Counting in Regexes Considered Harmful:
Exposing ReDoS Vulnerability of Nonbacktracking Matchers

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Brno University of Technology, Czech Republic

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USENIX Security'22

Regular Expression Denial of Service (ReDoS)

What is a ReDoS? (in this talk)

- DoS by giving a regex matcher a hard input text

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`normal.txt` (500 kB):

```
abcdefghijklmopqrstuvwxyz01234
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```
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`evil.txt` (500 kB):

```
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aaaaaaaaaaaaaaaaaaaaaaaaaaaaa...
```

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19× slower!

(this may be a ReDoS)

(. . . and this is only a very simple example)

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ReDoS

Real-world threat

- Stack Overflow, 2016: 34 minute outage (regex `"␣+$"`; line `"␣␣...␣a"` — $\overbrace{\text{␣␣...␣}}^{20{,}000\times}$)
- ReDoS vulnerability in Express.js (package `negotiator`), 2016
- ReDoS vulnerability in Node.js (package `url-regex`), 2020
- ...

Often caused by the use of backtracking matchers (PHP, JS, Perl, Ruby, .NET, ...)

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Solution: Use nonbacktracking matchers!

The Case of the Poisoned Event Handler: Weaknesses in the Node.js Event-Driven Architecture

James Davis, Virginia Tech, Blacksburg, VA, USA, davisjam@vt.edu
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A hybrid regex engine Except for back references, every feature of JavaScript regular expressions can be supported by a linear-time regular expression engine. As back

Freezing the Web: A Study of ReDoS Vulnerabilities in JavaScript-based Web Servers

Cristian-Alexandru Staicu, *Department of Computer Science, TU Darmstadt*
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Another defense mechanism could be to use a more sophisticated regular expression engine that guarantees linear matching time. The problem is that these en-

Testing Regex Generalizability And Its Implications: A Large-Scale Many-Language Measurement Study

James C. Davis, Daniel Moyer, and Ayaan M. Kazerouni, Department of Computer Science, Virginia Tech, {davisjam, dmoyer, ayaan}@vt.edu
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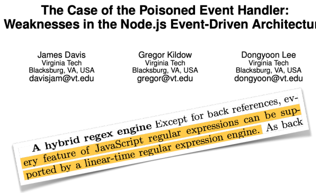
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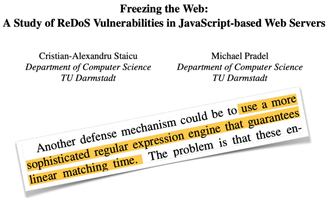
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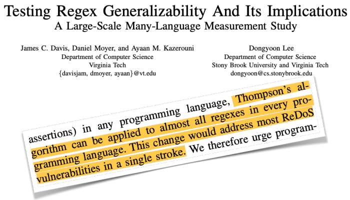
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...or is it?

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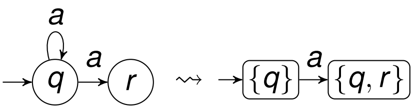
