Quantifying the computational security of multi-user systems

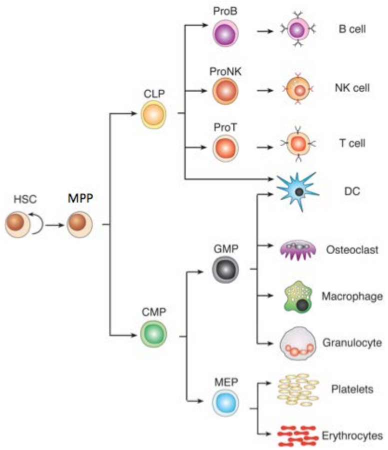
(Work with M. Christiansen, F. du Pin Calmon & M. Médard)

Ken Duffy

Hamilton Institute,
National University of Ireland Maynooth

Eurandom, July 2014

A stochastic network (?)



S. Orkin & L. Zion *Cell*, 2008, S. Naik et al., *Nature*, 2013, L. Perié et al. *Cell Reports*, 2014.

Quantifying the computational security of multi-user systems

M. Christiansen

F. du Pin Calmon (MIT)

M. Médard (MIT)

M. Christiansen, K. Duffy, F. du Pin Calmon & M. Médard, http://arxiv.org/abs/1405.5024

A model of computational security

Computationally secure:

- User selects X, a string, from a collection of possibilities.
- Inquisitor knows the collection of all objects and can query each in turn.
- Computationally secure if collection of keys is large.

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- Computationally secure if collection of keys is large.

Probability:

- What if X is picked probabilistically with a distribution known to the inquisitor?

Why non uniform?

Investigating the Distribution of Password Choices

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Kevin Maher
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D. Malone & K. Maher, *Proc. WWW*, 2012

Why non uniform?

Rank	Cyphertext	indicitive hint	inferred password	#users
1	EQ7fIpT7i/Q=	One to six in numeral form	123456	1905308
2	j9p+HwtWWT86aMjgZFLzYg==	1234567890 ohne 0	123456789	445971
3	L8qbAD3jl3jioxG6CatHBw==	answer is password	password	343956
4	BB4e6X+b2xLioxG6CatHBw==	adbeandonetwothree	adobe123	210932
5	j9p+HwtWWT/ioxG6CatHBw==	123456789 minus last number	12345678	201150
6	5djv7ZCI2ws=	1st 123456 letters	qwerty	130401
7	dQi0asWPYvQ=	1234567 is the password	1234567	124177
8	7LqYzKVeq8I=	6 number 1s	111111	113684
9	PMDTbP0LZxu03SwrFUvYGA==	adobe photo editing software	photoshop	83269
10	e6MPXQ5G6a8=	one two three one two three	123123	82606

Table III: Top 10 Adobe passwords.

