THE UNIVERSITY OF CHICAGO
Security, Usability, & Privacy Education & Research
RUHR UNIVERSITÄT BOCHUM RUB

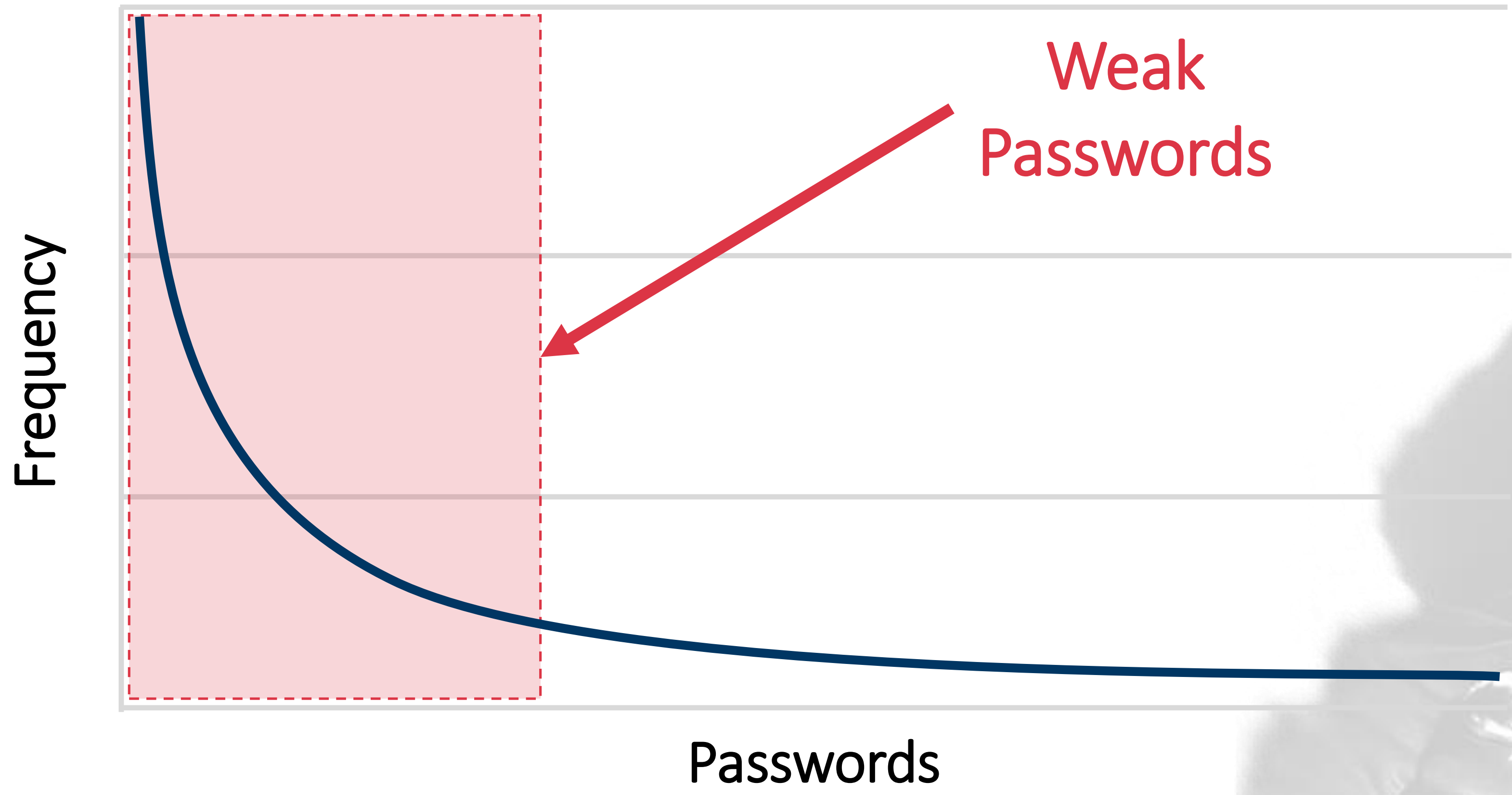
Reasoning Analytically About Password-Cracking Software

