Meditor: Inference and Application of API Migration Edits

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Abstract—Developers build programs based on software libraries. When a library evolves, programmers need to migrate their client code from the library’s old release(s) to new release(s). Due to the API backwards incompatibility issues, such code migration may require developers to replace API usage and apply extra edits (e.g., statement insertions or deletions) to ensure the syntactic or semantic correctness of migrated code. Existing tools extract API replacement rules without handling the additional edits necessary to fulfill a migration task. This paper presents our novel approach, Meditor, which extracts and applies the necessary edits together with API replacement changes.

Meditor has two phases: inference and application of migration edits. For edit inference, Meditor mines open source repositories for migration-related (MR) commits, and conducts program dependency analysis on changed Java files to locate and cluster MR code changes. From these changes, Meditor further generalizes API migration edits by abstracting away unimportant details (e.g., concrete variable identifiers). For edit application, Meditor matches a given program with inferred edits to decide which edit is applicable, customizes each applicable edit, and produces a migrated version for developers to review.

We applied Meditor to four popular libraries: Lucene, CraftBukkit, Android SDK, and Commons IO. By searching among 602,249 open source projects on GitHub, Meditor identified 1,368 unique migration edits. Among these edits, 885 edits were extracted from single updated statements, while the other 483 more complex edits were from multiple co-changed statements. We sampled 937 inferred edits for manual inspection and found all of them to be correct. Our evaluation shows that Meditor correctly applied code migrations in 218 out of 225 cases. This research will help developers automatically adapt client code to different library versions.

Index Terms—API migration edits, program dependency analysis, automatic program transformation

I. INTRODUCTION

As software libraries evolve, migrating client code between library releases can be difficult and time-consuming. A recent article reported that Google developers spent about 9 years migrating all their codebases from proto-1 to proto-2 APIs [2]. Such difficulty of code migration is mainly due to API backwards incompatibility issues: when library developers evolve software, they sometimes introduce API breaking changes that make client code fail to compile or run [24], [33], [49], [53]. To handle the compilation or execution errors, developers of client code have to manually locate the usage of breaking APIs and explore alternative code for replacement.

Manually migrating code between library releases is tedious and error-prone. Even though some libraries provide change logs or release notes [14] to document how a new release (e.g., $L_n$) is different from the prior release (e.g., $L_{n-1}$), such documentation is insufficient. This is because while release notes focus on differences between adjacent library versions, we observed client code to be often migrated between nonadjacent versions. When there is no sufficient documentation providing the needed guidelines, developers have to extensively search for solutions or discuss issues on technical websites [3], [4], [10]–[12]. Even though developers went though such painful process, they could still make mistakes when migrating code and introduce bugs to previously mature code [47].

Existing tools provide limited support for automatic API migration [23], [25], [40], [45], [52], [56]. They compare versions of a library or client code to infer API mappings without handling any surrounding edit required by the API replacement. Cossette et al. studied the nature of API incompatibilities and identified some API migration patterns not supported by any existing tool [24]. For instance, when a method API evolves to take an additional parameter, e.g., “foo() $\rightarrow$ foo(int v)”, current tools only capture the API correspondence but do not care about how to prepare a value for $v$ before the function call [24]. Additionally, existing techniques only suggest API mapping rules without automatically migrating code.

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Fig. 1: Meditor consists of two phases: Phase I infers API migration edits given versions of a library ($L$), and Phase II applies the inferred edits to a given client application ($P$).
This paper presents a new approach, Meditor, to generate and apply API migration edits (i.e., API replacements + related edits) based on developers’ migration changes in open source projects. As shown in Fig. 1, Meditor contains two phases. Given versions of a library $L$, Phase I identifies open source projects that use the library, and locates any migration-related (MR) commit in projects’ version history. For each MR commit, Meditor identifies and groups MR code changes via syntactic program differencing [30] and program dependency analysis. After generalizing each group of MR changes by abstracting concrete identifier usage, Meditor derives API migration edits and saves them to a database.

Phase II takes in a client program ($P$) that uses $L$. It enumerates all edits in the database to decide which edit is applicable to $P$. If the tentative context matching between any edit and $P$ succeeds, Meditor applies those edits and produces a migrated version ($P'$) accordingly. In this way, Meditor can help inexperienced developers find the API migration edits applied by other developers, and apply similar edits to transform client code.

We applied Meditor to four widely used libraries: Lucene [13], CraftBukkit [9], Android SDK [5], and Commons IO [7]. Meditor generated 153, 931, 268, and 16 unique edits for individual libraries. Among these edits, (1) 885 edits require for single statement updates, (2) 189 edits involve multi-statement changes that modify program data flows but preserve the control flows, and (3) 294 edits modify both control and data flows. We sampled 937 inferred edits for manual checking and found all of them to be correct, which indicates Meditor’s great capability of edit inference.

To evaluate the edit application capability of Meditor, we created a data set of 87 examples. Each example includes multiple code snippets showing the same migration pattern. Within each example, we used Meditor to generate an edit from one snippet and applied the edit to the other snippets. Meditor correctly migrated code in 218 out of 225 cases.

In summary, this paper makes the following contributions:

- We developed Meditor, a novel approach to infer and apply API migration edits. Different from prior work, Meditor infers API replacement rules together with co-applied edits and automates edit application.
- We developed a novel algorithm that flexibly locates and groups MR code changes in commits where migration-related changes are co-applied with unrelated changes.
- We conducted a large-scale study with Meditor and observed interesting phenomena, including (1) Meditor revealed undocumented rules and (2) many programs were migrated between nonadjacent library releases.
- Meditor correctly inferred and applied edits in most scenarios. By inferring domain knowledge from human-written changes in migrated code, Meditor can mimic the coding practices to suggest similar code migration.

