Observer-Resistant Password Systems (ORPSs): Usability vs. Security

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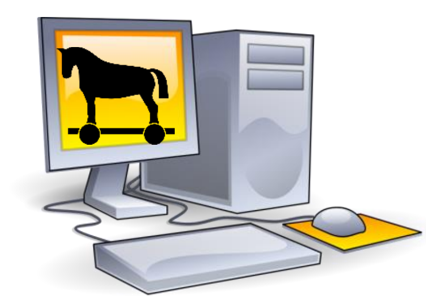
Outline

- What is it all about?
- Threat Model
- System and Attack Modelling
- Selected Work (1991-2015)
- Road Ahead?

- Acknowledgments
- Questions and Answers

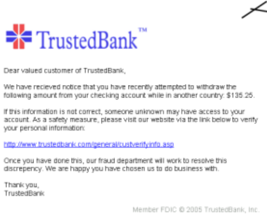
What is it all about?
Users, passwords and observers!

- Who?
  - Alice and Eve
- What?
  - Alice is typing her password.
  - Eve is looking at Alice’s fingers.
- How?
  - Eve is behind/beside Alice.
  - Eve installed a hidden camera.
  - Eve’s malware in Alice’s PC/phone.
  - …



What is it all about?
Different kinds of observers/attacks

- Shoulder-surfers
- Hidden cameras
- Keyloggers and other password recording devices
- Password stealing software tools
- Attacks based on electromagnetic / optical / acoustic emanations
- Phishers
- Malware
- Man-in-the-middle/browser/computer/phone
- Public terminals (@ cafés, airports, hotels, …)
- …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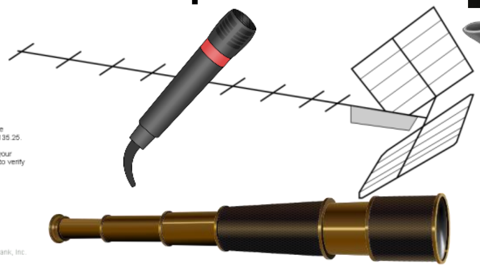
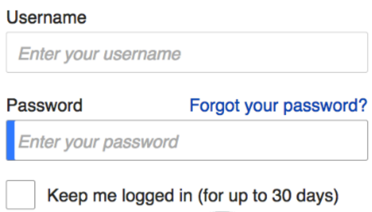
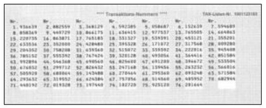


What is it all about?
Existing “solutions” against observers

- “What you know”
  - Static passwords: not secure at all
- “What you have”
  - One-time passwords (OTP) generators, cards + card readers, security tokens, …
  - Problems: not always secure, prone to theft and loss, higher implementation costs, less usable / portable, …
- “Who you are”
  - Problems: not always secure, you can’t change your secret (easily), privacy concerns, higher implementation costs, …
- Multi-factor authentication?





What is it all about? Name(s) of the game

- Observer-resistant/Observation-resistant password system (ORPS) (Li 2015)
- Leakage-resilient password system (LRPS) (Yan et al. NDSS 2012)
- Virtual passwords [Lei et al. ICC 2008 + CompComm 2008]
- Cognitive authentication (Weinshall IEEE S&P 2006)
- Secure Human-Computer Interface/Identification (SecHCI) (Li & Shum 2002-2005)
- Human-computer cryptography (Matsumoto CCS ’96)
- Human authentication/identification (protocol / system / scheme) (many researchers 1991-2015)
- …

Threat Model

Threat Model: Two basic requirements

1. The password should **remain secret after a number of (ideally infinite) authentication sessions are observed** by an untrusted party (= observer).
2. Any computation in the authentication process must be conducted by the **human user alone**. = The process should be **human-executable**. = **Any computing devices** beyond the human user's brain are **untrusted**.

