Parallel Changes: Detecting Semantic Interferences

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Abstract

Parallel changes are a basic fact of modern software development. Where previously we looked at prima facie interference, here we investigate a less direct form that we call semantic interference.

We reduce the forms of semantic interference that we are interested in to overlapping def-use pairs. Using program slicing and data flow analysis, we present algorithms for detecting semantic interference for both concurrent changes (allowed in optimistic version management systems) and sequential parallel changes (supported in pessimistic version management systems), and for changes that are both immediate and distant in time. We provide these algorithms for changes that are additions, showing that interference caused by deletions can be detected by considering the two sets of changes in reverse-time order.

Keywords: Parallel changes, local change analysis, semantic interference, program slicing, data flow analysis

Introduction

There are a number of factors that have made parallel development an increasingly serious and critically important problem.

- With the ever increasing size of software systems comes the fact that developers must work in parallel to meet market time pressures and schedules. This fact has always existed in large-scale software systems development.
- Increasing globalization results in the additional factor of parallel geographically distributed software development. Temporal and geographical separation make it extremely difficult to support the critical informal interactions that provide a significant means of problem solving.
- With the increasing size of systems as they evolve over time comes the fact that only an increasingly smaller proportion of a system is changed for any one release (a fact that makes traditional code ownership - the centralization of knowledge of code - an infeasible solution).
- And finally, as features and feature ownership increasingly drive software systems evolution, we find that software systems evolve on the basis of many independent as well as interdependent software developments. This emphasizes both the heterogeneity rather than the homogeneity of software systems evolution, and the centralization of the knowledge of changes.

Thus, a fundamental and important problem in building and evolving complex large-scale software systems is how to manage and to support the phenomena of parallel change. How do we support the people doing these parallel changes by organizational structures, by project management, by process, by methods and techniques, and by technology? How can we support these kinds of parallel change efforts and maintain the desired levels of quality as well as schedules in the affected software?

In our previous study [1], we described the landscape of parallel changes, determined the extent of *prima facie* interfering changes, and established a positive linear relationship between the degree of parallelism and the number of software faults. In this example, the variable b is common to both versions and a use of such variable is preserved in the program point pair (4,5) linked through application *A*. The immediate data predecessor relative to b - (3) for the former version and (4) for the latter - are not linked via *A* and therefore the variable definitions concerning a preserved use do not apply.

We attribute this to the fact that there is insufficient time to understand the changes made under these kinds of constraints.

In this paper, we present a local change analysis technique to detect changes that have a less direct effect – namely, *semantically interfering* changes. While all changes are intended to affect a program semantically, it is clearly the case that many changes have unintended effects – *cf* the fact that software faults are introduced in changes. [2,12] A change *semantically interferes* when modifications are made to the same slice [3,4,15] of the program and modify the program's behavior. We note that our analysis is done at the statement level (where we are concerned with the insertion, deletion and modification of lines of code) rather than at higher levels of abstractions such as in Chianti [21] where the focus is at the method level.

In our experience with large version history data [1,12], a local change analysis technique that reveals the locations of these semantic effects would be extremely helpful in preventing the introduction of multiple new faults with every modification made to the code.

Examples of Semantic Interference

In analyzing semantic conflicts we focus on how variables are assigned and used throughout the data flow.

```
program              program
  a := 1               a := 1
                       a := 2  ←
  b := a               b := a
end                  end
```

Fig. 1 - A simplistic version of the *def-use static overlapping* case of semantic interference

The simplest example of semantic interference is the *def-use static overlapping* (Fig.1). The left hand snippet shows a simple definition-use pair. The only execution path possible defines a value for the variable *a* and uses it in the next statement. As post-conditions on this code we expect *b* to carry the value *1* at the end of execution [9]. In the modified example an additional line has been inserted. The effect of this interference is clear: the variable *b* assumes the value 2 at the end of the execution, negating the post conditions that the author of the original code had intended. In this example we show only two versions of the code referring to the leftmost as the *original code* and to the rightmost as the *modified version*.[1]

The next example shows a simple variation that uses aliasing to disguise the def-use overlapping. The variable *a*, a middle link in the dereferencing chain, is modified in value and although the original value for *c* is not modified, *a** and *c* do no longer refer to the same entity. Lines (2-4) and lines (3-4) constitute the overlapping def-use pairs.

```
        program          program
1:        c := 1           c := 1
2:        a := &c          a := &c
3:                         a := a + 1  ←
4:        b := a*          b := a*
        end              end
```

Fig. 2 – A pointer variant.

While in the previous case the def-use pair involved assigning a value and accessing the location where the value was stored, in this case the interference occur during the pointer resolution process; in order to access the value of *a**, access to the value of the pointer is required. When line 3 is inserted, a new definition for the variable *a* is added. When the variable is used in order to resolve the value for *a**, interference occurs.

[1] We only identify two possible types of code modification: line insertions and line deletions; we will consider modifications as deletion-insertion pairs.

```
        program          program
          ...              ...
1:        a := &c          a := &c
2:        a* := 1          a* := 1
3:                         a* := 2  ←
4:        b := a*          b := a*
        end              end
```

Fig. 3 - Indirect effect.

Fig. 3 shows a simplified case of indirect semantic interference. A true indirect conflict occurs when despite the absence of apparent def-use overlapping involving the variables, the content of the memory location being referenced is modified before the value contained at that location can be accessed. While explicit pointers are the classic culprit of this type of interference, languages that implement implicit pointers (e.g. Java™, C#™) may simply obscure the conflict rather than prevent it.

In the specific example displayed in Fig. 3, a* is an alias for c. Although there is no apparent def-use overlapping for any of the variables (a or c), lines (2-4) and (3-4) still identify two overlapping def-use pairs for the entity referenced by a*. Although this falls within the given definition for indirect conflicts, because the subject entity is always referenced as a* while in no case is the value of a affected, this example has more affinity with direct conflicts such as those shown in Fig.1 and Fig. 2. It is sufficient to consider a* a stack variable, and static analysis of the code reveals the conflict.

