# Introduction to Password Cracking & Research on Passwords


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# Introductions

- Your name
- Your position and affiliation (e.g., Ph.D. student at Example University)
- What you'd like to learn in today's tutorial
- Any prior experience (if any) you have researching passwords
- The password for your email account

# Outline

1) 8:30am – 8:40am Intros

2) 8:40am – 8:50am Relevance of passwords

3) 8:50am – 9:05am Password security / threats

4) 9:05am – 9:35am Robust, reliable experiments on passwords

5) 9:35am – 10:00am What we know about passwords

*10:00am – 10:30am Break*

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# Why are we still talking about passwords?

# Advantages of Passwords

- Familiar to people
- You can have many different ones
- Difficult to coerce
  - (Disputed) protections from 5th Amendment
- Nothing to carry
- Easy to revoke / replace

Joseph Bonneau, Cormac Herley, Paul C. van Oorschot, Frank Stajano. The quest to replace passwords: A framework for comparative evaluation of web authentication schemes. In *Proc. IEEE S&P*, 2012.

# More Advantages of Passwords

- Accessibility
- Easy to deploy
- Low cost
- No proprietary aspects / patents
- Doesn't require a trusted third party
- Not linked to an individual

Joseph Bonneau, Cormac Herley, Paul C. van Oorschot, Frank Stajano. The quest to replace passwords: A framework for comparative evaluation of web authentication schemes. In *Proc. IEEE S&P*, 2012.

# What about Biometrics?

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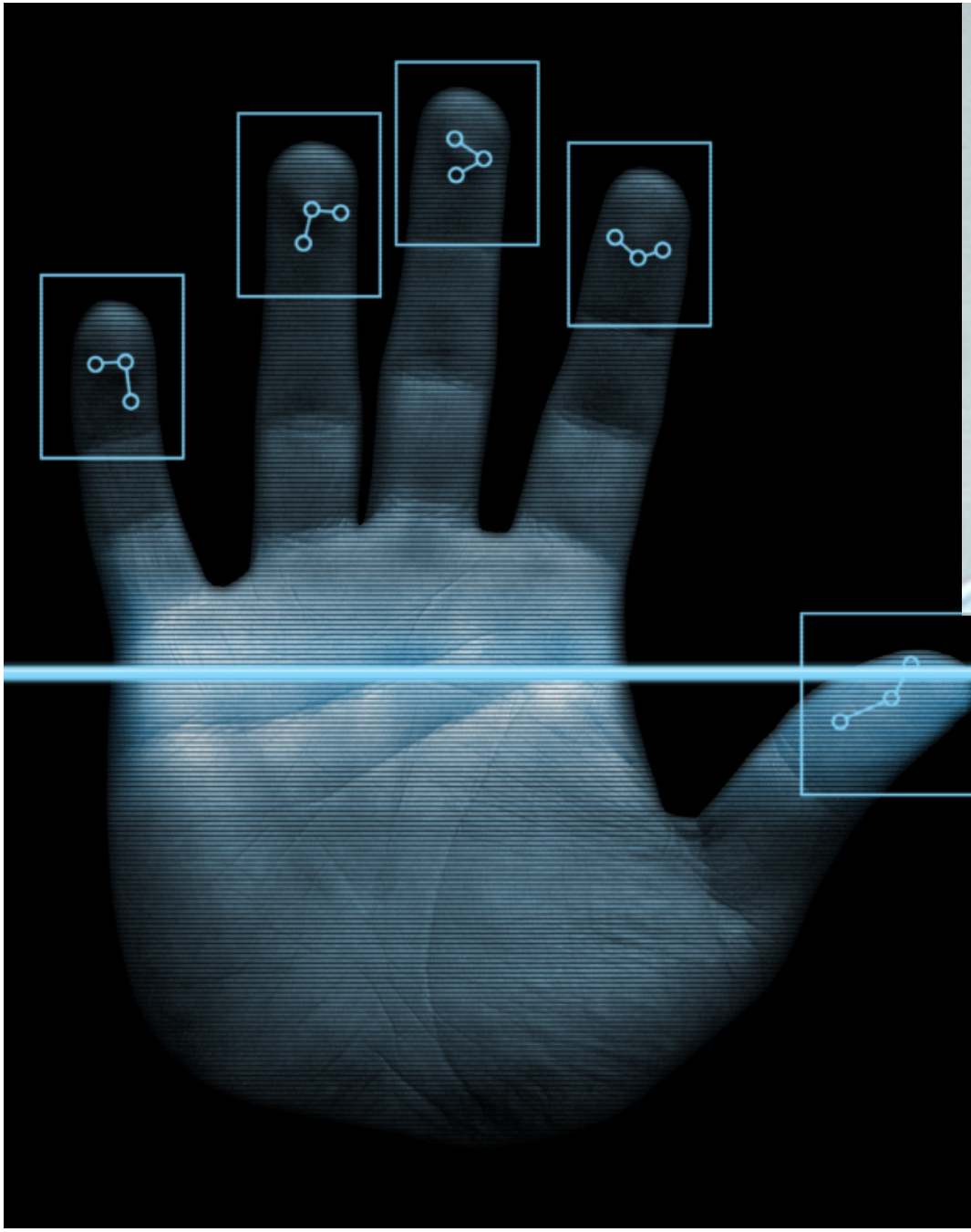

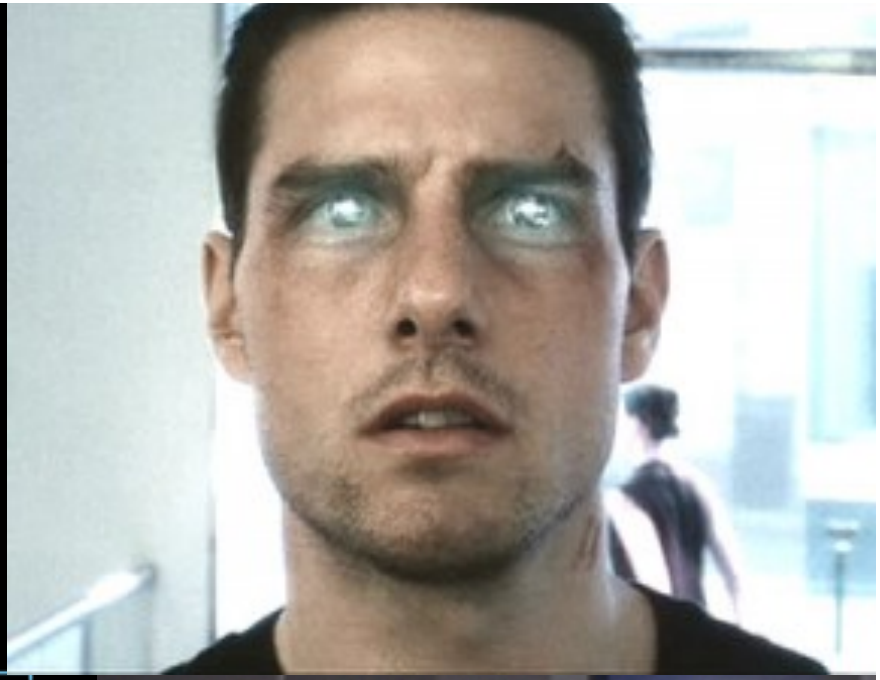

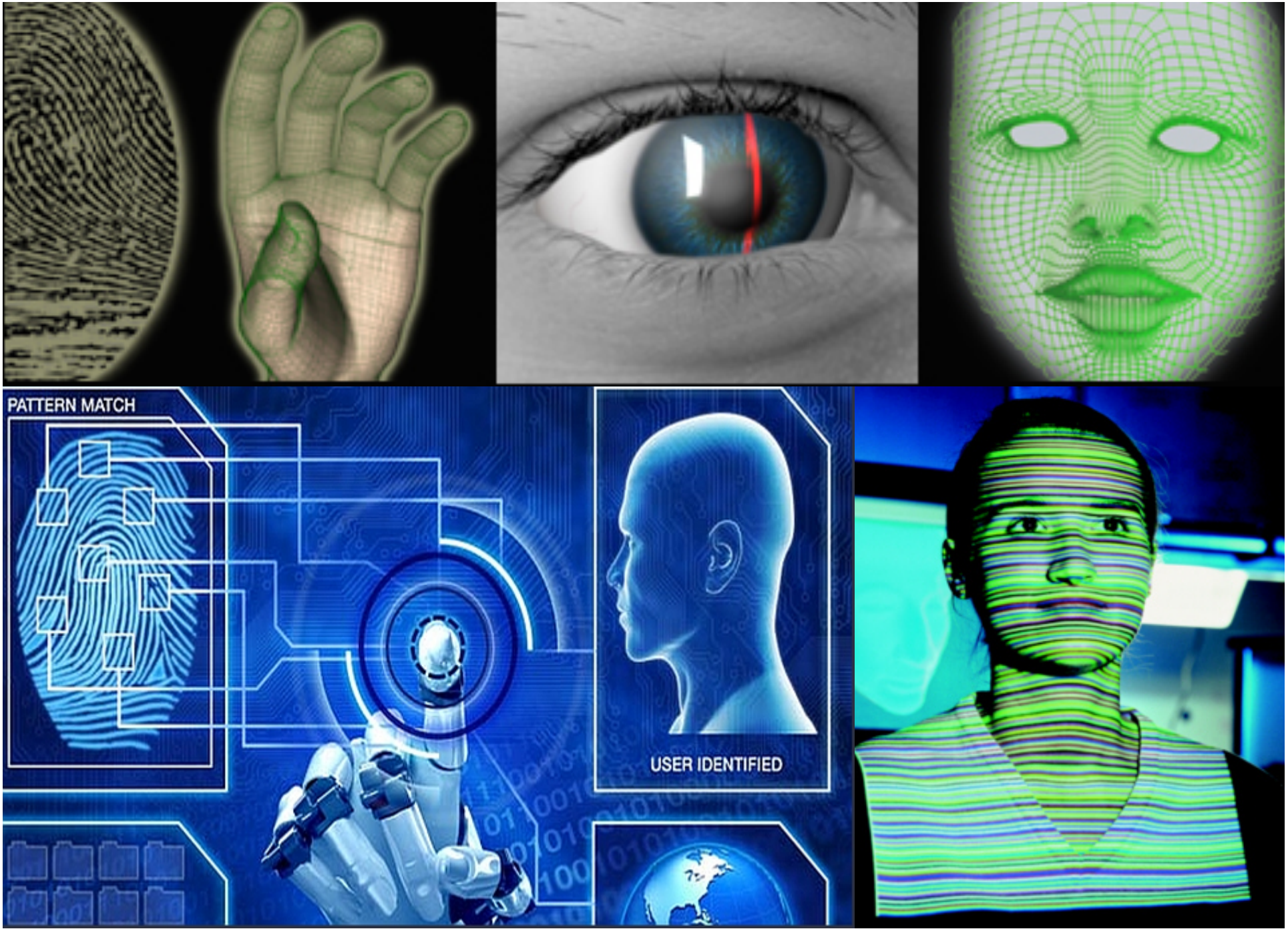


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SECTIONS HOME SEARCH

The New York Times

DealB%k WITH FOUNDER ANDREW ROSS SORKIN

# *Goodbye, Password. Banks Opt to Scan Fingers and Faces Instead.*

By MICHAEL CORKERY JUNE 21, 2016

# Biometrics

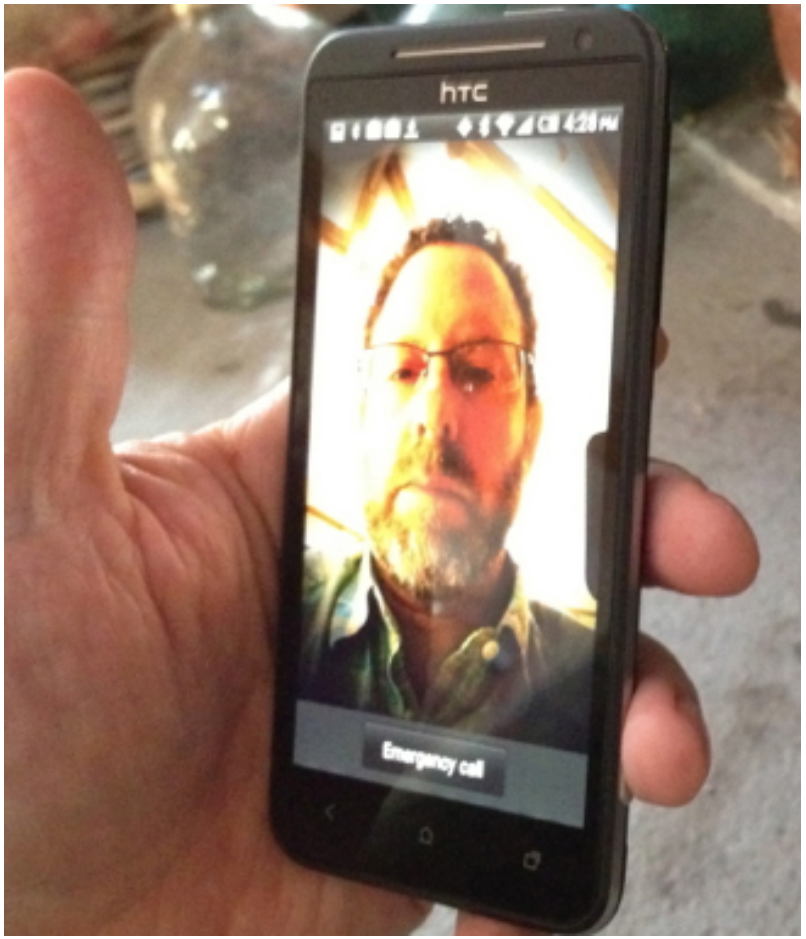
- Fingerprint
- Iris scans or retina scans
- Face recognition
- Finger/hand geometry
- Voice or speech recognition
- The way you type
- (Many others)

# Practical Challenges for Biometrics

- Immutable (can’t be changed)
- Potentially sensitive data
- High equipment costs
- Sensitive to changes in the environment
- Biometrics can change over time

# iPhone 5S Touch ID


# Android 4.0 Face Unlock






•Images fair use from androidcentral.com, creativebits.org, and businessinsider.com.

