Password Guessability with Markov Model

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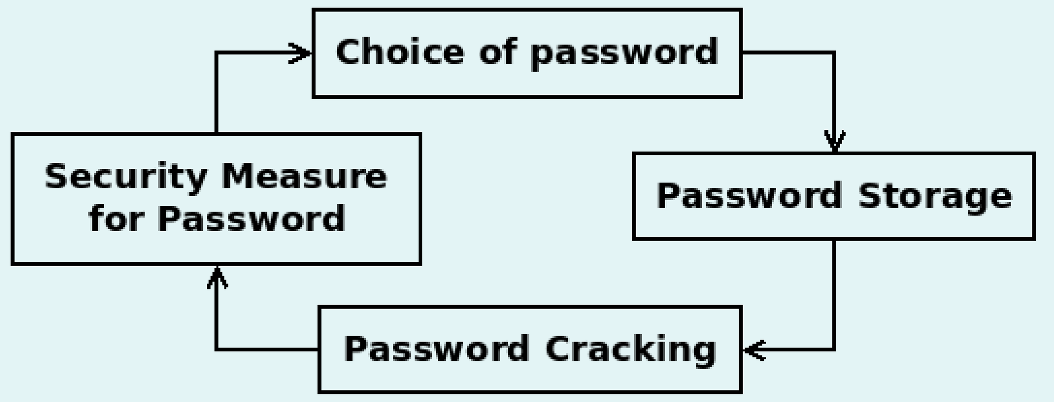
Introduction & Problem Statement

- Passwords has been and will be the most commonly used method of authentication.
- Common question: how many times does an adversary need in order to guess a password?
- Our goal: Study state-of-the-art password cracking techniques, and implement a look-up table to allow efficient guessability analysis with Markov model.