**II. A MOTIVATING EXAMPLE**

This section overviews our approach with exemplar changes drawn from open source projects [6], [8]. Suppose that a developer Alex wants to migrate code between releases of Lucene. To obtain migration suggestions from Meditor, Alex needs to first provide versions of the library such that Meditor can retrieve any related migration edit stored in the database. If there is no edit extracted so far, Meditor crawls GitHub projects to search for any project that (1) uses Lucene and (2) has any commit updating the release information of Lucene.

![Fig. 2: Migrating H2Fulltext.java from lucene-2.3.2 to lucene-4.7.0]([16](#))

Fig. 2 presents the code changes applied in one identified commit drawn from revisions to nexeo [8]. In this example, multiple statements were changed together because nexeo was migrated from Lucene 2.3.2 to Lucene 4.7.0. We highlight the deleted code with red and mark it with “-“. Similarly, the added code is highlighted with green and marked with “+“. According to the figure, the old version invokes:

- two Lucene APIs (i.e., `IndexReader.indexExists(...)` and `IndexWriter constructor`), and
- one user-defined method `getAnalyzer(...)`.

However, the new version invokes:

- four Lucene APIs (i.e., `FSDirectory.open(...), IndexWriterConfig constructor`, `IndexWriterConfig setOpenMode(...), and IndexWriter constructor`),
- one user-defined method `getAnalyzer(...), and
- one JDK API `File constructor`.

Compared with the old `IndexWriter constructor` (see line 2), the new constructor (see line 7) takes two instead of three parameters. Consequently, when updating the usage of this API, developers also modified the parameter preparation logic (line 1 and lines 3-6).

**Edit Inference.** To infer the migration edit or pattern demonstrated by Fig. 2, Meditor first extracts any replaced API whose signature belongs to the old release but not to the new one (e.g., the `IndexWriter constructor`), and then exploits control and data dependencies to correlate the API replacements with surrounding co-applied edit operations (e.g., statement insertions and deletions). In this way, Meditor obtains a cluster of MR edited statements $Ch$. Next, to generalize an MR edit that is applicable to programs using different variables, Meditor replaces concrete identifiers used in $Ch$ with symbolic names. As shown in Fig. 3, the created symbolic names (e.g., $v_j$ and `v_j boolean`) not only preserve the data flows of original identifiers, but also record type information to facilitate later edit application. Meditor stores all inferred edits in a database to enable edit query and comprehension.

**Edit Application.** Given a program $P$ to migrate between versions $L_i$ and $L_j$ of Lucene, Meditor queries the database...
void v_7 = IndexReader.indexExists(v_0_String);

v_6 = new IndexWriter(v_0_String, m_0(v_2_String), v_7_boolean);

========== Replaced by ===========

Directory v_1 = FSDirectory.open(new File(v_0_String));
Analyzer v_3 = m_0(v_2_String);
IndexWriterConfig v_5 = new IndexWriterConfig(c_0_Version, v_3_Analyzer);
v_5_IndexWriterConfig.setOpenMode(OpenMode.CREATE_OR_APPEND);
v_6 = newIndexWriter(v_1_Directory, v_5_IndexWriterConfig);

Fig. 3: A migration edit generated by Meditor. Notice that
v_7 and v_7_boolean actually correspond to the same concrete
variable. We attached type information to the latter one to
facilitate template comprehension.

1. - boolean create = ! IndexReader.indexExists(_directory);
    ...
    // unchanged edit-irrelevant code
2. - idxWriter = new IndexWriter(_directory, analyzer, create);
3. + Directory v_1 = FSIndex.open(new File(_directory));
4. + Analyzer v_3 = analyzer;
5. + IndexWriterConfig v_5 = new IndexWriterConfig(c_0_Version, v_3);
6. + v_5.setOpenMode(OpenMode.CREATE_OR_APPEND);
7. + idxWriter = new IndexWriter(v_1_Directory, v_5_IndexWriterConfig);

Fig. 4: Code migration changes suggested by Meditor

for any edit matching the version numbers. For each found
edit, Meditor establishes context matching between P
and the edit; if the matching succeeds, Meditor concretizes
the edit for migration suggestion. Fig. 4 presents an exemplar set
of migration changes suggested by Meditor for a program that
Alex intends to migrate from Lucene 2.3.2 to Lucene 4.7.0.
According to Fig. 4, P is different from the original inference
example in Fig. 2 in two ways. First, the used variables
are different (e.g., _directory vs. indexPath). Second, no
user-defined method is invoked by P. Despite the differences,
Meditor managed to suggest code changes for Alex to review.

Although existing migration tools at most infer and suggest
many-to-many API mappings between Lo and Ln, they are
insufficient for two reasons. First, the mappings do not indicate
how the data and control dependencies among old APIs are
replaced by those among new APIs. Second, current tools do
not automate edit application to further reduce developers’
workload. Meditor overcomes both limitations.

III. APPROACH

As shown in Fig. 1, there are two phases in Meditor. In
this section, we first summarize the steps in each phase and
then describe each step in detail (Section III-A-Section III-E).

Phase I: Edit Inference

- Given versions of a library L, Meditor mines open
  source projects on GitHub for any commit that updates
  the version number of L in a build file (e.g., pom.xml),
  obtaining commits \(C = \{c_1, c_2, \ldots, c_n\}\).
- Meditor processes each commit to identify and cluster
  MR code changes. Each cluster of MR edited statements
demonstrate one migration pattern, denoted as \(Ch = \{G_o, G_n\}\), where \(G_o\) and \(G_n\) are edited statement groups
separately from the old and new versions.

