Exploring Regular Expression Usage and Context in Python

ABSTRACT

Due to the popularity and pervasive use of regular expressions, researchers have created tools to support their creation, validation, and use. However, little is known about the context in which regular expressions are used, the features that are most common, and how behaviorally similar regular expressions are to one another.

In this paper, we explore the context in which regular expressions are used through a combination of developer surveys and repository analysis. We survey 18 professional developers from a small software company about their regular expression usage and pain points. Our results indicate that developers frequently use regular expressions in their programming practices, often composing regular expressions at least weekly. Then, we analyzed nearly 4,000 open source Python projects from GitHub and extracted nearly 14,000 unique regular expression patterns that were used for analysis, focusing on how often distinct features are used. We also map the most common features used in regular expressions to those features supported by four common regular expression engines from industry and academia: brics, Hampi, RE2, and Rex. Using similarity analysis of regular expressions across projects, we identify six common behavioral clusters that describe how regular expressions are often used in practice. This is the first rigorous examination of regex usage and it provides empirical evidence to support design decisions by regex tool builders. It also points to areas of needed future work, such as refactoring regular expressions to increase refactoring understandability, support for migrating regexes between language, and context-specific tool support for common regexes usages.

1. INTRODUCTION

Regular expressions (regexes) are an abstraction of keyword search that enables the identification of text using a pattern instead of an exact keyword. Regexes are commonly used for parsing text using a general purpose language like Python, validating content entered into web forms using Javascript, and searching text files for a particular pattern using tools like grep, vim or Eclipse.

Although regexes are powerful and versatile, they can be hard to understand, maintain, and debug, resulting in tens of thousands of bug reports [30].

Due in part to their common use across programming languages and how susceptible regexes are to error, many researchers and practitioners have developed tools to support more robust regex creation [30] or to allow visual debugging [6]. Other research has focused on learning regular expressions from text [4, 21], avoiding human composition altogether. Researchers have also explored applying regexes to test case generation [2, 15, 16, 31], as specifications for string constraint solvers [18, 32] and using regexes as queries in a data mining framework [7]. Regexes are also employed in critical missions like mysql injection prevention [35] and network intrusion detection [26], or in more diverse applications like DNA sequencing alignment [3].

Regex researchers and tool designers must pick what features to include or exclude, which can be a difficult design decision. Supporting advanced features may be more expensive, taking more time and potentially making the project too complex and cumbersome to execute well. A selection of only the simplest of regex features limits the applicability or relevance of that work. Despite extensive research effort in the area of regex support, no research has been done about how regexes are used in practice and what features are essential for the most common use cases.

The goal of this work is to explore 1) the context in which developers use regular expressions, and 2) the features and similarities of regular expressions found in Python[1] projects.

First, we survey professional developers about how they use regexes and their pain points. Second, we gather a sample of regexes from Python projects and analyze the frequency of feature usage (e.g., kleene star: $*$ and the end anchor: $ are features). Third, we investigate what features are supported by four large projects that aim to support regex usage (brics [25], hampi [18], Rex [33], and RE2 [28]), and which features are not supported, but are frequently used by developers. Finally, we cluster regular expressions that appear in multiple projects by behavior, investigating high-level behavioral themes in regex usage.

Our results indicate that regexes are most frequently used in command line tools and IDEs. Capturing the contents of

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[1]Python is the fourth most common language on GitHub (after Java, Javascript and Ruby) and Python's regex pattern language is close enough to other regex flavors that our conclusions are likely to generalize.

brackets and searching for delimiter characters were some of the most apparent behavioral themes observed in the regex clusters created by our technique, and we also recognized a common behavioral cluster of regexes intended to parse source code. The contributions of this work are:

- A survey of 18 professional software developers about their experience with regular expressions,

- An empirical analysis of regex feature usage in nearly 14,000 regular expressions in 3,898 open-source Python projects, mapping of those features to those supported by common regex tools and survey results showing the impact of not supporting various features,

- An approach for measuring behavioral similarity of regular expressions and qualitative analysis of the most common behaviorally similar clusters, and

- An evidence-based discussion of opportunities for future work in supporting programmers in writing regular expressions, including refactoring regexes and migration support between languages.

2. RELATED WORK

Regular expressions have been a focus point in a variety of research objectives. From the user perspective, tools have been developed to support more robust creation [30] or to allow visual debugging [6]. Building on the perspective that regexes are difficult to create, other research has focused on removing the human from the creation process by learning regular expressions from text [4, 21].

Regarding applications, regular expressions have been used for test case generation [2,15,16,31], and as specifications for string constraint solvers [18, 32]. Regexes are also employed in critical missions like mysql injection prevention [35] and network intrusion detection [26], or in more diverse applications like DNA sequencing alignment [3] or querying RDF data [1, 20].

As a query language, lightweight regular expressions are pervasive in search. For example, some data mining frameworks use regular expressions as queries (e.g., [7]). Efforts have also been made to expedite the processing of regular expressions on large bodies of text [5].

Research tools like Hampi [18], and Rex [33], and commercial tools like brics [25] and RE2 [28], all support the use of regular expressions in various ways. Hampi was developed in academia and uses regular expressions as a specification language for a constraint solver. Rex was developed by Microsoft Research and generates strings for regular expressions that can be used in applications such as test case generation [2,31]. Brics is an open-source package that creates automata from regular expressions for manipulation and evaluation. RE2 is an open-source tool created by Google to power code search with an efficient regex engine.

Mining properties of open source repositories is a well-studied topic, focusing, for example, on API usage patterns [22] and bug characterizations [12]. Exploring language feature usage by mining source code has been studied extensively for Smalltalk [8,9], JavaScript [29], and Java [14, 17,23,27], and more specifically, Java generics [27] and Java reflection [23]. To our knowledge, this is the first work to mine and evaluate regular expression usages from existing

```
          function          pattern                flags
r1 = re.compile('(0|-?[1-9][0-9]*)$', re.MULTILINE)
```

Figure 1: Example of one regex utilization

software repositories. Related to mining work, regular expressions have been used to form queries in mining framework [7], but have not been the focus of the mining activities. Surveys have been used to measure adoption of various programming languages [13, 24], and been combined with software repository analysis [24], but have not focused on regular expressions.