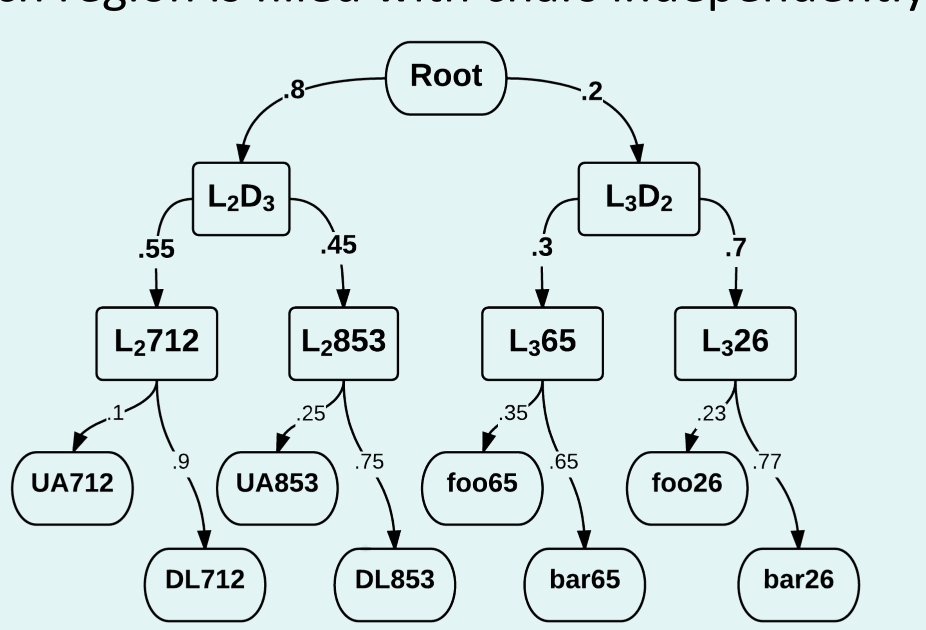


Password Cracking Techniques

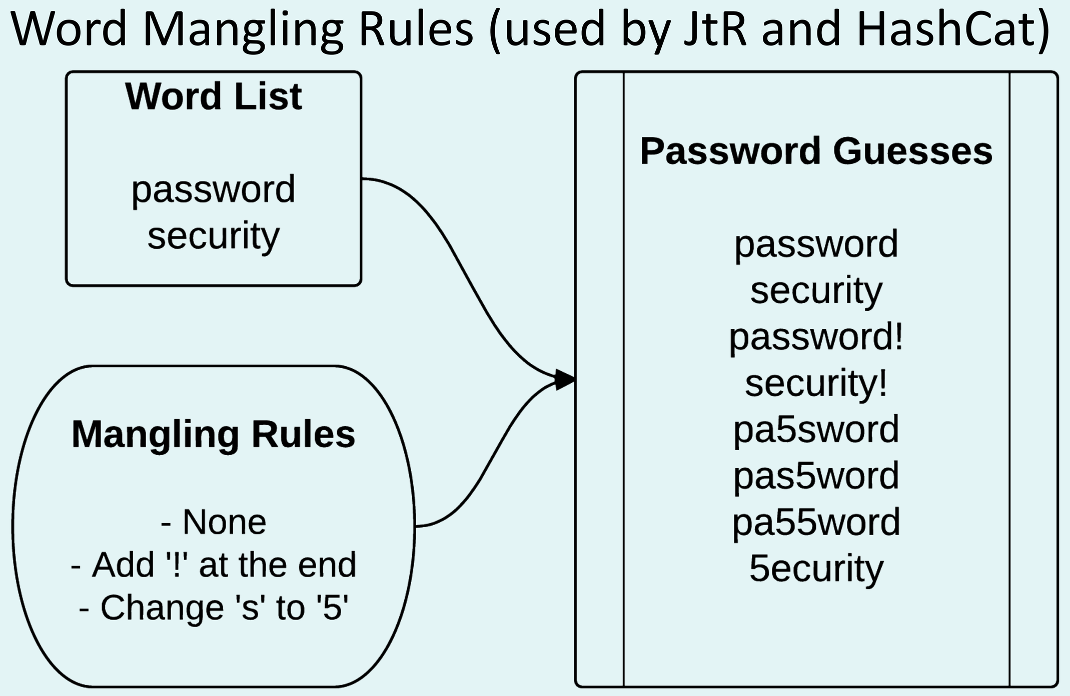
- Brute Force / Masked Brute Force:

```
aaa, aab, aac, ..., zzz
aaaa, aaab, aaac, ..., zzzz
```

- Probabilistic Conext-Free Grammar (PCFG):
  - Splits password into homogeneous "regions"
  - Different regions have different probability
  - Each region is filled with chars independently



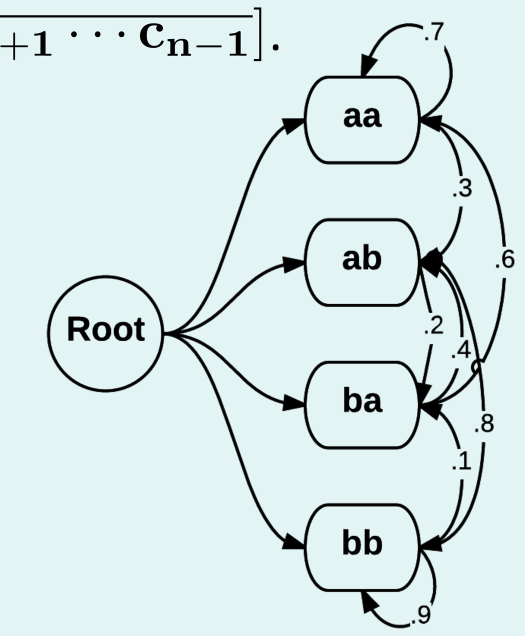
- Word Mangling Rules (used by JtR and HashCat)



Methodology

- Markov Model (k-gram):
  - Next character depends on its previous (k-1)-gram, i.e. $\Pr[\mathbf{c} \mid \overline{\mathbf{x_{n-k+1}\cdots c_{n-1}}}]$.

Pr[a | aa] = .7
Pr[b | aa] = .3
Pr[a | ab] = .2
Pr[b | ab] = .8
Pr[a | ba] = .6
Pr[b | ba] = .4
Pr[a | bb] = .1
Pr[b | bb] = .9



Step One: Learn Probability Parameters

$$\Pr[\mathbf{c} \mid \overline{\mathbf{x_{n-k+1}\cdots c_{n-1}}}] := \frac{\operatorname{count}(\overline{\mathbf{x_{n-k+1}\cdots c_{n-1}c}}) + \delta}{\operatorname{count}(\overline{\mathbf{x_{n-k+1}\cdots c_{n-1}\cdot}}) + \delta|\boldsymbol{\Sigma}|}$$

$$\Pr[\overline{\mathbf{x_0\cdots x_{k-2}}}] := \frac{\operatorname{count}(\overline{\mathbf{x_0\cdots x_{k-2}}}) + \delta}{|\mathcal{D}| + \delta|\boldsymbol{\Sigma}|^{\mathbf{k-1}}}$$

$$\Pr[\overline{\mathbf{x_{n-k+2}\cdots x_n}\perp}] := \frac{\operatorname{count}(\overline{\mathbf{x_{n-k+2}\cdots x_n}\perp}) + \delta}{|\mathcal{D}| + \delta|\boldsymbol{\Sigma}|^{\mathbf{k-1}}}$$