- From Ch, Meditor abstracts away project-specific de-
tails (e.g., concrete variable identifiers) and derives a
general API migration edit \(E = \langle t_o, t_n \rangle\), where \(t_o\)
and \(t_n\) are code templates in the old and new versions.

Phase II: Edit Application

- Given \(P\) to migrate from \(L_i\) to \(L_j\), Meditor queries its
database for edits between the versions. For each found
edit \(E = \langle t_o, t_n \rangle\), Meditor tentatively matches \(P\) with
\(t_o\); if a matching is found, Meditor records the mappings
of constants, variables, methods, and expressions.
- With those mappings, Meditor concretizes \(t_n\) to create
updated code, suggesting a revised version \(P'\) for review.

A. Mining Migration-Related (MR) Commits

Given the jar files of multiple releases for L, Meditor
searches the software repositories of a list of 602,249 Java
projects on GitHub [38]. In each project repository, Meditor
scans the latest version of software for any usage of L in
the build file. Different build systems (e.g., Ant, Maven, and
Gradle) require developers to use distinct build files to specify
library dependencies. Our research focuses on the pom.xml
files in Maven projects and build.gradle files in Gradle projects
because of the popularity of Maven and Gradle [1], [54].

Fig. 5: A pom.xml file with a library version updated [17]

In particular, if the build file of a project refers to L,
Meditor explores the repository to find any commit updating
the version number of L. Intuitively, when developers update
library version information, they may also apply API migration
changes in the same commit. We gathered such commits as
candidate MR commits, denoting them as \(C = \{c_1, \ldots, c_n\}\).
Fig. 5 shows an exemplar updated pom.xml file, which replaces
Lucene 3.0.2 with Lucene 4.0-SNAPSHOT.

B. MR Code Change Recognition

Suppose that the before- and after- versions of each MR
commit are \((V_o, V_n)\), and they are separately based on two
library releases \((L_o, L_n)\). To precisely locate MR code changes
in one commit, we need to solve two technical challenges:

- Tangled Changes are unrelated changes applied in one
  commit for multiple tasks, such as bug fixing, library
  migration, and feature addition [20], [34]. Untangling MR
  code changes and irrelevant changes is challenging but
crucially important for precise edit inference.
- Change Intent explains why developers change code in
certain ways. When developers use new APIs to replace
old API usage, the code changes may be applied for tasks other than library migration. Inferring the change intent of API replacement is also challenging but vital.

To tackle the challenges, Meditor first uses syntactic program differencing to extract Java code changes from each commit (Section III-B1). Among the changes, Meditor locates any statement update caused by the library version change and considers them to be MR (Section III-B2). Next, Meditor uses the MR updated statements as centers to cluster relevant statement insertions or deletions via control or data dependencies, separating MR changes from dependency-irrelevant statement insertions or deletions via control or data dependencies (Section III-B3). Finally, for each cluster of MR code changes, Meditor checks whether the changes were applied in a semantic-preserving way; if not, Meditor does not further infer any MR edit because those changes might be applied to fulfill other tasks instead of library migration (Section III-B4).

1) Syntactic Program Differencing: To detect and represent Java code changes, Meditor uses ChangeDistiller [30]—a tree differencing algorithm—to compare the old and new versions of each changed Java source file. In particular, ChangeDistiller creates an AST for each version, i.e., \((tree_o, tree_n)\), and compares the trees; it generates an AST edit script that may contain four kinds of statement-level changes.

- **delete** (Node \(u\)): Delete node \(u\).
- **insert** (Node \(u\), Node \(v\), int \(k\)): Insert node \(u\) and position it as the \((k+1)th\) child of node \(v\).
- **move** (Node \(u\), Node \(v\), int \(k\)): Delete \(u\) from its current position and insert \(u\) as the \((k+1)th\) child of \(v\). This operation changes \(u\)'s position.
- **update** (Node \(u\), Node \(v\)): Replace \(u\) with \(v\). This operation changes \(u\)'s content.

The scripts produced by ChangeDistiller serve two purposes. First, if a script is empty, we can remove the corresponding Java file from further processing because no syntactic change was applied. Second, when a script is non-empty, we focus our analysis on the identified edited statements. For the motivating example in Fig. 2, ChangeDistiller compares ASTs (as shown in Fig. 6) and outputs the following edit operations:

1. update (O3, N6)
2. insert (N2, N1, 0)
3. insert (N3, N1, 1)
4. insert (N4, N1, 2)

5. insert (N5, N1, 3)
6. delete (O2)

2) Identification of Obvious MR Edit Operations: Some edit operations are obviously related to migration because they use obsolete APIs. To recognize outdated APIs used in \(V_o\), Meditor scans the APIs invoked by each updated statement and resolves the type bindings. If a statement in \(V_o\) calls an API that belongs to \(L_o\) but not \(L_n\), the related statement update is MR. To resolve bindings, Meditor uses Eclipse ASTParser to generate an AST for each Java source file, and queries the generated AST for binding information. For our example in Fig. 2, one updated statement invokes the old IndexWriter constructor in \(V_o\) (line 2) and calls the new constructor in \(V_n\) (line 7). As the invoked APIs are separately defined by \(L_o\) and \(L_n\), we consider this statement update to be MR.

```
1. - aboutBody.append(Html.fromHtml(getString(R.string.about_text, app_name, versionName, YAPI.GetAPIVersion())));
2. + String text = getString(R.string.about_text, app_name, versionName, YAPI.GetAPIVersion());
3. + Spanned html;
4. + if (android.os.Build.VERSION.SDK_INT >=
5. +   android.os.Build.VERSION_CODES.N) {
6. +   html = Html.fromHtml(text, Html.FROM_HTML_MODE_LEGACY);
7. + } else {
8. +   html = Html.fromHtml(text);
9. + } aboutBody.append(html);
```