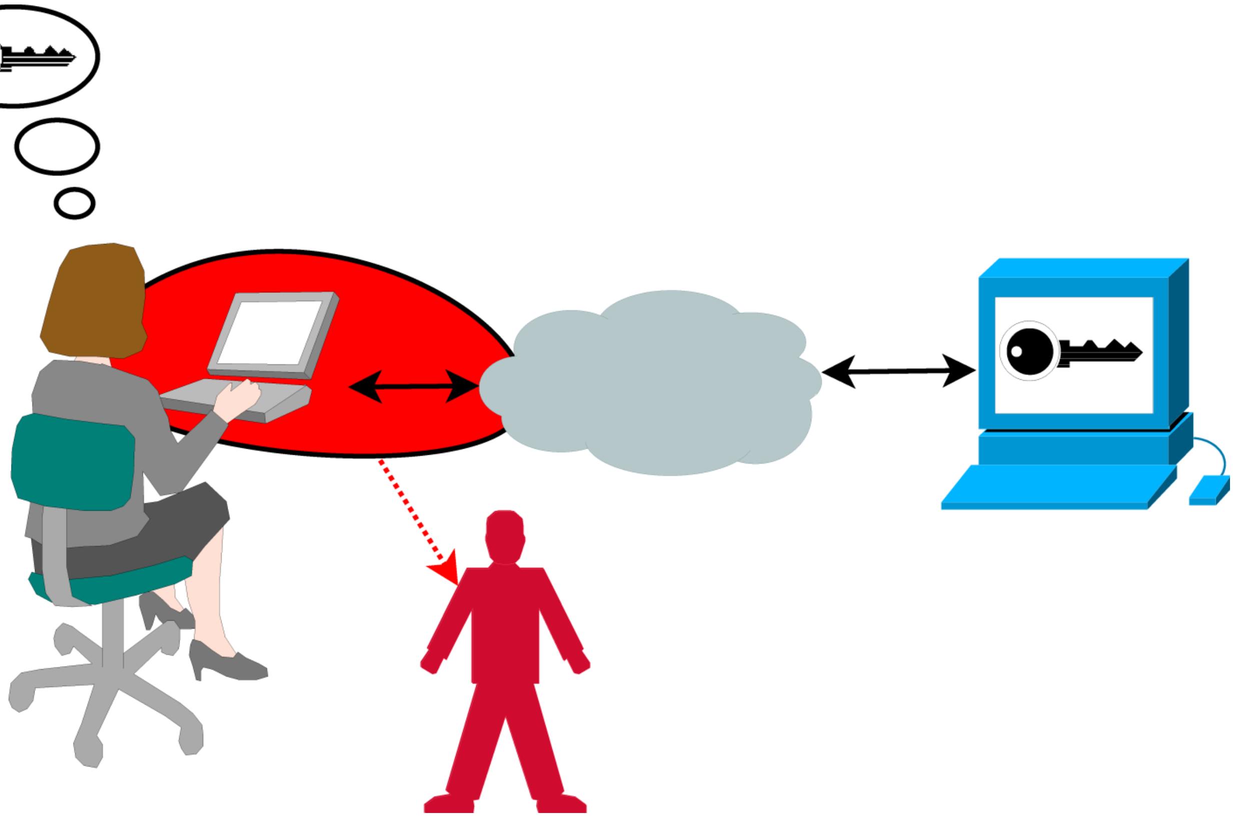
Here, the word "password" is a loose term referring to a secret shared between a human user (client) and a computer verifier (server).

Threat Model: Manuel Blum's words

- HUMANOIDs is a protocol that allows a **naked human inside a glass house** to authenticate securely to a non-trusted terminal. "Naked" means that the human carries nothing: no smart cards, no laptops, no pencil or paper. "Glass house" means that anybody can see what the human is doing, including everything that the human is typing.
- PhoneOIDs: HUMANOIDs over phone

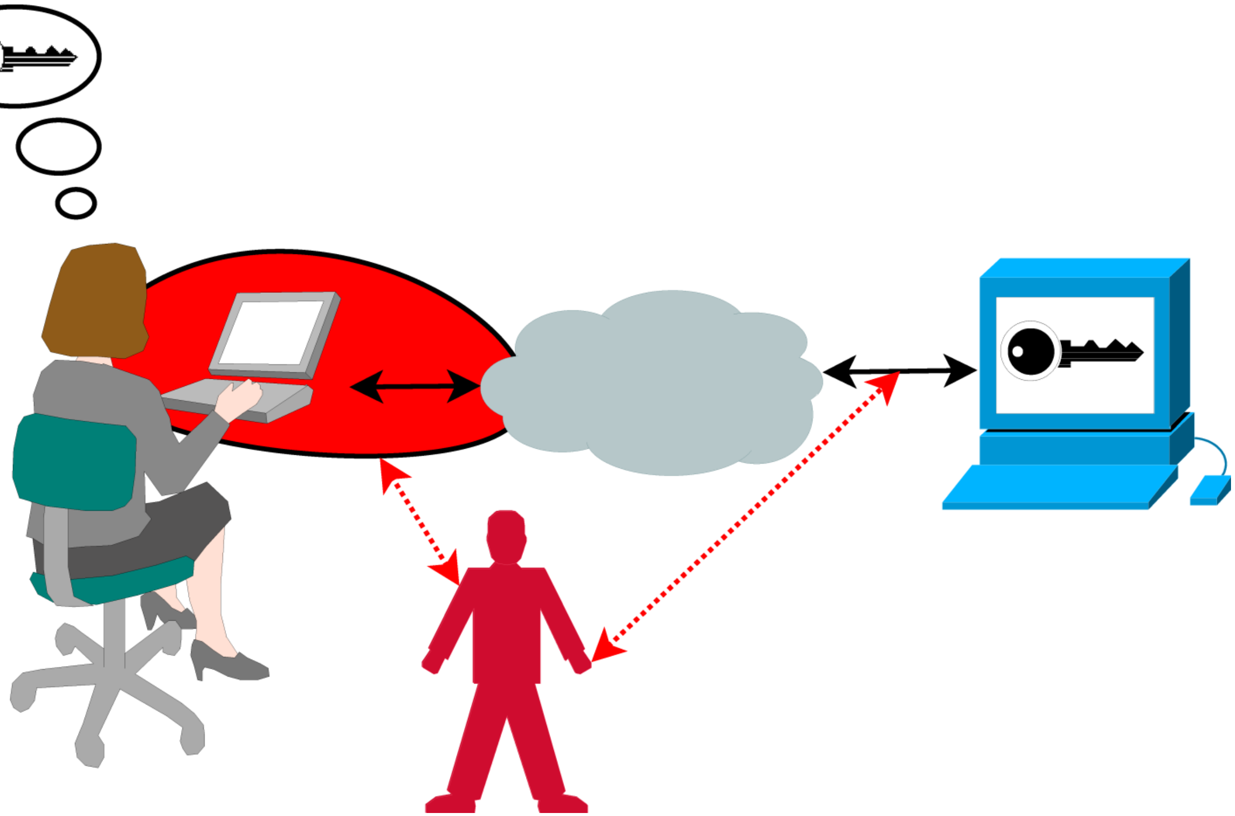
Threat Model:
Passive observers vs. Active observers

- Passive observers = Observers who only observe all authentication sessions passively (without manipulating any communications).



