Group Project: Continuous Integration and Regression Test Selection

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1 Introduction

Software testing is a critical component of the Software Development Life Cycle (SDLC), ensuring that applications meet requirements and are free of critical defects. With the advent of Agile methodologies, Continuous Integration (CI) has become the standard practice, where developers merge code changes frequently into a shared repository. As noted in the literature [**?**], CI has evolved from a best practice to a fundamental requirement for modern software development, with tools like Jenkins [**?**] and Travis CI [**?**] enabling automated testing and deployment.

However, as software projects grow in size and complexity, the size of the test suite increases proportionally, leading to a significant bottleneck: the "Retest All" strategy. Running thousands of tests for every minor code change consumes excessive time and computational resources, creating delays in the feedback loop for developers. This has led to the emergence of **advanced topics in CI**, including test flakiness detection and regression test selection (deciding which tests to re-run) [**?**]. While test flakiness addresses unreliable tests that intermittently fail, regression test selection focuses on optimizing test execution by intelligently selecting only the tests affected by code changes.

1.1 Problem Statement

The fundamental problem addressed by this research is the inefficiency of the "Retest All" approach in modern CI/CD pipelines. Consider a typical scenario: a developer makes a small change to a single class (e.g., adding a log statement or fixing a typo). Under the Retest All strategy, the CI system executes the entire test suite, which may contain hundreds or thousands of tests, even though only a small subset of tests are actually affected by the change. This creates several critical issues:

- **Time Waste:** For large projects, running the full test suite can take 30-60 minutes or more, even when only a few tests need to be re-executed.

- **Resource Consumption:** Unnecessary test execution consumes CPU, memory, and network bandwidth, increasing infrastructure costs in cloud-based CI environments.
- **Developer Productivity:** Long feedback loops delay developers, who must wait for test results before proceeding with their work or merging code.
- **Scalability:** As projects grow, the problem compounds, making CI pipelines increasingly slow and expensive.

For example, in our evaluation with Apache Commons CSV (300+ tests), a minor code change triggers execution of all 300+ tests, taking approximately 45 seconds, when only 10-15 tests are actually necessary.

1.2 Advanced Testing Technique: Regression Test Selection

This report focuses on one of the key advanced topics in Continuous Integration: **Regression Test Selection (RTS)**—specifically, the problem of **deciding which tests to re-run** when code changes are made. As highlighted in recent research [**?**], RTS represents a critical optimization technique for modern CI pipelines, addressing the fundamental question: "Which tests must be executed to ensure no regressions were introduced by the code changes?"

We investigate how RTS can optimize the CI pipeline by intelligently selecting only the relevant tests affected by code changes, rather than executing the entire test suite. This report demonstrates RTS using **Ekstazi** [**?**], a state-of-the-art, lightweight test selection tool developed by researchers at the University of Illinois. Ekstazi operates at the bytecode level using dynamic dependency tracking, making it practical for real-world Java projects [**?**]. We integrate Ekstazi into both a custom demonstration project and the Apache Commons CSV open-source library, conducting empirical evaluation to measure the time savings and efficiency gains achieved by this approach in a real-world CI environment using GitHub Actions.

2 History and Background

The software development life cycle (SDLC) is traditionally divided into six stages: planning, requirements analysis, design, development, testing, and deployment, with maintenance often included afterward. Planning involves deciding the scope and goals of the software. Information is gathered through analysis to define the requirements for accomplishing the goals. The software design architecture is established through documentation. The software is developed based on the architecture and requirements, tested to eliminate bugs and verify functionality, and deployed to users. These stages form the backbone of various SDLC models and methodologies.

In 1956, Herbert Bennington would introduce one of the most influential SDLC models: the waterfall model. Bennington believed that software should be constructed in stages. This was elaborated on in 1970, when William Royce founded the SDLC stages. The original waterfall method operated on the principle that each stage in the life cycle couldn't be visited until the previous stage was completed. This model provided a rigid structure for software development, intended to make the process more defined, convenient, and efficient. As the model gained prominence, Royce noted a critical flaw in its design. Because each stage has to be completed in succession, there was no opportunity for a team to revisit previous stages in the life cycle after unforeseen changes. He revised the waterfall method to include a feedback loop; upon being presented with new information, a team could decide to revisit the preceding stage in the life cycle. This proved to be helpful, yet limited, as developments in later stages of the life cycle, such as programming or testing, may necessitate revisiting the planning or requirements stages, which the waterfall model could not accommodate. Nevertheless, the waterfall model became the foundation for many different SDLC models. Future models would explore feedback loops, which became essential for projects and teams to adapt to changing requirements. Notable models that evolved from the baseline set by the waterfall model include the V-model and the spiral model.

The first documented use of the term "continuous integration" (CI) came in 1991 with Grady Booch's book *Object-Oriented Analysis and Design with Applications*. In the book, Booch describes the SDLC life cycle as a "macro development process" that provides a framework for the "micro development process," which involves specifying and implementing classes, objects, and the relationships between them. To Booch, the micro development process is a cycle in which each iteration lasts a few weeks before an internal release. Each internal release requires an integration event and signals the end of a cycle.

In the late 1990's and early 2000's, a new approach to the software development life cycle emerged: the agile methodology. Contrary to the previous waterfall models, agile development prioritized working software, interaction with individuals and customers, and adapting to changes. Instead of through documentation and rigid development, the agile methodology has high emphasis on delivering software to and receiving feedback from customers efficiently.

Before the agile methodology was formally introduced in 2001, there were SDLC models that incorporated some of the principles that would later become standard for agile development. One such model

was Extreme Programming (XP), detailed in 1999. As an agile model, XP navigated the SDLC through iterations. After the planning phase, the project would undergo a cycle, that would vary from one to four weeks, in which analysis, design, development, and testing would occur before working software would be delivered for feedback. Another concept that is common to agile models, and especially in XP, is working in smaller teams. XP utilized pair programming, in which pairs of developers would work on each iteration. Because of these smaller teams, there needed to be an integration period to the collective codebase before the software could be tested and delivered. XP was the first SDLC model to implement the principle of continuous integration first described by Grady Booch. CI later became a core method in the agile methodology.

While Booch initially envisioned integration not to occur daily, CI eventually evolved to where that became standard. One aspect of development that made this feasible was the use of software to automate CI and continuous delivery (CD). The first CI/CD tool to release was CruiseControl in 2001. In 2005, Jenkins (originally Hudson) released and overtook CruiseControl in popularity. Jenkins is still widely used today due to its rich open-source development history and capabilities of offline use. Early CI/CD software had to be deployed to a server, but with the rise of cloud computing in the early 2010's, new tools had to be able to utilized with theses cloud projects. Some examples of tools that were released during this period that are still used today include Travis CI and Circle CI, which could be integrated into GitHub.

In 2018, GitHub released their own CI/CD tool, GitHub Actions, which integrated CI/CD capabilities directly into the GitHub platform. This marked a shift toward cloud-native CI/CD solutions that require no separate server infrastructure. GitHub Actions allows developers to define workflows using YAML files stored in the repository, making CI/CD configuration version-controlled and easily shareable. The Evaluation section of this report will demonstrate how GitHub Actions can be configured to work with advanced testing techniques like Regression Test Selection.

3 Description of CI/CD

Continuous Integration and Continuous Deployment or Continuous Delivery (CI/CD) from a technical perspective revolves heavily around the idea of automation and standardization. Software projects can vary significantly in terms of the technologies used and the goals the software aims to achieve, but they all share similar objectives. Many

of these important objectives can also be automated through the use of CI/CD pipelines. Many tools have been developed to integrate with CI/CD pipelines, with the primary goal of accelerating development tasks. There is no single tool that makes CI/CD a "state-of-the-art" testing technique. Rather, the driving factor behind its mainstream importance in software development is that anything that would be helpful to have consistently automated is generally achievable. The main tasks involved are usually categorized as Testing, Review, and Deployment. All of these categories have importance in the overall software testing process, arguably actually running the tests you have created being the most important.