D. Malone, *tech. report*, 2014

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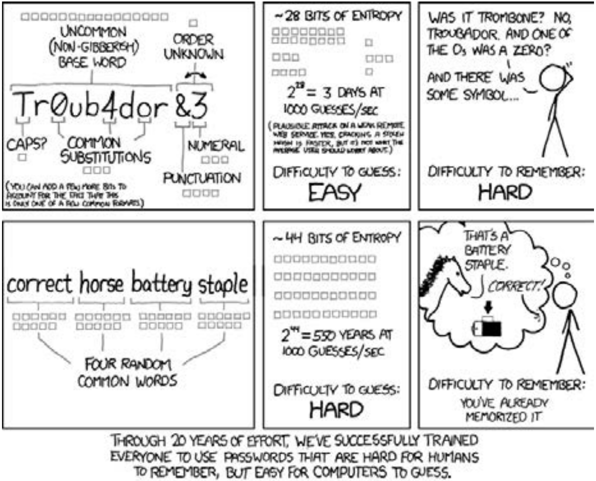
```
104544054-|--|-[redacted]@tue.nl-|-k04EOIj32H25n2auThm2+Q==-|-Mockstraat|--
85681613-|--|-[redacted]@student.tue.nl-|-f53DchUT4jFKSrr7+3WIJQ==-|-band|--
116152651-|--|-[redacted]@student.tue.nl-|-4cdiIQ49LSvbMwSfVulYkg==-|-always|--
102508026-|--|-[redacted]@student.tue.nl-|-czY0m424hNQ=-|-lekker|--
102532155-|--|-[redacted]@student.tue.nl-|-1lY/UUZSD20=-|-wer|--
102832797-|--|-[redacted]@student.tue.nl-|-dVhqe4UQmt66EtZxhuv+ew==-|-whats my style|--
103129231-|--|[redacted]@student.tue.nl-|-8fr4yvaAFh7ioxG6CatHBw==-|-huh?|--
103950186-|--|[redacted]@student.tue.nl-|-KkajmwR884g=-|-team|--
86311201-|--|[redacted]@student.tue.nl-|-urPuioT/3aDLj1wcIHdpUg==-|-moeilijk he!|--
99966113-|--|-[redacted]@tue.nl-|-4mWPXgpz1hj6MaxEGsHQkw==-|-Ongeluk|--
100011401-|--|[redacted]@student.tue.nl-|-sgvf5qDJ5yPioxG6CatHBw==-|-Ca|--
100113445-|--|-[redacted]@student.tue.nl-|-ULGoDNROwdaBkcrysXUKww==-|-TUE CODE|--
100382411-|--|[redacted]@tue.nl-|-nd9qkGw3tFC6THMRxdTo/A==-|-tja|--
71282804-|--|-[redacted]@tue.nl-|-QWgDPFLM8KjioxG6CatHBw==-|-paardje|--
75818292-|--|-[redacted]@tue.nl-|-eR52uEWa5avioxG6CatHBw==-|-call-0|--
80990272-|--|[redacted]@tm.tue.nl-|-joC17LahwbDioxG6CatHBw==-|-all|--
81381050-|--|[redacted]@tue.nl-|-XRP/O4egwNLioxG6CatHBw==-|-standaard|--
84045420-|--|-[redacted]@student.tue.nl-|-Qava9Ny648FiAkd+sFpx+Q==-|-naam hond|--
84215074-|--|-[redacted]@student.tue.nl-|-7MLKr9CfrNg=-|-bsdfgsdgfjasdfasdg|--
84384895-|--|[redacted]@student.tue.nl-|-HcIkIBkmErM=-|-codiT|--
102818800-|--|-[redacted]@student.tue.nl-|-QKzPv3iINYU=-|-lekker|--
```


D. Malone, *tech. report*, 2014

What makes a password good?



scriptsizexkcd.com/936/

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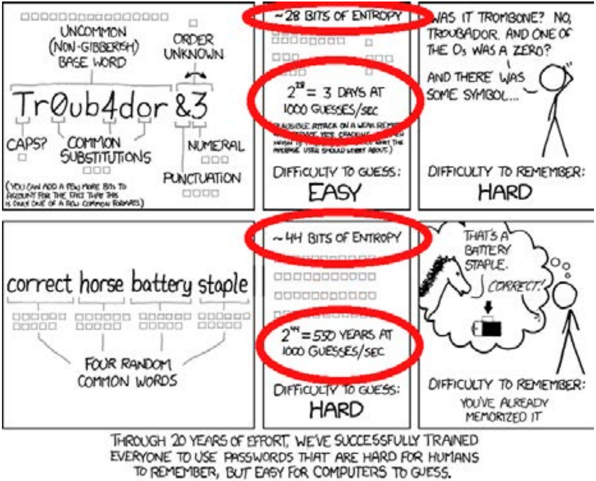

scriptsizexkcd.com/936/

Is Shannon Entropy the right measure?

Guessing and Entropy

James L. Massey

Signal & Info. Proc. Lab., Swiss Federal Inst. Tech, CH-8092 Zurich, Switzerland

J. L. Massey, *Proc. IEEE ISIT*, 1994.

Is Shannon Entropy the right measure?

- A word, W, picked from $\mathbb{A} = \{1, \ldots, m\}$, has Shannon entropy

$$H = -\sum_{i \in \mathbb{A}} P(W = i) \log P(W = i).$$

- How should the inquisitor guess W?