Threat Model:
Passive observers vs. <u>Active observers</u>

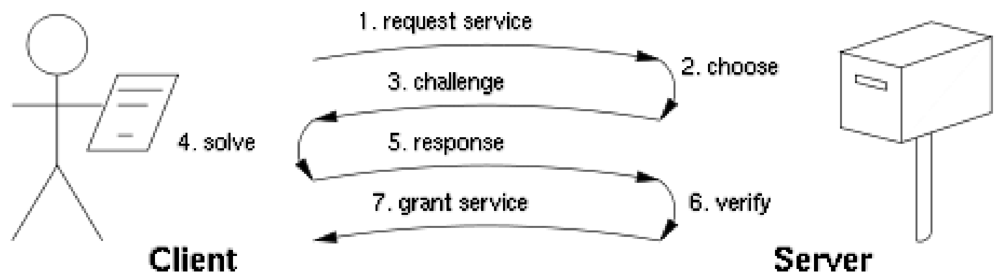
- Active observers = Observers who also try to manipulate the communications (e.g. to choose part of the authentication sessions).



System and Attack Modelling

System and Attack Modelling: Interactive challenge-response protocol

- A secret *S* shared between prover/human (H) and verifier/computer (C)



- Authentication is a challenge-response protocol
  - C $\Rightarrow$ H: t challenges $C_1(S)$, …, $C_t(S)$
  - H $\Rightarrow$ C: t responses $R_1=f_1(C_1(S),S)$, …, $R_t=f_t(C_t(S),S)$
  - C: Accept H if all the t responses are correct; otherwise reject H.
  - NB: For some designs, less than t (and/or more than $t'<t$) correct responses may still be acceptable.

System and Attack Modelling: Security and usability requirements

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- **The authentication process**: $\langle H(x), C(y)\rangle$ = accept, reject or attack detected
- ***p*-completeness**: $\forall z$, $\Pr[\langle H(z), C(z)\rangle = \text{accept}] \geq 1-p$
- **p-soundness**: $\forall x \neq y$, $\Pr[\langle H(x), C(y)\rangle = \text{accept}] \leq p$
- **(α,β,τ)-Human Executability**: $\forall H(x)$, $(1-\alpha)$ portion of the human population can execute $H(x)$ with the error probability β and within τ seconds
- **(p,k)-Security against Passive Observers**: $\forall z$, $\Pr[\langle \mathfrak{A}(T^k(H(z),C(z))), C(z)\rangle = \text{accept}] \leq p$
- **(p,k)-Security against Active Observers**: $\forall z$, $\Pr[\langle \mathfrak{A}(T^k(\mathfrak{A},H(z),C(z))), C(z)\rangle = \text{accept}] \leq p$
- **(q,k)-Detecting against Active Observers**: $\forall z$, $\Pr[\langle \mathfrak{A}(T^k(\mathfrak{A},H(z),C(z))), C(z)\rangle = \text{attack detected}] \geq 1-q$

System and Attack Modelling: Modelling observers

- The aim: Given n observed / chosen successful authentication sessions (= nt challenge-response pairs), try to solve the secret S with a computational complexity smaller than brute force (of S).
- $$\left.\begin{array}{l} R_1^{(1)}=f_1(C_1^{(1)}(S),S) \\ \ldots \\ R_t^{(1)}=f_t(C_t^{(1)}(S),S) \\ \ldots \\ R_1^{(n)}=f_1(C_1^{(n)}(S),S) \\ \ldots \\ R_t^{(n)}=f_t(C_t^{(n)}(S),S) \end{array}\right\} \Rightarrow \begin{array}{l} S=? \\ \text{Complexity} < \#(S) \end{array}$$

System and Attack Modelling: Information-theoretic perspective

- Assume 1) there are r>1 possible responses; 2) each possible response is equally possible for any challenge and any password; 3) all responses are independent of each other.
- Each challenge-response pair leaks $\log_2(r)$-bit information about S.
- $\Rightarrow$ After $\#(S)/\log_2(r)$ observed challenge-response pairs (= $\#(S)/\log_2(r)/t$ observed authentication sessions), S is revealed.
- **The design goal of ORPS**: the leaked information cannot be handled more effectively than a simple brute-force attack of S.