# Smartphone Biometrics

- Purpose is to reduce the number of times a user must enter his/her password
- Falls back to the password
- Face recognition can be tricked by a photo
- Fingerprint recognition can be tricked by a gummy mold
- Users find fingerprint unlock convenient, but do not particularly like face unlock

# Means of Authentication (1/2)

- Something you know
  - Password or PIN
- Something you have
  - Smart card
  - Private key (of a public-private key pair)
  - Phone (running particular software)
- Something you are
  - Biometrics (e.g., iris or fingerprint)

# Means of Authentication (2/2)

- Somewhere you are
  - Location-limited channels
- Someone you know (social authentication)
  - Someone vouches for you
  - You can identify people you should know
- Some system vouches for you
  - Single sign-on
  - PKI Certificate Authorities

# Disadvantages of Passwords

- Predictability
- Interference between multiple passwords
  - Limits of human memory
- Requiring a large portfolio of passwords
- Easy to deploy incorrectly / naively
  - System administrators
  - Users

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# Deploying Passwords

- Logging into an online or local account
  - /etc/shadow
  - Hashed passwords
- Encrypting a local file using a password
  - Password-Based Key Derivation Functions
  - Key used to encrypt data often stored in file

# Best Practices for Storing Passwords

- Hash function: one-way function
  - Designed for efficiency (e.g., MD5)
  - Password-specific hash functions (e.g., bcrypt, scrypt, PBKDF2, Argon2)
- hash("Blase") =

```
$2a
$04$iHdEgkI681VdDMc3f7edau9phRwOR
vhYjqWAIb7hb4B5uFJO1g4zi
```

# Best Practices for Storing Passwords

- Hash and salt passwords
- Salt: random string assigned per-user
  - Combine the password with the salt, then hash it
  - Salt stored alongside the hashed password
  - Prevents the use of rainbow tables

# Threats to Password Security

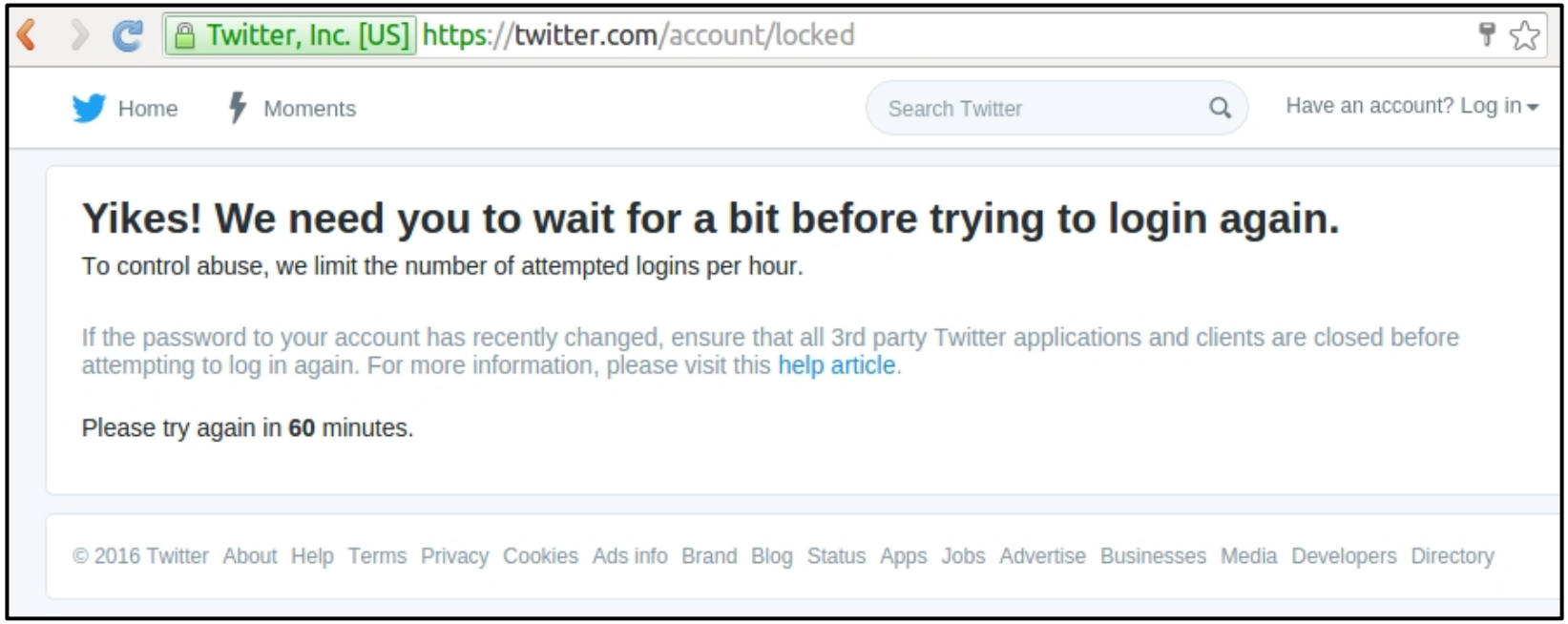
- Phishing attacks
- Shoulder surfing (observation)
- Poor implementation / deployment

# Threats to Password Security

- Online attack against live system

# Threats to Password Security

- Online attack against live system
  - Rate-limiting



# Threats to Password Security

- Online attack against live system
- Attack against password-protected file

# Threats to Password Security

- Online attack against live system
- Attack against password-protected file
- Offline attack against stolen database

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- Offline attack against stolen database

# Anatomy of an Offline Attack

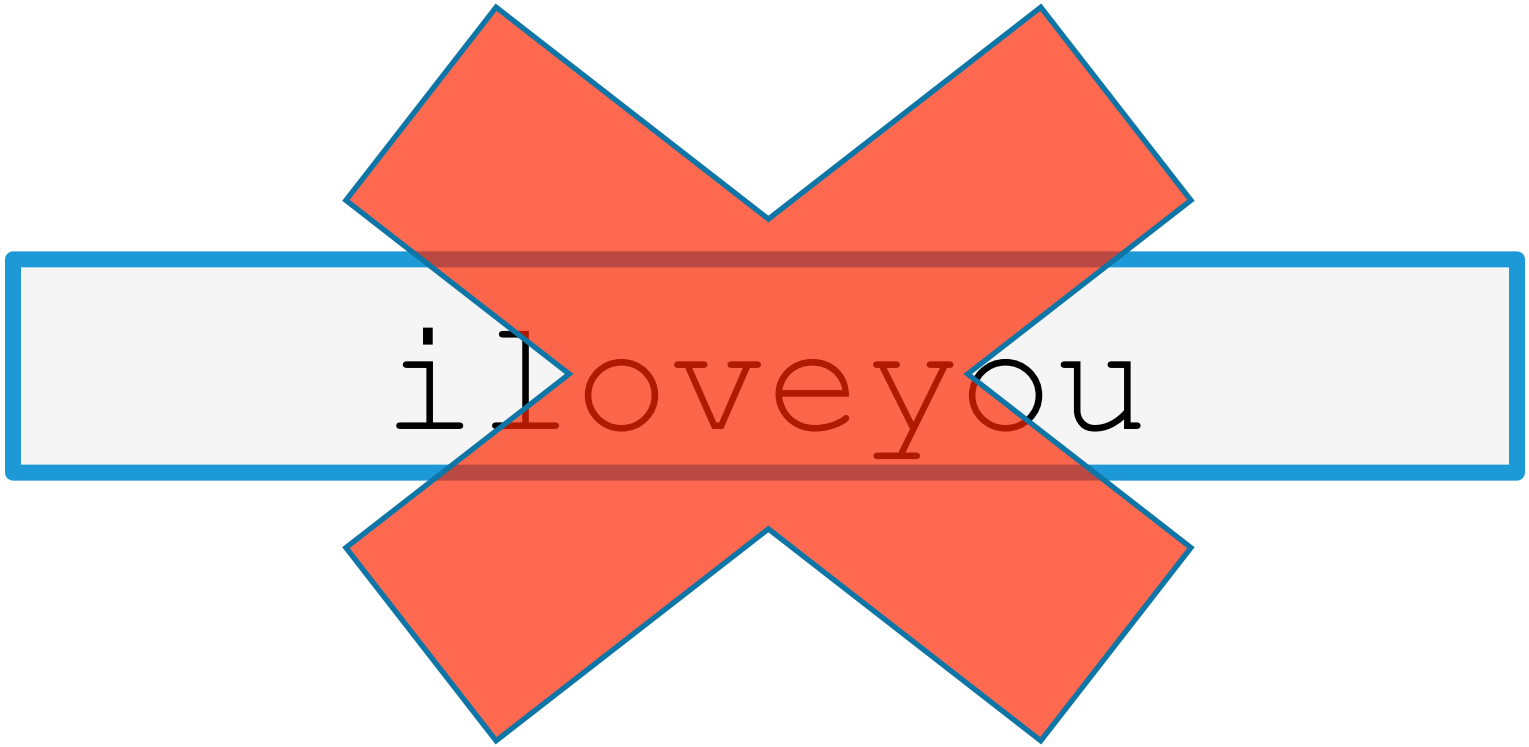
- Attacker compromises database
- Attacker makes and hashes guesses
- Finds match → try on other sites
  - Password reuse is a key problem


# How strong is a particular password?

# Why Measure Password Strength?

- Eliminate bad passwords
  - Organizational password audits
- Help users make better passwords
  - Determine if interventions are effective
  - Provide users feedback

```
iloveyou
```


iloveyou

```
n(c$JZX!zKc^bIAX^N
```

j@mesb0nd007!

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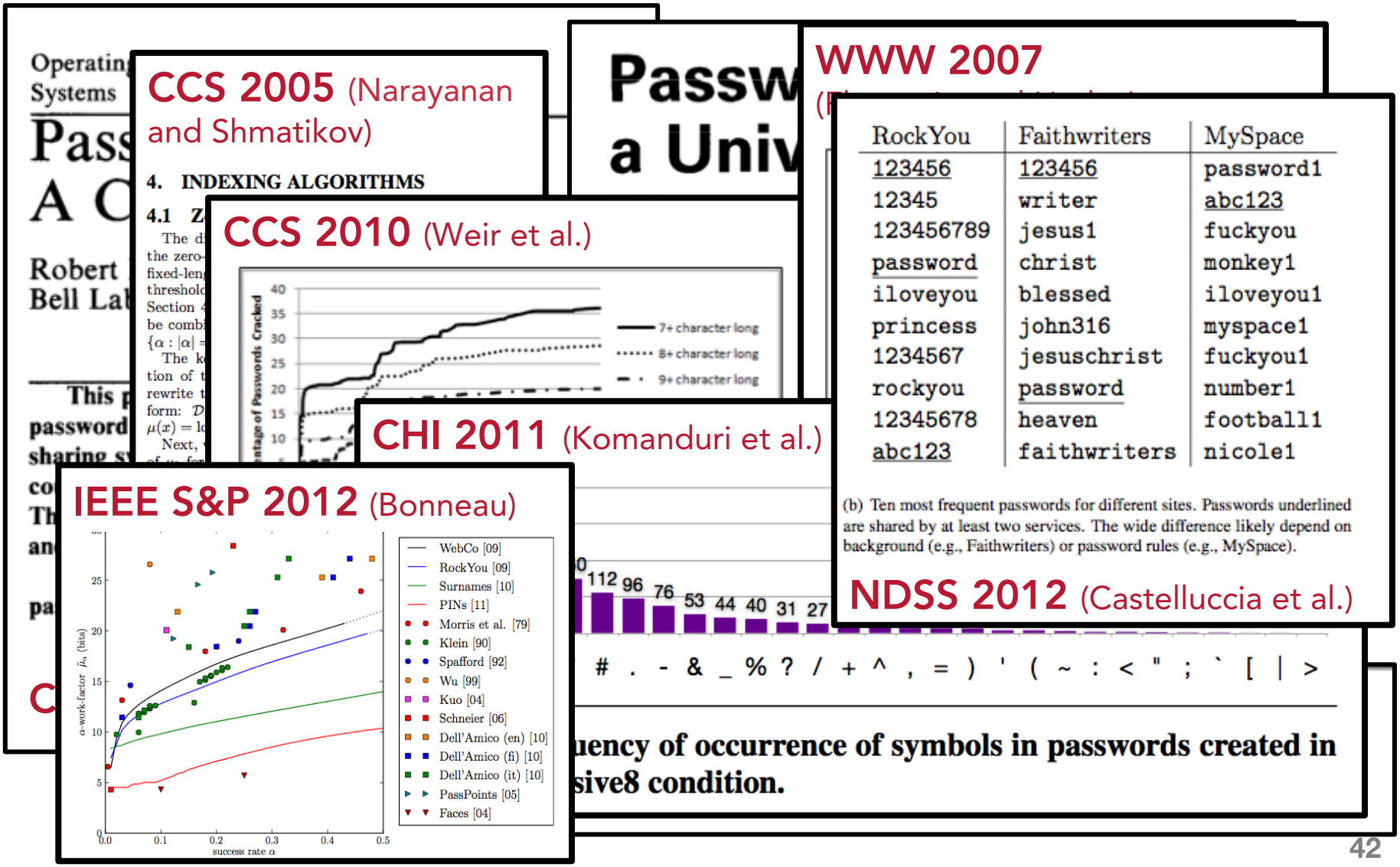
# Passwords research is everywhere



# … but is it reliable?

- How are strength, usability measured?
- How good is the data source?