J. L. Massey, *Proc. IEEE ISIT*, 1994.

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$$P(W = 1) \geq P(W = 2) \geq \ldots \geq P(W = m)$$

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& guess in order: the i^{th} most likely word on the i^{th} guess, $G : \mathbb{A} \mapsto \mathbb{N}$ such that $G(i) = i$ and

$$E(G(W)) = \sum_{i \in \mathbb{A}} i \, P(W = i).$$

J. L. Massey, *Proc. IEEE ISIT*, 1994.

What's the right measure of Guesswork?

An Inequality on Guessing and its Application to Sequential Decoding

Erdal Arikan, *Senior Member, IEEE*

E. Arikan, *IEEE Trans. Inf. Theory*, 1996.

What's the right measure of Guesswork?

A sequence $W_k \in \mathbb{A}^k$ made of i.i.d. letters. Define Rényi entropy

$$R_1(\beta) = \frac{1}{1-\beta} \log \sum_{w \in \mathbb{A}} P(W_1 = w)^\beta,$$

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Arikan's Proposition:

$$\lim_{k \to \infty} \frac{1}{k} \log \mathbb{E}(G(W_k)^\alpha) = \alpha R_1\left(\frac{1}{1+\alpha}\right) \text{ for } \alpha > 0.$$

E. Arikan, *IEEE Trans. Inf. Theory*, 1996.

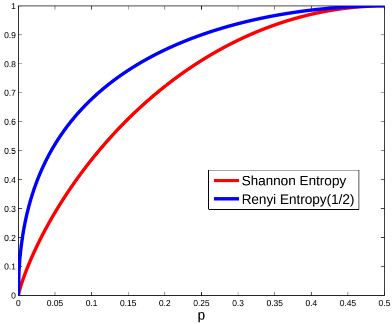
What's the right measure of Guesswork?

E.g. $\alpha = 1$, for large k

$$\mathbb{E}(G(W_k)) \approx \exp(kR_1(1/2))$$

where

$$R_1(1/2) = \log\left(\sum_{w\in\mathbb{A}} \sqrt{P(W_1 = w)}\right)^2.$$



E.g. Bernoulli Source, log base 2.

E. Arikan, *IEEE Trans. Inf. Theory*, 1996.

Source generalization of Arikan's Proposition

With the Rényi entropy of W_k being

$$R_k(\beta) = \frac{1}{1-\beta} \log \sum_{w \in \mathbb{A}^k} P(W_k = w)^\beta,$$

and $R(\beta) = \lim_{k\to\infty} \frac{1}{k} R_k(\beta)$, generalizations prove

$$\lim_{k\to\infty} \frac{1}{k} \log \mathbb{E}(G(W_k)^\alpha) = \alpha R\left(\frac{1}{1+\alpha}\right) \text{ for } \alpha > -1.$$

D. Malone and W. G. Sullivan, *IEEE Trans. Inf. Theory*, 2004.
C.-E. Pfister and W. G. Sullivan, *IEEE Trans. Inf. Theory*, 2004.
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M. Christiansen & K. Duffy, *IEEE Trans. Inf. Theory*, 2013.

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$$\lim_{k \to \infty} \frac{1}{k} \log \mathbb{E}(G(W_k)^\alpha) = \begin{cases} \alpha R\left(\frac{1}{1+\alpha}\right) & \text{for } \alpha > -1. \\ -R(\infty) & \text{for } \alpha \le -1. \end{cases}$$

D. Malone and W. G. Sullivan, *IEEE Trans. Inf. Theory*, 2004.
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Large deviations and guesswork distributions

Consider

$$\Lambda(\alpha) := \lim_{k\to\infty} \frac{1}{k} \log \mathbb{E}(G(W_k)^\alpha) = \lim \frac{1}{k} \log \mathbb{E}(e^{\alpha \log(G(W_k))}) = \begin{cases} \alpha R\left(\frac{1}{1+\alpha}\right) \\ -R(\infty) \end{cases}$$

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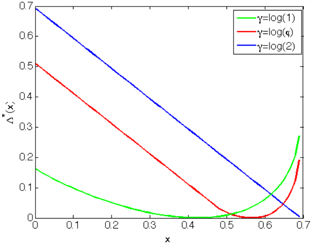
Suggestive of

$$dP\left(\frac{1}{k}\log G(W_k) \approx x\right) \asymp \exp(-k\Lambda^*(x))\,dx$$

where $\Lambda^*_X(x) = \sup_{\alpha\in\mathbb{R}}(\alpha x - \Lambda_X(\alpha))$.