Fig. 4 shows the simplest form of a truly indirect interference, for which no def-use overlap is detectable in the code without keeping track of pointers' values. The only variables present in both snippets are not explicitly affected by the change, although the value for the stack location indicated by *c*, to which *a* points, is changed through pointer dereferencing.

```
        program          program
1:        c  := 1          c := 1
2:                         a := &c  ←
3:                         a* := 2  ←
4:        b := c           b := c
        end              end
```

Fig. 4 – A truly indirect semantic interference.

Indeed, there is no explicitly visible def-use overlapping for lines (1-4) and (3-4) which do interfere. For both versions, lines (1-4) apparently constitute a perfectly valid def-use pair and line 3, which involves a different variable, should not affect this. It is also evident though – at least in this simple example - that *c* is semantically an alias for *a** at this point in the execution, and that an overlap does indeed occur. This kind of semantic interference poses a series of additional challenges for detection purposes and is more problematic for developers to deal with.

We have so far discussed only changes that inserted lines which interfere semantically with a preexisting reference version. The same distinctions and classifications that apply to line insertions apply to changes that remove or modify any existing line of code. As we show below, the analysis of all modifications can be elegantly reduced to a combination or reversal of the steps necessary for the detection of conflicts in the general case of line additions.

It should now appear clear that a semantic interference is an artifact in the semantics of program evolution that defies the postconditions intended by the original author by interleaving pairs of def-use instruction in any of the program execution slices.

Although this generalization seems well grounded, the actual interleaving mechanism may vary greatly. Pointer dereferencing can for instance involve multiple chained stages and interleaving def-use pairs may not appear as evident in these cases.

While all flavors of semantic conflicts can be reduced to direct and indirect interference through def-use overlapping, the actual mechanisms in which these effects occur may also vary. In the examples shown so far, the execution path was sequential. This is not always the case: control structures, subroutine calls, data-driven and event-driven execution schemes, all affect the number of different paths that the actual execution of code can take and thereby hide the effects of semantic interferences.

When non-determinism comes into play, as in multi-threaded operations, detection of undesired effects may be even more difficult.

Parallel Changes and Research Context

We delineate two different flavors of parallel changes in our approach to detecting semantic interference between any two versions.

- *Concurrent changes* are changes performed through an *optimistic version control* system which allows multiple valid copies of the same file at the same time [11]. The final version is a semi-automated integrated version. The merging process is usually dependent on the absence of syntactic and direct *prima facie* conflicts; indirect semantic interference may easily go undetected [9]. Changes of this sort are truly parallel and there is no assumed ordering among them. Concurrent modifications pose several additional challenges in detecting interfering changes.
- *Sequential parallel changes* are also parallel changes in a logical sense: they take place independently from each other and are committed by different developers in a relatively short span of time. In a *pessimistic version management system* [7] parallel changes are sequentialized because only one developer may have a file checked out at a time. The time of submission for a change determines the ordering of the changes. By default, every change is assumed to possibly conflict with previous changes, potentially disrupting or modifying the effects of previous modifications, without notifying any of the developers.

In both cases, it is very likely that indirect semantic interference will go undetected. In related work, Horwitz et al. [9] provide an algorithm for integrating non-interfering versions under certain assumptions. To our knowledge, the extent to which this algorithm is applicable is unknown. Some version management systems [7,10,16] also provide automated merging functions. Nonetheless, as we discuss below, merging strategies find applicability only in optimistic version control scenarios and are nonetheless subject to various kinds of semantic interference.

The context for this research is Lucent Technologies 5ESS™ system where there is massive parallel work done in the context of pessimistic version management [1,12]. The 5ESS™ change process relies on an initial modification request (IMR) that models a logical problem, such as feature additions, fault corrections, performance improvements, etc. Each IMR is split into a set of more manageable modification requests (MRs), representing partial solutions to the problem, that reduce the granularity of the change being made. Each MR is typically owned by one developer, who implements it through one or more *deltas*. A *delta* specifies the change in terms of which lines of code were added, changed or deleted and includes pointers/references to the versions of code pre and post change [12, 2, 14].

In our reference system, single MRs are often split into a multitude of atomic changes (*deltas*). One could argue that an MR produces one functionally consistent version of the software code[2], and that we should focus on versions produced by MRs rather than on single deltas. The reality is that in the context of pessimistic version management, the deltas that collectively represent one logical change are interleaved with deltas that represent other logical changes – that is, single deltas traceable to different MRs interleave changes to the code throughout the system's evolution in the sequential case. Therefore we consider *deltas* as the atomic originators of semantic interferences in parallel changes rather than MRs. This fine level of granularity however does introduce several complications addressed below.

Fig. 5 shows how changes from different MRs create versions of the code that overlap across MRs throughout time[3]. In general an arbitrary number of concurrently active MRs generate deltas applied in a non-foreseeable

[2] This is because one MR, owned by one developer, groups changes that have one common reason and stem from one initial logical request of modification (IMR)

[3] Note that the diagram assumes only two MRs for which interleaving deltas are submitted.

order. The study of two generic deltas for deciding whether the later interferes semantically with the earlier, must involve the analysis of four different versions of the source code about which no particular assumptions can be made. Only when two deltas are consecutive will the intermediate versions be identical.

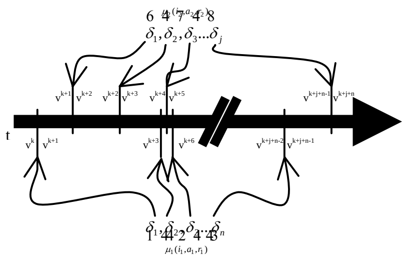


Fig. 5 – Deltas from different (independent) MRs, interleave non-deterministically in time. Adjacent deltas in a MR cannot be guaranteed to operate on adjacent versions of the code.