Enze "Alex" Liu, Amanda Nakanishi, Maximilian Golla, David Cash, and Blase Ur

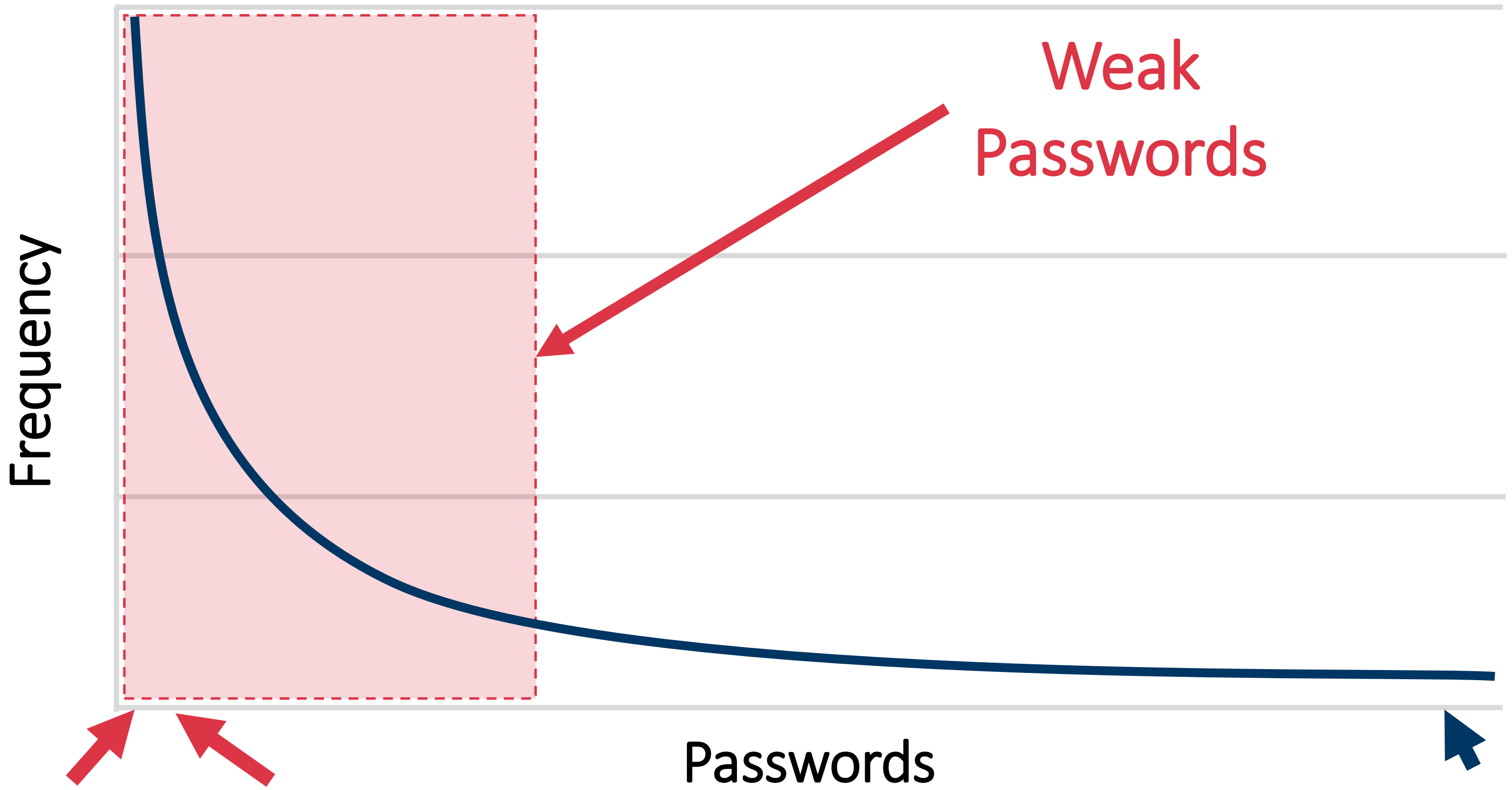
November 26, 2019 | PasswordsCon | Stockholm, Sweden

People Choose Weak Passwords

What Makes a Password “Weak”?



What Makes a Password “Weak”?



Guess #1
`123456`

Guess #387
`qwerty1`

Guess # 1.3 x 10^9
`nx71!iceCream`

Guess Number = Approximate Strength

Example:

`Johnny14!`

Guess #:

