Revisiting ReDoS: A Rough Idea of Data Exfiltration by ReDoS and Side-channel Techniques

Revisiting ReDoS: A Rough Idea of Data Exfiltration by ReDoS and Side-channel Techniques - Takashi Yoneuchi, Speaker Deck.

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Revisiting ReDoS: A Rough Idea of Data Exfiltration by ReDoS and Side-channel Techniques - Speaker Deck

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Update: you can find a blog article on this presentation at: https://diary.shift-js.info/blind-regular-expression-injection/

I presented about ReDoS and blind regular expression injection attack at OWASP Night (Japan) 2020. Please feel free to contact https://twitter.com/y0n3uchy if you have questions or find something wrong.

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Transcript

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Revisiting ReDoS Takashi Yoneuchi (@y0n3uchy) Flatt Security, Inc. Departme nt of

Information Science, Faculty of Science, The University of Tokyo A Rough Idea of Data Exfiltration by ReDoS and Side-channel Techniques

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Takashi Yoneuchi Twitter ja:@lmt_swallow en:@y0n3uchy Affiliation:

Flatt Security, Inc. Department of Information Science, Faculty of Science, the University of Tokyo I <3 Web Leader of @ctf4b Staff of @security_camp, #websecjp Member of TSG / dodododo (CTF team) See: https://shift-js.info

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Exfiltration by ReDoS and Side-channel Techniques Outline Introduction to Algorithmic Complexity Attack Definition and examples Regular Expression Denial of Service (ReDoS) 101 Rough sketch of implementations of regexp engines Definition and examples of ReDoS Mitigation of ReDoS (Maybe) New Idea: Blind Regular Expression Injection Attack Explanation of Blind Regular Expression Injection Attack 3

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Introduction to Algorithmic Complexity Attack

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Exfiltration by ReDoS and Side-channel Techniques Computational Complexity Preliminaries for the introduction to AC Attack Computational complexity for an algorithm is the amount of resources required for running it. Time complexity: the amount of the required time Space complexity: the amount of the size of the memory There are two kinds of computational complexity. Average-case complexity Worst-case complexity Examples: searching in a binary search tree (BST) The average-case time complexity: O(log n). The worst-case time complexity: O(n). 5

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Exfiltration by ReDoS and Side-channel Techniques Algorithmic Complexity Attack A low-bandwidth DoS attack A security aspect of algorithms: worst-case complexity. To prevent algorithmic complexity attacks, we have to care about worst-case complexity of an algorithm as well as average-case one. Algorithmic Complexity Attack: DoS by worst-case inputs In 2003, Crosby and Wallach proposed a class of DoS attacks by giving a crafted worst-case input for applications. S. A. Crosby and D. S. Wallach, “Denial of Service via Algorithmic Complexity Attacks,” in Proceedings of the 12th Conference on USENIX Security Symposium - Volume 12, 2003, p. 3. This class of attacks may cause a DoS with a small input; in other words, this is a low-bandwidth DoS attack. The class of low-bandwidth DoS attacks is often called asymmetric DoS (ADOS). 6

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Exfiltration by ReDoS and Side-channel Techniques Real-world Examples Algorithmic Complexity Attack There are a lot of real-world examples. The followings are a part of them: "Hash-flooding DoS reloaded: attacks and defenses" at 29C3 https://131002.net/siphash/siphashdos_appsec12_slides.pdf "I Came to Drop Bombs: Auditing the Compression Algorithm Weapon Cache" at BlackHat USA 2016 https://www.blackhat.com/docs/us-16/materials/us-16-Marie-I-Came-to-Drop-Bombs-Auditing-The-Compression-Algorithm- Weapons-Cache.pdf "Denial of Service with a Fistful of Packets: Exploiting Algorithmic Complexity Vulnerabilities" at BlackHat USA 2019

https://www.blackhat.com/us-19/briefings/schedule/#denial-of-service-with-a-fistful-of-packets-exploiting-algorithmic-complexity- vulnerabilities-16445 7