There is only one exception to this. In the case of truly concurrent changes in optimistic CMSs deltas are checked before integration (or contextually to it). There is therefore no possibility that other deltas occur between those under analysis. While this reduces the number of versions to three, the merged version must be brought into the process in order to successfully "catch" any conflicting behavior.

Overview: slicing and the detection process

The most computationally most intensive step of our analysis technique involves *slicing* the code associated with each of the four versions required by a pair of deltas.

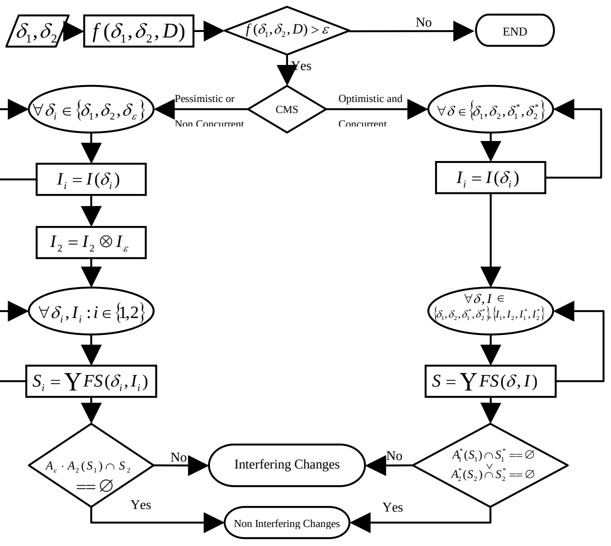
A *program slice* [3,4] represents the source code components of a software program that could potentially affect the semantics of the computation depending on a *slicing criterion*, usually a 2-tuple (program point, set of variables) and the task of computing program slices is called *program slicing*.

An important distinction is to be made between *static slicing* and *dynamic slicing*. Whereas static slices are computed without making assumptions regarding a program's input, and thereby include all potentially affected program points, dynamic slicing relies on specific test cases, on a specific set of input values for the program [3]. A program point is either an explicit instruction in the code such as an assignment, a control or a function call, a control point such as the entry point for a subprocedure, or a "hidden" program point such as assignment for formal/actual parameters and return values from subprocedures [4].

A Program Dependency Graph (PDG) is a directed graph for a single procedure in a program. Several PDGs representing the control components (subprocedures, etc.) of a system are interconnected in a System Dependency Graph (SDG). The vertices of such graphs are program points while the edges represent control and data dependencies. Computing a program slice is the process of determining a subset of the vertices of one SDG whose members influence, or are influenced by, a particular slicing criterion. This duality corresponds to the choice of computing a forward or a backward slice. [3] The intersection between a forward and a backward program slice is called a chop between two program points. [4]

Fig. 6 shows a flow-chart of the steps involved in detecting semantic conflicts among parallel changes. The process assumes that two deltas have been chosen; the data available are therefore two chosen deltas, δ_1 and δ_2.

Here we describe the process step by step, through the aid of examples. For simplicity, we start by discussing the general case in a pessimistic change management system. The general case also applies when two deltas are parallel in an optimistic CMS environment.



δ_1, δ_2
$f(\delta_1, \delta_2, D)$
$f(\delta_1, \delta_2, D) > \varepsilon$
No
END
Yes
CMS
Pessimistic or Non Concurrent
Optimistic and Concurrent
$\forall \delta_i \in \{\delta_1, \delta_2, \delta_\varepsilon\}$
$\forall \delta \in \{\delta_1, \delta_2, \delta_1^*, \delta_2^*\}$
$I_i = I(\delta_i)$
$I_2 = I_2 \otimes I_\varepsilon$
$\forall \delta_i, I_i : i \in \{1,2\}$
$S_i = \bigcup FS(\delta_i, I_i)$
$S = \bigcup FS(\delta, I)$
$A_\varepsilon \cdot A_2(S_1) \cap S_2 == \emptyset$
Interfering Changes
Non Interfering Changes
No
Yes

Fig. 6 – The flow diagram for the interference detection process[4].

As discussed earlier, for two generic deltas, δ_1 and δ_2, ordered in time[5], four different versions of the software system under development are referenced, ordered progressively according to their time sequence. If two deltas are greatly separated in time, V_2 and V_3 (i.e. the version generated by the older delta and the one from which the newer in time starts) will in general be different. Only when the two deltas are adjacent will these versions be identical. This distinction will be relevant below.

[4] The process shown is applied to two given deltas which are analyzed for interference. Note that two deltas that are concurrent in an optimistic CMS scenario always qualify as parallel changes, but in general two non concurrent changes may qualify as parallel and analyzed following the left branch of the diagram.

[5] Assuming $t_{\delta_1} < t_{\delta_2}$

Next, we construct a fictitious delta, δ_ε, which describes the sum of the changes made in the time lapsed between the two deltas under analysis. It can be simply shown that the combination of deltas is a closed operation in such a space, because the subsequent application of deltas can be seen as a combination of line insertions and line deletions. The role of δ_ε will be key in determining possible interferences between the two deltas.

Basic Defintions: Δ, A and NI_V

The central question that then arises is when do two deltas, rather than two versions, interfere semantically? We first define more formally how versions interfere semantically with each other.

Let *V* be a version of the source code of a software program. We can define the dependency set Δ as the set of the triples *(v,d,u)* as follows,

$$\Delta = \{v : d \ \alpha \ u\}$$

where *v* is a variable, *u* is a use of such a variable and *d* is the definition of the value for *v* that is effectively used in *u*. Such a set is fairly straightforwardly derivable from the program's SDG. *d* and *u* are by all definitions program points in the software dependency graph. In the simple examples used within this scope, they will always translate to source lines and will therefore be referenced by means of line numbers. Bear in mind however that several program points are often generated from the same source. Therefore program points in an SDG may not always show a one-to-one correspondence with source code lines.