- Recently, significant progress in both areas


http://adamwarrock.com/

# MEASURING PASSWORDS

# Strength is hard to measure

- Number of character classes?
- Shannon entropy?
- α-guesswork?
- John the Ripper?

**How do we know if a password (or a set of passwords) is secure?**

# Old metric: Entropy

- Calculated based on input symbol size (many)
  - Doesn't account for human patterns
- NIST back-of-envelope estimate (NIST 2006)
  - Vague, not empirical
- Estimated Shannon entropy (Shay 2010)
  - Requires big sample sizes, underestimates
- Average, doesn't tell you about your weak links

# Better 1: Statistical guesswork

- Alpha guesswork: Expected #/guesses per account to guess fraction alpha
- Assumes knowledge of underlying distribution
  - Sample = systematic underestimate
  - Requires enormous sample sizes
- Extrapolate via Poisson distribution

Joseph Bonneau. The science of guessing: Analyzing an anonymized corpus of 70 million passwords. IEEE S&P 2012.

# Better 2: Parameterized guessability

- How many guesses to reach password?
  - Subject to guessing algorithm, training data
  - Calculate quickly via lookup algorithm
- Result: guess number or beyond cutoff

Example:

| Password | Guess number |
|---|---|
| 12345678 | 4 |
| Password178 | $1.4 \times 10^6$ |
| jn%fKXsl!8@Df | Beyond cutoff |

Patrick Gage Kelley et al. Guess again (and again and again): Measuring password strength by simulating password-cracking algorithms. IEEE S&P 2012.

# Guesswork vs. guessability

- Optimal attacker
- Depends only on data set
- Can use hashes
- Describe entire set in one stat
- Sample size: enormous

- Model real attacker
- Depends on algorithm, training
- Requires plaintext
- Per-password estimates
- Sample size: large

# Range of usability metrics

- Memorability
  - Realism? Time, frequency, interference
- Creation time, attempts
- Login time
- Storage
- Self-reported sentiment
- False rejects (where applicable)

# SOURCING QUALITY DATA

# Problems with password data

- Small data sets
- Experimental rather than field data
- Self-reported surveys
- Leaked data of questionable validity
- Minimal-value accounts
- No access to plaintext passwords
- No controlled conditions

**Are the results generalizable?**

# Lab vs. online vs. real

- Anonymized plaintext dump of thousands of university students' passwords
- Online and lab studies, (no) priming
  - Same pool of students as plaintext dump
- Manual analysis for similarity
- 583 online, 63 lab participants

Sascha Fahl et al. On The Ecological Validity of a Password Study. SOUPS 2013.

# Results: Validity

| % | Online | Lab | Priming | Non | Total |
|---|---|---|---|---|---|
| Highly valid | 46 | 49 | 47 | 44 | **46** |
| Somewhat valid | 23 | 32 | 24 | 24 | **24** |
| Invalid | 31 | 18 | 29 | 32 | **30** |

- Overall, experimental data can be useful
  - Self-reporting of realistic behavior can help
- No significant difference from priming
- Lab slightly but significantly better than online

# CMU password set

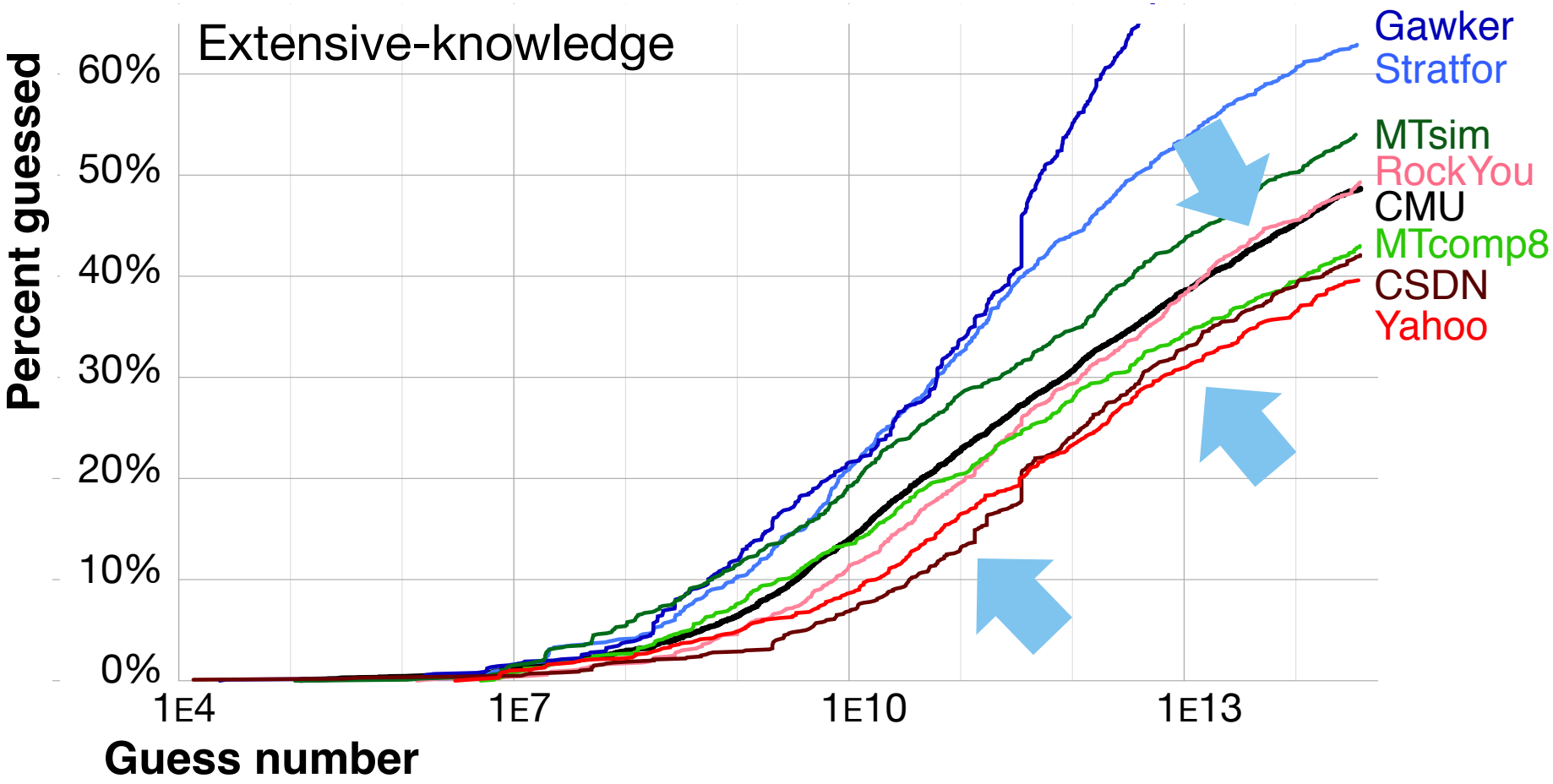
- 25,000 **real, high-value** CMU passwords
  - 8 char, 4 class, dictionary check
  - Email, financial, grades, taxes, health, etc.
- Use **conforming subset** for all leaked data
- Associated servers logs, personnel records
- Complex process for safe handling

Michelle Mazurek et al. Measuring password guessability for an entire university. CCS 2013.

# Real vs. online vs. leaked

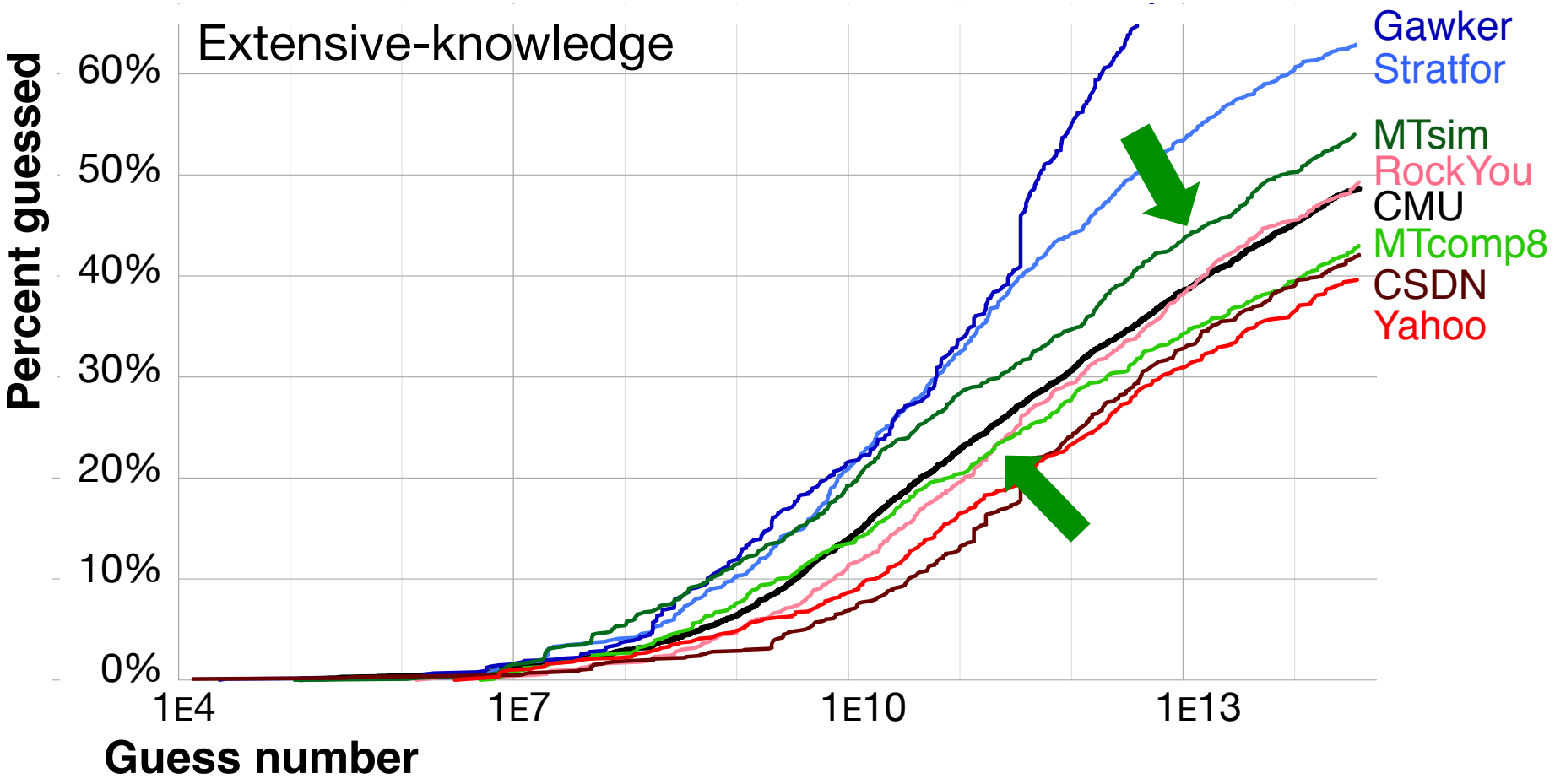
- Real CMU passwords
- Online studies
  - MTsim: Closest match to real CMU experience
  - MTcomp8: Similar password requirements
- Leaked: plaintext
  - RockYou, Yahoo!, CSDN
- Leaked: hashed and cracked
  - Gawker, StratFor