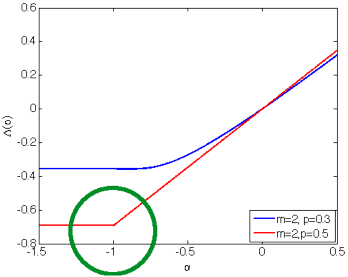
For large k, some jiggery-pokery gives

$$\boxed{P(G(W_k) = n) \approx \frac{1}{n}\exp\left(-k\Lambda^*\left(\frac{1}{k}\log n\right)\right).}$$

M. Christiansen & K. Duffy, *IEEE Trans. Inf. Theory*, 2013.

What's in a discontinuous derivative?

$$\Lambda(\alpha) = \begin{cases} \alpha R((1+\alpha)^{-1}) & \text{if } \alpha \geq -1 \\ -R(\infty) & \text{if } \alpha \leq -1 \end{cases}$$



Define:

$$\gamma = \lim_{\alpha \downarrow -1} \frac{d}{d\alpha}\Lambda(\alpha)$$
$$= \lim_{\beta \to \infty} \left(R(\beta) - \frac{R'(\beta)}{\beta^2} \right).$$

If i.i.d., then $\gamma = \log|\{w : P(W_1 = w) = P(G(W_1) = 1)\}|$.

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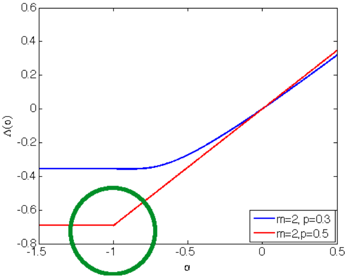

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If i.i.d., then $\gamma = \log |\{w : P(W_1 = w) = P(G(W_1) = 1)\}$.
If not, then approximately $e^{k\gamma}$ "most likely words" of length k.

An aside on most likely words

Lemma: For $\{W_k\}$ constructed of Markovian letters with $\mathbb{A} = \{0, 1\}$,

$$\gamma = \lim_{\alpha \downarrow -1} \Lambda'(\alpha) \in \{0, \log(\phi), \log(2)\},$$

where $\phi = (1 + \sqrt{5})/2$ is the Golden Ratio, and no other values are possible.

Uniformity, typical set coding etc.

Guessing a password over a wireless channel (on the effect of noise non-uniformity)

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Flávio du Pin Calmon and Muriel Médard
Research Laboratory of Electronics
Massachusetts Institute of Technology
Email: {flavio, medard}@mit.edu

Brute force searching, the typical set and Guesswork

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M. Christiansen, K. Duffy, F. du Pin Calmon & M. Medard, *Proc. Allerton*, 2013
M. Christiansen, K. Duffy, F. du Pin Calmon & M. Medard, *Proc. ISIT*, 2013

Multiple users

$V \in \mathbb{N}$ users, independently picking strings

$$\vec{W}_k = \left(W_k^{(1)}, \ldots, W_k^{(V)}\right) \in \mathbb{A}^{kV}.$$

Statistics of each user's selection known to an inquisitor who can query the veracity of (user, string) pair and we wishes to identify $U \leq V$ of them.

Optimality?

The Shannon Cipher System with a Guessing Wiretapper

Neri Merhav, *Fellow, IEEE*, and Erdal Arikan, *Senior Member, IEEE*

N. Merhav & E. Arikan, *IEEE Trans. Inf. Theory*, vol. 45, pp. 1860–1866, 1999.

Optimality?

The Shannon Cipher System with a Guessing Wiretapper

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Then, it is clear that the best guessing strategy (in any reasonable sense) is to first guess the most likely $\boldsymbol{X}$ given $\boldsymbol{Y}$, then try the second most likely guess, and so on, until eventually, the correct message is found.

