Mining Code Review Data to Understand Waiting Times Between Acceptance and Merging: An Empirical Analysis

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ABSTRACT

Increasing code velocity (or the speed with which code changes are reviewed and merged) is integral to speeding up development and contributes to the work satisfaction of engineers. While factors affecting code change acceptance have been investigated in the past, solutions to decrease the code review lifetime are less understood. This study investigates the code review process to quantify delays and investigate opportunities to potentially increase code velocity. We study the temporal characteristics of half a million code reviews hosted on Gerrit and Phabricator, starting from the first response, to a decision to accept or reject the changes, and until the changes are merged into a target branch. We identified two types of time delays: (a) the wait time from the proposal of code changes until first response, and (b) the wait time between acceptance and merging. Our study indicates that reducing the time between acceptance and merging has the potential to speed up Phabricator code reviews by 29–63%. Small code changes and changes made by authors with a large number of previously accepted code reviews have a higher chance of being immediately accepted, without code review iterations. Our analysis suggests that switching from manual to automatic merges can help increase code velocity.

CCS CONCEPTS

• Software and its engineering → Open source model; Software evolution; Software libraries and repositories.

KEYWORDS

Code review, code velocity, developer productivity, non-productive time

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1 INTRODUCTION

Code velocity or the speed with which code changes are reviewed and merged is an important industry metric [28, 54]. Increased code velocity also contributes to an engineer’s job satisfaction [28, 54]. In studies and surveys, engineers repeatedly point to delays in response times as pain points in their evaluation of the efficiency of code review process [9, 33].

Existing studies that analyze the code review process focus primarily on improving one aspect of the code review life cycle: the time it takes for the proposed changes to be accepted by a reviewer [6, 50]. For example, there are studies that examine how code size impacts the acceptance time [26, 28, 59, 60]. These studies systematically ignore potential inefficiencies that exist elsewhere in the code review process which, if removed, can increase code velocity perhaps at even lesser cost.

Our experience working at X and Y (names omitted in the peer review version to comply with the guidelines for double-blind review) suggests that often the proposed code changes sit idle with no response or action. This time spent idling with no productive action (also referred to herein as non-productive time) can happen during the different phases of code review. Understanding where and why such non-productive times occur can point to solutions to increase code velocity. Particularly, we investigate:

RQ1: Does non-productive time exist in the code review process? If so, how much?

We define the distinct phases of code review process starting from proposing a change, the first response, decision to accept or reject a change, until integration into target branch. We report descriptive statistics to quantify the extent of the problem. Contingent on the presence of non-productive time, we explore:

RQ2: What contributes to non-productive time in the code review process? Can we reduce it?

Building on the insights from RQ1 and our industry experience, we investigate what happens to the code reviews after they are accepted and explore a way to minimize code review iterations.
We collected data about 569,914 code reviews from Gerrit and Phabricator [19, 46] to quantify the phases of code review process and activities within and examine the non-productive time for potential solutions. The choice of the platforms is motivated by (a) the popularity of projects hosted on these platforms (e.g., Mozilla and Eclipse), (b) availability of archival data for investigation that is otherwise not possible on platforms like GitHub, and (c) the distinctive processes of the two platforms for comparison. To the best of our knowledge, this is the first study that quantifies non-productive time in Gerrit and Phabricator code reviews on a large scale.

Our study identifies two areas of time delays in the code review process: (a) from the time a change is proposed until it gets the first response, and (b) time between acceptance and integration. Our study suggests that the smaller size of code change and author’s prior successful code review experience speeds up the first response time, potentially influencing the overall integration time. Further, our findings indicate that switching to an automatic merge-on-acceptance model can potentially reduce the overall time-to-merge by eliminating non-productive time.

2 BACKGROUND AND RELATED WORK

2.1 Motivation

Modern Code Review sets high expectations for code review times and requires them to be completed in a timely manner. Existing research indicates that code reviews on Google, Microsoft, and open-source software (OSS) projects take approximately 24 hours [51]. Google’s recommended code review best practices state explicitly that “we expect feedback from a code review within 24 (working hours)” [62, p. 176]. Chromium code review guidelines recommend that “aim to provide some kind of actionable response within 24 hours of receipt (not counting weekends and holidays)” [11]. From the projects we investigate in this paper, FreeBSD and LLVM do not specify fixed deadlines [17, 32]. However, Mozilla recommends that “strive to answer in a couple of days, or at least under a week” [40]. Blender sets the expectation that “[d]evelopers are expected to reply to patches [in] 3 working days” [10]. Based on our industry experience at X and Y (names omitted in the peer review version to comply with the guidelines for double-blind review), getting the first response on the same day is highly desirable, with the 24-hour code review completion time being a default expectation.

Code velocity, or the speed with which code changes are reviewed and merged into the target branch, is an important metric both in the industry and OSS community. Facebook’s experience shows that increased code velocity leads to earlier detection of code defects and faster product deployments [54]. Survey of Mozilla developers finds that quick turnaround time is important for both reviewers and engineers submitting the code changes [28]. In some cases, being less thorough during Mozilla code reviews is an acceptable trade-off if it results in faster code reviews. CodeFlow Analytics is a system at Microsoft that collects code review data and generates metrics from that data [14]. Researchers analyzing the usage of CodeFlow Analytics find that every individual they talked to was interested in two code velocity related points in time: (a) when the first comment or sign-off from a reviewer occurs, and (b) when the code review has been marked as completed [9]. A study investigating the declining performance of code reviews in Xen hypervisor project finds that time-to-merge is the most important metric to understand the delays imposed by the code review process [25]. Another study from Microsoft shows that when it comes to the challenges faced during the code review, response time is the number one concern because “authors of code changes discussed how it’s hard getting feedback in a timely manner” [33].

