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Extending the PCRE Library with Static Backtracking Based Just-in-Time Compilation Support

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Outline

- Motivation
- PCRE-JIT compiler
- Static backtracking
- Results
  - Raw backtracking performance
  - PCRE-JIT engine

Motivation

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History of Regular Expressions

- Kleene: regular sets in 1950s
- Thompson: Deterministic Finite Automaton (DFA) in 1960s
  - A pattern was constructed from character sets, and few operators: star, vertical bar
- Purpose of 'real' regular expressions
  - Defining a pattern which matches a set of words
  - /c|ab*/ matches c, a, ab, abb, abbb, …

Regular Expressions Today

- Henry Spencer: backtracking engine in 1980s (open source)
  - Nondeterministic Finite Automaton (NFA)
- Improved later by PERL developers
  - Command based pattern matching language
  - Backward compatible
  - Closer to scripting languages
- Context sensitive decisions
  - Reduces complexity

Matches only when fox is outside of <> brackets:

PERL: /<((?:[^<>]*+(?:<(?1)|))++>?)(*SKIP)(*F)|fox/

Matches: <<fox>fox>fox

No match: <fox<<>fox>fox>

No match: <<fox>fox

Multibyte character sequences:

PERL: /a(?>\r\n|\r|\n){2}b/

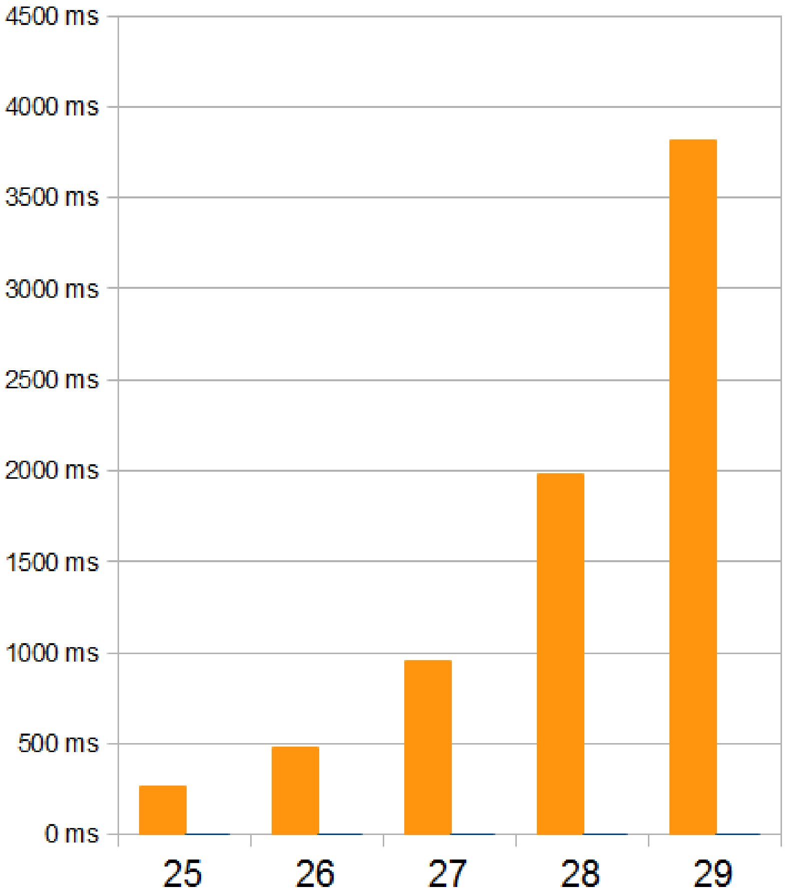
DFA: /a(?:\r(?:\n(?:\r\n|\r|\n)|\r\n)|\n\r\n?)b/

