

# Specifying and Detecting Meaningful Changes in Programs

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**Abstract**—Software developers are often interested in particular changes in programs that are relevant to their current tasks: not all changes to evolving software are equally important. However, most existing differencing tools, such as `diff`, notify developers of more changes than they wish to see. In this paper, we propose a technique to specify and automatically detect only those changes in programs deemed meaningful, or relevant, to a particular development task. Using four elementary annotations on the grammar of any programming language, namely *Ignore*, *Order*, *Prefer* and *Scope*, developers can specify, with limited effort, the type of change they wish to detect. Our algorithms use these annotations to transform the input programs into a normalised form, and to remove clones across different normalised programs in order to detect non-trivial and relevant differences. We evaluate our tool on a benchmark of programs to demonstrate its improved precision compared with other differencing approaches.

## I. INTRODUCTION

*Nothing endures but change.*

Heracitus (c.535 BC—475 BC)

This philosophy is largely true in most software development projects. However, not all changes are equally relevant to developers engaged in different development tasks. For example, changing the indentation of statements in a Java program does not necessarily alter its execution semantics. Nonetheless, most revision control systems, typically using text-based differencing tools such as the `diff` utility in Unix [1]), do not discard changes on the indentation of such programs. Although indentation is not meaningful to the execution semantics of Java programs, it can still be very important for the execution of Python programs. Furthermore, for those who are concerned with pretty-print of Java programs, indentation is still important. Another example is API evolution [2]: users of object-oriented programming libraries are encouraged to use the API instead of its implementation, according to the information hiding principle [3]. As a result, some developers may wish to identify only those changes made to the API, whilst others may want to find out changes in the API implementation only.

A change considered *meaningful* for one purpose may be irrelevant for another. For a given purpose, how can one specify the types of changes that are relevant to a specific development task? How can such a specification be used for automatic detection?

Most change detection tools are good either at reporting all changes through general purpose differencing algorithms

on programs represented as line-separated text and structured models [1], [4], [5]; or at finding out certain or all changes that are specific to one particular language such as UML class diagrams [6], dependency graphs [7], or Verilog [8]. Few techniques aim to provide a generic solution that can also be customised to the specific language and the specific needs of the developers.

In this paper, we propose a new way to specify meaningful changes as the composition of elementary changes that are defined on a *normalising* transformation of source programs. Two programs that are not different due to orderings, abstractions and preferences will be normalised into the same program, using three basic normalising transformations *Order*, *Ignore* and *Prefer* respectively. We show that such normalisations can be specified as simple annotations on the original “production rules” [9], while specific needs of further normalisation can be accommodated by user-defined functions. Each type of elementary normalisation corresponds to elementary type of transformation to a term in the production rules of the source language. Once such annotations are specified, a fully automated meta-transformation can turn them into a composed transformation that operates directly on the source programs, separating meaningful changes from the irrelevant ones.

The meta-transformation is written as a generic modification to the meta-grammar of the TXL transformation system [10], that is, the grammar of all TXL grammars. Therefore, it is applicable to any source language specifiable by TXL, which currently supports several general-purpose programming languages such as C, Java, C#, and Python as well as several modelling languages such as XML, XMI, GXL. An evaluation of our *Meaningful Change Tool* (hereafter *mct*) on the CVS repositories of two medium-sized software projects and one small hardware project shows that (i) few annotations are needed to specify typical meaningful changes, such as changes made to the API, and (ii) the tool is scalable.

The remainder of the paper is organised as follows: Section II introduces a running example illustrating the need for detecting meaningful change. Section III explains our approach to generate from meta-grammar specifications those normalisation transformations needed to detect meaningful changes. Section IV presents the results of a number of experiments in using the tool, and comparing the performance with existing differencing tools. Section V compares existing approaches with ours, highlighting some of our limitations. Section VI concludes the paper.

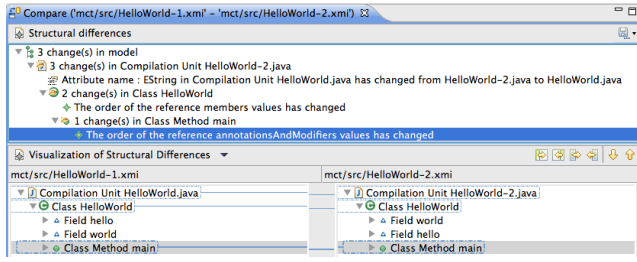


Fig. 1. The differences found by EMFCompare on the two EMF models

## II. A MOTIVATING EXAMPLE

The essence of meaningful change can be illustrated using a simple Java program in Listing 1. After some changes, the execution semantics in Listing 2 remains the same. The Unix diff utility [1] reports these changes, ignoring white spaces, as one deletion and one modification shown in Listing 3. A more advanced algorithm ldifff [4] reports these changes, again ignoring white spaces, as two insertions, one deletion and two modifications shown in Listing 4.

Listing 1. cat -n HelloWorld.java

```
1 public class HelloWorld
2 {
3     static private String hello = "Hello";
4     private static String world = "world";
5     static public void main(String args[]) {
6         System.out.println(hello + ", " + world + "!");
7     }
8 }
```

Listing 2. cat -n HelloWorld-2.java

```
1 public class HelloWorld
2 {
3     private static String world = "world";
4
5     static private String hello = "Hello";
6     public static void main(String args[]) {
7         System.out.println (hello + ", "
8             + world + "!");
9     }
10 }
```

Listing 3. diff -w HelloWorld.java HelloWorld-2.java

```
1 3d2
2 < static private String hello = "Hello";
3 5,6c4,8
4 < static public void main(String args[]) {
5 < System.out.println(hello + ", " + world + "!");
6 ---
7 >
8 > static private String hello = "Hello";
9 > public static void main(String args[]) {
10 > System.out.println (hello + ", "
11 > + world + "!");
```