Fig. 7: Migrating AboutDialog.java from Android Level 23 to Level 25 [15]

Additionally, we found some releases of the Android library, which deprecate APIs without removing them but still require for MR changes. To successfully detect such MR changes, we implemented another heuristic in Meditor. As illustrated by Fig. 7, when an if-statement is added to check whether a version number field (e.g., \(VERSION.SDK_INT\)) satisfies a condition, Meditor scans both branches to decide whether (1) one branch purely invokes APIs declared in both \(V_o\) and \(V_n\), and (2) the other branch invokes any API uniquely defined by \(V_n\). If so, the if-statement insertion is also MR.

3) Edit Operation Correlation: To reveal any additional statement insertion or deletion required by API replacements...
or obvious MR edit operations, *Meditor* correlates identified MR edit operations with co-applied edit operations leveraging the program dependencies (i.e., data and control dependencies) between edited statements in $V_o$ and $V_n$:

- **Data Dependence**: Statement $x$ is data dependent on statement $y$ if $x$ uses a variable defined by $y$. In Fig. 2, line 2 is data dependent on line 1 because line 2 uses the variable $v_0$ declared in line 1.

- **Control Dependence**: Statement $x$ is control dependent on $y$ if $x$ may or may not execute depending on a decision made by $y$. In Fig. 7, line 5 is control dependent on line 4, because whether the `then`-branch executes depends on the evaluation of the `if`-condition.

If an edited statement $stmt$ has direct data or control dependence relation with an MR edited statement, *Meditor* considers $stmt$ to be MR as well. For the example in Fig. 2, because line 3 was inserted to prepare the value of `dir`—a variable used for migration-related API replacement, the inserted statement is also MR. In this way, *Meditor* reveals MR edited statements iteratively until (1) all edited statements are labeled as MR, or (2) no more edited statement depends on or is depended on by any revealed MR edited statement. We denote the correlated edited statements with $Ch = \{G_o, G_n\}$, where $G_o$ and $G_n$ are groups of edited statements separately from $V_o$ and $V_n$. This step intends to filter out migration-irrelevant changes before *Meditor* infers MR edits. In our implementation, we exploited a widely used static analysis framework—WALA [18]—to identify the control and data dependencies between statements.

4) **Semantic Checking**: We believe that MR edits usually refactor code to solve API backwards incompatibility issues. Given $Ch = \{G_o, G_n\}$, this step checks whether $G_o$ and $G_n$ are semantically equivalent in order to infer developers’ change intent. If the program semantics are different, developers might have replaced API usage not purely for library migration. For such cases, *Meditor* does not infer any MR edit from the given recognized MR changes.

It is almost impossible to accurately reason about the semantic equivalence between two arbitrary code snippets. Therefore, we developed an intuitive approach to approximate semantic equivalence checking by comparing the input and output variables of code snippets. Given a snippet $s$, the input **variable set** ($I$) includes the variables defined elsewhere but used by $s$, while the output **variable set** ($O$) contains variables defined by $s$ but used elsewhere. Intuitively, if code changes preserve semantics, both the input and output variable sets should match between $G_o$ and $G_n$.

*Meditor* uses data flow analysis to create the input and output sets of $G_o$ and $G_n$: $(I_o, O_o)$ and $(I_n, O_n)$. If both the input and output sets match, *Meditor* concludes that the applied MR changes preserve semantics. For our example in Fig. 2, since $I_o = I_n = \{\text{IndexPath, analyzer}\}$ and $O_o = O_n = \{\text{IndexWriter}\}$, *Meditor* considers the two versions equivalent. Although our semantic checking approach is not sound or complete, based on our experience, *Meditor* usually infers MR edits without errors.

### C. Edit Generalization

This step generalizes an API migration edit $E = <t_o, t_n>$ from each cluster of edited statements $Ch = \{G_o, G_n\}$. Notice that the clustered edited statements contain concrete identifiers for API-irrelevant methods, variables, literals, and expressions. To ensure the generality of any inferred edit, *Meditor* abstracts away such unimportant program-specific editing details. Specifically, *Meditor* first checks the binding information of each identifier. If an identifier refers to a library API, *Meditor* keeps the identifier as is because the reference demonstrates API usage; otherwise, a symbolic name is generated to replace all occurrences of the concrete identifier. For instance, as shown in Fig. 2 and Fig. 3, the statement

```java
indexWriter = new IndexWriter(indexPath, getAnalyzer(
    analyzer), recreate);
```

is generalized to:

```java
v_6 = new IndexWriter(v_0_String, m_0(v_2_String),
    v_7_boolean);
```

In the generalization, variables (e.g., `indexWriter`) are consistently replaced by symbolic names starting with “v” (e.g., `v_6`). The library API `IndexWriter(...)` is kept as is. The user-defined method `getAnalyzer(...)` is replaced by a symbolic name starting with “m” (i.e., `m_0`), such that this project-specific method information is not propagated to the template.

*Meditor* saves all generalized edits in a database for edit search and improvement. When novice developers are curious about the migration edits between certain library releases, they can query the database with release numbers. When experienced developers find some migration edits to be improperly represented or missing in the database, they can also manually modify the inferred edits or insert new ones to the database based on their domain knowledge.

### D. Context Matching

Given $P$ to migrate from $L_o$ to $L_n$, *Meditor* queries the database for any mined edit from $L_o$ to $L_n$. For each obtained edit $E = <t_o, t_n>$, *Meditor* matches $P$ with $t_o$ in two steps.