Matches: a\r\r\nb

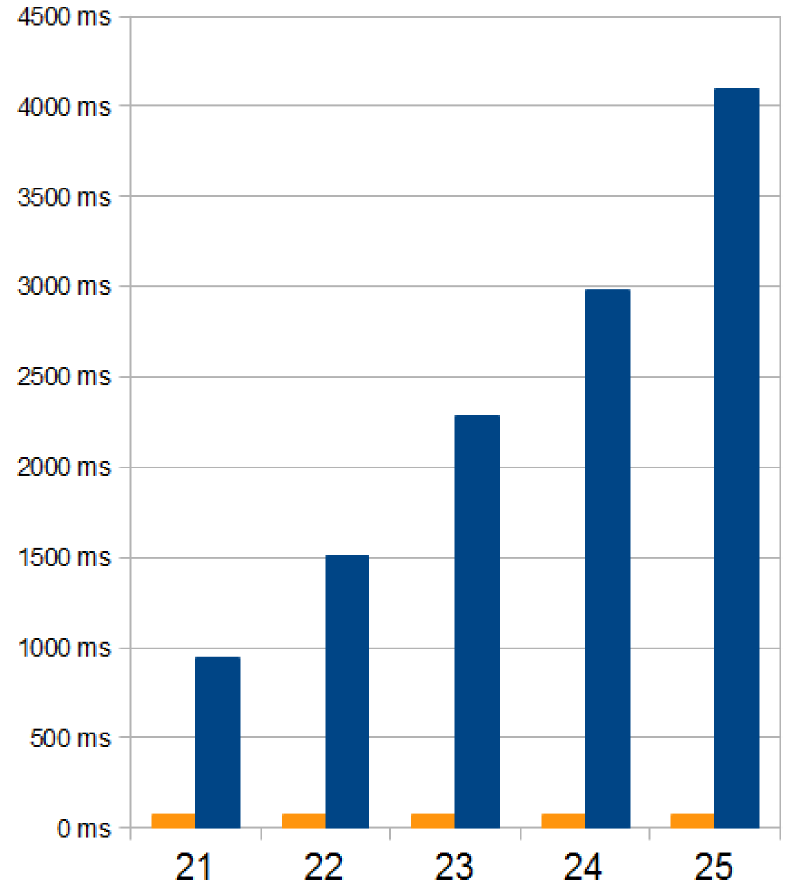
Matches: a\n\rb

No match: a\r\nb

/(x|x){n}y/



/a[^b]{n}abc/



PCRE RE2

Summary

- New approach is needed to accelerate these “regular expressions”
  - DFA is not enough anymore
- Command based languages can be efficiently accelerated by Just-in-time (JIT) compilation
  - 2009 Irregexp
  - 2009 YARR (Yet Another Regex Runtime)
  - 2011 PCRE-JIT

PCRE-JIT compiler

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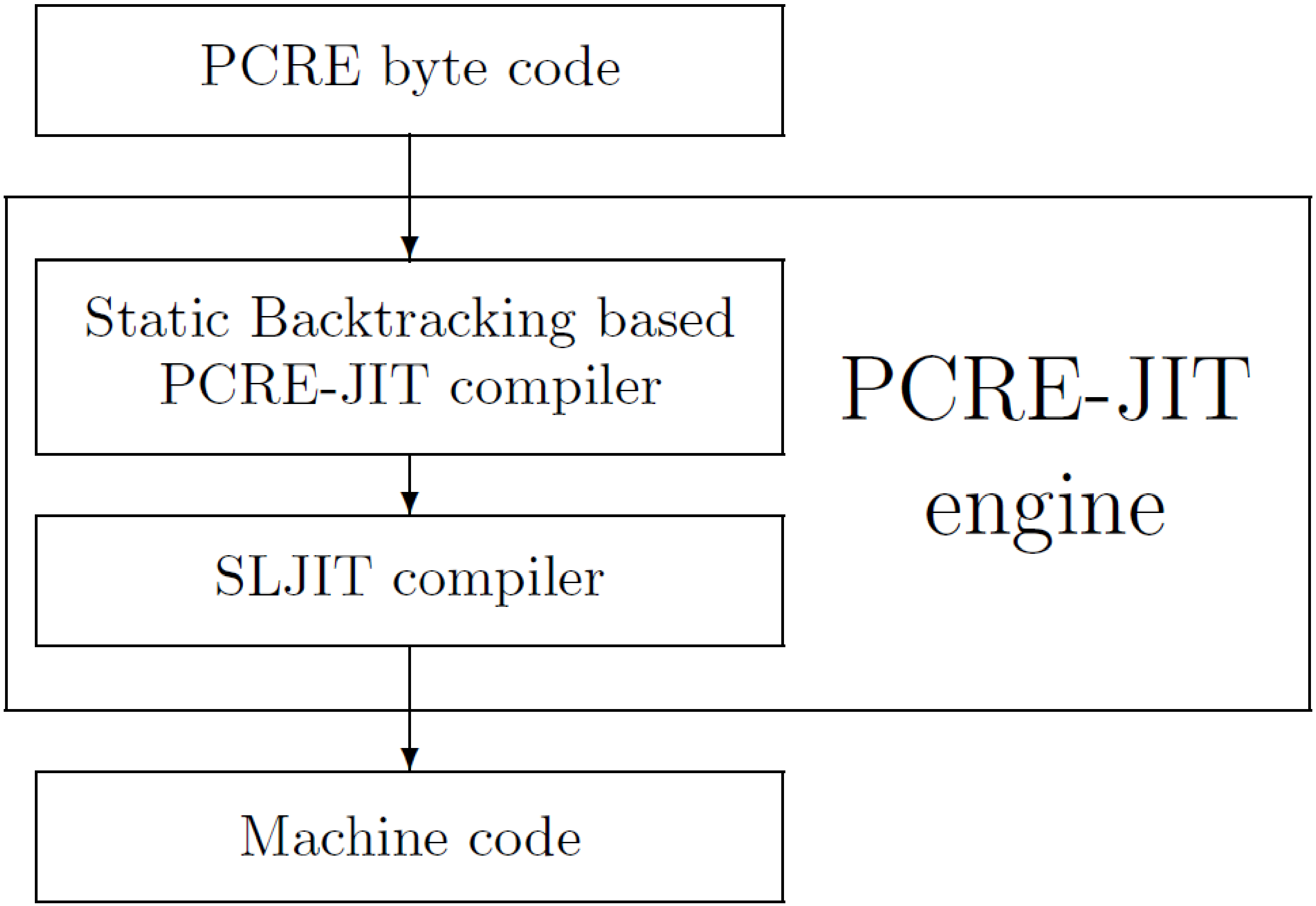
PCRE Overview

