

LLMorpheus: Mutation Testing using Large Language Models

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ABSTRACT

In mutation testing, the quality of a test suite is evaluated by introducing faults into a program and determining whether the program’s tests detect them. Most existing approaches for mutation testing involve the application of a fixed set of mutation operators, e.g., replacing a “+” with a “-”, or removing a function’s body. However, certain types of real-world bugs cannot easily be simulated by such approaches, limiting their effectiveness. This paper presents a technique for mutation testing where placeholders are introduced at designated locations in a program’s source code and where a Large Language Model (LLM) is prompted to ask what they could be replaced with. The technique is implemented in *LLMorpheus*, a mutation testing tool for JavaScript, and evaluated on 13 subject packages, considering several variations on the prompting strategy, and using several LLMs. We find *LLMorpheus* to be capable of producing mutants that resemble existing bugs that cannot be produced by *StrykerJS*, a state-of-the-art mutation testing tool. Moreover, we report on the running time, cost, and number of mutants produced by *LLMorpheus*, demonstrating its practicality.

ACM Reference Format:

Frank Tip, Jonathan Bell, and Max Schäfer. 2025. LLMorpheus: Mutation Testing using Large Language Models. In *Proceedings of XXX*. ACM, New York, NY, USA, 79 pages. <https://doi.org/10.1145/nnnnnnn.nnnnnnn>

1 INTRODUCTION

Mutation testing is an approach for evaluating the adequacy of a test suite and is increasingly adopted in industrial settings [48–50]. With mutation testing, an automated tool repeatedly injects a small modification to the system under test and executes the test suite on this mutated code. Mutation testing is premised on the *competent programmer hypothesis*, which posits that most buggy programs are quite close to being correct and that complex faults are *coupled* with simpler faults [18], i.e., a test that is strong enough to detect a simple fault should also be able to detect a more complex one. Hence, mutation analysis tools typically apply a relatively small set of mutation operators: replacing constants, replacing operators, modifying branch conditions, and deleting statements. Studies have shown that, given two test suites for the same system under test, the one that detects more mutants (even using only these limited mutation operators) is likely to also detect more real faults [30, 36].

However, not *all* real faults are coupled to mutants due to the limited set of mutation operators. For example, a fault resulting from calling the wrong method on an object is unlikely to be coupled to a mutant, as state-of-the-art mutation tools do not implement a “change method call” operator. While a far wider range of mutation operators has been explored in the literature [23, 28], state-of-the-practice tools like Pitest [12, 14], Major [29] and Stryker [54] typically do not implement them because of the implementation effort required and, especially, the increased cost of mutation analysis. Each additional mutation operator will result in more mutants that must be run and analyzed, and since each mutant must be evaluated in isolation, this may dramatically increase the time needed for developers that use the tool. Furthermore, some mutation operators might not be worthwhile to run, as noted in documentation from the developer of Pitest: “Although pitest provides a number of other operators, they are not enabled by default as they may provide a poorer experience” [13]. An alternative approach for generating mutants is to use a dataset of real faults to train a machine learning model to learn how to inject mutants [47, 55, 58]. However, the need for developers to train a model for their project is an impediment to adoption of such techniques.

Our approach, *LLMorpheus*, can be viewed as a generalization of rule-based mutation techniques [12, 14, 29, 54] in which the location of mutations is determined using a set of predefined rules, and where an LLM is asked to suggest a diversity of mutations that introduce buggy behavior at those locations. To this end, *LLMorpheus* repeatedly prompts an LLM to inject faults at designated locations into a code fragment using prompts that include: (i) general background on mutation testing (ii) (parts of) a source file in which a single code fragment is replaced with the word “PLACEHOLDER”, (iii) the original code fragment that was replaced by the placeholder, and (iv) a request to replace the placeholder with a buggy code fragment that has different behavior than the original code. After discarding syntactically invalid suggestions, we use *StrykerJS*, a state-of-the-art mutation testing tool for JavaScript that we modified to apply the mutations suggested by *LLMorpheus* instead of applying its standard mutators, classify mutants as killed, surviving, or timed out, and generate an interactive web site for inspecting the results.

The effectiveness of our approach hinges on the assumption that LLMs can understand the surrounding context of the code fragment represented by a PLACEHOLDER well enough to suggest syntactically valid and realistic buggy code fragments. To determine whether this assumption holds, we evaluate *LLMorpheus* on 13 subject applications written in JavaScript and TypeScript and measure how many mutants are generated and how they are classified (killed, survived, timed-out) using four “open” LLMs for which the training process is documented (Meta’s *codellama-34b-instruct*, *codellama-13b-instruct*,

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ACM ISBN 978-x-xxxx-xxxx-x/YY/MM...\$15.00
<https://doi.org/10.1145/nnnnnnn.nnnnnnn>

llama-3.3-70b-instruct and Mistral’s *mixtral-8x7b-instruct*) and one proprietary LLM (OpenAI’s *gpt-4o-mini*). We manually examine a subset of the surviving mutants to determine whether they are equivalent to the original source code or if they represent behavioral changes and contrast the results against mutants generated using *StrykerJS*’s standard mutators. The cost of *LLMorpheus* is assessed by measuring its running time and the number of tokens used for prompts and completions. We also report on experiments with alternative prompts that omit parts of the information encoded in default prompts and with different “temperature” settings of an LLM.

To investigate *LLMorpheus*’s ability to produce mutants that resemble real-world faults, we conducted a detailed case study involving four real-world bugs from the Bugs.js suite [25]. In this case study, we used *LLMorpheus* to mutate the *fixed* version of a program near the location of the fix, executed the program’s tests for each of these mutants and compared the test outcomes against those of the buggy version. In each case, *LLMorpheus* produced either a mutant that was identical to a bug that was originally observed, or one that caused the same test failures as a bug that was originally observed. Hence, we find *LLMorpheus* to be capable of generating a diverse set of mutants, some of which resemble real-world bugs that cannot be created by *StrykerJS*’ standard mutation operators.

For surviving mutants generated using *codellama-34b-instruct*, we find that the majority (78%) reflect behavioral differences and 20% are equivalent to the original code. Using the *codellama-34b-instruct* and *codellama-13b-instruct* models, results are generally stable at temperature 0.0 when experiments are repeated, but the use of higher temperatures yields more variable results. For *mixtral-8x7b-instruct*, *llama-3.3-70b-instruct*, and *gpt-4o-mini* models, there is already significant variability at temperature 0. The default template generally produces the largest number of mutants and surviving mutants, and removing different fragments of this prompt degrades the results to varying degrees. The *llama-3.3-70b-instruct* and *codellama-34b-instruct* LLMs generally produce the largest number of mutants and surviving mutants, but *LLMorpheus* is still effective when *codellama-13b-instruct*, *mixtral-8x7b-instruct*, and *gpt-4o-mini* are used.

In summary, the contributions of this paper are:

- (1) A technique for mutation testing in which placeholders are introduced at designated locations in a program’s source code, and where an LLM is prompted to ask what they could be replaced with.
- (2) An implementation of this technique in *LLMorpheus*, a practical mutation testing tool for JavaScript.
- (3) An empirical evaluation of *LLMorpheus* on 13 subject applications, demonstrating its practicality and comparing it to a standard approach to mutation testing based on mutation operators.

The remainder of this paper is organized as follows. Section 2 presents motivating examples that illustrate the potential of LLM-based mutation techniques to introduce faults resembling real bugs. In Section 3, an overview of our approach is presented. Section 4 presents an evaluation of *LLMorpheus* and Section 5 covers threats

Figure 1 consists of three code snippets labeled (a), (b), and (c).
 (a) shows a code block with line numbers 118 to 121. Line 120 has a minus sign (-) and line 121 has a plus sign (+). The code is a try block containing two await fs.promises.access calls. The first call is on line 120 and the second is on line 121. The code is:


```

118     }
119     try {
120 -       await fs.promises.access(srcFolder, fs.constants.R_OK | fs.constants.W_OK);
121 +       await fs.promises.access(srcFolder, fs.constants.R_OK); //eslint-disable-line
122       await fs.promises.access(targetBasePath, fs.constants.R_OK | fs.constants.W_OK);
  
```

 (b) shows a code block with line numbers 120 to 124. Line 122 has a minus sign (-) and line 123 has a plus sign (+). The code is a try block containing two await fs.promises.access calls. The first call is on line 122 and the second is on line 123. The code is:


```

120     try {
121       if (!isGlob(src)) {
122 -       await fs.promises.access(src, fs.constants.R_OK); //eslint-disable-line no-b
123 +       await fs.promises.access(src, fs.constants.W_OK); //eslint-disable-line no-b
124       }
125       await fs.promises.access(targetBasePath, fs.constants.R_OK | fs.constants.W_OK);
  
```

 (c) shows a code block with line numbers 120 to 125. Line 124 has a minus sign (-) and line 125 has a plus sign (+). The code is a try block containing two await fs.promises.access calls. The first call is on line 124 and the second is on line 125. The code is:


```

120     try {
121       if (!isGlob(src)) {
122       await fs.promises.access(src, fs.constants.R_OK); //eslint-disable-line no-b
123       }
124 -       await fs.promises.access(targetBasePath, fs.constants.R_OK | fs.constants.W_OK);
125 +       await fs.promises.access(targetBasePath, fs.constants.R_OK); //eslint-disable-line
126     } catch (e: any) {
  
```

Figure 1: (a) Fix for a bug reported in issue #36 in zip-a-folder. (b) A mutation suggested by *LLMorpheus* at the same line that involves replacing read-access with write-access. (c) A mutation suggested by *LLMorpheus* elsewhere in the same file that mirrors the change made by the developer.

to validity. Related work is discussed in Section 6. Lastly, Section 7 presents conclusions and directions for future work.

2 BACKGROUND AND MOTIVATION

In this section, we study a few bugs that do not correspond to mutation operators supported by state-of-the-art mutation testing tools but that are similar to mutations *LLMorpheus* could suggest.

Example 1. Zip-a-folder [4] is a library for compressing folders. On January 31, 2022, a user observed that the library required write-access for source-folders unnecessarily and opened issue #36, requesting that this access be removed. The developer applied the fix shown in Figure 1(a) on the same day, which involves replacing a binary bitwise-or expression with one of its operands.

LLMorpheus can suggest mutations that involve *changing or introducing* references to functions, variables, and properties. Figure 1(b) and (c) show two mutations that *LLMorpheus* suggests for this project and that could result in bugs similar to the one described above: part (b) shows a mutation at the same line where the bug was located that involves replacing read-access with write-access, and part (c) shows a mutation at a nearby location that mirrors the change made by the developer.

The state-of-the-art *StrykerJS* tool is unable to suggest either of these mutations because (i) it does not support the mutation of bitwise operator expressions such as `fs.constants.R_OK | fs.constants.W_OK` unless they appear as part of a control-flow predicate, nor (ii) mutations that involve replacing a binary expression with one of its operands. While adding support for mutating bitwise operator expressions would be straightforward, concerns have been expressed that adding more mutation operators to traditional mutation testing tools might result in too many mutants and degraded

```

28 28
29 29 function getOffsetStr(offset) {
30 - const hours = Math.floor(offset / 60);
30 + const hours = Math.floor(Math.abs(offset) / 60);
31 31 const min = offset % 60;
(a)
29 function getOffsetStr(offset) {
30 const hours = Math.floor(offset / 60);
31 const min = offset % 60;
32 const sign = offset < 0 ? '-' : '+';
33
34 return `${sign}${getNumStr(hours)}:${getNumStr(min)}';
35 }
36
37 function getNumStr(input) {
38 - const num = Math.abs(input);
38 + const num = Math.round(input);
39 const prefix = num < 10 ? '0' : '';
(b)

```

Figure 2: (a) Fix for a bug reported in issue #60 in `countries-and-timezones`. (b) A mutation suggested by *LLMorpheus* elsewhere in the same file.

performance [13, 31, 32]. More significantly, *StrykerJS* does not introduce or modify property access expressions and has very limited support for replacing an expression with a different expression¹.

Example 2. `Countries-and-timezones` [2] is a library for working with countries and timezones. In October 2023, a user reported a bug in function `getOffsetStr`, stating that it produces incorrect results when invoked with negative values. The developer proposed a simple fix that involves inserting a call to `Math.abs` to convert the argument value to a non-negative number, and a variation on this fix was quickly adopted by the developer, as shown in Figure 2(a).

This bug-fix involves the introduction of a function call, so to introduce bugs like this one, a mutation testing tool would have to remove function calls or change the function being invoked. *StrykerJS* only supports a very limited set of 20 mutations to function calls², such as replacing calls to `String.startsWith` with call to `String.endsWith` and removing a call to `Array.slice`. While one could extend *StrykerJS* with a mutator that removes calls to `Math.abs`, many other function calls could be handled similarly, and adding mutators for all of them would yield an overwhelmingly large number of mutants. Many such candidate functions would not be good choices for mutation, either because the function in question is not a function that a developer inadvertently might have selected, or because it would lead to syntactically invalid code.

LLMorpheus suggests mutations that involve introducing and replacing function calls. Figure 2(b) shows a mutation that *LLMorpheus* suggested elsewhere in the same source file that involves replacing a call to `Math.abs` with a call to `Math.round`, which could, in principle, introduce a bug like the one in Figure 2(a). Moreover, since LLMs are trained to generate code that resembles code written by developers, it is likely that the mutants produced by *LLMorpheus* involve the use of functions that a developer might have chosen.

Example 3. `image-downloader` is a module for downloading images. In February 2022, a user opened issue #27, entitled “If the

¹In particular, *StrykerJS* only replaces control-flow predicates in `if`-statements and loops with boolean constants, string literals with the value “*Stryker_was_here*”, and object literals with an empty object literal.

²See <https://stryker-mutator.io/docs/mutation-testing-elements/supported-mutators/>.

```

... @@ -19,9 +19,13 @@ module.exports.image = ({ extractFilename = true
19 19 const basename = path.basename(pathname);
20 20 const decodedBasename = decodeURIComponent(basename);
21 21
22 - options.dest = path.resolve(options.dest, decodedBasename);
22 + options.dest = path.join(options.dest, decodedBasename);
23 23 }
24 24 }
(a)
16 const pathname = url.pathname;
17 const basename = path.basename(pathname);
18 const decodedBasename = decodeURIComponent(basename);
19
20 - options.dest = path.join(options.dest, decodedBasename);
20 + options.dest = path.basename(options.dest, decodedBasename);
21 }
22 }
23
(b)

```

Figure 3: (a) Fix for a bug reported in issue #27 in `image-downloader`. (b) A mutation suggested by *LLMorpheus* at the same location that similarly involves calling a different function.

```

137 return new Promise((resolve, reject) => {
138 - output.on('close', resolve);
138 + output.on('end', resolve);
139 output.on('error', reject);

```

Figure 4: A mutation suggested by *LLMorpheus* that involves associating an event listener with the `end` event instead of with the `close` event.

directory name in `dest`: contains a dot “.” then the download fails.”, providing an example illustrating the problem. The developers soon responded with a fix, shown in Figure 3(a), that involves replacing a call to `path.resolve` with a call to `path.join`. While *LLMorpheus* does not produce a mutant that re-introduces this bug exactly, it does produce several at the same location³ that similarly replace the invoked function, including the one shown in Figure 3(b). As mentioned, *StrykerJS* has very limited support for mutations that involve calling different functions and so it cannot suggest mutations like the one shown in Figure 3(b).

Example 4. Figure 4 shows another mutant produced by *LLMorpheus* for `zip-a-folder`. Here, the mutation involves changing the name of the event with which an event listener is associated. Such errors often cause “dead listeners”, i.e., situations where an event handler is never executed because it is associated with the wrong event. Dead listeners are quite common in JavaScript, where the use of string values to identify events precludes static checking, and previous research has focused on static analysis [43] and statistical methods [5] for detecting such errors.

Discussion. The above examples illustrate just a few of the kinds of mutations that *LLMorpheus* may produce. Other mutations that it may suggest include: replacing a reference to a variable with a reference to a different variable, adding or removing arguments in function calls, and modifying object literals by adding or removing property-value pairs.

³The line numbers have shifted slightly as the code has evolved since the bug report.



Figure 5: Overview of approach.

In practice, the number of such mutations is effectively infinite, so an approach based on exhaustively applying a fixed set of mutation operators is unlikely to be practical. *LLMorpheus*' LLM-based approach leverages the collective wisdom of programmers who wrote the code on which the LLM was trained to develop mutations. As a result, suggested changes are likely to refer only to variables and functions that are in scope, and are likely to be type-correct.

3 APPROACH

LLMorpheus is capable of producing interesting mutants without requiring any training on a subject project, which is a key distinction compared to existing work that builds models of real bugs to generate mutants [47, 55, 58]. This is accomplished by querying an LLM with a prompt that includes part of an application's source code in which a code fragment is replaced with the text "<PLACEHOLDER>". Additional information provided in the prompt includes: (i) general background on mutation testing, (ii) the code fragment that was originally present at the placeholder's location, (iii) a request to apply mutation testing to the code by replacing the placeholder with a buggy code fragment, and (iv) suggestions how the code could be mutated. The LLM is asked to provide three possible replacements for the placeholder, each accompanied by an explanation how the mutation would change program behavior.

Figure 5 presents a high-level overview of our approach, which involves three components that work in concert: the *prompt generator*, the *mutant generator*, and a version of the *StrykerJS* mutation testing tool that has been modified to apply the mutants created by *LLMorpheus*⁴. We now discuss each of these components.

Prompt generator. This component takes as input a package and generates a set of prompts. The prompt generator parses the source files and identifies locations where mutations will be introduced. For ease of reference during prompting, the source code fragment corresponding to each location is replaced with the text "<PLACEHOLDER>". *LLMorpheus* considers the following locations as candidates for mutation: (i) conditions of *if*, *switch*, *while*, and *do-while* statements, (ii) initializers, updaters, and entire headers of loop statements, and (iii) receiver, arguments, and entire sequence of arguments for function calls. For each such location, a separate prompt is created. Figure 6 illustrates where placeholders are introduced into the source code.

The LLM is then given a prompt that is created by instantiating the template shown in Figure 7(a), by replacing `{{{ code }}}` with the original source code in which a placeholder has been inserted, and `{{{ orig }}}` with the code fragment that was replaced by the placeholder. Figure 7(b) shows the system prompt given to the LLM, which provides background on the role the LLM is expected to play

<code>if (x === y){ ... }</code>	<code>if (<PLACEHOLDER>){ ... }</code>
<code>switch (x === y){ ... }</code>	<code>switch (<PLACEHOLDER>){ ... }</code>
<code>while (x){ ... }</code>	<code>while (<PLACEHOLDER>){ ... }</code>
<code>do { ... } while (x);</code>	<code>do { ... } while (<PLACEHOLDER>);</code>
<code>for (let i=0; i < x; i++){ ... }</code>	<code>for (<PLACEHOLDER>; i < x; i++){ ... }</code>
<code>for (let i=0; i < x; i++){ ... }</code>	<code>for (let i=0; <PLACEHOLDER>; i++){ ... }</code>
<code>for (let i=0; i < x; i++){ ... }</code>	<code>for (let i=0; i < x; <PLACEHOLDER>){ ... }</code>
<code>for (let i=0; i < x; i++){ ... }</code>	<code>for (<PLACEHOLDER>){ ... }</code>
<code>for (o in obj){ ... }</code>	<code>for (<PLACEHOLDER> in obj){ ... }</code>
<code>for (o in obj){ ... }</code>	<code>for (o in <PLACEHOLDER>){ ... }</code>
<code>for (o in obj){ ... }</code>	<code>for (<PLACEHOLDER>){ ... }</code>
<code>for (o of obj){ ... }</code>	<code>for (<PLACEHOLDER> of obj){ ... }</code>
<code>for (o of obj){ ... }</code>	<code>for (o of <PLACEHOLDER>){ ... }</code>
<code>for (o of obj){ ... }</code>	<code>for (<PLACEHOLDER>){ ... }</code>
<code>a.m(x,y)</code>	<code><PLACEHOLDER>(x,y)</code> <code>a.m(<PLACEHOLDER>,y)</code> <code>a.m(x,<PLACEHOLDER>)</code> <code>a.m(<PLACEHOLDER>)</code>

Figure 6: Illustration of the insertion of placeholders to direct the LLM at source locations that need to be mutated.

in the conversation as a mutation testing expert. As can be seen in Figure 7(a), the prompt provides instructions for applying mutation testing to the specific source code at hand and details the specific format to which the completion should conform. Specifically, we require that the proposed mutants be provided inside "fenced code blocks" (i.e., code blocks surrounded by three backquote characters).

Mutant generator. This component takes the completions received from the LLM and extracts candidate mutants from the instantiated template by matching a regular expression against the completion to find the fenced code blocks. Candidate mutants identical to the original source code fragment or identical to previously generated mutants are discarded. The candidate mutants are then parsed to check if they are syntactically valid and discarded if this is not the case. The resulting mutants are written to a file `mutants.json` that is read by a customized version of *StrykerJS* that is described below. The mutant generator also saves all experimental data to files, including the generated prompts, completions received from the LLM, and the configuration options that were used (e.g., the LLM's temperature setting).

Custom version of StrykerJS. We modified *StrykerJS* to give it an option `--usePrecomputed` that, if selected, directs it to read its set of mutations from a file `mutants.json` instead. *StrykerJS* then executes all mutants and determines for each mutant whether it causes tests to fail or time out. When this analysis is complete, *StrykerJS* generates a report as an interactive web page allowing users to inspect the generated mutants. The previously shown Figures 1–4 show screenshots of our custom version of *StrykerJS*.

Pragmatics. While *LLMorpheus* implements a conceptually straightforward technique, considerable engineering effort was required

⁴In particular, we use *StrykerJS*' to (i) determine the impact of each mutant on an application's tests and classify it as "killed", "survived", or "timed-out" and (ii) generate an interactive web page for inspecting results.

```

Your task is to apply mutation testing to the following
code:
{{{code}}}

by replacing the PLACEHOLDER with a buggy code fragment
that has different behavior than the original code fragment,
which was:
{{{orig}}}

Please consider changes such as using different operators,
changing constants, referring to different variables, object
properties, functions, or methods.

Provide three answers as fenced code blocks containing a
single line of code, using the following template:

Option 1: The PLACEHOLDER can be replaced with:
<code fragment>
This would result in different behavior because
<brief explanation>.

Option 2: The PLACEHOLDER can be replaced with:
<code fragment>
This would result in different behavior because
<brief explanation>.

Option 3: The PLACEHOLDER can be replaced with:
<code fragment>
This would result in different behavior because
<brief explanation>.

Please conclude your response with "DONE."

```

(a)

```

You are an expert in mutation testing. Your job is to
make small changes to a project's code in order to find
weaknesses in its test suite. If none of the tests fail
after you make a change, that indicates that the tests
may not be as effective as the developers might have
hoped, and provide them with a starting point for
improving their test suite.

```

(b)

Figure 7: Prompt template (a) and system prompt (b) used by *LLMorpheus*.

to make it a practical tool. We use BabelJS [1] for parsing source code to identify locations where placeholders should be inserted, and to check syntactic validity of candidate mutants. Handlebars [3] is used for instantiating prompt templates. *StrykerJS* expects mutants to correspond to a single AST node, so for mutants that do not correspond exactly to a single AST node (e.g., loop headers and sequences of arguments passed in function calls), it is necessary to expand the mutation to the nearest enclosing AST node, for which we also rely on BabelJS.

LLMorpheus has command-line arguments for specifying the prompt template and system template to be used. Furthermore, it enables users to specify a number of LLM-specific parameters, such as the maximum length of completions that should be generated, the sampling temperature⁵, and number of lines of source code that should be included in prompts (by default, this is limited

⁵The sampling temperature is a parameter between 0 and 2 that controls the randomness of the completions generated by the LLM. Roughly speaking, the higher the temperature the more diverse the completions. At temperature zero, the LLM will always generate the most likely completion, which increases the chance that the same prompt will result in the same completion.

to 200 lines surrounding the location of the placeholder). Since many LLM installations have limited capacity or explicit rate limits, *LLMorpheus* provides two command-line options to work with such LLMs: `--rateLimit <N>` ensures that least N milliseconds will have elapsed between successive prompts and `--nrAttempts <N>` will try the same prompt up to N times if a 429 error occurs.

One possible concern with our approach is that *LLMorpheus* relies on a fixed set of locations where it introduces placeholders. The current placeholder scheme aims to strike a balance between creating a number of mutants that is practical and having mutants that are likely to result in different control flow or data flow and that are likely to be different than what can be achieved using mutation operators. It would be straightforward to modify *LLMorpheus* to use a different placeholder scheme. That said, the examples in Section 2 show that mutants produced by *LLMorpheus* (using its current placeholder scheme) involve changing references to variables, properties, and functions that cannot be produced using Stryker’s mutation operators and that correspond to real-world bugs.

An open-source release of *LLMorpheus* can be found at <https://github.com/neu-se/llmorpheus> and the customized version of *StrykerJS* that we used for classifying mutants can be found at <https://github.com/neu-se/stryker-js>.

4 EVALUATION

4.1 Research Questions

This evaluation aims to answer the following research questions:

- RQ1** How many mutants does *LLMorpheus* create?
- RQ2** How many of the surviving mutants produced by *LLMorpheus* are equivalent mutants?
- RQ3** What is the effect of using different temperature settings?
- RQ4** What is the effect of variations in the prompting strategy used by *LLMorpheus*?
- RQ5** How does the effectiveness of *LLMorpheus* depend on the LLM that is being used?
- RQ6** What is the cost of running *LLMorpheus*?
- RQ7** Is *LLMorpheus* capable of producing mutants that resemble existing bugs?

4.2 Experimental Setup

Selecting subject applications. Our goal is to evaluate *LLMorpheus* on real-world JavaScript packages that have test suites. Moreover, we want to compare the mutants generated by *LLMorpheus* to those generated using traditional mutation testing techniques, so we decided to focus on projects for which the state-of-the-art StrykerJS mutation testing tool [54] could be applied successfully. As a starting point for benchmark selection, we considered the 25 subject applications that were used to evaluate TestPilot [51], a recent LLM-based unit test generation tool. These applications are written in JavaScript or TypeScript, cover a range of different domains, and have test suites that can be executed successfully.

Of these 25 subject applications, 10 could not be used because StrykerJS does not work on them, either because its dependences conflict with those of the subject application itself⁶, or because

⁶Running StrykerJS on an application requires installing it locally among the subject project libraries. Stryker itself depends on various other packages that also need to be

application	description	weekly downloads	#LOC	#tests	coverage		StrykerJS					
					stmt	branch	#mutants	#killed	#survived	#timeout	mut. score	time (sec)
<i>Complex.js</i>	complex numbers	671K	1,425	216	71.82%	67.54%	1,302	763	539	0	58.60	405.08
<i>countries-and-timezones</i>	accessing countries and timezones data	152K	165	58	100%	92.55%	140	134	6	0	95.71	142.37
<i>crawler-url-parser</i>	URL parser for crawling	495	209	185	96.39%	92.5%	226	143	83	0	63.27	433.53
<i>delta</i>	Format for representing rich text documents and changes	1.76M	806	180	98.99%	95.89%	834	686	88	60	89.45	2747.04
<i>image-downloader</i>	downloading image to disk from a given URL	17.75K	64	11	100%	93.75%	43	28	11	4	74.42	284.20
<i>node-dirty</i>	key value store with append-only disk log	5,604	207	37	83.01%	71.15%	160	78	56	26	65.00	215.93
<i>node-geo-point</i>	calculations involving geographical coordinates	5,618	406	10	85.36%	70.58%	158	98	60	0	62.03	357.70
<i>node-jsonfile</i>	reading/writing JSON files	57.7M	102	43	97.87%	94.11%	61	31	5	25	91.80	188.91
<i>plural</i>	plural forms of nouns	2.271	103	14	95.38%	72.72%	180	143	37	0	79.44	53.66
<i>pull-stream</i>	pipeable pull-stream	57.8K	602	364	90.96%	80.84%	474	318	116	40	75.53	694.33
<i>q</i>	promises	10.1M	2,111	243	89.5%	70.92%	1,058	68	927	63	12.38	7,075.02
<i>spacel-core</i>	path-based access control	3	377	38	100%	100%	259	239	20	0	92.28	1,053.16
<i>zip-a-folder</i>	zip/tar utility	60.1K	156	22	100%	96.87%	74	38	8	28	89.19	513.27

Table 1: Subject applications used to evaluate *LLMorpheus*.

it crashes. On one package, *simple-statistics*, StrykerJS requires approximately 10 hours of running time, which makes using it impractical. We excluded another package, *fs-extra*, a utility library for accessing the file system, because we observed that mutating this application poses a significant security risk, as the mutated code was corrupting our local file system. This left us with 13 subject applications for which Table 1 provides key characteristics. The first set of columns in the table show, from left to right, the name of the package, a short description of its functionality, the number of weekly downloads according to npmjs.com, the number of lines of source code, the number of tests, and the statement and branch coverage achieved by those tests, respectively. The second set of columns shows the results of running *StrykerJS* on the applications: the total set of mutants, the number of mutants that were killed, survived, and that timed out, the *mutation score*⁷ reported by *StrykerJS*, and the time required to run *StrykerJS*, respectively.

LLM selection. RQ5 explores how the effectiveness of the proposed technique depends on the LLM being used. We use Meta’s *codellama-34b-instruct* model for our main experiments. In addition, we evaluate the technique with Meta’s *codellama-13b-instruct* and *llama-3.3-70b-instruct* models, with Mistral’s *mixtral-8x7b-instruct* model, and with OpenAI’s *gpt-4o-mini* model. The *codellama* models are specifically trained for tasks involving code. *llama-3.3-70b-instruct* is a newer and larger model from Meta that supercedes the smaller, specialized *codellama* models. *mixtral-8x7b-instruct* is a state-of-the-art general-purpose “mixture-of-experts” LLM developed by Mistral. *gpt-4o-mini* is a smaller, faster, and lower-cost variant of OpenAI’s popular *gpt-4o* model. The *codellama-34b-instruct*, *codellama-13b-instruct*, *llama-3.3-70b-instruct*, and *mixtral-8x7b-instruct* LLMs are “open” in the sense that their training process is documented. We relied on several commercial LLM service providers (<https://octo.ai>,

<https://openai.com>, and <https://openrouter.ai>) for the experiments reported on in this paper.

LLM Temperature settings. LLMs have a temperature parameter that reflects the amount of randomness or creativity in their completions. For a task such as mutation testing, randomness and creativity may determine whether generated mutants are killed or survive. Therefore, we conduct experiments using several temperature settings.

Similarity to real-world bugs. Previous work on evaluating mutation testing techniques has focused on “coupling” to determine whether mutants resemble real-world bugs [22, 30, 36]. This involves determining whether a test suite that detects particular mutants also detects particular real faults, and requires a curated dataset of isolated faults. While there is a wealth of such datasets constructed from open-source projects written in Java, we found only one JavaScript dataset, the Bugs.js suite [25]. Unfortunately, we found that most of these subjects could not be used at all due to their reliance on outdated versions of various libraries and because of their incompatibility with modern Node.js versions that *StrykerJS* requires, causing them to be incompatible with *LLMorpheus*. These projects also have flaky tests⁸, making it particularly challenging to perform mutation analysis [53]. We, therefore, opted to conduct a case study involving four real-world bugs from the Bugs.js suite that we could reproduce reliably.

4.3 RQ1: How many mutants does *LLMorpheus* create?

To answer this question, we ran *LLMorpheus* on the projects listed in Table 1 using the *codellama-34b-instruct* LLM at temperature 0.0 and the prompt templates shown in Figure 7. The results, shown in Table 2, show that *LLMorpheus* produces between 42 and 1,051 prompts for these projects. The next 4 columns in the table show the number of “candidate mutants”, i.e., code fragments obtained by replacing placeholders with code fragments suggested by the LLM. The subcolumn labeled “candidates” shows the total number

installed, and these packages may conflict with packages that the subject application itself depends upon.

⁷The mutation score aims to provide a measure of the quality of a test suite by calculating the fraction of the total number of mutants that are detected (i.e., killed or timed out), see <https://stryker-mutator.io/docs/General/faq/>.

⁸See <https://github.com/BugsJS/bug-dataset/issues/11>.

application	#prompts	LLMorpheus								StrykerJS					
		#candidates	#invalid	#identical	#duplicate	#mutants	#killed	#survived	#timeout	mut. score	#mutants	#killed	#survived	#timeout	mut. score
Complex.js	490	1,451	194	13	45	1,199	725	473	1	60.55	1,302	763	539	0	58.60
countries-and-timezones	106	318	89	0	12	217	188	29	0	86.64	140	134	6	0	95.71
crawler-url-parser	176	521	205	14	17	285	157	128	0	55.09	226	143	83	0	63.27
delta	462	1,367	565	10	25	767	634	101	32	86.83	834	686	88	60	89.45
image-downloader	42	124	33	2	0	89	72	17	0	80.90	43	28	11	4	74.42
node-dirty	154	450	153	15	7	275	163	100	12	63.64	160	78	56	26	65.00
node-geo-point	140	408	93	0	13	302	223	79	0	73.84	158	98	60	0	62.03
node-jsonfile	68	199	42	3	0	154	49	48	57	68.83	61	31	5	25	91.80
plural	153	442	101	42	18	281	205	75	1	73.31	180	143	37	0	79.44
pull-stream	351	1,028	238	12	9	769	441	271	57	64.76	474	318	116	40	75.53
q	1,051	3,121	1,000	34	52	2,035	158	1,792	85	11.94	1,058	68	927	63	12.38
spacel-core	134	395	140	10	6	239	199	39	1	83.68	259	239	20	0	92.28
zip-a-folder	49	143	41	1	1	100	23	3	74	97.00	74	38	8	28	89.19
Total	3,376	9,967	2,894	156	205	6,712	3,237	3,155	320	—	4,969	2,767	1,956	246	—

Table 2: Results from LLMorpheus experiment (run #312). Model: *codellama-34b-instruct*, temperature: 0.0, maxTokens: 250, template: *template-full.hb*, systemPrompt: *SystemPrompt-MutationTestingExpert.txt*.

	temp. 0.0 (run #312)				temp. 0.25 (run #348)				temp. 0.50 (run #318)				temp. 1.0 (run #341)			
	#mutants	#killed	#survived	#timeout	#mutants	#killed	#survived	#timeout	#mutants	#killed	#survived	#timeout	#mutants	#killed	#survived	#timeout
<i>Complex.js</i>	1,199	725	473	1	1,197	730	466	1	1,191	739	452	0	1,028	648	379	1
<i>countries-and-timezones</i>	217	188	29	0	219	181	38	0	224	194	30	0	186	156	30	0
<i>crawler-url-parser</i>	285	157	128	0	260	167	93	0	298	166	108	24	278	202	76	0
<i>delta</i>	767	634	101	32	781	642	111	28	769	642	93	34	698	583	83	32
<i>image-downloader</i>	89	72	17	0	86	71	15	0	89	68	21	0	75	53	22	0
<i>node-dirty</i>	275	163	100	12	279	175	93	11	277	158	107	12	246	150	84	12
<i>node-geo-point</i>	302	223	79	0	293	225	68	0	302	230	72	0	273	213	60	0
<i>node-jsonfile</i>	154	49	48	57	151	52	41	58	153	51	43	59	132	50	22	60
<i>plural</i>	281	205	75	1	273	208	63	2	289	219	69	1	299	229	69	1
<i>pull-stream</i>	769	441	271	57	779	452	270	57	796	465	278	53	743	461	235	47
<i>q</i>	2,035	158	1,792	85	2,050	153	1,813	84	2,073	163	1,823	87	1,899	147	1,671	81
<i>spacel-core</i>	239	199	39	1	223	187	36	0	250	210	39	1	218	180	38	0
<i>zip-a-folder</i>	100	23	3	74	97	24	4	69	87	48	33	6	96	54	38	4

Table 3: Number of mutants generated using the *codellama-34b-instruct* LLM at temperatures 0.0, 0.25, 0.5, and 1.0 (showing one run of each)

of candidate mutants, the subcolumn labeled “invalid” shows the number of candidate mutants that were found to be syntactically invalid, the subcolumn labeled “identical” shows the number of candidate mutants that were found to be identical to the original code, and the subcolumn labeled “duplicate” shows the number of candidate mutants that were found to be duplicated. From this data, it can be inferred that, on average, 29.0% (2,894/9,967) of candidate mutants are discarded because they are syntactically invalid, 1.6% (156/9,967) are discarded because they are identical to the original code, and 2.1% (205/9,967) are discarded because they are duplicates. This suggests that LLMs generally do not have too much trouble with generating syntactically correct code, which is consistent with recent findings by others [38, 51]. The next column, labeled “mutants”, shows the number of mutants that remain after discarding the useless candidate mutants. Here, the reader can see that between 89 and 2,035 mutants are generated for the subject packages. Of these mutants, between 23 and 725 are killed, between 3 and 1,792 survive, and between 0 and 85 time out. Aggregating the results over all projects, it can be seen that 48.2% (3,237/6,712) of all mutants are killed, 47.0% (3,155/6,712) of all mutants survive, and 4.8% (320/6,712) of all mutants time out.

The table also shows the *mutation score*⁹ as reported by StrykerJS, which aims to provide a measure of the quality of a test suite by calculating the fraction of the total number of mutants that are detected (i.e., killed or timed out).

To facilitate a quantitative comparison with *StrykerJS*, the last 5 columns in Table 2 repeat the results of running *StrykerJS* on the subject applications from Table 1. From this data, it can be seen that—in the aggregate for the 13 projects under consideration—*LLMorpheus* produces 3,155 surviving mutants whereas *StrykerJS* produces 1,956 surviving mutants. However, it should be noted that the difference in the number of mutants and surviving mutants varies significantly between subject applications. For example, for *Complex.js* *StrykerJS* produces more mutants (1,302 vs. 1,199) than *LLMorpheus*, of which more survive (539 vs. 473). On the other hand, for *q*, the situation is reversed with *StrykerJS* producing fewer mutants (1,058 vs. 2,035) and fewer surviving mutants (927 vs. 1,792) than *LLMorpheus*. We conjecture that such differences are due to the subject programs having different characteristics, which makes them amenable to different types of mutations. Here, *Complex.js* makes heavy use of arithmetic operators to implement mathematical operations on complex numbers, and such operators are prime candidates for *StrykerJS*’s standard mutation operators.

⁹ See <https://stryker-mutator.io/docs/General/faq/>.

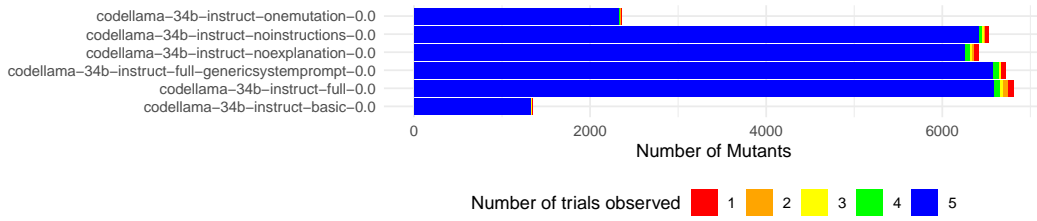


Figure 8: Stability of mutants generated by LLMorpheus with *codellama-34b-instruct* at temperature 0.0. For each replacement generated at each position, we count the number of trials (of 5 total) where that replacement was generated.

Project	LLMorpheus			Stryker.js		
	equiv	not equiv	unknown	equiv	not equiv	unknown
<i>Complex.js</i>	6	44	0	0	50	0
<i>countries-and-timezones</i>	17	11	1	0	6	0
<i>crawler-url-parser</i>	16	33	1	0	47	3
<i>delta</i>	2	48	0	2	48	0
<i>image-downloader</i>	4	12	1	0	4	4
<i>node-dirty</i>	13	36	1	0	46	4
<i>node-geo-point</i>	1	47	2	1	41	8
<i>node-jsonfile</i>	7	25	0	0	3	0
<i>plural</i>	16	34	0	0	36	1
<i>pull-stream</i>	3	44	3	0	48	2
<i>q</i>	2	48	0	0	48	2
<i>spacel-core</i>	18	21	0	2	12	6
<i>zip-a-folder</i>	0	0	0	0	6	0
Total	105	403	9	5	395	30

Table 4: Number of equivalent surviving mutants generated by LLMorpheus and StrykerJS.

Moreover, *q* makes heavy use of method calls, which are targeted by LLMorpheus’s placeholder-based strategy but much less so by StrykerJS’s mutation operators.

LLMs are nondeterministic, even at temperature 0, so a subsequent experiment may produce results that differ from those shown in Table 2. To determine to what extent this is the case, we repeated the same experiment 4 more times and measured how often the same mutants occur. We found that, at temperature 0.0, the results of LLMorpheus are generally stable across runs, with between 89.29% and 98.89% of all mutants being observed in all 5 experiments¹⁰. Figure 8 visualizes the stability of LLMorpheus when varying the prompt settings, and our supplemental materials include results across all settings of all models.

Using *codellama-34b-instruct* at temperature 0, LLMorpheus generates between 89 and 2,035 mutants, of which between 3 and 1,792 survive. These results are stable across experiments, with between 89.29% and 98.89% of all mutants being observed in all five experiments.

4.4 RQ2: How many of the surviving mutants are equivalent mutants?

One of the key challenges in mutation testing is the phenomenon of *equivalent mutants*: mutants that have equivalent behavior as the original code [18]. Mutants produced by LLMorpheus may involve arbitrary code changes, so it is entirely possible for the LLM to suggest code that is effectively a refactored version of the code that

was originally present. Determining mutant equivalence requires a deep understanding of the program’s intended behavior, as a mutant might change the behavior of the program but within bounds that are valid to the program’s specification. To determine to what extent surviving mutants produced by LLMorpheus are equivalent, we conducted a study in which two authors manually examined 50 surviving mutants¹¹ in each project and classified each mutant as “equivalent”, “not equivalent”, or “unknown”. After independently coding each sampled mutant, the two authors met, discussed disagreement, and came to a consensus on all mutants. We define these categories as follows.

We labeled a mutant as *equivalent* if we could determine that the change could not cause *any* observable difference in behavior. For example, mutants that added extra parameters to methods (beyond those accepted by the receiver method) are trivially equivalent, as they are discarded by the runtime. Other mutants are far from trivial to evaluate, and we manually wrote test code to attempt to discern the impact of, e.g., changing a condition from `if (!handler)` to `if (handler === undefined)`. Such a mutant is equivalent if handler is never any other “falsy” value (e.g., `null`, `false`, `NaN`, `0`, or the empty string `''`).

We labeled a mutant as *not equivalent* if it produced a change that could be observed as a behavioral change to a client of the library. For example, a mutant in the statement `const hours=Math.floor(totalMinutes/60)` that changes the call from `Math.floor` to `Math.round` will result in the value of `hours` being incorrect. Of course, if `hours` is never used (or it doesn’t matter that it is off-by-one), then the mutant could still be equivalent. Hence, we also found it necessary to trace through code to determine that some mutants were not equivalent.

In some cases, the mutant resulted in a change to the behavior of the program, but it was truly impossible to determine whether or not this change impacted the correctness of the program as intended by its developers. For example, a mutant that redirects a log statement from `console.error` to `console.warn` may or may not represent a mutant that developers find to deviate from the application’s intended behavior. Similarly, mutants that change the contents of error messages may or may not represent an equivalent mutant. We labeled all such cases *unknown*.