Anecdotally, we observe that not responding to code reviews in a timely manner causes frustration amongst engineers attempting to contribute to the project.1

“Do think I have proven to be sticking around and can be trusted to continue work on that in the future. inf act, the process has been so slow that pretty much anyone would have given up by now.

It’s been a month that this is just sitting there. You guys need to provide a way forward to get it as it is. I just can’t reimplement that in a new way every 2 month because nobody has any clue how to move forward on the subject. This is disrespectful of my work and hurtful for the project at large as you can’t get a better strategy to get contributor pissed of.”

Delaying the feedback also hinders the ability of a project to recruit new collaborators.2

“Nobody IS able to make changes, but not because of complexity!

We discourage away potential contributors/maintainers by leaving their reviews for weeks/months/years, not just not letting them in, not even discussing them.”

2.2 Related work

2.2.1 Literature reviews. There has been little focus on the efficiency of code reviews in comparison to the wide range of studies on code review process. A systematic literature review on Modern Code Review (in the year 2021) identifies only 4 papers related to code review time out of the 139 studies used for detailed analysis [15]. The literature classifies review time into three categories: (i) review delay (time from the first review request submission to the first reviewer feedback), (ii) review duration (time from the first review request submission to the review conclusion), and (iii) review speed (rate of SLOC reviewed per hour). Another systematic literature review of Modern Code Review practices (in the year 2020) finds only 3 papers (out of 51) on accelerating the software development process [41]. A systematic mapping study (in the year 2019) shows that out of 177 research papers categorized, only 9 focus on topics related to effectiveness and/or efficiency of Modern Code Review or integration delays of pull requests [3].

2.2.2 Existing studies. There are many definitions of Modern Code Review. One study defines code review as “a process that takes as input original source code (i.e., the first unreviewed change attempt), and outputs accepted source code” [6]. Another paper

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1https://reviews.llvm.org/D9766
2https://reviews.llvm.org/D40988
describes review time as “until the end of the discussion of the change” [50].

Most of the research relating to the effectiveness of Modern Code Review has focused on how to reduce the time it takes for changes to be reviewed, i.e., time-to-accept. Time-to-accept refers to the time when changes are submitted for review until some sort of a conclusion is reached. The prevailing wisdom is that engineers should attempt to submit smaller changes because they are easier to understand and will solicit actionable feedback [2]. Study on Mozilla project finds that developers feel that the size-related factors are the most important when it comes to code review time and decision [28]. A study on the patch acceptance in Linux kernel found a link between patch size and the time it takes to review the changes, but not the overall patch integration time [26].

We found very few studies dissecting the code review lifetime into separate intervals. A study on Gerrit code reviews categorizes a code review into pre-review time, review time, pre-integration time, and integration time [30]. Pre-review time starts when change is uploaded to Gerrit and ends when various builds and automated tests pass, and the author decides that the changes are either suitable for reviewing or more work is needed before another upload. Review time starts immediately after that and ends when a decision about the code changes has been reached. The pre-integration time is defined as the time after the review is completed, but the actual integration process is yet to start. The integration time is a measure of how long it takes for the change to be merged into the target branch after the review process is completed.

This implies that the code changes are not “real” until they are available for building, profiling, testing, and being executed in the production or test environments. That is possible only after they have been merged into the main branch used for daily development. Based on the above, the time until the code changes are integrated into a target branch seems a better metric.

2.2.3 Terminology. There are many ways to quantify code review time. The term review interval is defined as “the calendar time since the commit was posted until the end of discussion of the change” [50]. Another term utilized is time to completion that is defined as “the time between when the author submits the review to when it has been marked as completed (usually indicating that the change can be checked in)”. Two studies use the term review window meaning “the length of time between the creation of a review request and its final approval for integration” [35, 38]. The granularity of measurements is generally not specified, except one paper which defines review length as “time in days from the first patch submission” and response delay as “time in days from the first patch submission to the posting of the first reviewer message” [58]. In addition, there is also a concept of resolve time which is defined as “the time spent from submission to the final issue or pull request status operation (stopped at committed, resolved, merged, closed) of a contribution” [67].

In the context of GitHub and pull requests, the prevailing terms are pull request latency and pull request lifetime, which are respectively defined as “the time interval between pull request creation and closing date” and “the time interval between its opening and its closing” [39, 65]. When investigating code velocity for GitHub projects, the term merge delay (days between when a pull request was submitted and when it was merged) is also used [7]. GitHub Insights adds two more additional terms to the mix: code review turnaround as “the time elapsed between a review assignment and a completed review” and time to merge as “time between the first commit on a branch and the merge action of a pull request on that branch” [22].

2.2.4 Metrics. Inspired from the range of definitions available to describe code review time, we choose the following metrics to characterize code review process:

- **Time-to-first-response** [9, 33]: is defined as the time from the publication of a code change until the first acceptance, comment, inline comment (comment on specific code fragments), or rejection by a person (excludes bots) other than the author of the code.