Nonbacktracking matchers

Nonbacktracking matchers:

- textbook: construct NFA, **determinize** ($\mathcal{O}(2^{|A|})$), perform match — linear time
  - $\rightsquigarrow$ DFA might be too big!! (often thousands, millions of macrostates)



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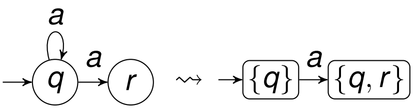
  3. **cache!** $\rightsquigarrow$ $\mathcal{O}(|w|)$ average-case complexity



- tools: `grep`, `re2`, Rust, SRM, HYPERSCAN*

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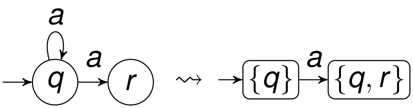

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- How can we systematically generate ReDoS texts for nonbacktracking matchers?

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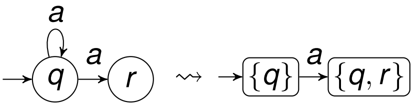

- tools: `grep`, `re2`, Rust, SRM, HyperScan*
- can still run slow! due to low cache utilization
- How can we systematically generate ReDoS texts for nonbacktracking matchers?
- Exploit **counting**! (a.k.a. quantifiers, bounded repetition, . . .)

Counting in regexes

`a{5,42}` `b{100}`

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How much are counting regexes prone to ReDoS?

- 609,992 regexes (GitHub, SNORT, Bro, RegExLib, Microsoft, TrustPort, …)
- removed unsupported (look-arounds/back-references/…)
- $\rightsquigarrow$ 443,265 regexes
- classify according to sum of upper bounds in counting, e.g., `a{5, 42 }`
- DFA Big: ≥1,000 states (often the size of DFA cache)

regex set	**#**	**#DFA big**	**%**
no counting	395,752	175	0.04 %
counting bounds ≤20	39,414	343	0.8 %
counting bounds >20	8,099	1,600	20. %

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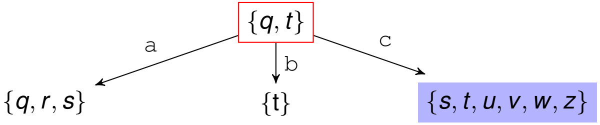
ReDoS generator for nonbacktracking matchers

- generate input text by search through the DFA
  - generate non-matching text
  - prefer macrostates that are
    1. unvisited (matcher cache miss)
    2. big (hard to compute successors)



  - $\rightsquigarrow$ try to enforce $\mathcal{O}(|w| \cdot |A|)$ runtime ($A =$ the NFA; $|A| = |Q| + |\Delta|$)

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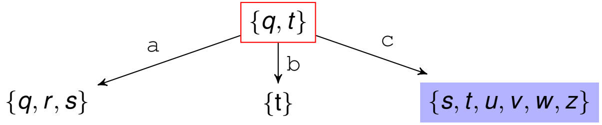

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  - DFA too big, cannot construct!
  - $\rightsquigarrow$ instead of DFA, use **Counting-Set Automaton** [OOPSLA'20]
    - allows compact deterministic representation of regexes with counting

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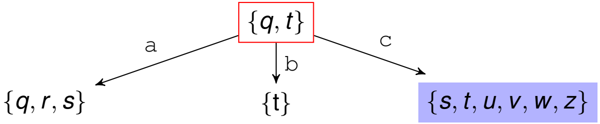

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- ReDoS generator `GadgetCA`

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Experiments

Dataset:

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- they target backtracking matchers

