

# Refactoring References for Library Migration—Appendix

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## Abstract

This report is a companion to the paper “Refactoring References for Library Migration” published at the *ACM SIGPLAN International Conference on Systems, Programming, Languages, and Applications: Software for Humanity (SPLASH) 2010*. It provides the detailed results mentioned therein.

## A. Motivation: Detailed Changes

Table 1 details the full set of changes and resulting errors in the Chartwell codebase, alluded to in the Motivation section from our SPLASH paper.

## B. API Change in the Wild: Detailed Results

Figures 2, 3, and 4 present the detailed results of the binary incompatibility analyses over multiple version transitions for HTMLUnit, JDOM, and log4j respectively.

## C. Case Studies: Detailed Observations

### C.1 Participant 1

#### C.1.1 Tool Treatment

The participant began the tool treatment by reviewing the list of API changes provided with the intention of grouping together changes of the same type or same degree of difficulty so they could be attempted together. He decided to begin by changing all the dangling field references of the `Priority` class into fields of the same name in the new `Level` class. Based on the high degree of lexical similarity between the

names, he reasoned that this would be a simple case of string replacement and thus most likely to succeed.

Having decided on a group of API changes to tackle together he began to iteratively apply the tool to enact the change. He selected a `Priority.ERROR` field reference as his first exemplar, and used Trident to perform a type search on the JaxMe code. Since these dangling fields followed the Java programming-style convention of using all upper case characters for describing constant variables and enums<sup>1</sup>, and he had not yet examined the JavaDoc associated with the `Priority` class, he assumed the dangling field references referred to a Java enumeration type. As this assumption was incorrect, the Trident type search yielded no results. His next attempt was to perform a type search on the `ERROR` field name. This search retrieved all simple names of type `Priority` which included the desired result, but also local variable declaration statements (e.g., `org.apache.log4j.Priority p`;). He tentatively accepted the excessively broad search results and moved on to the refactoring page. Here the participant realized that since his search was launched using the `ERROR` simple name he would only be able to change this suffix (i.e., the field name), when in fact he wanted to change the qualifying prefix (i.e., the type containing the field, specifically from `Priority` to `Level`). After these false starts, the participant performed a verbatim search on the fully qualified name of the type and field (`org.apache.log4j.Priority.ERROR`) which yielded the correct results. Since a qualified name was his exemplar for Trident, he was able to alter the entire name to point to a new field reference with the aid of a dialog box in the refactoring screen. The same strategy was employed to correct all the other dangling references pointing to fields in the `Priority` class.

With the corrections to field names complete, the participant began tackling the dangling method references.

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<sup>1</sup> See <http://java.sun.com/j2se/1.5.0/docs/guide/language/enums.html>, <http://incubator.apache.org/ace/java-coding-style-guide.html>

| Original   | Replacement  | Errors | Sample Change  |
|--|--|--------|--|
| Element.getParent()  | Element.getParentElement()                             | 140    | - Element header = rsp.getParent().getChild("msg");<br>+ Element header = rsp.getParentElement().getChild("msg")   |
| new XMLOutputter(String)<br>new XMLOutputter(String,<br>boolean) | XMLOutputter(Format f)                                 | 86     | - new XMLOutputter("", true).outputString(formElement)<br>+ new XMLOutputter(Format.getPrettyFormat()).<br>outputString(formElement)   |
| Element.detach(): Element  | Element.detach(): Content                              | 134    | - response = new responseXMLFormat(r.getRootElement().detach());<br>+ response =<br>new ResponseXMLFormat((Element)r.getRootElement().detach());   |
| Element.removeChildren(): boolean                                | Element.removeContent(): boolean                       | 11     | - children.removeChildren();<br>+ children.removeContent();  |
| Element.hasChildren(): boolean                                   | Element.getChildren(): List                            | 2      | - if(messages.hasChildren() == true) {<br>+ if(messages.getChildren().size() > 0) {  |
| XMLOutputter.setOmitEncoding(true)                               | XMLOutputter.getFormat().<br>setOmitDeclaration(true); | 94     | - XMLOutputter out = new XMLOutputter("", true)<br>- out.setOmitEncoding(true)<br>+ XMLOutputter out = new XMLOutputter(Format.getCompactFormat());<br>+ out.getFormat().setOmitDeclaration(true); |