- **Time-to-accept** [9]: refers to the time from when a code review is published for review until the acceptance of the code review by someone other than the author of the code (excludes bots).

- **Time-to-merge** [22, 28]: is defined as “…the time since the proposal of a change (…) to the merging in the code base …” [25].

Figure 1 is a visual presentation of the relationship among these metrics.

2.3 Modern Code Review Life cycle

Before Continuous Integration (CI) and Continuous Delivery (CD) became widely used approaches to releasing software, the workflow for an engineer to commit accepted code changes was relatively less time-consuming. Upon receiving the acceptance to commit code changes, an engineer must synchronize their local source tree with the latest changes, build the merged changes, re-run the relevant test cases, commit the changes, and push them to the target branch. With CI/CD being the methodology of choice for companies such as Amazon, Facebook, and Google, the amount of validation done after code changes have been accepted has increased. Introduction of CI/CD tools such as GitLab, Jenkins CI, Travis CI, added a varying amount of validation steps to the process of merging the changes [16]. Each of those steps can increase the time-to-merge.

Based on our industry experience, the overall code review timeline and its composition is depicted in Figure 1. The time-to-first-response is a subset of the time it takes to complete the first iteration of the code review. The time-to-accept contains all the iterations of the code review until it is accepted. The time-to-merge consists of time-to-accept and the time it takes for the changes to be merged.

A major difference between industry and OSS projects is the presence and scope of integration timeline. Our experience suggests that the amount of verification done in industry is higher. A modern industrial CI pipeline may consist of compiling the code changes for multiple CPU architectures, operating systems, and use different compilers. Validation steps such as linting code changes to verify conformance to coding standards, using static analyzers to preemptively detect coding errors, executing unit tests, executing a set of functional tests specific to the area, conducting performance experiments to avoid performance regressions, and even performing a deployment of changes in an internal testing environment are used [36, 37, 52]. Each of these steps can result in failures or
abnormal results (indicating a problem with the new code or validation suites themselves) that need to be investigated and explained. This can delay the merging of code changes. Engineers need to either to manually investigate the failures or rely on automated retry mechanisms to repeat the validation.

2.4 Overview of Gerrit and Phabricator

Gerrit and Phabricator are code collaboration tools which operate using a similar workflow. Engineers make code changes locally and when they decide that changes are ready to be reviewed then they submit the changes using the respective command-line or GUI tools. Reviewers are either picked by an author, assigned automatically, or self-selected once the code review becomes available. Reviewers can perform a variety of actions on the code review: accept, comment, reject, request new changes, etc. Comments can target specific lines of code (in terms of Phabricator these are called inline comments) or just be general comments. In Gerrit, an engineer can vote on a change by giving a response which by default ranges from “-2” to “+2”. Do not submit” to “+2 Looks good to me, approved”. By default, at least one “+2” vote without any “-2” votes is needed before the changes can be merged. Gerrit additionally introduces a separate label to signify that a change has been verified to work. Verification is typically performed by an automated bot and consists of tasks like compiling and linting the code, running unit tests or doing any other basic verification steps specific to a project. In Phabricator, the acceptance model is simpler and consists of actions such as acceptance, rejection or requesting changes. At any time, a new version of code changes can be submitted by the author which restarts the code review process.

One of the key differences between Gerrit and Phabricator is how changes are merged when accepted. For Gerrit, the default policy is to start the merging process automatically once the acceptance criteria are met. By default, the reviewer assigning “Code-Review+2” label to the code review will enable the automatic merging to take place. Each project can be also customized further to require a certain amount of acceptance with certain thresholds from specific people [35]. For Phabricator, either the author of code changes or someone who has an appropriate set of permissions will manually need to initiate the merging process.

Gerrit and Phabricator use different terminology. Gerrit uses “change” to refer to a set of code modifications proposed in the current iteration (referred to as “patch set”) of the code review. Phabricator uses “differential revision” which in practice gets shortened to a “diff”. The process of applying reviewed changes to the target branch is called “submitting” in Gerrit and “landing” in Phabricator. For the purposes of our paper, we will refer to that step as merging.

3 STUDY DESIGN

3.1 Choice of data

Tools that support sophisticated code review data analytics are widely used in industry. For example, Facebook uses Phabricator, Google utilizes Critique, and Microsoft conducts reviews via CodeFlow. Since the companies using such tools mainly follow a closed-source model, their data is not available for analysis.

For our study, we sought data from OSS projects with the following characteristics: (i) active multiyear development history, (ii) a sizeable number of core contributors, and (iii) popularity and relevance in their respective fields. Suitable projects must also formally track time-to-first-response, time-to-accept, and time-to-merge using their respective code review environments. In addition to the above, we selected projects that represent various software abstraction layers and usage scenarios. This includes a browser, an operating system, a compiler toolset, an office suite, and a 3D graphics creation suite.

Historically, the popular communication medium for conducting code reviews in the OSS community has been a mailing list. Some well-known example projects are Apache, Linux, OpenBSD, and PostgreSQL. However, mailing lists provide only an approximate means to gather acceptance related data captured semi-formally [8, 26]. For instance, recently Linux kernel started using “Reviewed-by:” tag to formally signify acceptance of patches, but not necessarily the final sign-off [31]. OpenBSD uses replies such as “ok @reviewer_alias” to denote reviewer acceptance of the changes.