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$\sim$50 MB input text from each generator for each regex and try on different matchers

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How many ReDoSes could we generate?

- ReDoS: time $>100\times$ longer than average for matcher on random input
  - results for other ReDoS criteria in the paper
- **`GadgetCA`**: different strategies for exploring the counting-set automaton
  - **OneLine**: special strategy to target HyperScan

Generators		$>100\times$ **AVG$_{REGEX}$-ReDoS attacks** (8,099 regexes)												
		grep	**re2**	**rust**	**srm**	**hyper-scan**	**ca**	**ruby**	**php**	**perl**	**python**	**java**	**java-Script**	**.NET**
`GadgetCA`	**Counting**	1157	1465	1066	279	2	3	1085	796	1252	407	142	140	171
`GadgetCA`	**OneLine**	966	15	57	16	23	0	199	9	208	277	232	228	238
`GadgetCA`	**Greedy**	878	14	57	12	0	0	164	9	174	232	190	194	203
`GadgetCA`	**Random**	1066	320	292	130	0	0	153	156	266	91	63	60	72
`RXXR2`		1	0	2	0	0	0	10	0	4	22	8	8	20
`RegexCheck`		4	0	4	0	0	0	3	0	0	4	3	2	2
`RegexStatic`		47	5	5	0	0	0	80	14	49	137	125	134	90
`Rescue`		1	2	4	0	0	1	12	2	6	15	7	6	14
		nonbacktracking						**backtracking**						

(**ca**: our matcher based on counting-set automata)

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Real-world security solutions

Real-life SNORT rule-sets (Emerging Threats Pro and 3CORESec, Talos)

- filtered out unsupported regexes and those with the sum of repetition bounds ≤ 20
- obtained 1,112 regexes (from 22,425)
- slowdown of **evil** vs. **random** text

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- HYPERSCAN: no cache (modified alg.)
- TCP reassembly off
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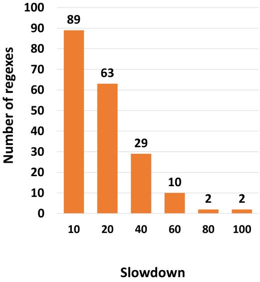

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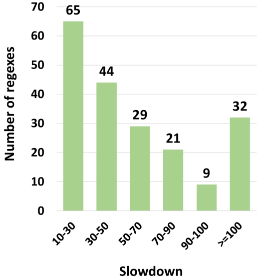

SNORT3@HYPERSCAN (9 kB)

examples	**1.5 kB**	**9 kB**
`"[?&]u=[^&\s]{35}"`	79×	214×
`"src\s*\x3D(3D)?\s*['"][^'"]{244}"`	71×	164×
`"[?&](cmd|pwd|usr)=[^&]{64}"`	43×	108×

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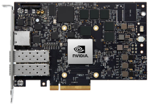
NVIDIA BlueField-2

- DPU: data processing unit (ASIC)
- 2×25 GbE interfaces, 8 ARMs
- HW-accelerated regex matching unit: ∼40 Gbps
- 100 GB files (continuous)
- 617 regexes (from 1,112; unsupported: 495)



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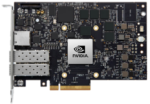

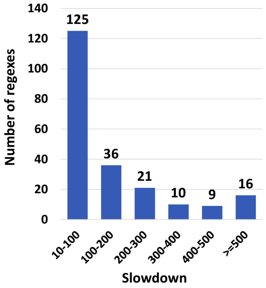

NVIDIA BlueField-2

examples	slowdown
"\sPARTIAL.*BODY\.PEEK\[[^\]]{1024}"	2,194×
"\s{230,}\.htr"	956×
"object\s[^>]*type\s*=\s*[\x22\x27][^\x22\x27]*\x2f{32}"	655×

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Conclusion

- nonbacktracking regex matchers are **NOT** a silver bullet against ReDoS
- they can still be slowed down, often by attacking counting, e.g., `a{100}`
