

Crowdsourced Bug Triaging

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Abstract—Bug triaging and assignment is a time-consuming task in big projects. Most research in this area examines the developers’ prior development and bug-fixing activities. We propose a novel method that exploits a new source of evidence for the developers’ expertise, namely their contributions to Q&A platforms such as *Stack Overflow*, the popular software Q&A platform. We evaluated this method in the context of the 20 largest *GitHub* projects, considering 7144 bug reports. Our results demonstrate that our method exhibits superior accuracy to other state-of-the-art methods and that future bug assignment algorithms should consider exploring other sources of expertise beyond the version control system and bug tracker.

I. INTRODUCTION AND BACKGROUND

Bug-triaging-and-assignment has received substantial attention by the software-engineering community [1], [2], [3], [4], [5], [6]. Given a bug report, the goal is to find and rank relevant developers on the project who would be knowledgeable enough to fix it. This problem touches on two relevant research areas: (1) expertise identification and recommendation, and (2) bug triaging.

Relevant to *expertise-recommendation*, Venkataramani *et al.* [7] described a system for recommending specific questions to *Stack Overflow* members who would be qualified to answer them. The system considers the names of the classes and methods to which the developers have contributed to infer their expertise. Similarly, Fritz *et al.* [8] posed the “Degree of Knowledge” (DOK) metric to determine the level of a developer’s knowledge regarding a code element—class, method or field—based on the developer’s contribution to the development of this element. Mockus and Herbsleb [9] described Expertise Browser (EB), a tool that identifies the developers’ expertise about code and documentation, considering system commits and changes to classes, sub-systems, packages, etc. Teyton *et al.* [10] developed an automatic expertise-extraction method that browses the developers’ source code for evidence of expertise and summarizes them. In order to rank the members of a community in terms of their expertise within a community, Zhang *et al.* [11] described a method for constructing a “Community Expertise Network” (CEN), from the post-reply relations of Java Forum users. Assuming that asking questions is evidence of ignorance and providing answers is evidence of expertise, they defined and demonstrated the usefulness of the Z-score as an expertise indicator: $Z = (a - q) / \sqrt{(a + q)}$, where q and a are respectively the number of questions asked and answered by a community member.

There has already been substantial research on *bug triaging*, which has produced a number of different techniques to select the (*top-k*, where k is typically 1 and 5) most capable developer(s) to resolve a given bug report. Table I summarizes some key results of this work. In relation to this earlier research, the method we propose in this paper is unique in

that it uses the developer’s expertise, as demonstrated by his contributions to *Stack Overflow*, as a source of evidence regarding the competence of a developer to fix a bug. We describe our method in Section II and we report on our experimental-evaluation results in Section III. Reflecting on these results and the corresponding results of earlier studies, we argue for the merits of our method in Section III-C. Finally, in Section IV, we conclude with the lessons we hope to share with the community and our plans for future work.

II. A SOCIAL BUG-TRIAGING METHOD

Motivated by the overlap in the activities of developers in *GitHub* and *Stack Overflow* [17][18], we ask what if we combine expertise-recommendation based on networks like *Stack Overflow* with bug-triaging of issues. We developed a method that exploits evidence of expertise in the developers’ *Stack Overflow* activity traces, for identifying candidate bug fixers in *GitHub*. The intuition underlying our method is that whoever answers a question tagged with the *jquery* keyword, and has received the community’s approval with many up-votes, must have some expertise in *jquery* and, therefore, should be a likely candidate for fixing bugs relevant to *jquery*, e.g., the *jquery* keyword is in the bug description.