GitHub added the functionality to capture the basic code review workflow in September 2016 [20]. However, the adoption rate of this feature on GitHub is insufficient for large scale analysis. We picked 100 random GitHub projects and found that only 4 of them used the code review workflow and even then, the usage pattern was inconsistent.
Our analysis is based on the publicly accessible data mined from Gerrit and Phabricator. We selected all publicly available projects in the Gerrit dataset [63, 64]. Here, Eclipse, LibreOffice, and OpenStack are individual projects while GerritHub (analogous to GitHub) is a collection of random projects. The selection, extraction, and cleaning of Gerrit data is described in the original paper [64]. Gerrit projects can have different code review policies (e.g., interpretations and use of labels, and number and role of reviewers). For example, a project may require an acceptance from two code reviewers instead of one [44]. Therefore, when calculating metrics such as time-to-accept, the policy specific to a project needs to be considered.

For Phabricator, we mined the full history of code reviews for Blender, FreeBSD, LLVM, and Mozilla. The selection of Phabricator projects is based on the list of publicly available projects maintained by Phabricator community [45]. We included all the projects with at least 10,000 code reviews accessible to us.

3.2 Selection and elimination criteria

To select code reviews that can offer meaningful insights, we applied one selection and many elimination criteria. We selected code reviews which have undergone complete code review life cycle, i.e., they have been published for review, accepted, and eventually merged into the code base. Our goal is not to investigate why code reviews do not get accepted or quantify the overall productivity lost by either producing or reviewing the code reviews which never end up being merged. These criteria imply that we removed code reviews that are committed without acceptance since we cannot measure time-to-accept for such reviews. We also ignored rejected code reviews or code changes without any activity. Typical reasons for the lack of activity are the code review either being abandoned by the author or ignored by the community. We removed code reviews without any changes, meaning no source code files or lines of code modified (e.g., binary files). Finally, to ensure that we are looking at valid data, we selected code reviews where timestamps follow the logical progression, i.e., time-to-accept comes after code review creation time, and time-to-merge after time-to-accept. We removed the code reviews where for example a reviewer is added, changes are accepted and cherry-picked at the same moment.3 This type of pattern indicates that at least formally no substantive code review took place.

Next, we manually inspected the data to look for patterns that otherwise can render the findings meaningless. We found a nontrivial amount of code reviews where the author was also the reviewer, and the changes were "self-accepted."4,5 For Gerrit approximately 18% of code reviews were self-accepted. For Phabricator the number was significantly smaller with approximately 0.19% of code reviews exhibiting this behavior. Some projects allow such a behavior if the author is a committer and also a long-time contributor. For the purposes of our study, we do not consider these code reviews to be a valid representation of a typical code review and exclude them.

Finally, to make sure that a real person is involved, we excluded code reviews where the only participants are the author and automated bots such as various CI related jobs. To exclude automated bots, we first filtered out the known accounts (e.g., "Jenkins", "LibreOffice gerrit bot", "RDO CI Service Account") and then manually inspected the name of each user account and their activity. This filter also helps us avoid situations where events such as the start of validation builds, or the status of sanity checks on the code changes counts as a first response or a substantive comment.

Our initial raw dataset had a total of 569,914 code reviews which reduced to 350,043 after applying the above selection and elimination criteria. For Gerrit projects, we started with 329,392 code reviews (conducted from 2013 to 2015). After applying all the filters, the resulting dataset contains 164,726 code reviews. For Phabricator, the initial set contains 240,522 code reviews (conducted from 2012 to 2021) and final set 185,317 code reviews.

3.3 Data extraction

The Gerrit dataset is distributed in the form of a MySQL database dump [63]. We developed custom SQL queries (based on the database schema) to analyze the data necessary for our study. To mine the publicly accessible code review data from the various instances of Phabricator, we used Phabry [12, 13]. Phabry outputs code review transaction history in a JSON format which we parse using a custom tool developed in C#. The resulting output is in plain text format6 that is analyzed and processed using R scripts.

4 NON-PRODUCTIVE TIME IN CODE REVIEW

4.1 Overview of data

We report statistically significant results at a $p < .001$ and use APA conventions [1]. The distribution of the time-to-first-response ($W = 0.13, p < .001$), time-to-accept ($W = 0.24, p < .001$), and time-to-merge ($W = 0.24, p < .001$) of the projects hosted on Gerrit and Phabricator is right skewed (insights from Shapiro-Wilk tests [55] applied on the data in Table 1). For our non-normally distributed code review time data, we use non-parametric tests (see Section 2.2.4).

When comparing the distinct phases of the code review time between Gerrit and Phabricator, we notice that:

- The median time-to-first-response for Gerrit code reviews ($Mdn = 4$ hours) is one hour lower than the Phabricator code reviews ($Mdn = 5$ hours). The difference is statistically significant as measured using the Mann-Whitney $U$ test [34] ($Z_{Gerrit} = 100,000; z = -10.34; p < .001$). Here, $N$ indicates the sample size of Gerrit and Phabricator code reviews respectively, $z$ refers to the $z$-score followed by the $p$-value indicating statistical significance.
- The median time-to-accept for Gerrit code reviews ($Mdn = 42$ hours) is 26 hours higher than the Phabricator code reviews ($Mdn = 16$ hours). The result is statistically significant with $z = 84.11$ and $p < .001$.
- The median time-to-merge for Gerrit code reviews ($Mdn = 49$ hours) is 3 hours lower than Phabricator code reviews ($Mdn = 52$ hours) with $z = -5.87$ and $p < .001$.