**Table 1.** Change cases involved in the Chartwell library migration scenario.

| Version transitions | Types   |                                  |        |           |                               |                                  |                                      |                  |                |                  | Methods |                                  |        |         |         |           |                      |            |            |                 | Constructors            |                     |         |                                  |            | Fields     |                 |                         |         |                                  |               |                         |   |   |   |   |   |
|---------------------|---------|----------------------------------|--------|-----------|-------------------------------|----------------------------------|--------------------------------------|------------------|----------------|------------------|---------|----------------------------------|--------|---------|---------|-----------|----------------------|------------|------------|-----------------|-------------------------|---------------------|---------|----------------------------------|------------|------------|-----------------|-------------------------|---------|----------------------------------|---------------|-------------------------|---|---|---|---|---|
|                     | deleted | visibility $\Delta_{\downarrow}$ | +final | +abstract | class $\rightarrow$ interface | superclass $\Delta_{\downarrow}$ | superinterface $\Delta_{\downarrow}$ | +abstract method | pull up method | push down method | deleted | visibility $\Delta_{\downarrow}$ | +final | +static | -static | +abstract | result type $\Delta$ | -parameter | +parameter | parameter moved | parameter type $\Delta$ | exceptions $\Delta$ | deleted | visibility $\Delta_{\downarrow}$ | -parameter | +parameter | parameter moved | parameter type $\Delta$ | deleted | visibility $\Delta_{\downarrow}$ | type $\Delta$ | constant value $\Delta$ |   |   |   |   |   |
| 1.0pre1-1.0pre2     | 1       | -                                | -      | -         | -                             | -                                | -                                    | -                | -              | -                | 1       | -                                | -      | -       | -       | -         | -                    | -          | -          | -               | -                       | -                   | -       | -                                | -          | -          | -               | -                       | -       | -                                | -             | -                       | - | - | - | - | - |
| 1.0pre2-1.0pre3     | -       | -                                | -      | -         | -                             | -                                | -                                    | -                | -              | -                | -       | -                                | -      | -       | -       | -         | -                    | -          | -          | -               | -                       | -                   | -       | -                                | -          | -          | -               | -                       | -       | -                                | -             | -                       | - | - | - | - | - |
| 1.0pre3-1.0pre4     | -       | -                                | -      | 1         | -                             | -                                | -                                    | -                | -              | -                | 22      | -                                | -      | -       | -       | -         | 1                    | -          | -          | -               | -                       | -                   | -       | -                                | -          | -          | -               | -                       | -       | -                                | -             | -                       | - | - | - | - | - |
| 1.0pre4-1.0pre5     | 1       | -                                | -      | -         | -                             | -                                | -                                    | -                | -              | -                | 2       | -                                | 3      | -       | -       | -         | -                    | -          | -          | -               | -                       | -                   | -       | -                                | -          | -          | -               | -                       | -       | -                                | -             | -                       | - | - | - | - | - |
| 1.0pre5-1.0         | -       | -                                | -      | -         | -                             | -                                | -                                    | -                | -              | -                | 10      | -                                | -      | -       | -       | -         | -                    | -          | -          | -               | -                       | -                   | -       | -                                | -          | -          | -               | -                       | -       | -                                | -             | -                       | - | - | - | - | - |
| 1.0-1.1pre1         | -       | -                                | 1      | -         | -                             | -                                | -                                    | -                | -              | -                | -       | -                                | 1      | -       | -       | -         | 1                    | -          | -          | -               | -                       | -                   | -       | -                                | -          | -          | -               | -                       | -       | -                                | -             | -                       | - | - | - | - | - |
| 1.1pre1-1.1pre2     | 1       | -                                | -      | -         | -                             | -                                | 2                                    | -                | -              | -                | -       | -                                | -      | -       | -       | -         | 4                    | -          | 2          | -               | -                       | -                   | -       | -                                | -          | -          | -               | -                       | -       | -                                | -             | -                       | - | - | - | - | - |
| 1.1pre2-1.1pre3     | 7       | -                                | 1      | -         | -                             | -                                | 1                                    | -                | -              | -                | 1       | -                                | -      | -       | -       | -         | -                    | -          | -          | -               | -                       | -                   | -       | -                                | -          | -          | -               | -                       | -       | -                                | -             | -                       | - | - | - | - | - |
| 1.1pre3-1.1pre4     | 1       | -                                | -      | -         | -                             | -                                | 5                                    | -                | -              | -                | 4       | -                                | 1      | -       | -       | -         | 5                    | -          | -          | -               | -                       | -                   | -       | -                                | -          | -          | -               | -                       | -       | -                                | -             | -                       | - | - | - | - | - |
| 1.1pre4-1.1pre5     | -       | -                                | -      | -         | -                             | -                                | -                                    | -                | -              | -                | -       | -                                | 1      | -       | -       | -         | -                    | -          | -          | -               | -                       | -                   | -       | -                                | -          | -          | -               | -                       | -       | -                                | -             | -                       | - | - | - | - | - |
| 1.1pre5-1.1pre1     | -       | -                                | -      | -         | -                             | -                                | 3                                    | -                | -              | -                | 2       | -                                | -      | 1       | -       | -         | 1                    | -          | 1          | -               | -                       | -                   | -       | -                                | -          | -          | -               | -                       | -       | -                                | -             | -                       | - | - | - | - | - |
| 1.1pre1-1.1pre2     | 1       | -                                | -      | -         | -                             | -                                | -                                    | -                | -              | -                | -       | -                                | -      | -       | -       | -         | 2                    | -          | -          | -               | -                       | -                   | -       | -                                | -          | -          | -               | -                       | -       | -                                | -             | -                       | - | - | - | - | - |
| 1.1pre2-1.1         | -       | -                                | -      | 1         | -                             | -                                | 3                                    | -                | -              | -                | 2       | -                                | -      | -       | -       | -         | 6                    | -          | 2          | -               | -                       | -                   | -       | -                                | -          | -          | -               | -                       | -       | -                                | -             | -                       | - | - | - | - | - |