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Exfiltration by ReDoS and Side-channel Techniques Academical Efforts For Algorithmic Complexity Attack By-hand Exploration: Crosby et al., 2003 (mentioned before), Cai et al., 2009, Sun et al., 2011, ... X. Cai, Y. Gui, and R. Johnson, “Exploiting Unix File-System Races via Algorithmic Complexity Attacks,” in 2009 30th IEEE Symposium on Security and Privacy, 2009, pp. 27–41. X. Sun, L. Cheng, and Y. Zhang, “A Covert Timing Channel via Algorithmic Complexity Attacks: Design and Analysis,” in 2011 IEEE International Conference on Communications (ICC), 2011, pp. 1–5. (Semi-) Automated Detection: Tools by Holland et al., 2016, SlowFuzz (Petsios et al., 2017), Badger (Noller and Kersten, 2018), ... T. Petsios, J. Zhao, A. D. Keromytis, and S. Jana, “SlowFuzz: Automated Domain-Independent Detection of Algorithmic Complexity Vulnerabilities,” in Proceedings of the 2017 ACM SIGSAC Conference on Computer and Communications Security, 2017, pp. 2155–2168. Y. Noller, R. Kersten, and C. S. Păsăreanu, “Badger: Complexity Analysis with Fuzzing and Symbolic Execution,” in Proceedings of the 27th ACM SIGSOFT International Symposium on Software Testing and Analysis, 2018, pp. 322–332. B. Holland, G. R. Santhanam, P. Awadhutkar, and S. Kothari, “Statically-Informed Dynamic Analysis Tools to Detect Algorithmic Complexity Vulnerabilities,” in 2016 IEEE 16th International Working Conference on Source Code Analysis and Manipulation (SCAM), 2016, pp. 79–84. 8

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ReDoS 101

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Exfiltration by ReDoS and Side-channel Techniques Regular Expressions a.k.a. regex, regexp Regular expressions (a.k.a. regex, regexp) are powerful and useful pattern matching language for strings. Two major security aspects of regexp: correctness and performance. Weak validation by incomplete (or incorrect) regular expressions. Example: preg_replace("/on/", "", $input) for detecting event handlers A lot of possible bypasses: oNload, Onload. ref. "Regexp Security Cheatsheet" https://github.com/attackercan/regexp-security-cheatsheet Too heavy computations. This causes Regular Expression Denial of Service; ReDoS. 10

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Exfiltration by ReDoS and Side-channel Techniques Implementation of RE Engines Convert regexp into NFA and simulate it Fact: Every regular expression has an equivalent Non-deterministic Finite Automaton (NFA) and vice versa. Thompson's Algorithm: regexp NFA. Kleene's Algorithm: NFA regexp. Implementation: After converting regexp into NFA (or DFA), ... 1. Choose one among possible next states and backtrack when it failed to match. 2. Choose all of

them and continue the simulation simultaneously. K. Thompson, “Regular expression search algorithm,” Comm. ACM, vol. 11, no. 6, pp. 419–422, 1968. https://www.fing.edu.uy/inco/cursos/intropln/material/p419-thompson.pdf R. Cox, "Regular Expression Matching Can Be Simple And Fast (but is slow in Java, Perl, PHP, Python, Ruby, ...) " https://swtch.com/~rsc/regexp/regexp1.html 11

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Exfiltration by ReDoS and Side-channel Techniques Backtracking (1) In the case of NFA-based engines Let an input for the regexp ^a+a+$ (the concatenation of two a+) be "aaaaa!". First a+ can match "a", "aa", ..., and "aaaaa". 12 Input: a a a a a !

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Exfiltration by ReDoS and Side-channel Techniques Backtracking (2) In the case of NFA-based engines Backtracking-based engines chooses one of the candidates (e.g. "aaaaa") and continues to match. When "aaaaa" was chosen, the second a+ cannot match. 13 Input: a a a a a ! : string matched for the first a+) (

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Exfiltration by ReDoS and Side-channel Techniques Backtracking (3) In the case of NFA-based engines Then the engines retries with another candidate and continues to match. This behavior is called backtracking. When "aaaa" was chosen, the second a+ can match "a". 14 Input: a a a a a ! : string matched for the first a+) (

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Exfiltration by ReDoS and Side-channel Techniques Catastrophic Backtracking What super-linear (SL) regex cause Problem: There are regular expressions that require a lot of backtracking (catastrophic backtracking). ^a+a+$ ... O(n^2) for aaaaa....aaaaa! ^(.+)+a$ ... O(2^n) for aaaaa ... aaaaa! They require non-linear time in length of an input for evaluation! Impact: a lot of RE engines adopt backtracking-based approach! Python, Node.js, Ruby, etc. 15 import timeit for i in range(0, 30): code = "import re; re.match(r'^(.+)+a$', '{}!')".format('a' * i) print(i, timeit.timeit(code, number=1)) Example of catastrophic backtracking

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Exfiltration by ReDoS and Side-channel Techniques ReDoS Regular Expression Denial of Service Attackers can use a lot of computational resources of a server when ... An (Web) application use

those backtracking-based RE engines. Attackers can control inputs for a vulnerable regular expression (= a super- linear regular expression) that is pre-defined or crafted by RE injection. This issue is called Regular Expression Denial of Service (ReDoS). Especially, ReDoS has a big impact on Node.js-based applications. Due to its single-threaded nature and backtracking-based RE engine! A great deal of ReDoS vulnerabilities npm modules are reported in 2019. ref. "ReDoS vulnerabilities in npm spikes by 143% and XSS continues to grow" by snyk https://snyk.io/blog/redos-vulnerabilities-in-npm-spikes-by-143-and-xss- continues-to-grow/ 16