- Perl Compatible Regular Expressions
  - Standalone C library, which supports PERL style patterns
- Started by Philip Hazel in 1997
- PCRE-JIT supports all of its features
  - Comparison of regular expression engines in Wikipedia: Only PCRE supports all 19 categories

http://en.wikipedia.org/wiki/Comparison_of_regular_expression_engines

Main Components of PCRE-JIT



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SLJIT Compiler

- Low-level assembly like language
  - Translated to machine code
- Platform independent
  - LIR is designed by uniting the common features of CPUs
- Supported architectures
  - x86-32/64, ARMv5/7/Thumb2, PowerPC-32/64, MIPS-32, SPARC-32
  - ARM-64 is close to done

Evolution of Backtracking Algorithms

Interpreting (?:B)+ Pattern

```
boolean recursive_match() {
  // Infinite loop for tail merging.
  while (TRUE) {
    switch (*current_opcode) {
    // ...

    case GREEDY_PLUS_CLOSE_BRACKET:
      if (recursive_match() == SUCCESS)
        return SUCCESS
      // Tail merge.
      current_opcode += opcode_size(
                GREEDY_PLUS_CLOSE_BRACKET)
      // Back to the while loop.
      break;

    // ...
    }
  }
}
```

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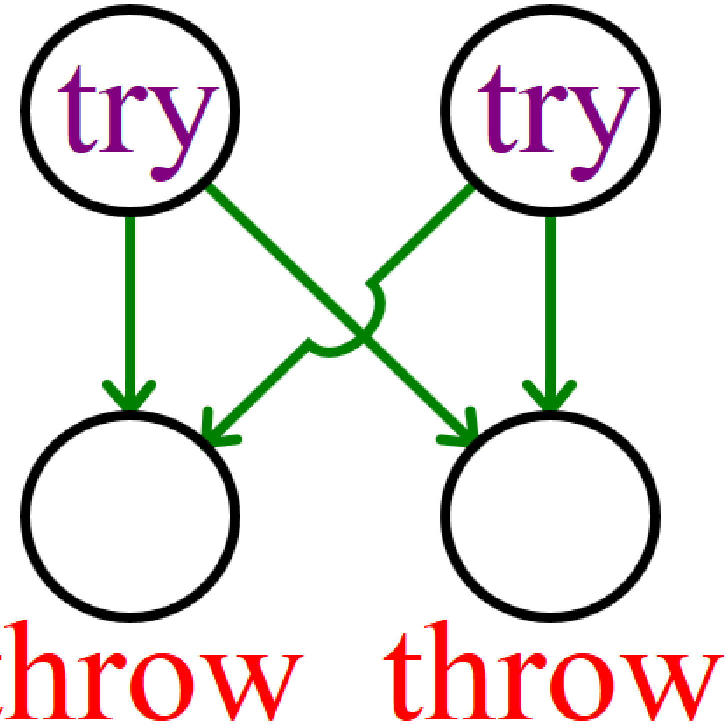
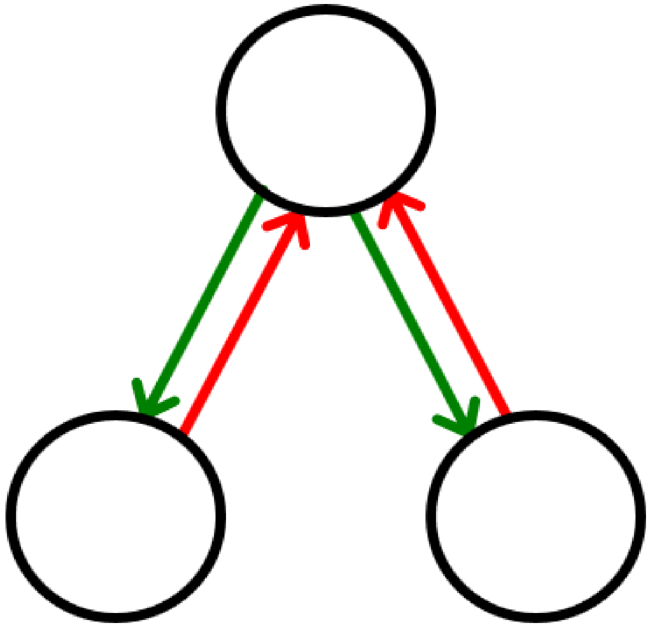
Static Backtracking

- JIT compilers replaced recursive function calls to try-catch blocks
  - Unknown destination when backtracking
- Our new approach: **Static Backtracking**
- Generating code from Abstract Syntax Tree (AST)
  - Each node has exactly one parent node, and it is known at compile time

Nondeterministic Finite Automaton



Abstract Syntax Tree



Continue matching: green lines
Perform backtracking: red lines / texts

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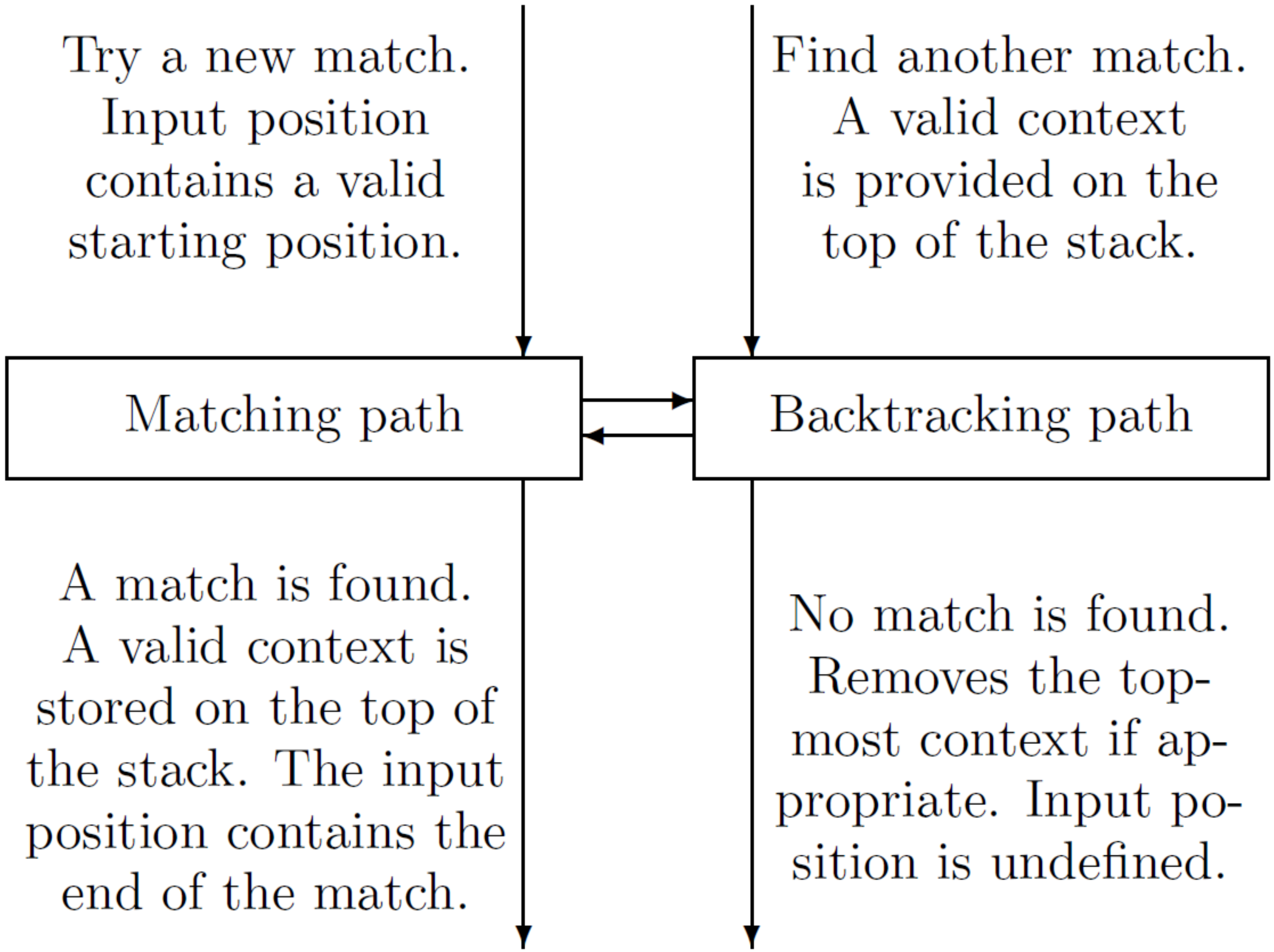
Static Backtracking (2)