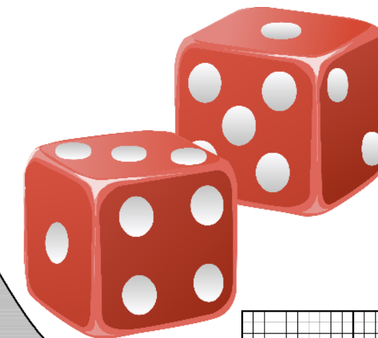
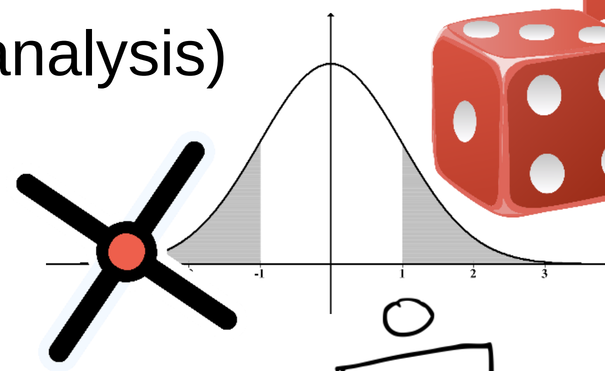
System and Attack Modelling: An *asymmetric* war

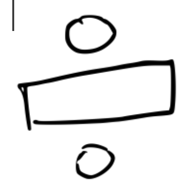
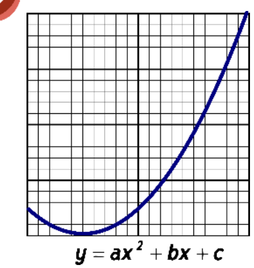
- **Security** requires $f_i(C_i(S),S)$ to be **sufficiently complicated** for **observers** to calculate S out of a number of ($C_i(S)$, R_i) pairs.
- **Usability** requires $f_i(C_i(S),S)$ to be **sufficiently simple** for **humans** to understand and execute.

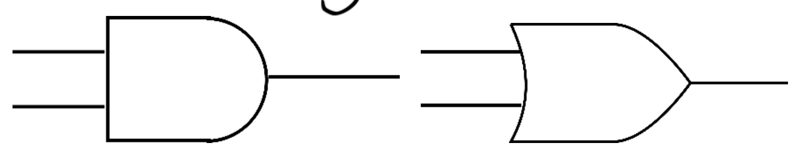
- **Observers** are computationally bounded adversaries, but they have access to **computers** as **auxiliary computing resources**.
- **Human users** have **only their brains** as the **computing resources**.
  - The only advantage human users have is knowledge of S.
  - $\Rightarrow$ We need a **human-executable trapdoor function**.

System and Attack Modelling: A large number of attacking strategies

- Random guess (base line “attack”)
- Statistical attacks (frequency analysis)
- Algebraic attacks
- Intersection attacks
- Divide and conquer attacks
- SAT solver based attacks
- Meet-in-the-middle attacks
- Side channel attacks
- Human behavior related attacks
- “Smarter” brute force attacks
- Partially-known-password attacks
- …

Selected Work: Where are we now?

- Some general principles have been identified.
- Some general design strategies have been proposed.
- A number of generic attacks have been known.
- Many ORPS schemes have been proposed.
- None of existing ORPS schemes have an acceptable balance between security (for a sufficiently large *k*) and usability.
- Clues have been found about theoretical impossibility of sufficiently secure and usable ORPS.
- Active observers are harder to handle.

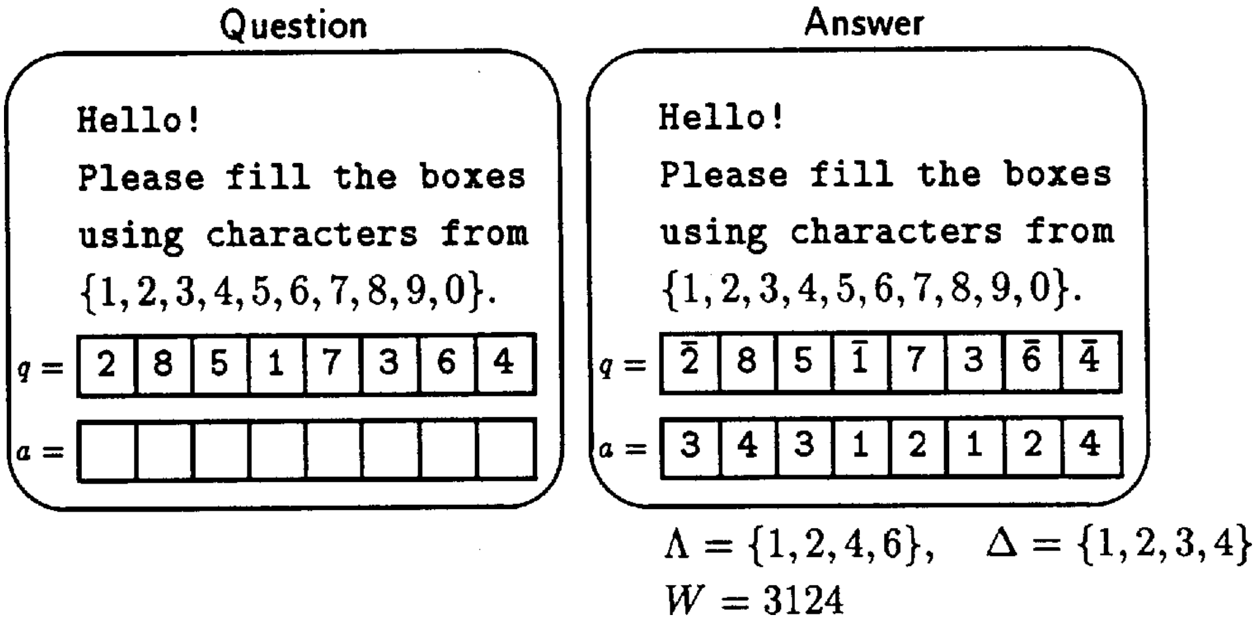
Selected Work: Security vs. Usability

- 7 example ORPS schemes compared [Yan et al. NDSS 2012] (a smaller usability score is better)

