Is Kernel Code Different From Non-Kernel Code?
A Case Study of BSD Family Operating Systems

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Abstract—Studies on software evolution explore code churn and code velocity at the abstraction level of a company or an entire project. We argue that this approach misses the differences among abstractions layers and subsystems of large projects. We conduct a case study on four BSD family operating systems: DragonFlyBSD, FreeBSD, NetBSD, and OpenBSD, to investigate the evolution of code churn and code velocity across kernel and non-kernel code. We mine commits for characteristics such as annual growth rate, commit types, change type ratio, and size taxonomy, indicating code churn. Likewise, we investigate code velocity in terms of code review periods, i.e., time-to-first-response, time-to-accept, and time-to-merge.

Our study provides evidence that software evolves differently at abstraction layers: kernel and non-kernel. The study finds similarities in the code base growth rate and distribution of commit types (neutral, additive, and subtractive) across BSD subsystems, however, (a) most commits contain either kernel or non-kernel code, (b) kernel commits are larger than non-kernel commits, and (c) code reviews for kernel code take longer than non-kernel code.

Index Terms—BSD, code churn, code velocity, kernel code, non-kernel code

I. INTRODUCTION

Software evolution is a continual change from a lesser or worse state to a higher or better state [1], [2]. The essence of this change is a “process by which programs are modified and adapted to their changing environment” [3].

Existing research on quantifying software evolution focuses either on an entire project or a company. For example, a study investigates the role of patch review in software evolution in the context of an entire Mozilla Firefox project [4].

We argue that viewing the entire system as a monolithic entity may lead to incorrect conclusions about the characteristics of a system. For example, statements like “the median code review size for X is N” are overly simplistic. They omit the potentially significant differences between various products and subsystems.

The unit of analysis we choose for this paper is a specific type of large software system—an operating system. We conduct a case study on a subset of BSD family operating systems to explore the evolutionary patterns in the operating systems’ code. We investigate if there is empirical evidence to show that software evolution differs between kernel and non-kernel code (see Section II-A and Section II-B for background and terminology).

While software evolution in the kernel has been studied [5], [6], we do not know how it differs from non-kernel code and why one should study the evolution of an entire operating system. We believe that our paper is the first comprehensive study to investigate software evolution in the context of an entire operating system.

We quantify software evolution using code churn [7], [8] and code velocity. At the lowest implementation level, code churn consists of modifications to lines of code (LOC) [9]. To quantify the code velocity, we measure the various code review intervals: time-to-first-response, time-to-accept, and time-to-merge. Both code churn (e.g., size of commits) [10], [11], [12], [10], [13], [14] and code reviews [15], [16], [17], [18], [19], [20] have been studied in the past at the level of an entire project or a company.

We pose the following research questions:

1) RQ1: are code churn characteristics different between kernel and non-kernel code?
2) RQ2: is the code velocity different between the kernel and non-kernel code?

We collect information by mining GitHub mirrors of all the operating systems that we study. We mine the Phabricator [21] instance used for FreeBSD code reviews to investigate code velocity. Phabricator is a modern code collaboration tool used by popular projects such as Mozilla and LLVM. The code reviews follow the Modern Code Review process [11].

We find that (a) engineers mainly make changes that are restricted to a specific abstraction level, i.e., they change either kernel or non-kernel code and rarely mix both in the same commit, (b) kernel commits are larger than non-kernel commits, (c) the size of the kernel and non-kernel subsystems increases at a similar rate, and (d) code reviews in FreeBSD kernel code take longer than for non-kernel code.
II. BACKGROUND AND RELATED WORK

A. Background

Our experience with operating systems development in the industry suggests that the communities developing kernel and non-kernel components are different. The differences manifest in the technical skills of developers, number of engineers working in an area, level of specialization, and cost of entry into the community. Based on our field observations, these groups of engineers also operate using different philosophies for attributes such as the focus on code quality and code velocity. Our reasoning for using this categorization relies on kernel and non-kernel code being distinct abstraction layers technically [22], [23], [24], historically, and culturally. Partitioning an operating system into the abstraction layers that separate it into the kernel and everything else is also an approach that operating systems research [24], [25], [26], [27] uses.

This study is the first attempt to examine the distinction in software evolution between kernel and non-kernel code in the context of an operating system using code churn and code velocity. Our paper offer insights into how future research should examine software evolution in the context of a larger system.

B. Terminology

1) Kernel and user mode: Various definitions for kernel exist in textbooks about operating systems. The kernel is defined as “single binary program” [28, p. 94], “provider of services” [29, p. 18], “interface between the hardware and the software” [30, p. 62], “core operating system code” [31, p. 2], or “[t]he most important program” [23, p. 8]. In this paper, we use the following definition: “[t]he kernel is the part of the system that runs in protected mode and mediates access by all user programs to the underlying hardware (e.g., CPU, keyboard, monitor, disks, network links) and software constructs (e.g., filesystem, network protocols)” [24, p. 22].

Code running as part of the kernel is called kernel mode. Sometimes kernel running as also called supervisor mode, “where everything is allowed” and “where the processor regulates direct access to hardware and unauthorized access to memory” [32, p. 18]. The consequences of defects in kernel mode are catastrophic. For example, “error in the kernel programming can block the entire system” [29, p. 18].

The counterpart to the kernel mode is the user mode. User mode is traditionally associated with the abstraction level at which code executes. It is not necessarily related to how the source tree layout is structured. Therefore, we use the term non-kernel code to describe all the source that is not part of the kernel. The definitions of user mode vary from describing it as a specific type of execution environment to a more technical scope. For example, “programs running outside the kernel” [28, p. 298], “[c]ompilers and editors run in user mode” [28, p. 3], or “certain areas of memory are protected from the user’s use and in which certain instructions may not be executed” [26, p. 58].