Listing 4. ldifff.pl -w -o diff HelloWorld.java HelloWorld-2.java

```
1 3,3d2
2 < static private String hello = "Hello";
3 4a4,5
4 >
5 > static private String hello = "Hello";
6 5,5c6,6
7 < static public void main(String args[]) {
8 ---
9 > public static void main(String args[]) {
```

```
10 6,6c7,7
11 < System.out.println(hello + ", " + world + "!");
12 ---
13 > System.out.println (hello + ", "
14 6a8,8
15 > + world + "!");
```

The EMFCompare tool (<http://eclipse.org/emf/compare>) is applied to the corresponding EMF models of the two Java examples parsed by the JaMoPP Java parser (<http://www.jamopp.org>), reporting three changes: one concerns the renamed compilation units, one concerns the class HelloWorld for “the order of the reference members”, and the final one concerns the method main for “the order of reference annotationsAndModifiers values”.

If only the differences in the execution semantics is meaningful to a programmer, none of the changes identified in this example is relevant: just as adding a newline or some white spaces would not change the syntax of the program, swapping the keywords public and static in the declaration of the main method makes no semantic difference.

## III. THE MCT SYSTEM

Our approach to finding meaningful change between two versions of a program has two steps shown in Figure 2:

- *Step 1. Specification:* A developer specifies annotations onto the grammar terms of programs, see dotted arrows in Figure 2;
- *Step 2. Detection:* The mct tool generates a refined parsing grammar and two sets of transformations, normalisations and clone-removals, from the specification in Step 1 and applies these transformations to a pair of two source programs, reporting any meaningful change to the developer. See solid arrows in Figure 2.

In a typical work flow the specification step is done manually by the developer, whilst the detection step is done automatically by the mct system to find meaningful changes of programs in revisions stored in the CVS repository.

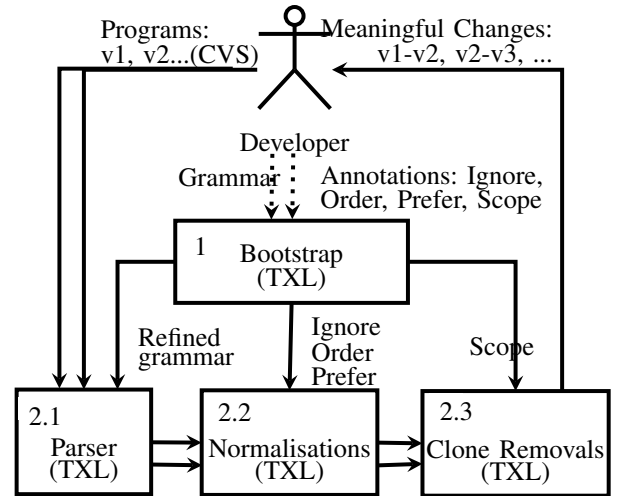


Fig. 2. Specifying and detecting meaningful changes using mct

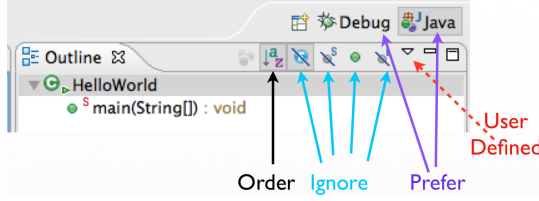


Fig. 3. The *outline* view of the Eclipse IDE helps programmers to select meaningful information interactively while reviewing a Java class. Typically, they care about the ordering (e.g., the “a-z” button), and may ignore certain details (e.g., the “hide fields”, “hide non-public members”, “hide static members” buttons), and express a preference (e.g., “Java” or “Debug” perspective). Other filtering options can be expressed by user-defined dialogues.

#### A. Specifying meaningful changes

We first define a few requirements for specifying *meaningful changes* through the concept of normalisation transformations.

**Definition 1: Equivalence classes by normalisation.** A program  $P$  is said to be meaningfully equivalent to program  $P'$  if and only if  $(P' = P) \vee (N(P') = N(P))$  where  $N(P)$  is the normalisation transformation of  $P$ . In other words,  $P'$  introduces no meaningful changes to  $P$ . Typically  $N(P)$  is a many-to-one transformation.

The exact meaning for ‘meaningful equivalent’ in the Definition 1 is intentionally left open to the user who defines the normalisation function appropriate to the tasks at hand.

This definition only provides the general criteria for determining whether a transformation is a suitable normalisation once it is clear what are meaningfully equivalent to the users: any trivial or irrelevant changes should be normalised to the same. After the normalisation transformation is defined, the detection of the meaningful changes becomes a comparison of two normalised programs.

According to Definition 1, however, a normalisation transformation can be a recursive function that does not terminate when applied. For example, adding white spaces can be regarded as a normalisation transformation but it would lead to infinite results when the transformation is applied recursively. Therefore, a useful normalisation transformation needs to be *terminable* so that no further transformation is necessary when a fixed point is reached.

**Definition 2: Fixed points of terminable normalisation.** A fixed point of normalisation  $N$  is a program  $P$  such that  $N(P) = N^0(P) = P$ . A normalisation transformation *terminates* upon its fixed point. The normalisation is *terminable* if any input program  $P$  can converge to a fixed point:  $N^{i+1}(P) = N^i(P)$ , where  $i \geq 0$  is a finite number. Every fixed point in  $FP(N)$  is the *representative element* for a class of meaningfully equivalent programs according to the normalisation  $N$ .

By this definition, the *identity* transformation is trivially terminable. There are non-trivial terminable normalisations. For example, ordering the modifiers (i.e., “private”, “static”) of all class members is a terminable transformation, because the number of inverse order of the modifiers is finite, so does the number of class members.

The following property guarantees that a composition of any two terminable normalisation transformations is still terminable, for a subset of fixed points.