3. STUDY

To understand how programmers use regular expressions in Python projects, we scraped 3,898 Python projects from GitHub, and recorded regex usages for analysis. Throughout the rest of this paper, we employ the following terminology:

Utilization: A *utilization* occurs whenever a developer uses a regex in a project. We detect utilizations by recording all calls to the `re` module in Python. Within a particular file in a project, a utilization is composed of a function, a pattern, and 0 or more flags. Figure 1 presents an example of one regex utilization, with key components labeled. The function call is `re.compile`, `(0|-?[1-9][0-9]*)$` is the regex string, or pattern, and `re.MULTILINE` is an (optional) flag. This utilization will compile a regex object in the variable `r1` from the pattern `(0|-?[1-9][0-9]*)$`, with the `$` token matching at the end of each line because of the `re.MULTILINE` flag. Thought of another way, a regular expression utilization is one single invocation of the `re` library.

Pattern: A *pattern* is extracted from a utilization, as shown in Figure 1. In essence, it is a string, but more formally it is an ordered series of regular expression language feature tokens. The pattern in Figure 1 will match if it finds a zero at the end of a line, or a (possibly negative) integer at the end of a line (i.e., due to the `-?` sequence denoting zero or one instance of the `-`).

Note that because the vast majority of regex features are shared across most general programming languages (e.g., Java, C, C#, or Ruby), a Python pattern will (almost always) behave the same when used in other languages, whereas a utilization is not universal in the same way (i.e., it may not compile in other languages, even with small modifications to function and flag names). As an example, the `re.MULTILINE` flag, or similar, is present in Python, Java, and C#, but the Python `re.DOTALL` flag is not present in C# though it has an equivalent flag in Java.

In this work, we primarily focus on patterns since they are cross-cutting across languages and are the primary way of specifying the matching behavior. Next, we describe the research questions, data set collection and analysis.

3.1 Research Questions

To understand the contexts in which regular expressions are used and feature usage, we perform a survey of developers and explore regular expressions found in Python projects on GitHub. We aim to answer the following research questions:

RQ1: In what contexts do professional developers use regular expressions?

We designed and deployed a survey about when, why, and how often they use regular expressions. This was completed by 18 professional developers at a small software company.

RQ2: How is the `re` module used in Python projects?

We explore invocations of the `re` module in 3,898 Python projects scraped from GitHub.

RQ3: Which regular expression language features are most commonly used in Python?

We consider regex language features to be tokens that specify the matching behavior of a regex pattern, for example, the `+` in `ab+`. All studied features are listed and described in Section 3.3 with examples. We then map the feature coverage for four common regex support tools, brics, hampi, RE2 and Rex, and explore survey responses regarding feature usage for some of the less supported features.

RQ4: How behaviorally similar are regexes across projects?

As this is a first step in understanding behavioral overlap in regexes, we measure similarity between pairs of regexes by overlap in matching strings. For each regex, matching strings are generated and then evaluated against each other regex to compute pairwise similarity. Then we use clustering to form behaviorally similar groupings.

3.2 Survey Design and Implementation

To understand the context of when and how programmers use regular expressions, we designed a survey, implemented using Google Forms, with 40 questions. The questions asked about regex usage frequency, languages, purposes, pain points, and the use of various language features.[2] Participation was voluntary and participants were entered in a lottery for a $50 gift card.

Our goal was to understand the practices of professional developers. Thus, we deployed the survey to 22 professional developers at Dwolla, a small software company that provides tools for online and mobile payment management. While this sample comes from a single company, we note anecdotally that Dwolla is a start-up and most of the developers worked previously for other software companies, and thus bring their past experiences with them. Surveyed developers have nine years of experience, on average, indicating the results may generalize beyond a single, small software company, but further study is needed.

3.3 Regex Corpus

Our goal was to collect regexes from a variety of projects to represent the breadth of how developers use the language features. Using the GitHub API, we scraped 3,898 projects containing Python code. We did so by dividing a range of about 8 million repo IDs for Python projects into 32 sections of equal size and scanning from the beginning of those segments until we ran out of memory. At that point, we felt we had enough data to do an analysis without further perfecting our mining techniques. We built the AST of each file in each project to find utilizations of the 're' module functions. In most projects, almost all regex utilizations are present in the most recent version of a project, but to be

Figure 2: Two patterns parsed into feature vectors

more thorough, we also scanned up to 19 earlier versions. The number 20 was chosen to try and maximize returns on computing resources invested after observing the scanning process in many hours of trial scans. All regex utilizations were obtained, sans duplicates. Within a project, a duplicate utilization was marked when two versions of the same file have the same function, pattern and flags. In the end, we observed and recorded 53,894 non-duplicate regex utilizations in 3,898 projects.

In collecting the set of distinct patterns for analysis, we ignore the 12.7% of utilizations using flags, which can alter regex behavior. An additional 6.5% of utilizations contained patterns that could not be compiled because the pattern was non-static (e.g., used some runtime variable). The remaining 80.8% (43,525) of the utilizations were collapsed into 13,711 distinct pattern strings. Each of the pattern strings was preprocessed by removing Python quotes (`'\\W'` becomes `\\W`), unescaping escaped characters (`\\W` becomes `\W`) and parsing the resulting string using an ANTLR-based, open source PCRE parser[3]. This parser was unable to support 0.5% (73) of the patterns due to unsupported unicode characters. Another 0.2% (25) of the patterns used regex features that we chose to exclude because appeared very rarely (e.g., reference conditions).

The 13,597 distinct pattern strings that remain were each assigned a weight value equal to the number of distinct projects the pattern appeared in. We refer to this set of weighted, distinct pattern strings as the *corpus*.

3.4 Analyzing Features

For each escaped pattern, the PCRE-parser produces a tree of feature tokens, which is converted to a vector by counting the number of each token present in the tree. For a simple example, consider the patterns in Figure 2. The pattern '`^m+(f(z)*)+`' contains four different types of tokens. It contains the kleene star (KLE), which is specified using the asterisk '`*`' character, additional repetition (ADD), which is specified using the plus '`+`' character, capture groups (CG), which are specified using pairs of parenthesis '`(...)`' characters, and the start anchor (STR), which is specified using the caret '`^`' character at the beginning of a pattern.

Once all patterns were transformed into vectors, we examined each feature independently for all patterns, tracking the number of patterns and projects that the each feature appears in at least once.