ORPS Scheme	Usability Score	Security Level
HB protocol (LPN)	33,874	No major attacks
APW protocol	18,787	No major attacks
CAS high	8,594	Best known attack: *O*(10) observed authentication sessions
CAS low	7,818	
Foxtail	3,513	Best known attack: *O*(100) observed authentication sessions
CHC	1,575	Best known attack: *O*(10) observed authentication sessions
PAS	924	Best known attack: *O*(10) observed authentication sessions

Selected Work: Matsumoto-Imai scheme (EuroCrypt'91)

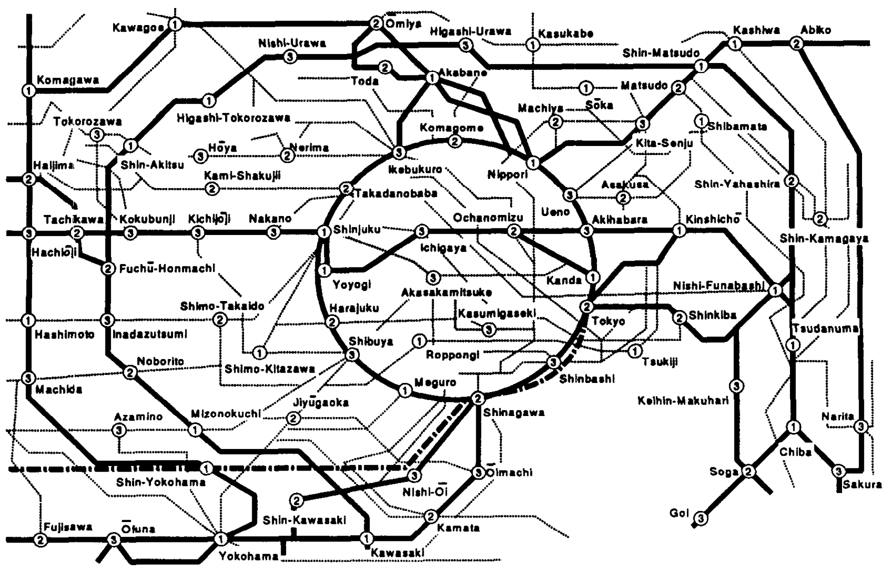
- Matsumoto-Imai scheme (EuroCrypt'91)
  -

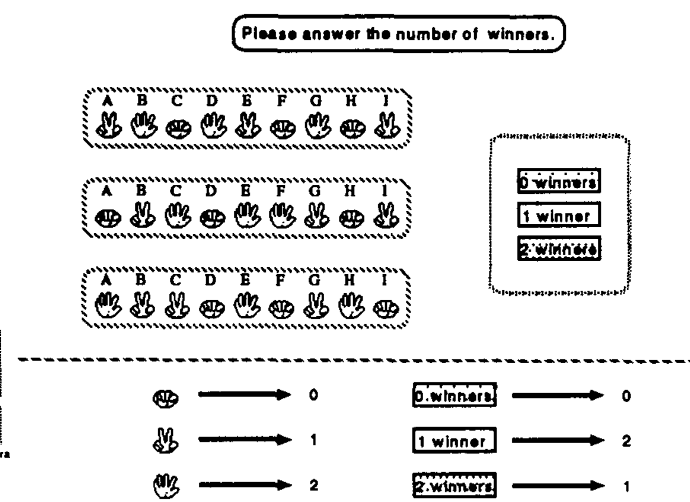


  - Too complicated for users $\Rightarrow$ Usability problem
  - Cryptanalyzed by Wang et al. (EuroCrypt'95)
- Enhanced MI scheme (Wang et al. EuroCrypt'95)
  - Too complicated for users $\Rightarrow$ Usability problem

Selected Work:
Matsumoto protocols (CCS'96)

- Dot-product based: $R_i = C_i \cdot K_i$, where K_i is a sub-password.
- The password can be derived with $O(v)$ authentication sessions, where v is the dimensionality of K_i.





Selected Work: Hopper-Blum protocols (AsiaCrypt'2001)

- A general strategy: designing ORPSs based on known (NP-)hard problems.
  - HB Protocol 1: Based on Learning Parity with Noise (LPN) problem
  - HB Protocol 2: Based on Sum of *k* Mins problem
- Plausible security vs. Usability problem
  - 166 seconds for login for an implementation of Protocol 1
- Find applications in light-weight cryptography (RFID chips replacing human users)