**Property 1: Composability of terminable normalisations**

If two normalisations  $N_1$  and  $N_2$  are terminable according to Definitions 1 and 2, then the functional composition  $(N_1 \oplus N_2)(P) = N_2(N_1(P)) = P$  is also a terminable normalisation, and  $FP(N_1 \oplus N_2) \subseteq FP(N_1) \cap FP(N_2)$ .

For example, ignoring the method bodies in all classes is a terminable normalisation composable with reordering the method modifiers. A program with method bodies ignored may not have the modifiers sorted, and vice versa. Only fewer programs with both the method bodies ignored *and* the modifiers ordered are the fixed points that terminate the composed normalisation transformation. In general, the more normalisation transformations are composed, the fewer fixed points can be distinguished.

In order to support most programming languages, at the meta-grammar level we aim to generate normalisation transformations by composing three elementary terminable normalisations derived from the production rules of grammars: *Ignore*, *Order* and *Prefer*. For every term of a production rule, one can check whether any one of these basic types of terminable normalisations is applicable to provide what programmers like to compare. For example, traditionally, Java programmers get help from an IDE such as Eclipse to obtain meaningful information into an “outline” view, as shown in Figure 3. The abstraction presented in the outline view can be further customised by clicking at the right buttons by the programmer. Our elementary normalisation operations already cover all the most commonly used meaningful selection buttons by the Eclipse IDE.

**Definition 3: Elementary normalisations: Ignore, Order and Prefer.** Let a production rule be  $N \leftarrow (\dots T_i[?|*] \dots) | \dots$  where  $N$  is a non-terminal, and  $T_i$  is the  $i$ -th term (which could be either terminal or non-terminal), and optionally the rule could contain more than one alternative sequence patterns. Every optional (denoted by “?”) term can be *ignored* if with or without the value it makes no difference to the developer; elements of a repeated (denoted by “\*”) term can be *ordered* if the ordering of the values is not important to the developer; and the whole element  $N$  matches a mandatory alternative can be *preferred* to another alternative (denoted by “|”), if the difference between these two alternatives are not significant to the developer.

Table I gives an example to each of these elementary transformations: by ignoring the members when they are private; by sorting the member declarations in ascending order; and by preferring the semicolon over the detailed method bodies.

These elementary normalisations can be used to preserve the conformance to the syntax of the source programming language, if one does not apply *Ignore* to mandatory terms. Since different programming language has different semantics, users may wish to preserve the semantics by avoiding certain normalisations. For example, one would not reorder

TABLE I  
BASIC ANNOTATIONS TO THE TERMS IN A TXL GRAMMAR

Transformation	Application scope	TXL annotations	Example
Ignore	Repeat/List (*), Optional ( )	[...ignored when F]	[repeat member_declaration <i>ignored when Private</i> ]
Order	Repeat/List (*)	[...ordered by F]	[member_declaration <i>ordered by Ascending</i> ]
Prefer	Alternative ( )	[...preferred with C]	[method_body <i>preferred with ';</i> ]
Scope	Any non-terminal term	[...scoped]	[class_body_declaration <i>scoped</i> ]

the statements in normalisation to avoid breaking the execution semantics of Java. Whether these syntax or semantics-preserving transformations are desirable really depends on the developer’s task.

**Property 2: Syntax conformance.** The normalised program by the three elementary transformations in Table I are valid programs in the *source* programming language.

Of course, syntax conformance of the normalised programs is not an issue when the purpose of checking meaningful changes is not to obtain a compilable program. One may choose to define the target grammar to be incompatible to the source language. The elementary normalisations can also be further customised. The unconditional ignored rule for an optional term ‘?’ can be associated with a conditional check, in the API extraction example, one would remove a declaration if and only if it does not have a ‘public’ or ‘protected’ modifiers. Similarly, the ordered rule for repeating terms ‘\*’ can be customised to ascending or descending orders, and the ordering criteria can be associated with certain foreign keys.

### B. Detecting meaningful changes

After each program revision is normalised, the next task is to detect the non-trivial changes. A simple method is to apply an existing diff algorithm on the normalised results, which however, may not detect the exact subtle differences smaller than one line of code. The method we take is to apply clone detection [11] to take advantage of knowing the meaningful structures independent of the line boundaries. As long as the normalised entities are the same, a clone detector could locate them. On the other hand, if the two entities are similar but not exactly the same, a meaningful context of the difference may need to be shown. After removing the clones across a pair of programs, their differences become evident. Note that we do not check intra-program clones as our purpose is not to detect clones, but only to *reuse* existing clone detection techniques for the sake of differencing. In principle any parametrised AST-based clone detector could be used for this purpose. To illustrate in this paper we use the simplest exact clone

scope for clone detection such that removing the inter-program clones at this level do not change the conformance of the source programming language. Any mandatory term in the grammar can be marked as possible clones if required, whilst the target programming language may violate the syntax rules of the source programming language.

The last row of Table I summarises the scoping annotation for clone removals.

### C. Running example: specifying normalisations for Java API

To illustrate the features of our method, we use here the example of the Java 5 grammar provided by the TXL website (<http://txl.ca>), containing 970 lines of code. TXL is a functional programming language in which a transformation is defined by either a non-recursive function or a recursive rule [10]. Instead of using pseudo code to illustrate the algorithms, in this paper, some of the exact declarative rules are used in order that the work can be easily reproduced.