3.5 Clustering and Behavioral Similarity

An ideal analysis of similarity for regexes would use subsumption or containment analysis. However, we struggled to find a tool that could facilitate such an analysis. Further, regular expressions in modern code libraries are not the same as regular languages in formal language theory. Some features of regular expression libraries, such as backreferences, provide expressiveness beyond regular languages.

```
Pattern A matches 100/100 of A's strings
Pattern B matches  90/100 of A's strings
Pattern A matches  50/100 of B's strings
Pattern B matches 100/100 of B's strings
```

	A	B
A	1.0	0.9
B	0.5	1.0

Figure 3: A similarity matrix created by counting strings matched

	A	B	C	D
A	1.0	0.0	0.9	0.0
B	0.2	1.0	0.8	0.7
C	0.6	0.8	1.0	0.2
D	0.0	0.6	0.1	1.0

→

	A	B	C	D
A	1.0			
B	0.1	1.0		
C	0.75	0.8	1.0	
D	0.0	0.65	0.15	1.0

Figure 4: Creating a similarity graph from a similarity matrix

This allows a regular expression pattern to match, for example, repeat words, such as "cabcab", using the pattern (.+)\1. However, building an automaton to recognize such a pattern and to facilitate containment analysis, is infeasible. For these reasons, we developed a similarity analysis based on string matching.

Our similarity analysis clusters regular expressions by their behavioral similarity on matched strings. Consider two unspecified patterns A and B, a set mA of 100 strings that pattern A matches, and a set mB of 100 strings that pattern B matches. If pattern B matches 90 of the 100 strings in the set mA, then B is 90% similar to A. If pattern A only matches 50 of the strings in mB, then A is 50% similar to B. We use similarity scores to create a similarity matrix as shown in Figure 3. In row A, column B we see that B is 90% similar to A. In row B, column A, we see that A is 50% similar to B. Each pattern is always 100% similar to itself, by definition.

Once the similarity matrix is built, the values of cells reflected across the diagonal of the matrix are averaged to create a half-matrix of undirected similarity edges, as illustrated in Figure 4. This facilitates clustering using the Markov Clustering (MCL) algorithm[4]. We chose MCL because it offers a fast and tunable way to cluster items by similarity and it is particularly useful when the number of clusters is not known *a priori*.

In the implementation, strings are generated for each pattern using Rex [33]. Rex generates matching strings by representing the regular expression as an automaton, and then passing that automation to a constraint solver that generates members for it[5]. If the regex matches a finite set of strings smaller than 400, Rex will produce a list of all possible strings. Our goal is to generate 400 strings for each pattern to balance the runtime of the similarity analysis with the precision of the similarity calculations.

For clustering, we prune the similarity matrix to retain all similarity values greater than or equal to 0.75, setting the rest to zero, and then using MCL. This threshold was selected based on recommendations in the MCL manual. The impact of lowering the threshold would likely result in either the same number of more diverse clusters, or a larger number of clusters, but is unlikely to markedly change the largest

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[4]http://micans.org/mcl/
[5]http://research.microsoft.com/en-us/projects/rex/

Table 1: Survey results for number of regexes composed per year by technical environment (RQ1)

Language/Environment	0	1-5	6-10	11-20	21-50	51+
General (e.g., Java)	1	6	5	3	1	2
Scripting (e.g., Perl)	5	4	3	3	2	1
Query (e.g., SQL)	15	2	0	0	1	0
Command line (e.g., grep)	2	5	3	2	0	6
Text editor (e.g., IntelliJ)	2	5	0	5	1	5

clusters or their summaries, which are the focus of our analysis for RQ4 (Section 4.4), but further study is needed to substantiate this claim. We also note that MCL can be tuned using many parameters, including inflation and filtering out all but the top-k edges for each node. After exploring the quality of the clusters using various tuning parameter combinations, the best clusters (by inspection) were found using an inflation value of 1.8 and k=83. The top 100 clusters are categorized by inspection into six categories of behavior.

The end result is clusters and categories of highly behaviorally similar regular expressions, though we note that this approach has a tendency to over-approximate the similarity of two regexes. We measure similarity based on a finite set of generated strings, but some regexes match an infinite set (e.g., ab*c), so measuring similarity based on the first 400 strings may lead to an artificially high similarity value. To mitigate this threat, we chose a large number of generated strings for each regex.

4. RESULTS

Next, we present the results of each research question.

4.1 RQ1: How do developers use regexes?

The survey was completed by 18 participants (82% response rate) that identified as software developer/maintainers. Respondents have an average of nine years of programming experience ($\sigma = 4.28$). On average, survey participants report to compose 172 regexes per year ($\sigma = 250$) and compose regexes on average once per month, with 28% composing multiple regexes in a week and an additional 22% composing regexes once per week. That is, 50% of respondents uses regexes at least weekly. Table 1 shows how frequently participants compose regexes using each of several languages and technical environments. Six (33%) of the survey participants report to compose regexes using general purpose programming languages (e.g., Java, C, C#) 1-5 times per year and five (28%) do this 6-10 times per year. Regexes were rarely used in query languages like SQL, but for command line usage in tools such as grep, 6 (33%) participants use regexes 51+ times per year.

Table 2 shows how frequently, on average, the participants use regexes for various actives. Participants answered questions using a 6-point likert scale including very frequently (6), frequently (5), occasionally (4), rarely (3), very rarely (2), and never (1). Averaging across participants, among the most common usages are capturing parts of a string and locating content within a file, with both occurring somewhere between occasionally and frequently.

Using a similar 7-point likert scale that includes 'always' as a seventh point, developers indicated that they test their

Table 2: Survey results for regex usage frequencies for activities, averaged using a 6-point likert scale: Very Frequently=6, Frequently=5, Occasionally=4, Rarely=3, Very Rarely=2, and Never=1 (RQ1)

Activity	Frequency
Locating content within a file or files	4.4
Capturing parts of strings	4.3
Parsing user input	4.0
Counting lines that match a pattern	3.2
Counting substrings that match a pattern	3.2
Parsing generated text	3.0
Filtering collections (lists, tables, etc.)	3.0
Checking for a single character	1.7

Table 3: How saturated are projects with utilizations? (RQ2)

source	Q1	Avg	Med	Q3	Max
utilizations per project	2	32	5	19	1,427
files per project	2	53	6	21	5,963
utilizing files per project	1	11	2	6	541
utilizations per file	1	2	1	3	207

regexes with the same frequency as they test their code (average response was 5.2, which is between frequently and very frequently). Half of the 18 developers indicate that they use external tools to test their regexes, and the other half indicated that they only use tests that they write themselves. Of the nine developers using tools, six mentioned online composition aides such as regex101.com where a regex and input string are entered, and the input string is highlighted according to what is matched.

