bob}} = 1$, the protocol cannot stop now and the remaining $t - \ell_{\texttt{Bob}} - 1$ executions of $PET^{\texttt{Bob}}_{i}$ need to be performed (with $x'_{\texttt{Alice},\ell}$ being set to some default value).

Alice and Bob also execute the same protocol with the roles of the parties swaped. Let $n_{\texttt{Alice}}$ be the value of n such that Alice can solve the Captcha $x_{\texttt{Bob},\ell}$. Of course, the players cannot just communicate to each other their respective values $n_{\texttt{Alice}}$ and $\ell_{\texttt{Bob}}$, since they would reveal to each other they their values of $human_{\texttt{Alice}}$ and $human_{\texttt{Bob}}$.[6] Therefore the players execute t^2 times the last two steps of the protocol. More precisely, for each pair $(\ell, n) \in \{1, \ldots, t\}^2$ they execute the Steps 6 and 7 with

[6] This is because if, e.g., Alice sends to Bob a message "I solved your ℓth Captcha" she would automatically reveal that $human_{\texttt{Alice}} = 1$. One could think about the following solution: if $human_{\texttt{Alice}} = 0$ then she sends to Bob a "false" information "I solved your ℓ_Rth Captcha", where ℓ_R is chosen randomly from $\{1, \ldots, t\}$. Unfortunately, it does not work since a malicious machine could prepare the Captchas that are extremely simple to solve, and hence if $\ell_R \neq 1$ it would strongly indicate that $human_{\texttt{Alice}} = 0$.

– Bob setting $x_{\mathtt{Bob}} := x_{\mathtt{Bob},n}$, and

$$x'_{\mathtt{Alice}} := \begin{cases} x'_{\mathtt{Alice},\ell_{\mathtt{Bob}}} & \text{if } \ell = \ell_{\mathtt{Bob}} \\ (0,\ldots,0) & \text{otherwise} \end{cases}$$

– Alice setting $x_{\mathtt{Alice}} := x_{\mathtt{Alice},\ell}$, and

$$x'_{\mathtt{Bob}} := \begin{cases} x'_{\mathtt{Bob},n_{\mathtt{Alice}}} & \text{if } n = n_{\mathtt{Alice}} \\ (0,\ldots,0) & \text{otherwise} \end{cases}$$

As a result, if they are both human, and they both succeeded in solving at least one Captcha, then in one of those t^2 steps (namely in $(n_{\mathtt{Alice}}, \ell_{\mathtt{Bob}})$) they will successfully establish a common key. If one of them is not a human then all the t^2 steps will fail. Therefore a machine-adversary will not learn if one of the parties is human or not. Note that performing t^2 steps described above may be computationally costly, it is however efficient from the point of view of human time spent on executing it.[7] We believe actually, that the computational complexity of this protocol can be improved, using some methods from the secure two-party computations literature. We leave it as a future work.

Human-generated puzzles Recall that Captcha stands for "Completely Automated Public Turing test to tell Computers and Humans Apart", and hence normally it is assumed that the puzzles are generated automatically. We note that actually in our case the Captcha puzzles can be generated with some human assistance (since the creator of Captcha is also a human). This opens a potential to create Captchas in non-automatic way, hence making them more resilient to the solvers based on artificial intelligence.

Pornography attacks As described in the introduction, in the pornography attack the attacker forwards a Captcha to a pornographic web-site, and the web-site users have to solve the Captcha before being allowed to view the web-site contents [38]. We note that our scheme is vulnerable to this kind of an attack (one has to hope that in practice it would not be economical to perform such an attack). An interesting feature of our protocol is that itself it cannot be used for a similar attack, in other words, the properties of our construction imply that the users cannot be used as oracle for solving Captchas (this is because the user never sends his Captcha solution to the other users).

5 Conclusions

We believe that the paradigm, especially the Simultaneous Turing Test presented in this paper my be useful also in other applications. We leave finding these applications as an open research problem.

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[7] We could actually get rid of the PET protocol and just execute the second step of the procedure. This however, would force the user to type-in Captcha solutions several times, even if he already solved some of them correctly (since the user would not have a method of verifying if his solution was correct).

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Functionality $\mathcal{F}_{\mathsf{pwKE}}$ The functionality $\mathcal{F}_{\mathsf{pwKE}}$ is parameterized by a security parameter k. It interacts with an adversary S and a set of parties via the following queries:

Upon receiving a query $(\mathsf{NewSession}, sid, P_i, Pj, pw, role)$ **from party** P_i**:**
Send $(\mathsf{NewSession}; sid, P_i, P_j, role)$ to S. In addition, if this is the first $\mathsf{NewSession}$ query, or if this is the second $\mathsf{NewSession}$ query and there is a record (P_j, P_i, pw_0), then record (P_i, P_j, pw) and mark this record fresh.

Upon receiving a query $(\mathsf{TestPwd}, sid, P_i, pw_0)$ **from the adversary** S
If there is a record of the form (P_i, P_j, pw) which is fresh, then do: If $pw = pw_0$, mark the record $\mathsf{compromised}$ and reply to S with "correct guess". If $pw \neq pw'$, mark the record $\mathsf{interrupted}$ and reply with "wrong guess".

Upon receiving a query $(\mathsf{NewKey}, sid, P_i, sk)$ **from** S**, where** $|sk| = k$**:**
If there is a record of the form (P_i, P_j, pw), and this is the first NewKey query for P_i, then:

- If this record is compromised, or either P_i or P_j is corrupted, then output (sid, sk) to player P_i.
- If this record is fresh, and there is a record (P_j, P_i, pw') with $pw' = pw$, and a key sk' was sent to P_j, and (P_j, P_i, pw) was fresh at the time, then output (sid, sk') to P_i.
- In any other case, pick a new random key sk' of length k and send (sid, sk') to P_i.

Either way, mark the record (Pi, Pj, pw) as $\mathsf{completed}$.

Fig. 4. The password-based key-exchange functionality $\mathcal{F}_{\mathsf{pwKE}}$ of [11]. The role of the *sid* variable is to distinguish between difference sessions. The role of the *role* variable is to give the users the possibility to check who initiated the protocol. For more on this see [11].