| 1.2-1.2.1           | -       | -                                | -      | -         | -                             | -                                | -                                    | -                | -              | -                | -       | -                                | -      | -       | -       | -         | -                    | -          | -          | -               | -                       | -                   | -       | -                                | -          | -          | -               | -                       | -       | -                                | -             | -                       | - | - | - | - | - |
| 1.2.1-1.2.2         | -       | -                                | -      | -         | -                             | -                                | 5                                    | -                | 1              | -                | 3       | -                                | -      | -       | -       | -         | 2                    | -          | -          | -               | -                       | -                   | -       | -                                | -          | -          | -               | -                       | -       | -                                | -             | -                       | - | - | - | - | - |
| 1.2.2-1.2.3         | 8       | -                                | -      | -         | -                             | -                                | 2                                    | -                | -              | -                | 27      | -                                | -      | -       | -       | -         | 8                    | -          | 2          | -               | -                       | -                   | -       | -                                | -          | -          | -               | -                       | -       | -                                | -             | -                       | - | - | - | - | - |
| 1.2.3-1.3pre1       | 1       | -                                | 2      | -         | -                             | -                                | 6                                    | 2                | -              | -                | 6       | -                                | -      | 1       | 1       | 1         | 2                    | -          | 2          | -               | -                       | -                   | -       | -                                | -          | -          | -               | -                       | -       | -                                | -             | -                       | - | - | - | - | - |
| 1.3pre1-1.3pre2     | 1       | -                                | -      | -         | 1                             | -                                | 1                                    | 3                | 1              | -                | 1       | -                                | -      | -       | -       | -         | 2                    | -          | -          | -               | -                       | -                   | -       | -                                | -          | -          | -               | -                       | -       | -                                | -             | -                       | - | - | - | - | - |
| 1.3pre2-1.3         | -       | -                                | -      | -         | -                             | -                                | -                                    | -                | -              | -                | -       | -                                | -      | -       | -       | -         | -                    | -          | -          | -               | -                       | -                   | -       | -                                | -          | -          | -               | -                       | -       | -                                | -             | -                       | - | - | - | - | - |
| 1.3-1.4             | 4       | -                                | -      | -         | -                             | -                                | 2                                    | 1                | -              | -                | 20      | 1                                | -      | -       | -       | -         | 10                   | 4          | 1          | -               | -                       | -                   | -       | -                                | -          | -          | -               | -                       | -       | -                                | -             | -                       | - | - | - | - | - |
| 1.4-1.5             | 3       | -                                | -      | -         | -                             | -                                | 2                                    | 2                | 13             | -                | 6       | -                                | -      | -       | -       | -         | 1                    | 3          | 3          | -               | -                       | -                   | -       | -                                | -          | -          | -               | -                       | -       | -                                | -             | -                       | - | - | - | - | - |
| 1.5-1.6             | 1       | 1                                | -      | -         | -                             | -                                | 2                                    | -                | -              | -                | 290     | 1                                | -      | -       | -       | -         | 1                    | -          | 1          | -               | -                       | -                   | -       | -                                | -          | -          | -               | -                       | -       | -                                | -             | -                       | - | - | - | - | - |
| 1.6-1.7             | 1       | -                                | -      | -         | -                             | -                                | -                                    | -                | -              | -                | 6       | -                                | -      | 2       | -       | -         | -                    | -          | -          | -               | -                       | -                   | -       | -                                | -          | -          | -               | -                       | -       | -                                | -             | -                       | - | - | - | - | - |
| 1.7-1.8             | 1       | -                                | 1      | -         | -                             | -                                | 2                                    | -                | -              | -                | 25      | 3                                | -      | -       | -       | -         | 2                    | 4          | -          | -               | -                       | -                   | -       | -                                | -          | -          | -               | -                       | -       | -                                | -             | -                       | - | - | - | - | - |
| 1.8-1.9             | -       | -                                | -      | -         | 1                             | -                                | -                                    | -                | -              | -                | -       | -                                | -      | -       | -       | -         | 1                    | -          | 2          | -               | -                       | -                   | -       | -                                | -          | -          | -               | -                       | -       | -                                | -             | -                       | - | - | - | - | - |
| 1.9-1.10            | 10      | -                                | -      | -         | -                             | -                                | -                                    | -                | -              | -                | 2       | -                                | -      | -       | -       | -         | 1                    | -          | 1          | -               | -                       | -                   | -       | -                                | -          | -          | -               | -                       | -       | -                                | -             | -                       | - | - | - | - | - |
| 1.10-1.11           | 5       | -                                | -      | -         | -                             | -                                | -                                    | 1                | -              | -                | 3       | -                                | -      | -       | -       | -         | 1                    | -          | -          | -               | -                       | -                   | -       | -                                | -          | -          | -               | -                       | -       | -                                | -             | -                       | - | - | - | - | - |
| 1.11-1.12           | 3       | -                                | -      | -         | -                             | -                                | -                                    | 2                | 3              | -                | 17      | -                                | -      | -       | -       | -         | 28                   | 1          | 2          | 1               | 21                      | -                   | -       | -                                | -          | -          | -               | -                       | -       | -                                | -             | -                       | - | - | - | - | - |
| 1.12-1.13           | -       | -                                | -      | -         | -                             | -                                | -                                    | -                | -              | -                | 4       | -                                | -      | -       | -       | -         | 1                    | -          | -          | -               | -                       | -                   | -       | -                                | -          | -          | -               | -                       | -       | -                                | -             | -                       | - | - | - | - | - |
| 1.13-1.14           | 3       | -                                | -      | -         | -                             | -                                | -                                    | -                | -              | -                | 7       | -                                | -      | -       | -       | -         | -                    | -          | -          | -               | -                       | -                   | -       | -                                | -          | -          | -               | -                       | -       | -                                | -             | -                       | - | - | - | - | - |