Limitations related to execution and resource access are the overall defining factor for user mode. User mode applications are said to see a “subset of the machine’s available resources and cannot perform certain system functions, directly access hardware, or otherwise misbehave” [22, p. 4].

Though some sources define an operating system as a “portion of the software that runs in kernel mode or supervisor mode” [28, p. 3], such definition is outdated. We use a more inclusive understanding where an operating system is defined as a “layer of software that manages a computer’s resources for its users and their applications” [27, p. 6].

2) Committers, contributors, and maintainers: The BSD development process and open-source software, in general, have clearly defined roles for engineers contributing code. Using definitions from FreeBSD,1 the roles are as follows: contributor, committer, and maintainer. From a data mining point of view, we cannot determine who exactly authored the code changes based purely on source code history. When a contributor submits a patch and the patch gets reviewed and approved, the committer makes the actual code change. There is no formal and uniform way to specify the original author.

In addition, code reviews are not mandatory for committers. Committers are “required to have any nontrivial changes reviewed by at least one other person before committing them to the tree” [24, p. 14]. Each committer can determine the interpretation of “nontrivial.” However, code reviews do not always have to be public and can be conducted by email, IRC, or other mechanisms.2 As a result, we have only access to a subset of all code reviews. We list this explicitly as a threat to validity in Section VII.

C. Related work

1) Code churn size: From industry studies, we know that median change size at AMD is 44 lines [10], the median number of lines modified at Google is 24 [11], at Facebook each deployed software update involved, on average, 92 lines of code [12], and for Lucent, the number of non-comment lines changed is 263 lines [10], [33]. We observe an order-of-magnitude difference in the size of code changes between companies. Including data about open-source software adds even more variety to our data set. In open-source software projects, the median change size ranges from 11 to 32 changed lines [13, p. 37]. For Android, the median change size is 44 lines, for Apache 25 lines, for Linux 32 lines, and Chrome 78 lines [10]. The median size of pull requests in GitHub is 20 total lines changed [14]. The critical observation from available data is that the size of changes varies significantly even between various open-source software projects. We did not find any existing studies differentiating the size of commits between various layers of abstraction in the same operating system.

2) Code velocity: Existing research about code churn and code velocity in operating systems focuses on open-source

1https://wiki.freebsd.org/ BecomingACommitter
2https://docs.freebsd.org/en/articles/committers-guide/
software such as FreeBSD or Linux. Industry researchers generally publish data within the scope of the company. We are not aware of any externally published research related to commercial operating systems, such as closed-source derivatives of Darwin (foundation for Apple’s operating systems such as iOS, macOS, and watchOS) or Microsoft Windows.

Based on current findings, we know that the code reviews at Google, Microsoft, and open-source software projects take approximately 24 hours [34]. In commercial software development (e.g., Google), 24 hours is the general expectation for the code review turnaround time [35, p. 176]. An immediate observation we make is that this number is an order of magnitude smaller than the time it takes to review the Linux kernel code. Code review practices for the Linux kernel have been studied [36]. However, that research mainly focuses on code review activity and its participants, not specifically on the code churn and velocity. A study on the Linux kernel finds that “33% of the patches makes it into a Linux release, and that most of them need 3 to 6 months for this” [18]. Another study analyzing 139,664 accepted patches in the Linux kernel states that review time (from patch being published to its acceptance) is on median 20 days [20]. An existing study on FreeBSD results in findings differing by an order of magnitude [19] albeit it is another UNIX-like operating system. The data source is approximately 25,000 code review submissions from FreeBSD mailing lists. The study defines resolve time as “the time spent from submission to the final issue or pull request status operation (stopped at committed, resolved, merged, closed) of a contribution.” The median resolve time for FreeBSD is 23 hours.

We observe from these data points at least an order-of-magnitude difference in code velocity even in the context of Linux. The kernel code (Linux), company-wide statistics (Google, Microsoft), and overall operating system scope (FreeBSD) have wide variance. Existing studies [18], [19], [20] show the difference in software evolution for code churn characteristics and code velocity at the scope of an entire project. We argue that these differences exist even within the same system. However, we also know that other metrics, such as code quality, do not significantly differ between operating systems based on a study [37] investigating the code quality metrics in FreeBSD, Linux, OpenSolaris, and Windows Research Kernel.

D. Classification, history, and scope of BSD

The history of UNIX [38], [39] and BSD family operating systems is extensively documented [24, p. 3–14]. All the operating systems we investigate have a common set of ancestors: (a) NetBSD has its roots in both 386BSD and 4.4BSD Lite, (b) OpenBSD is based on NetBSD source tree, (c) FreeBSD 1.0 is based on 386BSD 0.1, and (d) initial commit for DragonFlyBSD is based on FreeBSD 4.8.

Different flavors of BSD have a specific focus. For example, OpenBSD has a “fanatical attention to security, correctness, usability, and freedom” and “strives to be the ultimate secure operating system” [40, p. 4]. At the same time, “NetBSD’s main purpose is to provide an operating system that can be ported to any hardware platform” [30, p. xxxiii].

Another set of differences is related to the organizational aspects of BSD development when compared to commercial operating systems. The number of engineers working on similar open-source software and closed-source projects can differ by order of magnitude. BSD family operating systems have hundreds of committers (see Table 1). We know from grey literature that the team developing Microsoft Windows 2000 contained 3,100 engineers responsible for developing and testing the operating system [41]. For Windows Server 2003, the number of engineers reached 4,400 [42, p. xxxiii]. The team size has likely increased in the last 20 years.

Testament to the wide adoption of BSD in the consumer space (in addition to traditionally being thought of as a server software) is the fact that Apple’s closed-source operating systems such as iOS, macOS, watchOS base themselves on BSD [43], [44].