# Comparing sets – Guessability



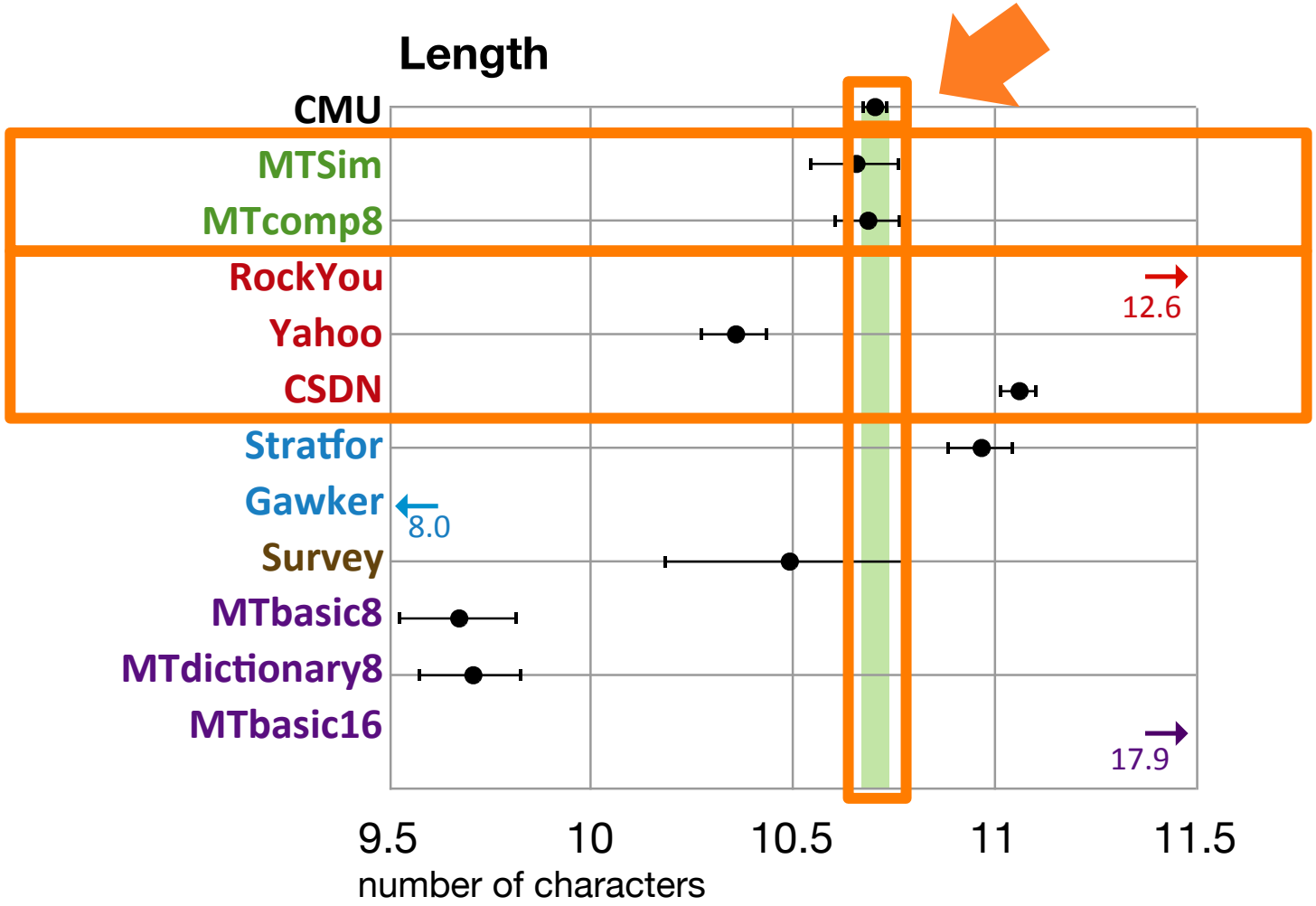

Leaked plaintext: RockYou close, others much tougher

# Comparing sets – Guessability




Online studies: Both close, MTcomp8 closer

# Comparing sets – Length




Overall: **Online studies closest** across metrics

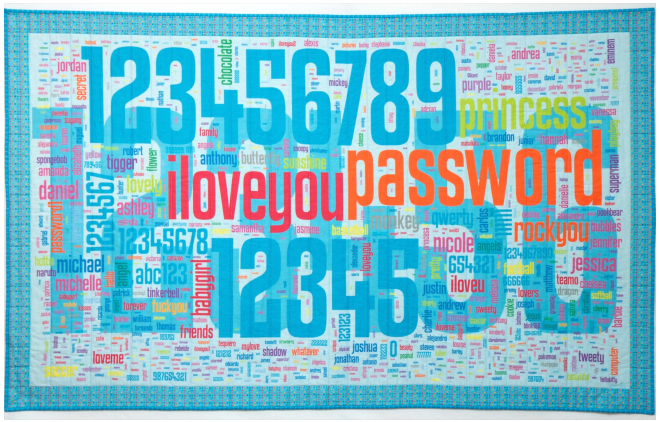
# Choosing a data source

- Lab: Higher quality data, deeper insights
  - Slow, small samples, expensive
- Online: Large samples, controlled experiments, fast
  - Specific samples, limited oversight
- Real: Most ecologically valid
  - Requires relationships, likely no experiments

# PASSWORD STUDY BEST PRACTICES

# Best practices: General

- Use a motivating scenario
- Ask whether behavior was realistic
- Use multiple usability metrics
- Require return for recall



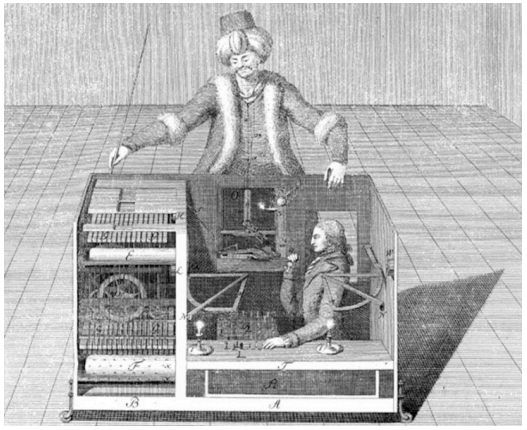
# Best practices: Lab studies

- Practice new schemes (graphical, gestures)
- Distraction tasks


usertesting.com

# Best practices: Online studies

- Ask about storage (and measure pasting)
- Offer a “show my password” option
- Control for language / geography
- Don’t ask for multiple passwords



siliconangle.com

# Reliable passwords research

- Carefully acquired experimental data is good
  - Real data is still better when possible
- Guesswork and guessability both reasonable
  - Depends on your specific context
  - Configure guessability effectively (or use PGS!)
- Good passwords research is expensive
  - Requires large samples
  - Can be computationally intensive

# Open questions

- What other metrics do we need?
  - Shoulder-surfing resistance
  - Resistance to online guessing
  - Resistance to targeted/insider attack
- How can we improve experimental validity?
  - In lab, online
  - Controlled experiments in the field?
  - Other security data beyond passwords

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# Summary of What We Already Know

- Purpose: highlight bodies of knowledge
  - Impossible to be comprehensive
  - Please speak up to fill in missing work
  - Discuss interesting / uninteresting directions
- Lots of interesting work out of scope
  - Graphical passwords (Robert Biddle et al. Graphical passwords: Learning from the first twelve years. CSUR 2012)
  - Android gestures
  - Phone locking / unlocking

# People Can Make Bad Passwords

- Robert Morris and Ken Thompson. Password security: A case history. CACM 22, 11 (1979).
- Moshe Zviran and William J. Haga. Password security: an empirical study. J. Mgt. Info. Sys., 15(4), 1999.
- Joseph Bonneau. The science of guessing: Analyzing an anonymized corpus of 70 million passwords. IEEE S&P 2012.
- Matteo Dell'Amico et al. Password strength: An empirical analysis. INFOCOM 2010.
- Many analyses of leaked/stolen passwords

# How People Make Passwords

- Markus Jakobsson and Mayank Dhiman. The Benefits of Understanding Passwords. HotSec 2012.
- Joseph Bonneau and Ekaterina Shutova. Linguistic properties of multi-word passphrases. USEC 2012.
- Rafael Veras et al. Visualizing semantics in passwords: The role of dates. VizSec 2012.
- Cynthia Kuo et al. Human selection of mnemonic phrase-based passwords. SOUPS 2006.
- Blase Ur et al. "I added '!' at the end to make it secure": Observing password creation in the lab. SOUPS 2015.

# There May be Cultural Dimensions

- Zhigong Li et al. A Large-Scale Empirical Analysis of Chinese Web Passwords. USENIX Security 2014.
- Joseph Bonneau and Rubin Xu. Of contraseñas, סיסמאות and 密码: Character encoding issues for web passwords. W2SP 2012.

# Password-Composition Policies

- Philip Inglesant and M. Angela Sasse. The true cost of unusable password policies: Password use in the wild. CHI 2010.
- Saranga Komanduri et al. Of passwords and people: Measuring the effect of password-composition policies. CHI 2011.
- Richard Shay et al. Can long passwords be secure and usable? CHI 2014.

# Mobile Passwords are Different

- Florian Schaub et al. Password Entry Usability and Shoulder Surfing Susceptibility on Different Smartphone Platforms. MUM 2012.
- Yulong Yang et al. Text entry method affects password security. LASER 2014.
- Emmanuel von Zezschwitz et al. Honey, I shrunk the keys: influences of mobile devices on password composition and authentication performance. NordiCHI 2014.
- William Melicher et al. Usability and security of text passwords on mobile devices. CHI 2016.

# Mental Models & Perceptions Matter

- Rick Wash. Folk models of home computer security. SOUPS 2010.
- L. Jean Camp. Mental models of privacy and security. IEEE T&S 2009.
- Adam J. Aviv and Dane Fichter. Understanding visual perceptions of usability and security of Android's graphical password pattern. ACSAC 2014.
- Blase Ur et al. Do Users' Perceptions of Password Security Match Reality? CHI 2016.
- Serge Egelman et al. Behavior Ever Follows Intention?: A Validation of the Security Behavior Intentions Scale (SeBIS). CHI 2016.
- Iulia Ion et al. "...no one can hack my mind": Comparing Expert and Non-Expert Security Practices. SOUPS 2015.

# Think About the Overall Ecosystem

- Anne Adams and M. Angela Sasse. Users are not the enemy. CACM, 42(12):40{46, 1999.
- Joseph Bonneau et al. The quest to replace passwords: A framework for comparative evaluation of Web authentication schemes. IEEE S&P 2012.
- Sonia Chiasson et al. Multiple password interference in text passwords and click-based graphical passwords. CCS 2009.
- Supriya Singh et al. Password sharing: Implications for security design based on social practice. CHI 2007.

# Password Management is Crucial

- Beate Grawemeyer and Hilary Johnson. Using and managing multiple passwords: A week to a view. Interacting with Computers, 23(3), June 2011.
- Shirley Gaw and Edward W. Felten. Password management strategies for online accounts. SOUPS 2006.
- Elizabeth Stobert and Robert Biddle. The password life cycle: User behaviour in managing passwords. SOUPS 2014.
- Elizabeth Stobert and Robert Biddle. Expert Password Management. Passwords 2016.

# Rethink Password Expiration

- Yinqian Zhang et al. The security of modern password expiration: An algorithmic framework and empirical analysis. CCS 2010.
- Sonia Chiasson and Paul C. van Oorschot. Quantifying the Security Advantage of Password Expiration Policies. DCC 2015.