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3https://gerrit.libreoffice.org/c/libpagemaker/+7373
4https://reviews.llvm.org/D20787
5https://figshare.com/s/892a48e4fe860fc158e05
6https://gerrit.libreoffice.org/c/core/+9496
We applied stratified sampling considering the number of code when Mozilla project started using Phabricator. It indicates that the various times (time-to-first-response, time-to-accept, and time-to-merge) are given in hours. N = total number, M = mean, Mdn = median, SD = standard deviation.

### Table 1: Descriptive statistics about Gerrit (first four entries) and Phabricator projects. SLOC is the size of the code review. Various times (time-to-first-response, time-to-accept, and time-to-merge) are given in hours. N = total number, M = mean, Mdn = median, SD = standard deviation.

| Project   | N   | SLOC      | Time-to-first-response | Time-to-accept | Time-to-merge |
|-----------|-----|-----------|------------------------|----------------|--------------|
|           | M   | Mdn      | SD                     | M   | Mdn      | SD             |
| Eclipse   | 2,259 | 818.94  | 32.00                  | 13319.63 | 125.95  | 16.17          | 424.27         | 210.39 | 25.52  | 641.07         | 231.82 | 36.58  | 661.86         |
| GerritHub | 16,509 | 601.87  | 27.00                  | 13993.87 | 42.84   | 2.87         | 158.95         | 94.24 | 14.16  | 282.53         | 116.64 | 20.86  | 315.20         |
| LibreOffice | 11,567 | 741.60  | 18.00                  | 14991.28 | 60.24   | 15.82       | 154.32         | 95.30 | 20.77  | 279.91         | 97.63  | 21.33  | 282.51         |
| OpenStack | 134,391 | 223.65  | 15.00                 | 5268.01  | 51.81   | 4.28       | 203.87         | 291.80 | 52.83  | 769.47         | 307.44 | 62.21  | 790.01         |
| Blender   | 6,365  | 386.34  | 24.00                  | 8133.78  | 126.05  | 8.36       | 654.99         | 326.90 | 19.86  | 1649.03        | 503.46 | 63.21  | 2057.73        |
| FreeBSD   | 14,820 | 254.72  | 17.00                  | 3568.09  | 101.84  | 4.35       | 634.62         | 226.04 | 9.61   | 1113.61        | 536.00 | 58.31  | 2135.51        |
| LLVM      | 66,221 | 283.25  | 51.00                  | 5296.55  | 83.99   | 5.53       | 525.88         | 255.32 | 23.48  | 1138.42        | 377.64 | 69.63  | 1433.68        |
| Mozilla   | 97,911 | 346.13  | 26.00                  | 6255.02  | 43.28   | 5.47       | 182.90         | 83.77 | 14.32  | 319.46         | 190.91 | 46.49  | 641.62         |

Previous studies have provided insights on code review time of FreeBSD and Mozilla projects [42, 57, 67]. A study on approximately 25,000 code review submissions in FreeBSD via mailing lists showed that the median resolve time (comparable to time-to-merge) is 23 hours and approximately 6 hours for the time-to-first-response [67]. In comparison, our data shows a median time-to-merge of 54 hours and median time-to-first-response of 4 hours (see Table 1). Another study on Mozilla about how fast code reviews are submitted as a response to bugs of different priority shows that, irrespective of the bug report priority, patches received a review within 24 hours [42]. One more point of comparison is a study about 39,770 recent Firefox code reviews have become shorter.

The time-to-first-response for both Gerrit and Phabricator is less than a day and, in most cases less than 8 hours (see Table 1). To understand the potential reasons for delay in the first response, we picked 100 random code reviews from both Gerrit and Phabricator. We applied stratified sampling considering the number of code reviews in each project where the time-to-first-response exceeds a typical eight-hour workday. Inspecting the history of these code reviews reveals that only in 2% of the cases the reviewer expressed a statement related to why their response was delayed. In most cases reviewers stated that they were occupied with something else, but no further details are provided. It is entirely feasible that the review itself was performed very efficiently, though the start of the reviewing process was delayed. Determining what exactly happened before someone decided to eventually respond to a code review is not possible because such data is not tracked anywhere. Since we cannot determine reasons for delay in time-to-first-response, we limit ourselves to suggest that it is desirable to shorten the time-to-first-response and reduce the number of iterations a code review goes through.

Projects Eclipse and LibreOffice are two notable exceptions for the median time-to-first-response by taking approximately twice the time. We manually inspected the history of 100 randomly selected code reviews from each project using stratified sampling. We did not find a reason that can explain why median time-to-first-response for these projects is higher. That said, there can be several confounding factors (e.g., number of available reviewers [65, 66], affiliation of authors [5, 53], and technical infrastructure [24, 65, 66]) that can potentially explain the difference.