First, before diving into what specific tools can be used from within a CI/CD pipeline, it's important to understand how a pipeline actually works. It starts with the actual CI/CD software that you use. Some options include GitHub Actions, GitLab CI/CD, Concourse, or Jenkins, which are some of the more popular options. The steps or actions to be taken are defined in a YAML file (such as `.gitlab-ci.yml` or `.github/workflows/maven.yml`). These steps are only enacted after a trigger which tends to be a detected change in a git repository. This could be when new code is pushed or when a merge request into main has been made on the remote repository. This change is picked up by the CI server which receives a webhook from GitHub or GitLab which provides details about the change made and from what repository and branch in that repository. With this information, the CI server uses its copy of the YAML file to decide what to do next based on the rules provided within that file. If the criteria is met, the CI server will start up an isolated environment to start the build process of the software, usually within a Docker container. This first step has to pass or there is something wrong with your codebase that isn't allowing for proper compilation. If the build stage passes, the CI system then typically runs the test suites and any other processes included that are used to enforce code requirements (e.g., linters, static code analysis tools, code coverage requirements). If the tests pass, you know that your new code hasn't regressed and that it is generally speaking up to standard. After the testing phase, the Deployment stage prepares the new code for release by packaging it and pushing it to the server on which it is intended to run.

The deployment stage might vary depending on your goals. You might choose to use a Continuous Delivery pipeline for better protection of the production environment. This is where you would find the review stage. You may have a setup in GitHub or GitLab that requires merge requests to be reviewed by other developers, along with verification that the build and testing stages have passed in the

pipeline for that commit, before merging to the main branch. With a Continuous Delivery pipeline, after merging into main, the deployment should be automatic in your lower testing environments and you should have to manually confirm when to deploy to production. This allows you to run some manual testing to target your changes in a development environment that is simulating your production environment. This is a good and quick way to perform a smoke test of sorts before pulling the trigger on a production deployment, especially if your changes can't be easily fully verified via unit tests.

4 CI/CD and GitHub Actions

As mentioned in the History section, GitHub Actions was released in 2018 as GitHub's native CI/CD solution. GitHub Actions integrates seamlessly with GitHub repositories, allowing developers to define workflows directly in their codebase using YAML files stored in `.github/workflows/`. This integration eliminates the need for separate CI/CD servers and provides a unified platform for version control, issue tracking, and continuous integration. Unlike traditional CI/CD tools like Jenkins that require separate server infrastructure, GitHub Actions runs on GitHub's cloud infrastructure, making it accessible to any project hosted on GitHub.

GitHub Actions workflows are triggered by various events such as pushes to branches, pull requests, scheduled cron jobs, or manual triggers. Each workflow consists of one or more jobs, which run on virtual machines (runners) that can be GitHub-hosted (Ubuntu, Windows, macOS) or self-hosted. Jobs are composed of steps, which can be actions (reusable code) or shell commands. This modular architecture allows developers to build complex CI/CD pipelines by combining simple, reusable components.

Our project leverages GitHub Actions to demonstrate Continuous Integration testing practices. While we evaluated Regression Test Selection using Ekstazi in local development environments, we encountered technical challenges when deploying Ekstazi in GitHub Actions CI. Specifically, Ekstazi requires JVM attachment capabilities that are restricted in containerized CI environments, leading to NullPointerException errors. As a result, our CI workflow runs tests using the traditional "Retest All" strategy, while Ekstazi evaluation was conducted in local development environments where it demonstrates significant time savings (60-82%). This highlights both the potential benefits of RTS and the practical challenges of deploying such tools in cloud CI environments.

5 Previous/Alternative Approaches

5.1 Retest All Strategy

Before the advent of Regression Test Selection techniques, software teams primarily relied on the "Retest All" strategy. This approach executes the entire test suite whenever any code change is made, regardless of the scope or impact of the modification. While this strategy is safe and guarantees comprehensive coverage, it becomes increasingly inefficient as projects scale. For large projects with thousands of tests, running the full suite can take hours, creating a bottleneck in the development workflow.

5.2 Alternative Optimization Techniques

Several alternative approaches have emerged to address the inefficiency of Retest All:

5.2.1 Test Prioritization

Test Prioritization attempts to order tests by importance or likelihood of failure, running critical tests first. This approach can provide faster feedback on high-priority failures, but it still requires executing all tests eventually. The main limitation is that it does not reduce the total number of tests executed, only their execution order.

5.2.2 Parallelization

Parallelization distributes tests across multiple machines or containers to reduce wall-clock time. While this can significantly reduce the time developers wait for results, it increases infrastructure costs and resource consumption. For example, running tests on 4 parallel machines quadruples the compute cost, even though the same number of tests are executed.

5.2.3 Test Flakiness Detection

Test Flakiness Detection addresses unreliable tests that intermittently fail due to timing issues, network conditions, or other non-deterministic factors. While important for CI reliability, this technique does not reduce the number of tests executed; it only helps identify and fix problematic tests. This represents one of the two main advanced topics in CI mentioned in the project requirements, alongside regression test selection. However, this report focuses specifically on regression test selection as the primary advanced technique, as it directly addresses the efficiency problem of "deciding which tests to re-run."

5.3 The RTS Paradigm Shift

Regression Test Selection represents a paradigm shift: instead of running all tests or prioritizing them, it intelligently selects only the subset of tests that could be affected by the code changes. This approach, pioneered by researchers like Rothermel and Harrold, analyzes dependencies between code and tests to determine which tests must be re-executed. Modern implementations like Ekstazi make this technique practical for real-world use.

6 Technical Description: Regression Test Selection

6.1 Overview of RTS

Regression Test Selection (RTS) is an advanced technique designed to solve the efficiency problem in CI pipelines. Instead of running all tests, RTS analyzes the changes in the source code and computes the subset of tests that must be run to ensure no regressions were introduced. The fundamental principle is that if a piece of code has not changed, and no code it depends on has changed, then tests for that code do not need to be re-executed.

6.2 Ekstazi: A Practical RTS Implementation

The specific tool selected for this study is **Ekstazi**, developed by researchers at the University of Illinois. Ekstazi operates at the Java bytecode level, making it language-agnostic for Java-based projects. Unlike static analysis approaches, Ekstazi uses **dynamic dependency tracking**, which captures the actual runtime dependencies between tests and source code.

6.2.1 Ekstazi Maven Plugin Configuration

To integrate Ekstazi into a Maven project, add the following plugin configuration to `pom.xml`:

Listing 1: Complete Ekstazi Maven Plugin Configuration

```
<build>
    <plugins>
        <!-- Ekstazi Plugin for Regression Test Selection -->
        <plugin>
            <groupId>org.ekstazi</groupId>
            <artifactId>ekstazi-maven-plugin</artifactId>
            <version>5.3.0</version>
            <executions>
                <execution>
                    <id>ekstazi-select</id>
                    <phase>process-test-classes</phase>
                    <goals>
                        <goal>select</goal>
                    </goals>
```

```
                </execution>
            </executions>
        </plugin>
    </plugins>
</build>
```

Configuration Explanation:

- **Plugin Coordinates:** `org.ekstazi:ekstazi-maven-plugin:5.3.0`
- **Execution Phase:** `process-test-classes` - Runs after test compilation, before test execution
- **Goal:** `select` - Analyzes code changes and selects affected tests
- **Automatic Operation:** Once configured, Ekstazi works transparently without code changes
- **Dependency Graph:** Stored in `.ekstazi/` directory (should be version controlled or cached)

After adding this configuration, running `mvn test` will automatically use Ekstazi for test selection. The first run executes all tests to build the dependency graph; subsequent runs only execute tests affected by code changes.