III. Study Design

A. Choice of data

We focus on operating systems that enable a clear distinction between kernel and non-kernel source code. Out of the widely used operating systems, only a few have open-sourced their code and history of changes to source code. Microsoft Windows uses a closed-source model. The Windows Research Kernel [45] is a subset of the Windows kernel made public to researchers. It contains only kernel code and is not accompanied by the history of source code changes. Though Apple makes some parts of the XNU kernel and Darwin open-source software, the complete source code and its history are not accessible to external researchers.

Linux source code and history of changes are public. Though Linux is open-source software, it is not suitable for this investigation. There are hundreds of Linux distributions available (everything from Android to Ubuntu) [46], [47]. However, determining what constitutes non-kernel code is highly dependent on a particular Linux distribution. Contrary to popular opinion, “the term Linux refers to only the kernel” [22, p. 3]. It is the nucleus “of an OS rather than the complete OS” [48, p. 3]. Linux “does not include all Unix applications, such as filesystem utilities, windowing systems and graphical desktops, system administrator commands, text editors, compilers, and so on” [23, p. 2]. Therefore, we exclude Linux from our analysis.

One of the discussion points in past studies that investigated kernel evolution at the subsystem level was related to how much the size of the driver code base influences the results [5], [6]. Past studies have shown that driver code is often cloned and sometimes duplicated [49], [50], [51]. In this paper, we treat drivers as a de facto part of the kernel and do not remove them from our dataset.

Given the limited number of popular open-source operating systems under active development, we use purposive sampling

3https://opensource.apple.com/
We collect the number of committers per op-tracked (see Sec-and formally FreeBSD, JSON and use APA conventions [54]. [10, 2022. 56 36,283 23,567 3,553,712 6,795,448 0dd847d4a4fb). N 9 05 N O M I T H A S H E S U S E D T O C A L C U L A T E data. All the statistical analysis is performed using BSD contains 1995 51 167 217,833 66,388 5,490,127 14,448,982 90c942502171. C We report statistically signif-
G master 1993 77 393 248,565 65,439 7,444,049 10,724,281 8a7404b2aeeb.FAMILY OPERATING SYSTEMS We focus on the main branch used F UMBER OF collaboration tool called Phabricator. The Phabricator instance for FreeBSD code reviews are performed using a code col-

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TABLE I
OVERVIEW OF BSD FAMILY OPERATING SYSTEMS. COMMIT HASHES USED TO CALCULATE LOC ARE BASED ON GITHUB MIRRORS. NUMBER OF COMMITTERS AND RELEASES ARE AS OF FEBRUARY 10, 2022.

| Project          | Established | Releases | Committers | Total commits | Files | Kernel LOC | Non-kernel LOC | Commit hash       |
|------------------|-------------|----------|------------|---------------|-------|------------|----------------|------------------|
| DragonFlyBSD     | 2003        | 76       | 56         | 36,283        | 23,567| 3,553,712  | 6,795,448      | 0dd847d4a4fb     |
| FreeBSD          | 1993        | 77       | 393        | 248,565       | 65,439| 7,444,049  | 10,724,281     | 8a7404b2aeeb     |
| NetBSD           | 1992        | 68       | 277        | 294,140       | 154,758| 8,677,777  | 39,446,639     | 557728ebea1      |
| OpenBSD          | 1995        | 51       | 167        | 217,833       | 66,388| 5,490,127  | 14,448,982     | 90c942502171     |

to select our study samples. We choose to target the BSD family of operating systems for the following reasons: (a) extensive and well-documented history of operating systems’ evolution, (b) source tree that contains a complete operating system, (c) similar nature of the operating systems to each other, and (d) in case of FreeBSD the availability of detailed information about code reviews over an extended period.

The operating systems we gather data for are DragonFlyBSD, FreeBSD, NetBSD, and OpenBSD. Table I describes the characteristics of each operating system. We calculate the LOC per operating system and category of code using scc [52]. We collect the number of committers per operating system (DragonFlyBSD, FreeBSD, NetBSD, and OpenBSD) from publicly available data.

Only FreeBSD uses a formal code collaboration tool (Phabricator) to conduct code reviews out of these operating systems. The rest of the operating systems use a code review model where not all the code reviews are public. Therefore, the author’s identity is not always formally tracked (see Section II-B2).

B. Data extraction

Source code repositories for each version of BSD use several different revision control systems: CVS, Git, Mercurial, and Subversion. To avoid switching between different environments and develop multiple versions of the same toolset, we utilize the fact that each operating system has an up-to-date GitHub mirror. To verify the validity of the mirror image, we select a random sample of 50 commits from each operating system and compare the data from the GitHub mirror to the changes in the original revision control system. We do not observe any discrepancies in the data. We use Git commands with custom shell scripts to fetch the information about the commit history. The collected data is parsed by an application developed in C#.

FreeBSD code reviews are performed using a code collaboration tool called Phabricator. The Phabricator instance used to review FreeBSD code has code review data starting from 2013. We use Phabry [53] to extract the information about code reviews. The extracted data is exposed in JSON format. We develop a custom application written in C# to parse the JSON data. All the statistical analysis is performed using custom code written in R.

C. Selection and elimination criteria

1) Filtering commits: We focus on the main branch used for the development of each operating system. Depending on the operating system, it is called main, master, or trunk. We use the --first-parent option for git log commands to have a linear commit history. We remove all the commits that do not have any code changes. The empty commits result from either commits containing only the binary files or “placeholder commits” (a side-effect of converting the source code change history from systems like CVS to GitHub mirror). Our initial dataset contained 797,879 commits, and after filtering, it decreased to 796,821 commits.