- generator that can exploit counting — **`GadgetCA`**

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- mitigation:
  - obvious ones (time limit, input limit, disallow counting)
  - overapproximate: `a{5,42}` ⇝ `a*`
  - detect vulnerable regexes with **`GadgetCA`**
  - use better regex matching technology (e.g., counting-set automata)

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Thank you!

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Appendix

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Generators		>100×$AVG_{MATCHER}$-ReDoS attacks												
		grep	re2	rust	srm	hyper-scan	ca	ruby	php	perl	python	java	java-Script	.NET
GadgetCA	GREEDY	1741	15	95	18	2	40	260	38	382	367	328	314	431
GadgetCA	COUNTING	2457	742	1016	300	5	67	1355	1596	1473	277	279	258	416
GadgetCA	RANDOM	2033	120	122	289	3	46	348	388	412	176	177	117	258
GadgetCA	ONELINE	1796	17	99	23	20	53	322	34	441	448	405	379	521
RXXR2		13	0	2	0	0	1	24	0	5	30	10	10	34
RegexCheck		104	0	5	0	1	0	7	1	7	11	8	4	14
RegexStatic		93	1	9	0	1	7	159	50	80	263	253	243	279
Rescue		12	0	3	0	0	2	23	2	5	23	13	12	26

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		grep	re2	rust	srm	hyper-scan	ca	ruby	php	perl	python	java	java-Script	.NET
GadgetCA	GREEDY	192	72	76	238	0	61	1087	1408	56	200	215	210	390
GadgetCA	COUNTING	216	110	96	272	0	45	1724	1979	89	218	242	211	419
GadgetCA	RANDOM	126	28	48	123	0	46	682	885	60	160	181	111	334
GadgetCA	ONELINE	192	17	32	23	0	56	333	40	187	433	414	378	584
RXXR2		7	0	2	0	0	1	24	0	4	30	11	11	34
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RegexStatic		34	1	5	0	0	8	160	63	69	262	253	243	285
Rescue		12	0	3	0	0	2	23	3	4	23	13	12	27
random text		52	4	11	17	0	82	33	47	23	109	162	36	231

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Generators		>10s-ReDoS attacks												
		grep	re2	rust	srm	hyper-scan	ca	ruby	php	perl	python	java	java-Script	.NET
GadgetCA	GREEDY	1058	703	274	311	1	135	5050	6580	837	1027	485	955	2629
	COUNTING	1181	1116	295	391	3	121	5440	6289	1294	1503	532	1317	3000
	RANDOM	713	135	259	242	1	106	4405	5389	361	523	385	410	2025
	ONELINE	576	17	78	30	6	130	540	69	402	678	637	485	1448
RXXR2		11	0	2	0	0	1	26	0	5	33	12	13	35
RegexCheck		25	0	3	0	1	0	7	3	7	18	15	9	36
RegexStatic		78	1	9	0	0	19	182	70	78	287	274	254	333
Rescue		11	0	3	0	0	4	24	2	5	26	13	13	28
random text		153	10	70	27	2	137	175	47	147	272	255	228	698

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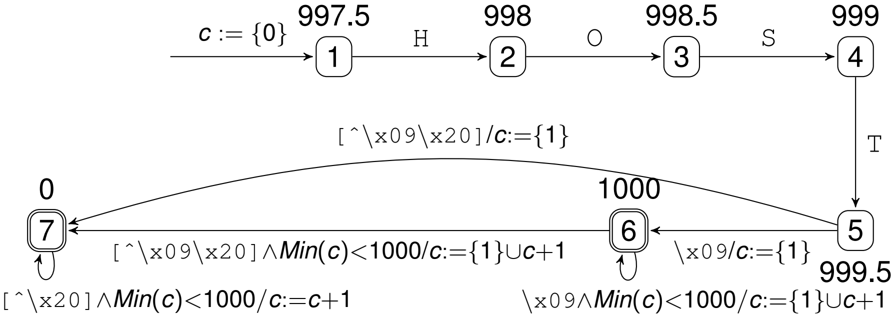
Counting-set automaton with weights



CSA with weights for the regex "^HOST\x09*[^\x20]{1000}"

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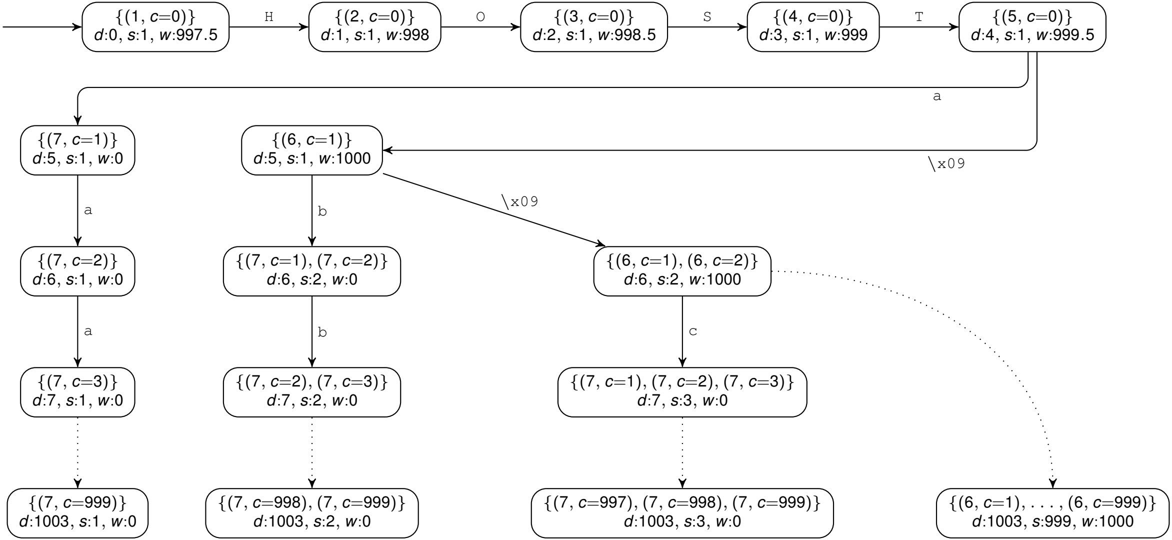

DFA states explored by our algorithm on the regex `"^HOST\x09*[^\x20]{1000}"`

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