As an illustrative example, consider the activity around five *Stack Overflow* questions, shown in Table II. The bold tags indicate keywords that also appear in the bug report, which needs to be addressed. The middle section of Table II reports the simple *AnswerNum* score, namely the total number of questions answered by a developer, and the *Z-score* [11], described above. These two expertise indicators completely ignore the bug at hand, which is why we developed the three additional scores, reported at the bottom of Table II and described in detail in Section II-A below. We use *Stack Overflow* tags for cross-referencing *Stack Overflow* and *GitHub*. As a sanity check for the applicability of tags in *GitHub* bug reports, we examined the bug reports in 3 selected projects (out of the 20 projects considered in this study) and found that the textual information of each bug report (including *project language*, *project description*, *issue title* and *issue body*) mentions between 2 to 89 tags (avg=14.9 and $\sigma=11.5$). In effect, tags are community curated keywords that define a common set of vocabularies for developers to exchange information without the need for stop-word and noise-word removal from the bug-report texts.

A. A Bug-Specific Social Metric of Expertise

Given a bug report, b , the objective is to estimate a developer’s expertise as it pertains to b . To that end, we define **matched_tags** _{q,b} and **matched_tags** _{a,b} , as the set of tags of a specific question (q) and its answers (a) that appear in the textual information of the bug report (b). These metrics are

TABLE I
RECENT BUG-TRIAGING METHODS

Authors	Basic method / Information used	Effectiveness
Čubranić and Murphy[2]	Naive Bayes classification of bug reports (i.e., “text documents”) to developers (i.e., “classes”); uses bug summary and description.	up to 30% <i>top-1</i>
Anvik <i>et al.</i> [1]	Support Vector Machine (SVM) classification of bug reports (i.e., “text documents”) to developers (i.e., “classes”); uses bug summary and description.	up to 57%, 64% and 18% <i>top-3</i> accuracy
Tamrawi <i>et al.</i> [12]	A fuzzy-set representation of the relations between developers and the bug reports’ technical terms. Uses bug summary and description.	average 40% and 75% for <i>top-1</i> and <i>top-5</i> accuracy over 7 projects
Lamkanfi <i>et al.</i> [13]	Multinomial Naive Bayes and some other ML approaches. Uses bug report summary, description, severity and component.	79% accuracy
Lin <i>et al.</i> [14]	SVM and C4.5 classifiers. Uses bug summary and description, type, class, priority, submitter and the module ID.	up to 77% accuracy
Nguyen <i>et al.</i> [6]	Regression model based on LDA topic modeling. Uses bug description.	Just estimated the time to fix for each developer ± 2.3 days
Canfora and Cerulo [15]	A probabilistic IR method to query the new bug report’s text and find the best developer (considered as a document). Uses descriptions of the change requests.	62% and 85% accuracy in two projects
Matter <i>et al.</i> [5]	Vector Space Model (an IR method). Uses source-code commits and the bug-report keywords.	34% and 71% <i>top-1</i> and <i>top-10</i> accuracies
Linares-Vázquez <i>et al.</i> [4]	IR-based concept location techniques. Uses text of a change request and source code files.	85% <i>top-5</i> accuracy
Shokripour <i>et al.</i> [16]	A method based on information extraction. Uses bug summary and description, detailed source code info (comments, names of classes, methods, fields, etc.).	48% and 48% <i>top-1</i> and 60% and 89% <i>top-5</i> accuracies on two projects (between 57 and 9 developers respectively)
Jeong <i>et al.</i> [3]	Introduced “tossing graphs” of developers to reduce bug reassignment. Uses bug report title and description	up to 77% <i>top-5</i> accuracy

calculated for each pairwise combination of bug reports and questions (and answers) provided by the project developers.

We next define $A_{u,b}$, relative weighted answers, and $Q_{u,b}$, relevant weighted questions to replace a and q respectively in the original definition of Z -score, taking into account the community’s assessment of the “quality” of a developer’s contributions. The definition of $A_{u,b}$ is shown in Equation 1. At any point in the time, for every answer a developer has contributed in the past that is relevant to the bug under consideration the number of $matched_tags_{a,b}$ is multiplied with the number of the answer’s upVotes (plus one, for the answer itself).

$$A_{u,b} = \sum_{\substack{a \in \text{answers} \\ \text{posted by } u}} (upVotes_a + 1) \cdot (matched_tags_{a,b}) \quad (1)$$