2) Filtering code reviews: We perform a thorough filtering process to ensure a valid comparison between kernel and non-kernel code reviews. The Phabricator instance for FreeBSD contained 32,884 code reviews during our data collection process. We fetch all the code reviews that are accessible to registered users. We use only the code reviews that have gone through the entire code review cycle, i.e., they were published, accepted, and eventually merged to the target branch. The code reviews that are abandoned, ignored, or still open are not suitable for analysis because we cannot calculate metrics such as time-to-merge (see Section V for definitions). We removed the code reviews where the author “self-accepted” the changes, and no other engineer was involved in the code review process. We eliminate the reviews where the only content is binary files. We require that the time-to-first-response is before time-to-accept, and time-to-merge is after time-to-accept. That restriction filters out code reviews submitted and accepted immediately without an actual review being conducted. After applying these selection criteria, our final dataset contains 14,875 code reviews conducted between 2013 and 2021.

D. Statistical analysis

1) Characteristics of data: We report statistically significant results at a $p < .05$ and use APA conventions [54]. Our initial observation based on the histogram of total code changes per commit is that the code churn per commit is not distributed normally. By code churn we mean the sum of the “added, removed or modified” lines [7]. We define different commit types that we use in our analysis in Section IV-A. We use the Shapiro-Wilk test [55] to confirm our observation

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9https://figshare.com/s/467523b4c41b51e80d7e
about non-normality of commit sizes for all the commit types. The tests confirm that commit sizes for neither kernel \((W = 0.085, p < .05)\), non-kernel code \((W = 0.061, p < .05)\) or mixed code \((W = 0.019, p < .05)\) commits are normally distributed.

We make a similar observation about the non-normality of various periods describing the code reviews: time-to-first-response \((W = 0.12, p < .05)\), time-to-accept \((W = 0.17, p < .05)\), and time-to-merge \((W = 0.25, p < .05)\).

See Section V for how we define these periods. The lack of normality in data leads us to use nonparametric statistical tests to analyze the relationships between different groups.

2) **Handling outliers:** As a part of data validation, we inspect the potential outlier values [56] for the commit dates, the total size of changes, and the duration of code reviews. We notice only one abnormal commit in DragonFlyBSD that, according to the Git log, was supposedly made in 1970,\(^{10}\) but the changes were committed in 2011. We observe that commit sizes have a non-normal (right-skewed) distribution. Because of skewed distribution, we did not apply techniques such as Tukey \(1.5 \times IQR\) fence exclusion criteria [57] to remove the potential outliers [58]. To investigate the potential outliers in more detail, we manually inspect a stratified sample of 100 commits where the size of a commit in LOC is more than 100,000. Similarly, we analyze 100 code reviews where time-to-merge exceeds a month to detect abnormalities. None of the changes were “inconsistent with the remainder of that set of data” [59, p. 4] or “surprising or discrepant to the investigator” [60].

We do not classify any of those changes as outliers based on our findings. We conduct our analysis using the complete dataset that remains after applying all the filters described in Section III-C.

**IV. RQ1: ARE CODE CHURN CHARACTERISTICS DIFFERENT BETWEEN KERNEL AND NON-KERNEL CODE?**

**A. Commit taxonomy**

For the BSD family of operating systems, the distinction in the location between kernel and non-kernel source code is clearly defined. All the kernel source files reside under the sys directory (relative to the root of the source tree) [61].

We use that fact to categorize each commit as follows:

- **Kernel.** Commit contains changes pertaining only to kernel code.
- **Non-kernel.** Commit contains changes related only to non-kernel code.
- **Mixed.** Commit contains changes to both kernel and non-kernel code.

The categorization applies only to the location of the source code. It does not mean that a commit contains code that is executed only at a specific level of abstraction during the runtime. For example, a user mode application can include headers describing kernel data structures to pass correct parameters to a syscall.

**TABLE II**

| Project       | Commits   | Kernel | Non-kernel | Mixed |
|---------------|-----------|--------|------------|-------|
| DragonFlyBSD  | 36,283    | 50.91% | 44.22%     | 4.87% |
| FreeBSD       | 248,565   | 52.44% | 45.10%     | 2.46% |
| NetBSD        | 294,140   | 52.68% | 46.04%     | 1.27% |
| OpenBSD       | 217,833   | 37.43% | 61.11%     | 1.46% |

The distribution of commits is displayed in Table II. The majority of commits contain either kernel or non-kernel code. Mixed commits represent, on average, only 2.5% of the population. We can observe that this trend is consistent across different operating systems.

1) **Mixed commits:** To further understand the composition of mixed commits, we investigate these commits in more detail. We use stratified random sampling to select 50 mixed commits for each operating system resulting in 200 samples. We then manually analyze the contents of each commit and record the presence of the following attributes: kernel code, non-kernel code, documentation (e.g., content for a manual page), configuration (e.g., contents of the operating system distribution, values for default settings), and test code (e.g., functional or unit test code).

Out of all the possible combinations \(2^5 = 32\), four combinations account for 88.5% of mixed commits.

- The presence of both kernel code and non-kernel code is responsible for 44.5% of mixed commits.
- Both kernel code and documentation account for 29%.
- Both kernel code and configuration account for 8.5%.
- The kernel code with non-kernel code and documentation account for 6.5%.

**Finding 1**

The majority of code changes are either in kernel or non-kernel code. On average, only 2.5% of code changes are a mix of these categories. In case of mixed changes, the dominating combinations are kernel with non-kernel code and kernel code with updates to accompanying documentation.

An alternative approach to classification is to ignore all the auxiliary changes because they are not code per se. We choose to categorize them separately. Based on our experience with operating system development, a similar amount of rigor and effort goes into reviewing changes to configuration and documentation, as to reviewing source code.