N. Merhav & E. Arikan, *IEEE Trans. Inf. Theory*, vol. 45, pp. 1860–1866, 1999.

Optimal strategy?

G is optimal W_k if and only if

$P\left(G(W_k) \leq n\right) \geq P\left(S(W_k) \leq n\right)$ for all strategies S and all $n \in \{1, \ldots, m^k\}$.

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Lemma

If $V = U$, the optimal strategies are those that guess from most likely to least likely.

If $U < V$, not guaranteed stochastic domination

Example: $V = 2$, $U = 1$ and $|\mathbb{A}| = 3$.

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User	Item	probability	
Sem	0.6	0.2	0.2
Johan	0.6	0.2	0.2

If $U < V$, not guaranteed stochastic domination

Example: $V = 2$, $U = 1$ and $|\mathbb{A}| = 3$.

User	Item probability		
Sem	$\cancel{0.6}$	0.5	0.5
Johan	0.6	0.2	0.2

If $U < V$, not guaranteed stochastic domination

Example: $V = 2$, $U = 1$ and $|\mathbb{A}| = 3$.

Move to Johan

User	Item probability		
Sem	$\cancel{0.6}$	0.5	0.5
Johan	$\cancel{0.6}$	0.5	0.5

Stick with Sem

User	Item probability		
Sem	$\cancel{0.6}$	$\cancel{0.5}$	1
Johan	0.6	0.2	0.2

There exist asymptotically optimal strategies - Round-robin

For each $v \in \{1, \ldots, V\}$ let $G^{(v)}$ denote its optimal strategy and define:

$$G_{\text{opt}}(U, V, \vec{W}_k) = \text{U-min}\left(G^{(1)}(W_k^{(1)}), \ldots, G^{(V)}(W_k^{(V)})\right),$$

where $\text{U-min} : \mathbb{R}^V \to \mathbb{R}$ gives the U^{th} smallest component.

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where $\text{U-min} : \mathbb{R}^V \to \mathbb{R}$ gives the U^{th} smallest component.
Then

$$G_{\text{opt}}(U, V, \vec{W}_k) \leq \text{ real performance of round-robin } \leq V\, G_{\text{opt}}(U, V, \vec{W}_k)$$

and, as $k \to \infty$, these have the same asymptote.

Asymptotically optimal strategies satisfy a LDP

Theorem

$\{k^{-1}\log G_{opt}(U,V,\vec{W}_k)\}$ *satisfies a large deviation principle. Defining*

$$\delta^{(v)}(x)=\begin{cases}\Lambda_G^{(v)^*}(x) & \text{if } x\le H^{(v)}\\ 0 & \text{otherwise,}\end{cases} \quad \text{and } \gamma^{(v)}(x)=\begin{cases}\Lambda_G^{(v)^*}(x) & \text{if } x\ge H^{(v)}\\ 0 & \text{otherwise,}\end{cases}$$

the rate function is

$$I_{G_{opt}}(U,V,x)=\max_{v_1,\dots,v_V}\left(\Lambda_G^{(v_1)^*}(x)+\sum_{i=2}^{U}\delta^{(v_i)}(x)+\sum_{i=U+1}^{V}\gamma^{(v_i)}(x)\right),$$

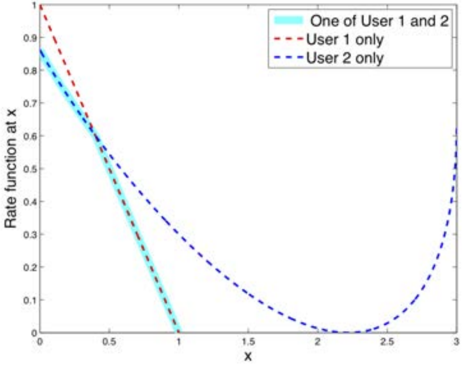
which may not be convex. The sCGF is

$$\begin{aligned}\Lambda_{G_{opt}}(U,V,\alpha)&=\lim_{k\to\infty}\frac{1}{k}\log E(\exp(\alpha\log G_{opt}(U,V,\vec{W}_k)))\\ &=\sup_{x\in[0,Vm]}\left(\alpha x-I_{G_{opt}}(U,V,x)\right).\end{aligned}$$