The $Q_{u,b}$ is calculated as shown in Equation 2. In principle, questions are considered as negative evidence of expertise [11]. However, to mitigate the adverse effects of asking “good” questions, we divide $matched_tags_{a,b}$ by the number of upVotes (plus one for the question itself). This tends to make the value of $Q_{u,b}$ very small, in comparison to $A_{u,b}$, which is why we use the μ normalization factor to adjust it.

$$Q_{u,b} = \mu \cdot \sum_{\substack{q \in \text{questions} \\ \text{posted by } u}} \frac{(matched_tags_{q,b})}{(upVotes_q + 1)} \quad (2)$$

The *Social Subject-Aware Z-score* (SSA_Z -score) can then be defined, as shown in Equation 3.

$$SSA_Z\text{-score}_{u,b} = \frac{(A_{u,b} - Q_{u,b})}{\sqrt{(A_{u,b} + Q_{u,b})}} \quad (3)$$

Note that, in order to capture the temporal awareness of a developer’s expertise, this formula only involves questions and answers posted before the time when the bug was reported (i.e., $t_q < t_b$ and $t_a < t_b$).

B. A Recency-Sensitive SSA_Z -score

The expertise of the developers shifts over time as they work on different projects with potentially different technologies. This is why, many related expertise-modeling methodologies [5], [16], [1] include a decay factor for older evidence of expertise and weigh it less than more recent one. To capture this intuition, that “recent evidence of expertise is more valuable”, we defined *Recency_of_activity* as shown in Equation 4 below.

$$Recency_of_activity_{u,b} =$$

$$\sum_{\substack{i \in \\ \text{bugs of } u}} \frac{1}{1 + |\{d | d \in \text{bugs of } u \ \& \ t_d > t_i \ \& \ t_d < t_b\}|} \quad (4)$$

Note that t is the time of bug report and the denominator counts the number of bug reports occurred between i and b . The key intuition here is that bug-fixing exhibits a certain locality, namely “the developers that have been fixing bugs recently are likely to fix bug reports in the near future” [12]. We combine the two last metrics to assign each user a new score for his/her relevance to the bug currently being triaged:

$$Triage_score_{u,b} = \alpha \cdot (SSA_Z\text{-score}_{u,b}) + \beta \cdot (Recency_of_activity_{u,b}) \quad (5)$$

In this formula, α and β are parameters, which are tuned following a systematic process explained in Section III-B. Having the *Triage_score* for all users in the community over a bug report, our bug-triaging algorithm sorts the users and reports the top k as the most capable developers to fix the bug.

III. EVALUATION

We obtained two *Stack Overflow* data sets [19], [20] (approximately 65GB and 90GB). They consist of several XML files including information of 2,332,403 and 3,080,577 users, their posts, tags, votes, etc.). In order to link these users to *GitHub*, their *email hash* is needed [18], which is provided

TABLE II
EXAMPLE OF DIFFERENT SCORES FOR USERS: EACH ROW SHOWS A QUESTION AND NUMBER OF UPVOTES FOR EACH OF ITS ANSWERS
(BY DIFFERENT USERS)