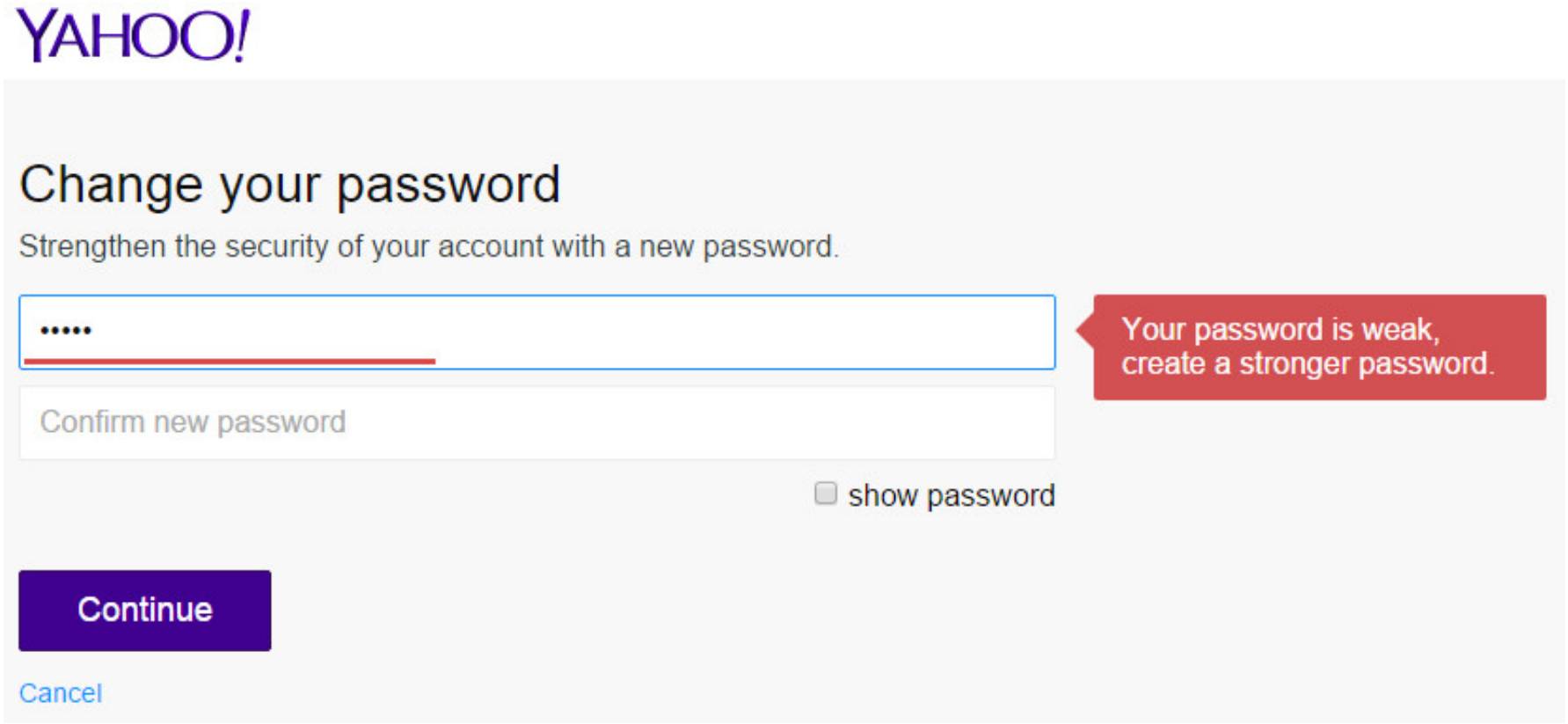
# People Reuse Passwords

- Dinei Florencio and Cormac Herley. A large-scale study of web password habits. WWW 2007.
- Anupam Das et al. The tangled web of password reuse. NDSS 2014.
- Rishab Nithyanand and Rob Johnson. The password allocation problem: Strategies for reusing passwords effectively. WPES 2013.
- Dinei Florencio et al. Password portfolios and the finite effort user: Sustainably managing large numbers of accounts. USENIX Security 2014.

# Proactive Checking & Meters Matter

- Matt Bishop and Daniel V. Klein. Improving system security via proactive password checking. Computers & Security, 14(3): 233-249, 1995.
- Francesco Bergadano et al. Proactive password checking with decision trees. CCS 1997.
- Stuart Schechter et al. Popularity is everything: A new approach to protecting passwords from statistical-guessing attacks. HotSec 2010.
- Blase Ur et al. How does your password measure up? The effect of strength meters on password creation. USENIX Security 2012.
- Serge Egelman et al. Does my password go up to eleven? The impact of password meters on password selection. CHI 2013.

# Current User Feedback Insufficient



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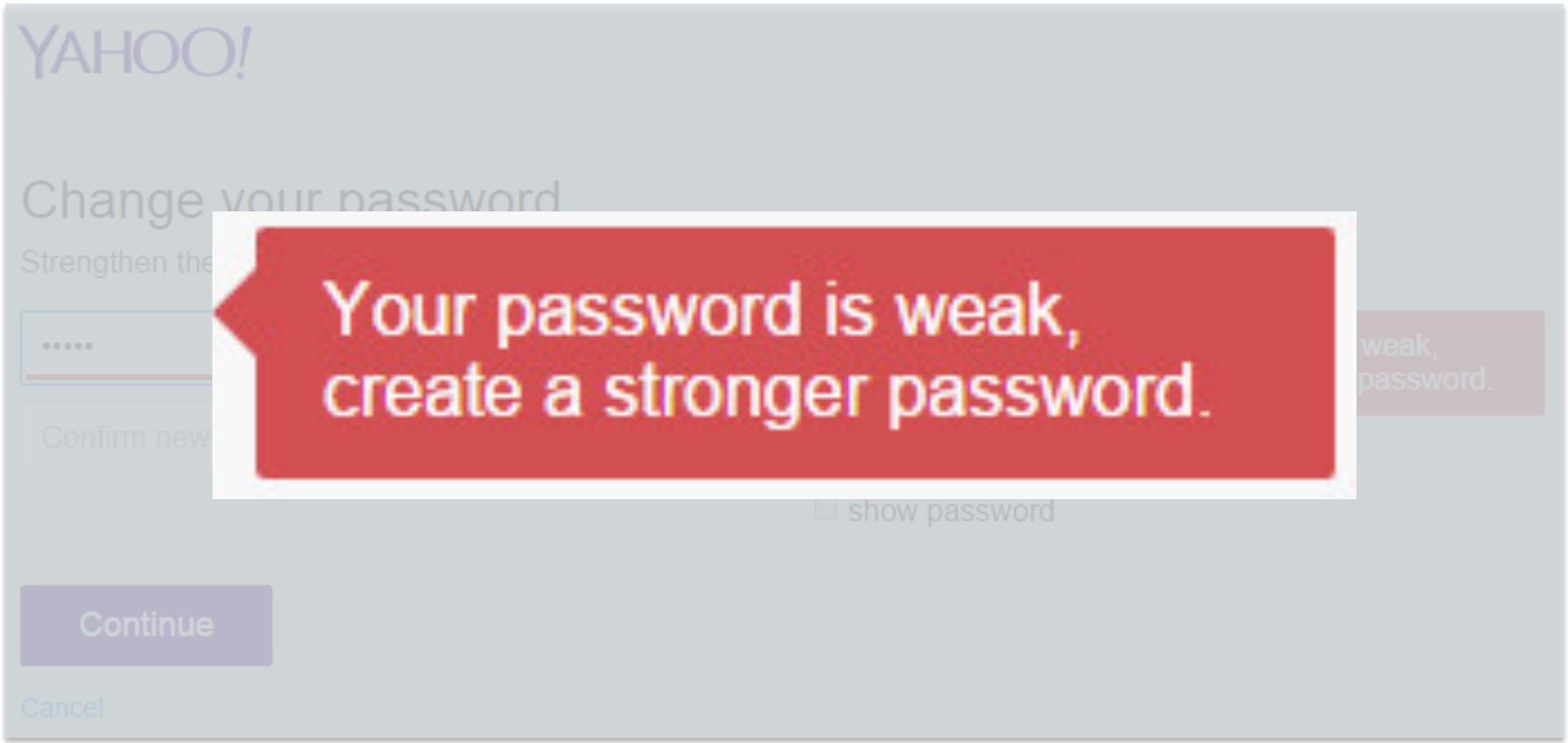
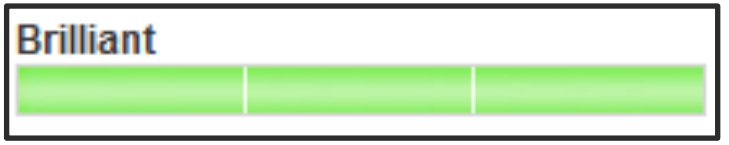


# Build Better Meters




- Xavier de Carne de Carnavalet and Mohammad Mannan. From very weak to very strong: Analyzing password-strength meters. NDSS 2014.
- Steven Acker et al. Password meters and generators on the web: From large-scale empirical study to getting it right. CODASPY 2015.
- Claude Castellucia et al. Adaptive password-strength meters from Markov models. NDSS 2012.
- Saranga Komanduri et al. Telepathwords: Preventing weak passwords by reading users' minds. USENIX Security 2014.
- Dan Wheeler. zxcvbn: Low-Budget Password Strength Estimation. USENIX Security 2016.

# One Can Nudge Users

- Alain Forget et al. Improving text passwords through persuasion. SOUPS 2008.
- Leah Zhang-Kennedy, S. Chiasson, and R. Biddle. Password advice shouldn't be boring: Visualizing password guessing attacks. eCRS, 2013.
- Andreas Sotirakopoulos et al. Motivating users to choose better passwords through peer pressure. SOUPS 2011 Poster.

# Take Into Account Human Memory

- Joseph Bonneau and Stuart Schechter. Towards reliable storage of 56-bit secrets in human memory. USENIX Security 2014.
- Manuel Blum and Santosh Vempala. Publishable Humanly Usable Secure Password Creation Schemas. HComp 2015.
- Jeremiah Blocki et al. Naturally Rehearsing Passwords. ASIACRYPT 2013.
- L. Jean Camp and Jacob Abbott. CPasswords: Leveraging Episodic Memory and Human-Centered Design for Better Authentication. HICSS 2016.
- Richard Shay et al. Correct horse battery staple: Exploring the usability of system-assigned passphrases. SOUPS 2012.
- Andreas Gutmann et al. ZETA - Zero-Trust Authentication: Relying on Innate Human Ability, not Technology. Euro S&P 2016.

# Store Passwords Smartly

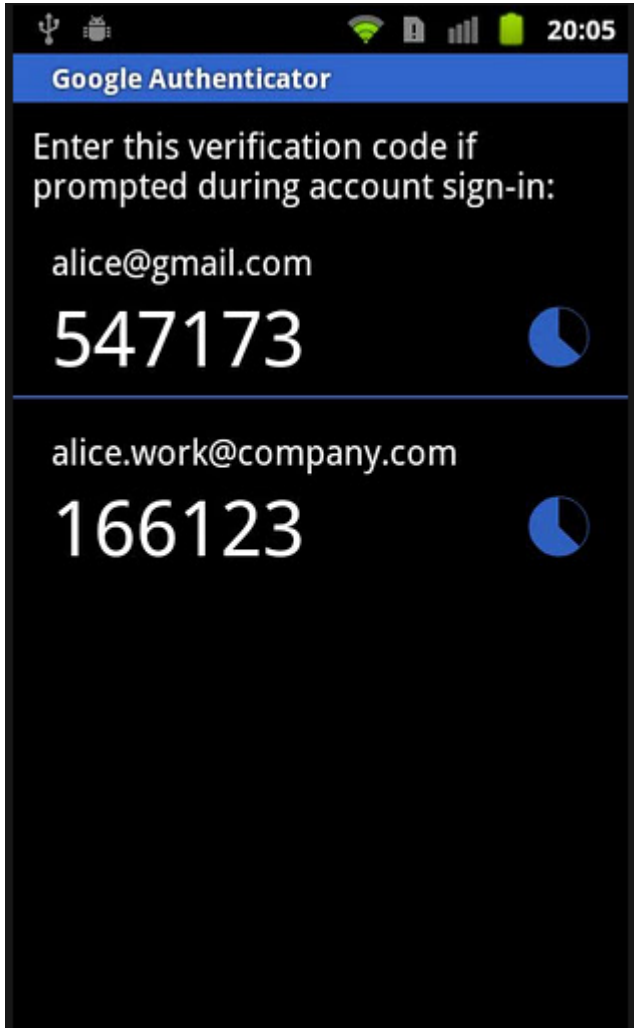
- Niels Provos and David Mazieres. A future-adaptable password scheme. In Proc. USENIX ATC 1999.
- Alex Biryukov et al. Fast and Tradeo -Resilient Memory-Hard Functions for Cryptocurrencies and Password Hashing. IACR Pre-print.
- Ari Juels and Ronald L. Rivest. Honeywords: Making password-cracking detectable. CCS, 2013.
- Rahul Chatterjee et al. Cracking-Resistant Password Vaults Using Natural Language Encoders. IEEE S&P 2015.
- Dinei Florencio et al. An administrator's guide to internet password research. LISA 2014.

# Single Sign-On


# Single Sign-On / Other Alternatives

- San-Tsai Sun et al. What Makes Users Refuse Web Single Sign-On? An Empirical Investigation of OpenID. SOUPS 2011.
- Lujo Bauer et al. A comparison of users' perceptions of and willingness to use Google, Facebook, and Google+ single-sign-on functionality. DIM 2013.
- Frank Stajano. Pico: No more passwords! SPW 2011.

# Two-Factor Auth



# Password Managers

- Trust all passwords to a single master password
  - Also trust software


1Password

# Improving Password Managers

- Daniel McCarney et al. Tapas: design, implementation, and usability evaluation of a password manager. ACSAC 2012.
- Zhiwei Li et al. The Emperor's New Password Manager: Security Analysis of Web-based Password Managers. USENIX Security 2014.
- Hristo Bojinov et al. Kamouflage: Loss-Resistant Password Management. ESORICS 2010.
- Ambarish Karole et al. A comparative usability evaluation of traditional password managers. ISC 2010.