Listing 5. cat -n java.annotated.grm

```

1 include "java.grm"
2 annotate package_declaration [opt package_header scoped]
3 annotate package_declaration [repeat import_declaration
  ignored]
4 annotate package_declaration [repeat type_declaration
  scoped ordered]
5 annotate class_or_interface_body [repeat
  class_body_declaration scoped ordered ignored when
  Private]
6 annotate method_declaration [repeat modifier ordered by
  Descending]
7 annotate method_declaration [method_body preferred with ';]
8 % ...
9 function Private A [class_body_declaration]
10   match [class_or_interface_body] B [
11     class_or_interface_body]
12   construct M [modifier *] _ [^ A]
13   construct PublicModifiers [modifier*] 'public '
14   protected
15   where not M [contains each PublicModifiers]
16 end function
17 rule Descending B [modifier]
18   match [modifier] A [modifier]
19   construct SA [stringlit] _ [quote A]
20   construct SB [stringlit] _ [quote B]
21   where SA [< SB]
22 end rule

```

Line 1 includes the original Java 5 grammar. The annotate rules in Table I are used or composed in some of the term extensions. Here we explain the rationale behind these extensions. The annotations “*scoped*” are appended to the terms such as “package\_header” (Line 2), “type\_declaration” (Line 4), “class\_body\_declaration” (Line 5). These instruct a clone detector to compare these three types of entities for possible clones. Although the technique is similar to a general-purpose clone detection, the purpose of the cross-program

Not all language constructs at all granularity levels should be considered as clones either. Apparently index variables of a for-loop, for example, are not so meaningful to detect as a clone because it makes little sense to scope the comparison at this level of details. To be able to specify which scope of the language construct needs to be considered as clones to remove, another kind of annotations are introduced to non-terminals.

**Property 3: Scoping the clone detection.** Any optional or repeat term in the production rule can be marked as possible



clone-removal is exactly the opposite: those non-clones are the differences to be detected.

However, the ordering of elements or appearance of ignorable details can get in the way of meaningful change detections. Therefore several normalisation transformations are required to be applied before the change detection step. Since one does not care whether a modifier is before another one or not (e.g., 'private static' is the same as 'static private'), the ordering of the elements in the array of repeat modifier is unimportant to the Java semantics. However, the default behaviour of TXL parser preserves the ordering of the modifiers in the parsing tree as they occur in the source program. To specify the "Order" normalisation, one only needs to insert ordered at the end of the [repeat modifier] term.

Furthermore, if one would like to normalise the elements by the descending order, a user-defined rule Descending (Lines 15-20) is added in Listing 5. This is just to illustrate how easy it is to customise the comparison function, in case one would like to define a different key or ordering for the structure to be normalised. For the sake of identifying meaningful changes in this particular case, ordering these members ascendingly is the same as ordering them descendingly.

The Ignore annotations (ignored), on the other hand, will replace the optional or repeated terms by empty. The terms import\_declaration at Line 3, class\_body\_declaration at Line 5, are examples. In particular, the Ignore annotation to class\_body\_declaration is conditional, it uses a user-defined function from Lines 9-14 to check when the term has not used the public or protected modifiers. As a result, it will achieve the effect of extracting API methods from all members.

Without specifying such user-defined functions, the default behaviour of Ignore extension would simply ignore the term, just as what import\_declaration. Because such terms are unconditionally ignored, therefore it is unnecessary to compose it with the Scope annotation as other sibling do. As a result, this will ignore the import statements in the API regardless, so any difference in such statements will not be considered as meaningful.

Finally, the Prefer annotations (preferred) are appended to the terms that have more than one alternative expansions. The user is free to choose a sequence of literals to make a constant instance of the terms in any one of its alternative production rules. For example, when the method\_body at Line 7 is annotated by preferred ';', which will lead to a transformation to turn any block into a semicolon.

#### D. Brief implementation of mct

The Meaningful Change Detection tool mct is implemented completely as a TXL program. The first part of the implementation is an extension to the TXL's meta-grammar (given in the file txl.grm). Listing 6 shows the extension to the existing typeSpec rule and the addition of four annotation rules orderedBy, ignoredWhen, preferred and scoped, corresponding respectively to the three elementary normalisations and the scoping rules.

Listing 6. cat -n norm.grm

```
1 include "txl.grm"
2 % The extension of the TxL grammar
3 keys
4   ... 'scoped' 'ordered' 'by' 'ignored' 'when' 'preferred' 'with'
      'annotate'
5 end keys
6 define typeSpec
7   ... [opt scoped] [opt orderedBy] [opt ignoredWhen] [opt
      preferredWith]
8 end define
9 define scoped 'scoped' end define
10 define orderedBy 'ordered' [opt byFunction] end define
11 define byFunction 'by' [id] end define
12 define ignoredWhen 'ignored' [opt whenFunction] end define
13 define whenFunction 'when' [id] end define
14 define preferred 'preferred' 'with' [literal+] end define
15 redefine statement ... | [MCT_annotate] end define
16 define MCT_annotate 'annotate' [id] ' ' [typeSpec] ' ' [NL]
      end define
```

The second part of the implementation is a specification of the normalisation transformations.

For brevity, we only discuss the extension for the Order transformation, shown in Listing 7. The transformation generates the rules for eliminating ordered annotations so that it is recognisable by TXL at runtime, and for producing the rules for ordering the parsed terms. Lines 44-64 specify how to generate the transformation rules Rules on the fly by checking every defineStatement in the TXL grammar such as those in Listings 5. For each occurrence of [repeat X ordered by F], the transformation in Lines 9-31 is invoked to generate a rule such as those instantiated in Lines 22-27. These rules have unique names constructed from the names of the defineStatement and the term X. By the end of the main transformation, the rule in Lines 2-8 are applied to eliminate the Order annotations from the extended grammar.