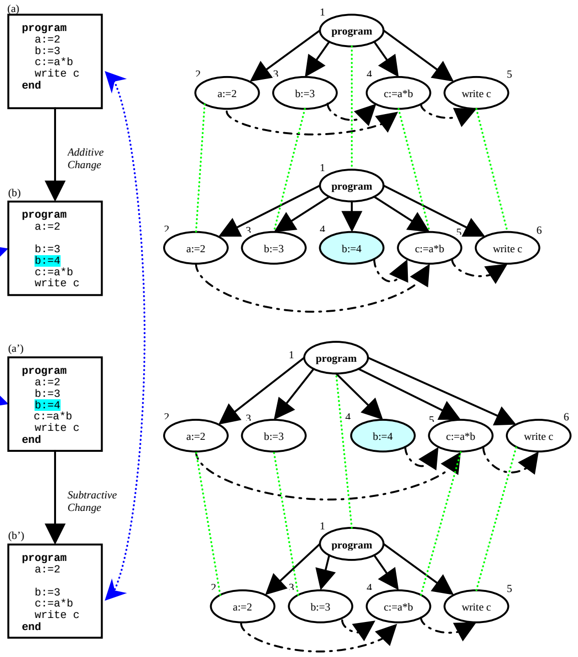
For each delta δ then, two dependency sets Δ_1 and Δ_2 can be determined, as well as an injection $A : SDG_1 \rightarrow SDG_2$ that transforms each program point in V_1 into a program point in V_2, thus codifying the changes in terms of program points.

Now, it should appear clear that the application *A* can only be an injection in SDG_2 when the only changes made from V_1 to V_2 are line insertions. Since a line change is a deletion followed by an insertion, it remains to be defined what happens in case of removed lines. A line deletion from V_1 to V_2 with $t_2 > t_1$ is equivalent to a line insertion where V_1 follows V_2 in time. For the purpose of determining semantic interferences a deletion is equivalent to an insertion reversed in time. In order to determine whether or not V_2 interferes semantically with V_1 over a set of deletions, we must therefore establish if V_1 interferes semantically with V_2 over the equivalent set of line insertions.

Consequently, the application *A* is logically an injection from SDG_1 to SDG_2 where the latter is the potentially interfering graph and the former is the one that is potentially interfered with.

In determining a condition of non-interference for versions *a* and *b* in Fig. 7, we argue that *a version interferes semantically with another when for any preserved use of a common variable, the immediate data predecessor or definition thereof, is not preserved.*

In this example, the variable b is common to both versions and a use of such variable is preserved in the program point pair (4,5) linked through application *A*. The immediate data predecessor relative to b - (3) for the former version and (4) for the latter - are not linked via *A* and therefore the variable definitions concerning a preserved use do not apply.


(a)
```
program
  a:=2
  b:=3
  c:=a*b
  write c
end
```
(b)
```
program
  a:=2

  b:=3
  b:=4
  c:=a*b
  write c
```
(a')
```
program
  a:=2
  b:=3
  b:=4
  c:=a*b
  write c
end
```
(b')
```
program
  a:=2

  b:=3
  c:=a*b
  write c
end
```

Fig. 7 – A simple program in two interfering versions and the corresponding SDG shown for additive and subtractive types of changes. The solid connectors represent flow dependencies, the black dashed ones represent data dependencies and the green pointed connectors show the application A from graph to graph. The blue connectors show the equivalence between the programs by looking at subtractive changes as additive changes in a reversed timeframe. Note that A is an injection in the case of additive changes (every node in (a) is connected to some node in (b)) and the inverse injection in case of subtractive changes (some node in (a') are connected to nodes in (b') exhausting the node space in (b').

The latter version, however, does therefore interfere semantically with the former. Let V_2 and V_1 be two versions of code. Consider the case in which the modifications made to the code are generic, consisting of insertions, deletions and modifications. We must therefore verify that V_1 does not interfere with V_2 over the set of line deletions, and that V_2 does not interfere with V_1 over the set of line insertions. We do so using the following condition of non interference.

Let $V = V_1 \cap V_2$ be the intersection of the sets of variables used in V_1 and V_2, and A_{V_1,V_2} be the injection from V_1 to V_2.

$$\forall v \in \mathcal{V}, \forall u_2, \exists (u_1, d_1, d_2), (u_1, u_2) \in A_{V_1,V_2}:$$
$$[v : d_1 \ \alpha \ \ u_1] \in \Delta_1 \wedge [v : d_2 \ \alpha \ \ u_2] \in \Delta_2 \Rightarrow (d_1, d_2) \in A_{V_1,V_2} \quad (NI_V)$$

Thus, **NI$_V$** means that *for every variable v common to both versions and for each use of that variable made in the latter version, if there exist an A-equal use in the dependency set of the former version, governed by an A-equal definition, the latter version does not interfere with the former.*

Handling Deleted Lines

It could seem that the distinction between additive and subtractive changes is unnecessary and that the above definition could be applied regardless of the nature of the changes being made. While this may sometimes be the case, it does not hold when the cardinality of the dependency sets is not maintained[6]. This may happen when programs show more complicated flow diagrams than those we have shown. The versions of the program in Fig. 8 interfere semantically. The latter version removes two lines from the original version. Nonetheless, were NI$_v$ to be directly applied, no interference would be caught. Since the changes are subtractive, in order to be sure to catch all possible interferences, NI$_v$ has to be applied switching the versions.