A Merhav & Arikan example, $U = 1$, $V = 2$

$W_k^{(1)}$, Bernoulli on $\{0, 1\}$,

$$P(W_1^{(2)} = i) = \begin{cases} 0.55 \text{ if } i = 0 \\ 0.1 \text{ if } i \in \{1, 2\} \\ 0.05 \text{ if } i \in \{3, \dots, 7\} \end{cases}$$



All things being equal

Corollary

If users' statistics are all (asymptotically) the same, then

$$\Lambda^*_{G_{opt}}(U, V, x) = \begin{cases} U{\Lambda_G}^*(x) & \text{if } x \leq H \\ (V - U + 1){\Lambda_G}^*(x) & \text{if } x \geq H \end{cases}$$

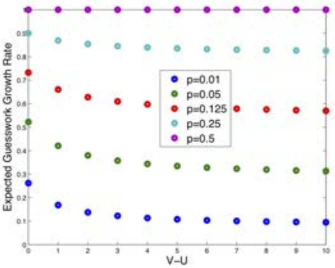
and

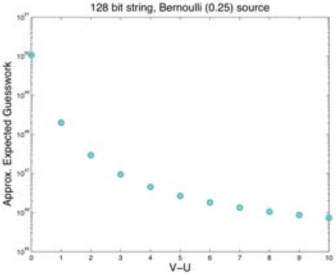
$$\Lambda_{G_{opt}}(U, V, \alpha) = \begin{cases} U\Lambda_G\left(\frac{\alpha}{U}\right) & \text{if } \alpha \leq 0 \\ (V - U + 1)\Lambda_G\left(\frac{\alpha}{V - U + 1}\right) & \text{if } \alpha \geq 0. \end{cases}$$

Multi-user guesswork growth rates

$n = V - U$, number of excess strings

$$\mathbb{E}(G_{\mathrm{opt}}(U, V, \vec{W}_k)) \approx \exp\left(kR\left(\frac{n+1}{n+2}\right)\right), \text{ where } \frac{n+1}{n+2} \in \left\{\frac{1}{2}, \frac{2}{3}, \frac{3}{4}, \ldots\right\}.$$





Concluding comments

- There's no "truly" optimal guessing strategy.
- Performance of asymptotically optimal strategies can be analysed.
- From an attacker's point of view, there's a law of diminishing returns in excess number of users.
- Shannon Entropy provides a universal lower bound on the guesswork growth rate of multi-user systems.

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- From an attacker's point of view, there's a law of diminishing returns in excess number of users.
- Shannon Entropy provides a universal lower bound on the guesswork growth rate of multi-user systems.
- If you had an Adobe password, change it everywhere.

Same as Facebook

108759368-|--|-[redacted]@mit.edu-|-RcjCaJFSHEvn1QXGvHdh5g==-|-same as facebook|--

Same as Facebook

```
108759368-|--|[redacted]@mit.edu-|-RcjCaJFSHEvn1QXGvHdh5g==-|-same as facebook|--
102833749-|--|[redacted]@uwo.ca-|-RcjCaJFSHEvn1QXGvHdh5g==-|-hotmail|--
99835647-|--|[redacted]@gmail.com-|-RcjCaJFSHEvn1QXGvHdh5g==-|-traksor|--
81179368-|--|[redacted]@hotmail.com-|-RcjCaJFSHEvn1QXGvHdh5g==-|-it's...|--
97533272-|--|[redacted]@aol.com-|-RcjCaJFSHEvn1QXGvHdh5g==-|-crazy|--
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169246561-|--|[redacted]@vianet.ca-|-RcjCaJFSHEvn1QXGvHdh5g==-|-same as always|--
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170751657-|--|[redacted]@gmail.com-|-RcjCaJFSHEvn1QXGvHdh5g==-|-reg|--
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187279970-|--|[redacted]@yahoo.com-|-RcjCaJFSHEvn1QXGvHdh5g==-|-what are you?|--
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