- Not all NFAs are supported
  - Enough for PERL compatible patterns: they are always compiled to an AST first
- Context dependent backtracking
- No need to set-up catch handlers
- Direct, conditional jumps
  - Indirect jumps are usually not conditional: two jumps are needed for checking a condition and backtrack on fail

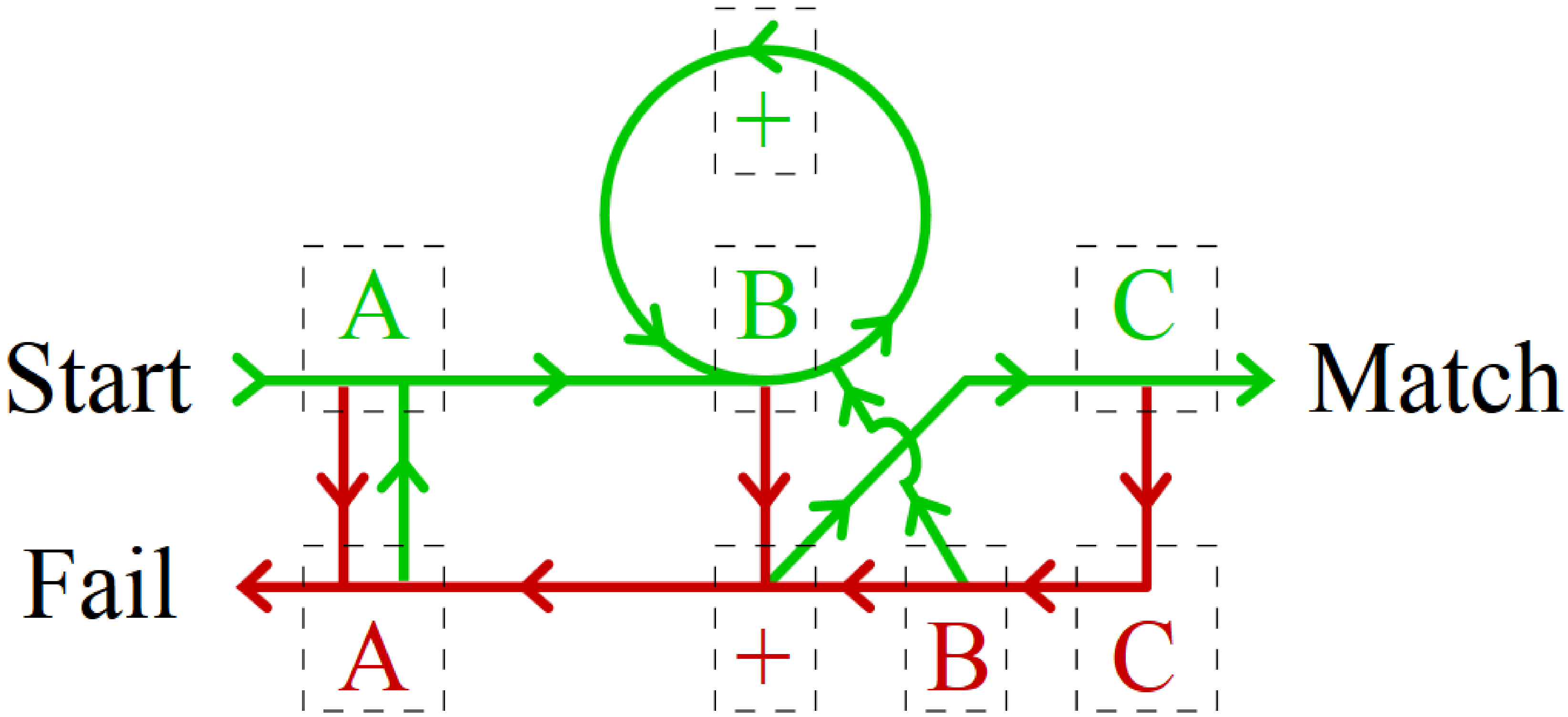
Overview of Building Blocks

- Two code paths are generated from each AST node
  - Matching path: action
  - Backtracking path: reverse action
- These two code paths form a single function
  - With two entry, two exit points
  - Optimization: these points can represent passing or returning a boolean value

Basic Building Block



Control Flow of /A(?:B)+C/



Matching path color: green

Backtracking path color: red

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Results

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Raw Backtracking Performance

- Measured on pathological cases
  - Exponential runtime, large amount of backt.
- Compared to Irregexp (in V8 JavaScript engine)
  - Traditional (indirect jump) based backtracking
  - Highly optimized engine
- These patterns cannot be optimized by backtracking elimination techniques
  - E.g: expected character check

Pathological Cases

	Pattern	Input	Irregexp (ms)	Irregexp ratio	PCRE JIT (ms)	PCRE JIT ratio
1	$/a?^{26}c\vert/$	$a^{26}bc$	777.0	2.20	$\underline{352.5}$	$\underline{1.00}$