The results are shown in Table 4. Of the 517 mutants under consideration, the majority 403 (78%) are “not equivalent”, 105 (20%) are “equivalent”, and remaining 9 (2%) are classified as “unknown”. To place these findings in perspective, we applied the same manual classification to up to 50 surviving mutants produced by StrykerJS and

¹⁰ All experimental data associated with this experiment and the other experiments are included with this submission as supplemental materials.

¹¹ For projects with fewer than 50 surviving mutants, we used as many as were available.

found that of 430 surviving mutants, 395 (92%) are “not equivalent”, 5 (1%) are “equivalent”, and 30 (7%) are classified as “unknown”.

We further examined the 105 equivalent mutants, and observed a number of common patterns, including: (i) checking for `null`-ness or `undefined`-ness in different ways (e.g., replacing `x != null` with `!x` or vice versa), (ii) refactoring of calls to the `String.substring` method with one of its near-equivalent counterparts `String.substr` and `String.slice`, (iii) adding modifiers such as `/g` or `/m` to a regular expression in cases where this does not have any effect, (iv) calls to the `Array.slice` method in cases where this does not have any effect, and (v) calling functions with more arguments than are declared. For the 105 equivalent mutants under consideration, approximately 40% fall into one of these categories. We expect that most of these equivalent mutants can be filtered out using an AST-based static analysis. However, further investigation is needed because some mutants that cause behavioral differences are syntactically similar to these patterns. This means that any pattern-matching-based approach should consider the context in which the mutation occurs to determine whether a mutant is likely to be equivalent. Section 7 will discuss future work that aims to reduce the number of equivalent mutants.

The majority (78%) of the surviving mutants produced by *LLMorpheus* are not equivalent to the original code fragments they replace. *LLMorpheus* produces significantly more “equivalent” mutants than *StrykerJS*. However, the number of “not-equivalent” mutants exceeds the number of equivalent mutants by more than a factor of three, and preliminary analysis reveals good potential for future work on automatically filtering out equivalent mutants using static analysis.

4.5 RQ3: What is the effect of different temperature settings?

To explore the impact of an LLM’s temperature setting, we repeated the experiment with the *codellama-34b-instruct* LLM using temperatures 0.25, 0.50, and 1.0. The results of these experiments are summarized in Table 3. As can be seen from the table, the total number of mutants and the number of surviving mutants at temperatures 0.0, 0.25, and 0.50 are generally fairly similar. However, at temperature 1.0, both the total number of mutants and the number of surviving mutants decline noticeably compared to the results for temperature 0.0. Inspection of the results revealed that this is partly because more of the generated mutants are syntactically invalid.

A secondary question is how temperature affects the variability of results. To answer this question, we repeated the experiment 5 times at each temperature and measured how many distinct mutants occur and how many mutants occur in all five runs. We found that, at higher temperatures, the number of distinct mutants increases rapidly and that the number of mutants common to all runs decreases accordingly. For example, for *Complex.js*, *LLMorpheus* generates 1,217 distinct mutants at temperature 0 of which 1,181 (97.04%) are common to all five runs. At temperature 0.25, the number of distinct mutants increases to 2,354, of which 447 (18.99%) are common to all five runs. At temperature 0.5, there are 3,196 distinct mutants of which 205 (6.41%) are common to all runs. At temperature 1.0, there are 4,200 distinct mutants, of which 17 (0.4%) are common to all runs, meaning that, effectively, at temperature 1.0 each run produces completely different mutants. The results

for the other subject applications are similar. The supplemental materials associated with this paper include an analysis showing the overall variability in mutants killed and survived across each of the five runs.

LLMorpheus generally produces similar numbers of mutants at temperatures ≤ 0.5 , of which a similar number survives. At temperature 1.0, the number of generated and surviving mutants decline noticeably because more candidate mutants are syntactically invalid. The variability of results is inversely dependent on the temperature, with mostly the same mutants being produced at temperature 0, and mostly different mutants at temperature 1 in different runs.

4.6 RQ4: What is the effect of variations in the prompting strategy used by *LLMorpheus*?

Thus far, we have evaluated the effectiveness of the prompt template of Figure 7(a) (henceforth referred to as *full*) by measuring how many mutants are generated and classifying them as “killed”, “survived”, or “timed-out” (see Table 2). To determine what the effect is of each component of this prompt, we experimented with the following variations¹²:

onemutation. This variant requests just one replacement of the placeholder instead of three possible replacements.

noexplanation. This variant omits the phrase “This would result in different behavior because <brief explanation>.”.

noinstructions. This variant omits the phrase “Please consider changes such as using different operators, changing constants, referring to different variables, object properties, functions, or methods.”

genericssystemprompt. In this variant, we replace the system prompt of Figure 7(b) with a generic message “You are a programming assistant. You are expected to be concise and precise and avoid any unnecessary examples, tests, and verbosity.”

basic. This minimal template only asks the LLM to provide a code fragment that the placeholder can be replaced with, without any additional context.

Table 5 shows, for each template, the total number of mutants, and the number that were killed, survived, and timed out, respectively. From these results, it can be seen that:

- *full* and *genericssystemprompt* produced the most mutants and performed similarly, demonstrating that the use of a specialized system prompt has minimal impact,
- *noexplanation* and *noinstructions* produce only slightly fewer mutants and surviving mutants than *full* and *genericssystemprompt*, so including instructions or requesting explanations for suggested mutations has limited impact,
- using *onemutation* dramatically reduces the number of mutants from 6,712 to 2,333, demonstrating that it is helpful to request multiple suggestions, and
- using *basic* reduces the number of mutants to 1,326, suggesting that additional context in prompts is helpful.

We separately analyzed the variability of these results (Table 5 presents the results from a single trial), and found the number of

¹²All prompt templates are included with the supplemental materials.

	full (run #312)				onemutation (run #365)				noexplanation (run #372)				noinstructions (run #378)				genericsystemprompt (run #384)				basic (run #390)			
	#mutants	#killed	#survived	#timeout	#mutants	#killed	#survived	#timeout	#mutants	#killed	#survived	#timeout	#mutants	#killed	#survived	#timeout	#mutants	#killed	#survived	#timeout	#mutants	#killed	#survived	#timeout
Complex.js	1,199	725	473	1	406	245	161	0	1,125	676	448	1	1,137	696	440	1	1,199	740	458	1	185	120	65	0
countries-and-timezones	217	188	29	0	79	65	14	0	211	183	28	0	218	174	44	0	217	191	26	0	48	44	4	0
crawler-url-parser	285	157	128	0	86	50	36	0	239	140	99	0	246	134	112	0	246	143	103	0	67	49	18	0
delta	767	634	101	32	266	221	37	8	734	598	110	26	759	612	115	32	790	659	99	32	201	167	28	6
image-downloader	89	72	17	0	34	26	8	0	77	62	15	0	84	69	15	0	88	72	16	0	10	7	3	0
node-dirty	275	163	100	12	99	55	41	3	258	146	99	13	260	146	103	11	277	162	104	11	44	24	18	2
node-geo-point	302	223	79	0	104	74	30	0	297	216	81	0	306	230	76	0	305	229	76	0	62	54	8	0
node-jsonfile	154	49	48	57	57	18	18	21	152	54	45	53	148	45	51	52	150	49	49	52	22	11	3	8
plural	281	205	75	1	100	70	30	0	273	198	74	1	261	189	71	1	272	209	62	1	92	78	14	0
pull-stream	769	441	271	57	280	165	95	20	774	440	278	56	781	467	248	66	763	442	266	55	149	88	54	7
q	2,035	158	1,792	85	703	46	630	27	1,856	138	1,635	83	1,958	138	1,726	94	2,007	145	1,770	92	401	38	350	13
spac-core	239	199	39	1	80	63	17	0	211	175	35	1	187	155	31	1	214	181	32	1	25	23	2	0
zip-a-folder	100	23	3	74	39	19	17	3	98	27	3	68	97	26	4	67	101	27	3	71	20	5	1	14
Total	6,712	3,237	3,155	320	2,333	1,117	1,134	82	6,305	3,053	2,950	302	6,442	3,081	3,036	325	6,629	3,249	3,064	316	1,326	708	568	50

Table 5: Number of mutants generated using the *codellama-34b-instruct* LLM at temperature 0.0 using templates full, onemutation, noexplanation, noinstructions, gen.system prompt, basic (showing one run of each).

	full	onemutation	noexplanation	noinstructions	generic sys. prompt	basic
Complex.js	4.27	3.37	5.09	4.27	4.17	11.98
countries-and-timezones	11.13	7.75	11.17	10.87	10.85	11.29
crawler-url-parser	9.50	6.41	9.46	9.49	9.30	20.04
delta	9.55	7.38	9.91	9.43	9.14	19.63
image-downloader	12.67	8.82	12.89	11.01	11.48	21.92
node-dirty	7.53	6.90	7.58	7.41	7.51	17.52
node-geo-point	8.86	6.10	8.79	7.75	8.66	15.66
node-jsonfile	9.73	6.98	9.76	7.77	8.91	11.64
plural	8.14	5.21	8.41	7.58	7.80	23.64
pull-stream	6.72	4.57	7.53	7.48	7.30	11.92
q	8.61	7.61	9.21	8.60	8.58	16.18
spac-core	9.30	5.86	10.44	9.43	9.44	14.27
zip-a-folder	9.85	5.33	9.02	10.05	10.10	24.60

Table 6: Average string similarity of mutants to the original code fragments that they replace, for mutants generated using each of the prompt templates at temperature 0.0 using *codellama-34b-instruct*.

mutants killed and survived to be quite stable across trials (the supplemental materials provide further detail).

We also investigated how similar mutants produced using the different prompt templates are to the original code fragments they replace. As manually inspecting sufficient samples of mutants from each of the different configurations would be infeasible, we instead rely on an automated measure. We calculate the Levenshtein string edit distance for each mutant between the mutated code and the original code. Table 6 reports the average string edit distance scores for each of the prompt templates by project.

Interpreting the results across different projects is challenging, as each project uses different code idioms that might lead to different mutations. However, we observe several interesting trends by comparing the mutant similarity across prompts (within the same project). We find the *basic* template to produce the mutants that are *least similar* to the original code. We examined samples of these mutants and found that many were creative changes that injected large code blocks in place of short, simple values. For example, in

crawler-url-parser, the mutant with the largest string edit distance (297) involves replacing a constant `TRUE` with an object literal. While the *onemutation* template tended to produce mutants most similar to the original code, this is likely due to the more limited sample space. We infer that prompting for multiple mutants can result in the LLM suggesting more significant code changes than it would otherwise have.

The *full* template produces the most mutants and surviving mutants overall. Using a specialized system prompt has a marginal effect. Including instructions on performing mutations and requesting explanations for mutations only modestly affects the number of mutants and surviving mutants. Requesting only one mutation dramatically reduces the number of generated and surviving mutants, and even greater reductions are observed if the LLM is only asked to fill in the placeholder without additional guidance.

4.7 RQ5: how does the effectiveness of *LLMorpheus* depend on the LLM being used?

The results discussed thus far were obtained with the *codellama-34b-instruct* LLM. To determine how the quality of results depends on the particular LLM being used; we also experimented with *codellama-13b-instruct*, *llama-3.3-70b-instruct*, *mistral-8x7b-instruct*, and *gpt-4o-mini* at temperature 0.0.

Table 7 shows the number of mutant candidates produced using each model (along with a breakdown how many of those candidates are syntactically invalid, identical to the original code, or duplicates), and the number of mutants produced using each model, classified as killed, surviving, and timed-out. Figure 9 shows a visual comparison of the total number of mutant candidates and mutants produced using each of the five LLMs under consideration, aggregated over all 13 subject applications. From these results, it can be seen that:

- The *codellama-34b-instruct* model generates the largest number of mutant candidates (9,967), though the number of mutant candidates produced by *codellama-13b-instruct*, *mistral-8x7b-instruct*, *llama-3.3-70b-instruct*, and *gpt-4o-mini* are quite similar. *codellama-13b-instruct* produces noticeably fewer mutant candidates (8,088).

	codellama-13b-instruct (run #354)								mixtral-8x7b-instruct (run #360)							
	#candidates	#invalid	#identical	#duplicate	#mutants	#killed	#survived	#timeout	#candidates	#invalid	#identical	#duplicate	#mutants	#killed	#survived	#timeout
Complex.js	1,410	339	116	28	955	553	401	1	1,272	310	0	15	962	589	373	0
countries-and-timezones	305	83	15	1	207	177	30	0	272	65	2	5	205	166	39	0
crawler-url-parser	494	186	51	12	247	129	118	0	411	165	0	3	234	130	104	0
delta	1,334	530	92	16	712	583	107	22	1,132	452	0	24	680	516	128	36
image-downloader	122	40	5	2	77	48	29	0	107	38	0	1	69	46	23	0
node-dirty	439	161	33	11	245	142	92	11	300	109	0	10	191	111	72	8
node-geo-point	390	64	21	16	304	237	67	0	341	88	0	11	247	166	81	0
node-jsonfile	191	43	10	7	138	43	45	50	155	23	0	4	132	54	32	46
plural	407	100	99	17	208	154	53	1	299	73	0	8	226	166	60	0
pull-stream	1,002	279	54	13	669	386	237	46	934	255	1	6	678	386	248	44
q	2,993	901	379	55	1,713	122	1,518	73	2,418	772	3	50	1,643	112	1,460	71
spacel-core	377	142	40	7	185	160	25	0	330	152	0	3	157	134	22	1
zip-a-folder	137	43	7	1	87	27	55	5	117	38	0	0	78	24	44	10
Total	9,601	2,911	922	186	5,582	2,761	2,777	209	8,088	2,540	6	140	5,402	2,600	2,686	216

	llama-3.3-70b-instruct (run #23)								gpt-4o-mini (run #58)							
	#candidates	#invalid	#identical	#duplicate	#mutants	#killed	#survived	#timeout	#candidates	#invalid	#identical	#duplicate	#mutants	#killed	#survived	#timeout
Complex.js	1,417	279	0	53	1,138	690	447	1	1,432	446	0	38	986	596	390	0
countries-and-timezones	304	64	0	14	240	207	33	0	308	99	0	9	209	171	38	0
crawler-url-parser	506	175	0	22	319	208	111	0	516	227	0	11	275	181	94	0
delta	1,333	539	0	54	794	626	130	38	1,345	636	2	40	707	564	108	35
image-downloader	122	43	0	5	79	54	25	0	123	58	0	3	65	45	20	0
node-dirty	453	121	1	10	331	168	142	21	453	188	0	9	265	154	103	8
node-geo-point	399	39	0	22	358	255	103	0	399	86	0	20	311	225	86	0
node-jsonfile	198	25	0	6	173	64	37	72	198	44	0	6	154	64	26	64
plural	427	96	0	29	331	244	87	0	428	110	5	26	313	257	55	1
pull-stream	1,044	262	0	10	782	465	265	52	1,037	302	0	16	735	420	247	68
q	3,074	855	0	80	2,219	127	2,006	86	3,084	1,287	2	69	1,795	137	1,597	61
spacel-core	383	134	0	18	236	203	32	1	392	158	0	10	215	195	20	0
zip-a-folder	145	24	0	2	121	87	5	29	143	62	0	4	81	14	7	60
Total	9,805	2,656	1	325	6,823	3,398	3,423	300	9,858	3,703	9	261	5,885	3,023	2,791	297

Table 7: Mutants generated with the *codellama-13b-instruct*, *mixtral-8x7b-instruct*, *llama-3.3-70b-instruct*, and *gpt-4o-mini* LLMs, using the following parameters: temperature: 0.0, maxTokens: 250, maxNrPrompts: 2000, template: *template-full.hb*, systemPrompt: *SystemPrompt-MutationTestingExpert.txt*, rateLimit: 0, nrAttempts: 3.

- All models produce a significant number of mutant candidates that is syntactically invalid, ranging from 3,703 in the case of *gpt-4o-mini* to 2,540 in the case of *mixtral-8x7b-instruct*.
- *codellama-13b-instruct* is the only model that produces a significant number of mutant candidates that are identical to the original code fragments that they replace (922).
- None of the models produces a significant number of mutant candidates that are duplicates.
- The number of mutants that remains after discarding the invalid, identical, and duplicate mutant candidates ranges from 5,402 in the case of *mixtral-8x7b-instruct* to 6,823 in the case of *llama-3.3-70b-instruct*, with *codellama-34b-instruct* producing almost as many valid mutants (6,712).
- *llama-3.3-70b-instruct* produces the most surviving mutants (3,423), followed by *codellama-34b-instruct* (3,155).

We also explored the variability of results produced using *codellama-13b-instruct*, *mixtral-8x7b-instruct*, *llama-3.3-70b-instruct* and *gpt-4o-mini* by conducting each experiment 5 times, and determined how many distinct mutants are produced and how many mutants occur in all five runs. We found that, at temperature 0, the results obtained with *codellama-13b-instruct* are very stable across runs, with 96.15%–100% of all mutants occurring in each of the five runs.

However, with *mixtral-8x7b-instruct*, *llama-3.3-70b-instruct* and *gpt-4o-mini* we encountered more variability. With *mixtral-8x7b-instruct*, between 34.22%–50% of mutants occur in all 5 runs, with *llama-3.3-70b-instruct*, between 28.26%–58.94% occur in all 5 runs, and with *gpt-4o-mini*, between 28.26%–58.94%. We also analyzed the variance of the number of mutants killed and survived, finding that, despite the diversity of mutants across trials, the mutation score was relatively stable. The supplemental materials include tables showing the average and standard deviation of the number of mutants killed and survived.

We also examined the string similarity of mutants produced by the five LLMs to the original code and found that the *mixtral-8x7b-instruct* model tends to generate mutants with the greatest string edit distance in the most projects. We examined the top 2 mutants with the greatest string edit distance generated by this model for each project, finding several cases of unusual completions. In *q*, *mixtral*’s most dissimilar mutants (distance 219) replaced a string literal that referred to the function "allResolved" with a declaration of the same function. In *delta*, *mixtral*’s most dissimilar mutants (distance 155) apply a reduce operation to an object before invoking `Object.keys` on it. We saw similar trends for *mixtral* across all projects, with mutants that tended to include large code declarations. Examining the mutants with the greatest string edit distance for the other four

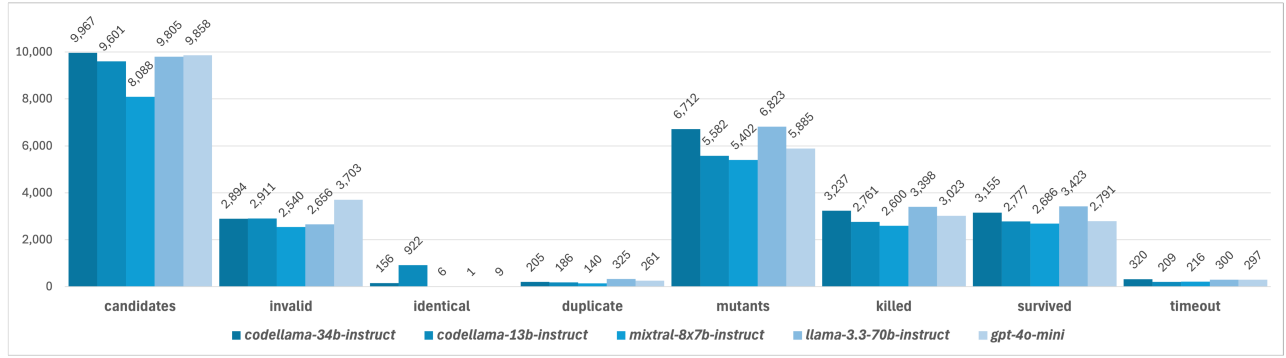


Figure 9: Comparison of the number of mutant candidates and mutants generated with the *codellama-13b-instruct*, *mixtral-8x7b-instruct*, *llama-3.3-70b-instruct*, and *gpt-4o-mini* LLMs at temperature 0.0. This chart was created from the data shown in Tables 2 and 7.

LLMs, we did not find significant trends that held across all targets. Further details can be found in the supplemental materials.

All five LLMs under consideration can be used successfully to generate large numbers of (surviving) mutants. *llama-3.3-70b-instruct* and *codellama-34b-instruct* tend to produce the largest number of surviving mutants, and *codellama-34b-instruct* tends to produce results that are stable across experiments when temperature 0 is used. *llama-3.3-70b-instruct*, *mixtral-8x7b-instruct*, and *gpt-4o-mini* produce highly variable results, even at temperature 0.

4.8 RQ6: What is the cost of running LLMorpheus?

The primary costs of running *LLMorpheus* are the time required to run experiments and the expenses associated with LLM usage. Regarding the latter, for the experiments reported on in this paper, we have relied on several commercial LLM service providers (octo.ai, openrouter.ai, and openai.com). Such costs tend to vary depending on the provider and the LLM being used, and are typically calculated as a function of the number of “tokens” used in the prompt and the completion¹³. The cost of commercial LLM providers also tends to vary over time, and when a newer version of an LLM is released, it often costs the same as the older version that it replaced. In our experiments, the total number of tokens used for running a full experiment with *LLMorpheus* varied by less than 20% for the five LLMs that we used¹⁴, suggesting that token usage is a reasonable proxy for the financial costs incurred. For these reasons, we use the number of input and output tokens used in our experiments as the primary cost metric for evaluating *LLMorpheus*’s LLM usage. For completeness, we also discuss the expense in US dollars at the time of running the experiments below, but the reader should be aware that these costs are likely to vary over time.

¹³Depending on the provider, there may also be additional costs associated with the number of requests, though that was not the case for our experiments.

¹⁴Calculated from the total number of tokens reported in the Supplemental Materials associated with this paper, for experiments using the “full” prompt template at temperature 0.

project	time (sec)		prompt	#tokens compl.	total
	LLMorpheus	StrykerJS			
Complex.js	3,050.00	637.85	967,508	102,517	1,070,025
countries-and-timezones	1,070.89	313.86	105,828	23,441	129,269
crawler-url-parser	1,642.70	929.43	386,223	39,175	425,398
delta	2,961.66	3,839.60	890,252	98,974	989,226
image-downloader	430.53	379.25	24,655	9,134	33,789
node-dirty	1,526.20	241.81	246,248	33,070	279,318
node-geo-point	1,411.11	987.17	316,333	30,013	346,346
node-jsonfile	690.61	474.78	57,516	14,797	72,313
plural	1,521.32	155.24	265,602	34,174	299,776
pull-stream	2,492.50	1,608.97	208,130	76,513	284,643
q	5,241.46	14,034.67	2,127,655	220,215	2,347,870
spacel-core	1,351.08	798.96	162,705	29,236	191,941
zip-a-folder	500.57	1,156.11	82,457	10,725	93,182
Total	23,890.64	25,557.70	5,841,112	721,984	6,563,096

Table 8: Results from LLMorpheus experiment (run #312). Model: *codellama-34b-instruct*, temperature: 0.0, max-Tokens: 250, template: *template-full.hb*, systemPrompt: *SystemPrompt-MutationTestingExpert.txt*

The **time** column in Table 8 shows the time needed to run *LLMorpheus* and the modified version of *StrykerJS* on each subject application. As can be seen in the table, *LLMorpheus* requires between 430.53 seconds (about 7 minutes) and 5,241.46 seconds (about 87 minutes) and *StrykerJS* between 155.24 seconds (about 2.5 minutes) and 14,034.67 seconds (about 234 minutes).

The last three columns of Table 8 show the number of tokens used in prompts and completions for each subject application and in the aggregate. From these results, it can be seen that running *LLMorpheus* required between 24,655 and 2,127,655 prompt tokens, and between 9,134 and 220,215 completion tokens. Hence, in the aggregate, 5,841,112 prompt tokens and 721,984 completion tokens were required. At the time of conducting the experiments, the cost of the *codellama-34b-instruct* LLM using octo.ai’s LLM service was \$0.50 per million input tokens and \$1.00 per million output tokens, so for running *LLMorpheus* on all 13 applications, a total cost of approximately \$3.62 was incurred. Moreover, at the time of conducting our experiments, the *llama-3.3-70b-instruct* model that we used can be accessed from \$0.12 per million input tokens and \$0.30 per million output tokens at openrouter.ai, and the *gpt-4o-mini* model that we used can be accessed from \$0.15 per million input tokens and \$0.60 per million output tokens from openai.com. Hence, a full


```

Bug-2 fix

diff --git a/lib/request.js b/lib/request.js
index c1392396..3bae7ad9 100644
--- a/lib/request.js
+++ b/lib/request.js
@@ -358,7 +358,7 @@ req._defineGetter('_', function() {
   'http';
   var trust = this.app.get('trust proxy fn');

-  if (!trust(this.connection.remoteAddress)) {
+  if (!trust(this.connection.remoteAddress, 0)) {
     return proto;
   }

```

```
$ git show Bug-12-fix
commit d50553e7f20181645465c5f1ceed6c9fba356528 (tag: Bug-12-fix)
Author: pigeonrunner <pigeonrunner.ICST.2019@gmail.com>
Date: Sun Oct 14 22:05:43 2018 +0200
```

```

Bug-12 fix

diff --git a/lib/hexo/post.js b/lib/hexo/post.js
index e1f0fffb..db1cc54 100644
--- a/lib/hexo/post.js
+++ b/lib/hexo/post.js
@@ -47,7 +47,7 @@ Post.prototype.create = function(data, replace, callback){
   var ctx = this.context;
   var config = ctx.config;

-  data.slug = slugize(data.slug || data.title, {transform: config.filename_case});
+  data.slug = slugize(data.slug || data.title, toString(), {transform: config.filename_case});
   data.layout = data.layout || config.default_layout.toLowerCase();
   data.date = data.date ? moment(data.date) : moment();

@@ -204,7 +204,7 @@ Post.prototype.publish = function(data, replace, callback){
   var ctx = this.context;
   var config = ctx.config;
   var draftDir = path.join(ctx.source_dir, '_drafts');
-  var slug = data.slug = slugize(data.slug, {transform: config.filename_case});
+  var slug = data.slug = slugize(data.slug, toString(), {transform: config.filename_case});
   var regex = new RegExp('^' + escapeRegExp(slug) + '(?:[\\s\\\\\\\\\\+]+)');
   var self = this;
   var src = this;

```

(a) Bug #2 in Hexo

```

Bug-4 fix

diff --git a/lib/v1/encoder.js b/lib/v1/encoder.js
index 9141c86..007bd3c 100644
--- a/lib/v1/encoder.js
+++ b/lib/v1/encoder.js
@@ -299,7 +299,9 @@ proto.writeObject = function (obj) {
   * : {$class: 'java.lang.Map', $: {a: 1}}
   */
   proto.writeObject = function (obj) {
-   if (is.nullOrUndefined(obj)) {
+   if (is.nullOrUndefined(obj)) || is.null()
+   // : { a: { '$class': 'xxx', '$': null } }
+   + (is.string(obj.$class) && is.nullOrUndefined(obj.$)) {
     debug('writeObject with a null');
     return this.writeNull();
   }

```

```
$ git show Bug-4-fix
commit 91ba7b454a6afe2abaa3fd05167b409ba15928b9 (tag: Bug-4-fix)
Author: pigeonrunner <pigeonrunner.ICST.2019@gmail.com>
Date:   Sun Oct 14 22:06:33 2018 +0200
```

```

Bug-4 fix

diff --git a/lib/reporter.js b/lib/reporter.js
index fca44ec..dab5574 100644
--- a/lib/reporter.js
+++ b/lib/reporter.js
@@ -49,7 +49,7 @@ var createErrorFormatter = function (basePath, emitter, SourceMapConsumer) {

     var file = findFile(path)

-    if (file && file.sourceMap) {
+    if (file && file.sourceMap && line) {
         line = parseInt(line || '0', 10)

         column = parseInt(column, 10)

```

(b) Bug #4 in Karma

Figure 10: Patches corresponding to 4 real-world bugs selected from the Bugs.js suite [25] that were used in a case study to determine *LLMorpheus*’s ability to generate mutants that resemble real-world bugs.

experiment can be run for less than \$1 with *llama-3.3-70b-instruct*, and for approximately \$1.30 with *gpt-4o-mini*.

It should be pointed out that the cost of the LLMs we used is significantly lower than that of larger state-of-the-art proprietary LLMs such as OpenAI’s *gpt-4o*, for which <https://openai.com/pricing> quotes a cost of \$2.50 per million input tokens and \$10 per million output tokens at the time of writing. While such models might be even more capable of suggesting useful mutants, it is encouraging to see that lower-cost LLMs can achieve good results.

LLMorpheus requires between 7 and 87 minutes to generate mutants for 13 subject applications. At the time of conducting our experiments, a full experiment with *LLMorpheus* on all 13 applications costs up to \$3.62 depending on the LLM being used, suggesting that cost is not a prohibitive limiting factor.

4.9 RQ7: Is *LLMorpheus* capable of producing mutants that resemble existing bugs?

To determine whether *LLMorpheus* is capable of producing mutants that resemble existing bugs, we conducted a case study involving 4 bugs from Bugs.js [25], a collection of 453 bugs from real-world JavaScript applications. For each of these bugs, the original faulty version is provided, along with a cleaned patch extracted from the bug fix and instructions on how to execute the test cases. In this study, we applied *LLMorpheus* to the *fixed* version of a program by introducing placeholders near the location of the fix, generating

mutants, executing the program’s tests for each of these mutants and checking if the observed test failures were identical to those caused by the original bug. Below, we report on our findings for 4 such bugs.

Express.js Bug#2. Figure 10(a) shows bug #2 in Express, a popular web framework for Node.js. This bug occurs at line 361 in the file `lib/request.js` and involves the invocation of a function `trust` with a single argument `this.connection.remoteAddress`. Here, the fix involved the addition of a second argument, `0`. Reintroducing this bug in the fixed version causes 2 tests to fail. When applied to the fixed version, *LLMorpheus* creates the following 3 mutants:

- replacing `! trust (this.connection.remoteAddress, 0)` with `trust (this.connection.remoteAddress, 1)`
- replacing `! trust (this.connection.remoteAddress, 0)` with `! trust (this.connection.remoteAddress)`
- replacing `! trust (this.connection.remoteAddress, 0)` with `trust (this.connection.localAddress, 0)`

The second mutant is identical to the original bug. The other two mutants cause multiple test failures that differ from those caused by the original bug.

We repeated the same experiment 4 more times¹⁵, and found that in some cases *LLMorph* produces mutants such as `!trust(this.connection.localAddress, 1)` that differ from the original bug but cause

¹⁵Data for 5 experiments with each of these bugs is included with supplemental materials.

the same test failures. Moreover, in one experiment, *LLMorpheus* produced a mutant `!this.app.get('trust_proxy')` that reproduces one of the two test failures that were caused by the original bug.

Hessian.js Bug#4. Figure 10(b) shows bug #4 in Hessian, a serialization framework. This bug occurs at line 302 in file `lib/v1/encoder.js` and involves the condition of an `if`-statement. Here, the fix for the bug involves changing the condition from `is.nullOrUndefined(obj)` to `is.nullOrUndefined(obj) || (is.string(obj.$class) && is.nullOrUndefined(obj.$))`. Reintroducing this bug in the fixed version results in a test failure.

When applied to the fixed version, *LLMorpheus* creates the following 3 mutants:

- replacing `is.nullOrUndefined(obj) || (is.string(obj.$class) && is.nullOrUndefined(obj.$))` with `obj === null`,
- replacing `is.nullOrUndefined(obj) || (is.string(obj.$class) && is.nullOrUndefined(obj.$))` with `is.nullOrUndefined(obj.$)`
- replacing `is.nullOrUndefined(obj) || (is.string(obj.$class) && is.nullOrUndefined(obj.$))` with `!obj`

In this case, none of the generated mutants are identical to the original bug. However, the first and the third mutants *cause exactly the same test failures as the original bug*. The second mutant causes multiple test failures that differ from those produced by the original bug. We repeated the same experiment 4 more times and while *LLMorpheus* never reproduced the original bug, it produced mutants with the same behavior as the original bug on multiple occasions.

Hexo Bug#12. Figure 10(c) shows bug #12 in Hexo, a blogging framework for Node.js. The bug involves lines 50 and 207 in file `lib/hexo/post.js`. Here, the fix involves inserting a call to `toString` on the expression that is passed as the first argument to a function `slugize` in each of these lines. This issue causes two test failures, one corresponding to each of the lines that was changed in the fix, so it can be viewed as two similar bugs that can be fixed independently.

We decided to focus on the slightly simpler expression at line 207, where *LLMorpheus* creates the following 7 mutants:

- (1) replacing `slugize((data.slug || data.title).toString(), transform: config.filename_case)` with `slugize((data.slug && data.title).toString(), transform: config.filename_case)`
- (2) replacing `data.slug.toString()` with `data.slug`
- (3) replacing `data.slug.toString()` with `data.title`
- (4) replacing `data.slug.toString()` with `data.slug + 'test'`
- (5) replacing `slugize(data.slug.toString(), transform: config.filename_case)` with `slugize(data.slug.toUpperCase(), transform: config.filename_case)`
- (6) replacing `slugize(data.slug.toString(), transform: config.filename_case)` with `slugize(data.title, transform: config.filename_case)`
- (7) replacing `slugize(data.slug.toString(), transform: config.filename_case)` with `slugize(data.slug + Math.random(), transform: config.filename_case)`

The second of these mutants is identical to the first part of the original bug and causes one of the two failures associated with the entire buggy code fragment. The other mutants cause multiple test failures that differ from the original bug.

4.10 Karma Bug #4

Figure 10(d) shows bug #4 in Karma, a testing framework. The bug occurs on line 46 in file `lib/reporter.js` where a buggy condition

`file && file.sourceMap` in an `if`-statement was changed to `file && file.sourceMap && line` in the fixed version.

When applied to the fixed version, *LLMorpheus* creates the following 3 mutants at this line:

- replacing `file && file.sourceMap && line` with `file && line`,
- replacing `file && file.sourceMap && line` with `file && file.sourceMap`, and
- replacing `file && file.sourceMap && line` with `file && !file.sourceMap && line`

The first of these mutants has the same behavior as the fixed version, i.e., it is a surviving mutant, indicating that testing may not be sufficiently rigorous. The second mutant is identical to the original bug. The third mutant causes multiple test failures that differ from those caused by the original bug.

In each of these cases, *LLMorpheus* produced either a mutant that was identical to a bug that was originally observed, or one that caused the same test failures as a bug that was originally observed. The latter case suggests that *LLMorpheus*'s ability to generate mutants that resemble real-world tests is not entirely due to training-set leakage.

In each of the experiments under consideration, *LLMorpheus* was able capable to produce mutants that resemble existing bugs.

4.11 Experimental Data

All experimental data associated with the experiments reported on in this paper can be found at <https://github.com/neu-se/mutation-testing-data>.

5 THREATS TO VALIDITY

The projects used to evaluate *LLMorpheus* may not be representative of the entire ecosystem of JavaScript packages. To mitigate this risk, we select popular packages used in prior JavaScript testing tool evaluations and report results per project, discussing the full range of behaviors we witness. As in many evaluations of LLM-based tools, the validity of our conclusions may be threatened by including our evaluation subjects in the training data for the models. If the model were in fact trained on bugs in some of the programs we asked it to create bugs in, one would expect its performance on those programs to vary significantly from those that it was not pre-trained on. We mitigate this risk by conducting experiments with five LLMs, four of which are “open” in the sense that the training process is documented, thus enabling reproducibility and detailed analysis of experimental results.

Truly determining if a mutant is equivalent requires significant effort and despite the best efforts of two authors to rigorously evaluate them, there may be errors in our categorizing of mutants.

One of the key evaluation criteria used in previous work on mutation testing is “coupling”, i.e., determining whether a test suite that detects particular mutants also detects particular real faults [22, 30, 36]. We investigated the feasibility of conducting such a study using the Bugs.js suite [25], but we found that most of these subjects could not be used at all due to their reliance on outdated versions of various libraries and because of their incompatibility with modern Node.js versions that *StrykerJS* requires, causing them

to be incompatible with *LLMorpheus*. These projects also have flaky tests, making it particularly challenging to perform mutation analysis [53]. We therefore opted for conducting a case study involving 4 real-world bugs from the Bugs.js suite that we were able to reproduce reliably. The results of this case study may be skewed because the code for previous buggy versions of the applications may have been included in the training set of the LLM that we used. However, in several cases, we observed that *LLMorpheus* produced mutants that *differed from the original bug but that caused the same test failures*. This suggests that *LLMorpheus*’s ability to produce mutants that resemble real-world bugs is not entirely due to training-set leakage.

Evaluating tools that rely on LLMs face significant reproducibility challenges. We mitigate these risks by (i) evaluating *LLMorpheus* using four open LLMs that are version-controlled and permanently archived (in addition to one popular proprietary LLM), (ii) repeating each experiment 5 times and (iii) making all experimental data available as supplemental materials, and (iv) making *LLMorpheus*, our evaluation scripts and results publicly available. Including all results for all experiments in the main body of this paper would significantly decrease the readability of the work. Where we observed significant variability in results, we include data regarding that distribution in the paper directly. In all cases, the supplemental materials associated with this paper include results for all trials of all experiments and summary tables that describe the observed variability for each configuration.

Lastly, a possible concern is that *LLMorpheus* only supports JavaScript and TypeScript, and that applicability beyond these languages may be unclear. Implementing the same approach for a different language would involve various steps (parsing ASTs, executing tests, etc.) that are language-specific and would involve very significant engineering effort, but should otherwise be straightforward.

6 RELATED WORK

Mutation testing, first introduced in the 1970’s [18], has a long history [46]. The era of “big code” and software repository mining has enabled the large-scale evaluation of the core hypothesis behind mutation testing, namely, that mutants are coupled to real faults. Just *et al.* mined real faults from Java applications and found a statistically significant correlation between mutation detection and real fault detection [30]. This finding has since been replicated on newer, larger datasets consisting of faults from even more Java programs [36]. Gay and Salahirad extended this methodology to examine the extent to which individual mutation operators are most coupled to real faults [22]. While this has demonstrated that test suites that detect more mutants are also likely to detect more bugs, it also underscores the need for new mutation approaches that can generate faults that are coupled to more real bugs.

ML for Mutation Testing: Several recent projects have considered the use of LLMs and other AI-based techniques for mutation testing. μ Bert [17, 34] resembles *LLMorpheus* in that both techniques select some designated code fragments, and query a model what they could be replaced with. μ Bert masks one token at a time, so its mutations involve changes to a single variable or operator. By contrast, *LLMorpheus*’ placeholders correspond to (sequences

of) AST nodes so it may suggest mutations involving more significant changes to complex expressions. A crucial difference between the techniques is that *LLMorpheus* utilizes prompts that provide an LLM with additional guidance whereas μ Bert provides no way of guiding the mutations at all, and is therefore completely at the mercy of what the model thinks masked tokens should be replaced with. In our experiments with different prompts (Section 4.6), the *basic* prompt is analogous to μ Bert in that it merely asks the LLM what placeholders should be replaced with. Our results show this to be much less effective at producing interesting mutants, thus demonstrating the usefulness of including additional information in prompts. Our work also differs from [17] by considering several LLMs, different temperatures and by targeting a different language.

In recent work, Garg *et al.* [21] explore the coupling between mutants generated using μ Bert and 45 reproducible vulnerabilities from the Vul4J dataset. They distinguish between *strongly coupled mutants* that fail the same tests for the same reasons as the vulnerabilities and *test coupled mutants* that fail the same tests but for some different reason as the vulnerabilities. While they find the majority (32 of 45) of μ Bert-generated mutants to be strongly coupled, they also find that strongly coupled mutants are scarce, representing just 1.17% of killable mutants. It would be interesting to explore whether the use of more elaborate prompting strategies such as those employed by *LLMorpheus* could be used to increase the ratio of strongly coupled mutants.

Tian *et al.* [56] consider the use of LLMs for determining whether mutants are equivalent and compare their effectiveness to that of traditional techniques for mutant equivalence detection. Their study considers the detection of equivalent mutants in 19 Java programs from the MutantBench suite [59], from which mutants were derived using standard mutation operators from μ Java [41]. Tian *et al.* experimented with 10 LLMs. They consider 10 state-of-the-art LLMs and several strategies for fine-tuning and prompting, and consider three widely used traditional techniques (compiler-based, ML-based, and Tree-Based Neural NetWork) as the baseline for comparison. Their results indicate that LLMs are significantly better than traditional techniques at equivalent mutant detection, with the fine-tuned code embedding strategy being the most effective. It would be interesting to explore to what extent these results carry over to the detection of mutants that were produced using LLMs using tools such as *LLMorpheus*.

Similar to our interests, Wang *et al.* [60] perform an exploratory study on using large language models to generate mutants. Unlike our prompting strategy that generates up to three mutants per-AST node, Wang *et al.* explore a strategy that generates mutants at the granularity of entire methods. We demonstrate the nuances of prompt engineering in this context by exploring performance under different prompts (RQ4). These complementary works demonstrate the potential of using LLMs for mutation testing.

Several projects [10, 33] have considered the use of LLMs as mutation operators in the context of Genetic and Search-Based techniques to improve the efficiency of the search. Brownlee *et al.* [10] consider the generation of alternate implementations for methods and experimented with prompts exhibiting different levels of detail, similar to our experiments reported on in Section 4.6, finding that more detailed prompting generally improves the number of successful patches.

Several other works rely on LLMs to validate the results of mutation testing tools. Li and Shin [40] use 4 syntactic mutation operators and then observe the change to the natural language description that an LLM generates of the mutated code. MuTAP [15] uses an off-the-shelf syntactic mutation tool to generate mutants for a Python program, and then prompts an LLM to generate a test that can detect those mutants.

Equivalent Mutants: Kushigian et al. [35] study the types and prevalence of equivalent mutants in Java programs, considering why they are equivalent and how challenging it is to detect that they are. Their study considers 19 Java open-source programs from which mutants are derived using Major [29], a rule-based mutation-testing framework for Java that supports similar mutation operators as *StrykerJS*. Their findings indicate that around 3% of mutants are equivalent, and these equivalent mutants are further classified according to criteria that reflect *why* a mutant is equivalent, and *how* this could be determined. Based on these findings, Kushigian et al. propose Equivalent Mutant Suppression (EMS), a collection of simple static checks for detecting equivalent mutants.

Improving Mutation operators: Other approaches for mutation testing aim to generate mutants that represent a wider variety of faults. “Higher-order mutation” combines multiple mutations concurrently, creating more complex faults, but still limited by the set of operators implemented [23, 27]. More recently, Brown *et al.* improve mutation by mining patches for new idioms to use as mutation operators [9]. Beller *et al.* design a similar tool and evaluate it at Facebook, with the goal of increasing adoption of mutation testing [8]. Taking this idea further, Tufano *et al.* create *DeepMutation*, an approach that learns models for performing mutation from real bugs [58]. This idea was refined by Tian *et al.*’s *LEAM*, which improves the search process by leveraging program grammars [55]. Patra and Pradel’s *SemSeed* learns to generate mutants from fixes of real-world identifier and literal semantic bugs [47]. Unlike these approaches, *LLMorpheus* uses a *pre-trained LLM*, requiring no training to apply it to a new project.

Mutation Testing Applications and Tools: Belén Sánchez et al. [7] report on a results of a qualitative study among open-source developers on the use of mutation testing. Their findings indicate that developers find mutation testing useful for improving test suite quality, detecting bugs, and improving code maintainability and that performance considerations are the biggest impediment to adoption. Much of the research advancing the state of mutation testing tooling has targeted Java, such as MuJava [41], Javalanche [52], Jumble [26], Judy [42] and Major [29]. Gopinath *et al.* empirically compared two of these research-oriented tools (Judy [42], Major [29]) with an industry-oriented tool (Pit [14]), finding that despite the stated similarities between the tools, each produced a somewhat different set of mutants [24]. Pit is actively maintained, and the open-source tool is also available packaged with professional plugins under the name ‘ArcMutate’ [12]. Also aimed at practitioners, the *Stryker* mutation tool is a framework that supports code written in JavaScript, TypeScript, C#, and Scala [54]. We build *LLMorpheus* atop Stryker. Deb *et al.* examine a new, language-agnostic approach to generating mutants using regular expressions [16]. Future work may examine the feasibility of implementing *LLMorpheus* using this approach.