### 4.3 Post-acceptance time

Referring to the time when a code change could have been merged and when the actual merge happens (see the time between “Accepted” and “Merged” in Figure 1), we notice that Phabricator projects spend a large part of the entire code review lifetime in the post-acceptance state in comparison to Gerrit (see Table 2). The percentage of the total code review lifetime accounting for the time between acceptance and merge for Gerrit code reviews (Mdn = 1.00%) is lower than for Phabricator code reviews (Mdn = 43.00%). A Mann-Whitney U test indicated that this difference is statistically significant \( U(\text{Gerrit} = 100,000, \text{Phabricator} = 100,000) = 6,735,634,167.5, z = -255.08, p < .001 \). This finding represents a noticeable opportunity to decrease time-to-merge in Phabricator code reviews.

Depending on a Phabricator project, between 29% and 63% of the overall code review lifetime is spent waiting for the accepted changes to be merged (see Table 2).

Switching to Gerrit, most Gerrit code reviews are merged in a matter of minutes after acceptance. The only exception is the OpenStack project which at some point in the project history started using synchronous validation builds that must complete before the changes are merged. Therefore, the time it takes to merge the OpenStack code changes is directly dependent on the duration of the build. Other than the exceptional behavior of the OpenStack project, the lower percentage difference between time-to-accept and time-to-merge for Gerrit projects was expected. We believe that this small difference is attributed to the automatic merge policy of the accepted changes in Gerrit.
We further investigated the root cause for the delays in Gerrit projects, where the merge time exceeded 5 minutes (more than the median time). As before, we randomly picked 100 code reviews using stratified sampling and explored the code review history for the causes. We observed that the main causes of delay relate to merge conflicts, build failures or the time it takes to complete the verification build(s). Only in 7% of the cases the reason for the delay was not explicitly clear. Based on our industry experience with CI systems, we suspect that typical infrastructure related delays such as intermittent networking issues or increased wait times for scheduled jobs can be other possible explanations. Although, we do not have logs from the CI systems to verify these theories.

In this section, we identified non-productive time in code reviews. Next, we explore the characteristics of the code review that can contribute to the non-productive time.

5 CONTRIBUTORS OF NON-PRODUCTIVE TIME

5.1 Time-to-first-response

An intuitive approach to reduce the overall time-to-merge is to minimize the number of code review iterations. In an ideal case, the initial published set of changes will be immediately accepted as possible. Acceptance of changes being associated with a first response is a desired outcome to increase the code velocity. The time it takes for a reviewer to respond to someone’s proposed changes is dependent on several factors, only a few of which an author can directly control.

Studies show that a code review is characterized by size and composition. It is also linked to the identity and reputation of the author and the reviewer(s). To understand the factors influencing the first response time, we build a decision tree using the above factors as input. Figure 2 shows how the key variables influence the first response time. The accuracy of the resulting decision tree is 68%.

![Decision tree for determining if the first response to a Phabricator code review is an acceptance.](image)

The analysis above is based on Phabricator data for which we have a complete code review history containing all the changes in the chronological order. The dataset from Gerrit contains only a subset of the code reviews for each project. That makes the Gerrit data unsuitable for calculating the author and reviewer ranks because to perform valid calculations we need a consecutive timeline for all the code reviews. Another issue with the Gerrit dataset is that it does not formally distinguish between various code review roles such as Author, Committer, Owner, Uploader.

As a result, we are not able to determine who exactly authored the code changes versus just committed them or had permissions to upload changes to the code review tool.

Decision tree indicates that smaller code changes (< 18 SLOC of new code) have a higher chance of immediately being accepted. For changes larger than that author’s rank (≥ 46 previously completed code reviews) becomes a factor.

The results from the decision tree direct us towards investigating if there is a trend associated with the size of the code reviews in SLOC and the percentage of code review request being accepted as part of the first response. We focus on the code reviews with a size of [1..100] SLOC. The subset of code reviews with a size up to

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1 https://git.eclipse.org/r/c/platform/eclipse-platform.ui/+/2311
2 https://gerrit.libreoffice.org/c/core/+/2713
3 https://git.eclipse.org/r/c/platform/eclipse-platform.ui/+/2310
4 https://review.opendev.org/c/openstack/python-swiftclient/+/91524
5 https://gerrit.libreoffice.org/c/core/+/2713
6 https://review.opendev.org/c/openstack/oslo.i18n/+/92678
100 SLOC accounts for approximately 75% of all the Phabricator and 79% of all the Gerrit code reviews. We can see in Figure 3 that for Phabricator, the percentage of acceptance decreases as the size of code review increases. Per Figure 4 we observe that there is similarly a decreasing trend for Gerrit, but it is less pronounced and has more variation. The percentage of first responses being an acceptance stays in a fixed range regardless of the code review size. Given that in Gerrit acceptance translates into an immediate merge request, we speculate that reviewers are more mindful of the impact their decision has. Therefore, only the code reviews in which the reviewer has an utmost confidence in are accepted during the first iteration. In contrast, with Phabricator, both the author and reviewers have a “safety buffer” during which time they can rethink the merging decision.