# Outline

1) 8:30am – 8:40am Intros

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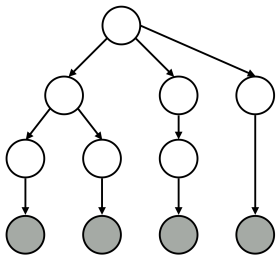
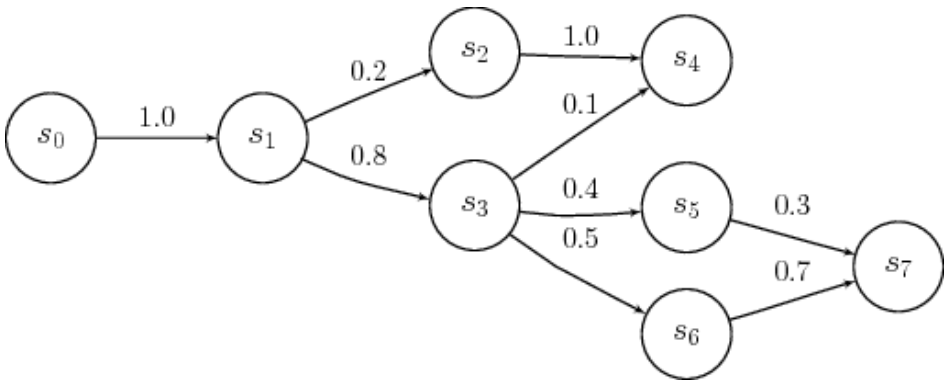
# Password-Guessing Attacks

- Guessing attacks are data-driven
  - Previously stolen passwords
  - Natural-language corpora
- Array of tools
  - Cracking software
  - Academic algorithms



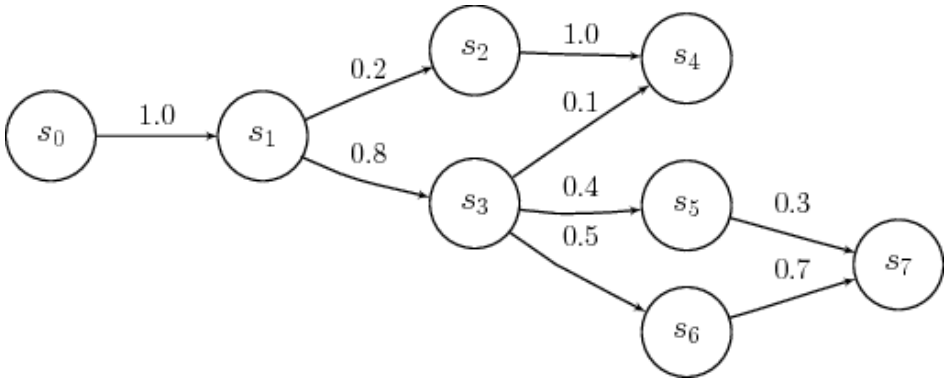

# Markov Models

- Predicts future characters from previous
- Approach requires weighted data:
  - Passwords
  - Dictionaries



# Markov Models

- Arvind Narayanan and Vitaly Shmatikov. Fast dictionary attacks on passwords using time-space tradeoff. CCS 2005.
- Jerry Ma et al. A study of probabilistic password models. IEEE S&P 2014.
- Markus Durmuth et al. OMEN: Faster password guessing using an ordered markov enumerator. ESSoS 2015.
- Matteo Dell'Amico and Maurizio Filippone. Monte Carlo strength evaluation: Fast and reliable password checking. CCS 2015.



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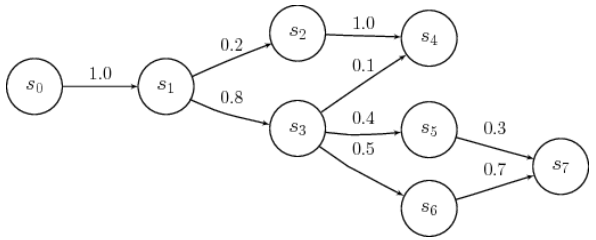
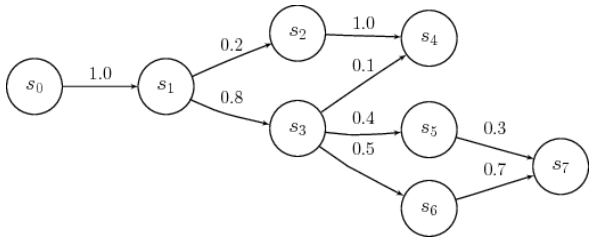



usenixsecurity

# Markov Models

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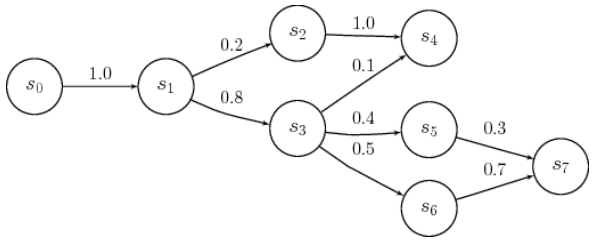


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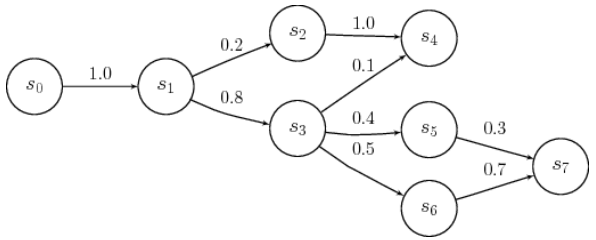


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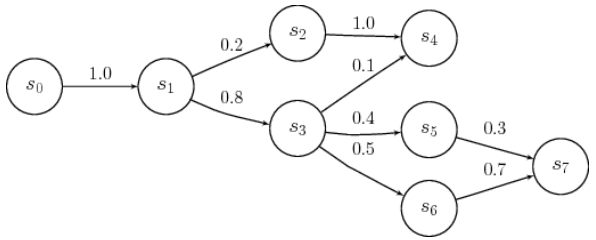
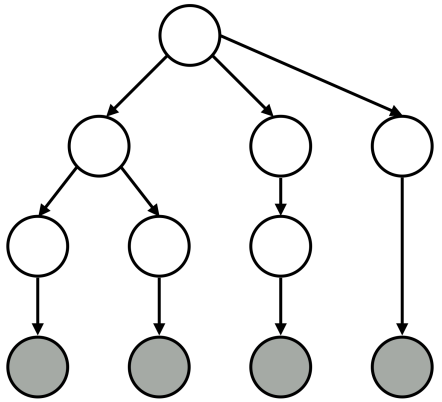



usenixsecurity

# Probabilistic Context-Free Grammars

- Generate password grammar
  - Structures
  - Terminals



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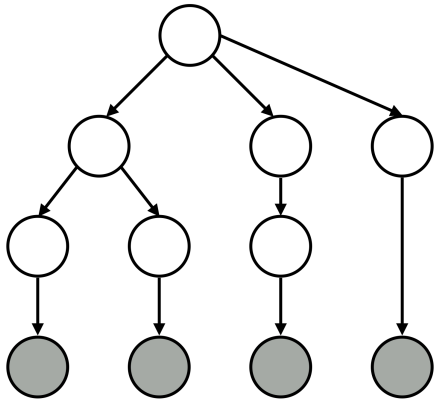
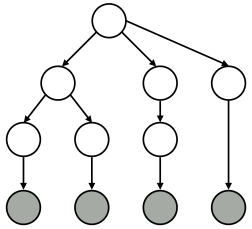


# Probabilistic Context-Free Grammars

- Matt Weir et al. Password cracking using probabilistic context-free grammars. IEEE S&P 2009.
- Patrick Gage Kelley et al. Guess again (and again and again): Measuring password strength by simulating password-cracking algorithms. IEEE S&P 2012.
- Rafael Veras et al. On the semantic patterns of passwords and their security impact. NDSS 2014.
- Saranga Komanduri. Modeling the adversary to evaluate password strength with limited samples. PhD thesis, CMU, 2015.

# PCFG



*passwordpassword*

*password123*

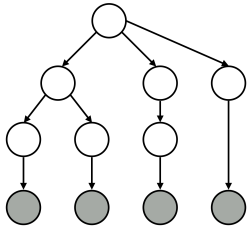
*usenix3*

*5ecurity*

*iloveyou*

*nirvana123*

# PCFG



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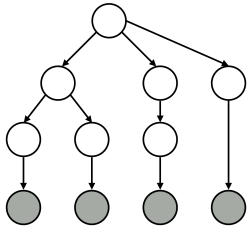

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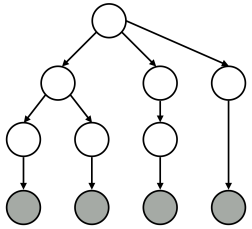

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# Neural Networks (Preview)

- William Melicher et al. Fast, lean, and accurate: modeling password guessability using neural networks. USENIX Security 2016.

# Wordlist tools

- John the Ripper, Hashcat


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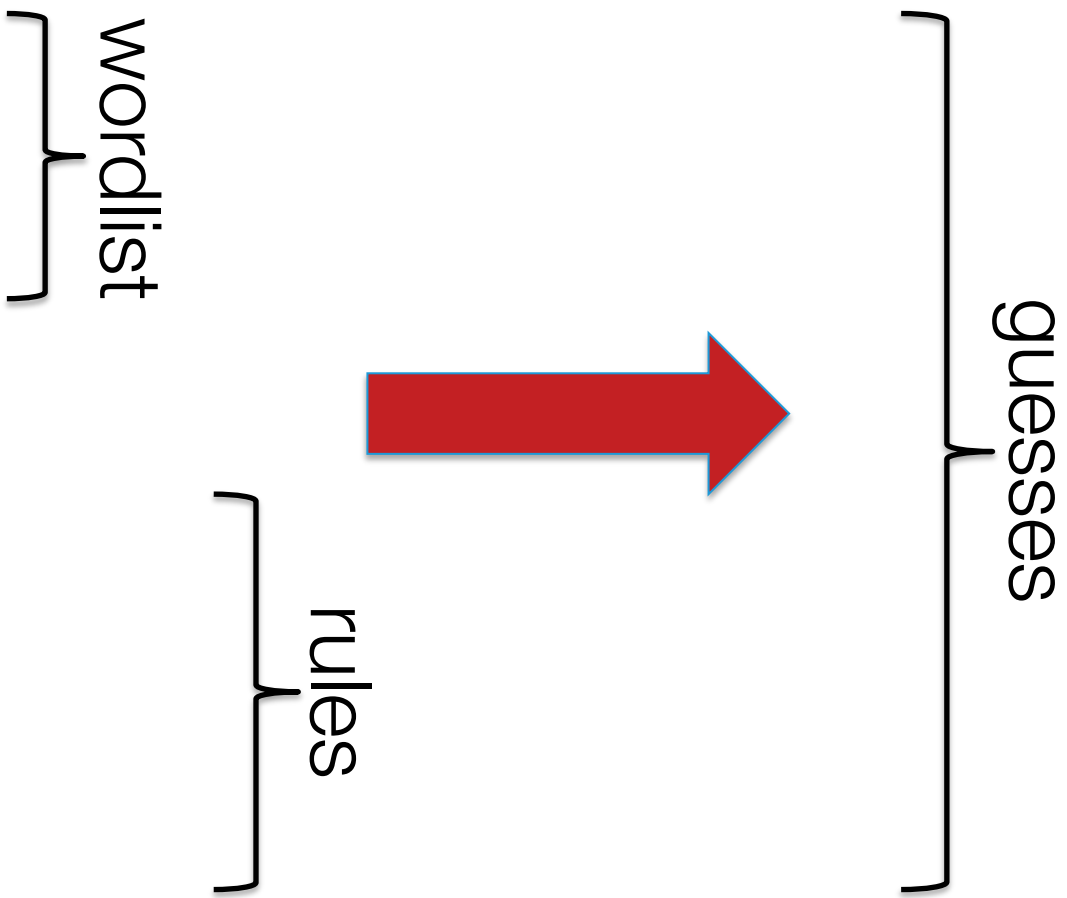
- Guess variants of input wordlist


# Wordlist tools

- John the Ripper, Hashcat
- Guess variants of input wordlist
- Wordlist mode requires:
  - Wordlist (passwords and dictionary entries)
  - Mangling rules


# John the Ripper



# John the Ripper


*blase*

*carnegie*

wordlist

rules

guesses

# John the Ripper


*blase*

*carnegie*

wordlist

[ ]

[add 1 at end]