Once again, for sake of clarity and simplicity we refer to program points in the following example by means of line numbers, binding each program point to the source code line that generated it.

```
1:    program(b)                    program(b)
2:      a:=0                          a:=0
3:      c:=0                          c:=0
4:      if (b==0)                     if (b==0)
5:           a:=2                       a:=2
6:      else              ←           fi
7:           c:=2         ←           d:=a*b*c
8:      fi                            write c
9:      d:=a*b*c                    end
10:     write d
      end
```

Fig. 8 – A change that removes lines from a precedent version ought to be checked for interference by applying the non-interference condition NI$_v$ switching the role of each version. This is equivalent to check for interference in line additions by considering a reversed timeframe.

A relatively straightforward analysis of the SDG of each of the two versions will reveal that:

$$\Delta_1 = \{[a:2\ \alpha\ \ 9], [a:5\ \alpha\ \ 9], [b:1\ \alpha\ \ 4], [b:1\ \alpha\ \ 9], [c:3\ \alpha\ \ 9], [c:7\ \alpha\ \ 9], [d:9\ \alpha\ \ 10]\}$$
$$\Delta_2 = \{[a:2\ \alpha\ \ 7], [a:5\ \alpha\ \ 7], [b:1\ \alpha\ \ 4], [b:1\ \alpha\ \ 7], [c:3\ \alpha\ \ 7], [d:7\ \alpha\ \ 8]\}$$

Since the dependency set is computed statically, one variable can allow multiple definitions to one use. In our approach code is sliced statically. There is therefore no way to predict what the data that drives the execution flow will be. In fact, if we sliced the code dynamically, the cardinality of each dependency set would be exactly equal to the number of uses made of all variables involved in that execution path, and therefore for every preserved use only one dependency in each set could be found.

An analysis of the information relative to the changes made (available through the change management system and associated with each delta) defines the function *A* as:

$$A = \{(1,1), (2,2), (3,3), (4,4), (5,5), (6,\varepsilon), (7,\varepsilon), (8,6), (9,7), (10,8)\}$$

To try to determine whether V$_2$ interferes with V$_1$ by applying NI$_v$ directly would erroneously lead to the conclusion that the two versions do not interfere. In fact for each preserved use[7] of c in V$_2$, the relative definitions (3,3) are preserved. However, if b equaled 0 in V$_1$ c would carry the value 2 instead of 0.

Simply reversing the roles of the dependency sets will do the trick. The universal quantifier is scoped over the version from which the lines were removed guaranteeing that the interference will be discovered. Since this phenomenon is triggered by the subtractive change, we argue that NI$_v$ must be applied in a reverse fashion for line deletions. In fact we argued that a deletion is a line insertion in a reversed timeframe. If the original version subject to subtractive changes would interfere with the modified version over the set of complementary additions, then the deletions in the modified version interfere semantically with the original version.

Interference Sets: Conflicting Deltas

We have at this point defined a formal condition for non interfering versions. We now define an **interference set** which describes how two versions interfere with each other. Such set represents the interferences that the latter version in time induced over the former independent of how NI$_v$ is applied.

For a generic set of line insertions, deletions and modifications between two versions V$_1$ and V$_2$, one set of deletions and one set of insertions can be constructed. We will call these two sets C$_{Del}$ and C$_{Ins}$.

We start applying NI$_v$ to (V$_{Del}$,V$_1$) where V$_{Del}$ is the version of code generated from the changes from C$_{Del}$ applied to V$_1$, i.e. C$_{Del}$(V$_1$) . We then apply NI$_V$ to (V$_1$,V$_{Ins}$) where analogously, V$_{Ins}$ is C$_{Ins}$(V$_1$). In both cases we define two sets, I$_{Del}$ and I$_{Ins}$ of interferences. Each element in an interference set is a dependency triple extracted from the dependency set of the "potentially interfering" version, which causes NI$_v$ to be not satisfied.

The interference set I for (V$_1$,V$_2$) is the union set of I$_{Del}$ and I$_{Ins}$ where each element is only taken once.

[6] i.e. dependencies are not simply modified but are introduced or removed

[7] the only use in V$_2$ is at program point 7 and (9,7) belongs to *A*

We now go back to the problem from which we started. In the context of this work we are interested in determining interfering deltas rather than interfering versions. The conclusion that we reach on the condition of non-interference for deltas stems from the idea that *when two changes – no matter how separated in time – are found to be parallel and should therefore not interfere, the latter change should have no semantic impact on the program points affected by the former change.* When we check a new delta for possible interferences we ask that the modifications introduced do not affect the same program points affected by the earlier change in an interfering fashion.

	V_1	**V_2=V_3**	**V_4**
1:	**program**	**program**	**program**
2:	a:=1	a:=1	a:=1
3:	b:=2	b:=2	a:=2
4:	c:=a+b	b:=3	b:=2
5:	return c	c:=a+b	b:=3
6:	**end**	return c	c:=a+b
7:		**end**	return c
8:			**end**

Fig. 9 – Two deltas that are adjacent in time will only refer to three different versions since V_2 and V_3 will be identical.

Let us consider first the case of two parallel adjacent changes[8]. Fig. 9 shows two adjacent deltas for a simple program similar to the ones analyzed so far.

Using the discussed technique we can determine Δ_1, Δ_2, A_1, A_2 and the interference sets I_1 and I_2.

$$\Delta_1 = \{[a:2\ \alpha\ \ 4],[b:3\ \alpha\ \ 4],[c:4\ \alpha\ \ 5]\},\quad \Delta_2 = \{[a:2\ \alpha\ \ 5],[b:4\ \alpha\ \ 5],[c:5\ \alpha\ \ 6]\}$$
$$\Delta_3 = \{[a:3\ \alpha\ \ 6],[b:5\ \alpha\ \ 6],[c:6\ \alpha\ \ 7]\},$$
$$A_1 = \{(2,2),(3,3),(\varepsilon,4),(4,5),(5,6)\},\quad A_2 = \{(2,2),(\varepsilon,3),(3,4),(4,5),(5,6),(6,7)\}$$
$$A_1 \bullet A_2 = \{(2,2),(\varepsilon,3),(3,4),(\varepsilon,5),(4,6),(5,7)\}\quad I_1 = \{[b:4\ \alpha\ \ 5]\},\quad I_2 = \{[a:3\ \alpha\ \ 6]\}$$

We also compute the composition of A_1 and A_2 which transforms the program points of V_1 in program points of V_4 as if only one composed delta had been applied.