To investigate the overall trend, we divided the existing code reviews into buckets of different ranges and calculated the percentage of first response being an acceptance. Each bucket contains approximately 10% of the overall population. The results are presented in Figure 5. An interesting observation from the acceptance pattern is that ≥ 180 SLOC, the percentage of immediate acceptance increases forming a bathtub curve [27, 43]. Based on our industry experience, one possible explanation for this behavior is that beyond a certain threshold, engineers tend to review bigger code changes lightly and accept them at a rate comparable to smaller changes. There can be multiple explanations for this observation. One of which is a harmful practice suggesting that beyond a certain threshold the thoroughness of code reviews decreases. Contingent on what takes place here, which the future studies should verify, using tools to automatically decompose proposed changes into smaller code reviews can be a potential mitigation technique [4].

5.2 Post-accept interval

This section is based on Phabricator code reviews only because the default Gerrit workflow immediately triggers a merge attempt after changes have been accepted. Our stratified sample of random 250 Gerrit code reviews indicates that merge conflicts or build failures happen in less than 1% of cases. We use the classifications below to describe what happens to differential revisions in Phabricator after they have been accepted. To understand the intent behind these actions we manually analyze a sample of random 100 instances from each category. Based on the results from the analysis we classify...
each type of post-accept behavior as a negative, positive, or neutral indicator.

- **No action**: There was no code review related activity triggered by a human between the acceptance and until the changes were eventually merged. We classify this as a positive event since this time can be reduced for increasing code velocity.

- **Changes requested**: The original or a new reviewer requested additional changes to the code, thereby invalidating the original acceptance. For decreasing code review lifetime we consider this to be a negative event. However, when it comes to code quality, this can be a positive development because a reviewer either found defect(s) which were not discovered before, realized that earlier acceptance was submitted by mistake or found something else which is significant enough to delay merging the code changes.

- **Diff updated**: refers to updated code changes. This action could indicate anything from author performing extra validation, resolution of merge conflicts or applying some optional feedback from the original code review. We consider this a neutral event. In majority of the cases the two main reasons behind this event are either the author making supposed improvements to the code or resolving merge conflicts.

- **Inline comments**: mean that someone commented on specific parts of code. Typically, this means either optional suggestions, something which was missed during the original code review (though not serious enough to warrant requesting changes) or, in some cases even positive feedback about code changes. We consider this to be a semi-negative event.

- **Comments**: refer to arbitrary text comment about the code review. This can have a variety of meaning ranging from a critique to thanking the author to an emoji to a reference from or to another code review. We consider this to be a neutral event.

In practice, we observe that each code review can have multiple events from each category associated with its post-acceptance. For example, an author can update accepted changes, another engineer can make a comment on the code, automated bot may attempt to apply changes to the latest version of source tree, etc. A percentage distribution of the post-accept behavior is presented in Table 3.

| Project  | No activity | Change request | Diff update | Code comments | Comments |
|----------|-------------|----------------|-------------|---------------|---------|
| Blender  | 59%         | 4%             | 19%         | 17%           | 31%     |
| FreeBSD  | 56%         | 1%             | 16%         | 22%           | 35%     |
| LLVM     | 45%         | 1%             | 22%         | 31%           | 44%     |
| Mozilla  | 42%         | 2%             | 46%         | 27%           | 41%     |

- The trade-off between merging potentially incorrect code versus increasing code velocity may depend on what a particular project values the most. The data in Table 3 shows that after acceptance, changes are requested on average only in 2% cases. Half of the code reviews have no post-accept activity associated with them.

- Reducing the difference between time-to-accept and time-to-merge may be as easy as modifying a project’s default configuration settings to merge code changes automatically. Modifying the default code review policy (and if needed then promptly reverting those changes) for projects enables quick experimentation. Tools like Gerrit and GitHub enable configuring a custom set of rules per repository or project [21, 23]. Those rules specify a set of conditions under which a commit is automatically merged. A default Gerrit rule is to attempt to merge changes when a code review has received at least one “Code-Review+2” response. For GitHub the “allow auto-merge” option can be enabled. Engineers can then configure a custom set of branch protection rules to determine the required number of reviewers and checks that code changes need to pass before the automatic merge is attempted. The public version of Phabricator does not support automatically landing the accepted changes as of writing this paper.

- Changing the merge policy may have unintended negative consequences. For the reviewer, automatic merging means that acceptance implies that code changes will be merged as is. Even the minor or optional feedback will require another iteration of updating the changes and accepting them again. Extra iteration(s) in turn may lengthen the time-to-merge which is the opposite of our desired outcome. For the author of changes the “safety buffer”, during which the author can reconsider merging the changes, make last minute updates or ask for feedback from additional reviewers, disappears. Additional risk increases the demands which are placed on verifying that the initial set of changes are correct by executing (potentially unnecessary) verification steps or delaying publishing the code review request.

- Optimizing time-to-first-response is a far more complex problem with many confounding variables and will require a separate study to be conducted. From our findings we can see those two variables (author’s rank and the number of lines of new code inserted) are key decision points in the decision tree. This feels right intuitively.

6 DISCUSSION

6.1 Interpretation of our results

One of the first questions that should be answered is whether the period we consider non-productive is wasteful. Modern Code Review is an asynchronous process by its nature. Engineers are not per se blocked from working on any other tasks till an event requiring their attention (e.g., code review feedback or acceptance, merge conflict with someone else’s code changes, failing build, etc.) occurs.
6.2 Implications for research and practice

(1) Commit-on-accept model increases code velocity. One of the core implications of our study is that the choice of the code review infrastructure and corresponding code review policy matters. In systems like Gerrit, the merging and committing of changes is done automatically. Similar policy can be configured for GitHub projects as well. We think that given the findings presented in Section 5 and given the low rate of errors on initial acceptance, the commit-on-accept model may be beneficial.