**B. Commit size and change ratio characteristics**

Extracting the contents of a diff from a revision control system and estimating precisely the commit size are complex tasks [62], [63]. In this paper, we use git show with the default diff algorithm and diffstat to calculate the code churn for each commit [64]. The diffstat outputs the number of inserted, deleted, and modified lines based on the
TABLE III

COMMIT SIZES PER OPERATING SYSTEM. N = TOTAL NUMBER, M = MEAN, Mdn = MEDIAN, SD = STANDARD DEVIATION.

| Project       | Kernel | Non-kernel | Mixed |
|---------------|--------|------------|-------|
|               | N      | M          | Mdn   | SD     | N      | M          | Mdn   | SD     | N      | M          | Mdn   | SD     |
| DragonFlyBSD  | 18,471 | 472        | 13    | 9,960  | 16,046 | 1,748    | 10    | 3,193  | 1,766  | 7,309    | 92    | 227,835|
| FreeBSD       | 130,348| 168        | 9     | 3,611  | 112,106| 298      | 6     | 11,085 | 6,111  | 1,777    | 71    | 14,447 |
| NetBSD        | 154,967| 186        | 9     | 6,421  | 135,426| 2,126    | 7     | 73,152 | 3,747  | 1,785    | 69    | 33,372 |
| OpenBSD       | 81,526 | 176        | 9     | 7,828  | 133,125| 644      | 9     | 26,662 | 3,182  | 1,801    | 51    | 65,444 |

contents of the diff. The sum of these lines is *commit size*. Descriptive statistics about commit sizes for different types of commits (kernel, non-kernel, and mixed) are displayed in Table III.

We compare our results with the existing data about code review sizes (see Section II-C1). Each commit does not necessarily have to result from the code review. For example, committers in an open-source software project are not obligated to send out a code review for each change (see Section II-B2) and can commit trivial changes without a code review. Therefore, only a subset of commits is reviewed by someone other than the author. We utilize the data about code review size as a close approximation because engineers tend to submit the contents of a code review as a single commit.

The median commit sizes in our dataset differ from the numbers presented in the existing studies (see Section II-C1). Our findings are smaller than the findings from various companies and open-source software projects. Multiple reasons may explain this outcome:

- For kernel and non-kernel commits, the median commit size is smaller than existing data points. We theorize that this is because committers can produce lots of small trivial changes. This behavior leads to the median values describing the commit size decreasing. We choose a stratified sample of 100 commits with the size of ≤ 5 LOC and inspect the contents of all these commits manually. Our observations confirm this theory.
- For mixed commits, the median size is larger. Based on our investigation in Section IV-A, we observe that mixed changes involve different layers of abstraction. For example, kernel, corresponding user mode libraries, test cases, and tools code in the same commit. Mixed commits quite often involve updates to documentation as well. In our industry experience, this is an expected result. Making atomic changes across different subsystems requires more work and increased code churn.
- Differences in calculation of commit or code review sizes. This paper uses the accepted definition of code churn, which means “added, removed or modified” LOC [7]. Without more formal details from each study, we speculate that it is possible that different methods of counting the LOC accounts for the variance we see.

A Kruskal-Wallis test for stochastic dominance [65] reveals that there is a statistically significant difference between the mean ranks of commit sizes for at least one pair of commit types \( H(2) = 16,010.20, p < .05 \). After performing a post hoc pairwise Dunn test [66], [67] with a Bonferroni correction [68], we observe a difference in commit sizes between all commit types \( p < .05 \).

### Finding 2

Kernel commits are bigger than non-kernel commits. Mixed commits involving both kernel and non-kernel code are the largest.

C. Commit impact on code base size

The fact that the total size of the software grows over time can be easily observed in open-source software and commercial software development. For Linux [69], [70], [71], and FreeBSD [72], the growth has been documented and studied.

![Fig. 1. Evolution of the size of various BSD source trees. LOC is calculated using the snapshot of the source tree on January 1st of each year using `scc`.](image)

We can see in Figure 1 that all the operating systems we study exhibit a pattern of continuous growth. The rate of the
annual increase in the code base size between operating systems is similar. The NetBSD growth pattern is an outlier, for which we lack an explanation. The self-declared focus of each operating system may partially account for the growth rates we observe. Future studies should investigate its relationship to the growth in the size of code base.

Finding 3

The median annual growth rate across all operating systems for kernel code is 7.15%. For non-kernel code, the growth rate is 6.19%. The size of both subsystems increases at a similar rate.

A limited amount of data about closed-source commercial operating systems is available to the public. Based on the grey literature, the growth trend is similar. Microsoft Windows NT 3.1, released in 1993, contained 4–5 million LOC [42, p. xxxiii]. In 10 years, the size of the code base increased by order of magnitude to approximately 50 million LOC during the release of Windows Server 2003 [42, p. xxxiii]. From our industry experience, we know that the size of the Windows code base has only continued to increase since.

A reasonable hypothesis is that most commits are either adding or modifying the code, with only a tiny subset of commits reducing the size of the code base. We do not know if that commit pattern applies equally to the kernel and non-kernel code. Based on our experience with commercial operating system development, we know that each unnecessary line in kernel code is generally treated as a liability due to the catastrophic consequences of kernel defects. Therefore, at least amongst the kernel engineers, there is a firm conviction and desire to constantly reduce the size of the code base and remove any unnecessary code.

To verify this theory, we investigate the impact of commits on the size of the code base in more detail. We categorize the commits into the following three categories:

- **Neutral.** All code changes are modifications (i.e., changing the existing LOC) or an equal number of insertions and deletions. Therefore, the commit does not increase the size of the code base.
- **Additive.** The number of LOC inserted is greater than the number of LOC deleted.
- **Subtractive.** The number of LOC deleted is greater than the number of LOC inserted.

From Table IV, we can see that the distribution of commits is uniform across different operating systems using this categorization. We can observe (a) more additive non-kernel commits than kernel commits, and (b) more subtractive kernel commits than non-kernel commits. However, the differences between the percentages of commit types for kernel and non-kernel code are relatively minor (approximately 1–5%). This finding is insufficient to confirm our intuition that kernel commits are focused more on eliminating the dead code or reducing the size of the kernel code base than non-kernel commits. In theory, a small number of commits may systematically remove large amounts of LOC from the kernel code base to remove dead code. Based on our stratified sampling of 100 commits that delete more than 1,000 LOC in the kernel, we do not find any evidence for this. In addition, given the general guidance for commit size in open-source software development, we find that the frequent usage of commits containing many LOC to remove code is unlikely. For example, Linux kernel guidelines state that kernel developers should “break their changes down into small, logical pieces” [71].