Listing 7. cat -n norm.Txl

```
1 include "norm.grm"
2 rule typeSpec_eliminateOrderedBy
3   replace * [typeSpec] T [typeSpec]
4   deconstruct T M [opt typeModifier] I [typeid] R [opt
      typeRepeater] O [orderedBy]
5   deconstruct O 'ordered' B [opt byField]
6   construct T1 [typeSpec] M I R
7   by T1
8 end rule
9 function typeSpec_repeat_byField DS [redefineStatement] T [
      typeSpec]
10   import Rules [statement*]
11   import RuleIDs [id*]
12   replace [statement*] _ [statement*]
13   deconstruct DS 'redefine' TID [typeid] TYPE [literalOrType
      *] REST [barLiteralsAndTypes*] 'end' 'define'
14   deconstruct T 'repeat' I [typeid] R [opt typeRepeater] O [
      opt orderedBy]
15   deconstruct O 'ordered' B [opt byField]
16   deconstruct B 'by' F [id]
17   construct StrID [id] _ [quote TID]
18   deconstruct I TypeID [id]
19   construct ID [id] 'normalise_list'
20   construct ruleID [id] ID [_ StrID] [_ TypeID]
21   construct S [statement*]
22   'rule ruleID
23     'replace '[ 'repeat' I ' ]
24     'N1 '[ I ' ] 'N2 '[ I ' ] 'Rest '[ 'repeat' I ' ]
25     'where 'N1 '[ F 'N2 ' ]
26     'by 'N2 'N1 'Rest
27   'end 'rule
28 export Rules Rules [ . S ]
29 export RuleIDs RuleIDs [ . ruleID ]
30 by S
```

```

31 end function
32 function DS_replace DS [redefineStatement]
33   replace [statement*] S0 [statement*]
34   construct T [typeSpec*] _ [^ DS]
35   construct S2 [statement*] _ [typeSpec_repeat_byField DS
      each T]
36   construct S [statement*] S0 [. S1] [. S2] [. S3]
37   by S
38 end function
39 function id_to_type ID [id]
40   replace [literalOrExpression*] L [literalOrExpression*]
41   construct T [literalOrExpression*] '[ ID ']'
42   by L [. T]
43 end function
44 function main
45   replace [program] P [program]
46   export Rules [statement*] _
47   export RuleIDs [id*] _
48   construct DS [defineStatement*] _ [^ P]
49   construct S [statement*] _ [DS_replace each DS]
50   import Rules
51   import RuleIDs
52   deconstruct P S0 [statement*]
53   construct ID [id*] RuleIDs [print]
54   construct PL [literalOrExpression*] 'Prg
55   construct PL2 [literalOrExpression*] _ [id_to_type each
      RuleIDs]
56   construct L [literalOrExpression*] _ [. PL] [. PL2]
57   construct REPLACE [replacement] L
58   construct MAIN [statement]
59   'function 'main 'replace '[ 'program '
60     'Prg '[ 'program ']' 'by REPLACE
61   'end 'function
62   construct P1 [program] S0 [. Rules] [. MAIN ]
63   by P1 [typeSpec_eliminateOrderedBy]
64 end function

```

#### E. Generated normalisation transformation

The above generic implementation is done on the meta-grammar of TXL. When it is applied to a concrete TXL grammar, such as the one specified in Listing 5, a concrete normalisation transformation is produced in the original syntax of TXL, as shown in Listing 8. Lines 2-9 are generated from the [repeat modifier ordered by Descending] annotations from the Line 6 of Listing 5, using the user-defined comparison function Descending, which was listed in Lines 15-20 in Listing 5.

```

Listing 8. cat -n java.Txl
1 include "java.grm"
2 rule normalise_list_method_declaration_modifier
3   replace [repeat modifier]
4     N1 [modifier] N2 [modifier] Rest [repeat
        modifier]
5   where
6     N1 [Descending N2]
7   by
8     N2 N1 Rest
9 end rule
10 function main
11   replace [program]
12     Prg [ program ]
13   by
14     Prg [ normalise_list_method_declaration_modifier ]
15 end function

```

#### F. The normalised programs and relevant changes

We have implemented the processor of all the four types of elementary annotations using TXL, which generates a few transformation rules per annotated term. Applying the composed normalisation transformation to the two Java programs in Listings 1 and 2 produces the normalised results that are

identical, as shown in Listing 9. Both hello and world members are removed because they are not public nor protected members of the class. The main method has the modifiers ordered ascendingly as public static, whilst its method body is replaced by the preferred simplification semicolon alternative. To display the differences of two compared programs, a generated transformation is applied to remove all inter-program cloned instances of the annotated terms. This transformation only applies to those “scoped” annotated terms, because one usually would not remove duplication of low-level term such as identifiers.

Listing 9. mct HelloWorld.java HelloWorld-2.java

```

1 public class HelloWorld {
2
3   public static void main (String args []);
4 }
5 public class HelloWorld {
6
7   public static void main (String args []);
8 }

```

As a result, there is no longer anything left, leaving the output empty as shown in Listing 10.

Listing 10. mct -diff HelloWorld.java HelloWorld-2.java

## IV. EXPERIMENTAL RESULTS

The mct tool has been applied to a benchmark of three evolving programs in the public domain: (i) GMF is a model-driven code generator for Eclipse Graph Editors, (ii) JHotDraw is a GUI framework for technical and structured Graphics, and (iii) OpenCores Uart16650 is a specification of FIFO queue for hardware, which was used for the study of Verilog Diff [8].

#### A. Specifying meaningful changes on Java and Verilog

The meaningful change we want to detect is differences in the API of these programs in different programming languages. Table II lists the sizes of the meta-grammar (txl.grm), Java 5 grammar (java5.Txl) and the Verilog grammars (v.Txl). The ‘+’ sign before the numbers is used for counting those incremental grammars that include the original one. The mct tool is implemented as mct.Txl, which consists of 28 additional rules that transform the 7 extended terms. The Java API normalisation tool is implemented by redefining terms using 22 (3 Scope, 14 Order, 3 Ignore and 2 Prefer) annotations, and 1 user-defined rule in addition to the original grammar. As a result, 47 new transformation rules are generated, which also defines 6 new refined terms. The Verilog annotations include 1 Scope, 1 Order and 1 Ignore, which generates 7 additional transformation rules.