(2) Focus on time-to-merge versus time-to-accept. Most of the existing papers focus on time-to-accept which from practitioners point of view is just an intermediate step until the point when code changes become verified and usable. Historically that focus may have been justified because there was no significant difference between these points in time. With the addition of modern CI pipelines and increased usage of single repository and "trunk based development" in industry, the process of getting the changes merged is more involved and time-consuming than a simple commit command [62, p. 339].

(3) Adopting bots to notify engineers of pending code reviews. One of the simplest explanations for why engineers do not react immediately to code reviews is because they are not aware that an action is expected from them. Most of the existing code review systems enable triggering notification emails. Based on our industry experience, direct requests coming from an engineer with whom the reviewer does not have an existing working relationship may be considered both as "nagging" and rude, and result in an opposite desired effect. A study investigating two projects which used code review bots for a couple of years found that the number of pull requests merged (monthly) increased after the adoption of a code review bot [61]. Automated bots can act as a neutral mechanism reminding engineers of pending tasks.

(4) Detailed understanding of the composition of CI pipeline. To determine what steps in the code review process can be optimized, we first need to understand how different parts contribute to the overall time-to-merge. The contents of the CI pipeline may highly depend on the project and organization. It is advisable that periodically projects use tools applicable to their platform (e.g., CodeFlow Analytics, Gerrit DevOps Analytics, and GitHub Insights) to monitor the performance of code reviews and the time taken during the different stages of CI process.

7 THREATS TO VALIDITY

Like any other study, the results we present in this paper are subject to certain categories of threats. In this section we enumerate the threats to construct, internal, and external validity [56].

The threats associated with construct validity are caused by not interpreting or correctly measuring the theoretical constructs discussed in the study. One of the core assumptions we make is that code review acceptance really means acceptance, i.e., changes can be submitted as is or with a trivial number of modifications needed. We also presume that the reviewer providing an acceptance for a code review has the authority to grant the permission for the changes to be made. Gerrit enables implementing custom code review policies for each project. We inspected these policies for the projects we studied and took the differences into account when implementing our data analysis algorithms. We found only one exception from the default Gerrit code review process. The OpenStack project has a policy requiring two positive reviews from core reviewers and uses "Workflow+1" label versus "Code-Review+2" label to signify the final acceptance [44].

One of the concerns for internal validity is the interpretation of the results and whether the conclusions we present can be drawn from the data available. We trust the data coming from the code review tool. To mitigate the errors present in source data we removed entries with inconsistent timestamps and also samples where a code review was clearly not conducted. For example, self-accepted code reviews and those with zero time-to-accept or time-to-merge. In addition, we manually sampled hundreds of code reviews and verified their content and timestamps in code review tool and version control system.

Threats to external validity are related to the application of our findings in other contexts. Our focus is restricted to the OSS projects utilizing code review tools which enable formally tracking the timestamps capturing both time-to-accept and time-to-merge. Though several organizations developing commercial software (e.g., Facebook, Google, and Microsoft) have embraced the OSS software in recent times, most of their code is still developed using a closed-source model. Due to this, as with all empirical studies, the results are not to be generalized outside of the existing context without further replication in other environments and contexts.

8 CONCLUSIONS AND FUTURE WORK

This study quantifies non-productive time in Gerrit and Phabricator code reviews and investigates what happens to the code reviews after they are accepted. Our study shows that in more than half of the cases no activity is done between acceptance and merge. Our exploration into the cause of delay offers actionable insights into potentially increasing code velocity. We estimate that in case of Phabricator projects the code velocity can be increased by 29–63%.

From here on, we foresee the following research directions:

(1) Reasons why additional code changes are requested after the initial acceptance. Are the instances when the first acceptance is considered incorrect caused by the initial reviewer missing defects they noticed later or by another reviewer discovering additional set of problems with the code? Is there a relationship between factors such as the size of changes, previous contribution history of the author, experience of the reviewer, etc.? Given that invalidating the initial acceptance is a failure in the code review process it is important to understand the etiology of these cases and explore potential for process improvements.

(2) Factors influencing the time-to-first-response. Because time-to-first-response is responsible for a significant portion of overall time-to-merge then shortening this time is the next obvious step when attempting to increase the code velocity. Several variables can impact how fast a qualified reviewer reacts to a code review. These variables can include...
from author’s identity, availability of reviewers, complexity and size of changes, interpersonal relationship between the reviewer and author, etc. The goal is to understand how a code change author can solicit a faster response.

(3) Implications of code review policy on defect density. We do not have data points on different code review policies (acceptance being gated by CI validation results, number of required reviewers per each change, committing changes automatically on accept versus manually by the author, etc.). One future research direction can be to investigate if differences in policy have a measurable impact on code quality or defect density. For example, do projects requiring two reviewers (instead of one) or mandating that all code changes must be reviewed by a member of core committers group, have a lower defect density? Is the Linus’s law stating that “given enough eyeballs, all bugs are shallow” supported by real evidence [49]?

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