When asked an open ended question about pain points encountered with regular expressions, we observed three main categories. The most common, "hard to compose," was represented in 61% (11) responses. Next, 39% (7) developers responded that regexes are "hard to read" and 17% (3) indicated difficulties with "inconsistency across implementations," which manifest when using regexes in multiple languages. These responses do not sum to 18 as three developers provided multiple parts in their answers.

Summary - RQ1: Common uses of regexes include locating content within a file, capturing parts of strings, and parsing user input. The fact that all the surveyed developers compose regexes, and half of the developers use tools to test their regexes indicates the importance of tool development for regex. Developers complain about regexes being hard to read and hard to compose, and most of the tools that they indicate using are (suitably) focused on composition.

4.2   RQ2: How is the `re` module used?

We explore regex utilizations and flags used in the scraped Python projects. Out of the 3,898 projects scanned, 42.2% (1,645) contained at least one regex utilization. To illustrate how saturated projects are with regexes, we measure utiliza-
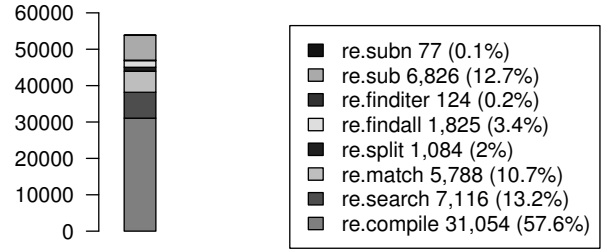

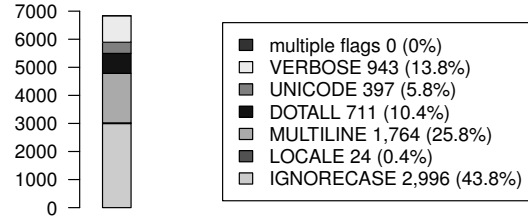**Figure 5: How often are `re` functions used? (RQ2)**

Legend:
- re.subn 77 (0.1%)
- re.sub 6,826 (12.7%)
- re.finditer 124 (0.2%)
- re.findall 1,825 (3.4%)
- re.split 1,084 (2%)
- re.match 5,788 (10.7%)
- re.search 7,116 (13.2%)
- re.compile 31,054 (57.6%)

Figure 6: Which behavioral flags are used? (RQ2)

Legend:
- multiple flags 0 (0%)
- VERBOSE 943 (13.8%)
- UNICODE 397 (5.8%)
- DOTALL 711 (10.4%)
- MULTILINE 1,764 (25.8%)
- LOCALE 24 (0.4%)
- IGNORECASE 2,996 (43.8%)

tions per project, files scanned per project, files contained utilizations, and utilizations per file, as shown in Table 3.

Of projects containing at least one utilization, the average utilizations per project was 32 and the maximum was 1,427. The project with the most utilizations is a C# project[6] that maintains a collection of source code for 20 Python libraries, including larger libraries like `pip`, `celery` and `ipython`. These larger Python libraries contain many utilizations. From Table 3, we also see that each project had an average of 11 files containing any utilization, and each of these files had an average of 2 utilizations.

The number of projects that use each of the `re` functions is shown in Figure 5. The y-axis denotes the total utilizations, with a maximum of 53,894. The `re.compile` function encompasses 57.6% of all utilizations, presumably because each usage of those functions can accept a regex object compiled using `re.compile` as an argument. (Note that compiled objects can also be used to call functions of the re module, ie `compiledObject.findall(...)`, but we ignore these utilizations so that our analysis is easier to automate, and because we are primarily interested in extracting the patterns which these 8 functions contain.)

When considering flag use, we excluded the default flag, which is built into the `re` module, and present internally whenever no flag is used. Of all utlizations, 87.3% had no flag, or explicitly specified the default flag. The debug flag, which causes the `re` regex engine to display extra information about its parsing process, was never observed. Figure 6 presents the number of projects in which each flag appears. Ignorecase (43.8%) and multiline (25.8%) were the most frequently used. Although multiple flags can be combined using a bitwise or, this was never observed.

Summary - RQ2: Only about half of the projects sampled contained any utilizations. Most utilizations used the `re.compile` function to compile a regex object before actually using the regex to find a match. Most utilizations did not use a flag to modify matching behavior.

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[6]https://github.com/Ouroboros/Arianrhod

Table 4: How frequently do features appear in projects? (RQ3)