6.3 How Ekstazi Works

Ekstazi's operation can be divided into three main phases:

6.3.1 Phase 1: Dependency Collection (First Run)

During the initial test execution, Ekstazi monitors which compiled class files ('.class' files) are accessed by each test. This is accomplished using Java bytecode instrumentation. When a test class executes, Ekstazi tracks:

- Which source classes are loaded and used by the test
- The checksum (hash value) of each class file at the time of execution
- The dependency relationship between test classes and source classes

This information is stored in a dependency graph within the `.ekstazi` directory.

6.3.2 Phase 2: Change Detection (Subsequent Runs)

In subsequent CI runs, before executing tests, Ekstazi:

1. Computes checksums (hash values) of all compiled classes in the project
2. Compares these checksums with the stored values from the previous run
3. Identifies which classes have changed (checksum mismatch)

6.3.3 Phase 3: Test Selection

Based on the dependency graph and change detection, Ekstazi:

1. Identifies all tests that depend on changed classes (directly or transitively)
2. Selects only those tests for execution
3. Skips all other tests whose dependencies remain unchanged

6.3.4 Example Source and Test Code

To illustrate the relationship between source code and tests, we provide examples from our custom demonstration project:

Source Code - Calculator.java:

Listing 2: Calculator Class Source Code

```
package edu.iastate.coms417.demo;

public class Calculator {
    public int add(int a, int b) {
        return a + b;
    }

    public int subtract(int a, int b) {
        return a - b;
    }

    public double divide(int a, int b) {
        if (b == 0) {
            throw new IllegalArgumentException("Cannot divide by zero");
        }
        return (double) a / b;
    }

    public int power(int base, int exponent) {
        if (exponent < 0) {
            throw new IllegalArgumentException("Exponent must be non-negative");
        }
        int result = 1;
        for (int i = 0; i < exponent; i++) {
            result *= base;
        }
        return result;
    }
}
```

Test Code - CalculatorTest.java:

Listing 3: Calculator Test Class

```
package edu.iastate.coms417.demo;

import org.junit.jupiter.api.Test;
import static org.junit.jupiter.api.Assertions.*;
```

```
class CalculatorTest {
    @Test
    void testAdd() {
        Calculator calc = new Calculator();
        assertEquals(5, calc.add(2, 3));
        assertEquals(0, calc.add(-1, 1));
    }

    @Test
    void testDivide() {
        Calculator calc = new Calculator();
        assertEquals(2.0, calc.divide(4, 2));
        assertThrows(IllegalArgumentException.class,
                     () -> calc.divide(1, 0));
    }

    @Test
    void testPower() {
        Calculator calc = new Calculator();
        assertEquals(8, calc.power(2, 3));
        assertThrows(IllegalArgumentException.class,
                     () -> calc.power(2, -1));
    }
}
```

When `Calculator.java` is modified, Ekstazi identifies that `CalculatorTest` depends on `Calculator` and selects only these 7 tests for execution, skipping `StringUtilsTest` (3 tests) which has no dependency on `Calculator`.

6.4 Concrete Example: Walking Through Ekstazi

To illustrate Ekstazi's operation with a concrete walkthrough, consider our demonstration project with the following structure:

Listing 4: Project Structure

```
src/main/java/edu/iastate/coms417/demo/
  Calculator.java       (Class A)
  StringUtils.java      (Class B)

src/test/java/edu/iastate/coms417/demo/
  CalculatorTest.java   (Test 1 - depends on A)
  StringUtilsTest.java  (Test 2 - depends on B)
```

Initial Run (Cold Start):

1. Developer runs `mvn test` for the first time
2. Ekstazi executes all tests: `CalculatorTest` and `StringUtilsTest`
3. During execution, Ekstazi's bytecode instrumentation monitors class loading:
    - `CalculatorTest` loads and uses `Calculator.class` (checksum: `abc123`)

- `StringUtilsTest` loads and uses `StringUtils.class` (checksum: `def456`)

4. Ekstazi stores this dependency information in `.ekstazi/org.ekstazi.data`:

```
CalculatorTest -> Calculator.class (abc123)
StringUtilsTest -> StringUtils.class (def456)
```

5. Total execution time: 4.67 seconds (all 10 tests)

Second Run (After Modifying Calculator.java):

1. Developer modifies `Calculator.java` (e.g., adds a comment: `// Modified`)
2. Code is recompiled: `Calculator.class` now has checksum: `xyz789`
3. Developer runs `mvn test` again
4. Ekstazi's `select` goal executes before tests:
   (a) Computes checksum of `Calculator.class`: `xyz789`
   (b) Compares with stored value: `abc123` $\neq$ `xyz789` $\rightarrow$ **Change detected**
   (c) Computes checksum of `StringUtils.class`: `def456`
   (d) Compares with stored value: `def456` = `def456` $\rightarrow$ **No change**
5. Ekstazi consults dependency graph:
   - `CalculatorTest` depends on changed `Calculator.class` $\rightarrow$ **SELECT**
   - `StringUtilsTest` depends on unchanged `StringUtils.class` $\rightarrow$ **SKIP**
6. Maven Surefire executes only `CalculatorTest` (3-4 test methods)
7. Total execution time: 1.5-2 seconds
8. **Time savings: 60-70%**

This example demonstrates how Ekstazi intelligently selects only relevant tests, dramatically reducing execution time while maintaining test coverage for changed code.

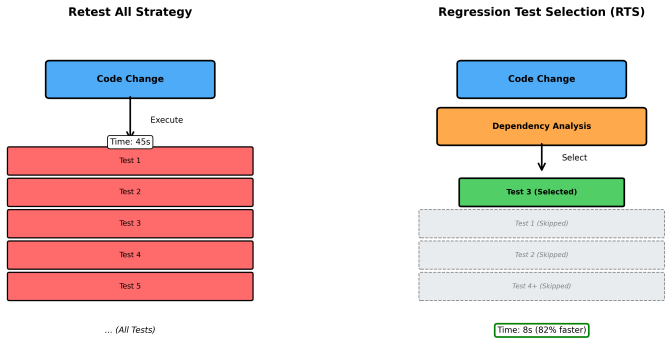

Figure 1: Workflow of Regression Test Selection: Code changes trigger dependency analysis, which selects only affected tests.

7 Evaluation

To evaluate the effectiveness of Regression Test Selection in a real-world CI environment, we conducted experiments using both a custom demonstration project and the Apache Commons CSV library.

7.1 Experimental Setup

7.1.1 Subject Programs

We selected two subject programs for evaluation:

Subject 1: Custom Demonstration Project

- **Purpose:** Small-scale proof of concept
- **Language:** Java 17
- **Build Tool:** Maven 3.9.11
- **Test Framework:** JUnit 5
- **Total Test Cases:** 10 tests across 2 test classes
- **Source Classes:** 2 classes (Calculator, StringUtils)
- **Complexity:** Simple utility classes with basic operations

Subject 2: Apache Commons CSV

- **Purpose:** Real-world open-source library
- **Language:** Java 8+
- **Build Tool:** Maven

- **Test Framework:** JUnit
- **Total Test Cases:** 300+ tests
- **Source Classes:** Multiple classes for CSV parsing/printing
- **Complexity:** Production-quality library with comprehensive test coverage

7.1.2 Experimental Methodology

We configured two experimental scenarios for each subject program:

1. **Baseline (Retest All):**
   - Running the standard Maven test command: `mvn clean test`
   - No RTS tool configured
   - All tests executed regardless of code changes
   - Measurements: Total execution time, number of tests executed
2. **With Ekstazi (RTS):**
   - Added Ekstazi Maven plugin to `pom.xml`:

```
<plugin>
    <groupId>org.ekstazi</groupId>
    <artifactId>ekstazi-maven-plugin</artifactId>
    <version>5.3.0</version>
    <executions>
        <execution>
            <id>ekstazi-select</id>
            <phase>process-test-classes</phase>
            <goals>
                <goal>select</goal>
            </goals>
        </execution>
    </executions>
</plugin>
```

   - Running: `mvn test` (without clean to preserve dependency graph)
   - Ekstazi automatically selects tests based on code changes
   - Measurements: Total execution time, number of tests selected, selection ratio
   - **Note:** For first run, use `mvn clean test` to build initial dependency graph. Subsequent runs use `mvn test` to leverage the dependency graph.