Mutation and Test Generation: There is a long line of research on test generation techniques that specifically target mutated code. DeMillo and Offutt [19] presented a technique that relies on solving systems of algebraic constraints to derive test cases that target mutated code. Fraser and Zeller [20] present μ TEST, an approach that automatically generates unit tests for object-oriented classes based on mutation analysis. Their test generation technique uses mutations as the coverage criterion that it aims to maximize and creates tests containing oracles that test the mutated value. Chekam et al. [11] present a test generation technique based on symbolic execution that systematically searches for situations where program behaviors of the original program diverges from that of mutated versions. Lee et al. [37] present a grey-box fuzzing technique that involves executing both the original and the mutated code in the same fuzzing driver to direct the generation of test inputs towards those that kill mutants. Adapting LLM-based test generation techniques [6, 51, 57] to target mutated code would be an interesting topic for future work.

LLMs and Testing: Beyond mutation testing, LLMs have also been used for test generation. Bareiß et al. [6] present an approach for test generation that follows a few-shot learning paradigm, outperforming traditional feedback-directed test generation [44]. Tufano et al. [57] present an approach for test generation using a BART transformer model [39] that is fine-tuned on a training set of functions and corresponding tests. Lemieux et al. [38] present an approach where tests generated by Codex are used to assist search-based testing techniques [45] in situations where such techniques get “stuck” because the generated test cases diverge too far from expected uses of the code under test. TestPilot [51] produces unit tests for JavaScript programs by prompting an LLM with the start of a test for an API function, with information about that function (signature, body, and usage examples mined from project documentation) embedded in code comments. In response, the LLM will produce a candidate test, which it executes to determine whether it passes or fails. In case of failure, TestPilot attempts to fix the failing test by re-prompting the LLM with the error message. In principle, *LLMorpheus* can be used to evaluate such test generation techniques by providing a means to assess the quality of the generated tests.

7 CONCLUSIONS AND FUTURE WORK

We have presented *LLMorpheus*, an LLM-based technique for mutation testing. In this approach, code fragments at designated locations in the program’s source code are replaced with the word “PLACEHOLDER”, and an LLM is given a prompt that includes: general background on mutation testing, the original code fragment, and instructions directing the LLM to replace the placeholder with a buggy piece of code. The mutants produced by *LLMorpheus* are passed to a modified version of the popular *StrykerJS* mutation testing tool, which runs the tests, classifies mutants, and creates an interactive web page for inspecting the results.

An empirical evaluation on 13 subject applications demonstrates that *LLMorpheus* is capable of producing mutants that resemble real bugs that cannot be produced using standard mutation operators. We found that the majority (78%) of surviving mutants produced by

LLMorpheus are behavioral changes and that 20% of them are equivalent mutants. Experiments with variations on the prompt template reveal that the “full” template that includes all information performs best and that omitting parts of the information from this template matters to varying degrees. From experiments with five LLMs, we found that *llama-3.3-70b-instruct* and *codellama-34b-instruct* generally produced the largest number of mutants and surviving mutants. Moreover, a case study involving four real-world bugs from the Bugs.js suite [25] revealed that, in each case, *LLMorpheus* produced either a mutant that was identical to a bug that was originally observed, or one that caused the same test failures as a bug that was originally observed.

The number of mutants produced by *LLMorpheus* can become quite large, and executing them can take considerable time. In future work, we plan to explore techniques for pruning and prioritizing mutants, focusing particularly on reducing the number of equivalent mutants. From a manual investigation of 105 equivalent mutants, we observed several common patterns, such as replacing an expression “`x`” with “`x === null`” or “`x === undefined`” or replacing call to `String.substr` with calls to `String.substr` and `String.slice`, two methods with similar semantics. We expect that most of these equivalent mutants can be filtered out using simple AST-based analysis. However, further investigation is needed because a few of the mutants that cause behavioral differences are syntactically similar to these patterns. This means that any pattern matching based approach should consider the context in which the mutation occurs to make a determination whether a mutant is likely to be equivalent. To deal with more challenging cases, future work could also explore the use of symbolic execution or efficient formal reasoning techniques for automatically identifying mutants that are likely to be equivalent.

In our research we have used LLMs in their default configuration, without any fine-tuning. The strong results obtained with the relatively small *codellama-34b-instruct* LLM that is trained for code-related tasks suggests that fine-tuning an LLM for the specific task of mutation testing might be worthwhile, particularly with the goal of optimizing the number of mutants that are not equivalent.

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A APPENDIX: EXPERIMENTAL DATA

This appendix contains the following experimental results:

- Section A.1 includes the results for 5 experiments using the *codellama-34b-instruct* LLM at temperature 0.0.
- Section A.2 includes the results for 5 experiments using the *codellama-34b-instruct* LLM at temperature 0.25.
- Section A.3 includes the results for 5 experiments using the *codellama-34b-instruct* LLM at temperature 0.5.
- Section A.3 includes the results for 5 experiments using the *codellama-34b-instruct* LLM at temperature 1.0.
- Section 1.5 includes the results of variability analysis of the mutants observed in 5 runs using *codellama-34b-instruct*, for each of the temperature settings under consideration.
- Section 1.7 includes results for 5 experiments using the *codellama-13b-instruct* LLM at temperature 0.0.
- Section 1.8 includes results for 5 experiments using the *mixtral-8x7b-instruct* LLM at temperature 0.0.
- Section 1.9 includes results for 5 experiments using the *gpt-4o-mini* LLM at temperature 0.0.
- Section 1.10 includes results for 5 experiments using the *llama-3.3-70b-instruct* LLM at temperature 0.0.
- Section 1.11 includes results for 5 experiments using the onemutation template.
- Section 1.12 includes results for 5 experiments using the noexplanation template.
- Section 1.13 includes results for 5 experiments using the noinstructions template.
- Section 1.14 includes results for 5 experiments using a generic system prompt.
- Section 1.15 includes results for 5 experiments using the basic template.
- Section 1.16 includes a summary of the variability of the results for all 5 experiments for all configurations of all models in the paper.
- Section 1.17 includes the results of running the standard mutation operators of *StrykerJS* on the subject applications.
- Section 1.18 reports measurements of the average string edit distance observed when using different LLMs.

A.1 Results for *codellama-34b-instruct*, full template, temperature 0.0

Tables 9–18 show the results for 5 experiments with the *codellama-34b-instruct* model at temperature 0.0 using the default prompt and system prompt shown in Figure 7.

application	#prompts	mutant candidates				#mutants	#killed	#survived	#timeout	mut. score
		total	invalid	identical	duplicate					
<i>Complex.js</i>	490	1,451	194	13	45	1,199	725	473	1	60.55
<i>countries-and-timezones</i>	106	318	89	0	12	217	188	29	0	86.64
<i>crawler-url-parser</i>	176	521	205	14	17	285	157	128	0	55.09
<i>delta</i>	462	1,367	565	10	25	767	634	101	32	86.83
<i>image-downloader</i>	42	124	33	2	0	89	72	17	0	80.90
<i>node-dirty</i>	154	450	153	15	7	275	163	100	12	63.64
<i>node-geo-point</i>	140	408	93	0	13	302	223	79	0	73.84
<i>node-jsonfile</i>	68	199	42	3	0	154	49	48	57	68.83
<i>plural</i>	153	442	101	42	18	281	205	75	1	73.31
<i>pull-stream</i>	351	1,028	238	12	9	769	441	271	57	64.76
<i>q</i>	1051	3,121	1,000	34	52	2,035	158	1,792	85	11.94
<i>spacel-core</i>	134	395	140	10	6	239	199	39	1	83.68
<i>zip-a-folder</i>	49	143	41	1	1	100	23	3	74	97.00
<i>Total</i>	3,376	9,967	2,894	156	205	6,712	3,237	3,155	320	—

Table 9: Results from LLMorpheus experiment (run #312). Model: *codellama-34b-instruct*, temperature: 0.0, maxTokens: 250, template: *template-full.hb*, systemPrompt: *SystemPrompt-MutationTestingExpert.txt*.

application	#prompts	mutant candidates				#mutants	#killed	#survived	#timeout	mut. score
		total	invalid	identical	duplicate					
<i>Complex.js</i>	490	1,450	194	13	45	1,198	726	471	1	60.68
<i>countries-and-timezones</i>	106	318	89	0	12	217	188	29	0	86.64
<i>crawler-url-parser</i>	176	521	208	14	17	282	156	126	0	55.32
<i>delta</i>	462	1,367	565	10	24	768	636	100	32	86.98
<i>image-downloader</i>	42	124	34	0	0	90	73	17	0	81.11
<i>node-dirty</i>	154	450	154	15	7	274	161	101	12	63.14
<i>node-geo-point</i>	140	410	95	0	13	302	223	79	0	73.84
<i>node-jsonfile</i>	68	199	43	3	0	153	49	47	57	69.28
<i>plural</i>	153	441	101	42	18	280	204	75	1	73.21
<i>pull-stream</i>	351	1,028	236	12	9	771	441	273	57	64.59
<i>q</i>	1051	3,123	1,004	34	54	2,031	159	1,788	84	11.96
<i>spacel-core</i>	134	394	138	10	7	239	197	41	1	82.85
<i>zip-a-folder</i>	49	143	41	1	1	100	23	3	74	97.00
<i>Total</i>	3,376	9,968	2,902	154	207	6,705	3,236	3,150	319	—

Table 10: Results from LLMorpheus experiment (run #314). Model: *codellama-34b-instruct*, temperature: 0.0, maxTokens: 250, template: *template-full.hb*, systemPrompt: *SystemPrompt-MutationTestingExpert.txt*.

application	#prompts	mutant candidates				#mutants	#killed	#survived	#timeout	mut. score
		total	invalid	identical	duplicate					
<i>Complex.js</i>	490	1,452	195	13	45	1,199	724	474	1	60.47
<i>countries-and-timezones</i>	106	318	89	0	12	217	188	29	0	86.64
<i>crawler-url-parser</i>	176	522	208	14	17	283	157	126	0	55.48
<i>delta</i>	462	1,367	566	10	26	765	633	100	32	86.93
<i>image-downloader</i>	42	124	35	0	0	89	72	17	0	80.90
<i>node-dirty</i>	154	450	154	14	7	275	161	102	12	62.91
<i>node-geo-point</i>	140	408	93	0	13	302	223	79	0	73.84
<i>node-jsonfile</i>	68	199	42	3	0	154	49	48	57	68.83
<i>plural</i>	153	442	101	42	18	281	205	75	1	73.31
<i>pull-stream</i>	351	1,028	237	12	9	770	441	272	57	64.68
<i>q</i>	1051	3,121	1,000	34	52	2,035	159	1,793	83	11.89
<i>spacel-core</i>	134	393	137	10	7	239	197	41	1	82.85
<i>zip-a-folder</i>	49	143	41	1	1	100	23	3	74	97.00
<i>Total</i>	3,376	9,967	2,898	153	207	6,709	3,232	3,159	318	—

Table 11: Results from LLMorpheus experiment (run #315). Model: *codellama-34b-instruct*, temperature: 0.0, maxTokens: 250, template: *template-full.hb*, systemPrompt: *SystemPrompt-MutationTestingExpert.txt*.

application	#prompts	mutant candidates				#mutants	#killed	#survived	#timeout	mut. score
		total	invalid	identical	duplicate					
<i>Complex.js</i>	490	1,452	195	13	45	1,199	725	473	1	60.55
<i>countries-and-timezones</i>	106	318	89	0	12	217	188	29	0	86.64
<i>crawler-url-parser</i>	176	521	207	14	17	283	157	125	1	55.83
<i>delta</i>	462	1,367	565	10	26	766	634	100	32	86.95
<i>image-downloader</i>	42	124	35	0	0	89	72	17	0	80.90
<i>node-dirty</i>	154	450	153	15	8	274	160	102	12	62.77
<i>node-geo-point</i>	140	410	95	0	13	302	222	80	0	73.51
<i>node-jsonfile</i>	68	200	43	3	0	154	49	48	57	68.83
<i>plural</i>	153	441	101	43	18	279	203	75	1	73.12
<i>pull-stream</i>	351	1,028	237	13	9	769	444	268	57	65.15
<i>q</i>	1051	3,121	1,001	34	54	2,032	158	1,790	84	11.91
<i>spacel-core</i>	134	394	139	10	7	238	197	40	1	83.19
<i>zip-a-folder</i>	49	143	41	1	1	100	23	3	74	97.00
<i>Total</i>	3,376	9,969	2,901	156	210	6,702	3,232	3,150	320	—

Table 12: Results from LLMorpheus experiment (run #316). Model: *codellama-34b-instruct*, temperature: 0.0, maxTokens: 250, template: *template-full.hb*, systemPrompt: *SystemPrompt-MutationTestingExpert.txt*.

application	#prompts	mutant candidates				#mutants	#killed	#survived	#timeout	mut. score
		total	invalid	identical	duplicate					
<i>Complex.js</i>	490	1,450	194	13	44	1,199	726	472	1	60.63
<i>countries-and-timezones</i>	106	317	89	0	12	216	187	29	0	86.57
<i>crawler-url-parser</i>	176	521	205	14	17	285	157	128	0	55.09
<i>delta</i>	462	1,367	565	10	25	767	636	100	31	86.96
<i>image-downloader</i>	42	124	32	2	0	90	73	17	0	81.11
<i>node-dirty</i>	154	450	153	15	7	275	161	102	12	62.91
<i>node-geo-point</i>	140	409	94	0	13	302	223	79	0	73.84
<i>node-jsonfile</i>	68	199	42	3	0	154	49	48	57	68.83
<i>plural</i>	153	442	101	43	18	280	204	75	1	73.21
<i>pull-stream</i>	351	1,028	236	12	9	771	441	273	57	64.59
<i>q</i>	1051	3,122	1,003	34	54	2,031	159	1,788	84	11.96
<i>spacel-core</i>	134	394	138	10	7	239	198	40	1	83.26
<i>zip-a-folder</i>	49	143	41	1	1	100	23	3	74	97.00
<i>Total</i>	3,376	9,966	2,893	157	207	6,709	3,237	3,154	318	—

Table 13: Results from LLMorpheus experiment (run #317). Model: *codellama-34b-instruct*, temperature: 0.0, maxTokens: 250, template: *template-full.hb*, systemPrompt: *SystemPrompt-MutationTestingExpert.txt*.

project	time (sec)		#tokens		
	<i>LLMorpheus</i>	<i>StrykerJS</i>	prompt	compl.	total
<i>Complex.js</i>	3,050.00	637.85	967,508	102,517	1,070,025
<i>countries-and-timezones</i>	1,070.89	313.86	105,828	23,441	129,269
<i>crawler-url-parser</i>	1,642.70	929.43	386,223	39,175	425,398
<i>delta</i>	2,961.66	3,839.60	890,252	98,974	989,226
<i>image-downloader</i>	430.53	379.25	24,655	9,134	33,789
<i>node-dirty</i>	1,526.20	241.81	246,248	33,070	279,318
<i>node-geo-point</i>	1,411.11	987.17	316,333	30,013	346,346
<i>node-jsonfile</i>	690.61	474.78	57,516	14,797	72,313
<i>plural</i>	1,521.32	155.24	265,602	34,174	299,776
<i>pull-stream</i>	2,492.50	1,608.97	208,130	76,513	284,643
<i>q</i>	5,241.46	14,034.67	2,127,655	220,215	2,347,870
<i>spacel-core</i>	1,351.08	798.96	162,705	29,236	191,941
<i>zip-a-folder</i>	500.57	1,156.11	82,457	10,725	93,182
<i>Total</i>	23,890.64	25,557.70	5,841,112	721,984	6,563,096

Table 14: Results from LLMorpheus experiment (run #312). Model: *codellama-34b-instruct*, temperature: 0.0, maxTokens: 250, template: *template-full.hb*, systemPrompt: *SystemPrompt-MutationTestingExpert.txt*

project	time (sec)		prompt	#tokens	
	<i>LLMorpheus</i>	<i>StrykerJS</i>		compl.	total
Complex.js	3,087.58	637.10	967,508	102,428	1,069,936
countries-and-timezones	1,070.89	313.12	105,828	23,427	129,255
crawler-url-parser	1,645.11	679.89	386,223	39,210	425,433
delta	2,941.55	3,838.23	890,252	98,951	989,203
image-downloader	430.54	377.12	24,655	9,175	33,830
node-dirty	1,526.11	248.57	246,248	33,038	279,286
node-geo-point	1,411.06	999.59	316,333	29,959	346,292
node-jsonfile	690.69	478.32	57,516	14,829	72,345
plural	1,521.04	147.85	265,602	34,164	299,766
pull-stream	2,477.99	1,400.76	208,130	76,398	284,528
q	5,231.88	14,004.86	2,127,655	220,252	2,347,907
spacl-core	1,351.05	805.30	162,705	29,283	191,988
zip-a-folder	500.57	1,152.62	82,457	10,705	93,162
<i>Total</i>	23,886.05	25,083.32	5,841,112	721,819	6,562,931

Table 15: Results from LLMorpheus experiment (run #314). Model: *codellama-34b-instruct*, temperature: 0.0, maxTokens: 250, template: *template-full.hb*, systemPrompt: *SystemPrompt-MutationTestingExpert.txt*

project	time (sec)		prompt	#tokens	
	<i>LLMorpheus</i>	<i>StrykerJS</i>		compl.	total
Complex.js	3,000.46	630.00	967,508	102,314	1,069,822
countries-and-timezones	1,070.90	314.35	105,828	23,438	129,266
crawler-url-parser	1,644.58	1,051.08	386,223	39,105	425,328
delta	3,006.51	3,795.29	890,252	98,978	989,230
image-downloader	430.54	376.08	24,655	9,186	33,841
node-dirty	1,526.69	247.49	246,248	33,089	279,337
node-geo-point	1,411.05	1,003.93	316,333	30,010	346,343
node-jsonfile	690.67	478.93	57,516	14,803	72,319
plural	1,521.23	148.33	265,602	34,082	299,684
pull-stream	2,492.02	1,392.68	208,130	76,599	284,729
q	5,296.20	14,072.49	2,127,655	220,395	2,348,050
spacl-core	1,351.09	802.30	162,705	29,334	192,039
zip-a-folder	500.56	1,155.04	82,457	10,764	93,221
<i>Total</i>	23,942.51	25,467.99	5,841,112	722,097	6,563,209

Table 16: Results from LLMorpheus experiment (run #315). Model: *codellama-34b-instruct*, temperature: 0.0, maxTokens: 250, template: *template-full.hb*, systemPrompt: *SystemPrompt-MutationTestingExpert.txt*

project	time (sec)		prompt	#tokens	
	<i>LLMorpheus</i>	<i>StrykerJS</i>		compl.	total
Complex.js	3,034.16	631.23	967,508	102,497	1,070,005
countries-and-timezones	1,070.91	309.40	105,828	23,444	129,272
crawler-url-parser	1,644.09	1,022.89	386,223	39,174	425,397
delta	2,983.03	3,969.11	890,252	99,003	989,255
image-downloader	430.51	374.45	24,655	9,148	33,803
node-dirty	1,563.30	251.17	246,248	33,068	279,316
node-geo-point	1,411.00	1,001.75	316,333	30,041	346,374
node-jsonfile	690.69	474.83	57,516	14,750	72,266
plural	1,521.09	151.19	265,602	34,132	299,734
pull-stream	2,541.67	1,398.89	208,130	76,567	284,697
q	5,399.09	13,959.40	2,127,655	220,191	2,347,846
spacl-core	1,351.08	959.37	162,705	29,287	191,992
zip-a-folder	510.58	1,154.14	82,457	10,725	93,182
<i>Total</i>	24,151.21	25,657.83	5,841,112	722,027	6,563,139

Table 17: Results from LLMorpheus experiment (run #316). Model: *codellama-34b-instruct*, temperature: 0.0, maxTokens: 250, template: *template-full.hb*, systemPrompt: *SystemPrompt-MutationTestingExpert.txt*

project	time (sec)		#tokens		
	<i>LLMorpheus</i>	<i>StrykerJS</i>	prompt	compl.	total
Complex.js	3,019.69	669.52	967,508	102,524	1,070,032
countries-and-timezones	1,070.82	313.99	105,828	23,425	129,253
crawler-url-parser	1,641.20	958.26	386,223	39,160	425,383
delta	3,013.74	3,867.52	890,252	99,031	989,283
image-downloader	430.56	378.47	24,655	9,117	33,772
node-dirty	1,527.49	251.95	246,248	33,113	279,361
node-geo-point	1,451.19	1,042.75	316,333	29,894	346,227
node-jsonfile	690.66	479.95	57,516	14,803	72,319
plural	1,521.18	150.87	265,602	34,163	299,765
pull-stream	2,486.78	1,384.03	208,130	76,520	284,650
q	5,250.40	14,006.76	2,127,655	220,193	2,347,848
spacl-core	1,350.99	808.62	162,705	29,297	192,002
zip-a-folder	500.63	1,171.49	82,457	10,705	93,162
<i>Total</i>	23,955.33	25,484.18	5,841,112	721,945	6,563,057

Table 18: Results from LLMorpheus experiment (run #317). Model: *codellama-34b-instruct*, temperature: 0.0, maxTokens: 250, template: *template-full.hb*, systemPrompt: *SystemPrompt-MutationTestingExpert.txt*

A.2 Results for *codellama-34b-instruct*, full template, temperature 0.25

Tables 19–28 show the results for 5 experiments with the *codellama-34b-instruct* model at temperature 0.25 using the default prompt and system prompt shown in Figure 7.

application	#prompts	mutant candidates				#mutants	#killed	#survived	#timeout	mut. score
		total	invalid	identical	duplicate					
<i>Complex.js</i>	490	1,460	210	9	44	1,197	730	466	1	61.07
<i>countries-and-timezones</i>	106	315	86	0	10	219	181	38	0	82.65
<i>crawler-url-parser</i>	176	515	216	7	12	260	167	93	0	64.23
<i>delta</i>	462	1,366	550	10	25	781	642	111	28	85.79
<i>image-downloader</i>	42	125	38	1	0	86	71	15	0	82.56
<i>node-dirty</i>	154	457	157	9	12	279	175	93	11	66.67
<i>node-geo-point</i>	140	381	76	1	8	293	225	68	0	76.79
<i>node-jsonfile</i>	68	202	45	4	2	151	52	41	58	72.85
<i>plural</i>	153	440	104	44	19	273	208	63	2	76.92
<i>pull-stream</i>	351	1,030	236	7	8	779	452	270	57	65.34
<i>q</i>	1051	3,126	1,011	23	42	2,050	153	1,813	84	11.56
<i>spacel-core</i>	134	396	140	11	4	223	187	36	0	83.86
<i>zip-a-folder</i>	49	141	41	1	1	97	24	4	69	95.88
<i>Total</i>	3,376	9,954	2,910	127	187	6,688	3,267	3,111	310	—

Table 19: Results from LLMorpheus experiment (run #348). Model: *codellama-34b-instruct*, temperature: 0.25, maxTokens: 250, template: *template-full.hb*, systemPrompt: *SystemPrompt-MutationTestingExpert.txt*.

application	#prompts	mutant candidates				#mutants	#killed	#survived	#timeout	mut. score
		total	invalid	identical	duplicate					
<i>Complex.js</i>	490	1,460	202	13	45	1,200	729	471	0	60.75
<i>countries-and-timezones</i>	106	316	87	1	5	223	198	25	0	88.79
<i>crawler-url-parser</i>	176	518	206	13	15	269	163	106	0	60.59
<i>delta</i>	462	1,362	576	5	29	752	608	110	34	85.37
<i>image-downloader</i>	42	123	35	3	0	85	67	18	0	78.82
<i>node-dirty</i>	154	457	165	17	4	271	163	96	12	64.58
<i>node-geo-point</i>	140	412	85	0	13	311	243	68	0	78.14
<i>node-jsonfile</i>	68	204	42	4	0	158	50	54	54	65.82
<i>plural</i>	153	438	101	35	19	283	213	68	2	75.97
<i>pull-stream</i>	351	1,027	241	9	5	772	450	265	57	65.67
<i>q</i>	1051	3,125	1,037	45	63	1,980	144	1,756	80	11.31
<i>spacel-core</i>	134	393	134	10	6	225	194	30	1	86.67
<i>zip-a-folder</i>	49	140	41	0	1	95	36	53	6	44.21
<i>Total</i>	3,376	9,975	2,952	155	205	6,624	3,258	3,120	246	—

Table 20: Results from LLMorpheus experiment (run #350). Model: *codellama-34b-instruct*, temperature: 0.25, maxTokens: 250, template: *template-full.hb*, systemPrompt: *SystemPrompt-MutationTestingExpert.txt*.

application	#prompts	mutant candidates				#mutants	#killed	#survived	#timeout	mut. score
		total	invalid	identical	duplicate					
<i>Complex.js</i>	490	1,451	199	12	45	1,195	737	457	1	61.76
<i>countries-and-timezones</i>	106	315	88	0	12	215	189	26	0	87.91
<i>crawler-url-parser</i>	176	512	211	16	19	247	144	103	0	58.30
<i>delta</i>	462	1,362	554	8	24	776	647	100	29	87.11
<i>image-downloader</i>	42	123	36	0	0	87	71	16	0	81.61
<i>node-dirty</i>	154	454	156	14	10	274	162	100	12	63.50
<i>node-geo-point</i>	140	413	103	0	13	294	218	76	0	74.15
<i>node-jsonfile</i>	68	201	43	4	0	154	55	43	56	72.08
<i>plural</i>	153	439	98	36	19	286	204	81	1	71.68
<i>pull-stream</i>	351	1,029	239	12	5	773	442	280	51	63.78
<i>q</i>	1051	3,118	1,038	32	46	2,002	146	1,780	76	11.09
<i>spacel-core</i>	134	396	142	9	3	228	193	35	0	84.65
<i>zip-a-folder</i>	49	145	43	2	2	98	24	3	71	96.94
<i>Total</i>	3,376	9,958	2,950	145	198	6,629	3,232	3,100	297	—

Table 21: Results from LLMorpheus experiment (run #351). Model: *codellama-34b-instruct*, temperature: 0.25, maxTokens: 250, template: *template-full.hb*, systemPrompt: *SystemPrompt-MutationTestingExpert.txt*.

application	#prompts	mutant candidates				#mutants	#killed	#survived	#timeout	mut. score
		total	invalid	identical	duplicate					
<i>Complex.js</i>	490	1,457	222	7	36	1,192	721	471	0	60.49
<i>countries-and-timezones</i>	106	317	86	2	2	227	200	27	0	88.11
<i>crawler-url-parser</i>	176	513	213	15	12	260	151	109	0	58.08
<i>delta</i>	462	1,370	576	7	22	765	619	109	37	85.75
<i>image-downloader</i>	42	122	37	0	3	82	62	20	0	75.61
<i>node-dirty</i>	154	454	160	12	15	267	158	97	12	63.67
<i>node-geo-point</i>	140	414	92	2	9	308	226	82	0	73.38
<i>node-jsonfile</i>	68	201	48	1	1	151	48	47	56	68.87
<i>plural</i>	153	440	101	36	24	279	212	66	1	76.34
<i>pull-stream</i>	351	1,033	243	8	9	773	443	277	53	64.17
<i>q</i>	1051	3,121	1,009	17	51	2,044	141	1,822	81	10.86
<i>spacel-core</i>	134	397	145	14	8	214	183	30	1	85.98
<i>zip-a-folder</i>	49	142	35	1	1	105	27	2	76	98.10
<i>Total</i>	3,376	9,981	2,967	122	193	6,667	3,191	3,159	317	—

Table 22: Results from LLMorpheus experiment (run #352). Model: *codellama-34b-instruct*, temperature: 0.25, maxTokens: 250, template: *template-full.hb*, systemPrompt: *SystemPrompt-MutationTestingExpert.txt*.

application	#prompts	mutant candidates				#mutants	#killed	#survived	#timeout	mut. score
		total	invalid	identical	duplicate					
<i>Complex.js</i>	490	1,451	226	11	46	1,168	717	451	0	61.39
<i>countries-and-timezones</i>	106	313	80	0	8	225	199	26	0	88.44
<i>crawler-url-parser</i>	176	523	204	15	19	268	161	107	0	60.07
<i>delta</i>	462	1,368	574	11	23	760	620	106	34	86.05
<i>image-downloader</i>	42	126	34	3	1	85	71	14	0	83.53
<i>node-dirty</i>	154	450	161	17	7	265	167	86	12	67.55
<i>node-geo-point</i>	140	412	93	1	19	296	220	76	0	74.32
<i>node-jsonfile</i>	68	203	41	3	1	158	55	49	54	68.99
<i>plural</i>	153	441	100	30	20	291	215	75	1	74.23
<i>pull-stream</i>	351	1,029	237	9	8	775	448	276	51	64.39
<i>q</i>	1051	3,132	1,018	20	53	2,041	151	1,803	87	11.66
<i>spacel-core</i>	134	395	132	10	9	226	189	36	1	84.07
<i>zip-a-folder</i>	49	140	35	0	1	104	48	50	6	51.92
<i>Total</i>	3,376	9,983	2,935	130	215	6,662	3,261	3,155	246	—

Table 23: Results from LLMorpheus experiment (run #353). Model: *codellama-34b-instruct*, temperature: 0.25, maxTokens: 250, template: *template-full.hb*, systemPrompt: *SystemPrompt-MutationTestingExpert.txt*.

project	time (sec)		#tokens		
	<i>LLMorpheus</i>	<i>StrykerJS</i>	prompt	compl.	total
<i>Complex.js</i>	3,044.19	631.79	967,508	101,588	1,069,096
<i>countries-and-timezones</i>	1,070.90	327.25	105,828	23,471	129,299
<i>crawler-url-parser</i>	1,646.30	818.05	386,223	39,000	425,223
<i>delta</i>	2,954.37	3,844.00	890,252	99,341	989,593
<i>image-downloader</i>	430.54	348.86	24,655	9,217	33,872
<i>node-dirty</i>	1,532.06	232.35	246,248	32,400	278,648
<i>node-geo-point</i>	1,708.63	961.35	291,061	26,301	317,362
<i>node-jsonfile</i>	740.73	502.52	57,516	14,400	71,916
<i>plural</i>	1,537.89	149.38	265,602	33,182	298,784
<i>pull-stream</i>	2,522.38	1,395.14	208,130	76,091	284,221
<i>q</i>	5,294.80	14,085.10	2,127,655	218,620	2,346,275
<i>spacel-core</i>	1,351.05	728.32	162,705	29,167	191,872
<i>zip-a-folder</i>	500.56	1,086.06	82,457	10,557	93,014
<i>Total</i>	24,334.42	25,110.17	5,815,840	713,335	6,529,175

Table 24: Results from LLMorpheus experiment (run #348). Model: *codellama-34b-instruct*, temperature: 0.25, maxTokens: 250, template: *template-full.hb*, systemPrompt: *SystemPrompt-MutationTestingExpert.txt*

project	time (sec)		prompt	#tokens	
	LLMorpheus	StrykerJS		compl.	total
Complex.js	3,029.62	629.66	967,508	100,540	1,068,048
countries-and-timezones	1,070.85	314.98	105,828	23,186	129,014
crawler-url-parser	1,777.23	867.78	386,223	38,916	425,139
delta	2,978.88	3,758.68	890,252	99,176	989,428
image-downloader	430.55	366.05	24,655	9,223	33,878
node-dirty	1,528.73	237.16	246,248	32,776	279,024
node-geo-point	1,411.08	1,021.61	316,333	29,301	345,634
node-jsonfile	690.69	485.24	57,516	14,071	71,587
plural	1,521.09	154.20	265,602	33,560	299,162
pull-stream	2,503.60	1,383.12	208,130	76,551	284,681
q	5,379.31	13,584.78	2,127,655	217,699	2,345,354
spacl-core	1,350.98	739.03	162,705	29,184	191,889
zip-a-folder	500.57	531.10	82,457	10,753	93,210
<i>Total</i>	24,173.19	24,073.41	5,841,112	714,936	6,556,048

Table 25: Results from LLMorpheus experiment (run #350). Model: *codellama-34b-instruct*, temperature: 0.25, maxTokens: 250, template: *template-full.hb*, systemPrompt: *SystemPrompt-MutationTestingExpert.txt*

project	time (sec)		prompt	#tokens	
	LLMorpheus	StrykerJS		compl.	total
Complex.js	3,026.34	650.01	967,508	101,118	1,068,626
countries-and-timezones	1,070.91	309.33	105,828	23,331	129,159
crawler-url-parser	1,644.86	811.88	386,223	39,215	425,438
delta	2,962.02	3,896.15	890,252	99,274	989,526
image-downloader	430.54	373.38	24,655	9,163	33,818
node-dirty	1,526.45	247.44	246,248	32,894	279,142
node-geo-point	1,421.09	935.39	316,333	29,830	346,163
node-jsonfile	690.68	504.57	57,516	14,702	72,218
plural	1,521.32	151.42	265,602	33,298	298,900
pull-stream	2,497.56	1,351.06	208,130	76,100	284,230
q	5,341.32	13,704.14	2,127,655	218,805	2,346,460
spacl-core	1,351.03	756.66	162,705	28,939	191,644
zip-a-folder	500.57	1,119.70	82,457	10,786	93,243
<i>Total</i>	23,984.67	24,811.13	5,841,112	717,455	6,558,567

Table 26: Results from LLMorpheus experiment (run #351). Model: *codellama-34b-instruct*, temperature: 0.25, maxTokens: 250, template: *template-full.hb*, systemPrompt: *SystemPrompt-MutationTestingExpert.txt*

project	time (sec)		prompt	#tokens	
	LLMorpheus	StrykerJS		compl.	total
Complex.js	3,031.72	631.91	967,508	102,075	1,069,583
countries-and-timezones	1,070.83	324.27	105,828	23,502	129,330
crawler-url-parser	1,642.15	835.28	386,223	39,240	425,463
delta	2,969.01	3,912.89	890,252	99,383	989,635
image-downloader	430.57	486.28	24,655	9,228	33,883
node-dirty	1,527.16	237.65	246,248	32,850	279,098
node-geo-point	1,411.10	1,015.42	316,333	28,895	345,228
node-jsonfile	690.64	496.41	57,516	14,557	72,073
plural	1,521.03	148.10	265,602	33,162	298,764
pull-stream	2,509.05	1,370.63	208,130	75,917	284,047
q	5,300.14	14,131.12	2,127,655	218,921	2,346,576
spacl-core	1,351.01	712.33	162,705	28,809	191,514
zip-a-folder	500.63	1,266.61	82,457	10,707	93,164
<i>Total</i>	23,955.04	25,568.93	5,841,112	717,246	6,558,358

Table 27: Results from LLMorpheus experiment (run #352). Model: *codellama-34b-instruct*, temperature: 0.25, maxTokens: 250, template: *template-full.hb*, systemPrompt: *SystemPrompt-MutationTestingExpert.txt*

project	time (sec)		#tokens		
	<i>LLMorpheus</i>	<i>StrykerJS</i>	prompt	compl.	total
Complex.js	3,082.97	613.65	967,508	101,316	1,068,824
countries-and-timezones	1,070.86	326.66	105,828	22,979	128,807
crawler-url-parser	1,641.17	853.01	386,223	38,790	425,013
delta	2,952.50	3,773.99	890,252	99,524	989,776
image-downloader	470.58	359.76	24,655	8,898	33,553
node-dirty	1,526.98	239.71	246,248	32,476	278,724
node-geo-point	1,411.01	1,001.71	316,333	29,427	345,760
node-jsonfile	690.74	500.76	57,516	14,495	72,011
plural	1,521.11	158.00	265,602	33,838	299,440
pull-stream	2,510.21	1,355.46	208,130	75,432	283,562
q	5,390.06	14,133.05	2,127,655	217,855	2,345,510
spacel-core	1,350.98	752.72	162,705	29,399	192,104
zip-a-folder	520.57	564.11	82,457	10,749	93,206
<i>Total</i>	24,139.74	24,632.57	5,841,112	715,178	6,556,290

Table 28: Results from LLMorpheus experiment (run #353). Model: *codellama-34b-instruct*, temperature: 0.25, maxTokens: 250, template: *template-full.hb*, systemPrompt: *SystemPrompt-MutationTestingExpert.txt*

A.3 Results for *codellama-34b-instruct*, full template, temperature 0.5

Tables 29–38 show the results for 5 experiments with the *codellama-34b-instruct* model at temperature 0.5 using the default prompt and system prompt shown in Figure 7.

application	#prompts	mutant candidates				#mutants	#killed	#survived	#timeout	mut. score
		total	invalid	identical	duplicate					
<i>Complex.js</i>	490	1,448	211	7	39	1,191	739	452	0	62.05
<i>countries-and-timezones</i>	106	311	81	3	3	224	194	30	0	86.61
<i>crawler-url-parser</i>	176	510	185	14	13	298	166	108	24	63.76
<i>delta</i>	462	1,369	560	13	27	769	642	93	34	87.91
<i>image-downloader</i>	42	126	35	1	1	89	68	21	0	76.40
<i>node-dirty</i>	154	454	162	8	7	277	158	107	12	61.37
<i>node-geo-point</i>	140	409	87	2	18	302	230	72	0	76.16
<i>node-jsonfile</i>	68	201	41	3	4	153	51	43	59	71.90
<i>plural</i>	153	438	105	23	21	289	219	69	1	76.12
<i>pull-stream</i>	351	1,037	225	10	6	796	465	278	53	65.08
<i>q</i>	1051	3,114	977	25	39	2,073	163	1,823	87	12.06
<i>spacel-core</i>	134	393	132	3	8	250	210	39	1	84.40
<i>zip-a-folder</i>	49	122	33	1	1	87	48	33	6	62.07
<i>Total</i>	3,376	9,932	2,834	113	187	6,798	3,353	3,168	277	—

Table 29: Results from LLMorpheus experiment (run #318). Model: *codellama-34b-instruct*, temperature: 0.5, maxTokens: 250, template: *template-full.hb*, systemPrompt: *SystemPrompt-MutationTestingExpert.txt*.

application	#prompts	mutant candidates				#mutants	#killed	#survived	#timeout	mut. score
		total	invalid	identical	duplicate					
<i>Complex.js</i>	490	1,456	250	7	33	1,166	714	452	0	61.23
<i>countries-and-timezones</i>	106	316	81	4	10	221	192	29	0	86.88
<i>crawler-url-parser</i>	176	515	176	11	18	310	173	137	0	55.81
<i>delta</i>	462	1,366	548	8	18	792	668	89	35	88.76
<i>image-downloader</i>	42	126	36	3	5	82	54	28	0	65.85
<i>node-dirty</i>	154	456	147	8	13	288	173	104	11	63.89
<i>node-geo-point</i>	140	414	91	2	12	309	230	79	0	74.43
<i>node-jsonfile</i>	68	200	44	3	1	152	53	38	61	75.00
<i>plural</i>	153	440	102	30	23	285	215	70	0	75.44
<i>pull-stream</i>	351	1,028	218	9	17	784	463	270	51	65.56
<i>q</i>	1051	3,125	1,017	36	52	2,020	166	1,774	80	12.18
<i>spacel-core</i>	134	392	120	10	5	257	221	35	1	86.38
<i>zip-a-folder</i>	49	143	36	3	1	103	29	5	69	95.15
<i>Total</i>	3,376	9,977	2,866	134	208	6,769	3,351	3,110	308	—

Table 30: Results from LLMorpheus experiment (run #319). Model: *codellama-34b-instruct*, temperature: 0.5, maxTokens: 250, template: *template-full.hb*, systemPrompt: *SystemPrompt-MutationTestingExpert.txt*.

application	#prompts	mutant candidates				#mutants	#killed	#survived	#timeout	mut. score
		total	invalid	identical	duplicate					
<i>Complex.js</i>	490	1,459	232	10	35	1,182	730	452	0	61.76
<i>countries-and-timezones</i>	106	315	86	4	3	222	199	23	0	89.64
<i>crawler-url-parser</i>	176	516	201	15	16	284	166	117	1	58.80
<i>delta</i>	462	1,357	567	9	21	760	621	104	35	86.32
<i>image-downloader</i>	42	125	33	3	4	85	60	25	0	70.59
<i>node-dirty</i>	154	457	156	9	13	279	166	101	12	63.80
<i>node-geo-point</i>	140	371	88	3	11	269	211	58	0	78.44
<i>node-jsonfile</i>	68	200	46	4	0	150	54	39	57	74.00
<i>plural</i>	153	417	88	22	14	293	208	84	1	71.33
<i>pull-stream</i>	351	1,034	205	5	11	813	476	278	59	65.81
<i>q</i>	1051	3,127	987	30	53	2,057	143	1,838	76	10.65
<i>spacel-core</i>	134	395	124	7	4	260	217	42	1	83.85
<i>zip-a-folder</i>	49	143	27	0	2	114	31	4	79	96.49
<i>Total</i>	3,376	9,916	2,840	121	187	6,768	3,282	3,165	321	—

Table 31: Results from LLMorpheus experiment (run #320). Model: *codellama-34b-instruct*, temperature: 0.5, maxTokens: 250, template: *template-full.hb*, systemPrompt: *SystemPrompt-MutationTestingExpert.txt*.

application	#prompts	mutant candidates				#mutants	#killed	#survived	#timeout	mut. score
		total	invalid	identical	duplicate					
<i>Complex.js</i>	490	1,456	216	9	41	1,190	716	474	0	60.17
<i>countries-and-timezones</i>	106	306	70	6	9	221	191	29	1	86.88
<i>crawler-url-parser</i>	176	512	202	18	13	279	158	121	0	56.63
<i>delta</i>	462	1,358	554	12	17	775	634	105	36	86.45
<i>image-downloader</i>	42	125	36	2	2	85	68	17	0	80.00
<i>node-dirty</i>	154	454	166	12	7	269	152	105	12	60.97
<i>node-geo-point</i>	140	409	81	3	13	312	229	83	0	73.40
<i>node-jsonfile</i>	68	201	40	1	0	160	58	36	66	77.50
<i>plural</i>	153	435	96	30	13	296	232	63	1	78.72
<i>pull-stream</i>	351	1,034	232	5	8	789	466	268	55	66.03
<i>q</i>	1051	3,126	1,015	23	55	2,033	152	1,784	97	12.25
<i>spacel-core</i>	134	391	118	5	6	262	223	38	1	85.50
<i>zip-a-folder</i>	49	144	41	1	2	100	45	50	5	50.00
<i>Total</i>	3,376	9,951	2,867	127	186	6,771	3,324	3,173	274	—

Table 32: Results from LLMorpheus experiment (run #321). Model: *codellama-34b-instruct*, temperature: 0.5, maxTokens: 250, template: *template-full.hb*, systemPrompt: *SystemPrompt-MutationTestingExpert.txt*.