390,000

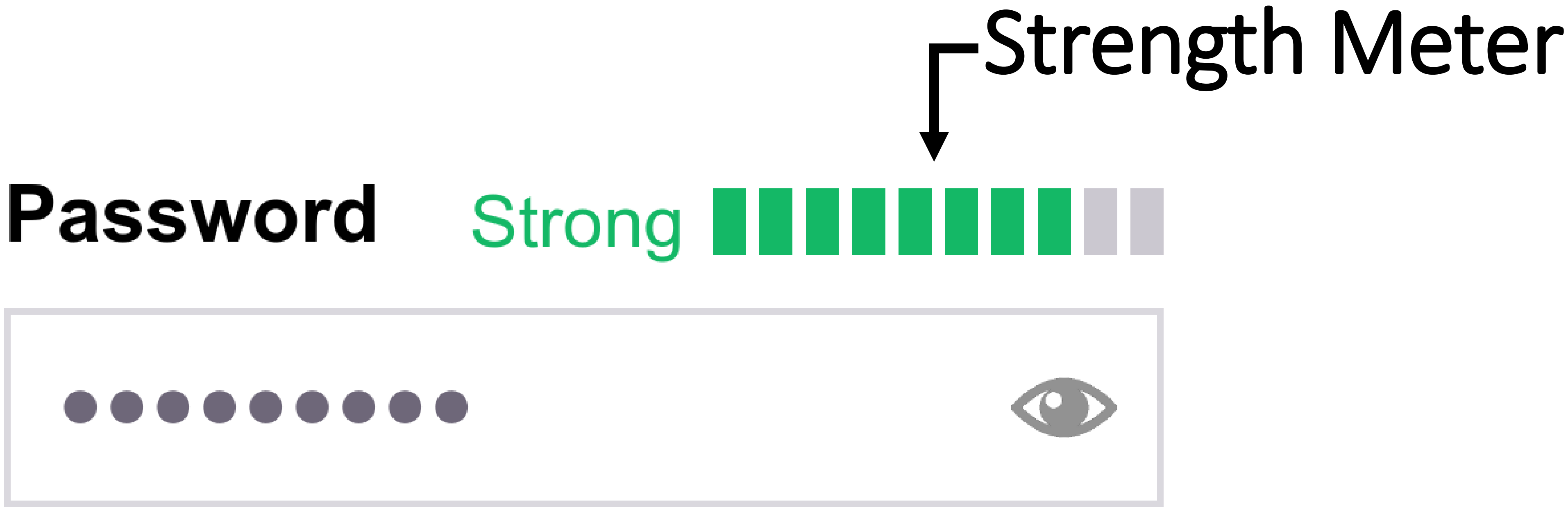
Guess Number

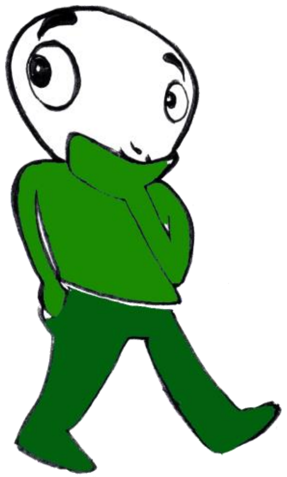
/gɛs ˈnʌmbə/

noun

1. The number of guesses required to guess a password.

Application 1: Strength Meters





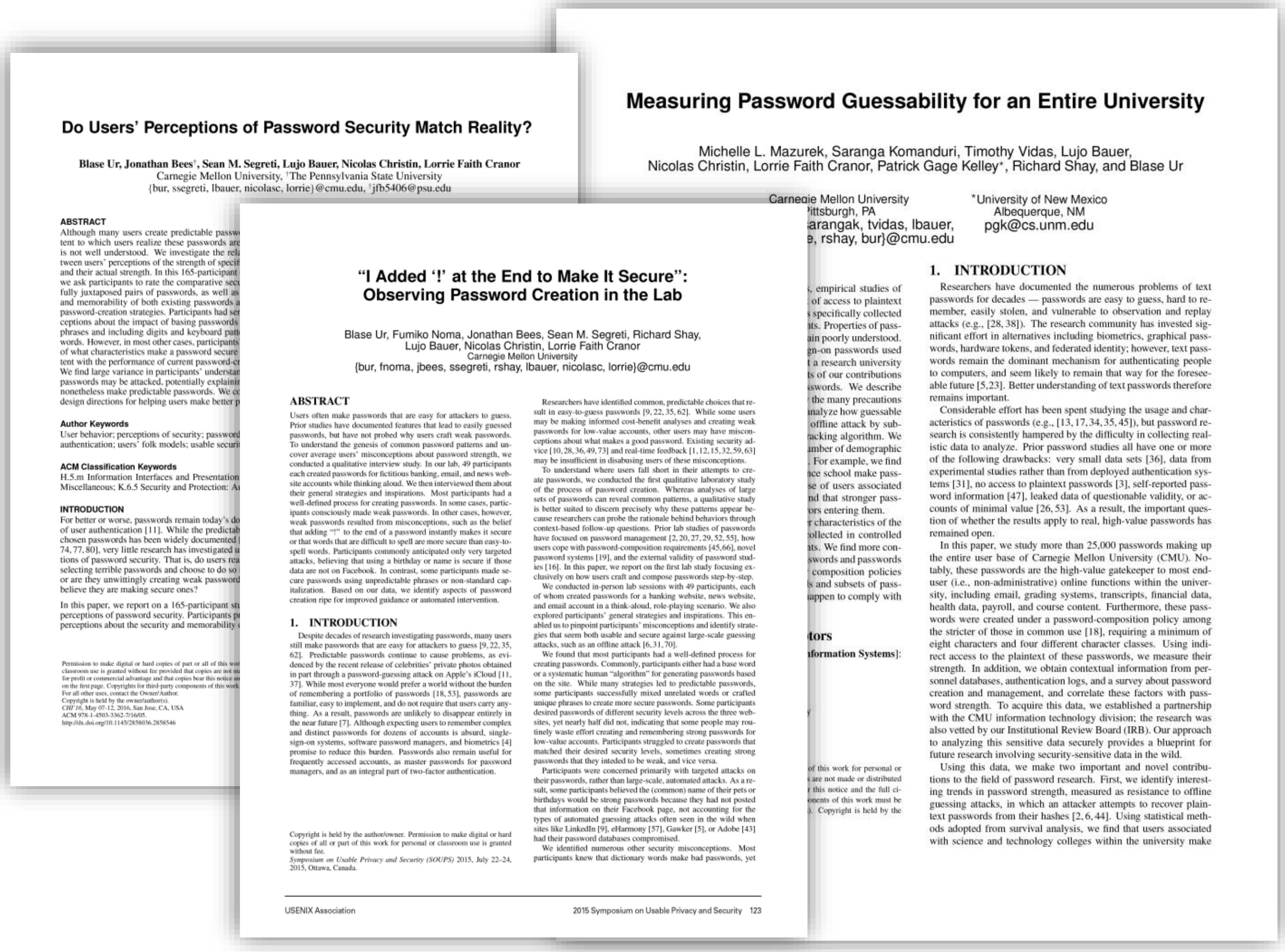
Application 2: Proactive Checking

Password123!