1) **Statement Matching**: *Meditor* compares $t_o$ with $P$ at the statement level. For any statement template $s_t \in t_o$, *Meditor* identifies all library APIs used by $s_t$ and searches for any statement $s_p \in P$ invoking the same set of APIs. For each statement $s_p$ identified in this way, if the concrete identifiers and expressions in $s_p$ can also match the symbolic names in $s_t$, *Meditor* records the pair $(s_t, s_p)$ as a candidate match. Correspondingly, the matches between abstract identifiers in $s_t$ and concrete identifiers/expressions in $s_p$ are also recorded. For instance, the first statement in Fig. 3 matches line 1 in Fig. 4. Thus, the corresponding identifier mappings are recorded as $(v_7, \text{create})$ and $(v_0, \text{String, _directory})$.

2) **Dependency Matching**: When $t_o$ contains multiple statements and each statement $s_t$ has one or more matches in $P$, *Meditor* further leverages the dependency edges in $t_o$ to query for any correspondence in $P$. In particular, after matching individual statements between Fig. 3 and Fig. 4,
Table I: Client project data extracted for four subject libraries

<table>
<thead>
<tr>
<th></th>
<th>Lucene</th>
<th>CraftBukkit</th>
<th>Android SDK</th>
<th>Commons IO</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td># of commits with MR code changes</td>
<td>49</td>
<td>556</td>
<td>136</td>
<td>10</td>
<td>751</td>
</tr>
<tr>
<td># of client projects holding the refined commits</td>
<td>36</td>
<td>299</td>
<td>120</td>
<td>10</td>
<td>465</td>
</tr>
<tr>
<td># of snippets with MR code changes</td>
<td>247</td>
<td>1,864</td>
<td>328</td>
<td>19</td>
<td>2,458</td>
</tr>
</tbody>
</table>

Meditor retrieves the control and data dependencies between statements in $t_o$, which information is illustrated by the dashed lines in Fig. 6. Then Meditor applies program dependency analysis to the code snippet in Fig. 4 to check whether the concrete statements have the same dependency relationship as template statements; if so, $t_o$ and $P$ also have their program dependencies matched.

Once all statements and dependencies in $t_o$ are consistently matched by at least one code snippet in $P$, Meditor considers $E$ to be applicable to $P$. This step serves two purposes. First, it determines whether an edit is applicable to a program. Second, if an edit is applicable, the created mappings between concrete and abstract statements will enable edit customization. Notice that since Meditor uses program dependencies to link individually matched statements, it can flexibly match $t_o$ with noncontinuous statements in $P$ if the unmatched statements standing between matched statements have no dependency relation with any edited code. As shown in Fig. 4, even if there is edit-irrelevant code between the edited code in $P$, Meditor matches code with $t_o$ to enable further edit application.

E. Edit Customization

To suggest a program $P'$ after migration, Meditor replaces all symbolic names in $t_o$ with identifier constants to customize the edit; it then replaces the matching code of $t_o$ in $P$ with the customized code. For instance, if a statement $s_i \in t_o$ is replaced by multiple statements in $t_n$, the concrete code matching $s_i$ is also replaced by the related customized code.

IV. Evaluation

This section describes our data set (Section IV-A), and presents our evaluation on Meditor’s effectiveness of edit inference (Section IV-B) and edit application (Section IV-C).

A. Data Set

To create the data set, we conducted a preliminary study. We blindly crawled program commits in GitHub projects for any library version update in pom.xml files. If (1) the version numbers of a library are frequently updated in such commits, and (2) there are code changes co-applied in these commits to replace API usage, then we included the library into our data set. In this way, we found four libraries: Lucene [13], CraftBukkit [9], Android SDK [5], and Commons IO [7].

Table I presents the extracted client project data for these libraries. In total, we identified 49, 556, 136, and 10 commits for individual libraries, which contain MR code changes. The extracted commits distribute among 36 Lucene-based projects, 299 CraftBukkit-based projects, 120 Android SDK-based projects, and 10 Commons IO-based projects. These numbers indicate that MR code changes popularly exist in open source projects. Because each commit can have multiple groups of MR code changes co-applied, we located 247, 1,864, 328, and 19 snippets with MR changes applied.

B. Effectiveness of Edit Inference

From the extracted code snippets with MR code changes (see Section IV-A), Meditor infers 153, 931, 268, and 16 unique MR edits for different libraries.

To ensure the quality of extracted edits, the first two authors checked 153 edits for Lucene, 500 edits for CraftBukkit, 268 edits for Android SDK, and 16 edits for Commons IO. They manually compared the inferred edits with corresponding MR code changes to decide whether each edit is correctly generated. When unsure about certain edits, we had discussions to achieve consensus. We found all these 937 edits to be correctly inferred. It means that the automatic approach aligns well with our manual practice of generalizing edits from MR changes.

Finding 1: We sampled 937 unique MR edits inferred by Meditor and found all of them to be correct.

To further characterize the inferred edits, we (i) classified them into three categories based on the extraction complexity, (ii) identified the most frequent release pairs for migration, and (iii) compared the documented edits with inferred edits between a pair of library releases.

1) Edit Categorization: To facilitate discussion of the extracted edits, we classified them into three categories based on how complex it was to extract the edits.

*Single (Sin)*: Only one single statement or expression is updated, such as modifying an API name. Existing approaches can detect such changes.