2	$/a+^{14}c\vert/$	$a^{26}b^{14}c$	221.6	1.21	$\underline{182.8}$	$\underline{1.00}$
3	$/(?:a+)+c\vert/$	$a^{23}bc$	101.2	1.44	$\underline{70.5}$	$\underline{1.00}$
4	$/(?:(?:a)+)+c\vert/$	$a^{23}bc$	102.8	1.20	$\underline{85.9}$	$\underline{1.00}$
5	$/(?:(?:aa)+)+c\vert/$	$a^{46}bc$	99.5	1.18	$\underline{84.2}$	$\underline{1.00}$
6	$/((a)+)+c\vert/$	$a^{23}bc$	220.1	1.70	$\underline{129.2}$	$\underline{1.00}$
7	$/(?:(?:(?:aa)+)+)+c\vert/$	$a^{30}bc$	217.7	2.14	$\underline{101.7}$	$\underline{1.00}$
8	$/(((aa)+)+)+c\vert/$	$a^{28}bc$	364.6	2.16	$\underline{168.6}$	$\underline{1.00}$
9	$/(?:a\vert a)^{26}c\vert/$	$a^{26}bc$	$\underline{110.5}$	$\underline{1.00}$	400.7	3.63
10	$/(?:aa\vert a)^{24}c\vert/$	$a^{48}bc$	194.2	1.93	$\underline{100.4}$	$\underline{1.00}$
11	$/(aa\vert a)^{24}c\vert/$	$a^{48}bc$	179.4	1.15	$\underline{155.6}$	$\underline{1.00}$

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Overall Speedup

- Benchmark set provided by SNORT Intrusion Detection System (IDS)
  - >1000 HTTP content filtering patterns
- Compared to PCRE Interp. , and Irregexp
  - All engine optimizations are enabled (including backtracking eliminations)
- Backtracking is not a rare event
  - About 46% of matching attempts are failed in the PCRE interpreter

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PCRE-JIT vs PCRE Interpreter