| Version transitions | Types   |                                  |        |           |                               |                                  |                                      |                  |                |                  | Methods |                                  |        |         |         |           |                      |            |            |                 | Constructors            |                     |         |                                  |            | Fields     |                 |                         |         |        |                                  |               |                         |   |   |   |   |
|---------------------|---------|----------------------------------|--------|-----------|-------------------------------|----------------------------------|--------------------------------------|------------------|----------------|------------------|---------|----------------------------------|--------|---------|---------|-----------|----------------------|------------|------------|-----------------|-------------------------|---------------------|---------|----------------------------------|------------|------------|-----------------|-------------------------|---------|--------|----------------------------------|---------------|-------------------------|---|---|---|---|
|                     | deleted | visibility $\Delta_{\downarrow}$ | +final | +abstract | class $\rightarrow$ interface | superclass $\Delta_{\downarrow}$ | superinterface $\Delta_{\downarrow}$ | +abstract method | pull up method | push down method | deleted | visibility $\Delta_{\downarrow}$ | +final | +static | -static | +abstract | result type $\Delta$ | -parameter | +parameter | parameter moved | parameter type $\Delta$ | exceptions $\Delta$ | deleted | visibility $\Delta_{\downarrow}$ | -parameter | +parameter | parameter moved | parameter type $\Delta$ | deleted | +final | visibility $\Delta_{\downarrow}$ | type $\Delta$ | constant value $\Delta$ |   |   |   |   |
| b3-b6               | -       | -                                | -      | -         | -                             | -                                | -                                    | -                | -              | -                | -       | -                                | -      | -       | -       | -         | -                    | -          | -          | -               | -                       | -                   | -       | -                                | -          | -          | -               | -                       | -       | -      | -                                | -             | -                       | - | - | - | - |
| b6-b7               | 1       | -                                | -      | -         | -                             | -                                | 1                                    | -                | -              | -                | 2       | 1                                | -      | -       | -       | -         | -                    | -          | -          | -               | -                       | -                   | -       | -                                | -          | -          | -               | -                       | -       | -      | -                                | -             | 3                       | - | - | - | - |
| b7-b8               | -       | -                                | -      | -         | -                             | -                                | -                                    | -                | -              | -                | 28      | -                                | -      | -       | -       | -         | -                    | -          | -          | -               | -                       | -                   | -       | -                                | -          | -          | -               | -                       | -       | -      | -                                | -             | 4                       | - | - | - | - |
| b8-b9               | 1       | -                                | -      | -         | -                             | -                                | -                                    | -                | -              | -                | 16      | -                                | -      | -       | -       | -         | -                    | -          | -          | -               | -                       | -                   | -       | -                                | -          | -          | -               | -                       | -       | -      | -                                | -             | 2                       | - | - | - | - |
| b9-b10              | 2       | -                                | -      | -         | -                             | -                                | -                                    | -                | -              | -                | 15      | 10                               | -      | -       | -       | -         | -                    | -          | -          | -               | -                       | -                   | -       | -                                | -          | -          | -               | -                       | -       | -      | -                                | -             | 2                       | - | - | - | - |
| b10-1.0             | -       | -                                | -      | -         | -                             | -                                | -                                    | -                | -              | -                | -       | -                                | -      | -       | -       | -         | -                    | -          | -          | -               | -                       | -                   | -       | -                                | -          | -          | -               | -                       | -       | -      | -                                | -             | -                       | - | - | - | - |
| 1.0-1.1             | -       | -                                | -      | -         | -                             | -                                | -                                    | -                | -              | -                | -       | -                                | -      | -       | -       | -         | -                    | -          | -          | -               | -                       | -                   | -       | -                                | -          | -          | -               | -                       | -       | -      | -                                | -             | -                       | - | - | - | - |
| 1.1-1.1.1           | -       | -                                | -      | -         | -                             | -                                | -                                    | -                | -              | -                | -       | -                                | -      | -       | -       | -         | -                    | -          | -          | -               | -                       | -                   | -       | -                                | -          | -          | -               | -                       | -       | -      | -                                | -             | -                       | - | - | - | - |