application	#prompts	mutant candidates				#mutants	#killed	#survived	#timeout	mut. score
		total	invalid	identical	duplicate					
<i>Complex.js</i>	490	1,451	219	7	39	1,186	725	461	0	61.13
<i>countries-and-timezones</i>	106	311	78	1	8	224	197	27	0	87.95
<i>crawler-url-parser</i>	176	518	200	8	13	297	173	124	0	58.25
<i>delta</i>	462	1,362	535	8	28	791	660	92	39	88.37
<i>image-downloader</i>	42	125	40	1	4	80	68	12	0	85.00
<i>node-dirty</i>	154	455	159	8	5	283	161	110	12	61.13
<i>node-geo-point</i>	140	413	98	0	10	305	239	66	0	78.36
<i>node-jsonfile</i>	68	204	41	2	1	160	51	42	67	73.75
<i>plural</i>	153	439	97	30	23	289	225	64	0	77.85
<i>pull-stream</i>	351	1,032	216	3	7	806	490	255	61	68.36
<i>q</i>	1051	3,120	1,002	31	59	2,028	141	1,801	86	11.19
<i>spacel-core</i>	134	397	133	8	4	252	212	39	1	84.52
<i>zip-a-folder</i>	49	144	39	1	1	103	27	5	71	95.15
<i>Total</i>	3,376	9,971	2,857	108	202	6,804	3,369	3,098	337	—

Table 33: Results from LLMorpheus experiment (run #322). Model: *codellama-34b-instruct*, temperature: 0.5, maxTokens: 250, template: *template-full.hb*, systemPrompt: *SystemPrompt-MutationTestingExpert.txt*.

project	time (sec)		#tokens		
	<i>LLMorpheus</i>	<i>StrykerJS</i>	prompt	compl.	total
<i>Complex.js</i>	3,016.85	592.07	967,508	100,627	1,068,135
<i>countries-and-timezones</i>	1,070.93	319.44	105,828	22,932	128,760
<i>crawler-url-parser</i>	1,668.66	1,244.64	386,223	38,920	425,143
<i>delta</i>	2,980.99	3,869.42	890,252	98,347	988,599
<i>image-downloader</i>	430.55	365.90	24,655	8,925	33,580
<i>node-dirty</i>	1,532.57	247.29	246,248	32,995	279,243
<i>node-geo-point</i>	1,411.06	1,006.90	316,333	29,454	345,787
<i>node-jsonfile</i>	720.71	494.61	57,516	15,051	72,567
<i>plural</i>	1,522.56	152.03	265,602	33,550	299,152
<i>pull-stream</i>	2,506.81	1,378.63	208,130	75,239	283,369
<i>q</i>	5,332.46	14,311.02	2,127,655	217,886	2,345,541
<i>spacel-core</i>	1,351.01	850.39	162,705	28,919	191,624
<i>zip-a-folder</i>	900.98	471.62	72,362	9,438	81,800
<i>Total</i>	24,446.14	25,303.97	5,831,017	712,283	6,543,300

Table 34: Results from LLMorpheus experiment (run #318). Model: *codellama-34b-instruct*, temperature: 0.5, maxTokens: 250, template: *template-full.hb*, systemPrompt: *SystemPrompt-MutationTestingExpert.txt*

project	time (sec)		prompt	#tokens	
	<i>LLMorpheus</i>	<i>StrykerJS</i>		compl.	total
Complex.js	3,065.41	611.71	967,508	100,190	1,067,698
countries-and-timezones	1,070.87	313.43	105,828	22,897	128,725
crawler-url-parser	1,643.05	1,045.88	386,223	39,148	425,371
delta	3,028.61	4,054.65	890,252	99,121	989,373
image-downloader	430.56	496.08	24,655	8,793	33,448
node-dirty	1,527.72	252.26	246,248	33,054	279,302
node-geo-point	1,411.09	1,060.50	316,333	28,836	345,169
node-jsonfile	690.68	520.06	57,516	14,997	72,513
plural	1,522.17	146.72	265,602	33,944	299,546
pull-stream	2,517.82	1,365.08	208,130	75,400	283,530
q	5,232.53	13,865.94	2,127,655	217,305	2,344,960
spacel-core	1,351.05	848.71	162,705	28,593	191,298
zip-a-folder	500.59	1,105.81	82,457	10,544	93,001
<i>Total</i>	23,992.16	25,686.82	5,841,112	712,822	6,553,934

Table 35: Results from LLMorpheus experiment (run #319). Model: *codellama-34b-instruct*, temperature: 0.5, maxTokens: 250, template: *template-full.hb*, systemPrompt: *SystemPrompt-MutationTestingExpert.txt*

project	time (sec)		prompt	#tokens	
	<i>LLMorpheus</i>	<i>StrykerJS</i>		compl.	total
Complex.js	3,080.04	618.08	967,508	102,242	1,069,750
countries-and-timezones	1,070.88	311.67	105,828	22,556	128,384
crawler-url-parser	1,645.90	965.22	386,223	38,423	424,646
delta	2,992.70	3,820.99	890,252	99,184	989,436
image-downloader	430.53	500.27	24,655	9,240	33,895
node-dirty	1,527.92	252.60	246,248	32,911	279,159
node-geo-point	1,740.11	890.54	289,389	26,285	315,674
node-jsonfile	690.70	487.19	57,516	14,355	71,871
plural	1,677.14	158.69	249,979	30,944	280,923
pull-stream	2,510.30	1,455.39	208,130	75,369	283,499
q	5,453.21	14,010.80	2,127,655	217,999	2,345,654
spacel-core	1,351.08	861.29	162,705	28,654	191,359
zip-a-folder	500.56	1,278.26	82,457	10,677	93,134
<i>Total</i>	24,671.06	25,610.98	5,798,545	708,839	6,507,384

Table 36: Results from LLMorpheus experiment (run #320). Model: *codellama-34b-instruct*, temperature: 0.5, maxTokens: 250, template: *template-full.hb*, systemPrompt: *SystemPrompt-MutationTestingExpert.txt*

project	time (sec)		prompt	#tokens	
	<i>LLMorpheus</i>	<i>StrykerJS</i>		compl.	total
Complex.js	3,025.70	617.91	967,508	101,251	1,068,759
countries-and-timezones	1,070.86	333.07	105,828	23,224	129,052
crawler-url-parser	1,686.57	939.88	386,223	39,014	425,237
delta	3,020.99	3,992.69	890,252	99,683	989,935
image-downloader	430.56	347.98	24,655	9,059	33,714
node-dirty	1,526.16	227.18	246,248	32,693	278,941
node-geo-point	1,411.04	1,057.16	316,333	29,723	346,056
node-jsonfile	690.68	565.63	57,516	14,528	72,044
plural	1,521.10	156.75	265,602	34,049	299,651
pull-stream	2,516.94	1,385.89	208,130	75,071	283,201
q	5,280.14	14,131.09	2,127,655	217,911	2,345,566
spacel-core	1,350.99	879.83	162,705	28,767	191,472
zip-a-folder	510.57	542.42	82,457	10,709	93,166
<i>Total</i>	24,042.30	25,177.49	5,841,112	715,682	6,556,794

Table 37: Results from LLMorpheus experiment (run #321). Model: *codellama-34b-instruct*, temperature: 0.5, maxTokens: 250, template: *template-full.hb*, systemPrompt: *SystemPrompt-MutationTestingExpert.txt*

project	time (sec)		#tokens		
	<i>LLMorpheus</i>	<i>StrykerJS</i>	prompt	compl.	total
Complex.js	3,058.33	648.14	967,508	100,962	1,068,470
countries-and-timezones	1,070.88	328.85	105,828	23,165	128,993
crawler-url-parser	1,645.45	966.36	386,223	38,649	424,872
delta	2,954.29	4,010.15	890,252	97,995	988,247
image-downloader	430.57	330.02	24,655	9,182	33,837
node-dirty	1,528.13	239.77	246,248	32,568	278,816
node-geo-point	1,411.08	1,024.88	316,333	29,330	345,663
node-jsonfile	690.67	543.04	57,516	14,833	72,349
plural	1,522.09	148.56	265,602	33,906	299,508
pull-stream	2,509.37	1,433.54	208,130	75,574	283,704
q	5,254.98	13,947.69	2,127,655	216,579	2,344,234
spacel-core	1,351.03	834.35	162,705	29,103	191,808
zip-a-folder	500.60	1,144.50	82,457	10,347	92,804
<i>Total</i>	23,927.46	25,599.86	5,841,112	712,193	6,553,305

Table 38: Results from LLMorpheus experiment (run #322). Model: *codellama-34b-instruct*, temperature: 0.5, maxTokens: 250, template: *template-full.hb*, systemPrompt: *SystemPrompt-MutationTestingExpert.txt*

1.4 Results for *codellama-34b-instruct*, full template, temperature 1.0

Tables 39–48 show the results for 5 experiments with the *codellama-34b-instruct* model at temperature 1.0 using the default prompt and system prompt shown in Figure 7.

application	#prompts	mutant candidates				#mutants	#killed	#survived	#timeout	mut. score
		total	invalid	identical	duplicate					
<i>Complex.js</i>	490	1,405	345	5	27	1,028	648	379	1	63.13
<i>countries-and-timezones</i>	106	300	108	2	4	186	156	30	0	83.87
<i>crawler-url-parser</i>	176	490	202	4	6	278	202	76	0	72.66
<i>delta</i>	462	1,250	519	11	22	698	583	83	32	88.11
<i>image-downloader</i>	42	118	42	1	0	75	53	22	0	70.67
<i>node-dirty</i>	154	438	175	9	8	246	150	84	12	65.85
<i>node-geo-point</i>	140	405	118	4	10	273	213	60	0	78.02
<i>node-jsonfile</i>	68	187	52	1	2	132	50	22	60	83.33
<i>plural</i>	153	417	96	8	14	299	229	69	1	76.92
<i>pull-stream</i>	351	999	239	8	9	743	461	235	47	68.37
<i>q</i>	1051	3,012	1,057	23	33	1,899	147	1,671	81	12.01
<i>spacel-core</i>	134	381	147	9	7	218	180	38	0	82.57
<i>zip-a-folder</i>	49	142	45	0	1	96	54	38	4	60.42
<i>Total</i>	3,376	9,544	3,145	85	143	6,171	3,126	2,807	238	—

Table 39: Results from LLMorpheus experiment (run #341). Model: *codellama-34b-instruct*, temperature: 1.0, maxTokens: 250, template: *template-full.hb*, systemPrompt: *SystemPrompt-MutationTestingExpert.txt*.

application	#prompts	mutant candidates				#mutants	#killed	#survived	#timeout	mut. score
		total	invalid	identical	duplicate					
<i>Complex.js</i>	490	1,382	363	9	23	987	611	376	0	61.90
<i>countries-and-timezones</i>	106	254	79	7	4	164	145	19	0	88.41
<i>crawler-url-parser</i>	176	497	228	6	6	257	177	80	0	68.87
<i>delta</i>	462	1,307	580	7	19	701	596	75	30	89.30
<i>image-downloader</i>	42	115	52	1	3	59	46	13	0	77.97
<i>node-dirty</i>	154	438	159	4	7	268	164	96	8	64.18
<i>node-geo-point</i>	140	404	123	1	10	270	209	61	0	77.41
<i>node-jsonfile</i>	68	199	42	4	3	150	67	16	67	89.33
<i>plural</i>	153	442	114	11	12	304	245	58	1	80.92
<i>pull-stream</i>	351	1,012	255	11	5	741	460	238	43	67.88
<i>q</i>	1051	3,025	1,080	16	35	1,894	169	1,652	73	12.78
<i>spacel-core</i>	134	372	162	0	5	205	173	32	0	84.39
<i>zip-a-folder</i>	49	130	44	2	0	84	23	4	57	95.24
<i>Total</i>	3,376	9,577	3,281	79	132	6,084	3,085	2,720	279	—

Table 40: Results from LLMorpheus experiment (run #342). Model: *codellama-34b-instruct*, temperature: 1.0, maxTokens: 250, template: *template-full.hb*, systemPrompt: *SystemPrompt-MutationTestingExpert.txt*.

application	#prompts	mutant candidates				#mutants	#killed	#survived	#timeout	mut. score
		total	invalid	identical	duplicate					
<i>Complex.js</i>	490	1,378	346	7	23	1,002	637	365	0	63.57
<i>countries-and-timezones</i>	106	297	94	1	4	198	177	21	0	89.39
<i>crawler-url-parser</i>	176	491	207	6	9	269	173	96	0	64.31
<i>delta</i>	462	1,296	535	11	23	727	611	85	31	88.31
<i>image-downloader</i>	42	118	39	1	0	78	70	8	0	89.74
<i>node-dirty</i>	154	437	180	4	8	245	136	97	12	60.41
<i>node-geo-point</i>	140	399	132	3	5	259	194	65	0	74.90
<i>node-jsonfile</i>	68	190	41	2	1	146	68	14	64	90.41
<i>plural</i>	153	429	109	9	16	295	236	58	1	80.34
<i>pull-stream</i>	351	1,008	249	12	7	740	443	248	49	66.49
<i>q</i>	1051	3,048	1,040	19	47	1,941	147	1,707	87	12.06
<i>spacel-core</i>	134	378	143	5	5	225	196	29	0	87.11
<i>zip-a-folder</i>	49	140	44	2	0	94	28	4	62	95.74
<i>Total</i>	3,376	9,609	3,159	82	148	6,219	3,116	2,797	306	—

Table 41: Results from LLMorpheus experiment (run #343). Model: *codellama-34b-instruct*, temperature: 1.0, maxTokens: 250, template: *template-full.hb*, systemPrompt: *SystemPrompt-MutationTestingExpert.txt*.

application	#prompts	mutant candidates				#mutants	#killed	#survived	#timeout	mut. score
		total	invalid	identical	duplicate					
<i>Complex.js</i>	490	1,385	318	3	22	1,042	667	374	1	64.11
<i>countries-and-timezones</i>	106	290	84	1	3	202	183	19	0	90.59
<i>crawler-url-parser</i>	176	504	221	4	3	276	200	76	0	72.46
<i>delta</i>	462	1,296	531	5	16	744	639	71	34	90.46
<i>image-downloader</i>	42	116	38	2	1	75	49	26	0	65.33
<i>node-dirty</i>	154	412	142	7	3	260	145	100	15	61.54
<i>node-geo-point</i>	140	398	127	2	10	259	205	54	0	79.15
<i>node-jsonfile</i>	68	192	46	1	2	143	56	24	63	83.22
<i>plural</i>	153	439	120	5	11	303	242	60	1	80.20
<i>pull-stream</i>	351	1,006	237	9	8	752	456	238	58	68.35
<i>q</i>	1051	3,030	1,109	18	24	1,879	130	1,659	90	11.71
<i>spacel-core</i>	134	377	129	3	5	240	221	19	0	92.08
<i>zip-a-folder</i>	49	139	40	1	2	96	38	3	55	96.88
<i>Total</i>	3,376	9,584	3,142	61	110	6,271	3,231	2,723	317	—

Table 42: Results from LLMorpheus experiment (run #345). Model: *codellama-34b-instruct*, temperature: 1.0, maxTokens: 250, template: *template-full.hb*, systemPrompt: *SystemPrompt-MutationTestingExpert.txt*.

application	#prompts	mutant candidates				#mutants	#killed	#survived	#timeout	mut. score
		total	invalid	identical	duplicate					
<i>Complex.js</i>	490	1,366	318	6	24	1,018	640	378	0	62.87
<i>countries-and-timezones</i>	106	298	88	1	2	207	177	30	0	85.51
<i>crawler-url-parser</i>	176	494	232	4	6	252	178	74	0	70.63
<i>delta</i>	462	1,315	617	4	13	679	564	83	32	87.78
<i>image-downloader</i>	42	122	41	0	6	75	56	17	2	77.33
<i>node-dirty</i>	154	435	165	2	1	267	155	103	9	61.42
<i>node-geo-point</i>	140	400	123	3	11	263	198	65	0	75.29
<i>node-jsonfile</i>	68	195	46	1	7	141	60	25	56	82.27
<i>plural</i>	153	438	109	11	10	308	245	60	3	80.52
<i>pull-stream</i>	351	999	246	10	2	741	457	237	47	68.02
<i>q</i>	1051	3,024	1,106	14	36	1,868	130	1,652	86	11.56
<i>spacel-core</i>	134	379	149	3	3	224	202	21	1	90.63
<i>zip-a-folder</i>	49	145	40	1	2	102	28	1	73	99.02
<i>Total</i>	3,376	9,610	3,280	60	123	6,145	3,090	2,746	309	—

Table 43: Results from LLMorpheus experiment (run #347). Model: *codellama-34b-instruct*, temperature: 1.0, maxTokens: 250, template: *template-full.hb*, systemPrompt: *SystemPrompt-MutationTestingExpert.txt*.

project	time (sec)		#tokens		
	<i>LLMorpheus</i>	<i>StrykerJS</i>	prompt	compl.	total
<i>Complex.js</i>	3,090.47	545.31	967,508	101,516	1,069,024
<i>countries-and-timezones</i>	1,070.88	268.04	105,828	23,041	128,869
<i>crawler-url-parser</i>	1,786.52	902.86	377,644	36,825	414,469
<i>delta</i>	3,134.68	3,531.25	877,266	93,814	971,080
<i>image-downloader</i>	430.55	457.54	24,655	9,002	33,657
<i>node-dirty</i>	1,526.84	215.86	246,248	32,721	278,969
<i>node-geo-point</i>	1,411.05	897.39	316,333	29,494	345,827
<i>node-jsonfile</i>	710.73	477.34	57,516	14,447	71,963
<i>plural</i>	1,533.27	157.43	265,602	31,993	297,595
<i>pull-stream</i>	2,504.20	1,268.62	208,130	73,625	281,755
<i>q</i>	5,355.10	13,120.09	2,127,655	213,824	2,341,479
<i>spacel-core</i>	1,351.04	679.82	162,705	28,574	191,279
<i>zip-a-folder</i>	500.58	493.11	82,457	10,747	93,204
<i>Total</i>	24,405.89	23,014.65	5,819,547	699,623	6,519,170

Table 44: Results from LLMorpheus experiment (run #341). Model: *codellama-34b-instruct*, temperature: 1.0, maxTokens: 250, template: *template-full.hb*, systemPrompt: *SystemPrompt-MutationTestingExpert.txt*

project	time (sec)		prompt	#tokens	
	LLMorpheus	StrykerJS		compl.	total
Complex.js	3,099.95	515.00	967,508	99,831	1,067,339
countries-and-timezones	1,537.50	234.01	96,352	19,743	116,095
crawler-url-parser	1,643.69	843.29	386,223	36,746	422,969
delta	3,119.28	3,448.69	890,252	95,930	986,182
image-downloader	430.53	351.02	24,655	8,785	33,440
node-dirty	1,526.21	216.70	246,248	31,856	278,104
node-geo-point	1,422.53	877.31	316,333	30,037	346,370
node-jsonfile	690.70	537.75	57,516	14,738	72,254
plural	1,521.12	159.03	265,602	32,288	297,890
pull-stream	2,659.93	1,222.06	208,130	73,902	282,032
q	5,264.59	12,818.11	2,127,655	212,677	2,340,332
spacel-core	1,361.03	682.26	162,705	27,970	190,675
zip-a-folder	500.58	908.74	82,457	9,890	92,347
Total	24,777.63	22,813.96	5,831,636	694,393	6,526,029

Table 45: Results from LLMorpheus experiment (run #342). Model: *codellama-34b-instruct*, temperature: 1.0, maxTokens: 250, template: *template-full.hb*, systemPrompt: *SystemPrompt-MutationTestingExpert.txt*

project	time (sec)		prompt	#tokens	
	LLMorpheus	StrykerJS		compl.	total
Complex.js	3,024.06	525.74	967,508	98,687	1,066,195
countries-and-timezones	1,070.86	293.27	105,828	23,318	129,146
crawler-url-parser	1,644.85	845.43	386,223	36,638	422,861
delta	2,948.43	3,663.87	890,252	96,381	986,633
image-downloader	430.52	274.68	24,655	9,228	33,883
node-dirty	1,526.11	216.05	246,248	31,882	278,130
node-geo-point	1,411.07	852.26	316,333	29,152	345,485
node-jsonfile	690.73	549.73	57,516	13,670	71,186
plural	1,521.17	153.33	265,602	31,946	297,548
pull-stream	2,506.18	1,294.61	208,130	72,667	280,797
q	5,178.82	13,300.53	2,127,655	213,258	2,340,913
spacel-core	1,351.08	743.18	162,705	27,865	190,570
zip-a-folder	500.55	1,038.21	82,457	10,518	92,975
Total	23,804.42	23,750.90	5,841,112	695,210	6,536,322

Table 46: Results from LLMorpheus experiment (run #343). Model: *codellama-34b-instruct*, temperature: 1.0, maxTokens: 250, template: *template-full.hb*, systemPrompt: *SystemPrompt-MutationTestingExpert.txt*

project	time (sec)		prompt	#tokens	
	LLMorpheus	StrykerJS		compl.	total
Complex.js	3,070.12	559.72	967,508	100,998	1,068,506
countries-and-timezones	1,070.86	285.32	105,828	22,109	127,937
crawler-url-parser	1,644.31	872.80	386,223	38,267	424,490
delta	2,974.80	3,703.16	890,252	96,594	986,846
image-downloader	430.54	438.80	24,655	8,660	33,315
node-dirty	1,527.36	248.76	246,248	31,479	277,727
node-geo-point	1,411.07	843.77	316,333	29,660	345,993
node-jsonfile	690.69	512.58	57,516	14,276	71,792
plural	1,521.47	156.91	265,602	32,805	298,407
pull-stream	2,495.10	1,354.27	208,130	73,802	281,932
q	5,350.94	13,107.50	2,127,655	213,504	2,341,159
spacel-core	1,351.11	811.62	162,705	28,193	190,898
zip-a-folder	500.61	968.74	82,457	10,354	92,811
Total	24,038.96	23,863.96	5,841,112	700,701	6,541,813

Table 47: Results from LLMorpheus experiment (run #345). Model: *codellama-34b-instruct*, temperature: 1.0, maxTokens: 250, template: *template-full.hb*, systemPrompt: *SystemPrompt-MutationTestingExpert.txt*

project	time (sec)		#tokens		
	<i>LLMorpheus</i>	<i>StrykerJS</i>	prompt	compl.	total
Complex.js	3,021.09	531.51	967,508	100,183	1,067,691
countries-and-timezones	1,070.89	297.61	105,828	23,229	129,057
crawler-url-parser	1,642.94	776.31	386,223	36,920	423,143
delta	2,984.22	3,374.88	890,252	96,698	986,950
image-downloader	430.54	435.23	24,655	9,024	33,679
node-dirty	1,528.77	227.23	246,248	32,731	278,979
node-geo-point	1,411.05	858.36	316,333	29,774	346,107
node-jsonfile	690.66	494.30	57,516	14,127	71,643
plural	1,521.30	172.76	265,602	32,844	298,446
pull-stream	2,481.70	1,251.69	208,130	73,022	281,152
q	5,205.03	13,013.51	2,127,655	214,495	2,342,150
spacel-core	1,351.07	731.40	162,705	27,723	190,428
zip-a-folder	500.58	1,168.69	82,457	10,656	93,113
<i>Total</i>	23,839.84	23,333.49	5,841,112	701,426	6,542,538

Table 48: Results from LLMorpheus experiment (run #347). Model: *codellama-34b-instruct*, temperature: 1.0, maxTokens: 250, template: *template-full.hb*, systemPrompt: *SystemPrompt-MutationTestingExpert.txt*

1.5 Results for variability analysis for *codellama-34b-instruct*

Tables 49–52 show the variability of the mutants observed in 5 runs using *codellama-34b-instruct*, for each of the temperature settings that were previously discussed in Sections A.1–1.4.

application	#min	#max	#distinct	#common
Complex.js	1,198	1,199	1,217	1,181 (97.04%)
countries-and-timezones	216	217	218	215 (98.62%)
crawler-url-parser	282	285	289	278 (96.19%)
delta	765	768	787	746 (94.79%)
image-downloader	89	90	90	89 (98.89%)
node-dirty	274	275	283	266 (93.99%)
node-geo-point	302	302	307	297 (96.74%)
node-jsonfile	153	154	158	149 (94.30%)
plural	279	281	288	274 (95.14%)
pull-stream	758	760	770	746 (96.88%)
q	2,031	2,035	2,053	2,014 (98.10%)
spacl-core	238	239	252	225 (89.29%)
zip-a-folder	100	100	102	98 (96.08%)

Table 49: Variability of the mutants generated in 5 runs of *LLMorpheus* using the *codellama-34b-instruct* LLM at temperature 0.0 (run #312,#314,#315,#316,#317). The columns of the table show, from left to right: (i) the minimum number of mutants observed in any of the runs, (ii) the maximum number of mutants observed in any of the runs, (iii) the total number of distinct mutants observed in all runs, and (iv) the number (percentage) of mutants are observed in all runs.

application	#min	#max	#distinct	#common
Complex.js	1,168	1,200	2,354	447 (18.99%)
countries-and-timezones	215	227	551	53 (9.62%)
crawler-url-parser	266	285	700	67 (9.57%)
delta	752	781	1,706	247 (14.48%)
image-downloader	82	88	202	27 (13.37%)
node-dirty	265	279	600	82 (13.67%)
node-geo-point	296	314	660	99 (15.00%)
node-jsonfile	151	158	369	42 (11.38%)
plural	273	291	678	79 (11.65%)
pull-stream	764	770	1,664	280 (16.83%)
q	1,980	2,050	4,491	714 (15.90%)
spacl-core	230	244	613	58 (9.46%)
zip-a-folder	98	105	233	36 (15.45%)

Table 50: Variability of the mutants generated in 5 runs of *LLMorpheus* using the *codellama-34b-instruct* LLM at temperature 0.25 (run #348,#350,#351,#352,#353). The columns of the table show, from left to right: (i) the minimum number of mutants observed in any of the runs, (ii) the maximum number of mutants observed in any of the runs, (iii) the total number of distinct mutants observed in all runs, and (iv) the number (percentage) of mutants are observed in all runs.

application	#min	#max	#distinct	#common
Complex.js	1,166	1,191	3,196	205 (6.41%)
countries-and-timezones	221	224	735	13 (1.77%)
crawler-url-parser	279	310	966	31 (3.21%)
delta	760	792	2,322	94 (4.05%)
image-downloader	80	89	273	13 (4.76%)
node-dirty	269	288	831	33 (3.97%)
node-geo-point	269	312	905	44 (4.86%)
node-jsonfile	150	160	487	15 (3.08%)
plural	285	296	893	30 (3.36%)
pull-stream	779	809	2,183	161 (7.38%)
q	2,020	2,073	5,964	327 (5.48%)
spacl-core	250	262	782	23 (2.94%)
zip-a-folder	87	114	313	17 (5.43%)

Table 51: Variability of the mutants generated in 5 runs of *LLMorpheus* using the *codellama-34b-instruct* LLM at temperature 0.5 (run #318,#319,#320,#321,#322). The columns of the table show, from left to right: (i) the minimum number of mutants observed in any of the runs, (ii) the maximum number of mutants observed in any of the runs, (iii) the total number of distinct mutants observed in all runs, and (iv) the number (percentage) of mutants are observed in all runs.

application	#min	#max	#distinct	#common
Complex.js	987	1,042	4,200	17 (0.40%)
countries-and-timezones	164	207	835	2 (0.24%)
crawler-url-parser	252	278	1,171	1 (0.09%)
delta	681	744	3,013	2 (0.07%)
image-downloader	59	78	298	1 (0.34%)
node-dirty	245	268	1,075	2 (0.19%)
node-geo-point	259	273	1,111	2 (0.18%)
node-jsonfile	132	150	606	1 (0.17%)
plural	295	308	1,316	5 (0.38%)
pull-stream	736	749	2,814	30 (1.07%)
q	1,868	1,942	7,695	43 (0.56%)
spacl-core	205	240	958	2 (0.21%)
zip-a-folder	84	102	366	6 (1.64%)

Table 52: Variability of the mutants generated in 5 runs of *LLMorpheus* using the *codellama-34b-instruct* LLM at temperature 1.0 (run #341,#342,#343,#345,#347). The columns of the table show, from left to right: (i) the minimum number of mutants observed in any of the runs, (ii) the maximum number of mutants observed in any of the runs, (iii) the total number of distinct mutants observed in all runs, and (iv) the number (percentage) of mutants are observed in all runs.

1.6 Visualization of variability across all configurations

Figure 11 visualizes the variability of *LLMorpheus* across all configurations. The figure shows, in the aggregate for all 13 subject applications, in how many runs each mutant was observed.

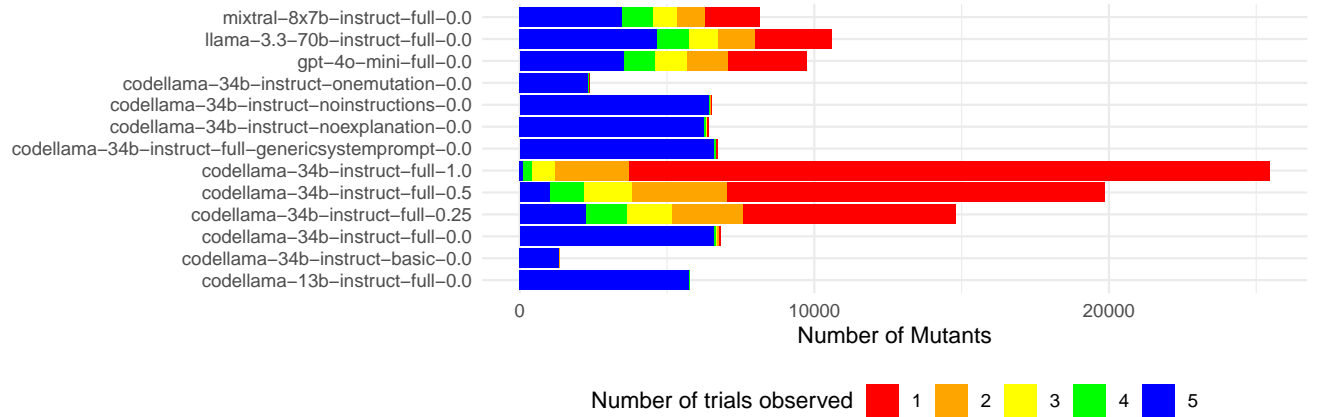


Figure 11: Variability of mutants generated by *LLMorpheus*. For each replacement generated at each position, we count the number of trials (of 5 total) where that replacement was generated.

1.7 Results for *codellama-13b-instruct*

Tables 53–62 show the results for 5 experiments with the *codellama-13b-instruct* model at temperature 0.0 using the default prompt and system prompt shown in Figure 7. Table 63 shows the variability of the mutants observed in 5 runs using *codellama-13b-instruct* at temperature 0.0.

application	#prompts	mutant candidates				#mutants	#killed	#survived	#timeout	mut. score
		total	invalid	identical	duplicate					
<i>Complex.js</i>	490	1,438	339	116	28	955	553	401	1	58.01
<i>countries-and-timezones</i>	106	306	83	15	1	207	177	30	0	85.51
<i>crawler-url-parser</i>	176	506	186	51	12	247	129	118	0	52.23
<i>delta</i>	462	1,350	530	92	16	712	583	107	22	84.97
<i>image-downloader</i>	42	124	40	5	2	77	48	29	0	62.34
<i>node-dirty</i>	154	450	161	33	11	245	142	92	11	62.45
<i>node-geo-point</i>	140	406	64	21	16	304	237	67	0	77.96
<i>node-jsonfile</i>	68	198	43	10	7	138	43	45	50	67.39
<i>plural</i>	153	424	100	99	17	208	154	53	1	74.52
<i>pull-stream</i>	351	1,015	279	54	13	669	386	237	46	64.57
<i>q</i>	1051	3,048	901	379	55	1,713	122	1,518	73	11.38
<i>spacel-core</i>	134	384	142	40	7	185	160	25	0	86.49
<i>zip-a-folder</i>	49	138	43	7	1	87	27	55	5	36.78
<i>Total</i>	3,376	9,787	2,911	922	186	5,747	2,761	2,777	209	—

Table 53: Results from LLMorpheus experiment (run #354). Model: *codellama-13b-instruct*, temperature: 0.0, maxTokens: 250, template: *template-full.hb*, systemPrompt: *SystemPrompt-MutationTestingExpert.txt*.

application	#prompts	mutant candidates				#mutants	#killed	#survived	#timeout	mut. score
		total	invalid	identical	duplicate					
<i>Complex.js</i>	490	1,439	340	116	28	955	553	401	1	58.01
<i>countries-and-timezones</i>	106	306	83	15	1	207	177	30	0	85.51
<i>crawler-url-parser</i>	176	506	186	51	12	247	129	118	0	52.23
<i>delta</i>	462	1,350	530	92	16	712	583	107	22	84.97
<i>image-downloader</i>	42	124	40	5	2	77	48	29	0	62.34
<i>node-dirty</i>	154	450	161	33	11	245	142	92	11	62.45
<i>node-geo-point</i>	140	406	64	21	16	304	237	67	0	77.96
<i>node-jsonfile</i>	68	198	45	10	6	137	43	45	49	67.15
<i>plural</i>	153	410	98	96	16	200	148	51	1	74.50
<i>pull-stream</i>	351	1,015	279	54	13	669	386	237	46	64.57
<i>q</i>	1051	3,047	899	379	55	1,714	122	1,519	73	11.38
<i>spacel-core</i>	134	384	142	40	7	185	160	25	0	86.49
<i>zip-a-folder</i>	49	138	43	7	1	87	27	55	5	36.78
<i>Total</i>	3,376	9,773	2,910	919	184	5,739	2,755	2,776	208	—

Table 54: Results from LLMorpheus experiment (run #355). Model: *codellama-13b-instruct*, temperature: 0.0, maxTokens: 250, template: *template-full.hb*, systemPrompt: *SystemPrompt-MutationTestingExpert.txt*.

application	#prompts	mutant candidates				#mutants	#killed	#survived	#timeout	mut. score
		total	invalid	identical	duplicate					
<i>Complex.js</i>	490	1,439	340	116	28	955	553	401	1	58.01
<i>countries-and-timezones</i>	106	306	83	15	1	207	177	30	0	85.51
<i>crawler-url-parser</i>	176	506	186	51	12	247	129	118	0	52.23
<i>delta</i>	462	1,350	530	92	16	712	583	107	22	84.97
<i>image-downloader</i>	42	124	40	5	2	77	48	29	0	62.34
<i>node-dirty</i>	154	450	161	33	11	245	142	92	11	62.45
<i>node-geo-point</i>	140	406	64	21	16	304	237	67	0	77.96
<i>node-jsonfile</i>	68	198	45	10	6	137	43	45	49	67.15
<i>plural</i>	153	424	100	99	17	208	154	53	1	74.52
<i>pull-stream</i>	351	1,015	280	54	13	668	386	236	46	64.67
<i>q</i>	1051	3,046	899	379	55	1,713	122	1,518	73	11.38
<i>spacel-core</i>	134	384	142	40	7	185	160	25	0	86.49
<i>zip-a-folder</i>	49	138	43	7	1	87	27	55	5	36.78
<i>Total</i>	3,376	9,786	2,913	922	185	5,745	2,761	2,776	208	—

Table 55: Results from LLMorpheus experiment (run #356). Model: *codellama-13b-instruct*, temperature: 0.0, maxTokens: 250, template: *template-full.hb*, systemPrompt: *SystemPrompt-MutationTestingExpert.txt*.

application	#prompts	mutant candidates				#mutants	#killed	#survived	#timeout	mut. score
		total	invalid	identical	duplicate					
<i>Complex.js</i>	490	1,439	340	116	28	955	553	401	1	58.01
<i>countries-and-timezones</i>	106	306	83	15	1	207	177	30	0	85.51
<i>crawler-url-parser</i>	176	506	186	51	12	247	129	118	0	52.23
<i>delta</i>	462	1,350	530	92	16	712	583	107	22	84.97
<i>image-downloader</i>	42	124	40	5	2	77	48	29	0	62.34
<i>node-dirty</i>	154	450	161	33	11	245	142	92	11	62.45
<i>node-geo-point</i>	140	406	64	21	16	304	237	67	0	77.96
<i>node-jsonfile</i>	68	198	45	10	6	137	43	45	49	67.15
<i>plural</i>	153	424	100	99	17	208	154	53	1	74.52
<i>pull-stream</i>	351	1,015	279	54	13	669	387	236	46	64.72
<i>q</i>	1051	3,047	898	379	55	1,715	122	1,520	73	11.37
<i>spacel-core</i>	134	384	142	40	7	185	160	25	0	86.49
<i>zip-a-folder</i>	49	138	43	7	1	87	27	55	5	36.78
<i>Total</i>	3,376	9,787	2,911	922	185	5,748	2,762	2,778	208	—

Table 56: Results from LLMorpheus experiment (run #358). Model: *codellama-13b-instruct*, temperature: 0.0, maxTokens: 250, template: *template-full.hb*, systemPrompt: *SystemPrompt-MutationTestingExpert.txt*.

application	#prompts	mutant candidates				#mutants	#killed	#survived	#timeout	mut. score
		total	invalid	identical	duplicate					
<i>Complex.js</i>	490	1,439	340	116	28	955	553	401	1	58.01
<i>countries-and-timezones</i>	106	306	83	15	1	207	177	30	0	85.51
<i>crawler-url-parser</i>	176	506	186	51	12	247	124	118	5	52.23
<i>delta</i>	462	1,349	530	91	16	712	583	107	22	84.97
<i>image-downloader</i>	42	124	40	5	2	77	48	29	0	62.34
<i>node-dirty</i>	154	450	161	33	11	245	142	92	11	62.45
<i>node-geo-point</i>	140	406	64	21	16	304	237	67	0	77.96
<i>node-jsonfile</i>	68	198	45	10	6	137	43	45	49	67.15
<i>plural</i>	153	424	100	99	17	208	154	53	1	74.52
<i>pull-stream</i>	351	1,015	279	54	13	669	387	236	46	64.72
<i>q</i>	1051	3,046	899	379	55	1,713	123	1,518	72	11.38
<i>spacel-core</i>	134	384	142	40	7	185	159	26	0	85.95
<i>zip-a-folder</i>	49	138	43	7	1	87	27	55	5	36.78
<i>Total</i>	3,376	9,785	2,912	921	185	5,746	2,757	2,777	212	—

Table 57: Results from LLMorpheus experiment (run #359). Model: *codellama-13b-instruct*, temperature: 0.0, maxTokens: 250, template: *template-full.hb*, systemPrompt: *SystemPrompt-MutationTestingExpert.txt*.

project	time (sec)		#tokens		
	<i>LLMorpheus</i>	<i>StrykerJS</i>	prompt	compl.	total
<i>Complex.js</i>	3,041.69	525.25	967,508	104,246	1,071,754
<i>countries-and-timezones</i>	1,070.79	310.80	105,828	23,971	129,799
<i>crawler-url-parser</i>	1,637.98	803.17	386,223	39,906	426,129
<i>delta</i>	2,993.70	3,529.05	890,252	103,085	993,337
<i>image-downloader</i>	430.56	460.64	24,655	9,339	33,994
<i>node-dirty</i>	1,526.96	211.68	246,248	34,892	281,140
<i>node-geo-point</i>	1,411.04	1,000.74	316,333	30,715	347,048
<i>node-jsonfile</i>	690.65	425.39	57,516	15,398	72,914
<i>plural</i>	1,521.00	111.98	265,602	34,926	300,528
<i>pull-stream</i>	2,489.93	1,188.59	208,130	77,308	285,438
<i>q</i>	5,187.67	11,850.22	2,127,655	231,175	2,358,830
<i>spacel-core</i>	1,350.97	616.43	162,705	30,694	193,399
<i>zip-a-folder</i>	500.51	496.32	82,457	11,494	93,951
<i>Total</i>	23,853.45	21,530.25	5,841,112	747,149	6,588,261

Table 58: Results from LLMorpheus experiment (run #354). Model: *codellama-13b-instruct*, temperature: 0.0, maxTokens: 250, template: *template-full.hb*, systemPrompt: *SystemPrompt-MutationTestingExpert.txt*

project	time (sec)		prompt	#tokens	
	LLMorpheus	StrykerJS		compl.	total
Complex.js	3,065.29	504.22	967,508	104,246	1,071,754
countries-and-timezones	1,070.80	296.35	105,828	23,971	129,799
crawler-url-parser	1,646.62	799.72	386,223	39,938	426,161
delta	2,972.99	3,511.68	890,252	103,085	993,337
image-downloader	430.51	461.29	24,655	9,339	33,994
node-dirty	1,527.57	208.98	246,248	34,892	281,140
node-geo-point	1,411.07	1,010.61	316,333	30,715	347,048
node-jsonfile	690.63	424.92	57,516	15,398	72,914
plural	1,696.97	108.86	255,187	33,552	288,739
pull-stream	2,488.59	1,182.03	208,130	77,307	285,437
q	5,141.59	11,793.14	2,127,655	231,269	2,358,924
spacl-core	1,350.98	624.29	162,705	30,694	193,399
zip-a-folder	500.55	488.31	82,457	11,494	93,951
<i>Total</i>	23,994.15	21,414.40	5,830,697	745,900	6,576,597

Table 59: Results from LLMorpheus experiment (run #355). Model: *codellama-13b-instruct*, temperature: 0.0, maxTokens: 250, template: *template-full.hb*, systemPrompt: *SystemPrompt-MutationTestingExpert.txt*

project	time (sec)		prompt	#tokens	
	LLMorpheus	StrykerJS		compl.	total
Complex.js	3,041.58	506.22	967,508	104,246	1,071,754
countries-and-timezones	1,070.84	308.67	105,828	23,971	129,799
crawler-url-parser	1,639.49	858.45	386,223	39,915	426,138
delta	2,978.12	3,447.64	890,252	103,085	993,337
image-downloader	430.52	459.07	24,655	9,339	33,994
node-dirty	1,527.40	208.98	246,248	34,892	281,140
node-geo-point	1,411.02	1,011.58	316,333	30,715	347,048
node-jsonfile	690.68	420.13	57,516	15,398	72,914
plural	1,521.00	112.81	265,602	34,926	300,528
pull-stream	2,481.30	1,179.99	208,130	77,302	285,432
q	5,249.72	11,806.54	2,127,655	231,355	2,359,010
spacl-core	1,351.04	617.86	162,705	30,694	193,399
zip-a-folder	500.58	495.97	82,457	11,494	93,951
<i>Total</i>	23,893.29	21,433.91	5,841,112	747,332	6,588,444

Table 60: Results from LLMorpheus experiment (run #356). Model: *codellama-13b-instruct*, temperature: 0.0, maxTokens: 250, template: *template-full.hb*, systemPrompt: *SystemPrompt-MutationTestingExpert.txt*

project	time (sec)		prompt	#tokens	
	LLMorpheus	StrykerJS		compl.	total
Complex.js	3,045.49	511.92	967,508	104,246	1,071,754
countries-and-timezones	1,070.84	308.11	105,828	23,971	129,799
crawler-url-parser	1,639.50	877.27	386,223	39,906	426,129
delta	2,975.67	3,533.28	890,252	103,025	993,277
image-downloader	430.50	458.40	24,655	9,339	33,994
node-dirty	1,527.47	209.67	246,248	34,892	281,140
node-geo-point	1,411.06	994.07	316,333	30,715	347,048
node-jsonfile	690.64	421.39	57,516	15,398	72,914
plural	1,521.06	112.22	265,602	34,926	300,528
pull-stream	2,493.00	1,182.21	208,130	77,307	285,437
q	5,177.80	11,862.47	2,127,655	231,214	2,358,869
spacl-core	1,350.98	606.49	162,705	30,694	193,399
zip-a-folder	500.52	486.21	82,457	11,494	93,951
<i>Total</i>	23,834.54	21,563.71	5,841,112	747,127	6,588,239

Table 61: Results from LLMorpheus experiment (run #358). Model: *codellama-13b-instruct*, temperature: 0.0, maxTokens: 250, template: *template-full.hb*, systemPrompt: *SystemPrompt-MutationTestingExpert.txt*

project	time (sec)		prompt	#tokens	
	<i>LLMorpheus</i>	<i>StrykerJS</i>		compl.	total
Complex.js	3,065.97	514.43	967,508	104,246	1,071,754
countries-and-timezones	1,070.82	328.45	105,828	23,951	129,779
crawler-url-parser	1,638.27	905.63	386,223	39,906	426,129
delta	2,954.39	3,471.08	890,252	103,085	993,337
image-downloader	430.50	458.13	24,655	9,339	33,994
node-dirty	1,526.96	207.80	246,248	34,892	281,140
node-geo-point	1,411.06	1,003.76	316,333	30,715	347,048
node-jsonfile	690.67	421.74	57,516	15,398	72,914
plural	1,521.03	111.45	265,602	34,926	300,528
pull-stream	2,483.02	1,186.04	208,130	77,307	285,437
q	5,276.52	11,824.34	2,127,655	231,254	2,358,909
spacl-core	1,350.99	617.51	162,705	30,694	193,399
zip-a-folder	500.53	490.95	82,457	11,494	93,951
<i>Total</i>	23,920.75	21,541.32	5,841,112	747,207	6,588,319

Table 62: Results from LLMorpheus experiment (run #359). Model: *codellama-13b-instruct*, temperature: 0.0, maxTokens: 250, template: *template-full.hb*, systemPrompt: *SystemPrompt-MutationTestingExpert.txt*

application	#min	#max	#distinct	#common
Complex.js	955	955	955	955 (100.00%)
countries-and-timezones	207	207	207	207 (100.00%)
crawler-url-parser	257	257	257	257 (100.00%)
delta	712	712	713	711 (99.72%)
image-downloader	77	77	77	77 (100.00%)
node-dirty	245	245	245	245 (100.00%)
node-geo-point	305	305	305	305 (100.00%)
node-jsonfile	137	138	138	137 (99.28%)
plural	200	208	208	200 (96.15%)
pull-stream	663	664	666	661 (99.25%)
q	1,713	1,715	1,725	1,702 (98.67%)
spacl-core	195	195	197	193 (97.97%)
zip-a-folder	87	87	87	87 (100.00%)

Table 63: Variability of the mutants generated in 5 runs of LLMorpheus using the *codellama-13b-instruct* LLM at temperature 0.0 (run #354,#355,#356,#358,#359). The columns of the table show, from left to right: (i) the minimum number of mutants observed in any of the runs, (ii) the maximum number of mutants observed in any of the runs, (iii) the total number of distinct mutants observed in all runs, and (iv) the number (percentage) of mutants are observed in all runs.