### Table IV

| Project       | Commit type | = | ↑ | ↓ |
|---------------|-------------|---|---|---|
| DragonFlyBSD  | Kernel      | 18.16% | 58.22% | 23.62% |
|               | Non-kernel  | 23.83% | 53.30% | 22.88% |
| FreeBSD       | Kernel      | 22.27% | 55.26% | 22.47% |
|               | Non-kernel  | 28.31% | 54.49% | 17.21% |
| NetBSD        | Kernel      | 24.99% | 55.15% | 19.86% |
|               | Non-kernel  | 29.77% | 54.48% | 15.75% |
| OpenBSD       | Kernel      | 22.56% | 53.88% | 23.56% |
|               | Non-kernel  | 27.44% | 51.74% | 20.82% |

Finding 4

Both kernel and non-kernel commits have similar neutral, additive, and subtractive commit distributions. More than 50% of commits in both categories increase the size of the code base.

**D. Ratio of code changes in a commit**

To further understand the composition of commits, we investigate the commit content in more detail. We calculate a percentage ratio of different types of code changes (insertions, deletions, and modifications) per each commit. For example, we define the percentage of insert ratio as:

\[
\text{Total insertions (LOC)} / \text{Commit size (LOC)} \times 100.
\]

Similarly, we calculate the delete ratio and modify ratio. We present the percentages of various ratios for each operating system and commit type in Table V. On average only 2.5% of code changes are mixed (see Section IV-A1). Our analysis is primarily interested in the differences between kernel and non-kernel code.

As an immediate observation, we notice that the median delete ratio is 0% for almost all the categories. Based on the discussion in Section IV-C this is an expected finding. The only outlier behavior in DragonFlyBSD has a 5.25% of delete ratio in mixed commits. To investigate this finding, we pick a random sample of 100 DragonFlyBSD commits where the delete ratio was more than 50% and analyze each commit manually. Our analysis indicates that 82% of commits are...
TABLE V

RATIO OF CODE CHANGES PER OPERATING SYSTEM AND COMMIT TYPE. N = TOTAL NUMBER OF COMMITS, M = MEAN, MDN = MEDIAN, SD = STANDARD DEVIATION.

| Project info     | Insert ratio | Delete ratio | Modification ratio |
|------------------|--------------|--------------|--------------------|
|                  | N            | M     | Mdn   | SD   | M     | Mdn   | SD   | M     | Mdn   | SD   |
|                  |              | Mean  |       |      | Mean  |       |      | Mean  |       |      |
| DragonFlyBSD     |              |       |       |      |       |       |      |       |       |      |
| Kernel           | 18,471       | 40.94 | 40.00 | 36.98 | 17.99 | 0.00  | 29.53 | 41.07 | 33.33 | 35.31 |
| Non-kernel       | 16,046       | 37.80 | 28.57 | 38.47 | 16.34 | 0.00  | 29.49 | 45.86 | 40.00 | 37.97 |
| Mixed            | 1,766        | 44.98 | 46.86 | 36.79 | 22.76 | 5.25  | 32.56 | 32.26 | 21.43 | 32.18 |
| FreeBSD          |              |       |       |      |       |       |      |       |       |      |
| Kernel           | 130,348      | 41.47 | 36.84 | 39.40 | 17.73 | 0.00  | 30.51 | 40.81 | 31.71 | 38.15 |
| Non-kernel       | 112,106      | 40.72 | 33.33 | 40.60 | 13.17 | 0.00  | 27.91 | 46.12 | 40.00 | 40.18 |
| Mixed            | 6,111        | 54.64 | 63.93 | 37.81 | 16.47 | 0.00  | 29.15 | 28.90 | 16.67 | 31.97 |
| NetBSD           |              |       |       |      |       |       |      |       |       |      |
| Kernel           | 154,967      | 33.91 | 27.27 | 34.06 | 12.59 | 0.00  | 24.13 | 53.50 | 50.00 | 34.29 |
| Non-kernel       | 135,426      | 34.22 | 25.00 | 35.44 | 10.13 | 0.00  | 22.65 | 55.65 | 50.00 | 35.94 |
| Mixed            | 3,747        | 43.86 | 44.57 | 36.55 | 13.84 | 0.00  | 25.43 | 42.31 | 33.33 | 34.88 |
| OpenBSD          |              |       |       |      |       |       |      |       |       |      |
| Kernel           | 81,526       | 35.47 | 30.95 | 35.01 | 15.51 | 0.00  | 26.78 | 49.02 | 44.44 | 34.30 |
| Non-kernel       | 133,125      | 33.02 | 22.99 | 35.17 | 13.59 | 0.00  | 25.76 | 53.40 | 50.00 | 35.87 |
| Mixed            | 3,182        | 42.60 | 41.68 | 36.02 | 15.50 | 0.00  | 28.02 | 41.90 | 34.48 | 33.49 |

associated with a deliberate effort to remove obsolete features and functionality. Therefore, mixed commits have a very high delete ratio percentage (up to 100%). Consequently, that increases both the mean and median values for mixed commits. The rest of the commits are associated with tasks such as refactoring, reverting previous commits, or general code hygiene related work.