On a server running RedHat Enterprise Linux 5.0, with a 3.16 GHz Intel Xeon X5464 CPU, 6MB cache, 24GB memory, the automated generation of these normalisation rules takes no more than 0.07 seconds. The programming language grammars in TXL (L) and the generated normalisation transformation rules in TXL (M) were then used in the remaining experiments.

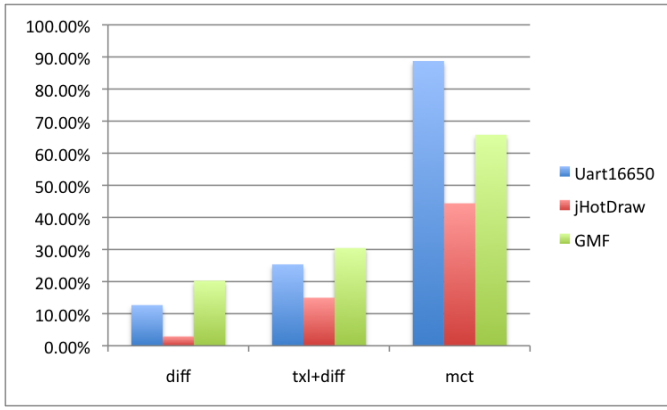


Fig. 4. Contrast the effectiveness of change detection at the file level as the percentage of reduced changed files

TABLE V  
ABSOLUTE TIME PERFORMANCE IN SECONDS

Program Commits	Tool	T(J)	txl T(L)	mct T(M)
uart16650 128	codegen	0.0	1.7	2.8
	diff	0.2	0.2	
	ldiff	18.5	18.0	
jhotdraw 1,582	codegen	0.0	16.5	120.4
	diff	18.7	24.1	
	ldiff	633.5	866.7	
gmf 17,522	codegen	0.0	845.2	23,954.3
	diff	105.5	193.5	
	ldiff	42,740.0	18,525.0	

TABLE II  
SIZE OF THE FULLY EXTENDED GRAMMARS AND TIME TO GENERATE THE NORMALISATION RULES

Grammar	Description	LOC	Terms	Rules
txl.grm	meta-grammar	408	58	1
mct.Txl	Implementation	1081(+673)	65(+7)	29(+28)
java5.Txl (L)	Java 5 grammar	976	168	1
java.norm	annotation	1108(+132)	189(+21)	2(+1)
java.Txl (M)	result	1837(+729)	194(+5)	45(+43)
v.Txl (L)	Verilog grammar	233	37	1
verilog2.norm	annotation	254(+21)	41(+4)	1(+0)
verilog2.Txl (M)	result	469(+215)	46(+5)	8(+7)

TABLE III  
CHANGE OF SOURCE PROGRAMS WITH COMMENTS/WHITE SPACES (J), W/O WHITE SPACES/COMMENTS (L) OR AFTER NORMALISATIONS (M)

Program	File Commit	LOC(J)	LOC(L)	LOC(M)
$\Delta = \text{diff}$		$\Delta \text{ LOC(J)}$	$\Delta \text{ LOC(L)}$	$\Delta \text{ LOC(M)}$
uart16650	12	51,601	28,805	417
(mct)	8	19	19	19
(diff)	128	1,864	879	29
(ldiff)	71	1,552	694	29
jhotdraw	1,012	316,248	212,145	41,614
(mct)	724	2,506	2,506	2,506
(diff)	1,582	29,088	21,479	3,472
(ldiff)	1,264	28,882	28,699	3,284
gmf	5,263	8,944,841	4,288,931	453,181
(mct)	4,810	31,797	31,797	31,797
(diff)	17,522	437,860	274,835	44,516
(ldiff)	14,046	440,160	278,190	37,838

## B. Detecting meaningful changes on three projects

We accessed the history of gmf and jhotdraw by analysing all commits from their public CVS repositories; whilst we were using the same set of selected revisions of Uart16650 provided by Dulay et al [8]. Let ‘J’ stand for the original code, ‘L’ stand for the comment-less code and ‘M’ stand for the normalised code. The Java parsers obtained from the TXL website is already designed to removed all the comments and white spaces in the Java programs. Thus it is perhaps better to compare the normalised results (M) with the unparsed ones (L) rather than with the original code (J).

Table III lists the size metrics of these programs. The metric ‘LOC’ is the number of accumulated lines of code of all the revisions; ‘ $\Delta \text{ LOC}$ ’ is the number of accumulated lines of changes detected by the diff/ldiff utilities.

All the size metrics show that Uart16650  $\ll$  JHotDraw  $\ll$  GMF, roughly by a magnitude of 10. The accumulated lines of code in the GMF CVS repository has close to 9 million lines of code. Taking out white spaces/comments does help reduce the size to nearly a half, indicating that the three open-source programs were all well-commented. The performance

TABLE IV  
COMPARING FILE-LEVEL CHANGES

Program	Pairs	diff	txl+diff	mct
Uart16650	71	62(-12.7%)	53(-25.4%)	8(-88.7%)
jHotDraw	1,302	1,264(-2.9%)	1,107(-15.0%)	724(-44.4%)
GMF	14,046	11,196(-20.3%)	9,767(-30.5%)	4,810(-65.8%)

of ldiff in terms of detecting file-level changes is the same as that of diff. However, ldiff generally reduces the amount of information presented to developers when changes did occur.

The absolute size of the normalised code LOC(M) is almost 10 times smaller than LOC(L), and the change  $\Delta \text{ LOC(M)}$  is also much smaller than the counterparts. As a result, in all the three examples, fewer file-level changes are found by diff/ldiff. Table IV highlights the ratio of reduction of the file-level changes after diff, txl+diff and mct are applied, where mct has the most effective result. The ratios are compared in Figure 4.