Application 2: Proactive Checking

Per Thorsheim, founder of PasswordsCon

Application 3: Academic Research



Guess # Depends on Model

We don't think in "cracks," we think in guess numbers!

Hashcat / LinkedIn	!=	Dropbox / John the Ripper	!=	Yahoo! / PCFG	!=	RNN / last.fm
Guess #: **1,928,730,033**		Guess #: **8,346,290,721**		Guess #: **inf.**		Guess #: **390,000**

Password Cracking:

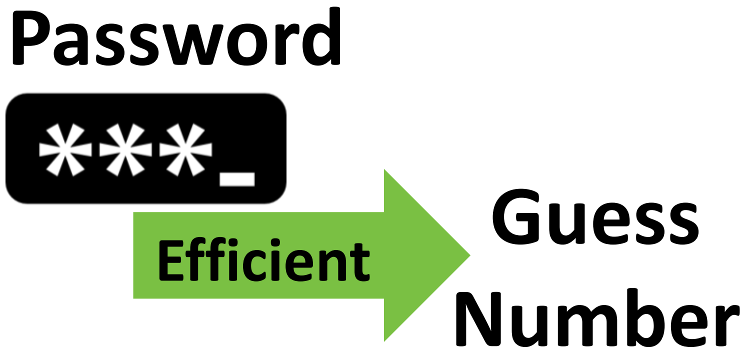
Johnny14! - **cracked**

Guess Number:

Depends on "trained" model

Goals For Guess Numbers

1. Compute guess numbers efficiently
2. Configure guessing method systematically
3. Approximate real-world attack



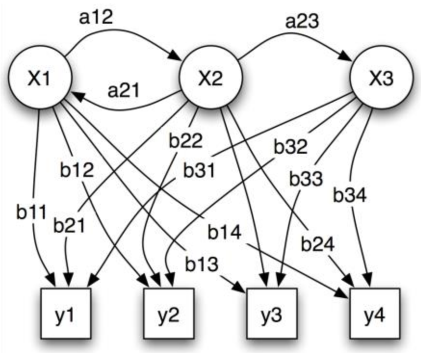
Real-World

Outline

1. State of the art
2. How software password-cracking tools work
3. Our efficient techniques for guess numbers
4. Our techniques for systematic configuration

Password-Cracking Methods

Probabilistic Models



Software Tools

Probabilistic Models

Markov Models [Narayanan and Shmatikov, CCS 2005]

Probabilistic Context-Free Grammars [Weir et al., S&P 2009]

Neural Networks [Melicher et al., USENIX Security 2016]

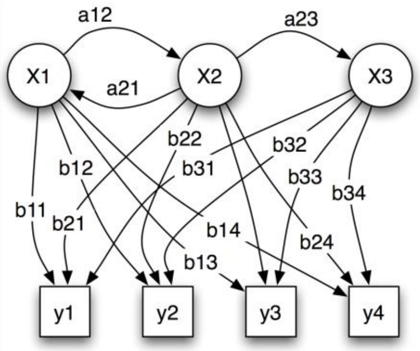
Guess # ✓

Configuration ✓

Real ☹

Password-Cracking Methods

Probabilistic Models



Software Tools

John the Ripper

Hashcat

Software Tools

John the Ripper

Hashcat

Guess Number by Enumeration

1. 123456
2. password

Does Not Scale !!!

5. p@ssw0rd
6. Johnny14!

Software Tools

John the Ripper

Hashcat

Guess #

Configuration

Real

Reasoning Analytically About Password-Cracking Software

[S&P 2019]

Enze Liu, Amanda Nakanishi, Maximilian Golla†, David Cash, Blase Ur
University of Chicago, † Ruhr University Bochum

Outline

1. State of the art
2. How software password-cracking tools work
3. Our efficient techniques for guess numbers
4. Our techniques for systematic configuration

Mangled Wordlist Attack

Wordlist

Super
Password
Chicago

Rulelist

1. Append "1"
2. Replace "a" → "4"
3. Lowercase all

Guesses

Super1
Password1
Chicago1
Super
P4ssword
Chic4go

Mangled Wordlist Attack

Wordlist

Super
Password
Chicago

Rulelist

1. Append “1”
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Guesses

Super1
Password1
Chicago1
Super
P4ssword
Chic4go
super
password
chicago

Example Wordlists and Rulelists

Wordlist

Linkedin (≈ 60,000,000)

HIBP (≈ 500,000,000)

Rulelist

Korelogic (≈ 5,000)

Megatron (≈ 15,000)

Generated2 (≈ 65,000)

→ 10^9 – 10^{15+} guesses

\+ Professionals' private word/rule lists

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Is This Password in the Guesses?