Target CPU	Average speedup (x as fast)	< 3.0 x as fast		$3.0 - \infty$ x as fast	
		% of patterns	% of total runtime	% of patterns	% of total runtime
x86/32	6.84	84.99%	3.66%	15.01%	96.34%
x86/64	5.55	82.92%	3.80%	17.08%	96.20%
ARM-V7/32	6.76	82.24%	3.71%	17.76%	96.29%
ARM-THUMB2/32	7.24	84.59%	3.78%	15.41%	96.22%
PowerPC/32	5.48	88.13%	6.47%	11.87%	93.53%
PowerPC/64	5.55	88.42%	6.38%	11.58%	93.62%
SPARC/32	5.85	83.61%	4.08%	16.39%	95.92%
MIPS/32	7.59	81.35%	3.27%	18.65%	96.73%
Average	6.36	84.53%	4.39%	15.47%	95.61%
Std. dev.	0.79	2.42%	1.19%	2.42%	1.19%

Overall: PCRE-JIT is 1.63x faster than Irregexp

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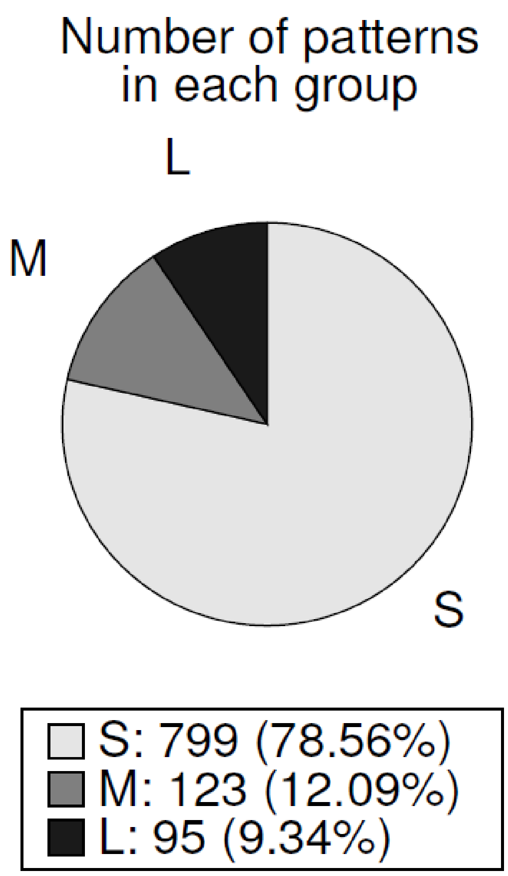