1.8 Results for *mixtral-8x7b-instruct*

Tables 64–73 show the results for 5 experiments with the *mixtral-8x7b-instruct* model at temperature 0.0 using the default prompt and system prompt shown in Figure 7. Table 74 shows the variability of the mutants observed in 5 runs using *mixtral-8x7b-instruct* at temperature 0.0.

application	#prompts	mutant candidates				#mutants	#killed	#survived	#timeout	mut. score
		total	invalid	identical	duplicate					
<i>Complex.js</i>	490	1,287	310	0	15	962	589	373	0	61.23
<i>countries-and-timezones</i>	106	277	65	2	5	205	166	39	0	80.98
<i>crawler-url-parser</i>	176	414	165	0	3	234	130	104	0	55.56
<i>delta</i>	462	1,156	452	0	24	680	516	128	36	81.18
<i>image-downloader</i>	42	108	38	0	1	69	46	23	0	66.67
<i>node-dirty</i>	154	310	109	0	10	191	111	72	8	62.30
<i>node-geo-point</i>	140	352	88	0	11	247	166	81	0	67.21
<i>node-jsonfile</i>	68	159	23	0	4	132	54	32	46	75.76
<i>plural</i>	153	307	73	0	8	226	166	60	0	73.45
<i>pull-stream</i>	351	940	255	1	6	678	386	248	44	63.42
<i>q</i>	1051	2,468	772	3	50	1,643	112	1,460	71	11.14
<i>spacel-core</i>	134	333	152	0	3	157	134	22	1	85.99
<i>zip-a-folder</i>	49	117	38	0	0	78	24	44	10	43.59
<i>Total</i>	3,376	8,228	2,540	6	140	5,502	2,600	2,686	216	—

Table 64: Results from LLMorpheus experiment (run #360). Model: *mixtral-8x7b-instruct*, temperature: 0.0, maxTokens: 250, template: *template-full.hb*, systemPrompt: *SystemPrompt-MutationTestingExpert.txt*.

application	#prompts	mutant candidates				#mutants	#killed	#survived	#timeout	mut. score
		total	invalid	identical	duplicate					
<i>Complex.js</i>	490	1,313	303	0	21	989	608	381	0	61.48
<i>countries-and-timezones</i>	106	270	67	2	5	196	157	39	0	80.10
<i>crawler-url-parser</i>	176	403	177	0	1	211	114	97	0	54.03
<i>delta</i>	462	1,136	446	0	24	666	509	123	34	81.53
<i>image-downloader</i>	42	103	37	0	1	65	42	23	0	64.62
<i>node-dirty</i>	154	342	124	0	9	209	125	76	8	63.64
<i>node-geo-point</i>	140	357	79	0	16	257	180	77	0	70.04
<i>node-jsonfile</i>	68	158	24	0	5	129	56	27	46	79.07
<i>plural</i>	153	314	70	1	11	232	174	58	0	75.00
<i>pull-stream</i>	351	936	235	1	6	694	402	243	49	64.99
<i>q</i>	1051	2,404	748	4	43	1,609	114	1,423	72	11.56
<i>spacel-core</i>	134	335	152	0	4	158	135	22	1	86.08
<i>zip-a-folder</i>	49	119	33	0	0	86	32	46	8	46.51
<i>Total</i>	3,376	8,190	2,495	8	146	5,501	2,648	2,635	218	—

Table 65: Results from LLMorpheus experiment (run #361). Model: *mixtral-8x7b-instruct*, temperature: 0.0, maxTokens: 250, template: *template-full.hb*, systemPrompt: *SystemPrompt-MutationTestingExpert.txt*.

application	#prompts	mutant candidates				#mutants	#killed	#survived	#timeout	mut. score
		total	invalid	identical	duplicate					
<i>Complex.js</i>	490	1,302	306	0	16	980	594	386	0	60.61
<i>countries-and-timezones</i>	106	272	70	2	3	197	154	43	0	78.17
<i>crawler-url-parser</i>	176	404	168	0	1	223	121	102	0	54.26
<i>delta</i>	462	1,136	455	0	21	660	497	129	34	80.45
<i>image-downloader</i>	42	103	35	0	1	67	41	26	0	61.19
<i>node-dirty</i>	154	349	126	0	10	213	123	81	9	61.97
<i>node-geo-point</i>	140	356	86	0	11	254	177	77	0	69.69
<i>node-jsonfile</i>	68	155	24	0	5	126	52	24	50	80.95
<i>plural</i>	153	311	71	0	11	229	169	60	0	73.80
<i>pull-stream</i>	351	920	244	1	4	671	389	236	46	64.83
<i>q</i>	1051	2,470	756	3	53	1,658	115	1,477	66	10.92
<i>spacel-core</i>	134	332	149	0	2	159	134	24	1	84.91
<i>zip-a-folder</i>	49	122	41	0	0	81	23	51	7	37.04
<i>Total</i>	3,376	8,232	2,531	6	138	5,518	2,589	2,716	213	—

Table 66: Results from LLMorpheus experiment (run #362). Model: *mixtral-8x7b-instruct*, temperature: 0.0, maxTokens: 250, template: *template-full.hb*, systemPrompt: *SystemPrompt-MutationTestingExpert.txt*.

application	#prompts	mutant candidates				#mutants	#killed	#survived	#timeout	mut. score
		total	invalid	identical	duplicate					
Complex.js	490	1,299	305	0	25	969	587	382	0	60.58
countries-and-timezones	106	270	61	2	4	203	160	43	0	78.82
crawler-url-parser	176	401	167	0	1	220	118	102	0	53.64
delta	462	1,122	440	0	22	660	500	126	34	80.91
image-downloader	42	103	39	0	0	64	41	23	0	64.06
node-dirty	154	338	125	0	10	203	120	77	6	62.07
node-geo-point	140	358	81	0	15	258	178	80	0	68.99
node-jsonfile	68	166	25	1	5	135	56	32	47	76.30
plural	153	310	71	0	7	232	171	61	0	73.71
pull-stream	351	946	251	1	7	687	398	245	44	64.34
q	1051	2,504	790	3	51	1,660	116	1,477	67	11.02
spacel-core	134	329	148	0	3	157	134	22	1	85.99
zip-a-folder	49	116	38	0	0	78	27	42	9	46.15
Total	3,376	8,262	2,541	7	150	5,526	2,606	2,712	208	—

Table 67: Results from LLMorpheus experiment (run #363). Model: *mixtral-8x7b-instruct*, temperature: 0.0, maxTokens: 250, template: *template-full.hb*, systemPrompt: *SystemPrompt-MutationTestingExpert.txt*.

application	#prompts	mutant candidates				#mutants	#killed	#survived	#timeout	mut. score
		total	invalid	identical	duplicate					
Complex.js	490	1,313	328	0	16	969	580	389	0	59.86
countries-and-timezones	106	269	64	2	4	199	156	43	0	78.39
crawler-url-parser	176	404	178	0	1	212	117	95	0	55.19
delta	462	1,148	458	0	16	674	521	116	37	82.79
image-downloader	42	107	40	0	1	66	42	24	0	63.64
node-dirty	154	339	121	0	10	208	124	73	11	64.90
node-geo-point	140	362	84	0	15	258	176	82	0	68.22
node-jsonfile	68	144	20	0	3	121	50	25	46	79.34
plural	153	319	75	0	12	232	177	55	0	76.29
pull-stream	351	926	241	1	6	678	390	242	46	64.31
q	1051	2,446	751	3	48	1,644	117	1,455	72	11.50
spacel-core	134	337	156	0	3	156	134	21	1	86.54
zip-a-folder	49	114	39	0	0	75	25	42	8	44.00
Total	3,376	8,228	2,555	6	135	5,492	2,609	2,662	221	—

Table 68: Results from LLMorpheus experiment (run #364). Model: *mixtral-8x7b-instruct*, temperature: 0.0, maxTokens: 250, template: *template-full.hb*, systemPrompt: *SystemPrompt-MutationTestingExpert.txt*.

project	time (sec)		#tokens		
	LLMorpheus	StrykerJS	prompt	compl.	total
Complex.js	3,756.38	507.41	960,545	96,072	1,056,617
countries-and-timezones	1,080.09	296.25	104,291	22,693	126,984
crawler-url-parser	1,697.04	762.88	384,404	33,495	417,899
delta	3,636.95	3,476.06	882,477	90,094	972,571
image-downloader	430.46	387.36	24,140	8,238	32,378
node-dirty	1,665.69	159.16	234,503	24,705	259,208
node-geo-point	1,497.29	833.16	315,891	27,864	343,755
node-jsonfile	691.90	425.95	56,273	12,371	68,644
plural	1,583.06	115.03	259,916	25,067	284,983
pull-stream	2,802.21	1,201.97	204,431	70,423	274,854
q	7,003.28	11,371.39	2,103,232	192,284	2,295,516
spacel-core	1,369.93	534.67	162,695	26,484	189,179
zip-a-folder	506.29	470.28	81,279	9,124	90,403
Total	27,720.59	20,541.58	5,774,077	638,914	6,412,991

Table 69: Results from LLMorpheus experiment (run #360). Model: *mixtral-8x7b-instruct*, temperature: 0.0, maxTokens: 250, template: *template-full.hb*, systemPrompt: *SystemPrompt-MutationTestingExpert.txt*

project	time (sec)		#tokens		
	<i>LLMorpheus</i>	<i>StrykerJS</i>	prompt	compl.	total
Complex.js	3,372.45	520.01	960,545	98,260	1,058,805
countries-and-timezones	1,071.57	285.14	104,291	22,228	126,519
crawler-url-parser	1,669.78	698.95	384,404	32,771	417,175
delta	3,199.74	3,398.17	882,477	89,050	971,527
image-downloader	432.08	378.08	24,140	8,005	32,145
node-dirty	1,554.61	185.18	242,671	26,837	269,508
node-geo-point	1,416.99	850.15	318,251	28,316	346,567
node-jsonfile	740.68	431.76	56,273	12,101	68,374
plural	1,546.99	120.70	261,626	25,293	286,919
pull-stream	2,660.01	1,259.31	204,431	70,142	274,573
q	6,149.24	11,173.93	2,103,232	188,223	2,291,455
spacl-core	1,416.02	534.70	162,695	26,751	189,446
zip-a-folder	500.53	489.08	81,279	9,372	90,651
<i>Total</i>	25,730.68	20,325.15	5,786,315	637,349	6,423,664

Table 70: Results from LLMorpheus experiment (run #361). Model: *mixtral-8x7b-instruct*, temperature: 0.0, maxTokens: 250, template: *template-full.hb*, systemPrompt: *SystemPrompt-MutationTestingExpert.txt*

project	time (sec)		#tokens		
	<i>LLMorpheus</i>	<i>StrykerJS</i>	prompt	compl.	total
Complex.js	3,359.29	519.50	960,545	96,727	1,057,272
countries-and-timezones	1,074.42	277.16	104,291	22,353	126,644
crawler-url-parser	1,661.26	731.82	384,404	32,772	417,176
delta	3,170.76	3,384.81	882,477	89,334	971,811
image-downloader	430.53	386.39	24,140	7,934	32,074
node-dirty	1,530.96	182.12	244,297	27,524	271,821
node-geo-point	1,413.38	829.76	318,251	27,995	346,246
node-jsonfile	690.64	444.51	56,273	11,970	68,243
plural	1,524.56	117.41	261,626	25,277	286,903
pull-stream	2,644.38	1,205.37	204,431	69,081	273,512
q	6,079.84	11,465.34	2,103,232	192,672	2,295,904
spacl-core	1,354.60	540.52	162,695	26,151	188,846
zip-a-folder	500.60	464.06	81,279	9,340	90,619
<i>Total</i>	25,435.21	20,548.77	5,787,941	639,130	6,427,071

Table 71: Results from LLMorpheus experiment (run #362). Model: *mixtral-8x7b-instruct*, temperature: 0.0, maxTokens: 250, template: *template-full.hb*, systemPrompt: *SystemPrompt-MutationTestingExpert.txt*

project	time (sec)		#tokens		
	<i>LLMorpheus</i>	<i>StrykerJS</i>	prompt	compl.	total
Complex.js	3,511.86	522.92	960,545	96,846	1,057,391
countries-and-timezones	1,073.78	299.00	104,291	22,090	126,381
crawler-url-parser	1,664.52	748.35	384,404	32,721	417,125
delta	3,343.71	3,332.02	882,477	88,421	970,898
image-downloader	440.52	362.20	24,140	7,972	32,112
node-dirty	1,532.40	164.86	244,297	26,801	271,098
node-geo-point	1,436.26	842.23	318,251	28,074	346,325
node-jsonfile	692.85	440.06	56,273	12,731	69,004
plural	1,525.78	117.87	261,626	25,198	286,824
pull-stream	2,725.42	1,227.21	204,431	70,751	275,182
q	6,622.34	11,507.75	2,103,232	194,705	2,297,937
spacl-core	1,359.32	532.62	162,695	26,100	188,795
zip-a-folder	500.56	463.12	81,279	9,118	90,397
<i>Total</i>	26,429.31	20,560.22	5,787,941	641,528	6,429,469

Table 72: Results from LLMorpheus experiment (run #363). Model: *mixtral-8x7b-instruct*, temperature: 0.0, maxTokens: 250, template: *template-full.hb*, systemPrompt: *SystemPrompt-MutationTestingExpert.txt*

project	time (sec)		#tokens		
	<i>LLMorpheus</i>	<i>StrykerJS</i>	prompt	compl.	total
Complex.js	3,649.24	528.79	960,545	98,038	1,058,583
countries-and-timezones	1,087.49	295.42	104,291	22,259	126,550
crawler-url-parser	1,672.78	705.16	384,404	32,640	417,044
delta	3,494.16	3,421.43	882,477	90,244	972,721
image-downloader	430.50	378.73	24,140	8,213	32,353
node-dirty	1,530.34	197.97	244,297	26,982	271,279
node-geo-point	1,432.72	865.00	318,251	28,015	346,266
node-jsonfile	702.02	419.40	56,273	11,348	67,621
plural	1,533.26	118.22	261,626	25,664	287,290
pull-stream	2,763.15	1,206.16	204,431	69,471	273,902
q	6,879.90	11,339.61	2,103,232	191,046	2,294,278
spacl-core	1,409.48	527.44	162,695	26,807	189,502
zip-a-folder	500.54	444.67	81,279	9,009	90,288
<i>Total</i>	27,085.58	20,447.99	5,787,941	639,736	6,427,677

Table 73: Results from LLMorpheus experiment (run #364). Model: *mixtral-8x7b-instruct*, temperature: 0.0, maxTokens: 250, template: *template-full.hb*, systemPrompt: *SystemPrompt-MutationTestingExpert.txt*

application	#min	#max	#distinct	#common
Complex.js	962	989	1,425	604 (42.39%)
countries-and-timezones	196	205	287	132 (45.99%)
crawler-url-parser	225	246	349	144 (41.26%)
delta	660	680	958	431 (44.99%)
image-downloader	64	69	95	42 (44.21%)
node-dirty	191	213	307	120 (39.09%)
node-geo-point	253	263	368	169 (45.92%)
node-jsonfile	121	135	187	81 (43.32%)
plural	226	232	374	128 (34.22%)
pull-stream	669	692	981	451 (45.97%)
q	1,609	1,660	2,438	999 (40.98%)
spacl-core	178	181	261	113 (43.30%)
zip-a-folder	75	86	112	56 (50.00%)

Table 74: Variability of the mutants generated in 5 runs of *LLMorpheus* using the *mixtral-8x7b-instruct* LLM at temperature 0.0 (run #360,#361,#362,#363,#364). The columns of the table show, from left to right: (i) the minimum number of mutants observed in any of the runs, (ii) the maximum number of mutants observed in any of the runs, (iii) the total number of distinct mutants observed in all runs, and (iv) the number (percentage) of mutants are observed in all runs.

1.9 Results for *gpt-4o-mini*

Tables 75–84 show the results for 5 experiments with the *gpt-4o-mini* model at temperature 0.0 using the default prompt and system prompt shown in Figure 7. Table 85 shows the variability of the mutants observed in 5 runs using *gpt-4o-mini* at temperature 0.0.

application	#prompts	mutant candidates				#mutants	#killed	#survived	#timeout	mut. score
		total	invalid	identical	duplicate					
<i>Complex.js</i>	490	1,470	446	0	38	986	596	390	0	60.45
<i>countries-and-timezones</i>	106	317	99	0	9	209	171	38	0	81.82
<i>crawler-url-parser</i>	176	527	227	0	11	275	181	94	0	65.82
<i>delta</i>	462	1,385	636	2	40	707	564	108	35	84.72
<i>image-downloader</i>	42	126	58	0	3	65	45	20	0	69.23
<i>node-dirty</i>	154	462	188	0	9	265	154	103	8	61.13
<i>node-geo-point</i>	140	419	86	0	20	311	225	86	0	72.35
<i>node-jsonfile</i>	68	204	44	0	6	154	64	26	64	83.12
<i>plural</i>	153	454	110	5	26	313	257	55	1	82.43
<i>pull-stream</i>	351	1,053	302	0	16	735	420	247	68	66.39
<i>q</i>	1051	3,153	1,287	2	69	1,795	137	1,597	61	11.03
<i>spacl-core</i>	134	402	158	0	10	215	195	20	0	90.70
<i>zip-a-folder</i>	49	147	62	0	4	81	14	7	60	91.36
<i>Total</i>	3,376	10,119	3,703	9	261	6,111	3,023	2,791	297	—

Table 75: Results from LLMorpheus experiment (run #58). Model: *gpt-4o-mini*, temperature: 0.0, maxTokens: 250, template: *template-full.hb*, systemPrompt: *SystemPrompt-MutationTestingExpert.txt*.

application	#prompts	mutant candidates				#mutants	#killed	#survived	#timeout	mut. score
		total	invalid	identical	duplicate					
<i>Complex.js</i>	490	1,470	453	0	35	982	597	385	0	60.79
<i>countries-and-timezones</i>	106	318	105	0	9	204	166	38	0	81.37
<i>crawler-url-parser</i>	176	527	238	0	9	266	175	91	0	65.79
<i>delta</i>	462	1,385	651	1	35	698	566	97	35	86.10
<i>image-downloader</i>	42	126	58	0	2	66	41	25	0	62.12
<i>node-dirty</i>	154	462	195	0	8	259	153	99	7	61.78
<i>node-geo-point</i>	140	420	88	0	25	305	217	88	0	71.15
<i>node-jsonfile</i>	68	204	43	0	6	155	67	24	64	84.52
<i>plural</i>	153	453	114	6	22	311	255	55	1	82.32
<i>pull-stream</i>	351	1,053	300	0	14	739	436	240	63	67.52
<i>q</i>	1051	3,153	1,289	7	71	1,786	132	1,588	66	11.09
<i>spacl-core</i>	134	402	157	0	10	216	198	18	0	91.67
<i>zip-a-folder</i>	49	147	63	0	2	82	22	4	56	95.12
<i>Total</i>	3,376	10,120	3,754	14	248	6,069	3,025	2,752	292	—

Table 76: Results from LLMorpheus experiment (run #59). Model: *gpt-4o-mini*, temperature: 0.0, maxTokens: 250, template: *template-full.hb*, systemPrompt: *SystemPrompt-MutationTestingExpert.txt*.

application	#prompts	mutant candidates				#mutants	#killed	#survived	#timeout	mut. score
		total	invalid	identical	duplicate					
<i>Complex.js</i>	490	1,470	455	0	33	982	594	388	0	60.49
<i>countries-and-timezones</i>	106	318	97	0	13	208	174	34	0	83.65
<i>crawler-url-parser</i>	176	527	236	0	9	268	178	90	0	66.42
<i>delta</i>	462	1,385	644	2	39	700	561	105	34	85.00
<i>image-downloader</i>	42	126	57	0	3	66	45	21	0	68.18
<i>node-dirty</i>	154	462	196	0	9	257	146	103	8	59.92
<i>node-geo-point</i>	140	419	83	0	23	310	221	89	0	71.29
<i>node-jsonfile</i>	68	204	45	0	7	152	67	25	60	83.55
<i>plural</i>	153	455	110	5	27	313	254	58	1	81.47
<i>pull-stream</i>	351	1,053	299	0	14	740	431	244	65	67.03
<i>q</i>	1051	3,153	1,296	3	81	1,773	128	1,580	65	10.89
<i>spacl-core</i>	134	401	160	0	12	211	195	16	0	92.42
<i>zip-a-folder</i>	49	147	62	0	2	82	17	4	61	95.12
<i>Total</i>	3,376	10,120	3,740	10	272	6,062	3,011	2,757	294	—

Table 77: Results from LLMorpheus experiment (run #60). Model: *gpt-4o-mini*, temperature: 0.0, maxTokens: 250, template: *template-full.hb*, systemPrompt: *SystemPrompt-MutationTestingExpert.txt*.

application	#prompts	mutant candidates				#mutants	#killed	#survived	#timeout	mut. score
		total	invalid	identical	duplicate					
Complex.js	490	1,470	443	0	36	991	603	388	0	60.85
countries-and-timezones	106	318	99	0	11	208	173	35	0	83.17
crawler-url-parser	176	528	235	0	12	268	176	92	0	65.67
delta	462	1,385	641	1	40	703	563	103	37	85.35
image-downloader	42	126	55	0	3	68	44	24	0	64.71
node-dirty	154	462	190	0	9	263	157	99	7	62.36
node-geo-point	140	419	85	0	27	305	218	87	0	71.48
node-jsonfile	68	204	46	0	7	151	66	24	61	84.11
plural	153	455	114	4	22	315	262	53	0	83.17
pull-stream	351	1,053	299	0	11	743	432	244	67	67.16
q	1051	3,153	1,298	7	70	1,778	123	1,595	60	10.29
spacl-core	134	401	153	0	12	220	200	20	0	90.91
zip-a-folder	49	147	59	0	4	83	18	4	61	95.18
Total	3,376	10,121	3,717	12	264	6,096	3,035	2,768	293	—

Table 78: Results from LLMorpheus experiment (run #61). Model: *gpt-4o-mini*, temperature: 0.0, maxTokens: 250, template: *template-full.hb*, systemPrompt: *SystemPrompt-MutationTestingExpert.txt*.

application	#prompts	mutant candidates				#mutants	#killed	#survived	#timeout	mut. score
		total	invalid	identical	duplicate					
Complex.js	490	1,468	441	0	39	988	603	385	0	61.03
countries-and-timezones	106	318	103	0	7	208	173	35	0	83.17
crawler-url-parser	176	528	235	0	9	271	181	90	0	66.79
delta	462	1,385	644	1	42	698	558	104	36	85.10
image-downloader	42	126	56	0	2	68	49	19	0	72.06
node-dirty	154	462	187	0	10	265	152	106	7	60.00
node-geo-point	140	419	86	0	24	307	216	91	0	70.36
node-jsonfile	68	204	46	0	7	151	60	30	61	80.13
plural	153	455	112	5	26	312	261	51	0	83.65
pull-stream	351	1,053	300	0	14	739	432	246	61	66.71
q	1051	3,153	1,288	4	74	1,787	132	1,594	61	10.80
spacl-core	134	402	158	0	12	216	200	16	0	92.59
zip-a-folder	49	147	63	0	3	81	18	4	59	95.06
Total	3,376	10,120	3,719	10	269	6,091	3,035	2,771	285	—

Table 79: Results from LLMorpheus experiment (run #63). Model: *gpt-4o-mini*, temperature: 0.0, maxTokens: 250, template: *template-full.hb*, systemPrompt: *SystemPrompt-MutationTestingExpert.txt*.

project	time (sec)		#tokens		
	LLMorpheus	StrykerJS	prompt	compl.	total
Complex.js	3,126.98	305.91	788,189	96,972	885,161
countries-and-timezones	1,070.51	223.26	82,293	21,679	103,972
crawler-url-parser	1,663.34	529.03	288,452	36,368	324,820
delta	2,954.87	2,245.12	705,441	91,727	797,168
image-downloader	430.37	363.94	19,697	8,185	27,882
node-dirty	1,526.46	149.87	198,716	31,214	229,930
node-geo-point	1,534.64	731.35	254,246	26,052	280,298
node-jsonfile	692.89	470.97	46,918	13,532	60,450
plural	1,522.37	93.31	218,037	32,037	250,074
pull-stream	2,570.39	1,189.58	171,725	70,357	242,082
q	5,661.54	11,513.31	1,694,668	207,545	1,902,213
spacl-core	1,350.59	881.31	137,862	26,728	164,590
zip-a-folder	500.39	819.97	65,869	10,140	76,009
Total	24,605.34	19,516.91	4,672,113	672,536	5,344,649

Table 80: Results from LLMorpheus experiment (run #58). Model: *gpt-4o-mini*, temperature: 0.0, maxTokens: 250, template: *template-full.hb*, systemPrompt: *SystemPrompt-MutationTestingExpert.txt*

project	time (sec)		#tokens		
	LLMorpheus	StrykerJS	prompt	compl.	total
Complex.js	3,231.94	306.23	788,189	97,504	885,693
countries-and-timezones	1,071.30	212.00	82,293	21,875	104,168
crawler-url-parser	1,667.41	521.15	288,452	36,277	324,729
delta	3,101.18	2,248.14	705,441	91,878	797,319
image-downloader	430.36	374.81	19,697	8,207	27,904
node-dirty	1,536.82	141.77	198,716	31,186	229,902
node-geo-point	1,411.39	711.52	254,246	25,773	280,019
node-jsonfile	690.45	478.21	46,918	13,386	60,304
plural	1,589.51	93.88	218,037	32,039	250,076
pull-stream	2,599.70	1,147.49	171,725	70,365	242,090
q	5,669.28	11,541.55	1,694,668	207,750	1,902,418
spacl-core	1,353.11	900.14	137,862	26,648	164,510
zip-a-folder	502.44	765.68	65,869	10,124	75,993
<i>Total</i>	24,854.90	19,442.55	4,672,113	673,012	5,345,125

Table 81: Results from LLMorpheus experiment (run #59). Model: *gpt-4o-mini*, temperature: 0.0, maxTokens: 250, template: *template-full.hb*, systemPrompt: *SystemPrompt-MutationTestingExpert.txt*

project	time (sec)		#tokens		
	LLMorpheus	StrykerJS	prompt	compl.	total
Complex.js	2,839.62	303.29	788,189	97,203	885,392
countries-and-timezones	1,070.52	210.16	82,293	21,852	104,145
crawler-url-parser	1,646.04	509.26	288,452	36,258	324,710
delta	2,774.38	2,206.72	705,441	91,952	797,393
image-downloader	430.38	370.79	19,697	8,198	27,895
node-dirty	1,527.61	142.70	198,716	31,200	229,916
node-geo-point	1,410.64	716.58	254,246	25,833	280,079
node-jsonfile	690.45	453.09	46,918	13,455	60,373
plural	1,520.69	94.22	218,037	31,898	249,935
pull-stream	2,438.84	1,171.72	171,725	69,914	241,639
q	4,712.10	11,452.86	1,694,668	207,508	1,902,176
spacl-core	1,353.02	848.87	137,862	26,698	164,560
zip-a-folder	500.38	816.75	65,869	10,016	75,885
<i>Total</i>	22,914.67	19,297.01	4,672,113	671,985	5,344,098

Table 82: Results from LLMorpheus experiment (run #60). Model: *gpt-4o-mini*, temperature: 0.0, maxTokens: 250, template: *template-full.hb*, systemPrompt: *SystemPrompt-MutationTestingExpert.txt*

project	time (sec)		#tokens		
	LLMorpheus	StrykerJS	prompt	compl.	total
Complex.js	2,952.22	307.21	788,189	96,710	884,899
countries-and-timezones	1,070.49	220.94	82,293	21,677	103,970
crawler-url-parser	1,647.14	494.72	288,452	36,287	324,739
delta	2,877.05	2,256.62	705,441	91,533	796,974
image-downloader	430.38	371.91	19,697	8,175	27,872
node-dirty	1,527.58	142.81	198,716	31,147	229,863
node-geo-point	1,410.65	713.98	254,246	25,849	280,095
node-jsonfile	690.43	464.79	46,918	13,608	60,526
plural	1,527.23	88.79	218,037	31,950	249,987
pull-stream	2,481.90	1,186.52	171,725	70,548	242,273
q	4,829.57	11,485.59	1,694,668	207,651	1,902,319
spacl-core	1,350.62	891.52	137,862	26,626	164,488
zip-a-folder	500.41	820.40	65,869	10,073	75,942
<i>Total</i>	23,295.67	19,445.81	4,672,113	671,834	5,343,947

Table 83: Results from LLMorpheus experiment (run #61). Model: *gpt-4o-mini*, temperature: 0.0, maxTokens: 250, template: *template-full.hb*, systemPrompt: *SystemPrompt-MutationTestingExpert.txt*

project	time (sec)		#tokens		
	<i>LLMorpheus</i>	<i>StrykerJS</i>	prompt	compl.	total
Complex.js	2,993.67	305.57	788,189	96,526	884,715
countries-and-timezones	1,070.53	212.32	82,293	21,735	104,028
crawler-url-parser	1,650.74	510.52	288,452	36,399	324,851
delta	3,461.17	2,263.13	705,441	92,146	797,587
image-downloader	430.40	376.81	19,697	8,150	27,847
node-dirty	1,531.95	145.81	198,716	31,238	229,954
node-geo-point	1,619.27	717.56	254,246	25,924	280,170
node-jsonfile	691.27	455.30	46,918	13,572	60,490
plural	1,527.63	89.76	218,037	31,989	250,026
pull-stream	2,527.67	1,150.99	171,725	70,511	242,236
q	5,162.96	11,468.80	1,694,668	207,007	1,901,675
spacl-core	1,350.59	885.50	137,862	26,516	164,378
zip-a-folder	501.32	792.67	65,869	10,026	75,895
<i>Total</i>	24,519.16	19,374.74	4,672,113	671,739	5,343,852

Table 84: Results from LLMorpheus experiment (run #63). Model: *gpt-4o-mini*, temperature: 0.0, maxTokens: 250, template: *template-full.hb*, systemPrompt: *SystemPrompt-MutationTestingExpert.txt*

application	#min	#max	#distinct	#common
Complex.js	982	991	1,484	613 (41.31%)
countries-and-timezones	204	209	362	95 (26.24%)
crawler-url-parser	280	289	472	153 (32.42%)
delta	698	707	1,094	413 (37.75%)
image-downloader	65	68	127	31 (24.41%)
node-dirty	257	265	417	147 (35.25%)
node-geo-point	307	313	492	189 (38.41%)
node-jsonfile	151	155	250	80 (32.00%)
plural	311	315	585	145 (24.79%)
pull-stream	728	734	1,176	411 (34.95%)
q	1,773	1,795	2,740	1,093 (39.89%)
spacl-core	229	236	408	109 (26.72%)
zip-a-folder	81	84	131	50 (38.17%)

Table 85: Variability of the mutants generated in 5 runs of *LLMorpheus* using the *gpt-4o-mini* LLM at temperature 0.0 (run #58,#59,#60,#61,#63). The columns of the table show, from left to right: (i) the minimum number of mutants observed in any of the runs, (ii) the maximum number of mutants observed in any of the runs, (iii) the total number of distinct mutants observed in all runs, and (iv) the number (percentage) of mutants are observed in all runs.

1.10 Results for *llama-3.3-70b-instruct*

Tables 86–95 show the results for 5 experiments with the *llama-3.3-70b-instruct* model at temperature 0.0 using the default prompt and system prompt shown in Figure 7. Table 96 shows the variability of the mutants observed in 5 runs using *gpt-4o-mini* at temperature 0.0.

application	#prompts	mutant candidates				#mutants	#killed	#survived	#timeout	mut. score
		total	invalid	identical	duplicate					
<i>Complex.js</i>	490	1,470	279	0	53	1,138	690	447	1	60.72
<i>countries-and-timezones</i>	106	318	64	0	14	240	207	33	0	86.25
<i>crawler-url-parser</i>	176	528	175	0	22	319	208	111	0	65.20
<i>delta</i>	462	1,387	539	0	54	794	626	130	38	83.63
<i>image-downloader</i>	42	127	43	0	5	79	54	25	0	68.35
<i>node-dirty</i>	154	463	121	1	10	331	168	142	21	57.10
<i>node-geo-point</i>	140	421	39	0	22	358	255	103	0	71.23
<i>node-jsonfile</i>	68	204	25	0	6	173	64	37	72	78.61
<i>plural</i>	153	456	96	0	29	331	244	87	0	73.72
<i>pull-stream</i>	351	1,054	262	0	10	782	465	265	52	66.11
<i>q</i>	1051	3,154	855	0	80	2,219	127	2,006	86	9.60
<i>spacel-core</i>	134	401	134	0	18	236	203	32	1	86.44
<i>zip-a-folder</i>	49	147	24	0	2	121	87	5	29	95.87
<i>Total</i>	3,376	10,130	2,656	1	325	7,121	3,398	3,423	300	—

Table 86: Results from LLMorpheus experiment (run #23). Model: *meta-llama/llama-3.3-70b-instruct*, temperature: 0.0, maxTokens: 250, template: *template-full.hb*, systemPrompt: *SystemPrompt-MutationTestingExpert.txt*.

application	#prompts	mutant candidates				#mutants	#killed	#survived	#timeout	mut. score
		total	invalid	identical	duplicate					
<i>Complex.js</i>	490	1,471	292	0	56	1,123	677	445	1	60.37
<i>countries-and-timezones</i>	106	318	65	0	13	240	205	35	0	85.42
<i>crawler-url-parser</i>	176	529	182	0	21	315	201	114	0	63.81
<i>delta</i>	462	1,388	537	0	48	803	640	126	37	84.31
<i>image-downloader</i>	42	126	44	0	5	77	45	32	0	58.44
<i>node-dirty</i>	154	463	128	1	14	320	160	141	19	55.94
<i>node-geo-point</i>	140	420	40	0	26	351	256	95	0	72.93
<i>node-jsonfile</i>	68	204	28	0	5	171	63	39	69	77.19
<i>plural</i>	153	455	91	0	25	339	239	100	0	70.50
<i>pull-stream</i>	351	1,053	265	0	12	776	462	262	52	66.24
<i>q</i>	1051	3,155	863	0	87	2,205	124	1,995	86	9.52
<i>spacel-core</i>	134	401	131	0	16	244	210	33	1	86.48
<i>zip-a-folder</i>	49	147	25	0	2	120	18	5	97	95.83
<i>Total</i>	3,376	10,130	2,691	1	330	7,084	3,300	3,422	362	—

Table 87: Results from LLMorpheus experiment (run #24). Model: *meta-llama/llama-3.3-70b-instruct*, temperature: 0.0, maxTokens: 250, template: *template-full.hb*, systemPrompt: *SystemPrompt-MutationTestingExpert.txt*.

application	#prompts	mutant candidates				#mutants	#killed	#survived	#timeout	mut. score
		total	invalid	identical	duplicate					
<i>Complex.js</i>	490	1,470	285	0	59	1,126	678	447	1	60.30
<i>countries-and-timezones</i>	106	318	67	0	11	240	199	41	0	82.92
<i>crawler-url-parser</i>	176	528	179	0	24	315	203	112	0	64.44
<i>delta</i>	462	1,387	542	0	47	798	625	134	39	83.21
<i>image-downloader</i>	42	126	46	0	4	76	45	31	0	59.21
<i>node-dirty</i>	154	465	126	2	11	326	160	146	20	55.21
<i>node-geo-point</i>	140	421	39	0	19	360	257	103	0	71.39
<i>node-jsonfile</i>	68	204	28	0	5	171	62	41	68	76.02
<i>plural</i>	153	455	93	0	26	336	245	91	0	72.92
<i>pull-stream</i>	351	1,053	270	0	8	775	467	256	52	66.97
<i>q</i>	1051	3,155	837	1	80	2,237	129	2,027	81	9.39
<i>spacel-core</i>	134	401	131	0	15	241	205	35	1	85.48
<i>zip-a-folder</i>	49	147	27	0	2	118	17	5	96	95.76
<i>Total</i>	3,376	10,130	2,670	3	311	7,119	3,292	3,469	358	—

Table 88: Results from LLMorpheus experiment (run #25). Model: *meta-llama/llama-3.3-70b-instruct*, temperature: 0.0, maxTokens: 250, template: *template-full.hb*, systemPrompt: *SystemPrompt-MutationTestingExpert.txt*.

application	#prompts	mutant candidates				#mutants	#killed	#survived	#timeout	mut. score
		total	invalid	identical	duplicate					
Complex.js	490	1,473	273	0	64	1,136	683	452	1	60.21
countries-and-timezones	106	318	62	0	13	243	208	35	0	85.60
crawler-url-parser	176	527	178	0	21	316	201	115	0	63.61
delta	462	1,388	545	0	50	793	634	128	31	83.86
image-downloader	42	128	43	0	4	81	57	24	0	70.37
node-dirty	154	464	121	1	10	332	174	140	18	57.83
node-geo-point	140	421	40	0	17	361	256	105	0	70.91
node-jsonfile	68	204	27	0	6	171	63	38	70	77.78
plural	153	460	92	0	29	339	248	91	0	73.16
pull-stream	351	1,053	266	0	9	778	464	266	48	65.81
q	1051	3,155	853	1	83	2,218	131	2,007	80	9.51
spacel-core	134	401	124	0	14	250	215	34	1	86.40
zip-a-folder	49	147	28	0	2	117	85	5	27	95.73
Total	3,376	10,139	2,652	2	322	7,135	3,419	3,440	276	—

Table 89: Results from LLMorpheus experiment (run #26). Model: *meta-llama/llama-3.3-70b-instruct*, temperature: 0.0, maxTokens: 250, template: *template-full.hb*, systemPrompt: *SystemPrompt-MutationTestingExpert.txt*.

application	#prompts	mutant candidates				#mutants	#killed	#survived	#timeout	mut. score
		total	invalid	identical	duplicate					
Complex.js	490	1,477	283	1	65	1,128	680	447	1	60.37
countries-and-timezones	106	318	67	0	12	239	201	38	0	84.10
crawler-url-parser	176	528	179	0	21	318	203	115	0	63.84
delta	462	1,387	539	0	47	801	643	120	38	85.02
image-downloader	42	127	42	0	5	80	57	23	0	71.25
node-dirty	154	463	124	1	10	328	172	140	16	57.32
node-geo-point	140	421	36	0	22	360	264	96	0	73.33
node-jsonfile	68	204	25	0	4	175	67	36	72	79.43
plural	153	453	89	0	26	338	249	89	0	73.67
pull-stream	351	1,053	269	0	8	776	467	259	50	66.62
q	1051	3,155	850	0	80	2,225	124	2,022	79	9.12
spacel-core	134	401	128	0	16	244	206	37	1	84.84
zip-a-folder	49	148	26	0	2	120	18	5	97	95.83
Total	3,376	10,135	2,657	2	318	7,132	3,351	3,427	354	—

Table 90: Results from LLMorpheus experiment (run #27). Model: *meta-llama/llama-3.3-70b-instruct*, temperature: 0.0, maxTokens: 250, template: *template-full.hb*, systemPrompt: *SystemPrompt-MutationTestingExpert.txt*.

project	time (sec)		#tokens		
	LLMorpheus	StrykerJS	prompt	compl.	total
Complex.js	2,035.43	359.18	785,856	99,437	885,293
countries-and-timezones	503.27	250.43	82,111	20,809	102,920
crawler-url-parser	810.25	606.98	283,056	35,138	318,194
delta	1,881.70	2,576.74	700,458	90,055	790,513
image-downloader	199.98	362.58	19,515	7,900	27,415
node-dirty	739.35	257.29	197,447	30,494	227,941
node-geo-point	688.13	840.31	252,643	27,340	279,983
node-jsonfile	334.39	527.30	46,029	13,579	59,608
plural	748.74	93.78	218,344	32,058	250,402
pull-stream	1,483.02	1,141.94	170,717	68,203	238,920
q	3,563.55	14,535.02	1,690,971	205,818	1,896,789
spacel-core	631.83	898.43	136,724	26,473	163,197
zip-a-folder	260.98	451.69	64,841	10,049	74,890
Total	13,880.61	22,901.67	4,648,712	667,353	5,316,065

Table 91: Results from LLMorpheus experiment (run #23). Model: *meta-llama/llama-3.3-70b-instruct*, temperature: 0.0, maxTokens: 250, template: *template-full.hb*, systemPrompt: *SystemPrompt-MutationTestingExpert.txt*

project	time (sec)		#tokens		
	<i>LLMorpheus</i>	<i>StrykerJS</i>	prompt	compl.	total
Complex.js	1,935.55	354.56	785,902	98,758	884,660
countries-and-timezones	517.60	248.81	82,111	21,228	103,339
crawler-url-parser	862.45	606.56	283,056	35,246	318,302
delta	1,894.76	2,611.62	700,458	90,310	790,768
image-downloader	197.05	453.31	19,515	7,908	27,423
node-dirty	714.96	253.07	197,447	30,659	228,106
node-geo-point	700.66	831.74	252,643	27,406	280,049
node-jsonfile	325.93	518.65	46,029	13,248	59,277
plural	791.02	95.56	218,344	32,292	250,636
pull-stream	1,417.60	1,132.73	170,717	68,708	239,425
q	3,506.09	14,435.66	1,690,971	205,518	1,896,489
spacel-core	665.00	997.34	136,724	26,424	163,148
zip-a-folder	262.84	1,296.03	64,841	10,226	75,067
<i>Total</i>	13,791.51	23,835.63	4,648,758	667,931	5,316,689

Table 92: Results from LLMorpheus experiment (run #24). Model: *meta-llama/llama-3.3-70b-instruct*, temperature: 0.0, maxTokens: 250, template: *template-full.hb*, systemPrompt: *SystemPrompt-MutationTestingExpert.txt*

project	time (sec)		#tokens		
	<i>LLMorpheus</i>	<i>StrykerJS</i>	prompt	compl.	total
Complex.js	1,951.37	356.92	785,856	99,172	885,028
countries-and-timezones	522.56	246.91	82,111	21,238	103,349
crawler-url-parser	804.63	604.74	283,056	35,252	318,308
delta	1,862.31	2,566.04	700,458	90,059	790,517
image-downloader	195.17	449.66	19,515	7,845	27,360
node-dirty	724.87	254.24	197,447	31,135	228,582
node-geo-point	664.03	860.50	252,643	27,500	280,143
node-jsonfile	353.83	501.73	46,029	13,505	59,534
plural	742.45	96.06	218,344	32,077	250,421
pull-stream	1,454.40	1,137.23	170,717	68,279	238,996
q	3,808.92	14,578.83	1,690,971	204,821	1,895,792
spacel-core	632.50	974.79	136,724	26,240	162,964
zip-a-folder	261.77	1,272.87	64,841	10,055	74,896
<i>Total</i>	13,978.80	23,900.50	4,648,712	667,178	5,315,890

Table 93: Results from LLMorpheus experiment (run #25). Model: *meta-llama/llama-3.3-70b-instruct*, temperature: 0.0, maxTokens: 250, template: *template-full.hb*, systemPrompt: *SystemPrompt-MutationTestingExpert.txt*

project	time (sec)		#tokens		
	<i>LLMorpheus</i>	<i>StrykerJS</i>	prompt	compl.	total
Complex.js	1,965.89	356.55	785,856	99,239	885,095
countries-and-timezones	520.83	252.88	82,111	21,050	103,161
crawler-url-parser	845.23	415.43	283,056	35,204	318,260
delta	1,820.88	2,526.25	700,458	90,336	790,794
image-downloader	199.63	376.57	19,515	8,115	27,630
node-dirty	732.92	248.37	197,447	30,614	228,061
node-geo-point	648.30	852.65	252,643	27,289	279,932
node-jsonfile	337.73	504.46	46,029	13,500	59,529
plural	771.86	96.38	218,344	32,276	250,620
pull-stream	1,482.72	1,117.82	170,717	68,160	238,877
q	3,818.36	14,500.22	1,690,971	205,244	1,896,215
spacel-core	661.68	1,006.28	136,724	26,127	162,851
zip-a-folder	261.75	423.42	64,841	10,119	74,960
<i>Total</i>	14,067.79	22,677.29	4,648,712	667,273	5,315,985

Table 94: Results from LLMorpheus experiment (run #26). Model: *meta-llama/llama-3.3-70b-instruct*, temperature: 0.0, maxTokens: 250, template: *template-full.hb*, systemPrompt: *SystemPrompt-MutationTestingExpert.txt*

project	time (sec)		#tokens		
	<i>LLMorpheus</i>	<i>StrykerJS</i>	prompt	compl.	total
Complex.js	1,949.16	359.45	785,856	98,758	884,614
countries-and-timezones	518.42	249.03	82,111	21,290	103,401
crawler-url-parser	843.83	610.56	283,056	35,543	318,599
delta	1,930.29	2,578.87	700,458	90,277	790,735
image-downloader	199.97	357.91	19,515	7,985	27,500
node-dirty	711.46	241.03	197,447	30,092	227,539
node-geo-point	664.09	878.84	252,643	27,234	279,877
node-jsonfile	334.95	526.44	46,029	13,288	59,317
plural	756.46	95.20	218,344	31,877	250,221
pull-stream	1,444.48	1,125.62	170,717	68,975	239,692
q	3,636.06	14,547.79	1,690,971	205,379	1,896,350
spacl-core	641.07	1,006.59	136,724	26,304	163,028
zip-a-folder	255.10	1,275.79	64,841	9,904	74,745
<i>Total</i>	13,885.34	23,853.13	4,648,712	666,906	5,315,618

Table 95: Results from LLMorpheus experiment (run #27). Model: *meta-llama/llama-3.3-70b-instruct*, temperature: 0.0, maxTokens: 250, template: *template-full.hb*, systemPrompt: *SystemPrompt-MutationTestingExpert.txt*

application	#min	#max	#distinct	#common
Complex.js	1,123	1,138	1,712	698 (40.77%)
countries-and-timezones	239	243	374	139 (37.17%)
crawler-url-parser	325	331	559	186 (33.27%)
delta	793	803	1,222	492 (40.26%)
image-downloader	76	81	131	40 (30.53%)
node-dirty	320	332	511	189 (36.99%)
node-geo-point	354	364	533	232 (43.53%)
node-jsonfile	171	175	273	97 (35.53%)
plural	331	339	598	169 (28.26%)
pull-stream	768	775	1,158	500 (43.18%)
q	2,205	2,237	2,898	1,708 (58.94%)
spacl-core	249	263	445	131 (29.44%)
zip-a-folder	117	121	172	78 (45.35%)

Table 96: Variability of the mutants generated in 5 runs of *LLMorpheus* using the *meta-llama/llama-3.3-70b-instruct* LLM at temperature 0.0 (run #23,#24,#25,#26,#27). The columns of the table show, from left to right: (i) the minimum number of mutants observed in any of the runs, (ii) the maximum number of mutants observed in any of the runs, (iii) the total number of distinct mutants observed in all runs, and (iv) the number (percentage) of mutants are observed in all runs.