Chic4go

Guesses

Super1
Password1
Chicago1
Super
P4ssword
Chic4go
super
password
chicago

Is This Password in the Guesses?

Wordlist

Super
Password
Chicago

Rulelist

1. Append “1”
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Guesses

Super1
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super
password
chicago

Insight

We can work backwards!

Insight

“Rule Reversal”

Marechal (PasswordsCon 2012)

Kacherginsky (PasswordsCon 2013)

and many others

Inversion Process

Rulelist | Password

✖

1. Append "1"
2. Replace "a" → "4"
3. Lowercase all

← Chic4go

Inversion Process

Preimages | Rulelist | Password

Preimages

Chicago
Chic4go

Rulelist

1. Append "1"
2. Replace "a" → "4"
3. Lowercase all

Password

Chic4go

Count Guesses

Wordlist

Super
Password
Chicago

Rulelist

1. Append "1"
2. Replace "a" → "4"
3. Lowercase all

Guesses

Super1
Password1
Chicago1
Super
P4ssword
Chic4go
super
password
chicago

Count Guesses

Wordlist

Sup
Pas
Chic

3

Rulelist

1. Append “1”
2. Replace “a” → “4”
3. Lowercase all

Guesses

Supe
Pass
Chica

3

Super
P4ssword
Chic4go
super
password
chicago

Count Guesses

Wordlist	Rulelist	Guesses
Super Password Chicago	1. Append “1” 2. Replace “a” → “4” 3. Lowercase all	Super1 Password1 Chicago1 Super P4ssword Chic4go super password chicago

Approach

- **Invert** each password for each rule
  - Identify the first rule, if any, that guesses it
  - Sum guesses made by previous rules
- **Count guesses** per rule (JtR) / word (Hashcat)
  - Do this once per wordlist / rulelist combo

Why is this non-trivial?

Inverting Passwords

Name	Function	Description	Example Rule	Input Word	Output Word	Note
Nothing	:	do nothing	:	p@ss-W0rd	p@ssW0rd	
Lower-case	l	Lowercase all letters	l	p@ss-W0rd	p@ssw0rd	
Upper-case	u	Uppercase all letters	u	p@ss-W0rd	P@SSW0RD	
Capital-ize	c	Capitalize the first letter and lower the rest	c	p@ss-W0rd	P@ssw0rd	
Invert Capital-ize	C	Lowercase first found character, uppercase the rest	C	p@ss-W0rd	p@SSW0RD	
Toggle Case	t	Toggle the case of all characters in word.	t	p@ss-W0rd	P@SSw0RD	
Toggle @	TN	Toggle the case of characters at position N	T3	p@ss-W0rd	p@sSW0rd	*
Reverse	r	Reverse the entire word	r	p@ss-W0rd	dr0Wss@p	
Dupli-cate	d	Duplicate entire word	d	p@ss-W0rd	p@ssW0rdp@ssW0rd	
Dupli-cate N	pN	Append duplicated word N times	p2	p@ss-W0rd	p@ssW0rdp@ssW0rdp@ssW0rd	
Reflect	f	Duplicate word reversed	f	p@ss-W0rd	p@ssW0rd-dr0Wss@p	
Rotate Left	{	Rotates the word left.	{	p@ss-W0rd	@ssW0rdp	
Rotate Right	}	Rotates the word right	}	p@ss-W0rd	dp@ssW0r	
Append Charac-ter	$X	Append character X to end	$1	p@ss-W0rd	p@ssW0rd1	
Prepend Charac-ter	^X	Prepend character X to front	^1	p@ss-W0rd	1p@ssW0rd	
Truncate left	[	Deletes first character	[	p@ss-W0rd	@ssW0rd	
Trucate right	]	Deletes last character	]	p@ss-W0rd	p@assW0r	
Delete @ N	DN	Deletes character at position N	D3	p@ss-W0rd	p@sW0rd	*
Extract range	xNM	Extracts M characters, starting at position N	x04	p@ss-W0rd	p@ss	* #
Omit range	ONM	Deletes M characters, starting at position N	O12	p@ss-W0rd	psW0rd	*
Insert @ N	iNX	Inserts character X at position N	i4!	p@ss-W0rd	p@ss!W0rd	*
Over-write @ N	oNX	Overwrites character at position N with X	o3$	p@ss-W0rd	p@s$W0rd	*
Truncate @ N	'N	Truncate word at position N	'6	p@ss-W0rd	p@ssW0	*
Replace	sXY	Replace all instances of X with Y	ss$	p@ss-W0rd	p@$$W0rd	
Purge	@X	Purge all instances of X	@s	p@ss-W0rd	p@W0rd	+