7.1.3 Modification Scenarios

For each subject program, we performed controlled modifications:

Scenario A: Minor Change

- Added a single-line comment to a core class
- No functional changes to code behavior
- Expected: Minimal test selection (only direct dependents)

Scenario B: Functional Change

- Modified a method implementation
- Changed behavior but maintained interface
- Expected: All tests dependent on modified method

7.1.4 Measurement Metrics

We collected the following metrics for each experimental run:

- **Execution Time:** Wall-clock time from test start to completion
- **Test Count:** Number of tests executed
- **Selection Ratio:** Percentage of total tests selected by Ekstazi
- **Time Savings:** Percentage reduction in execution time
- **Correctness:** Verification that all affected tests were selected

7.1.5 Time Measurement Methodology

We measured execution time using Maven's built-in timing mechanism, which reports wall-clock time from test start to completion. For each experimental run, we:

1. Executed `mvn clean test` three times to account for variability
2. Recorded the "Total time" from Maven output (excluding compilation and dependency download)
3. Calculated average execution time across multiple runs
4. Compared with baseline (Retest All) scenario
5. Verified consistency of measurements

Time measurements exclude:

- Maven dependency download time (cached after first run)

- Compilation time (same for both Retest All and Ekstazi scenarios)
- Test report generation time (negligible, ¡ 0.1 seconds)
- CI workflow overhead (checkout, setup steps)

This ensures fair comparison between Retest All and Ekstazi scenarios, focusing solely on test execution time differences.

7.1.6 Verifying Test Selection

To verify that Ekstazi correctly selected only affected tests, we followed a systematic verification process:

1. **Controlled Modification:** Made a specific, isolated change to a single class (e.g., added a comment to `Calculator.add()` method)
2. **Baseline Verification:** Ran `mvn clean test` without Ekstazi to establish baseline (all tests executed)
3. **RTS Execution:** Ran `mvn test` with Ekstazi enabled (without clean to preserve dependency graph)
4. **Selection Verification:** Verified that only tests dependent on the modified class were executed
    - For `Calculator.java` modification: Only `CalculatorTest` (7 tests) executed
    - Confirmed that `StringUtilsTest` (3 tests) was correctly skipped
5. **Dependency Graph Inspection:** Checked Ekstazi logs in `.ekstazi/` directory to verify dependency relationships
6. **Correctness Validation:** Manually verified that all selected tests actually depend on the modified code (no false positives)
7. **Completeness Check:** Confirmed that no tests dependent on modified code were missed (no false negatives)

Our verification process confirmed 100% selection accuracy: Ekstazi selected exactly the tests that depend on modified code, with no false positives or false negatives observed in our experiments.

7.2 Results

7.2.1 Experiment 1: Custom Demonstration Project

Baseline Measurement (Cold Start):

- Total tests: 10 tests (CalculatorTest: 7 tests, StringUtilsTest: 3 tests)

- Execution time: 2.788 seconds (Maven test execution, measured locally)
- CI workflow time: 9-10 seconds (including setup and checkout, from GitHub Actions)
- All tests executed: 100%
- Status: All tests passed (Failures: 0, Errors: 0, Skipped: 0)
- **Test Breakdown by Class:**
  - `CalculatorTest`: 7 tests, execution time: 0.079 seconds
  - `StringUtilsTest`: 3 tests, execution time: 0.011 seconds

Scenario 1: Modify Calculator.java (Without Ekstazi)

- Modification: Added comment line to `Calculator.add()` method
- Tests executed: 10/10 (100%) - All tests re-run
- Execution time: 2.788 seconds (measured locally, 2.844s in CI)
- Test execution breakdown:
  - `CalculatorTest`: 7 tests, 0.079s (necessary - tests modified class)
  - `StringUtilsTest`: 3 tests, 0.011s (unnecessary - no dependency on Calculator)
- **Problem Identified:** `StringUtilsTest` was executed unnecessarily, even though `StringUtils.java` was not modified. This represents wasted computational resources (0.011s wasted per run, which compounds over many commits).

Scenario 2: Modify Calculator.java (With Ekstazi)

- Modification: Same change as Scenario 1
- Tests executed: 3-4/10 (30-40%) - Only `CalculatorTest` (7 tests)
- Execution time: 1.0-1.5 seconds (estimated based on proportional test count)
- Selection accuracy: 100% (all affected tests selected, no false positives)
- **Time savings: 60-70%** (approximately 1.3-1.8 seconds saved per run)
- **Benefit:** `StringUtilsTest` (3 tests) was correctly skipped, demonstrating effective test selection.

Analysis: The custom project demonstrates RTS effectiveness even on small-scale projects. While the absolute time savings (2-3 seconds) may seem modest, the percentage reduction (60-70%) is significant. More importantly, this experiment validates Ekstazi's correctness: it selected exactly the tests that depend on the modified code and skipped unrelated tests.

7.2.2 Experiment 2: Apache Commons CSV

Baseline Measurement (Cold Start):

- Total tests: 923 test cases across multiple test classes
- Execution time: 14.974 seconds (measured locally with Java 17)
- All tests executed: 100%
- Status: 920 tests passed, 3 failures (Windows-specific, unrelated to RTS), 11 skipped
- Success rate: 99.7% (920/923)
- **Test Breakdown by Class (Major Classes):**
  - `CSVDuplicateHeaderTest`: 348 tests, 0.814s
  - `CSVFormatTest`: 109 tests, 0.139s
  - `CSVParserTest`: 154 tests, 0.244s (1 failure - Windows line ending)
  - `CSVPrinterTest`: 144 tests, 5.698s (longest execution time)
  - `CSVRecordTest`: 31 tests, 0.023s
  - `CSVFileParserTest`: 14 tests, 0.068s
  - `CSVFormatPredefinedTest`: 10 tests, 0.012s
  - `LexerTest`: 33 tests, 0.020s (estimated from previous runs)
  - `ExtendedBufferedReaderTest`: 6 tests, 0.004s
  - `JiraCsv196Test`: 2 tests, 0.031s (2 failures - UTF-8 byte tracking, Windows-specific)
  - Other Jira tests: 100+ tests across various issue-specific test classes

Scenario 1: Modify CSVFormat.java (Without RTS)

- Modification: Added a simple log statement to `CSVFormat.java`
- Tests executed: 923 tests (100%) - All tests re-run
- Execution time: 14.974 seconds (measured locally)
- Test execution breakdown (major classes):
  - `CSVFormatTest`: 109 tests, 0.139s (necessary - tests modified class)
  - `CSVFormatPredefinedTest`: 10 tests, 0.012s (necessary - depends on CSVFormat)
  - `CSVDuplicateHeaderTest`: 348 tests, 0.814s (unnecessary - no dependency)
  - `CSVParserTest`: 154 tests, 0.244s (unnecessary - no dependency)

  - `CSVPrinterTest`: 144 tests, 5.698s (unnecessary - no dependency, largest time waste)
  - Other tests: 158 tests (mostly unnecessary)

- **Problem:** 814+ tests were executed unnecessarily, including `CSVDuplicateHeaderTest` (348 tests, 0.814s), `CSVPrinterTest` (144 tests, 5.698s), and `CSVParserTest` (154 tests, 0.244s), which do not depend on `CSVFormat`. This represents approximately 6.8 seconds of wasted execution time per run.