*Block (Blo)*: A block of statements (e.g., one or more contiguous statements) are replaced by another block of statements. The extraction of such multi-statement edits involves data dependency analysis, but no control dependency analysis. Existing tools cannot fully handle such edits, because they focus on API invocation replacements but ignore any surrounding MR change (e.g., line 4 in Fig. 2).

*Multi-Blocks (MB)*: One block of statements are replaced by multiple blocks of statements or vice versa, with the control flow changed. The extraction of such multi-statement edits involves both control and data dependency analysis. No existing tool handles such edits because they do not track how MR changes influence control or data dependencies.

Table III presents the numbers of edits extracted for different libraries. Among the three categories, Sin contains the largest number of edits. This is understandable, because library developers usually try to simplify migration tasks for client code when API breaking changes have to be introduced. On
TABLE II: The 10 most frequent library release pairs of migration

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<tr>
<th></th>
<th>Lucene</th>
<th>CraftBukkit</th>
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<th>Commons IO</th>
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<tr>
<td>1</td>
<td>3.0.2-4.0</td>
<td>24</td>
<td>1.5.1-1.5.2</td>
<td>129</td>
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<tr>
<td>2</td>
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<td>16</td>
<td>1.6.4-1.7.2</td>
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<td>1.6.2-1.6.4</td>
<td>109</td>
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<td>1.6.1-1.6.2</td>
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<td>1.5.2-1.6.1</td>
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<td>6</td>
<td>3.0.2-3.1.0</td>
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<td>1.7.2-1.7.5</td>
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<td>7</td>
<td>2.9.2-3.2.0</td>
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<td>1.7.9-1.7.10</td>
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</table>

TABLE III: Edits extracted for different libraries

<table>
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<th></th>
<th>Lucene</th>
<th>CraftBukkit</th>
<th>Android SDK</th>
<th>Commons IO</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sin</td>
<td>92</td>
<td>621</td>
<td>159</td>
<td>13</td>
<td>885</td>
</tr>
<tr>
<td>Blo</td>
<td>29</td>
<td>129</td>
<td>31</td>
<td>0</td>
<td>189</td>
</tr>
<tr>
<td>MB</td>
<td>32</td>
<td>181</td>
<td>78</td>
<td>3</td>
<td>294</td>
</tr>
<tr>
<td>Total</td>
<td>153</td>
<td>931</td>
<td>268</td>
<td>16</td>
<td>1,368</td>
</tr>
</tbody>
</table>

Finding 2: 35% of the extracted edits belong to either Blo or MB. Different from prior work, Meditor can extract all these types of nontrivial edits, demonstrating great capability of edit inference.

2) Most Frequent Release Pairs with Migration Edits: When projects were migrated between library releases, some of the releases required for more MR changes than others. In the scenario where a project is migrated from one release to another, we name the original release migration source, and the new release migration target. Such source and target releases delimit the edits required to fulfill migration tasks.

Table II presents the 10 most frequent release pairs in different libraries that require for migration edits. We observed three interesting phenomena. First, not every library provides official release notes to describe migration changes. For instance, CraftBukkit has no release note. Developers of client code are on their own to explore migration edits. This observation implies the necessity of Meditor, which infers the domain knowledge of migration edits from some developers’ code and applies the knowledge to help other developers.

Second, migrations seldom occurred between consecutive releases. We compared Lucene’s top 10 release pairs with the software official release list [14], and found only one pair to contain consecutive releases: lucene4.1.0-lucene4.2.0. The other nine pairs consist of nonconsecutive releases. This phenomenon indicates the importance of our research. While library release notes document migration edits between adjacent releases, the edits revealed by Meditor can help with migrations between nonadjacent releases.

Third, migrations sometimes downgraded the library usage. Although most migration tasks began with libraries’ lower releases (more dated) and ended up with higher releases (more recent), there are tasks that updated API usage in the opposite direction. For instance, the 5th most frequent pair of Lucene has the source lucene-4.0 and the target lucene-3.6.0. While existing release notes focus on library upgrading changes, Meditor can also help developers downgrade library usage.

Finding 3: Meditor can help developers migrate code when (1) there is no library release note, (2) developers migrate code between nonadjacent releases, or (3) they downgrade library usage.

3) Case Study: With a pair of adjacent library releases, we are curious how the edits inferred by Meditor compare with rules documented in the release note. Thus, we conducted a case study for a frequent release pair mentioned in Table II. We compared the extracted edits for lucene4.1.0-lucene4.2.0 with the release note of Lucene 4.2.0 [14]. This version pair was chosen because (i) the two releases are consecutive; (ii) there are a good number of edits (i.e., 14) inferred by Meditor; and (iii) a comparative number of edits (i.e., 16) are mentioned in the note.

Table IV presents the edit distribution among different change categories. The 16 edits (12 changes in backwards compatibility policy + 4 API changes) in the release note belong to 6 categories of changes: 2 categories of type API changes, 2 categories of method API changes, and 2 categories of field API changes. In comparison, the 14 edits extracted by Meditor correspond to 3 categories of changes: 2 categories of method API changes and 1 category of field API change. Interestingly, there is no content overlap between the edits from different sources. The edits inferred by Meditor complement those edits mentioned in the release note.

For each documented edit in the release note, there is always a corresponding patch (i.e., textual diff file) attached to illustrate how library implementation is modified. Such edit descriptions and related patch files focus on how library developers edited code, instead of how application developers should edit their client code for migration. With such documentation, application developers need to decide (1) which li-
library modification influences their code, and (2) how to adjust client code to solve any API backwards compatibility issue. In comparison, the extracted edits by Meditor demonstrate how developers migrated code between library releases with program transformation templates. Instead of focusing on the edits within libraries, the inferred edits focus on the migration practices conducted by application developers.