Name	Function	Description	Example Rule	Note
Reject less	<N	Reject plains if their length is greater than N	<G	*
Reject greater	>N	Reject plains if their length is less or equal to N	>8	*
Reject equal	_N	Reject plains of length not equal to N	_7	*
Reject contain	!X	Reject plains which contain char X	!z	
Reject not contain	/X	Reject plains which do not contain char X	/e	
Reject equal first	(X	Reject plains which do not start with X	(h	
Reject equal last	)X	Reject plains which do not end with X	)t	
Reject equal at	=NX	Reject plains which do not have char X at position N	=1a	*
Reject contains	%NX	Reject plains which contain char X less than N times	%2a	*
Reject contains	Q	Reject plains where the memory saved matches current word	rMrQ	e.g. for palindrome

Name	Function	Description	Example Rule	Input Word	Output Word	Note
Swap front	k	Swaps first two characters	k	p@ssW0rd	@pssW0rd	
Swap back	K	Swaps last two characters	K	p@ssW0rd	p@ssW0dr	
Swap @ N	*NM	Swaps character at position N with character at position M	*34	p@ssW0rd	p@sWs0rd	*
Bitwise shift left	LN	Bitwise shift left character @ N	L2	p@ssW0rd	p@æsW0rd	*
Bitwise shift right	RN	Bitwise shift right character @ N	R2	p@ssW0rd	p@9sW0rd	*
Ascii increment	+N	Increment character @ N by 1 ascii value	+2	p@ssW0rd	p@tsW0rd	*
Ascii decrement	-N	Decrement character @ N by 1 ascii value	-1	p@ssW0rd	p?ssW0rd	*
Replace N + 1	.N	Replaces character @ N with value at @ N plus 1	.1	p@ssW0rd	psssW0rd	*
Replace N - 1	,N	Replaces character @ N with value at @ N minus 1	,1	p@ssW0rd	ppssW0rd	*
Duplicate block front	yN	Duplicates first N characters	y2	p@ssW0rd	p@p@ss-W0rd	*
Duplicate block back	YN	Duplicates last N characters	Y2	p@ssW0rd	p@ssW0r-drd	*
Title	E	Lower case the whole line, then upper case the first letter and every letter after a space	E	p@ssW0rd w0rld	P@ssw0rd W0rld	+
Title w/separator	eX	Lower case the whole line, then upper case the first letter and every letter after a custom separator character	e-	p@ssW0rd-w0rld	P@ssw0rd-W0rld	+

Approach to Inverting Passwords

`Chic4go`

- Represent preimages as ≈ regex
- Few: [{C} {h} {i} {c} {a,4} {g} {o}]
- Many: 4444 → [{a,4} {a,4} {a,4} {a,4}]
- ("Purge 1" reversed): [{1}* {C} {1}* {h} {1}* {i} {1}* {c} {1}* {a,4} {1}* {g} {1}* {o} {1}*]
  - Represent wordlist as trie

Counting Guesses For Each Rule

Wordlist		Rule		Guesses
Super Password Chicago	×	Reject if no "a"; Replace a→ 4	=	2
Super Password Chicago	×	Replace e→ a Reject if no "a"; Replace a→ 4	=	3

Advantages and Disadvantages

- Method is preferable:
  - Few target passwords
  - Need guess number quickly
- Not preferable:
  - Many target passwords

Fast Guess Number Estimation

LinkedIn + SpiderLabs $= 3.01 \times 10^{14}$ Guesses

	Enumeration	Our Approach
Size	~ 3 PB	~ 10 GB
Preprocessing	> 2 years	< 1 day
Mean Lookup	???	< 1 second