The generic element of an interference set, as discussed, is a variable dependency, i.e. a variable and its effective definition for a use made thereof. It therefore defines a reference to two program points, the one in which the variable is defined and the one in which the variable is used. A variable definition associated with a program point, as in this case, is a valid candidate for a slicing criterion. A *forward slice* of such a criterion will compute exactly the set of program points affected by such a definition, i.e. the set of program points corresponding to that part of code on which the change had impact.

Since in general a set of program points is produced for each interference, we define the set S, called *impact set* as

$$S = \bigcup_{i \in I} FS(V,i)$$

i.e. the union set of all the impact sets created by computing forward slices of a version V of the code, using each interference in an interference set as the slicing criteria. When impact sets are computed, the version that is being sliced is the version produced by the change. For our example:

$$S_1 = S_{\delta_1} = \bigcup_{i \in I_1} FS(V_2,i) \qquad S_2 = S_{\delta_2} = \bigcup_{i \in I_2} FS(V_4,i)$$

The domains from which the elements of each set are drawn therefore are not the same. While the first impact set will be made of program points of V_2, the second impact set will accommodate program points of V_4. We define a particular composition of an *A*-application as

$$A(S_\delta) = \{p : \forall q \in S_\delta, (q,p) \in A\}$$

with proper extensions for composed applications.

The non-interference condition for adjacent deltas will thus be the following.

$$A(S_{\delta_1}) \cap S_{\delta_2} = \varnothing \qquad (NI_\delta)$$

i.e. the set of program points impacted by the original change and the set of program points affected by the second change ought to be separated.

The General Case: Non-Adjacent Changes

Fig. 6 shows the flow graph for the general case of non-adjacent changes. In this case the number of versions involved grows to four, but we must also adjust the definition of semantic interferences between changes.

	V_1	**V_2**	
1:	**program**	**program**	
2:	a:=2	a:=2	
3:	b:=&a	b:=&a	
4:	c:=a+2	a:=3	🡐
5:	d:=*b	c:=a+2	
6:	e=c*d	d:=*b	
7:	write e	e:=c*d	
8:	**end**	write e	
9:		**end**	

	V_3	**V_4**	
1:	**program**	**program**	
2:	a:=2	a:=2	
3:	b:=&a	b:=&a	
4:	a:=3	a:=3	
5:	c:=a+2	a:=4	🡐
6:	c:=4	c:=a+2	
7:	d:=*b	c:=4	
8:	e:=c*d	c:=5	🡐
9:	write e	d:=*b	
10:	**end**	e:=c*d	
11:		write e	
12:		**end**	

Fig. 10 - Two generic deltas involve four different versions of code. In general, the differences between the intermediate versions will be consistent, especially when the deltas are greatly separated in time. In the example,δ_2 inserts two lines and while both manifestly interfere with V_3, only the insertion of line 5 interferes with the changes made in δ_1.

[8] In this case the artificial delta δ_ε is irrelevant since V_2 and V_3 will be identical

When two deltas are not adjacent, the intermediate versions V_2 and V_3 will usually be very different. Specifically, V_3 will often interfere semantically with V_4 accordingly to NI_v because of the many deltas that may not have been parallel in the original context and that occurred in the lapsed time. Since the latter delta, which must be guaranteed not to interfere with the former delta, starts from a consolidated version V_3, it is reasonable to assume that the interferences introduced by V_3 over V_2 have been tested, accepted and integrated in the system.

These interferences, independently from whether or not they conflict with the intended changes made in δ_1, should be intentionally prevented from being the trigger of a positive assessment of interference between δ_1 and δ_2. With this rationale in mind, we define an operation between interference sets: the ***variable subtraction*** operation between interference sets, indicated by $\otimes$ is therefore defined as follows.

Let I_1 and I_2 be two interference sets. [9]

$$I_1 \otimes I_2 = \{[v : d \;\alpha\; u] : [v : d \;\alpha\; u] \in I_1 \wedge (\forall (d_2, u_2), [v : d_2 \;\alpha\; u_2] \notin I_2)\}$$

An example will greatly simplify the understanding of this very simple operation.

$$\begin{aligned} I_1 &= \{[a:1\;\alpha\; 3],[a:4\;\alpha\; 5],[b:2\;\alpha\; 3],[b:6\;\alpha\; 7],[c:7\;\alpha\; 8]\} \\ I_2 &= \{[b:2\;\alpha\; 8],[b:9\;\alpha\; 10],[b:9\;\alpha\; 12],[c:6\;\alpha\; 7],[d:8\;\alpha\; 9]\} \\ I_1 \otimes I_2 &= \{[a:1\;\alpha\; 3],[a:4\;\alpha\; 5]\},\quad I_2 \otimes I_1 = \{[d:8\;\alpha\; 9]\} \end{aligned}$$

In other words the operation deletes from the first interference set the dependencies defined over variables for which some dependency is also defined in the second operand. I_2, in the example above, has dependencies defined for b and c and so does I_1. Therefore the dependencies relative to these variables are removed from I_1. The example also shows clearly that this operation is not commutative.

As it is shown in the flow chart of Fig. 7, the process of detecting semantic interferences between generic changes is a three step process. First, three interference sets are determined. These three sets represent the semantic interferences introduced by δ_1 and δ_2 by modifying V_1 and V_3 and the set of interferences introduced by the combination δ_ε of all changes submitted between δ_1 and δ_2.