**Table 3.** Binary incompatibilities between versions of JDOM. “ $\Delta$ ” denotes a change, and “ $\Delta_{\downarrow}$ ” denotes more specifically a reduction.

| Version transitions | Types   |                                  |        |           |                               |                                  |                                      |                  |                |                  | Methods |                                  |        |         |         |           |                      |            |            |                 | Constructors            |                     |         |                                  |            | Fields     |                 |                         |         |        |                                  |               |                         |   |   |
|---------------------|---------|----------------------------------|--------|-----------|-------------------------------|----------------------------------|--------------------------------------|------------------|----------------|------------------|---------|----------------------------------|--------|---------|---------|-----------|----------------------|------------|------------|-----------------|-------------------------|---------------------|---------|----------------------------------|------------|------------|-----------------|-------------------------|---------|--------|----------------------------------|---------------|-------------------------|---|---|
|                     | deleted | visibility $\Delta_{\downarrow}$ | +final | +abstract | class $\rightarrow$ interface | superclass $\Delta_{\downarrow}$ | superinterface $\Delta_{\downarrow}$ | +abstract method | pull up method | push down method | deleted | visibility $\Delta_{\downarrow}$ | +final | +static | -static | +abstract | result type $\Delta$ | -parameter | +parameter | parameter moved | parameter type $\Delta$ | exceptions $\Delta$ | deleted | visibility $\Delta_{\downarrow}$ | -parameter | +parameter | parameter moved | parameter type $\Delta$ | deleted | +final | visibility $\Delta_{\downarrow}$ | type $\Delta$ | constant value $\Delta$ |   |   |
| 1.0.4-1.1.3         | 3       | -                                | -      | -         | -                             | -                                | -                                    | -                | -              | -                | 9       | -                                | -      | -       | -       | -         | -                    | -          | -          | -               | -                       | -                   | 2       | -                                | -          | -          | -               | -                       | 7       | 3      | 5                                | -             | 1                       |   |   |
| 1.1.3-1.2.1         | 4       | -                                | -      | -         | -                             | 2                                | -                                    | -                | -              | 72               | -       | -                                | -      | -       | -       | 1         | 5                    | 7          | 3          | -               | 3                       | -                   | 2       | -                                | -          | -          | -               | 1                       | 2       | 47     | -                                | -             | -                       |   |   |
| 1.2.1-1.2.2         | -       | -                                | -      | -         | -                             | -                                | -                                    | -                | -              | -                | -       | -                                | -      | -       | -       | -         | -                    | -          | -          | -               | -                       | -                   | -       | -                                | -          | -          | -               | -                       | -       | -      | -                                | -             | -                       |   |   |
| 1.2.2-1.2.3         | -       | -                                | -      | -         | -                             | -                                | -                                    | -                | -              | -                | -       | -                                | -      | -       | -       | -         | -                    | -          | -          | -               | -                       | -                   | -       | -                                | -          | -          | -               | -                       | -       | -      | -                                | -             | -                       |   |   |
| 1.2.3-1.2.4         | -       | -                                | -      | -         | -                             | -                                | -                                    | -                | -              | -                | -       | -                                | -      | -       | -       | -         | -                    | -          | -          | -               | -                       | -                   | -       | -                                | -          | -          | -               | -                       | -       | -      | -                                | -             | -                       |   |   |
| 1.2.4-1.2.5         | 2       | -                                | -      | -         | -                             | -                                | -                                    | -                | -              | 1                | -       | -                                | -      | -       | -       | -         | -                    | -          | -          | -               | -                       | -                   | -       | -                                | -          | -          | -               | 2                       | -       | -      | -                                | -             | -                       |   |   |
| 1.2.5-1.2.6         | 1       | -                                | -      | -         | -                             | -                                | -                                    | -                | -              | 6                | -       | -                                | -      | -       | -       | -         | -                    | -          | -          | -               | -                       | 1                   | -       | -                                | -          | -          | -               | -                       | -       | -      | -                                | -             | -                       | - |   |
| 1.2.7-1.2.8         | 1       | -                                | -      | -         | -                             | -                                | -                                    | -                | -              | -                | -       | -                                | -      | -       | -       | -         | -                    | -          | -          | -               | -                       | -                   | -       | -                                | -          | -          | -               | -                       | -       | -      | -                                | -             | -                       | - |   |
| 1.2.8-1.2.9         | 1       | -                                | -      | -         | -                             | -                                | -                                    | -                | -              | -                | -       | -                                | -      | -       | -       | -         | -                    | -          | -          | -               | -                       | -                   | -       | -                                | -          | -          | -               | -                       | -       | -      | -                                | -             | -                       | - |   |
| 1.2.9-1.2.10        | -       | -                                | -      | -         | -                             | -                                | -                                    | -                | -              | -                | -       | -                                | -      | -       | -       | -         | -                    | -          | -          | -               | -                       | -                   | -       | -                                | -          | -          | -               | -                       | -       | -      | -                                | -             | -                       | - |   |
| 1.2.10-1.2.11       | -       | -                                | -      | -         | -                             | -                                | -                                    | -                | -              | -                | -       | -                                | -      | -       | -       | -         | -                    | -          | -          | -               | -                       | -                   | -       | -                                | -          | -          | -               | -                       | -       | -      | -                                | -             | -                       | - |   |
| 1.2.11-1.2.12       | -       | -                                | -      | -         | -                             | -                                | -                                    | -                | -              | -                | -       | -                                | -      | -       | -       | -         | -                    | -          | -          | -               | -                       | -                   | -       | -                                | -          | -          | -               | -                       | -       | -      | -                                | -             | -                       | - | - |
| 1.2.12-1.2.13       | -       | -                                | -      | -         | -                             | -                                | -                                    | -                | -              | -                | -       | -                                | -      | -       | -       | -         | -                    | -          | -          | -               | -                       | -                   | -       | -                                | -          | -          | -               | -                       | -       | -      | -                                | -             | -                       | - | - |
| 1.2.13-1.2.14       | -       | -                                | -      | -         | -                             | -                                | -                                    | -                | -              | -                | -       | -                                | -      | -       | -       | -         | -                    | -          | -          | -               | -                       | -                   | -       | -                                | -          | -          | -               | -                       | -       | -      | -                                | -             | -                       | - | - |
| 1.2.14-1.2.15       | -       | -                                | -      | -         | -                             | -                                | -                                    | -                | -              | -                | -       | -                                | -      | -       | -       | -         | -                    | -          | -          | -               | -                       | -                   | -       | -                                | -          | -          | -               | -                       | -       | -      | -                                | -             | -                       | - | - |

**Table 4.** Binary incompatibilities between versions of log4j. “ $\Delta$ ” denotes a change, and “ $\Delta_{\downarrow}$ ” denotes more specifically a reduction.