[change e to 3]

rules

guesses

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rules

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carnegie

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carnegie1

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carn3gi3

guesses

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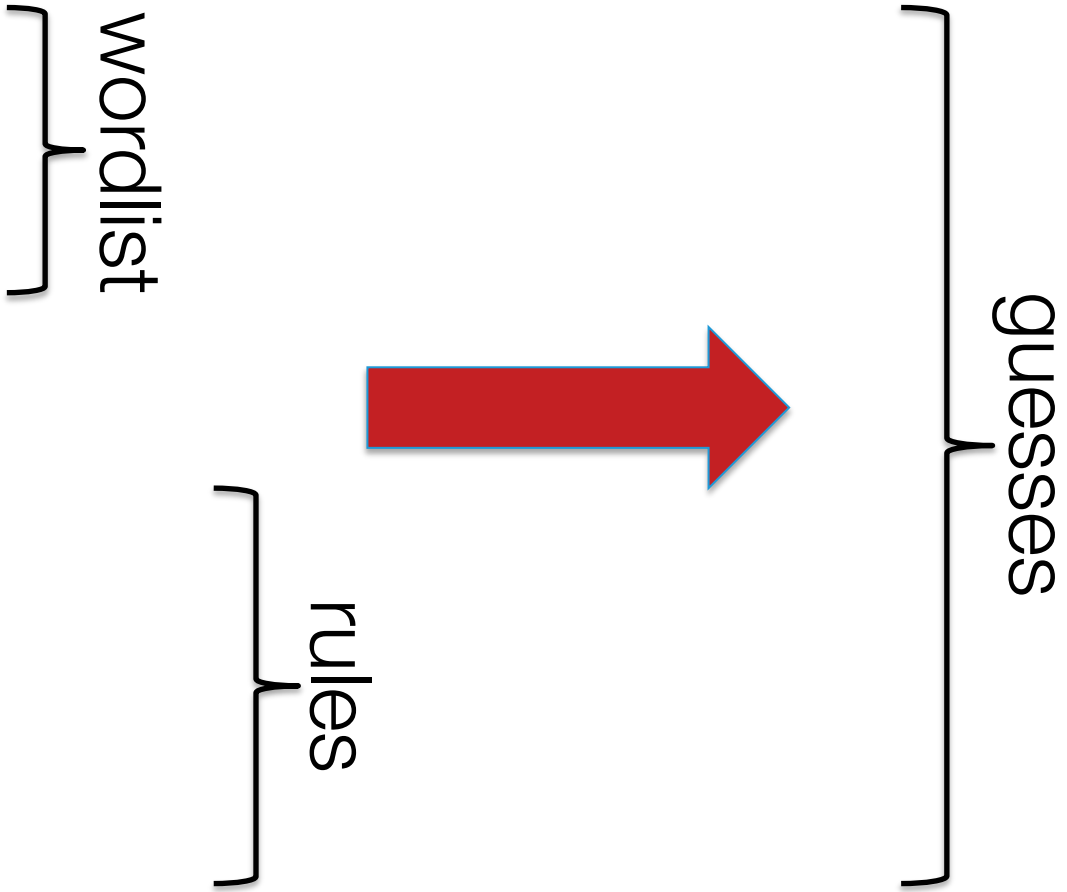
guesses

# Hashcat


hashcat
advanced
password
recovery


wordlist
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guesses

# Other Work on Password Guessing

- Markus Durmuth et al. When privacy meets security: Leveraging personal information for password cracking. CoRR 2013.
- Joseph Bonneau. Statistical metrics for individual password strength. WPS 2012.
- Matt Weir et al. Testing metrics for password creation policies by attacking large sets of revealed passwords. CCS 2010.
- Yiannis Chrysanthou. Modern password cracking: A hands-on approach to creating an optimised and versatile attack. Master's thesis, Royal Holloway, University of London, 2013.
- http://arstechnica.com/security/2012/08/passwords-under-assault/
- AbdelRahman Abdou et al. What Lies Beneath? Analyzing Automated SSH Bruteforce Attacks. Passwords 2016.

# Recall: Advantages of Guessability

- Straightforward
- Models an attacker
- Per-password strength estimates

Blase Ur et al. Measuring real-world accuracies and biases in modeling password guessability. USENIX Security 2015.

# Guessability in Practice

- Default (inexpert) configurations
- Single guessing approach

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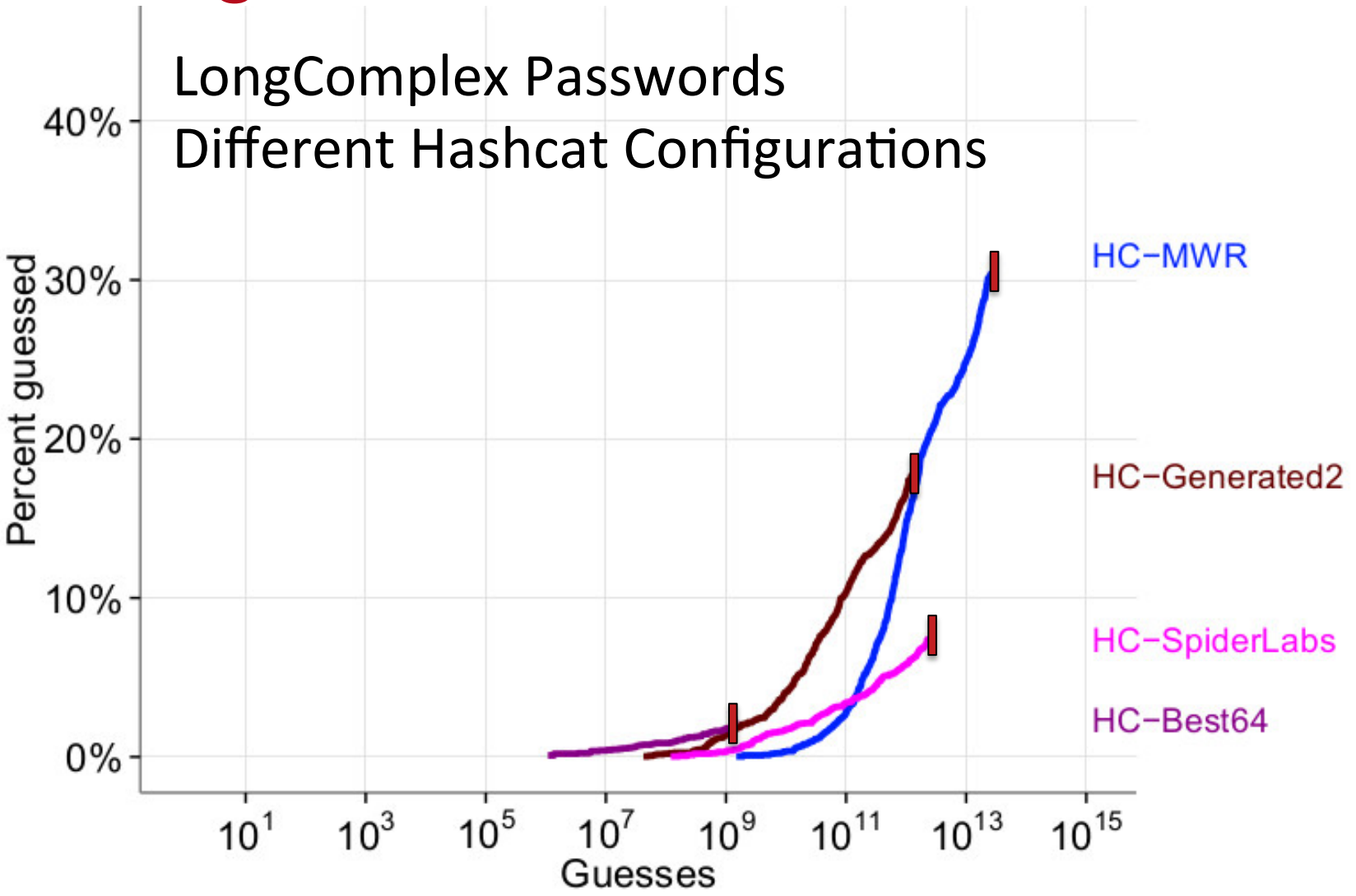
- Default (inexpert) configurations
- Single guessing approach

- How does this compare to professionals?
- How does it impact research results?

# Configuration Is Crucial



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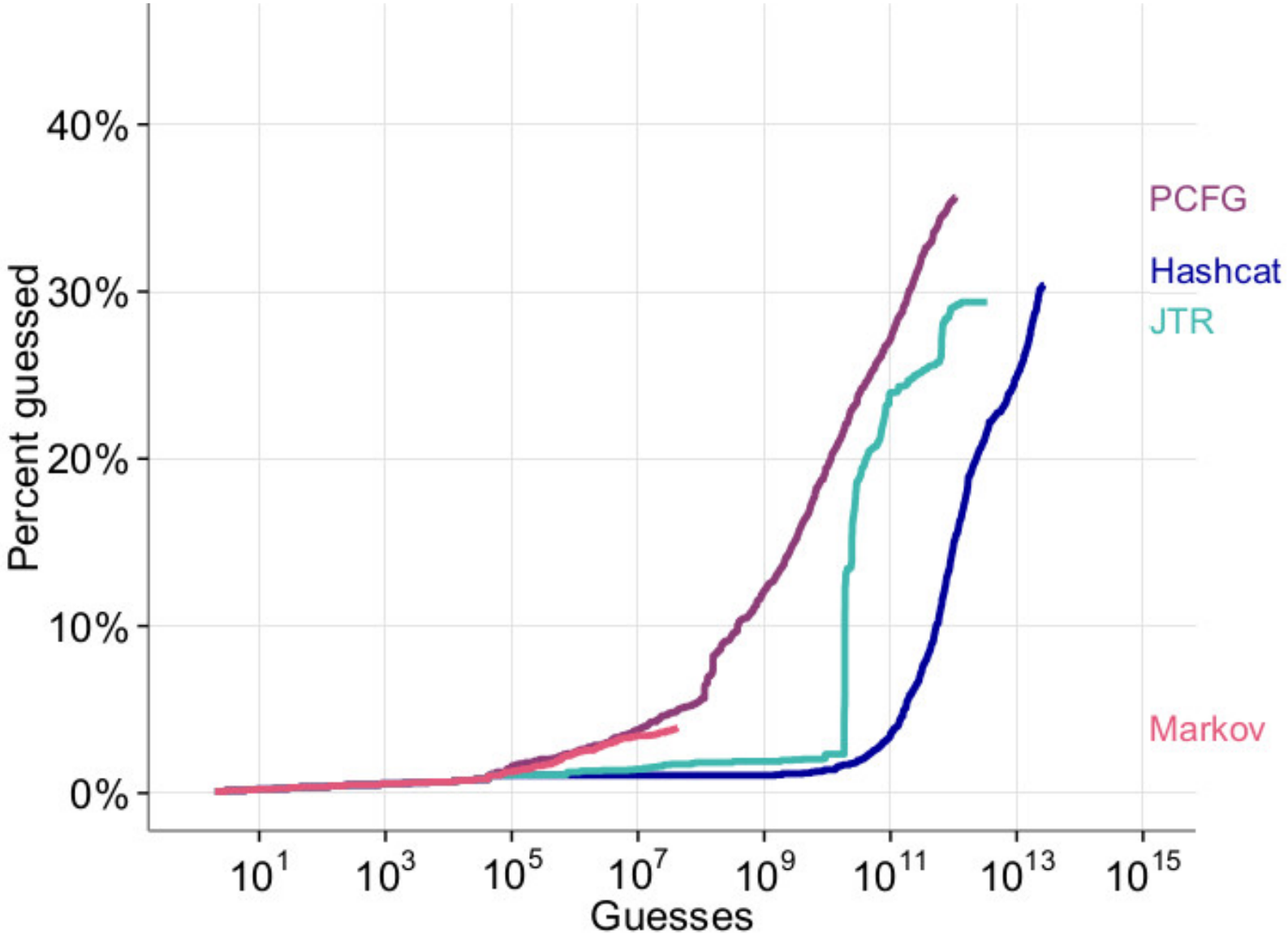