Step Two: Discretize Probabilities

- Initially proposed by Duermuth, et al. In 2015
- Reduce continuous variables to discrete variables:

$$\hat{\ell}[\cdot] = -\operatorname{round}(\log(\mathbf{c_1 p + c_2})).$$

- Parameters: $\ell_{\max}, \mathbf{c_1}, \mathbf{c_2}$, satisfying:

$$\begin{cases} -\log(\mathbf{c_2}) = \ell_{\max} \\ \log(\mathbf{c_1 p_{\max} + c_2}) = \mathbf{0} \end{cases}$$

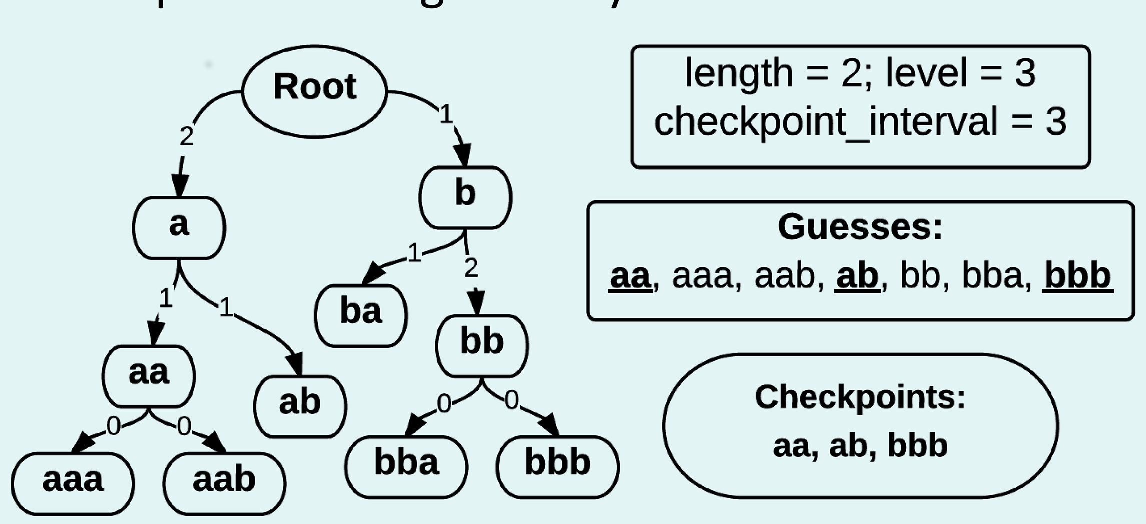
$$\implies (\mathbf{c_1}, \mathbf{c_2}) = \left(\frac{\mathbf{1} - \exp(-\ell_{\max})}{\mathbf{p_{\max}}}, \exp(-\ell_{\max})\right).$$

Step Three: Build Enumeration Index

- Level of a password = sum of the levels of its Markov probabilities, e.g:

$$\mathbf{lvl}(\text{"ab"}) := \hat{\ell}[\text{"a"}] + \hat{\ell}[\text{"b"} \mid \text{"a"}] + \hat{\ell}[\text{"a}\perp\text{"}].$$

For each (length, level)-pair, enumerate passwords with certain length and level with DFS and create "checkpoints" along the way for future use:



Methodology (Cont'd)

- **Step Four: Guess Count Calculation**
- Pick up the DFS process from the most recent checkpoint (if exists), and continue until finding the password. Overall, the guess number of password is:

$$\mathbf{g(x)} = \left(\sum_{\text{prior (len, lvl)}} |\mathcal{I}_{\text{len, lvl}}|\right) + \mathbf{g}_{\text{len, lvl}}(\mathbf{x}).$$

Results & Evaluation

- Input data: RockYou leaked passwords (weighted with counts), Unix English dictionary
- Performance evaluation on personal machine: Ubuntu 14.04; Intel i5-3210 @ 2.50GHz; 8G RAM.
- $\mathbf{k = 3}, \ell_{\max} = \mathbf{10}, \mathrm{max\_passwd\_len} = \mathbf{12}.$