Referring back to the list of API changes, he settled on `Category.getRoot()` to `Logger.getRootLogger()` as the next change to address. He began by selecting the method name `getRoot()` to initiate a search with Trident, and then decided that other unrelated `getRoot()` methods might be used in different contexts in the system. Accordingly he revised his exemplar selection to `cat.getRoot()`, in which `cat` is an instance variable of type `Category`. (The `getRoot()` method is static, and while the practice is discouraged, JaxMe sometimes accesses such static methods through an object of that type, as is the case here.) He used Trident to perform a verbatim search on the method name and a type search on the method expression. Satisfied with the search results, he proceeded with the refactoring, and in the final preview screen he was pleased to note that though his exemplar had been `cat.getRoot()` (with the intention of transforming it to `cat.getRootLogger()`), by employing a type search on the method expression he had also captured direct class invocations of the form `Category.getRoot()`, and these were also being correctly refactored to `Logger.getRootLogger()`.

For the next API change, he chose to transform `Category.setPriority(...)` to `Level.setLevel(...)`. Following the previous example, he conducted a type search on the method expression, and a verbatim search on the method name. In this case, the participant noticed that unlike the previous cases he dealt with, `setPriority(...)` takes an argument. He decided to not have Trident restrict the search based on parameter types and numbers; he said that he wanted to ignore the arguments because he wanted “to use Trident to find the different kinds of arguments being passed in, before I decide on what changes to make.” He suspected that a fully qualified field name is the most common argument supplied to `setPriority()` based on what he had observed in the JaxMe source code, but was not sure that this covered all of the cases in which the method was used. The participant chose `Category.setPriority(org.apache.log4j.Level.DEBUG)` as his exemplar input into Trident, and saw that other cases exist where the argument is a local variable reference, or the result of a method invocation. He decided to accept that the method arguments varied, and chose to have Trident replace all `Category.setPriority()` invocations with `Level.setLevel()`, without altering in any way the arguments supplied to the original method invocation. He reasoned that this ought to deal with the majority of the situations, allowing him to then address the hopefully smaller number of compilation errors that should arise due to inconsistent parameters. After Trident performed the refactoring, the participant found he only had a handful of compilation errors left to deal with. After looking at the error list, he decided that while he could use Trident to fix the remaining cases, each case differed sufficiently that he would not be able to use Trident to refactor more than one

dangling reference at a time, eliminating the effort savings of using the tool; he instead chose to manually locate and edit the final locations.

### C.1.2 Manual Treatment

The participant returned three days later to perform the manual treatment of the case study. He was provided with the Eclipse IDE again, loaded with the JaxMe software system in the same state as it was prior to the start of the Tool Treatment, but with the Trident plugin removed.

As in the tool treatment, he began by attempting to transform dangling references to fields on `Priority` into field references on `Level`. Based on the lexical similarity between each dangling reference and its replacement, he decided to use Java Search in Eclipse to find and replace the dangling `Priority` field references with their equivalent `Level` reference. He decided to start by replacing all strings of the form “`org.apache.log4j.Priority.DEBUG`”, but discovered that Java search performs only search, there is no provision for replacing the search matches with a new string. Undeterred, the participant resorted to using Eclipse’s File Search and Replace functionality, which he noted would allow him to write regular expression patterns to do the matching with more flexibility than a standard find-and-replace search.

The first four attempts at creating a regular expression for locating `Priority` references failed to return any results, despite the fact that Eclipse File Search provides inline regular expression assistance. Two errors arose while trying to determine if the periods in the qualified name should be escaped<sup>2</sup>, and two more errors arose because of whitespace mismatches. He finally created a pattern (“`org.apache.log4j.Priority.(\\w+)`”) to match the common type qualifier for the field names, while accounting for the differences in the actual field names by simply capturing the field name with `\\w+`. He wrapped the last part of the pattern in parentheses to designate that portion of the pattern as a capturing group, to use in the replacement string. He then crafted a replacement expression (“`org.apache.log4j.Level.\\1`”) that used the capture group defined above to append the field name at the end of the `Priority` matches (e.g., `DEBUG` from `org.apache.log4j.Priority.DEBUG`) to a new string while replacing “`Priority`” with “`Level`”. He then had Eclipse show him a preview of the proposed alterations, and decided to enact the search and replace. Afterwards, he discovered unexpected effects:

- In JaxMe’s `Main` class, the local variable declaration `org.apache.log4j.Priority p` was transformed into

<sup>2</sup>The participant was initially confused since, in this case, escaping the dot (`.`) operator had no discernible effect on the pattern matching. The dot operator matches any single character, while an escaped dot operator (`\\.`) matches only a period, yet both seemed to be (at first) equally effective in the JaxMe system when searching against fully qualified Java type names.

a field access statement: `org.apache.log4j.Level.p`. The pattern he wrote captured the space separating the type from the instantiation in the declaration, resulting in the local variable's name being appended as a field access. Because regular expressions have no syntactic or semantic awareness, the search was not aware that the lack of a period after `Priority`, and its replacement instead with a space, was significant.

- Static method calls to `org.apache.log4j.Priority.setPriority(...)` were replaced with `org.apache.log4j.Level.setPriority(...)`. He noted that although this change could work as an intermediate step in the eventual transformation of `org.apache.log4j.Priority.setPriority(...)` to `org.apache.log4j.Level.setLevel(...)`, it was an unintended side effect of the replacement and not his intention.

These consequences prompted him to comment, "The big problem with `grep` and regular expressions is that you capture things that you don't expect".

He remarked that the compilation error count in the project barely decreased at this point, with many of the files displaying errors at the locations where the string replacement has taken place. After investigating, he discovered that the problem was that the `Level` type could not be resolved, since the appropriate import statement was missing from the affected classes. To fix this, the developer used Eclipse's Organize Imports feature to automatically resolve unknown type declarations by importing the appropriate classes.