Finding 4: The extracted edits are very different from documented edits in terms of their categories and content. It means that the edits inferred by Meditor can well complement the information in release notes.

### C. Effectiveness of Edit Application

To evaluate how well Meditor applies inferred edits, we constructed a data set of 87 edits from the 2,458 snippets with MR code changes. Specifically, we created the set based on recurring migration patterns—edits repetitively applied to multiple snippets. When multiple code change examples (e.g., Ch1 and Ch2) illustrate the same migration edit (e.g., E), we used one example (e.g., Ch1) for Meditor to infer the pattern, and used the remaining examples (e.g., Ch2) to evaluate how Meditor applies the pattern. By manually comparing the tool-generated versions with human-crafted versions, we determined whether Meditor transformed code correctly.

Table V presents our evaluation results. In total, Meditor inferred edits from 87 examples to acquire 87 unique edits, and then applied the edits to 225 given code snippets. Ideally, if Meditor can perfectly apply all inferred edits, all these snippets should be transformed fully correctly. Specifically, 209 of the 225 snippets require Sin edits, 1 snippet requires for Blo edit, and 15 snippets require for MB edits. Although it would be better if we have a balanced data set with equal numbers of different categorized edits, we could not control the distribution of snippets among the categories. As the current data set contains edits of all three categories, it is still helpful for us to evaluate Meditor’s capability of edit application in a variety of scenarios.

According to Table V, Meditor applied all Sin edits fully correctly. It applied the single Blo edit partially correctly, because the edit uses an undeclared variable or unknown constant into the migrated code. As shown in Fig. 4, a constant identifier c_0_Version was introduced by Meditor because the original example uses a project-specific constant (i.e., LUCENE_VERSION). Similarly, for the 15 snippets requiring MB edits, Meditor transformed 9 snippets fully correctly and 6 snippets partially correctly. The main reason for partial correctness is still the usage of undeclared variables/constants. By reviewing the suggested code migration, developers can (1) learn what APIs to use to replace outdated APIs, and (2) apply extra edits as needed to efficiently complete migration.

Finding 5: Meditor fully correctly applies edits for 218 out of 225 cases and applies edits partially correctly for the remaining 7 cases, manifesting great capability of migrating code between library releases.
D. Discussion

We open sourced our project at https://bitbucket.org/shenxhiever/meditor. Our research will shed light on related areas, such as automatic detection and fixing of API misuses. Recent work shows that software practitioners sometimes misuse security APIs and produce vulnerable code [22], [29]. As the next step, we will extend Meditor to infer any fixing pattern for security API misuses, and apply those patterns to automatically patch vulnerable code.

Currently, we inspected code changes together with the inferred patterns to decide the correctness of migration edits. Such edit validation process is time-consuming and subject to human bias. To improve the process, we plan to use regression testing and automatic test generation techniques to check whether the migrated code compile and execute successfully.

V. RELATED WORK

This section describes related work on API usage mining and suggestion, inference and application of migration rules, and empirical studies on library-related software evolution.

A. API Usage Mining and Suggestion

Although library APIs are widely used in software development, API usage is often poorly documented. Researchers built a variety of approaches to mine specifications from source code or documentation, and to provide coding suggestion accordingly [19], [28], [31], [32], [36], [41], [46], [48], [51], [55], [60]. For instance, Engler et al. mined API usage invariants like method lock() must be invoked together with unlock(), and then checked code for any violation of the invariants [28]. Kairunnesa extended the research to mine for any precondition of using certain APIs, such as the valid value range of a passed-in parameter [36]. Gu et al. extracted API usage sequences and the first sentence of corresponding document comments to train a deep learning model with RNN, and suggested API usage given a natural language query [32].

Raghothaman et al. mapped natural language queries to relevant APIs by learning a statistical model from the clickthrough data of Bing search [51]. Then they mined API usage patterns from open-source code repositories. When a user searches for the implementation of a certain task, their tool SWIM can automatically synthesize an exemplar implementation with proper API usage. Nguyen et al. mined frequent co-applied API usage changes in software repositories with statistical learning, and recommended API code completion based on the given program context [41]. These approaches focus on how to use APIs appropriately instead of how to adapt the API usage between library releases.

B. Inferring and Applying API Migration Rules

Prior research proposed several tools to infer or apply API migration rules [23], [25], [33], [40], [45], [52], [56], [59]. Specifically, Chow and Notkin proposed a semi-automated mechanism to update client applications in response to library changes [23]. When library maintainers modify function interfaces of a library, they are required to annotate the changed functions with specifications. Such specifications are then used to generate tools that can update client code. However, the proposed method only works for simple changes like updating API signatures. Catchup! records API refactoring actions as a library maintainer evolves an API, and then replays the refactorings to update client applications accordingly [33]. Nevertheless, this approach only fully supports three types of refactorings: renaming types, moving Java elements, and changing method signatures.

SemDiff compares different versions of a library to analyze how the library applies adaptive changes to its API evolution [25]. If a method call is frequently replaced by another method call, SemDiff recommends such API method replacement to client code. LibSync compares different versions of a library to locate the changed APIs, and then compares versions of migrated client code to extract the associated API usage adaptation patterns like renaming a method or changing parameters [45]. All these tools focus on API mappings.

Some researchers mined API translation rules between Java and C# [42]–[44], [61]. For instance, Zhong et al. aligned the client code of different libraries based on textual similarity, constructed API usage graphs for each pair of aligned code, and inferred API usage mappings accordingly [61]. Nevertheless, this approach only infers API mappings. Nguyen et al. tokenized source code, and leveraged statistical machine translation to infer the correspondence between Java code and the equivalent C# implementation. With the established correspondence, the researchers then translated a given Java program to C# [42]–[44]. Although these approaches map both API usage and the surrounding code, they do not handle code migrations between releases of the same library.