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Exfiltration by ReDoS and Side-channel Techniques Prevalence Is ReDoS a popular issue? ReDoS vulnerabilities are in the news! Academical Survey: a large-scale analysis on ReDoS vulnerabilities and reported a lot of possible ReDoS vulnerabilities. C.-A. Staicu and M. Pradel, “Freezing the Web: A Study of ReDoS Vulnerabilities in JavaScript-based Web Servers,” in 27th USENIX Security Symposium (USENIX Security 18), 2018, pp. 361–376. J. C. Davis, C. A. Coghlan, F. Servant, and D. Lee, “The Impact of Regular Expression Denial of Service (ReDoS) in Practice: An Empirical Study at the Ecosystem Scale,” in Proceedings of the 2018 26th ACM Joint Meeting on European Software Engineering Conference and Symposium on the Foundations of Software Engineering, 2018, pp. 246–256. Real-world Examples: a lot of CVEs! Google "ReDoS CVE". 17

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Exfiltration by ReDoS and Side-channel Techniques Mitigation How can we mitigate ReDoS? There are three major approaches to mitigate ReDoS vulnerabilities. Abort the evaluation of heavy regular expressions. .NET provides optional regex timeouts. https://docs.microsoft.com/en-us/dotnet/api/system.text.regularexpressions.regex.matchtimeout?view=netframework-4.8 Python's "regexp" module (not a built-in one) provides the timeout too. https://pypi.org/project/regex/ Use non-backtracking engines. For instance, RE2 guarantees linear-time performance. "RE2 was designed and implemented with an explicit goal of being able to handle regular expressions from untrusted users without risk." https://github.com/google/re2/wiki/WhyRE2 Avoid anti-patterns. Do NOT nest quantifiers, Do NOT repeat same patterns with quantifiers, ... 18

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Blind Regular Expression Injection Attacks

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Exfiltration by ReDoS and Side-channel Techniques Assumption For Blind Regular Expression Injection We assume the following conditions: A victim application evaluates a regexp with a secret. Attackers can control the regexp with using ... the valid feature of applications (e.g. string matching in searching feature). unsafe construction of a regexp (i.e. regular expression

injection). Attackers can know or guess the set of characters that might be included in the secret. Example: An application takes a regexp to search a records in secrets. After evaluating regexp for all possible records, it checks whether an user has the permission to see the search results. 20

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Exfiltration by ReDoS and Side-channel Techniques Test case An example of a vulnerable application 21 This (pseudo-) Python script takes a regexp for `secret` as an input from a user, returning no information after the search. It is clear that this application has a ReDoS vulnerability due to `re` module, a backtracking-based regexp engine. import re import sys secret = "this_is_secret_value" r = input("Give a regexp to search: ") _ = timeout(re.match(r, secret), 5) print("Done. I won't give you search results :P") Example: a vulnerable application

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Exfiltration by ReDoS and Side-channel Techniques Research Question What does the prevention by resource limiting cause? Research Question: If developers handle a regexp under the strict timeouts for prevention, can we utilize this for malicious use? Idea for RQ: ReDoS + side-channel techniques Resource limitation prevents ReDoS vulnerabilities; we can use as many resources (e.g. time, memory, ...) as the limitation multiple times. i.e. Evaluation of RE may cause a change of resource usage without DoS. Resource usage might be observed by side-channel techniques. e.g. the time to evaluate a regexp on the server side can be approximated by round-trip time. If we can construct a regexp whose resource usage changes according to the text to be searched, we can build an oracle for secret records! 22

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Exfiltration by ReDoS and Side-channel Techniques Blind RE Injection Attacks A new class of regular expression injection attacks? Under the threat model, attackers can reveal the secret by ... 1. Constructing the following oracle with regexp injection vulnerabilities or its valid features. The oracle receives a proposition on the secret as a regexp. The oracle returns 1 if the proposition holds, otherwise 0. 2. Querying `length_is(n)` to the oracle again and again to get len(the secret). `length_is(n)` ... whether len(the secret) is n or not. 3. Querying `starts_with(s)` to the oracle repeatedly to get the whole of the secret. `starts_with(s)` ... whether the secret starts with the string `s` or not. I'd like to call this kind of attacks blind regular expression injection attacks. 23