Next, the participant attempted to replace occurrences of `Category.getInstance(...)` with `Logger.getLogger(...)` using File Search and Replace. Using a similar regular expression pattern as before, he was successful in enacting the change, but again encountered the problem that `Logger` was an unresolved type. This particular string replacement was widespread, affecting 44 files and causing a dramatic boost to the compilation error count. Employing the same strategy as before, he invoked Eclipse's Organize Imports feature, but this time received an error message for each file: "ambiguous references, user interaction is required." The problem was that two different yet semantically similar `Logger` classes existed in the project's classpath: the `org.apache.log4j.Logger` class which the participant was trying to use, and the `java.util.Logger` class which is part of the standard Java Software Development Kit. Unable to distinguish between which of the two identically named classes should be imported, Eclipse is unable to automatically handle this for the participant.

The participant was not keen on manually inserting import statements in every file, and decided to look at a few of the errors to see if there was a workaround he could attempt. He noticed that in the JaxMe code base, invocations of `Category.getInstance(...)` re-

turn a singleton object usually assigned to a static member variable. The format of this statement was, after his previous transformations, `public static final Category cat = Logger.getLogger(...)`; the participant wondered if maybe the assignment of `Logger` to type `Category` was confusing Eclipse's Organize Imports feature. He wrote a regular expression to change such declarations to `public static final Logger cat = Logger.getLogger(...)`, but this boosted the compilation error count to 240, as it created more locations in the code where the `Logger` type could not be resolved. He undid the change, and decided that import statements had to be added first.

To avoid manually editing every file, the participant decided to write a regular expression that would recognize the package declaration at the start of a Java file, adding an import statement for the `Logger` class afterwards. To do this, he created the search expression "`package\s+\S+`" to find all package declarations in files, and the replacement expression "`\0 import org.apache.log4j.Logger;`" to append the import statements to the end of the package declaration. In doing so, the participant acknowledged that the import statement would be added even to classes which did not need it, but he reasoned it would be easy to clean up afterwards using the Eclipse tooling. Enacting this change dropped the error count from 240 to 42, fixing the unresolved imports issue. He then ran Organize Imports to eliminate those import statements that had been unnecessarily introduced.

However, he also introduced a new problem: in the `JavaSource` class, a string literal happened to match the participant's regular expression. The participant noticed a new compilation error in the list which was a syntax error, making it stand out from the other problems. On investigation, he recognized that the code snippet `result.append("package ");` in the `JavaSource` class was detected as a match by his original regular expression pattern. As a result, the line had been altered to read `result.append("package "); import org.apache.log4j.Logger;`, creating a syntax error that he manually fixed.

He then transformed calls to the static method `Category.getRoot()` into `Logger.getRootLogger()`, again noticing JaxMe's inconsistent treatment of static method invocations: sometimes it invokes static methods via a call on an instance variable (e.g., `cat.getRoot()`), while in others the method is invoked directly from the class (e.g., `Category.getRoot()`). Though the two cases are semantically similar, each required its own regular expression pattern to resolve. The participant noted that his replacement for `getRoot()` on static `Category` variables relied heavily on the code convention that all such variables were named `cat`. If `Category` variables had been declared under a bunch

of different names (e.g. 'category', 'myCategory', etc) this change would have been much more difficult.

On reaching this point, the developer had only 8 errors left, each of which were sufficiently different that he decided to manually fix each problem.

## C.2 Participant 2

### C.2.1 Tool Treatment

At first, the participant had difficulty in selecting the proper exemplar with which to initiate the Trident tool. In attempting to transform `org.apache.log4j.Priority.DEBUG` into `org.apache.log4j.Level.DEBUG`, he selected just the simple name `DEBUG` and performed a verbatim search for other simple names with the same string pattern. When the search returned only two matches, he was suspicious and decided to broaden his scope to a verbatim search for all qualified names containing `org.apache.log4j.Priority`. After seeing the large number of search results returned, he requested assistance from the investigator. After an impromptu tutorial on how exemplars should be chosen, he was able to quickly refactor all the fully qualified dangling field references to the `Level` class.

He then noted in the error view that an unqualified field reference to `Priority.WARN` had not been refactored. Rather than use Trident, he decided to manually correct this single case by overwriting `Priority` with `Level`, and using Eclipse's Quick Assist to resolve and import the class. This resulted in another compile error stating that `WARN` could not be resolved. The participant's confusion was resolved when he realized that there were multiple classes with the name `Level` on the class path, and he had imported the wrong one.

The participant continued by refactoring `Category.getInstance(...)` to `Logger.getLogger(...)`, and noted that `getInstance()` is static and is present in three different overloaded formats. Based on this information, he decided to do a type search on the method expression, a verbatim search on the method name and ignore all the arguments. Trident returned 44 matches, and upon enacting the change from `Category` to `Logger`, the error count dropped to 37.

Next, he looked at changing `Category.getRoot()` to `Logger.getRootLogger()` by applying the same search pattern as he had done for `Category.getInstance()`. On examining the search results, he noted that although he intended to look only at invocations of `getRoot()` occurring directly on the `Category` class, some static instance variables (of type `Category`) were also captured in the search. Consequently, the participant was uncertain about the correctness of his anticipated change, and wondered if he should examine each search result to filter out all the cases he did not expect to find, and handle such cases individually. He decided to instead refactor all the search results since Trident provides global "undo" functionality, and can revert the

refactoring if it causes problems. On seeing in the final preview pane that Trident introduced comments above all the new `<localvariable>.getRootLogger()` statements to make it clear that a static method was being invoked on an instance variable, he was encouraged and thought that it was highly likely this was the refactoring he wished to do.

