Alice and Bob in Love:

Cryptographic Communication Using Natural Entropy

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17th International Workshop on Security Protocols
April 2, 2009

Outline

1. Natural Entropy
2. Protocol
3. Experimental Results
4. Discussion Questions

Human Memory and Entropy

- Evolved to remember emotion, experience
- Can't remember high-entropy crypto keys
- Many pairs of people naturally share a huge entropy pool
    - Lovers
    - Siblings
    - Close friends

Human Challenge-Response

What was the name of the family who lived in the Hill House in Fond-du-Lac, Wisconsin?

Human Challenge-Response

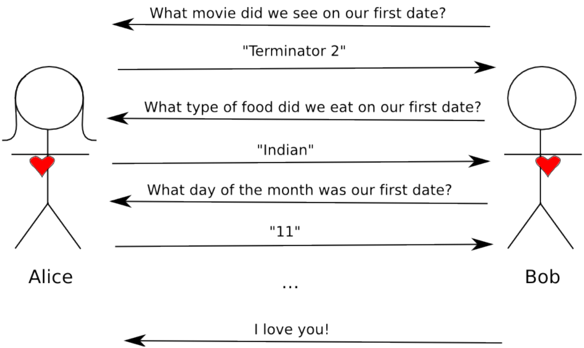
Calvin: i came here for a vacation and i was robbed by some gang
Calvin: i want you to loan me $900
Calvin: you can have the money send via western union

Evan: ok well i want to help you, since we're friends
Evan: ok one question
Evan: what was the name of our high school mascot?

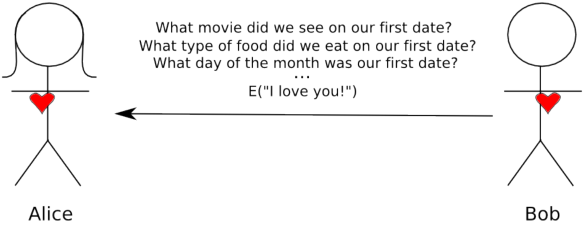
Calvin: Shawnee Mission Northwest High '01

Evan: good luck finding someone stupid
Evan: bye now

Human Challenge-Response



Human Challenge-Response, 1-way?



Applications

- Emergency distress
- Drafting a will
- Password backup

Goals

- Extract cryptographically secure amount of entropy ($\geq$64 bits)
- Minimal recipient sophistication
- Maximise use of available entropy
- Maximise decryption probability

Non-Goals

- Performance
  - Memory overhead
  - Encryption/Decryption processing
- Sender simplicity
  - Grandmother can receive, not send
- Anonymity/Steganography

Building Blocks

- Password Backup Systems
  - Carl Ellison, Chris Hall, Randy Milbert, and Bruce Schneier. "Protecting Secret Keys with Personal Entropy." *Future Generation Computer Systems*, 2000.
    - Use traditional secret-sharing
  - Nyklas Frykholm and Ari Juels. "Error-tolerant Password Recovery." *Computer and Communications Security*, 2001.
    - Use error-correcting code
- Personal Knowledge Questions studied empirically
  - Mostly in the context of online "re-authentication"

Improvements

- Flexible
  - Arbitrary entropy in answers
  - Arbitrary recall probability
- Key Strengthening

Question Generation

- Sender picks a set Q of questions $\{q_0, q_1, \ldots, q_m\}$
  - Also specify answers $A = \{a_0, a_1, \ldots, a_m\}$
- For each quesion q_i, annotate:
  - Entropy for attacker, H_i
  - Recall probability for recipient, r_i
  - Optional: multiple-choice answers

Example

<question>
<entropy>**3**</entropy>
<recall>**0.95**</recall>
<prompt>**What type of restaurant did we go to before a concert at St. John's?**</prompt>
<option>**Chinese**</option>
<option>**Sushi**</option>
<option>**Italian**</option>
<option>**Lebanese**</option>
<option>**Brazilian**</option>
<option>**Mexican**</option>
<option>**Thai**</option>
<option>**Indian**</option>
<answer>**Thai**</answer>
</question>

Encryption

(NB: Protocol tweaked from pre-proceedings paper)

Encryption

- Critical step - Designate subsets of keys which can decrypt:

$$A^* = \{A_i \in A : \text{ knowledge of } A_i \text{ shall enable decryption}\}$$

- Secret-sharing by brute-force
- Will add storage, work overhead proportional to $|A^*|$
  - In practice, this won't kill us

Encryption

- For each decrypting subset A_i, store an offset O_i to recover the master key K_{M}:

$$K_i^0 = \bigoplus_{a_j \in A_i} \mathbf{H}(a_j || j)$$

$$K_i^1 = \mathbf{H}^{2^s}(K_i^0)$$

$$O_i = K_i^1 \oplus K_{\mathrm{M}}$$

- Encryption requires $|A^*|$ storage, $|A^*| \cdot 2^s$ work

Encryption

- Alice sends the following to Bob:
  - $\mathbf{E}_{K_{\mathrm{M}}}(M||A||Q||O)$
  - $\mathbf{MAC}_{K_{\mathrm{M}}}(\mathbf{E}_{K_{\mathrm{M}}}(M||A||Q||O))$
  - Q
  - O
- Decryption straightforward
  - requires searching over $|A^*|$