We notice after observing mean and median values for the insert ratio that kernel commits tend to have a higher insert ratio than non-kernel commits A Mann-Whitney U test [73] indicates that this difference was statistically significant $U(N_{Kernel} = 100,000, N_{Non-kernel} = 100,000) = 10,133,125,316.5, z = 10.61, p < .05$. Similarly, we observe that modification ratio tends to be smaller for kernel code than non-kernel code. Based on Mann-Whitney U test the difference was statistically significant $U(N_{Kernel} = 100,000, N_{Non-kernel} = 100,000) = 9,699,003,058.5, z = -23.50, p < .05$.

One possible explanation for the higher insert ratio in the kernel is our anecdotal observation that engineers who want to work on operating systems generally tend to work on kernel code as opposed to non-kernel code, focusing on new features and improvements to the kernel. That means code changes to support new hardware platforms, modern networking protocols, or port over existing device drivers. We find that theory plausible because improving kernel is beneficial for the operating system’s adoption rate.

For the lower modification ratio in the kernel, we speculate that engineers are more careful when changing the existing code than adding new code. With new code, the author has detailed knowledge about why the code is being added and what it does. The existing code, especially in the kernel, which may be decades old, may have a limited test coverage (if any), and there is often no context or sufficient documentation to understand the implementation details. Making kernel changes under those constraints is riskier than adding new code.

In non-kernel code, the consequences of introducing defects are less severe, and therefore engineers are willing to take more risks when updating existing code. Future studies should test that speculative intuition.

Finding 5

The delete ratio is slightly more than 0% across all commit types. The insert ratio in kernel code is higher than in non-kernel code. The modification ratio in kernel code is lower than in non-kernel code.

V. RQ2: IS THE CODE VELOCITY DIFFERENT BETWEEN THE KERNEL AND NON-KERNEL CODE?

We define code velocity as the speed with which code changes are reviewed and merged into a destination branch. Code velocity is an essential metric in the industry and is associated with engineers’ job satisfaction [74], [75]. In environments using CI/CD (e.g., Facebook), the code velocity is essential to the entire development process [76]. To investigate the code velocity in FreeBSD, we use the metrics previously found to be meaningful in the industry.

- We define time-to-first-response as the time from publishing the code review to the first interaction on the code review by someone else than the author (excluding automated bots). An existing study from Microsoft that researches challenges encountered during the code review process indicates that delayed response time is the number one concern [15]. Another Microsoft study identifies two points in time that engineers consider critical: the first comment or sign-off from a reviewer and when the code review has been marked as completed [16].
- We define time-to-accept as the time from publishing the code review to when someone else than the author accepts the code changes. Once accepted, the changes are ready to be merged into the target branch.
We define time-to-merge as the time from publishing the code review to when changes are merged to the target branch. A study that focuses on code review performance in Xen hypervisor finds that time-to-merge is a crucial metric to help to investigate the delays caused by the code review process [17].

We calculate these metrics for each type of commit (kernel, non-kernel, and mixed). We present an overview of various code review periods in Table VI. The median size of FreeBSD code review is 17 LOC. An initial observation we make is that initial engagement from reviewers is similar. Median time-to-first-response for all commit types is ± 1 hour. After that, the completion of various code review milestones significantly diverges between commit types. Comparison between medians shows that while time-to-first-response for kernel code reviews is only 9.85% longer than for non-kernel commits, time-to-accept is 51.23%, and time-to-merge is 55.2% longer.

A Kruskal-Wallis test for stochastic dominance reveals that there is a statistically significant difference between the mean ranks of time-to-first-response, time-to-accept, and time-to-merge for at least one pair of commit types. For time-to-first-response the test returned ($H(2) = 6.42, p < .05$), for time-to-accept ($H(2) = 165.81, p < .05$), and for time-to-merge ($H(2) = 344.16, p < .05$). After performing a post hoc pairwise Dunn test with a Bonferroni correction, we observe a difference between all commit types for time-to-accept and time-to-merge ($p < .05$) and only between kernel and non-kernel commits for time-to-first-response ($p < .05$).

### Table VI

| Period                  | Kernel (6,405 reviews) | Non-kernel (7,573 reviews) | Mixed (897 reviews) |
|-------------------------|------------------------|----------------------------|---------------------|
|                         | $M$ | $Mdn$ | $SD$     | $M$ | $Mdn$ | $SD$     | $M$ | $Mdn$ | $SD$     |
| Time-to-first-response  | 97.86 | 4.57 | 578.13   | 107.10 | 4.16 | 682.67   | 90.17 | 4.55 | 588.79   |
| Time-to-accept          | 219.18 | 11.66 | 1019.39  | 221.88 | 7.71 | 1185.22  | 445.75 | 22.43 | 1866.96  |
| Time-to-merge           | 476.57 | 71.44 | 1678.20  | 547.36 | 46.03 | 2411.48  | 1013.39 | 157.41 | 2895.97  |

Existing data about FreeBSD code velocity is limited. FreeBSD study [19] finds that the median resolve time (comparable to time-to-merge) is 23 hours and approximately 6 hours for the time-to-first-response. The times for time-to-first-response are comparable to what we present in Table VI. The values for time-to-merge are longer for the code reviews we analyzed. Several reasons can cause the differences. For example, we compare our data from 2013 to 2021 to code reviews from 1995 to 2006. Another reason is that we focus only on code reviews that were accepted and merged. That restriction is necessary to calculate the values for time-to-accept and time-to-merge. That means ignoring the category of patches that the study classified as resolved or closed.

### VI. Discussion

**Code churn characteristics** We find that, on average, approximately 49% of code changes are in non-kernel code (see Table II). This finding suggests that to meaningfully contribute to operating system development, an engineer does not have to work exclusively on the kernel or know the intrinsic details of the development of an operating system. The fact that the insert ratio in kernel code changes is bigger than in non-kernel code changes implies innovative opportunities (e.g., implement a new feature) to contribute to the kernel code base. A surprising finding is that kernel code changes are bigger than non-kernel code changes. This contradicts what authors have anecdotally observed when participating in the development of commercial operating systems in industry.