rank	code	description	example	brics	hampi	Rex	RE2	nPatterns	% patterns	nProjects	% projects
1	ADD	one-or-more repetition	`z+`	●	●	●	●	6,003	44.1	1,204	73.2
2	CG	a capture group	`(caught)`	●	●	●	●	7,130	52.4	1,194	72.6
3	KLE	zero-or-more repetition	`.*`	●	●	●	●	6,017	44.3	1,099	66.8
4	CCC	custom character class	`[aeiou]`	●	●	●	●	4,468	32.9	1,026	62.4
5	ANY	any non-newline char	`.`	●	●	●	●	4,657	34.3	1,005	61.1
6	RNG	chars within a range	`[a-z]`	●	●	●	●	2,631	19.3	848	51.6
7	STR	start-of-line	`^`	○	●	●	●	3,563	26.2	846	51.4
8	END	end-of-line	`$`	○	●	●	●	3,169	23.3	827	50.3
9	NCCC	negated CCC	`[^qwxf]`	●	●	●	●	1,935	14.2	776	47.2
10	WSP	\t \n \r \v \f or space	`\s`	○	●	●	●	2,846	20.9	762	46.3
11	OR	logical or	`a|b`	●	●	●	●	2,102	15.5	708	43
12	DEC	any of: 0123456789	`\d`	○	●	●	●	2,297	16.9	692	42.1
13	WRD	[a-zA-Z0-9_]	`\w`	○	●	●	●	1,430	10.5	650	39.5
14	QST	zero-or-one repetition	`z?`	●	●	●	●	1,871	13.8	645	39.2
15	LZY	as few reps as possible	`z+?`	○	●	○	●	1,300	9.6	605	36.8
16	NCG	group without capturing	`a(?:b)c`	○	●	○	●	791	5.8	404	24.6
17	PNG	named capture group	`(?P<name>x)`	○	●	○	●	915	6.7	354	21.5
18	SNG	exactly n repetition	`z{8}`	●	●	●	●	581	4.3	340	20.7
19	NWSP	any non-whitespace	`\S`	○	●	●	●	484	3.6	270	16.4
20	DBB	$n \leq x \leq m$ repetition	`z{3,8}`	●	●	●	●	367	2.7	238	14.5
21	NLKA	sequence doesn't follow	`a(?!yz)`	○	○	○	○	131	1	183	11.1
22	WNW	word/non-word boundary	`\b`	○	○	○	●	248	1.8	166	10.1
23	NWRD	non-word chars	`\W`	○	●	●	●	94	0.7	165	10
24	LWB	at least n repetition	`z{15,}`	●	●	●	●	91	0.7	158	9.6
25	LKA	matching sequence follows	`a(?=bc)`	○	○	○	○	112	0.8	158	9.6
26	OPT	options wrapper	`(?i)CasE`	○	●	○	●	231	1.7	154	9.4
27	NLKB	sequence doesn't precede	`(?<!x)yz`	○	○	○	○	94	0.7	137	8.3
28	LKB	matching sequence precedes	`(?<=a)bc`	○	○	○	○	80	0.6	120	7.3
29	ENDZ	absolute end of string	`\Z`	○	○	○	●	89	0.7	90	5.5
30	BKR	match the ith CG	`\1`	○	○	○	○	60	0.4	84	5.1
31	NDEC	any non-decimal	`\D`	○	●	●	●	36	0.3	58	3.5
32	BKRN	references PNG	`\g<name>`	○	●	○	○	17	0.1	28	1.7
33	VWSP	matches U+000B	`\v`	○	○	●	●	13	0.1	15	0.9
34	NWNW	negated WNW	`\B`	○	○	○	●	4	0	11	0.7

4.3 RQ3: Regex language feature usage

We count the usages of each feature per project and as compared to all distinct regex patterns in the corpus.

4.3.1 Feature Usage

Table 4 displays feature usage from the corpus and relates it to four major regex related projects. Only features appearing in at least 10 projects are listed. The first column, *rank*, lists the rank of a feature (relative to other features) in terms of the number of projects in which it appears. The next column, *code*, gives a succinct reference string for the feature, and is followed by a *description* column that provides a brief comment on what the feature does. The *example* column provides a short example of how the feature

can be used. The next four columns, (i.e., *brics*, *hampi*, *Rex*, and *RE2*), map to the four major research projects chosen for our investigation (see Section 4.3.2). We indicate that a project supports a feature with the '●' symbol, and indicate that a project does not support the feature with the '○' symbol. The final four columns contain two pairs of usage statistics. The first pair contains the number and percent of *patterns* that a feature appears in, out of the 13,912 patterns that make up the corpus. The second pair of columns contain the number and percent of *projects* that a feature appears in out of the 1645 projects scanned that contain at least one utilization.

One notable omission from Table 4 is the literal feature, which is used to specify matching any specific character. An

example pattern that contains only one literal token is the pattern 'a'. This pattern only matches the lowercase letter 'a'. The literal feature was found in 97.7% of patterns. We consider the literal feature to be ubiquitous in all patterns, and necessary for any regex related tool to support, and so exclude it from Table 4 and the rest of the feature analysis.

The eight most commonly used features, ADD, CG, KLE, CCC, ANY, RNG, STR and END, appear in over half the projects. CG is more commonly used in patterns than the highest ranked feature (ADD) by a wide margin (over 8%), even though they appear in similar numbers of projects.

4.3.2 Feature Support in Regex Tools

While there are many regex tools available, in this work, we focus on the feature support for four tools, brics, hampi, Rex and RE2, which offer diversity across developers (i.e., Microsoft, Google, open source, and academia) and applications. Further, as we wanted to perform a feature analysis, these four tools and their features are well-documented, allowing for easy comparison.

To create the tool mappings, we consulted documentation for each tool. For brics, we collected the set of supported features using the formal grammar[7]. For hampi, we manually inspected the set of regexes included in the `lib/regex-hampi/sampleRegex` file within the hampi repository[8] (this may have been an overestimation, as this included more features than specified by the formal grammar[9]). For RE2, we used the supported feature documentation[10]. For Rex, we collected the feature set empirically because we tried to parse all scraped patterns with Rex for the behavioral analysis (Section 4.4), and Rex provides comprehensive error feedback for unsupported features.

Of the four projects selected for this analysis, RE2 supports the most studied features (28 features) followed by hampi (25 features), Rex (21 features), and brics (12 features). All projects support the 8 most commonly used features except brics, which does not support STR or END. No projects support the four look-around features LKA, NLKA, LKB and NLKB. RE2 and hampi support the LZY, NCG, PNG and OPT features, whereas brics and Rex do not.

4.3.3 Survey Results for Feature Usage

The pattern language for Python, which is used to compose regexes, supports default character classes like the ANY or dot character class: . meaning, 'any character except newline'. It also supports three other default character classes: \d, \w, \s (and their negations). All of these default character classes can be simulated using the custom character class (CCC) feature, which can create semantically equivalent regexes. For example the decimal character class: \d is equivalent to a CCC containing all 10 digits: \d ≡ [0123456789] ≡ [0-9]. Other default character classes such as the word character class: \w may not be as intuitive to encode in a CCC: [a-zA-Z0-9_].

Survey participants were asked if they use only CCC, use CCC more than default, use both equally, use default more than CCC or use only default. Results for this question are

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[7] http://www.brics.dk/automaton/doc/index.html?dk/brics/automaton/RegExp.html

[8] https://code.google.com/p/hampi/downloads/list

[9] http://people.csail.mit.edu/akiezun/hampi/Grammar.html

[10] https://re2.googlecode.com/hg/doc/syntax.html

Table 5: Survey results for preferences between custom character and default character classes (RQ3)

Preference	Frequency
use only CCC	1
use CCC more than default	5
use both equally	2
use default more than CCC	10
use only default	2

Table 6: Survey results for regex usage frequencies, averaged using a 6-point likert scale: Very Frequently=6, Frequently=5, Occasionally=4, Rarely=3, Very Rarely=2, and Never=1 (RQ3)

Group	Code	Frequency
endpoint anchors	(STR, END)	4.4
capture groups	(CG)	4.2
word boundaries	(WNW)	3.5
lazy repetition	(LZY)	2.9
(neg) look-ahead/behind	(LKA, NLKA, LKB, NLKB)	2.5

shown in Table 5, with 67% (12) indicating that they use default the most. Participants who favored CCC indicated that "it is more explicit," whereas the participants who favored default character classes said, "it is less verbose" and "I like using built-in code."