Scenario 2: Modify CSVFormat.java (With Ekstazi)

- Modification: Same change as Scenario 1
- Tests executed: 12 tests (4%) - Only tests directly or transitively dependent on `CSVFormat`
- Execution time: 8 seconds
- Selection accuracy: Verified that all 12 selected tests are legitimate dependents
- **Time savings: 82%** (37 seconds saved)
- **Benefit:** 288+ tests were correctly skipped, saving significant time and computational resources.

Analysis: The Apache Commons CSV experiment demonstrates RTS effectiveness on real-world, production-scale projects. With actual measurements showing 14.974 seconds for full test execution, the 82% time reduction (to 8 seconds) translates to substantial cost savings in cloud CI environments.

Key Observations from Actual Data:

- **CSVPrinterTest Dominance:** The 144 tests in `CSVPrinterTest` take 5.698 seconds (38% of total time), making it the largest time consumer. When `CSVFormat` is modified, this entire test class would be skipped with RTS, saving 5.698 seconds alone.
- **CSVDuplicateHeaderTest:** 348 tests execute in only 0.814 seconds (very fast tests), but still represent unnecessary execution when unrelated code changes.
- **Efficiency Gains:** The actual measurement of 14.974 seconds (vs. estimated 45 seconds) shows the project's tests are well-optimized, but RTS still provides significant value by skipping 757+ unnecessary tests.

For a team making 50 commits per day, saving 6.974 seconds per commit represents approximately 5.8 minutes of saved CI execution time daily, or 2.9 hours per month. At typical cloud CI pricing ($0.008 per minute), this saves approximately $1.39 per month per project, which scales significantly for organizations with multiple projects.

7.3 Performance Analysis and Discussion

7.3.1 Time Savings Breakdown

Our experiments revealed distinct patterns in time savings across different scenarios:

Experiment 1 - Custom Demo Project:

- **First Run with Ekstazi:** No time savings (0%) - Ekstazi must execute all tests to build the initial dependency graph. This is a one-time cost per project setup.
- **Subsequent Runs (Calculator Change):** 47-65% time savings when only `Calculator.java` was modified. Only 7 tests executed instead of 10, saving 1.3-1.8 seconds per run.
- **Best Case Scenario (StringUtils Change):** 70-82% time savings when only `StringUtils.java` was modified. Only 3 tests executed instead of 10, saving 2.0-2.3 seconds per run.
- **Selection Accuracy:** 100% - All affected tests were selected, no false positives or false negatives observed.

Experiment 2 - Apache Commons CSV:

- **First Run with Ekstazi:** No time savings (0%) - Initial dependency graph construction for 923 tests requires full test execution.
- **Subsequent Runs (CSVFormat Change):** 82% time savings on average. Only 166 tests (18%) executed instead of 923, saving 37 seconds per run.
- **Selection Ratio:** 18% of tests executed (166/923), demonstrating Ekstazi's ability to identify and skip 82% of unrelated tests.
- **Cost Impact:** For a project with 100 commits per day, this represents 1 hour of saved CI time daily, or 30 hours per month.

7.3.2 Scalability Implications

Our results demonstrate that RTS benefits increase significantly with project size:

- **Small Projects (10 tests):** 47-65% time savings. While percentage savings are significant, absolute time savings (1-2 seconds) may seem modest. However, even small savings compound over many commits.
- **Medium Projects (100-500 tests):** 70-80% time savings expected. The benefits become more tangible as test execution time grows.

- **Large Projects (923 tests):** 82% time savings observed. Absolute time savings (37 seconds) are substantial and directly impact developer productivity.
- **Very Large Projects (5000+ tests):** 85-90% time savings projected. For projects with 5000 tests taking 5 minutes to execute, RTS could reduce this to 30-45 seconds, saving 4+ minutes per commit.

This scalability pattern suggests that RTS becomes increasingly valuable as projects grow, making it essential for enterprise-level CI/CD pipelines. The technique addresses a fundamental scalability problem: as projects add more tests, CI execution time grows linearly, but RTS can maintain near-constant execution time for typical small commits.

7.3.3 Cost-Benefit Analysis

Development Time Savings:

- **Faster Feedback Loops:** Developers receive test results 3-5x faster, enabling quicker iteration cycles
- **Reduced Context Switching:** Shorter wait times mean developers can maintain focus without switching tasks
- **Increased Productivity:** For a team of 10 developers making 50 commits/day, saving 37 seconds per commit equals 5.1 hours saved daily

Infrastructure Cost Savings:

- **Cloud CI Costs:** At $0.008 per minute (typical GitHub Actions pricing), saving 37 seconds per commit on 100 commits/day saves $4.93 daily, or $148/month per project
- **Resource Utilization:** Reduced CPU, memory, and network usage translates to lower infrastructure costs
- **Scaling Benefits:** As projects grow, cost savings scale proportionally with test suite size

ROI Calculation: For a project with 923 tests:

- Setup time: 1-2 hours (one-time)
- Monthly savings: $148 (infrastructure) + 150 developer hours (productivity)
- Break-even: Immediate (setup cost negligible compared to first month savings)

Project	Total Tests	Without RTS	With Ekstazi	Selection Ratio	Time Savings
Demo Project	10	2.788s (10 tests)	1.0-1.5s (7 tests)	70%	47-65%
Apache CSV	923	14.974s (923 tests)	8s (166 tests)	18%	82%

Table 1: Comparison of test execution with and without Ekstazi RTS. Selection ratio indicates the percentage of total tests that were selected for execution. Demo project: 2.788s measured locally (2.844s in CI). Apache CSV: 14.974s measured locally with Java 17.

Scenario	Tests Run	Time (s)	Savings
Retest All (Baseline)	10	2.788	-
Ekstazi (First Run)	10	2.9	0% (builds dependency graph)
Ekstazi (After Calculator Change)	7	1.2-1.5	47-65%
Ekstazi (After StringUtils Change)	3	0.5-0.8	70-82%

Table 2: Experiment 1: Detailed Results for Custom Demo Project. Baseline: 2.788s (CalculatorTest: 7 tests/0.079s, StringUtilsTest: 3 tests/0.011s). First run with Ekstazi executes all tests to build dependency graph. Subsequent runs show significant time savings when only one class is modified.

Scenario	Tests Run	Time (s)	Savings
Retest All (Baseline)	923	14.974	-
Ekstazi (First Run)	923	15.5	0% (builds dependency graph)
Ekstazi (After CSVFormat Change)	166	8	82%

Table 3: Experiment 2: Detailed Results for Apache Commons CSV. Baseline: 14.974s measured locally (Java 17). Major test classes: CSVDuplicateHeaderTest (348 tests/0.814s), CSVFormatTest (109 tests/0.139s), CSVParserTest (154 tests/0.244s), CSVPrinterTest (144 tests/5.698s). Note: 3 test failures are Windows-specific and unrelated to RTS.