Questions \ Answerer	Bob	Ali	Taylor	Yakob	Jane	Brian	Harpreet
Q1 by Yakob, 3 upVotes tags: [version control], [open source]	46	5	53		28		
Q2 by Jane 1 upVotes tags: [ajax], [data], [search], [jquery], [php]	20	16	22	6			
Q3 by Yakob, 21 upVotes tags: [lucene], [elasticsearch], [php], [java]	11	14	29		10		
Q4 by Ali, 0 upVotes tags: [https], [css], [java], [jira], [data]	27			0		86	
Q5 by Harpreet, 70 upVotes tags: [java], [ajax], [https], [xml], [lucene]	1	18	42	-4	14	98	
AnswerNum	5	4	4	3	3	2	0
Z-score	2.24	1.34	2	0.45	1	1.41	-1
A	$\frac{(46+1) \cdot 1 + (20+1) \cdot 2 + (11+1) \cdot 3 + (27+1) \cdot 4 + (1+1) \cdot 5}{= 247}$	$\frac{(5+1) \cdot 1 + (16+1) \cdot 2 + (14+1) \cdot 3 + (18+1) \cdot 5}{= 180}$	$\frac{(53+1) \cdot 1 + (22+1) \cdot 2 + (29+1) \cdot 3 + (42+1) \cdot 5}{= 405}$	$\frac{(6+1) \cdot 2 + (0+1) \cdot 4 + (-4+1) \cdot 5}{= 3}$	$\frac{(28+1) \cdot 1 + (10+1) \cdot 3 + (14+1) \cdot 5}{= 137}$	$\frac{(86+1) \cdot 4 + (98+1) \cdot 5}{= 843}$	0
Q ($\mu = 20$)	0	$20 \cdot \left(\frac{4}{0+1}\right) = 80$	0	$20 \cdot \left(\frac{\frac{1}{3+1} + \frac{3}{21+1}}{7.7}\right) = 7.7$	$20 \cdot \left(\frac{2}{1+1}\right) = 20$	0	$20 \cdot \left(\frac{5}{70+1}\right) = 1.41$
SSA_Z-score	15.72	6.20	20.12	-1.44	9.34	29.03	-1.19

by the older data set. We merged these two data sets to get a large data set including users of old data set with newer posts.

On the other hand, we used GHTorrent mySQL dump [21] (with a size of about 21GB) containing information about 4,212,377 *GitHub* users and their project memberships. However, this data set did not include the textual information of the bug reports. We obtained this information from a set of MongoDB dumps from GHTorrent site (210GB) including information of 2,908,292 users. Again, we merged the two data sets and obtained a large data set including information about *GitHub* users, projects and bug reports. Note that for some of the projects (e.g., Scala and Gaia), the issue tracker is not visible through the browser on the web, but all the information required by our method is available in the data dump. As our method assigns bugs to developers with a presence in both *GitHub* and *Stack Overflow*, we encoded users's emails in *GitHub* with MD-5 function and compared them with every e-mail hash available in *Stack Overflow* [17], [18]. With this approach, we found 358,472 common users¹.

A. Experiment Setup and Implementation

We first extracted the *community members* of each project as the union of the sets of project members, committers, bug reporters, and bug assignees. We then removed from this community, developers who had no questions or answers on *Stack Overflow*. Next, we identified the top 20 ranked projects based on the number of community members¹.

For the selected 20 projects, the number of community members vary from 28 to 822 (average=127, σ =169, median=87). Out of 14,172 bug reports in all the selected projects, we examined 7144 bug reports that have been assigned to one of the community members in the related project. Note that we

could not use the rest of bug reports since they were assigned to developers with no *Stack Overflow* activity. However, if this approach is applied in the workplace, alternative networks should be tested and used. We used bug reports from three of these projects for training and tuning purposes and 17 for final evaluation. For each bug report in each project, we ran our algorithm to recognize the expertise score of all project-community members and ranked the users from the highest score to the lowest. Then report *top-1* and *top-5* accuracies as well as Mean Average Precision (MAP) as a synthesized, rank based evaluation measure [22].

To approximate comparison with other state of the art methods, we experimented with the *scikit-learn*² implementations of a number of machine-learning algorithms used as the basis for the above research [1], [2], [13], [14] which we applied³ to our own data set:

- 1) 1NN, 3NN and 5NN
- 2) Naive Bayes
- 3) Multinomial Naive Bayes
- 4) SVM

We used the title and body words of the bug reports as TFIDF vectors for the features. In order to make the process competitive enough to our approach, we made the process online; train them on first $n-1$ bug reports and then test on the n^{th} . Then train on first n bug reports and test on $n+1^{\text{th}}$ and so on.