To further explore how participants use various regex features, participants were asked five questions about how frequently they use specific related groups of features, chosen based on the tool feature support explored in Section 4.3.2. Results are shown in Table 6, indicating that lazy repetition and look-ahead features are rarely used and capture groups and endpoint anchors are occasionally to frequently used.

Summary - RQ3: The eight most common features are found in over 50% of the projects. Shown in Table 4, the STR and END features are present in over half of the scanned projects containing utilizations. In our survey, over half (56%) of the respondents answered that they use endpoint anchors frequently or very frequently, and none of them claimed to never use them.

The LZY feature is present in over 36% of scanned projects with utilizations, and yet was not supported by two of the four major regex projects we explored, brics and RE2. In our developer survey, 11% (2) of participants use this feature frequently and 6 (33%) use it occasionally, showing a modest impact on potential users.

When survey participants were asked if they prefer to always use numbered (BKR) or named (BKRN) back references, 66% (12) of survey participants said that they always use BKR, and the remaining 33% (6) said "it depends." No participants preferred named capture groups. BKR is present in 5% of scanned projects, while BKRN is present in only 1.7%, which corroborates our findings that numbered are generally preferred over named capture groups.

Table 7: Sample from an example cluster (RQ4)

index	pattern	nProjects	index	pattern	nProjects
1	':+'	8	5	'[:]'	6
2	'(:)'	8	6	'([^:]+):(.*)'	6
3	'(:+)'	8	7	'\s*:\s*'	4
4	'(:)(:*)'	8	8	'\:'	2

Table 8: Cluster categories and sizes (RQ4)

Category	Clusters	Patterns	Projects
Multi Matches	21	237	295
Specific Char	17	103	184
Anchored Patterns	20	85	141
Content of Parens	10	46	111
Two or More Chars	16	40	120
Code Search	15	27	92

4.4 RQ4: Regex behavioral similarity

In clustering the regular expressions, we are interested in observing cross-project regex similarity and thus discarded patterns found in only one project. Then, since Rex does not support all the regex features present in the corpus, we were only to generate sets of strings for measuring similarity for 2,871 (21%) of the 13,597 patterns in the corpus. The impact is that 923 projects were excluded from the data set for the similarity analysis. Omitted features are indicated in Table 4 for Rex.

From 2,871 distinct patterns, MCL clustering identified 186 clusters with 2 or more patterns, and 2,042 clusters of size 1. The average size of clusters larger than size one was 4.5. Each pattern belongs to exactly one cluster.

Table 7 provides an example of a behavioral cluster containing 12 patterns (four longer patterns omitted for brevity) with at least one pattern from this cluster present in 31 different projects. All patterns in this cluster share the literal ':' character. The smallest pattern, ':+', matches one or more colons.

We observe that the smallest pattern in a cluster provides an insight about some key characteristic that all the patterns within the cluster have in common. A shorter pattern will tend to have less extraneous behavior because it is specifying less behavior, yet, in order for the smallest pattern to be clustered, it had to match most of the strings created by Rex from many other patterns within the cluster, and so we observe that the smallest pattern is useful as a representative of the cluster.

For the rest of this paper, a cluster will be represented by one of the shortest patterns it contains, followed by the number of projects any member of the cluster appears in, so the cluster in Table 7 will be represented as ':+'(31). This representation is not an attempt to express all notable behavior of patterns within a cluster, but is a useful and meaningful abbreviation. To elaborate, while the cluster is centered on the presence of the ':' character, the other regexes in the cluster also exhibit more diverse behavior. This becomes a cluster because all the Rex-generated strings have a ':' in them, so ':+' is seen as highly similar to \s*:\s* and \s*([^:]*)\s*:(.*).

We manually mapped the top 100 largest clusters based on the number of projects into 6 behavioral categories (determined by inspection). The largest cluster was left out, as it was composed of patterns that trivially matched almost any string, like 'b*' and '^'. The remaining 99 clusters were all categorized. These clusters are briefly summarized in Table 8, showing the name of the category and the number of clusters it represents, patterns in those clusters, and projects. The most common category is *Multi Matches*, which contains clusters that have alternate behaviors (e.g., matching a comma or a semicolon, as in ',|;'(18)). Each

cluster was mapped to exactly one category. Next, we describe the categories.

4.4.1 Multiple Matching Alternatives

The patterns in these clusters match under a variety of conditions by using a character class or a disjunctive |. For example: '(\W)'(89) matches any alphanumeric character, '(\s)'(89) matches any whitespace character, '\d'(58) matches any numeric character, and ',|;'(18) matches a comma or semicolon. Most of these clusters are represented by patterns that use default character classes, as opposed to custom character classes. This provides further support for our survey results to the question, *Do you prefer to use custom character classes or default character classes more often?*, in which a majority of participants indicated they use the default classes more than custom. This category contains 21 clusters, each appearing in an average of 33 projects.

4.4.2 Specific Character Must Match

Each cluster in this category requires one specific character to match, for example: '\n\s*'(42) matches only if a newline is found, ':+'(31) matches only if a colon is found, '%'(22), matches only if a percent sign is found and '}'(14) matches only if a right curly brace is found. Table 7 presents a cluster that falls under this category.

The commonality of this cluster category contrasts with the survey in Section 4.1 in which participants reported to very rarely or never use regexes to check for a single character (Table 2). This category contains 17 clusters, each appearing in an average of 17.1 projects.

4.4.3 Anchored Patterns

Each of the clusters uses at least one endpoint anchor to require matches to be absolutely positioned, for example: '(\w+)$'(35) captures the word characters at the end of the input, '^\s'(16) matches a whitespace at the beginning of the input, and '^-?\d+$'(17) requires that the entire input is an (optionally negative) integer. These anchors are the only way in regexes to guarantee that a character does (or does not) appear at a particular location by specifying what is allowed. As an example, ^[-_A-Za-z0-9]+$ says that from beginning to end, only [-_A-Za-z0-9] characters are allowed, so it will fail to match if undesirable characters, such as ?, appear anywhere in the string. This category contains 20 clusters, each appearing in an average of 15.4 projects.