In a second step, the set of interferences caused by δ_2 is $\otimes$-filtered of those interferences which overlap with interferences introduced by any of the intermediate deltas.

$$I_2 = I_2 \otimes I_\varepsilon$$

By means of this operation we are indeed avoiding to look at those variables whose dependencies have already been affected by some change which occurred before δ_2. Such changes have been submitted at some point in the past and yet they have been assimilated in the version history and accepted (admittedly, we do not know whether they interfered or not with δ_1 and if they did, if the did so with good reason); therefore we argue that any further change that affects semantically what has already been affected by some δ_ε cannot constitute a semantic interference of δ_2 on δ_1.

Applying this procedure to the example of Fig. 11, we compute the four dependency sets,

$$\begin{aligned} \Delta_1 &= \{[a:1\;\alpha\; 3],[a:2\;\alpha\; 4],[a:2\;\alpha\; 5],[b:3\;\alpha\; 5],[c:4\;\alpha\; 6],[d:5\;\alpha\; 6],[e:6\;\alpha\; 7]\} \\ \Delta_2 &= \{[a:1\;\alpha\; 3],[a:4\;\alpha\; 5],[a:4\;\alpha\; 6],[b:3\;\alpha\; 6],[c:5\;\alpha\; 7],[d:6\;\alpha\; 7],[e:7\;\alpha\; 8]\} \\ \Delta_3 &= \{[a:1\;\alpha\; 3],[a:4\;\alpha\; 5],[a:4\;\alpha\; 7],[b:3\;\alpha\; 7],[c:6\;\alpha\; 8],[d:7\;\alpha\; 8],[e:8\;\alpha\; 9]\} \\ \Delta_4 &= \{[a:1\;\alpha\; 3],[a:5\;\alpha\; 6],[a:5\;\alpha\; 9],[b:3\;\alpha\; 9],[c:8\;\alpha\; 10],[d:9\;\alpha\; 10],[e:10\;\alpha\; 11]\} \end{aligned}$$

and the three A-applications that transform program points from one version to the next,

$$\begin{aligned} A_1 &= \{(1,1),(2,2),(3,3),(\varepsilon,4),(4,5),(5,6),(6,7),(7,8)\} \\ A_\varepsilon &= \{(1,1),(2,2),(3,3),(4,4),(5,5),(\varepsilon,6),(6,7),(7,8),(8,9)\} \\ A_2 &= \{(1,1),(2,2),(3,3),(4,4),(\varepsilon,5),(5,6),(6,7),(\varepsilon,8),(7,9),(8,10),(9,11)\} \end{aligned}$$

The four dependency sets show some particularities. The different versions of the program of Fig. 11 show for the first time in our analysis the use of pointers. We mentioned how pointers and pointer analysis affect the classification of semantic interferences and how special operations with these objects greatly affect the degree of side-effects that can be manifest in code and the difficulty, therefore, of detecting interferences. If we look at V_1 as the version we refer to, we notice that the variable a has a dependency from program point (1) to program point (3), in which variable b is defined as a pointer to a. In the model we present, we use program point (1) to indicate the allocation of local variables on the stack along with their respective memory addresses. What is used at line 3 therefore is a memory address that was defined at such a program point, in order to be assigned to b. Under the same assumptions, we have two further dependencies, for a and for b, from program points (2) and (3) respectively, to program point (5). At line 5, only variable b is explicitly mentioned. Nonetheless, by dereferencing b, a use of both its direct value (defined at (3)) and indirect value (the value of a, defined at (2)) is made. This particularity is present in all further versions and is a characteristic of how we describe dependencies when pointers are involved.

Following the flow diagram of Fig. 7 and the process that we described this far, we compute the three interference sets, I_1, I_ε, and I_2.

$$I_1 = \{[a:4\;\alpha\; 5],[a:4\;\alpha\; 6]\},\; I_\varepsilon = \{[c:6\;\alpha\; 8]\},\; I_2 = \{[a:5\;\alpha\; 6],[a:5\;\alpha\; 9],[c:8\;\alpha\; 10]\}$$

We can easily see that the cumulative change δ_ε from V_2 to V_3 introduces a semantic interference on variable c. The potentially interfering delta in our inspection process (δ_2) also interferes on variable c. Such interference should not be considered a possible cause of conflict between δ_2 and δ_1 as c has been already

[9] This formula reads as following: *the variable subtraction set between two interference sets is an interference set whose members are members of the first operand, for which there are no members of the second operand set that specify a dependency for the same variable.*

interfered upon by changes that – one way or the other – have been successfully integrated in the version history. Following once again the process described in Fig. 7 we $\otimes$-subtract the set of intermediate interferences from the interferences introduced by δ_2.

$$I_2 = I_2 \otimes I_\varepsilon = \{[a:5\alpha\ 6],[a:5\alpha\ 9]\}$$

Looking at δ_2 and at the modifications it makes to the code, and considering the previous versions altogether, we recognize that while the insertion of *a:=4* disrupts the intended flow on the original data successors of *a:=3*, the same cannot hold for the interference on the variable c, as the data flow on this variable's definition's successors has already been disrupted by the cumulative change δ_ε. If we were trying to investigate the interferences between δ_2 and that particular change that originally changed the data flow for c we might be likely to reach the conclusion that the two deltas do indeed interfere; nonetheless in our particular case, the effects of δ_ε have made so that the impact of δ_2 on δ_1 is reduced. We indeed expect our technique to show that, only the addition of a:=4 introduced a semantic conflict with δ_2.

We now ought to compute the impact that each interference set has on the global system dependency graph. The first impact set, S_1 is created as the union set of the forward slices of V_2 when each interference in I_1 is used as a slicing criterion.

```
1: program
2:   a:=2
3:   b:=&a
4:   a:=3
5:   c:=a+2
6:   d:=*b
7:   e:=c*d
8:   write e
9: end
```

$$I_1 = \{[a:4\alpha\ 5],[a:4\alpha\ 6]\} \rightarrow S_1 = \{5,6,7,8\}$$

In this case, since the two interferences are related to the same definition program point, the impact set and the only forward slice computed, coincide. In general, a set of program points for each interference set will be produced.