Finally, the participant converted all the static variable declarations of the form `public static final Category cat = ...` into variable declarations of the form `public static final Logger cat = ...`, by selecting a `Category` reference as his exemplar and performing a type search in Trident to find other locations where `Category` is part of a simple type reference. He asked the investigator if it was possible to restrict the search only to type declarations within variable declaration statements (as opposed to catch clauses, method declarations, etc), but was informed that context restricted searches were not yet supported. He continued with the refactoring, reducing the error count to 5. At this point, he decided to fix the remainder manually.

### C.2.2 Manual Treatment

The participant was brought back the following day to perform the manual treatment of the case study. He was provided with the Eclipse IDE again, loaded with the JaxMe software system in the same state as it was prior to the start of the Tool Treatment, with the Trident plugin removed.

He began by reasoning that the API change of `org.apache.log4j.Priority` to `org.apache.log4j.Level` represented a refactoring that moved fields from one type to another. Upon examining the list of Eclipse refactorings for a suitable match, he activated the "Move" to attempt to enact this refactoring automatically, and was greeted with an error message that stated, "Destination type does not exist." He realized that Move refactorings are intended to move declarations and not references, and that none of the Eclipse refactorings can be applied to dangling references.

With refactorings clearly unavailable, he decided to try Eclipse's Java Search tooling, but was confused by the lack of a replace option. After spending a few minutes examining every Eclipse search menu he could find, he eventually located a lexical replacement option under Eclipse's File Search tool. He then proceeded to use case sensitive search to find and correctly replace all of the `Priority` dangling field references with the `Level` type.

In an attempt to quickly reduce the task to a more manageable size, he noted that the API change `Category.getInstance(...)` to `Logger.getLogger(...)` was the most common source of errors, and he decided to attempt it next. Using case sensitive search on `Category.getInstance()`, he replaced it with `Logger.getLogger()`. Expressing trepidation at the size of the change, the participant conducted an exhaustive review of every search match and change in the text preview



screen. After satisfying himself with the accuracy of the change, he enacted the modification, and was surprised to find that almost all the errors remained. He recognized that the errors were now because the new `Logger` type could not be resolved, and so tried to apply Eclipse's "Quick Fix" to the entire group of errors in the problems view, but could not as it can only be applied to individual errors. He decided to resort to opening each of the 37 affected files one by one, and adding an import statement to address the problem. The tedium of this task prompted him to say that "I am beginning to realize what a pain this really is. Initially I had thought Eclipse search and replace would do this for me." As he came close to finishing, he remembered that there was a refactoring scripts option in Eclipse, which he hoped could be adapted to create a macro to complete this task for him. However, he quickly realized that for refactoring scripts to work, the underlying Eclipse refactorings must also work; a precondition that does not hold with dangling references. Resignedly, he finished the manual modification.

The next problem the participant addressed was the change of `Category.getRoot()` to `Logger.getRootLogger()`. As previously noted, the `getRoot()` method is sometimes invoked on static instance variables, and sometimes invoked directly on the class. Fortunately, in all of the cases involving static instance variables, the name of the instance variable is consistently "cat", thus allowing for a relatively easy lexical search and replace. He uses the same string search and replace to convert `Category.getRoot()` style method invocations into `Logger.getRootLogger()`, but makes a copy-and-paste error in the replacement field, causing an extra, empty pair of parentheses to be attached to the end of the new method invocation. He attempted to undo this change, but found that the Eclipse File Search tooling does not provide global undo capability; the participant needed to undertake a second round of search-and-replace to fix his previous mistake.

The last major change that remained for him was transforming the instance variables of the form `static Category cat = ...` into `static Logger cat = ...`. However, his previous refactorings had partially altered the right hand side of these statements so that were now they were now found as `public static Category cat = Logger.getRootLogger(...)`. The participant decides that a regular expression is his best strategy to enact the change in this case. Using the left hand side of the assignment as an "anchor", he wrote the regular expressions "`Category\s+cat\s*=\s*Logger.getRootLogger`" to search for matches, and "`Logger cat = Logger.getRootLogger()`" as the pattern to replace it with. With the change complete he sees the error count jump from 34 to 66, and realizes he had intended to use the replacement expression `Logger cat = Logger.getLogger()`. Since undo functionality is not available, he decides to try another round of search-and-

replace using "`Logger.getRootLogger()`" as his search expression, but committed yet another copy-and-paste error using "`Looger.getLogger()`" as his replacement. This error might have been caught in the text preview pane, but he accidentally hit the "Update" button instead of "Preview", thus committing the change to the workspace, and causing the error count to jump to 72 as both the method name and the method expression are incorrect. At this point, he said "This is a nightmare. Is it okay if I quit this task?"

The participant decided to continue working, but ran into more difficulties as he tried to continue to fix his previous errors by using `Looger.getLogger()` as the search expression, and replacing it with `Logger.getLogger()`. However, the absence of the parenthesis in the first pattern, and its presence in the second, created cases like `Logger.getLogger(` which further increased the error count to 83. Gradually and carefully, the participant managed to fix the consequences of this series of errors, and returned to an error count of 23. He decided at this point to manually correct all the remaining compiler errors, staying clear of regular expression-based tooling. Finally, he reduced the error count to 0, noting that "the task seemed easy but the [manual change process] was really messy and I am not confident in the solution".