The time it took for the experiment is shown in Table V, in the units of second. ‘T(X)’ is the time it took to generate the programs, and to measure the differences using diff or ldiff between pairs of consequent revisions. For the original (X=J) program, no computation is needed from generate the program for the diff/ldiff measurements. The generation of the pretty printed (X=L) is done by the default TXL parser, and generation of the normalised (X=M) programs is done by the mct generated transformations.

Amongst the three evolving programs, diff is the fastest, on average only as little as  $(0.2 + 18.5 + 105.7) / (128 + 1582 + 17522) = 124.4 / 19232 < 0.007$  seconds per revision pair; whilst using txl then ldiff is the slowest, on average  $44255.4 / 19232 = 2.30$  seconds per revision. On average, the normalisations and clone removals in one step mct takes about  $24077.5 / 19232 = 1.25$  seconds per revision.

TABLE VI  
SCALABILITY: TIME RELATIVE TO THE INPUT SIZE (SEC/MLOC)

LOC(J)	txl +ldiff	ldiff	mct	txl +diff	diff
51,601	391.5	358.5	54.3	36.8	3.9
316,248	2055.3	2003.2	380.7	128.4	59.1
8,944,841	4872.7	4778.2	2678.0	116.1	11.8

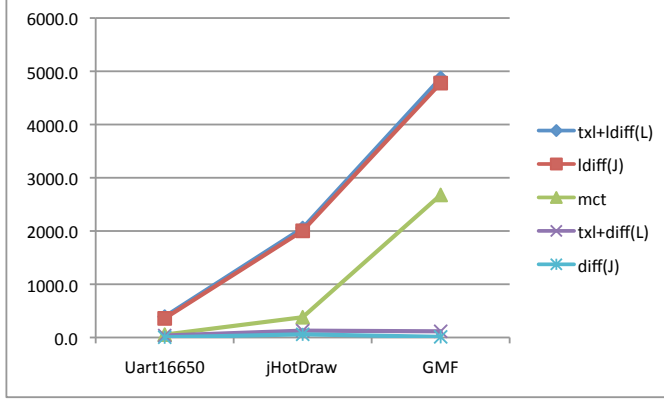


Fig. 5. Contrast the scalability of the experimented command line tools

Finally, Table VI lists the time performance relative to the input size, in seconds per million lines of code. The columns are ordered by the last row, in the order from the slowest on the leftmost to the fastest on the rightmost. We only compare the scalability of five configurations for detecting changes, using a combination of 4 tools, *diff*, *ldiff*, *txl* and *mct*. Figure 5 plots the data in this table.

### C. Threats to validity

Although some of our experiments were large scale, we should not over-generalise our findings. The GMF project is model-driven, and an unknown portion of CVS commits are attribute to the code generations, thus are less relevant to the API-evolution compared to those manual changes in the JHotDraw project. In these experiments, however, we did not separate generated code from the CVS repository. The Verilog normalisation applies fewer annotated transformations than that of the Java API, which could explain why the average time/MLOC performance of Verilog is better than JHotdraw. The performance of *ldiff* in terms of file level change detection is not better than that of *diff*, however, the quality of *diff*-chunks in *ldiff* may be finer than that of *diff*. Therefore we included experiments of both to indicate how *mct* compares with the scalable *ldiff* tool. To avoid any skewing of the running environment, we took the timing measurement 5 times and the minimal elapsed time. However, a different hardware configuration may lead to slight different measurements in the figures. Finally, we did not compare the interactive supervised *diff* results as some of the related work does because such supervisions require a large amount of time on the code base, and it also requires truthful interpretation from the developers which are intrusive to the development projects. As a trade-off, our command line tool *mct* could

substitute the underlying *diff* algorithms for the interactive use cases.

## V. RELATED WORK

**General problem.** Brunet et al [12] define the challenges of model managements in terms of *merge*, *match*, *diff*, *split* and *slice* operations and the properties that should be preserved by those operations. Their operations and properties are independent of models and modelling languages. Our *normalisation* steps are similar to *slice* operations because they are a series of transformations performed from model to model based on slicing criteria. And the *clone removal* step is similar to the *diff* operation that transforms two models to a set of changes. Model matching and merging [13] are also related to our work in the sense that they handle how to merge the detected changes. Our emphasis is on ensuring the transformed programs (or models) remain valid according to the original language syntax so that it is easier to compare the differences to the original programs.

**Structural diff.** Xing and Stroulia [6] propose an approach to recover UML design models (such as class diagrams) from Java code, then compare their structural changes. The approach is specific to UML, which uses similarity metrics for names and structures to determine the types of changes made. Schmidt and Gloetzner [14] describe an approach that integrates the *SiDiff* tool to detect semantic changes on diagram structures. It then visualises the changes on UML diagrams and SimuLink models. These diagrams, in principle, can be specified in domain specific languages such as UMLasSketch<sup>1</sup>. Thus it is possible to apply our tool to detect changes on the textual models. The main difference with our work is that our approach allows the tool user to specify selective changes to be detected.

Apiwattanapong et al [15] present a graph-based algorithm for differencing API of Java programs. Since their approach and the tool *JDiff* is geared towards Java, there is explicit support of Java-specific features, such as the exception hierarchies. Their tool is therefore not language-independent as ours. In addition, we can also specify the meaningful changes to extract UML models and to isolate user-specified “generated NOT” elements from model-driven software development with only a few additional semantic rules in TXL. These are beyond the scope of *JDiff*.

Beyer et al [16] present an efficient relational calculator *crocopat* that can perform *diff* calculation on two sets of tuples very efficiently, and thus has been widely used in *visualisation* reverse engineered facts such as call graphs or inheritance/aggregation relationships. However, *crocopat* treats all differences in sets rather than ordered lists. Therefore it is not suitable to check the differences among ordered structures such as statements or parameter lists.