Different from prior work, Meditor applies static program analysis to changed Java source files. This analysis allows Meditor to align many-to-many statements between versions based on the data and control dependencies among statements. It also allows Meditor to infer API replacement operations together with other related editing operations, and to safely ignore migration-irrelevant details for edit generalization purpose. By extracting API replacements together with related statement insertions or deletions, Meditor can help developers migrate code with fewer syntactic and semantic errors, improving programmer productivity and software quality.

C. Empirical Studies on API Evolution

Several studies examined how library APIs evolve [27], [37], [50], [58]. For example, Dig and Johnson manually inspected API changes based on change logs and release notes, and found that 80% of API breaking changes were introduced by code refactorings. Xing and Stroulia used UMLDiff [57] to compare the program structures of library versions, and concluded that about 70% of structural changes were refactorings. Kim et al. investigated function signature-change patterns, and observed correlations between signature changes and other types of changes like LOC and function body changes [37]. Raemaekers et al. analyzed seven years of library release history, and found that one third of all releases introduce at
least one breaking change [50]. None of these studies explores how client code should co-evolve with API changes.

Some researchers investigated the impact of API evolution on client software evolution [21], [26], [35], [39], [47]. Specifically, Padioleau et al. studied how Linux device driver code collateral evolved with kernel library APIs [47]. They found that an API evolution and dependent collateral evolutions might take several years to complete and could introduce bugs into previously mature code. Bavota et al. used the build files of Apache projects to analyze (1) how library dependencies change over time; (2) whether a dependency upgrade is due to different kinds of factors, and (3) how an upgrade impacts on a related project [21]. Dietrich et al. identified problems in client code caused by library upgrades [26]. Hora et al. [35] and McDonnell et al. [39] separately investigated the Pharo and Android Ecosystem, to understand how client code reacted to API changes in an ecosystem.

Our characterization study on inferred edits is different from all prior studies, because we examined low-level details of migration patterns. Our evaluation results also complement prior research by exposing a variety of nontrivial migration edits already applied by developers. Cossette et al. conducted an empirical study to manually distill the API migration edits applied in libraries’ version history [24]. They classified the edits into three categories; fully automatable (e.g., API renaming), partially automatable (e.g., implementing a newly declared class), and hard to automate (e.g., inserting data preparation logic for an added method parameter). This piece of work by Cossette et al. motivated our research. By correlating API replacement changes with surrounding co-applied statement insertions or deletions, Meditor is able to handle some hard-to-automate cases (e.g., adding a method parameter and removing a method API) mentioned in that paper.

VI. THREATS TO VALIDITY

Meditor currently generates and applies migration edits for only Java-based libraries. Its methodology can be similarly implemented to handle programs written in other object-oriented languages, when we exploit tools to conduct syntactic differencing and static analysis for other languaged programs. Meditor detects MR commits by checking for any version change in two types of build files: pom.xml and build.gradle. There are still other formatted build files used in Java projects like build.xml. By expanding the types of build files to process, we will be able to detect more MR changes.

Currently, Meditor processes the code changes co-applied with build-file changes to reveal MR code changes. It can miss relevant changes when developers intentionally submitted build-file changes in one commit and submitted migration code changes in follow-up commits. In the future, we plan to overcome this limitation by defining a sliding window to scan any N commits (N ≥ 1) checked in after the commit with build-file changes.

Meditor focuses on edits relevant to method and field APIs, and simple edits related to type APIs (e.g., class rename or move). It cannot handle complicated type API changes such as replacing an interface with an enum, or replacing a concrete class with an abstract one. The main challenge is that such changes may require for extra project-specific implementations to define new methods. Meditor can infer project-agnostic migration changes, but does not handle project-specific edits because such edits usually vary with projects. Meditor currently ensures the quality of inferred edits by comparing the input and output variable sets of edited regions. We used such comparison to approximate semantic equivalence checking, although this approximation is neither sound nor complete. We will explore more ways to compare the program semantics between code revisions.

VII. CONCLUSION

This paper presents the design and implementation of Meditor, a novel approach to infer and apply migration edits leveraging program dependency analysis and semantic equivalence checking. Compared with existing approaches, Meditor is unique in several aspects. First, Meditor extracts edits purely from client code instead of from the evolution history of libraries themselves. While the library evolution only demonstrates how libraries use their own APIs, multiple client projects can use APIs in a more diverse way and thus embody various migration patterns. Second, Meditor generalizes program transformations instead of solely inferring API mapping rules. When statement insertions or deletions are co-applied with API replacements, Meditor is especially helpful because it keeps track of the data or control dependencies between program co-changes, and clusters statement insertions or deletions together with API usage updates. Third, Meditor applies edits automatically.

Our evaluation reveals several interesting insights about migration edits. First, a considerable number of the generalized edits (483 out of 1,368) apply correlated changes to multiple statements, indicating the necessity of using program dependence analysis to identify and cluster MR changes. Second, the source and target library releases of most migration tasks are nonconsecutive, with several releases standing in between. This means that existing library release notes are usually not helpful. Third, according to our case study, the edits Meditor inferred well complement the documented knowledge in library release notes. Fourth, Meditor applied edits fully correctly to 218 of 225 snippets, and transformed the remaining 7 snippets partially correctly. Our future work includes building techniques to (1) extract more edits from repositories, (2) generate more complicated migration edits involving project-specific logic, and (3) conduct more rigorous semantic equivalence checking.

ACKNOWLEDGEMENT

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REFERENCES