1.11 Results for template-onemutation-0.0

Tables 97–106 show the results for 5 experiments with the *codellama-34b-instruct* model at temperature 0.0 using the prompt template of Figure 12 and using the system prompt shown in Figure 7.

application	#prompts	mutant candidates				#mutants	#killed	#survived	#timeout	mut. score
		total	invalid	identical	duplicate					
<i>Complex.js</i>	490	490	67	6	11	406	245	161	0	60.34
<i>countries-and-timezones</i>	106	106	24	1	2	79	65	14	0	82.28
<i>crawler-url-parser</i>	176	175	70	8	5	86	50	36	0	58.14
<i>delta</i>	462	461	182	4	9	266	221	37	8	86.09
<i>image-downloader</i>	42	42	8	0	0	34	26	8	0	76.47
<i>node-dirty</i>	154	155	50	3	3	99	55	41	3	58.59
<i>node-geo-point</i>	140	140	32	0	3	104	74	30	0	71.15
<i>node-jsonfile</i>	68	68	11	0	0	57	18	18	21	68.42
<i>plural</i>	153	153	39	8	6	100	70	30	0	70.00
<i>pull-stream</i>	351	351	67	3	1	280	165	95	20	66.07
<i>q</i>	1051	1,052	306	26	17	703	46	630	27	10.38
<i>spacel-core</i>	134	134	41	3	2	80	63	17	0	78.75
<i>zip-a-folder</i>	49	49	9	0	1	39	19	17	3	56.41
<i>Total</i>	3,376	3,376	906	62	60	2,333	1,117	1,134	82	—

Table 97: Results from LLMorpheus experiment (run #365). Model: *codellama-34b-instruct*, temperature: 0.0, maxTokens: 250, template: *template-onemutation.hb*, systemPrompt: *SystemPrompt-MutationTestingExpert.txt*.

application	#prompts	mutant candidates				#mutants	#killed	#survived	#timeout	mut. score
		total	invalid	identical	duplicate					
<i>Complex.js</i>	490	490	67	6	11	406	244	162	0	60.10
<i>countries-and-timezones</i>	106	106	24	1	2	79	66	13	0	83.54
<i>crawler-url-parser</i>	176	175	70	8	5	86	50	36	0	58.14
<i>delta</i>	462	461	181	4	9	267	222	37	8	86.14
<i>image-downloader</i>	42	42	8	0	0	34	26	8	0	76.47
<i>node-dirty</i>	154	155	50	3	3	99	55	41	3	58.59
<i>node-geo-point</i>	140	140	32	0	3	104	74	30	0	71.15
<i>node-jsonfile</i>	68	68	11	0	0	57	18	18	21	68.42
<i>plural</i>	153	153	39	8	6	100	70	30	0	70.00
<i>pull-stream</i>	351	351	67	3	1	280	164	96	20	65.71
<i>q</i>	1051	1,052	306	26	17	703	46	630	27	10.38
<i>spacel-core</i>	134	134	41	3	2	80	63	17	0	78.75
<i>zip-a-folder</i>	49	49	9	0	1	39	19	17	3	56.41
<i>Total</i>	3,376	3,376	905	62	60	2,334	1,117	1,135	82	—

Table 98: Results from LLMorpheus experiment (run #366). Model: *codellama-34b-instruct*, temperature: 0.0, maxTokens: 250, template: *template-onemutation.hb*, systemPrompt: *SystemPrompt-MutationTestingExpert.txt*.

application	#prompts	mutant candidates				#mutants	#killed	#survived	#timeout	mut. score
		total	invalid	identical	duplicate					
<i>Complex.js</i>	490	485	67	6	11	401	241	160	0	60.10
<i>countries-and-timezones</i>	106	106	24	1	2	79	66	13	0	83.54
<i>crawler-url-parser</i>	176	175	71	8	5	85	50	35	0	58.82
<i>delta</i>	462	461	181	4	9	267	222	37	8	86.14
<i>image-downloader</i>	42	42	8	0	0	34	26	8	0	76.47
<i>node-dirty</i>	154	155	50	3	3	99	55	41	3	58.59
<i>node-geo-point</i>	140	140	32	0	3	104	74	30	0	71.15
<i>node-jsonfile</i>	68	68	11	0	0	57	18	18	21	68.42
<i>plural</i>	153	153	39	7	6	101	71	30	0	70.30
<i>pull-stream</i>	351	351	67	3	1	280	165	95	20	66.07
<i>q</i>	1051	1,052	306	26	16	704	45	632	27	10.23
<i>spacel-core</i>	134	134	41	3	2	80	63	17	0	78.75
<i>zip-a-folder</i>	49	49	9	0	1	39	19	17	3	56.41
<i>Total</i>	3,376	3,371	906	61	59	2,330	1,115	1,133	82	—

Table 99: Results from LLMorpheus experiment (run #369). Model: *codellama-34b-instruct*, temperature: 0.0, maxTokens: 250, template: *template-onemutation.hb*, systemPrompt: *SystemPrompt-MutationTestingExpert.txt*.

application	#prompts	mutant candidates				#mutants	#killed	#survived	#timeout	mut. score
		total	invalid	identical	duplicate					
<i>Complex.js</i>	490	490	67	6	11	406	245	161	0	60.34
<i>countries-and-timezones</i>	106	106	24	1	2	79	66	13	0	83.54
<i>crawler-url-parser</i>	176	175	69	8	5	87	51	36	0	58.62
<i>delta</i>	462	461	182	4	9	266	221	37	8	86.09
<i>image-downloader</i>	42	42	8	0	0	34	26	8	0	76.47
<i>node-dirty</i>	154	155	50	4	3	98	55	40	3	59.18
<i>node-geo-point</i>	140	140	32	0	3	104	74	30	0	71.15
<i>node-jsonfile</i>	68	68	11	0	0	57	18	18	21	68.42
<i>plural</i>	153	153	39	7	6	101	71	30	0	70.30
<i>pull-stream</i>	351	351	67	3	1	280	165	95	20	66.07
<i>q</i>	1051	1,052	306	26	17	703	46	630	27	10.38
<i>spacl-core</i>	134	134	41	3	2	80	63	17	0	78.75
<i>zip-a-folder</i>	49	49	9	0	1	39	19	17	3	56.41
<i>Total</i>	3,376	3,376	905	62	60	2,334	1,120	1,132	82	—

Table 100: Results from LLMorpheus experiment (run #370). Model: *codellama-34b-instruct*, temperature: 0.0, maxTokens: 250, template: *template-onemutation.hb*, systemPrompt: *SystemPrompt-MutationTestingExpert.txt*.

application	#prompts	mutant candidates				#mutants	#killed	#survived	#timeout	mut. score
		total	invalid	identical	duplicate					
<i>Complex.js</i>	490	490	67	6	11	406	245	161	0	60.34
<i>countries-and-timezones</i>	106	106	24	1	2	79	66	13	0	83.54
<i>crawler-url-parser</i>	176	175	69	8	5	87	51	36	0	58.62
<i>delta</i>	462	461	182	4	9	266	221	37	8	86.09
<i>image-downloader</i>	42	42	8	0	0	34	26	8	0	76.47
<i>node-dirty</i>	154	155	50	4	3	98	55	40	3	59.18
<i>node-geo-point</i>	140	140	32	0	3	104	74	30	0	71.15
<i>node-jsonfile</i>	68	68	11	0	0	57	18	18	21	68.42
<i>plural</i>	153	153	39	7	6	101	71	30	0	70.30
<i>pull-stream</i>	351	351	67	3	1	280	165	95	20	66.07
<i>q</i>	1051	1,052	306	26	17	703	46	630	27	10.38
<i>spacl-core</i>	134	134	41	3	2	80	63	17	0	78.75
<i>zip-a-folder</i>	49	49	9	0	1	39	19	17	3	56.41
<i>Total</i>	3,376	3,376	905	62	60	2,334	1,120	1,132	82	—

Table 101: Results from LLMorpheus experiment (run #371). Model: *codellama-34b-instruct*, temperature: 0.0, maxTokens: 250, template: *template-onemutation.hb*, systemPrompt: *SystemPrompt-MutationTestingExpert.txt*.

project	time (sec)		#tokens		
	<i>LLMorpheus</i>	<i>StrykerJS</i>	prompt	compl.	total
<i>Complex.js</i>	2,784.11	210.86	927,818	39,567	967,385
<i>countries-and-timezones</i>	1,071.07	117.59	97,242	8,518	105,760
<i>crawler-url-parser</i>	1,636.44	292.18	371,967	15,504	387,471
<i>delta</i>	2,676.03	1,251.08	852,830	37,401	890,231
<i>image-downloader</i>	430.61	139.23	21,253	3,459	24,712
<i>node-dirty</i>	1,526.39	77.95	233,774	12,906	246,680
<i>node-geo-point</i>	1,411.29	330.28	304,993	11,192	316,185
<i>node-jsonfile</i>	690.81	183.43	52,008	5,846	57,854
<i>plural</i>	1,521.37	54.03	253,209	13,450	266,659
<i>pull-stream</i>	2,400.61	499.06	179,699	30,228	209,927
<i>q</i>	4,195.04	4,866.38	2,042,524	82,318	2,124,842
<i>spacl-core</i>	1,351.30	271.81	151,851	10,803	162,654
<i>zip-a-folder</i>	500.63	219.06	78,488	4,405	82,893
<i>Total</i>	22,195.69	8,512.94	5,567,656	275,597	5,843,253

Table 102: Results from LLMorpheus experiment (run #365). Model: *codellama-34b-instruct*, temperature: 0.0, maxTokens: 250, template: *template-onemutation.hb*, systemPrompt: *SystemPrompt-MutationTestingExpert.txt*

project	time (sec)		#tokens		
	<i>LLMorpheus</i>	<i>StrykerJS</i>	prompt	compl.	total
Complex.js	2,757.00	215.00	927,818	39,486	967,304
countries-and-timezones	1,091.07	116.98	97,242	8,527	105,769
crawler-url-parser	1,636.38	300.85	371,967	15,532	387,499
delta	2,681.00	1,235.39	852,830	37,383	890,213
image-downloader	460.67	139.42	21,253	3,476	24,729
node-dirty	1,526.36	75.52	233,774	12,907	246,681
node-geo-point	1,411.28	327.69	304,993	11,211	316,204
node-jsonfile	730.85	184.62	52,008	5,779	57,787
plural	1,521.30	53.73	253,209	13,418	266,627
pull-stream	2,397.86	497.98	179,699	30,310	210,009
q	4,204.99	4,839.22	2,042,524	82,262	2,124,786
spacl-core	1,351.25	273.58	151,851	10,809	162,660
zip-a-folder	500.62	219.57	78,488	4,403	82,891
<i>Total</i>	22,270.63	8,479.55	5,567,656	275,503	5,843,159

Table 103: Results from LLMorpheus experiment (run #366). Model: *codellama-34b-instruct*, temperature: 0.0, maxTokens: 250, template: *template-onemutation.hb*, systemPrompt: *SystemPrompt-MutationTestingExpert.txt*

project	time (sec)		#tokens		
	<i>LLMorpheus</i>	<i>StrykerJS</i>	prompt	compl.	total
Complex.js	2,820.16	211.48	916,945	39,061	956,006
countries-and-timezones	1,071.10	117.43	97,242	8,548	105,790
crawler-url-parser	1,636.46	288.17	371,967	15,519	387,486
delta	2,686.73	1,239.88	852,830	37,432	890,262
image-downloader	430.69	142.46	21,253	3,475	24,728
node-dirty	1,536.37	75.72	233,774	12,869	246,643
node-geo-point	1,411.33	338.80	304,993	11,209	316,202
node-jsonfile	690.78	183.73	52,008	5,845	57,853
plural	1,521.35	54.18	253,209	13,392	266,601
pull-stream	2,398.19	499.73	179,699	30,182	209,881
q	4,188.82	4,807.59	2,042,524	82,120	2,124,644
spacl-core	1,351.23	272.94	151,851	10,813	162,664
zip-a-folder	500.64	222.35	78,488	4,405	82,893
<i>Total</i>	22,243.85	8,454.47	5,556,783	274,870	5,831,653

Table 104: Results from LLMorpheus experiment (run #369). Model: *codellama-34b-instruct*, temperature: 0.0, maxTokens: 250, template: *template-onemutation.hb*, systemPrompt: *SystemPrompt-MutationTestingExpert.txt*

project	time (sec)		#tokens		
	<i>LLMorpheus</i>	<i>StrykerJS</i>	prompt	compl.	total
Complex.js	2,754.08	218.66	927,818	39,566	967,384
countries-and-timezones	1,071.03	119.64	97,242	8,579	105,821
crawler-url-parser	1,636.41	281.15	371,967	15,525	387,492
delta	2,676.11	1,249.77	852,830	37,449	890,279
image-downloader	430.60	138.45	21,253	3,475	24,728
node-dirty	1,526.42	73.92	233,774	12,859	246,633
node-geo-point	1,411.28	329.40	304,993	11,210	316,203
node-jsonfile	690.77	183.71	52,008	5,787	57,795
plural	1,521.36	53.81	253,209	13,434	266,643
pull-stream	2,397.58	499.25	179,699	30,160	209,859
q	4,211.46	4,819.77	2,042,524	82,203	2,124,727
spacl-core	1,361.19	269.34	151,851	10,818	162,669
zip-a-folder	500.61	217.85	78,488	4,400	82,888
<i>Total</i>	22,188.89	8,454.73	5,567,656	275,465	5,843,121

Table 105: Results from LLMorpheus experiment (run #370). Model: *codellama-34b-instruct*, temperature: 0.0, maxTokens: 250, template: *template-onemutation.hb*, systemPrompt: *SystemPrompt-MutationTestingExpert.txt*

project	time (sec)		#tokens		
	<i>LLMorpheus</i>	<i>StrykerJS</i>	prompt	compl.	total
Complex.js	2,763.09	214.80	927,818	39,505	967,323
countries-and-timezones	1,071.04	115.36	97,242	8,565	105,807
crawler-url-parser	1,636.32	285.19	371,967	15,616	387,583
delta	2,676.35	1,249.33	852,830	37,349	890,179
image-downloader	430.63	137.29	21,253	3,461	24,714
node-dirty	1,526.34	74.50	233,774	12,868	246,642
node-geo-point	1,411.31	337.02	304,993	11,183	316,176
node-jsonfile	690.79	183.54	52,008	5,774	57,782
plural	1,521.35	52.33	253,209	13,401	266,610
pull-stream	2,403.01	497.08	179,699	30,238	209,937
q	4,196.27	4,832.34	2,042,524	82,120	2,124,644
spacel-core	1,351.29	269.13	151,851	10,793	162,644
zip-a-folder	500.65	220.66	78,488	4,403	82,891
<i>Total</i>	22,178.44	8,468.57	5,567,656	275,276	5,842,932

Table 106: Results from LLMorpheus experiment (run #371). Model: *codellama-34b-instruct*, temperature: 0.0, maxTokens: 250, template: *template-onemutation.hb*, systemPrompt: *SystemPrompt-MutationTestingExpert.txt*

```

Your task is to apply mutation testing to the following code:
...
{{{code}}}
...

by replacing the PLACEHOLDER with a buggy code fragment that has different
behavior than the original code fragment, which was:
...
{{{orig}}}
...

Please consider changes such as using different operators, changing constants,
referring to different variables, object properties, functions, or methods.

Provide your answer as a fenced code block containing a single line of code,
using the following template:

The PLACEHOLDER can be replaced with:
...
<code fragment>
...

This would result in different behavior because <brief explanation>.

Please conclude your response with "DONE."

```

Figure 12: Variation on the template of Figure 7 that requests only one mutation.

1.12 Results for template-noexplanation-0.0

Tables 107–112 show the results for 5 experiments with the *codellama-34b-instruct* model at temperature 0.0 using the prompt template of Figure 13 and using the system prompt shown in Figure 7.

application	#prompts	mutant candidates				#mutants	#killed	#survived	#timeout	mut. score
		total	invalid	identical	duplicate					
<i>Complex.js</i>	490	1,465	276	27	37	1,125	676	448	1	60.18
<i>countries-and-timezones</i>	106	307	84	2	10	211	183	28	0	86.73
<i>crawler-url-parser</i>	176	514	216	23	19	239	140	99	0	58.58
<i>delta</i>	462	1,375	592	29	20	734	598	110	26	85.01
<i>image-downloader</i>	42	126	41	4	2	77	62	15	0	80.52
<i>node-dirty</i>	154	458	160	30	10	258	146	99	13	61.63
<i>node-geo-point</i>	140	414	103	3	9	297	216	81	0	72.73
<i>node-jsonfile</i>	68	204	48	4	0	152	54	45	53	70.39
<i>plural</i>	153	449	110	50	16	273	198	74	1	72.89
<i>pull-stream</i>	351	1,037	236	16	11	774	440	278	56	64.08
<i>q</i>	1051	3,143	1,106	122	59	1,856	138	1,635	83	11.91
<i>spacel-core</i>	134	395	143	17	5	211	175	35	1	83.41
<i>zip-a-folder</i>	49	143	41	3	1	98	27	3	68	96.94
<i>Total</i>	3,376	10,030	3,156	330	199	6,305	3,053	2,950	302	—

Table 107: Results from LLMorpheus experiment (run #372). Model: *codellama-34b-instruct*, temperature: 0.0, maxTokens: 250, template: *template-noexplanation.hb*, systemPrompt: *SystemPrompt-MutationTestingExpert.txt*.

application	#prompts	mutant candidates				#mutants	#killed	#survived	#timeout	mut. score
		total	invalid	identical	duplicate					
<i>Complex.js</i>	490	1,465	276	27	37	1,125	678	446	1	60.36
<i>countries-and-timezones</i>	106	307	84	2	10	211	183	28	0	86.73
<i>crawler-url-parser</i>	176	514	216	23	19	239	140	99	0	58.58
<i>delta</i>	462	1,375	595	28	19	733	598	108	27	85.27
<i>image-downloader</i>	42	126	41	4	2	77	62	15	0	80.52
<i>node-dirty</i>	154	458	160	30	10	258	146	99	13	61.63
<i>node-geo-point</i>	140	414	103	2	9	298	216	82	0	72.48
<i>node-jsonfile</i>	68	204	48	4	0	152	54	45	53	70.39
<i>plural</i>	153	449	110	50	16	273	198	74	1	72.89
<i>pull-stream</i>	351	1,037	236	16	11	774	439	279	56	63.95
<i>q</i>	1051	3,143	1,107	122	60	1,854	138	1,633	83	11.92
<i>spacel-core</i>	134	395	143	18	6	209	175	33	1	84.21
<i>zip-a-folder</i>	49	143	41	3	1	98	26	3	69	96.94
<i>Total</i>	3,376	10,030	3,160	329	200	6,301	3,053	2,944	304	—

Table 108: Results from LLMorpheus experiment (run #374). Model: *codellama-34b-instruct*, temperature: 0.0, maxTokens: 250, template: *template-noexplanation.hb*, systemPrompt: *SystemPrompt-MutationTestingExpert.txt*.

application	#prompts	mutant candidates				#mutants	#killed	#survived	#timeout	mut. score
		total	invalid	identical	duplicate					
<i>Complex.js</i>	490	1,465	280	27	37	1,121	674	446	1	60.21
<i>countries-and-timezones</i>	106	307	84	2	10	211	183	28	0	86.73
<i>crawler-url-parser</i>	176	514	216	23	19	239	140	99	0	58.58
<i>delta</i>	462	1,375	595	28	19	733	597	110	26	84.99
<i>image-downloader</i>	42	126	41	4	2	77	62	15	0	80.52
<i>node-dirty</i>	154	458	160	30	10	258	146	99	13	61.63
<i>node-geo-point</i>	140	414	103	2	9	298	216	82	0	72.48
<i>node-jsonfile</i>	68	204	48	4	0	152	54	45	53	70.39
<i>plural</i>	153	449	110	50	16	273	198	74	1	72.89
<i>pull-stream</i>	351	1,037	236	16	11	774	439	279	56	63.95
<i>q</i>	1051	3,143	1,107	122	59	1,855	138	1,634	83	11.91
<i>spacel-core</i>	134	396	144	18	6	209	175	33	1	84.21
<i>zip-a-folder</i>	49	143	41	3	1	98	26	3	69	96.94
<i>Total</i>	3,376	10,031	3,165	329	199	6,298	3,048	2,947	303	—

Table 109: Results from LLMorpheus experiment (run #375). Model: *codellama-34b-instruct*, temperature: 0.0, maxTokens: 250, template: *template-noexplanation.hb*, systemPrompt: *SystemPrompt-MutationTestingExpert.txt*.

application	#prompts	mutant candidates				#mutants	#killed	#survived	#timeout	mut. score
		total	invalid	identical	duplicate					
<i>Complex.js</i>	490	1,465	275	27	37	1,126	679	446	1	60.39
<i>countries-and-timezones</i>	106	307	84	2	10	211	183	28	0	86.73
<i>crawler-url-parser</i>	176	514	216	23	19	239	140	99	0	58.58
<i>delta</i>	462	1,375	598	25	19	733	597	109	27	85.13
<i>image-downloader</i>	42	126	41	4	2	77	62	15	0	80.52
<i>node-dirty</i>	154	458	160	30	10	258	146	99	13	61.63
<i>node-geo-point</i>	140	414	103	2	9	298	216	82	0	72.48
<i>node-jsonfile</i>	68	204	48	4	0	152	54	45	53	70.39
<i>plural</i>	153	449	110	50	16	273	198	74	1	72.89
<i>pull-stream</i>	351	1,037	239	16	9	773	440	277	56	64.17
<i>q</i>	1051	3,143	1,108	121	60	1,854	136	1,634	84	11.87
<i>spacl-core</i>	134	396	144	18	6	209	177	31	1	85.17
<i>zip-a-folder</i>	49	143	41	3	1	98	27	3	68	96.94
<i>Total</i>	3,376	10,031	3,167	325	198	6,301	3,055	2,942	304	—

Table 110: Results from LLMorpheus experiment (run #376). Model: *codellama-34b-instruct*, temperature: 0.0, maxTokens: 250, template: *template-noexplanation.hb*, systemPrompt: *SystemPrompt-MutationTestingExpert.txt*.

application	#prompts	mutant candidates				#mutants	#killed	#survived	#timeout	mut. score
		total	invalid	identical	duplicate					
<i>Complex.js</i>	490	1,465	276	27	37	1,125	678	446	1	60.36
<i>countries-and-timezones</i>	106	307	84	2	10	211	183	28	0	86.73
<i>crawler-url-parser</i>	176	514	213	26	19	239	140	99	0	58.58
<i>delta</i>	462	1,375	595	28	19	733	597	110	26	84.99
<i>image-downloader</i>	42	126	41	4	2	77	62	15	0	80.52
<i>node-dirty</i>	154	458	160	30	10	258	146	99	13	61.63
<i>node-geo-point</i>	140	414	106	2	9	295	213	82	0	72.20
<i>node-jsonfile</i>	68	204	48	4	0	152	54	45	53	70.39
<i>plural</i>	153	449	110	50	16	273	198	74	1	72.89
<i>pull-stream</i>	351	1,037	236	16	11	774	438	280	56	63.82
<i>q</i>	1051	3,143	1,107	121	59	1,856	137	1,635	84	11.91
<i>spacl-core</i>	134	396	144	18	6	209	175	33	1	84.21
<i>zip-a-folder</i>	49	143	41	3	1	98	27	3	68	96.94
<i>Total</i>	3,376	10,031	3,161	331	199	6,300	3,048	2,949	303	—

Table 111: Results from LLMorpheus experiment (run #377). Model: *codellama-34b-instruct*, temperature: 0.0, maxTokens: 250, template: *template-noexplanation.hb*, systemPrompt: *SystemPrompt-MutationTestingExpert.txt*.

project	time (sec)		#tokens		
	<i>LLMorpheus</i>	<i>StrykerJS</i>	prompt	compl.	total
<i>Complex.js</i>	3,056.33	600.05	948,398	75,551	1,023,949
<i>countries-and-timezones</i>	1,070.68	309.71	101,694	23,742	125,436
<i>crawler-url-parser</i>	1,656.21	778.34	379,359	31,115	410,474
<i>delta</i>	2,870.28	3,625.25	872,234	64,880	937,114
<i>image-downloader</i>	430.47	329.74	23,017	9,110	32,127
<i>node-dirty</i>	1,526.57	243.81	240,242	24,279	264,521
<i>node-geo-point</i>	1,411.01	1,009.62	310,873	26,100	336,973
<i>node-jsonfile</i>	690.59	482.67	54,864	15,154	70,018
<i>plural</i>	1,522.48	146.41	259,635	26,465	286,100
<i>pull-stream</i>	2,632.74	1,388.06	194,441	73,821	268,262
<i>q</i>	4,694.78	12,908.57	2,086,666	127,647	2,214,313
<i>spacl-core</i>	1,350.87	711.26	157,479	28,201	185,680
<i>zip-a-folder</i>	500.54	1,097.23	80,546	10,243	90,789
<i>Total</i>	23,413.56	23,630.72	5,709,448	536,308	6,245,756

Table 112: Results from LLMorpheus experiment (run #372). Model: *codellama-34b-instruct*, temperature: 0.0, maxTokens: 250, template: *template-noexplanation.hb*, systemPrompt: *SystemPrompt-MutationTestingExpert.txt*

project	time (sec)		prompt	#tokens	
	LLMorpheus	StrykerJS		compl.	total
Complex.js	3,088.22	620.07	948,398	75,464	1,023,862
countries-and-timezones	1,070.66	302.71	101,694	23,766	125,460
crawler-url-parser	1,653.80	799.42	379,359	31,089	410,448
delta	2,871.99	3,718.30	872,234	65,148	937,382
image-downloader	430.48	328.19	23,017	9,096	32,113
node-dirty	1,526.65	242.49	240,242	24,129	264,371
node-geo-point	1,410.97	985.29	310,873	26,143	337,016
node-jsonfile	690.54	481.86	54,864	15,125	69,989
plural	1,522.07	145.74	259,635	26,527	286,162
pull-stream	2,643.33	1,393.56	194,441	73,922	268,363
q	4,623.16	12,860.56	2,086,666	127,954	2,214,620
spacl-core	1,360.90	649.12	157,479	28,174	185,653
zip-a-folder	500.51	1,117.51	80,546	10,267	90,813
Total	23,393.28	23,644.84	5,709,448	536,804	6,246,252

Table 113: Results from LLMorpheus experiment (run #374). Model: *codellama-34b-instruct*, temperature: 0.0, maxTokens: 250, template: *template-noexplanation.hb*, systemPrompt: *SystemPrompt-MutationTestingExpert.txt*

project	time (sec)		prompt	#tokens	
	LLMorpheus	StrykerJS		compl.	total
Complex.js	3,054.59	596.41	948,398	75,593	1,023,991
countries-and-timezones	1,070.75	306.48	101,694	23,740	125,434
crawler-url-parser	1,653.25	791.38	379,359	31,096	410,455
delta	2,869.41	3,656.14	872,234	64,872	937,106
image-downloader	430.47	328.44	23,017	9,109	32,126
node-dirty	1,526.59	236.98	240,242	24,096	264,338
node-geo-point	1,410.99	992.09	310,873	26,143	337,016
node-jsonfile	690.55	485.04	54,864	15,130	69,994
plural	1,521.62	145.62	259,635	26,482	286,117
pull-stream	2,631.99	1,391.93	194,441	73,754	268,195
q	4,695.78	12,866.72	2,086,666	127,918	2,214,584
spacl-core	1,350.86	706.03	157,479	28,159	185,638
zip-a-folder	500.51	1,109.02	80,546	10,227	90,773
Total	23,407.38	23,612.27	5,709,448	536,319	6,245,767

Table 114: Results from LLMorpheus experiment (run #375). Model: *codellama-34b-instruct*, temperature: 0.0, maxTokens: 250, template: *template-noexplanation.hb*, systemPrompt: *SystemPrompt-MutationTestingExpert.txt*

project	time (sec)		prompt	#tokens	
	LLMorpheus	StrykerJS		compl.	total
Complex.js	3,053.84	617.90	948,398	75,377	1,023,775
countries-and-timezones	1,070.72	306.03	101,694	23,805	125,499
crawler-url-parser	1,656.36	838.63	379,359	31,102	410,461
delta	2,886.73	3,644.21	872,234	64,947	937,181
image-downloader	430.48	330.08	23,017	9,107	32,124
node-dirty	1,526.82	243.25	240,242	24,153	264,395
node-geo-point	1,410.93	999.44	310,873	26,143	337,016
node-jsonfile	690.54	480.47	54,864	15,130	69,994
plural	1,522.37	144.72	259,635	26,473	286,108
pull-stream	2,649.32	1,395.27	194,441	73,826	268,267
q	4,627.96	12,851.25	2,086,666	127,807	2,214,473
spacl-core	1,350.90	680.52	157,479	28,203	185,682
zip-a-folder	500.52	1,098.96	80,546	10,244	90,790
Total	23,377.51	23,630.74	5,709,448	536,317	6,245,765

Table 115: Results from LLMorpheus experiment (run #376). Model: *codellama-34b-instruct*, temperature: 0.0, maxTokens: 250, template: *template-noexplanation.hb*, systemPrompt: *SystemPrompt-MutationTestingExpert.txt*

project	time (sec)		#tokens		
	<i>LLMorpheus</i>	<i>StrykerJS</i>	prompt	compl.	total
Complex.js	3,048.61	622.31	948,398	75,411	1,023,809
countries-and-timezones	1,070.74	302.32	101,694	23,740	125,434
crawler-url-parser	1,653.97	835.85	379,359	30,947	410,306
delta	2,880.16	3,648.84	872,234	65,086	937,320
image-downloader	430.49	326.72	23,017	9,110	32,127
node-dirty	1,526.71	230.04	240,242	24,142	264,384
node-geo-point	1,410.98	963.40	310,873	26,313	337,186
node-jsonfile	690.67	530.41	54,864	15,130	69,994
plural	1,522.04	148.93	259,635	26,465	286,100
pull-stream	2,630.34	1,397.17	194,441	73,763	268,204
q	4,627.86	12,869.01	2,086,666	127,790	2,214,456
spacel-core	1,350.91	714.31	157,479	28,174	185,653
zip-a-folder	500.51	1,073.84	80,546	10,244	90,790
<i>Total</i>	23,344.00	23,663.14	5,709,448	536,315	6,245,763

Table 116: Results from LLMorpheus experiment (run #377). Model: *codellama-34b-instruct*, temperature: 0.0, maxTokens: 250, template: *template-noexplanation.hb*, systemPrompt: *SystemPrompt-MutationTestingExpert.txt*

```

Your task is to apply mutation testing to the following code:
...
{{{code}}}
...

by replacing the PLACEHOLDER with a buggy code fragment that has different
behavior than the original code fragment, which was:
...
{{{orig}}}
...

Please consider changes such as using different operators, changing constants,
referring to different variables, object properties, functions, or methods.

Provide three answers as fenced code blocks containing a single line of code,
using the following template:

Option 1: The PLACEHOLDER can be replaced with:
...
<code fragment>
...

Option 2: The PLACEHOLDER can be replaced with:
...
<code fragment>
...

Option 3: The PLACEHOLDER can be replaced with:
...
<code fragment>
...

Please conclude your response with "DONE."
```

Figure 13: Variation on the template of Figure 7 that does not request explanations for the suggested mutations.