Similarly for S_2,

```
1:   program
2:     a:=2
3:     b:=&a
4:     a:=3
5:     a:=4
6:     c:=a+2
7:     c:=4
8:     c:=5
9:     d:=*b
10:    e:=c*d
11:    write e
12:  end
```

$$I_2 = \{[a:5\alpha\ 6],[a:5\alpha\ 9]\} \rightarrow S_2 = \{6,9,10,11\}$$

Naturally, the example that we are discussing is a very simple one. In general though, the slicing operation will reveal more subtle data dependencies and less obvious impact sets. As extensions to this work we plan to adapt and analyze more complicated and interesting examples. It should be easy to imagine though that the interferences introduced by two deltas can be completely unrelated and the respective impact sets completely separated. In this case we deem that the two changes do not conflict with each other. In our example though,

$$A = A_\varepsilon \cdot A_2 = \{(1,1),(2,2),(3,3),(4,4),(\varepsilon,5),(5,6),(\varepsilon,7),(\varepsilon,8),(6,9),(7,10),(8,11)\}$$
$$A(S_1) = \{6,9,10,11\},\ S_2 = \{6,9,10,11\},\ A(S_1) \cap S_2 = \{6,9,10,11\} \neq \varnothing$$

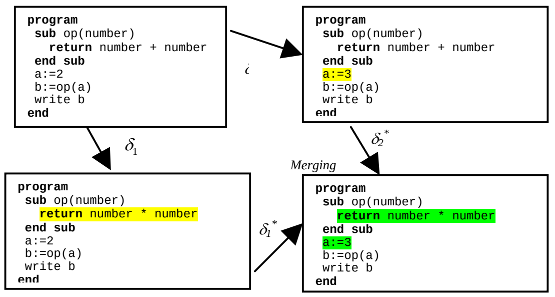
The two impact sets are not separated – in our example, as a matter of fact they completely overlap – showing that the considered interferences have impact on common program points. We decide that δ_2 interferes with δ_1 under the assumptions and definitions used this far.

Optimistic CMS and Concurrent Changes

While two deltas that are submitted for integration in a concurrency situation are simpler to classify as parallel, they also are rather counter-intuitive to define in terms of inter-deltas interference.

While being not simpler than the sequential one, the concurrent case is not particularly harder. There still are four versions involved: *the original version, two concurrent modified versions, and a unified version produced by a chosen merging algorithm.* These versions are not linearly ordered on a time scale, and four deltas $(\delta_1, \delta_2, \delta_1^*, \delta_2^*)$ govern the variations between the versions.

First, when concurrent changes are made to the code, a merging strategy is necessary. At any given time there ought to be only one consistent version of the code which is allowed to be modified, and all modifications stemming from the same reference version are considered concurrent.



```
program
 sub op(number)
   return number + number
 end sub
 a:=2
 b:=op(a)
 write b
end
```

```
program
 sub op(number)
   return number + number
 end sub
 a:=3
 b:=op(a)
 write b
end
```

```
program
 sub op(number)
   return number * number
 end sub
 a:=2
 b:=op(a)
 write b
end
```

```
program
 sub op(number)
   return number * number
 end sub
 a:=3
 b:=op(a)
 write b
end
```

Fig. 11 – Merging versions which do not present local conflicts but affect each other impact slices, may produce a version that defies the original changes or conflicts with the behavior expected by each or either one of the developers that submitted the changes.

Several merging strategies and algorithms have been proposed [9] and while some involve looking at syntactic conflicts and slicing for delineating local interferences in the program flow, they produce integrated versions which might include elements that defy the original intents of either one or both the authors of the concurrent versions. Fig. 12 shows an example of such a phenomenon.

We believe that deciding whether or not two concurrent changes interfere is equivalent to deciding whether or not the merged version interferes semantically with them.

The last flow block of the rightmost branch of Fig. 7 incorporates this duality. We argue that δ_1 interferes with the concurrent change δ_2 if and only if the respective changes necessary to construct the merged version starting from V_1 and V_2 interfere semantically with either one of the original deltas.

In symbols, δ_1 and δ_2 are concurrent changes, δ_1^* and δ_2^* are the changes that bring each concurrent version in the merged one, and the symbol $<>$ indicates semantic interference (see Fig. 12),

$$\delta_1 <> \delta_2 \Leftrightarrow \left(\delta_1^* <> \delta_1\right) \vee \left(\delta_2^* <> \delta_2\right)$$

Note that while the leftmost part of the above expression is a commutative interference between concurrent changes, the interference relations contained in the rightmost part of the equivalence are non commutative interferences between adjacent time-ordered changes.

One could easily verify that the process sketched in Fig. 6 realizes the equivalence above. In doing so, one should remember that A_1^* is the application that links program points of V_i to program points of the merged version V_U.

Conclusion

In this paper, we showed how parallel changes may interfere semantically, subverting intended modifications and causing unintended behavior. We described some ways in which software changes may interact and interfere at a semantic, rather than syntactic, level, and we showed that semantic interferences derive from intrusions in the established data flow of an execution slice, through *def-use overlapping*. We then described a technique based on code slicing and dataflow analysis to detect semantic conflicts at a local level among parallel changes. We extended the notion of semantic interferences between versions of source code to that of conflicts between changes and we defined a formal notion of parallel changes as modifications to the code that work against the intent of the author of the original modification.

For future directions of this research, we plan to build a prototype of the SCA [19], to perform empirical studies [20] to evaluate the efficacy of our technique and its performance under different sets of environmental conditions and constraints, and to use the prototype to determine the extent of both interfering and non-interfering parallel changes.

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