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Exfiltration by ReDoS and Side-channel Techniques 1. Construct a Oracle Predicates on the secret 24 # length_is(n) .{n}$ # starts_with(s) s.* # ends_with(s) *.s$ # nth_char_is(n, c) .{n-1}c.* The

following predicates on the secret can be described as regexps. length_is(n): the length of the secret is `n`. starts_with(s): the secret starts with the string `s`. ends_with(s): the secret ends with the string `s`. nth_char_is(n, c): the n'th character of the secret is the char `c`. Predicates on the secret

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Exfiltration by ReDoS and Side-channel Techniques 1. Construct a Oracle redos_if function 25 # here we assume the secret does not ends with the string "hoge". def redos_if(prop): return "^(?={})((.))*hoge$".format(prop) *Let prop be a proposition on the secret written as a regexp. e.g. length_is(3) The evaluation of ^(?=prop)((.)*)*hoge$ takes ..* a lot of time if prop holds. little time if prop does not hold. Therefore, we can encode the truth value of prop into the time needed for the evaluation of redos_if(prop)!

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Exfiltration by ReDoS and Side-channel Techniques 1. Construct a Oracle Combining redos_if and timing measurement(s) This snippet do the followings: give a regexp redos_if(prop) to a victim application. measure how much time it takes for the application to return the response. returns whether the measured time exceeds the threshold or not. We achieved the construction of an oracle that returns whether a proposition (prop) on `secret` holds or not! 26 import time def oracle(prop): threshold = 1 prev = time.process_time() # (request w/ redos_if(prop) and wait the response) return time.process_time() - prev > threshold Construction of an oracle with prop.

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Exfiltration by ReDoS and Side-channel Techniques 2. Leak len(the secret) Blind Regular Expression Injection Let ub_of_len be an upper bound of the length of the secret. It can be guessed :P For each i in a closed range [1, ub_of_len], we can check whether length_is(i) holds or not by the oracle. Querying length_is(i) for all i in the range reveals the length of the secret. 27 ub_of_len = 100 length_is = lambda n: ".{" + str(n) + "}$" for i in range(1, ub_of_len+1): if oracle(length_is(i)) break # len(the secret) == i Naive algorithm to leak len(secret)

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Exfiltration by ReDoS and Side-channel Techniques 3. Leak the secret Blind Regular Expression Injection Let S be the set of possible characters in the secret. For each position of the secret (= i) and for each possible character (= c, i.e. the element of S), we can check whether nth_char_is(i, c) holds or not. In this naive way, we can leak the secret by O(n |S|), where n is the length of the secret (length_of_secret). 28 secret = "" nth_char_is = lambda n, c: ".{" + str(n) + "-1}" + c for i in

range(0, length_of_secret): for c in S: if oracle(nth_char_is(i, c)): secret += c Naive algorithm to leak the secret

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Exfiltration by ReDoS and Side-channel Techniques Optimization by binary search Blind Regular Expression Injection A optimized algorithm with binary search finishes in O(n log|S|). We can determine the len(the secret) by binary-searching among [1, (upper bound of the length)]. Similarly, the secret can be leaked by binary-searching among S with nth_char_in. 29 # length_in(n, m) .{n-m}$ # nth_char_in(n, S) # where s = ''.join(S) .{n-1}[s].* (e.g. .[abc]$ for S = {a, b, c}) Predicates on the secret

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Exfiltration by ReDoS and Side-channel Techniques Implications What blind regular expression injection attack implies Blind regular expression injection attack requires ... Evaluation of arbitrary regexps in backtracking-based regexp engines. If regexps used in the applications are constant or safely constructed from user- controllable values. Enough number of evaluation. If a malicious regexp may cause DoS, attackers can't fetch enough information to leak the secret. Here is the important thing: Abortion of the evaluation of use-controllable regexps might induce the exploitability by blind regular expression injection attacks, even though the abortion is for ReDoS prevention! 30

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Exfiltration by ReDoS and Side-channel Techniques Takeaways Revisiting ReDoS: A Rough Idea of Data Exfiltration by ReDoS and Side-channel Techniques I presented new class of attacks: Blind Regular Expression Injection Attacks. To the best of my knowledge, this is the first report of this kind of attacks, although it seems to be a CTF-like technique :P I believe that there are some real-world examples. To avoid security issues related to regexp, you should ... Construct your regexp safely. Do NOT use user-controllable regexp with backtracking-based engines! Use non-backtracking engines (e.g. RE2). Resource limitation including timeouts on backtracking-based engines might induce the issue like my report :O Avoid anti-patterns of ReDoS. 31

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Thank you for listening. Feel free to contact me: @y0n3uchy

(@lmt_swallow) https://shift-js.info