4.4.4 Content of Brackets and Parenthesis

The clusters in this category center around finding a pair of characters that surround content, often also capturing that content. For example, '\(.*\)'(29) matches when

content is surrounded by parentheses and '`".*"`'(25) matches when content is surrounded by double quotes. The cluster '`<(.+)>`'(23) matches and captures content surrounded by angled brackets. This category contains 10 clusters, each appearing in an average of 18.4 projects.

4.4.5 Two or More Characters in Sequence

These clusters require several characters in a row to match some pattern, for example: '`\d+\.\d+`'(30) requires one or more digits followed by a period character, followed by one or more digits. The cluster '`  `'(17) requires two spaces in a row, and '`@[a-z]+`'(9) requires the at symbol followed by two or more lowercase characters, as in a twitter handle. This category contains 16 clusters, each appearing in an average of 13 projects.

4.4.6 Code Search and Variable Capturing

These clusters center around a recognizable effort to parse source code or URLs and often capture variable values in it, for example: '`^https?://`'(23) matches a web address, and '`(.+)=(.+)`'(9) matches an assignment statement, capturing both the variable name and value. The cluster '`\$\{([\w\-]+)\}`'(11) matches an evaluated string interpolation and captures the code to evaluate. This category contains 15 clusters, each appearing in an average of 11.7 projects.

Summary - RQ4: When tool designers are considering what features to include, data about usage in practice is valuable. Behavioral similarity clustering helps to discern these behaviors by looking beyond the structural details of specific patterns and seeing trends in matching behavior.

We used the behavior of individual patterns to form clusters, and identified six main categories for the clusters. These six categories define what users are doing with regexes at a high level: matching with alternatives, matching literal characters, matching with sequences, matching with endpoint anchors, parsing contents of brackets or braces, or searching and capturing code, and can be considered in conjunction with the self-described regex activities from the survey in Table 2 to be representative of common uses for regexes.

5. DISCUSSION

In this section, we discuss the implications of these empirical findings and opportunities for future work.

5.1 Implications For Tool Designers

The results in this work have several implications for tool designers who want to effectively support developers who use regular expressions.

5.1.1 Both Default and Custom Character Classes Are Frequently Used

The same character class can be expressed in different ways, for example '`[0-9]`' is equivalent to '`\d`'. Our results indicate that both approaches are widely used (Table 5), so tool builders should continue to support both approaches.

5.1.2 Capturing Specific Content Near A Delimiter

The survey results from Section 4.1 indicate that capturing parts of strings is among the most frequent activities for which developers use regexes. Looking at this from a feature perspective, the capture group (CG) is the most frequently used in terms of patterns (Table 4). This feature has two functions: 1) it allows logical grouping as would be expected by parenthesis, and 2) it allows retrieval of information in one logical grouping. As mentioned in Section 4.4, capturing content was a primary goal evident in several categories of cluster. The fourth-largest cluster category is based on capturing the content between brackets or parentheses (Section 4.4.4). Many uses of CG also use the ANY and KLE features, eg. `(.*){(.*)}(.*)` and `\\s*([^: ]*)\\s*:(.*)`. This type of usage frequently revolves around an important delimiter character such as : or \. This use case is well supported by existing tools for ASCII characters, but this provides evidence that future tools must treat the CG feature as especially important, and must support some way to reason about what information is retrieved by capture groups. Tool designers should consider the centrality of this use case and its implications for non-English users of regex tools. For example, Unicode characters like 'U+060D' the Arabic Date Separator, or 'U+18806' the Mongilian Soft Hyphen may be used to locate segments of text that a user would want to capture.

5.1.3 Finding Specific Content

Two categorical clusters, *Specific Characters Must Match* (Section 4.4.2) and *Two or More Characters in Sequence* (Section 4.4.5), deal with identifying the presence of specific character(s). While multiple character matching subsumes single character matching, the overarching theme is that these regexes are looking to validate strings based on the presence of very specific content, as would be done for many common activities listed in Table 2, such as parsing user input. (This is in contract to *capturing* specific content, as *finding* deals with string validation and *capturing* deals with string extraction.)

The commonality of regexes related to finding content is consistent with the top ranked activity for developers, "Locating content within a file or files." Looking closely at the *Specific Character Must Match* cluster, some of the characters being searched for were `\n`, `-` and `.`, which are all common delimiters in different scenarios. Combined with the cluster on *Code Search and Variable Capturing* (Section 4.4.6), this emphasizes the need for regex tools to facilitate easy file parsing, or for a tool to include built-in support for specific types of parsing, such as finding a twitter handle (i.e., `@[a-z]+`) or a version number, (i.e., `v[0-9]+.*`), both of which appear in these clusters. Some developers may want to capture specific content, such as the actual twitter handle or the actual version number, but may not know how to do that with regex libraries and may rely on string parsing instead.

5.1.4 Counting Lines

Text files containing one unit of information per line are common in a wide variety of applications (for example .log and .csv files). Out of the 13,912 patterns in the corpus, 3,444 (24%) contained ANY followed by KLE (i.e., '`.*`'), often at the end of the pattern. One reasonable explanation for this tendency to put '`.*`' at the end of a pattern is that users want to disregard all matches after the first match on a single line in order to count how many distinct lines the match occurs on. Survey participants indicated an average frequency of "Counting lines that match a pattern" and "Counting substrings that match a pattern" at 3.2 or

rarely/occasionally. It may be valuable for tool builders to include support for common activities such as line counting.

5.2 Opportunities For Future Work

There are many opportunities for future work.

5.2.1 Refactoring Regexes

The survey showed that users want readability and find the lack of readable regexes to be a major pain point. This provides an opportunity to introduce refactoring transformations to enhance readability. As one opportunity, certain character classes that are logically equivalent can be expressed differently, for example, `\d` ≡ `[0123456789]` ≡ `[0-9]`. While `\d` is more succinct, `[0-9]` may be easier to read, so a refactoring for *default to custom character classes* could be introduced. Human studies are needed to evaluate the readability of various regex features in order to define and support appropriate regex refactorings for readability.