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Software Tools Depend On

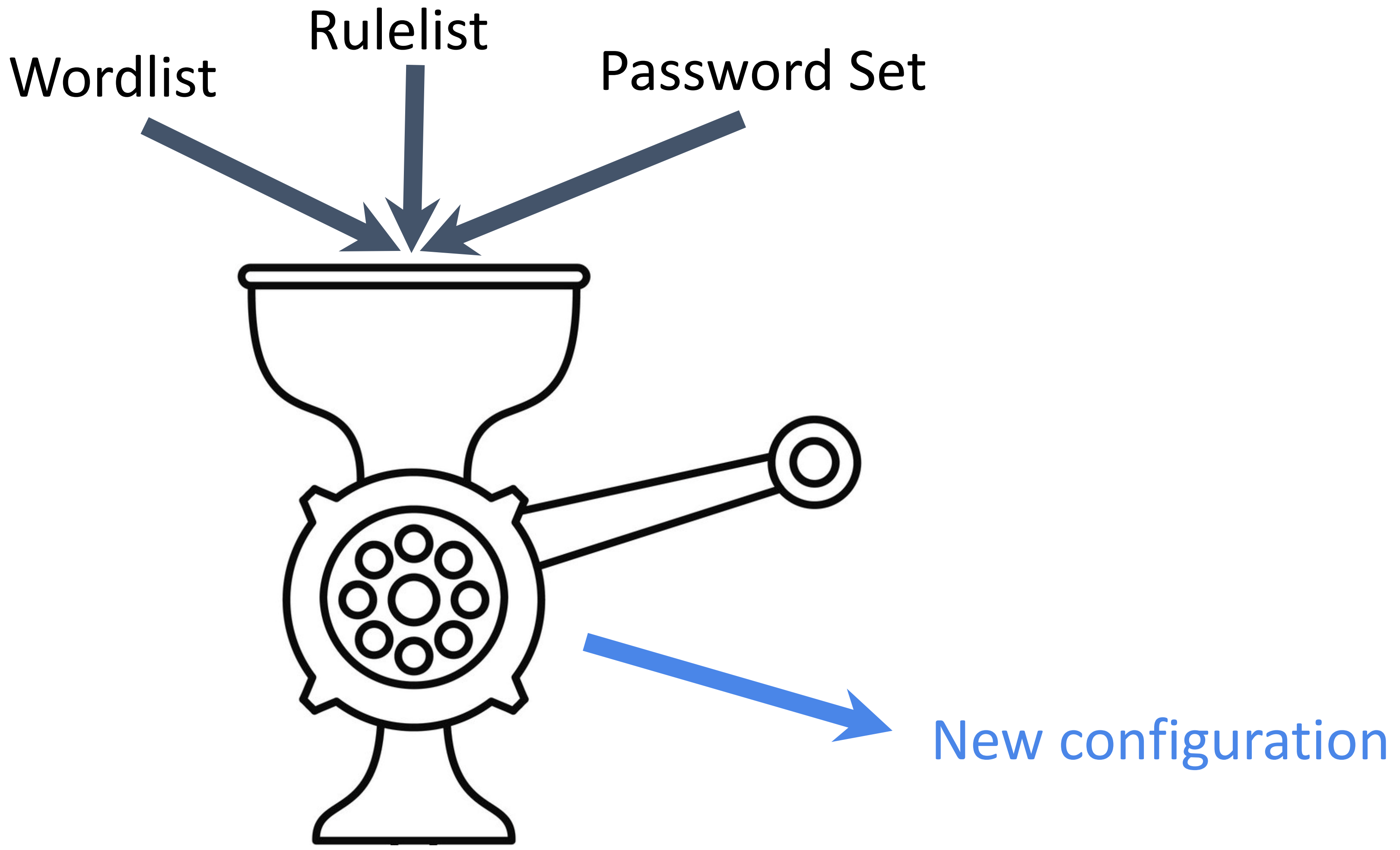
Contents of the wordlist

Order of words

Contents of the rulelist

Order of rules

Insight: Data-Driven Configuration



Data-Driven Configuration

Contents of the wordlist

Order of words

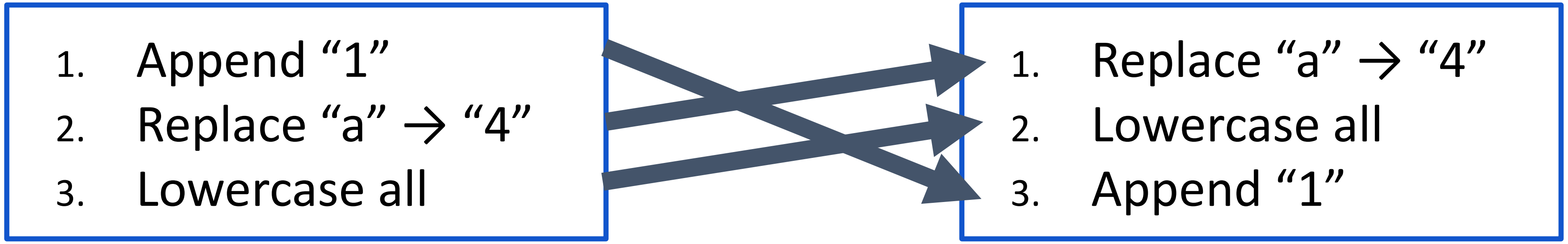
Contents of the rulelist

Order of rules

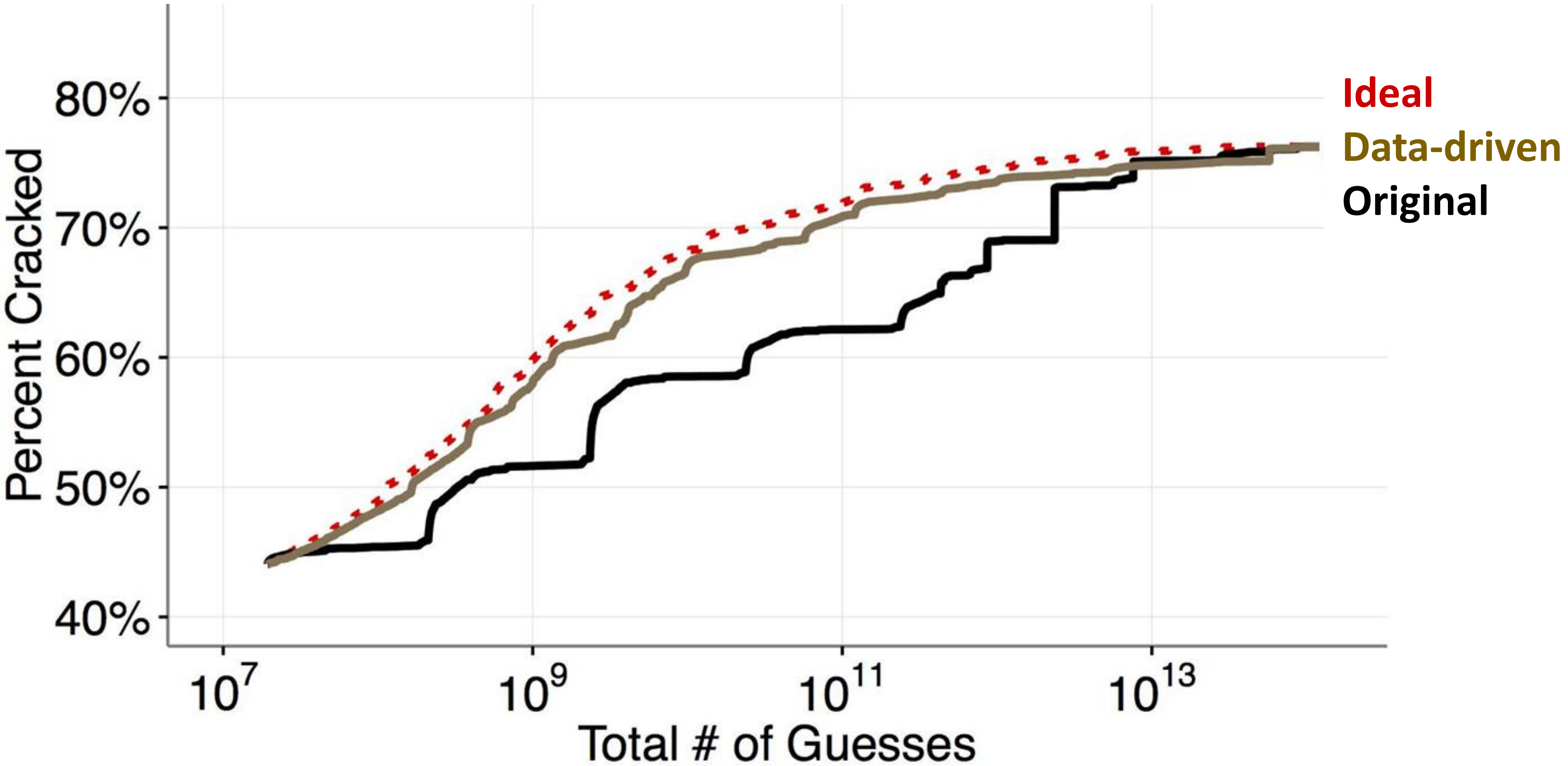
Rule Ordering

Should the rules be in a different order?

Key idea: Order by # cracks per guess



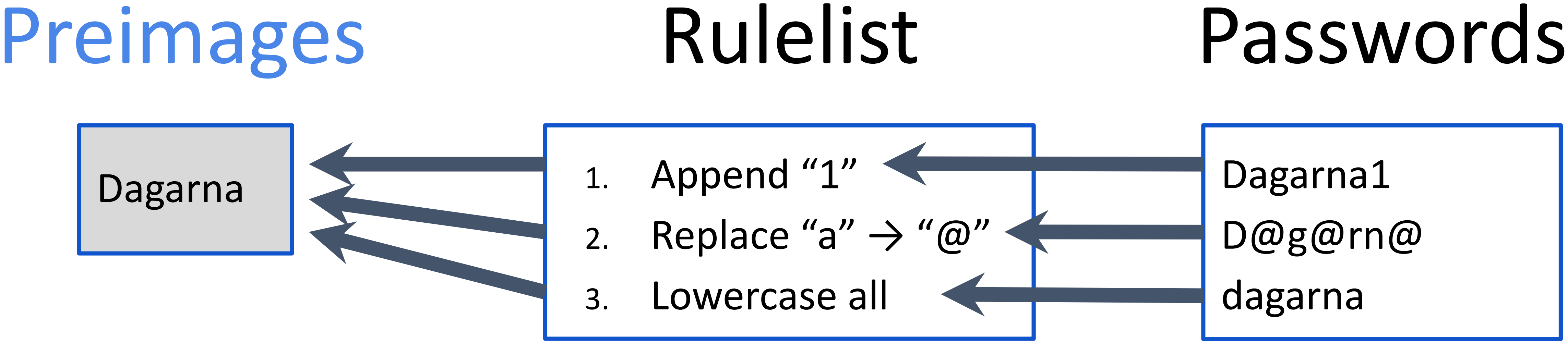
Rule Ordering Results



Word Completeness

Should other words be in the wordlist?

Key idea: Add frequent preimage “misses”



Word Completeness (Sample Results)

Category	Examples
Set-specific	bfheros; ilovmyneopets””””

Word Completeness (Sample Results)

Category	Examples
Set-specific	bfheros; ilovmyneopets””””
Meaningful	MaSterBrain; la la la
Short strings	a2; a23; 7a; b2; q2

Takeaway

https://github.com/UChicagoSUPERgroup

Guess Number | Configuration

Analytical Tools

Reasoning Analytically About Password-Cracking Software

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