Optimisation

- How to pick A^*?
- For any set candidate subset $\tilde{A}^* \subset \text{powerset}(A)$ can compute:
  - Minimum entropy brute force path for attacker
  - Estimated success probability for recipient
- Given a desired value for either, can find optimal A^* easily

Structure

- 1 sender (me)
- 8 receivers whom I've had a close relationship with
    - Mother
    - Father
    - Brother
    - Sister
    - Girlfriend
    - Ex-Girlfriend
    - College Roommate
    - High School Friend

Sender Process

- 60 minutes spent per recipient
- Questions created prior to discussing research with subjects
- No external aids (ie photo albums) used
- Chose A^* to yield 64 bits of entropy
- All messages had estimated decryption probability > 0.99

Entropy Estimates

Answer Category	Entropy (bits)
Color	3
TV Title	4
University	5
Movie Title	6
First Name	8
Last Name	10

Recipient Process

- 24 hours to respond
  - All reported ∼10 minutes to complete
- All recipients given other recipients' questions
  - Simulation of inside attacker

Message Stats

Receiver	$\lvert Q \rvert$	H_{total}	$p_{success}$	$\lvert A^* \rvert$
Mother	13	88	0.997	306
Father	14	95	0.998	2,027
Brother	17	98	0.999	9,332
Sister	13	87	0.994	518
Girlfriend	16	89	0.999	3,318
Ex-girlfriend	15	84	0.997	189
Ex-Roommate	13	93	0.999	808
HS Friend	15	101	0.999	10,762
Average	**14.4**	**91.9**	**0.998**	**3,408**

Actual Success Rates

- 6 of 8 messages successfully decrypted
- Overall, 75% of questions answered correctly
    - Predicted 95% . . .

Results

Receiver	$\|Q\|$	Correct	Input	Forgot	Result	Guessed
Mother	13	8	3	2	✖	3
Father	14	7	4	3	✖	3
Brother	17	13	2	2	✔	4
Sister	13	10	2	1	✔	2
Girlfriend	16	14	2	0	✔	0
Ex-girlfriend	15	13	1	1	✔	0
Ex-Roommate	13	10	0	3	✔	1
HS Friend	15	10	0	5	✔	1
Average	**114**	**83**	**14**	**17**		**14**

Error types

- Spelling
  - Vowels Only - '**Rachel**' vs. '**Rachael**'
  - Complex - '**Fruit and Fibre**' vs. '**Fruit 'N Fibre**'
- Phrasing
  - Synonyms - '**shoes**' instead of '**boots**'
  - Grammar - '**ride a bike**' instead of '**riding a bike**'
- Actual Forgetfulness
  - $\frac{1}{3}$ indicated directly as '**don't know**'
  - One answer provided wrong by sender!

Error Breakdown

Result	Frequency
Correct	74%
Vowel errors	3%
Spelling errors	2%
Synonyms	7%
Forgotten	14%

Normalisation

- Expecting some issues, normalisation implemented
  - Conversion to lower case
  - Removal of all punctuation, white-space
  - elimination of ‘the,’ ‘and,’ trailing ‘s’
- Prevented some errors, but not enough
- Normalisation has some limits . . .

Conclusions

- Encryption is possible using natural entropy
  - Appears to be secure
- Usability is terrible for sender
  - Very hard to come up with questions
- Reliability is also lacking
  - hard to accurately predict recall probability

Authentication

- Some implicit authentication
- Encrypt all answers along with message
- Much weaker than confidentiality level
- Adversary can use *any* known information to fool Bob
  - Dumpster diving
  - Malware
  - E-mail/social network account compromise

Experimental Design

- Sample size $N=8$ is insufficient
- Difficult to run a larger study
  - Need fairly sophisticated senders
  - Need sender's actual close relations
- Is the data collected PII?

Experimental Design

- How to model a “real” attacker?
  - Participants unlikely to be highly motivated
- Extremely time-consuming
  - Every question requires different investigation

Privacy Concerns

- How much is given up if the questions Q get published?

Better Sender Interface

- Standard classes of question - mostly useless
- Estimating recall - probably impossible
- Estimating entropy - very difficult
- Standardised multiple choice answers - might help

Normalisation

- More aggressive normalisation possible
  - Soundex & variants
  - User defined (ie only consider first 4 characters)
- Intuition - Hard to get fancy without leaking information
  - Eventually doing homomorphic encryption

Estimating Entropy Automatically

- Realistically only works for multiple choice
- Variation within answer categories
  - *What was the name of our waiter in Dallas?* - high entropy
  - *Which co-worker of yours plays the violin?* - lower entropy
- Requires huge amount of domain-specific knowledge
  - *Where did we stay driving from Phoenix to LA?*

Fuzzy Matching

- "Close" answers mean something
  - *What year did Alissa and Mike get married?* **'2008'**
  - **'2007'** is much better than **'1997'**
- Not quite like normalisation-want to give partial credit
- Cheap solution: divide answer character by character
  - Close answer can still miss badly, ie **'2000'** vs **'1999'**
- Multiple questions, encode close answers at lower entropy level
  - Destroys performance

More Memorable Items

- Humans even better at dealing with images, sounds, smell
- Huge entropy pool available
- Difficult to encode
- Difficult for sender to come up with

Thank You

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