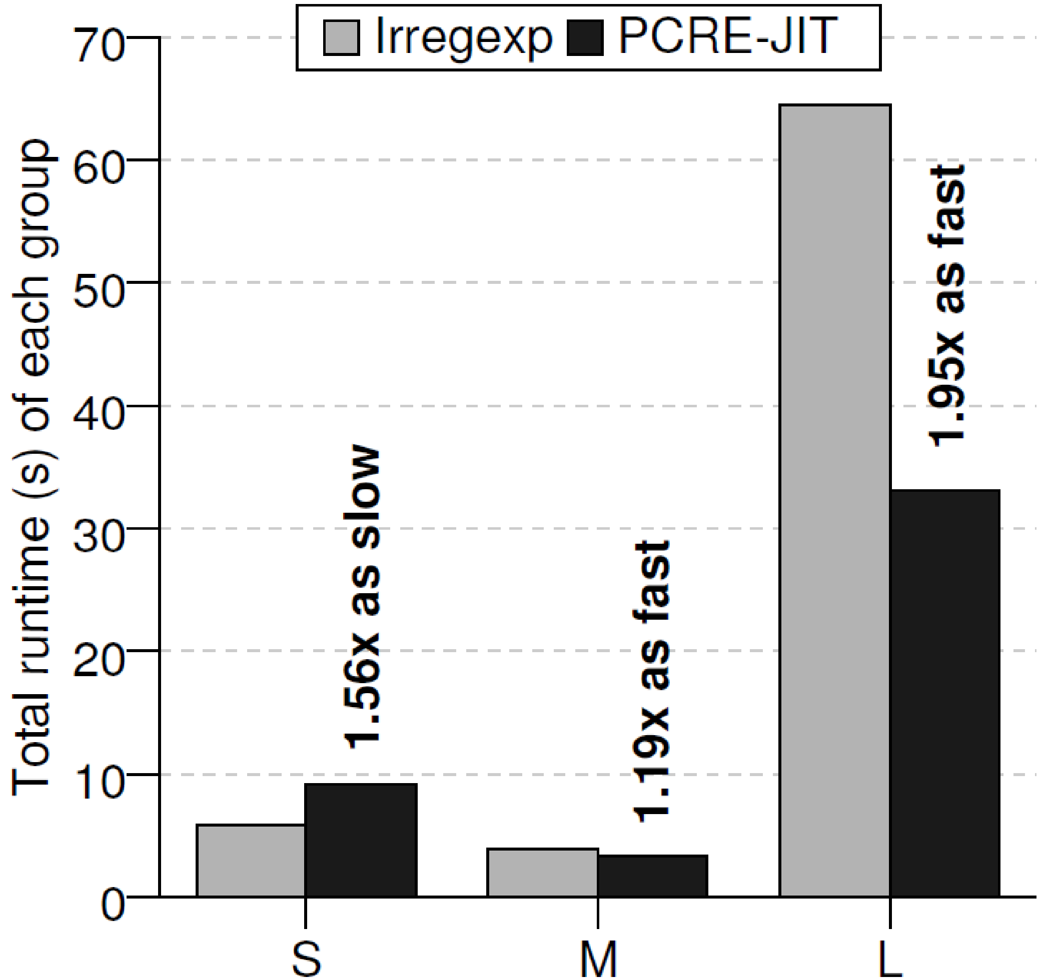

S: Patterns with short runtime (0-20 ms)
M: Patterns with medium runtime (20-200 ms)
L: Patterns with long runtime (200-2000ms)

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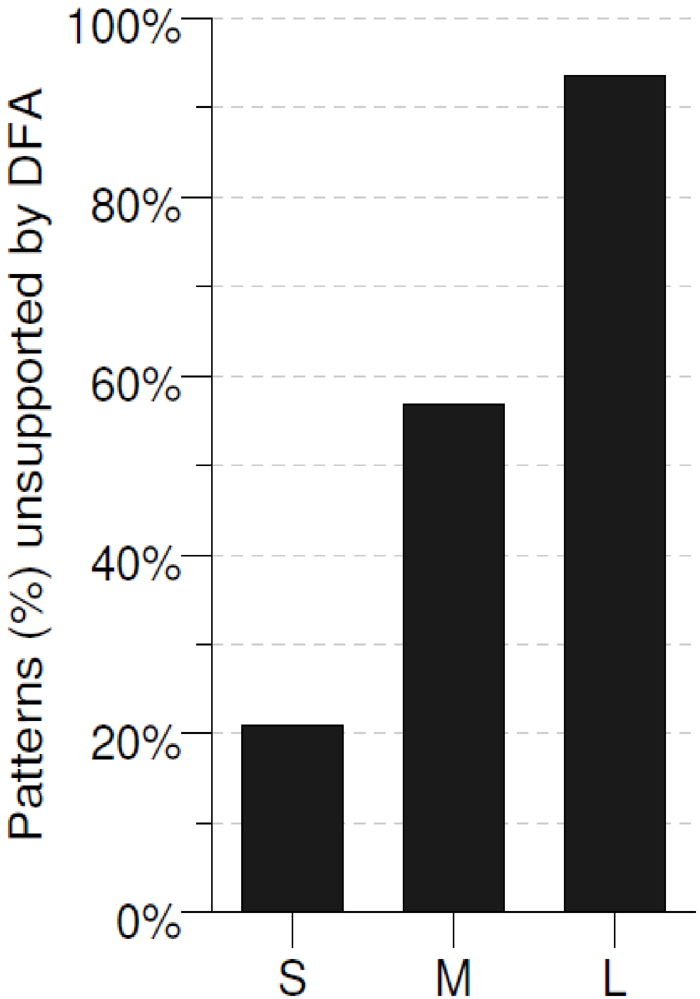
Patterns(%) Unsupported by DFA



- Most patterns in group L are not supported by DFA based engines!
- DFA is not a viable option to accelerate these long running patterns

Conclusion and Future Work

Conclusion

- Regular expressions are changed
  - Better to optimize them using JIT compiling
- Traditional NFA based backtracking can be improved by AST based backtracking
  - Context dependent backtracking
- Results (SNORT benchmark set)
  - 6.36x faster than interpreter
  - 1.63x faster than Irregexp

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Future Work

- Further improve the JIT compiler
  - Integrating optimizations used by other engines
  - A simplified Boyer-Moore string search was already implemented
- Support more CPUs (in SLJIT)
  - MIPS-64, SPARC-64

PCRE-JIT Is Production Ready

- NGINX Web Server
- Qt Framework (since 5.0)
- Suricata Intrusion Detection System
- Apache ModSecurity Firewall
- GNU grep (with -P option)
- HAProxy Load Balancer
- Sigil E-book Editor

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Thanks for listening

Questions?