We find similar patterns related to commit sizes and taxonomy emerging across all different operating systems we investigate. Our findings about kernel code reviews taking longer than non-kernel code reviews match with our industry experience when working on the development of commercial operating systems. Findings about mixed changes are also in agreement with our past experiences.

Though we expected all operating systems to have annual code growth, the size of growth in OpenBSD during the last 10 years is surprising to us. OpenBSD has historically identified itself as an operating system focused on leanness and security [40]. These goals encourage developers to constantly “prune” (i.e., delete) and polish their source code to reduce the attack surface [77]. Nevertheless, the code base size has doubled in the last 10 years.

### Finding 6

Different phases of the code review (time-to-first-response, time-to-accept, and time-to-merge) take longer for the kernel code than for non-kernel code. Mixed code reviews take the most time to be accepted and merged.

This finding feels intuitively correct. It is reasonable to assume that reviewing kernel code requires greater care because of the consequences of potential defects and the technical level of knowledge required. Mixed commits contain approximately in 44.5% cases code from both kernel and non-kernel code. These commits may need more reviewers (e.g., a maintainer for each affected subsystem) or require a reviewer who understands the nuances of multiple components.

Drawing conclusions based on system-wide metrics When characterizing a particular company or a more extensive system, researchers need to be careful with interpreting the results
and drawing conclusions from them. For example, companies like Apple, Facebook, Google, and Microsoft have tens of complex products in development. Each of them may evolve at a different cadence or speed. Researchers need to be more precise when describing various evolutionary characteristics of the code base and fine-tune the scope of inquiry.

Separation of abstractions layers. One of the findings in our study is that mixed code changes represent a small fraction of all the changes. Intuitively, that makes sense based on inspecting a sample of mixed commits and our industry experiences. Code contributions spanning different components are rarer than code changes made to each component in separation. The mixed changes also take the longest to review and contain the largest amount of code. We speculate that longer reviews times are mainly caused because of the size of changes, lack of reviewers with expertise at multiple abstraction layers, and a need to have approvals from multiple individuals. Based on our findings, we speculate that the presence of code changes from different abstraction layers is a valuable predictor to indicate that code reviews for those changes can take longer.

Accepted practice in the industry and open-source software is that the main branch is always kept in a working state. The guidance for the Linux kernel is that “[e]ach patch should, when applied, yield a kernel which still builds and works properly” [71, p. 4]. Working state means both an ability to build the code without errors and the majority of the features working. As an implication this means that any commit cannot break this assumption. Based on the taxonomy of commits in Table II (a tiny number of commits changing kernel and non-kernel code simultaneously), we can infer that it is possible to work efficiently on kernel and non-kernel code in separation. This finding implies that various components are sufficiently independent of each other to make changes in separation.

VII. THREATS TO VALIDITY

Like any other study, the results we present in our paper are subject to specific categories of threats. We enumerate the threats to construct, internal, and external validity [78].

We thoroughly validate raw data to avoid issues with construct validity and interpretation of theoretical constructs. We analyze the potential outlier commits to verify that we calculate code churn correctly. We filter out code reviews where the meaningful reviews did not occur (e.g., “self-accepted” changes or the only changes to binary files). We verify that kernel and non-kernel code locations include the code that is supposed to run at that abstraction layer.

Threats to internal validity include impact by potential unknown factors which may influence the results. When analyzing the code review related periods for FreeBSD, we do not have insight into all confounding variables that can influence code review times. For example, the availability of reviewers, the time-zone for authors or reviewers, or the state of a CI system. No system records that data, and the lack of data may limit internal validity. Another threat in this category is that code reviews are not required part of the FreeBSD development process for committers. “FreeBSD committers are only required to respect each other by asking for code review before committing code to files that are actively maintained by other committers” [79]. Our analysis bases itself on a subset of all FreeBSD code reviews.

Concerns related to external validity focus on applying our findings in other contexts. We do not have access to the commit history and source code of commercial operating systems such as Darwin derivatives or Microsoft Windows. We do know from grey literature [80], [81], [82] and our industry experience that the characteristics of a development process for commercial and open-source software operating systems are different. For example, motivation for product development, number of engineers involved, and development methodology. Our findings may not be applicable in that context.

VIII. CONCLUSIONS AND FUTURE WORK

We conduct a large-scale study on four BSD family operating systems: DragonFlyBSD, FreeBSD, NetBSD, and OpenBSD. Based on the literature review, we are the first to explore the differences between commit sizes, commit taxonomy, and code velocity in kernel and non-kernel code in the context of operating systems development.

Our key finding is that researchers and practitioners should view a larger software system as a collection of subsystems and sub-components, not just one entity. Our analysis shows that when making code changes (a) developers modify either kernel or non-kernel code, but rarely code belonging to both categories, (b) the median size of commits to kernel code is larger than non-kernel commits, (c) both kernel and the non-kernel code bases have a similar annual growth rate, and (d) in FreeBSD, the code reviews for kernel code take longer than code reviews for non-kernel code.

As part of our future research, we intend to focus on the following topics:

- Do developers gravitate towards kernel as they gain more experience with operating systems development? It is typical for new contributors joining an open-source software project to start contributing by making more straightforward changes. Generally, the opportunities associated with the least amount of risk are in user mode, e.g., making changes in a command-line tool. As engineers gain more confidence and experience, do they change their focus to areas where the stakes are higher than in user mode, e.g., device drivers?
- Do developers mainly contribute to their abstraction layer of choice? It is common in BSD and Linux development to have maintainers for each area. One of the interesting questions is related to the distribution between “specialists” (engineers who contribute only to a few narrow areas) and “generalists” (engineers who make changes in various components). Based on the Linux kernel research, we know that most engineers (62%) who contribute to the kernel have a narrow specialist profile [83]. We do not know if this holds in the context of an entire operating system.
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