Fluri et al [17] describe an approach to find differences on abstract syntax trees. The criteria for measuring the size of differences is the length of minimal number of editing operations,

<sup>1</sup><http://martinfowler.com/bliki/UmlAsSketch.html>



such as *insert*, *delete*, *move*, *update*. They also define several refactoring-based operations, such as condition expression change, method renaming, parameter delete, ordering change, type change, statement insertion, parent changes, and so on. Most of their basic editing operations can be expressed using a composition of the four basic annotations rules used in this paper. On the other hand, the refactoring changes on semantic behaviour preserving require more advanced transformations that depends much on the specific Java semantics. Our design considers that specificity with the generalisable principle so that a substantially different programming language such as Verilog can also be supported. In principle, refactoring type of transformations can be supported by specifying those changes as user-defined equivalence functions.

**Semantic diff.** There are several differencing tool working at the semantic level which may be complementary to us. Jackson and Ladd [7] use dependency between input and output variables of a procedure as a way to detect certain changes. The dependency is represented as a graph and any difference in two graphs is taken as a change to the semantics of the procedure. There are, of course, changes that affect other kinds of semantics but not the dependency graph, such as the changes in constants. Working at the level of program grammar, our tool presents all the choices for the user to decide whether a change in constant should be ignored or not.

Kawaguchi et al [18] present a static semantic diff tool called *SymDiff*, which uses the notion of partial/conditional equivalence where two versions of a program is equivalent for a subset of inputs. The tool can infer certain conditions of equivalence, and therefore behavioural differences can be lazily computed. Our tool does not work at the level of program semantics.

Duley et al [8] present *VDiff* for differencing non-sequential, “position independent” Verilog programs. Their algorithm extracts the abstract syntax trees of the programs, and matches the sub-trees in the AST’s whilst traversing them top-down. Furthermore, Boolean expressions are checked using a SAT solver and the results of differencing are presented as Verilog-specific change types. In this work, we used their datasets to demonstrate that our work can be applied to this language too. Although we do not classify the changes into 25 types as they did, we can also classify the changes according to annotated terms.

**Applications.** Wenzel et al [19] present a view that the evolution history of models can be traced into modelling elements and visualise the change metrics. When large amount of data are being processed, again it is important to be able to extract the relevant information to compare with each other. Our work has shown that it is not only possible to trace the history of evolution, but also possible to specify such views based on the relevance to programming tasks. On the other hand, adding some visualisation capability to our command-line tools should be possible, especially since we have obtained the exact structures in the comparisons.

Dagenais and Robillard [20] present a promising way to use change detection for recommendation systems, especially

for the framework evolution. Recently, Kawrykow and Robillard [21] demonstrate the *DiffCat* tool to classify both CVS and SVN change sets of Java programs for non-essential changes such that those induced by cosmetic refactoring operations can be ignored. It also ignores the changes to white space and comments. *DiffCat* aims to *classify* the changes as input data that might be non-essential for automated techniques, instead of defining for Java programmers which changes are essential or meaningful. On the other hand, our approach can be used to define a suitable normalisation for each of these classified change types. For example, a local variable renaming could be normalised by renaming any local variable to the surrounding context of its declaration. Therefore it is possible to combine the two approaches further for classifying the different types of meaningful changes.

Kim and Notkin [22] present the *LSdiff* tool to automatically identify structural changes. Similar to us, there are no predefined change types in *LSdiff*, though the abstraction of *LSdiff* is at the level of code element and structural dependencies. While both *LSdiff* and *mct* share a common goal of helping programmers to understand changes at a high level, instead of focusing on identifying and summarizing systematic structural differences, right now our tool focuses on programmer-provided annotations on the production rules to filter out meaningless changes.

Godfrey and Zou [23] introduce the notion of “origin analysis” for detecting structural changes made to program entities, in order to find out reasons for merging and splitting of code. With more precise changes identified on the structure, it is possible to increase the chance of identifying such origins.

Refactoring transformations improve program structures without introducing behavioural changes (see Mens and Tourwé [24]). The four basic annotations may already express simple forms of refactorings, which “normalises” the structures in order to remove irrelevant changes when evolving programs are compared. To detect an advanced refactoring, especially those happened to the API’s (see Dig et al [2]), a user-defined function works on a term of appropriate scope (e.g., *class\_declaration*, or *method\_body*), depending on the nature of the refactoring.

**Implementation.** Although our implementation is based on TXL [10], the implementation of the concepts could be replaced using other generic transformation systems/ language engineering tools such as GrammarWare [25].

## VI. CONCLUSIONS AND FUTURE WORK

In this paper, we presented a declarative approach to specify changes in programs that are relevant to different programming tasks. In particular, we demonstrated its use in extracting the changes at the API levels for evolving Java programs and hardware specifications. We showed that four elementary annotations can account for all light-weight syntactical normalisations by default, and can be customised for more advanced semantic changes through user-defined functions. Our declarative specification approach already works on several programming and domain-specific languages. Our automated

tool was implemented on top of a generic transformation system, TXL, and the results of detecting relevant differences in the three programs are evaluated and compared with other diff utilities such as line-based diff, showing more precise detection and acceptable scalability and time performance. The tool and results can be downloaded from <http://sead1.open.ac.uk/mct>. The tool currently supports a long list of programming languages inherited from <http://txl.ca>, as well as several requirements modelling languages including i\* [26], Problem Frames [27] and argumentation [28], [29].

Currently our implementation of the clone removal is limited to exact clones. We will integrate near-miss clones detector such as NiCAD [11] to ignore more structural changes. Recent work on requirements monitoring [30], [31] have indicated that it is important to detect meaningful changes at run-time. In a generic graph-based approach, high-level meaningful changes are expressed declaratively as *change patterns* [32], and detected either at run-time or in an off-line comparison scenario. We will investigate how to extend our meta-annotation approach to generate such change patterns for detecting runtime meaningful changes.

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