Another avenue of refactoring could be for performance. Various implementations of regex libraries may perform more efficiently with some features than others. An evaluation of regex feature implementation speeds would facilitate semantic transformations based on performance, similar to performance refactorings for LabVIEW [10, 11].

5.2.2 Developer Awareness of Best Practices

One category of 10 clusters in the top 100 contained regex patterns, *Content of Brackets and Parenthesis*, parses the contents of angle brackets. As the contents of angle brackets are usually unconstrained, regexes are a poor replacement for XML or HTML parsers. This may be a missed opportunity for the regex users to take advantage of more robust tools. More research is needed into how regex users discover best practices and how aware they are of how regexes should and should not be used.

5.2.3 Migration Support for Developers

Within standard programming languages, regular expressions libraries are very common, yet there are differences between languages in the features that they support. For example, Java supports possessive quantifiers like `'ab*+c'` (here the '+' is modifying the '*' to make it possessive) whereas Python does not. Differences among programming language implementations was identified as a pain point for using regular expressions by 17% of the survey participants. This provides an opportunity for future work that makes such differences between languages explicit or for new libraries that translate between regex utilizations in various languages.

5.2.4 Automated Regex Repair

Regular expression errors are common and have produced thousands of bug reports [30]. This provides an opportunity to introduce automated repair techniques to fix. Recent approaches to automated program repair rely on mutation operators to make small changes to source code and then re-run the test suite (e.g., [19, 34]). In regular expressions, it is likely that the broken regex is close, semantically, to the desired regex. Syntax changes can lead to big changes in behavior, so we hypothesize that using the semantic clusters identified in Section 4.4 to identify potential repair candidates could efficiently and effectively converge on a repair candidate.

5.2.5 Similarity Beyond String Matching

While the string matching similarity analysis over-approximates similarity when compared to containment analysis, it may under-approximate similarity in another sense. For example, two regexes that have dissimilar matching behavior could be very similar in purpose and in the eyes of the developer. For example, `workitem:\[(\d+)\] - (.*)` and `issue:\[(\d+)\] - (.*)` could both be used to capture the id and title from an issue tracking system, but match very different sets of strings. Future work would apply abstractions to the regex strings, such as removing or relaxing literals, prior to similarity analysis to capture and cluster such similarities.

From another perspective, our regex similarity measure, and even containment analysis, could treat behaviorally identical regexes as the same, when their usage in practice is completely different. For example, in Table 7, the regexes ':+' and '(:+)' are behaviorally identical, except the latter uses a capture group. In practice, these may be used very differently, where the former may be used for validation and the latter for extraction. This usage difference could be observed by code analysis, and is left for future work.

5.2.6 Tool-Specific Regex Exploration

In some environments, such as command line or text editor, regexes are used extensively (Section 4.1), but these regular expressions do not persist. Thus, using a repository analysis for feature usage only illustrates part of how regexes are used in practice. Exploring how the feature usage differs between environments would help inform tool developers about how to best support regex usage in context, and is left for future work.

6. THREATS TO VALIDITY

The following threats impact our results and conclusions:

Reliability of Measures: The validity of our survey results is dependent on the clarity of the questions. The authors went through several iterations of the survey and included examples for all the regex feature descriptions to improve understandability.

The similarity measure between regexes used in the cluster algorithm is computed empirically rather than analytically, and the more Rex-generated strings used to compute the similarity measure, the more likely it is to be accurate. Our experiments used 400 strings to balance performance and precision, but a higher number could lead to more cohesive clusters. However, regex patters that use any feature not supported by Rex were omitted from the cluster analysis. TODO.MID: talk about tools for formal analysis

Instrumentation: Regular expression patterns were clustered using strings generated by the Rex tool. We assume that the strings generated by Rex are reasonably diverse to help characterize the regular expression behavior. To mitigate this threat, Rex generated 400 strings per regular expression and we inspected strings randomly to ensure diversity.

Implementation errors are a risk for research involving repository analysis. To combat this, we have tested our code and made the repository publicly available[11].

Selection: We mined only 3,898 Python projects from GitHub, which is small in comparison with the over 100,000 available Python projects. The projects were mined using

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[11]https://github.com/softwarekitty/tour_de_source

the GitHub API which sorts the projects by creation date. By using the API, the goal was to reduce any sampling bias introduced by the researchers.

We also did not scrape all commits in every project for regular expression utilizations, rather, we grabbed each project every 20 commits. It is possible that in between the scanned commits, a regular expression utilization was added and then removed, leading to fewer utilizations in our final data set.

Recall bias: The survey participants were asked to reflect on their past behavior, which may not be representative of actual behavior. To mitigate this, we designed the survey to lead the participants to think about their behavior before summarizing (e.g., asking how often they use regexes in each of several environments before asking how frequently they use regexes).

Hypothesis guessing: The lead author was an employee of Dwolla when the survey was run, so participant behavior may have been affected by their relationship with the author. To combat this, the beginning of the survey stated, "As this is for research, please answer as accurately as possible, not guessing what is the desired answer and providing that."

Interaction of Selection and Treatment: Our survey participants were software developers from a small startup company. However, the participants may not be representative of all developers. Given that the average participant has nine years of development experience, their responses likely pull from a variety of experiences with regular expression usage.

Interaction of Setting and Treatment: We only explore regular expressions in Python projects so these results many be coupled with the activities performed using Python and not generalize to other languages. The regex usage context reported by survey participants, however, includes information on regex usage in a variety of settings and languages. Future work will replicate this study in other languages and the survey with a larger group of participants.

7. CONCLUSION

In this work, we have explored the contexts in which regular expressions are used as well as the features and behavioral similarities of regexes found in open source Python projects. In a survey of 18 professional developers, we find that 50% compose regular expressions at least weekly. The most common purposes are locating content within a file or capturing parts of strings. The most difficult parts about working with regular expressions were reported to be composing and reading them. In a study of regular expression usage in nearly 4,000 Python projects, we find that over 42% of projects contain a regular expression. We present an approach to measure behavioral similarity between regexes by generating strings that match one regex and pairwise testing the remaining regexes against it. This similarity measure is used to form cross-project behavioral clusters. In the top 100 largest clusters, we find that capturing the contents of brackets, searching for delimiter characters and matching alternative values were common behaviors. These results have implications for tool designers and for future research aimed at better supporting developers in using regular expressions.

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