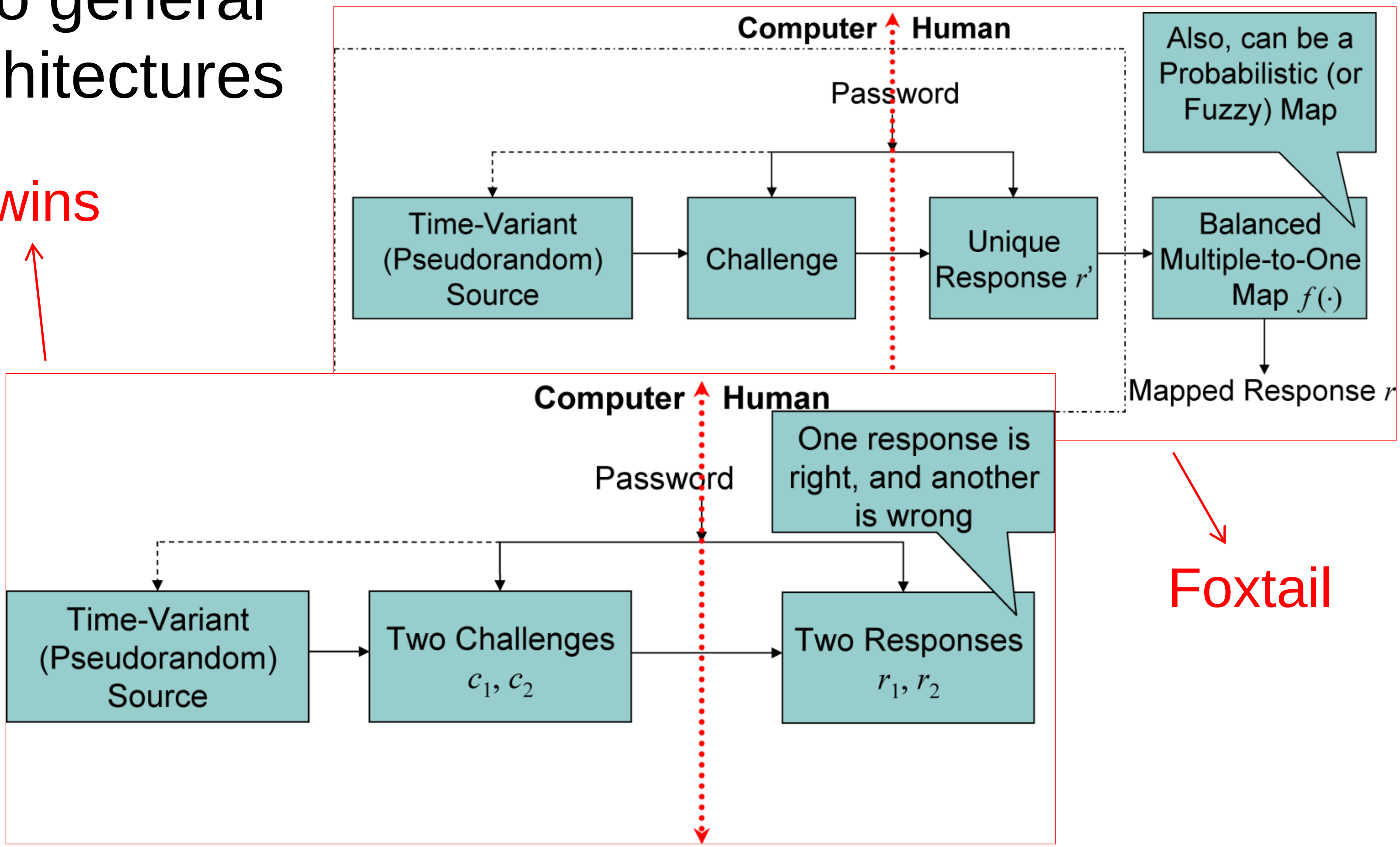
Selected Work:
Convex Hull Click protocols (2002-2006)

- First proposed by Sobrado and Birget in 2002 and further extended by Wiedenbeck et al. in 2006
- A number of variants proposed
- Usability: Better for small parameters
- Two statistical attacks: Insecure against *O*(10) observed authentication sessions (my work @ ISC 2010 and IJIS 2013)

Selected Work:
Twins and Foxtail (my work 2004-2005)

Two general architectures

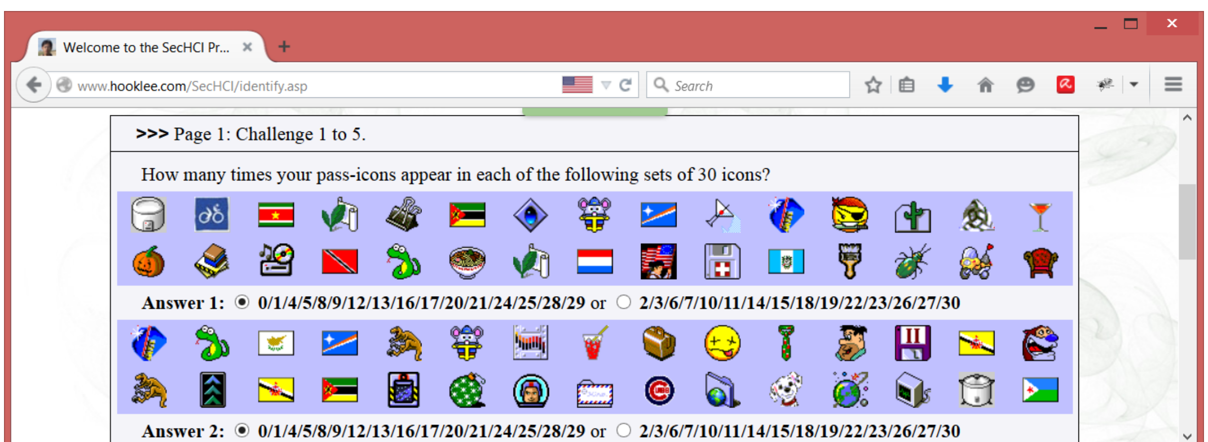
Twins



Foxtail

Selected Work:
A Foxtail protocol (my work 2004-2005)