1.13 Results for template-noinstructions-0.0

Tables 117–126 show the results for 5 experiments with the *codellama-34b-instruct* model at temperature 0.0 using the prompt template of Figure 14 and using the system prompt shown in Figure 7.

application	#prompts	mutant candidates				#mutants	#killed	#survived	#timeout	mut. score
		total	invalid	identical	duplicate					
<i>Complex.js</i>	490	1,453	235	36	45	1,137	696	440	1	61.30
<i>countries-and-timezones</i>	106	315	85	8	4	218	174	44	0	79.82
<i>crawler-url-parser</i>	176	518	211	23	20	246	134	112	0	54.47
<i>delta</i>	462	1,366	563	26	18	759	612	115	32	84.85
<i>image-downloader</i>	42	126	39	2	0	84	69	15	0	82.14
<i>node-dirty</i>	154	457	162	26	9	260	146	103	11	60.38
<i>node-geo-point</i>	140	413	85	7	13	306	230	76	0	75.16
<i>node-jsonfile</i>	68	200	42	9	1	148	45	51	52	65.54
<i>plural</i>	153	444	109	57	17	261	189	71	1	72.80
<i>pull-stream</i>	351	1,040	224	19	16	781	467	248	66	68.25
<i>q</i>	1051	3,130	1,019	94	59	1,958	138	1,726	94	11.85
<i>spacel-core</i>	134	395	158	30	7	187	155	31	1	83.42
<i>zip-a-folder</i>	49	144	41	5	1	97	26	4	67	95.88
<i>Total</i>	3,376	10,001	2,973	342	210	6,442	3,081	3,036	325	—

Table 117: Results from LLMorpheus experiment (run #378). Model: *codellama-34b-instruct*, temperature: 0.0, maxTokens: 250, template: *template-noinstructions.hb*, systemPrompt: *SystemPrompt-MutationTestingExpert.txt*.

application	#prompts	mutant candidates				#mutants	#killed	#survived	#timeout	mut. score
		total	invalid	identical	duplicate					
<i>Complex.js</i>	490	1,453	235	36	45	1,137	696	440	1	61.30
<i>countries-and-timezones</i>	106	315	85	8	4	218	174	44	0	79.82
<i>crawler-url-parser</i>	176	518	211	23	20	246	134	112	0	54.47
<i>delta</i>	462	1,366	563	26	18	759	610	117	32	84.58
<i>image-downloader</i>	42	126	39	2	0	84	70	14	0	83.33
<i>node-dirty</i>	154	457	162	26	9	260	146	103	11	60.38
<i>node-geo-point</i>	140	413	85	7	13	306	230	76	0	75.16
<i>node-jsonfile</i>	68	200	42	9	1	148	45	51	52	65.54
<i>plural</i>	153	444	109	57	17	261	189	71	1	72.80
<i>pull-stream</i>	351	1,040	224	19	16	781	467	248	66	68.25
<i>q</i>	1051	3,130	1,017	93	60	1,960	137	1,728	95	11.84
<i>spacel-core</i>	134	395	157	30	7	188	156	31	1	83.51
<i>zip-a-folder</i>	49	144	41	5	1	97	26	4	67	95.88
<i>Total</i>	3,376	10,001	2,970	341	211	6,445	3,080	3,039	326	—

Table 118: Results from LLMorpheus experiment (run #379). Model: *codellama-34b-instruct*, temperature: 0.0, maxTokens: 250, template: *template-noinstructions.hb*, systemPrompt: *SystemPrompt-MutationTestingExpert.txt*.

application	#prompts	mutant candidates				#mutants	#killed	#survived	#timeout	mut. score
		total	invalid	identical	duplicate					
<i>Complex.js</i>	490	1,453	235	36	45	1,137	696	440	1	61.30
<i>countries-and-timezones</i>	106	315	85	8	4	218	174	44	0	79.82
<i>crawler-url-parser</i>	176	518	211	23	20	246	134	112	0	54.47
<i>delta</i>	462	1,365	562	26	18	759	611	116	32	84.72
<i>image-downloader</i>	42	126	39	2	0	84	69	15	0	82.14
<i>node-dirty</i>	154	457	162	26	9	260	146	103	11	60.38
<i>node-geo-point</i>	140	412	84	7	13	306	230	76	0	75.16
<i>node-jsonfile</i>	68	200	42	9	1	148	45	51	52	65.54
<i>plural</i>	153	444	109	57	17	261	189	71	1	72.80
<i>pull-stream</i>	351	1,040	224	19	16	781	466	249	66	68.12
<i>q</i>	1051	3,132	1,021	94	60	1,957	137	1,727	93	11.75
<i>spacel-core</i>	134	395	158	30	7	187	155	31	1	83.42
<i>zip-a-folder</i>	49	144	41	5	1	97	26	4	67	95.88
<i>Total</i>	3,376	10,001	2,973	342	211	6,441	3,078	3,039	324	—

Table 119: Results from LLMorpheus experiment (run #380). Model: *codellama-34b-instruct*, temperature: 0.0, maxTokens: 250, template: *template-noinstructions.hb*, systemPrompt: *SystemPrompt-MutationTestingExpert.txt*.

application	#prompts	mutant candidates				#mutants	#killed	#survived	#timeout	mut. score
		total	invalid	identical	duplicate					
Complex.js	490	1,452	234	36	46	1,136	695	440	1	61.27
countries-and-timezones	106	315	85	8	4	218	174	44	0	79.82
crawler-url-parser	176	518	211	23	20	246	134	112	0	54.47
delta	462	1,366	563	26	18	759	612	115	32	84.85
image-downloader	42	126	39	2	0	84	70	14	0	83.33
node-dirty	154	457	162	26	9	260	147	102	11	60.77
node-geo-point	140	413	85	7	13	306	230	76	0	75.16
node-jsonfile	68	200	42	9	1	148	45	51	52	65.54
plural	153	445	109	57	17	262	189	72	1	72.52
pull-stream	351	1,040	226	19	16	779	464	249	66	68.04
q	1051	3,131	1,019	96	60	1,956	138	1,725	93	11.81
spacel-core	134	395	158	30	7	187	155	31	1	83.42
zip-a-folder	49	144	41	5	1	97	26	4	67	95.88
Total	3,376	10,002	2,974	344	212	6,438	3,079	3,035	324	—

Table 120: Results from LLMorpheus experiment (run #381). Model: *codellama-34b-instruct*, temperature: 0.0, maxTokens: 250, template: *template-noinstructions.hb*, systemPrompt: *SystemPrompt-MutationTestingExpert.txt*.

application	#prompts	mutant candidates				#mutants	#killed	#survived	#timeout	mut. score
		total	invalid	identical	duplicate					
Complex.js	490	1,453	235	36	45	1,137	696	440	1	61.30
countries-and-timezones	106	315	85	8	4	218	174	44	0	79.82
crawler-url-parser	176	518	211	23	20	246	134	112	0	54.47
delta	462	1,366	563	26	18	759	612	115	32	84.85
image-downloader	42	126	39	2	0	84	69	15	0	82.14
node-dirty	154	457	159	26	10	262	149	102	11	61.07
node-geo-point	140	413	85	7	13	306	230	76	0	75.16
node-jsonfile	68	200	42	9	1	148	45	51	52	65.54
plural	153	443	108	57	17	261	189	71	1	72.80
pull-stream	351	1,040	226	19	16	779	465	248	66	68.16
q	1051	3,130	1,019	93	60	1,958	137	1,728	93	11.75
spacel-core	134	395	158	30	7	187	155	31	1	83.42
zip-a-folder	49	144	41	5	1	97	26	4	67	95.88
Total	3,376	10,000	2,971	341	212	6,442	3,081	3,037	324	—

Table 121: Results from LLMorpheus experiment (run #382). Model: *codellama-34b-instruct*, temperature: 0.0, maxTokens: 250, template: *template-noinstructions.hb*, systemPrompt: *SystemPrompt-MutationTestingExpert.txt*.

project	time (sec)		#tokens		
	LLMorpheus	StrykerJS	prompt	compl.	total
Complex.js	3,363.13	610.09	953,788	104,944	1,058,732
countries-and-timezones	1,070.70	333.60	102,860	23,506	126,366
crawler-url-parser	1,668.12	865.68	381,295	38,817	420,112
delta	3,242.91	4,060.50	877,316	99,522	976,838
image-downloader	430.47	361.71	23,479	8,905	32,384
node-dirty	1,530.58	228.43	241,936	33,033	274,969
node-geo-point	1,410.89	1,019.95	312,413	28,975	341,388
node-jsonfile	690.55	469.01	55,612	14,598	70,210
plural	1,523.05	141.16	261,318	34,491	295,809
pull-stream	2,608.43	1,433.25	198,302	74,144	272,446
q	5,802.92	13,526.38	2,098,227	218,277	2,316,504
spacel-core	1,350.79	626.46	158,953	29,519	188,472
zip-a-folder	500.51	1,087.03	81,085	10,694	91,779
Total	25,193.04	24,763.25	5,746,584	719,425	6,466,009

Table 122: Results from LLMorpheus experiment (run #378). Model: *codellama-34b-instruct*, temperature: 0.0, maxTokens: 250, template: *template-noinstructions.hb*, systemPrompt: *SystemPrompt-MutationTestingExpert.txt*

project	time (sec)		prompt	#tokens	
	LLMorpheus	StrykerJS		compl.	total
Complex.js	3,324.82	606.13	953,788	104,909	1,058,697
countries-and-timezones	1,070.79	314.67	102,860	23,502	126,362
crawler-url-parser	1,673.87	789.35	381,295	38,816	420,111
delta	3,186.56	3,835.89	877,316	99,463	976,779
image-downloader	430.46	362.97	23,479	8,961	32,440
node-dirty	1,530.82	229.51	241,936	33,036	274,972
node-geo-point	1,410.92	1,035.06	312,413	28,975	341,388
node-jsonfile	691.16	471.51	55,612	14,598	70,210
plural	1,523.31	142.93	261,318	34,484	295,802
pull-stream	2,610.16	1,428.74	198,302	74,195	272,497
q	5,806.23	13,570.79	2,098,227	218,057	2,316,284
spacl-core	1,350.78	598.84	158,953	29,457	188,410
zip-a-folder	500.50	1,065.03	81,085	10,694	91,779
Total	25,110.38	24,451.42	5,746,584	719,147	6,465,731

Table 123: Results from LLMorpheus experiment (run #379). Model: *codellama-34b-instruct*, temperature: 0.0, maxTokens: 250, template: *template-noinstructions.hb*, systemPrompt: *SystemPrompt-MutationTestingExpert.txt*

project	time (sec)		prompt	#tokens	
	LLMorpheus	StrykerJS		compl.	total
Complex.js	3,340.83	597.34	953,788	105,056	1,058,844
countries-and-timezones	1,070.75	323.54	102,860	23,502	126,362
crawler-url-parser	1,659.88	803.01	381,295	38,801	420,096
delta	3,211.07	3,830.91	877,316	99,521	976,837
image-downloader	430.47	362.10	23,479	8,905	32,384
node-dirty	1,530.67	228.98	241,936	33,033	274,969
node-geo-point	1,410.92	997.90	312,413	29,053	341,466
node-jsonfile	690.56	466.32	55,612	14,598	70,210
plural	1,522.82	141.80	261,318	34,484	295,802
pull-stream	2,609.79	1,444.02	198,302	74,220	272,522
q	6,945.19	13,543.90	2,098,227	218,309	2,316,536
spacl-core	1,350.87	605.57	158,953	29,527	188,480
zip-a-folder	500.50	1,075.42	81,085	10,694	91,779
Total	26,274.31	24,420.80	5,746,584	719,703	6,466,287

Table 124: Results from LLMorpheus experiment (run #380). Model: *codellama-34b-instruct*, temperature: 0.0, maxTokens: 250, template: *template-noinstructions.hb*, systemPrompt: *SystemPrompt-MutationTestingExpert.txt*

project	time (sec)		prompt	#tokens	
	LLMorpheus	StrykerJS		compl.	total
Complex.js	3,492.66	629.00	953,788	104,886	1,058,674
countries-and-timezones	1,177.99	323.34	102,860	23,502	126,362
crawler-url-parser	1,751.37	786.06	381,295	38,800	420,095
delta	3,365.20	3,872.79	877,316	99,562	976,878
image-downloader	441.26	358.96	23,479	8,961	32,440
node-dirty	1,608.97	228.53	241,936	33,053	274,989
node-geo-point	1,492.54	1,035.93	312,413	28,984	341,397
node-jsonfile	717.49	465.56	55,612	14,548	70,160
plural	1,630.97	140.39	261,318	34,444	295,762
pull-stream	2,738.37	1,433.35	198,302	74,222	272,524
q	6,155.10	13,521.99	2,098,227	218,163	2,316,390
spacl-core	1,440.32	585.59	158,953	29,512	188,465
zip-a-folder	509.75	1,063.09	81,085	10,694	91,779
Total	26,522.01	24,444.59	5,746,584	719,331	6,465,915

Table 125: Results from LLMorpheus experiment (run #381). Model: *codellama-34b-instruct*, temperature: 0.0, maxTokens: 250, template: *template-noinstructions.hb*, systemPrompt: *SystemPrompt-MutationTestingExpert.txt*

project	time (sec)		#tokens		
	<i>LLMorpheus</i>	<i>StrykerJS</i>	prompt	compl.	total
Complex.js	3,378.96	601.89	953,788	104,940	1,058,728
countries-and-timezones	1,080.75	325.94	102,860	23,502	126,362
crawler-url-parser	1,660.11	741.99	381,295	38,801	420,096
delta	3,233.82	3,810.62	877,316	99,525	976,841
image-downloader	430.46	361.68	23,479	8,905	32,384
node-dirty	1,531.35	234.89	241,936	33,044	274,980
node-geo-point	1,410.90	1,014.28	312,413	28,969	341,382
node-jsonfile	690.54	466.32	55,612	14,598	70,210
plural	1,523.06	136.58	261,318	34,492	295,810
pull-stream	2,606.22	1,436.07	198,302	74,135	272,437
q	5,921.20	13,597.41	2,098,227	218,214	2,316,441
spacel-core	1,350.81	585.65	158,953	29,520	188,473
zip-a-folder	500.48	1,078.08	81,085	10,745	91,830
<i>Total</i>	25,318.67	24,391.40	5,746,584	719,390	6,465,974

Table 126: Results from LLMorpheus experiment (run #382). Model: *codellama-34b-instruct*, temperature: 0.0, maxTokens: 250, template: *template-noinstructions.hb*, systemPrompt: *SystemPrompt-MutationTestingExpert.txt*

```

Your task is to apply mutation testing to the following code:
...
{{{code}}}
...

by replacing the PLACEHOLDER with a buggy code fragment that has different
behavior than the original code fragment, which was:
...
{{{orig}}}
...

Provide three answers as fenced code blocks containing a single line of code,
using the following template:

Option 1: The PLACEHOLDER can be replaced with:
...
<code fragment>
...
This would result in different behavior because <brieif explanation>.

Option 2: The PLACEHOLDER can be replaced with:
...
<code fragment>
...
This would result in different behavior because <brieif explanation>.

Option 3: The PLACEHOLDER can be replaced with:
...
<code fragment>
...
This would result in different behavior because <brieif explanation>.

Please conclude your response with "DONE."
```

Figure 14: Variation on the template of Figure 7 that does not provide instructions on how to create mutants.

1.14 Results for template-full-genericssystemprompt-0.0

Tables 127–136 show the results for 5 experiments with the *codellama-34b-instruct* model at temperature 0.0 using the prompt template of Figure 7 and the generic system prompt of Figure 15.

application	#prompts	mutant candidates				#mutants	#killed	#survived	#timeout	mut. score
		total	invalid	identical	duplicate					
<i>Complex.js</i>	490	1,459	201	9	50	1,199	740	458	1	61.80
<i>countries-and-timezones</i>	106	316	90	0	9	217	191	26	0	88.02
<i>crawler-url-parser</i>	176	522	226	16	19	246	143	103	0	58.13
<i>delta</i>	462	1,373	553	7	23	790	659	99	32	87.47
<i>image-downloader</i>	42	123	34	1	0	88	72	16	0	81.82
<i>node-dirty</i>	154	450	153	12	8	277	162	104	11	62.45
<i>node-geo-point</i>	140	414	95	1	11	305	229	76	0	75.08
<i>node-jsonfile</i>	68	199	47	2	0	150	49	49	52	67.33
<i>plural</i>	153	442	104	45	21	272	209	62	1	77.21
<i>pull-stream</i>	351	1,039	252	15	9	763	442	266	55	65.14
<i>q</i>	1051	3,128	1,037	30	54	2,007	145	1,770	92	11.81
<i>spacel-core</i>	134	397	146	12	8	214	181	32	1	85.05
<i>zip-a-folder</i>	49	145	40	1	2	101	27	3	71	97.03
<i>Total</i>	3,376	10,007	2,978	151	214	6,629	3,249	3,064	316	—

Table 127: Results from LLMorpheus experiment (run #384). Model: *codellama-34b-instruct*, temperature: 0.0, maxTokens: 250, template: *template-full.hb*, systemPrompt: *SystemPrompt-Generic.txt*.

application	#prompts	mutant candidates				#mutants	#killed	#survived	#timeout	mut. score
		total	invalid	identical	duplicate					
<i>Complex.js</i>	490	1,459	201	9	50	1,199	740	458	1	61.80
<i>countries-and-timezones</i>	106	316	90	0	9	217	191	26	0	88.02
<i>crawler-url-parser</i>	176	522	226	16	19	246	143	103	0	58.13
<i>delta</i>	462	1,372	555	6	23	788	657	99	32	87.44
<i>image-downloader</i>	42	123	34	1	0	88	72	16	0	81.82
<i>node-dirty</i>	154	450	153	12	8	277	162	104	11	62.45
<i>node-geo-point</i>	140	414	95	1	11	305	229	76	0	75.08
<i>node-jsonfile</i>	68	200	47	2	0	151	49	49	53	67.55
<i>plural</i>	153	443	105	45	21	272	209	62	1	77.21
<i>pull-stream</i>	351	1,040	252	15	9	764	443	266	55	65.18
<i>q</i>	1051	3,127	1,035	30	54	2,008	145	1,771	92	11.80
<i>spacel-core</i>	134	397	146	12	8	214	181	32	1	85.05
<i>zip-a-folder</i>	49	145	40	1	2	101	27	3	71	97.03
<i>Total</i>	3,376	10,008	2,979	150	214	6,630	3,248	3,065	317	—

Table 128: Results from LLMorpheus experiment (run #385). Model: *codellama-34b-instruct*, temperature: 0.0, maxTokens: 250, template: *template-full.hb*, systemPrompt: *SystemPrompt-Generic.txt*.

application	#prompts	mutant candidates				#mutants	#killed	#survived	#timeout	mut. score
		total	invalid	identical	duplicate					
<i>Complex.js</i>	490	1,459	201	9	50	1,199	740	458	1	61.80
<i>countries-and-timezones</i>	106	316	90	0	9	217	191	26	0	88.02
<i>crawler-url-parser</i>	176	522	226	16	19	246	143	103	0	58.13
<i>delta</i>	462	1,373	551	6	24	792	660	100	32	87.37
<i>image-downloader</i>	42	123	34	1	0	88	72	16	0	81.82
<i>node-dirty</i>	154	450	153	12	8	277	162	104	11	62.45
<i>node-geo-point</i>	140	415	96	1	11	305	229	76	0	75.08
<i>node-jsonfile</i>	68	200	47	2	0	151	49	49	53	67.55
<i>plural</i>	153	442	106	45	21	270	207	62	1	77.04
<i>pull-stream</i>	351	1,039	252	15	9	763	440	268	55	64.88
<i>q</i>	1051	3,127	1,035	30	55	2,007	144	1,771	92	11.76
<i>spacel-core</i>	134	396	146	12	8	216	183	32	1	85.19
<i>zip-a-folder</i>	49	145	40	1	2	101	27	3	71	97.03
<i>Total</i>	3,376	10,007	2,977	150	216	6,632	3,247	3,068	317	—

Table 129: Results from LLMorpheus experiment (run #386). Model: *codellama-34b-instruct*, temperature: 0.0, maxTokens: 250, template: *template-full.hb*, systemPrompt: *SystemPrompt-Generic.txt*.

application	#prompts	mutant candidates				#mutants	#killed	#survived	#timeout	mut. score
		total	invalid	identical	duplicate					
Complex.js	490	1,459	201	9	49	1,200	741	458	1	61.83
countries-and-timezones	106	316	90	0	9	217	191	26	0	88.02
crawler-url-parser	176	522	226	16	19	246	144	102	0	58.54
delta	462	1,372	551	6	24	791	659	100	32	87.36
image-downloader	42	123	34	1	0	88	72	16	0	81.82
node-dirty	154	450	153	12	8	277	163	103	11	62.82
node-geo-point	140	414	95	1	11	305	229	76	0	75.08
node-jsonfile	68	200	47	2	0	151	49	49	53	67.55
plural	153	442	106	45	21	270	207	62	1	77.04
pull-stream	351	1,039	252	15	9	763	442	266	55	65.14
q	1051	3,125	1,036	29	54	2,006	144	1,770	92	11.76
spacl-core	134	397	146	12	8	214	181	32	1	85.05
zip-a-folder	49	145	40	1	2	101	27	3	71	97.03
Total	3,376	10,004	2,977	149	214	6,629	3,249	3,063	317	—

Table 130: Results from LLMorpheus experiment (run #387). Model: *codellama-34b-instruct*, temperature: 0.0, maxTokens: 250, template: *template-full.hb*, systemPrompt: *SystemPrompt-Generic.txt*.

application	#prompts	mutant candidates				#mutants	#killed	#survived	#timeout	mut. score
		total	invalid	identical	duplicate					
Complex.js	490	1,459	201	9	50	1,199	740	458	1	61.80
countries-and-timezones	106	292	81	0	9	202	179	23	0	88.61
crawler-url-parser	176	522	226	16	19	246	143	103	0	58.13
delta	462	1,373	551	6	24	792	660	100	32	87.37
image-downloader	42	123	34	1	0	88	72	16	0	81.82
node-dirty	154	450	153	12	8	277	162	104	11	62.45
node-geo-point	140	414	95	1	11	305	229	76	0	75.08
node-jsonfile	68	200	47	2	0	151	49	49	53	67.55
plural	153	442	104	45	21	272	209	62	1	77.21
pull-stream	351	1,039	252	15	9	763	442	266	55	65.14
q	1051	3,127	1,039	30	53	2,005	146	1,768	91	11.82
spacl-core	134	397	145	12	8	215	182	32	1	85.12
zip-a-folder	49	145	40	1	2	101	27	3	71	97.03
Total	3,376	9,983	2,968	150	214	6,616	3,240	3,060	316	—

Table 131: Results from LLMorpheus experiment (run #388). Model: *codellama-34b-instruct*, temperature: 0.0, maxTokens: 250, template: *template-full.hb*, systemPrompt: *SystemPrompt-Generic.txt*.

project	time (sec)		#tokens		
	LLMorpheus	StrykerJS	prompt	compl.	total
Complex.js	3,198.91	631.03	943,498	97,397	1,040,895
countries-and-timezones	1,070.69	306.50	100,634	22,822	123,456
crawler-url-parser	1,666.72	773.61	377,599	38,968	416,567
delta	3,188.39	3,973.51	867,614	96,702	964,316
image-downloader	430.51	376.36	22,597	8,748	31,345
node-dirty	1,531.02	243.07	238,702	32,642	271,344
node-geo-point	1,410.94	993.80	309,473	28,703	338,176
node-jsonfile	690.59	470.19	54,184	13,966	68,150
plural	1,523.29	146.19	258,105	33,232	291,337
pull-stream	2,621.42	1,374.37	190,931	73,130	264,061
q	5,911.30	13,892.03	2,076,156	216,002	2,292,158
spacl-core	1,350.90	688.46	156,139	28,052	184,191
zip-a-folder	500.50	1,139.30	80,056	10,370	90,426
Total	25,095.20	25,008.45	5,675,688	700,734	6,376,422

Table 132: Results from LLMorpheus experiment (run #384). Model: *codellama-34b-instruct*, temperature: 0.0, maxTokens: 250, template: *template-full.hb*, systemPrompt: *SystemPrompt-Generic.txt*

You are a programming assistant. You are expected to be concise and precise and avoid any unnecessary examples, tests, and verbosity.

Figure 15: Generic system prompt.

project	time (sec)		prompt	#tokens	
	<i>LLMorpheus</i>	<i>StrykerJS</i>		compl.	total
Complex.js	3,198.28	628.16	943,498	97,360	1,040,858
countries-and-timezones	1,070.75	313.88	100,634	22,817	123,451
crawler-url-parser	1,667.00	785.35	377,599	38,968	416,567
delta	3,193.53	4,061.32	867,614	96,672	964,286
image-downloader	430.50	373.49	22,597	8,748	31,345
node-dirty	1,530.73	243.51	238,702	32,641	271,343
node-geo-point	1,411.00	1,029.33	309,473	28,703	338,176
node-jsonfile	690.57	473.38	54,184	13,976	68,160
plural	1,523.28	142.88	258,105	33,183	291,288
pull-stream	2,622.56	1,368.80	190,931	73,002	263,933
q	5,761.33	13,943.75	2,076,156	216,075	2,292,231
spacl-core	1,350.88	668.94	156,139	28,048	184,187
zip-a-folder	500.52	1,170.72	80,056	10,370	90,426
<i>Total</i>	24,950.92	25,203.51	5,675,688	700,563	6,376,251

Table 133: Results from LLMorpheus experiment (run #385). Model: *codellama-34b-instruct*, temperature: 0.0, maxTokens: 250, template: *template-full.hb*, systemPrompt: *SystemPrompt-Generic.txt*

project	time (sec)		prompt	#tokens	
	<i>LLMorpheus</i>	<i>StrykerJS</i>		compl.	total
Complex.js	3,246.58	637.01	943,498	97,351	1,040,849
countries-and-timezones	1,070.74	317.35	100,634	22,822	123,456
crawler-url-parser	1,666.54	828.48	377,599	38,968	416,567
delta	3,141.81	3,972.35	867,614	96,648	964,262
image-downloader	430.53	375.91	22,597	8,740	31,337
node-dirty	1,531.64	237.14	238,702	32,632	271,334
node-geo-point	1,410.80	1,007.52	309,473	28,670	338,143
node-jsonfile	690.60	479.57	54,184	13,982	68,166
plural	1,523.32	141.62	258,105	33,221	291,326
pull-stream	2,590.59	1,371.20	190,931	73,097	264,028
q	5,912.17	13,970.49	2,076,156	216,015	2,292,171
spacl-core	1,461.05	690.80	156,139	28,074	184,213
zip-a-folder	500.51	1,128.17	80,056	10,370	90,426
<i>Total</i>	25,176.88	25,157.62	5,675,688	700,590	6,376,278

Table 134: Results from LLMorpheus experiment (run #386). Model: *codellama-34b-instruct*, temperature: 0.0, maxTokens: 250, template: *template-full.hb*, systemPrompt: *SystemPrompt-Generic.txt*

project	time (sec)		prompt	#tokens	
	<i>LLMorpheus</i>	<i>StrykerJS</i>		compl.	total
Complex.js	3,229.79	627.53	943,498	97,331	1,040,829
countries-and-timezones	1,070.66	315.55	100,634	22,813	123,447
crawler-url-parser	1,677.85	830.94	377,599	39,015	416,614
delta	3,135.61	3,928.08	867,614	96,647	964,261
image-downloader	430.47	374.42	22,597	8,748	31,345
node-dirty	1,530.49	236.58	238,702	32,642	271,344
node-geo-point	1,410.83	1,012.70	309,473	28,703	338,176
node-jsonfile	690.54	473.16	54,184	13,999	68,183
plural	1,523.30	142.61	258,105	33,221	291,326
pull-stream	2,590.76	1,370.63	190,931	73,109	264,040
q	5,913.75	13,931.58	2,076,156	216,172	2,292,328
spacl-core	1,350.92	677.55	156,139	28,048	184,187
zip-a-folder	500.55	1,132.09	80,056	10,370	90,426
<i>Total</i>	25,055.51	25,053.41	5,675,688	700,818	6,376,506

Table 135: Results from LLMorpheus experiment (run #387). Model: *codellama-34b-instruct*, temperature: 0.0, maxTokens: 250, template: *template-full.hb*, systemPrompt: *SystemPrompt-Generic.txt*

project	time (sec)		#tokens		
	<i>LLMorpheus</i>	<i>StrykerJS</i>	prompt	compl.	total
Complex.js	3,200.91	614.84	943,498	97,375	1,040,873
countries-and-timezones	1,501.26	297.33	95,530	21,102	116,632
crawler-url-parser	1,664.69	819.62	377,599	38,970	416,569
delta	3,159.72	4,099.01	867,614	96,624	964,238
image-downloader	430.49	373.69	22,597	8,748	31,345
node-dirty	1,555.91	239.75	238,702	32,632	271,334
node-geo-point	1,410.92	994.48	309,473	28,709	338,182
node-jsonfile	690.59	467.78	54,184	13,996	68,180
plural	1,523.33	146.45	258,105	33,232	291,337
pull-stream	2,596.08	1,354.67	190,931	73,098	264,029
q	5,912.23	13,931.75	2,076,156	216,129	2,292,285
spacl-core	1,350.85	689.90	156,139	28,037	184,176
zip-a-folder	530.56	1,147.59	80,056	10,370	90,426
<i>Total</i>	25,527.53	25,176.85	5,670,584	699,022	6,369,606

Table 136: Results from LLMorpheus experiment (run #388). Model: *codellama-34b-instruct*, temperature: 0.0, maxTokens: 250, template: *template-full.hb*, systemPrompt: *SystemPrompt-Generic.txt*

1.15 Results for template-basic-0.0

Tables 137–146 show the results for 5 experiments with the *codellama-34b-instruct* model at temperature 0.0 using the prompt template of Figure 16 and using the system prompt shown in Figure 7.

application	#prompts	mutant candidates				#mutants	#killed	#survived	#timeout	mut. score
		total	invalid	identical	duplicate					
<i>Complex.js</i>	490	490	212	92	1	185	120	65	0	64.86
<i>countries-and-timezones</i>	106	106	36	22	0	48	44	4	0	91.67
<i>crawler-url-parser</i>	176	176	75	27	1	67	49	18	0	73.13
<i>delta</i>	462	462	201	54	6	201	167	28	6	86.07
<i>image-downloader</i>	42	42	21	11	0	10	7	3	0	70.00
<i>node-dirty</i>	154	154	70	38	2	44	24	18	2	59.09
<i>node-geo-point</i>	140	140	39	33	6	62	54	8	0	87.10
<i>node-jsonfile</i>	68	68	17	28	1	22	11	3	8	86.36
<i>plural</i>	153	152	35	21	4	92	78	14	0	84.78
<i>pull-stream</i>	351	351	115	87	0	149	88	54	7	63.76
<i>q</i>	1051	1,051	405	232	13	401	38	350	13	12.72
<i>spacel-core</i>	134	134	65	37	1	25	23	2	0	92.00
<i>zip-a-folder</i>	49	49	18	11	0	20	5	1	14	95.00
<i>Total</i>	3,376	3,375	1,309	693	35	1,326	708	568	50	—

Table 137: Results from LLMorpheus experiment (run #390). Model: *codellama-34b-instruct*, temperature: 0.0, maxTokens: 250, template: *template-basic.hb*, systemPrompt: *SystemPrompt-MutationTestingExpert.txt*.

application	#prompts	mutant candidates				#mutants	#killed	#survived	#timeout	mut. score
		total	invalid	identical	duplicate					
<i>Complex.js</i>	490	490	213	92	1	184	119	65	0	64.67
<i>countries-and-timezones</i>	106	106	36	22	0	48	43	5	0	89.58
<i>crawler-url-parser</i>	176	176	75	27	1	67	49	18	0	73.13
<i>delta</i>	462	462	200	54	6	202	168	28	6	86.14
<i>image-downloader</i>	42	42	21	11	0	10	7	3	0	70.00
<i>node-dirty</i>	154	154	70	38	2	44	24	18	2	59.09
<i>node-geo-point</i>	140	140	39	33	6	62	54	8	0	87.10
<i>node-jsonfile</i>	68	68	17	28	1	22	11	3	8	86.36
<i>plural</i>	153	152	35	21	4	92	78	14	0	84.78
<i>pull-stream</i>	351	351	115	87	0	149	88	54	7	63.76
<i>q</i>	1051	1,051	405	232	13	401	38	350	13	12.72
<i>spacel-core</i>	134	134	65	37	1	25	23	2	0	92.00
<i>zip-a-folder</i>	49	49	18	11	0	20	5	1	14	95.00
<i>Total</i>	3,376	3,375	1,309	693	35	1,326	707	569	50	—

Table 138: Results from LLMorpheus experiment (run #391). Model: *codellama-34b-instruct*, temperature: 0.0, maxTokens: 250, template: *template-basic.hb*, systemPrompt: *SystemPrompt-MutationTestingExpert.txt*.

application	#prompts	mutant candidates				#mutants	#killed	#survived	#timeout	mut. score
		total	invalid	identical	duplicate					
<i>Complex.js</i>	490	490	213	92	1	184	119	65	0	64.67
<i>countries-and-timezones</i>	106	106	36	22	0	48	43	5	0	89.58
<i>crawler-url-parser</i>	176	176	75	27	1	67	49	18	0	73.13
<i>delta</i>	462	462	201	54	6	201	167	28	6	86.07
<i>image-downloader</i>	42	42	21	11	0	10	7	3	0	70.00
<i>node-dirty</i>	154	154	71	38	2	43	24	17	2	60.47
<i>node-geo-point</i>	140	140	39	33	6	62	54	8	0	87.10
<i>node-jsonfile</i>	68	68	17	28	1	22	11	3	8	86.36
<i>plural</i>	153	152	35	21	4	92	78	14	0	84.78
<i>pull-stream</i>	351	351	115	87	0	149	88	54	7	63.76
<i>q</i>	1051	1,051	405	231	13	402	38	351	13	12.69
<i>spacel-core</i>	134	134	65	37	1	25	23	2	0	92.00
<i>zip-a-folder</i>	49	49	18	11	0	20	5	1	14	95.00
<i>Total</i>	3,376	3,375	1,311	692	35	1,325	706	569	50	—

Table 139: Results from LLMorpheus experiment (run #392). Model: *codellama-34b-instruct*, temperature: 0.0, maxTokens: 250, template: *template-basic.hb*, systemPrompt: *SystemPrompt-MutationTestingExpert.txt*.

application	#prompts	mutant candidates				#mutants	#killed	#survived	#timeout	mut. score
		total	invalid	identical	duplicate					
<i>Complex.js</i>	490	490	213	92	1	184	119	65	0	64.67
<i>countries-and-timezones</i>	106	106	36	22	0	48	43	5	0	89.58
<i>crawler-url-parser</i>	176	176	75	27	1	67	49	18	0	73.13
<i>delta</i>	462	462	201	54	6	201	167	28	6	86.07
<i>image-downloader</i>	42	42	21	11	0	10	7	3	0	70.00
<i>node-dirty</i>	154	154	70	38	2	44	24	18	2	59.09
<i>node-geo-point</i>	140	140	39	33	6	62	54	8	0	87.10
<i>node-jsonfile</i>	68	68	17	28	1	22	11	3	8	86.36
<i>plural</i>	153	150	35	20	4	91	78	13	0	85.71
<i>pull-stream</i>	351	351	115	87	0	149	88	54	7	63.76
<i>q</i>	1051	1,051	405	231	13	402	38	351	13	12.69
<i>spacel-core</i>	134	134	65	37	1	25	23	2	0	92.00
<i>zip-a-folder</i>	49	49	18	11	0	20	5	1	14	95.00
<i>Total</i>	3,376	3,373	1,310	691	35	1,325	706	569	50	—

Table 140: Results from LLMorpheus experiment (run #393). Model: *codellama-34b-instruct*, temperature: 0.0, maxTokens: 250, template: *template-basic.hb*, systemPrompt: *SystemPrompt-MutationTestingExpert.txt*.

application	#prompts	mutant candidates				#mutants	#killed	#survived	#timeout	mut. score
		total	invalid	identical	duplicate					
<i>Complex.js</i>	490	490	212	92	1	185	120	65	0	64.86
<i>countries-and-timezones</i>	106	106	36	22	0	48	44	4	0	91.67
<i>crawler-url-parser</i>	176	176	75	27	1	67	49	18	0	73.13
<i>delta</i>	462	462	202	54	6	200	166	28	6	86.00
<i>image-downloader</i>	42	42	21	11	0	10	7	3	0	70.00
<i>node-dirty</i>	154	154	71	38	2	43	24	17	2	60.47
<i>node-geo-point</i>	140	140	39	33	6	62	54	8	0	87.10
<i>node-jsonfile</i>	68	68	17	28	1	22	11	3	8	86.36
<i>plural</i>	153	152	35	21	4	92	78	14	0	84.78
<i>pull-stream</i>	351	351	115	87	0	149	88	54	7	63.76
<i>q</i>	1051	1,051	404	232	13	402	38	351	13	12.69
<i>spacel-core</i>	134	134	65	37	1	25	23	2	0	92.00
<i>zip-a-folder</i>	49	49	18	11	0	20	5	1	14	95.00
<i>Total</i>	3,376	3,375	1,310	693	35	1,325	707	568	50	—

Table 141: Results from LLMorpheus experiment (run #394). Model: *codellama-34b-instruct*, temperature: 0.0, maxTokens: 250, template: *template-basic.hb*, systemPrompt: *SystemPrompt-MutationTestingExpert.txt*.

project	time (sec)		#tokens		
	<i>LLMorpheus</i>	<i>StrykerJS</i>	prompt	compl.	total
<i>Complex.js</i>	2,731.54	97.72	893,966	14,460	908,426
<i>countries-and-timezones</i>	1,071.22	73.08	89,939	3,087	93,026
<i>crawler-url-parser</i>	1,636.67	215.52	359,498	5,557	365,055
<i>delta</i>	2,659.93	910.49	820,541	13,472	834,013
<i>image-downloader</i>	430.67	65.98	18,348	1,448	19,796
<i>node-dirty</i>	1,526.59	39.53	223,071	4,425	227,496
<i>node-geo-point</i>	1,411.43	204.76	295,321	4,217	299,538
<i>node-jsonfile</i>	690.87	77.82	47,346	1,831	49,177
<i>plural</i>	1,521.52	48.57	241,953	5,075	247,028
<i>pull-stream</i>	2,382.28	245.31	156,016	9,287	165,303
<i>q</i>	4,158.17	2,697.98	1,970,359	30,059	2,000,418
<i>spacel-core</i>	1,351.47	85.42	142,466	4,013	146,479
<i>zip-a-folder</i>	500.75	235.31	75,033	1,594	76,627
<i>Total</i>	22,073.11	4,997.50	5,333,857	98,525	5,432,382

Table 142: Results from LLMorpheus experiment (run #390). Model: *codellama-34b-instruct*, temperature: 0.0, maxTokens: 250, template: *template-basic.hb*, systemPrompt: *SystemPrompt-MutationTestingExpert.txt*

project	time (sec)		#tokens		
	LLMorpheus	StrykerJS	prompt	compl.	total
Complex.js	2,732.79	102.55	893,966	14,472	908,438
countries-and-timezones	1,071.27	72.88	89,939	3,113	93,052
crawler-url-parser	1,636.61	211.77	359,498	5,557	365,055
delta	2,667.43	897.69	820,541	13,458	833,999
image-downloader	430.64	65.54	18,348	1,448	19,796
node-dirty	1,526.57	38.93	223,071	4,422	227,493
node-geo-point	1,411.51	203.69	295,321	4,218	299,539
node-jsonfile	690.88	77.42	47,346	1,831	49,177
plural	1,521.47	47.92	241,953	5,075	247,028
pull-stream	2,382.21	245.17	156,016	9,288	165,304
q	4,159.06	2,700.88	1,970,359	30,059	2,000,418
spacl-core	1,351.31	85.36	142,466	4,007	146,473
zip-a-folder	500.73	227.68	75,033	1,594	76,627
Total	22,082.48	4,977.48	5,333,857	98,542	5,432,399

Table 143: Results from LLMorpheus experiment (run #391). Model: *codellama-34b-instruct*, temperature: 0.0, maxTokens: 250, template: *template-basic.hb*, systemPrompt: *SystemPrompt-MutationTestingExpert.txt*

project	time (sec)		#tokens		
	LLMorpheus	StrykerJS	prompt	compl.	total
Complex.js	2,730.84	97.59	893,966	14,461	908,427
countries-and-timezones	1,071.16	72.83	89,939	3,113	93,052
crawler-url-parser	1,636.68	220.83	359,498	5,576	365,074
delta	2,659.86	887.50	820,541	13,473	834,014
image-downloader	430.65	65.72	18,348	1,449	19,797
node-dirty	1,526.53	37.30	223,071	4,496	227,567
node-geo-point	1,411.50	195.42	295,321	4,230	299,551
node-jsonfile	690.89	77.90	47,346	1,831	49,177
plural	1,521.54	49.08	241,953	5,075	247,028
pull-stream	2,382.22	248.75	156,016	9,288	165,304
q	4,158.01	2,694.11	1,970,359	30,070	2,000,429
spacl-core	1,351.43	85.92	142,466	4,013	146,479
zip-a-folder	500.71	229.75	75,033	1,594	76,627
Total	22,072.01	4,962.71	5,333,857	98,669	5,432,526

Table 144: Results from LLMorpheus experiment (run #392). Model: *codellama-34b-instruct*, temperature: 0.0, maxTokens: 250, template: *template-basic.hb*, systemPrompt: *SystemPrompt-MutationTestingExpert.txt*

project	time (sec)		#tokens		
	LLMorpheus	StrykerJS	prompt	compl.	total
Complex.js	2,730.22	96.64	893,966	14,459	908,425
countries-and-timezones	1,071.13	74.16	89,939	3,112	93,051
crawler-url-parser	1,636.64	206.03	359,498	5,556	365,054
delta	2,659.88	897.06	820,541	13,471	834,012
image-downloader	430.66	65.63	18,348	1,449	19,797
node-dirty	1,526.57	38.82	223,071	4,425	227,496
node-geo-point	1,411.45	200.23	295,321	4,217	299,538
node-jsonfile	690.84	77.61	47,346	1,831	49,177
plural	1,556.64	47.70	238,779	5,029	243,808
pull-stream	2,382.19	247.28	156,016	9,288	165,304
q	4,156.62	2,695.05	1,970,359	30,071	2,000,430
spacl-core	1,351.45	84.84	142,466	4,008	146,474
zip-a-folder	500.75	235.51	75,033	1,594	76,627
Total	22,105.05	4,966.57	5,330,683	98,510	5,429,193

Table 145: Results from LLMorpheus experiment (run #393). Model: *codellama-34b-instruct*, temperature: 0.0, maxTokens: 250, template: *template-basic.hb*, systemPrompt: *SystemPrompt-MutationTestingExpert.txt*

project	time (sec)		#tokens		
	<i>LLMorpheus</i>	<i>StrykerJS</i>	prompt	compl.	total
Complex.js	2,730.17	96.67	893,966	14,460	908,426
countries-and-timezones	1,071.19	73.83	89,939	3,086	93,025
crawler-url-parser	1,636.65	205.98	359,498	5,577	365,075
delta	2,659.91	887.25	820,541	13,475	834,016
image-downloader	430.71	65.63	18,348	1,449	19,797
node-dirty	1,526.60	38.47	223,071	4,500	227,571
node-geo-point	1,411.44	197.24	295,321	4,217	299,538
node-jsonfile	690.88	78.16	47,346	1,831	49,177
plural	1,522.37	47.69	241,953	5,075	247,028
pull-stream	2,382.20	245.09	156,016	9,290	165,306
q	4,154.13	2,691.66	1,970,359	30,055	2,000,414
spacl-core	1,351.41	83.75	142,466	4,013	146,479
zip-a-folder	500.72	232.15	75,033	1,594	76,627
<i>Total</i>	22,068.39	4,943.55	5,333,857	98,622	5,432,479

Table 146: Results from LLMorpheus experiment (run #394). Model: *codellama-34b-instruct*, temperature: 0.0, maxTokens: 250, template: *template-basic.hb*, systemPrompt: *SystemPrompt-MutationTestingExpert.txt*

```

Consider the following code fragment:

{{{code}}}


Please provide a code fragment that PLACEHOLDER can be replaced with.

Provide your answer as a fenced code block containing a single line of code,
using the following template:

The PLACEHOLDER can be replaced with:

<code fragment>


Please conclude your response with "DONE."

```

Figure 16: A minimal template for requesting a replacement for the PLACEHOLDER.

1.16 Summary of variability of results for all models examined in the paper

For each configuration of *LLMorpheus*, this section provides a summary of the mutation results, showing the average of each value across all five trials, along with the standard deviation for that value.