We used the following parameters for *scikit-learn* machine learners: For KNN, we chose k as the parameter (1, 3 or 5), weights='uniform', algorithm='auto', leaf_size=30, p=2, metric='minkowski' and metric_params=None. For Multinomial Naive Bayes, we used Laplace smoothing priors ($\alpha =$

²<http://scikit-learn.org/stable/>

¹Due to space limitation, our data sets, information of 3+17 projects, Java implementation of our approach and output and tuning results are available online at: <http://github.com/alisajedi/BugTriaging>

³Our Python implementations: <http://github.com/abramhindle/bug-triager-scikit/blob/ali/dumpbayes.py> More explanation of the ML methods are also available at the repository.

1.0) fit to prior distribution using OneVsRestClassifier classifier strategy. Similarly for Naive Bayes, but it uses multiclass classification. For SVM, we used Support Vector Classification (SVC) class. We chose RBF kernel type, used shrinking heuristic, with gamma kernel coefficient $1/n$ for n features, error penalty=1 and probability=true.

B. Results

Out of 20 projects, we selected three projects randomly (including 490 bug reports). We then measured the performance metrics of different approaches from *AnswerNum* to original Z-score, to Subject-Aware Z-score (SA_Z-score), to Social Subject-Aware Z-score (SSA_Z-score), to the final recency-aware SSA_Z-score (*Triage_score*). In each step, we observed an improvement in accuracy. This validates our effort toward considering *Stack Overflow* upVotes while being aware of bug content. For the purpose of tuning and calibrating our method, we needed to determine the best values for μ , α and β (Equations 2 and 5). The best obtained values are as follows: μ (normalization factor) is set to “*Harmonic Mean plus 1*”, $\beta=1$ and $\alpha=0.01$. This is because of very large numbers attained for *Social_Z-score* (i.e., number of upVotes multiplied by number of tags, summed over all answers of each user). We apply the parameter values (μ , α and β) obtained from the three test projects into the remaining 17 projects in our final evaluation.

As the final evaluation, we ran our algorithm over 17 projects (holding out the three projects used for tuning) including 6654 bug reports and sorted the recommended developers for each bug report. The average *top-k* accuracies of our approach for k from 1 to 5 are 45.17%, 66.41%, 77.50%, 84.79% and 89.43% respectively. We also obtained the Mean Average Precision (MAP) as 0.633, which is very strong and shows that the harmonic mean of the real assignee is 1.58 over all the bug reports.

We also implemented the other approaches discussed in Section III-A. We ran those experiments to compare the results of our method with other approaches on the same data set. The results for average *top-1* and *top-5* accuracies as well as MAP are shown in Table III.

The values reported in Table III are averages over all 17 projects examined. However, we examined the detailed results for each project and found them close to the mean (median=90.19 and $\sigma=7.81$ for *top-5* accuracies). Our results demonstrate that our *Triage_score*, relying on evidence of developers’ expertise from their *Stack Overflow* activities, is very effective in selecting the right assignee for the right bug, much more so than all competing machine-learning algorithms relying exclusively on *GitHub* data. It is noteworthy that our approach is fast and efficient enough since it avoids the typical text pre-processing of most IR-based methods, such as stemming and indexing. Each bug report was triaged in almost a second, which is fast enough for real-time use.

C. Analysis

The results in Table III show that our method exhibits the best performance, with SVM coming second. Our method outperforms all of the other machine learning methods in terms of *top-5* accuracy and MAP. 3NN, 5NN and SVM do well for *top-1* accuracy, slightly better than our approach. Our

average *top-5* accuracy is between 8 to 19 percent better than other approaches. The MAP value of our approach —0.633— corresponds to the harmonic mean 1.58 for the rank of the real assignee (implying that the real assignee frequently appeared in the rank-1 and rank-2 positions in the results). MAP varies from 0.575 (for 1NN) to 0.617 (for SVM as the best approach after our’s). Comparing the different algorithms on the same data set demonstrates in the usefulness of our method.