- Password: *k* pass-icons out of a pool of *n* icons
- Challenge: *m* randomly selected icons + *m* icons in which the number of pass-icons is 0-3 with equal probability
- Response: floor((#(pass-icons) mod 4) / 2) = 0 or 1
- Usability: 2-3 mins for login for 20 challenges (not usable)
- Statistical attacks: insecure against *O*(100) observed authentication sessions (Yan et al. NDSS 2012)

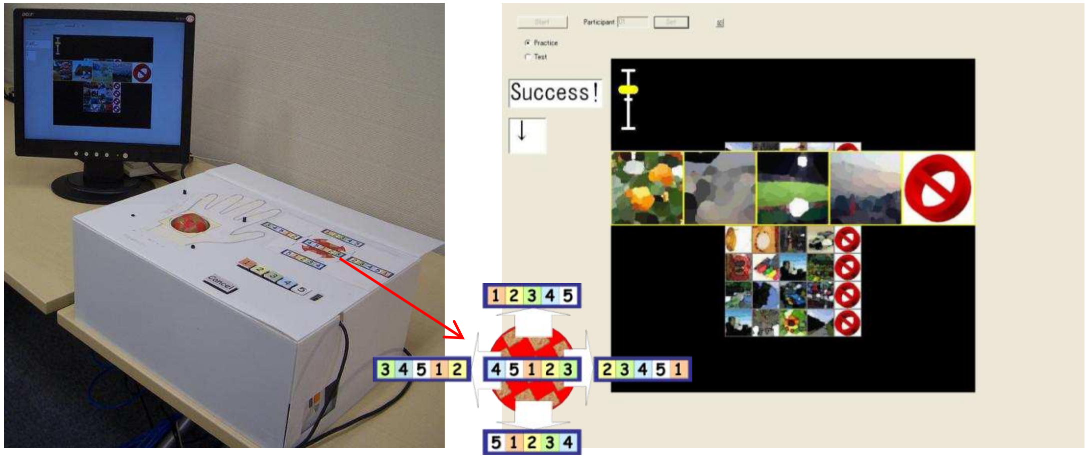


Selected Work:
Weinshall's CAS (IEEE S&P 2006)

- CAS = Cognitive Authentication Scheme
  - Usability problem (30/60 secret pictures to recall, 1-3 minutes for login)
  - SAT solver based attack: Insecure against *O*(10) observed authentication sessions (IEEE S&P 2007)

Selected Work: Undercover (ACM CHI 2008)

- A general strategy: Hiding part of challenges via a trusted channel (a tracking ball covered by hand)
- A trusted channel is not always available.
- Intersection attacks and human behavior based timing attacks reported (my work @ SOUPS 2011)
- The timing attack has its root in an improper GUI design.



Selected Work: Bai et al.'s PAS (ACSAC 2008)

- PAS = Predicate-based Authentication Service
- A very involved system with a number of tables for each challenge and a list of tuples as password
- CAPTCHAs are used to disable automated attacks
- Security and usability: PAS ≈ Less secure and less usable OTP (my work @ ACSAC 2009)

(1,1) D F G H K R T U V W X Y Z	(1,2) A B D F G L M O R S U W Y	(1,3) A B F G J K L N S U W X Z	(1,4) D G H L M N P R U V W X Z	(1,5) C D E F K M O P S T U X Z
(2,1) D E F H J K O P S T U V W	(2,2) C H K L N O P Q R V X Y Z	(2,3) C E H L N O R S U W X Y Z	(2,4) D E F G J K O Q S T V Y Z	(2,5) A B C D E F G K L M O R X
(3,1) A F G H J K M O Q R S T V	(3,2) A E F H K Q R S U W X Y Z	(3,3) B C E F H J L O P Q U W Z	(3,4) A E G H J L M O Q T U V W	(3,5) D F G H K M N O Q T W X Y
(4,1) A B E F G J K N P S T X Z	(4,2) B C D E F H M Q S T U X Y	(4,3) A G H J K M N P Q T U W Y	(4,4) A B C D G H L M N O P V X	(4,5) A C E G L M N P R S T X Z
(5,1) A C E G K M N O R T W X Y	(5,2) C D E F G H J M O Q S T U	(5,3) B C H K M N R T V W X Y Z	(5,4) C D E F H J L M Q R S T V	(5,5) E F G H L N O Q R S T X Z

(1,1) C E H K L M N P Q R U V W	(1,2) C E K L N O P Q R S V Y Z	(1,3) A B E G K L O Q S T V W Y	(1,4) A C F L M O P Q R S U V Z	(1,5) A B C D H K O R S T U W Z
(2,1) B C E F M O P Q S T V W Y	(2,2) A C D E F J N O P Q S T X	(2,3) A C E H J M N P Q T U Y Z	(2,4) A C D G H J K L N Q S T X	(2,5) A C E F K M N Q R T X Y Z
(3,1) B C D F H J M N Q R S V Y	(3,2) A D E F G H L M P Q R U Y	(3,3) A B E J L N Q R S V W X Y	(3,4) A D E G K M N O P Q R T U	(3,5) A C D F H J M O Q R S U Z
(4,1) B D E K O P Q S T U V X Z	(4,2) A C E F K M N P R S T V W	(4,3) A B F G K O Q S T V W X Z	(4,4) A B D E J K L P S T U V X	(4,5) B G H J K N O Q R S V W X
(5,1) B C D E F L N P Q R U V X	(5,2) C D J K N O P Q S U X Y Z	(5,3) A B C H K O P R S T V Y Z	(5,4) A C F G J L N Q R T U V W	(5,5) A D F H J K N P R V W X Z