- Model codellama-13b-instruct with template full at temperature 0.0: Table 147
- Model codellama-34b-instruct with template basic at temperature 0.0: Table 148
- Model codellama-34b-instruct with template full at temperature 0.0: Table 149
- Model codellama-34b-instruct with template full at temperature 0.25: Table 150
- Model codellama-34b-instruct with template full at temperature 0.5: Table 151
- Model codellama-34b-instruct with template full at temperature 1.0: Table 152
- Model codellama-34b-instruct with template full at temperature genericsystemprompt-0.0: Table 153
- Model codellama-34b-instruct with template noexplanation at temperature 0.0: Table 154
- Model codellama-34b-instruct with template noinstructions at temperature 0.0: Table 155
- Model codellama-34b-instruct with template onemutation at temperature 0.0: Table 156
- Model gpt-4o-mini with template full at temperature 0.0: Table 157
- Model llama-3.3-70b-instruct with template full at temperature 0.0: Table 158
- Model mixtral-8x7b-instruct with template full at temperature 0.0: Table 159

Table 147: Summary of mutants for codellama-13b-instruct-full-0.0 (runs 354, 355, 356, 358, 359). Each column shows the average number of mutants from all runs, \pm the standard deviation.

application	#prompts	Candidates	Invalid	Identical	Duplicate	#mutants	#killed	#survived	#timeout	mut. score
<i>Complex.js</i>	490 \pm 0	1,411 \pm 0	340 \pm 0	116 \pm 0	28 \pm 0	955 \pm 0	553 \pm 0	401 \pm 0	1 \pm 0	58.01 \pm 0
<i>countries-and-timezones</i>	106 \pm 0	305 \pm 0	83 \pm 0	15 \pm 0	1 \pm 0	207 \pm 0	177 \pm 0	30 \pm 0	0 \pm 0	85.51 \pm 0
<i>crawler-url-parser</i>	176 \pm 0	494 \pm 0	186 \pm 0	51 \pm 0	12 \pm 0	257 \pm 0	128 \pm 2	118 \pm 0	1 \pm 2	52.23 \pm 0
<i>delta</i>	462 \pm 0	1,334 \pm 0	530 \pm 0	92 \pm 0	16 \pm 0	712 \pm 0	583 \pm 0	107 \pm 0	22 \pm 0	84.97 \pm 0
<i>image-downloader</i>	42 \pm 0	122 \pm 0	40 \pm 0	5 \pm 0	2 \pm 0	77 \pm 0	48 \pm 0	29 \pm 0	0 \pm 0	62.34 \pm 0
<i>node-dirty</i>	154 \pm 0	439 \pm 0	161 \pm 0	33 \pm 0	11 \pm 0	245 \pm 0	142 \pm 0	92 \pm 0	11 \pm 0	62.45 \pm 0
<i>node-geo-point</i>	140 \pm 0	390 \pm 0	64 \pm 0	21 \pm 0	16 \pm 0	305 \pm 0	237 \pm 0	67 \pm 0	0 \pm 0	77.96 \pm 0
<i>node-jsonfile</i>	68 \pm 0	192 \pm 0	45 \pm 1	10 \pm 0	6 \pm 0	137 \pm 0	43 \pm 0	45 \pm 0	49 \pm 0	67.2 \pm 0.11
<i>plural</i>	153 \pm 0	404 \pm 6	100 \pm 1	98 \pm 1	17 \pm 0	206 \pm 4	153 \pm 3	53 \pm 1	1 \pm 0	74.52 \pm 0.01
<i>pull-stream</i>	351 \pm 0	1,002 \pm 0	279 \pm 0	54 \pm 0	13 \pm 0	669 \pm 0	386 \pm 1	236 \pm 1	46 \pm 0	64.65 \pm 0.08
<i>q</i>	1,051 \pm 0	2,992 \pm 1	899 \pm 1	379 \pm 0	55 \pm 0	1,714 \pm 1	122 \pm 0	1,519 \pm 1	73 \pm 0	11.38 \pm 0
<i>spacl-core</i>	134 \pm 0	377 \pm 0	142 \pm 0	40 \pm 0	7 \pm 0	195 \pm 0	160 \pm 0	25 \pm 0	0 \pm 0	86.38 \pm 0.24
<i>zip-a-folder</i>	49 \pm 0	137 \pm 0	43 \pm 0	7 \pm 0	1 \pm 0	87 \pm 0	27 \pm 0	55 \pm 0	5 \pm 0	36.78 \pm 0
<i>Total</i>	3,376	9,599	2,911	921	185	5,766	2,759	2,777	209	63.41

Table 148: Summary of mutants for codellama-34b-instruct-basic-0.0 (runs 390, 391, 392, 393, 394). Each column shows the average number of mutants from all runs, \pm the standard deviation.

application	#prompts	Candidates	Invalid	Identical	Duplicate	#mutants	#killed	#survived	#timeout	mut. score
<i>Complex.js</i>	490 \pm 0	489 \pm 0	213 \pm 1	92 \pm 0	1 \pm 0	184 \pm 1	119 \pm 1	65 \pm 0	0 \pm 0	64.75 \pm 0.1
<i>countries-and-timezones</i>	106 \pm 0	106 \pm 0	36 \pm 0	22 \pm 0	0 \pm 0	48 \pm 0	43 \pm 1	5 \pm 1	0 \pm 0	90.42 \pm 1.14
<i>crawler-url-parser</i>	176 \pm 0	175 \pm 0	75 \pm 0	27 \pm 0	1 \pm 0	73 \pm 0	49 \pm 0	18 \pm 0	0 \pm 0	73.13 \pm 0
<i>delta</i>	462 \pm 0	456 \pm 0	201 \pm 1	54 \pm 0	6 \pm 0	201 \pm 1	167 \pm 1	28 \pm 0	6 \pm 0	86.07 \pm 0.05
<i>image-downloader</i>	42 \pm 0	42 \pm 0	21 \pm 0	11 \pm 0	0 \pm 0	10 \pm 0	7 \pm 0	3 \pm 0	0 \pm 0	70 \pm 0
<i>node-dirty</i>	154 \pm 0	152 \pm 0	70 \pm 1	38 \pm 0	2 \pm 0	44 \pm 1	24 \pm 0	18 \pm 1	2 \pm 0	59.64 \pm 0.76
<i>node-geo-point</i>	140 \pm 0	134 \pm 0	39 \pm 0	33 \pm 0	6 \pm 0	62 \pm 0	54 \pm 0	8 \pm 0	0 \pm 0	87.1 \pm 0
<i>node-jsonfile</i>	68 \pm 0	67 \pm 0	17 \pm 0	28 \pm 0	1 \pm 0	22 \pm 0	11 \pm 0	3 \pm 0	8 \pm 0	86.36 \pm 0
<i>plural</i>	153 \pm 0	148 \pm 1	35 \pm 0	21 \pm 0	4 \pm 0	92 \pm 0	78 \pm 0	14 \pm 0	0 \pm 0	84.97 \pm 0.42
<i>pull-stream</i>	351 \pm 0	351 \pm 0	115 \pm 0	87 \pm 0	0 \pm 0	149 \pm 0	88 \pm 0	54 \pm 0	7 \pm 0	63.76 \pm 0
<i>q</i>	1,051 \pm 0	1,038 \pm 0	405 \pm 0	232 \pm 1	13 \pm 0	402 \pm 1	38 \pm 0	351 \pm 1	13 \pm 0	12.7 \pm 0.02
<i>spacl-core</i>	134 \pm 0	133 \pm 0	65 \pm 0	37 \pm 0	1 \pm 0	31 \pm 0	23 \pm 0	2 \pm 0	0 \pm 0	92 \pm 0
<i>zip-a-folder</i>	49 \pm 0	49 \pm 0	18 \pm 0	11 \pm 0	0 \pm 0	20 \pm 0	5 \pm 0	1 \pm 0	14 \pm 0	95 \pm 0
<i>Total</i>	3,376	3,340	1,310	692	35	1,337	707	569	50	74.3

Table 149: Summary of mutants for codellama-34b-instruct-full-0.0 (runs 312, 314, 315, 316, 317). Each column shows the average number of mutants from all runs, \pm the standard deviation.

application	#prompts	Candidates	Invalid	Identical	Duplicate	#mutants	#killed	#survived	#timeout	mut. score
<i>Complex.js</i>	490 \pm 0	1,406 \pm 1	194 \pm 1	13 \pm 0	45 \pm 0	1,199 \pm 0	725 \pm 1	473 \pm 1	1 \pm 0	60.58 \pm 0.08
<i>countries-and-timezones</i>	106 \pm 0	306 \pm 0	89 \pm 0	0 \pm 0	12 \pm 0	217 \pm 0	188 \pm 0	29 \pm 0	0 \pm 0	86.63 \pm 0.03
<i>crawler-url-parser</i>	176 \pm 0	504 \pm 0	207 \pm 2	14 \pm 0	17 \pm 0	284 \pm 1	157 \pm 0	127 \pm 1	0 \pm 0	55.36 \pm 0.31
<i>delta</i>	462 \pm 0	1,342 \pm 1	565 \pm 0	10 \pm 0	25 \pm 1	767 \pm 1	635 \pm 1	100 \pm 0	32 \pm 0	86.93 \pm 0.06
<i>image-downloader</i>	42 \pm 0	124 \pm 0	34 \pm 1	1 \pm 1	0 \pm 0	89 \pm 1	72 \pm 1	17 \pm 0	0 \pm 0	80.98 \pm 0.12
<i>node-dirty</i>	154 \pm 0	443 \pm 0	153 \pm 1	15 \pm 0	7 \pm 0	275 \pm 1	161 \pm 1	101 \pm 1	12 \pm 0	63.07 \pm 0.34
<i>node-geo-point</i>	140 \pm 0	396 \pm 1	94 \pm 1	0 \pm 0	13 \pm 0	302 \pm 0	223 \pm 0	79 \pm 0	0 \pm 0	73.77 \pm 0.15
<i>node-jsonfile</i>	68 \pm 0	199 \pm 0	42 \pm 1	3 \pm 0	0 \pm 0	154 \pm 0	49 \pm 0	48 \pm 0	57 \pm 0	68.92 \pm 0.2
<i>plural</i>	153 \pm 0	424 \pm 1	101 \pm 0	42 \pm 1	18 \pm 0	280 \pm 1	204 \pm 1	75 \pm 0	1 \pm 0	73.23 \pm 0.08
<i>pull-stream</i>	351 \pm 0	1,019 \pm 0	237 \pm 1	12 \pm 0	9 \pm 0	770 \pm 1	442 \pm 1	271 \pm 2	57 \pm 0	64.75 \pm 0.23
<i>q</i>	1,051 \pm 0	3,068 \pm 1	1,002 \pm 2	34 \pm 0	53 \pm 1	2,033 \pm 2	159 \pm 1	1,790 \pm 2	84 \pm 1	11.93 \pm 0.03
<i>spacl-core</i>	134 \pm 0	387 \pm 1	138 \pm 1	10 \pm 0	7 \pm 0	239 \pm 0	198 \pm 1	40 \pm 1	1 \pm 0	83.17 \pm 0.34
<i>zip-a-folder</i>	49 \pm 0	142 \pm 0	41 \pm 0	1 \pm 0	1 \pm 0	100 \pm 0	23 \pm 0	3 \pm 0	74 \pm 0	97 \pm 0
<i>Total</i>	3,376	9,760	2,898	155	207	6,707	3,235	3,154	319	69.72

Table 150: Summary of mutants for codellama-34b-instruct-full-0.25 (runs 348, 350, 351, 352, 353). Each column shows the average number of mutants from all runs, \pm the standard deviation.

application	#prompts	Candidates	Invalid	Identical	Duplicate	#mutants	#killed	#survived	#timeout	mut. score
<i>Complex.js</i>	490 \pm 0	1,413 \pm 7	212 \pm 12	10 \pm 2	43 \pm 4	1,190 \pm 13	727 \pm 8	463 \pm 9	0 \pm 1	61.09 \pm 0.5
<i>countries-and-timezones</i>	106 \pm 0	308 \pm 5	85 \pm 3	1 \pm 1	7 \pm 4	222 \pm 5	193 \pm 8	28 \pm 5	0 \pm 0	87.18 \pm 2.55
<i>crawler-url-parser</i>	176 \pm 0	501 \pm 4	210 \pm 5	13 \pm 4	15 \pm 4	278 \pm 8	157 \pm 9	104 \pm 6	0 \pm 0	60.25 \pm 2.47
<i>delta</i>	462 \pm 0	1,341 \pm 6	566 \pm 13	8 \pm 2	25 \pm 3	767 \pm 12	627 \pm 17	107 \pm 4	32 \pm 4	86.01 \pm 0.66
<i>image-downloader</i>	42 \pm 0	123 \pm 2	36 \pm 2	1 \pm 2	1 \pm 1	86 \pm 2	68 \pm 4	17 \pm 2	0 \pm 0	80.43 \pm 3.22
<i>node-dirty</i>	154 \pm 0	445 \pm 5	160 \pm 4	14 \pm 3	10 \pm 4	271 \pm 6	165 \pm 6	94 \pm 5	12 \pm 0	65.19 \pm 1.82
<i>node-geo-point</i>	140 \pm 0	394 \pm 12	90 \pm 10	1 \pm 1	12 \pm 4	303 \pm 8	226 \pm 10	74 \pm 6	0 \pm 0	75.36 \pm 2.01
<i>node-jsonfile</i>	68 \pm 0	201 \pm 2	44 \pm 3	3 \pm 1	1 \pm 1	154 \pm 4	52 \pm 3	47 \pm 5	56 \pm 2	69.72 \pm 2.82
<i>plural</i>	153 \pm 0	419 \pm 2	101 \pm 2	36 \pm 5	20 \pm 2	282 \pm 7	210 \pm 4	71 \pm 7	1 \pm 1	75.03 \pm 2.12
<i>pull-stream</i>	351 \pm 0	1,023 \pm 1	239 \pm 3	9 \pm 2	7 \pm 2	774 \pm 3	447 \pm 4	274 \pm 6	54 \pm 3	64.67 \pm 0.8
<i>q</i>	1,051 \pm 0	3,073 \pm 8	1,023 \pm 14	27 \pm 11	51 \pm 8	2,023 \pm 31	147 \pm 5	1,795 \pm 27	82 \pm 4	11.3 \pm 0.33
<i>spacl-core</i>	134 \pm 0	389 \pm 3	139 \pm 5	11 \pm 2	6 \pm 3	240 \pm 6	189 \pm 4	33 \pm 3	1 \pm 1	85.05 \pm 1.23
<i>zip-a-folder</i>	49 \pm 0	140 \pm 2	39 \pm 4	1 \pm 1	1 \pm 0	101 \pm 4	32 \pm 10	22 \pm 27	46 \pm 36	77.41 \pm 26.94
<i>Total</i>	3,376	9,771	2,943	136	200	6,692	3,242	3,129	283	69.13

Table 151: Summary of mutants for codellama-34b-instruct-full-0.5 (runs 318, 319, 320, 321, 322). Each column shows the average number of mutants from all runs, \pm the standard deviation.

application	#prompts	Candidates	Invalid	Identical	Duplicate	#mutants	#killed	#survived	#timeout	mut. score
<i>Complex.js</i>	490 \pm 0	1,417 \pm 7	226 \pm 16	8 \pm 1	37 \pm 3	1,183 \pm 10	725 \pm 10	458 \pm 10	0 \pm 0	61.27 \pm 0.72
<i>countries-and-timezones</i>	106 \pm 0	305 \pm 6	79 \pm 6	4 \pm 2	7 \pm 3	222 \pm 2	195 \pm 3	28 \pm 3	0 \pm 0	87.59 \pm 1.26
<i>crawler-url-parser</i>	176 \pm 0	500 \pm 3	193 \pm 12	13 \pm 4	15 \pm 2	294 \pm 12	167 \pm 6	121 \pm 11	5 \pm 11	58.65 \pm 3.1
<i>delta</i>	462 \pm 0	1,340 \pm 5	553 \pm 12	10 \pm 2	22 \pm 5	777 \pm 14	645 \pm 19	97 \pm 7	36 \pm 2	87.56 \pm 1.12
<i>image-downloader</i>	42 \pm 0	122 \pm 2	36 \pm 3	2 \pm 1	3 \pm 2	84 \pm 3	64 \pm 6	21 \pm 6	0 \pm 0	75.57 \pm 7.56
<i>node-dirty</i>	154 \pm 0	446 \pm 3	158 \pm 7	9 \pm 2	9 \pm 4	279 \pm 7	162 \pm 8	105 \pm 3	12 \pm 0	62.23 \pm 1.48
<i>node-geo-point</i>	140 \pm 0	390 \pm 18	89 \pm 6	2 \pm 1	13 \pm 3	299 \pm 17	228 \pm 10	72 \pm 10	0 \pm 0	76.16 \pm 2.27
<i>node-jsonfile</i>	68 \pm 0	200 \pm 2	42 \pm 3	3 \pm 1	1 \pm 2	155 \pm 5	53 \pm 3	40 \pm 3	62 \pm 4	74.43 \pm 2.05
<i>plural</i>	153 \pm 0	415 \pm 7	98 \pm 7	27 \pm 4	19 \pm 5	290 \pm 4	220 \pm 9	70 \pm 8	1 \pm 1	75.89 \pm 2.87
<i>pull-stream</i>	351 \pm 0	1,023 \pm 7	219 \pm 10	6 \pm 3	10 \pm 4	798 \pm 12	472 \pm 11	270 \pm 9	56 \pm 4	66.17 \pm 1.28
<i>q</i>	1,051 \pm 0	3,071 \pm 6	1,000 \pm 17	29 \pm 5	52 \pm 8	2,042 \pm 22	153 \pm 11	1,804 \pm 27	85 \pm 8	11.67 \pm 0.71
<i>spacl-core</i>	134 \pm 0	388 \pm 4	125 \pm 7	7 \pm 3	5 \pm 2	256 \pm 5	217 \pm 6	39 \pm 3	1 \pm 0	84.93 \pm 1.01
<i>zip-a-folder</i>	49 \pm 0	138 \pm 9	35 \pm 5	1 \pm 1	1 \pm 1	101 \pm 10	36 \pm 10	19 \pm 21	46 \pm 37	79.77 \pm 22.09
<i>Total</i>	3,376	9,755	2,853	121	194	6,782	3,336	3,143	303	69.38

Table 152: Summary of mutants for codellama-34b-instruct-full-1.0 (runs 341, 342, 343, 345, 347). Each column shows the average number of mutants from all runs, \pm the standard deviation.

application	#prompts	Candidates	Invalid	Identical	Duplicate	#mutants	#killed	#survived	#timeout	mut. score
<i>Complex.js</i>	490 \pm 0	1,359 \pm 13	338 \pm 20	6 \pm 2	24 \pm 2	1,015 \pm 22	641 \pm 20	374 \pm 6	0 \pm 1	63.12 \pm 0.83
<i>countries-and-timezones</i>	106 \pm 0	284 \pm 20	91 \pm 11	2 \pm 3	3 \pm 1	191 \pm 17	168 \pm 16	24 \pm 6	0 \pm 0	87.55 \pm 2.79
<i>crawler-url-parser</i>	176 \pm 0	489 \pm 7	218 \pm 13	5 \pm 1	6 \pm 2	266 \pm 12	186 \pm 14	80 \pm 9	0 \pm 0	69.79 \pm 3.43
<i>delta</i>	462 \pm 0	1,274 \pm 28	556 \pm 41	8 \pm 3	19 \pm 4	710 \pm 25	599 \pm 28	79 \pm 6	32 \pm 1	88.79 \pm 1.09
<i>image-downloader</i>	42 \pm 0	116 \pm 2	42 \pm 6	1 \pm 1	2 \pm 3	72 \pm 8	55 \pm 9	17 \pm 7	0 \pm 1	76.21 \pm 9.17
<i>node-dirty</i>	154 \pm 0	427 \pm 10	164 \pm 15	5 \pm 3	5 \pm 3	257 \pm 11	150 \pm 11	96 \pm 7	11 \pm 3	62.68 \pm 2.25
<i>node-geo-point</i>	140 \pm 0	392 \pm 3	125 \pm 5	3 \pm 1	9 \pm 2	265 \pm 6	204 \pm 8	61 \pm 5	0 \pm 0	76.95 \pm 1.81
<i>node-jsonfile</i>	68 \pm 0	190 \pm 4	45 \pm 4	2 \pm 1	3 \pm 2	142 \pm 7	60 \pm 8	20 \pm 5	62 \pm 4	85.71 \pm 3.84
<i>plural</i>	153 \pm 0	420 \pm 12	110 \pm 9	9 \pm 2	13 \pm 2	302 \pm 5	239 \pm 7	61 \pm 5	1 \pm 1	79.78 \pm 1.62
<i>pull-stream</i>	351 \pm 0	999 \pm 6	245 \pm 7	10 \pm 2	6 \pm 3	743 \pm 5	455 \pm 7	239 \pm 5	49 \pm 6	67.82 \pm 0.77
<i>q</i>	1,051 \pm 0	2,993 \pm 11	1,078 \pm 30	18 \pm 3	35 \pm 8	1,896 \pm 28	145 \pm 16	1,668 \pm 23	83 \pm 7	12.02 \pm 0.47
<i>spacl-core</i>	134 \pm 0	372 \pm 3	146 \pm 12	4 \pm 3	5 \pm 1	222 \pm 13	194 \pm 19	28 \pm 8	0 \pm 0	87.36 \pm 4.02
<i>zip-a-folder</i>	49 \pm 0	138 \pm 5	43 \pm 2	1 \pm 1	1 \pm 1	94 \pm 7	34 \pm 12	10 \pm 16	50 \pm 27	89.46 \pm 16.3
<i>Total</i>	3,376	9,454	3,201	73	131	6,179	3,130	2,759	290	72.86

Table 153: Summary of mutants for codellama-34b-instruct-full-genericssystemprompt-0.0 (runs 384, 385, 386, 387, 388). Each column shows the average number of mutants from all runs, \pm the standard deviation.

application	#prompts	Candidates	Invalid	Identical	Duplicate	#mutants	#killed	#survived	#timeout	mut. score
<i>Complex.js</i>	490 \pm 0	1,409 \pm 0	201 \pm 0	9 \pm 0	50 \pm 0	1,199 \pm 0	740 \pm 0	458 \pm 0	1 \pm 0	61.81 \pm 0.01
<i>countries-and-timezones</i>	106 \pm 0	302 \pm 11	88 \pm 4	0 \pm 0	9 \pm 0	214 \pm 7	189 \pm 5	25 \pm 1	0 \pm 0	88.14 \pm 0.26
<i>crawler-url-parser</i>	176 \pm 0	503 \pm 0	226 \pm 0	16 \pm 0	19 \pm 0	261 \pm 0	143 \pm 0	103 \pm 0	0 \pm 0	58.21 \pm 0.18
<i>delta</i>	462 \pm 0	1,349 \pm 1	552 \pm 2	6 \pm 0	24 \pm 1	791 \pm 2	659 \pm 1	100 \pm 1	32 \pm 0	87.4 \pm 0.05
<i>image-downloader</i>	42 \pm 0	123 \pm 0	34 \pm 0	1 \pm 0	0 \pm 0	88 \pm 0	72 \pm 0	16 \pm 0	0 \pm 0	81.82 \pm 0
<i>node-dirty</i>	154 \pm 0	442 \pm 0	153 \pm 0	12 \pm 0	8 \pm 0	277 \pm 0	162 \pm 0	104 \pm 0	11 \pm 0	62.52 \pm 0.17
<i>node-geo-point</i>	140 \pm 0	403 \pm 0	95 \pm 0	1 \pm 0	11 \pm 0	307 \pm 0	229 \pm 0	76 \pm 0	0 \pm 0	75.08 \pm 0
<i>node-jsonfile</i>	68 \pm 0	200 \pm 0	47 \pm 0	2 \pm 0	0 \pm 0	151 \pm 0	49 \pm 0	49 \pm 0	53 \pm 0	67.51 \pm 0.1
<i>plural</i>	153 \pm 0	421 \pm 0	105 \pm 1	45 \pm 0	21 \pm 0	271 \pm 1	208 \pm 1	62 \pm 0	1 \pm 0	77.14 \pm 0.09
<i>pull-stream</i>	351 \pm 0	1,030 \pm 0	252 \pm 0	15 \pm 0	9 \pm 0	763 \pm 0	442 \pm 1	266 \pm 1	55 \pm 0	65.1 \pm 0.12
<i>q</i>	1,051 \pm 0	3,073 \pm 1	1,036 \pm 2	30 \pm 0	54 \pm 1	2,007 \pm 1	145 \pm 1	1,770 \pm 1	92 \pm 0	11.79 \pm 0.03
<i>spacl-core</i>	134 \pm 0	389 \pm 0	146 \pm 0	12 \pm 0	8 \pm 0	231 \pm 1	182 \pm 1	32 \pm 0	1 \pm 0	85.09 \pm 0.06
<i>zip-a-folder</i>	49 \pm 0	143 \pm 0	40 \pm 0	1 \pm 0	2 \pm 0	102 \pm 0	27 \pm 0	3 \pm 0	71 \pm 0	97.03 \pm 0
<i>Total</i>	3,376	9,787	2,976	150	214	6,662	3,247	3,064	317	70.66

Table 154: Summary of mutants for codellama-34b-instruct-noexplanation-0.0 (runs 372, 374, 375, 376, 377). Each column shows the average number of mutants from all runs, \pm the standard deviation.

application	#prompts	Candidates	Invalid	Identical	Duplicate	#mutants	#killed	#survived	#timeout	mut. score
<i>Complex.js</i>	490 \pm 0	1,428 \pm 0	277 \pm 2	27 \pm 0	37 \pm 0	1,124 \pm 2	677 \pm 2	446 \pm 1	1 \pm 0	60.3 \pm 0.1
<i>countries-and-timezones</i>	106 \pm 0	297 \pm 0	84 \pm 0	2 \pm 0	10 \pm 0	211 \pm 0	183 \pm 0	28 \pm 0	0 \pm 0	86.73 \pm 0
<i>crawler-url-parser</i>	176 \pm 0	495 \pm 0	215 \pm 1	24 \pm 1	19 \pm 0	256 \pm 0	140 \pm 0	99 \pm 0	0 \pm 0	58.58 \pm 0
<i>delta</i>	462 \pm 0	1,356 \pm 0	595 \pm 2	28 \pm 2	19 \pm 0	733 \pm 0	597 \pm 1	109 \pm 1	26 \pm 1	85.08 \pm 0.12
<i>image-downloader</i>	42 \pm 0	124 \pm 0	41 \pm 0	4 \pm 0	2 \pm 0	79 \pm 0	62 \pm 0	15 \pm 0	0 \pm 0	80.52 \pm 0
<i>node-dirty</i>	154 \pm 0	448 \pm 0	160 \pm 0	30 \pm 0	10 \pm 0	258 \pm 0	146 \pm 0	99 \pm 0	13 \pm 0	61.63 \pm 0
<i>node-geo-point</i>	140 \pm 0	405 \pm 0	104 \pm 1	2 \pm 0	9 \pm 0	299 \pm 1	215 \pm 1	82 \pm 0	0 \pm 0	72.47 \pm 0.19
<i>node-jsonfile</i>	68 \pm 0	204 \pm 0	48 \pm 0	4 \pm 0	0 \pm 0	152 \pm 0	54 \pm 0	45 \pm 0	53 \pm 0	70.39 \pm 0
<i>plural</i>	153 \pm 0	433 \pm 0	110 \pm 0	50 \pm 0	16 \pm 0	273 \pm 0	198 \pm 0	74 \pm 0	1 \pm 0	72.89 \pm 0
<i>pull-stream</i>	351 \pm 0	1,026 \pm 1	237 \pm 1	16 \pm 0	11 \pm 1	774 \pm 0	439 \pm 1	279 \pm 1	56 \pm 0	63.99 \pm 0.13
<i>q</i>	1,051 \pm 0	3,084 \pm 1	1,107 \pm 1	122 \pm 1	59 \pm 1	1,855 \pm 1	137 \pm 1	1,634 \pm 1	83 \pm 1	11.9 \pm 0.02
<i>spacl-core</i>	134 \pm 0	390 \pm 0	144 \pm 1	18 \pm 0	6 \pm 0	228 \pm 1	175 \pm 1	33 \pm 1	1 \pm 0	84.24 \pm 0.62
<i>zip-a-folder</i>	49 \pm 0	142 \pm 0	41 \pm 0	3 \pm 0	1 \pm 0	98 \pm 0	27 \pm 1	3 \pm 0	68 \pm 1	96.94 \pm 0
<i>Total</i>	3,376	9,832	3,162	329	199	6,341	3,051	2,946	303	69.67

Table 155: Summary of mutants for codellama-34b-instruct-noinstructions-0.0 (runs 378, 379, 380, 381, 382). Each column shows the average number of mutants from all runs, \pm the standard deviation.

application	#prompts	Candidates	Invalid	Identical	Duplicate	#mutants	#killed	#survived	#timeout	mut. score
<i>Complex.js</i>	490 \pm 0	1,408 \pm 1	235 \pm 0	36 \pm 0	45 \pm 0	1,137 \pm 0	696 \pm 0	440 \pm 0	1 \pm 0	61.29 \pm 0.01
<i>countries-and-timezones</i>	106 \pm 0	311 \pm 0	85 \pm 0	8 \pm 0	4 \pm 0	218 \pm 0	174 \pm 0	44 \pm 0	0 \pm 0	79.82 \pm 0
<i>crawler-url-parser</i>	176 \pm 0	498 \pm 0	211 \pm 0	23 \pm 0	20 \pm 0	264 \pm 0	134 \pm 0	112 \pm 0	0 \pm 0	54.47 \pm 0
<i>delta</i>	462 \pm 0	1,348 \pm 0	563 \pm 0	26 \pm 0	18 \pm 0	759 \pm 0	611 \pm 1	116 \pm 1	32 \pm 0	84.77 \pm 0.12
<i>image-downloader</i>	42 \pm 0	126 \pm 0	39 \pm 0	2 \pm 0	0 \pm 0	85 \pm 0	69 \pm 1	15 \pm 1	0 \pm 0	82.62 \pm 0.65
<i>node-dirty</i>	154 \pm 0	448 \pm 0	161 \pm 1	26 \pm 0	9 \pm 0	260 \pm 1	147 \pm 1	103 \pm 1	11 \pm 0	60.6 \pm 0.31
<i>node-geo-point</i>	140 \pm 0	400 \pm 0	85 \pm 0	7 \pm 0	13 \pm 0	308 \pm 0	230 \pm 0	76 \pm 0	0 \pm 0	75.16 \pm 0
<i>node-jsonfile</i>	68 \pm 0	199 \pm 0	42 \pm 0	9 \pm 0	1 \pm 0	148 \pm 0	45 \pm 0	51 \pm 0	52 \pm 0	65.54 \pm 0
<i>plural</i>	153 \pm 0	427 \pm 1	109 \pm 0	57 \pm 0	17 \pm 0	261 \pm 0	189 \pm 0	71 \pm 0	1 \pm 0	72.74 \pm 0.13
<i>pull-stream</i>	351 \pm 0	1,024 \pm 0	225 \pm 1	19 \pm 0	16 \pm 0	780 \pm 1	466 \pm 1	248 \pm 1	66 \pm 0	68.16 \pm 0.09
<i>q</i>	1,051 \pm 0	3,071 \pm 1	1,019 \pm 1	94 \pm 1	60 \pm 0	1,958 \pm 1	137 \pm 1	1,727 \pm 1	94 \pm 1	11.8 \pm 0.05
<i>spacl-core</i>	134 \pm 0	388 \pm 0	158 \pm 0	30 \pm 0	7 \pm 0	200 \pm 0	155 \pm 0	31 \pm 0	1 \pm 0	83.44 \pm 0.04
<i>zip-a-folder</i>	49 \pm 0	143 \pm 0	41 \pm 0	5 \pm 0	1 \pm 0	97 \pm 0	26 \pm 0	4 \pm 0	67 \pm 0	95.88 \pm 0
<i>Total</i>	3,376	9,790	2,972	342	211	6,476	3,080	3,037	325	68.95

Table 156: Summary of mutants for codellama-34b-instruct-onemutation-0.0 (runs 365, 366, 369, 370, 371). Each column shows the average number of mutants from all runs, \pm the standard deviation.

application	#prompts	Candidates	Invalid	Identical	Duplicate	#mutants	#killed	#survived	#timeout	mut. score
<i>Complex.js</i>	490 \pm 0	478 \pm 2	67 \pm 0	6 \pm 0	11 \pm 0	405 \pm 2	244 \pm 2	161 \pm 1	0 \pm 0	60.24 \pm 0.13
<i>countries-and-timezones</i>	106 \pm 0	104 \pm 0	24 \pm 0	1 \pm 0	2 \pm 0	79 \pm 0	66 \pm 0	13 \pm 0	0 \pm 0	83.29 \pm 0.56
<i>crawler-url-parser</i>	176 \pm 0	170 \pm 0	70 \pm 1	8 \pm 0	5 \pm 0	92 \pm 1	50 \pm 1	36 \pm 0	0 \pm 0	58.47 \pm 0.31
<i>delta</i>	462 \pm 0	452 \pm 0	182 \pm 1	4 \pm 0	9 \pm 0	266 \pm 1	221 \pm 1	37 \pm 0	8 \pm 0	86.11 \pm 0.03
<i>image-downloader</i>	42 \pm 0	42 \pm 0	8 \pm 0	0 \pm 0	0 \pm 0	34 \pm 0	26 \pm 0	8 \pm 0	0 \pm 0	76.47 \pm 0
<i>node-dirty</i>	154 \pm 0	152 \pm 0	50 \pm 0	3 \pm 1	3 \pm 0	99 \pm 1	55 \pm 0	41 \pm 1	3 \pm 0	58.83 \pm 0.32
<i>node-geo-point</i>	140 \pm 0	137 \pm 0	32 \pm 0	0 \pm 0	3 \pm 0	105 \pm 0	74 \pm 0	30 \pm 0	0 \pm 0	71.15 \pm 0
<i>node-jsonfile</i>	68 \pm 0	68 \pm 0	11 \pm 0	0 \pm 0	0 \pm 0	57 \pm 0	18 \pm 0	18 \pm 0	21 \pm 0	68.42 \pm 0
<i>plural</i>	153 \pm 0	147 \pm 0	39 \pm 0	7 \pm 1	6 \pm 0	101 \pm 1	71 \pm 1	30 \pm 0	0 \pm 0	70.18 \pm 0.16
<i>pull-stream</i>	351 \pm 0	350 \pm 0	67 \pm 0	3 \pm 0	1 \pm 0	280 \pm 0	165 \pm 0	95 \pm 0	20 \pm 0	66 \pm 0.16
<i>q</i>	1,051 \pm 0	1,035 \pm 0	306 \pm 0	26 \pm 0	17 \pm 0	703 \pm 0	46 \pm 0	630 \pm 1	27 \pm 0	10.35 \pm 0.07
<i>spacl-core</i>	134 \pm 0	132 \pm 0	41 \pm 0	3 \pm 0	2 \pm 0	88 \pm 0	63 \pm 0	17 \pm 0	0 \pm 0	78.75 \pm 0
<i>zip-a-folder</i>	49 \pm 0	48 \pm 0	9 \pm 0	0 \pm 0	1 \pm 0	39 \pm 0	19 \pm 0	17 \pm 0	3 \pm 0	56.41 \pm 0
<i>Total</i>	3,376	3,315	905	62	60	2,348	1,118	1,133	82	64.97

Table 157: Summary of mutants for gpt-4o-mini-full-0.0 (runs 58, 59, 60, 61, 63). Each column shows the average number of mutants from all runs, \pm the standard deviation.

application	#prompts	Candidates	Invalid	Identical	Duplicate	#mutants	#killed	#survived	#timeout	mut. score
<i>Complex.js</i>	490 \pm 0	1,433 \pm 3	448 \pm 6	0 \pm 0	36 \pm 2	986 \pm 4	599 \pm 4	387 \pm 2	0 \pm 0	60.72 \pm 0.25
<i>countries-and-timezones</i>	106 \pm 0	308 \pm 2	101 \pm 3	0 \pm 0	10 \pm 2	207 \pm 2	171 \pm 3	36 \pm 2	0 \pm 0	82.64 \pm 0.98
<i>crawler-url-parser</i>	176 \pm 0	517 \pm 1	234 \pm 4	0 \pm 0	10 \pm 1	283 \pm 4	178 \pm 3	91 \pm 2	0 \pm 0	66.1 \pm 0.48
<i>delta</i>	462 \pm 0	1,346 \pm 3	643 \pm 5	1 \pm 1	39 \pm 3	701 \pm 4	562 \pm 3	103 \pm 4	35 \pm 1	85.25 \pm 0.52
<i>image-downloader</i>	42 \pm 0	123 \pm 1	57 \pm 1	0 \pm 0	3 \pm 1	67 \pm 1	45 \pm 3	22 \pm 3	0 \pm 0	67.26 \pm 3.9
<i>node-dirty</i>	154 \pm 0	453 \pm 1	191 \pm 4	0 \pm 0	9 \pm 1	262 \pm 4	152 \pm 4	102 \pm 3	7 \pm 1	61.04 \pm 1.08
<i>node-geo-point</i>	140 \pm 0	395 \pm 3	86 \pm 2	0 \pm 0	24 \pm 3	310 \pm 3	219 \pm 4	88 \pm 2	0 \pm 0	71.33 \pm 0.71
<i>node-jsonfile</i>	68 \pm 0	197 \pm 1	45 \pm 1	0 \pm 0	7 \pm 1	153 \pm 2	65 \pm 3	26 \pm 2	62 \pm 2	83.09 \pm 1.74
<i>plural</i>	153 \pm 0	430 \pm 2	112 \pm 2	5 \pm 1	25 \pm 2	313 \pm 1	258 \pm 4	54 \pm 3	1 \pm 1	82.61 \pm 0.84
<i>pull-stream</i>	351 \pm 0	1,039 \pm 2	300 \pm 1	0 \pm 0	14 \pm 2	739 \pm 3	430 \pm 6	244 \pm 3	65 \pm 3	66.96 \pm 0.43
<i>q</i>	1,051 \pm 0	3,080 \pm 5	1,292 \pm 5	5 \pm 2	73 \pm 5	1,784 \pm 9	130 \pm 5	1,591 \pm 7	63 \pm 3	10.82 \pm 0.32
<i>spacl-core</i>	134 \pm 0	390 \pm 2	157 \pm 3	0 \pm 0	11 \pm 1	233 \pm 3	198 \pm 3	18 \pm 2	0 \pm 0	91.66 \pm 0.86
<i>zip-a-folder</i>	49 \pm 0	144 \pm 1	62 \pm 2	0 \pm 0	3 \pm 1	82 \pm 1	18 \pm 3	5 \pm 1	59 \pm 2	94.37 \pm 1.68
<i>Total</i>	3,376	9,857	3,727	11	263	6,120	3,026	2,768	292	71.06

Table 158: Summary of mutants for llama-3.3-70b-instruct-full-0.0 (runs 23, 24, 25, 26, 27). Each column shows the average number of mutants from all runs, \pm the standard deviation.

application	#prompts	Candidates	Invalid	Identical	Duplicate	#mutants	#killed	#survived	#timeout	mut. score
<i>Complex.js</i>	490 \pm 0	1,413 \pm 3	282 \pm 7	0 \pm 0	59 \pm 5	1,130 \pm 6	682 \pm 5	448 \pm 3	1 \pm 0	60.39 \pm 0.19
<i>countries-and-timezones</i>	106 \pm 0	305 \pm 1	65 \pm 2	0 \pm 0	13 \pm 1	240 \pm 2	204 \pm 4	36 \pm 3	0 \pm 0	84.86 \pm 1.34
<i>crawler-url-parser</i>	176 \pm 0	506 \pm 1	179 \pm 3	0 \pm 0	22 \pm 1	328 \pm 2	203 \pm 3	113 \pm 2	0 \pm 0	64.18 \pm 0.65
<i>delta</i>	462 \pm 0	1,338 \pm 3	540 \pm 3	0 \pm 0	49 \pm 3	798 \pm 4	634 \pm 8	128 \pm 5	37 \pm 3	84.01 \pm 0.69
<i>image-downloader</i>	42 \pm 0	122 \pm 1	44 \pm 2	0 \pm 0	5 \pm 1	79 \pm 2	52 \pm 6	27 \pm 4	0 \pm 0	65.52 \pm 6.21
<i>node-dirty</i>	154 \pm 0	453 \pm 2	124 \pm 3	1 \pm 0	11 \pm 2	327 \pm 5	167 \pm 7	142 \pm 2	19 \pm 2	56.68 \pm 1.07
<i>node-geo-point</i>	140 \pm 0	400 \pm 4	39 \pm 2	0 \pm 0	21 \pm 3	361 \pm 4	258 \pm 4	100 \pm 5	0 \pm 0	71.96 \pm 1.09
<i>node-jsonfile</i>	68 \pm 0	199 \pm 1	27 \pm 2	0 \pm 0	5 \pm 1	172 \pm 2	64 \pm 2	38 \pm 2	70 \pm 2	77.81 \pm 1.31
<i>plural</i>	153 \pm 0	429 \pm 2	92 \pm 3	0 \pm 0	27 \pm 2	337 \pm 3	245 \pm 4	92 \pm 5	0 \pm 0	72.79 \pm 1.33
<i>pull-stream</i>	351 \pm 0	1,044 \pm 2	266 \pm 3	0 \pm 0	9 \pm 2	777 \pm 3	465 \pm 2	262 \pm 4	51 \pm 2	66.35 \pm 0.45
<i>q</i>	1,051 \pm 0	3,073 \pm 3	852 \pm 9	0 \pm 1	82 \pm 3	2,221 \pm 12	127 \pm 3	2,011 \pm 13	82 \pm 3	9.43 \pm 0.19
<i>spacl-core</i>	134 \pm 0	385 \pm 1	130 \pm 4	0 \pm 0	16 \pm 1	256 \pm 5	208 \pm 5	34 \pm 2	1 \pm 0	85.93 \pm 0.74
<i>zip-a-folder</i>	49 \pm 0	145 \pm 0	26 \pm 2	0 \pm 0	2 \pm 0	119 \pm 2	45 \pm 37	5 \pm 0	69 \pm 38	95.8 \pm 0.06
<i>Total</i>	3,376	9,812	2,665	2	321	7,145	3,352	3,436	330	68.9

Table 159: Summary of mutants for mixtral-8x7b-instruct-full-0.0 (runs 360, 361, 362, 363, 364). Each column shows the average number of mutants from all runs, \pm the standard deviation.

application	#prompts	Candidates	Invalid	Identical	Duplicate	#mutants	#killed	#survived	#timeout	mut. score
<i>Complex.js</i>	490 \pm 0	1,284 \pm 11	310 \pm 10	0 \pm 0	19 \pm 4	974 \pm 11	592 \pm 10	382 \pm 6	0 \pm 0	60.75 \pm 0.63
<i>countries-and-timezones</i>	106 \pm 0	267 \pm 3	65 \pm 3	2 \pm 0	4 \pm 1	200 \pm 4	159 \pm 5	41 \pm 2	0 \pm 0	79.29 \pm 1.2
<i>crawler-url-parser</i>	176 \pm 0	404 \pm 4	171 \pm 6	0 \pm 0	1 \pm 1	233 \pm 9	120 \pm 6	100 \pm 4	0 \pm 0	54.54 \pm 0.81
<i>delta</i>	462 \pm 0	1,118 \pm 14	450 \pm 7	0 \pm 0	21 \pm 3	668 \pm 9	509 \pm 10	124 \pm 5	35 \pm 1	81.37 \pm 0.89
<i>image-downloader</i>	42 \pm 0	104 \pm 2	38 \pm 2	0 \pm 0	1 \pm 0	66 \pm 2	42 \pm 2	24 \pm 1	0 \pm 0	64.04 \pm 1.97
<i>node-dirty</i>	154 \pm 0	326 \pm 15	121 \pm 7	0 \pm 0	10 \pm 0	205 \pm 8	121 \pm 6	76 \pm 4	8 \pm 2	62.98 \pm 1.27
<i>node-geo-point</i>	140 \pm 0	343 \pm 3	84 \pm 4	0 \pm 0	14 \pm 2	260 \pm 4	175 \pm 5	79 \pm 2	0 \pm 0	68.83 \pm 1.14
<i>node-jsonfile</i>	68 \pm 0	152 \pm 7	23 \pm 2	0 \pm 0	4 \pm 1	129 \pm 5	54 \pm 3	28 \pm 4	47 \pm 2	78.28 \pm 2.19
<i>plural</i>	153 \pm 0	302 \pm 3	72 \pm 2	0 \pm 0	10 \pm 2	230 \pm 3	171 \pm 4	59 \pm 2	0 \pm 0	74.45 \pm 1.19
<i>pull-stream</i>	351 \pm 0	928 \pm 10	245 \pm 8	1 \pm 0	6 \pm 1	682 \pm 9	393 \pm 7	243 \pm 4	46 \pm 2	64.38 \pm 0.61
<i>q</i>	1,051 \pm 0	2,409 \pm 34	763 \pm 18	3 \pm 0	49 \pm 4	1,643 \pm 20	115 \pm 2	1,458 \pm 22	70 \pm 3	11.23 \pm 0.29
<i>spacl-core</i>	134 \pm 0	330 \pm 3	151 \pm 3	0 \pm 0	3 \pm 1	179 \pm 1	134 \pm 0	22 \pm 1	1 \pm 0	85.9 \pm 0.6
<i>zip-a-folder</i>	49 \pm 0	118 \pm 3	38 \pm 3	0 \pm 0	0 \pm 0	80 \pm 4	26 \pm 4	45 \pm 4	8 \pm 1	43.46 \pm 3.81
<i>Total</i>	3,376	8,086	2,532	7	142	5,547	2,610	2,682	215	63.81

1.17 StrykerJS standard mutation operators

Table 160 shows the results of running the standard mutation operators of *StrykerJS* on the subject applications.

1.18 String edit distance measurements for different LLMs

Table 161 shows average string similarity for each project, for each of the five LLMs under consideration.

	application	#mutants	#killed	#survived	#timeout	mut. score	time
scriptsize	<i>Complex.js</i>	1,302	763	539	0	58.60	405.08
	<i>countries-and-timezones</i>	140	134	6	0	95.71	142.37
	<i>crawler-url-parser</i>	226	143	83	0	63.27	433.53
	<i>delta</i>	834	686	88	60	89.45	2,747.04
	<i>image-downloader</i>	43	28	11	4	74.42	284.20
	<i>node-dirty</i>	160	78	56	26	65.00	215.93
	<i>node-geo-point</i>	158	98	60	0	62.03	357.70
	<i>node-jsonfile</i>	61	31	5	25	91.80	188.91
	<i>plural</i>	180	143	37	0	79.44	53.66
	<i>pull-stream</i>	474	318	116	40	75.53	694.33
	<i>q</i>	1,058	68	927	63	12.38	7,075.02
	<i>spacl-core</i>	259	239	20	0	92.28	1,053.16
	<i>zip-a-folder</i>	74	38	8	28	89.19	513.27
	<i>Total</i>	4,969	2,767	1,956	246	—	14,164.20

Table 160: Results of applying the standard mutation operators of StrykerJS.

Project	<i>codellama-34b-instruct</i>	<i>codellama-13b-instruct</i>	<i>llama-3.3-70b-instruct</i>	<i>gpt-4o-mini</i>	<i>mixtral-8x7b-instruct</i>
<i>Complex.js</i>	4.27	4.63	6.90	6.35	8.95
<i>countries-and-timezones</i>	11.13	9.78	11.71	11.33	13.65
<i>crawler-url-parser</i>	9.50	8.82	10.71	10.05	12.65
<i>delta</i>	9.55	8.88	13.01	11.44	14.15
<i>image-downloader</i>	12.67	10.74	12.66	13.88	14.21
<i>node-dirty</i>	7.53	7.42	12.08	10.20	12.08
<i>node-geo-point</i>	8.86	8.15	8.97	9.53	15.27
<i>node-jsonfile</i>	9.73	10.07	11.10	11.00	10.81
<i>plural</i>	8.14	6.29	9.27	8.31	10.37
<i>pull-stream</i>	6.72	8.71	7.82	8.06	9.67
<i>q</i>	8.61	9.71	11.17	9.92	13.23
<i>spacl-core</i>	9.30	10.84	8.95	8.70	12.61
<i>zip-a-folder</i>	9.85	12.38	11.87	11.23	11.61

Table 161: Average string similarity to the original code fragments that they replace, for mutants generated using five LLMs at temperature 0.0.