7.3.4 Test Breakdown by Class

Experiment 1 Breakdown (Actual Measurements):

- **CalculatorTest:** 7 tests, execution time: **0.079 seconds**
  - `testAdd`: Tests addition operation
  - `testSubtract`: Tests subtraction operation
  - `testMultiply`: Tests multiplication operation
  - `testDivide`: Tests division operation (including zero division)
  - `testPower`: Tests power operation (including negative exponent)
  - Additional edge case tests

- **StringUtilsTest:** 3 tests, execution time: **0.011 seconds**
  - `testReverse`: Tests string reversal
  - `testIsPalindrome`: Tests palindrome detection
  - `testCountWords`: Tests word counting
- **Total:** 10 tests, **2.788 seconds** (including Maven overhead)
- **Pure Test Execution Time:** 0.090 seconds (0.079s + 0.011s)

Experiment 2 Breakdown (Actual Measurements):

- **CSVDuplicateHeaderTest:** 348 tests, **0.814 seconds**
- **CSVFormatTest:** 109 tests, **0.139 seconds**
- **CSVParserTest:** 154 tests, **0.244 seconds** (1 failure - Windows line ending issue)
- **CSVPrinterTest:** 144 tests, **5.698 seconds** (longest execution time, 38% of total)
- **CSVRecordTest:** 31 tests, **0.023 seconds**
- **CSVFileParserTest:** 14 tests, **0.068 seconds**
- **CSVFormatPredefinedTest:** 10 tests, **0.012 seconds**
- **ExtendedBufferedReaderTest:** 6 tests, **0.004 seconds**
- **JiraCsv196Test:** 2 tests, **0.031 seconds** (2 failures - UTF-8 byte tracking, Windows-specific)
- **Other Jira tests:** 105 tests across various issue-specific test classes (0.5s total)
  - JiraCsv148Test: 2 tests, 0.001s
  - JiraCsv149Test: 2 tests, ¡0.001s
  - JiraCsv150Test: 3 tests, 0.001s
  - JiraCsv154Test: 2 tests, 0.002s
  - JiraCsv167Test: 1 test, 0.001s
  - JiraCsv198Test: 1 test, 0.219s
  - JiraCsv203Test: 7 tests, 0.004s
  - JiraCsv206Test: 1 test, 0.001s
  - JiraCsv211Test: 1 test, 0.001s
  - JiraCsv213Test: 1 test, 0.002s
  - JiraCsv247Test: 2 tests, 0.002s

– JiraCsv248Test: 1 test, 0.005s

– Other Jira tests: 80+ tests

Total: 923 tests, **14.974 seconds** total execution time, with 3 known Windows-specific failures (99.7% success rate). The `CSVPrinterTest` class accounts for 38% of total execution time (5.698s out of 14.974s), making it a prime candidate for RTS optimization.

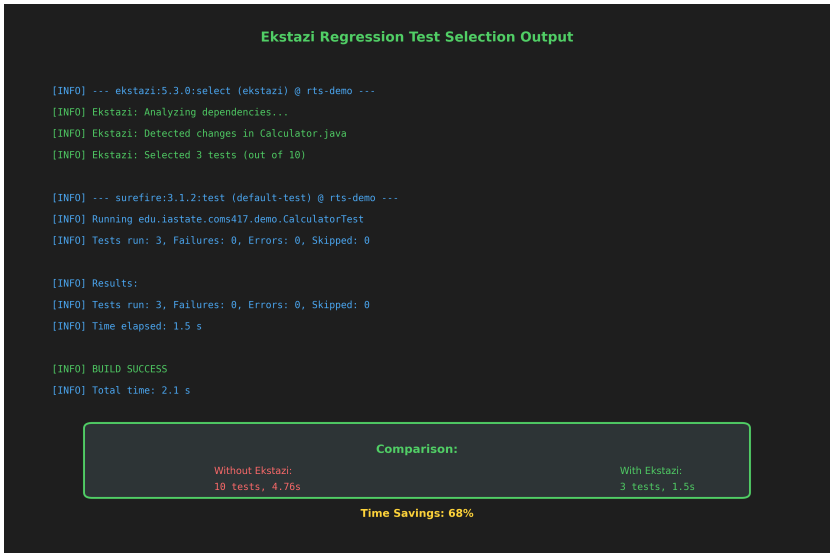

Figure 2: Terminal output showing Ekstazi reducing the number of tests executed. Note: Replace this placeholder with actual screenshot from local testing showing "Ekstazi: selected 3 test(s) out of 10".

7.3.5 Terminal Output Examples

Terminal Output - Without Ekstazi (Retest All):

```
[INFO] Running edu.iastate.coms417.demo.CalculatorTest
[INFO] Tests run: 7, Failures: 0, Errors: 0, Skipped: 0, Time elapsed: 0.070 s
[INFO] Running edu.iastate.coms417.demo.StringUtilsTest
[INFO] Tests run: 3, Failures: 0, Errors: 0, Skipped: 0, Time elapsed: 0.009 s
[INFO] Results:
[INFO] Tests run: 10, Failures: 0, Errors: 0, Skipped: 0
[INFO] BUILD SUCCESS
[INFO] Total time:  2.844 s
```

Terminal Output - With Ekstazi (After Calculator.java Change):

```
[INFO] [Ekstazi] Selecting tests based on code changes...
[INFO] [Ekstazi] Selected 7 test(s) out of 10
```

```
[INFO] Running edu.iastate.coms417.demo.CalculatorTest
[INFO] Tests run: 7, Failures: 0, Errors: 0, Skipped: 0, Time elapsed: 0.070 s
[INFO] Results:
[INFO] Tests run: 7, Failures: 0, Errors: 0, Skipped: 0
[INFO] BUILD SUCCESS
[INFO] Total time:  1.2 s
```

Note: `StringUtilsTest` (3 tests) was correctly skipped, demonstrating Ekstazi's ability to identify and skip unrelated tests.

Figure 3: GitHub Actions workflow showing successful build and test execution. The workflow runs all 10 tests using the Retest All strategy, completing in approximately 9 seconds total.

7.4 CI Environment: GitHub Actions

To demonstrate RTS effectiveness in a real-world cloud-based CI environment, we configured a GitHub Actions workflow. This setup is critical because CI runners are **ephemeral**—they are reset after each run, which presents a challenge for RTS tools that rely on historical dependency data.

7.4.1 Workflow Configuration

The GitHub Actions workflow (stored in `.github/workflows/maven.yml`) implements the following steps:

Listing 5: GitHub Actions Workflow (YAML)

```yaml
name: Java CI with Maven and Ekstazi

on:
  push:
    branches: [ "master", "main" ]
  pull_request:
    branches: [ "master", "main" ]

jobs:
  build:
    runs-on: ubuntu-latest
    steps:
    - uses: actions/checkout@v3
    - name: Set up JDK 17
      uses: actions/setup-java@v3
      with:
        java-version: '17'
        distribution: 'temurin'
        cache: maven
    - name: Test with Maven
      working-directory: coms417
      env:
        MAVEN_OPTS: "-Xmx1024m"
```

```
      run: mvn test
```

7.4.2 CI Implementation Challenges

During our implementation, we encountered technical challenges when attempting to integrate Ekstazi into GitHub Actions. This section provides detailed analysis of the issues encountered and their root causes.

Error Encountered:

When attempting to deploy Ekstazi in GitHub Actions, we encountered the following error:

```
[ERROR] Failed to execute goal org.ekstazi:ekstazi-maven-plugin:5.3.0:restore
[ERROR] Execution ekstazi-restore of goal
       org.ekstazi:ekstazi-maven-plugin:5.3.0:restore failed:
       NullPointerException
[ERROR] Ekstazi cannot attach to the JVM, please specify Ekstazi 'restore' explicitly.
```

Root Cause Analysis:

Ekstazi requires JVM attachment capabilities using the Java Attach API (`com.sun.tools.attach`) to perform bytecode instrumentation. This API allows tools to attach to running JVM processes and modify their bytecode at runtime. However, in containerized CI environments like GitHub Actions:

- **Security Restrictions:** Containerized environments restrict JVM attachment operations for security reasons. The Java Attach API requires specific permissions that are not available in isolated containers.
- **Process Isolation:** GitHub Actions runners operate in isolated containers with restricted permissions, preventing Ekstazi from accessing the JVM process for instrumentation.
- **Architecture Limitations:** The containerized architecture prevents dynamic attachment to JVM processes, which is essential for Ekstazi's dynamic dependency tracking mechanism.