	2: No No	2: No Yes	2: Yes No	2: Yes Yes
1: No No				
1: No Yes				
1: Yes No				
1: Yes Yes				

Selected Work: Yan et al.'s NDSS 2012 work

- The most comprehensive review of ORPS schemes
  - Yan et al. a different "Leakage-Resilient Password Systems" (LRPSs)
- One of two outstanding papers of NDSS 2012
- A number of security-oriented principles for ORPS design
- **<u>A quantitative usability evaluation framework</u>** based on cognitive workload and memory demand models
- A new 2-D statistical attack showing insecurity of my Foxtail protocol (against *O*(100) observed authentication sessions)

Selected Work: My NDSS 2013 work

- A rigorous theoretical treatment of the 2-D statistical attacks discovered by Yan et al. at NDSS 2012.
- Discovery of two families of the statistical attacks on some ORPSs: "**response-independent frequency analysis**" and "**response-dependent frequency analysis**".
  - Why they work? – Statistical asymmetry between pass- and non-pass-objects in the password.
  - Yan et al.'s 2-D attack is just a special case.
  - A less effective 1-D attack exists ($O(1000)$ sessions required).
- Each family contains **infinite** number of attacks $\Rightarrow$ Implies theoretical impossibility of security against all those attacks for ORPSs with **finite** number of parameters?
- Two new principles and fixed Foxtail protocols proposed

Selected Work: New timing attacks (IEEETIFS 2015)

- Further development based on my SOUPS 2011 work on Underwork by my collaborators Perković and Čagalj.
- Generalized human behavior based timing attacks to two new ORPS schemes: HB protocol 1 and a patented Mod10 method
  - Why do they work? – **Cognitive asymmetry**: Different cognitive loads required for different challenges
- Level of success: for HB protocol 1 (default parameters) with $O(100)$ observed sessions the password can be derived fully with high probability.
- New ORPS design principle proposed on asymmetry related to cognitive load and user interface

Selected Work:
My latest work (IEEETIFS 2015)

- Two ORPS schemes modelled as linear systems of congruences linked to the learning with (structured) noise (LwE) problem.
  - A fixed Foxtail protocol (my work @ NDSS 2013)
  - A Twins protocol (Catuogno and Galdi WISTP 2008)
- Various attacking strategies studied
  - Linear algebra, lattice and coding theory based attacks
- Results
  - The fixed Foxtail protocol: insecure against $O(n^2)$ observed authentication sessions where n is the number of objects
  - CG protocol: insecure against $O(n)$ observed sessions
- Results generalizable to other ORPS schemes
- Open question: ORPSs secure against $\geq O(n^2)$ sessions?

Road Ahead?

Road Ahead?
General design strategies and principles

- Designing ORPSs based on more candidate (NP-)hard problems.
  - Fixed-parameter intractable problems and paraNP-hard problems are of particular interests.
  - Three key parameters: n – number of objects, k – size of password (number of pass-objects), m – size of challenge (number of objects in a challenge, may be equal to n)
- Pay attention to ALL known attacks.
  - Pay special attention to details in user interface and how human users interact with the interface.
- Twins and Foxtail protocols still stand as good ORPS architectures.

Road Ahead?
Automating security/usability evaluation

- Current practice does not allow a large number of potential ORPS designs and implementations to be checked quickly.
- First quantitative usability evaluation framework has appeared (Yan et al. NDSS 2012) but not complete nor computable.
- Use of cognitive models has proved useful.
  - CPM-GOMS was used in two recent papers on ORPSs against shoulder surfers for modelling shoulder surfers' cognitive powers.
- Security evaluation automation is possible (mathematical models + Monte Carlo methods)
- Software tools are still missing.
  - Some cognitive modelling tools exist, but cannot be used directly.

Road Ahead?
Studies on impossibility

- Humans' cognitive limitations are largely known.
  - Miller's law: The magic number of 7±2 in human's working memory (*Psychological Review* 1956)
  - Cowan's law: The magic number of 4 in human's short-term memory (Behavioral and Brain Sciences 2001)
  - …
- Requirements on security and usability are largely known if application context is given.
- ORPSs have a general mathematical model.
- Some clues have been seen (e.g. my work @ NDSS 2013)
- $\Rightarrow$ Can impossibility be proved at least for some applications?

Back Matter

Acknowledgments: Research institutes + Funders

- Microsoft Research Asia (2002)
  - Student Intern
- Xi’an Jiaotong University (2002-2003)
  - PhD Student
- Universität Konstanz and German Research Foundation (DFG), Germany (2009-2011)
  - 5-Year Zukunftskolleg Fellow
- University of Surrey, UK (2011-present)
  - Senior Lecturer

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  - FESB, University of Split, Croatia (2010-)
- Prof. Josef Pieprzyk
  - Queensland University of Technology (2014-)
  - Macquarie University, Australia (2009-2013)
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  - Technische Universität Darmstadt, Germany (2012-)
  - Ruhr-Universität Bochum, Germany (2009-2011)
- Dr. Heung-Yeung (Harry) Shum
  - Microsoft Research Asia, China (2002)






Thanks for your attention!

Questions?