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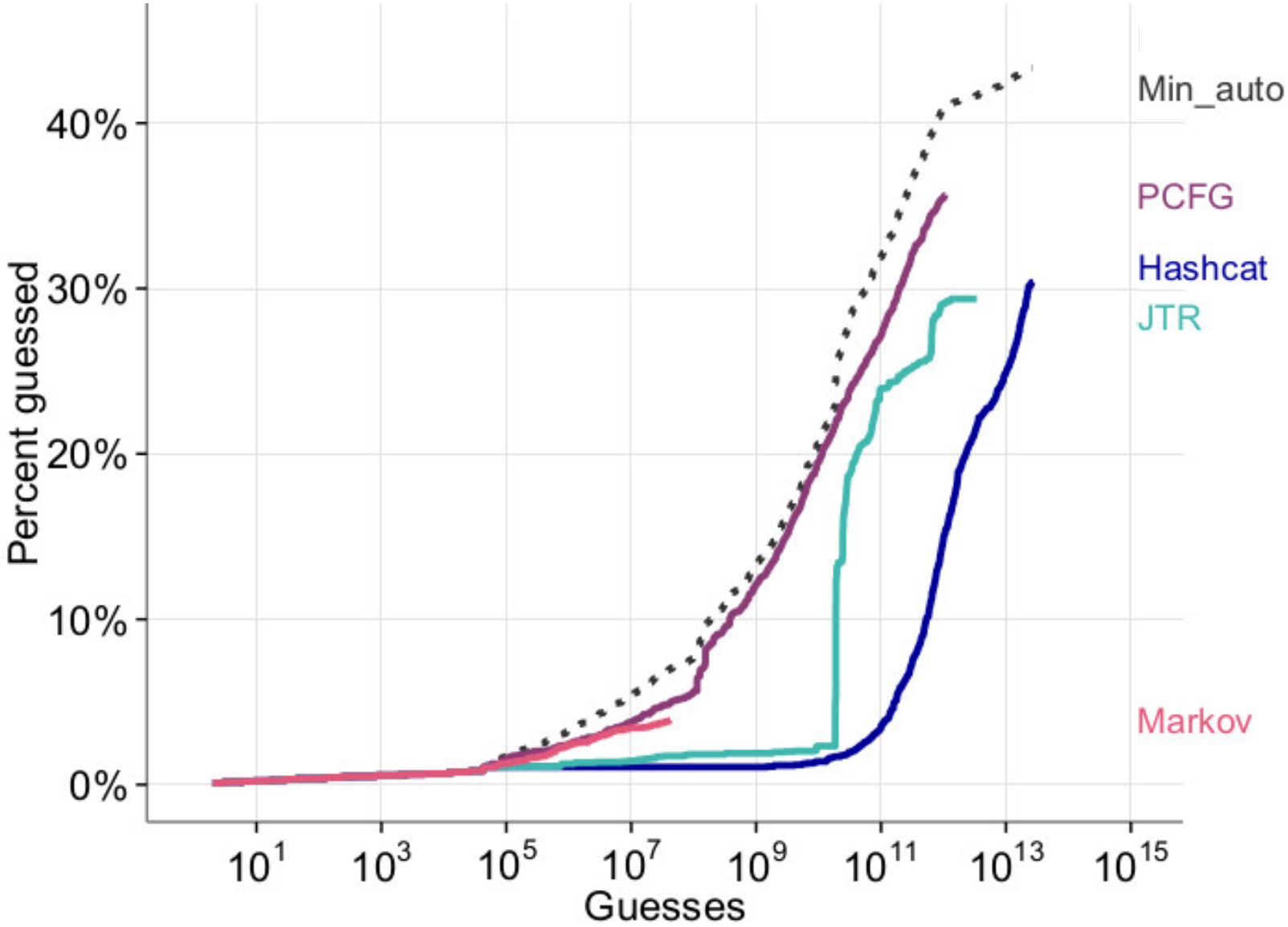
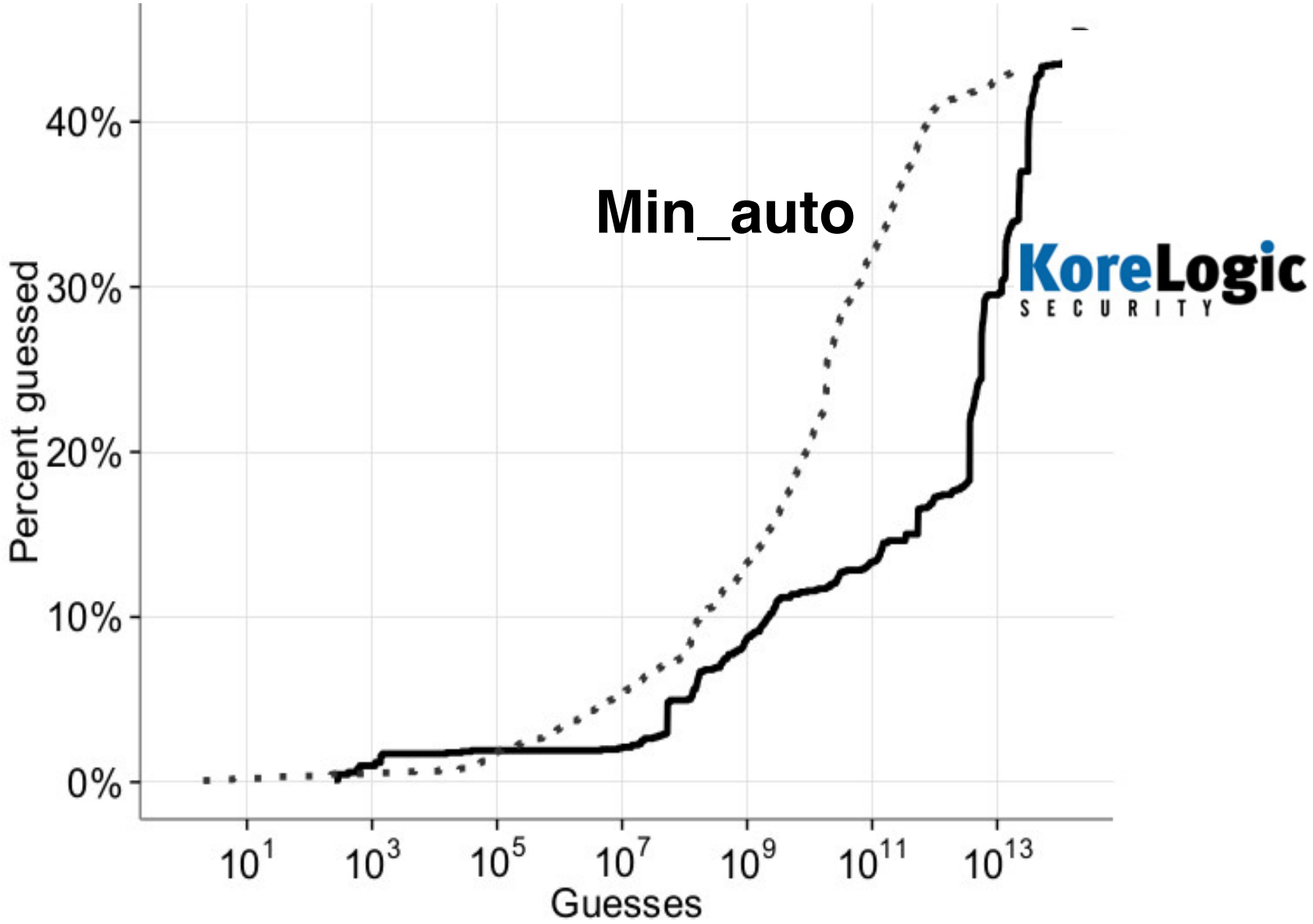


# Min_auto Conservative Proxy for Pros



# Per-Password Highly Impacted

```
P@ssw0rd!
```

# Per-Password Highly Impacted

- JTR guess # 801


```
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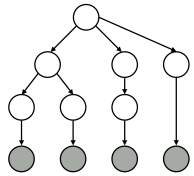

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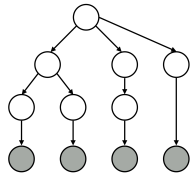

P@ssw0rd!

# Conclusions

- Running a single approach is insufficient
  - Especially out of the box
- Multiple approaches proxy for pros

# Password Guessability Service (PGS)

- Guessability of plaintext passwords

**https://pgs.ece.cmu.edu**

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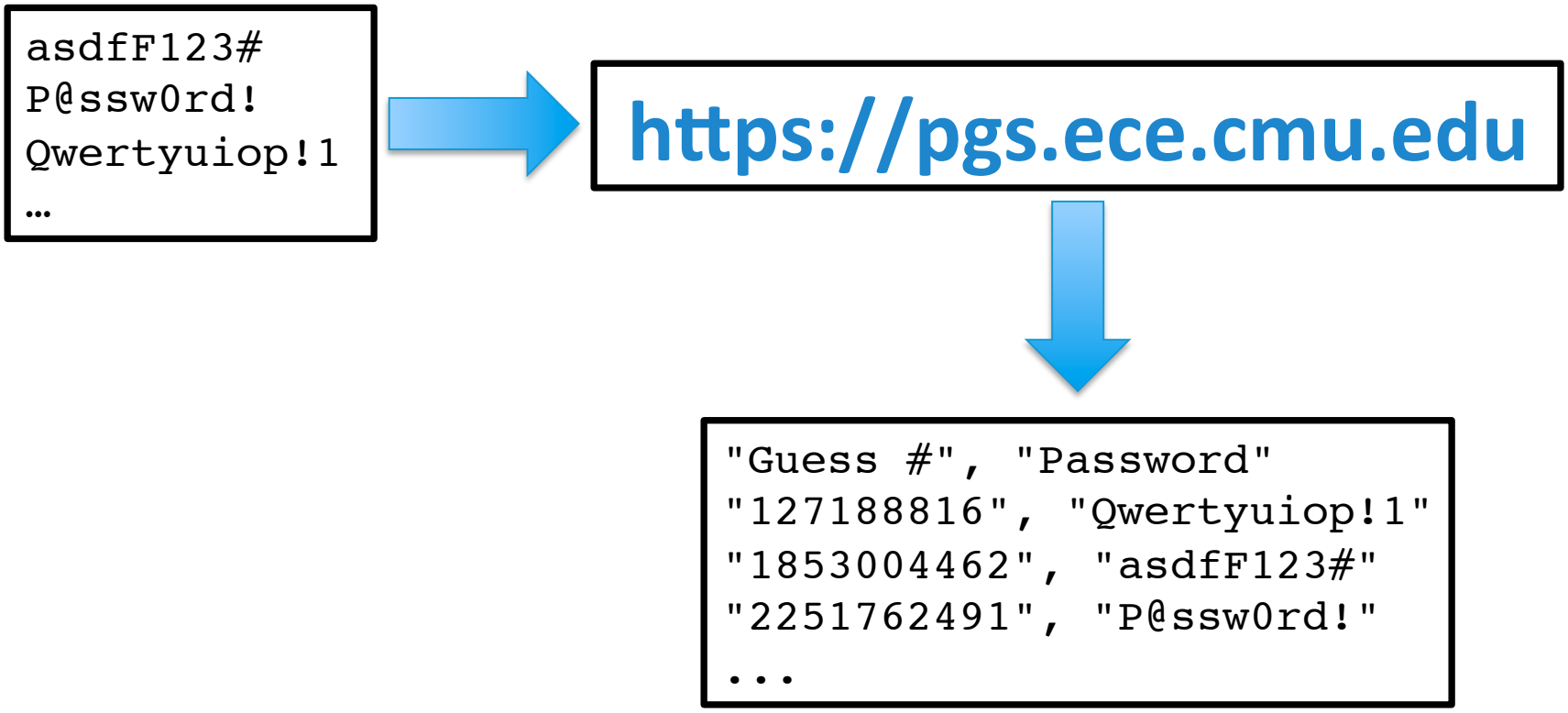

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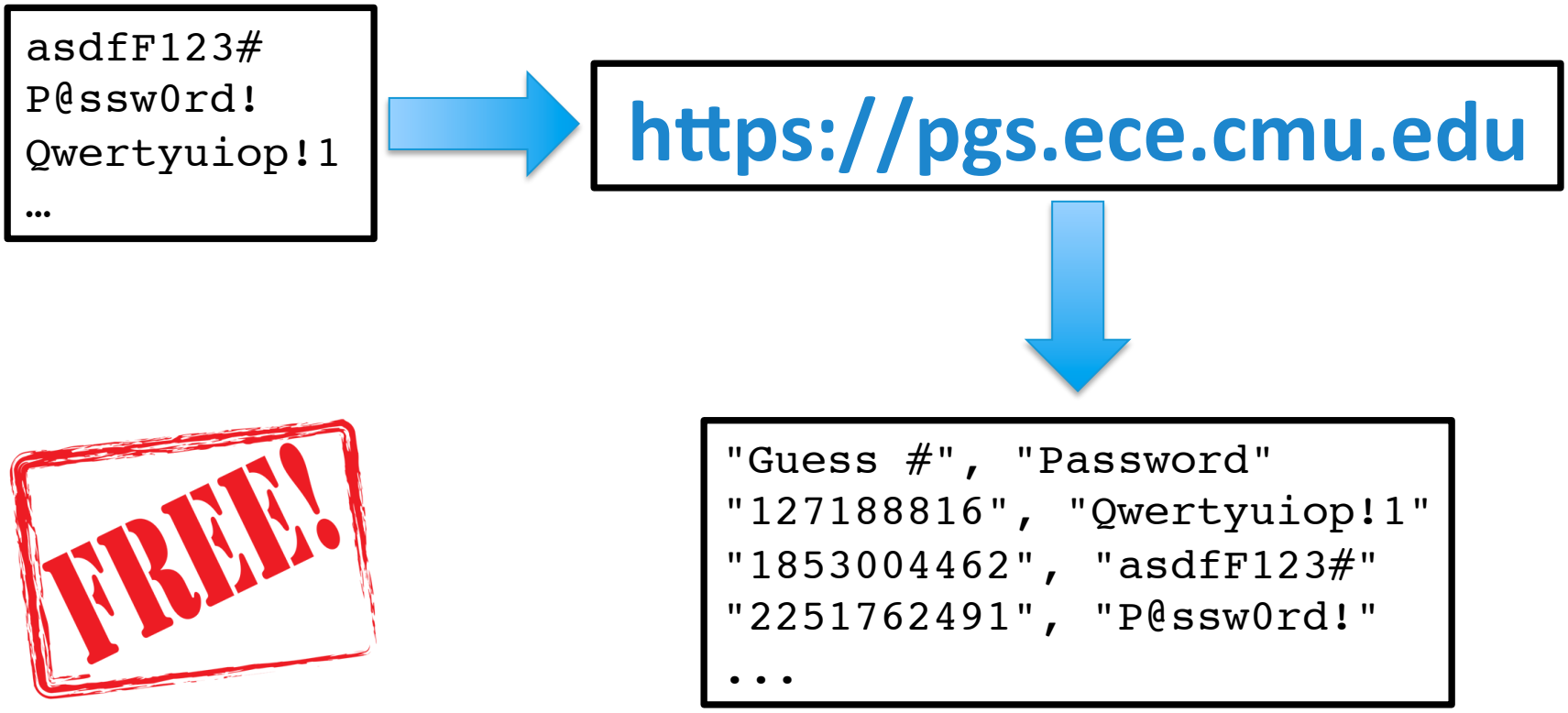

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