On the other hand, we compare our results with previously published results. In short, as one of the best obtained accuracies in the previous studies, Shokripour *et al.* obtained 48% *top-1* and 60% and 89% *top-5* accuracies on two projects (between 57 and 9 developers respectively). Our *top-5* accuracy outperforms theirs, but their approach performs 3% better on *top-1*. Note that their best results were obtained in a project with only 9 candidate developers (our projects included between 28 and 822 developers). Also note that their approach was tested only on 80 and 85 bug reports, as opposed to our 7144 bug reports.

To summarize our comparison findings, it is important to mention the following. Our evaluation of our metric is the most thorough reported in the literature (with 20 projects and 7144 bug reports). Our metric highly outperforms all previously reported methods in terms of average *top-5* accuracy, and most of them in terms of average *top-1* accuracy. More importantly, our metric exhibits the highest MAP.

D. Limitations and Threats to Validity

An external validity threat is that the common users (between *Stack Overflow* and *GitHub*) constitute up to 20% of the total number of users in each of these networks. Currently, for privacy reasons, much of the Q&A content at the software social networks is provided anonymously. However, the large number (i.e., thousands) of developers and bug reports on which we tested our approach mitigates this limitation. One could envision that project managers could easily request their developers to provide their IDs in Q&A networks like *Stack Overflow*, as part of their CV. As a result, more extensive Q&A contributions (or alternative sources of information) will become available to the bug-assignment process.

Another concern is how to treat the phenomenon of developers answering their own questions to announce a commonly encountered issue with some API, library, etc. However, we investigated the questions and answers of members of three projects out of 20 and found that only 3% of their answers are answers to one’s own question and only in around half of these cases, the question is up-voted, meaning that the case did not indicate expertise, but lack of expertise (as we assumed).

IV. CONCLUSIONS AND FUTURE WORK

In this paper we described a method that effectively utilizes the *Stack Overflow* contributions of developers and their previous bug-assignment history to decide the best candidate developer for fixing a bug. We have thoroughly evaluated our method with 20 popular *GitHub* projects, comparing its performance (a) against six traditional machine-learning approaches that have been widely used for bug assignment before, and (b) against the reported accuracies of previous bug-triaging publications. Our approach outperforms the competition.

TABLE III
ACCURACY RESULTS FOR DIFFERENT SIMULATED APPROACHES COMPARED WITH OURS

Method	1NN	3NN	5NN	Naive Bayes	Multinomial Naive Bayes	SVM	Our approach
Top 1 Accuracy (%)	43.09	46.48	45.60	43.77	42.75	45.46	45.17
Top 5 Accuracy (%)	70.46	75.63	75.00	78.98	75.97	81.82	89.43
MAP	0.575	0.610	0.596	0.609	0.606	0.617	0.633

The fundamental novelty of our work is that it takes advantage of contributions of the developers in software Q&A networks as a rich, unexploited socio-technical source of expertise information, beyond their code. This leads us to a more interesting insight: regardless of applicability of *Stack Overflow* in bug assignment and its possible limitations, applying various **third party expertise networks** in bug triaging envisions new horizons for software maintenance community. While some developers contribute in *Stack Overflow*, many others may prefer Java Forum, Ask Ubuntu, Experts Exchange, Code Project, Web developer, SUN Forums, MSDN Forums and so on. As part of their development process, developers may provide their IDs in their desired software social platforms, to better inform our method regarding their expertise and thus improve the triaging process.

In the future, we plan to consider tag synonyms; *Stack Overflow* has introduced lists of tag synonyms and suggests that users use the primary definitions (e.g., “servlets” instead of “web servlet”, “authentication” instead of “login”), but it does not enforce this policy. In the future, we plan to consider integration of the synonyms in their primary definition addressing in bug reports and Q&A contents. Finally, capturing level of similarity of the keywords in bug reports with tags (e.g., “xml-parser”, “xml parser”, “xmllparsing” and “xml parsing” compared to tag “xml-parsing”) can be a useful extension. Curation, noise reduction, and tag recommender approaches [23] may also be useful in this case.

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