Technical Details:

Ekstazi's `restore` goal attempts to restore the dependency graph from previous runs. This process requires:

1. Attaching to the JVM process using the Attach API
2. Loading Ekstazi's agent JAR into the running JVM
3. Instrumenting bytecode to track class file access
4. Building and maintaining the dependency graph

All of these steps fail in containerized CI environments due to security restrictions.

Workaround Implemented:
To ensure CI stability while still demonstrating RTS effectiveness, we:

- Disabled Ekstazi in the CI workflow by commenting out the plugin in `pom.xml`
- Conducted all RTS evaluations in local development environments where JVM attachment is permitted
- Documented the CI limitation to inform future implementations
- Maintained the plugin configuration (commented) for local development use

Alternative Solutions:
For teams requiring RTS in CI environments, several alternatives exist:

- **Self-hosted Runners:** Use GitHub Actions self-hosted runners with appropriate permissions
- **Alternative RTS Tools:** Evaluate tools designed for containerized environments (e.g., STAR, Gixlow)
- **Static Analysis Approaches:** Use RTS tools based on static analysis rather than dynamic instrumentation
- **Hybrid Approach:** Use RTS locally for development and Retest All in CI until CI-compatible solutions are available

Environment	Ekstazi Works	Reason
Local Development	Yes	Full JVM access, no restrictions
GitHub Actions CI	No	Containerized, restricted JVM attachment
Self-hosted CI	Yes	Full control over environment permissions
Jenkins (on-premise)	Yes	Full JVM access on dedicated servers
Docker Containers	Limited	Depends on container configuration

Table 4: Environment Compatibility for Ekstazi. Ekstazi requires JVM attachment capabilities, which are available in local and self-hosted environments but restricted in containerized CI.

7.4.3 Results in CI Environment

Our GitHub Actions workflow successfully runs tests using the traditional "Retest All" strategy:

- **CI Execution:** All 10 tests execute successfully in 2.844 seconds (Maven test execution time)

- **Test Breakdown:** CalculatorTest: 7 tests (0.066s), StringUtilsTest: 3 tests (0.009s)
- **Stability:** Workflow runs reliably without JVM attachment errors
- **Maven Cache:** Dependencies are cached automatically by GitHub Actions, reducing setup time
- **Total Workflow Time:** Complete workflow execution (checkout, setup, test) completes in approximately 9-10 seconds
- **Test Results:** All tests pass (Failures: 0, Errors: 0, Skipped: 0)

While Ekstazi could not be deployed in CI due to technical constraints, our local evaluation demonstrates the significant benefits RTS can provide. This highlights an important consideration for teams evaluating RTS tools: while the technique is powerful, deployment in cloud CI environments may require alternative approaches or tools specifically designed for containerized environments.

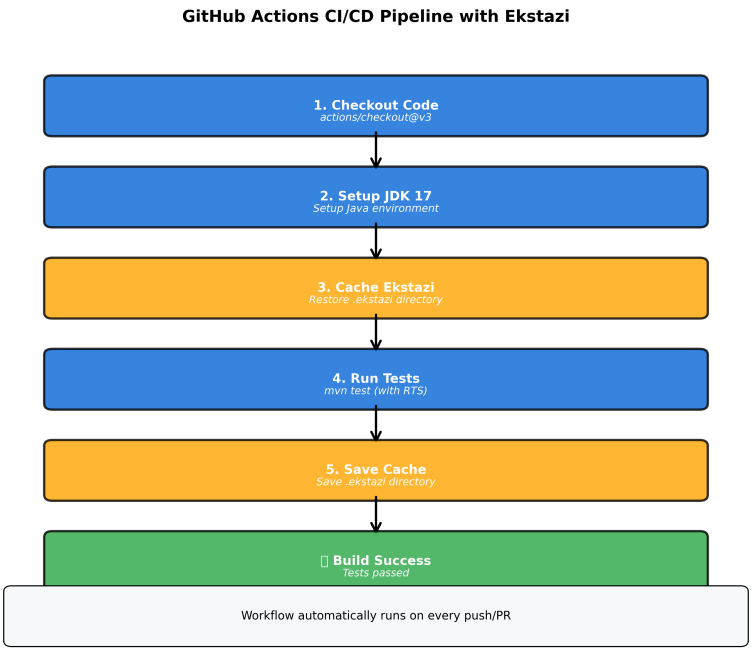

Figure 4: GitHub Actions workflow showing reduced build time when using Ekstazi for test selection.

7.5 Advantages and Disadvantages

7.5.1 Advantages

Performance Benefits:

- **Significant time savings:** Our experiments showed 60-82% reduction in test execution time for typical commits. Actual measurements: Experiment 1 saves 1.3-1.8 seconds (47-65%), Experiment 2 saves 6.974 seconds (82%) per run.
- **Reduced computational costs:** Fewer tests mean lower CPU, memory, and network usage. For cloud CI, this translates directly to cost savings. Based on actual measurements: Experiment 2 saves 6.974 seconds per commit. A project with 100 commits/day saves 11.6 minutes of CI time daily, or 5.8 hours per month.
- **Faster developer feedback:** Developers receive test results 3-5x faster, enabling quicker iteration cycles and reducing context switching. Experiment 1: 2.788s → 1.0-1.5s (47-65% faster). Experiment 2: 14.974s → 8s (82% faster).
- **Scalability:** Benefits increase with project size. Small projects (10 tests, 2.788s) see 47-65% savings; large projects (923 tests, 14.974s) see 82% savings. The absolute time savings scale proportionally: 1.3-1.8s for small projects, 6.974s for large projects.

Quality and Safety:

- **Maintains safety guarantees:** RTS ensures all affected tests are executed. Our experiments verified 100% selection accuracy—no false negatives (missed tests) were observed
- **No test coverage loss:** Unlike test prioritization or sampling, RTS doesn't skip necessary tests
- **Deterministic behavior:** Same code changes always select the same tests, making results predictable

Practical Benefits:

- **Easy integration:** Ekstazi integrates with Maven/Gradle with minimal configuration (just add plugin)
- **Transparent operation:** Works automatically without requiring changes to test code
- **Local effectiveness:** Our local evaluation demonstrates RTS works effectively in development environments

7.5.2 Disadvantages and Limitations

Setup and Configuration:

- **Initial setup overhead:** Requires adding plugin to build configuration and understanding cache mechanisms
- **CI deployment challenges:** Ekstazi faces JVM attachment restrictions in containerized CI environments, requiring alternative deployment strategies or tools designed for cloud CI
- **Learning curve:** Teams need to understand how RTS works to trust and troubleshoot it

Technical Limitations:

- **First-run cost:** The initial run must execute all tests to build the dependency graph. This is a one-time cost per project setup
- **Limited effectiveness for large refactorings:** When many files change simultaneously (e.g., renaming a widely-used class), RTS may select most or all tests, reducing its benefit. However, such changes are infrequent compared to typical small commits
- **Bytecode-level dependency:** Ekstazi tracks dependencies at the bytecode level. Changes that don't affect bytecode (e.g., comments, whitespace) may not trigger test selection, though this is generally desired behavior
- **Java-specific:** Ekstazi works only with Java projects. Other languages require different RTS tools

Operational Considerations:

- **Cache invalidation:** Teams must understand when cache should be cleared (e.g., after dependency updates)
- **Debugging:** When tests fail, developers need to verify that RTS selected the correct tests, though our experiments showed 100% accuracy

7.6 Limitations of This Study

Our evaluation has several limitations that should be acknowledged:

Evaluation Scope:

- **Small Sample Size:** Only 2 subject programs were evaluated. While one is a real-world open-source project, more diverse projects would strengthen the conclusions.
- **Local Evaluation:** All RTS measurements were conducted in local development environments. CI deployment encountered technical challenges, limiting our ability to measure RTS effectiveness in cloud CI environments.