Step One: Index Builder

- Time taken: 6m52s
- Memory usage: peak at *3.625 GB*
- Storage: 1.6 GB for all modes
- Output format:

$$\{\mathbf{1} \mapsto [\text{"aa"}, \text{"ab"}], \mathbf{2} \mapsto [\text{"bb"}], \cdots\}$$

$$\{\text{"aa"} \mapsto \{\mathbf{0} \mapsto [\text{'c'}], \cdots\}, \text{"ab"} \mapsto \{\mathbf{2} \mapsto [\perp]\}, \cdots\}$$

Step Two: Checkpoint Builder

- Data range: All passwords with total level ≤ 22, totaling approx. 10^{11} passwords
- Time taken: 20+ hours
- Memory usage: peak at *150 MB / thread*
- Storage: 55MB for all checkpoints
- Output format: passwords & count

<u>len5-lvl10.out</u>

12da0
meiia
mizwa
roe87
dau14
… … …

1125991

Step Three: Guess Count Calculator

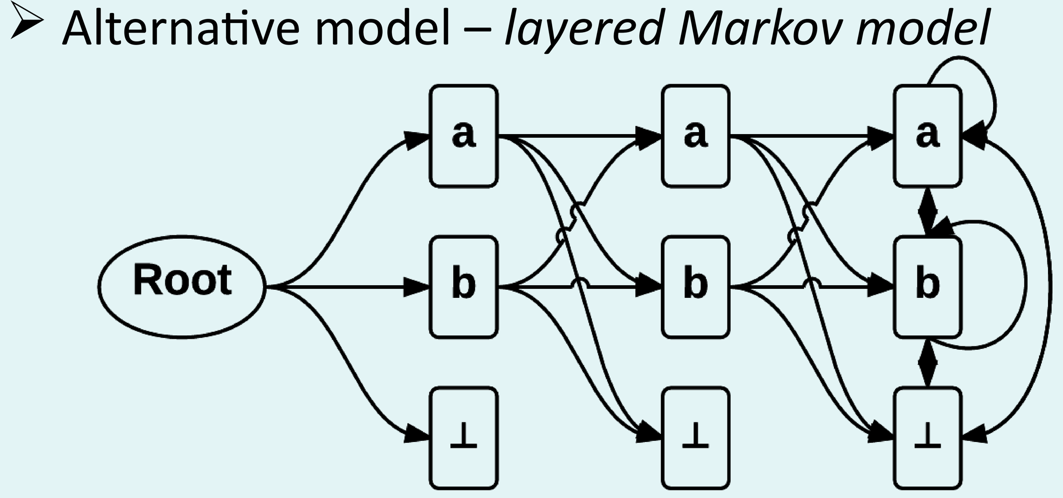
- Time per password: < 15 seconds (mostly loading index / checkpoints)
- Memory usage: peak at 150 MB
- Storage: None
- Output format:

```
> python guess.py
Input password to guess > juniker
Password length: 7; Total level: 9
Using binary search to calculate guess count...
Result: 14586299
```

Overall: Memory likely to hit resource limit first; guess count calculation time strongly correlated to checkpoint frequency.

Remarks & Future Work

- Time-space tradeoff:
  - More storage used for checkpointing gives faster run-time for guess number calculation; vice versa.
- Alternative model – *layered Markov model*



- Other smoothing techniques, e.g. Good-Turing:

$$\hat{c}(s) = \begin{cases} 0.22 & \text{for } \mathbf{c(s) = 1} \\ \mathbf{0.88} & \text{for } \mathbf{c(s) = 2} \\ \mathbf{c(x) - 1} & \text{for } \mathbf{c(s) > 2} \\ \text{previously deducted count} & \text{otherwise} \end{cases}$$

- Fine-tuned implementation based on our algorithm can be incorporated in a Guessability-as-a-Service module, like in [2].
- Source code and final report for the project is available in our Github repo [1], and intermediate output data (> 2GB) is available upon request.

Selected References

- M. Durmuth, F. Angelstorf, C. Castelluccia, D. Perito, and A. Chaabane. OMEN: faster password guesing using an ordered markov enumerator. In *Proc. ESSoS*, 2015.
- J. Ma, W. Yang, M. Luo, and N. Li. A study of probabilistic password models. In *Proc. IEEE Symp. On Security and Privacy*, 2014.
- B. Ur, S. M. Segreti, L. Bauer, N. Christin, L. F. Cranor, S. Komanduri, D. Kurilova, M. L. Mazurek, W. Melicher, and R. Shay. Measuring real-world accuracies and biases in modeling password guessability. In *Proc. USENIX Security*, 2015.

(Full list of references is available in the final report.)

Acknowledgements

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[1] https://github.com/ymzong/password-guessability
[2] https://pgs.ece.cmu.edu

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