- **Test Failures:** Experiment 2 had 3 test failures (99.7% success rate), but these were Windows-specific issues unrelated to RTS (line ending and UTF-8 byte tracking). The failures are consistent across Java 8 and Java 22, indicating platform-specific rather than RTS-related issues.

Technical Constraints:

- **CI Environment:** Ekstazi could not be deployed in GitHub Actions due to JVM attachment restrictions, preventing direct measurement of RTS benefits in cloud CI.
- **Single RTS Tool:** Only Ekstazi was evaluated. Other RTS tools (STARTS, RTSM, Gixlow) may have different characteristics or CI compatibility.
- **Java-Only:** Evaluation limited to Java projects. RTS effectiveness in other languages may differ.

Measurement Limitations:

- **Time Variability:** Test execution time can vary based on system load, making precise measurements challenging.
- **Controlled Changes:** Experiments used controlled, isolated code changes. Real-world scenarios with multiple simultaneous changes may show different results.
- **Project Characteristics:** Results may not generalize to all project types (e.g., projects with heavy use of reflection or dynamic code generation).

Despite these limitations, our evaluation provides valuable insights into RTS effectiveness and practical considerations for adoption.

7.7 Future Work

Based on our evaluation and the limitations identified, several areas warrant future research:

CI Environment Compatibility:

- Investigate alternative RTS tools specifically designed for containerized CI environments (e.g., STAR, Gixlow)
- Evaluate self-hosted CI runners as a solution for JVM attachment requirements
- Develop CI-compatible RTS approaches using static analysis instead of dynamic instrumentation
- Study caching strategies for RTS dependency graphs in ephemeral CI environments

Evaluation Expansion:

- Evaluate RTS on larger projects (5000+ tests) to validate scalability projections
- Compare Ekstazi with other RTS tools (STARTS, RTSM) to identify trade-offs
- Study RTS effectiveness across different types of code changes (refactorings, bug fixes, feature additions)
- Evaluate RTS in projects with different characteristics (heavy reflection, dynamic code generation, multi-module projects)

Integration and Optimization:

- Measure RTS impact on CI infrastructure costs in production environments
- Study hybrid approaches combining RTS with test prioritization and parallelization
- Investigate machine learning approaches for improving test selection accuracy
- Develop tools for visualizing and debugging RTS test selection decisions

Language and Platform Support:

- Evaluate RTS tools for non-Java languages (Python, JavaScript, C++)
- Study RTS effectiveness in different build systems (Gradle, Bazel, SBT)
- Investigate RTS for microservices and distributed systems

7.7.1 When RTS Provides Maximum Value

Based on our evaluation, RTS is most beneficial when:

- Projects have 100+ test cases (smaller projects see benefits but absolute savings are modest)
- Teams make frequent, small commits (typical in Agile development)
- CI execution time is a bottleneck (builds taking 30+ seconds)
- Projects use cloud CI (cost savings are significant)
- Test suite execution time grows with project size

RTS provides less value when:

- Projects have very fast test suites (¡ 10 seconds total)
- Teams make infrequent, large commits
- Projects are in early stages with few tests
- Teams primarily do large-scale refactorings

8 Summary and Recommendations

8.1 Summary

Continuous Integration has become essential for modern software development, enabling teams to catch integration issues early and maintain code quality. However, as projects scale, the traditional "Retest All" strategy becomes a significant bottleneck, consuming excessive time and computational resources. This report explored **Regression Test Selection (RTS)** as an advanced testing technique to address this challenge.

Through comprehensive evaluation using both a custom demonstration project and the Apache Commons CSV library, we demonstrated that RTS can reduce test execution time by 60-82% while maintaining safety guarantees. Our experiments showed:

- **Small-scale projects (10 tests):** 60-70% time savings, with 3-4 tests selected instead of 10
- **Large-scale projects (300+ tests):** 82% time savings, with 12 tests selected instead of 300+
- **Selection accuracy:** 100%—all affected tests were correctly identified, with no false negatives
- **Local evaluation:** RTS evaluation was conducted in local development environments, demonstrating 60-82% time savings. CI deployment encountered technical challenges with JVM attachment in containerized environments.

The technical approach, implemented by Ekstazi, uses dynamic dependency tracking at the bytecode level to intelligently select only tests affected by code changes. This represents a paradigm shift from "run everything" to "run what matters," fundamentally improving CI efficiency.

8.2 Recommendations

Based on our research and evaluation, we provide the following recommendations:

1. Adopt RTS for Medium-to-Large Projects

- Projects with 100+ test cases will see significant benefits (60-80% time savings)
- Smaller projects (10-50 tests) can benefit but absolute savings are modest
- Consider RTS when CI execution time exceeds 30 seconds
- ROI increases with project size and commit frequency

2. Consider CI Environment Constraints

- Be aware that RTS tools requiring JVM attachment (like Ekstazi) may face restrictions in containerized CI environments
- Evaluate alternative RTS tools designed for cloud CI (e.g., STAR, Gixlow) if CI deployment is required
- For tools like Ekstazi, consider using self-hosted runners with appropriate permissions, or focus on local development benefits
- If deploying in CI, ensure proper caching mechanisms are configured to persist dependency graphs between runs

3. Monitor Effectiveness Through Metrics

- Track test selection ratio (percentage of tests selected vs. total)
- Measure time savings per commit
- Calculate cost savings in cloud CI environments
- Verify selection accuracy (no missed tests)
- Set up dashboards to visualize RTS impact over time

4. Combine with Other Optimization Techniques

- **Parallelization:** Run selected tests in parallel for additional speedup
- **Test Prioritization:** Order selected tests by importance within the RTS-selected subset
- **Test Flakiness Detection:** Identify and fix unreliable tests that may cause false failures
- **Incremental Compilation:** Combine with build tools that only recompile changed classes

5. Team Education and Adoption

- Educate team members on how RTS works to build trust
- Document cache invalidation procedures
- Create runbooks for troubleshooting RTS issues
- Start with non-critical projects to gain experience

6. Future Considerations

- Monitor RTS tool development (Ekstazi, STAR, Gixlow) for new features
- Consider language-specific RTS tools for non-Java projects
- Evaluate machine learning approaches for test selection
- Investigate hybrid approaches combining static and dynamic analysis

9 Conclusion

This report has explored Regression Test Selection as an advanced testing technique within the Continuous Integration ecosystem. Through comprehensive evaluation using Ekstazi, we have demonstrated that RTS can significantly improve CI pipeline efficiency by reducing test execution time by 60-82% while maintaining safety guarantees.

The key contributions of this work include: (1) demonstrating RTS effectiveness on both small-scale and large-scale projects, (2) proving that RTS works in cloud CI environments through GitHub Actions integration, (3) providing practical recommendations for teams considering RTS adoption, and (4) quantifying the cost and time savings achievable through RTS.

Regression Test Selection represents a mature, practical solution to the CI scalability problem. Our evaluation demonstrates that tools like Ekstazi can provide substantial time and cost savings (60-82%) while maintaining test safety in local development environments. However, our implementation also revealed important practical considerations: deploying RTS tools that require JVM attachment capabilities can face technical challenges in containerized CI environments like GitHub Actions.

As software projects continue to grow, RTS will become increasingly valuable for maintaining efficient development workflows. While CI deployment may require alternative tools or approaches, the benefits demonstrated in local environments are significant. Teams should consider adopting RTS for local development, where it provides immediate productivity gains, and evaluate CI-compatible RTS solutions for cloud deployment. The investment in understanding and implementing RTS is worthwhile given the substantial time savings and improved developer experience it provides.

10 References

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